Hydrodynamics of Soft Active Matter

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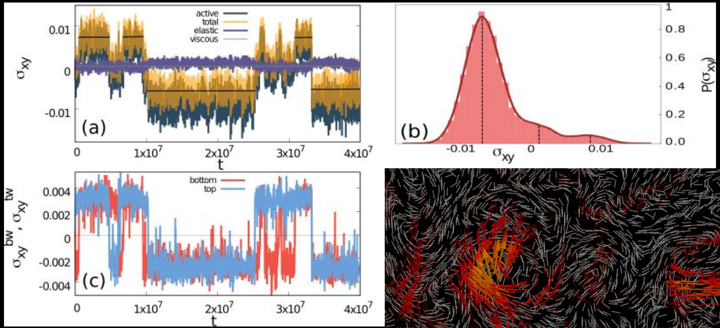
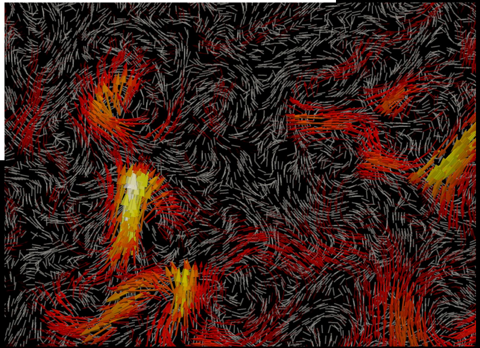
Summary

- Overview of research activity
- Brief overview on active matter
- A theoretical model for active polar emulsions
- Hydrodynamic instabilities in active nematics
- Morphological control of active emulsions
- Active turbulence vs. Kolmogorov turbulence

Overview of research activity



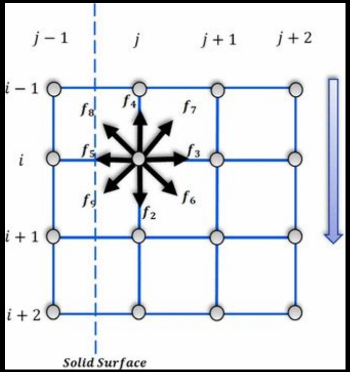


<u>Active gels</u>:

- Turbulence
- Rheology

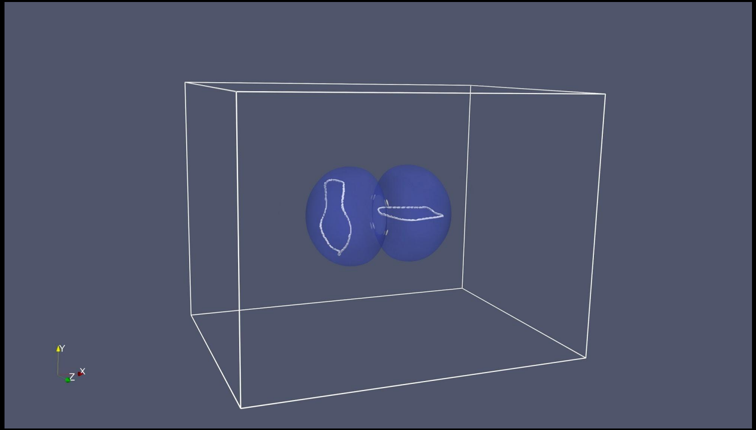
<u>Numerical Methods</u>

- Lattice Boltzmann
- High Performance Computing



<u>Passive Liquid Crystals</u>

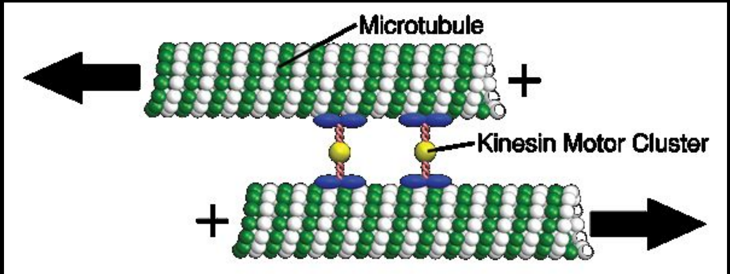
- Topological defect characterization



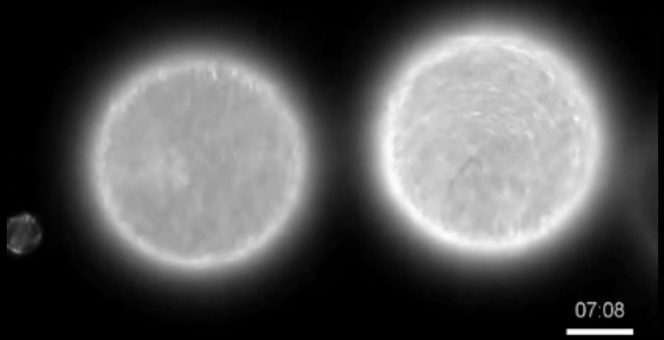
List of Publications

1. G. Negro, **L.N. Carenza**, P. Digregorio, G. Gonnella, and A. Lamura. Morphology and flow patterns in highly asymmetric active emulsions. Physica A, 503:464 – 475, 2018.
2. F. Bonelli, **L.N. Carenza**, G. Gonnella, D. Marenduzzo, E. Orlandini, and A. Tiribocchi. Lamellar ordering, droplet formation and phase inversion in exotic active emulsions. Scientific Reports, 9, 2019.
3. **L.N. Carenza**, G. Gonnella, A. Lamura, G. Negro. Dynamically asymmetric and bicontinuous morphologies in active emulsions, International Journal of Modern Physics C, 2019.
4. G. Negro, **L.N. Carenza**, P. Digregorio, G. Gonnella, A. Lamura. In silico characterization of asymmetric active polar emulsions, AIP Conference Proceedings 2071 (1), 020012, 2019.
5. **L.N. Carenza**, G. Gonnella, A. Lamura, G. Negro, A. Tiribocchi. Lattice Boltzmann methods and active fluids.Eur. Phys. J. E, 42(6):81, 2019.
6. G. Negro, **L.N. Carenza**, A. Lamura, A. Tiribocchi and G. Gonnella. Rheology of active polar emulsions: from linear to unidirectional and unviscid flow, and intermittent viscosity. Soft Matter, 2019.
7. **L.N. Carenza**, G. Gonnella, D. Marenduzzo, G. Negro. Rotation and propulsion in 3d active chiral droplets. PNAS, 2019.
8. **L.N. Carenza**, G. Gonnella, L. Biferale. Multi-scale control of active emulsion dynamic. arXiv:1906.05968, 2019.

Biological Active Matter



Swimming bacteria



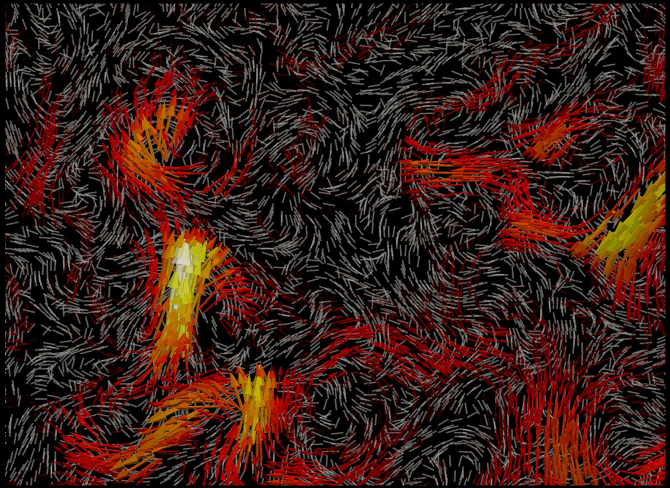
Keber *et al.* Topology and dynamics of active nematic vesicles, Science, Sept 2014; 345(6201), 1135-1139.

