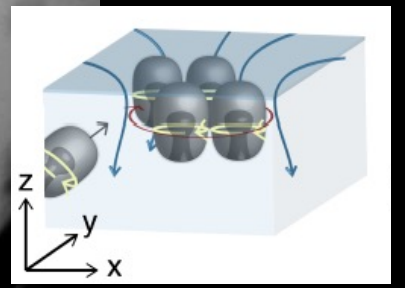
00:00 (hh:mm)

Odd dynamics in living chiral crystals

Tzer Han Tan

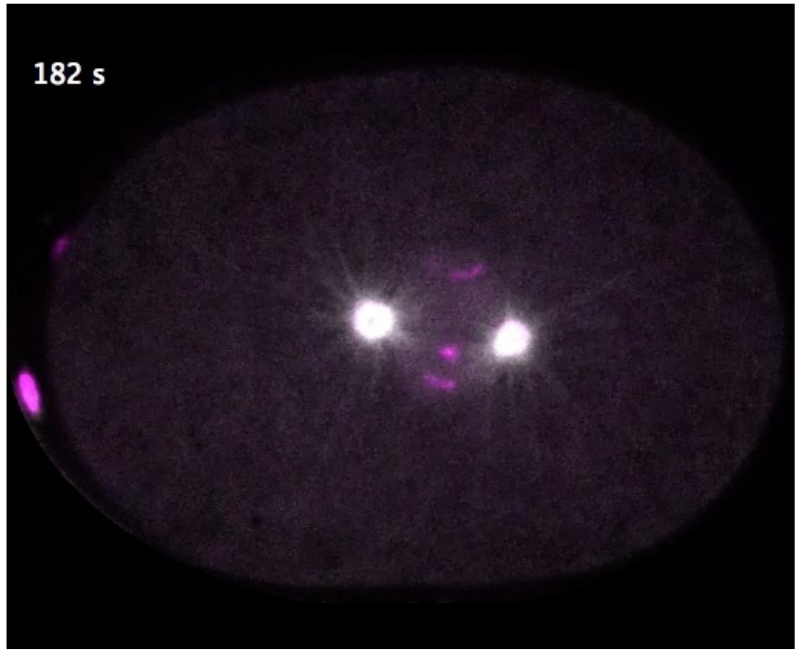
Assistant Professor of Physics

UC San Diego



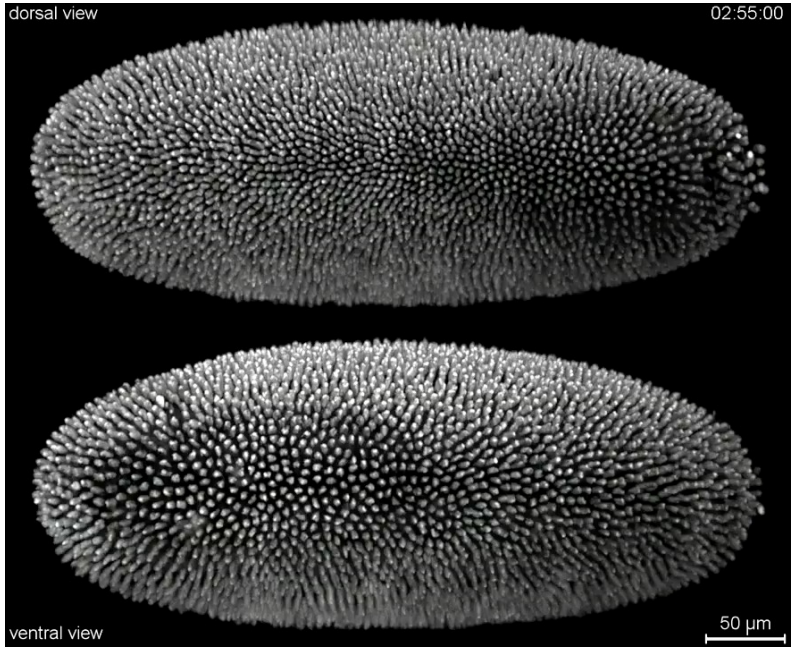
Emergent phenomena in living matter

Mitotic spindle (~1um)



Fielmich et. al. 2018 eLife

Embryogenesis (~100um)



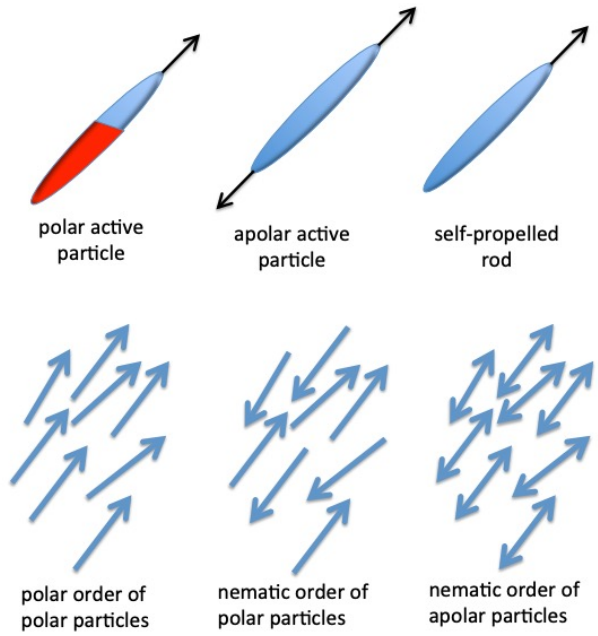
Keller Lab 2014

Bird flocks (~1 m)

Jukin media

Active matter as a unifying framework

Active matter: microscopic particles consume energy for organized motion + interactions → macroscopic states



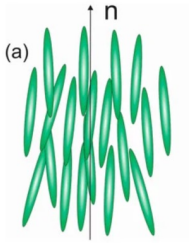
- Types of active particles (Isotropic, nematic, …)
- Symmetry of interactions (Polar, nematic, …)

Marchetti et. al. 2013

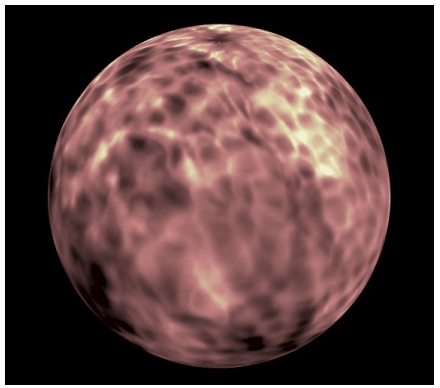
- Nonequilibrium order-disorder transitions,
- Pattern formation on mesoscopic scales,
- Unusual mechanical and rheological properties,

Biological active matter as active nematic liquid crystal

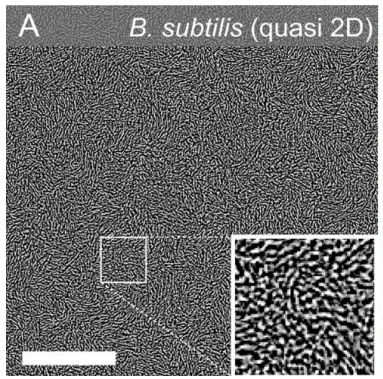
Cells as active nematics



Spontaneous flow & active turbulence

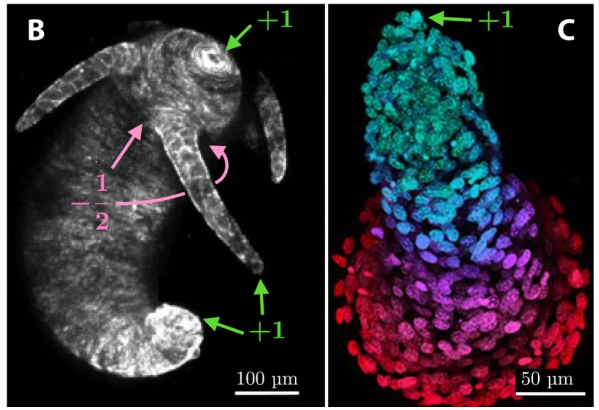


***THT**, Amiri*, Barandiaran* et. al. (2024) PRX Life*



Wensink et. al. 2012 PNAS

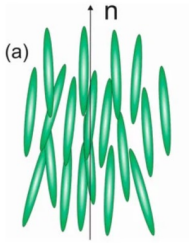
Topological defects as organization centers of morphogenesis



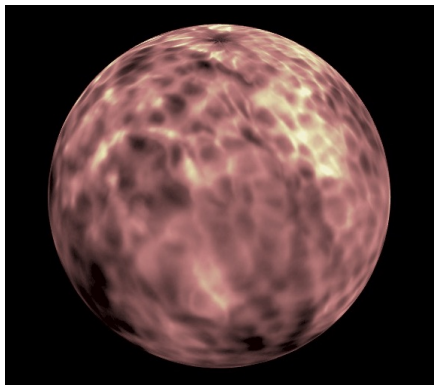
Maroudas-Sacks et. al. 2020 Nat. Phys.; Guillamat et. al. 2022 Nat. Mat.; Hoffman et. al. 2022 Sci. Adv.

