WAVES
Côte d'Azur

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A transdisciplinary conference on nonlinearity and disorder in wave phenomena, from microscopic to physiologic and astronomical scales

Plenary speakers

- **Alain Aspect**, Institut d'Optique, Université Paris Saclay
- **Jacqueline Bloch**, Centre de Nanosciences et de Nanotechnologies, Palaiseau
- **John Bush**, Massachusetts Institute of Technology, Cambridge
- **Claudio Conti**, University Sapienza, Rome
- **Mathias Fink,** Institut Langevin, Paris
- **Eva Kanso**, University of Southern California, Los Angeles
- **Evgenii Kuznetsov**, Landau Institute for Theoretical Physics, Chernogolovka
- **Stéphane Nonnenmacher**, Université Paris-Sud
- **Annick Pouquet**, Center for Atmospheric Research, Boulder
- **Laure Saint-Raymond**, Ecole Normale Supérieure de Lyon
- **Evelyne Sernagor,** Newcastle University
- **Jean-Marc Vanden Broeck**, University College London

Topical meetings

- Nonlinear waves and turbulence in space plasmas
- Nonlinear waves at interfaces
- Nonlinear waves in biology
- Partial differential equations and modelization
- Spatio-temporal phenomena in nonlinear optics
- Wave phenomena in disordered systems

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Contents

Plenary sessions

Hanbury Brown-Twiss, Hong-Ou-Mandel, and other landmarks in quantum optics : from photons to atoms

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Keywords: *quantum optics, entanglement, bell's inequalities*

The second quantum revolution is based on entanglement, discovered by Einstein and Schrödinger in 1935. Its extraordinary character has been experimentally demonstrated by landmark experiments in quantum optics.

At Institut d'Optique, we are currently revisiting these landmarks using atoms instead of photons, and after the observation of the atomic HBT [1] and HOM effects [2], we are progressing towards a test of Bell's inequalities with pairs of momentum entangled atoms [3].

This talk will be an opportunity to know "Everything you always wanted to know about HBT, HOM, Bell… (but were afraid to ask)."

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[2] Lopes, R., Imanaliev, A., Aspect, A., Cheneau, M., Boiron, D., and Westbrook, C. I. (2015). Atomic Hong-Ou-Mandel experiment. Nature, 520(7545), 66-68.

[3] P. Dussarrat, M. Perrier, A. Imanaliev, R. Lopes, A. Aspect, M. Cheneau, D. Boiron, and C. I. Westbrook, "Two-Particle Four-Mode Interferometer for Atoms," Physical Review Letters 119 (17) (2017).

Quantum fluids of light in semiconductor lattices

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Keywords: *light-matter interaction, quantum simulation, non-linear optics, semiconductor*

When confining photons in semiconductor lattices, it is possible deeply modifying their physical properties. Photons can behave as finite or even infinite mass particles, photons inherit topological properties and propagate along edge states without back scattering, photons can become superfluid and behave as interacting particles. These are just a few examples of properties that can be imprinted into fluids of light in semiconductor lattices. Such manipulation of light present not only potential for applications in photonics, but great promise for fundamental studies. During the talk, I will illustrate the variety of physical systems we can emulate with fluids of light by presenting a few recent experiments: a photonic benzene molecule that emits helical photons, a photonic 1D lattice with topological edge states and photonic graphene with exotic Dirac cones. Perspectives in terms of quantum simulation will be discussed.

Pilot-wave hydrodynamics

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Keywords: *walking droplets, pilot waves, quantum analogs*

Yves Couder and coworkers in Paris discovered that droplets walking on a vibrating fluid bath exhibit several features previously thought to be exclusive to the microscopic, quantum realm. These walking droplets propel themselves by virtue of a resonant interaction with their own wave field, and so represent the first macroscopic realization of a pilot-wave system of the form proposed for microscopic quantum dynamics by Louis de Broglie in the 1920s. New experimental and theoretical results allow us to rationalize the emergence of quantum-like behavior in this hydrodynamic pilot-wave system in a number of settings, and explore its potential and limitations as a quantum analog.

Waves and complexity, towards deep neural networks with light

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Keywords: *nonlinear waves, disorder, topology, machine learning*

Complexity is a notion that has several denotations. When applied to wave propagation, firstly, we tackle with Anderson localization, then we consider statistical phenomena, as rare events, and lastly, we resort to strongly interacting systems, with frustration and nonlinearity, as in turbulence and spin glasses. Surprisingly - or not - nonlinear optics cover the whole aspects of this journey in complexity, leading to impressive results as the observation of replica-symmetry breaking. The tour also includes the more recent topological concepts, which are useful in classifying extreme waves, like shocks, rogues, and soliton gases. Nowadays, one reaches the world of machine learning and artificial intelligence, as the highly nonlinear and disordered models have a remarkable rule in large-scale deep neural networks. One can use waves to solve computationally demanding tasks, as in the optical Ising machines. Reservoir computing in multiple scattering media may open the way to new applications in quantum optics and biomedicine. In my talk, I will review all these aspects linking waves and complex systems.

Wave Control and Antenna Radiation Mechanism in "Time Materials"

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Keywords: *time material, time reversal, radiation*

Photonic crystals and Metamaterials are made from assemblies of multiple elements usually arranged in repeating patterns at scales of the order or smaller than the wavelengths of the phenomena they influence. Because time and space play a similar role in wave propagation, wave propagation is affected as well by spatial modulation or by time modulation of the refractive index. Here we emphasize the role of time modulation. We show that sudden changes of the medium properties generate instant wave sources that emerge instantaneously from the entire wavefield and can be used to control wavefield and to revisit the way to create time-reversed waves. Experimental demonstrations of this approach will be presented. Periodic time manipulations can also be studied in order to extend the concept of photonic crystals in the time domain. The difference between periodic time modulation and periodic spatial modulation will be emphasized and the way an antenna radiates in these two kind of situation will be discussed.

Ciliary Waves

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Keywords: *fluid dynamics, biological system, cilia*

Motile cilia are micron-scale hair-like protrusions from epithelial cells that beat collectively to transport fluid. Individual cilia are driven into oscillatory motion by dynein molecular motors acting on an intricate structure of microtubule doublets referred to as the central axoneme. On the tissue level, cilia beat in a coordinated way and serve diverse biological functions, from mucociliary clearance in the airways to cerebrospinal fluid transport in the brain ventricles. Yet, the relationship between the structure and organization of ciliated tissues and their biological function remains elusive. Here, I will present a series of physics-based models that take into account minimal cilia features in order to examine: (1) the emergence of self-sustained oscillations in individual cilia, (2) the coordinated beating of neighboring cilia, and (3) the role of cilia-driven flows in particle transport, mixing, capture and filtering. I will conclude by commenting on the implications of these models to understanding the biophysical mechanisms underlying the interaction of ciliated tissues with microbial partners.

Folding in fluids and MHD

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Keywords: *vorticity, mhd*

The formation of the coherent vortical structures in the form of thin pancakes for three-dimensional flows and quasi-shocks of the vorticity in two-dimensional turbulence is studied at the high Reynolds regime when, in the leading order, the development of such structures can be described within the Euler equations for ideal incompressible fluids. Numerically and analytically on the base of the vortex line representation we show that compression of such structures and respectively increase of their amplitudes are possible due to the compressibility of the vorticity ω in the 3D case and of the di-vorticity field $\mathbf{B} = \mathrm{rot}\,\omega$ for 2D geometry. It is demonstrated that, in both cases, this growth has an exponential behavior and can be considered as folding (analog of breaking) for the divergence-free fields of both vorticity and di-vorticity. At high amplitudes this process in 3D has a self-similar behavior connected the maximal vorticity and the pancake width by the relation of the universal type [1]: $\omega_{\max} \propto l^{-2/3}$. For the 2D turbulence numerically it is shown that $B_{max}(t)$ depends on the quasi-shock thickness according to the same power law: $B_{max}(t) \sim \ell^{-\alpha}(t)$, where the exponent $\alpha \approx 2/3$, that indicates also in favor of folding for the di-vorticity field [2]. Appearance of the $2/3$-law in fluids is a consequence of frozenness for both vorticity and di-vorticity fields. In this talk we consider also the problem of generation of strong magnetic fields in MHD due to the folding mechanism predicted in [3]. On our opinion, the formation of magnetic filaments in the convective zone of the Sun can be explained by this mechanism. At the end of this talk we discuss the role of folding structures in the formation of the Kolmogorov spectrum in 3D and the Kraichnan spectrum for two-dimensional turbulence.

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geometrical properties of the vortex line representation, Phys. Fluids **30**, 095104-13 (2018).

[2] E.A. Kuznetsov and E.V. Sereshchenko, *Folding in two-dimensional hydrodynamic turbulence*, Pis'ma ZhETF, **109**, 231 – 235 (2019) [JETP Letters, **109**, issue 4 (2019), DOI 10.1134/S0021364019040039].

[3] E.A. Kuznetsov, T. Passot and P.L. Sulem, *Compressible dynamics of magnetic field lines for incompressible MHD flows*, Physics of Plasmas, **11**, 1410-1415 (2004).

Waves in chaotic cavities: dispersion and delocalization

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Keywords: *quantum chaos, open wave chaos, eigenmodes concentration, semiclassical analysis*

Linear (scalar) waves propagating inside a closed cavity resonate a certain frequencies, determined by the shape of the cavity: at these frequencies the waves exhibit stationary modes (eigenmodes of the Laplacian in the cavity). At high frequencies the structure of these eigenmodes may be complicated and diverse; it is strongly influenced by the properties of the ray dynamics inside the cavity (billiard dynamics).

We will address the situations where this ray dynamics is chaotic, which defines the realm of Wave (or Quantum) Chaos. I will explain how the two main ingredients of chaos (instability of trajectories, and infinite recurrence of the trajectories) lead to a fast dispersion of the waves, and the impossibility for the stationary modes to localize (concentrate) on a small region of the cavity; most eigenmodes rather spread uniformly all over the cavity.

This fast wave dispersion is also at work when "open" the chaotic cavity. The stationary modes are then replaced by metastable (or resonant) modes with finite lifetimes. We will show how the dispersion induced by the chaotic ray dynamics influences the distribution of the lifetimes, and thereby the behaviour of the waves at large times.

Eddies and waves in rotating stratified turbulence

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Keywords: *inertia-gravity waves, rotation, stratification, turbulence, atmosphere*

In a stratified fluid, the velocity field couples to density fluctuations, supporting inertia-gravity waves in the presence of rotation, with an anisotropic dispersion relation, and leading to a variety of turbulence regimes resulting from the interactions between nonlinear eddies and waves. What are the delimiting factors of these regimes, and what differentiate them? Several issues will be briefly discussed, such as structures which lead to dissipation related to dual energy cascades.

Using simple classical models of turbulence, it can be demonstrated phenomenologically and numerically that strong localized instabilities lead to an effective dissipation in rotating stratified turbulence which is proportional to the Froude number (ratio of the wave period to the eddy turnover time). It is correlated to a high kurtosis of the vertical velocity, as found e.g. in the atmosphere. This law also governs the ratio of the amount of energy going, in a constant-flux solution, to the large scales because of rotation to that going to the small scales because of stratification. It thus determines the mixing efficiency in such flows, and it allows to bridge the gap between strong-wave and strong-eddy flow systems in a simple manner.

Internal waves in a domain with topography

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Keywords: *internal waves, continous spectrum, cascades*

Stratification of the density in an incompressible fluid is responsible for the propagation of internal waves. In domains with topography, these waves exhibit interesting properties. In particular, numerical and lab experiments show that in 2D these waves concentrate on attractors for some generic frequencies of the forcing (see Dauxois et al). At the mathematical level, this behavior can be analyzed with tools from spectral theory and microlocal analysis.

Changing synaptic networks during the ontogeny of neonatal retinal waves

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Keywords: *neonatal developement, action potential, retina, vision, plasticity*

In the developing retina, spontaneous waves sweep across the layer of retinal ganglion cells (RGCs), the output cells of the retina. Experimental evidence indicates that retinal waves play a crucial role in guiding the refinement of visual connectivity. Using a large-scale, high-density array of 4,096 electrodes covering the RGC layer in the neonatal mouse, we have characterized wave spatiotemporal properties at unprecedented resolution from postnatal day (P) 2 to P13 (eye opening), when they disappear, replaced by visual experience. Wave dynamics undergo profound developmental changes. From initial gap junction communication during late gestation (Stage 1), they become controlled by directly interconnected cholinergic starburst amacrine cells (SACs), the only retinal cholinergic cells (Stage 2 waves). Stage 2 waves are initially wide spreading with random propagation patterns and low cellular recruitment. Around P6-7, they begin to shrink because of emerging GABAergic inhibitory connections and become denser, with many more immediate neighbouring RGCs recruited within waves. Direct connections between SACS withdraw at P10. Waves become then driven by newly formed glutamatergic connections originating from bipolar cells (Stage 3 waves, P10-eye opening). Recent observations from our lab are challenging the hypothesis that Stage 2 waves are driven by SACs. Indeed, we found a "novel" transient population of cholinergic cells present from P2-9. These cells co-exist with SACs, but they are larger, forming tight clusters in an annulus pattern around the optic disc at P2-3. That annulus expands towards the periphery with development, until the cell clusters disappear at P10, coinciding with the disappearance of Stage 2 waves, suggesting that they may represent a transient hyper-excitable cellular hub responsible for the generation of Stage 2 waves. In support, we found that wave origins follow a centrifugal pattern between P2-P9 as well. Stage 3 glutamatergic waves completely change spatiotemporal patterns, gradually becoming activity hotspots that tile the entire retinal surface. We propose that Stage 2 waves are important for guiding the establishment of eye-specific segregation and refinement of topographic maps in retinal central targets. Stage 3 waves, on the other hand, may be important for carving local retinal networks underlying the establishment of retinal receptive fields that become functional immediately after eye opening.

Hydroelastic waves and related problems

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Keywords: *hydroelastic, waves*

Nonlinear waves propagating at the surface of a fluid bounded above by an elastic sheet are considered. The fluid is assumed to be incompressible and inviscid and the flow to be irrotational. Gravity is included in the dynamic boundary condition. This configuration can be viewed as a model for waves propagating under an ice sheet. The understanding of the properties of these waves is important in polar regions in assuring the safety of human activities, such as transportation over ice sheets. The mathematical formulation is similar to that of the classical problem of gravity capillary waves. The main difference is that the curvature term in the dynamic boundary condition is now replaced by a nonlinear term involving higher derivatives of the curvature of the free surface. This allows for the existence of new types of waves. We will show how to obtain fully nonlinear solutions by boundary integral equation methods. Both two-dimensional and three-dimensional waves will be studied. Periodic waves, solitary waves, generalised solitary waves and dark solitons are among the solutions to be presented.

Nonlinear Waves and Turbulence in Space Plasma

Exact relations in fully developed turbulence: energy cascade rate from the MHD to the ion-scales

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Keywords: *turbulence, magnetohydrodynamics, hall effect*

Exact laws derived for incompressible magnetohydrodynamics (IMHD) turbulence have been widely used to gain insight into the problem of solar wind (SW) heating through the estimation of the turbulent energy cascade rate. While the incompressibilty assumption can, to some extent, be justified to address large scale SW turbulence where alfvénic fluctuations dominate, it is likely to fail to accurately describe sub-ion scale physics, as well as other more compressible plasmas such as planetary magnetospheres or the interstellar medium. Here, we will review a set of recent analytical and numerical results obtained for compressible flows within the isothermal closure. First, we will discuss the new exact law derived for compressible MHD (CMHD) and emphasize the major differences with IMHD, in particular the role of the mean (background) magnetic field and plasma density. In the next step, we will discuss the extension of the laws to compressible Hall-MHD (CHMHD) and discuss the physics brought up by the new terms due to the Hall current. The incompressiblity limit is further studied using a more compact form that include only increments of the turbulent fields and compared to previous derivations. The validation of the various exact laws are done using 3D direct numerical simulations (GHOST code for the compressible flows and TURBO for the incompressible models). Potential applications of the models to estimate the energy cascade rate of turbulence over a broad range of scales that span both the inertial and sub-ion (dispersive) ranges in spacecraft data will be discussed.

Runaway solar-wind electrons and space plasma turbulence

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Keywords: *solar wind, electron distribution function, plasma turbulence*

The solar wind contains fast, suprathermal electrons that stream from the sun along the Parker-spiraled magnetic field lines. These electrons experience very weak Coulomb collisions and they get collimated in a narrow beam (strahl). When Coulomb collisions are not efficient, the strahl is broadened by interactions with plasma turbulence. We argue that at high energies, the strahl electrons can efficiently interact with whistler waves. We demonstrate how pitch-angle scattering by whistler turbulence can be incorporated into the kinetic theory of electron strahl broadening. By measuring the strahl width, one can estimate the parameters of whistler turbulence.

The electron vortex magnetic hole and its relatives

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Keywords: *plasma waves and structures, electron scale phenomena, plasma simulations, space plasma observations*

Two-dimensional full particle simulations of turbulence led to the discovery of the electron vortex magnetic hole (Haynes et al., Physics of Plasmas 22, 012309 (2015); https://doi.org/10.1063/1.4906356), a coherent plasma structure with cylindrical symmetry identified by a strong dip in the magnetic field driven by a population of trapped electrons with petal-like orbits. Subsequently, Cluster and MMS observations in the plasmasheet and magnetosheath have confirmed that such structures, with scales of order several electron gyroradii, exist and have the predicted spatial pattern in the electron distribution function. The properties of these coherent nonlinear structures are explored, and the observational evidence is summarized. In addition, other related structures - magnetic dips and bumps - with similar cylindrical symmetry are discussed in the context of semi-analytical Vlasov solutions. The possible role of such structures in turbulence at electron scales is also discussed.

Study of the dissipation scale in collisionless plasma turbulence

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Keywords: *reconnection, turbulence, vlasov equation, dissipation*

It has been observed experimentally the occurrence of a new process, namely electron-only reconnection, where the reconnection dynamics is driven only by electrons (e-rec-only) [1]. Recently, a theoretical study in the context of plasma magnetized turbulence has given evidence about the possibility to drive e-rec-only by fluctuations at scales of the order of the ion scale length [2] (see Faganello abstract, this Conference). By considering two Vlasov simulations of magnetized plasma turbulence where "standard" reconnection or e-rec-only separately occur, we make a compared study of the turbulence statistical properties, in particular of the structure functions in order to separate the contribution of the ions at the so-called dissipative scale. We found, in agreement with experimental [3] and theoretical [4] studies a non-Gaussian statistics in both the fluid and sub-ion range with a transition from an intermittent to a self-similar behavior. Our main finding here is that the transition is observed at a scale length of the order of several de instead that around di independently from the ion dynamics. The transition seems to be driven mainly by the small scale electron dynamics around the reconnection structures where the electron inertial terms become non-negligible.

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[3] Kiyani et al., Global Scale-Invariant Dissipation in Collisionless Plasma Turbulence, Phys. Rev. Lett., 2009.
[4] E. Leonardis et al., Multifractal scaling and intermittency in hybrid Vlasov-Maxwell simulations of plasma turbulence, Physics of Plasmas, 2016.

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The good, the bad and the ugly: kinetic plasma turbulence in a 3D3V phase space

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Keywords: *kinetic plasma turbulence, space plasmas, solar wind, numerical simulations, 3d3v phase-space dynamics*

Turbulence and kinetic processes in magnetized space plasmas have been extensively investigated over the past decades via theoretical models, *in-situ* spacecraft measurements, and numerical simulations. In particular, multi-point high-resolution measurements from the *Cluster* and *MMS* space missions brought to light an entire new world of kinetic processes, taking place at the plasma microscales, and exposed new challenges for their theoretical interpretations. A long-lasting debate concerns the nature of ion and electron scale fluctuations in solar-wind turbulence and their dissipation via collisionless plasma mechanisms. Alongside observations, numerical simulations have always played a central role in providing a test ground for existing theories and models.

In this talk, the current advances achieved with 3D3V kinetic simulations, as well as the main questions left open (or raised) by these studies will be discussed. This includes assessing the spectral properties and intermittency of turbulent fluctuations in the sub-ion range[1] and the existence of an anisotropic turbulent cascade involving the entire phase space[2] (i.e., a cascade of free energy that is anisotropic with respect to the ambient magnetic field in both real and velocity space). Finally, also preliminary combined results from recent numerical studies will be presented to assess similarities and/or differences in the properties of kinetic-scale plasma turbulence, estimated from these state-of-the-art 3D kinetic simulations [1,2,3,4].

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Kinetic Turbulence and Damping in the Magnetosheath

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Keywords: *turbulence, magnetosheath, damping, mms*

With the launch of the MMS spacecraft a few years ago, we now have the capability to study turbulence in the magnetosheath at higher resolution than ever before. Here, I will present recent work using the MMS data to investigate the nature of kinetic turbulence at electron scales and the nature of the damping mechanisms of the turbulence at these scales. Focussing on an interval of magnetosheath data near the magnetopause, the nature of the turbulence was found to change as the electron inertial scale is reached, transitioning to a regime of inertial kinetic Alfven turbulence - I will present observations and a theoretical model for this turbulence. I will also describe our recent application of a field-particle correlation technique to the MMS data, which enables the energy transfer in velocity space to be determined. The results of this are consistent with the presence of electron Landau damping in the kinetic range.

Electron-only magnetic reconnection in plasma turbulence

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Keywords: *magnetized turbulence, magnetic reconnection, vlasov simulations, electron-magnetohydrodynamics*

Recently MMS satellites measured a turbulent regime in the solar wind plasma, downstream of the Earth's bow shock, where magnetic reconnection acting in all the observed current sheets (at the electron skin depth scale) is completely ruled by electrons. These "electron-only" reconnection events are characterized by electron jets unaccompanied by ion outflows, contrary to the standard picture of magnetic reconnection. Hybrid-Vlasov-Maxwell simulations of magnetized plasma turbulence, including non-linear electron inertia effects in the generalized Ohm.s law, are able to reproduce this behavior as soon as the fluctuation energy is injected at scales close the ion-kinetic scales. In this case ions turn out to be de-magnetized over the whole numerical domain while electrons follow a nearly electron-magnetohydrodynamic evolution leading to electron-only reconnection. The injection scale seems to be the control parameter of this behavior: if energy is injected at larger scales ion outflows do form in reconnecting sheets.

Interpreting spacecraft observations of plasma turbulence with kinetic numerical simulations in the low electron beta regime

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Keywords: *plasma turbulence, space physics, hybrid simulations, kinetic alfvén waves*

We present numerical results from high-resolution hybrid and fully kinetic simulations of plasma turbulence, following the development of the energy cascade from large magnetohydrodynamic scales down to electron characteristic scales. We explore a regime of plasma turbulence where the electron plasma beta is low, typical of environments where the ions are much hotter than the electrons, e.g., the Earth's magnetosheath and the solar corona, as well as regions downstream of collisionless shocks. In such range of scales, recent theoretical models predict a different behaviour in the nonlinear interaction of dispersive wave modes with respect to what is typically observed in the solar wind, i.e., the presence of so-called inertial kinetic Alfvén waves. We also extend our analysis to scales around and smaller than the electron gyroradius, where hints of a further steepening of the magnetic and electric field spectra have been recently observed by the NASA's Magnetospheric Multiscale mission, although not yet supported by theoretical models. Our numerical simulations exhibit a remarkable quantitative agreement with recent observations by MMS in the magnetosheath, allowing us to investigate simultaneously the spectral break around ion scales and the two spectral breaks at electron scales, the magnetic compressibility, and the nature of fluctuations at kinetic scales.

Gravitational wave turbulence in the primordial universe

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Keywords: *turbulence, cosmology, waves, inflation*

The non-linear nature of the Einstein's equations of general relativity suggests that space-time can be turbulent. Such a turbulence is expected during the primordial universe (first second) when gravitational waves (GW) have been excited through eg. the merger of primordial black holes. The analytical theory of weak GW turbulence, published in 2017 [1], is built from a diagonal space-time metric reduced to the variables t, x and y [2]. The theory predicts the existence of a dual cascade driven by 4–wave interactions with a direct cascade of energy and an inverse cascade of wave action. In the latter case, the isotropic Kolmogorov-Zakharov spectrum N(k) has the power law index -2/3 involving an explosive phenomenon. In this context, we developed a fourth-order and a second-order nonlinear diffusion models in spectral space to describe GW turbulence in the approximation of strongly local interactions [3]. We showed analytically that the model equations satisfy the conservation of energy and wave action, and reproduce the power law solutions previously derived from the kinetic equations. We show numerically by computing the second-order diffusion model that, in the non-stationary regime, the isotropic wave action spectrum N(k) presents an anomalous scaling which is understood as a self-similar solution of the second kind. The regime of weak GW turbulence is actually limited to a narrow wavenumber window and turbulence is expected to become strong at larger scales. Then the phenomenology of critical balance can be used. The formation of a condensate may happen and its rapid growth can be interpreted as an accelerated expansion of the universe that could be at the origin of the cosmic inflation. We can show with this scenario that the fossil spectrum obtained after inflation is compatible with the latest data obtained with the Planck/ESA satellite [4].

