Active Self-Organizing Matter

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Niels Bohr International Academy

NBIA MSc day, October 2020

Active matter: nature's engines that power life

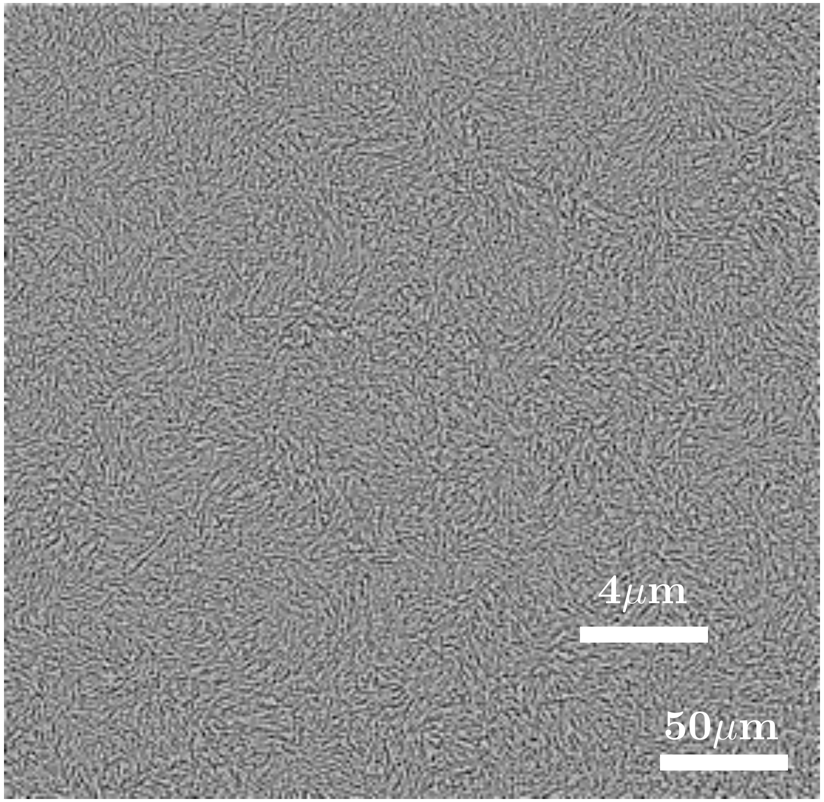
Each individual cell works as an engine:
consumes energy to create motion

https://www.youtube.com/watch?v=hacbn_xcZdU

Active matter: nature's engines that power life

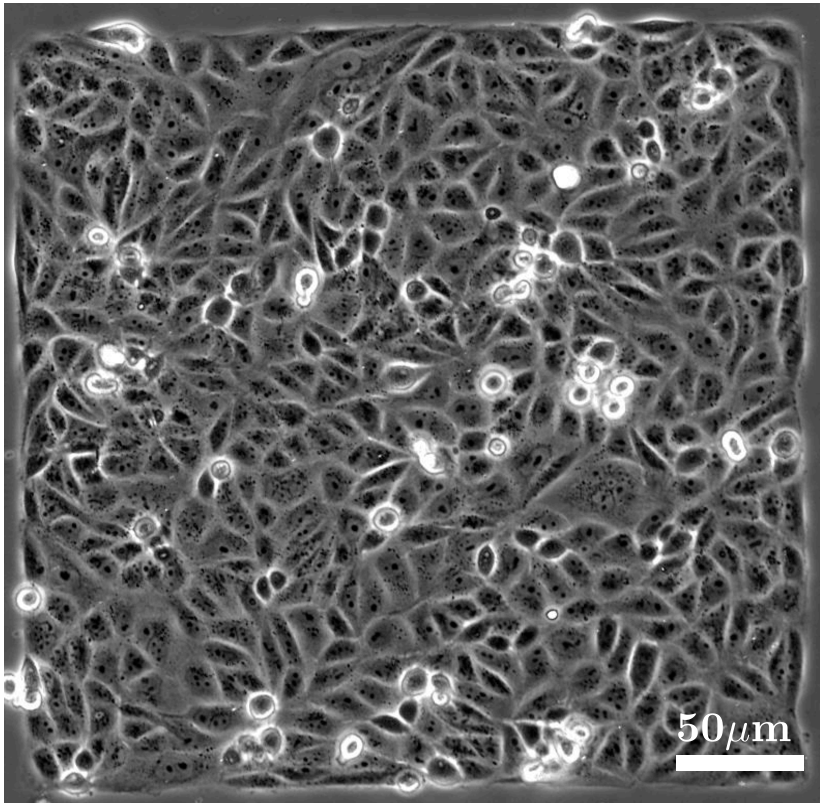
- Out of thermodynamic equilibrium
- Local energy injection
- Collective Motion

E. coli bacteria



Bacterial swarm, Wensink et al, PNAS (2012)

Cellular tissue



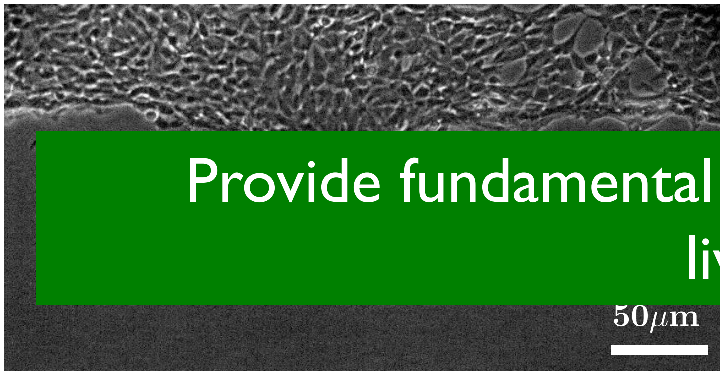
Benoit Ladoux's Lab, CNRS, Paris

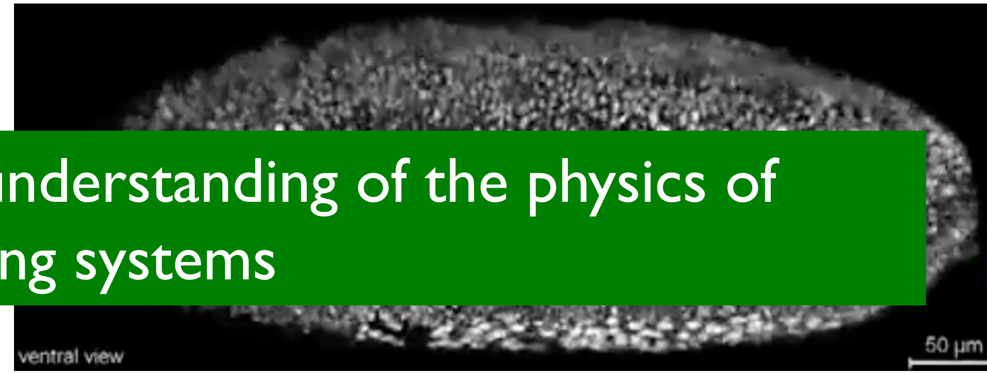
Significance

- **Biology and Health**

Cell invasion

Organ development (morphogenesis)