Biological active matter as active nematic liquid crystal

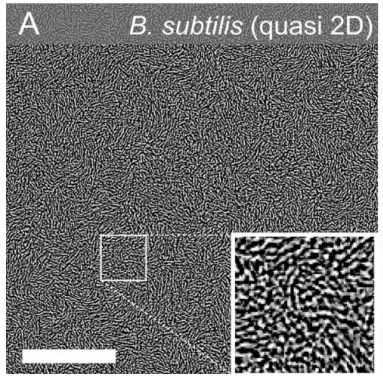
Cells as active nematics



Spontaneous flow & active turbulence



THT, Amiri*, Barandiaran* et. al. (2024) PRX Life*



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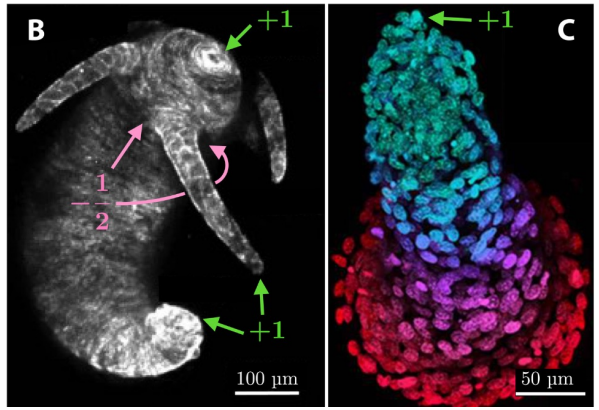
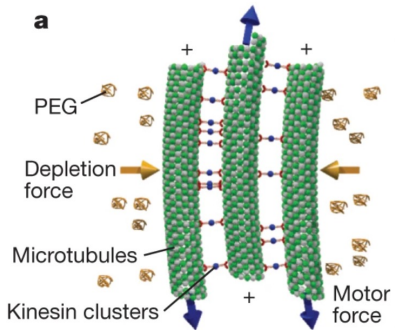
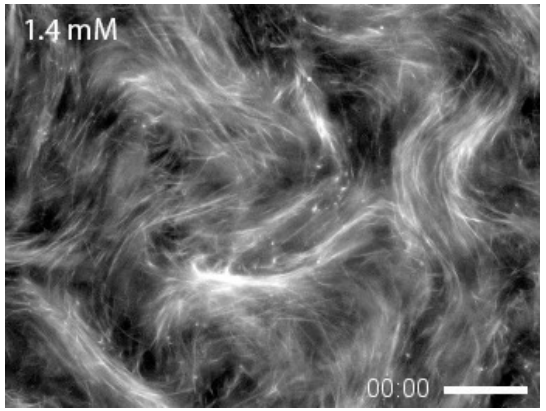
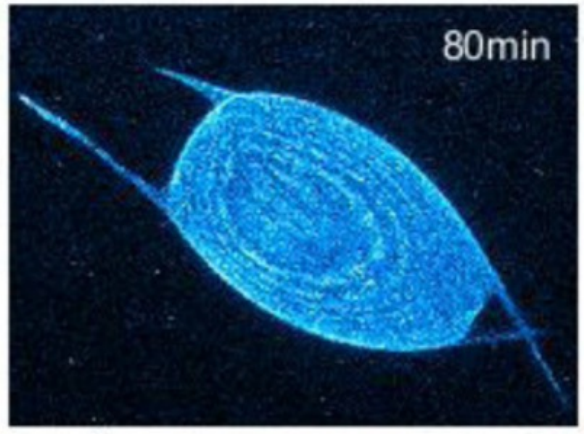


Maroudas-Sacks et. al. 2020 Nat. Phys.; Guillamat et. al. 2022 Nat. Mat.; Hoffman et. al. 2022 Sci. Adv.

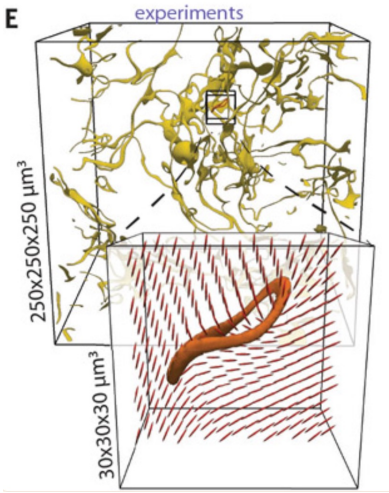
Cytoskeleton as active nematics







Keber et. al. Science 2014

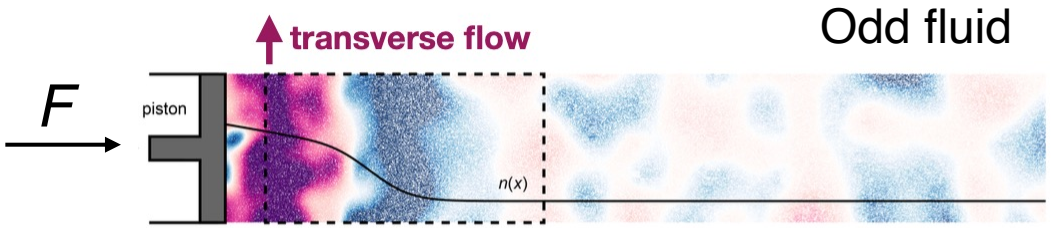


Duclos et. al. Science 2020

Chiral active matter with ‘odd’ properties

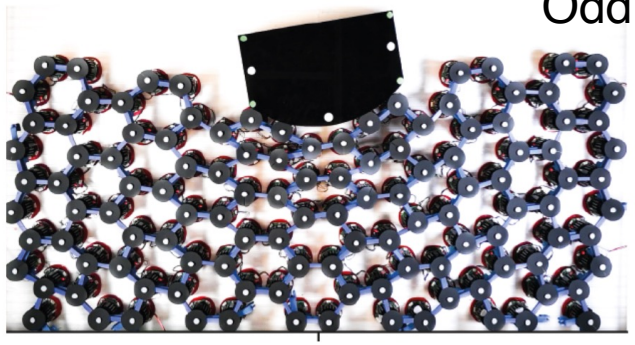
Chiral active matter: constituent particle inject both *energy (broken time reversal symmetry)* and *angular momentum (broken chiral symmetry)* at microscopic level

Transverse response



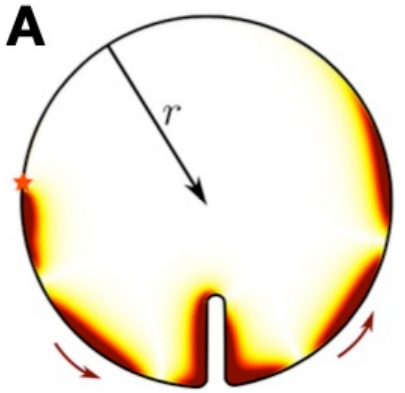
Han et. al. Nat Phys 2021

Odd solid

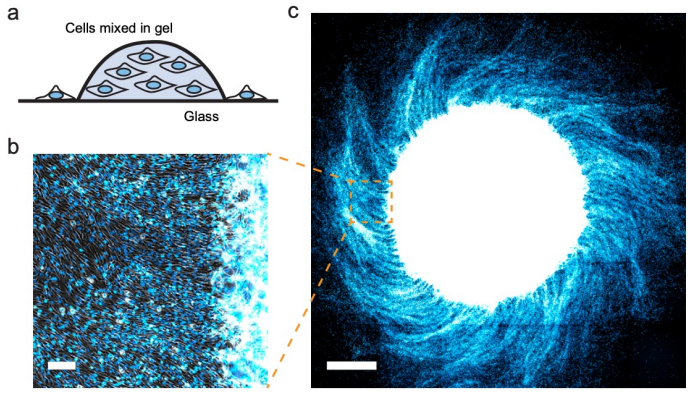


Brandenbourger et. al. arXiv 2021

Edge modes and currents



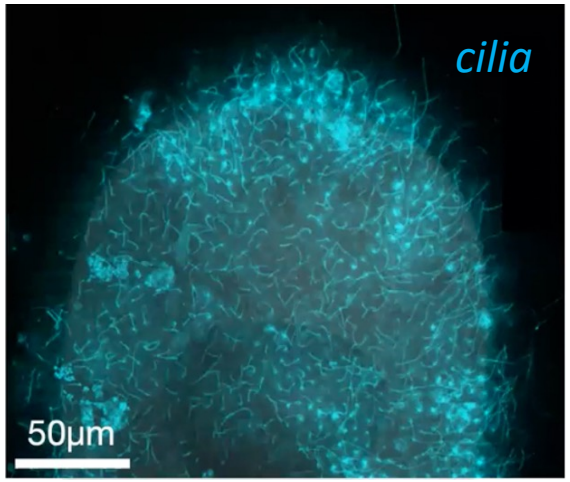
Souslov et. al. PRL 2019

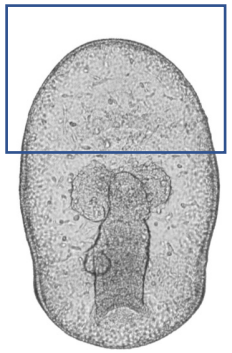


Yamauchi et. al. arXiv 2020

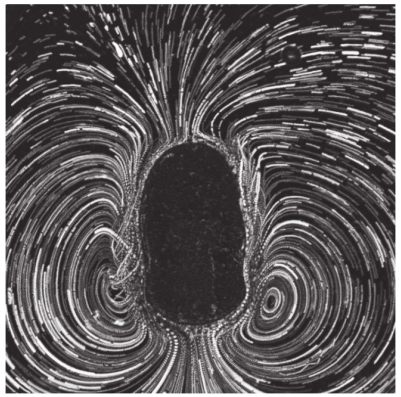
Review: “Odd Viscosity and Odd Elasticity”
Fruchart et. al. 2023, Annu. Rev. Condens. Matter Phys