[1] Galtier & Nazarenko, Turbulence of weak gravitational waves in the early universe, Phys. Rev. Lett. 119, 221101 (2017).

[2] Hadad & Zakharov, Transparency of strong gravitational waves, J. Geom. Phys. 80, 37 (2014).

[3] Galtier, Nazarenko, Buchlin & Thalabard, Nonlinear diffusion models for gravitational wave turbulence Physica D 390, 84 (2019).

[4] Galtier, Nazarenko & Laurie, Cosmic inflation driven by space-time turbulence (2019).

Two-fluid plasmas: turbulence, reconnection and shocks

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Keywords: *mhd, turbulence, reconnection, shocks*

In space plasmas, turbulence, magnetic reconnection and shock propagation are ubiquitous physical processes that have been traditionally studied using a one-fluid resistive MHD description.

Within the theoretical framework of two-fluid MHD, we retain the effects of the Hall current and electron inertia. Also, this description brings two new spatial scales into play, such as the ion and electron inertial lengths. We perform numerical simulations of the two-fluid equations and study the physical processes arising at sub-ion and even electron scales both three important phenomena in space plasmas: turbulence, magnetic reconnection and perpendicular shocks.

When a stationary turbulent regime is established, our simulations show changes in the slope of the energy power spectrum at the ion and electron inertial lengths, in agreement with the slopes obtained using dimensional analysis. Using non-dissipative two-fluid simulations, we confirm that magnetic reconnection arises only when the effects of electron inertia are retained. In a stationary regime, we obtain that the reconnection rate is proportional to the ion inertial length, as it also emerges from a scaling law derived from dimensional arguments. Finally, using 1D two-fluid simulations, we show the generation of fast-mode perpendicular shocks with a thickness of a few electron inertial lengths.

Plasma turbulence vs. fire hose instabilities: 3-D HEB simulations

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Keywords: *plasma turbulence, kinetic instabilities*

The relationship between a decaying plasma turbulence and proton fire hose instabilities in a slowly expanding plasma is investigated using three-dimensional hybrid expanding box simulations. We impose an initial ambient magnetic field perpendicular to the radial direction simulation box, and we start with an isotropic spectrum of large-scale, linearly-polarized, random-phase Alfvenic fluctuations with zero cross-helicity. A turbulent cascade rapidly develops and leads to a weak proton heating that is not sufficient to overcome the expansion-driven perpendicular cooling. The plasma system eventually drives the parallel and oblique fire hose instabilities that generate quasi-monochromatic wave packets that reduce the proton temperature anisotropy. The fire hose wave activity has a low amplitude with wave vectors quasi-parallel/oblique with respect to the ambient magnetic field outside of the region dominated by the turbulent cascade and is discernible in one-dimensional power spectra taken only in the direction quasi-parallel/oblique with respect to the ambient magnetic field; at quasi-perpendicular angles the wave activity is hidden by the turbulent background. The fire hose wave activity reduces intermittency and the Shannon entropy but increases the Jensen-Shannon complexity of magnetic fluctuations.

Overview of the structure and dynamics of the interaction between solar wind and cometary plasmas after the Rosetta Mission

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Keywords: *space plasma, comet, rosetta, magnetosphere, solar wind*

Cometary induced magnetospheres are archetypes of mass-loaded, partially collisional, partially ionised plasmas, characterised by a wide range of varying plasma parameters, where the interplay between collisionless and collisional processes are essential to give a global picture of the plasma dynamics. While several cometary fly-by missions have enabled to pave the way towards the exploration of cometary environments, the Rosetta mission was the first space mission to escort a comet along its orbit around the Sun. During more than two years (2014-2016), the Rosetta orbiter has monitored comet 67P/CG and its ionised environment, at heliocentric distances ranging from 1.2 to 3.8 AU accounting for a variety of cometary activity, and at distances from the comet nucleus ranging from 1500 km down to the comet nucleus surface itself during the Rosetta Orbiter's final descent. This was the first extensive, long-term, in situ survey of the expanding ionosphere of a comet which interaction with the solar wind forms an induced magnetosphere. In this context, I will review the results obtained from in situ observations made by the different instruments of the Rosetta Plasma Consortium (RPC), combined to state-of-art numerical modelings of cometary plasma environments, to give an overview of the current understanding of the structure and dynamics of a cometary induced magnetosphere. Among different mechanisms, I will show how plasma waves traces the signature of plasma mixing at different interfaces (e.g., electron temperature discontinuities, strong density gradients) and describe some acceleration mechanisms at play in the inner cometary plasma.

A Wave-Coherent Structure Duality in Plasma Turbulence: Are They Two Sides of the Same Coin?

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Keywords: *nonlinear waves, current sheets, turbulence, dissipation*

The dynamics and dissipation of turbulence in weakly collisional space plasmas throughout the heliosphere remains a controversial topic at the forefront of space physics research. Both fluid and kinetic simulations of plasma turbulence ubiquitously generate coherent structures—in the form of current sheets—at small scales, and the locations of these current sheets appear to be associated with enhanced rates of dissipation of the turbulent energy. The quest to understand the physical mechanisms by which the energy of turbulent fluctuations is converted to particle energy or plasma heat has driven vigorous debate about the relative roles of wave damping processes vs. localized dissipation mechanisms associated with current sheets, such as magnetic reconnection. A major unanswered question is how these coherent structures arise in the first place. Recent analytical and numerical work has demonstrated that strongly nonlinear interactions among counterpropagating Alfvén wavepackets—known as Alfvén wave collisions—naturally generate current sheets self-consistently. Subsequent work has shown that the dissipation of the turbulent energy is localized near these current sheets but is clearly mediated through the process of collisionless Landau damping. Together, these results suggest that framing the debate as a choice between waves or coherent structures may be a false dichotomy. Rather, is there a duality between wave or coherent structure descriptions of the turbulence? Are they merely alternative descriptions of the same dynamics? I will close with the question about whether there exist aspects of the turbulence that cannot be described as either waves or structures.

Self-defeating Alfvén waves and self-sustaining sound in a collisionless, high-beta plasma

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Keywords: *waves, instabilities, kinetic, firehose, mirror*

Many space and astrophysical plasmas are so hot and dilute that they cannot be rigorously described as fluids. These include the solar wind, low-luminosity black-hole accretion flows, and the intracluster medium of galaxy clusters. We present theory and hybrid-kinetic simulations of the propagation of shear-Alfvén and ion-acoustic waves in such weakly collisional, magnetized, high-beta plasmas. Following Squire et al. (2016), we demonstrate that shear-Alfvén waves "interrupt" at sufficiently large amplitudes by adiabatically driving a field-biased pressure anisotropy that both nullifies the restoring tension force and excites a sea of ion-Larmor-scale instabilities (viz., firehose) that pitch-angle scatter particles. This physics places a beta-dependent limit on the amplitude of shear-Alfvén waves, above which they do not propagate effectively. We also demonstrate that similar physics afflicts compressive fluctuations, except that it is the collisionless damping of such waves that is interrupted. Above a beta-dependent amplitude, compressive fluctuations excite ion-Larmor-scale mirror and firehose fluctuations, which trap and scatter particles, thereby impeding phase mixing of the distribution function and yielding MHD-like dynamics. Implications for

magnetokinetic turbulence and transport will be discussed.

On the properties of spectral anisotropies and intermittency in ion-kinetic scale turbulence.

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Keywords: *space and astrophysical plasmas, plasma turbulence, numerical simulations, plasma kinetic theory, hybrid model*

The spectral properties at ion kinetic scales are studied by means of high-resolution three-dimensional numerical simulations using a hybrid codes which integrates the Vlasov system equations for the ions while it treats the electron as a neutralising fluid. We show that the observed anisotropy is less than what expected by theories of plasma turbulence at such scales. More specifically, we observe that the spectral anisotropy is frozen once the magnetic energy cascade reaches the ion kinetic scales. However, the non-linear energy transfer is still in the perpendicular direction with respect to the magnetic field, only advected in the parallel direction as expected balancing the non-linear energy transfer time and the decorrelation time. Such result can be explained by a phenomenological model based on the formation of strong intermittent two-dimensional structures in the plane perpendicular to the local mean field that fulfill some prescribed aspect ratio eventually depending on the scale. This model supports the idea that small scales structures, such as reconnecting current sheets, contribute significantly to the formation of the turbulent cascade at kinetic scales.

1/f spectra in collisionless magnetized plasmas: a lesson from solar wind in situ observations

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Keywords: *plasmas, turbulence, mhd, solar wind*

A puzzling property of fast solar wind magnetic fluctuations is that, despite their large amplitude, they induce little variations in the strength of the magnetic field, thus maintaining a low level of compressibility in the plasma.

At the same time, in addition to the well-known Kolmogorov MHD inertial range spectrum with slope -5/3, larger scales of fast streams are characterised by a shallower slope, close to -1. This 1/f range is considered the energy reservoir feeding the turbulent cascade at smaller scales, although its origin is not well understood yet.

These aspects are usually addressed as separate properties of the plasma, however, we suggest that a link between the two exists and we propose a phenomenological model in which a 1/f spectrum for large scales can be derived as a consequence of the low magnetic compressibility condition. Remarkably this model, although simple, can capture most of the variability observed in situ in the solar wind and explain spectral differences in wind regimes. Moreover, our model provides a prediction for the evolution of the 1/f range close to the Sun that it will be possible to test soon thanks to the forthcoming observations of Parker Solar Probe.

Fluidization of collisionless plasma turbulence

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Keywords: *plasma turbulence, landau damping, plasma echo, solar wind*

Two textbook physical processes compete to thermalize turbulent fluctuations in collisionless plasmas: Kolmogorov's "cascade" to small spatial scales, where dissipation occurs, and Landau's damping, which transfers energy to small scales in velocity space via "phase mixing", also leading to dissipation. By direct numerical simulations and theoretical arguments, I will show during this presentation that in a magnetized plasma, another textbook process, plasma echo, brings energy back from phase space and on average cancels the effect of phase mixing. Energy cascades effectively as it would in a fluid system and thus Kolmogorov wins the competition with Landau for the free energy in a collisionless turbulent plasma. This reaffirms the universality of Kolmogorov's picture of turbulence and explains, for example, the broad Kolmogorov-like spectra of density fluctuations observed in the solar wind.

Rotating MHD turbulence

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Keywords: *mhd, turbulence, magnetostrophic waves*

Turbulence in rotating Magneto-hydrodynamic systems is studied theoretically and numerically. In the linear limit, when the velocity and magnetic perturbations are small, the system supports two types of waves. When the rotation effects are stronger than the ones of the external magnetic field, one of these waves contains most of the kinetic energy (inertial wave) and the other–most of the magnetic energy (magnetostrophic wave). The weak wave turbulence (WWT) theory for decoupled inertial and magnetospheric wave systems was previously derived by Galtier (2014). In the present paper, we derive theory of strong turbulence for such waves based on the critical balance (CB) approach conjecturing that the linear and nonlinear timescales are of similar magnitudes in a wide range of turbulent scales. Regimes of weak and strong wave turbulence are simulated numerically. The results appear to be in good agreement with the WWT and CB predictions, particularly for the exponents of the kinetic and magnetic energy spectra.

Energy cascade rate in compressible MHD and Hall-MHD flows: spacecraft observations in the near-Earth space vs theoretical predictions

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Keywords: *solar wind, turbulence, data, mhd*

Compressible turbulence has been a subject of active research within the space physics community over the past years. It is thought to be essential for understanding the physics of the solar wind (for instance the heating of the fast wind), planetary magnetospheres and the interstellar medium (star formation). Using recently derived exact laws of compressible isothermal MHD and the THEMIS and CLUSTER spacecraft data we investigate the physics of the fast and slow solar winds and the Earth magnetosheath. We emphasize the role of density fluctuations in enhancing both the energy cascade rate and the turbulence spatial anisotropy by analyzing different types of turbulent fluctuations (magnetosonic and Alfvénic-like), and show how kinetic instabilities can regulate the energy cascade rate. This has motivated further investigation of the sub-ion scale cascade using MMS high time resolution data and the exact laws of the Hall-MHD model (see talk by Andrés et al.). Preliminary results on the estimation of the fluid cascade rate at sub-ion and its possible connection to kinetic dissipation will be discussed.

Partition of turbulent energy between particle species in astrophysical plasmas

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Keywords: *plasma turbulence, gyrokinetics, heating*

Perhaps the most popular and most productive route by which the theoretical machinery of fusion science has been ported to astrophysical plasmas was the application of gyrokinetic theory to the problem of collisionless plasma turbulence in accretion flows and in the heliosphere, in particular to the question of how energy is partitioned between species (ions and electrons) when this turbulence is thermalised. After many years of promising, but perhaps not entirely conclusive advances in this area, the latest news is that we finally have some quantitative grasp on the answer: GK turbulence promotes disequilibration of species: at high beta, ions are preferentially heated; at low beta, electrons are. This conclusion is supported by GK simulations, which are finally able to give us a heating vs. beta and Ti/Te curve [Kawazura et al. 2019, PNAS 116, 771] and, in the case of low beta, also by relatively rigorous theory [Schekochihin et al. 2019, JPP in press/arXiv:1812.09792]. I will review this progress, spell out caveats (of course there are caveats), and describe the next steps, including some theoretical progress on the high-beta regime.

Phase-space cascade in turbulent plasmas: observations and theory

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Keywords: *turbulence, plasmas, kinetic theory*

Plasma turbulence has been investigated using high-resolution ion velocity distribution measurements by the Magnetospheric Multiscale mission (MMS) in the Earth's magnetosheath. This novel observation of a highly structured particle distribution suggests a cascade process in velocity space. Complex velocity space structure is investigated using a three-dimensional Hermite transform, revealing, for the first time in observational data, a power-law distribution of moments. In analogy to hydrodynamics, a Kolmogorov approach leads directly to a range of predictions for this phase-space transport. The combined use of state-of-the-art MMS data sets, novel implementation of a Hermite transform method, scaling theory of the velocity cascade and kinetic simulations opens new pathways to the understanding of plasma turbulence and the crucial velocity space features that lead to dissipation in plasmas.

Modeling imbalanced Alfvén-wave turbulence from MHD to electron scales

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Keywords: *space plamas, turbulence, alfvén waves, gyrofluids*

After discussing some open problems concerning Alfvén and kinetic Alfvén wave turbulence in the solar wind, and the transition between these two regimes, we introduce a two-field reduced gyrofluid model which includes ion finite Larmor radius corrections, parallel magnetic fluctuations and electron inertia, and thus covers a spectral range extending from MHD to electron scales [1]. The model reproduces the usual phenomenology of balanced turbulence in the regimes of dispersive, kinetic and inertial Alfvén waves and provides, as suggested by preliminary direct numerical simulations, an efficient tool to address the sub-ion dynamics in the imbalanced regime. Furthermore, starting from the kinetic equations of weak turbulence, a nonlinear diffusion model retaining only strongly local interactions is derived and phenomenologically extended to strong turbulence by a suitable modification of the transfer time which, in the case of balanced turbulence, is consistent with critical balance [2]. The associated scale anisotropy turns out to be affected by the degree of imbalance. In this framework, Landau damping is modeled using the dissipation rate given by the linear kinetic theory, with a modification of the transfer time taking into account the effect of temperature homogenization along the magnetic field lines. Extension of the gyro-fluid model including coupling to slow magnetosonic waves and thus permitting the decay instability will be briefly discussed.

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Hamiltonian reduced gyrofluid models

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Keywords: *gyrofluid models, hamiltonian systems*

Reduced fluid models provide a useful tool for qualitative investigations of low-frequency phenomena in plasmas, in the presence of a strong, mean component of the magnetic field. Applications of such models include, for example, magnetic reconnection and turbulence, both in laboratory and astrophysical plasmas. In particular, when investigating phenomena occurring on scales comparable with the ion Larmor radius, the so called reduced gyrofluid models become especially relevant. In the non-dissipative limit, reduced gyrofluid models are supposed to possess a Hamiltonian structure, as is the case for all dynamical plasma models. In addition to its relevance for guaranteeing correct qualitative properties of the dynamics, the knowledge of the Hamiltonian structure can also be of use, for instance, for the identification of families of invariants, particularly relevant in the two-dimensional limit, or for stability analyses. In this talk I will present a rather general framework for deriving a class of Hamiltonian reduced gyrofluid models accounting for equilibrium temperature anisotropies and magnetic perturbations parallel to the mean magnetic field, which could make such models relevant for applications to space plasmas.

Energy Dissipation and Phase Space Dynamics in Eulerian Vlasov-Maxwell Plasmas

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Keywords: *vlasov simulations, kinetic processes, turbulence, space physics*

We present a novel algorithm for the numerical solution of the multi-species, non-relativistic, Vlasov-Maxwell system in the Gkeyll simulation framework, which uses high order discontinuous Galerkin finite elements to discretize the system on an upto a 3D-3V phase space grid. The resulting numerical method is robust and retains a number of important properties of the continuous system, such as conservation of mass and energy, yet the method is computationally efficient and performs well at scale on cutting edge high performance computational resources. We leverage the pristine phase space representation made possible by directly discretizing phase space to examine energy dissipation in a variety of systems relevant to space and astrophysical plasmas. Specifically, we employ the field-particle correlation technique and Fourier-Hermite decomposition in phase space to directly diagnose the exchange of energy between fields and particles and the flow of energy in phase space. We present results from a variety of simple systems, including magnetic pumping, resonant wave damping, and Langmuir turbulence, and we also apply the field-particle correlation technique to 2D-3V Vlasov-Maxwell simulations of reconnection and turbulence.

Velocity-space cascade in nearly collisionless plasmas

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Keywords: *plasma turbulence, vlasov simulations, kinetic processes*

Multi-dimensional Eulerian simulations of the hybrid Vlasov-Maxwell model[1] have been employed to investigate the role kinetic effects in turbulent plasmas at typical ion scales. Numerical results suggest that kinetic effects manifest through the deformation of the ion distribution function, with patterns of non-Maxwellian features being concentrated near regions of strong magnetic gradients. The velocity-space departure from Maxwellian of the ion velocity distributions has been also recovered in observational data from spacecraft. In a recent paper, Servidio et al.[2] investigated the velocity-space cascade process suggested by the highly structured shape of the ion velocity distribution detected by the NASA Magnetospheric Multiscale mission. Through a tree-dimensional Hermite transform, these authors pointed out a power-law distribution of moments and provided a theoretical prediction for the scaling, based on a Kolmogorov approach. Here, the possibility of a velocity-space cascade is investigated in the strongly magnetized case, in kinetic simulations of turbulence at ion scales. Through the Hermite decomposition of the ion velocity distribution from the simulations, we found that (i) the plasma displays spectral anisotropy in velocity space, due to the presence of the background magnetic field, (ii) the distribution of energy is in agreement with the prediction in Ref. [2] and (iii) the activity in velocity space shows a clear intermittent character in space, being enhanced close to coherent structures, such as the reconnecting current sheets produced by turbulence. Finally, in order to explore the possible role of interparticle collisions, collisional and collisionless simulations of plasma turbulence have been compared using Eulerian Hybrid Boltzmann-Maxwell simulations, that explicitly model the proton-proton collisions through the nonlinear Dougherty operator.

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The Debye mission: measuring electron-scale turbulence in the solar wind

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Keywords: *electron-scales, space mission, turbulence, wave-particle interactions, instabilities*

Debye is a proposed and pre-selected mission concept in response to ESA's F-class call. Debye will consist of a main spacecraft with instrumentation to measure electrons, ions, electric fields, and magnetic fields; and up to three deployable spacecraft that measure magnetic fields only. The deployable spacecraft will fly around the main spacecraft, covering different and varying baselines. In this configuration, Debye will measure electron-scale fluctuations and their effects on the electron distribution function. The key science question for the Debye mission is: How are electrons heated in astrophysical plasmas? In order to answer this top-level science question, Debye's first objective is to identify the nature of electron-scale turbulent fluctuations. Then it will measure the rapid transfer of energy from the fields to the particles through high-cadence and high-resolution electron measurements. Finally, Debye will study the partition of energy between particle species and the dependence of the energy transfer on the plasma conditions.

In this presentation, we discuss the science questions and our proposed pathways to science closure for the Debye mission. Moreover, we discuss the implications of Debye science for the turbulence-research communities in the fields of space, astrophysics, and laboratory plasma physics.

Nonlinear Waves at Interfaces

Scaling the viscous Hydraulic Jump

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Keywords: *hydraulic jump, fluid surface*

The formation mechanism of hydraulic jumps has been proposed by Belanger in 1828 and rationalised by Lord Rayleigh in 1914. As the Froude number becomes higher than one, the flow super criticality induces an instability which yields the emergence of a steep structure at the fluid surface. Strongly deformed liquid-air interface can be observed as a jet of viscous fluid impinges a flat boundary at high enough velocity. In this experimental setup, the location of the jump depends on the viscosity of the liquid, as shown by T. Bohr et al. in 1997. In 2014, A. Duchesne et al. have established the constancy of the Froude number at jump. Hence, it remains a contradiction, in which the radial hydraulic jump location might be explained through inviscid theory, but is also viscosity dependent. We present a model based on the 2011 Rojas et al. PRL, which solves this paradox. The agreement with experimental measurements is excellent not only for the prediction of the position of the hydraulic jump, but also for the determination of the fluid thickness profile. We predict theoretically the critical value of the Froude number, which matches perfectly to that measured by Duchesne et al.

scikit-fdiff, a new tool for PDE solving

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Keywords: *pde, finite difference, software*

Scikit-FDiff (formerly known as Triflow) is a new tool, written in pure Python, that focus on reducing the time between the developpement of the mathematical model and the numerical solving. It allows an easy and automatic finite difference discretization, thanks to a symbolic processing that can deal with systems of multi-dimensional partial differential equation with complex boundary conditions.

Using finite differences and the method of lines, it allows the transformation of the original PDE into an ODE, providing a fast computation of the temporal evolution vector and the Jacobian matrix. The later is pre-computed in a symbolic way and sparse by nature. It can be evaluated with as few computational resources as possible, allowing the use of implicit and explicit solvers at a reasonable cost.

Classic ODE solvers have been implemented (or made available from dedicated python libraries), including backward and forward Euler scheme, Crank-Nickolson, explicit Runge-Kutta. More complexes ones, like improved Rosenbrock-Wanner schemes up to the 6th order, are also available. The time-step is managed by a built-in error computation, which ensures the accuracy of the solution. The main goal of the software is to minimize the time spent writting numerical solvers to focus on model development and data analysis.

Scikit-Fdiff is then able to solve toy cases in a few line of code as well as complex models. Extra tools are available, such as data saving during the simulation, real-time plotting and post-processing. It has been validated with the shallow-water equation on dam-breaks and the steady-lake case. It has also been applied to heated falling-films, dropplet spread and simple moisture flow in porous medium.

Nonlinear, short-crested and localized waves

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Keywords: *directional localizations, solitons, rogue waves*

Solitons and breathers are known to model stationary and extreme localizations in nonlinear dispersive media. Indeed, a series of laboratory experiments, for instance in water waves, optics and BEC, confirmed the validity of the the unidirectional nonlinear Schrödinger equation (NLSE) to describe the spatio-temporal dynamics of such waves. In this study, we report observations of slanted, and thus, directional localized envelope soliton and breather dynamics in a water wave basin. The water surface displacement has been stereo-reconstructed using a marker-net, deployed at the center of the basin, and two synchronized high-speed cameras. The results are in very good agreement with the hyperbolic 2D+1 NLS predictions and confirm for the first time that short-crested as well as slanted strongly-localized waves can be also described by a simplified nonlinear wave framework.

On an improved model for long internal gravity waves

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Keywords: *internal wave, shallow layers, improved* *dispersion*

We consider 2D irrotational flows of incompressible fluids stratified in two homogeneous shallow layers, bounded below by a horizontal impermeable bottom and above by a rigid lid. Weakly dispersive fully nonlinear equations of Serre-Green-Nagdhi type are often used to model long internal waves. We show how to improve these equations with better dispersive properties and reduced Kelvin-Helmholtz instability, while remaining asymptotically consistent and keeping all the conservation laws.

Experimental evidence of hydrodynamic instantons and their unifying role in the theory of rogue waves

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Keywords: *surface gravity waves, extreme events, instanton, large deviation theory*

We interpret the formation of rogue waves in a wave flume in light of tools of large deviation theory. By numerical optimization we compute the instantons of the problem, i.e. the most likely realizations leading to extreme surface elevations via the governing nonlinear Schroedinger dynamics. We show that strikingly the typical extreme events of the experiment closely follow the instanton evolution, with small fluctuations around it. This is true accross all of the explored forcing regimes, unifying and extending the existing limiting results for the linear and highly nonlinear cases.

