Inertia-induced mechanism for giant enhancement of transport generated by active fluctuations

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Active matter is one of the hottest topics in physics nowadays. As a prototype of living systems operating in viscous environments it has usually been modeled in terms of the overdamped dynamics. Recently, active matter in the underdamped regime has gained a place in the spotlight. In this poster we unveil another remarkable face of active matter. In doing so we demonstrate an inertia-induced mechanism of giant enhancement of transport driven by active fluctuations which does emerge neither in the overdamped nor in the underdamped limit but occurs exclusively in the strong damping regime. It may be relevant not only for living systems where fluctuations generated by the metabolism are active by default but also for artificial ones, in particular for designing ultrafast micro and nano-robots.

Unsteady flow effects in cilia-mediated transport

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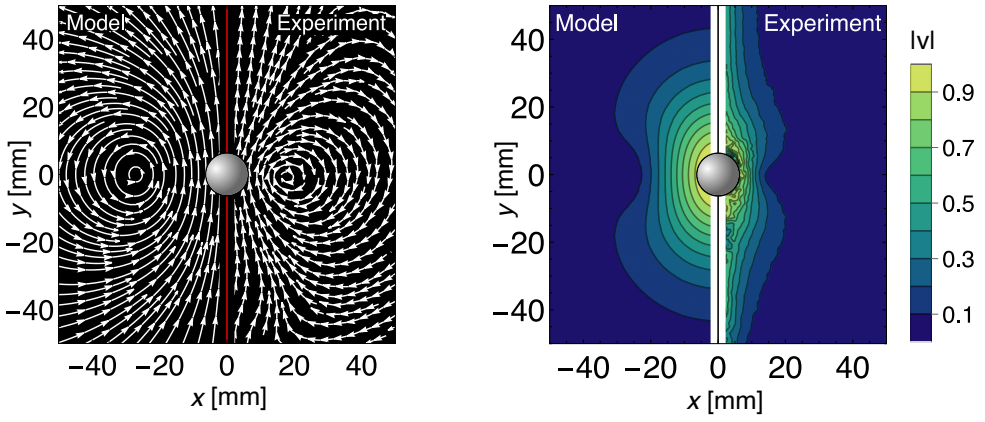
Cilia play a crucial role in biological systems, facilitating locomotion in unicellular eukaryotes, nutrient uptake in marine organisms, and fluid transport in human tissues. While ciliary flows are often modeled as steady, the role of unsteady, inertial effects in low Reynolds number environments remains underexplored. Ciliary beating generates unsteady Stokes flows when the actuation timescale is comparable to or shorter than the viscous diffusion timescale [1]. To investigate these dynamics, we analyze a model governed by time-dependent, linear Stokes equations, which we solve using Green's functions with analytically defined memory kernels [2].

We examine flows induced by time-varying forces that mimic individual and collective ciliary motion, using the "Pufflet"—a point-like hydrodynamic singularity—as a fundamental building block. Combining theoretical analysis, simulations, and experiments (comparison shown in the figure below), we explore fluid transport under rapid actuation. We show that unsteady effects enhance fluid mixing by breaking time-reversal symmetry. Vorticity diffusion in this regime generates complex trajectories of advected particles, significantly altering transport efficiency. When multiple actuation sites are introduced, we identify emergent transport patterns that can be optimized through spatial and temporal tuning of the forcing.

Our findings reveal fundamental differences between steady and unsteady Stokes flows, shedding light on microscale transport mechanisms. Understanding these effects may inform the design of bio-inspired fluid systems and optimized microscale mixing strategies.



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Elastic Adaptation of Streamer Biofilms to Reversible Flow Patterns

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Microorganisms are well-known for colonizing surfaces and fluid environments by forming organized structures called biofilms [1]. These structures are prevalent in natural, industrial, and medical contexts, often presenting a risk of contamination. Understanding the mechanisms behind their formation and interactions with the environment is essential for controlling their growth and dissemination. A unique type of biofilm is the streamer—a microbiological filament composed of cells connected by an extracellular matrix. Streamers typically form in environments where flow prevents complete attachment to surfaces.

In this work, we explore a novel theoretical and computational approach to measuring the bending stiffness of biofilms. A streamer, anchored to a cylindrical post, is placed in a microfluidic channel and exposed to a uniform external flow [2,3]. After reaching a steady, the flow is reversed, and the streamer's deformation is analyzed. By examining the shape and local curvature of the filament over time, we infer its elastic properties.

In our numerical model, the biofilm is represented as a one-dimensional elastic filament with uniform mechanical characteristics. The streamer is modeled as a series of beads connected by springs to account for its extensibility and bending stiffness. Bending is represented using harmonic potential based on dihedral angles between adjacent beads, coupled with Lennard-Jones interactions between all beads. Viscous hydrodynamic interactions are captured using the Rotne-Prager-Yamakawa (RPY) approximation [4].

We focus on the deformation of the filament anchored at one end when subjected to a uniform flow that is subsequently reversed. During this process, the filament flips and undergoes complex deformations influenced by its bending stiffness, length, and the fluid's properties. This study aims to characterize this transition and explore how system parameters affect the filament's behavior.

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Sediment pattern formed by random walks

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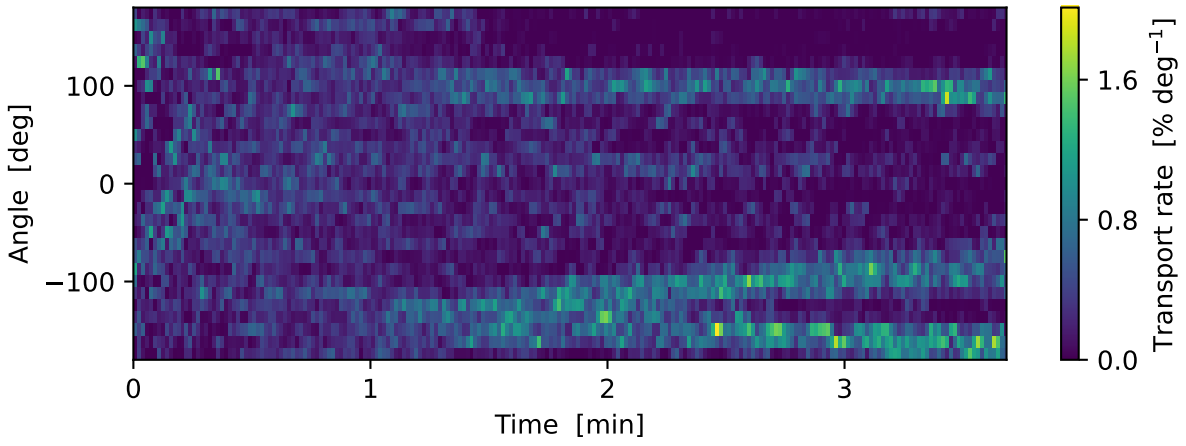
The slightest perturbation would cause the bank of a river to collapse, if it was not for the diffusion of sediment which, over time, pushes it back towards the side of the channel [1, 2]. This statistical flux results from the fluctuations of a sediment grain's trajectory as it travels downstream [3]. Such a grain, indeed, follows a random walk across the river's bed, the roughness of which induces a macroscopic temperature. This Brownian motion drives the sediment, on average, from areas of intense transport to quieter places [4]. Surprisingly, this process can also be a destabilizing force which could, at least in theory, produce streamwise streaks along the channel [5]. As it grows, this pattern might turn a single-thread river into a braid of intertwined channels—a common feature of mountainous streams. This instability, however, has never been seen in a laboratory experiment. We present the first observation of this phenomenon in a controlled environment, and propose a tentative interpretation for it in terms of heterogeneous diffusivity [6].



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Dynamics of quantum droplets in circular potential

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In the times of then-recently nascent field of quantum mechanics Satyendra Bose and Albert Einstein predicted a new state of matter now called the Bose-Einstein condensate (BEC) [1]. Bosonic particles, when cooled down to cryogenic temperatures, tend to occupy the same lowest quantum state, which causes the system to exhibit quantum properties macroscopically. The first experimental realization of BEC did not come about until 1995 when Eric Cornell and Carl Wieman cooled down rubidium atoms. This achievement earned them the Nobel Prize in Physics in 2001.