Provide fundamental understanding of the physics of living systems

Breast cancer cells, Lene Oddershede, NBI

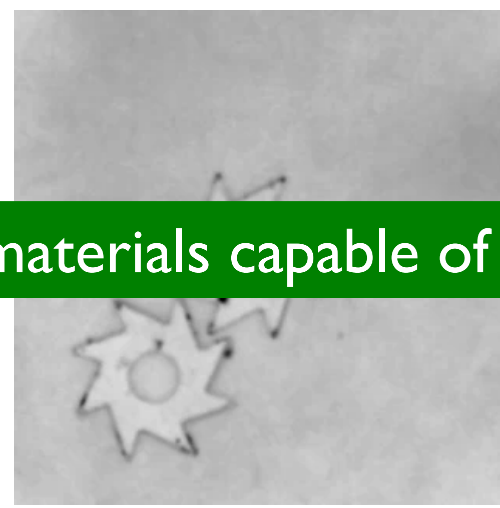
Fly embryo, Tomer, et al., Nature. Meth.,2012

- **(bio) Technology**

Biomimetic design / micromachines

Mi

Emulate nature to make materials capable of self-organisation



Microgears in bacterial bath, Sokolov et al., PNAS, 2010

Self-deforming droplets, Keber et al., Science, 2014

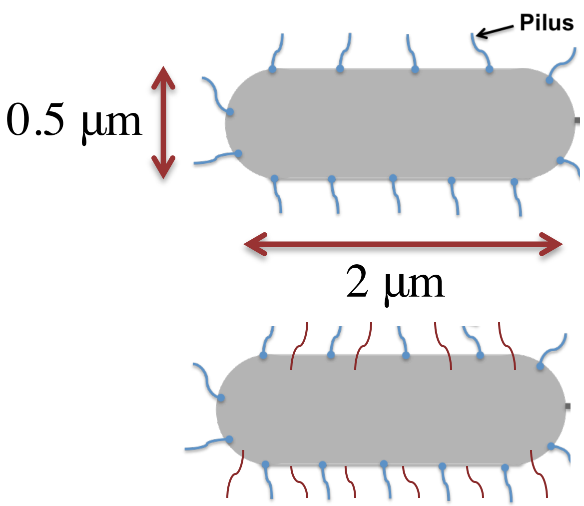
Cell Competition

with Oliver Meacock (Oxford Zoology)
William Durham (University of Sheffield)

Two competing bacteria types

- Make fast moving and slow moving bacteria, which one spreads faster?
- Pseudomonas. aeruginosa: infectious, antibiotic resistant bacteria

Nasty picture of Pseudomonas infection



Wild type

Hyper-piliated
~ 2 faster

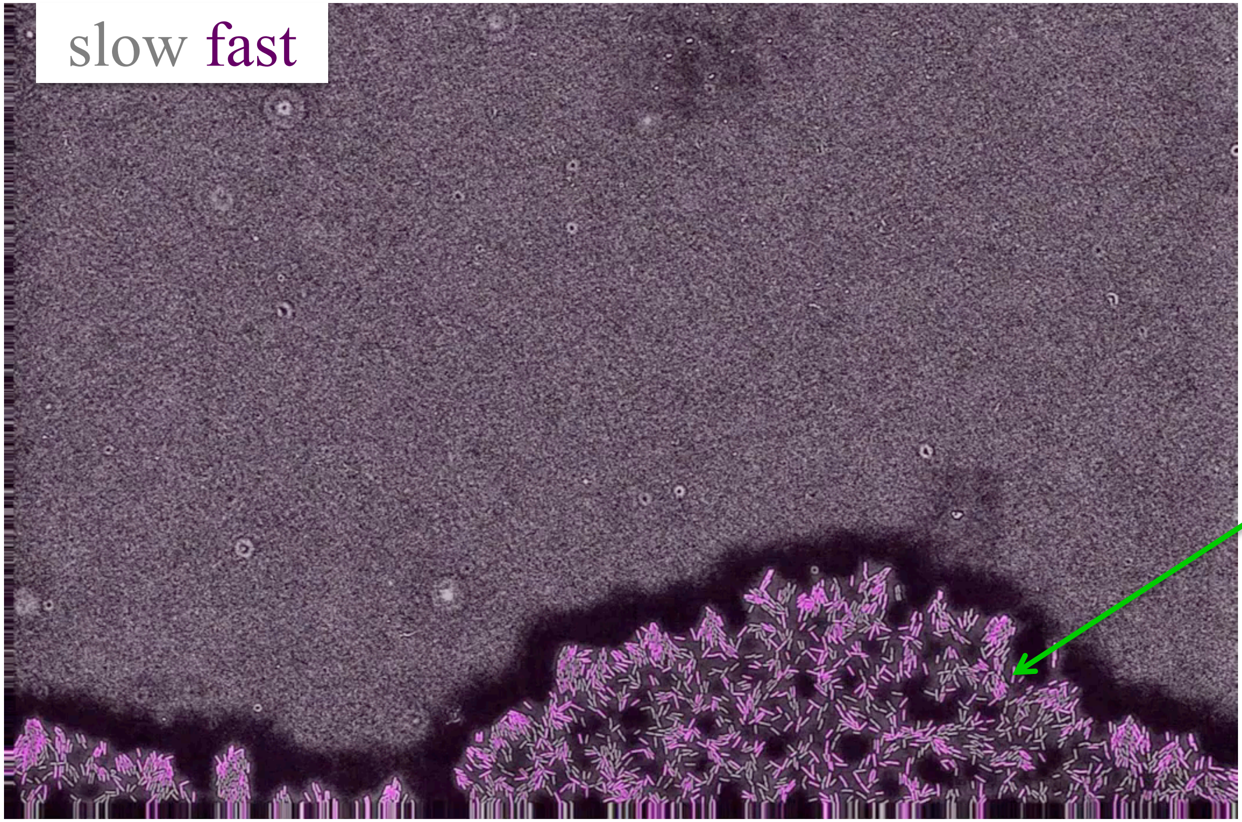
Slow vs fast bacteria: collective invasion

- Individual $\Delta pilH$ cells are ~ 2 times faster than individual WT cells

Slow moving bacteria (normal) outcompetes the fast (hyper-mutated) one !