Interfacial nonlinearities to damp sloshing waves

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Keywords: *sloshing, foams, contact angle hysteresis*

Sloshing describes the oscillations of liquids in reservoirs. It is often detrimental and can lead e.g. to coffee spilling, or to destabilisation of tankers and spacecrafts, especially in its large-amplitude, nonlinear regimes. Therefore, understanding and optimising its damping is of primary importance for applications. Presenting experimental measurements and the associated theoretical modeling, I will discuss two ways to increase sloshing damping by interfacial effects: either using a foam layer, or, in the case of partial wetting, tuning the contact angle hysteresis. Interestingly, these two strategies lead to novel nonlinearities which, contrary to the usual large-amplitude effects, manifest themselves all the most that sloshing amplitude is small, leading to singularities like the finite-time arrest of the oscillations of the liquid/air interface.

Birth of a hydraulic jump

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Keywords: *hydraulic jump,*

The hydraulic jump, i.e., the sharp transition between a supercritical and a subcritical free-surface flow, has been extensively studied. However, an important question has been left unanswered: How does a hydraulic jump form? We present here an experimental and theoretical study of the formation of stationary hydraulic jumps in centimeter-sized channels.

We start with an empty channel and then change the flow rate abruptly from zero to a constant value. This leads to the formation of a stationary hydraulic jump in a two stage process. Firstly, the channel fills quickly (~ 1 s). Initially the liquid layer shows a linearly increasing height profile and a front position with a square root dependence on time. When the height of the liquid front reaches a critical value, it remains constant throughout the rest of the filling process. At low flow rate the jump forms during the filling of the channel whereas the jump appears at a later stage when the flow rate is high. Secondly, the influence of the downstream boundary condition makes the jump move slowly (~ 10 s) upstream to its final position with exponentially decreasing speed.

Hypergravity Wave Turbulence

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Keywords: *wave turbulence, nonlinear waves, high-gravity experiments, fluid mechanics*

Wave turbulence occurs in various domains of physics (plasma physics, elasticity, or fluid mechanics) but is far to be completely understood, notably for ocean surface waves. By using a large-diameter centrifuge, we are able to tune the gravity field up to 20 times the Earth acceleration. This new technique then allows us to report the first observation of gravity wave turbulence on the surface of a fluid in hyper-gravity environment. This is also a unique solution to significantly expands the inertial range of gravity wave turbulence in laboratory. Wave turbulence properties are then reported as function of the gravity level, and we show that the usual energy transfer by nonlinear wave interactions are modified by large-scale container modes.

Internal gravity waves generated by turbulent flows

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Keywords: *internal waves, thermal convection*

Many geophysical and astrophysical fluids, including planetary atmospheres, stars and oceans, consist of turbulent flows adjacent to stably-stratified fluid layers. Because waves can drive large-scale flows, increase scalar mixing and are sometimes easier to observe than turbulent motions, two important questions for these fluids are: how much energy goes from the turbulence into internal waves in the stable layer? What kind of waves (i.e. what wavenumbers and frequencies) are generated most efficiently?

In this talk we will answer these two questions by presenting a theoretical prediction for the energy flux spectrum of waves generated by turbulent convection and comparing it with results from 3D direct numerical simulations (DNS) of self-organised convective–stably-stratified fluids. We will show that DNS and theory agree well for the range of strong turbulence-strong stratification parameters tested, giving some confidence in the analytical expression for the energy flux spectrum of the waves, which is based on a theory that assumes waves are generated by Reynolds stresses due to eddies in the turbulent region. We hope that our results will help quantify wave generation in geophysical and astrophysical fluids.

Leidenfrost Effect: The life of a levitating water droplet on a hot vapour layer

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Keywords: *drops, leidenfrost*

The Leidenfrost effect is a physical phenomenon in which a liquid droplet floats on its own evaporating vapour due to the presence of a hot substrate underneath. This effect was discovered by Johan Leidenfrost in 1771 and investigated by John Tyndall as narrated in his book "Heat: a mode of motion (1875). Leidenfrost droplets constitutes an interesting out of equilibrium system which can be a nice playground for laboratory experiments on capillarity and fluid motion. In my talk, I will review the recent experimental and theoretical studies that we have undergone in our laboratory. I will discuss the behaviour of Leidenfrost droplets in the superlevitation regime [1,2] which takes place for a very small droplet radius and reveals the signature of the end of the lubrication regime. I will also discuss a new technique for generating Leidenfrost droplet at ambient temperature (20 Celcius) by using a low-pressure atmosphere [3]. These droplets could have applications as micro-reactors. Finally, I will expose theoretical and experimental results on Leidenfrost droplets which are confined in a two-dimensional geometry by means of a Hele-Shaw cell [4,5], in particular their oscillations and the dynamics of a growing hole. Finally, I will conclude with some questions on their interface fluctuations when the system is close to the Leidenfrost transition.

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Singularity turbulence

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Keywords: *turbulence, singularity, cascades*

We will discuss the singularity induced turbulence obtained using a simple model based on the focusing non-linear Schrödinger equation. We observe a transition from a smooth dynamics towards a strong turbulence regime as the control parameters increase. This strong turbulence regime consists of the midst of the singularities of the NLS equations healed by the viscosity. Kolmogorov-like spectra are observed and will be discussed in the context of the cascade phenomenology. Co-authors: Yves Pomeau and Sergio Rica

Energy cascade in internal wave attractors

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Keywords: *internal waves, stratified flows, instabilities, laboratory experiments*

Internal gravity waves play an important role in

Nonlinear Waves at Interfaces

various geophysical flows. Oceans or atmospheres are indeed stratified in density and support the propagation of such waves. They significantly contribute in the mixing of the ocean, the redistribution of energy and momentum in the middle atmosphere or the transport of sediments and plankton. The subsequent mechanism for the energy transfer from large scales of the injected energy to small scales where dissipation occurs is therefore a critical issue in the dynamics of the ocean or the atmosphere, and also an important fundamental question. In this talk, we will focus on the fate of internal gravity waves in a trapezoidal geometry of the confined fluid domain. The peculiar dispersion relation of these waves lead to strong variation of the wave beam upon reflection on a slope. In such a configuration, the focusing of internal waves prevails, leading to convergence of internal wave rays toward closed loops, the internal wave attractors. The high concentration of energy in attractors make them prone to instabilities. We will show that this experimental set-up models a cascade of triadic interactions and provide an efficient energy pathway from global scale motions to small scale overturning events, which induces significant mixing.

Resonances of Internal Gravity Waves in Stratified Shear Flows

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Keywords: *gravity, waves, resonance, stratification, instability*

We will present here a new instability mechanism that affects the Plane Couette flow and the Plane Poiseuille flow when these flows are stably stratified in density along the vertical direction, i.e. orthogonal to the horizontal shear. Stratified shear flows are ubiquitous in nature and in a geophysical context, we may think to water flows in submarine canyons, to winds in deep valleys, to currents along sea shores or to laminar flows in canals where density stratification can be due to temperature or salinity gradients. Our study is based on two sets of laboratory experiments with salt stratified water flows, on linear stability analyses and on direct numerical simulations. It follows recent investigations of instabilities in stratified rotating or non rotating shear flows: the stratorotational instability [2],[3], the stratified boundary layer instability [4] where it was shown that these instabilities belong to a class of instabilities caused by the resonant interaction of Doppler shifted internal gravity waves. Our laboratory experiments for Plane Couette and Plane Poiseuille flows, based on visualizations and PIV measurements, show in both cases the appearance of braided wave patterns when the experimental parameters, depending on the Reynolds and Froude numbers, are above a threshold. The non linear saturation of the instability leads to a meandering in the horizontal plane arranged in layers stacked along the vertical direction [5]. Comparison with theoretical predictions for the instability threshold and the critical wavenumbers calculated by linear analysis is excellent. Moreover, direct numerical simulations permit to complete the description of this instability that can be interpreted as a resonant interaction of boundary trapped waves [6].

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Transition from inertial wave turbulence to geostrophic turbulence in rotating fluids - an experimental study

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Keywords: *instability, rotating fluids, geophysics, inertial waves, turbulence*

We present an experimental investigation of the turbulent saturation of the flow driven by parametric resonance of inertial waves in a rotating fluid. In our setup, a half-meter wide ellipsoid filled with water is brought to solid body rotation, and then undergoes sustained harmonic modulation of its rotation rate. This triggers the exponential growth of a pair of inertial waves via a mechanism called the libration-driven elliptical instability. Once the saturation of this instability is reached, we observe a turbulent state for which energy is supplied through the resonant inertial waves only. Depending on the amplitude of the rotation rate modulation, two different saturation states are observed. At large forcing amplitudes, the saturation flow main feature is a steady, geostrophic anticyclone. Its amplitude vanishes as the forcing amplitude is decreased while remaining above the threshold of the elliptical instability. Below this secondary transition, the saturation flow is a superposition of inertial waves which are in weakly non-linear resonant interaction, a state that could asymptotically lead to inertial wave turbulence. In addition to being a first experimental observation of a wave-dominated saturation in unstable rotating flows, the present study is also an experimental confirmation of the model of Le Reun et al, PRL 2017 who introduced the possibility of these two turbulent regimes. The transition between these two regimes and there relevance to geophysical applications are finally discussed.

Circular hydraulic jump and inclined jump

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Keywords: *hydraulic jump, waves*

We have investigated the flow and interface structures involved in a circular hydraulic jump formed by impacting a large horizontal disk with a jet of viscous liquid. Among other results, we found that the Froude number at the jump entry seems to be locked to a critical, constant value. This empirical condition, when combined with the large scale lubrication flow structure leads to a "à la Bohr" scaling, with Logarithmic corrections that can be explicitly calculated, in agreement with recent theoretical and numerical modeling. In a second step, we have investigated the jump structure formed when the jet and the impacted disk are inclined of the same amount, after varying the wetting conditions on the disk (hydrophilic, partial wetting and superhydrophobic). The results are very sensitive to the wetting properties as well as to the flow rate and plate inclination. We have tried to interpret the scaling laws observed with simple models generalizing Watson approach of the circular hydraulic jump.

Statistics and models for Faraday pilot waves

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Keywords: *faraday waves, hydrodynamic quantum analogies, complex system*

Faraday pilot waves are a newly discovered hydrodynamic structure that consists a bouncing droplet which creates, and is propelled by, a Faraday wave. These pilot waves can behave in extremely complex ways exhibiting a classical form of wave-particle duality, and result in dynamics mimicking quantum mechanics, including multiple quantisation and probabilistic particle distributions reminiscent of QM. I will show a simple surface wave-droplet fluid model derived from the fluid equations, that captures many of the features observed, and focus on rationalising the emergence of the statistics of complex states and on building models describing particle statistics.

Wave turbulence at the surface of water: the role of bound waves on intermittency

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Keywords: *gravity waves, wave turbulence, intermittency*

By using a stereoscopic imaging technique, we could obtain a space-time resolved measurement of wave turbulence at the surface of water in a 13-m diameter tank. Wave are excited by meter-sized wedge wave makers that are close to omnidirectional. A frequency-wavenumber analysis shows that a turbulent regime develops that is made of a superposition of free waves and bound waves as expected for gravity surface waves. These bound waves result from triadic nonlinear interaction that provide energy to Fourier modes that are not lying on the linear dispersion relation (and thus non resonant). By performing a filtering in the Fourier space, we can remove the bound wave contribution to keep only the free wave one and we show, first, that the observed weak turbulence is indeed weakly nonlinear and, second, that the filtered field is much closer to Gaussian statistics. Furthermore the observed intermittency is strongly reduced so that the free-wave field is close to Gaussian at all scales.

Bacteria display optimal transport near surfaces

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Keywords: *bacteria, surface, mobility*

The near-surface swimming patterns of bacteria are determined by hydrodynamic interactions between the bacteria and the surface, which trap the bacteria in smooth circular trajectories that lead to inefficient surface exploration. Here, we combine experiments with a data-driven mathematical model to show that the surface exploration of a pathogenic strain of Escherichia coli results from a complex interplay between motility and transient surface adhesion events. These events allow the bacteria to break the smooth circular trajectories and regulate their transport properties by exploiting stop events that are facilitated

Nonlinear Waves at Interfaces

by surface adhesion and lead to characteristic intermittent motion on surfaces. We find that the experimentally measured frequency of these stop-adhesion events coincides with the value that maximizes bacterial surface diffusivity according to our mathematical model. We discuss the applicability of our experimental and theoretical results to other bacterial strains on different surfaces. Our findings suggest that swimming bacteria use transient adhesion as a generic mechanism to regulate surface motion.

Intermittency and Leray singularities

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Keywords: *turbulence, intermittency, leray singularities*

Real turbulent flows display intense and short lived velocity fluctuations. This is the phenomenon of intermittency. In 1934 Leray introduced the idea of finite time singularities of the incompressible fluid equations with smooth initial data. Leray singularities occur at given points of space and time. Their analysis give a precise relation between the large velocity and the large acceleration one should observe, a result opposite to the prediction of K41 scaling laws. Leray-like scaling are amazingly well verified in the velocity records of turbulence measured in Modane wind tunnel. I'll introduce Leray's idea and make the connection with the presentation by Christophe Josserand at this conference.

Spin lattices of walking droplets

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Keywords: *hydrodynamic analogs, walking droplets, wave-mediated collective motion*

A droplet bouncing on the surface of a vibrating liquid bath can self-propel across the surface through interaction with the wave field it generates by bouncing. These walking droplets or "walkers" comprise a droplet and its guiding wave, and have been shown to exhibit several behaviors analog to quantum systems. Most analogs consider a single walker interacting with boundaries or experiencing external forces. Controlling multiple walkers is challenging as their continuous wave-mediated interactions usually lead to pair bound states and droplet-droplet coalescence. Here I show that multiple walkers can be manipulated by designing the bottom topography of the vibrating bath as a lattice composed of deeper regions separated by shallow regions. Specifically, I show that circular wells at the bottom of the fluid bath encourage individual droplets to walk in clockwise or counter-clockwise direction along circular trajectories centered at the lattice sites. A thin fluid layer between the wells enables wave-mediated interactions between neighboring walkers resulting in ordered rotation dynamics across the lattice. When the pair coupling is sufficiently strong, interactions between neighboring droplets may induce local spin flips leading to ferromagnetic or anti-ferromagnetic order. In addition, an anti-ferromagnetic to ferromagnetic transition is obtained when the whole bath is rotating. Our experiments demonstrate the spontaneous emergence of collective behavior of walkers that mimic spin lattices.

This work has been done at Massachusetts Institute of Technology with Pedro J. Saenz, Sam E. Turton, Alexis Goujon, Rodolfo R. Rosales, Jörn Dunkel and John W. M. Bush.

When wind waves become Francis solitons

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Keywords: *wind-waves, solitons*

When wind blows above a liquid surface, wind-waves form. We will show that if the liquid is viscous enough these waves becomes strongly non-linear solitary waves.

Nonlinear waves in Plateau borders

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Keywords: *plateau border, hydraulic jump, capillarity*

Plateau borders are the liquid microchannels found at the intersection between bubbles inside liquid foams. They concentrate most of the mass and their role is essential to account for the foams drainage and mechanical properties. During this presentation, experiments and results will be shown about the relaxation of a single Plateau border that is subject to external perturbations. We will see how a negative effective surface tension drives the dynamics, with a special emphasis on regimes dominated by inertial flows and nonlinear waves.

Sheared falling film flows: a numerical study

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Keywords: *falling and sheared films, continuation methods*

This work is devoted to the analysis of a counter-current gas-liquid film flow in an inclined channel. Our purpose is to consider how travelling waves generated at the free surface of the film by the classical Kapitza instability mechanism are affected by the gaseous turbulent flow. We aim at reproducing the experimental results obtained by Sophie mergui and Nicolas Kofman at FAST laboratory. Travelling wave solutions, i.e. waves which remain stationary in their moving frame, have been found numerically. The approach is one-sided as the interfacial stress is a function of the interface position only (we use Camassa's model to compute the shear exerted by the gas flow onto the liquid). A pseudo-spectral approach is followed where a projection of the unknowns onto Chebyshev polynomial functions is performed and the primitive equations are evaluated at the Gauss-Lobatto points, which results in the elimination of the normal coordinate. By invoking a penalization method to account for the continuity of the stresses at the free surface, an autonomous dynamical system of large dimension is obtained. Travelling wave solutions are then obtained as Hopf bifurcations of the Nusselt flat-film solution by means of a predictor-corrector continuation method (ATO07p software. A good agreement is found at a relatively low superficial gas speed. Though only qualitative, the proposed one-sided modelling is able to retrieve qualitatively the experimental observations: enhancement of wave amplitude, lowering of phase velocity and reduction of the number of capillary ripples.

Interference Model for an Array of Wave-Energy-Absorbing Flexible Structures

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Keywords: *surface waves, interference, energy harvesting*

The present work focuses on the local effects of wave-structure interactions within an array of oscillating absorbers to optimize global effects, such as reflection, damping, and energy absorption. We use a model system of flexible blades, subjected to monochromatic waves, and develop a simplified one-dimensional model to predict optimal configurations, depending on various parameters, which include the number of blades, their spacing, and their flexibility. Optimal configurations are found to be close to regular patterns, and the impact of array configurations is shown to be limited regarding wave dissipation, mainly due to a competition between reflection and absorption.

Nonlinear Waves in Biology

A sub-Riemannian model with frequency-phase and its application to orientation map construction

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Keywords: *cortical models, sub-riemannian geometry, orientation maps, neurogeometry, visual perception*

Our objective is to develop a geometrical model of the primary visual cortex in accordance with the neural characteristics of the cortex and construct orientation maps by using the relevant model geometry. Our departure point is the visual cortex model of the orientation selective cortical neurons, which was presented in [1] by Citti and Sarti. We spatially extend this model to a five dimensional sub-Riemannian geometry and provide a novel geometric model of the primary visual cortex which models orientation-frequency selective, phase shifted cortical cell behavior and the associated neural connectivity. This model extracts orientation, frequency and phase information of any given two dimensional input image. We employ in particular an input image with uniformly distributed white noise as the mathematical interpretation of internal stimulation on the retinal plane. Then, we start from the very first step mechanisms of visual perception and by using our sub-Riemannian model in order to extract visual features from the noise image, we provide a neurally inspired geometric procedure for multi-feature orientation map construction.

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Scaling up individual behavior to predict population spread: experiments with microscopic insects

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Keywords: *spatial spread, diffusion, individual interactions, movement, insects, group dynamics*

Understanding how behavioral processes, inter-individual variability and interactions shape the spatial spread and dispersal of animal populations is a major challenge in ecology. Trichogramma parasitic waps are among the smallest insects in the world (less than 500 micrmeters long). They are grown and released by millions in the field to protect crops from insect pests, so that understanding their spatial propagation dynamics is critical to predict performance. I'll present how a novel experimental system coupled with high-throughput tracking of individual movements by computer vision can give insight into the spatial spread of groups of parasitoid individuals over large temporal (one entire day) and spatial (six meters, ca. 12,000 body lengths) scales in the lab. In particular I'll show how population spread is well described by heterogeneous diffusion, whereby individuals switch between two states dynamically (active versus sedentary) depending on their encounter with other individuals or with resource items. I'll also show how these rather complex movement strategies ultimately generate a fairly simple Gaussian spatial distribution of host parasitism around the release point.

The role of cortical waves in shaping the dynamic processing of visual information

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Keywords: *visual neuroscience, cortical wave, motion integration*

Since the pioneering work of the Hubel and Wiesel, the visual system is mostly conceived as a feed-forward hierarchical flow of sensory information. Accordingly, low-level visual information (such as position and orientation) is extracted locally within stationary receptive fields and is rapidly cascaded to downstream areas to encode more complex features. Such a framework implies that processing at each level of processing must be fast, efficient and mostly confined to network of neurons with overlapping receptive fields. In recent work, however, we have demonstrated that any local stationary stimulus is, in itself, generating waves propagating within each cortical steps of visual processing. Visual information thus does not stay confined to a particular retinotopic location but instead invades neighboring cortical territory, connecting neurons with neighboring receptive fields. What could be the computational advantage of cortical waves in the processing visual information? We have shown that, in response to a non-stationary sequence of visual stimuli, such as an object moving along a trajectory, these waves interact non-linearly with feedforward and feedback streams. They hereby shape the representation of moving stimuli within cortical retinotopic maps to encode accurately the object velocity.

Evolutionary path to a minimal biological clock

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Keywords: *switch-like behavior, oscillatory behavior, cell regulation*

Switch-like and oscillatory dynamical systems are widely observed in biology. We investigate the simplest biological switch that is composed of a single molecule that can be autocatalytically converted between two opposing activity forms. We propose that this single molecule system could work as a primitive biological sensor and show by steady state analysis of a mathematical model of the system that it could switch between possible states for changes in environmental signals. Particularly, we show that a single molecule phosphorylation-dephosphorylation switch could work as a nucleotide or energy sensor. We also notice that a given set of reductions in the reaction network can lead to the emergence of oscillatory behaviour. We propose that evolution could have converted this switch into a single molecule oscillator, which could have been used as a primitive timekeeper. I will discuss how the structure of the simplest known circadian clock regulatory system, found in cyanobacteria, resembles the proposed single molecule oscillator. Besides, I will speculate if such minimal systems could have existed in an RNA world. I will also present how the regulatory network of the cell cycle could have emerged from this system and what are the consequences of this possible evolution from a single antagonistic kinase-phosphatase network.

Coupled oscillators in mammalian cells

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Keywords: *coupled oscillators, mammalian cells*

Most organisms have evolved a circadian timing system to adapt their physiology and behaviour to the daily environmental changes resulting from the rotation of the earth on its axis. This is achieved through a self-sustained oscillatory gene network present in virtually all cells and which temporally coordinates a plethora of molecular, cellular and physiological processes. Interestingly, daily synchronous rhythms of the cell division cycle are observed in many species including humans. This strongly suggests that the circadian clock and the cell cycle machineries are functionally connected. Consistently, several molecular mechanisms underlying this crosstalk have been uncovered during the last 10-15 years. However, despite this mechanistic knowledge, how the temporal organization of cell division at the single cell level produces coherent daily rhythm at the tissue level and how the clock and cell cycle dynamics are coordinated have remained elusive. Using multispectral fluorescent imaging of genetically modified single live cells, computational methods and mathematical modelling we have addressed this issue in mouse fibroblastic cells. This approach revealed that in unsynchronized cells, the cell cycle and circadian clock robustly phase-lock each other in a 1:1 fashion so that in an expanding cell population the two oscillators oscillate in a synchronized way with a common frequency. Further, pharmacological synchronization of cellular clocks reveals additional phase-locked clock states. The temporal coordination of cell division by phase-locking to the clock at a single cell level has significant implications because circadian disruption is increasingly being linked to the pathogenesis of many diseases including metabolic diseases and cancer.

Nonlinear propagating waves in the awake brain and their possible role

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Keywords: *mean-field model, excitation, inhibition, visual cortex*

Various propagating waves occur in the brain, at different spatial and temporal scales. We report here on a mixed theoretical and experimental study of propagating waves in visual cortex of the awake monkey. Optical imaging measurements of the primary visual cortex (V1) revealed that every visual stimulus is followed by a propagating waves at sub-millimeter scale and with a propagating velocity of about half a meter per second. When two propagating waves collide, their combined action is largely sublinear, which reveals suppressive effects. Mean-field models can reproduce this nonlinear interaction if inhibitory neurons have a higher gain than excitatory neurons, and if they interact via conductance-based mechanisms. Finally, an external decoder can correctly discern the two stimuli, but only if the propagating waves are suppressive. We conclude that the suppressive nonlinearity of propagating waves enable to disambiguate visual stimuli and thus participate to a finer visual discrimination. Supported by the CNRS, ANR and the EU (Human Brain Project).

Studying self-organized patterning of peatland ecosystems with Appropriate Complexity Landscape Modeling

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Keywords: *peatland ecosystems, self-organization, vegetation patterns, scale-dependent feedback, critical transitions*

The surface of northern and tropical peatland ecosystems frequently exhibits self-organized patterning of densely vegetated hummocks and more sparsely vegetated hollows. Theoretical studies so far suggest multiple alternative mechanisms that could be driving this pattern formation. The long time span associated with peatland surface pattern formation, however, limits possibilities for empirically testing cause-effect relationships through field manipulations. We present a reaction-advection-diffusion model that describes spatial interactions between vegetation, nutrients, hydrology, and peat. Modification of the model's reaction terms and the hydraulic conductivity function enable the study of pattern formation as driven by three different mechanisms: peat accumulation, water ponding, and nutrient accumulation. By on-and-off switching of each mechanism, we created a full-factorial design to see how these mechanisms affected surface patterning (pattern of vegetation and peat height) and underlying patterns in nutrients and hydrology.