The model

Dynamical field:

- **Concentration field** φ
- **Polarization field** P
- **Velocity field** $\mathbf{v}$

$$\partial_t \varphi + \nabla \cdot (\varphi \mathbf{v}) = \nabla \cdot \left(M \nabla \frac{\delta \mathcal{F}}{\delta \varphi} \right)$$

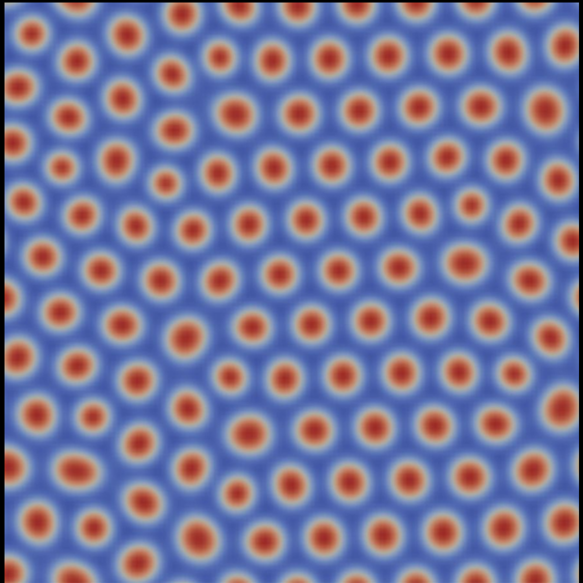


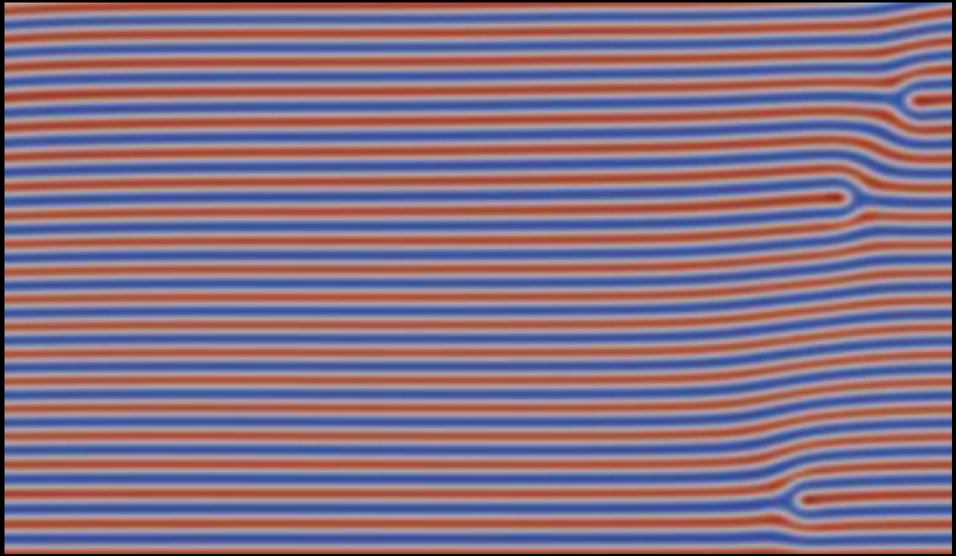
$$\frac{\partial \mathrm{P}}{\partial t} + (\mathbf{v} \cdot \nabla)\, \mathrm{P} = -\underline{\underline{\Omega}} \cdot \mathrm{P} + \xi \underline{\underline{D}} \cdot \mathrm{P} - \frac{\mathbf{h}}{\Gamma}$$

$$(\partial_t + \mathbf{v} \cdot \nabla)\mathbf{v} = \nabla \cdot \left[\sigma^{pass} + \sigma^{act} \right]$$

Landau-De Gennes Theory

$$\mathcal{F}[\phi, \mathbf{P}] = \int d\mathbf{r} \left[\frac{a}{4\phi_{cr}^2}\phi^2(\phi - \phi_0)^2 + \frac{k_\phi}{2}(\nabla\phi)^2 + \frac{c}{4}(\nabla^2\phi)^2 \right.$$
$$\left. -\frac{\alpha}{2}\frac{(\phi - \phi_{cr})}{\phi_{cr}}\mathbf{P}^2 + \frac{\alpha}{4}\mathbf{P}^4 + \frac{k_P}{2}(\nabla\mathbf{P})^2 + \beta\mathbf{P}\cdot\nabla\phi \right]$$





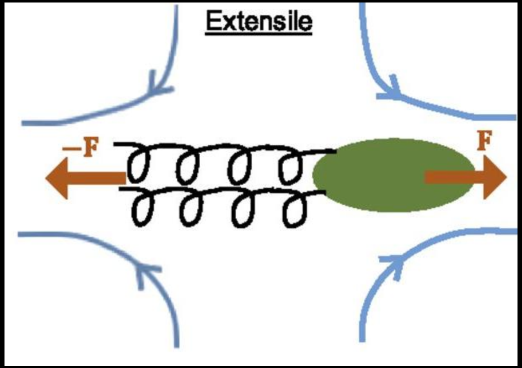
The active stress tensor

$$(\partial_t + \mathbf{v}\cdot\nabla)\mathbf{v} = \nabla\cdot\left[\sigma^{pass} + \sigma^{act}\right]$$