Competition in a mixture of fast & slow bacteria

- Mixing fast moving and slow moving bacteria, which one spreads faster?

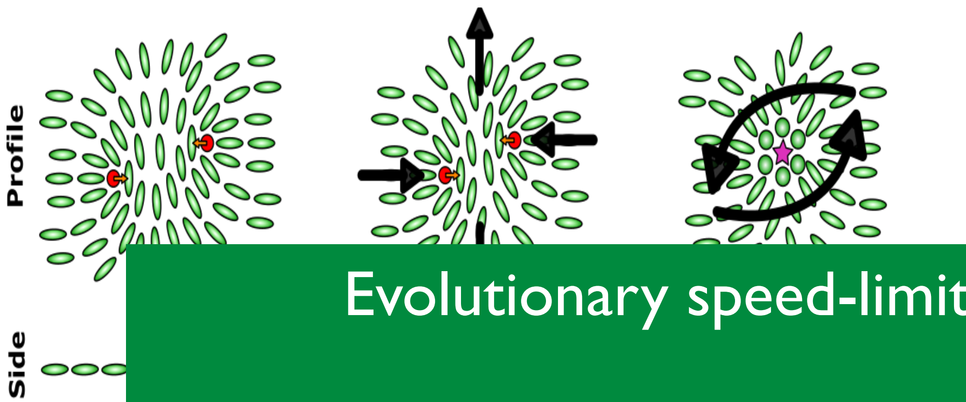


Rosettes from

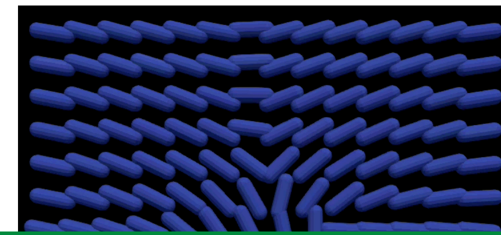
Slow moving bacteria (normal) outcompetes the fast (hyper-mutated) one !

Bacteria stand up when two defects collide

Fast defect collision pushes bacteria out of plane



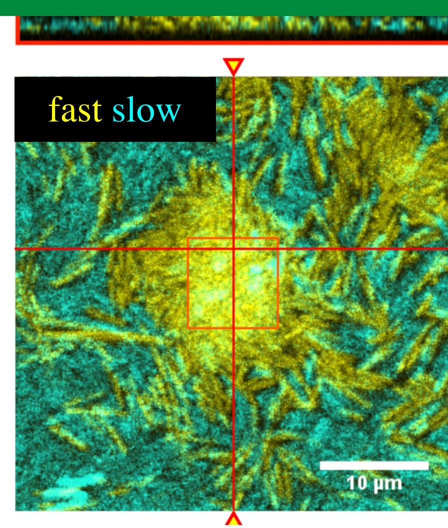
Defects collision in fast moving rods



Evolutionary speed-limit on bacterial colonies

Fast bacteria get trapped in structures of their own creation

Experiments:
fast moving bacteria (yellow) stand up when two defects approach and once stood up they can not spread anymore

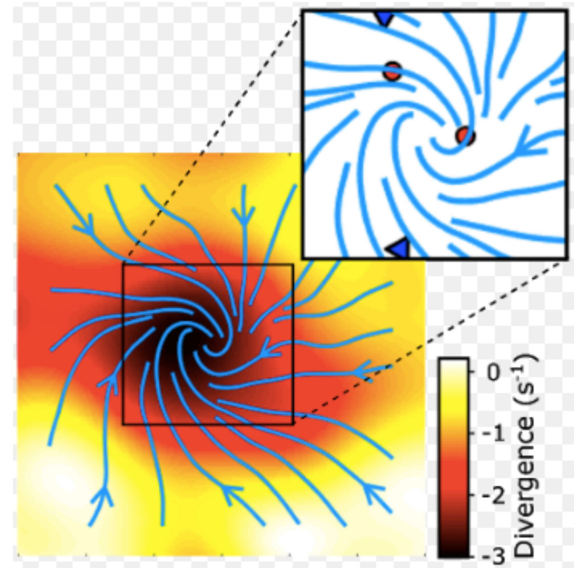


Project: analytical + computational

Calculating the flow field associated with rosettes

Involves:

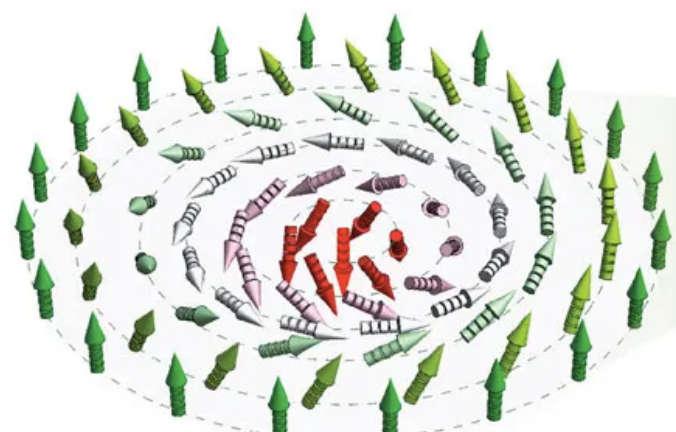
- mean field theory of active liquid crystal
- topological excitations
- Green's function calculation
- Collaboration with experimental group in Oxford



Experimentally measured flow field

Are they half-skyrmions?

Skyrmions are topological solitons reported in Bose-Einstein condensates, superconductors, thin magnetic films, and chiral nematic liquid crystals.