Results revealed that different combinations of structuring mechanisms lead to similar types of peatland surface patterning but contrasting underlying patterns in nutrients and hydrology. These contrasting underlying patterns suggested that the presence or absence of the structuring mechanisms can be identified by relatively simple short-term field measurements of nutrients and hydrology, meaning that longer-term field manipulations could be circumvented. Performing these empirical tests in similarly patterned peatland complexes along a Eurasian climatic gradient, we found that the underlying patterns in nutrients and hydrology reversed along the climatic gradient, corroborating the main prediction of the model framework.

This study follows the Appropriate Complexity Landscape Modelling approach, in that it explores multiple pattern-forming mechanisms in a model environment, and subsequently confront these predictions to empirical data. This approach may not only be useful for northern peatlands but for (sub)tropical peatlands as well. This notion is illustrated with current work in progress, in which we study multiple mechanisms that may drive peatland pattern formation in the Florida Everglades.

Steady and wave-like patterns in flux-based auxin transport models

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Keywords: *active transport, ode models, nonlinear dynamics*

Auxin is a major plant hormone, and its spatial distribution in plant tissues is a key driver of plant structure and geometry. Auxin transport is a complex process, combining cell-to-cell diffusion and active transport. The latter is mediated by membrane-bound transporters whose inhomogeneous distribution is controlled by auxin itself. The details of this process are still largely unknown, despite numerous recent advances. In this work, the focus is on a mathematical model implementing one of the current biological assumptions, which is that auxin flux is the variable controlling transporters' distribution. We show that identical auxin patterns can be achieved by distinct transporters distributions, and characterize these in graph theoretical terms. Under a condition of regularity of the dependence of transporters on the flux, we can prove that one of these steady states, with zero flux everywhere, is asymptotically stable for any choice of parameters. When the condition of regularity is not satisfied the same steady state may undergo bifurcations and become unstable. In particular, we can observe stable oscillations taking the form of a travelling wave of auxin, on a row of cells.

Self-organization of mitotic waves depends on the spatial geometry of the system

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Keywords: *mitotic waves, cell cycle*

Whether a cell will grow and divide is a highly regulated decision that is controlled by a large and complex network of genes and proteins. Our understanding of how these network components collectively work together in space and time is still limited. In our lab, we combine theory of nonlinear dynamics and complex systems with biological experiments in order to gain new insights into cell cycle regulation. Here, I will discuss our work on cell division coordination in frog embryos. Upon fertilization, the early Xenopus leavis frog egg quickly divides about ten times to go from a single cell with a diameter of a millimeter to several thousands of cells of somatic cell size (tens of microns). Using frog cell-free extracts, one can reconstitute in vitro the biochemical reactions that regulate these clock-like cell divisions. On the one hand, such extract experiments allow us to identify how the presence of feedback loops in the molecular network ensures robust cell cycle oscillations. On the other hand, we find that cell division is spatially coordinated via biochemical waves, whose properties depend on the dimensions of the spatial environment. By carrying out experiments in Teflon tubes of varying diameter, we show that mitotic waves are driven by an internal pacemaker in thinner tubes, while they are boundary-driven in thicker tubes. We show how changing the spatial geometry of the system effectively tunes the relative strength of two pacemaker regions, thus reversing the direction of propagation of mitotic waves.

Pattern formation in marine clonal plant meadows

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Keywords: *pattern formation, ecology, clonal plants, competition*

Competition for water or nutrients or interactions with herbivores drive spatial instabilities in landscapes of terrestrial plants, resulting in pattern formation phenomena that have been a subject of intense research in the last years. Observations from aerial images and side -scan sonar data have recently revealed analogous pattern forming phenomena in submerged vegetation in the Mediterranean Sea [1], mainly in meadows of seagrasses such as Posidonia oceanica and Cymodocea nodosa. Starting from growth rules of these clonal plants, we have derived a macroscopic model for the plant density able to provide an explanation to the observed submarine hexagonal patterns or isolated ‘fairy circles’, and landscapes of spots and stripes. The essential ingredient is a competitive interaction at a distance of 20-30m. Beyond a qualitative description of the observed patterns, and their prevalence under different meadow conditions, the model fits well measurements of the population density of Posidonia, which show great variability close to the coast, where patterns typically appear.

Circadian rhythms: a theoretical and practical view on internal 24-hour timing

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Keywords: *circadian rythms, cell oscillators*

Circadian clocks are endogenous oscillators that drive 24-hour rhythms in physiology, metabolism and behaviour of almost all life on earth. Circadian clocks are found at all levels -from cells, tissues and organs to the entire organism. In mammals, the master circadian clock resides in the hypothalamic suprachiasmatic nuclei (SCN) and coordinates daily rhythms of sleep and wakefulness, core body temperature and hormone secretion (such as cortisol, melatonin and many others). It is synchronized to Earth’s rotation primarily by light-dark cycles – a process called ‘entrainment’, which is crucial for an organisms’ fitness. Little is known about which oscillator qualities determine entrainment, i.e. entrainment range, phase and amplitude. Using mathematical modelling combined with experimental studies we found that coupling among single cell oscillators governs fundamental properties of circadian clock systems. In addition, we will present our recent development that allows the assessment of the phase of human circadian rhythms by a single time-point measurement using machine-learning algorithms at high dimensional time-series data from human blood cell transcriptomes. Since the internal circadian phase of humans is different for each individual and does not correspond to external clock time, such a precision medicine tool (BodyTime) enabling the personalization of healthcare according to the patient’s circadian clock is urgently needed.

Reaction-Diffusion Systems on Structured and Evolving Manifolds

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Keywords: *pattern formation, manifolds, growth, heterogeneity*

I will discuss recent work with biologists related to understanding particular structural characteristics in the whiskers of mice, and in synthetic quorum-sensing mechanisms of bacteria. These scientific problems are typically modelled using reaction-diffusion systems, and one is often interested in emergent spatial and spatiotemporal patterns from instabilities of a homogeneous equilibrium. I will use these scientific questions to motivate fundamentally mathematical questions regarding instabilities and the emergence of patterns in complex domains. First I will discuss the well-known effects of how manifold structure impacts the modes which may become unstable in reaction diffusion systems, and hence how the kinds of patterns we may observe on manifolds can change due to geometry directly. More strikingly, I will discuss recent work where coupling between two different simple planar geometries leads to highly non-intuitive results regarding the role of geometry. Finally I will discuss results on instabilities on a large class of time-evolving manifolds, and show that one can derive a meaningful notion of instability of the homogeneous state even in this explicitly time-dependent setting. The technical Theorems in this last part may also have application far beyond the realm of developmental biology, as they generalize notions of instability to a large class of non-autonomous systems.

Modeling cortical spreading depression induced by the hyperactivity of interneurons

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Keywords: *cortical spreading depression, biophysical modeling*

Cortical spreading depression (CSD) is a wave of transient intense neuronal firing leading to a long lasting depolarizing block of neuronal activity. It is a proposed pathological mechanism of migraine with aura. Some molecular/cellular mechanisms of migraine with aura and of CSD have been identified studying a rare genetic form: familial hemiplegic migraine (FHM). FHM type 1 & 2 are caused by mutations of the CaV 2.1 Ca2+ channel and the glial Na+/K+ pump, respectively, leading to facilitation of CSD in mouse models mainly because of increased glutamatergic transmission/extracellular glutamate build-up. FHM type 3 mutations of the SCN1A gene, coding for the voltage gated sodium channel NaV 1.1, cause gain of function of the channel and hyperexcitability of GABAergic interneurons. This leads to the counterintuitive hypothesis that intense firing of interneurons can cause CSD ignition. To test this hypothesis in silico, we developed a computational model of an E-I pair (a pyramidal cell and an interneuron), in which the coupling between the cells in not just synaptic, but takes into account also the effects of the accumulation of extracellular potassium caused by the activity of the neurons and of the synapses. In the context of this model, we show that the intense firing of the interneuron can lead to CSD. We have investigated the effect of various biophysical parameters on the transition to CSD, including the levels of glutamate or GABA, frequency of the interneuron firing and the efficacy of the KCC2 co-transporter. The key element for CSD ignition in our model was the frequency of interneuron firing and the related accumulation of extracellular potassium, which induced a depolarizing block of the pyramidal cell. This constitutes a new mechanism of CSD ignition.

Timing of fungal spore release dictates survival during atmospheric transport

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Keywords: *atmospheric transport, fungal spore, turbulence, dispersal*

The fungi disperse spores to move across landscapes and spore liberation takes different patterns. While many species release spores intermittently, others release spores at specific times of day or night according to intrinsic rhythms. Despite intriguing evidence of diurnal rhythms, why the timing of spore liberation would matter to a fungus remains an open question. Here we use state-of-the-art numerical simulations of atmospheric transport with meteorological data to follow the trajectory of many spores released in the open atmosphere at different times of day, during different seasons and at different locations across North America. While individual spores follow un-predictable trajectories due to turbulence, in the aggregate patterns emerge: statistically, spores released during the day fly for several days, while spores released at night return to the ground within a few hours. Differences are caused by intense turbulence during the day and weak turbulence at night. The pattern is widespread but its reliability varies, for example, day/night patterns are stronger in southern regions, where temperatures are warmer. Results provide a set of testable hypotheses explaining intermittent and regular patterns of spore release as strategies to maximize spore survival in the air. Species with short lived spores reproducing where there is strong and regular turbulence during the day, for example in Mexico, will maximize survival by routinely releasing spores at night. Where cycles are weak, for example in Canada during spring, there will be no benefit to releasing spores at the same time every day. We also challenge the perception of atmospheric dispersal as risky, wasteful, and beyond control of a sporocarp; our data suggest the timing of spore liberation may be finely tuned by a fungus to maximize fitness during atmospheric transport.

Waves of cerebral cortex depolarization: focus on a novel mechanism of migraine-linked cortical spreading depression induced by hyperactivation of GABAergic neurons.

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Keywords: *spreading depolarization, cortical spreading depression, migraine, sodium channels, gabaergic neurons.*

Spreading depolarization (SD) refers to waves of abrupt, sustained mass depolarization in the gray matter of the central nervous system, observed in different pathological conditions. Cortical spreading depression (CSD) is a SD generated in well-nourished and oxygenated tissue, and characterized by transient intense neuronal firing leading to a long lasting depolarizing block of neuronal activity. CSD is a proposed pathological mechanism of migraine. Some molecular/cellular mechanisms of migraine with aura and of CSD have been identified studying a rare genetic form: familial hemiplegic migraine (FHM). FHM type 3 is caused by mutations of the SCN1A gene, leading to gain of function of NaV1.1 sodium channels, which are essential for GABAergic neurons' excitability. I will present our recent results about mechanisms of induction of CSD caused by gain of function of Nav1.1. Acute activation of Nav1.1 with a selective toxin in brain slices, mimicking the effect of FHM3 mutations, induce SD selectively in the cerebral cortex. We tested the role of GABAergic neurons by activating them with optogenetic techniques. Hyperactivity of interneurons is sufficient to ignite CSD by spiking-induced extracellular K+ build-up in the cerebral cortex, but not in other brain structures. GABAergic and glutamatergic synaptic transmission was not required for CSD initiation, but glutamatergic transmission was implicated in CSD propagation in the cortex. These results reveal the key role of Nav1.1 and GABAergic neurons in a novel mechanism of CSD initiation, which can be relevant for FHM3 and possibly also for other types of migraine.

Modelling spontaneous propagating waves in the early retina

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Keywords: *retinal waves, dynamical systems, biophysical modelling, nonlinear dynamics*

During early retina development, waves of activity propagate across the retina and play a key role in building the early visual system. In vertebrates species, upon maturation and before eye-opening, transient networks of cells generate these waves, characterized by 3 consecutive stages. Here, we focus on the biophysical detailed modelling of the second stage (stage II), during which waves are controlled by directly interconnected specific cells, the cholinergic starburst amacrine cells (SACs) which are able to burst autonomously. We propose plausible underlying mechanisms for: i) waves generation at the single neuron level, ii) propagation at the network level in a landscape marked by previous waves prints and iii) waves termination. Based on a bifurcation analysis we show how biophysical parameters control retinal waves characteristics and we provide a theoretical condition for waves propagation and disappearance. Moreover, we show that the continuous decrease of the strength of the acetylcholine synaptic coupling, associated with the crossing of a synchronization transition, impacts dramatically the waves distribution. We report especially on the existence of power law distributions of the avalanche size not only at the synchronization threshold, but also for a whole range of coupling strength. This may play a key role in the ability of the retina to respond to visual stimuli by maximizing its dynamical range.

Cellular waves formed during collective bacterial predation

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Keywords: *biochemical oscillations, bacteria, rippling waves, motility*

A current challenge in developmental biology is to bridge molecular and multicellular scales. This task is especially complex in animals given that the dimension gap spans several orders of magnitude. In this context, multicellular microbes can be especially powerful because their lifecycle rarely exceeds a few days and it can be captured over relatively small surfaces in devices as simple as a petri dish. In addition, these organisms allow sophisticated genetic manipulations and imaging approaches. In our laboratory, we study Myxococcus xanthus for its ability to predate and develop collectively over other microbial preys. During this presentation, I will present an interdisciplinary approach combining genetics, quantitative imaging and mathematical modeling to decipher how single Myxococcus cells direct their movements and cooperate to develop collectively and form periodic patterns called rippling waves over prey bacteria. In general, the findings suggest that symmetry breaking and pattern formation arise by biochemical oscillations, that arise from short range interactions and propagated from discrete sites in the community.

An exact firing rate model reveals the differential effects of chemical versus electrical synapses in spiking networks

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Keywords: *firing rate models, neural field models, synchronization, oscillations, spiking neuron networks*

Chemical and electrical synapses shape the collective dynamics of neuronal networks. Numerous theoretical studies have investigated how, separately, each of these type of synapses contributes to the generation of neuronal oscillations, but their combined effect is less understood. This limitation is further magnified by the impossibility of traditional neuronal mean field models —often referred to as firing rate models— to account for electrical synapses. Here we perform a comparative analysis of the dynamics of heterogeneous populations of quadratic integrate-and-fire neurons with chemical, electrical, and both chemical and electrical coupling. In the thermodynamic limit, we show that the population's mean-field dynamics is exactly described by a system of two ordinary differential equations for the center and the width of the distribution of membrane potentials -or, equivalently, for the population-mean membrane potential and firing rate. These firing rate equations describe, in a unified framework, the collective dynamics of the ensemble of spiking neurons, and reveal that both chemical and electrical coupling are mediated by the population firing rate. Furthermore, while chemical coupling shifts the center of the distribution of membrane potentials, electrical coupling tends to reduce the width of this distribution promoting the emergence of synchronization. The analysis of the firing rate equations allows us to obtain exact formulas for all Saddle-Node and Hopf boundaries, and to construct phase diagrams characterizing the dynamics of the original network of spiking neuron. In networks with instantaneous chemical synapses the phase diagram is characterized by a codimension-two Cusp point, and by the presence of persistent states for strong excitatory coupling. In contrast, the phase diagram for electrically coupled networks is determined by a Takens-Bogdanov codimension-two point, which entails the presence of oscillations and greatly reduces the possibility of persistent states. In this case oscillations arise either via a Saddle-Node-Invariant-Circle bifurcation, or through a supercritical Hopf bifurcation -as shown using weakly nonlinear stability analysis. Finally, we show that the Takens-Bogdanov bifurcation scenario is generically present in networks with both chemical and electrical coupling.

Traveling waves shape neural computations in vision

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Keywords: *computational neuroscience, systems neuroscience, vision*

New recording technologies allow neuroscientists to record from cortex with high spatial and temporal resolution. For the first time, we can visualize the complex activity patterns in cortical populations during natural sensory behaviors. Because these imaging experiments occur in intact biological systems, however, certain restrictions are inevitable. In particular, the signal-to-noise ratio (SNR) remains low relative to other scientific imaging domains.

In our research, we have developed new signal processing techniques to analyze nonlinear waves in high-noise multisite data. With these tools, we have found unexpected structure in the dynamics of cortical populations during natural sensory behavior. First, we found that small visual stimuli evoke far-reaching propagating waves in the awake monkey. In recent work, we have found that spontaneous, internally-generated traveling waves modulate sensitivity to visual stimuli in the awake marmoset. These results indicate that traveling waves shape neural computations during normal vision and have more general implications for the way we think about noise in the brain.

Waves in viscously coupled chains of overdamped oscillators: The gecko's papilla.

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Keywords: *excitability, oscillations, hearing, otoacoustic-emissions*

The hearing organ of lizards -papilla- has been modelled as a chain of over-damped (inertia-less) bio-mechanical self-oscillators mutually coupled by a combination of viscous and elastic forces. In the extreme case when the elastic ones are negligible the combination of viscous coupling and overdamping leads to the study of unusual class of extended dynamical systems defined by a nonlocal spatial operator. In other words, the lack of inertia in the dynamics of the individual oscillators effectively mutates the original, locally defined coupling into one defined by a global, albeit exponentially weakening, prescription. In this talk we present a number of counterintuitive consequences of this phenomenon on the propagation of perturbations along the media, as well as on the expected synchronization behaviour of the chain. Other characteristics of papillae is tonotopy: the oscillators proper frequencies are arranged in an increasing order along the chain. The combination of different types of couplings and tonotopy, produces characteristic collective frequency spectra that one could associate with distinguishably stable spontaneous otoacoustic emissions observed in individual of certain lizards' species like tokkai gecko for instance. We explore this phenomenon in simple settings.

Halfway between phase and amplitude oscillators

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Keywords: *collective dynamics, partial synchrony*

Collective properties of oscillators are often analysed by running simulations for increasingly large ensembles of elements. Therefore, analytical approaches/results are definitely welcome as they play the role of references for validating the results on the various scenarios that are otherwise only numerically observed. Here we show that the well known model of mean-field coupled, Stuart-Landau oscillators can be semi- analytically studied at a macroscopic level in an intermediate regime, where the oscillators maintain some typical features of phase-oscillators (remaining aligned along a closed smooth curve), but amplitude oscillations manifest themselves as fluctuations of the curve itself. Our approach allows characterising the collective dynamics for different values of the coupling strengths and in particular to find evidence of self-consistent partial synchrony and an intriguing collective-chaos regime characterised by a small number of positive exponents and a seemingly high-dimensional dynamics.

Ubiquitous abundance scaling of plankton distributions and ocean dynamics from a network theory approach

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Keywords: *network theory, plankton, abundance distributions, lagrangian transport, marine ecology*

I will first focus on scaling properties obtained from the analysis of Species Abundance Distributions (SADs) of planktonic organisms. Using the dataset gathered by the Tara Oceans expedition for marine microbial eukaryotes (protists) we explore how SADs of planktonic local communities vary across the global ocean. We find that the decay in abundance of more than the 99% of species is commonly governed by a power-law. Moreover, the power-law exponent varies by less than 10% across locations and does not show biogeographical signatures suggesting that large-scale ubiquitous ecological processes could govern the assembly of such communities.

I will then introduce a Network Theory framework developed for the characterization of fluid transport dynamics in the ocean. The discretization of the sea surface in small equal-sized cells brings to the construction of a new kind of network networks, called Lagrangian Flow Networks (LFNs), that describe water exchanges between different regions of the seascape. Using Network Theory concepts & tools we can study dispersion and mixing at both local and global scales evidencing relationships between network measures and dynamical properties of the flow. Among possible applications, such a framework provides a systematic characterization of the dispersal of planktonic life-stages of marine organisms which helps to understand the connectivity and structural complexity of marine populations.

I will finally discuss possible perspectives to investigate the effects of ocean transport and mixing on planktonic community assembly in the Mediterranean using the LFN methodology.

Selection of striped, gapped and spotted vegetation patterns in a reaction-advection-diffusion model

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Keywords: *vegetation patterns, self-organisation, turing instability, drylands*

Spatial vegetation patterns with different morphologies (gaps, stripes/labyrinths, spots) have been observed in many drylands worldwide. These patterns are thought to be caused by a water flux from bare to vegetated areas.

Reaction(-advection)-diffusion models can help explain why these spatial patterns form. But how does the pattern morphology depend on the choice of model? And what does this imply for real ecosystems?

Computational modeling of seizure spread on a cortical surface and the theta-alpha electrographic pattern

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Keywords: *epilepsy, computational modeling, seizure propagation*

Intracranial electroencephalography is a standard tool in clinical evaluation of patients with focal epilepsy. Various early electrographic seizure patterns differing in frequency, amplitude, and waveform of the oscillations are observed in intracranial recordings. The pattern most common in the areas of seizure propagation is the so-called theta-alpha activity (TAA), whose defining features are oscillations in the theta-alpha range and gradually increasing amplitude. A deeper understanding of the mechanism underlying the generation of the TAA pattern is however lacking. We show by means of numerical simulation that the features of the TAA pattern observed on an implanted depth electrode in a specific epileptic patient can be plausibly explained by the seizure propagation across an individual folded cortical surface. In order to demonstrate this, we employ following pipeline: First, the structural model of the brain is reconstructed from the T1-weighted images, and the position of the electrode contact are determined using the CT scan with implanted electrodes. Next, the patch of cortical surface in the vicinity of the electrode of interest is extracted. On this surface, the simulation of the seizure spread is performed using The Virtual Brain framework. As a mathematical model the Epileptor model in its field formulation is employed. The simulated source activity is then projected to the sensors using the dipole model, and this simulated stereo-electroencephalograpic (SEEG) signal is compared with the recorded one. The results show that the simulation on the patient-specific cortical surface gives a better fit between the recorded and simulated signals than the simulation on generic surrogate surfaces. Furthermore, the results indicate that the spectral content and dynamical features might differ in the source space of the cortical gray matter activity and among the intracranial sensors, questioning the previous approaches to classification of seizure onset patterns done in the sensor space, both based on spectral content and on dynamical features. In conclusion, we demonstrate that the investigation of the seizure dynamics on the level of cortical surface can provide deeper insight into the large scale spatiotemporal organization of the seizure. At the same time it highlights the need for a robust techniques for inversion of the observed activity from sensor to source space that would take into account the complex geometry of the cortical sources and the position of the intracranial sensors.

A neural field model for color perception unifying assimilation and contrast

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Keywords: *color-space interactions, color perception in context, neural field, color matching*

We address the question of color-space interactions in the brain by proposing a neural field model of color perception with spatial context, for the visual area V1 of the cortex. Our framework reconciles two opposing perceptual phenomena, known as simultaneous contrast and chromatic assimilation. They have been previously shown to act synergistically, so that at some point in an image, the color seems perceptually more similar to that of the adjacent neighbors, while being more dissimilar from that of remote ones. Thus their combined effects are enhanced in the presence of a spatial pattern, and can be measured as larger shifts in color matching experiments. Our model supposes a hypercolumnar structure coding for colors in V1, and relies on the notion of color opponency introduced by Hering. The connectivity kernel of the neural field exploits the balance between attraction and repulsion in color and physical spaces, so as to reproduce the sign reversal in the influence of neighboring points. The color sensation at a point, defined from a steady state of the neural activities, is then extracted as a nonlinear percept conveyed by an assembly of neurons. It connects the cortical and perceptual levels, because we describe the search for a color match in asymmetric matching experiments as a mathematical projection of color sensations. We validate our color neural field alongside this color matching framework, by performing a multi-parameter regression to psychophysical data produced by Monnier & Shevell (2004, 2008), and ourselves. All the results show that we are able to explain the nonlinear behavior of shifts along one or two dimensions in color space, which cannot be done using a simple linear model.

Anticipation in the retina and the primary visual cortex : towards an integrated retino-cortical model for motion processing

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Keywords: *retina, primary visual cortex, anticipation, connectivity, dynamical systems*

The retina is able to perform complex tasks and general feature extraction, allowing the visual cortex to process visual stimuli with more efficiency. With regards to motion processing, an interesting and useful task performed by the retina is anticipation and trajectory extrapolation. Anticipation in the retina lies in the fact that the peak of retinal ganglion cells response is shifted, occurring before the object reaches the center of the receptive field, and can be explained by gain control mechanisms occurring at the level of bipolar and ganglion cells. Trajectory extrapolation on the other hand is related to a rise in the activity before the object enters the receptive field of the cell and is carried out through electrical synapses (gap junctions) connecting ganglion cells. This extrapolation has also been observed at the level of the primary visual cortex, where lateral propagation drives the activity ahead of the input, denoting predictive computations. Motion encoding in the retina also involves amacrine cells, which connect bipolar cells to either bipolar or ganglion cells, but their role has not been investigated yet in motion anticipation.

