"COMPLEX FLOWS AND COMPLEX FLUIDS 2025"

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BOOK OF ABSTRACTS

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INVITED TALKS

1. Learning to navigate in complex flows

Antonio Celani
ICTP, Trieste, Italy

I will review some selected problems inspired by animal and robotic navigation in complex flows, applying reinforcement learning techniques to understand and optimize their movement strategies.

2. Weaving tangled vortex webs

William Irvine
University of Chicago, Chicago, USA

Vortices imbue flow with dynamism: in isolation, their mesmerizing evolution provides a window onto some of the most fundamental aspects of flow. Combined into a space-filling tangle they provide the scaffold of turbulence. I will talk about experimental techniques to controllably weave vortex webs on demand, from making isolated vortices with interesting topologies to using vortices like lego to assemble and endow turbulence with tunable cocktails of conserved quantities. Finally, I will discuss how these isolated turbulent blobs can provide insight into the expansion of turbulence into quiescence.

3. Order and Chaos in Massive Schools of Fish

Eva Kanso
University of Southern California, USA

Nature is in a perpetual state of reorganization. In animal groups on the move, such as in bird flocks, fish schools, and insect swarms, local social interactions result in cohesive global patterns. However, while these cohesive patterns are regularly documented in groups of moderate size, it is unclear how they scale with increasing group size: do large groups remain cohesive or do they undergo dynamic reorganization? I will address this question in massive simulations of schools of fish, consisting of up to 50,000 individuals that interact through self-generated flows and follow behavioral rules inferred directly from experimental data in shallow water environments. I will show that "more is different." Where smaller groups maintain cohesive and polarized formations, larger groups spontaneously reorganize, constantly fragmenting, scattering and reassembling. I will analyze this emergent dynamics and comment on its potential role in group size regulation, behavioral adaptations, and dispersion in living animal groups.

4. Active Phase Separation and Interfaces

Cristina Marchetti
University of California, Santa Barbara, USA

There are many situations where active fluids coexist with passive ones. In bacterial swarms internal boundaries separate cells of different type or live and dead cells. In cell biology the discovery of membrane-free condensates has fueled interest in the role of activity in liquid-liquid phase separation and the properties of the resulting soft active interfaces. The ability to spatially and temporally tune activity with light has ignited interest in the behavior of the resulting active/passive boundaries. Inspired by in-vitro experiments that mix molecular motors and their associated biofilaments with water-soluble phase-separating polymers, we have used continuum models to demonstrate how active stresses provide an alternative method for tuning phase separation and the properties of liquid-liquid interfaces. I will show in this talk how activity can both arrest and suppress phase separation, drive giant and anisotropic interfacial fluctuations and system-wide traveling capillary waves in the absence of inertia. Extensile active stresses additionally change the morphology of the phase-separated state, yielding system-spanning filamentary active fluid networks that resemble those formed by organisms such as slime molds or some fungi.

5. Topological quasiparticles in active turbulence

Davide Marenduzzo
University of Edinburgh, Edinburgh, UK

Quasiparticles are low-energy excitations with important roles in condensed matter physics. An intriguing example is provided by Majorana quasiparticles, which are equivalent to their antiparticles. Here we propose a purely classical realisation of Majorana quasiparticles in terms of local defect profiles and 3-dimensional disclination lines in active nematics. The underlying reason is the well-known equivalence, in 3D, between a +1/2 local defect profile and a -1/2 profile, which acts as its antiparticle. We combine topological considerations and numerics to show that active nematics under confinement spontaneously create in their interior topologically charged disclination lines and loops, akin to Majorana quasiparticles. The analogy between 3D nematic defects and topological quasiparticles further suggests that active turbulence can be viewed as a topological phase, where defects percolate to form delocalised topological quasiparticles similar to those observed in the channel.

6. Settling and collisions of ice crystals in turbulent clouds

Aurore Naso
CNRS, École Centrale de Lyon, Lyon, France

Understanding the angular dynamics of non-spherical particles in turbulent flows is a challenging fundamental problem, significantly complicated when the particles are denser than the surrounding fluid. However, the settling of anisotropic particles in a flow is of importance in many geophysical and engineering problems, including cloud microphysics. Depending on the range of temperatures, ice crystals in clouds are indeed shaped like plates or like rods.

The main part of the talk will be devoted to the settling of ice crystals shaped like platelets, in turbulent clouds. Their statistical orientation will be characterized as a function of their geometric properties and of the turbulence intensity. The collisions between crystals, an important step in the formation of snow aggregates, will be then investigated. It will be shown that the collision rates obtained numerically can be understood as resulting from three main physical mechanisms: turbulent velocity gradients, differential settling, and particle inertia. The collisions between ice crystals and supercooled water droplets, leading in mixed phase clouds to the crystals growth through riming, will also be investigated and discussed.

Preliminary results on the settling of columnar ice crystals in turbulent clouds will finally be presented.

7. Solving problems in hydrodynamic turbulence by leaning on ideas from many-body systems

Samriddhi Sankar Ray
ICTS-IFR, Bengaluru, India

Recent ideas of many-body chaos in classical Hamiltonian systems — namely decorrelators or the classical analogues of OTOCs — have opened an interesting window to revisit problems in non-linear, out of equilibrium flows. In this talk we will introduce this idea through a classical spin chain model and then motivate how the same can be applied to nonlinear, Hamiltonian, thermalised fluids to show how the Lyapunov exponent scales with temperature in a classical many-body system. We then take two further examples from non-Hamiltonian, out-of-equilibrium systems — namely fully developed high Reynolds number classical turbulence and low Reynolds active turbulence of bacterial suspensions — to further exploit such decorrelators in order to see how the Lyaponov exponent λ scales with the Reynolds number Re in the first and activity in the second case. In particular, for the high Reynolds number fully developed turbulence problem, we show $\lambda \propto \mathrm{Re}^{\alpha}$ and investigate the interplay of the competing effects of viscous dissipation and nonlinearity. We obtain a precise value of $\alpha = 0.59 \pm 0.04$ and show that the departure from the Kolmogorov mean field result $\lambda \propto \sqrt{\mathrm{Re}}$ is a consequence of the intermittent fluctuations in the velocity-gradient tensor. The robustness of our results are further confirmed in a local, dynamical systems model for turbulence.

8. Octopus inspired multi-agent prediction and navigation in a turbulent environment

Agnese Seminara
Machine Learning Genoa Center & Dept. Civil, Chemical and Environmental Engineering, via Montallegro 1, 16145, Università di Genova, Italy

Octopuses collect mechanical and chemical information from their surroundings by means of receptors located in their suckers. Hundreds of suckers cover their eight arms and are controlled by a remarkably distributed nervous system, with only about 30% of neurons situated in the central nervous system. Sensing and navigation in this distributed organism may be further hindered by noisy proprioception. Indeed, while behavioral studies suggest that octopuses may be endowed with at least a rudimentary sense of proprioception, the molecular mechanisms that enable proprioception remain elusive, suggesting octopus may not enjoy a full awareness of their body parts position and speed at any given time. In this talk I will discuss octopus-inspired models for prediction and navigation using chemical cues in a turbulent environment.

9. Experimental Investigation of Flowing Emulsions in Wall-Bounded Turbulence

Chao Sun
Tsinghua University, Beijing, China

Turbulent emulsions are ubiquitous in chemical engineering, food processing, pharmaceuticals, and other industries. However, our understanding of these systems remains limited due to the multiscale nature of turbulent flows and the presence of extensive interfaces, which pose significant challenges for both experimental measurements and numerical simulations. In this talk, we present recent studies on emulsions in wall-bounded turbulent Taylor-Couette flow, focusing on the statistics of the dispersed phase and the global momentum transport of the system. We also discuss new measurements of local velocity statistics in the continuous phase of turbulent emulsions at high dispersed-phase volume fractions, made possible by precisely matching the refractive indices of the two phases. Finally, we examine catastrophic phase inversions, which occur when the volume fraction of the dispersed phase exceeds a critical threshold during dynamic emulsification.

10. Emulating high-Reynolds-number flows with ensembles of lower-Reynolds-number flows

Michael Wilczek
University of Bayreuth, Bayreuth, Germany

Spatio-temporal intermittency is a defining feature of high-Reynolds-number flows. Intermittency is particularly apparent through the spatio-temporally heterogeneous distribution of small-scale quantities such as local enstrophy and dissipation. In this contribution, we show that the velocity gradient statistics of high-Reynolds-number flows can be captured by heterogeneous ensembles of lower-Reynolds-number flows. Heterogeneity is introduced by varying the energy injection rate to mimic the strong variations of small-scale activity of high-Reynolds number flows across ensemble members. On the theoretical side, the formulation of this ensemble approach naturally links to the well-known multifractal picture of turbulence. Combined with multifractal modeling, we demonstrate that our ensemble simulations establish a computationally affordable approach to extrapolate to high Reynolds numbers.

CONTRIBUTED TALKS

1. Matching small and large scales in weakly-porous grid flows

Hossameldin Abdelaziz and Francesco Romanò
Univ. Lille, CNRS, ONERA, Arts et Métiers Institute of Technology, Centrale Lille, UMR 9014-LMFL-Laboratoire de Mécanique des Fluides de Lille - Kampé de Fériet, F-59000, Lille, France

Flow across grids has a wide range of industrial applications. Despite their simplicity, understanding downstream flow is challenging for low-porosity configurations, which are essential for passive flow control via pressure drops. Conversely, high porosity enhances mixing by increasing downstream stirring. Our research bridges the gap between these regimes by studying weakly porous rigid grids, which passively regulate flow while enhancing chaotic mixing without relying on turbulence. The study focuses on the separation of scales in flow modeling, specifically small-scale flow (SSF) near the grid's pores and large-scale flow (LSF) farther upstream/downstream. The conventional Darcy-Forchheimer model, which represents the grid as a porous medium, captures leading-order pressure drop but inaccurately predicts the downstream velocity field. We improve the flow modeling in porous media by introducing a body-force correction based on the flow structure of SSF in order to achieve a scale-matched flow for weakly porous grids. This approach is demonstrated for various grid geometries and Reynolds numbers.

2. The Multiscale Ocean Circulation

Hussein Aluie, M. Buzzicotti, S. Griffies, M. Hecht, H. Khatri, M. Maltrud, S. Rai, M. Sadek, B. Storer, G. Vallis
University of Rochester, USA

Gyrescale currents and chaotic weather systems (mesoscales) pervade the global ocean and play a central role in the general circulation and climate. The coupling between scales ranging from $O(10^4)$ km down to $O(1)$ mm presents a major difficulty in understanding, modeling, and predicting oceanic circulation and mixing, where constraints on the energy budget suffer from large uncertainties. To address this problem, we are working toward mapping out a Lorenz Energy Cycle concurrently in (i) scale, (ii) space, and (iii) time. We have developed a commutative coarse-graining framework on the sphere that is more versatile and powerful than classical mean field approaches. Coarse-graining has a rigorous mathematical foundation and is closely related to well-established physics techniques, including macroscopic electromagnetism, renormalization group, and large eddy simulation. I will focus on three applications using satellite and model data: the killing of ocean eddies by winds, measuring the first spectrum of the global ocean's kinetic energy, and the cascade of energy across scales. The cascade analysis reveals significant energy exchanges between ocean-weather and the climate-scale circulation via a "piston-effect," which is induced by the atmospheric cells (Hadley, Ferrel, Polar). This pathway is absent from established theories of the global ocean-atmosphere circulation.