Dissipative/Reactive terms

Non-Equilibrium terms

Force dipole

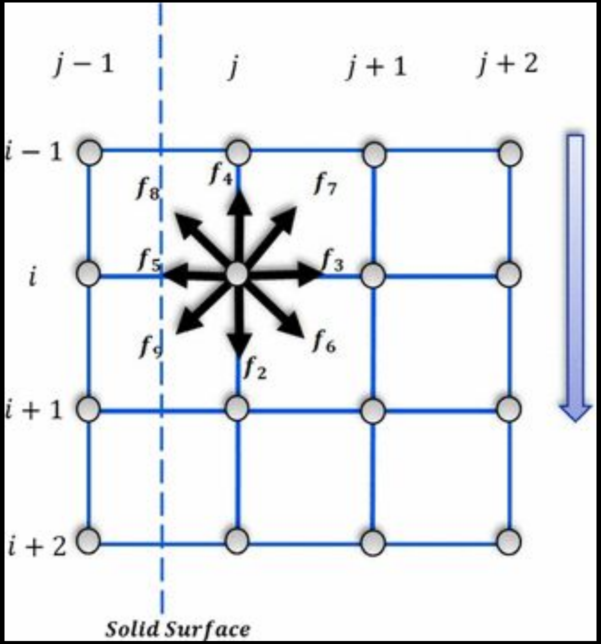


$$\sigma^{active}_{\alpha\beta} = -\zeta\phi\left(P_\alpha P_\beta - \frac{I}{3}P^2\right)$$

The Lattice Boltzmann Method

- **Discretized version of the Boltzmann equation:** **<u>space and velocity</u>**

$$f_i(\vec{r}+\vec{\xi}_i\Delta t, t+\Delta t)-f_i(\vec{r},t) = \mathcal{C}(\{f_i\},t)$$



- **BGK approximation**

$$\mathcal{C}(\{f_i\},t) = -\frac{1}{\tau}(f_i - f_i^{eq})$$

- **Observables**

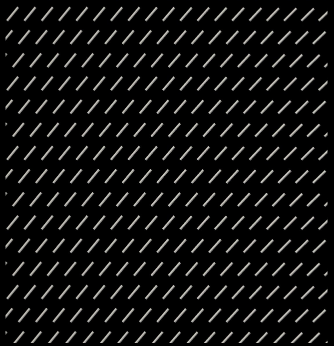
$$\rho(\vec{r},t) = \sum_i f_i(\vec{r},t)$$