In 2015 D.S. Petrov showed theoretically that a mixture of two kinds of bosons in a condensate might form liquid-like droplets [2]. When the interspecies attraction strength is equal to the geometric mean of intraspecies repulsion, this balance produces a droplet stable against evaporation. Dynamics of quantum droplets are an active area of research and have been studied in recent years [3]. The droplets are governed by a set of extended Gross-Pitaevskii equations with Lee-Huang-Yang term:

$$-\frac{1}{2}\nabla^2\phi_1 + g(n_1 - \sqrt{a}n_2)\phi_1 + \delta g n_2\phi_1 + D(n_1 + an_2)^{\frac{3}{2}}\phi_1 = \mu_1\phi_1$$
$$-\frac{1}{2}\nabla^2\phi_2 + g\sqrt{a}(\sqrt{a}n_2 - n_1)\phi_2 + \delta g n_1\phi_2 + aD(n_1 + an_2)^{\frac{3}{2}}\phi_2 = \mu_2\phi_2$$

Where $a = a_{22}/a_{11}$ ratio of intraspecies scattering lengths, $n_1 = |\phi_i|^2$, $g = \frac{3a_{11}(\sqrt{a}+1)}{2|\delta a|}$ in which $\delta a = a_{12} + \sqrt{a_{11}a_{22}}$, $\delta g = -\frac{3}{2}(\sqrt{a}+1)$, $D = \frac{5}{2}\frac{1}{\sqrt{a}(1+\sqrt{a})^{3/2}}$ and μ_i is the species' chemical potential. One interesting aspect is that droplets of the same wavefunction phase attract, while droplets with phase difference π repel. This mechanic of attraction and repulsion lends itself to an interesting avenue of research of droplet dynamics.

In our work we construct a system with the so-called sombrero potential $V(\rho,\phi,z)_{R,V_0} = \frac{V_0}{R^4}\rho^4 - 2\frac{V_0}{R^2}\rho^2 + V_0$ and populate its minimum at $\rho = R$ with equally-spaced ground state droplets of alternating phase. We introduce a perturbation to the system by nudging the droplets from the equilibrium and try to induce different vibrational modes of the system.

Better understanding of the dynamics of BEC droplets might pave the way for designing experiments to benchmark quantum many-body theories. Theorized applications of BECs include quantum information processing and precision measurement.

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Classification of algebraic tangles

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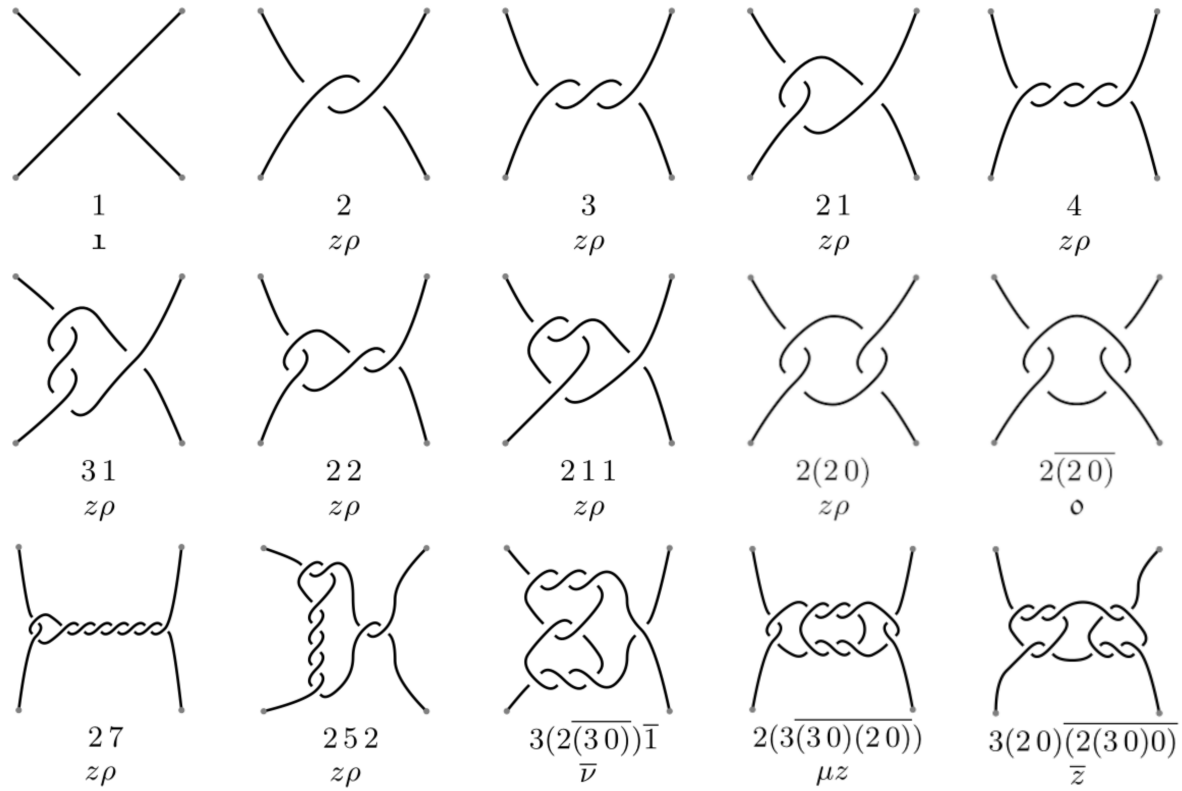
In 1970 John Conway created a notion of a "tangle" [1]. Tangles can be seen as building blocks of knots and are a basis of knot tabulation. Using tangles Conway managed to tabulate all knots up to 11 crossings, and links up to 10 crossings. Moreover, he found a bijection relation between rational numbers and a subclass of tangles called "rational tangles", thus fully classifying this subset of algebraic tangles.

Over 50 years later we extended Conway's work. We introduced a binary tree notation, which helped us to define a unique "canonical representation" for algebraic tangles. This let us classify algebraic tangles up to 14 crossings. Moreover, we studied the symmetry groups of algebraic tangles.



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Modelling ecological corridors in Poland

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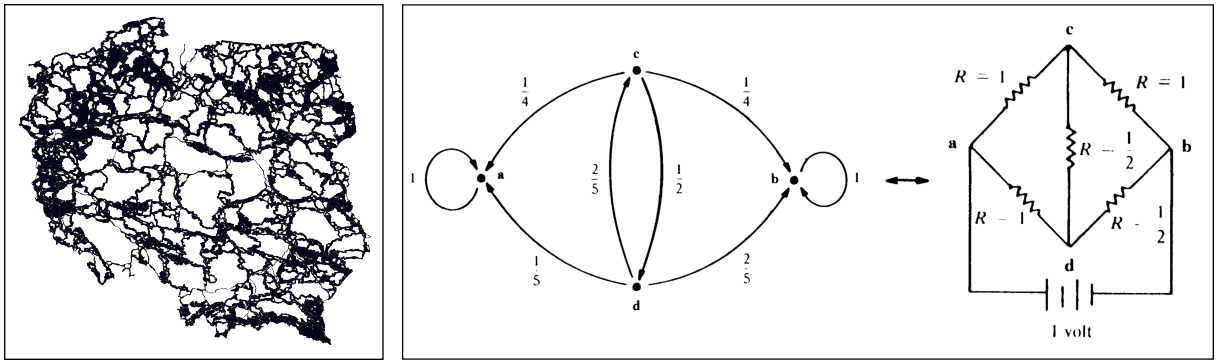
Ecological corridors are essential components of biodiversity conservation strategies, enabling species movement between habitat fragments disrupted by human activities such as urbanization, agriculture, infrastructure, and forestry [1]. These corridors are particularly critical for wide-ranging species like large mammals, which require extensive, connected habitats to maintain viable populations and avoid negative genetic and demographic effects caused by isolation. Corridor maps provide a strategic tool for conservation planning, helping prioritize areas for protection or restoration to maintain ecological connectivity at a national scale.



In this study, we aim to create a national-scale mapping of ecological corridors across Poland using a landscape connectivity model based on a circuit theory [2, 3]. This method treats the landscape as an electrical resistance surface, with resistance values reflecting the ease or difficulty of movement for organisms across various land cover types. By placing electrodes in key habitat areas, we simulate current flow across the landscape to identify potential movement pathways. The circuit theory exhibits a strong mathematical relationship with Markov chain models [4] – a duality explored in detail on this poster.

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Monte Carlo-Based Simulation of Cellular Behavior and Oncogenesis

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Understanding how cells behave over time—how they grow, die, accumulate damage, and occasionally transform into cancer cells—is essential for cancer and radiotherapy research. The inherent complexity and randomness of these processes require investigation using simulations and experiments. Cells and tissues can be viewed as a physical complex system, where numerous interacting components give rise to unpredictable behaviors. To better explore these dynamics, a computational approach is needed to complement experimental work and provide insights into long-term tissue behavior.