Starfish embryos self-assemble into living chiral crystal

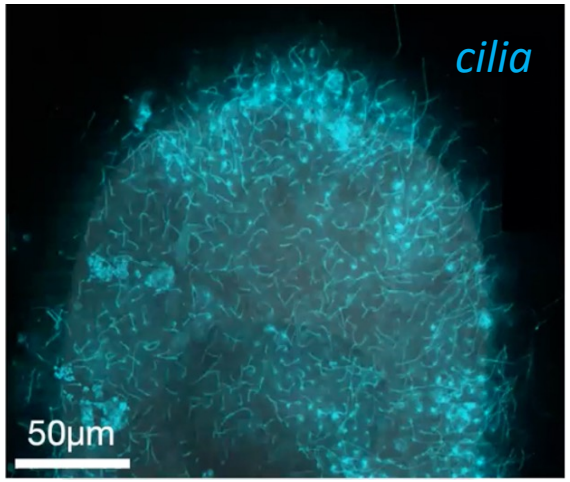


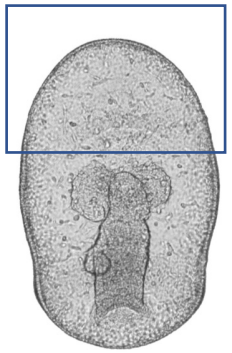


100um



Starfish embryos self-assemble into living chiral crystal





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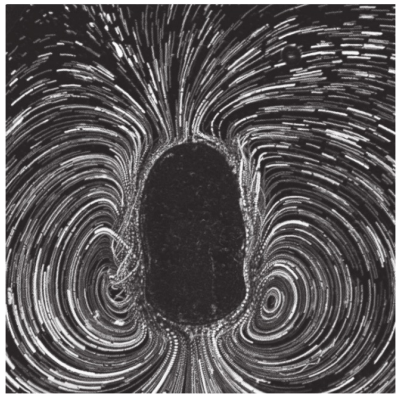
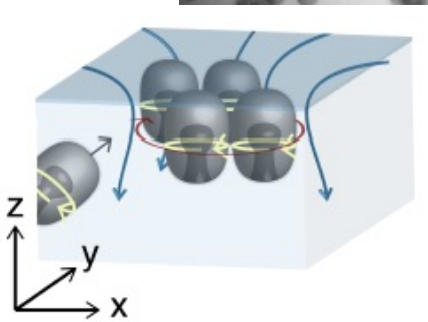
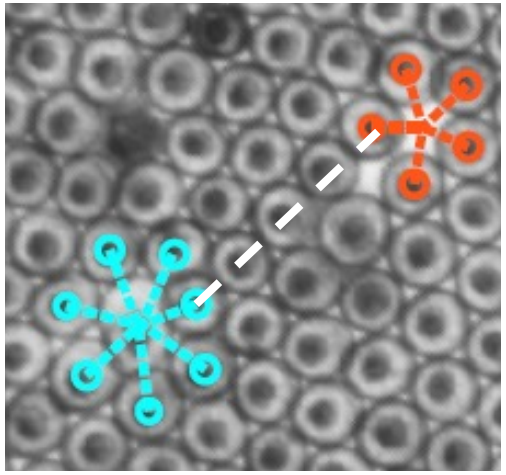
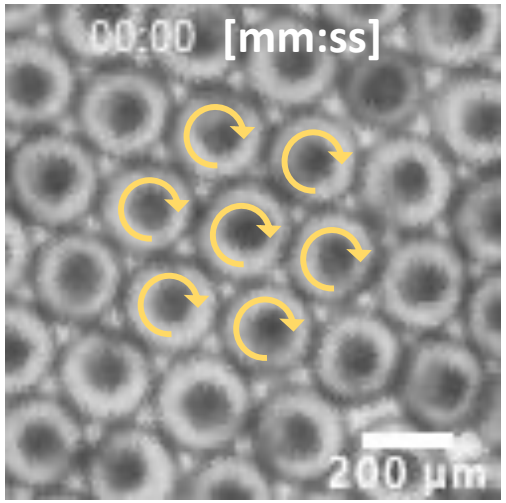
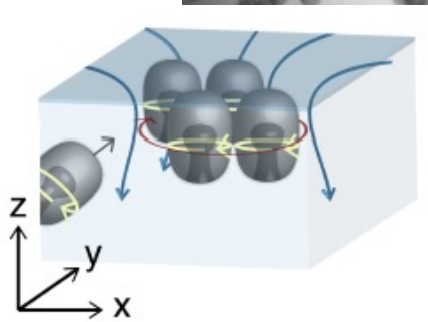