$$\rho(\vec{r},t)\vec{v}(\vec{r},t) = \sum_i f_i(\vec{r},t)\vec{\xi}_i$$

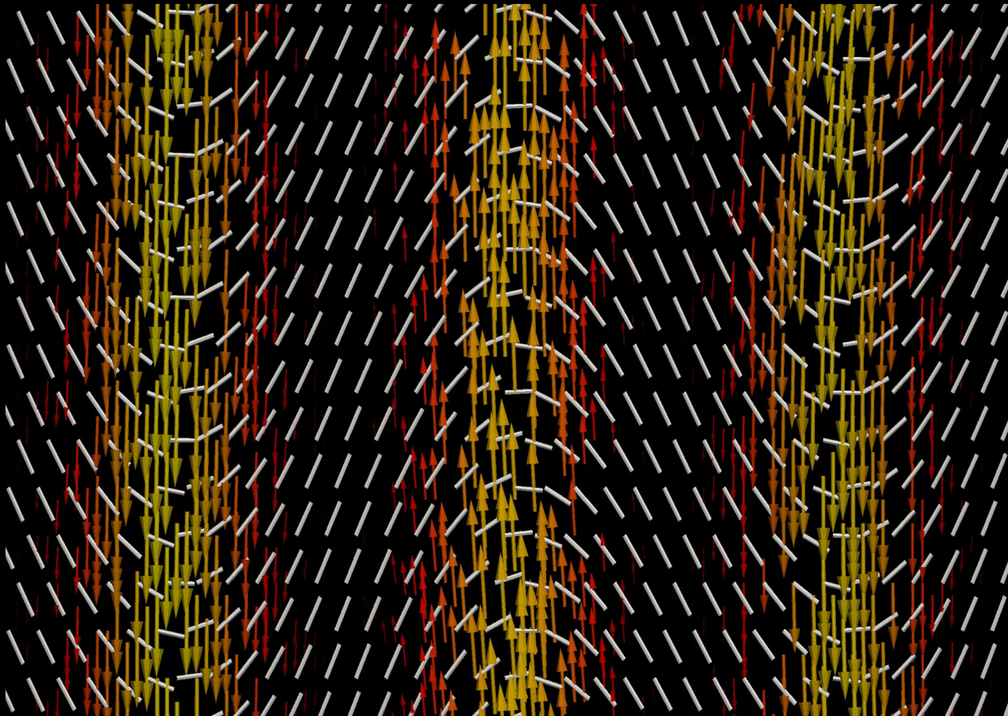
$$\sum_i f_i^{eq}\xi_{i\alpha}\xi_{i\beta} = -\sigma_{\alpha\beta} + \rho v_\alpha v_\beta$$