We developed a computational model that simulates cellular dynamics using Monte Carlo methods [1]. This effort is part of a broader modeling of complex systems, where emergent behavior is studied through the interaction of simple, probabilistically defined rules. The model represents a population of individual cells governed by probabilistic rules for division, death, damage accumulation, and transformation (such as mutations or carcinogenesis). Radiation is introduced as an external factor, and both natural behavior and external influences are treated as stochastic processes evolving over time. The framework includes mechanisms that account for intercellular interactions [2] and history-dependent sensitivity, allowing for a more biologically informed simulation of tissue behavior. These features help capture the variability and complexity observed in real cellular systems.

Through repeated simulations of various conditions, the model illustrates how different scenarios can lead to diverse outcomes, even under similar starting parameters. This variability underscores the importance of stochastic processes in tissue behavior and cancer development. The model provides a flexible, virtual platform for exploring how different conditions influence long-term outcomes. It can support research into treatment planning, biological mechanisms underlying disease progression, and the impact of various interventions, helping generate hypotheses and refine experimental focus.

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Ballistic macroscopic fluctuation theory via mapping to point particles

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Ballistic Macroscopic Fluctuation Theory (BMFT) captures the evolution of fluctuations and correlations in systems where transport is strictly ballistic. We show that, for *generic integrable models*, BMFT can be constructed through a direct mapping onto ensembles of classical or quantum point particles. This mapping generalises the well-known correspondence between hard spheres and point particles: the two-body *scattering shift* now plays the role of an effective rod length for arbitrary interactions. Within this framework we re-derive both the full-counting statistics and the long-range correlation functions previously obtained by other means, thereby providing a unified derivation. Our results corroborate the general picture that all late-time fluctuations and correlations stem from the initial noise, subsequently convected by Euler-scale hydrodynamics.

Formation of Rhythmic Band Structures in Agates

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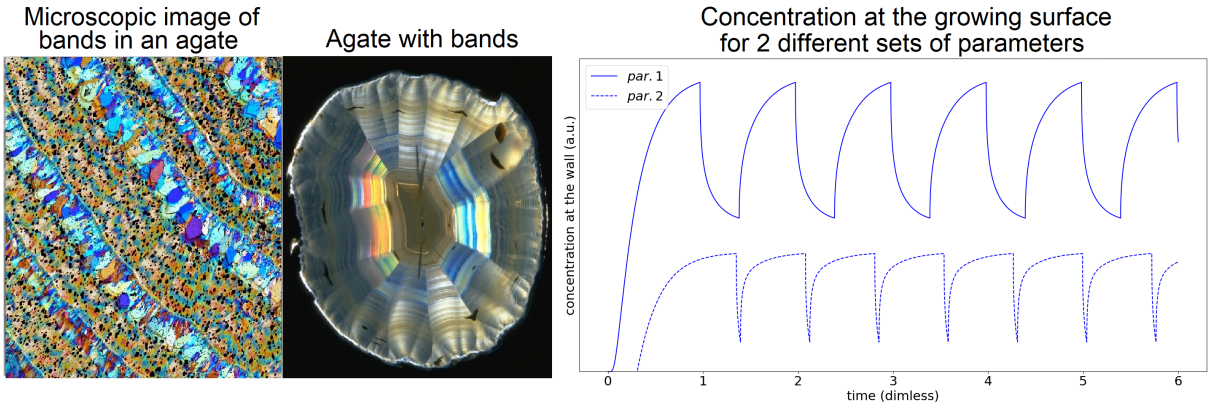
During crystallization, quartz can assume various forms, resulting in many minerals of scientific and aesthetic interest. One particularly captivating example is agate – a rock characterized by its rhythmic banding pattern composed of alternating layers with distinct colors. Despite extensive research efforts over many decades, the precise mechanisms responsible for agate band formation remain unresolved.

In this study, we introduce a phenomenological model to explain the formation of agate's rhythmic band structures, inspired by the work of Heaney and Davis [1]. In their model, rhythmic precipitation arises from self-organized oscillations in silica concentration at the mineral–solution interface, driven by competing processes of silica polymerization and diffusion-controlled transport. This interplay results in periodic changes in silica concentration, leading to the formation of distinct alternating layers characteristic of agate.

By solving the diffusion equation with suitable boundary conditions, we show that the concentration at the growing interface undergoes periodic oscillations, which effectively replicate the observed banding patterns. We investigate how the wavelength of these oscillations depends on the physical parameters of the system and identify conditions required for their emergence. Additionally, building upon findings from [2], we provide an analytical description of the concentration variations at the growing interface. These results can serve as a basis for understanding how physical and chemical parameters influence the development of rhythmic banding, and offer a simple framework for interpreting the conditions under which such patterns may arise during agate formation.



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Hybrid Sampling Method for BEC Fluctuations

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We demonstrate the advantages of a new hybrid sampling method to solving the problem of ensemble BEC fluctuations for the cases of many interacting bosons in various system geometries: harmonic traps (1D, symmetric and asymmetric 3D) and boxes with periodic boundary conditions.

We combine the field's workhorse – the classical fields approximation (CF) – with our new method – Fock state sampling (FSS) – and we obtain an extremely robust method without the problems of CF, i.e. without the "cutoff problem" (UV divergency). The method maintains its general applicability to many different systems and allows us to study a wide range of properties, not only BEC fluctuations.

FSS was first demonstrated in [1] where we compare experimental data (first experimental measurement of BEC fluctuations) with our theoretical predictions. Since then, FSS was applied for many different systems and geometries [2], providing us with access to both canonical and microcanonical ensembles for the study of BEC statistics. Our new hybrid sampling method retains this ability to study different ensembles and geometries.

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Investigating the Leverage Effect on the Polish Stock Market Using Principal Regression Analysis

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The impact of past directional changes — such as negative returns in a stock market — on dynamical features such as fluctuations and correlations is fundamental to risk modeling in complex systems. Among the well-studied phenomena in this context is the leverage effect — where declining asset prices are accompanied by increased fluctuations (also referred to as volatility). The contribution of time-varying correlations to this effect has been widely explored [1, 2], but their behaviour in smaller systems like the Polish stock market remains relatively unknown.

In this study, we analyse daily data for companies listed on the Polish stock exchange from 2010 to 2024. We construct a synthetic observable — an index — that reflects the collective state of the system at each point in time. We regress the system's global volatility, average local volatilities, and mean pairwise correlations on delayed fluctuations in the global observable to investigate its predictive relationships across various time lags. Additionally, we apply principal regression analysis and model matrix correlations dependence on lagged index returns [1]:

$$\mathbf{C}(I) = \mathbf{C} + I\mathbf{D}\,.$$

Lastly, we examine the structure of response matrices $\mathbf{D}$ through eigenvalue decomposition to better understand the dynamics of market movements. Preliminary observations suggest that the Polish market exhibits distinct behaviours compared to more established foreign markets, with lower in amplitude — but still influential — negative correlations. These insights help highlight differences in market dynamics and can inform Polish investors on how standard models perform for local conditions.

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Hydrodynamics of nearly integrable systems

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Integrable systems feature an infinite number of conserved charges and on hydrodynamic scales are described by generalised hydrodynamics (GHD). This description breaks down when the integrability is weakly broken and sufficiently large space-time-scales are probed. The emergent hydrodynamics depends then on the charges conserved by the perturbation.
In my contribution I will focus on nearly-integrable Galilean-invariant systems with con- served particle number, momentum and energy. Basing on the Boltzmann approach to integrability-breaking we describe dynamics of the system with GHD equation supplemented with a collision term. Employing Chapman-Enskog formalism and nonlinear fluctuating hydrodynamics I will show that depending on the length scales, one can distinguish three hydrodynamic regimes: generalised hydrodynamics, Navier-Stokes (NS) regime and Kardar-Parisi-Zhang (KPZ) superdiffusion known to occur in generic 1d non-integrable fluids. Moreover, I will show how we can compute transport coefficients characterising the fluid in NS and KPZ regimes.