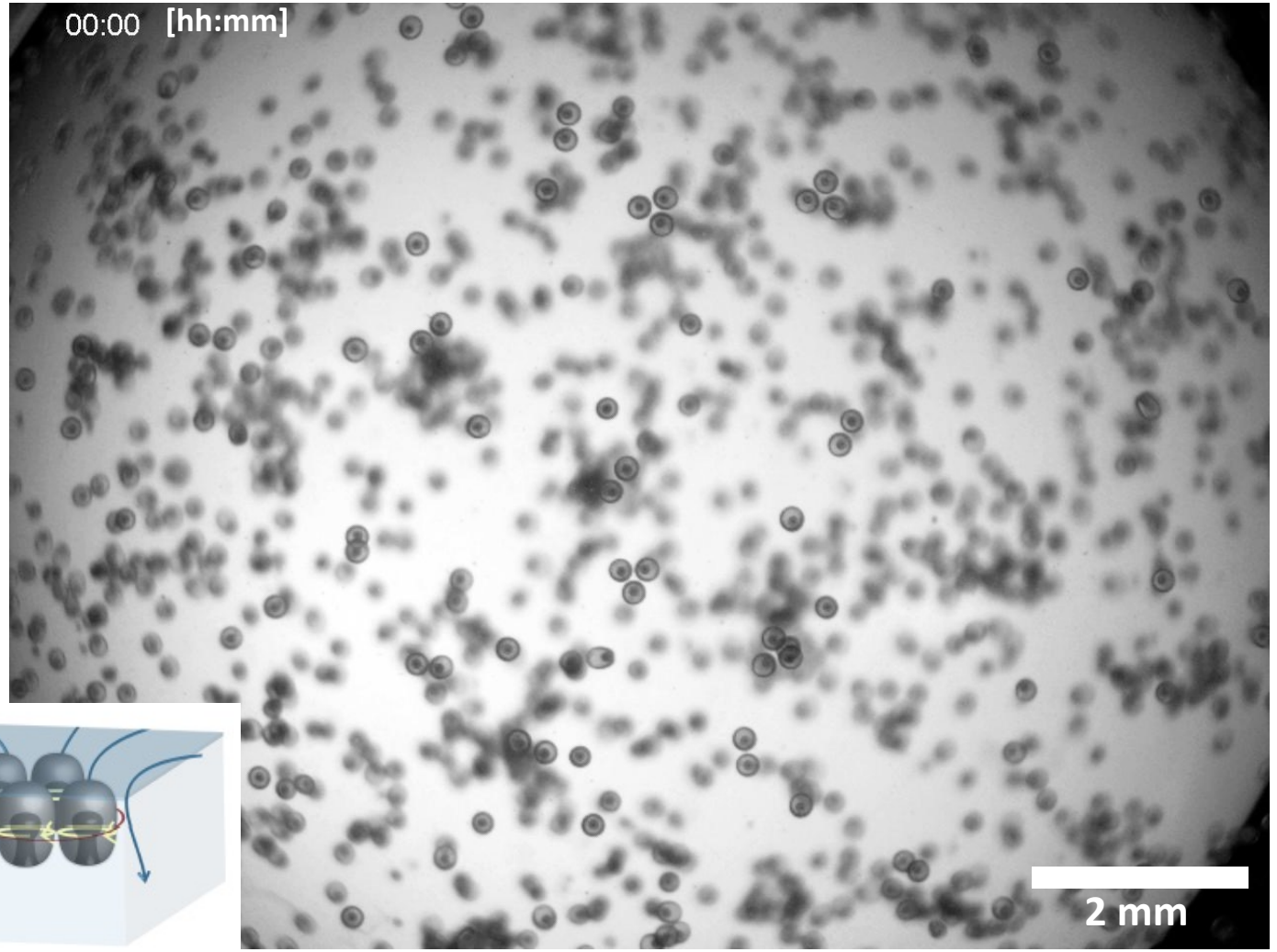


Starfish embryos self-assemble into living chiral crystal

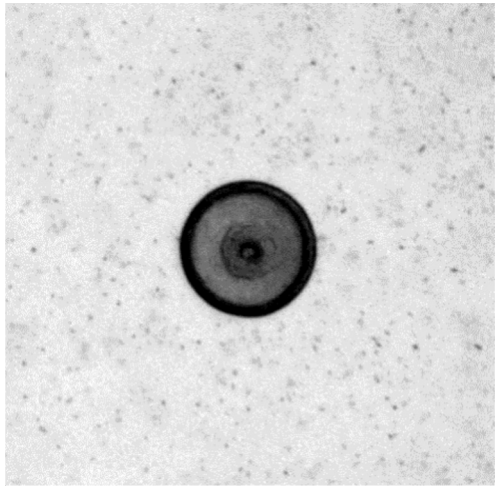


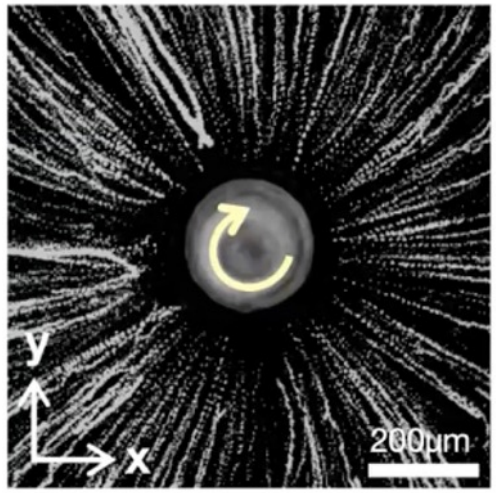


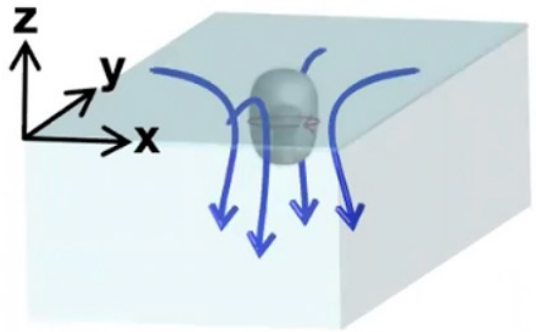


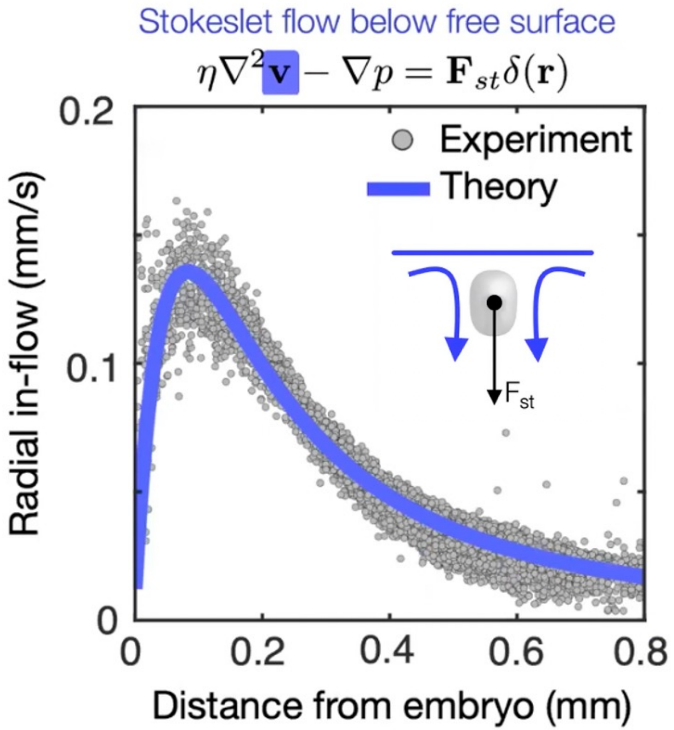


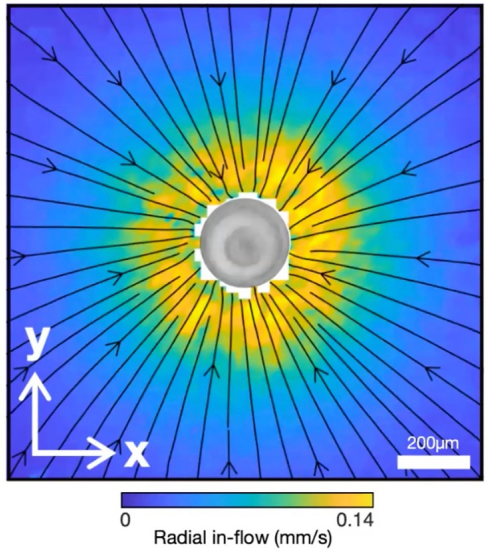
Single embryo hydrodynamics



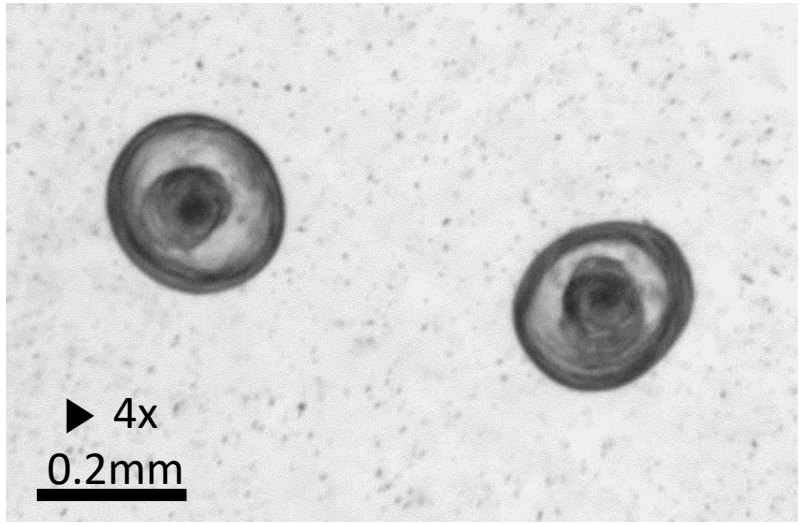


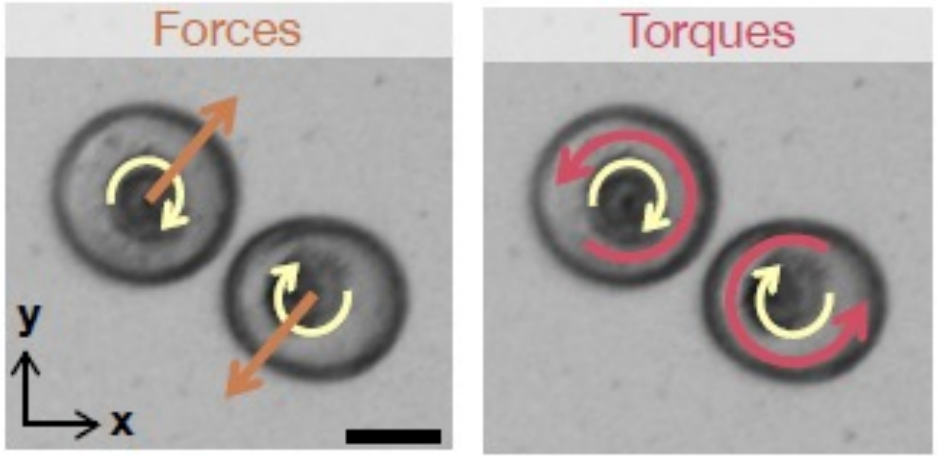


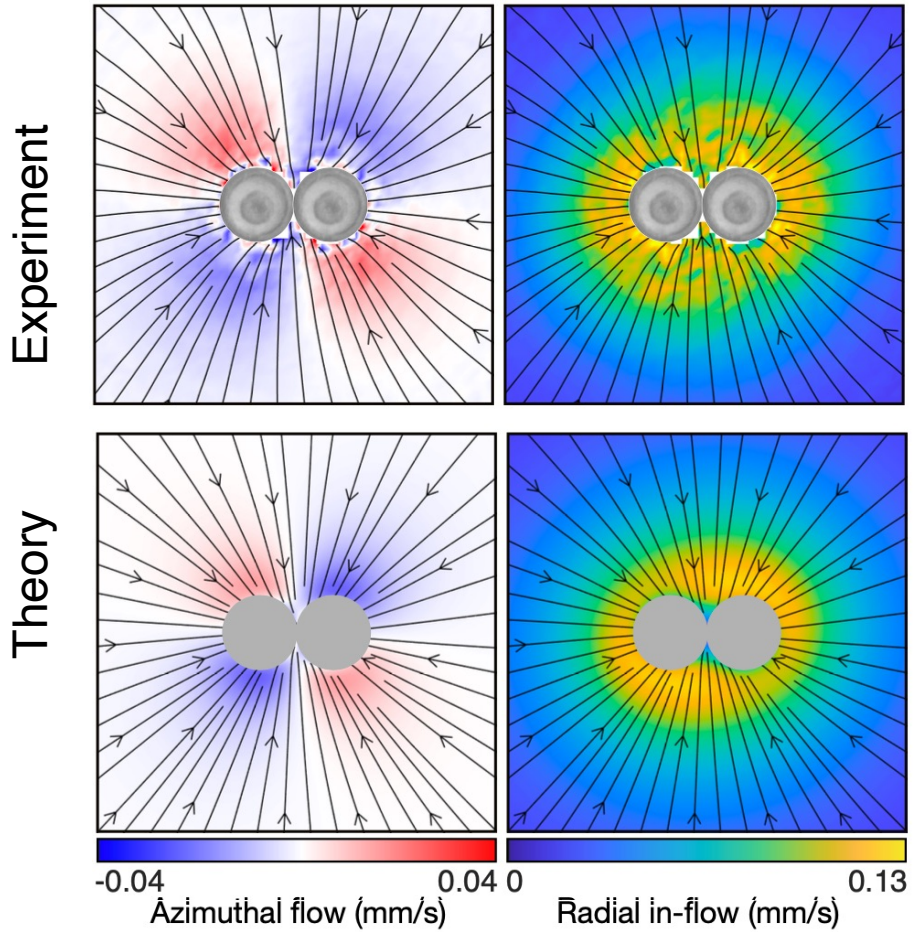




Pairwise embryo hydrodynamic

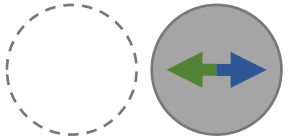






Minimal model of chiral crystal formation

Longitudinal Forces



Stokeslet attraction
Steric repulsion

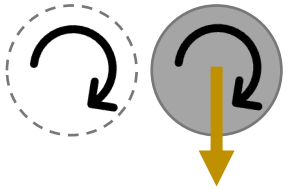
$$\frac{d\mathbf{r}_i}{dt} = \sum_j \left[\mathbf{f}^{(\mathrm{attr})}(r_{ij}) + \mathbf{f}^{(\mathrm{rep})}(r_{ij})\right] + \sum_{\mathcal{N}_i} f_\eta(r_{ij})(\omega_i + \omega_j)\hat{\mathbf{r}}_{ij} \times \mathbf{e}_z$$

Stokeslet attraction

Short-ranged steric repulsion

Force from chiral interaction

Transverse Forces (chiral)



Cilia & hydrodynamic Interaction

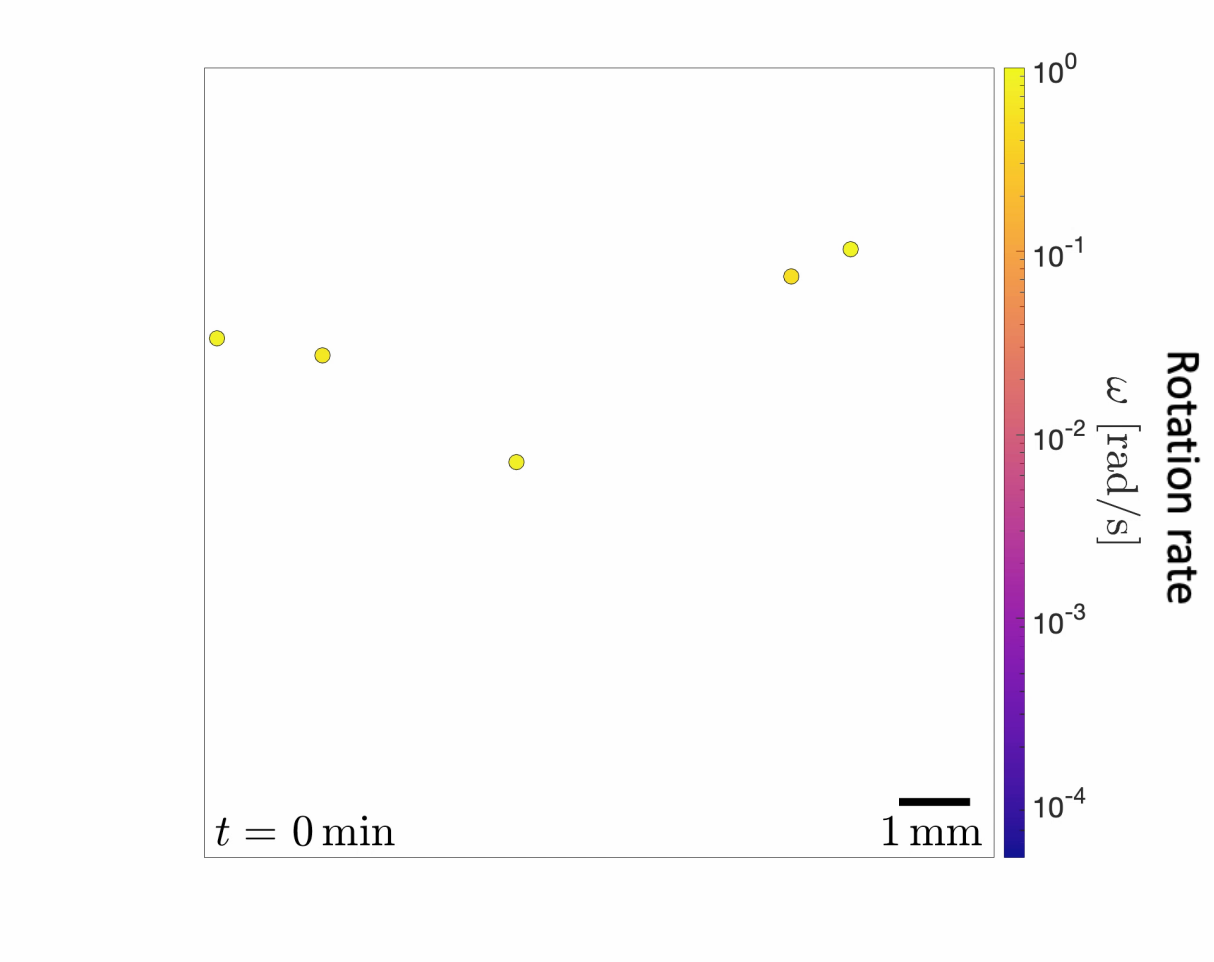
$$\omega_i = \omega_0 - \sum_{\mathcal{N}_i} \tau_\eta(r_{ij})(\omega_i + \omega_j)$$