The first contribution of our work lies in the development of a generalized 2D model of the retina with three layers of ganglion cells : Fast OFF cells with gain control accounting for anticipation, direction selective cells connected via gap junctions, and Y-cells connected through amacrine cells, accounting for motion extrapolation.This model affords a mathematical analysis via dynamical systems theory and allows to outline the role of lateral connectivity (gap junctions and amacrine cells) in motion perception, anticipation and trajectory extrapolation. The second contribution is the use of the output of our retina model as an input to a mean field model of the primary visual cortex to reproduce motion anticipation as observed in VSDI recordings of V1. We present results of the integrated retino-cortical model for motion processing, and study how anticipation and extrapolation depend on stimuli parameters such as speed, shape and trajectory. Through the integrated retina-cortical model we emphasize the mechanisms defining motion anticipation, due to the cooperation of gain control and lateral connectivity at the level of the retina and lateral connectivity in the cortex. Moreover, we show how cortical nonlinearities due to a different gain between excitatory and inhibitory neurons shape the cortical response thus affecting object recognition.

Networks of piecewise linear neural mass models

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Keywords: *neural mass models, networks, synchrony, nonsmooth dynamics*

Neural mass models are ubiquitous in large scale brain modelling. At the node level they are written in terms of a set of ordinary differential equations with a nonlinearity that is typically a sigmoidal shape. Using structural data from brain atlases they may be connected into a network to investigate the emergence of functional dynamic states, such as synchrony. With the simple restriction of the classic sigmoidal nonlinearity to a piecewise linear caricature we show that the famous Wilson-Cowan neural mass model can be explicitly analysed at both the node and network level. The construction of periodic orbits at the node level is achieved by patching together matrix exponential solutions, and stability is determined using Floquet theory. For networks with interactions described by circulant matrices, we show that the stability of the synchronous state can be determined in terms of a low-dimensional Floquet problem parameterised by the eigenvalues of the interaction matrix. Moreover, this network Floquet problem is readily solved using linear algebra, to predict the onset of spatio-temporal network patterns arising from a synchronous instability. We further consider the case of a discontinuous choice for the node nonlinearity, namely the replacement of the sigmoid by a Heaviside nonlinearity. This gives rise to a continuous-time switching network. The stability of a periodic orbit is now treated with a modification of Floquet theory to treat the evolution of small perturbations through switching manifolds via the use of saltation matrices. At the network level the stability analysis of the synchronous state is considerably more challenging.

Front pinning due to spatial heterogeneity in a reaction-diffusion model of tropical tree cover

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Keywords: *spatial ecology, reaction-diffusion equations, travelling fronts, maxwell point*

Previous empirical work has hypothesised that tropical forest and savanna are two alternative stable states as a result of fire-vegetation feedbacks. The hysteresis associated with such dynamic implies that when an area of tropical forest is exposed to shocks such as deforestation or drought, it can remain locked into a savanna state unless it experiences large increases in rainfall. In my PhD, I have provided empirical and theoretical evidence that instead of two alternative stable states and hysteresis, there is only a predictable front, occurring at a single tipping point, the Maxwell point. This becomes clear after spatial heterogeneity and spatial interaction are taken into account.

In the presentation, I will start with some background on tropical tree cover bistability. Then, I use a simple reaction-diffusion equation with bistable reaction term to explain travelling wave fronts under homogeneous forcing and front pinning under heterogeneous forcing. After showing how the pinning location can be derived from data, I will briefly show the data analysis results. I will then finally introduce and analyse the reaction-diffusion model of Amazonian tree cover. It will become clear towards the end that spatial heterogeneity can lead to the false impression of bistability and hysteresis when in fact there is only a front.

Partial Differential Equations and Modelization

Asymptotics properties of the small data solutions of the Vlasov-Maxwell system

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Keywords: *hyperbolic pdes, vector field method, null structure, non linear equations*

The Vlasov-Maxwell system is a classical model in plasma physics. Glassey and Strauss proved global existence for the small data solutions of this system under a compact support assumption on the initial data. I will present how vector field methods can be applied to revisit this problem. In particular, it allows to remove all compact support assumptions on the initial data and obtain sharp asymptotics on the solutions. We will also discuss the null structure of the system which constitutes a crucial element of the proof.

Branches of traveling waves for the Nonlinear Schrödinger equation

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Keywords: *schrödinger equation, traveling waves, vortices*

We consider the cubic Nonlinear Schrödinger equation in the plane with condition of modulus one at infinity. This model possesses traveling waves. We shall present two types of results of existence of (smooth) branches of traveling waves: a theoretical one obtained in collaboration with E. Pacherie for small speeds and numerical results obtained in collaboration with C. Sheid on the excited states for this model.

On singularity formation for the unsteady Prandtl's system

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Keywords: *boundary layers, prandtl's equations, separation, singularity*

Prandtl's equations arise in the description of boundary layers in fluid dynamics. Solutions might form singularities in finite time, with the first reliable numerical studies performed by Van Dommelen and Shen in the early eighties, and a rigorous proof done later in the nineties in the seminal work of E and Engquist in two dimensions. This singularity formation is intimately linked with a phenomenon: the separation of the boundary layer. The precise structure of the singularity has however not been confirmed yet mathematically. This talk will first describe the dynamics of the inviscid model, for which we explain how the Van Dommelen and Shen singularity appears generically. Then, for the full viscous model, the second part of the talk will focus on the obtention of detailed asymptotics for the solution at a relevant particular location. This is a collaboration with T.-E. Ghoul, S. Ibrahim and N. Masmoudi.

Two asymptotic regimes of the Landau-Lifshitz equation

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Keywords: *landau-lifshitz equation, sine-gordon equation, schrödinger equation*

The Landau-Lifshitz equation gives account of the dynamics of magnetization in ferromagnets. The goal of this talk is to describe the rigorous derivation of two aymptotic regimes of this equation corresponding to the Sine-Gordon equation and the cubic Schrödinger equation. This talk is based on two papers in collaboration with André de Laire (University of Lille).

Long time behavior of the solutions of NLW on the d-dimensional torus

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Keywords: *non linear wave equation, control of high sobolev norms, normal forms.*

We consider the non linear wave equation (NLW) on the d-dimensional torus

$$u_{tt} - \Delta u + mu + f(u) = 0 \quad x \in T^d$$

where $f = \partial_u F$ is analytic on a neighborhood of the origin and which is at least of order 2 at the origin. Let $u(t)$ be a solution corresponding to a small initial datum $u(0) \in H^s(T^d)$. We prove that we control $[u(t)]_s$ that mix the H^s norm of the $\varepsilon^{-\beta(r)}$ lower Fourier modes of the solution u and the energy norm of the remaining higher modes during long times of order ε^{-r}.

Our general strategy applies to any Hamiltonian PDEs whose linear frequencies satisfy only a first Melnikov condition. In particular it also applies to the Hamiltonian Boussinesq $abcd$ system and the Whitham-Boussinesq system in water waves theory. Joint work with Joackim Bernier and Erwan Faou.

Nonlinear stability and instability results for gravitational kinetic models

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Keywords: *stability and instability, kinetic models, gravitational systems*

The orbital nonlinear stability of steady states solutions to the gravitational Vlasov-Poisson system, which are decreasing functions of the energy, has been proved in 2012. However, this result is partially based on compactness arguments and does not provide a complete quantitative information on the perturbation. In this talk, I will start by presenting a quantitative version of this nonlinear stability result. In particular a refined functional inequality on extended rearrangements of functions is proved, which is then combined with a Poincaré-like inequality. Another advantage of this approach is its applicability to other systems like the so-called Hamiltonian Mean Field (HMF), where the space domain is bounded and where the decreasing property of the steady states is no more sufficient to guarantee their stability. In fact, an additional explicit criteria is needed for HMF, under which the non-linear stability is proved. In a last part of this talk, we show that this criteria is sharp by proving a nonlinear instability result for HMF when the criteria is not satisfied. To this aim, we use an iterative procedure that was introduced by Grenier in a different context.

Equidistribution of toral eigenfunctions along hypersurfaces

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Keywords: *harmonic analysis, laplace eigenfunctions*

I will discuss asymptotic properties of Laplace eigenfunctions on the flat torus in the high frequency limit. I will present results showing equidistribution of these eigenfunctions along hypersurfaces with nonvanishing curvature. This is a joint work with Hamid Hezari (U.C. Irvine).

Control of nonlinear parabolic PDEs

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Keywords: *control of pdes, carleman estimates*

It is by now well known that the use of Carleman estimates allows to establish the controllability to trajectories of nonlinear parabolic equations. However, by this approach, it is not clear how to decide whether a given function is indeed reachable. That issue has obtained very recently almost sharp results in the linear case. In this talk, we investigate the set of reachable states for a nonlinear heat equation in dimension one. The nonlinear part is assumed to be an analytic function of the spatial variable x, the unknown y, and its derivative y_x. By investigating carefully a nonlinear Cauchy problem in x in some space of Gevrey functions, and the relationship between the jet of space derivatives and the jet of time derivatives, we derive an exact controllability result for small initial and final data that can be extended as analytic functions on some ball of the complex plane. This is a joint work with Camille Laurent (Sorbonne Université). It time allows, works in progress about the reachable states for KdV and for ZK will be outlined.

Uniqueness and non-degeneracy for a class of semilinear elliptic equations

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Keywords: *uniqueness, non-degeneracy, nonlinear schrödinger equation*

In this talk, I will present a result on the uniqueness and the non-degeneracy of positive radial solutions for a class of semilinear elliptic equations. Next, I will illustrate this result with two examples: a nonlinear Schrödinger equation for a nucleon and a Schrödinger equation with a double power non-linearity. This talk is based on joint works with Mathieu Lewin.

Resonances of random quantum systems

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Keywords: *scattering resonances, random potentials, wave scattering*

The resonances of Schrödinger operators can be used to describe the large time behaviour of a wave scattered by a potential. In this context, the resonances which are the closest from the real axis are the most relevant. The distribution of resonances for potentials which decay rapidly at infinity has been studied a lot. On the other hand, for random potentials, there are very few known results. In this talk, I will discuss some recent results concerning the distribution of resonances for some random Schrödinger operators (joint work with F. Klopp).

Wave Phenomena in Disordered Systems

Fluctuating Forces Induced by Non Equilibrium and Coherent Light Flow

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Keywords: *non equilibrium, disordered media*

In this work we present an unexpected example of fluctuation induced forces caused by classical light propagating in a scattering medium. In weakly disordered media, light intensity has long ranged spatial fluctuations (speckle) associated to mesoscopic coherent effects. These intensity fluctuations induce a new type of measurable radiation forces.

The effect is fully understood and characterized by means of an effective Langevin description of the light flow, where coherent mesoscopic effects are the source of the noise.

This approach is of particular interest since it maps the problem of coherent multiple light scattering onto an effective non equilibrium light flow. A clear asset of this type of approach is in its dependence upon two parameters only, thus making it a candidate to efficient machine learning algorithms.

Experimental evidence for Band Gap Formation and Anderson localization regimes for microwaves in hyperuniform 2D materials

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Keywords: *photonic band gap, disorder, hyperuniformity, anderson localization, microwaves*

Recently, it has been shown that disordered dielectrics can show a photonic band gap in the presence of structural correlations [1], but 30 years after John's seminal proposal on the interplay between the photonic pseudo band gap in disordered photonic crystals and Anderson localization [2], a controlled experimental study of the transport properties in between ordered and disordered states is still lacking. In this talk, I present new experimental and numerical results obtained for a 2D system composed of high index dielectric cylinders in air [3] placed according to stealthy hyperuniform point patterns [1]. Measurements are performed in the microwave range (1 to 10 GHz). In addition to the (local) density of states and the Thouless conductance, we can access experimentally the field amplitude which allows us to unambiguously visualize single eigenmodes in finite size open systems for all the transport regimes such as stealthy-transparent, diffusion, Anderson-localization and the band gap [4], as a function of the degree of stealthiness χ. Our observations are supported by the analysis of the spreading of the wave in the time domain.

[1] M. Florescu, S. Torquato, and P. J. Steinhardt *Designer disordered materials with large, complete photonic band gaps* PNAS **106**, 20658 (2009) [2] S. John *Strong localization of photons in certain disordered dielectric superlattices* Phys. Rev. Lett. **58**, 2486 (1987).

[3] D. Laurent et al. *Localized Modes in a Finite-Size Open Disordered Microwave Cavity* Phys. Rev. Lett. **99**, 253902 (2007). [4] L. Froufe-Pérez et al., *Band gap formation and Anderson licalization in disordered photonic materials with structural correlations* PNAS **114**, 9570 (2017).

Fluctuations at the Anderson localization transition of 3D light

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Keywords: *light scattering in disordered media, anderson localization*

Anderson localization of 3D light has eluded definitive experimental proofs for many years, both for technical and fundamental reasons. Apart from the difficulty of producing highly scattering samples, a major challenge is identifying an unambiguous signature of the phase transition in experimentally feasible situations. We here discuss the correspondence between the collapse of the conductance, the increase in intensity fluctuations at the localization transition and the Ioffe-Regel criterion, thus connecting the macroscopic and microscopic approaches of localization. Intensity fluctuations thus appear as a proper signature to study the localization transition in 3D.

Far from equilibrium dynamics of a 2D ultracold Bose gas in an harmonic trap : dynamical symmetry and breathers

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Keywords: *quantum gas, 2d bose gas, scale invariance, gross-pitaevskii/non-linear schrodinger equation, breathers*
We study experimentally the dynamics of a cold gas of particles confined in a single plane. We prepare uniformly-filled clouds with different shapes (disk, squares, triangles) and monitor the time evolution of their density profile when applying an isotropic harmonic confinement. We operate in a regime where the gas is well described by a classical field whose evolution is given by the Gross-Pitaevskii (GP) equation. We show that the presence of a dynamical symmetry, described by the SO(2,1) group, leads to conserved quantities in the time evolution and allows us to relate different experimental situations by a scaling transform. Suprisingly, we also observe, for specific shapes, time periodic solutions of the GP equation, that we identify as breathers. Reference : arXiv:1903:04528

Light scattering and dipole-dipole interactions in cold and hot vapors

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Keywords: *dipole-dipole interactions, light scattering, dense atomic vapors*
This talk will present recent experiments that we performed on the study of near-resonance light scattering in dense laser-cooled and hot atomic vapors. In both cases, the large density results in a strong influence of the interactions between light-induced dipoles. We will compare our measurements of the coherent scattering on both systems to theoretical models and show that while the qualitative behaviors are correctly reproduced for hot and cold vapors, the quantitative agreement is only achieved in the hot vapor case. The talk will also come back to the origin of the collective Lamb shift in hot atomic vapors and present it as an indirect consequence of the dipole-dipole interactions between atoms.

Transmission eigenchannels in diffusive media

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Keywords: *diffusion, localization, coherent wave transport, transmission matrix, transmission eigenchannel*
Transmission eigenchannels are building blocks of coherent wave transport through multiple-scattering media. High transmission eigenchannel can have near unity transmittance. Wavefront shaping techniques have been developed to selectively couple light into such channels to enhance light transmittance through multiple-scattering media. It has been shown that coupling light into high-transmission channels not only enhances the transmittance, but also modifies the depth profile of energy density inside the medium. We discover that the transmission eigenchannels of a wide multiple-scattering slab exhibit transversely localized incident and outgoing intensity profiles, even in the diffusive regime far from Anderson localization. Such transverse localization can be understood with optical reciprocity, local coupling of spatial modes, and non-local intensity correlations of multiply-scattered light. Experimentally, we observe transverse localization of high-transmission channels with finite illumination area. Transverse localization of high-transmission channels enhances optical energy densities inside and on the back surface of the turbid media, which will be important for imaging and sensing applications. We further demonstrate that selective coupling of light into a single transmission eigenchannel modifies the range of angular memory effect. High-transmission channels have a broader range of memory effect than a plane wave or a Gaussian beam. Thus will provide a wider field-of-view for memory-effect-based imaging through multiple-scattering media.

Focusing and imaging through disordered media using all optical feedback

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Keywords: *focusing and imaging in scattering media, optical feedback,*
Focusing and imaging through inhomogeneous, disordered media challenges many applications in optics. Examples range from focusing through atmospheric turbulence in optical communication and LIDAR applications, to focusing through biological tissues in optical microscopy and laser nano-surgery applications. Wavefront shaping with spatial light modulators can focus light through a disordered medium but finding the desired wavefront requires long acquisition times. Here, we exploit an all optical feedback in order to image and focus light through a disordered media at much shorter time scales.

We experimentally demonstrate that by placing the scattering medium directly inside the laser cavity, the appropriate wavefront, which focuses and images the light through the medium, is chosen by the laser itself. This occurs as a result of mode competition and without the need for complicated computer controlled phase modulators and electronic feedback algorithms. The optimal wavefront is found by the laser in less than 500 ns, which is orders of magnitude faster than the reported wavefront shaping record.

The Quantum Boomerang Effect

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Keywords: *cold atmos, anderson localization*

When a wavepacket is launched with a finite velocity in free space, it follows a balistic motion, both in classical and quantum mechanics. In the presence of a disordered potential, the generic classical behavior, described by the Boltzman equation, is a random walk - that is a diffusive motion at long time - whose charateristic length is the mean free path. The center of mass of the classical "wavepacket" first drifts balistically in the direction of the initial velocity, slowly slows down and ends up at long time displaced by one mean free path. The quantum dynamics is drastically different: the center of mass first drifts balistically, but rapidly performs a U-turn and slowly returns to its initial position. I will describe this "Quantum Boomerang" effect both numerically and analytically in dimension 1, and show that it is partially destroyed by weak particle interactions which act as a decoherence process. The Quantum Boomerang effect is also present in higher dimensions, provided the dynamics is Anderson localized.

Intensity correlations to probe light scattering in optically thick cold atomic cloud

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Keywords: *intensity correlation, light scattering, optically thick cold atomic cloud*

The study of fluctuations and correlations often gives access to information not contained in averaged values. Among the many statistical properties of a fluctuating field, the intensity correlation function is largely used in a number of areas, from astronomy, to quantum optics, particle physics, and to mesoscopic optics. In the latter, it has been applied to the fluctuations of light scattered by a disordered medium. First used in the single-scattering regime with a technique known as dynamic light scattering or quasielastic light scattering, it was then extended to strong multiple-scattering regime.

In this talk, I will present different results obtained with intensity correlation measurements on light scattered by a cold atomic cloud. We first applied this technique to cold atoms under purely ballistic motion and we investigate the transition between the single and the multiple-scattering regime. When the atoms are driven by a strong laser field, one measures the well-known Mollow triplet, a fundamental signature of quantum optics. Finally, by coupling the intensity correlation to the beat note technique, one has access to the first and second order correlation functions, allowing in particular to test the validity of the Siegert relation in different configurations.

Uncorrelated configurations and extreme statistics of the field in reverberation chambers stirred by tunable metasurfaces

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Keywords: *reconfigurable metasurface, chaotic reverberation chamber, extreme value statistics, random matrix theory*

Reverberation chambers are currently involved in a large variety of applications ranging from computational imaging to electromagnetic (EM) compatibility testing as well as the characterization of antenna efficiency, wireless devices or MIMO systems . In most of the above mentioned applications, the related measurements are based on statistical averages and their fluctuations. We introduce a very efficient mode stirring process based on electronically reconfigurable metasurfaces (ERMs) developed by the young start-up GREENERWAVE . By locally changing the field boundary conditions, the ERMs allow to generate a humongous number of uncorrelated field realizations even within small reverberation chambers. We fully experimentally characterize this stirring process by determining the number of uncorrelated realizations via the autocorrelation function of the transmissions. Thanks to the huge size of uncorrelated samples thus produced, we are able to experimentally investigate the extreme value statistics of the EM field very precisely and compare them with theorical predictions deduced from the random matrix theory (RMT). Based on the fluctuations of field's maxima, the IEC-standard uniformity criterion parameter σ_{dB} is for instance investigated and reveals the performance of the stirring with ERM's. We compare the experimental results on the uniformity criterion parameter with a corresponding RMT model where the only parameter, the modal overlap, is extracted via the quality factor. We find a very good agreement.

Strong disorder in correlated potentials such as speckles and topological systems and their relevance to experiments

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Keywords: *disorder, correlated potentials*

Adding disorder to a system of quantum particles or excitations can lead to dramatic changes of their properties, including Anderson localization. While there are effective approximations to describe consequences of disorder, such as the Born approximation, they generally fail at large disorder. Here will we review an approach based on a non-linear approximation, which can be applied to arbitrary correlated potentials and which is also effective at high disorder strengths. This formalism leads to interesting results in experimental systems, such as speckle potentials, disordered quantum wires and vibrational topological states in graphene, which will be discuss in this talk.

Elastic Scattering Time of Ultracold Atoms in Disordered Potentials

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Keywords: *ultracold atoms, disordered systems, anderson localization*

I will report on an extensive study of the elastic scattering time $\tau_m athrms$ of matter-waves in optical disordered potentials. Using direct experimental measurements, numerical simulations and comparison with first-order Born approximation based on the knowledge of the disorder properties, we explore the behavior of time $\tau_m athrms$ over more than three orders of magnitude, ranging from the weak to the strong scattering regime. We study in detail the location of the crossover and, as a main result, we reveal the strong influence of the disorder statistics, especially on the relevance of the widely used Ioffe-Regel-like criterion time $kl_m athrms \sim 1$. While it is found to be relevant for Gaussian-distributed disordered potentials, we observe significant deviations for laser speckle disorders that are commonly used with ultracold atoms. Our results open the path for a better connection between experimental investigations of complex transport phenomena, such as Anderson localization, to microscopic theories.

Topological physics with microwaves

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Keywords: *topological photonics, interface states, reflective limiters*

Band theory has been one of the major achievements of condensed matter physics during the second half of the last century. Tight-binding model and Bloch theorem give a clear understanding of electronic dispersion relations in metals and semiconductors. The discovery of quantum Hall effect in the 80's marks the emergence of topology in transport properties: The recognition that the Hall conductance at the plateaus can be understood in terms of topological invariants known as Chern numbers. Playing the role of an order parameter in a "topological phase transition", Chern number and others topological invariants are nowadays intensively studied in the active field of topological insulators. These concepts extend far beyond the scope of solid-state physics, and several research groups proposed alternative experimental platforms using cold atoms, photons, polaritons, and other classical waves. The Waves in Complex Systems group in Nice has developed artificial condensed-matter systems by means of microwave resonator lattices. I will present a selection of results obtained the last 5 years.

Subradiance, collective anti-resonance and energy transfer of coupled quantum emitters in confined geometries

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Keywords: *coupled quantum emitters, subradiance*

An array of closely spaced, dipole coupled quantum emitters exhibits collective energy shifts as well as super- and subradiance with characteristic tailorable spatial radiation patterns. Ring shape configurations exhibit exponential suppression of spontaneous emission and lossless excitation transport. Optimizing the geometry with respect to the spatial profile of a near resonant optical structures allows to increase the ratio between light scattering into the cavity mode and free space by orders of magnitude. This comes with very distinct nonlinear particle number scaling for the strength of coherent light-matter interactions versus collective decay. In particular, for subradiant states the collective cooperativity increases much faster than the linear N dependence of independent emitters in the low excitation regime. This extraordinary collective enhancement is manifested both, in the intensity and phase profile of the sharp collective emitter anti-resonances detectable at the cavity output port via transmission spectroscopy. Subradiant atomic excitations show a much larger effective cooperativity than superradiant states.

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Introducing the random anti-laser: coherent perfect absorption in disordered media

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Keywords: *scattering, disorder, wave front shaping*

Abstract: In my talk I will present the concept of random anti-lasing, i.e., the time-reverse of random lasing. In the same way as a random laser emits a spatially complex but coherent wave at its first lasing threshold, the random anti-laser absorbs such a complex incoming field perfectly. We recently implemented this concept in a microwave experiment, where an absorber is embedded in the middle of a disordered medium [1]. Measuring the 8x8 scattering matrix of this structure allows us to calculate and then generate an incoming wave field that gets absorbed by more then 99.7

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Quantum and nonlinear effects in transmission of light through planar arrays of atoms

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Keywords: *atom-light interactions, cold atoms*

We simulate the coupled quantum dynamics of closely-spaced atoms and light by solving the quantum many-body master equation. In the forward scattering of light from planar arrays and uniform slabs of cold atoms we identify quantum many-body effects that are robust to position fluctuations and strong dipole-dipole interactions. This is obtained by comparing the full quantum solution to a semiclassical model that ignores quantum fluctuations.