Cluster Tomography for Soft and Active Matter

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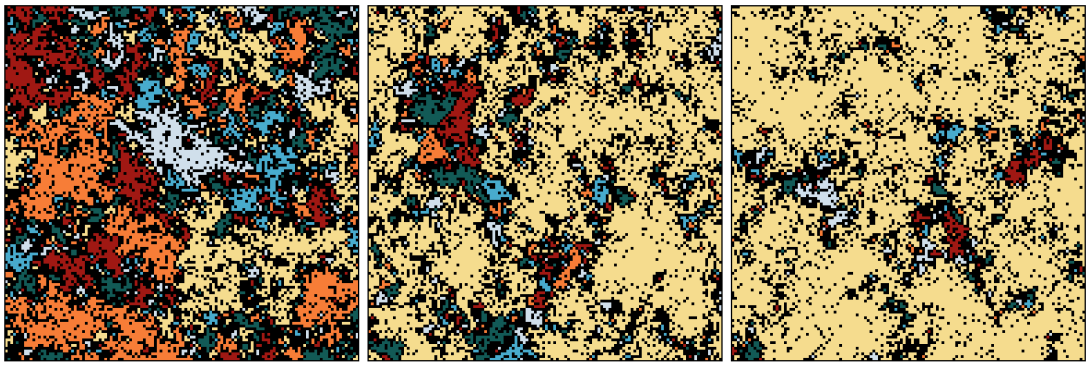
Bacteria swarming, cell migration, and the collective motion of animal groups are all examples of active matter that exhibit cluster formation. As we address active systems of increasing complexity, it becomes challenging to identify a priori the right order parameters to characterize different phases and the transitions between them. Using athermal phase separations of active Brownian particles as a paradigmatic example, we show that cluster tomography [**?**]—i.e., studying one-dimensional cross-sections of the emerging clusters—is a versatile tool for locating and characterizing phase transitions even in the absence of system-specific order parameters. This cluster-based, geometric approach, grounded in conformal field theory [**?**], can be applied to both first- and second-order phase transitions and helps identify the universality class. Furthermore, inspired by the notion of burstiness in complex systems, we put forward an analogous, cluster-based measurement that can be employed to characterize the dynamical behavior of active systems in different phases.



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Cauliflower shapes of bacterial clusters in the off-lattice Eden model

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We will present our results of an off-lattice Eden model used to simulate the growth of bacterial colonies in the three-dimensional geometry of a Petri dish [1]. In contrast to its two-dimensional counterpart, our model takes a three-dimensional set of possible growth directions and employs additional constraints on growth, which are limited by access to the nutrient layer. We rigorously tested the basic off-lattice Eden implementation against literature data for a planar cluster. We then extended it to three-dimensional growth (see Fig.).

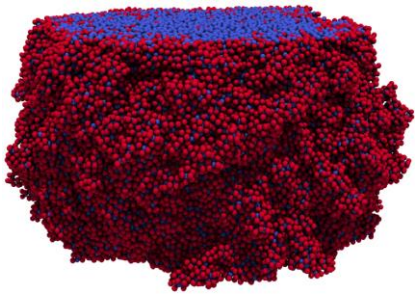

Figure: Exemplary cluster simulated with our 3D Eden Off-Lattice model [1].

Our model successfully demonstrated the non-trivial dependency of the cluster morphology, non-monotonous dependency of the cluster density, and power law of the thickness of the boundary layer of clusters as a function of the nutrient layer height. Moreover, we revealed the fractal nature of all the clusters by investigating their fractal dimensions. Our density results allowed us to estimate the basic transport properties, namely the permeability and tortuosity of the bacterial colonies.

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Cauliflower shapes of bacterial clusters in the off-lattice Eden model for bacterial growth in a Petri dish, Phys. Rev. E. 111, 14406 (2025)

How to (numerically) calculate tortuosity in porous media?

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Tortuosity is the third parameter (after porosity and permeability) that is most often computed in investigation of transport through porous media. It characterizes the elongation of emergent paths of diffusive, hydrodynamic or electric transport. In this poster we will present several ways of tortuosity computation. Initially, we spotlight the streamline-based approach. To facilitate this, our docker-integrated OpenFOAM (FVM) framework —engineered to efficiently construct porous media and execute pore-scale fluid flow simulations — will be supplemented with Python script to compute multiple streamlines. We will then compare results derived from this method with those from the velocity-based procedure. The poster will shed light on the challenges posed by these methodologies, especially in conditions like the inertial regime where non-linear dynamics become prominent [1,2]. Additionally, we will discuss meshless interpolation techniques suitable to both for streamlines as well as for the Lattice Boltzmann solver in the context of tortuosity. Concluding, we will explore a novel procedure utilizing a deep learning Convolutional Neural Network (CNN) approach [3], designed to determine tortuosity in randomized porous media. This approach proficiently calculates hydrodynamic and diffusive tortuosity.

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[8] Sci. Rep. 13, 9769 (2023)

Stokes flow with odd viscosity around a single sphere

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Understanding the flow around small particles is of essential importance in applications ranging from colloidal suspensions to biological systems. In these exemplary applications, the low-Reynolds number regime is of specific interest, which is governed by the Stokes equation. It is well known that there is an exact analytical solution for incompressible Stokes flow around a single sphere immersed in an isotropic fluid described by a single shear viscosity. In this work, our goal is to extend this solution to anisotropic fluids. Not only does the anisotropy facilitate the presence of anisotropic shear and rotational viscosities, but also there is the possibility of having so called odd viscosities when the anisotropy is odd under a time-reversal operation. We model the viscous properties of the fluid by a simplified viscosity tensor with just two coefficients $\eta_s,\ \eta_o$ corresponding to the shear and odd response, respectively. This allows us to study the new flow effects introduced by odd viscosity; odd viscosities do not contribute to dissipation and can generate axial flows which are not present in ordinary Stokes flow. We envisage applications of our analysis to liquid crystals and chiral active fluids, which are governed by an even and odd time-reversal anisotropy, respectively.

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Studying the diffusion coefficients of E. Coli colonies

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Unicellular prokaryotes live in a world where Brownian motion occurs on the order of magnitude of the lengths of entire cells. Therefore, diffusion plays a principal role in their lives. It governs cell size and geometry [1], and determines their ability to acquire nutrients and probe their surroundings. Whilst extensive work has focused on various strains of bacteria, less is known about how growth conditions influence diffusion.

To address this problem, we cultivated non-motile colonies of *E. coli* in both a rich (LB) and poor (M9) medium. Using time-lapse microscopy videos, we tracked individual cells to extract their size and position. We then applied particle tracking software to compute the mean square displacement (MSD) in each colony (Fig. 1). By analyzing cell shapes and aspect ratios from microscopy images, we modeled cells in the M9 medium as spheres and estimated their theoretical diffusion coefficients using the Stokes-Einstein relation.

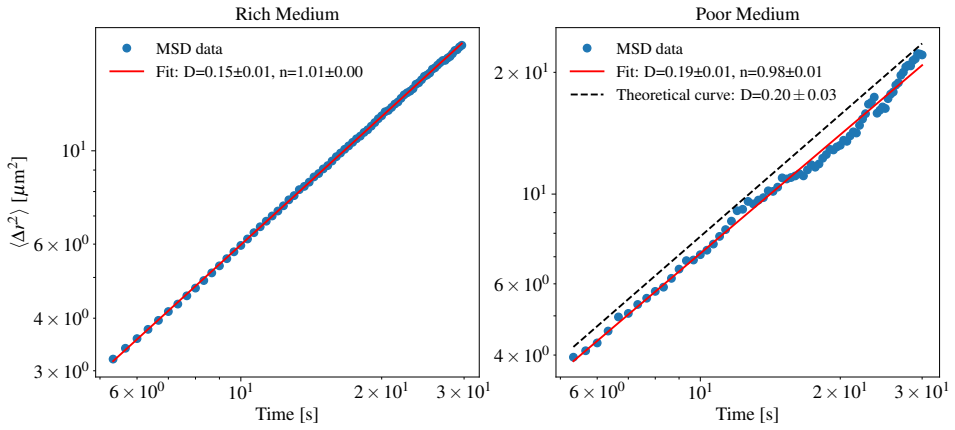

Figure 1: Mean square displacement (MSD) curves for non-motile *E. coli* colonies grown in rich (LB) and poor (M9) media. Solid lines represent MSD fits used to extract effective diffusion coefficients, the dashed line represents the theoretical calculation.

Finally, we used the known diffusion coefficients of oblate spheroids [2] to obtain the effective dynamic viscosity of the LB rich medium after incubating an *Escherichia coli* colony overnight. We report a previously unmeasured value of $\eta = 1.48 \cdot 10^{-3}$ Pa $\cdot$ s, contributing a novel result to the literature characterizing bacterial motility and environments.