3. Liquid-Droplet Coalescence: CNN-based Reconstruction of Flow Fields from Concentration Fields

Vasanth Kumar Babu, Nadia Bihari Padhan and Rahul Pandit
Indian Institute of Science, India

The coalescence of liquid droplets or lenses poses problems of great practical and theoretical interest in fluid dynamics and the statistical mechanics of multi-phase flows. During mergers, there is an intricate interplay between interfaces and the flow field; the latter is harder to visualise, in experiments, than concentration fields. We employ two-dimensional (2D) encoder-decoder CNNs, 2D U-Nets, and three- dimensional (3D) U-Nets to obtain flow fields from concentration fields. For network training, we use concentration and flow fields, from simulations of droplet and lens mergers in the Cahn-Hilliard-Navier-Stokes (CHNS) partial differential equations (PDEs) in both 2D and 3D. We then show that, given test images of concentration fields, our trained models accurately predict the flow fields at both high and low viscosities. Finally, we use data from recent experiments on droplet coalescence to show how our method can be used to obtain the flow field from measurements of the concentration field.

4. Homogeneous turbophoresis of heavy particles

Jérémie Bec and Robin Vallee
CNRS, Institut de Physique de Nice, France

Dispersed particles in turbulent flows appear in nature and industry as droplets, dust, or sediments. When denser than the fluid, they are expelled from intense vortices by inertia and centrifugal forces. Over time, this small-scale mechanism induces a large-scale drift, moving particles away from agitated regions into calmer zones, leading to uneven spatial distributions. This process, known as turbophoresis, explains particle accumulation in low-turbulence regions of non-homogeneous flows. We show that turbophoretic effects are equally crucial in statistically homogeneous, isotropic turbulence. Instantaneous fluctuations in turbulent activity generate local fluxes that shape inhomogeneities within the inertial range. Using direct numerical simulations, we analyze particle accelerations and their scale-averaged properties conditioned on local turbulence. These results highlight the role of energy dissipation in spatial turbulence fluctuations and lead to an effective coarse-grained model, describing particle detachment and expulsion via a space-time-dependent non-Fickian diffusion process.

5. Triad phase dynamics determine flux in 2D turbulence

Santiago Benavides and Miguel D. Bustamante
Universidad Politecnica de Madrid, Spain

We investigate how the dynamics of complex Fourier velocity phases influence the flux of conserved quantities in two-dimensional hydrodynamical (2D HD) turbulence. Although often overlooked in turbulence studies, the phase dynamics are key to the energy evolution at each wavenumber and the flux between scales. The phase dynamics, like energy evolution, are influenced by contributions from all neighboring triads, making the full problem intractable. Instead, we make the assumption that the dynamics of the triad phase are determined solely by the so-called self-interaction term, and treat the other neighboring triad terms as noise. This transforms the phase dynamics into that of a noisy phase oscillator, which we solve analytically to predict phase statistics. We validate this assumption with direct numerical simulations of 2D HD turbulence. Our results allow us to extend Kraichnan's work, showing that triad phase dynamics imply a negative energy flux for -5/3 spectral slope, a forward enstrophy flux for -3, and total desynchronization (and hence zero energy flux) for statistical equilibrium solutions. This work opens the door for future studies on the triad phase dynamics, and its implication for fluxes, in other systems such as 3D HD and geophysical turbulent systems.

6. Nonhomogeneous elastic turbulence in two-dimensional confined geometry

Stefano Berti, Zhongxuan Hou, Francesco Romanò, Teodor Burghelea
Université de Lille, France

Elastic turbulence is a spatially and temporally disordered flow state appearing in viscoelastic fluids at vanishing fluid inertia and large elasticity. The resulting flows have broad technological interest, particularly to enhance mixing and heat transfer in microdevices. Although its experimental characterization is now well established in different setups, its theoretical understanding and numerical reproducibility remain challenging, especially in wall-bounded geometries. By means of extensive numerical simulations, we investigate the onset of elastic turbulence and the characteristics of the developed turbulent-like states in the two-dimensional, confined, Taylor-Couette system. We find that the purely elastic instability is supercritical, which clarifies previously contrasting evidences. We then show that the fully nonlinear dynamics are weakly anisotropic and strongly nonhomogeneous. Indeed, they are confined in a dynamically active region adjacent to the inner wall, akin to the elastic boundary layer from previous predictions. Within this region, the statistical and spectral turbulent properties are close to the theoretical expectations and experimental observations.

7. Emulators of turbulent flows, atmosphere dynamics and extreme events

Freddy Bouchet, Amaury Lancelin, Alex Wikner, Dorian Abbot, Jonathan Weare, and Pedram Hassanzadeh
CNRS and ENS/PSL, Paris, France

Understanding, deriving, and computing effective dynamics has been a central pursuit of statistical and theoretical physics for centuries. Recent advancements in machine learning are transforming this field by providing powerful tools to develop effective models for problems that were previously intractable. One notable example is the turbulent dynamics of the atmosphere. In recent years, dynamical weather emulators trained on reanalysis datasets have demonstrated the ability to match or even surpass traditional physical weather models across several forecast metrics. Building on these remarkable results, there is a growing international effort to apply these tools to create dynamical emulators (effective dynamics) for climate model components. The goal is to produce emulators that faithfully reproduce the dynamics and statistics of climate models, while drastically reducing the computational cost. In this talk, I will present our latest work on climate model emulators, highlight their ability to capture effective dynamics, and explore their potential to study extreme events with significant impacts—such as extreme heat waves and the climate-related extremes affecting the resilience of future electrical systems.

8. Helical Triad Phase Synchronisation in Extreme 3D Navier-Stokes Flows

Miguel Bustamante, Di Kang, Brendan P. Murray and Bartosz Protas
University College Dublin, Ireland

We present convincing evidence of the relation between the spectral energy cascade and the synchronisation of helical triad phases with regards to 3D Navier-Stokes turbulent flow, in particular the extreme flows from (Kang et al. 2020, JFM 893, A22). These extreme flows realise, at fixed values of viscosity and spatial resolution, the strongest possible transient turbulent state. While in 1D Burgers turbulence the Fourier triad phases synchronise globally across scales (Murray & MDB 2018, JFM 850, 624; Protas et al. 2024, PRE 109, 055104), in 3D Navier-Stokes the vast majority of the triads are not involved in the coherent structures that form: searching for the relevant helical triads is akin to "finding a needle in a haystack". We accomplished this impossible task by constructing a joint probability density function: flux intensity p vs. triad phase f, where $flux = p\cos(f)$, over the set of all triads involved in the spectral energy flux across spatial scales. By ordering the triads from higher to lower p, we quantify a clear preference of high-p triads to have phases f close to zero: The sum of $\cos(f)$ over the first N high-p triads asymptotes like CN^a, with a near 1 indicating synchronisation events.

9. Generation and Reconstruction of Lagrangian Turbulence with Stochastic Generative Models

Michele Buzzicotti, Luca Biferale, Tianyi Li, Fabio Bonaccorso, Luca Centurioni
University of Rome Tor Vergata, Italy

Lagrangian turbulence lies at the core of numerous applied and fundamental problems. However, despite decades of theoretical, numerical, and experimental research, no existing model can accurately reproduce particle trajectories' statistical and topological properties in turbulent flows. This talk presents a machine learning framework based on a state-of-the-art diffusion model to generate single particle trajectories in three-dimensional turbulence at high Reynolds numbers [1]. This approach bypasses the need for direct numerical simulations or experiments to obtain reliable Lagrangian data. Our results show that the model reproduces key statistical features across time scales, including fat-tailed velocity increment distributions, and anomalous scaling laws. Additionally, we extend this method to reconstruct missing spatial and velocity data along trajectories of small objects passively advected by turbulent flows, such as oceanic drifters from NOAA's Global Drifter Program [2]. The method accurately reconstructs velocity signals while preserving non-Gaussian, intermittent scale-by-scale properties. The model is flexible enough to handle different data gap configurations and to exploit correlations enabling superior performance over traditional Gaussian Process Regression methods. This work highlights the potential of machine learning in advancing Lagrangian turbulence research and addressing longstanding challenges in the field.
This work was supported by the ERC under the European Union's Horizon 2020 research and innovation programme

Smart-TURB (Grant Agreement No. 882340).

[1] Li, T., Biferale, L., Bonaccorso, F., Scarpolini, M. A., Buzzicotti, M., Synthetic Lagrangian turbulence by generative diffusion models, Nature Machine Intelligence 1–11 (2024). [2] Li, T., Biferale, L., Bonaccorso, F., Buzzicotti, M., Centurioni, L., Stochastic Reconstruction of Gappy Lagrangian Turbulent Signals by Conditional Diffusion Models, arXiv:2410.23971, Communications Physics (in press, 2025).

10. Harnessing swarms to optimize transport of interacting active particles

Chiara Calascibetta, Laetitia Giraldi, Zakarya El Khiyati and Jérémie Bec
Centre Inria d'Université Côte d'Azur, Nice, France

We investigate the potential of global control strategies to improve the transport efficiency of swarms of interacting self-propelled particles in confined geometries. Building on previous work [1], which showed that the uncontrolled system leads to wall-induced particle accumulation, clogging, and band formation due to both the self-organization dynamics and the channel geometry, we now investigate whether an external global control mechanism - such as an external magnetic field acting on all particles - can optimize the collective dynamics [2]. Using a discrete model with Vicsek-like interactions, we investigate how global alignment controls, optimized by reinforcement learning algorithms, can mitigate these unfavorable configurations and maximize the flux of particles in the streamwise direction. This work was supported by the OPAL infrastructure at Université Côte d'Azur, the UCA-JEDI Future Investments (Grant No. ANR-15-IDEX-01), the Agence Nationale de la Recherche (Grants No. ANR-21-CE45-0013, No. ANR-21-CE30-0040-01), the ERC under Horizon 2020 (Smart-TURB, Grant No. 882340), and the Italian NRRP (Project CO-SEARCH, code 202249Z89M, CUP MASTER B53D23003920006, in particular, CUP E53D23001610006). [1] Calascibetta, Giraldi, El Khiyati and Bec. Phys. Rev. E 110, 064601 (2024). [2] Calascibetta, Giraldi, El Khiyati and Bec. In preparation (2025).

11. Hydrodynamics of odd-interacting systems

Lorenzo Caprini, Umberto Marini Bettolo Marconi
Sapienza University of Rome, Italy

Fluids composed of strongly rotating units are described by hydrodynamic theories with odd transport coefficients, such as odd diffusion and odd viscosity. These systems span a broad range of artificial and biological examples, including colloidal magnets, granular spinners, and starfish embryos. We demonstrate that odd transport coefficients arise from transverse forces, referred to as odd interactions, which generate a non-equilibrium transition from a homogeneous to a non-homogeneous phase. This transition results in the formation of stable bubbles with edge currents. The stability of the bubble phase is theoretically analyzed through a coarse-grained hydrodynamic approach derived from the particle dynamics, which allows us to formulate a hydrostatic description: A bubble is stable when the standard pressure, resulting from volume exclusion, is balanced by the effective surface tension induced by odd-driven centrifugal forces. These findings are experimentally verifiable in systems governed by odd interactions and could play a pivotal role in understanding the emergent properties of materials characterized by odd viscosity.

12. Rheology of a Chiral Active System

Lucio Mauro Carenza, Giuseppe Negro, Demian Levis, Giuseppe Gonnella
Università degli Studi di Bari Aldo Moro, Italy

We investigate a two-dimensional chiral fluid composed of Brownian disks interacting via a Lennard-Jones potential and subjected to a nonconservative transverse force, mimicking colloids spinning at a given rate. Focusing on the liquid phase, characterized by rotating hexatic patches, we demonstrate that increasing chiral activity modifies the system's effective temperature. In the solid phase, the introduction of chiral activity alone induces melting, driving a transition from a yielding regime to Newtonian-like behavior. Furthermore, we observe shear thinning, where the shear viscosity of the system decreases under increasing shear rates. Under sufficiently large shear rates, the particles organize into pronounced string-like flows, with layers of particles sliding past each other along the shear direction. This string formation is further enhanced when the rotation of the particles opposes the shear direction. These findings clarify how chiral activity influences the rheological behavior of particle assemblies, advancing our understanding of flow dynamics in active chiral fluids.