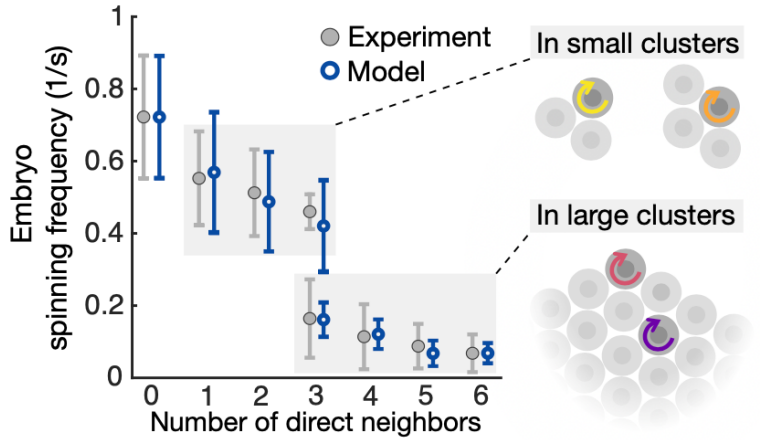
Free Rotation Speed

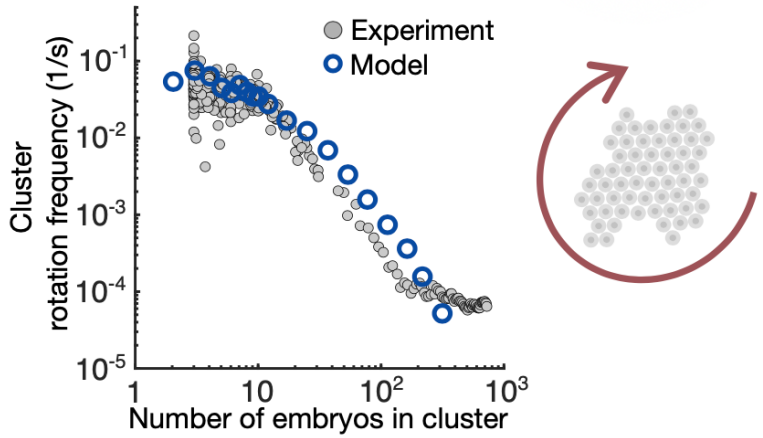
'Torque' from chiral interaction

Theory colloborator: Alexander Mietke (Dunkel Group, currently U. of Oxford)

Minimal model of chiral crystal formation







Odd elasticity and strain cycles

stress *Elastic modulus tensor* *strain*

$$\begin{pmatrix} \\ \\ \\ \\ \end{pmatrix} = \begin{pmatrix} B & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & \mu \end{pmatrix} \begin{pmatrix} \\ \\ \\ \\ \end{pmatrix}$$

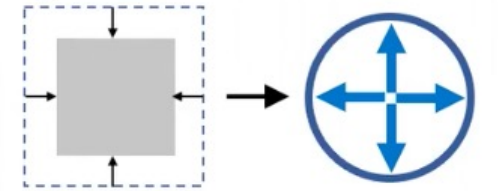
Dilation

Curl

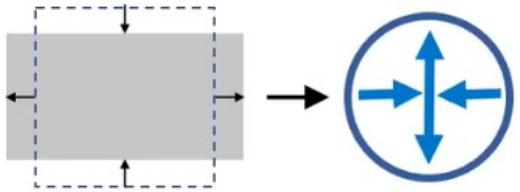
Shear 1

Shear 2

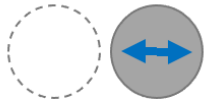
Compression modulus $B \sim k$



Shear modulus $G \sim k$



Longitudinal Forces



Stokeslet attraction
Steric repulsion

Scheibner et. al. 2020 Nature Physics

Odd elasticity and strain cycles

A (couples compression to internal torque density)

K^o (antisymmetric shear coupling)

stress *Elastic modulus tensor* *strain*

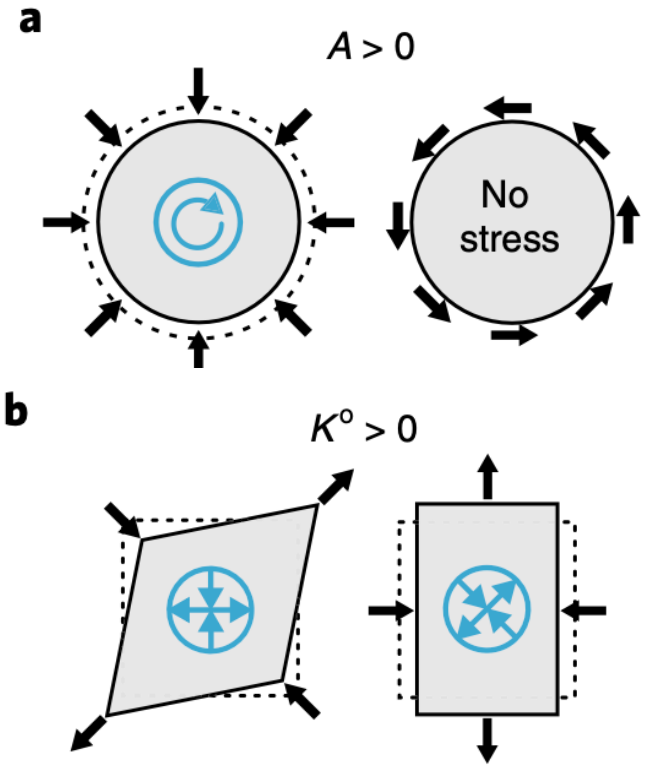
$$\begin{pmatrix} \\ \\ \\ \\ \end{pmatrix} = \begin{pmatrix} B & 0 & 0 & 0 \\ A & 0 & 0 & 0 \\ 0 & 0 & \mu & K^o \\ 0 & 0 & -K^o & \mu \end{pmatrix} \begin{pmatrix} \\ \\ \\ \\ \end{pmatrix}$$

Dilation

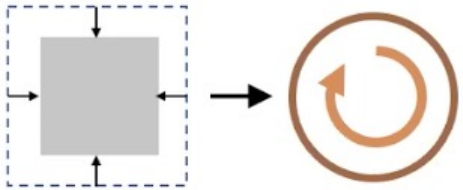
Curl

Shear 1

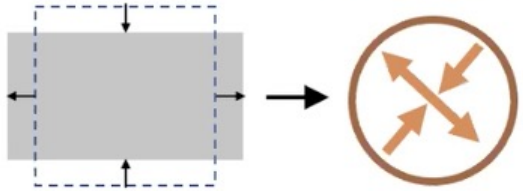
Shear 2



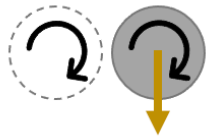
Odd *compression modulus* $A \sim k_\perp$



Odd *shear modulus* $K^o \sim k_\perp$



Transverse Forces (chiral)