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Effective mass of soft spheres, classical and quantum (and no equivalence)

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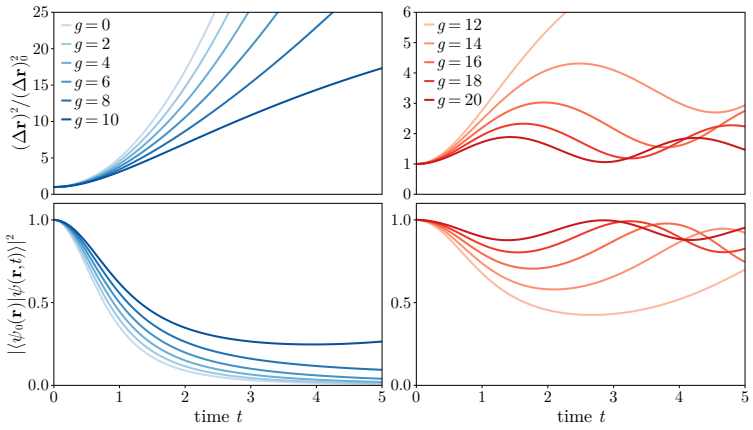
We consider the problem of a charged impurity exerting a weak, slowly decaying force on its surroundings, treating the latter as an ideal compressible fluid. In the semiclassical approximation, the ion is described by the Newton equation coupled to the Euler equation for the medium. After linearization, we obtain a simple closed formula for the effective mass M_{eff} of the impurity, depending on the interaction potential V, the mean medium density ρ_0, and sound velocity c as well as the bare masses of the particle M and the atom of the environment m, given by

$$M_{\text{eff}} = M + \frac{\rho_0}{mc^4}\int |V(r)|^2 dr.$$

Thus, once the interaction and the equation of state of the fluid is known, an estimate of the hydrodynamic effective mass can be quickly provided. Going beyond the classical case, we show that replacing the Newton with Schrödinger equation can drastically change the behavior of the impurity. Our approach is via looking at the variance of the particle's position in time:



We see it is parabolic for weak interactions, enabling us to define the dispersive mass via

$$\frac{M^*}{M} = \sqrt{\frac{\langle p^2\rangle(0)}{A}}$$

We note that M^* and M_{eff} behave differently. In particular, the scaling of the Fermi polaron effective mass with the medium density is opposite in quantum and classical scenario. Our results are relevant for experimental systems featuring low energy impurities in Fermi or Bose systems, such as ions immersed in neutral atomic gases.

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Critical Casimir Levitation of Colloid Above a Bull's-Eye Pattern

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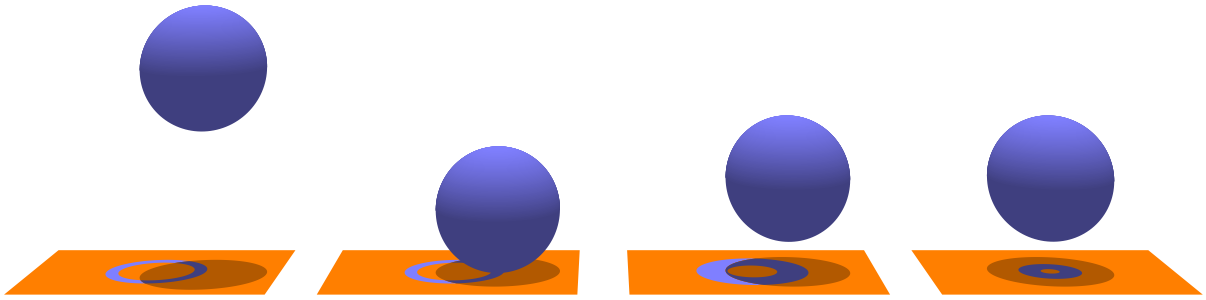
Critical Casimir forces emerge among particles or surfaces immersed in a near-critical fluid, with the sign of the force determined by surface properties and with its strength tunable by minute temperature changes. The poster shows how such forces can be used to trap a colloidal particle and levitate it above a substrate with a bull's-eye pattern consisting of a ring with surface properties opposite to the rest of the substrate. Using the Derjaguin approximation and mean-field calculations, we find a rich behavior of spherical colloids at such a patterned surface (see figure below), including sedimentation toward the ring and levitation above the ring (ring levitation) or above the center of bull's-eye pattern (point levitation). Within the Derjaguin approximation, we calculate a levitation diagram for point levitation showing the depth of the trapping potential and the height at which the colloid levitates, both depending on the pattern properties, the colloid size, and the solution temperature. Our calculations reveal that the parameter space associated with point levitation shrinks if the system is driven away from a critical point, while, surprisingly, the trapping force becomes stronger. We also propose application of critical Casimir levitation for sorting colloids by size and for determining the thermodynamic distance to criticality.



away | ring sticking | ring levitation | point levitation

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Cellular Potts Model Simulation of VEGF-Mediated Angiogenesis

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The formation of new blood vessels, or angiogenesis, is critically influenced by the Vascular Endothelial Growth Factor (VEGF), with varying levels experimentally shown to produce distinct vascular structures[1]. This project employs the Cellular Potts Model (CPM) to theoretically investigate the early cellular mechanisms driving these VEGF-mediated angiogenic events.
Our computational model simulates endothelial cells as VEGF sinks, establishing a dynamic signaling landscape by solving the VEGF diffusion equation. This gradient directs chemotaxis in leading tip cells and stimulates proliferation in stalk cells, facilitating sprout elongation. The model incorporates cell differentiation into quiescent, tip, and stalk phenotypes, where tip cells actively remodel the extracellular matrix (ECM) to create pathways for migration while the stalk cells form the body of the newly formed sprouts. This differentiation into stalk cells is influenced by signaling pathways such as Notch, which, in conjunction with VEGF signaling, plays a critical role in determining cell fate and the spatial arrangement of tip and stalk cells within the developing sprout.
By simulating these intricate interactions, this research aims to show how different VEGF concentrations guide the self-organization of endothelial cells into diverse vascular patterns during the initial stages of angiogenesis.

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Effective action and superfluid density of the Γ-subsystem of the Ising superconductor

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Recently, some non-centrosymmetric two-dimensional materials called Ising superconductors ($NbSe_2$, MoS_2, WS_2) have attracted great interest. Due to their structural features, singlet and triplet pairing can coexist in superconducting state [1]. In addition, the strong spin-orbit interaction makes the superconducting state stable against the in-plane Zeeman field $\boldsymbol{B}$. Because of the small thickness of the monolayer, orbital effects do not contribute, and the only way the magnetic field can influence the electronic states is through the paramagnetic effect. As a result, the in-plane critical field B_c increases to values above the Pauli limit [2].

We construct a gauge-invariant action of $\Gamma-$subsystem of Ising superconductor that contains both triplet and singlet interactions. A similar action for the $K^{\pm}-$subsystem was derived in [3]. The triplet pairing turns out to be dependent on the external vector potential $\boldsymbol{A}$ due to the requirement of gauge invariance. However, at constant $\boldsymbol{A}$ or constant magnetic field $\boldsymbol{B}$ this dependence disappears. The action generalizes the previously used models, since the interaction in it is local in space. This allows us to consider inhomogeneous systems and current states. Analyzing action, we obtain an expression for the superconducting density ρ of the system:

$$\rho_s(T) = \rho_s(0) - 2\int \frac{d\boldsymbol{k}}{(2\pi)^2}\left(1 - 6\sqrt{2}m\frac{\Delta_{\text{so}}}{k_F^3}\boldsymbol{k}_x\right)^2 \boldsymbol{k}_y^2\left(-\frac{\partial f}{\partial E}\right), \tag{1}$$

where $E_{\boldsymbol{k}} = \sqrt{\left(\xi_{\boldsymbol{k}} + \Delta_{\text{so}}\widehat{\gamma}_{\boldsymbol{k}}\right)^2 + \frac{1}{2}\left|\Delta_s + \Delta_t\widehat{\gamma}_{\boldsymbol{k}}\right|^2}$, $\xi_{\boldsymbol{k}}$ - normal state dispersion, Δ_s, Δ_t - singlet and triplet order parameters, Δ_{so} - spin-orbital splitting, $\widehat{\gamma}_{\boldsymbol{k}} = \sqrt{2}\cos(3\varphi_{\boldsymbol{k}})$ - factor corresponding to the trigonal symmetry of the lattice, k_F - Fermi momentum, $f(E)$ - Fermi distribution.