"Polar jets of bacteria carry microscopic cargoes", Nature Physics 2020
"Binding self-propelled topological defects in active turbulence", Phys. Rev. Research 2020

Cell Decision-making

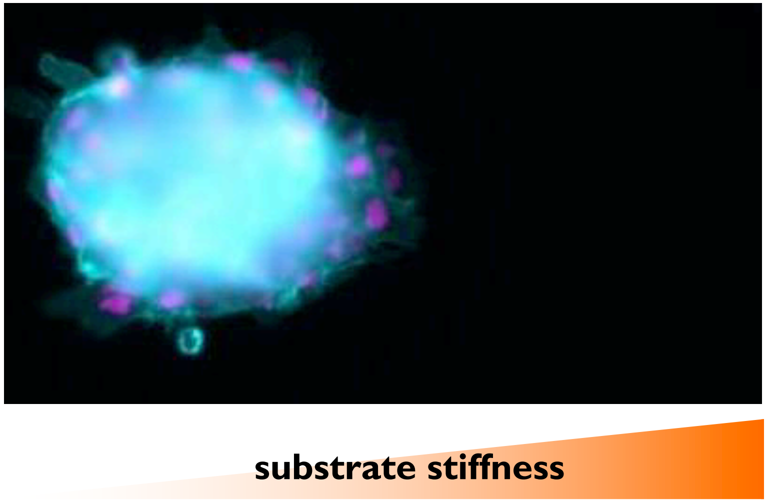
Cells sense mechanical forces

Renaissance in Biophysics

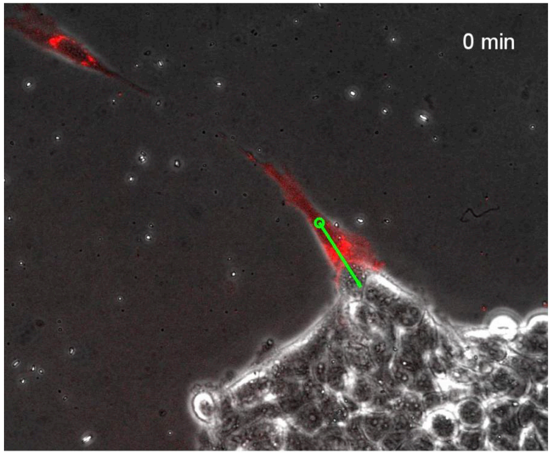
- Force measurement at single cell and at tissue level

- Mechanotransduction:
read mechanical cues ➔ translate into cell function (cell division/death, migration)

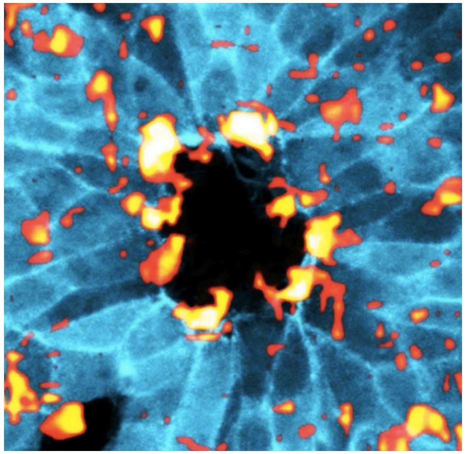
- Master regulator: YAP (yes-associated protein)



Tissue stiffening coordinates cell migration in organ development



Cell-level force guiding tumour mass

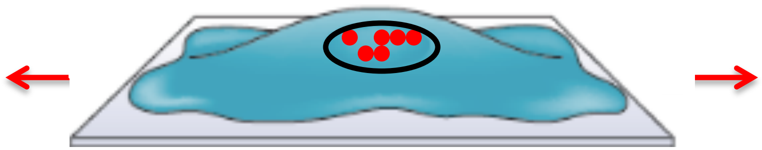
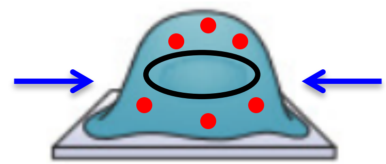


Tissue level forces driving wound healing

Mechanical forces determine cell response

- Reading forces by shuttling protein (YAP) between nucleus & cytoplasm:

Physical deformation of cell

Stretching	compression
	
Protein in nucleus	Protein in cytoplasm
➔	➔
active (ON)	inactive (OFF)
➔	➔
cell division cell migration	cell death impaired motility

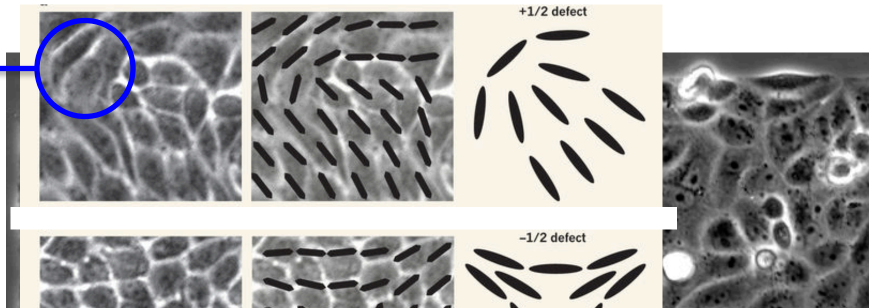
Regulation of signaling ➔ shapes organ during development

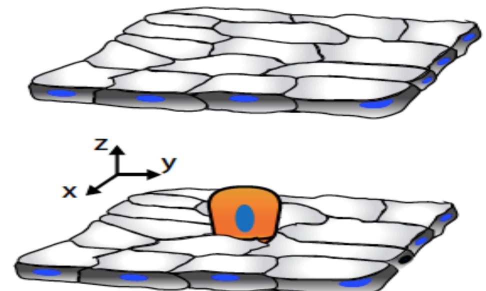
Deregulation of signaling ➔ leads to multiple diseases

Excessive force ➔ signal overactivation ➔
- Unrestrained division
- Cancer development

Defects control cell death

cells die and expelled in this area



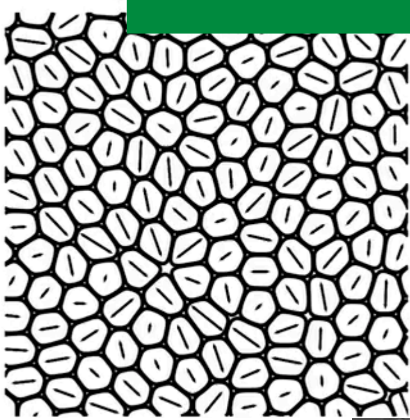


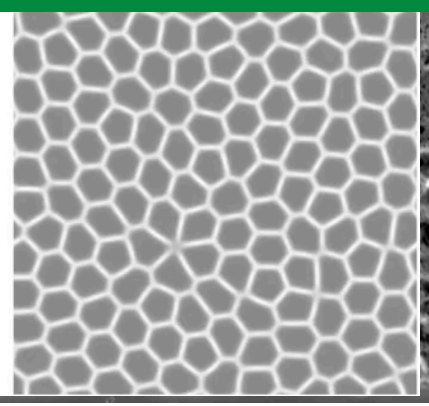
High levels of mechanical stress at topological defects