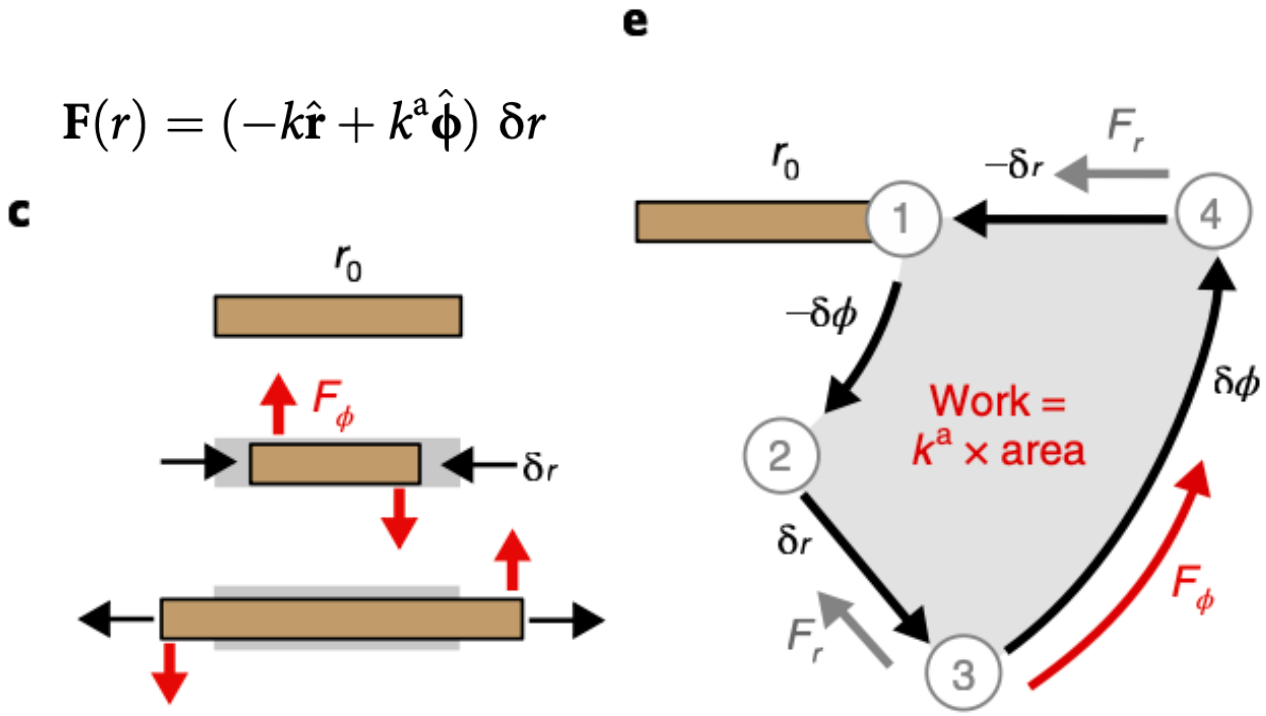


Cilia & hydrodynamic Interaction

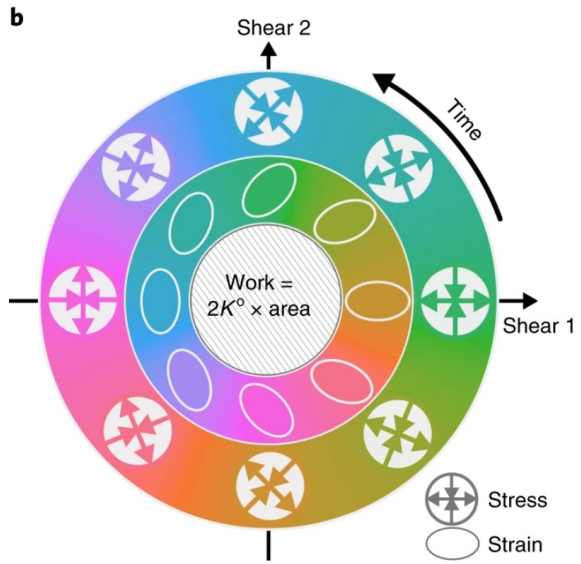
Scheibner et. al. 2020 Nature Physics

Odd elasticity and strain cycles

$$\mathbf{F}(r) = (-k\hat{\mathbf{r}} + k^{a}\hat{\boldsymbol{\phi}})\ \delta r$$



Can extract work from quasistatic cycle

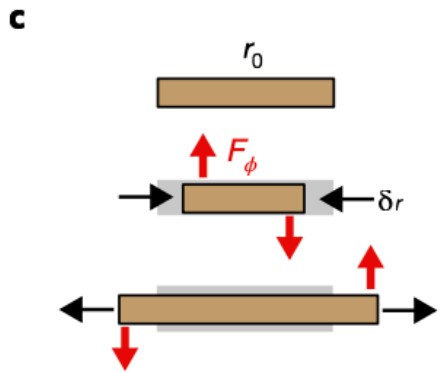


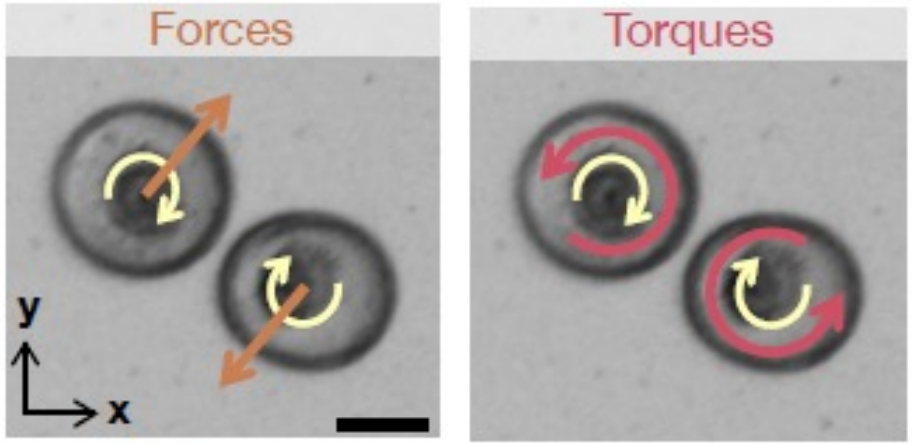
- Odd elastic materials can exhibit odd elastic wave, even when system is overdamped
- Trajectory of wave in strain space traces out a cycle
- Emergence of self-sustaining elastic engine cycle (internal energy converted into mechanical work)

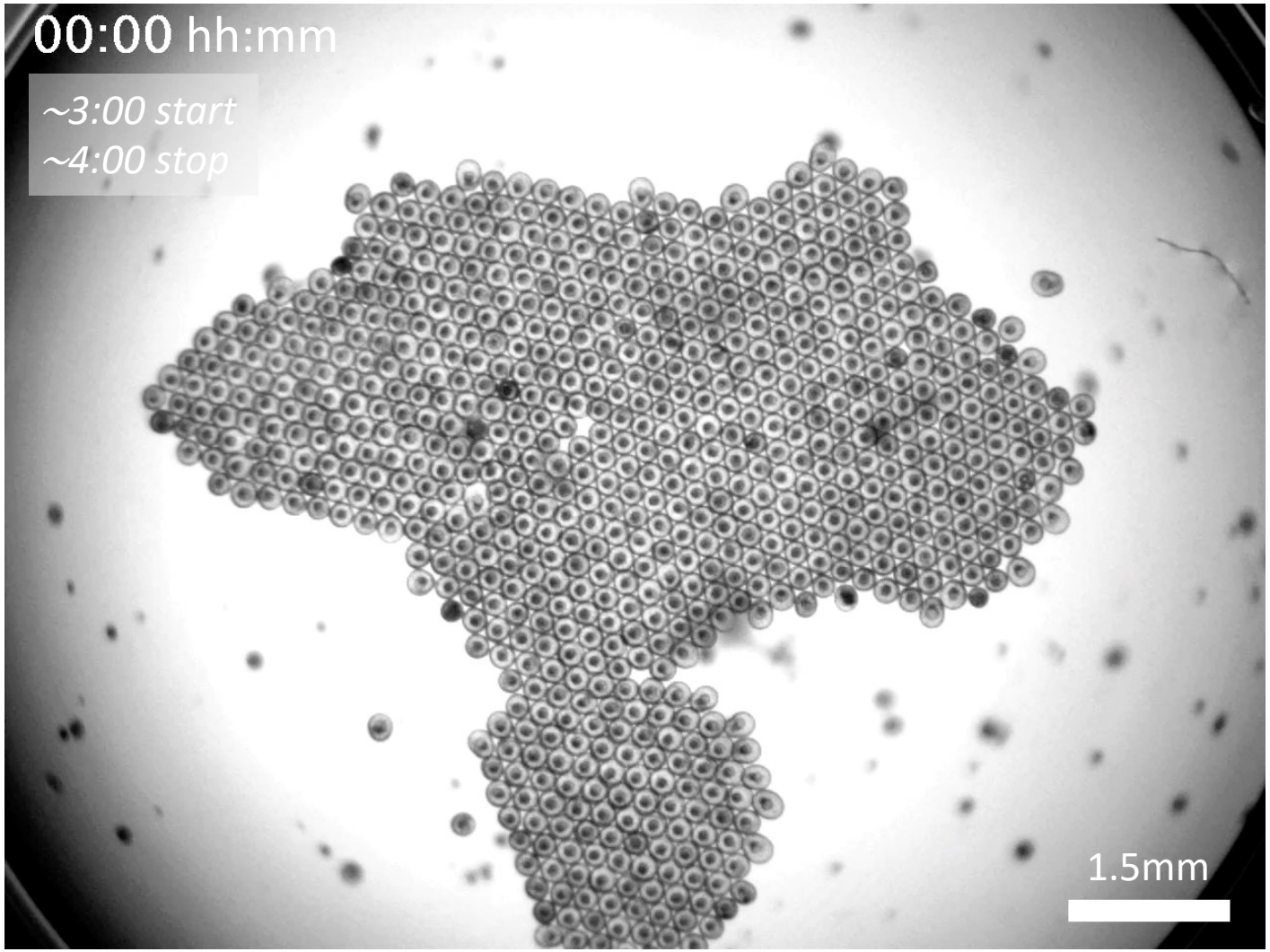
Scheibner et. al. 2020 Nature Physics

Vibrational modes of living chiral crystal

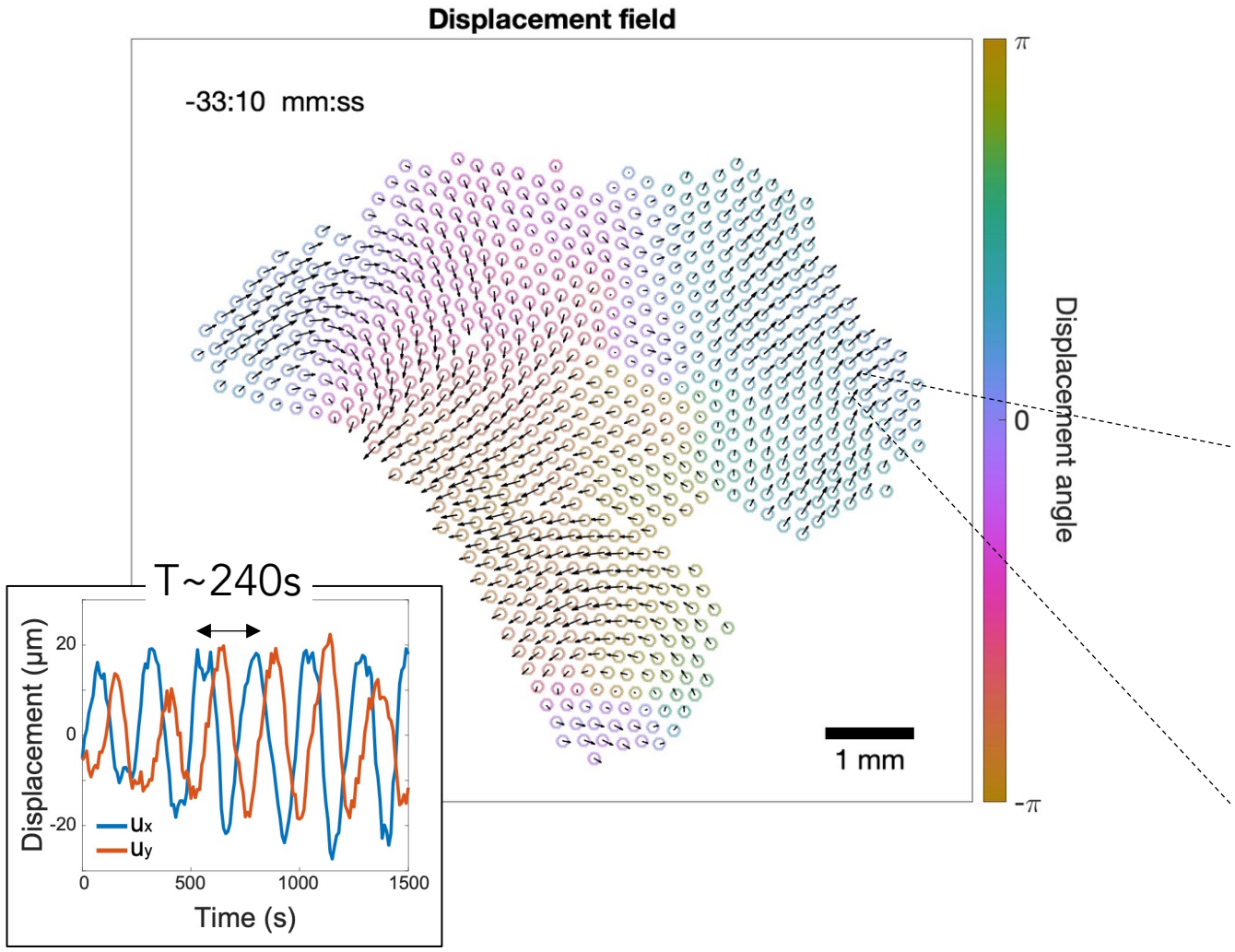
$$\mathbf{F}(r) = (-k\hat{\mathbf{r}} + k^{a}\hat{\boldsymbol{\phi}})\ \delta r$$