13. Supramolecular Polymers for Turbulent Drag Reduction

F. Serafini, F. Battista, P. Gualtieri, **Carlo Massimo Casciola**
Sapienza Università di Roma, Italy

It took five decades from Tom's discovery before DNS demonstrated viscoelasticity as crucial in polymer-induced drag reduction (DR) – Sureshkumar (1997), De Angelis (2002). The polymer chain was modeled as a dumbbell with two massless beads connected by a nonlinear spring stretched by the solvent (FENE model). To make the model tractable, the Peterlin approximation was adopted (FENE-P model). Recently, see the review by Ching (2024), such approximation was removed by following every single dumbbell – Serafini (2022) – and the analysis was extended to multiple beads, Serafini (2024). Covalently bonded polymers suffer from mechanical degradation, eventually rendering them futile. Here, we intend to move forward, addressing supramolecular polymers that can assemble and de-assemble, making them particularly interesting for DR. They also present anti-mist properties useful in preventing explosions, e.g., in the event of aircraft crashes. In the talk, besides presenting state-of-the-art and new numerical results for the more usual covalently bonded chains, a statistical mechanics model for supramolecular polymers will be illustrated, discussing preliminary results concerning their behavior in turbulence.

14. Beating Dynamics of Flagella Under Traveling-Wave Perturbations

Fabio Cecconi, Dario Lucente, Andrea Puglisi, Massimiliano Viale
CNR-Istituto Sistemi Complessi, Rome, Italy

Flagella and cilia play a crucial role in microscale fluid dynamics, powering the motion of cells and driving flows in biological systems. In this work, we present a theoretical framework to understand how semiflexible filaments respond to traveling-wave perturbations that mimic the action of molecular motors. By modeling the flagellum as a worm-like chain (WLC), we explore the competition between active forcing and intrinsic bending rigidity, revealing how this interplay selects spatiotemporal beating patterns akin to those observed in sperm tails, Chlamydomonas cilia, and eukaryotic flagella in general. Through a systematic analysis of the WLC's response, we identify the key physical parameters that shape flagellar motion and discuss their implications for biological propulsion and artificial microswimmers. Our findings offer insights into the fundamental mechanics governing active filament dynamics in complex fluid environments.

15. Control of Small Spontaneous Turbulence Using Generative AI

Michael Chertkov
University of Arizona, USA

Small Spontaneous Turbulence (SST) involves turbulence patches that emerge spontaneously in space and time, requiring localized and effective control. Our focus is on two key examples: 1) controlling airfoil lift and drag influenced by vortex shedding, and 2) managing elastic turbulence in polymer solutions at low Reynolds numbers. These SST scenarios challenge traditional PDE-based approaches like Navier-Stokes and Oldroyd-B models due to surface irregularities, heat release, or limited applicability in capturing effects of polymers on the flow. To address this, we propose a Physics-Informed & AI-Assisted (PIA) methodology that leverages DNS simulations and experimental data. The approach integrates state-of-the-art Generative AI techniques, including Graph-Flow-Networks combining auto-regressive transformers for sequential modeling, Bayesian diffusion models for uncertainty quantification, and reinforcement learning for adaptive control. This framework bridges cutting-edge AI and domain-specific physics to enable scalable and interpretable control solutions for diverse SST applications.

16. Enhancing lattice kinetic schemes for fluid dynamics with Lattice-Equivariant Neural Networks

Alessandro Corbetta
Technical University of Eindhoven, The Netherlands

We present a new class of equivariant neural networks, hereby dubbed Lattice-Equivariant Neural Networks (LENNs), designed to satisfy local symmetries of a lattice structure. Our approach develops within a recently introduced framework aimed at learning neural network-based surrogate models Lattice Boltzmann collision operators. Whenever neural networks are employed to model physical systems, respecting symmetries and equivariance properties has been shown to be key for accuracy, numerical stability, and performance. Here, hinging on ideas from group representation theory, we define trainable layers whose algebraic structure is equivariant with respect to the symmetries of the lattice cell. Our method naturally allows for efficient implementations, both in terms of memory usage and computational costs, supporting scalable training/testing for lattices in two spatial dimensions and higher, as the size of symmetry group grows. We validate and test our approach considering 2D and 3D flowing dynamics, both in laminar and turbulent regimes. Our work opens towards practical utilization of machine learning-augmented Lattice Boltzmann CFD in real-world simulations.

17. Classically studied coherent structures only paint a partial picture of wall-bounded turbulence

Andrés Cremades Botella, S Hoyas, R Vinuesa
KTH, Stokholm, Sweden

Due to the complex behavior of turbulent flows, one of the most common approaches to understanding wall-bounded turbulence has been their analysis through coherent structures. Different definitions have been applied, some structures, such as the Q events, focus on the Reynolds stress, while others focus on the turbulent kinetic energy, such as the streaks or the rotation, as the vortices. However, none of these definitions focus directly on the importance for the evolution of the flow. This work proposes a novel methodology to address these importance-based coherent structures using a data-driven approach. This approach uses the SHAP values (importance scores) to determine the effect of each grid point in the evolution of the flow. The methodology comprises three main stages: first, a deep learning model is trained to predict the flow evolution; then, the SHAP of each grid point is obtained; finally, the importance field is used to percolate the SHAP structures. The SHAP structures are, then, compared to the traditional coherent structures, showing different levels of agreement for a turbulent channel. This work aims to link the physical definitions of coherent structures with their importance for the evolution of the flow, providing a new framework that can be applied to a wide range of problems, such as flow control, sparse reconstruction, or turbulence modeling.

18. How small droplets form in turbulent multiphase flows

Marco Crialesi-Esposito, Guido Boffetta, Luca Brandt, Sergio Chibbaro, Stefano Musacchio
Universitá degli Studi di Modena e Reggio Emilia, Italy

The formation of small droplets and bubbles in turbulent flows is a crucial process in geophysics and engineering, whose underlying physical mechanism remains a puzzle. It is now known that turbulent multiphase flows are strongly intermittent, and that the most intermittent events correlate to regions of strong velocity gradients. In this letter, we address this problem by means of high-resolution numerical simulations, comparing a realistic multiphase configuration with a numerical experiment in which we attenuate the presence of strong velocity gradients either across the whole mixture or in the disperse phase only. Our results show unambiguously that the formation of small droplets is governed by the internal dynamics which occurs during the break-up of large drops and that the high vorticity and the extreme dissipation associated to these events are the consequence and not the cause of the breakup.

19. Learning a dynamical system for Lagrangian particle trajectories using the Mori-Zwanzig formalism

Xander de Wit, Alessandro Gabbana, Michael Woodward, Federico Toschi, Daniel Livescu
Eindhoven University of Technology, The Netherlands

Trajectories of Lagrangian particles in turbulence have highly non-trivial statistics. Finding a good substitute model that reproduces these statistics without running the full direct numerical simulations has proven to be a difficult task. However, novel data-driven machine learning techniques can be very powerful in capturing and reproducing complex statistics. Here, we show how one can learn a surrogate dynamical system that is able to evolve a turbulent Lagrangian trajectory in a way that is point-wise accurate at the short times (with respect to Kolmogorov time) and is statistically accurate at the long times. It is based on the Mori-Zwanzig formalism, stating that the full dynamical system, which would require knowledge of the entire fully resolved flow field, can be reduced by considering only a reduced set of observables, in this case only the state of the Lagrangian particle, when augmented by a limited history of the reduced state.

20. Interface dynamics of a turbulent water layer

Giulio Foggi Rota and M. E. Rosti
Okinawa Institute of Science and Technology Graduate University, Japan

We investigate numerically the turbulent flow of water and air over an inclined wall, focusing on the dynamics of the interface separating the two fluids. Fully resolved simulations are performed using our well-tested solver Fujin in a computational box bounded at the bottom by a no-slip wall and at the top by a free-slip plane. The lower half of the domain is occupied by water, and the upper half by air, with realistic density and viscosity ratios imposed. By inclining the entire domain 7° with respect to the horizontal direction, a flow with a bulk Reynolds number of approximately 20,000 (1,000 in wall units) and a Froude number of about 10 is established. Our choice of surface tension yields a bulk Weber number of approximately 100 (1 in wall units), for which the interface is stable. The turbulent wall cycle drives the velocity fluctuations in the water, which are thus transmitted to the air through the interface, sustaining its turbulent motion. We observe the propagation of both gravity and capillary waves at the interface. During the workshop, we will describe the turbulent flow in detail and discuss the effects of the turbulent forcing on the interface dynamics.

21. Fluctuating hydrodynamics description of phase change in fluids

Mirko Gallo, Filippo Occhioni, Matteo Teodori, Carlo Massimo Casciola
Sapienza Università di Roma, Italy

The precise identification of thermodynamic conditions for phase change inception is a daunting task. Fluids can be held in metastable states (supersaturated conditions) for a long time without phase transitions. The incipit of phase change is nucleation, a process driven by stochastic events of free-energy barrier crossing, corresponding to nanobubbles/droplets formation. A proper description of the process should link the microscopic features of nucleation with the macroscopic behaviour during bubble/droplet expansions. Nowadays, molecular dynamics is a unique tool to investigate such thermally activated processes. However, its computational cost limits its application to small systems and short times, preventing the study of hydrodynamics and thermal transport processes. In this talk, I will discuss how fluctuating hydrodynamics coupled with diffuse interface thermodynamics can describe the boiling and condensation process from nucleation up to macroscopic hydrodynamics. The focus will be on the role of heterogeneous nucleation in lowering boiling temperatures and condensation pressures.

22. Examining the dissipation range of polymeric turbulence

Piyush Garg, Marco Rosti
Complex Fluids and Flows Unit, Okinawa Institute of Science and Technology, Japan

The addition of polymer molecules has been well known to drastically alter inertia driven turbulence but a detailed physical understanding of the same is still lacking. In this talk, we examine the homogeneous isotropic turbulence of polymeric fluids using high resolution direct numerical simulations. We use the Oldroyd-B equation as the constitutive model for the polymer stress coupled to the Navier-Stokes equations for the fluid velocity field. The governing equations are solved using the in-house code Fujin which has been extensively validated. We focus on the large Reynolds and large Deborah number parameter regime. We present a quantitative characterization of the statistical properties of the flow across the Kolmogorov length scale. While at the largest scales we recover inertial turbulence, we show that particularly surprising behavior occurs at length scales below the Kolmogorov scale in polymeric turbulence. In Newtonian turbulence, viscous dissipation alone dominates the flow at the smallest scales such that the energy spectrum decays exponentially. In contrast, we show that the polymers continue to strongly affect the flow in the dissipation range, and both elastic and viscous stresses dominate which leads to a novel 'elastic-dissipation' range at the smallest scales instead. We present a discussion of the various statistical properties of this novel range.

23. Directional Fluidity induced by Asymmetric Wall Roughness

Giacomo Guastella, Daniele Filippi, Matteo Pierno, Giampaolo Mistura, Davide Ferraro
Dipartimento di Fisica e Astronomia 'Galileo Galilei', Via Marzolo, 8 - 35131 Padova (PD) - Italy

The yielding transition is critical in technologies like additive manufacturing, injection molding, food rheology, and oil transport. It is known that microroughness patterned on microchannel walls induces local plastic rearrangements, reducing viscosity and facilitating flow. We investigate two roughness geometries, herringbone-riblet and wedge-like patterns, that introduce topological asymmetry along the flow direction. With yield stress emulsions, these geometries enhance the flow either along a specific direction or for specific positions on the channel cross-section. In particular, herringbone patterns produce flow banding across the channel cross-section, with maximum effects on the herringbone tip. Conversely, ramps enhance the flow in the rising direction of the wedges along the whole cross-channel section. Numerical simulations by 2D Lattice Boltzmann complement experimental results, highlighting the interplay of pressure, geometry, and rheology. Additionally, we validated a protocol to measure stress within the channel, providing a reliable method to quantify local mechanical responses under different flow conditions.