Instability in active nematics

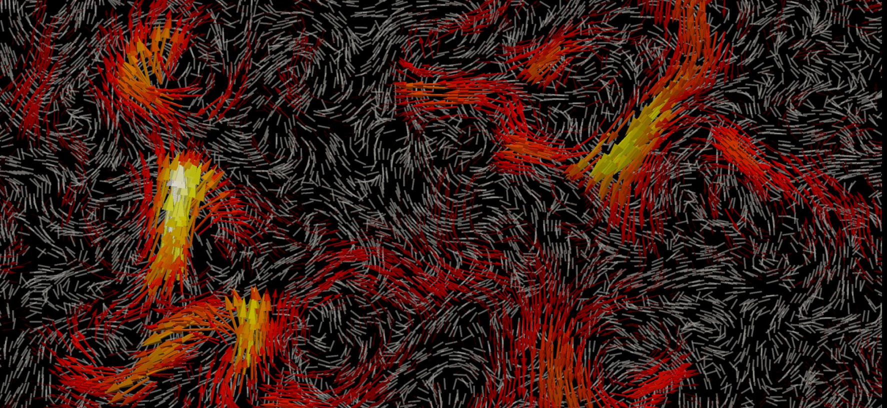
- Small activity: quiescent state



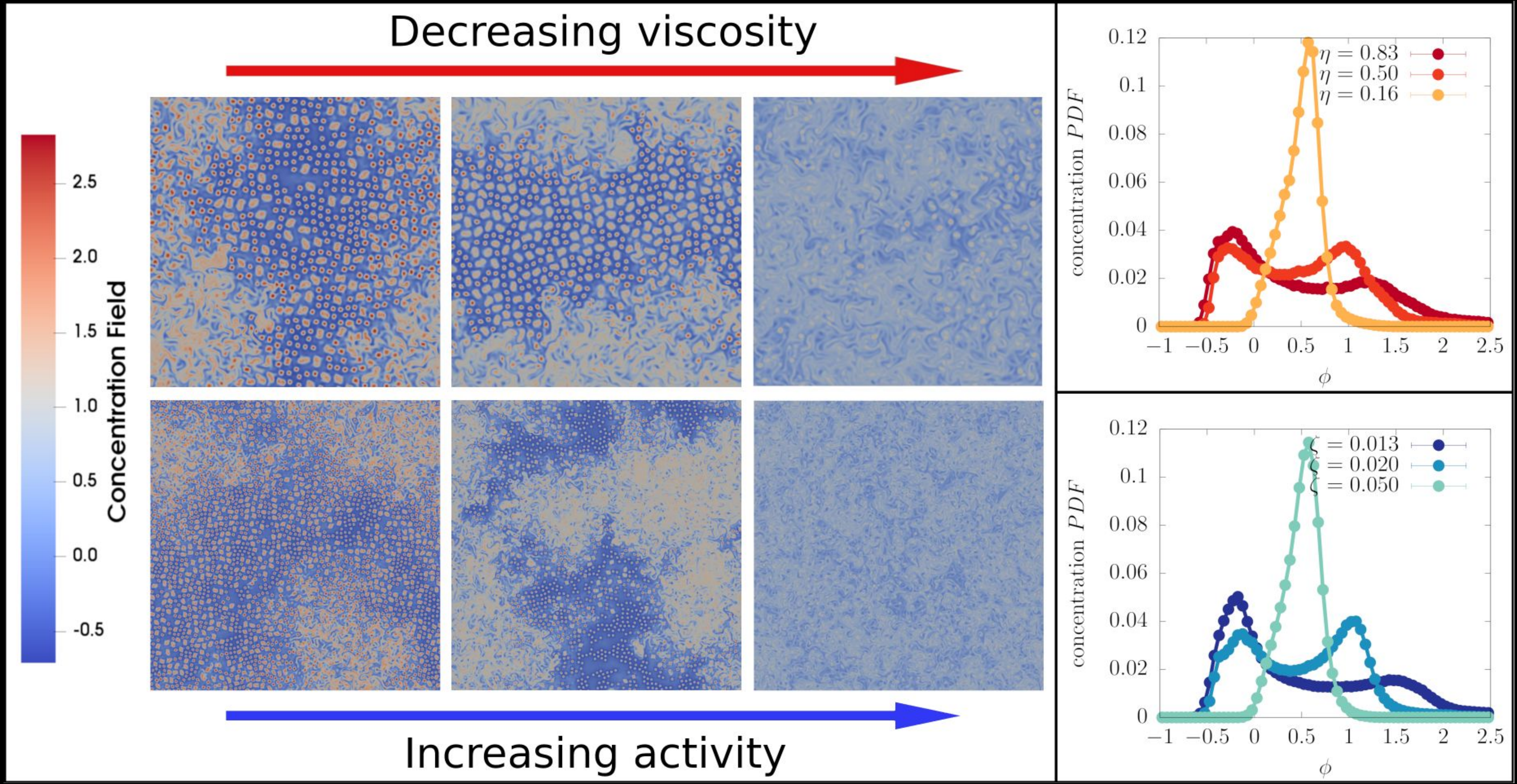
- Intermidiate activity: spontaneous flow