Resolution of the "exponent puzzle" for the Anderson transition in doped semiconductors

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Keywords: *anderson localization, metal-insulator transition, doped semi-conductors, electronic structure*

The Anderson metal-insulator transition (MIT) is central to our understanding of the quantum mechanical nature of disordered materials. Despite extensive efforts by theory and experiment, there is still no agreement on the value of the critical exponent

u describing the universality of the transition—the so-called “exponent puzzle.” In this talk, going beyond the standard Anderson model, we employ ab initio methods to study the MIT in a realistic model of a doped semiconductor. We use linear-scaling density functional theory to simulate prototypes of sulfur-doped silicon (Si:S). From these we build larger tight-binding models close to the critical concentration of the MIT. When the dopant concentration is increased, an impurity band forms and eventually delocalizes. We characterize the MIT via multifractal finite-size scaling, obtaining the phase diagram and estimates of

u. Our results suggest an explanation of the long-standing exponent puzzle, which we link to the hybridization of conduction and impurity bands.

Light diffusion, Band gap formation and Localization in Hyperuniform Dielectric Materials

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Keywords: *disordered photonics, photonic band gap materials anderson localization, mesoscopic wave transport, hyperuniform structures*

We report on the fabrication and characterization of disordered hyperuni- form photonic materials in two and three dimensions. We first discuss the fabrication of polymer templates of network structures using direct laser writing (DLW) lithography. Next we demonstrate how these mesoscopic polymer networks can be converted into silicon materials by infiltration and double-inversion. The resulting hyperuniform photonic materials display a pronounced pseudo gap in the optical transmittance in the short-wave infrared. To obtain a deeper understanding of the physical parameters dictating the properties of disordered photonic materials we investigate band gaps, and we report Anderson localization in hyperuniform structures using numerical simulations of the density of states and optical transport. Our results show that, depending on the frequency of in- cident radiation, a disordered, but highly correlated, dielectric material can transition from photon diffusion to Anderson localization and to a bandgap. In two dimensions we can also identify a regime, near the gap, dominated by tunnelling between weakly coupled states. 1) N. Muller, J. Haberko, C. Marichy, and F. Scheffold, Silicon Hyper- uniform Disordered Photonic Materials with a Pronounced Gap in the Shortwave Infrared, Adv. Optical Mater. 2, 115-119 (2014) 2) Luis S. Froufe-Pérez, M. Engel, P. F. Damasceno, N. Muller, J. Haberko, S. C. Glotzer, and F. Scheffold, Role of short-range order and hyperuni- formity in the formation of band gaps in disordered photonic materials, Phys. Rev. Lett. 117, 053902 (2016) 3) Luis S. Froufe-Pérez, M. Engel, J.J. Saenz, F. Scheffold, Band gap formation and Anderson localization in disordered photonic materials with structural correlations, Proceedings of the National Academy of Sciences, 114 (36), 05130 (2017) 4) J. Haberko,Luis S. Froufe-Pérez,and F. Scheffold, https://arxiv.org/abs/1812.02095

Topological mode selection

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Keywords: *disorder, topological photonics, lasers*

Topological photonics aims to replicate fermionic symmetries as feats of precision engineering. Here I show how to enhance these systems via effects such as gain, loss and nonlinearities that do not have a direct electronic counterpart. This leads to a topological mechanism of mode selection [1,2,3], formation of compactons in flat band condensates [4], and topological excitations in lasers when linearized around their working point [5]. The resulting effects show a remarkable practical robustness against disorder, which arises from the increased spectral isolation of the manipulated states.

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Anderson localization of vector waves

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Keywords: *anderson localization, disorder, scattering,*

Anderson localization was first discovered for electrons in disordered solids but later was shown to take place for various types of waves in disordered media. For three-dimensional (3D) disorder, it takes place only in a restricted band of frequencies, separated from the rest of the spectrum by mobility edges, and only when the disorder is strong enough. Our recent results indicate that the vector nature of waves (microwaves, light, elastic waves) used in the experiments on Anderson localization, plays an important role. In particular, the transverse electromagnetic waves cannot be localized by a random 3D arrangement of resonant point-like scatterers (atoms), whereas the elastic waves, which have a longitudinal component as well, can be localized in a way very similar to scalar waves. However, the localization of light can still be made possible by putting the atoms in a strong external magnetic field. We will present a unified view on Anderson localization and compute the localization phase diagrams and the critical parameters (mobility edges and critical exponents) of Anderson localization transitions for elastic waves and light scattered by atoms in a strong magnetic field. Despite the differences between these two systems, they turn out to belong to the same universality class.

Light induced collective dynamics and long-range interactions between nanoparticles

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Keywords: *optical binding, random fields, collective phenomena, dispersion forces, non-conservative optical forces*

We review a number of intriguing predictions regarding the dynamics of plasmonic nanoparticles under crossed laser fields [1]. As a recent example, we will discuss the self-organized collective behavior of gold nanoparticles moving in aqueous solution under a non-conservative optical vortex lattice. As we will see, above a critical field intensity and concentration, the interplay between optical forces, thermal fluctuations and hydrodynamic pairing leads to a spontaneous transition towards synchronized motion [2].

Light induced forces are usually strongly anisotropic depending on the interference landscape of the external fields. This is in contrast with the familiar isotropic van der Waals and, in general, Casimir-Lifshitz interactions between neutral bodies arising from random electromagnetic waves generated by equilibrium quantum and thermal fluctuations. It has been recently shown that non-equilibrium, quasi-monochromatic, random fluctuating light fields can be used to induce and control isotropic, translational invariant, dispersion forces between small colloidal particles [3]. Interestingly, when the light frequency of a quasi-monochromatic isotropic random field is tuned to an absorption line (at the so-called Fröhlich resonance) we will see that the attractive force between two identical molecules or resonant nanoparticles follows a gravity-like inverse square distance law [4]. Our results generalize Lorentz's [5] (and Spitzer-Gamow's "Mock Gravity" [6]) electromagnetic version of the remarkable Fatio-LeSage's corpuscular theory of gravity introduced as early as in 1690.

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Influencing subradiance by thermal motion

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Keywords: *cold atoms, subradiance, cooperative decay*

We experimentally and numerically study the subradiant decay in an ensemble of cold atoms as a function of the temperature. In the experiment we are recording the temporal switch-off dynamics of the light scattered by a cold-atom sample driven by a weak laser pulse (linear-optics regime). As subradiance is usually interpreted as an interference effect, it is not obvious that the finite temperature of the sample and for this the atomic motion don't introduce a source of dephasing with direct impact on the decay dynamics. We observe that subradiance is rather robust against an increase of the temperature, the measurements show only a slight decrease of the subradiant decay time when increasing the temperature up to several millikelvins, and in particular we measure subradiant decay rates that are much smaller than the Doppler broadening, which might be counter-intuitive. In the numerical simulations we can observe a complete breakdown of subradiance, which occurs at high temperature, when the Doppler broadening is larger than the natural decay rate of a single atom.

Non-Hermiticity in optical microcavities

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Keywords: *microcavities, exceptional points, nonorthogonality*

We discuss two aspects of non-Hermiticity in optical microcavities. First, we theoretically demonstrate third-order exceptional points in whispering-gallery cavities. Second, we reveal the role of mode nonorthogonality in the dynamics of waves propagating in open systems with localized losses.

Controlling light and matter with cooperative radiation

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Keywords: *superradiance, subradiance, atomic array, single-photon nonlinearity*

It is well known that spontaneous emission, typically assumed to be an independent process for each atom, can be correlated due to the interference of light emitted by different atoms. Cooperative radiation phenomena such as Dicke's superradiance has been explored in systems ranging from individual atoms to black holes. Recently, such cooperative radiation emerged as a promising method for manipulating systems ranging from unordered gases to ordered atomic arrays to two-dimensional semiconductor materials. I will discuss several theoretical ideas relating to super- and subradiance as well as potential applications of such effects.

Spatiotemporal Phenomena in Nonlinear Optics

Complex solitons in vertical-cavity surface-emitting lasers with frequency-selective feedback

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Keywords: *vcsel, vector vortex beams, solitons, light bullet*

Broad-area vertical-cavity surface-emitting lasers (VCSELs) with feedback from an external cavity emerged as a highly controllable and versatile tool to investigate spatio-temporal self-organization. The external cavity provides natural means for control and to induce time-dependent behavior, which -via space-time analogy in systems with delay- can lead to quasi-3D spatial dynamics, in particular spatio-temporal solitons and potentially light bullets. The high circular symmetry of VCSELs also allows for the investigation of vectorial effects in light-matter coupling. I will present investigations on the spontaneous appearance of vector vortex beams in a VCSEL with frequency-selective feedback with a radial, spiral and hyperbolic polarization structure and their interpretation as high order vectorial solitons. The role of the feedback loop in controlling birefringence will be elucidated. Potential extensions to spin-orbit coupling of light, topological states and the inclusion of carrier spin are discussed as well as mode-locking these states.

Controlling light by light

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Keywords: *solitons, rogue waves, analogue gravity, ultrashort pulses, four wave mixing*

We discuss propagation of ultrashort solitary pulses in nonlinear single-mode optical fibers. Each pulse creates a moving perturbation of the refractive index; the perturbation is capable to scatter co-propagating pulses. An ultrashort optical soliton serves, under suitable conditions, as an impenetrable mirror for the group-velocity matched small-amplitude waves. Reflection of such waves by a quickly moving mirror in dispersive media is a rich source of the intriguing phenomena including analogue event horizons and radiation at negative frequencies. On the other hand, energy exchange between the scattered pump waves and the soliton provides an effective way to manipulate the soliton, e.g., to fix its frequency or to compress it to a large extent.

Soliton Explosions and Optical Rogue Waves

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Keywords: *fibre lasers, mode-locking, nonlinear optics,*

We will present our recent results regarding the observation of soliton explosions in an all-normal dispersion fibre laser. Using a real time dispersive Fourier transform we were able to make single shot measurements of the spectrum showing how the explosion happens in frequency space and how this translates to the temporal behaviour of the pulse. Simulations of the generalised nonlinear Schrodinger equation agree well with the experimental results and highlight the regions between stability and chaos in such systems. Further investigations highlight the presence of optical rogue waves and chimera states in such a laser which will be discussed in the presentation.

Asymmetric balance in symmetry breaking

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Keywords: *spontaneous symmetry breaking, nonlinear optics, optical resonators, polarization dynamics, optical fibres*

Spontaneous symmetry breaking is central to our understanding of physics and explains many natural phenomena, from cosmic scales to sub-atomic particles. Its use for applications requires devices with a high level of symmetry, but engineered systems are always imperfect. Surprisingly, the impact of such imperfections has barely been studied, and restricted to a single asymmetry. Here, we experimentally study spontaneous symmetry breaking in presence of two controllable asymmetries. We remarkably find that the characteristic features of spontaneous symmetry breaking, while dramatically destroyed by one asymmetry, can be entirely restored when a second asymmetry is introduced. In essence, asymmetries are found to balance each other. Our study illustrates aspects of the universal unfolding of the pitchfork bifurcation, and provides new insights into a key fundamental process. It also has practical implications, showing that asymmetry can be exploited as a new degree of freedom. In particular, it would enable sensors based on symmetry breaking or exceptional points to reach divergent sensitivity even in presence of imperfections. Our experimental implementation built around an optical fibre ring additionally constitutes the first observation of the polarization symmetry breaking of passive driven nonlinear resonators.

Laser modelocking beyond Haus: the coherent master equation

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Keywords: *laser modelocking, master equation, coherent effects*

Haus master equation (HME) is the standard theoretical approach to laser modelocking which has proven successful in many different situations. However HME is unable to account for light-matter coherent effects which are at the basis of certain types of laser modelocking and frequency comb generation in, e.g., quantum-dot and quantum-cascade lasers. Here we present a new theoretical framework for master equation laser modelocking modeling, which consistently incorporates coherent effects: the coherent master equation (CME). As a proof of its coherent nature, CME captures the Risken-Nummedal-Graham-Haken self-modelocking instability. We apply the new approach to an amplitude-modulated mode-locked laser, whose CME yields predictions that differ from HME which are most prominent when the gain recovery time is comparable or shorter than the cavity roundtrip time. These divergent predictions include the existence of non-Gaussian pulses and the asymmetric effect of the modulation frequency, which are verified experimentally in an actively modelocked semiconductor laser with a long external cavity.

Nonlinear Interaction and Symmetry Breaking of Light in Optical Microresonators

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Keywords: *nonlinear optics, microresonators, symmetry breaking, photonics, kerr effect*

Ultra-high-Q microresonators can confine extremely large amounts of optical energy in tiny mode volumes. This talk will focus on recent realizations of nonlinear interaction of counter-propagating light in these resonators. Particularly, above a certain threshold power, light of a given frequency can only circulate in one direction. Experimental and theoretical results show spontaneous symmetry breaking that follows from the interaction of the counterpropagating light. The resulting nonreciprocity of the light propagation in the microresonators can be used for novel applications including integrated photonic isolators and circulators.

Giant broadband refraction and nonlinear optics in ferroelectric super-crystals

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Keywords: *nonlinear optics, photonics, ferroelectrics, super-crystals, second-harmonic-generation*

We review recent progress in the study of linear and nonlinear propagation in ferroelectric super-crystals. The three-dimensional super-lattice of spontaneous polarization vortices leads to giant broadband refraction across the entire visible spectrum. Absence of diffraction, chromatic dispersion, and propagation normal to the crystal facets is compatible with giant values of index of refraction larger that 25. The huge values of optical susceptibility greatly enhance second-harmonic generation efficiency with broadband spectral and angular acceptance.

Spatio-temporal molding of light in caustic networks

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Keywords: *caustics, random matter, spatio-temporal pattern formation, extreme waves, branched flows, rogue waves,*

Caustic light revolutionized optics in the last decade in the areas of structured light and random waves. On the one hand, tailored caustic beams serve as fabricating light for (nonlinear) material processing, transfer complex momentum flows for advanced micro-manipulation, and enable novel high-resolution imaging methods. On the other hand, the random focusing of light rays forms networks of caustics that appear as high-intensity ramifications in many optical systems. This linear focusing, caused by strong wavefront aberrations and denoted as branched flow, yields waves with extreme amplitudes – so called rogue waves, originally studied in oceanography. Optics has proven to be a vast testbed to investigate different linear and nonlinear mechanisms for the formation of

rogue waves as spatio-temporal wave phenomena. Though there are indications that the two different mechanisms described above, branched flows and nonlinear modulation instabilities, contribute to the formation of rogue waves, the influence of their mutual interplay on the rogue wave statistic is still an open question.

In our contribution, we exploit a nonlinear photorefractive material as an optical platform to investigate these different mechanisms for rogue wave formation simultaneously in a single system. We show that free-space branched flows of light caused by wavefront distortions in form of correlated Gaussian random fields (GRFs) focus to caustic networks with controllable extension and sharpness, which in turn determine the probability for the occurrence of optical rogue waves. This focusing can be enhanced by propagating GRFs in a nonlinear refractive index structure with focusing nonlinearity. Beyond propagating in homogeneous media, we fabricate two-dimensional tailored photonic disorder in such a photorefractive crystal and investigate the mutual interplay of linear focusing by GRFs and scattering. We find optimal conditions for enhanced focusing of waves with extreme intensities by controlling the size and strength of the disordered photonic refractive index structure.

Thus, in our contribution, we will link different mechanisms for rogue wave formation that are commonly studied separately and discuss their interplay. Our work demonstrates that different focusing mechanisms can enhance or depress the formation of rogue waves, thereby introducing an optical platform that allows exploring rogue waves far beyond the optical realization, and allows new insights into general spatio-temporal wave dynamics.

Nonlinear polariton fluids

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Keywords: *polaritons, strong coupling, nonlinear fluids, solitons, quantum vortices*

Polaritons are very interesting quasiparticles, that are generated in semiconductors as a hybrid mixture of light and the material's optical excitation. They inherit a strong nonlinearity from the exciton component while keeping a high coherence as well as a nonparabolic dispersion from the photon counterpart. These features can activate, among other effects, Bose-Einstein condensation [1], nonlinear quantum fluid dynamics [2] and even quantum correlations [3]. In this talk we will show variegated nonlinear spatiotemporal reshaping phenomena in microcavity polaritons, where the whole fluid can be described by a collective wavefunction characterised by bistability regions, solitons and quantum vortices. We will also discuss the fundamental repulsive nonlinearity of exciton-polaritons, which can trigger the formation of two-dimensional X-waves [4], or ignite expanding shock waves and sustain stable dark soliton rings [5]. In particular, we will describe a novel effect of retarded nonlinearity inversion, that results in the dynamical formation of a bright soliton [5]. The simultaneous presence of the central density singularity and the radially-expanding cloud recall the exotic structures that are also seen in condensed matter bosonic supernovas. Finally, we will show how we can seed and track quantum vortices in the polariton fluid on the picosecond timescale. These quantum vortices are characterized by a central phase singularity surrounded by an azimuthally-winding cloud. The observations highlight a rich nonlinear phenomenology, such as the vortex spiralling, splitting, and the ordered branching into newly generated secondary couples [6]. These events remind of the particle pair generation effect. Remarkably, we also observe that vortices placed in close proximity experience attractive-repulsive scenarios. Such nonlinear vortex pair-interactions can be described by a tuneable effective potential [7], reminiscent of Lennard-Jones potential existing between molecules.

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Real-time measurement of instabilities in optical fibres and optical fibre lasers

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Keywords: *solitons, lasers, ultrafast optics*

There have been many recent dramatic advances in the real-time measurement of ultrafast non-repetitive optical signals based on the use of the dispersive Fourier transform in the frequency domain, or time-lens approaches and related techniques in the time domain. In the context of propagation in nonlinear optical fibres, these real-time methods were initially used to study modulation instability, supercontinuum generation and rogue-wave phenomena, but were rapidly applied to study instabilities in modelocked lasers. In this presentation, we will review our recent work in this area, including results studying single-pass instabilities in optical fibre, as well as recent work studying complex pulse evolution behavior observed during the generation of dissipative soliton structures in a fiber laser. These results provide a unique picture of the internal evolution of dissipative solitons in a laser system, and we anticipate further applications in understanding the underlying laser dynamics and optimizing laser performance and stability.

Analogue gravity in rotating spacetimes

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Keywords: *photon fluids, analogue gravity*

Superradiant gain is the process in which waves are amplified via their interaction with a rotating body, examples including evaporation of a spinning black hole and electromagnetic emission from a rotating metal sphere. We will first discuss the case of photon fluids, i.e. room temperature superfluids generated by a laser beam propagating in a non-linear defocusing material. Prior work has already demonstrated the superfluid nature of the 2D beam profile in this setting and we have recently studied that by injecting a vortex pump beam, it is possible to generate a rotating spacetime metric and experimentally identify the horizon and ergo-sphere. Numerical studies based on the Nonlinear Schrodinger equation now illustrate the conditions under which experiments are expected to observe superradiance by analyzing the optical currents in the system. Finally, we will examine a different scenario, more akin to the sutation examined in 1971 by Zel'dovich, i.e. a rotating cylinder. We elucidate theoretically how superradiance may be realized in the field of acoustics, and predict the possibility of non-reciprocally amplifying or absorbing acoustic beams carrying orbital angular momentum by propagating them through an absorbing medium that is rotating. We discuss a possible geometry for realizing the superradiant amplification process using existing technology.

Predicting Extreme Events in Modulation Instability Using Machine Learning

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Keywords: *modulation instability, real-time measurements, machine learning*

The study of instabilities that drive extreme events is central to nonlinear science. Perhaps, the most canonical form of nonlinear instabilities is modulation instability (MI) describing the exponential growth of a weak perturbation on top of a continuous background. In optical fibres, when driven initially by small-amplitude noise, MI has been shown to lead to the emergence of localized temporal breathers with random statistics. It has also been suggested that these dynamics may be associated with the emergence of extreme events or rogue waves [1,2]. However, direct measurement in the time-domain of the breather properties is extremely challenging, requiring complex time-lens systems that typically suffer from drastic experimental constraints [3,4]. Real-time spectral measurement techniques such as the dispersive Fourier transform (DFT) on the other hand are commonly used to measure ultrafast instabilities [5]. Although relatively simple to implement, the DFT only provides spectral information. Here, we show how machine learning can overcome this restriction to study time-domain properties of optical fibre modulation instability based only on spectral intensity measurements. Specifically, we demonstrate that it is possible to train a supervised neural network to correlate the spectral and temporal properties of modulation instability using numerical simulations, and then apply the trained neural network to the analysis of high dynamic range experimental MI spectra and yield the temporal probability distribution for the highest peaks in the instability field [6].

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The LANER: optical networks as complex lasers

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Keywords: *lasers, networks, dynamics, fibers, optics*

We present the main features of a recently introduced system capable of laser action: the complex active optical network, or lasing network (LANER). The system is experimentally realized with optical fibers linked each other with couplers and with one or more coherently amplifying sections. A linear theoretical description shows how the LANER can be considered as a generalization of the laser with the physical network acting as a complicated cavity, and can be represented by directed graphs disclosing the analogies with the problem of quantum chaos on graphs. Experiments in simple configurations are reported, with evidence of lasing action and its characterization. Examples of spectra of the detected emitted intensity are obtained in different cases, in a phenomenological agreement with the numerical findings of the theory.

Third Order Dispersion in Time-Delayed Systems: Applications to the Passive Mode-locking of VECSELs

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Keywords: *third order dispersion, ultrashort pulses, mode-locking, time delayed systems*

Time-Delayed dynamical systems (DDSs) materialize in situations where distant, point-wise, nonlinear nodes exchange information that propagates at a finite speed. They describe a large number of phenomena in nature and they exhibit a wealth of dynamical regimes such as localized structures, fronts and chimera states. A fertile perspective lies in their interpretation as spatially extended diffusive systems which holds in the limit of long delays. However, DDSs are considered devoid of dispersive effects, which are known to play a leading role in pattern formation and wave dynamics. In particular, second order dispersion in nonlinear extended media governs the Benjamin-Feir (modulational) instability and also controls the appearance of cavity solitons in injected Kerr fibers. Third order dispersion is the lowest order non-trivial parity symmetry breaking effect, which leads to convective instabilities and drifts.

In this contribution, we review our recent results regarding how second and third order dispersion may appear naturally in DDSs by using a more general class of Delayed Systems, the so-called Delay Algebraic Delay Differential Equations. This class of DDS appears for instance in the modeling of Vertical External-Cavity Surface-Emitting Lasers (VECSELs) and we illustrate our general result studying the effect of third order dispersion onto the optical pulses found in the output of a passively mode-locked VECSEL and link our results with the Gires-Tournois interferometer. We show that third order dispersion leads to the creation of satellites on one edge of the pulse which induces a new form of pulse instability. Our results are in good agreement with the experiment. Finally, we connect these results with the possibility of obtaining Light bullets, that is to say, pulses of light that are simultaneously confined in the transverse and the propagation directions, in mode-locked VECSELs.

Nonlinear polariton phenomena in semiconductor microcavities and slab waveguides

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Keywords: *polariton, soliton, continuum generation, cherenkov*

When light propagates through an optically active semiconductor material hybridisation of the optical and electronic excitations (photons and excitons) may occur. This leads to the formation of novel quasi-particles, so-called polaritons. The exciton component in the polariton wavefunction leads to giant repulsive interactions between the two colliding quasi-particles (giant Kerr-like nonlinearity), which enable control of light by light at ultrafast speeds. This is potentially useful for applications in all-optical signal processing. The strong polariton nonlinearity also results in many-body phenomena ranging from superfluid-like behaviour of light to Bose-Einstein condensation and ultra-low power soliton physics which develop on short time- and length-scale at very weak excitation powers. In my talk I am going to review several nonlinear polariton phenomena including backward Cherenkov radiation by polariton solitions, spin domain formation, vortex-vortex generation, polygon pattern formation and spatio-temporal continuum generation [1-5] .

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Statistical properties of the speckle pattern at the output of a multimode optical fiber

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Keywords: *speckle pattern, speckle contrasts*

Speckle patterns are intensity patterns produced by coherent waves interfering with each other. They typically occur due to reflections of coherent laser light in rough surfaces or in media with scattering particles on the scale of the wavelength. Speckle is often undesired in imaging because of the grainy image produced. On the other hand, the spatial correlations present in the speckle pattern contain information that can be used to reconstruct the object that generates the speckle. Low-cost vibration sensors have been demonstrated, which measure the frequency of the vibrations by monitoring the speckle pattern that changes in time. As speckle patterns are wavelength-dependent, after calibration they can also be exploited for implementing low-cost high precision wavemeter. In this contribution we study experimentally how the statistical properties of the speckle pattern at the output of a multimode fiber, generated by using as light source a diode laser in the visible range, depend on the exposure time of the CCD camera and on the degree of coherence of the light, which is controlled by varying the laser pump current from below to above the threshold. Using the standard speckle contrast measure (the mean intensity of the pattern normalized to the standard deviation), we determine under which conditions the speckle pattern can be either minimized or maximized.