24. Unveiling the Spatial Organization of Vortices in Active Turbulence

Kirti Kashyap, Kiran Kolluru, **Anupam Gupta**
Indian Institute of Technology, Hyderabad, India

The spatiotemporal structures observed in dense suspensions of active matter qualitatively resemble those found in inertial turbulent systems. Extensive studies have been conducted to investigate whether active turbulence shares similarities with or deviates from inertial turbulence. These investigations often focus on identifying universal features, such as power-law scaling and intermittency, which are hallmarks of turbulent systems. We have used Toner-Tu-Swift-Hohenberg (TTSH) equation to model and investigate the active fluid systems, where activity parameter, introduces energy at smaller length scales when negative. Our analysis reveals a significant shift in the nature of these patterns beyond a critical threshold of activity. Increasing activity leads to the formation of streaky structures accompanied by regions of high vorticity with inhomogeneous distribution. These observations have been quantified using statistical approach like the giant number fluctuation of the vorticity centers, the radial distribution, and area distribution through voronoi construction about these centers.

25. Efficient microswimmer navigation

Navid Mousavi, Jingran Qiu, Bernhard Mehlig, Lihao Zhao, **Kristian Gustavsson**
University of Gothenburg, Department of Physics, Sweden

Swimming microorganisms and artificial microswimmers use environmental cues to guide their movement, enabling tasks such as exploiting flow to reach specific regions, enhancing transport and mixing, or escaping dangerous hydrodynamic fluctuations. Understanding their navigation in turbulent environments is essential for studying plankton behavior and advancing engineered applications, such as drug delivery and hazard cleanup. In turbulent flows, microswimmers must navigate with limited information and maneuverability. We address this challenge using Reinforcement Learning (RL) and analytical perturbation theory. RL identifies efficient navigation strategies through iterative interactions between microswimmers and their environment, often revealing interpretable mechanisms. However, RL does not guarantee finding the optimal strategy. Perturbation theory complements RL by identifying true optimal strategies in specific cases. By combining these approaches, we develop robust navigation strategies for tasks crucial to plankton survival, such as swimming against gravity and avoiding high-strain regions. This interdisciplinary approach enhances our understanding of natural microswimmers and informs the design of engineered ones for practical applications.

26. Non-Uniqueness and Inadmissibility of the Vanishing Viscosity Limit of the Passive Scalar Transport Equation

Lucas Huysmans, Edriss S. Titi
Max Planck Institute for Mathematics in the Sciences, Germany

We study selection by vanishing viscosity for the transport of a passive scalar $f(x,t) \in \mathbb{R}$ advected by a bounded, divergence-free vector field $u(x,t) \in \mathbb{R}^2$. This is described by the initial value problem to the PDE $\frac{\partial f}{\partial t} + \nabla \cdot (uf) = 0$, or with positive viscosity/diffusivity $\nu > 0$, to the PDE $\frac{\partial f}{\partial t} + \nabla \cdot (uf) - \nu \Delta f = 0$. We demonstrate the failure of the vanishing viscosity limit to select (a) unique solutions or (b) physically admissible solutions in the sense of non-increasing energy/entropy.

27. Subcritical transition to elastic turbulence in parallel shear flows: Recent progress

Damiano Capocci, Martin Lellep, **Moritz Linkmann**, Alexander Morozov
School of Mathematics and Maxwell Institute for Mathematical Sciences, University of Edinburgh, UK

Solutions of long, flexible polymer molecules are complex fluids that simultaneously exhibit fluid-like and solid-like behaviour. When subjected to an external flow, dilute polymer solutions exhibit elastic turbulence - a unique, chaotic flow state absent in Newtonian fluids, like water. Unlike its Newtonian counterpart, elastic turbulence is caused by polymer molecules stretching and aligning in the flow, and can occur at vanishing inertia. While experimental realisations of elastic turbulence are well-documented, there is currently no understanding of its mechanism. In this talk we review recent progress in identifying the mechanism of elastic turbulence in pressure-driven flows through straight channels. Using large-scale direct numerical simulations, we demonstrate that the transition to elastic turbulence is sub-critical, giving rise to spot-like flow structures that, further away from the transition, eventually spread throughout the domain. Circumstantial evidence suggests that the transition to elastic turbulence proceeds similar to the transition to turbulence in Newtonian parallel shear flows, that is, mediated by exact unstable solutions of the equations of motion.

28. Turbulent Boundary Layer on Logarithmic Lattices

Adrien Lopez, Amaury Barral, Guillaume Costa, Quentin Pikeroen, Bérengère Dubrulle, and Anne-Laure Dalibard
Université Paris-Saclay, Paris, France

Introduced in 2019, the Logarthmic Lattice method is an idealized model to simulate fully turbulent fluids, akin to a multidimensional generalization of shell models. It is based on an exponential sampling of the Fourier modes. This allows to save up memory and computational resources and makes possible simulations with parameters like the Reynolds number in a geophysical or astronomical range. In its original formulation, it is difficult to accommodate boundary conditions, which are necessary for any relevant geophysical modelling. Indeed, the method is purely spectral and the link with physical space is compromised by the decimation of modes. This new method consists in formulating Navier-slip boundary conditions (where boundary tangential stress is proportional to tangential velocity) in Fourier space. This approach gives a tunable parameter (slip length) to phenomenologically model the properties of a flat boundary (like roughness). By varying this parameter, two regimes are identified in the turbulent limit of high Reynolds number with different scaling laws.

29. Coherent magnetic structures in various MHD turbulence systems and their impact on cosmic ray transport

Jeremiah Lübke, Frederic Effenberger, Mike Wilbert, Horst Fichtner, Rainer Grauer
Ruhr-Universität Bochum, Germany

Turbulence in Magnetohydrodynamics exhibits a rich variety of coherent magnetic structures, depending on the presence of a strong uniform background field, active forcing, as well as magnetic and cross-helicity. We review the generating mechanisms of these structures - an inverse cascade due to the presence of additional conserved quantities in the decaying case and intermittent alignment in the forced case - and discuss their geometric characteristics. We conclude by assessing their role in the transport of cosmic rays in various astrophyiscal systems and the implications for realistic models for synthetic turbulence.

30. Hidden symmetry in 3D turbulence: Navier-Stokes vs Smagorinsky

Bruno Magacho, S. Thalabard, M. Buzzicotti, F. Bonaccorso, L. Biferale, and A. A. Mailybaev
IMPA, Rio de Janeiro, Brasil

The 3D incompressible Navier-Stokes (NS) equations give rise to hidden scaling symmetries (HS) after a proper dynamical rescaling of space and time. It is conjectured that the HS is restored in the inertial interval of the statistically stationary state, thereby, replacing the 1/3 rule of the Kolmogorov K41 theory. Though direct numerical simulations demonstrate footprints of the HS, a deeper analysis is hampered by insufficient resolution, since the viscous term breaks the HS. To overcome this difficulty, we propose to study the HS for the Smagorinsky (LES) closure. This closure is Galilean and time-scale invariant and, therefore, preserves the HS at all small scales of motion. Then the recovery of HS is verified through the computation of PDFs of Kolmogorov multipliers between simulations with different cutoff parameters, and also by comparing these results to the original NS statistics. We show that this approach provides a powerful tool for understanding the multi-scale properties of turbulence in terms of the new (hidden scaling) symmetries of the underlying equations of motion.

31. Inertia induces strong orientation fluctuations of non-spherical atmospheric particles

T. Bhowmick, J. Seesing, K. Gustavsson, J. Guettler, Y. Wang, A. Pumir, **Bernhard Mehlig**, G. Bagheri
University of Gothenburg, Sweden

The orientation of non-spherical particles in the atmosphere, such as volcanic ash and ice crystals, influences their residence times, and the radiative properties of the atmosphere. Here, we demonstrate experimentally that the orientation of heavy submillimeter spheroids settling in still air exhibits decaying oscillations, whereas it relaxes monotonically in liquids. Theoretical analysis shows that these oscillations are due to particle inertia, caused by the large particle-fluid mass-density ratio. This effect must be accounted for to model solid particles in the atmosphere.

32. Stratified turbulence forced by large scale internal waves: experiments in the Coriolis facility

Nicolas Mordant, Pierre Augier, Costanza Rodda
Université Grenoble Alpes, France

Oceans are stratified in density and this has a major impact on their dynamics. The stratification enables the propagation of internal gravity waves, which play a major role in the global turbulence by dissipating the large-scale energy at small scales by a forward wave turbulence cascade or by strong dissipation due to wave breaking. To better understand such wave-induced turbulence, we built a simplified experimental setup in the large-scale Coriolis facility. The tank is 13m in diameter and 1m deep and we generate a density stratification using vertically varying concentration of salt. Large scale waves are forced by large vertical panels that can oscillate around a horizontal axis placed at mid-depth of the water. Various regimes at low Froude number and high Reynolds number could be identified when varying the frequency and magnitude of the forcing. At weak forcing a regime of weak wave turbulence was observed. When increasing the forcing, internal waves break and generate small scales and high frequency strongly non-linear turbulence. Some similarities are observed with the Garrett & Munk spectrum.

33. Evidence of resonant interactions in ocean wave data

Miguel Onorato, Davide Maestrini, Alberto Villois, Alvise Benetazzo
Università di Torino - Dipartimento di Fisica, Italy

Surface gravity wave forecasting systems rely on numerical simulations of the Wave Kinetic Equation (WKE), which is modified by the inclusion of a source term—accounting for wind input from atmospheric models—and a sink term, representing wave dissipation. The WKE serves a role analogous to that of the Boltzmann equation in kinetic gas theory, governing the statistical evolution of a sea state. According to the WKE, energy and action are exchanged among waves only when specific resonance conditions are satisfied. However, whether such resonant interactions are actually observable in the ocean remains an open question. In this study, we analyze space-time surface elevation data recorded using a stereoscopic technique from a CNR platform in the Adriatic Sea. By computing the fourth-order correlator from the data, we demonstrate that a non-trivial contribution emerges, aligning with the predictions of Wave Turbulence theory as formulated by V. Zakharov.

34. Experimental Realization of Autonomous Navigation of Active Microswimmer in Complex Flow Fields using Reinforcement Learning

Diptabrata Paul, Frank Cichos
Leipzig University, Germany

In living systems, the ability to sense and dynamically respond to environmental stimuli are fundamental to functions spanning sub-cellular processes to organism-level navigation strategies like chemotaxis and phototaxis. In contrast, artificial microswimmers lack the ability to process and adapt to static or dynamic environmental perturbations, limiting their autonomous navigation and task performance. Integrating real-time responsiveness and adaptation is thus critical for robust navigation in complex, stochastic environments. In this context, we experimentally implement real-time particle detection with a machine learning-driven feedback loop—leveraging an actor-critic reinforcement learning algorithm to navigate a microswimmer under the influence of Brownian motion and flow fields. We demonstrate that in a microfluidic settings, the RL trained agents learn effective navigation strategy across variable initial states and flow configurations. Unlike rule-based approaches, which fail under fluctuating noise and flow disturbances, RL-trained policies achieve high success rates even as stochasticity increases, adapting to both unsteady flows and spatial uncertainties. This study highlights the potential of RL in adaptive control strategies for microswimmers in microfluidic applications, advancing the understanding of active transport in complex hydrodynamic settings.

35. Intermittency, dynamical regimes and role of emulsifiers in emulsions under Rayleigh-Bénard thermal convection

Francesca Pelusi, Andrea Scagliarini, Mauro Sbragaglia, Massimo Bernaschi, Roberto Benzi
CNR - Istituto per le Applicazioni del Calcolo "Mauro Picone" (IAC), Rome, Italy

We present a comprehensive study on thermal convection in emulsions with finite-sized droplets using lattice Boltzmann simulations. Emulsions are analyzed with varying volume fractions (ϕ), spanning from Newtonian to non-Newtonian yield-stress rheology, in the Rayleigh-Bénard setup, where buoyancy forces are quantified by the Rayleigh number (Ra). For yield-stress emulsions, convection follows intermittent transient dynamics with fluidization-rigidity transitions driven by rheology and plastic activity, leading to phase inversion via droplet coalescence. Further, by mapping the phase diagram (Ra vs. ϕ), we observe two regimes: at high Ra, low-to-moderate ϕ systems exhibit breakup-dominated dynamics, while high ϕ systems show phase inversion. Both processes significantly alter emulsion rheology and heat transfer properties. In this scenario, droplet stabilization against coalescence (emulsifiers) is crucial for the resulting dynamics, as evidenced by a dedicated comparative study between stable emulsions, where the stabilization mechanism is present, and multiphase flows, where it is absent. This work highlights the interplay between thermal forces, emulsion structure, and rheology.