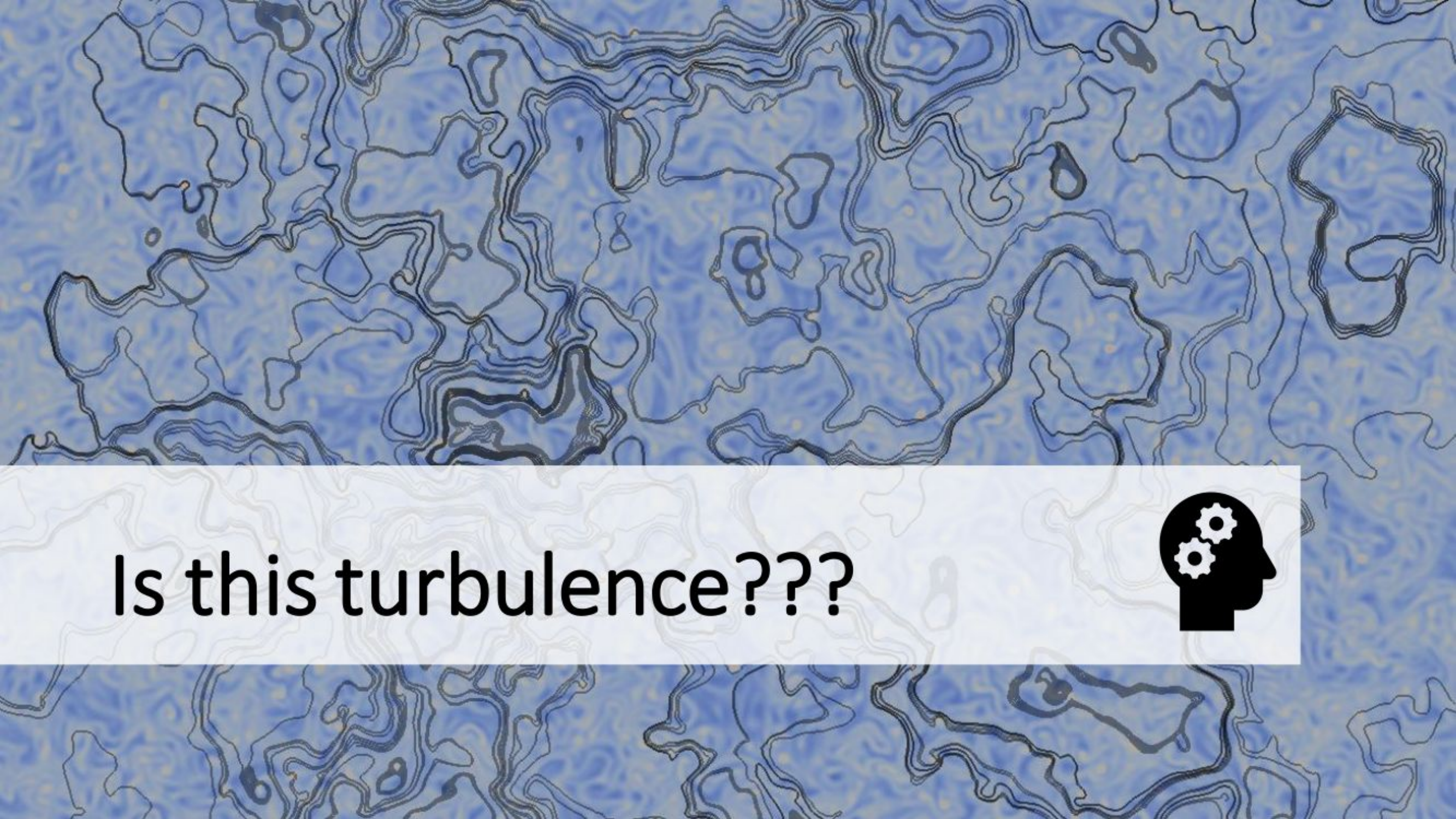


- High activity: active turbulence

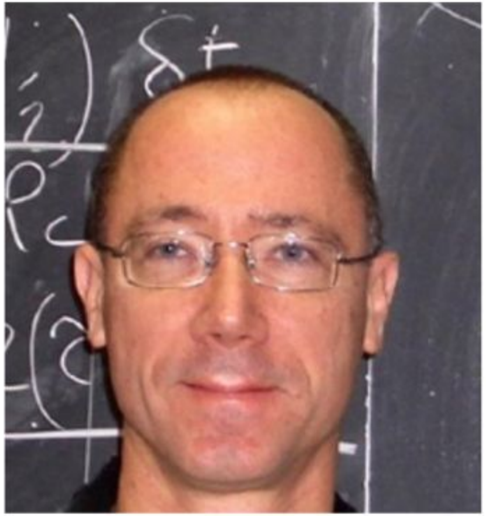


Asymmetric Extensile Mixtures





Is this turbulence???



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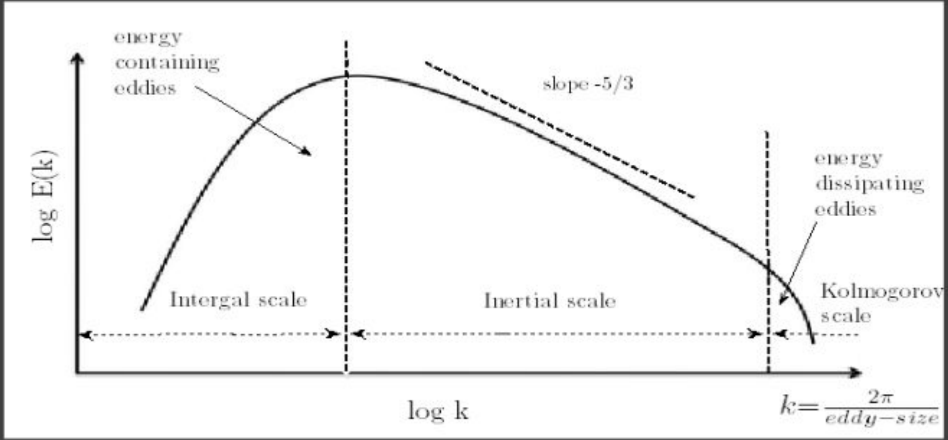
...we don't think so!!!