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Behavior of light-activated Janus particles in binary mixtures near a planar wall and in confinement

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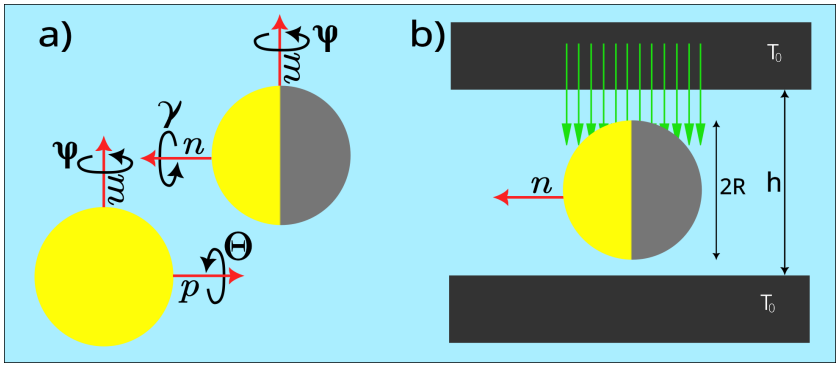
It has been experimentally shown that a micrometer-sized Janus particle, half coated with a photosensitive material and suspended in a near-critical binary solvent, moves spontaneously when illuminated with low-intensity light. Since then, such light-activated self-propellers have been extensively used to study active matter. Although the self-propulsion mechanism of these systems is already quite well understood, very little is known about the behavior of these particles near substrates and in confined geometry, where wetting properties may play the role. Here we address these issues theoretically, using a mesoscopic description, the so-called Fluid Particle Dynamics method, which takes into account both diffusion and hydrodynamics.



For a Janus particle confined in a channel, we numerically determine its trajectory and velocity as a function of its initial orientation, size, and illumination intensity. For an initial orientation parallel to the channel walls, we observe a strong correlation between the propelling velocity and the channel width. We find various dynamic interactions of the particle with a single wall and analyze their dependence on experimentally relevant parameters. Since our spatial domain is limited (but periodical), we face the challenge of the particle flowing into its own trace, which we try to combat by varying the viscosity of the mixture. Our study can help guide further research to design artificial microswimmers that mimic the behavior of their biological counterparts.

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Nonlinear Flow in Porous Media Under Pressure: Insights from Espresso Extraction

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Brewing espresso presents a rich physical system for investigating fluid flow through porous media under pressure. In this process, hot water is forced through a compacted puck of ground coffee, often modeled using Darcy's law, which predicts a linear relationship between pressure and flow rate. However, coffee is a complex, reactive medium that swells, dissolves, and rearranges during brewing, making the situation far from ideal.

Realistic brewing conditions typically involve high pressures (6–11 bar), raising questions about the validity of simple Darcy-based models. We present new experimental measurements and a developed theoretical framework describing the pressure–flow relationship during espresso extraction.

At low pressures (2–5 bar), we observe a linear increase in flow rate, consistent with Darcy's law. At higher pressures (>5 bar), however, the flow rate saturates and even slightly decreases, indicating a clear deviation. We propose that this nonlinearity results from microstructural changes in the coffee bed under mechanical stress, such as pore collapse or compaction.

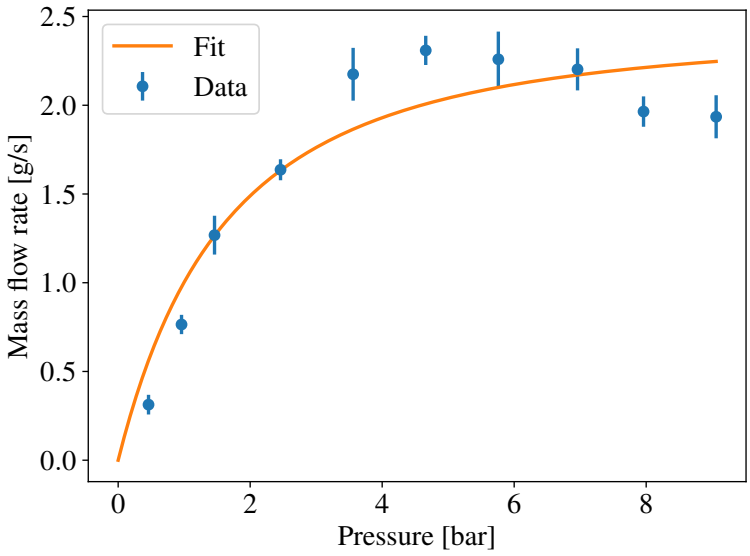

Figure 1: Realtion between flow and pressure, orange line - theoretical model Hewitt (2016).

These findings suggest that standard porous flow models may be insufficient to capture behavior under high-pressure brewing conditions. They highlight the need for new constitutive models tailored to espresso extraction and contribute to a broader understanding of pressure-driven transport in deformable and reactive granular media.

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Influence of rock structure on the morphology of wormholes

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Dissolution is a highly non-linear process in which the interplay of flow, transport, and reaction leads to the emergence of reaction-infiltration instabilities. In dissolving rocks at certain flow conditions, these instabilities give rise to the formation of a network of competing channels known as dissolution channels or wormholes. The wormholes compete for the available flow, with the winning wormhole attracting a larger flow and solute concentration, screening the rest of the network and forming a highly permeable conduit through the rock. In this study, we investigate how the rock structure, such as packed layers of low porosity, can influence the shape of evolving dissolution channels. We analyze the shape of experimentally formed wormholes in two different types of limestone using geometric measures that account for tortuosity and branching. These measures indicate that wormholes formed perpendicular to the packed layers are more tortuous and contain more branches compared to those formed along the packed layer in higher porosity regions. We verify these observations by analyzing the pore architecture of the respective samples, obtained from microtomography scans

Diffusion of axisymmetric non-spherical particles in complex fluid

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The diffusion coefficient is a crucial parameter as it provides insights into various physical properties, such as the size of a particle or the rate of chemical reactions. While the Stokes-Einstein relation describes diffusion in simple fluids, there is no general description of the diffusion coefficient in complex fluids. This challenge becomes more pronounced when the macroscopic viscosity (η_{macro}) of the complex fluid deviates substantially from the viscosity (η_0) of the solvent in which its constituent particles are suspended. Here, we analytically study the diffusion of axisymmetric non-spherical particles in complex fluids and determine their mobility coefficients in the parallel $(\mu_{||})$ and perpendicular $(\mu_{\perp})$ directions. Our findings reveal that the mobility ratio approaches isotropy $(\mu_{||}/\mu_{\perp} \to 1)$ as (η_{macro}/η_0) increases, implying that under such conditions, an axisymmetric non-spherical particle behaves like a spherical one.
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The shape of ideal volcanoes

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We analyze the growth process of stratovolcanoes, assuming that they form through the solidification of lava flows emerging from their craters. Within this framework, we succeed in identifying an invariant shape that ideal volcanoes adopt under steady-state conditions in the absence of external disturbances. To validate our theoretical model, we conducted an analysis of stratovolcanoes from the Wolfram Database, identifying specimens exhibiting high degrees of axisymmetry. Despite the inherent simplicity of our model, it successfully reproduces the profiles of highly symmetrical volcanic cones, including iconic examples such as the Philippines' Mayon Volcano and Japan's Mount Fuji. These findings suggest that fundamental physical principles may govern volcanic morphology more strongly than previously recognized.

How geophysical simulations can help in underground carbon storage?

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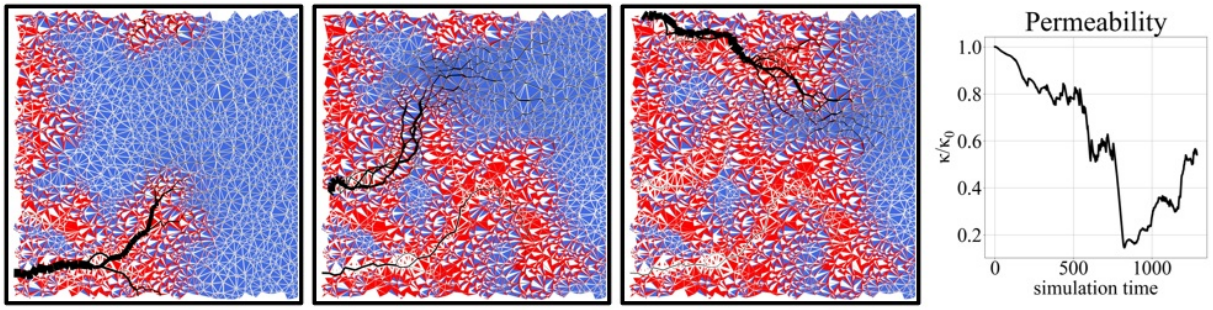
Mineral carbonation—binding CO_2 permanently as solid carbonates in subsurface rocks—offers a secure, long-term storage option, yet its efficiency is often limited by pore-scale phenomena such as flow-path blockage by precipitates or the formation of passivating layers that stop further reactions. To identify operating conditions that keep reactions active and maximize storage capacity, we built a pore network model that couples fluid flow, multistep reaction kinetics, solute transport, and pore space evolution caused by both dissolution and precipitation [1, 2]. The framework also allows topological changes, including the merging or closure of pores.