36. Scale-by-scale energy transfers in bubbly flows

Hridey Narula, Vikash Pandey, Dhrubaditya Mitra, and **Prasad Perlekar**
TIFR Hyderabad, India

Turbulent multiphase flows are inherently multi-scale. In single phase turbulent flows, either Karman-Howarth-Monin (KHM) relation or filtering approach can be used to understand energy transfers. The equivalence of the two approaches is well-estabilished in the single phase flows. However, such an equivalence is not clear in bubbly flows. In fact, multiple definitions of energy and its transfer are possible. We compare energy transfer using both KHM relation and filtering approach for the case of buoyancy-driven bubbly flows. We show that when interpreted correctly, all approaches give identical interpretation of the energy transfer mechanism.

37. Policy heterogeneity improves collective olfactory search in 3-D turbulence"

Lorenzo Piro[1], Robin A. Heinonen[1], Maurizio Carbone[2], Luca Biferale[1], Massimo Cencini[2]
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The survival of many living beings hinges on their ability to track odor signals in turbulent environments, a task made difficult by the sparseness and randomness of olfactory signals. Over millions of years, individual organisms have evolved strategies where balancing exploration and exploitation is key. This has inspired information-seeking policies for individual search like Infotaxis and its variant Space-Aware-Infotaxis. Moreover, it has been recently shown that cooperation by sharing information among group members using the same strategy enhances the search efficiency of the individual. Here, we propose an alternative way to balance exploration and exploitation in groups of cooperating agents to improve their olfactory search performance in real-world scenarios. Using odor signals generated from direct numerical simulations of the Navier-Stokes equations to simulate odor transport in the atmosphere, we compare space-aware-infotactic swarms to those with a mix of infotactic and greedy agents. Our findings reveal that heterogeneous groups with an optimal fraction of greedy agents outperform homogeneous swarms. We can attribute this improvement to a reduced clustering among heterogeneous agents, which mitigates the adverse effects of spatial correlations in turbulent odor signals. Our study highlights the advantages of policy diversity in distributed search, potentially beneficial in studying biological systems and real-world applications.
This work was supported by the ERC under the European Union's Horizon 2020 research and innovation programme Smart-TURB (Grant Agreement No. 882340), and by the NRRP, Mission 4 Component 2 Investment 1.1 - Call No. 104 – Project: CO-SEARCH, code 202249Z89M – (CUP MASTER B53D23003920006, CUP E53D23001610006).

38. Smart navigation of a gravity-driven glider with adjustable centre-of-mass

Jingran Qiu[1], Xinyu Jiang[2], Kristian Gustavsson[1] , Bernhard Mehlig[1], Lihao Zhao[2]
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Artificial gliders are designed to disperse as they settle through a fluid, requiring precise navigation to reach target locations. We show that a glider can achieve such navigation by dynamically adjusting its centre-of-mass. Using fully resolved direct numerical simulations and reinforcement learning, we identify optimal navigation strategies that allows the glider to reach its target location accurately. These strategies depend sensitively on the interaction with the surrounding fluid, which is quantified by the particle Reynolds number, a measure of the non-dimensional settling speed. At small Reynolds number, the glider mainly settles at a fixed orientation that maximises horizontal travel. At larger Re p it tumbles, generating a horizontal force that extends its range. By analysing how the glider navigate by repeatedly adjusting its centre-of-mass, we explain how the optimal strategies depend on the settling speed.

39. On the stability of a collection of sedimenting spheres

Dylan Reynolds and Rama Govindarajan
International Centre for Theoretical Sciences, India

The study of sedimenting particles has a long history, and many applications. In the dilute zero Reynolds numberlimit this process can be understood rigorously from a theoretical standpoint. Of utmost importance, in both industrial applications and natural phenomena, is the stability of a collection of particles interacting under hydrodynamics forces alone. The work of Crowley in the 1970s shows that a 1D chain of spherical particles, and a 2D lattice of spherical particles, both suffer a viscous instability upon sedimentation; any slight deviation from a regular array will lead to clumping. However, in 3D, for an initially homogeneous distribution of spheres, this instability is not present, e.g., a 3D array of particles is stable and supports propagating density waves. In this work we employ a two phase continuum theory of particulate flows to explain why lower dimensional collections of sedimenting spheres are unstable as opposed to their 3D counterparts. We see that in the limit of vanishing volume fraction the incompressibility of the fluid provides a rigid constraint against particle density perturbations, which only allows the instabilities to manifest in 1D and 2D. This work sets the stage for a more general theory of sedimenting blob dynamics, and the stability of large collections of sedimenting particles.

40. Natural olfactory scene statistics in a model of turbulent odor dispersion

Nicola Rigolli, Gautam Reddy, Antonio Celani, Massimo Vergassola
Ecole Normale Superieure Paris, France

Modeling odor dispersion in the atmospheric boundary layer (ABL) is a critical challenge due to the complexity of turbulence-driven transport. Traditional numerical simulations of the Navier-Stokes equations, while accurate, are computationally expensive. In this work, we present a computationally efficient solver that generates realistic odor time series while preserving key statistical properties of natural odor plumes. Our approach captures the essential features of turbulent dispersion and the stochastic dynamics governing the temporal evolution of the odor. By representing odor plumes as a collection of advected and expanding puffs, we model spatial and temporal odor statistics in agreement with experimental observations. The simulation framework accurately reproduces whiff and blank duration distributions, plume concentration scaling, and the conical structure of odor plumes in turbulence. This method enables faster and more accessible plume simulations, with potential applications in olfactory navigation, robotics, and environmental monitoring.

41. Weak and strong turbulence in self-focusing and defocusing media

Vladimir Rosenhaus, Gregory Falkovich
CUNY Graduate Center,USA

While the focusing and defocusing Nonlinear Schrodinger Equations have similar behavior in the weak turbulence regime, their behavior must differ dramatically in the strong turbulence regime. Here, we show that this difference is already present at next-to-leading order in the nonlinearity in the weak turbulence regime, where the one-loop interaction vertex correction suppresses repulsion (like screening in electrodynamics), leading to a steeper spectrum in the defocusing case. In contrast, attraction enhancement (like antiscreening in chromodynamics) makes the spectrum less steep in the focusing case. To describe strong turbulence, we consider a vector model in the limit of a large number of components. A large-N kinetic equation, valid at all scales, can be derived analytically. It has an inverse-cascade solution whose two asymptotics, at high and low wavenumbers, describe weak and strong turbulence, respectively. We find two forms of universality appear in the strong turbulence spectrum: in focusing media it is independent of the flux magnitude, while in defocusing media it is independent of the bare coupling constant, with the largest scale appearing instead.

42. Turbulence in a fluid with variable viscosity

Marco Edoardo Rosti
Okinawa Institute of Science and Technology, Japan

Non-Newtonian fluids possess unique features such as shear-dependent viscosity, fluid elasticity or yield stress, which lead to complex flowing dynamics. In this work we focus on the shear-dependent viscosity, a feature possessed by several non-Newtonian fluids; in particular, we describe the viscosity of the fluid with the inelastic Carreau model, in which the viscosity is a function of the local applied shear rate, and we study how turbulence is modified when the fluid is shear-thinning. Turbulence is a common phenomenon observed in all kinds of fluid flows, yet our understanding is largely limited to Newtonian turbulence, whose fundamentals were laid down by the pioneering works of Kolmogorov in 1941. In the current work, we generalize the Kolmogorov theory to fluids with a variable viscosity. The analysis is based on the data from direct numerical simulations of forced homogeneous isotropic turbulence at a Taylor Reynolds number of approximately 420.

43. Weak turbulence of internal gravity waves

Michal Shavit, Oliver Buhler and Jalal Shatah
Courant NYU, USA

Our work contributes to a nearly 60-year quest to derive the turbulent spectrum of weakly interacting internal gravity waves from first principles, a problem that has posed significant theoretical challenges. A promising avenue lies in the kinetic approach; however, the Boussinesq equation both in 2D and 3D is an anisotropic, non-canonical Hamiltonian equation, making the classical wave turbulence approach almost irrelevant. Previous attempts at weak wave turbulence analysis in three dimensions have fallen short of providing a definitive prediction for the energy spectrum. While observations emphasize the central role dispersive internal gravity waves play in natural processes like the ocean's climate cycle, decoupling these from the evolution of slow modes - degrees of freedom with vanishing frequency - proves difficult. Here we consider the 2D problem. We offer a new approach – we regularize the kinetic equation around the curve of vanishing frequency and look for steady solutions with nonzero energy fluxes. In the limit of a vanishing regulator, we find the turbulent spectrum of weakly interacting internal gravity waves. Our spectrum exactly matches the phenomenological oceanic Garrett-Munk spectrum in the limit of large vertical wave numbers and zero rotation. Notably, this is the first time that such a matching has been achieved.

44. Collective Nutrient Search by Active Chemotactic Agents in Two Dimensional Flows

Sudipto Bagchi, Anupam Gupta, **Vishwanath Shukla**
Indian Institute of Technology Kharagpur, India

Often motile cells and microorganisms can exhibit motion and reorientation in response to external chemical gradients. For example, the survival of marine microbes in a nutrient scarce landscape of an ocean depends strongly on their rapid chemotactic response. We consider a minimal model to describe a collection of chemotactic, active and interacting Brownian particles in two-dimensional flows. We expect the activity and chemotaxis, in general, to be beneficial for the microorganisms in nutrient search and escaping the nutrient-scarce areas. However, the interplay of the underlying fluid flow, activity, and chemotactic sensing can give rise to dynamical regimes that can have consequences for nutrient uptake and limited access to the nutrient source area. We find that the collective dynamics exhibits several interesting dynamical regimes depending on the self-propulsion speed and the chemotactic strength: (i) A fluid-like phase; (ii) a mixed phase, wherein the fluid contribution, activity and chemotaxis compete with each other; (iii) a chemotaxis dominated phase. The characterization of transport properties suggests the presence of dynamical regimes that are consistent with ballistic, diffusive and sub-diffusive transport. Our results are relevant to the complex collective nutrient search by microorganisms, such as bacteria, in a fluid environment.

45. Physics of the complex interface dynamics in bubble/drop laden turbulence

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Institute of Fluid Mechanics & Heat Transfer, TU Wien Getreidemarkt 9,1060, Vienna, Austria

The presence of drops and bubbles in turbulent flows is governed by their interfacesthin transition layers that bridge the molecular scale and macroscopic phenomena. These interfaces play a crucial role in numerous environmental and industrial processes, as momentum, heat, and mass transfer occur across them. In this talk, new experimental investigations in homogeneous Isotropic turbulence and corresponding phase-field based numerical simulations will de described in an attempt to discuss flow scenarios where surface tension, density, and viscosity are varied.

46. Stochastic resonance in low-inertia viscoelastic channel flow

Victor Steinberg
Weizmann Institute of Science, Israel

Stochastic resonance in inertia-less viscoelastic channel flow Victor Steinberg I report on stochastic resonance (SR) found above elastic instability onset, Wi_c, in low-inertia viscoelastic channel flow and white noise perturbations, despite proven linearly stability of parallel shear flow, similar to Newtonian one. Since linearized equations of viscoelastic channel flow are non-Hermitian, non-normal mode elastic instability takes place resulting in direct transition from laminar to chaotic Wi_c. Then at $Wi > Wi_c$, 3 chaotic flow regimes: transition, elastic turbulence (ET) and drag reduction (DR), accompanied by earlier discovered elastic waves, are found. We show experimentally that elastic waves play key role in synchronized energy transfer from main flow to wall-normal vorticity fluctuations that promote sustained chaotic flow. However, at $Wi > Wi_c$, elastic waves are very weak and in lower sub-region of transition regime at $Wi > Wi_c$, SR is found via periodic spikes in time dependence of stream-wise velocity resulted in peak in its spectrum, Eu. The peak orders of magnitude larger than pin elastic wave span-wise velocity spectrum, Ew. At $Wi > Wi_c$, Ew remains flat. Thus, SR occurs at 3 conditions: chaotic Eu, flat Ew and weak elastic waves.