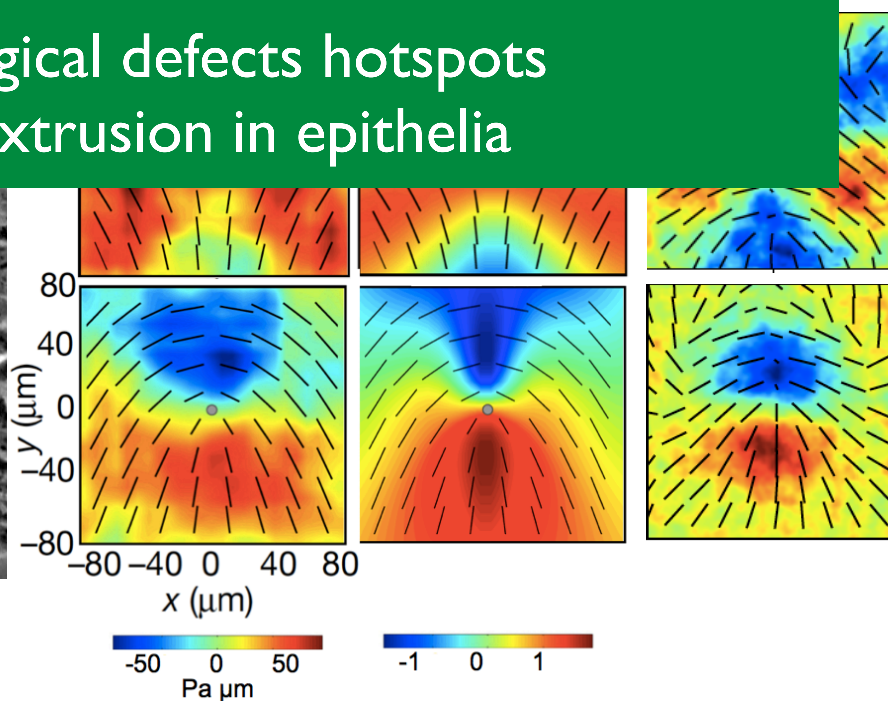
This makes topological defects hotspots for cell death & extrusion in epithelia

Resol

phase







"Topological defects in epithelia govern cell apoptosis and extrusion", Nature (2017)

"Emergence of active nematic behavior in monolayers of isotrorpic cells", PRL (2019)

Project: Analytical + computational

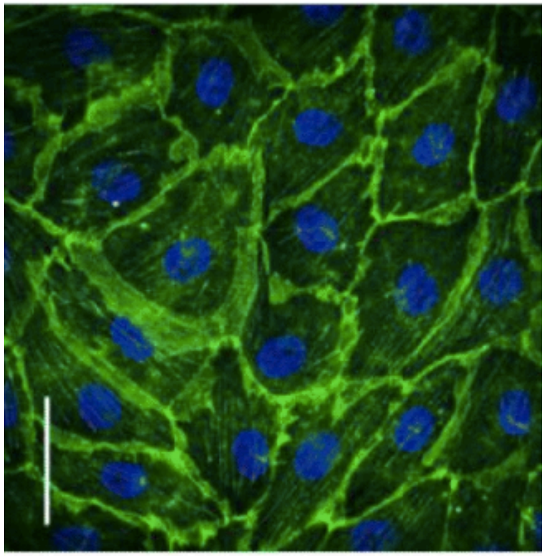
Studying the defects in stress field & their cross-talk with defects in orientation field

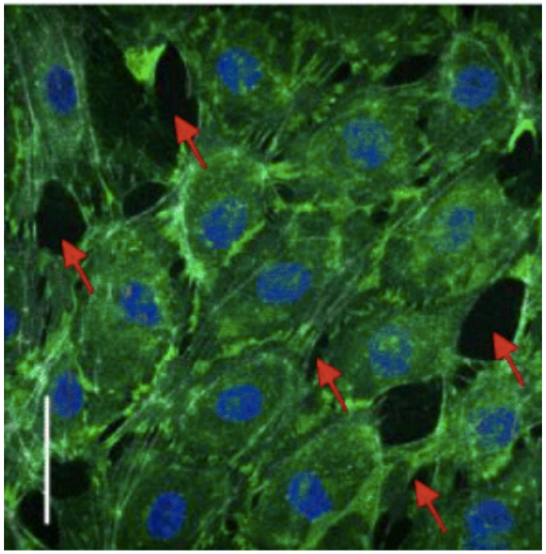
Involves:

- mean field theory of active liquid crystal
- topological defects
- Numerical simulations of active matter
- Collaboration with experimental groups in Paris & Japan

Do they have a biological functionality?

We examine a hypothesis that defects in stress field are responsible for gap formation in tissues.