Simulations across a range of reactant concentrations and injection rates reveal three distinct regimes: formation of dominant channels that focus flow and reactions, cyclic channel blockage and self-reopening that sustains reaction progress, and complete clogging that prematurely halts CO_2 uptake. The second regime provides conditions in which new conductive pathways continually emerge while the total mineralized volume is maximized. Comparison with laboratory data on limestone dissolution and gypsum precipitation confirms the model predictive capability [3].

The results provide quantitative guidelines for selecting flow rates and fluid compositions that favour sustained mineral replacement and, consequently, higher CO_2 storage efficiency in geological formations.



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Deposition dynamics in asymmetric coffee rings

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The coffee ring effect is a ubiquitous phenomenon observed in evaporating droplets containing suspended particles, commonly witnessed in everyday life through stains left by dried beverages such as coffee, tea, or wine. This effect manifests as a darkened peripheral ring, formed due to the accumulation of solute particles at the droplet's edge during evaporation. The underlying mechanism is driven by capillary flow: as evaporation occurs more rapidly at the droplet's edge—where the contact line remains pinned—liquid from the interior flows outward to replenish the loss, transporting suspended particles toward the periphery [1]. However, droplets rarely stay axially symmetric, and irregularities in the curvature of the contact line induce asymmetric accumulation of the material at the rim.

To understand the relationship between the curvature and ring formation dynamics, we use optical microscopy to study the temporal changes of optical density of drying droplets and quantify the mass density distribution throughout the evaporation process. We examine the associated bulk flow. Using coffee as working fluid, we reproduce the original effect known from culinary fluid dynamics [2]. In addition, we vary coffee powder grind size to alter the solute particle size distribution but retaining a realistic variability.

The curvature of the initial droplet determines both the shape and size of the coffee ring. We study how variations of the key parameters, such as initial solute concentration and droplet volume, affect the dynamics of ring formation.

Keywords: Coffee ring effect, evaporation, sediment transport, deposition, particle-laden flows

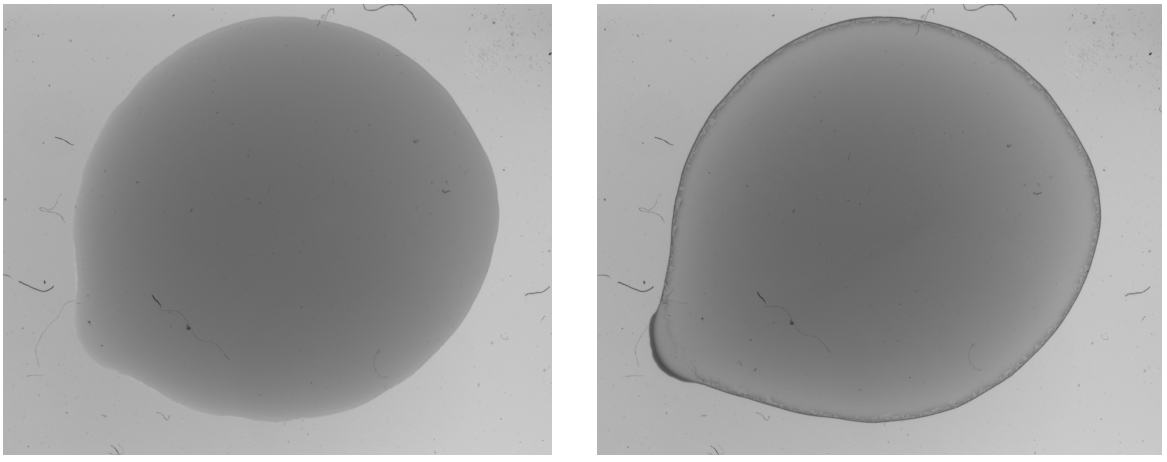

Figure 1. *Optical microscopy images of an asymmetric coffee droplet of ca. 1 cm in diameter, freshly spilt (left) and fully dried (right). Clear differences in the rim thickness are visible at locations of increased curvature.*

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Electrophoretic mobility in odd viscous liquids in the Smoluchowski limit

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Understanding the motion of colloidal particles in complex fluids is key to unlocking new insights in soft matter. We explore the electrophoretic behaviour of a charged spherical particle immersed in an electrolyte solution where the surrounding fluid exhibits odd viscosity—a non-dissipative, time-reversal symmetry-breaking component of the stress tensor found in systems such as chiral active fluids. Focusing on the Smoluchowski limit [1], where the Debye screening length is much smaller than the particle radius, we investigate theoretically how odd viscosity modifies the mobility of colloidal particles due to electrophoresis.

Using the Lorentz reciprocal theorem, we derive expressions for the electrophoretic mobility of the particle based on the analytical solution of the flow field of a spherical particle in a fluid with odd viscosity [2]. Moreover, we numerically solve the coupled Poisson-Nernst-Planck-Stokes equations using the program OpenFOAM in the low Reynolds number regime. The presence of odd viscosity introduces transverse velocity components and non-reciprocal hydrodynamic responses, breaking the mirror symmetry of the flow. This leads to anomalous forces and torques on the particle, distinct from predictions based on conventional viscous fluids.

Our preliminary results demonstrate that odd viscosity leads to directional asymmetries in the ion cloud and flow field, suggesting mechanisms for active control of colloidal motion in engineered or biological systems where parity-breaking effects are significant. This work extends classical electrokinetic theory into the realm of non-equilibrium fluids, providing a theoretical basis for future experimental validation in active or chiral media.

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Topological phase transition from cyclic to tree structures in evolving transport networks

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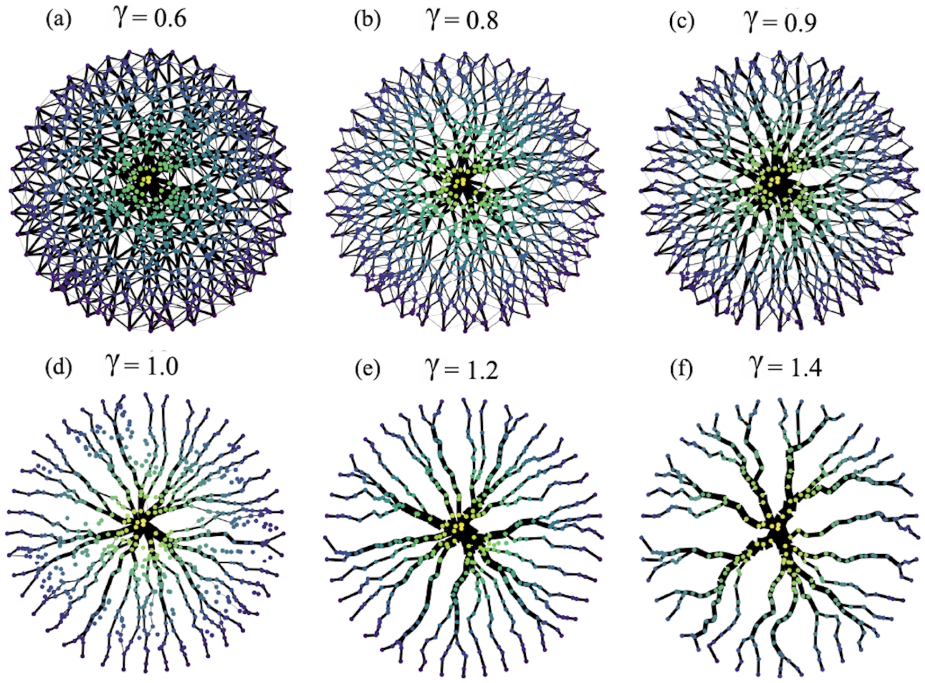
Transport networks in nature—such as vascular systems, river basins, and plant xylem—often adapt their structure in response to external flow stimuli. This work investigates the topological transition between cyclic and tree-like configurations in such adaptive networks. Using a model based on the Hagen–Poiseuille equation coupled with a conductivity adaptation law, we simulate network evolution under steady-state flow. A critical transition is identified at the feedback exponent $\gamma = 1.0$, where the system shifts from a highly redundant, looped structure to an acyclic, tree-like topology. We analyze the emergent geometries and their statistical properties, providing insights into how local adaptation rules drive global organization. The findings offer insights into the optimization and robustness of transport systems and have potential applications in the design of human-made infrastructure networks.