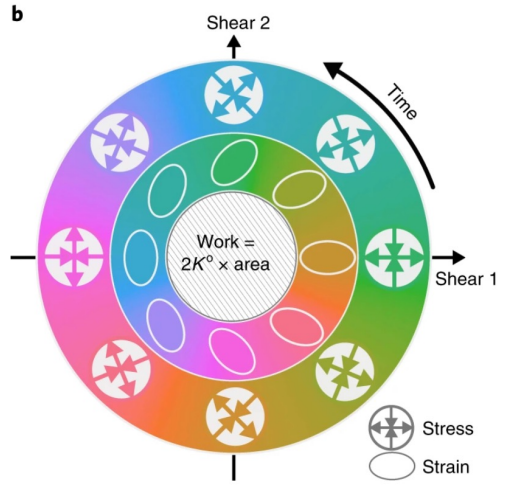


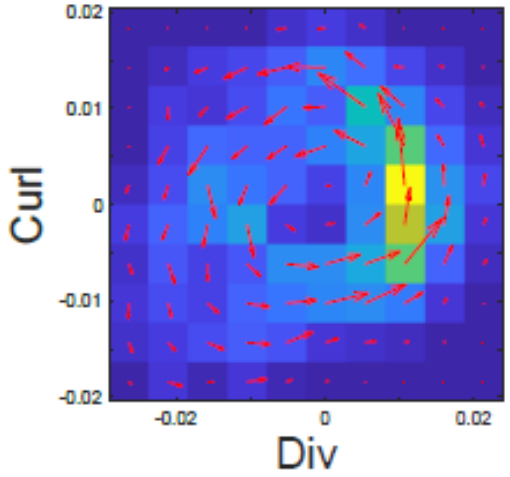


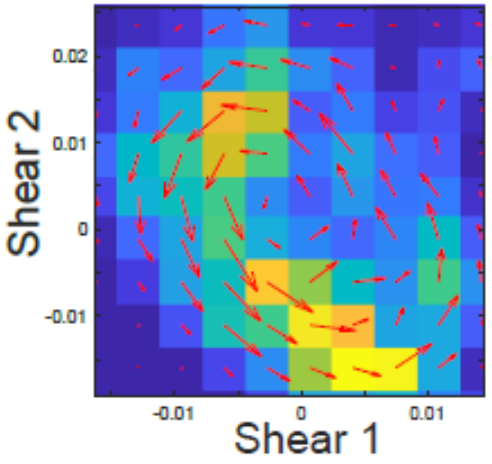


Signatures of odd elasticity in strain cycles

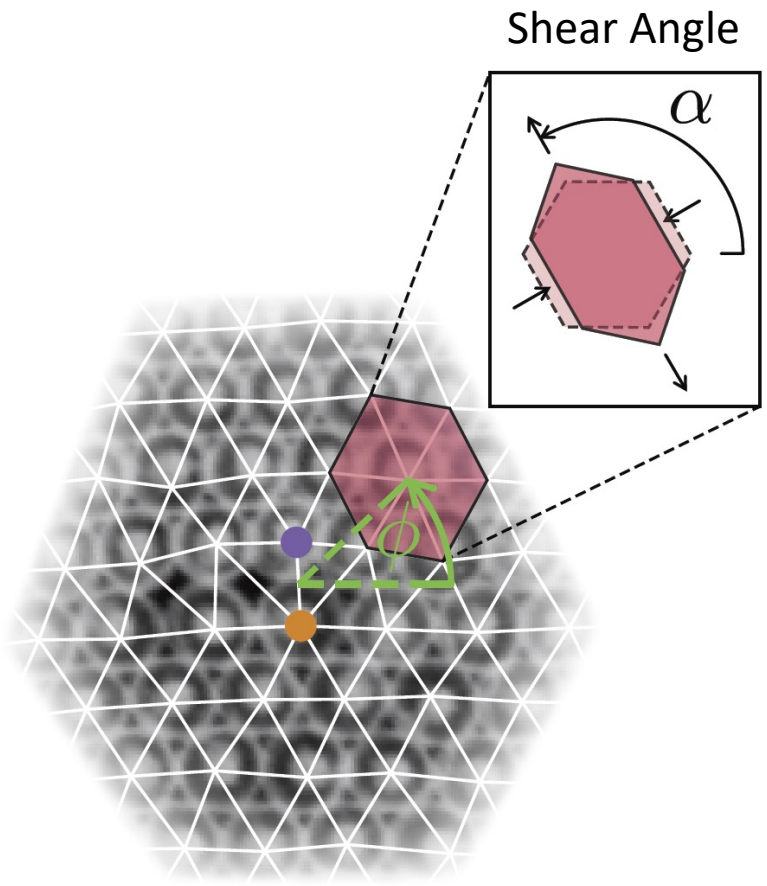








Can we measure the odd elastic moduli?

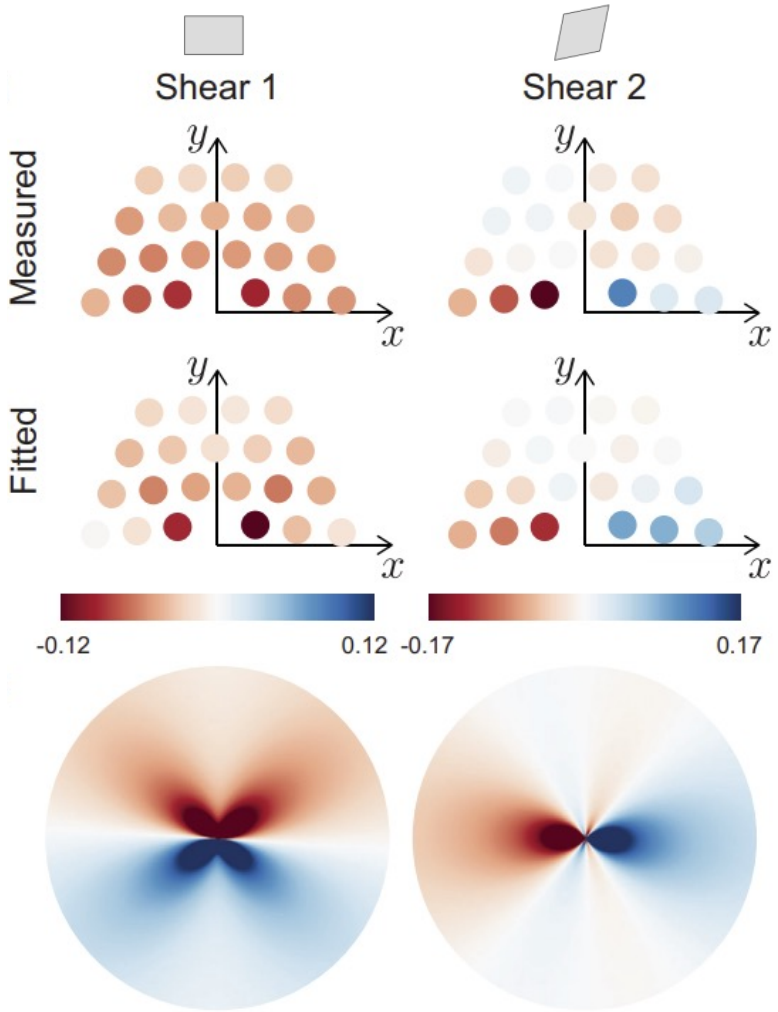


- Crystal harbors defects like edge dislocations
- Defect strain field encodes information about material moduli.

Topological Defects in Solids with Odd Elasticity

Lara Braverman, Colin Scheibner, Bryan VanSaders, and Vincenzo Vitelli
Phys. Rev. Lett. **127**, 268001 – Published 20 December 2021

Inferring odd moduli from defect strain field



Moduli from best fit

Modulus	Estimate	Standard Error
A/μ	7.7	0.61
K^o/μ	7.1	0.59

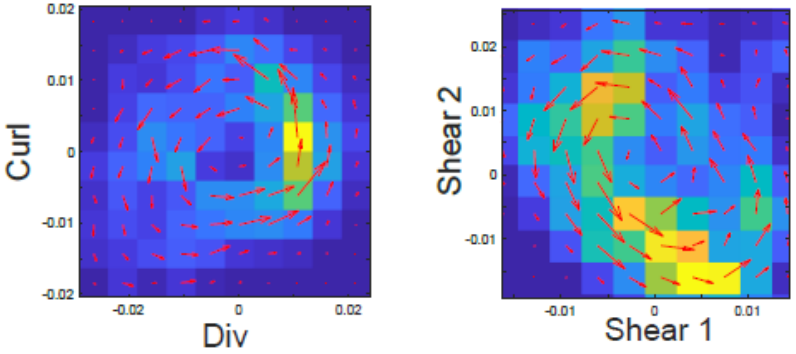
Moduli from model coarse-graining

$$A, K^o > 0$$

$$A = \frac{\sqrt{3}}{2}\left(k_a + \frac{F_0^\perp}{r_0}\right) \approx 1.9\,\mathrm{s}^{-1}$$

$$K^o = \frac{\sqrt{3}}{4}\left(k_a - \frac{F_0^\perp}{r_0}\right) \approx 0.8\,\mathrm{s}^{-1}.$$