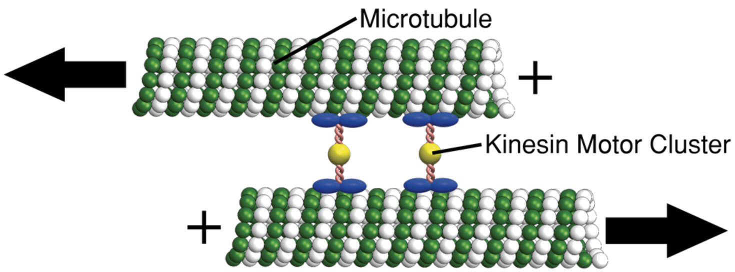


Gap formation in cells lining surface of blood vessels

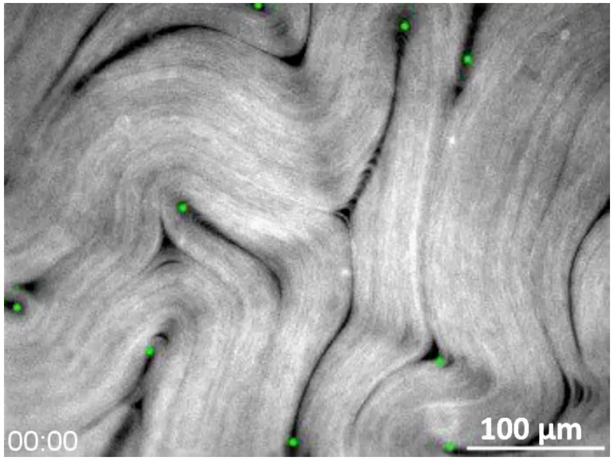
Bioinspired, Self-Pumping Fluid

Bioinspired self-organizing matter

System made of subcellular filaments + motor protein



Sanchez et al., Nature 2012

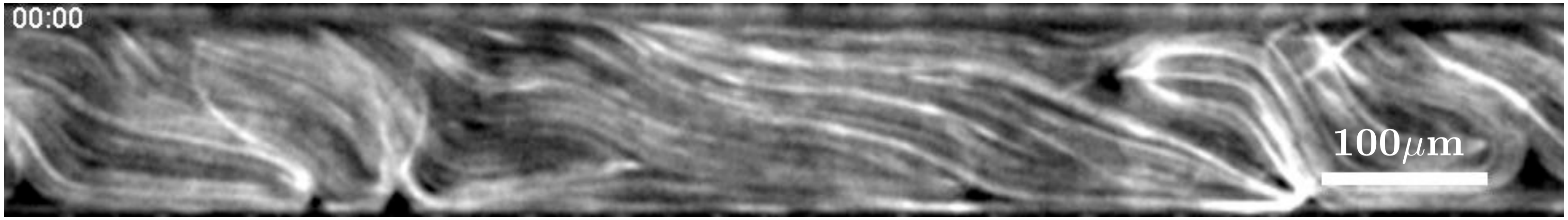


"*Active nematics*", Nature comm, 2018

● : +1/2 defects

Are active flows always disorderly?

Filaments organise themselves into a shear flow when put under confinement

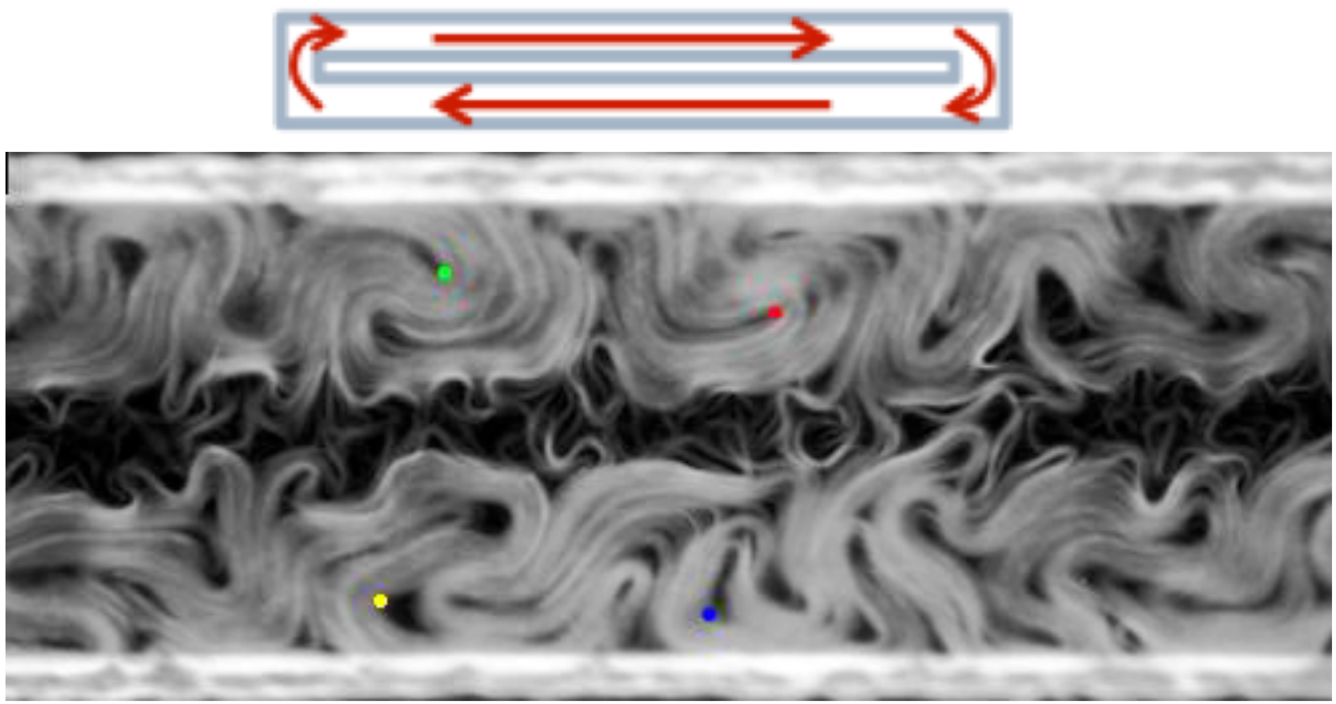


Francesc Sagues's Lab, Barcelona

Self-pumping flows emerge

- Spontaneous symmetry breaking in a racetrack geometry:
  Material moves as one coherent unit
- Universality of self-pumping:
  Occurs in cells, bacteria, subcellular filaments