Hydrodynamic Turbulence

Hydrodynamic turbulence usually occurs in fluids at **high Reynolds numbers**, a regime found when advective phenomena dominate over viscous dissipation.

Universal scaling exponent -5/3 characterizes the statistical flow properties of a turbulent fluids in the **inertial range**.

Energy cascades due to **advective transfer**, from typical injection scales towards the dissipation scale where energy is consumed by viscosity.



Flows and energy injection

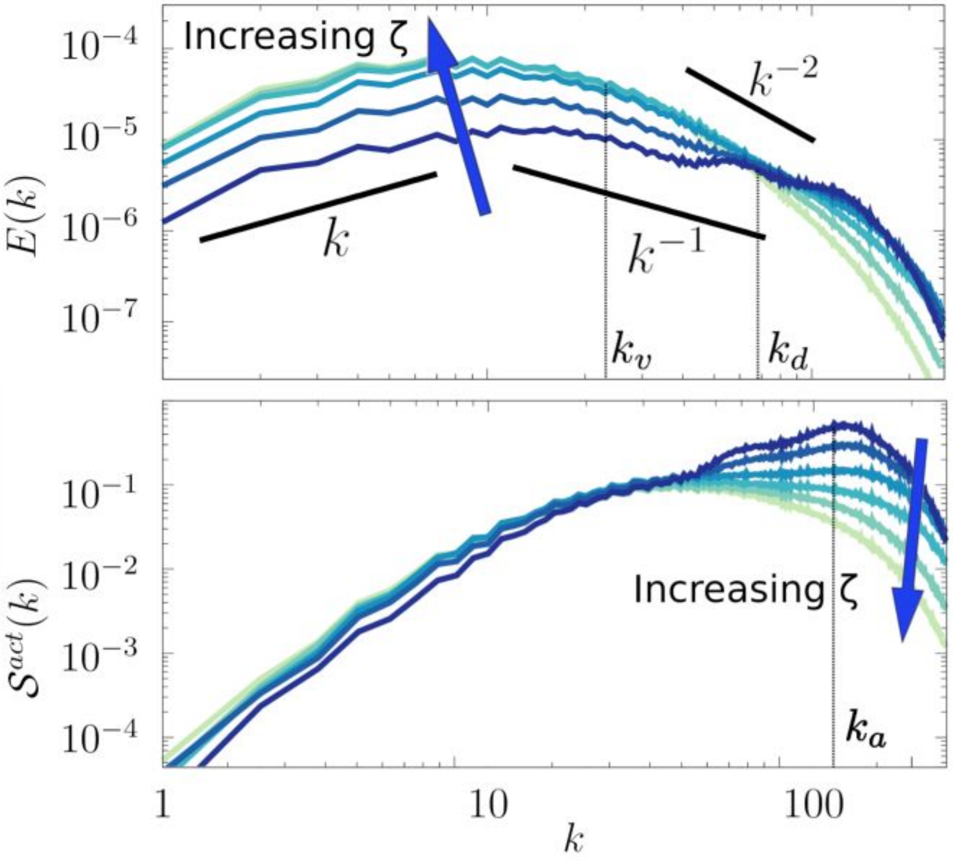
$$E(k) = \frac{1}{2}\langle|\mathbf{v}(\mathbf{k})|^2\rangle$$

$$\mathcal{S}^{act}(k,t) = \langle \mathbf{v}^*(\mathbf{k},t) \cdot \mathbf{F}^{act}(\mathbf{k},t)\rangle$$

$$\mathbf{F}^{act}(k,t) = \frac{2\pi i}{L}\mathbf{k} \cdot \tilde{\sigma}^{act}(\mathbf{k},t)$$

- <u>NO universal behavior</u>
- <u>Active injection lenght-scales differ from typical flow scales (SMALL SCALE PUMPING)</u>
- <u>Kinetic energy increases as active pumping is reduced at increasing activity</u>

ANALYSIS OF FLUXES TO DISENTAGLE TRANSFER MECHANISM



Conclusions

- **Instabilities of an active polar gel are able to set up a coherent flow states that may end up into chaotic dynamics**
- **Energy propagates at scales relevantly different from the ones typical of energy injection due to the non-trivial interaction between activity and dissipative/reactive phenomena**
- **Active turbulence does not involve advection as leading mechanism for the spreading of energy among different length-scales**

Thank you!