47. Shapes and dynamic regimes of an active fluid droplet under confinement

Adriano Tiribocchi, M. Durve, M. Lauricella, A. Montessori, D. Marenduzzo, S. Succi
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Active droplets are artificial microswimmers built from a liquid dispersion by microfluidic tools and showing self-propelled motion. These systems hold particular interest for mimicking biological phenomena, such as cell locomotion, as well as for the design of biologically inspired materials, such as engineered tissues. Growing evidence suggests that geometrical confinement crucially affects their morphology and motility, but the driving physical mechanisms are poorly understood. Here, we study the effect of activity on a droplet containing a contractile polar fluid confined within microfluidic channels of various sizes. We find a variety of shapes and dynamic regimes, whose mechanics is regulated by a subtle interplay between contractile stress, droplet elasticity, and microchannel width. They range from worm-like shaped droplets displaying an oscillating behavior within wider channels to bullet-shaped droplets exhibiting rectilinear motion in narrower slits. Our findings support the view that geometrical confinement can provide a viable strategy to control and predict the propulsion direction of active droplets.

48. Stochastic resonance of magnetic particles in turbulence

Federico Toschi
Eindhoven University of Technology, The Netherlands

The chaotic dynamics of small-scale vorticity plays a key role in understanding and controlling turbulence, with direct implications for energy transfer, mixing, and coherent structure evolution. However, measuring or controlling its dynamics remains a major conceptual and experimental challenge due to its transient and chaotic nature. Here we use a combination of experiments, theory and simulations to show that small magnetic particles of different densities, exploring flow regions of distinct vorticity statistics, can act as effective probes for measuring and forcing turbulence at its smallest scale. The interplay between the magnetic torque, from an externally controllable magnetic field, and hydrodynamic stresses, from small-scale turbulent vorticity, reveals an extremely rich phenomenology. Notably, we present the first observation of stochastic resonance for particles in turbulence: turbulent fluctuations, effectively acting as noise, counterintuitively enhance the particle rotational response to external forcing. We identify a pronounced resonant peak in particle rotational phase-lag when the applied magnetic field matches the characteristic intensity of small-scale vortices. Furthermore, we uncover a novel symmetry-breaking mechanism: an oscillating magnetic field with zero-mean angular velocity remarkably induces net particle rotation in turbulence with zero-mean vorticity, as turbulent fluctuations aid the particle in "surfing" the magnetic field. Our findings offer insights into flexible particle manipulation in complex flows and open up a novel magnetic resonance-based approach for measuring vorticity: magnetic particles as probes emit detectable magnetic fields, enabling turbulence quantification even under optically-inaccessible conditions.
`https://arxiv.org/abs/2504.08346`

49. Scaling and Predictability in Surface Quasi-Geostrophic Turbulence

Victor Valadão, Filippo De Lillo, Stefano Musacchio, Guido Boffetta
Università degli Studi di Torino, Italy

The Surface Quasi-Geostrophic (SQG) equation models flow dynamics at the surface of a rotating, stratified fluid and applies to geophysical contexts like Earth's atmosphere, ocean surfaces, and Jupiter's atmosphere. When forcing and dissipation are turned on, turbulence develops in SQG. Interestingly, this turbulent state shares many statistical properties with three-dimensional (3D) turbulence, including an energy cascade with a Kolmogorov spectrum $E(k) \propto k^{-5/3}$. This motivates SQG as a simplified model for understanding 3D turbulence. We study the scaling properties of SQG turbulence, focusing on energy flux, spectrum, and Eulerian predictability via finite-time Lyapunov exponents (FTLE) in numerical simulations over a wide range of Reynolds numbers (Re). We find that Kolmogorov scaling emerges only at high Re, while at lower Re, the energy spectrum exponent $\xi(Re)$ is steeper than $-5/3$, indicating a non-constant energy flux. The Lyapunov exponent $\lambda(Re)$ scales as $\lambda \propto \mathrm{Re}^{0.7}$, deviating from the expected $\lambda \propto \mathrm{Re}^{1/2}$ scaling. Similar deviations occur in 3D turbulence, suggesting a common mechanism for solution separation in both SQG and 3D turbulence despite their differences.

50. Collective dynamics of simple model microswimmers

Francesco Michele Ventrella, Filippo De Lillo, Guido Boffetta and Massimo Cencini
University of Turin, Italy

We describe the pair and collective dynamics resulting from the hydrodynamic interactions of low-Re swim- mers described by a simple numerical model implemented within a direct numerical integration of the Navier- Stokes equations. Each swimmer is described by a rigid structure defined by the positions of three regularized point forces representing propulsion and fluid drag. We discuss the relative alignment induced by hydrodynamic interactions as well as the effects of swimmer geometry.

51. Phase transitions of active tracer particles in two-dimensional isotropic turbulence

Minping Wan
Southern University of Science and Technology, China

Active particles, characterized by self-propelled motion, exhibit collective behaviors that transition between ordered and disordered states as noise levels vary. We investigate the phase transition of active tracer particles in two-dimensional (2D) isotropic turbulence using direct numerical simulations based on a modified Vicsek model (VM). Our study reveals that the critical noise intensity is significantly lower in turbulence compared to the case with only Gaussian noise, indicating that turbulence accelerates the onset of the phase transition. Critical exponents are determined, showing distinct behaviors between turbulence and Gaussian noise backgrounds. Additionally, we find that the forcing wavenumber in 2D turbulence has a minimal impact on the critical behavior of the particles, suggesting that the integral length scale of turbulence does not strongly influence the phase transition process. Our results demonstrate that active tracer particles in turbulence exhibit properties consistent with second-order phase transitions, providing new insights into the dynamics of active matter in complex flow environments.

52. Discovery of intrinsic dynamics from kinetic data

Xiao Xue, Xiaoyuan Cheng, Yiming Yang, Yi He, Yukun Hu, Peter V. Coveney
University College London, UK

Dynamical systems are integral to scientific research and engineering, with their evolution traditionally described by ordinary or partial differential equations that model macroscopic states. However, underlying these macroscopic models are mesoscopic dynamics that dictate the evolution of single-particle distribution functions. These s-PDFs are central to kinetic theory, providing a deeper, parallel framework to the macroscopic continuum PDEs. A significant challenge in modeling s-PDF evolution through the Boltzmann kinetic equation arises from the collision kernel, which accounts for changes in the distribution function due to particle collisions. Existing kinetic-based machine-learning approach rely on approximating the collision kernel. In this study, we introduce a novel approach to understanding particle distribution functions evolution using function approximation theory, effectively circumventing the constraints imposed by the mean free path on the collision kernel. We validated its effectiveness by successfully modeling the evolution of various dynamical systems. This kinetic, data-driven machine learning approach represents a transformative advancement, opening new ways for addressing a wide range of challenging problems in physics and engineering.

53. Global drag reduction and local flow statistics in Taylor-Couette turbulence with dilute polymer additives

Yi-Bao Zhang, Yaning Fan, Jinghong Su, Heng-Dong Xi, Chao Sun
Tsinghua University, China

We present an experimental study on the drag reduction by polymers in Taylor-Couette turbulence at Reynolds numbers (Re) ranging from 4000 to 25000. Polyacrylamide polymers with two different average molecular weights are used. It is found that the drag reduction rate increases with polymer concentration and approaches the maximum drag reduction (MDR) limit. At MDR, the friction factor follows the -0.58 scaling, similar to channel/pipe flows. However, the drag reduction rate is about 20% at MDR, which is much lower than that in channel/pipe flows at comparable Re. We also find that the Reynolds shear stress does not vanish and the slope of the mean azimuthal velocity profile in the logarithmic layer remains unchanged at MDR. These behaviours are reminiscent of the low drag reduction regime reported in channel flow. We reveal that the lower drag reduction rate originates from the fact that polymers strongly suppress the turbulent flow while only slightly weaken the mean Taylor vortex. We further show that polymers stabilize the velocity boundary layer and suppress the small-scale Gortler vortices in the near-wall region. The former effect reduces the emission rate of both intense fast and slow plumes detached from the boundary layer, resulting in less flux transport from the inner cylinder to the outer one and reduces energy input into the bulk turbulent flow.

POSTERS

1. Liquid Brain: Biomimetic neuromorphic wetware for analogue embedding of material properties and single shot classification of biomolecules.

Joe Bailey
Apoha

Apoha is London based start-up with it's origins in foundational research on the thermodynamics of signal processing in biomimetic neurons. We are building a novel technology (the Liquid Brain®) for generating high-dimensional analogue embeddings of materials grounded in their state diagrams. Using as little as $10\mu g$ of lipids, minerals and proteins, it performs single-shot classification of material behaviour via the physics interfacial waves and out-or-equilibrium thermodynamics of excitable liquid substrates. Our approach is generating actionable insights in a range areas, from predicting the developability risk profile of an early stage drug candidate to the flavour profile of a fine single malt whisky. In this flash talk I will present an overview of our technology and our benchmark study of over 100 clinical-stage antibodies, demonstrating our technologies ability to uncover insights beyond prevalent perspectives on mAB drug screening.

2. Immersed Boundary-Lattice Boltzmann Simulations of Droplet's Spreading

Elisa Bellantoni[1,2,3], Nikos Savva[1,4], Mihalis Nicolaou[1], Andreas Demou[1], Fabio Guglietta[2], Mauro Sbragaglia[2], Francesca Pelusi[5], Mathieu Desbrun[6], Kiwon Um[3]
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The study of wetting is a captivating problem laying at the intersection between physics, chemistry and engineering. The multi-scale nature of this phenomenon makes it challenging to model, calling for advanced numerical techniques. We present an immersed boundary-lattice Boltzmann (IB-LB) method to tackle this task, improving on existing work [Pelusi et al., Physics of Fluids 35, 082126 (2023)] in scope and applicability, in order to reproduce droplets on a horizontal, homogeneous solid substrate ranging from hydrophobic to hydrophilic wetting regimes. The droplet's non-ideal sharp interface, modelled via the immersed boundary (IB) method, is coupled to the inner and outer fluids resolved via the lattice Boltzmann (LB) method; the wetting interaction with the substrate is achieved through a force term designed with the key computational advantage of providing a regularization of the interface profile close to the contact line, avoiding abrupt curvature changes that would cause numerical instabilities. Extensive model validations against analytical results for equilibrium droplet shape and scaling laws for droplet spreading dynamics are addressed This research is supported by European Union's HORIZON MSCA Doctoral Networks programme under Grant Agreement No. 101072344 project AQTIVATE (Advanced computing, QuanTum algorIthms and data-driVen Approaches for science, Technology and Engineering).

3. Mesoscale model for cavitation in lipid membranes

Marco Bussoletti, Riccardo Consolandi, Matteo Bottacchiari, Mirko Gallo, Carlo Massimo Casciola
Sapienza Università di Roma, Italy

Cavitation — formation of vapor bubbles in a liquid under tension — has catastrophic consequences when uncontrolled. At ambient temperature, pure water withstands extremely negative pressures (¡ -100MPa) whereas at biological conditions, when contaminated, several events per day are observed. Recent molecular simulations suggested this drop in tensile resistance is due to lipid structures in the liquid. However, being cavitation thermally activated, quantitative predictions on its occurrence inherit strong uncertainties from the exponential scaling with the activation energy. We develop a mesoscale model of cavitation within lipid membranes that accounts for their elasticity while reproducing microscopic interactions between leaflets. Rare event techniques and fluctuating membrane dynamics are combined with a diffuse description of leaflets to compute activation energies, critical bubble configurations, and the corresponding diffusion coefficients. The resulting cavitation pressure is consistent with previous estimates. This approach provides a versatile and computationally cheap link between microscopic features of the lipid interface and the hydrodynamics of the nucleated bubble.