Microtubules racetrack

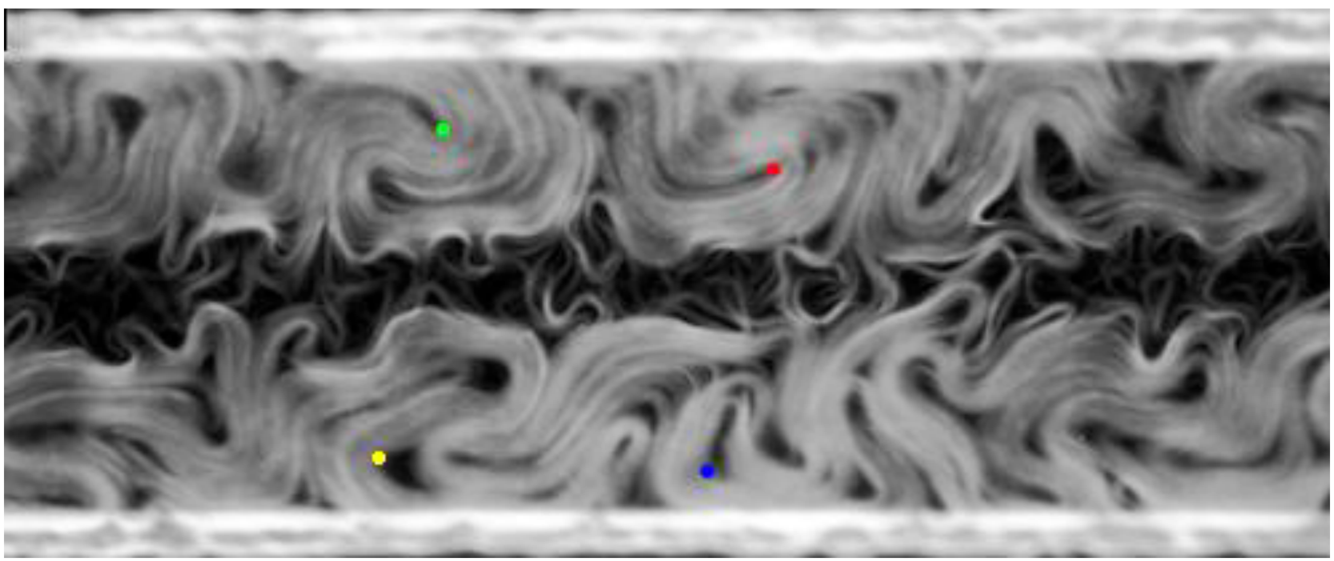


Project: Analytical + computational

Under what physical conditions self-pumping flows can be created?

Involves:

- Lattice-Boltzmann simulations of active fluids
- Examining the effect of boundary properties
- Collaboration with experimental group in Barcelona &theoretical group in Oxford

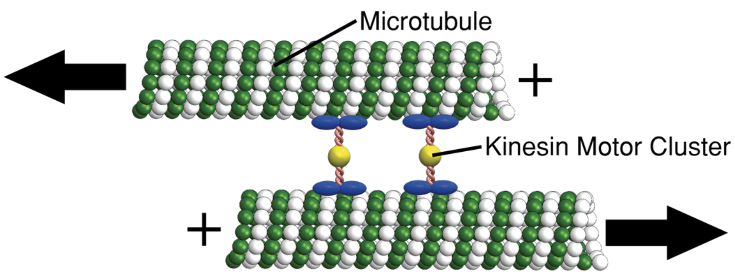


“*Active nematics*”, Nature comm, 2018
“*Flow states and transitions of an Active Nematic in a Three-Dimensional Channel*”, Phys. Rev. Lett. , 2020