Parametric interactions in multimode fibers

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Keywords: *nonlinear parametric interaction, grin multimode fiber, self-imaging effect, geometric parametric instability, intermodal four wave mixing and modulational instability*

Over the last few years, it has been demonstrated that multimode fibers (MMFs) offer novel opportunities to explore the nonlinear coupling between the temporal and spatial effects. In particular, the process of periodic self-imaging (SI) of light occurring inside graded-index (GRIN) MMFs has been found to play a major role in the nonlinear propagation of optical pulses with normal dispersion. In this talk, we focus on the spectral evolutions of an input narrowband multimode beam induced by the SI effect. First, we show that when a large number of modes is initially excited in a highly multimode fiber, SI leads to an original phenomenon of geometric parametric instability characterized by the generation of an intense frequency comb spanning from the near-ultraviolet to the near infrared. On the other hand, for powerful pulses, all parametric sidebands are characterized by a bell-shape beam similar to that emerging from a single-mode fiber. By limiting the nonlinear interactions to the lowest order fiber modes only, we study the influence of a superimposed seed centered on the first-order parametric Stokes sideband, on the efficiency of the multiple sideband generation processes. We show that the injected seed can stimulate the generation of new spectral sidebands in the visible and near-infrared regions of the spectrum. The second part of the talk is dedicated to intermodal four-wave-mixing and modulational instability that occur in a few-mode GRIN fiber. We show that far-detuned (from 200 up to 450 THz) frequency conversion is obtained via intermodal four-wave-mixing with an important role played by a secondary pump in the subsequent supercontinuum generation. Moreover, we observe a strong power dependence of intermodal modulational instability. Finally, we introduce the concept of spectral control of parametric sidebands in GRIN MMFs by tailoring their linear refractive index profile with a Gaussian dip into the refractive index profile.

Symmetry breaking of the non nonlinear stage of modulation instability : a complete experimental characterization in optical fibers

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Keywords: *fpu recurence, modulation instability, four wave mixing, soliton, akhmediev breather*

We report an original method enabling a non invasive characterization in phase and intensity of the longitudinal evolution of the main spectral components involved in the Fermi Pasta Ulam recurence process. We will show that it allows to evidence the symmetry breaking of the process.

Future prospects and recent results will be presented.

Rotating spatio-temporal structures and rotating cavity solitons in scalar and vectorial Kerr resonators

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Keywords: *turing patterns, cavity solitons, orbital angular momentum*

We consider generalisations of the Lugiato-Lefever models for transverse Kerr cavities with one or two field components and pumped by beams carrying optical angular momentum (OAM). These studies complete early investigations that focused on optical parametric oscillators, semiconductor heterostructures and photorefractive materials, respectively [1]. In particular we find analytical expressions that fully describe two-dimensional rotating Turing structures and rotating cavity solitons in single field (scalar) Kerr resonators. Rotating localised states on a transverse ring can be considered as slow light pulses with fully controllable speed and structure for use in optical quantum memories and delay lines.

The inclusion of a second field component in the light-matter interaction inside the cavity offers further degrees of control in the shape, rotation and polarization of the nonlinear structures. Numerical simulations of coupled circularly polarized beams with inputs of equal, opposite and different OAM, result in fully-structured optical beams made of periodic or localised nonlinear structures and a multitude of shapes, phases, polarization, singularities and dynamics. Applications of these rotating structures to particle manipulation, optical beam shaping and photonic devices will also be discussed.

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Non linear diffraction

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Keywords: *wave breaking, dispersive shock waves, airy beams*

In a nonlinear medium, the phase and amplitude of a coherent beam are affected by nonlinearity. This modifies the laws of geometrical optics and may also lead to a gradient catastrophe resulting in complex optical patterns. I will discuss two such configurations resulting in the formation of a dispersive shock in a local nonlinear medium and of an Airy beam in a highly nonlocal one.

Disorder-induced acceleration of wave condensation in multimode fibers

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Keywords: *optical turbulence, condensation, thermalization, multimode fibers*

Recent studies on wave turbulence revealed that a purely classical system of random waves can exhibit a process of condensation that originates from the divergence of the Rayleigh-Jeans (RJ) equilibrium distribution, in analogy with the quantum Bose-Einstein condensation (see references in [1]). However, the observation of optical wave condensation in a conservative (cavity-less) configuration is hindered by the prohibitive large propagation lengths required to achieve the RJ thermalization.

A phenomenon of spatial beam self-cleaning has been recently discovered in multimode optical fibers (MMFs), whose underlying mechanism still remains debated [2]. Light propagation in MMFs is affected by a structural disorder of the material. We formulate a wave turbulence kinetic description of the random waves accounting for the impact of the disorder. The theory unexpectedly reveals a dramatic acceleration of thermalization and condensation by several orders of magnitudes, which can probably explain the effect of spatial beam self-cleaning as a macroscopic population of the fundamental mode of the MMF [1]. The theory also explains why spatial beam self-cleaning has not been observed in step-index MMFs.

Our experiments in MMFs evidence the transition to light condensation: By decreasing the kinetic energy ('temperature') below a critical value, we observe a transition from the incoherent thermal RJ distribution to wave condensation [1]. These observations are corroborated by the experimental evidence that beam self-cleaning is characterized by a turbulence cascade of kinetic energy toward the higher-order modes of the MMF [3].

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Single-shot observations of modulation instability in optical fibres : full complex field acquisition and space-time evolution

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Keywords: *modulational instability, optical fibers, fast detection, nonlinear schrodinger equation*

Light propagating in optical fibers might undergo a modulation instability which leads to the break-up of a continuous wave field. In this presentation, we review recent experiments where both the intensity and phase of the field are recorded at the output of a fiber thanks to an improved temporal imaging system, showing in details the formation of ultra-fast nonlinear structures. We also show how the spatio-temporal evolution of the intensity can be revealed using a recirculating fiber loop.

Competing mechanisms of nonlinear modulation instability

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Keywords: *modulation instability, breathers*

The nonlinear stage of modulation instability (MI) is extremely rich. For periodic perturbations multiple recurrences occurs according to a complex homoclinic structure that represents the continuation of MI in the depleted stage. When the perturbation becomes localized the MI recurrences break down and different scenarios are possible. A quite universal scenario is the development of an auto-modulation, i.e. a strongly oscillating structure within a characteristic wedge-shaped region that smoothly connect to the background. However, for sufficiently generic perturbations the auto-modulation can be accompanied by the emission of breather pairs. In this talk we discuss how to predict the parameters of such breathers in terms of simple formulas.

Spatio-temporal dynamics in fibre lasers

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Keywords: *coherent structures, spatio-temporal dynamics, fibre lasers*

Understanding of the properties of nonlinear photonic systems is important both for the fundamental science and because of their relevance to numerous applications of light technology. Nonlinearity is an essential component in the design of numerous photonic devices, but it is often shunned by engineers in view of its practical intractability and greatly increased difficulty of comprehension of system behavior. The understanding and mastering of nonlinear effects can translate into improving performance of the existing devices and enabling a new generation of engineering concepts. However, many measurement techniques and signal processing methods have been developed and optimised for linear systems. Understanding of nonlinear dynamics would greatly benefit from new measurement approaches. I will review our recent works on the nonlinear science of fibre lasers, including spatio-temporal dynamics and new approaches for theoretical and experimental analysis of such systems.

Molded nonlinear light wave packets and applications

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Keywords: *filaments, extreme fields, thz, silicon photonics, materials engineering*

The nonlinear propagation of ultrashort laser pulses in the form of solitons, filaments and light bullets is an exciting research field [1]. Beyond the basic studies on the complex spatio-temporal phenomena involved, the field is driven significantly by its numerous applications, like for example in materials engineering, remote spectroscopy, but also for their use as powerful secondary sources across the electromagnetic spectrum [2]. Here we discuss our recent advances in molding the shape, temporal and spectral properties of filaments [3] and some corresponding applications enabled through these advances. We demonstrate how it becomes possible, for the first time after 20 years of research, to achieve localized and controlled modification of the index of refraction in the bulk of silicon [4]. This advance opens the way for laser processing in the exciting field of silicon photonics. We also discuss our recent advances in developing intense THz secondary sources using tailored laser filaments. We demonstrate that one may obtain powerful THz radiation using unconventional media, like liquids, where the medium presents strong linear absorption [5]. The mechanism responsible for this counterintuitive result is a phase locked second harmonic component in the filament that results in strong transient electron currents that radiate intense THz fields. Finally, we will also be discussing the way in achieving extreme THz electric and magnetic fields, in excess of GV/cm and kilo-Tesla strengths respectively, using intense two-color mid-infrared filaments [6,7].

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Nonlinear wave phenomena in delay differential models of multimode lasers

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Keywords: *multimode lasers, mode-locking, delay differential equations, bifurcations, dissipative solitons*

Multimode lasers are widely used in medical, industrial, and technological applications. In particular, mode-locked semiconductor lasers are low cost, compact, and efficient sources of short optical pulses with high repetition rates suitable for application in telecommunication networks. A conventional technique to the theoretical studies of these lasers is based on numerical integration of a system of partial differential equations for the electric field envelope and carrier density. Here we use an alternative approach to describe multimode lasers, based on the use of delay differential equations (DDEs). We investigate DDE models of different multimode laser devices, - nonlinear mirror mode-locked lasers generating short optical pulses, frequency swept lasers with a long dispersive fiber delay line, and broad area external cavity semiconductor lasers. In addition to numerical simulations of these models we perform an analytical linear stability analysis that reveals modulational, Turing-type, and flip instabilities of CW regimes. We demonstrate the existence of bistability, chaotic regimes, square waves, as well as temporal and spatio-temporal (light bullets) localised structures of light and discuss their properties and interaction.

Spatiotemporal multimode light waves

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Keywords: *optical fibers; nonlinear optics, fiber amplifiers, kerr effect*

Nonlinear propagation of optical pulses in multimode fibers is subject to complex spatio-temporal phenomena. We outline different strategies for the control and optimization of nonlinear mode coupling. The first approach involves transverse wavefront shaping of the input beams, which permits to launch an optimized mode combination, that results in the generation of a stable nonlinear mode alphabet at the fiber output. The second approach involves the longitudinal variation of the core diameter of multimode active and passive tapers, which leads to tailored supercontinuum generation with high spatial beam quality.

including numerical and experimental comparisons.

Poster session

The number after the title corresponds to the poster spot during the poster session.

Hybrid-Kinetic Simulations of Low- and High-Beta Turbulence ①

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Keywords: *turbulence, instabilities*

A lot of astrophysical environments, such as accretion flows around black holes, the intracluster medium, and the solar wind, are weakly collisional (or collisionless) and well magnetized. We present results from hybrid-kinetic simulations of turbulence relevant to these systems. Our low-beta simulations (where beta is the ratio of thermal and magnetic pressures) reproduce the observed preferential perpendicular ion heating and the development of non-thermal beams in the ion distribution function in the solar wind. Our high-beta simulations focus on the effects of kinetic micro-instabilities on the turbulent cascade, in particular, how they disrupt inertial-range Alfven waves and introduce an effective collisionality in otherwise collisionless plasma.

Quantum Fluids of light in atomic vapors ②

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Keywords: *shockwaves, rubidium, thermal vapors, fluids of light*

Since its discovery in 1995, Bose-Einstein Condensation (BEC) is a powerful object for quantum experiments. Its coherence offers a lot of possibilities for measuring quantum phenomena. Even though BEC is well studied with ultracold atoms cloud, an analogy for classical waves propagating in a non-linear medium can be established and condensation of classical waves has been predicted. Our experiment is based on the use of an atomic vapor as a non linear medium. By heating a Rubidium cell, we create a nonlinear medium with adjustable non linearity. By modifying the properties of the incident laser beam (shape, size, frequency, etc) we are able to study a wide range of phenomena. After the observation of precondensation of classical waves in this system, we turned to a study of shock wave creation in this system. We will present first results on this investigation,

Towards the generation of light-bullets in semiconductor lasers ③

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Keywords: *solitons, semiconductor lasers, localized structures*

Localized structures (LS) are nonlinear solutions of dissipative systems characterized by a correlation range much shorter than the size of the system. Since they are individually addressable, LS can be used as fundamental bits for information processing in optical resonators. While spatial LS are confined peaks of light appearing in the transverse section of broad-area resonators, temporal LSs are short pulses travelling back and forth in the longitudinal direction of the cavity. Spatial and temporal LS have been observed independently in semiconductor lasers systems based on a gain medium coupled to a saturable absorber.

In this work we present preliminary results for the generation of spatio-temporal localized structures, also called “Light bullets”, in semiconductor lasers. In this case, light is stored in the three spatial dimensions, leading to information processing with disruptive performances in terms of bit rate, resilience and agility. Despite the effort made in nonlinear optics, only fading LB have been observed so far experimentally. Our approach consists of chasing “dissipative” LB, which will be robust and suitable to applications. Accordingly, once LB will be obtained and characterized, their application to information processing will be addressed by targeting a three-dimensional electro/optical buffer. The results shown were obtained using a vertical external cavity surface emitting laser, composed by a gain mirror and a semiconductor saturable absorber mirror (SESAM). These components have been properly engineered for matching the parameters requirements for implementing light bullets, which require a cavity roundtrip time much larger than the carrier relaxation time, a large Fresnel number and a bistable response of the system. We show that self-imaging condition between the gain section and the SESAM enables the first two conditions, while bistability can be obtained by designing the modulation depth of the SESAM.

MMS observations of particle velocity distribution functions and field-particle correlator ④

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Keywords: *plasma, mms, data*

We present our current work on the analysis of MMS data carried out in particular with particle velocity distribution functions (VDF). We propose methods that tackle the high time resolution of these four-dimensional data sets, in various reference frames and coordinate systems. In particular, we explore the feasibility of obtaining spatial and time derivatives of the VDF, with the inherent price in terms of time resolution/integration. Together with field measurements, these derivatives enable the quantification of the various terms of the Poisson-Vlasov equations, with the ultimate goal of a direct measurement of the energy exchange taking place between fields and particles, as a function of velocity, following the effort initiated by Howes et al. 2017 and Chen et al. 2019.

Study of brownian motion at short time scales ⑤

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Keywords: *optical tweezer, brownian motion*

We experimentally study the brownian motion of an optically trapped micrometric particle in liquids at ultrashort timescales in order to reveal the effects of fluid compressibility on its dynamics.

To that purpose, standard trapping and detection schemes are coupled to femtosecond "pump-probe" experiment to take advantage of the high temporal resolution of time resolved ultrafast spectroscopy experiments. The goal is to achieve a proper measurement of the instantaneous velocity of the brownian particle beyond the ballistic regime to probe the influence of compressibility effects on the motion of the trapped sphere, measurement that has never been made and remains elusive. The expected spatial and temporal resolutions (0.15 fm at 1 ps) provided by these techniques will allow us to measure the Velocity Auto Correlation Function to obtain an evidence of compressibility effects on the particle dynamic.

This type of study provides new features into investigations of non equilibrium physics related to brownian motion and optical tweezers.

Structure and evolution of magneto-hydrodynamic solitary waves with Hall and finite Larmor radius effects ⑥

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Keywords: *magnetohydrodynamics, solitary waves*

There exist a broad variety of nonlinear-wave phenomena in the solar wind. Different types of stable large-amplitude solitary waves are typically observed in these plasmas. The study of small amplitude waves can be described by well-known equations: Korteweg-de-Vries (KdV), modified KdV, Derivative Nonlinear Schrödinger (DNLS) and triple-degenerate DNLS. However, magneto-hydrodynamic (MHD) fluid equations are more suitable for the analysis of large-amplitude structures, which is the approach used in this work [1] —to be precise, MHD equations with Hall effect and Finite Larmor Radius (FLR) corrections to the double adiabatic pressure tensor. Assuming travelling wave solutions, the system of partial differential equations yields a set of 5 ordinary differential equations (ODEs) governing the spatial profile of the velocity and magnetic-field vectors —if double adiabatic equations of state are used for the gyrotropic pressures. The procedure to derive these equations follows Ref. [2], but some discrepancies are shown [1]. The existence of solitary-wave solutions in different parametric regimes is rigorously proved in this system of ODEs using concepts and tools from the theory of dynamical systems. Two key features of the concerning ODEs are: (1) the system is reversible and (2) the existence of an invariant which allows reducing the effective dimension of the system from 5 to 4. These characteristics are guaranteed if equations of state are used for the pressures. Nevertheless, only stable structures have physical interests and are expected to be observed in space. The global stability of the solitary waves is investigated by numerical spectral simulations using two different closures for the pressures: (1) double adiabatic equations and (2) evolution equations including the FLR work terms [3], which guarantee energy conservation and better reproduces the real physics. In case (1), it is found that the solitary waves may have a stable core even if the background is unstable. The background instability seems to disappear when the energy-conserving model (2) is considered. In this case, stable solitary waves are found that survive long time without significant deformation.

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Deformation of an elastic material paired with a tree structure ⑦

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Keywords: *respiratory physiotherapy, elasticity, fluid mechanics*

In order to model effects of automated treatment of respiratory physiotherapy with focused pulses, we study deformation of an elastic material under oscillating constraints on its boundaries. Moreover the system is linked to a symmetrical and dichotomous tree built as series of cylinders, idealizing bronchial tree. To do so, under infinitesimal strain theory, we consider that a change a volume on an area of the material creates airflow. Then we force it to flow in the tree and to go through hydrodynamic resistance. This coupling adds friction to the system and gives information on total airflow created at the top of the tree, i.e. at the mouth, under pressure on boundaries.

Plasma acceleration by the non-linear interaction of three crossed parallel Alfvén wave packets ⑧

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Keywords: *electron acceleration, alfvén waves collision, phase-mixing, nonlinear phenomena, numerical simulation*

We are doing numerical simulation with a (PIC) code to interact a parallel Alfvén wave packet with two another parallel Alfvén wave packets that have already interacted. The crossing of the two initial Alfvén waves generates density gradients in the plasma (APAWI process, Mottez (2012, 2015)). Then, the passage of the third Alfvén wave across this interaction region gives rise to powerful accelerated electron beams in the parallel direction through phase-mixing process. The efficiency of this process depends substantially on the polarity and the amplitude of the wave packets.

Competition between Kelvin-Helmholtz and nonlinear Lower Hybrid drift instabilities along Mercury-like magnetopause ⑨

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Keywords: *kelvin-helmholtz instability, lower hybrid drift instability, particle-in-cell simulations*

Boundary layers in space plasmas are always the locations of many phenomena allowing the mixing of plasma. But for a given boundary, different mechanisms can coexist and compete one with each others. In our work, we look at velocity shear boundary layers with a gradient of density and/or magnetic field. We observe that in presence of a density gradient, a lower hybrid drift instability (LHDI) develops along the layer much quicker than the Kelvin-Helmotz instability (KHI). Although the two instability develops at different scales (both spatial and temporal), we observe that the nonlinear phase of the LHDI can compete and even suppress the KHI, depending on the density gradient in the layer. Such a result can make us reconsider the main mixing mechanisms in plasma layers with strong density gradient, such as Mercury magnetopause.

Optimal Analog Data Compression with Reconfigurable Wave-Chaotic Systems ⑩

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Keywords: *analog wave-based signal processing, reconfigurable wave-chaotic system, metasurface, wave front shaping, chaotic microwave cavity*

Propagation of waves through wave-chaotic systems completely scrambles incident wave fronts. Recent computational imaging devices leverage this property to take compressed measurements of multiple input data streams. Here, we demonstrate that carefully configured wave-chaotic systems can optimally compress multiple incoming data streams. Using tunable metasurfaces, we reconfigure the boundary conditions of chaotic microwave cavities and report an experimental in-situ proof of the concept.

Smooth branch of travelling waves for the Gross-Pitaevskii equation in dimension 2 for small speed (11)

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Keywords: *travelling wave, gross-pitaevskii, pde*

We construct a smooth branch of travelling wave solutions for the 2 dimensional Gross-Pitaevskii equations for small speed. These travelling waves exhibit two vortices far away from each other. We also compute the leading order term of the derivatives with respect to the speed. We construct these solutions by an implicit function type argument. In collaboration with David Chiron

Fluids of light in nonlinear crystals (12)

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Keywords: *fluids of light, photorefractive effect, superfluidity*

Quantum fluids of light merge many-body physics and nonlinear optics, revealing quantum hydrodynamic features of light when it propagates in nonlinear media. One of the most outstanding evidence of light behaving as an interacting fluid is its ability to carry itself as a superfluid. Here, we report a direct experimental detection of the transition to superfluidity in the flow of a fluid of light past an obstacle in a bulk nonlinear crystal. In this cavityless all-optical system, we extract a direct optical analog of the drag force exerted by the fluid of light and measure the associated displacement of the obstacle. Both quantities drop to zero in the superfluid regime characterized by a suppression of long-range radiation from the obstacle. The experimental capability to shape both the flow and the potential landscape paves the way for simulation of quantum transport in complex systems.

Alternative exact law for homogeneous compressible turbulent flows: from Hall-MHD to hydrodynamics (13)

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Keywords: *mhd, hall effect, exact laws*

Fluid and plasma turbulence is a longstanding problem in physics. Studying its dynamics can help understanding various processes such as mass transport and energy dissipation, in particular in collisionless systems like most of the astrophysical plasmas. The solar wind heating problem, which is manifested by a slower decrease of the ion temperature as function of the heliocentric distance than the prediction from the adiabatic expansion model of the wind, is one example of such problems where turbulence can help give an explanation.

A way to study fluid or plasma turbulence is to estimate the total energy cascade rate, which is the energy transferred from the largest scales into the dissipative scales of the system. This is made possible by the use of exact laws, which link the energy cascade rate to the physical variables of the flow. Significant progress has been made in recent years on deriving various forms of exact laws for different compressible flows: HydroDynamics (HD), MagnetoHydroDynamics (MHD) and Hall-MagnetoHydroDynamics (HMHD). Some of them were used successfully to estimate the energy cascade rate in the solar wind and the magnetosheath, but at the expense of making additional assumptions that made different mathematical terms involved in the laws accessible to in-situ measurements.

Here we present an alternative exact law for compressible Hall-MHD turbulence. This law is more compact and easier to compute in numerical simulations and spacecraft data, thus reducing the memory load and time required to compute the energy cascade rate. We also show the validity of this new law in the limit of compressible HD using high-resolution simulation data of HD turbulence spanning the subsonic and supersonic regimes.

Light scattering by arrays of ultracold atoms with sub-walength spacing (14)

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Keywords: *ultracold atoms, light-matter interactions, cooperative scattering*

Ultracold atoms offer a unique platform to study the interaction of near-resonant light with an ensemble of resonant emitters. Our experiments probe an ensemble of alkali atoms cooled to a temperature where the inhomogeneous Doppler broadening is negligible and a two-level system can be isolated, so that cooperative scattering effects take place. We study in particular the dense regime where the interatomic distance is shorter than the wavelength of the light. In this regime the atoms interact strongly via the resonant dipole-dipole interactions, and their collective response is significantly modified with respect to the individual one. The geometrical arrangement plays in addition a crucial role in the enhancement of cooperative effects. We will present our recent experimental progress towards tailoring atomic ensembles with sub-wavelength interatomic distance, as well as perspectives in the short term for light-matter interaction experiments in such ensembles.

Propagation of waves along superfluid vortices trapping particles ⑮

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Keywords: *superfluid, vortex, waves, particles*

Superfluids like liquid helium or ultracold atomic Bose-Einstein condensates are an exotic state of matter in which quantum effects appear on a macroscopic scale. One of the main features of superfluids is the presence of topological defects with quantised circulation, known as quantum vortices. These vorticity filaments can reconnect dissipating energy through sound emission and thus they play a central role in superfluid turbulence. At the same time, helicoidal waves (called Kelvin waves) can propagate along the vortex filaments and interact nonlinearly among themselves, contributing to the energy transfer towards small scales. An important experimental breakthrough occurred in 2006, when quantum vortices were directly visualised by using micrometer-sized hydrogen particles. Since these particles are trapped inside the vortex core they can be used to track the motion of vortices themselves. Thanks to this method, quantum vortex reconnections and Kelvin wave propagation have been observed. Nowadays, particles are still the main experimental tool used to visualise quantum vortices and to study their dynamics. Our aim is to study the propagation of waves along a superfluid vortex filament, when active particles are trapped inside its core. We perform numerical simulations of a self-consistent model based on the Gross-Pitaevskii (GP) equation, in which particles are described as localised potentials depleting the superfluid and following a Newtonian dynamics. In a former work we have shown that this model is able to reproduce the capture of a particle by a quantum vortex line. Now we study how the dynamics of a collection of particles (impurities) already set inside the vortex reflects the motion of the vortex itself. We measure the spatiotemporal spectra of the system, showing how the presence of particles induces a nontrivial modification of the vortex wave dispersion relation. In order to explain the numerical results, we develop a theory that mixes hydrodynamic equations and basic solid-state concepts. In particular, we point out a remarkable analogy with the propagation of electrons in a crystal lattice.