4. Tracking moving targets: olfactory search for persistent prey in turbulence

Maurizio Carbone[1], Lorenzo Piro[2], Robin A. Heinonen[3], Luca Biferale[2], Antonio Celani[4], Massimo Cencini[1];
[1]*Istituto dei Sistemi Complessi, CNR & INFN "Tor Vergata"- Rome, Italy;* [2]*Department of Physics & INFN, University of Rome "Tor Vergata" - Rome, Italy;* [3]*University of Genoa, Genoa, Italy* [4]*Quantitative Life Sciences, The Abdus Salam International Centre for Theoretical Physics - Trieste, Italy*

Olfactory search is a ubiquitous behavior in living organisms that enables the localization of nutrients or mates and plays a major role in robotic search-and-rescue operations. The searcher navigates a turbulent flow where tracers emitted from a source undergo stretching and diffusion, resulting in sparse and patchy odour detections. In biological systems, source motion typically transitions from ballistic at small scales to diffusive at larger scales, facilitating nutrient foraging while complicating predator pursuit. Motivated by this, we propose a heuristic strategy for agents to locate a moving source undergoing a persistent random walk. Our approach builds on infotaxis, a prototypical and effective strategy for locating stationary targets. However, for moving targets, infotaxis leads to excessive exploration rather than direct pursuit once the target is localized. To address this, we introduce a hybrid strategy that combines infotaxis with a greedy policy derived from the associated Bellman equation, assuming complete knowledge of the source state. We test this strategy on realistic run-and-tumble trajectories, showing it significantly reduces both the mean and variance of search times.
This work was supported by the ERC under the European Union's Horizon 2020 research and innovation programme Smart-TURB (Grant Agreement No. 882340), and by the NRRP, Mission 4 Component 2 Investment 1.1 - Call No. 104 – Project: CO-SEARCH, code 202249Z89M – (CUP MASTER B53D23003920006, CUP E53D23001610006).

5. Formation and evolution of density interfaces in simulations of Boussinesq flows

Niccolò Cocciaglia[1] Luca Biferale[1] , Fabio Bonaccorso[1] , Alessandra S. Lanotte[2]
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Experiments with stirred fluids having a linear density (salinity) profile displayed the formation of vertical layers, characterized by almost homogeneous density, separated by high-gradient density jumps (density interfaces). While this behaviour was understood and also reproduced with models of reduced complexity, a numerical investigation of the full equations pushed long enough to observe the interface dynamics seems still lacking. We report here, using DNS of the Boussinesq equation, what the formation and evolution of density layers and interfaces entails for the energy redistribution, the relation between vertical density flux and vertical density gradient, and the different intermittent statistics displayed in layers and interfaces.
This work was supported by the ERC under the European Union's Horizon 2020 research and innovation programme Smart-TURB (Grant Agreement No. 882340), and by the NRRP, Mission 4 Component 2 Investment 1.1 - Call No. 104 – Project: CO-SEARCH, code 202249Z89M – (CUP MASTER B53D23003920006, CUP E53D23001610006).

6. Viscosity measurement via Janus particles in an Optical Vortex

Romie Seth M. Florida, Emil Vincent Llanes, Khate Cheryl C. Bayer and **Mark Nolan Confesor**
Department of Physics, MSU-Iligan Institute of Technology, Philippines

We explore the dynamics of chromium-coated Janus particle illuminated by an optical vortex for varying medium viscosity. The optical vortex results to a circular trajectory of the Janus particle with angular velocity that is dependent on the laser power. The angular velocity of the Janus particle is found to monotonically decrease at increasing fluid viscosity. Nonetheless, the angular velocity is still much bigger than the case of a pure Polystyrene (PS) bead under the same illumination condition. At high viscosity, the angular velocity of PS bead saturates and thus limits the range of viscosity measurement in comparison to using Janus particle.

7. Machine learning for atmospheric disperison

Ben Devenish
Met Office/Imperial College, UK

The ability of machine learning diffusion models to generate Lagrangian trajectories in a realistic atmospheric flow will be assessed. In particular, I will consider whether such a model captures the rate at which material escapes from the top of the atmospheric boundary layer; dispersion in a convective atmospheric boundary layer which is characterised by high levels of skewness; and deep convection which leads to discontinuities in a particle's trajectory as material is moved rapidly upwards.

8. Coexistence of Defect Morphologies in Three-Dimensional Active Nematics

Pasquale Digregorio, Ignacio Pagonabarraga, Federico Toschi
Università degli Studi di Bari, Italy

Synthetic assemblies of microtubules and kinesin motors are paradigmatic examples of an active material, where the system is stirred at the level of the single components and evolves out of thermal equilibrium. The presence of activity drives chaotic flow at the large scale and a sustained proliferation of topological defects. We use numerical simulations of a model of nematic liquid crystals in the presence of a microscopic active stress in 3D to study the morphology and dynamics of these topological defects to deduce fundamental properties of the turbulent state. Activity selects a crossover length scale in between the size of small defect loops and that of long and tangled defect lines of fractal dimension 2. In a 3D periodic geometry, a statistically relevant wrapping component is present and quantitatively compatible with a phenomenon of defects percolation. The average length of the wrapping component verifies an inverse quadratic dependence on the active length. The shorter is the active length scale, the more times the defect lines wrap around the periodic boundaries, resulting in extremely long and tangled structures.

9. Inferring Multi-scale Dynamics from Sparse Data in a Shell Model of Turbulence

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Shell models provide a simplified yet effective framework for representing key features of turbulent flows, such as multiscale energy transfer and small-scale intermittency. These properties make them particularly suitable for evaluating the performance of Data Assimilation (DA) techniques, especially for understanding how mesoscale observations (i.e., inertial-range scales) can enhance the prediction of both large- and small-scale intermittent dynamics. In this study, we investigate and compare the performance of three DA methods—Ensemble Kalman Filter (EnKF), Ensemble 4D-Var, and Nudging—by systematically varying the temporal sparsity of measurements as well as the specific subset of

observed shells. Our results indicate that the EnKF outperforms the other methods when the observation frequency exceeds the characteristic timescale of the fastest observed scales. Under these conditions, full statistical synchronization of the larger-scale dynamics can be achieved, provided that measurements are available over at least two adjacent shells within the inertial range. Furthermore, we demonstrate that the application of a tailored, scale-aware inflation scheme is critical for maintaining the numerical stability and physical consistency of the assimilation process, particularly in the presence of sparse and noisy data. These findings offer practical insights into the design of DA strategies for turbulent systems governed by nonlinear multiscale interactions, serving as a foundational step toward applications in more complex geophysical systems.
This research is supported by European Union's HORIZON MSCA Doctoral Networks programme under Grant Agreement No. 101072344 project AQTIVATE (Advanced computing, QuanTum algorIthms and data-driVen Approaches for science, Technology and Engineering) and by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme Smart-TURB (Grant Agreement No. 882340).

10. Lagrangian analysis of turbulent blood flow in the human left heart

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Accurately modeling blood flow, pressure, and structural deformation in the human heart is vital for advancing cardiovascular research and diagnosis. Direct in-vivo measurements, however, are limited by invasiveness and resolution. Patient-specific digital twins (i.e., computational models tailored to individual anatomy) offer a non-invasive alternative. We present a multi-GPU simulation framework that integrates Fluid–Structure–Electrophysiology Interaction (FSEI) to reproduce cardiac mechanics with high fidelity [1]. The model includes biophysically detailed electrophysiology, realistic valve dynamics, and patient-specific anatomical data. Using this setup, we assess realism and robustness against physiological variability. A Lagrangian analysis based on passive tracers reveals multiscale turbulence features in the left heart, such as strong intermittency and persistent flow structures. Results highlight how heart rate and valve stiffness affect flow, showing the promise of combining clinical data with high-performance computing to build predictive cardiac digital twins. This research was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme Smart-TURB (Grant Agreement No. 882340), and by the project MUR-FARE R2045J8XAW.
[1] Viola et al., Scientific Reports, 13(1) (2023).

11. Parameter selection for olfactory search in turbulent flows"

Robin A. Heinonen[1], Luca Biferale[2], Antonio Celani[3], Agnese Seminara[1], Massimo Vergassola[4]
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Tracking the sources of odors being advected by a turbulent flow is a challenging task relevant to animal behavior and robots applications. A common approach to this problem involves maintaining a spatial probability map and updating it using Bayes' theorem after every measurement of the local concentration, which enables finding quasi-optimal Bayesian policies using the formalism of partially observable Markov decision processes (POMDP). In this work, we obtain quasi-optimal Bayesian policies with respect to realistic turbulent flow data and study the scalings of the mean arrival time to the source with key parameters of the searcher: the threshold concentration of observation and the rate of observation. By considering together the time of arrival and the typical rate of search opportunities, we argue for the existence of a unique, nontrivial optimal threshold. We also find that correlations in the concentration field set an optimum observation rate. We also explore these ideas in a model-free setting using reinforcement learning.
This work was supported by the European Research Council under the grants Smart-TURB (No. 882340) and RIDING (No. 101002724), by the Air Force Office of Scientific Research (grant FA8655-20-1-7028), and the National Institute of Health under grant R01DC018789.

12. Improving Velocity Gradient Statistical Topology using Parameterized Lagrangian Deformation Tensor Networks

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We develop a Physics-Informed Neural Stochastic Ordinary Differential Equation-based closure model for the Velocity Gradient (VG) in isotropic homogeneous turbulence, extending the Tensor Basis Neural Network (TBNN) framework. Our new model, called the Lagrangian Deformation Tensor Network (LDTN), introduces a Neural Network-based parameterization for the unresolved terms in the Navier-Stokes equations for the VG. This parameterization is expressed as a nonlinear, auto-regressive and stochastic functional of the VG evaluated along a Lagrangian path. The "deformation" in the model's name reflects a reference to the previously reported phenomenological closures, which utilize both the VG and the Lagrangian deformation tensor. Consequently, our model encapsulates both the TBNN and the phenomenological deformation approaches by incorporating the Lagrangian memory into. The Physics-Informed nature of the LDTN model allows new insights into temporal correlations of the Lagrangian memory kernel and thus the strain-rate tensor's history, and significantly improving predictions related to the pressure Hessian-VG relationship.

13. High-Fidelity 3D Turbulence Generation and Reconstruction via Physics-Constrained Diffusion Models

Tianyi Li[1] , Michele Buzzicotti[1] , Fabio Bonaccorso[1] , Luca Biferale[1] , Alessandra S. Lanotte [2]
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Generative diffusion models (DMs) have shown strong promise in fluid dynamics, but most existing work remains limited to 1D signals or 2D flow fields, restricting both the enforcement of essential physical constraints, such as incompressibility, and the generation of realistic 3D turbulence with complex spatial structures. In this work, we extend DMs to generate 3D rotating Eulerian turbulence on a 64^3 grid, a high-dimensional setting where direct training fails to converge. To address this, we explore two training strategies: (1) progressive training along the rotation axis, and (2) physics-constrained training, where incompressibility is enforced via projection using both relaxed and strict formulations. These approaches enhance training stability and improve the physical fidelity of the generated fields. We quantitatively and systematically evaluate the resulting 3D turbulence via energy spectra and velocity/vorticity PDFs. All models satisfy the incompressibility condition with accuracy comparable to second-order finite differences. Furthermore, we confirm the generalizability of physics-constrained DMs by showing highly correlated outputs under shared noise realizations. Finally, we leverage the trained DM as a prior for training-free reconstruction using Diffusion Posterior Sampling (DPS) [1], enabling the recovery of physically consistent 3D flow fields from partial observations.
This work was supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme Smart-TURB (Grant Agreement No. 882340). We thank Mauro Sbragaglia and Giulio Cimini for useful discussions.
[1] Chung, H., Kim, J., Mccann, M. T., Klasky, M. L., & Ye, J. C. (2022). Diffusion posterior sampling for general noisy inverse problems. arXiv preprint arXiv:2209.14687.