From frustrated to integrable: exact and numerical results for q-deformed Majumdar Ghosh model in magnetic field

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Majumdar-Ghosh (MG) model is the special case of the Heisenberg model with nearest neighbor (NN) antiferromagnetic (AFM) $J_1 > 0$ and next-to-nearest neighbor (NNN) $J_2 > 0$ interactions, whose Hamiltonian is given by:

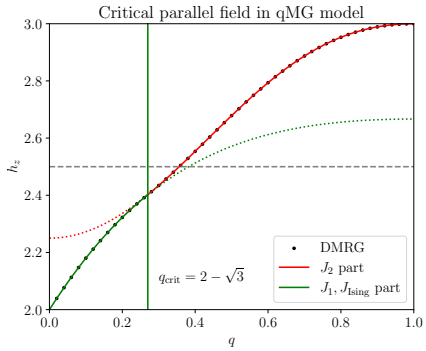
$$H_{MG} = J \sum_j [\mathbf{S}_j \mathbf{S}_{j+1} + \frac{1}{2} \mathbf{S}_j \mathbf{S}_{j+2}] - \sum_j h_x S_j^x \tag{1}$$

The two types of interactions in this model compete for AFM ordering on NN and NNN sites. Such a phenomenon is called geometric frustration and may result in ground states unseen in other systems. In the absence of a magnetic field, the MG model has an exactly solvable dimerized ground state; however, this solvability is lost once a field h is introduced. However, we can find a simpler model where all states are known exactly (integrable model): the transverse field Ising model, given by:

$$H_{TFI} = J \sum_j S_j^z S_{j+1}^z - \sum_j h_x S_j^x \tag{2}$$

Following work of Batchelor and Yung [1] using q-deformation we investigate smooth transition from MG model ($q = 1$) to TFI model ($q = 0$) where in between ($0 < q < 1$) we have q-deformed MG model.

Using exact diagonalisation and density matrix renormalization group (DMRG), we investigate numerically how criticality changes with the q parameter. We obtain the central charge c from the entanglement entropy, and as we go from the Ising-type to the Heisenberg-type model with increasing q.



Using linear spin wave approximation, we obtain the critical parallel field h_z analytically as shown in the picture above. We compare models with a parallel or transverse field applied. Finally, we construct order parameters to study dimer phases, which lay the ground for future work for other q-deformed models of this class.

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Mechanisms Behind Abrupt Morphological Changes in Mineral Dendrites

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Mineral dendrites are tree-like, branched patterns commonly found on or within rocks, typically formed by the deposition of minerals like manganese or iron oxides. In natural systems these patterns exhibit diverse morphologies and shapes, varying in thickness or degree of branching. This study focuses on quasi-planar dendritic patterns growing along fractures and bedding planes. In these dendrites, abrupt morphological transitions, where their thickness changes suddenly, are often observed. Understanding the mechanisms behind this phenomenon is the aim of this work.

Dendrites form through the infiltration of fractured rocks by manganese- or –iron-bearing fluids. When these fluids mix with oxygenated solutions, metal oxides precipitate, creating the dendritic patterns. The exact deposition mechanism remains debated. One model suggests that as the fluids mix, nanoscale particles of manganese or iron oxide are first formed. These nanoparticles then aggregate, resulting in the formation of mineral dendrites.

In such a scenario, the final dendrite morphology turns out to be highly sensitive to the initial concentrations of manganese (or iron) in the system. We show that morphological transitions can be triggered by subsequent infiltrations of metal-bearing fluids, characterized by different concentrations of manganese/iron ions. However, we also point to another factor that can induce morphological transitions in dendrites, this time related to the change in the aperture of the fracture or bedding plane along which they grow. We show that larger fracture apertures correlate with the formation of thicker dendritic structures. We analyze the characteristics of both transitions, focusing on the features that allow them to be distinguished from one another.

The ultimate goal would be to establish a link between the morphology of the dendrites and the physicochemical conditions in which they grew. This connection would allow for the decoding of the hydrogeochemical history of the dendrite-bearing rock strata.

Endothelial Network Morphogenesis on Microparticle Arrays: A Combined Imaging and Modeling Approach

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Endothelial cells, which form the inner lining of blood vessels, can self-organize into capillary-like networks, a key process in vascular morphogenesis. We investigated how the spatial arrangement of microparticles affects endothelial network formation. Using time-lapse confocal microscopy and a custom Python-based image analysis pipeline, we quantified the influence of inter-particle spacing on network morphology, including e.g. area or connectivity, providing insight into the dynamics of capillary growth under geometric constraints. We also examined the effects of cytostatic drugs and tumor cells on network development. To support the experimental findings, we developed a Python implementation of the Cellular Potts Model based on [1], iterated via the Metropolis Monte Carlo algorithm, and extended it to include diffusive transport of angiogenic factors and proliferation. Currently, the model captures some fundamental cellular behaviors in simplified single-microparticle systems, aligned with our previous experimental work [2], but it does not yet reproduce the full complexity of network formation on microparticle arrays. The ongoing integration of experimental and modeling approaches offers a versatile tool to investigate the principles of vascular network formation, including the impact of system geometry on endothelial cells behavior.

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Thick elastic sheets and complex tissue shape: theory and modeling

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Morphogenesis can be driven by in-plane forces that lead to effective spontaneous mechanical incompatibilities and the subsequent emergence of complex 3D forms. In this study, we investigate both the forward and inverse problems associated with the 3D morphologies arising from prescribed in-plane deformation gradients. The forward problem is modeled using a spring-lattice framework applied to a thick elastic sheet subject to isotropic or uniaxial in-plane deformations. Our particular interest is the biologically relevant scenario of epithelial tissues, where deformation is localized primarily at the apical surface, while the basal surface remains mechanically passive. We analyze how the interplay between intrinsic curvature (associated with the surface metric) and extrinsic curvature (arising from area mismatch) guides the system toward energy-minimizing configurations. For the inverse problem, we aim to determine the in-plane deformation required to produce a given 3D shape. Building on established methods of Ricci flow on discrete surfaces, we implement this framework to recover the deformation gradient from a target geometry via conformal mapping.[1] Our goal is to identify deformation gradients that are either purely isotropic or purely anisotropic. This decomposition is particularly relevant in a biological context, where isotropic and anisotropic growth often arise from distinct cellular mechanisms.

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The interplay of physics and geometry in the morphogenesis of the jellyfish canal network

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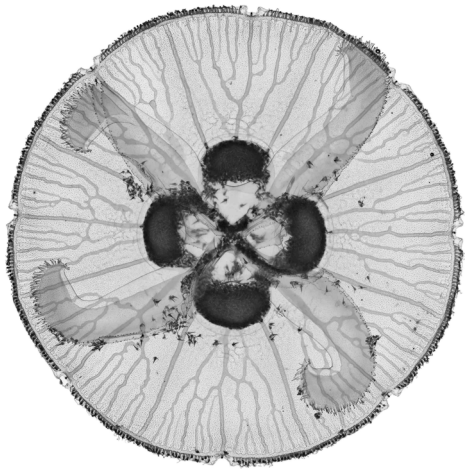
The jellyfish gastrovascular system is an example of a biological transport network providing nutrients to the tissues of the animal. As the jellyfish grows, new canals appear at the circular canal at the rim and grow towards the stomachs in the center (Fig. 1). We study the morphogenesis of this canal network both in experiments in vivo and in numerical models. The growth of the canals occurs only at their tips. We investigate how the direction of their propagation is related to the physical mechanisms at play in the jellyfish - pressure inside the canals and tension in the tissue. The cells at the tip of a growing canal may sense the pressure or tension gradients, and similarly to the pattern formation processes in physics, be guided by the gradients of these physical fields. The changing geometry of the developing canal network affects the distribution of pressure in the canals [1] and stress in the tissue [2]. We study the feedback loop between changing geometry of the network and the physical fields around. We show how the canal network develops in time and what parameters are at play in morphogenesis of this network.



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