Magnetic coherent structures in the presence of equilibrium temperature anisotropy ⑯

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Keywords: *magnetic vortices, temperature anisotropy, gyrofluid models, hamiltonian systems*

Coherent magnetic structures such as magnetic vortex chains have been observed in the solar wind close to the Earth by the Cluster space mission (Perrone et al. (2016, 2017)). Making use of a gyrofluid model, we investigate the existence of analytical solutions of magnetic vortex type and study their stability. The adopted model can provide a nonlinear description of turbulent collisionless magnetized plasmas accounting for ion finite Larmor radius, equilibrium temperature anisotropy and fluctuations of the component of the magnetic field parallel to the direction of a strong and uniform guide field. The model possesses a noncanonical Hamiltonian structure which provides a convenient framework for the use of analytical tools, such as the Energy-Casimir method for determining stability conditions. We carry out investigations for some asymptotic regimes of the model, such as for instance in the limit of a large ion-to-electron perpendicular equilibrium temperature ratio, with negligible electron inertia effects, and compare our results with those found recently in the framework of a reduced magnetohydrodynamics model (Jovanovic et al. 2018).

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Kinetic Turbulence in Astrophysical Plasmas: Waves and/or Structures? ⑰

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Keywords: *plasma turbulence, waves, coherent structures*

The question of the relative importance of coherent structures and waves has for a long time attracted a great deal of interest in astrophysical plasma turbulence research, with a more recent focus on kinetic scale dynamics. Here we utilize high-resolution observational and simulation data to investigate the nature of waves and structures emerging in a weakly collisional, turbulent kinetic plasma. Observational results are based on in situ solar wind measurements from the Cluster and MMS spacecraft, and the simulation results are obtained from an externally driven, three-dimensional fully kinetic simulation. Using a set of novel diagnostic measures we show that both the large-amplitude structures and the lower-amplitude background fluctuations preserve linear features of kinetic Alfvén waves to order unity. This quantitative evidence suggests that the kinetic turbulence cannot be described as a mixture of mutually exclusive waves and structures but may instead be pictured as an ensemble of localized, anisotropic wave packets or "eddies" of varying amplitudes, which preserve certain linear wave properties during their nonlinear evolution.

A Hamiltonian regularisations of barotropic Euler equations ⑱

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Keywords: *barotropic euler equations, regularisations*

The inviscid Burgers, Euler and Saint-Venant equations are nonlinear hyperbolic PDEs modeling fluid flows and surface water waves propagating in shallow water. These equations, prominent in physics, are the subject of numerous mathematical and numerical investigations. It is well-known that these equations develop shocks in finite time, even for regular initial conditions. These shocks are problematic, in particular, for numerical simulations. Therefore, several techniques have been proposed to regularized these equations. Adding viscosity or/and dispersion into the equations can avoid the formation of shocks. Here, we study a regularization of barotropic Euler equations, which conserves the energy, and generalize the conservative regularization of the Saint-Venant equations proposed by Clamond and Dutykh in 2017.

Short-distance propagation of nonlinear optical pulses ⑲

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Keywords: *nonlinear fluid, fluid of light, optics, dispersive shock waves*

We theoretically describe the quasi one-dimensional transverse spreading of a light pulse propagating in a defocusing nonlinear optical material in the presence of a uniform background light intensity. For short propagation distances the pulse can be described within a nondispersive approximation by means of Riemann's approach. We are also able to calculate the wave-breaking time, at which nonlinear nondispersive spreading leads to a gradient catastrophe. The theoretical results are in excellent agreement with numerical simulations. Experimental and theoretical studies have demonstrated the occurence of wave breaking even in absence of background. Our results exhibit this feature and the corresponding theoretical wave-breaking time agrees very well with simulations.

2D spatiotemporal extreme event in quadratic nonlinear crystal ⑳

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Keywords: *cascading process, quadratic soliton, second harmonic generation*

Solitonic waves are nonlinear self-sustained waves observable in a large number of conditions and various fields of physics, from electronics to optics via fluidics. Quadratic quasi-solitons have been early predicted by Karamzin et al. [1] and later observed by Torruellas et al. [2]. These types of self-guided beams have been seen, after modulation instability, in 2D spatial structures [3]. More recently, it has been shown that Peregrine solitons, and Akhmediev Breathers, could be obtained in quadratic materials [4].

In this paper we show spontaneous 2D quadratic extreme events, generated and controlled with non-collinear beams. We launched a large collimated beam (R = 200 µm, 30 ps) in a 8X8X30 mm KTP crystal cut for type II second harmonic generation. Beams first experienced a strong self-focusing leading to a stable 2D confined propagation. Because of the spatial walk-off due to the nonlinear crystal anisotropy, the trapped beams come with spatial reorientation, controlable by the initial polarization state. Additional self-confined events can appear in the transverse output pattern by increasing the input peak power. Such nonlinear spatial reshaping of the initial beam can also provide a way to control the apparition of 2D nonlinear periodic structures, a situation that reminds the Akhmediev Breathers solution, only valid in 1D.

These effects could be used to implement all-optical logic functions with ultrafast switching, but also to mimic the effect of a nonlinear saturable absorber able to realize ultrafast temporal pulse reshaping. The self-trapping process acts like a spatial self-cleaning process, which changes a set of initial non-collinear beams into a single one.

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A microwave realization of the chiral GOE ㉑

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Keywords: *random matrix theory, chiral ensembles*

The universal features of the spectra of chaotic systems are well reproduced by the corresponding quantities of the random matrix ensembles [1]. Depending on symmetry with respect to time reversal and the presence or absence of a spin 1/2 there are three ensembles: the Gaussian orthogonal (GOE), the Gaussian unitary (GUE), and the Gaussian symplectic ensemble (GSE). With a further particle-antiparticle symmetry there are in addition the chiral variants of these ensembles [2]. Relativistic quantum mechanics is not needed to realize the latter symmetry. A tight-binding system made up of two subsystems with only interactions between the subsystems but no internal interactions, such as a graphene lattice with only nearest neighbor interactions, will do it as well. First results of a microwave realization of the chiral GOE (the BDI in Cartan's notation) will be presented, where the tight-binding system has been constructed by a lattice made up of dielectric cylinders [3].

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Local energy transfers in incompressible MHD turbulence ㉒

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Keywords: *turbulence, magntohydrodynamics, energy transfers*

We present a local (in space and time) approach to the study of scale-to-scale energy transfers in magnetohydrodynamic (MHD) turbulence. This approach is based on performing local averages of the physical fields, which amounts to filtering scales smaller than some parameter ℓ. A key step in this work is the derivation of a local Kármán-Howarth-Monin relation which can be interpreted as a coarse-grained energy balance. This provides a local form of Politano and Pouquet's 4/3-law without any assumption of homogeneity or isotropy, which is exact, non-random, and connects well to the usual statistical notions of turbulence. After a brief presentation of this approach, we first apply it to turbulent data obtained via a three dimensional direct numerical simulation of the forced, incompressible MHD equations from the John Hopkins turbulent database. The local Kármán-Howarth-Monin relation holds well. The space statistics of local cross-scale transfers is studied, their means and standard deviations being maximum at inertial scales, and their probability density functions (PDFs) displaying very wide tails. Events constituting the tails of the PDFs are shown to form structures of strong transfers, either positive or negative, which can be observed over the whole available range of scales. As ℓ is decreased, these structures become more and more localized in space while contributing to an increasing fraction of the mean energy cascade rate. Second, we show how the same approach can be applied to spacecraft data where the main difficulty lies in the fact that measurements are restricted to few points, in one small region of space at a time, and a single scale. We compare our approach to results obtained from Cluster and MMS data using the LET proxy, and highlight its importance to the understanding of solar wind turbulence and solar wind heating.

Investigating properties of solar wind turbulence at sub-ion scales with in situ data and numerical simulations ㉓

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Keywords: *plasmas, turbulence, kinetic physics, solar wind, hybrid simulations*

We investigate the transition of the solar wind turbulent cascade from MHD to sub-ion range by means of in situ observations and hybrid numerical simulations. First, we focus on the angular distribution of wave-vectors in the kinetic range, between ion and electron scales, using Cluster mag-

netic field measurements. Observations suggest the presence of a quasi-2D gyrotropic distribution around the mean field, confirming that turbulence is characterised by fluctuations with $k_\perp \gg k_\parallel$ in this range; this is consistent with what is usually found at larger MHD scales, and in good agreement with our hybrid simulations.

We then consider the magnetic compressibility associated with the turbulent cascade and its evolution from large-MHD to sub-ion scales. The ratio of field-aligned to perpendicular fluctuations, typically low in the MHD inertial range, increases significantly when crossing ion scales and its value in the sub-ion range is a function of the total plasma beta, with higher magnetic compressibility for higher beta. Moreover, we observe that this increase has a gradual trend from low to high beta in the data; this behaviour is well captured by the numerical simulations. The level of magnetic field compressibility that is observed in situ and in the simulations is in fairly good agreement with the prediction based on kinetic Alfvén waves (KAW), especially at high beta, suggesting that in the kinetic range explored the turbulence is supported by KAW-like fluctuations.

Imbalanced kinetic Alfvén wave turbulence ㉔

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Keywords: *kinetic, gyrofluid, leith, turbulence, simulation*

A Hamiltonian 2-field reduced gyrofluid model for kinetic Alfvén waves taking into account ion FLR corrections, parallel magnetic field fluctuations and electron inertia, is used to study turbulent cascades, from the MHD to the electron ranges, in the case of imbalance between waves propagating along or opposite to the direction of the ambient magnetic field. The weak turbulence formalism in the absence of electron inertia leads to kinetic equations for the spectral densities of total energy and generalized cross-helicity, which reduce to those of RMHD at large scales, and REMHD at small scales. Leith-type nonlinear diffusion equations are derived in the limit of ultra-local interactions and a phenomenological formulation is obtained for the strong turbulence regime. These equations are studied analytically and integrated numerically. For a given level of imbalance in the MHD range, the flux of cross-helicity is much smaller when a dispersive range is present before dissipation scales are reached. Large imbalance leads to steeper sub-ion range spectra.

Combination of Kerr Beam Self-Cleaning and Supercontinuum Generation in Tapered Ytterbium-doped Multimode Fiber with Parabolic Core Refractive Index and Doping Profile ㉕

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Keywords: *nonlinear optics fibers, kerr effect, fiber optics amplifiers, supercontinuum generation*

The non-linear multimode optical fibers are opened a new window to study the spectral, spatial and temporal degrees of freedom of light beams that has been received a great fundamental and applicative interest during the last decades. In this article, we demonstrate spatial beam self-cleaning and supercontinuum generation in a new type of multimode fiber amplifier, consisting of a Ytterbium-doped (Yb-doped) multimode fiber taper with parabolic index refractive and doping profile, and a length of 9.5 m with a core diameter exponentially decreasing along its length from 120 to 40 microns. The beam self-cleaning, a bell-shaped output beam profile, has been achieved in passive configuration with an input beam peak power threshold of 20 kW and further increasing the input power causes no significant frequency conversion that can be attributed to the first Raman Stokes sideband. In active configuration, the gain leads to combine self-cleaning with super-continuum generation, spanning from the visible to the mid-infrared (520-2600 nm), which is due to the geometric parametric instability and the Raman stokes sideband. In both configurations, the self-beam cleaning in the tapered fiber can be ascribed to the accelerated self-imaging. Finally, we studied the evolution of self-cleaning and super continuum generation as a function of taper length in active configuration to analyze the spatial and spectral beam dynamics resulting accelerated self-imaging. We observed that the speckled output spatial distribution in the first meters evolved into a dual lobe, LP11 mode, and finally into the fundamental mode (LP01). The results obtained confirm the combination of accelerated self-imaging with landscape dissipative in the tapered Yb-doped multimode fiber with graded index profile that leads to control spectral and spatial light beams in the active mode.

Multidimentional Iterative Filtering: a new approach for investigating plasma turbulence in numerical simulations (26)

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Keywords: *magnetic reconnection, plasma turbulence, numerical simulations*

Turbulent space and astrophysical plasmas have a complex dynamics, which involve nonlinear coupling across different temporal and spatial scales. There is growing evidence that impulsive events, such as magnetic reconnection instabilities, bring to a spatially localized enhancement of energy dissipation, thus speeding up the energy transfer at small scales. Indeed, capturing such a diverse dynamics is challenging. In this work, we employ the Multidimensional Iterative Filtering (MIF) method, a novel multiscale technique for the analysis of non-stationary non-linear multidimensional signals. Unlike other traditional methods (e.g., based on Fourier or wavelet decomposition), MIF natively performs the analysis without any previous assumption on the functional form of the signal to be identified. Using MIF, we carry out a multiscale analysis of Hall-MHD and Hybrid particle-in-cell numerical simulations of decaying plasma turbulence. Preliminary results assess the ability of MIF to detect localized coherent structures and to separate and characterize their contribution to the turbulent dynamics.

Dissipation induced modulation instabilities: gain-through-losses in nonlinear optics (27)

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Keywords: *modulation instabilities, parametric amplification, loss-induced amplification*

We present results on a dissipative modulation instability caused by the presence of asymmetric spectral losses for signal and idler waves. Such instability can occur without satisfying standard phase-matching conditions and has applications in a variety of nonlinear optical systems especially in the design of a novel class of fiber optics parametric amplifiers, optical parametric oscillators and optical frequency combs sources.

Loss-induced tuneable optical frequency combs in a normal dispersion fibre resonator (28)

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Keywords: *modulation instability, optical frequency combs*

We present a novel method to generate Kerr optical frequency combs with tuneable repetition rate in normal dispersion externally driven optical resonators. Our novel technique is based on a peculiar way of achieving phase-matching thanks to intracavity filtering. We demonstrate experimentally an optical frequency comb with 100 GHz tuneability in the repetition rate and we provide a theoretical formula to predict the filter-induced phase-matching condition. Our results could be particularly relevant for tuneable optical frequency combs generation in the visible part of the electromagnetic spectrum where normal dispersion prevents exploiting existing techniques.

Temporal solitons in a delayed model of a semiconductor laser (29)

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Keywords: *semiconductor laser, chromatic dispersion, temporal solitons*

In the last few years temporal localised structures such as dissipative solitons observed in optical ring cavities received significant experimental and theoretical attention. Under some simplifying assumptions these solitons can be studied phenomenologically in the standard PDE frameworks of Lugiato-Lefever equation (LLE) and Haus master equation. On the other hand, delayed differential equation (DDE) models of semiconductor lasers proved to be very useful in qualitative analysis of various dynamical regimes for very wide realistic parameter ranges, and they can adequately represent different experimental set-ups. Recently, we demonstrated how the effect of chromatic dispersion arising due to dispersive element in the cavity such as a fiber loop can be modelled using a time-delay system, and derived a condition for modulational instability in the anomalous dispersion regime. This result allows us to make a theoretical connection between DDE models and LLE, and discuss the conditions under which solitons can be observed in semiconductor lasers.

Electron physics in Kelvin-Helmholtz instability in magnetized plasmas ㉚

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Keywords: *kinetic instabilities, numerical simulations*

Rolled-up vortices associated to the Kelvin-Helmholtz instability (KHI) have been detected by in-situ observations around the Earth, Saturn and Mercury magnetospheres due to the interaction with the solar wind. KHI in magnetized plasmas have been widely studied numerically in the framework of a fluid, hybrid, and full kinetic approach, while only very few studies have focused on the physics of electrons because of computational constraints. In this work we present a full kinetic particle in cell study of the KHI spanning a range of scales going from fluid to electron scales. The simulation is initialized with an extended fluid equilibrium including finite ion Larmor radius effects. Our large-scale configuration includes two-possible alignment of the vorticity with the background magnetic field each one corresponding to the interaction of the solar wind with the dawn and dusk side of a planet. We discuss electron heating and acceleration by analyzing temperature anisotropy and particle distribution functions. Two fluid simulations have suggested that KHI instability can lead to the onset of the mirror instability. Our full kinetic approach confirms such hypothesis. We discuss the formation of mirror modes in our simulations.

Can the state space of spatially extended systems and of time delayed systems be reconstructed from the time series of a scalar variable? ㉛

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Keywords: *spatially extended systems, bistable system, manifold, delayed feedback, reconstructed, pseudo-space*

The space-time representation of high-dimensional dynamical systems that have a well defined characteristic time scale has proven to be very useful to deepen the understanding of such systems and to uncover hidden features in their output signals. By using the space-time representation many analogies between one-dimensional spatially extended systems (1D SESs) and time delayed systems(TDSs) have been found, including similar pattern formation and propagation of localized structures.An open question is whether such analogies are limited to the space-time representation, or it is also possible to recover similar evolution in a low-dimensional pseudo-space. To address this issue, we analyze a 1D SES (a bistable reaction-diffusion system), a scalar TDS (a bistable system with delayed feedback), and a non-scalar TDS (a model of two delay-coupled lasers). In these three examples, we show that we can reconstruct the dynamics in a three-dimensional phase space, where the evolution is governed by the same polynomial potential. We also discuss the limitations of the analogy between1D SESs and TDSs.

Olfactory navigation by hunting octopuses: how to take decisions using a broken signal ㉜

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Keywords: *navigation, octopus, turbulence, olfaction*

Biological systems are surrounded by fluids and evolved spectacular adaptations to decode the sparse information brought by turbulence. My research project focuses on octopuses hunting in the ocean: they localize their prey using turbulent odor, water movement and pressure. I model octopuses and their environment using statistical fluid dynamics and decision theory. In my simulations a turbulent scalar (odor) evolves in water from a localized source (prey). Odor is an intermittent quantity that spreads from the source disgregating in fluctuating puffs. The shape of these intermittent puffs changes as they are deformed by the turbulent airflow far from the source. Detections occur within a conical volume which is the typical shape of the plume. I am currently developing algorithms to understand how can a octopus interpret this fluctuating signal to find its prey. Does it need a spatial or temporal memory for successful inference? I will show that simple inferences can be accomplished simply by averaging over the body of the octopus. However, to extract reliable information for more complex tasks, the dynamic features of this broken signal must be used.

Nozaki-Bekki Holes in a Long Laser ㉝

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Keywords: *nozaki-bekki holes, long laser, fdml, oct*

Long cavity fiber-based swept source lasers are promising devices with a wide range of potential applications ranging from communications to life sciences. For example, Fourier Domain Mode-Locked (FDML) lasers, which are commonly used for Optical Coherence Tomography (OCT) imaging applications, are long cavity lasers incorporating an intra-cavity resonator which is driven in resonance with the cavity round trip time. The coherence properties of such swept sources are of major importance as they define the image quality. The purpose of this work is to analyze the mechanism that deteriorates the coherence of long lasers. In our experiment, the laser included a 100nm wide semiconductor optical amplifier at 1310nm and a fiber cavity that could vary from 20m to 20km. The laser emission wavelength was controlled using a fiber based intra-cavity filter with a bandwidth of 10GHz. Near the lasing threshold and/or for fast carrier decay rate, we observed the appearance of periodic power dropouts with stable Nozaki-Bekki holes (NBH) that circulate in the laser cavity. As a function of the injection current, the laser could operate in various regimes including bi-stability between NBH and stable (cw) operation, unstable NBH or chaotic operation. Such behavior indicates that the interplay between the injection current and carrier decay rate can lead to highly coherent emission of a long cavity laser.

A simplified model of aquatic locomotion ㉞

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Keywords: *aquatic locomotion, inviscid flow theory*

We have developed a simple model of aquatic locomotion. Using the theory of complex variables, we have estimated the hydrodynamic forces acting on an infinite thin rigid plate of length L, following the seminal Work of Theordorsen [1].

By considering the different possible motions of the swimmer, we calculate the velocity potential to derive the pressure by means of the generalised Bernoulli relation. We show that the effect of flow unsteadiness is the principal mechanism for locomotion [2].

We impose a periodic rotation of the tail in order to approximate the undulatory motion of the swimmer. We show the linear dependence of longitudinal velocity on the angular frequency predicted by Gazzola et al [3] . We also predict that the transverse motion presents the same frequency as the forcing whereas the longitudinal motion is a linear function of time plus a periodic term with double frequency.

Finally, by taking the angle of the tail as a small parameter we perform a perturbative expansion to obtain an equation linking swimming velocity to the different parameters involved in swimming. The results arised from this perturbative method are in high accordance with the numerical results.

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Neuron-like dynamics of semiconductor lasers with optical feedback ㉟

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Keywords: *photonic neurons, semiconductor lasers, optical feedback, excitability, time series analysis*

Neuromorphic photonics is a new paradigm for ultra-fast neuro-inspired optical computing that can revolutionize information processing and artificial intelligence systems. To implement practical photonic neural networks is crucial to identify low-cost energy-efficient laser systems that can mimic neuronal activity. Here we study experimentally the spiking dynamics of a semiconductor laser with optical feedback under periodic modulation of the pump current, and compare with the dynamics of a neuron that is simulated with the stochastic FitzHugh-Nagumo model, with an applied periodic signal whose waveform is the same as that used to modulate the laser current. Sinusoidal and pulse-down waveforms are tested. We find that the laser response and the neuronal response to the periodic forcing, quantified in terms of the variation of the spike rate with the amplitude and with the period of the forcing signal, is qualitatively similar. We also compare the laser and neuron dynamics using symbolic time series analysis. The characterization of the statistical properties of the relative timing of the spikes in terms of ordinal patterns unveils similarities, and also some differences. Our results indicate that semiconductor lasers with optical feedback can be used as low-cost, energy-efficient photonic neurons, the building blocks of all-optical signal processing systems; however, the external cavity needed for optical feedback limits the laser integration in photonic integrated circuits

Multisection semiconductor laser for optical coherence tomography ㊱

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Keywords: *multisection lasers, optical coherence tomographie, sweep source, vernier effect*

Optical coherence tomography (OCT) is a non-invasive three-dimensional imaging technique of scattering media used in applications such as medical diagnostics and industrial testing in manufacturing lines. Swept Source-OCT (SS-OCT) requires a laser whose wavelength can be rapidly and continuously swept over a broad spectral range. Nowadays, most swept source lasers (SSL) technologies rely on mechanical filters whose sweeping speed is limited to 100 kHz. Multisection semiconductor lasers are electrically tunable lasers that offer the possibility to reach sweeping speeds up to the MHz regime. The technology is based on semiconductor slot mirrors having comb reflectivity spectra. The spacing of the comb spectral lines is imposed by the periodicity of the slots. The electrical injection of these mirror sections allows to shift the reflectivity spectra by the variation of the refractive index of the medium. By ensuring that the period of the slots are different between the front and back mirrors, two incommensurate comb reflection spectra can be formed. The Vernier effect occurs due to the interference of the two offset combs when independent electrical tuning of the two mirror sections is realised. This Vernier effect is responsible for wide and fast frequency sweeps. However such SS lasers based on the Vernier effect display mode hops during the laser operation that induce a loss of coherence.

In this work, we analyse the spectral features of semiconductor multisection slot lasers when the mirror sections are electrically tuned. Based on our cartographies of the laser emission wavelength as a function of the mirrors currents, we intend to provide an electrical path for a rapid and quasi-continuous wavelength sweep over a broad bandwidth. This work paves the way for further explorations of the opto-electronic control of the multisection lasers coherence during a full wavelength sweep.

Spontaneous Symmetry Breaking, Instability, and Chaos in Ring Resonators

37

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Keywords: *symmetry, oscillations, chaos, resonators*

When a ring resonator is pumped with laser light of sufficient intensity, then the refractive index – and so the resonant frequency – of the resonator can be modulated by the intensity of the light within it – a phenomenon known as the Kerr nonlinearity. If the resonator is pumped with two laser beams, then this effect can give rise to spontaneous symmetry breaking in the two optical modes within the resonator. We present analytical, numerical, and experimental evidence for a rich range of exotic behaviours exhibited by this symmetry-broken light, including oscillations (implying periodic energy exchange between the modes), period-doubling, and chaos. These optical modes are described by the following coupled system of ordinary differential equations:

$$\dot{e}_{1,2} = \tilde{e}_{1,2} - [1 + i(A|e_{1,2}|^2 + B|e_{2,1}|^2 - \Delta_{1,2})]e_{1,2},$$

Where $\tilde{e}_{1,2}$ and $e_{1,2}$ are the input and coupled electric field amplitudes for each beam, respectively, and $\Delta_{1,2}$ are the frequency detunings of the laser beams, with respect to the non-Kerr-shifted cavity resonance frequency. The coefficients A and B denote the strengths of self- and cross-phase modulation, respectively – i.e., the extent to which the modes interact with themselves and with each other. The physics of this dynamical system is not only of fundamental interest, but is also important for the construction of integrated all-optical circuitry and devices, such as isolators, circulators, logic gates, advanced sensors, oscillators, and scramblers.

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