14. Emergent turbulent and crystalline states in an active-spinner fluid.

Biswajit Maji , Nadia Bihari Padhan, Rahul Pandit
Phd student, Indian Institute of Science, Bengaluru, India

We investigate emergent turbulent and crystalline states in the active-rotor Cahn-Hilliard- Navier-Stokes partial differential equations, with a scalar field ϕ coupled to the fluid velocity u; $\phi > 0$ ($\phi < 0$) in regions with clockwise (anticlockwise) rotation of the spinners. Rotor activity is governed by the strength τ of the torque generated by the spinners. First we consider the case with an equal number of clockwise (C) anticlockwise and (A) rotating spinners. We show that, at low values of τ , the nonequilibrium state exhibits phase separation into C-rich and A-rich states separted by interfaces; as we increase τ this phase separation is suppressed by emergent statistically steady active-rotor turbulence. This turbulent state exhibits a remarkable proportionality of ϕ and the fluid vorticity. We show that active-rotor this turbulence has statistical properties that are markedly different from those of two-dimensional (2D) fluid turbulence and active-fluid turbulence in a variety of systems. Next we explore the case in which the mean C density is different from the mean Adensity. Here we find the formation of triangular lattice of spinning triplets of vorticesand antivortices. We characterize the crystalline order by using methods from condensed-matter physics and we examine the dependence of this crystalline state on the mean C density and the bottom friction.

15. Evidence of Stochastic Resonance in Multi-Sensor Odor Source Localisation

Francesco Marcolli, Martin James, Agnese Seminara
University of Genova, Italy

Octopuses can perform odor search using the suckers they have spread all over their body. Odor plumes convey useful information about the source that generates them and several animals use it to locate or navigate the source. Experimental evidence shows that octopuses can perform the challenging task of finding the source of the odor even in a dark and turbulent environment. The octopus suckers are modeled as a series of chemical sensors that collectively cooperate to locate the source of the odor. The main question is how many chemical sensors collectively infer the location of a chemical source. In my setting, the odor develops into convoluted and sparse clouds, due to turbulent transport, and each sensor measures the odor concentration at its location. I examine the ideal case, perfect knowledge of sensors' relative position and combine their measures using Bayesian inference. Then, I insert noise into the relative position information between sensors. Error affects prediction accuracy. The inference process can be improved under certain conditions if the error is not restored. This counterintuitive result is in accord with recent results in stochastic resonance. My results set the basis for understanding whether and how imperfect proprioception may affect the olfactory behavior of animals with distributed nervous systems.

16. Turbulent flows are not uniformly multifractal

Ritwik Mukherjee, Sugan Durai Murugan, Ritwik Mukherjee, Samriddhi Sankar Ray
International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, India

Understanding turbulence rests delicately on the conflict between Kolmogorov's 1941 theory of nonintermittent, space-filling energy dissipation characterized by a unique scaling exponent and the overwhelming evidence to the contrary of intermittency, multiscaling, and multifractality. Studies of multifractality in turbulence are typically global, relying on statistics constructed across the full dissipation field, missing local variations. Given the significant variation in turbulent fields, where regions of high dissipation coexist with low-activity patches, we propose a tiling approach to measure local, space-dependent multifractality to better understand turbulence. We construct a measure of the local multifractality which allows us to map turbulence into monofractal regions and multifractal "islands". Remarkably, much of the dissipation field remains monofractal, consistent with Kolmogorov's theory, while multifractality emerges as isolated regions, its strength growing logarithmically with local energy dissipation fluctuations. We further investigate the spatiotemporal correlations in local multifractality, and its connection to the correlations in the dissipation field.

17. Active turbulence invasion in a quiescent bath: fluctuations, front propagation and mixing

Siddhartha Mukherjee
Department of Mechanical Engineering, Indian Institute of Technology (IIT) Kanpur, India

Living fluids like dense bacterial suspensions self-organize into complex dynamical states, often echoing the signatures of inertial turbulence. Numerical studies so far have treated activity as a spatio-temporally uniform, or at best spatially patterned, source of energy injection in the flow. Experiments, however, hint that activity may not be uniform, and it is natural for active fluids to intermix with passive ones. We hence ask, via DNS of a modified bacterial turbulence model, how an active fluid patch invades and mixes with a quiescent bath, hence agitating it. Such flows develop sharp activity gradients separating coexisting flow phases and convoluted activity front propagation. We quantify the fluctuations of the growing front, and Lagrangian mixing characteristics of this complex flow. Our findings shall inspire experiments with heterogeneous active colonies, and lead to parallels with other problems of front propagation like nonlinear stochastic growth exhibited by the Kardar-Parisi-Zhang equation, along with (inertial) turbulent/non-turbulent interface analogies from mixing layers and jets.

18. Lévy jumps in lattice-Fokker-Planck models of fluid dynamics

Kasper Juel Petersen
University of Oxford, UK

Mathematical models for simulation of complex fluids undergoing phase transitions, phase separations, and/or chemical reactions are conventionally described in either microscopic or continuum settings disjointed from each other, due to the span of relevant length and time scales. At one end of the spectrum, the Lagrangian dynamics of molecules that leads to nucleation of nanoscale embryonic phases, can be computationally simulated for infinitesimally small volumes and rapid time scales. In contrast, continuum descriptions of fluids rely on mean-field approximations or empirical equations of state accounting for the microscale effects that eventually lead to the formation of large-scale, developed homophases. This talk revolves around upscaling the microscopic effects of thermal fluctuations in a mesoscale statistical model that obeys thermo-hydrodynamic conservation laws. In particular, an integro-differential Fokker-Planck equation will form the basis for modelling the non-Gaussian Lévy velocity-jump statistics that lead to rare, anomalous disturbances in the macroscopic variables. To facilitate many-degrees-of-freedom simulations, the model is discretized on a space-filling lattice. Applications to thermal and bio-fluid dynamics problems will be discussed.

19. Heat transfer modulation in Phase Change Materials via fin insertion

Paolo Proia, Giacomo Falcucci, Mauro Sbragaglia
Università di Roma "Tor Vergata", Roma, Italy

Phase Change Materials (PCMs) are a key component in the ecological transition because, thanks to their large latent heat, they can store excess heat by absorbing it during a phase transition and release it when necessary by reversing the process. However, since these materials usually have low thermal conductivity, it becomes necessary to improve their heat transfer performance. This can be accomplished in several ways; in this study, we focus specifically on the insertion of a single source-like fin inside the enclosure containing a solid substance undergoing melting. The presence of the fin influences the behavior of the system, as its position and size can promote the development of convective fluid motion, which plays a fundamental role in heat transfer. We conduct a parametric investigation into the position and size of the fin, measuring the total melting time of the system and relating it to the formation of convective plumes, confirming that convection-favored configurations are the most efficient in terms of heat transfer and melting velocity.

20. A Kolmogorovean Casting of Elasto-Inertial Turbulence

Alessandro Chiarini, **Rahul Kumar Singh**, Marco Edoardo Rosti
Okinawa Institute of Science and Technology, Okinawa, Japan

The addition of polymers drives turbulence statistics away from the classical K41 self-similarity. We now show that polymeric turbulence (PT) statistics can be cast in the classical Kolmogorov phenomenology by deriving equivalent Kármán-Howarth-Monin-Hill equation (PKHMH) beginning from the governing modified Navier-Stokes equations. The PKHMH yields the equivalent of Kolmogorov's 4/5th-law in PT and leads us to define the extended velocity increments and their moments, the extended structure functions (ESFs). A general pth-order ESF exhibits a self-similar behaviour in the elasto-inertial range of scales, but whose exponents deviate from the predicted value of p/3 using K41-like dimensional arguments. These deviations are accounted for by invoking the Refined Kolmogorov Similarity Hypotheses which relate turbulence statistics to the scale-local average of the total dissipation. We provide further evidence by considering the statistics of Kolmogorov Multipliers which are the ratio of the extended increments at two different scales. We show that the multiplier distributions are scale invariant and they collapse for the same scale ratio, over a wide range of choices.

21. A finite difference method for turbulent thermal convection of complex fluids

Jiaxing Song, Chang Xu and Olga Shishkina
Max Planck Institute for Dynamics and Self-Organization, Germany

An efficient and robust finite difference algorithm for three-dimensional direct numerical simulations (DNS) of turbulent thermal convection of complex fluids has been developed. To study the complicated fluid elasticity and plasticity, the simulated non-Newtonian fluids are modelled by either viscoelastic Oldroyd-B or FENE-P, or Saramito elastoviscoplastic constitutive equations based on the conformation tensor. The present algorithm is demonstrated to preserve the properties of symmetry, boundedness and positive definiteness of the conformation tensor up to large Weissenberg numbers $Wi \sim 10^2$ and high Rayleigh number $Ra \sim 10^{10}$. To validate and assess the code, both two-dimensional and three-dimensional DNS of viscoelastic Rayleigh–Bénard convection are performed. A comparison with available DNS results in the literature shows a very good agreement. To validate the elastoviscoplastic model used in the code, the DNS of elastoviscoplastic turbulent channel flows at friction Reynolds number $Re_\tau = 180$ and different Bingham numbers Bi are performed, which also show good agreement with the available results. Single plume dynamics and turbulent Rayleigh–Bénard convection of Newtonian, viscoplastic, viscoelastic and elastoviscoplastic fluids are also studied in the DNS to show the versatility of the code.

22. Turbulence modeling in the QR space

Flavio Tuteri, Alexandros Alexakis, Sergio Chibbaro
Laboratoire de Physique de l'Ecole normale superieure, France

Turbulence is omnipresent in dynamical description of fluids, a huge class of phenomena sharing the multiscaling complexity which results in a very large number of degrees of freedom. This has made it impossible to Directly Numerically Simulate systems of engineering interest and is the reason why modelling is the highway. Starting from incompressible 3D Navier-Stokes, a standard approach is to apply a spatial coarse graining and solve the equation for the large-scale field. Closing the model means give a shape to the unsolved action of the small-scales. The energy local flux across scales is then given, so the problem is intimately related to the hundred-year mystery of the energy cascade. The velocity gradient tensor, describing the flow local topology, has played a prominent role in recent developments. As new instrument of investigation we set the analysis conditioned to the QR space, the invariants of this tensor. Notably, one can clearly distinguish the region with mean dominated by backscatter and the others dominated by the direct cascade. The same analysis can be done for a modelled flux. Of particular interest for this work is the Clark model, the local-in-scale approximation for a Gaussian filtering. Fluctuations from the mean are also studied continuing previous works in the literature.

23. Analyzing the transition-to-turbulence in Rayleigh-Benard flows through latent space representations

Melisa Vinograd, Patricio Clark di Leoni
Universidad de San Andrés, Universidad de Buenos Aires, Argentina

We analyze Convolutional Autoencoders for generating reduced-order representations of Rayleigh-Bénard flows, focusing on identifying the smallest representations that capture all relevant physics. Our method estimates the minimum latent dimensions required to capture all scales, making it more suitable for highly multiscale flows than criteria used for lower-dimensional systems. At the onset of turbulence, these flows exhibit large-scale convective structures and small-scale eddies. As the Rayleigh number increases, more scales are activated, synchronization between field components is lost, and the flow becomes dominated by small-scale structures. By compressing the phase space at each Rayleigh number, we track how the number of degrees of freedom evolves with growing turbulence, revealing a sharp nonlinear transition around $Ra \sim 10^7$. We compare our architecture with two regularized variants and linear methods, demonstrating the advantages of nonlinear dimensionality reduction in understanding scale activation. By analyzing the latent space, we offer insights into how turbulent structures emerge and evolve.