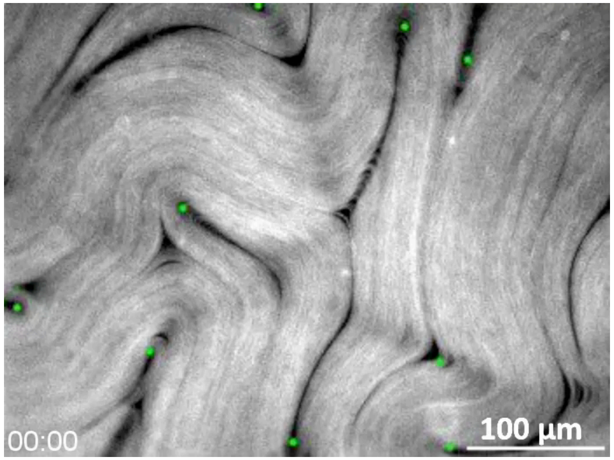
Designing a Material that Evolves

Bioinspired self-organizing matter

System made of subcellular filaments + motor protein



Sanchez et al., Nature 2012
Guillamat et al., PNAS 2016

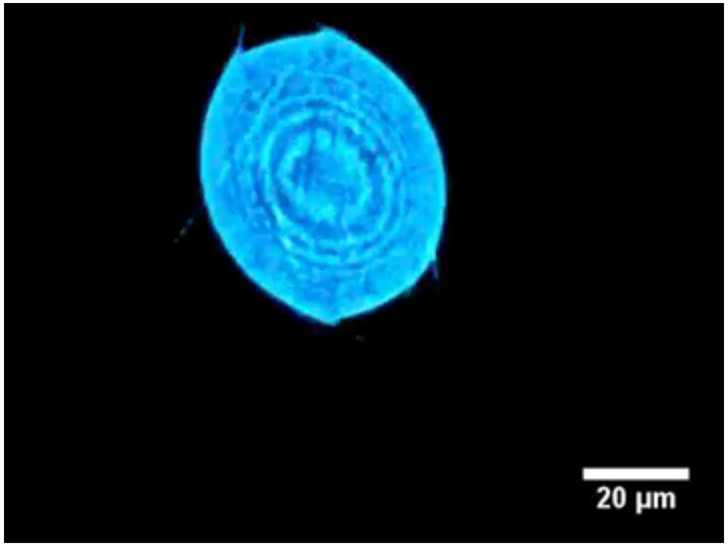


● : +1/2 defects

Doostmohammadi, Ignés, Yeomans, Sagués., "*Active nematics*", Nature comm, 2018

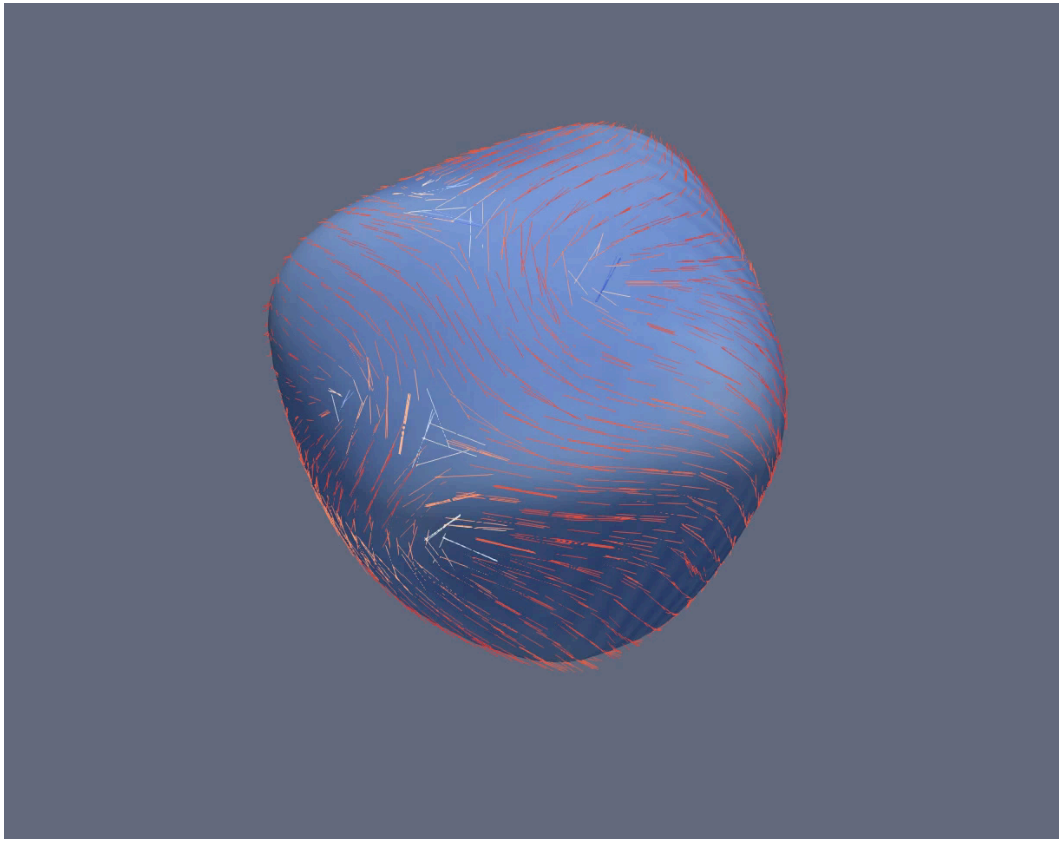
Topological control of active matter?

Self-deforming vesicles



Keber et al., Science (2015)

Activity controls the morphology of the shell

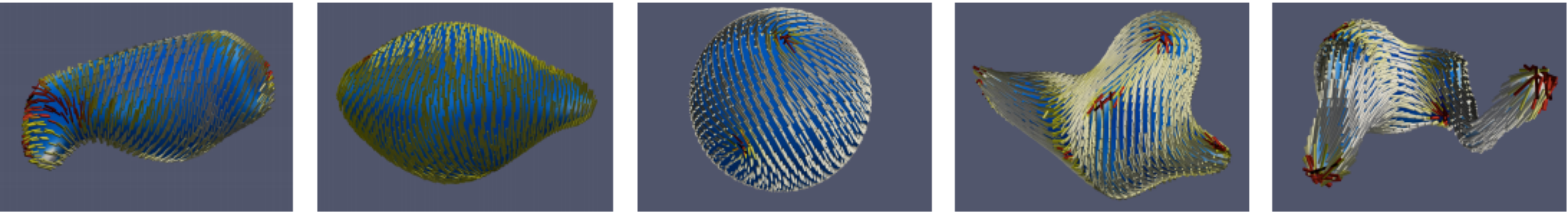


Project: Computational

Studying local activity to control the shape

Involves:

- Lattice-Boltzmann method
- Phase-field formulation
- Machine learning and neural networks
- Collaboration with experimental groups in Barcelona and Santa Barbara



"Topology & morphology of self-deforming active shells", Phys. Rev. Lett. (2019)

Active Self-organizing Matter

What is New

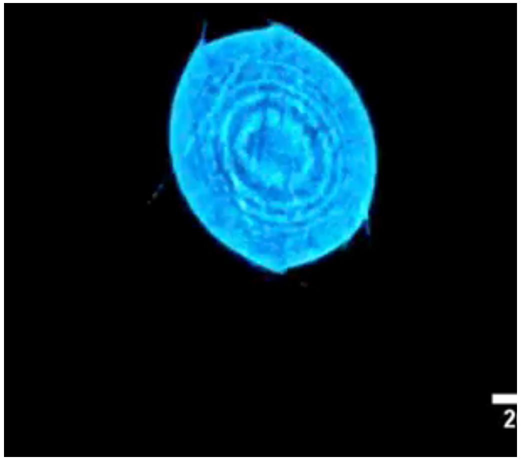
- A physics understanding of fundamental biological processes
- Designing new ways of controlling active materials

What is Exciting

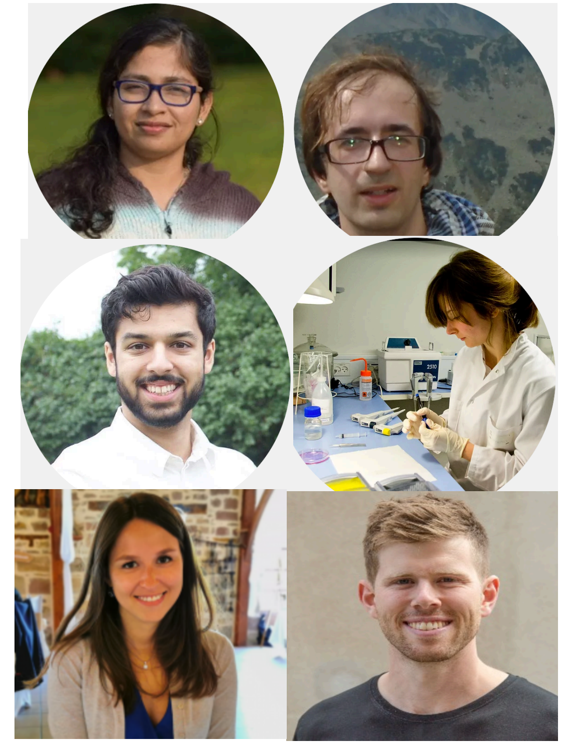
- To predict cell fate based on its mechanical features
- To program materials that are capable of self-organization, self pumping, self-healing
- To work on interdisciplinary projects with international collaborations

Projects

- Cell competition: calculating flow fields of half-skyrmions
- Cell decision-making: studying stress topological defects
- Self-pumping fluids: how they emerge?
- Designing materials that evolve



What you gain



Being part of a

- **diverse**
- **collaborative**
- **Interdisciplinary (condensed matter physics | fluid mechanics | mathematics | biochemistry)**

group

Expand your future career prospects

In academia

- Previous students now PhD in Oxford, Cambridge, Stanford

Outside academia

- Demand for physicists with the knowledge of statistical mechanics, pattern formation
- Previous students now in Goldman Sacks, JP Morgan, Nordea

www.doostmohammadilab.com