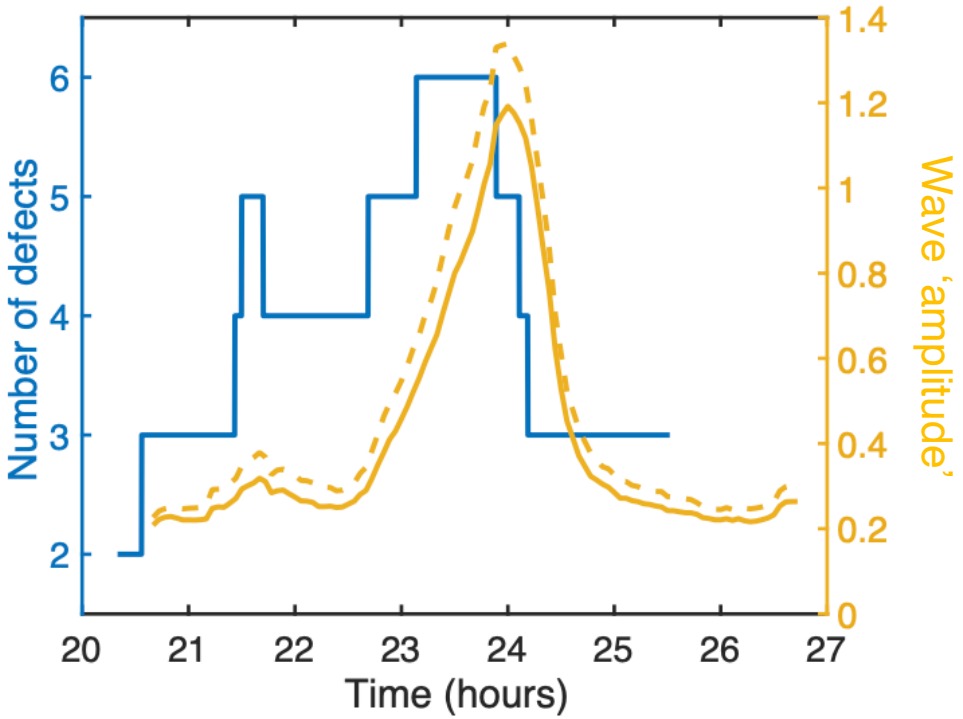
CCW cycles do work on the environment



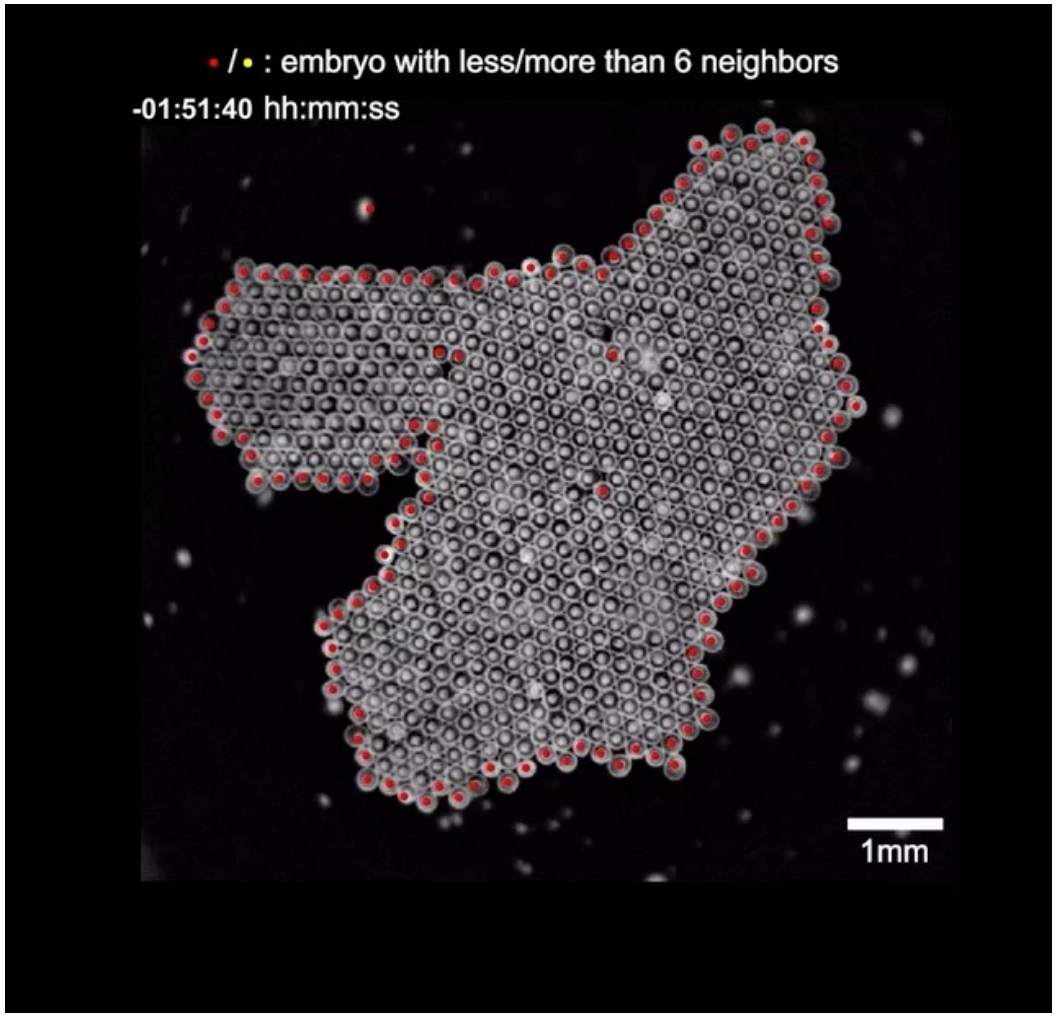
How to excite the wave?

Defect dynamics ⇔ wave dynamics

How to excite the wave?



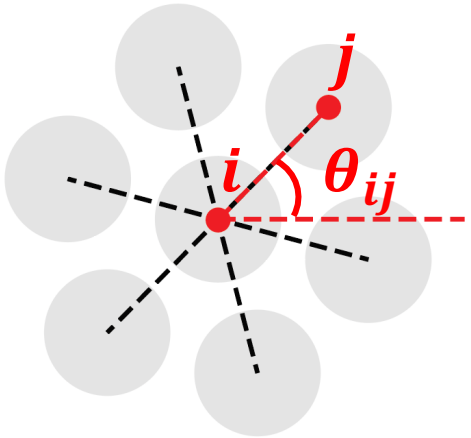
Geometric frustration of the



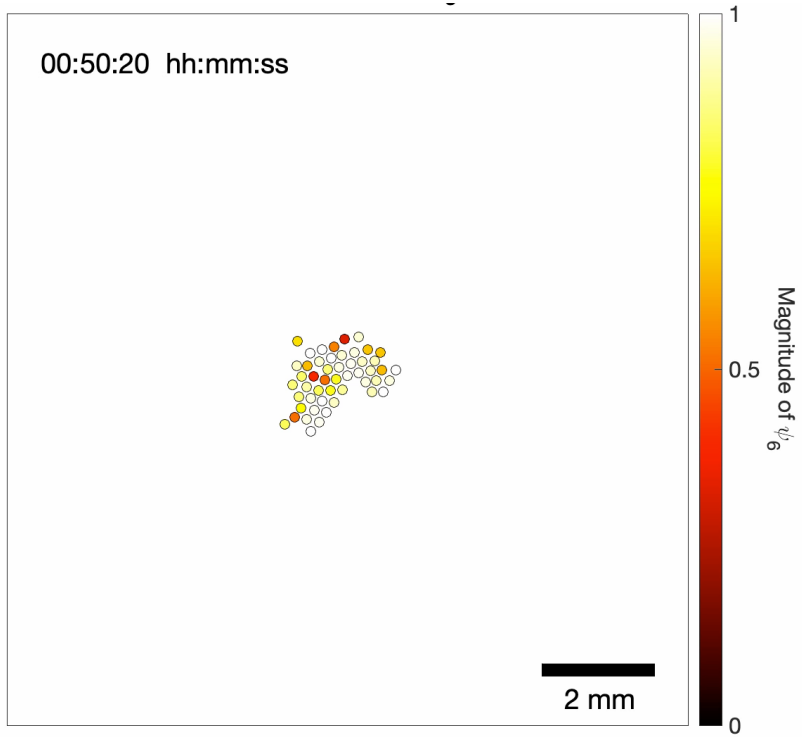
Autonomous order-disorder transition in living chiral crystal

Local bond orientational order parameter

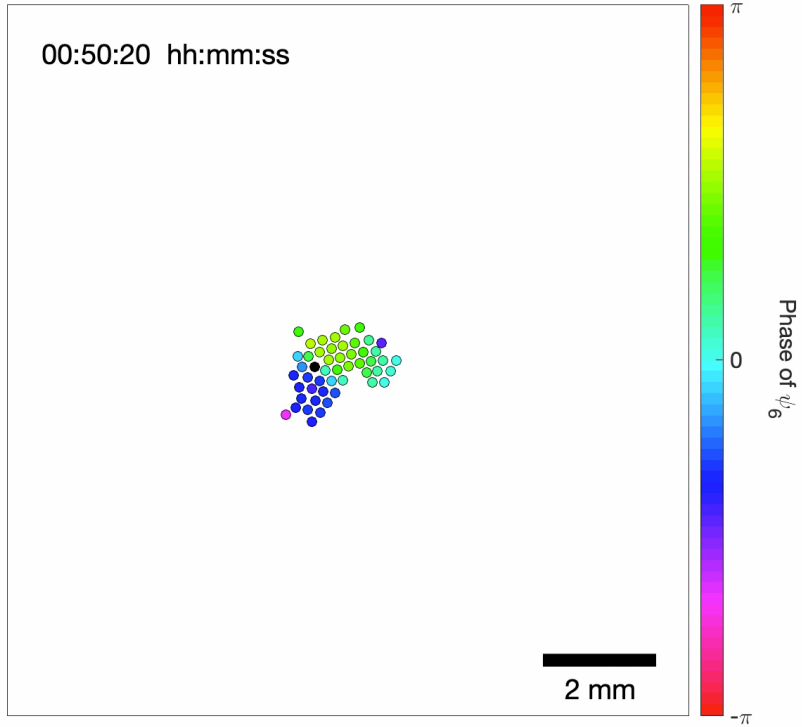
$$\psi_6(\mathbf{r}_i) = \frac{1}{N_j}\sum_{j=1}^{N_j} e^{i6\theta_{ij}} \equiv A_i e^{\phi_i}$$



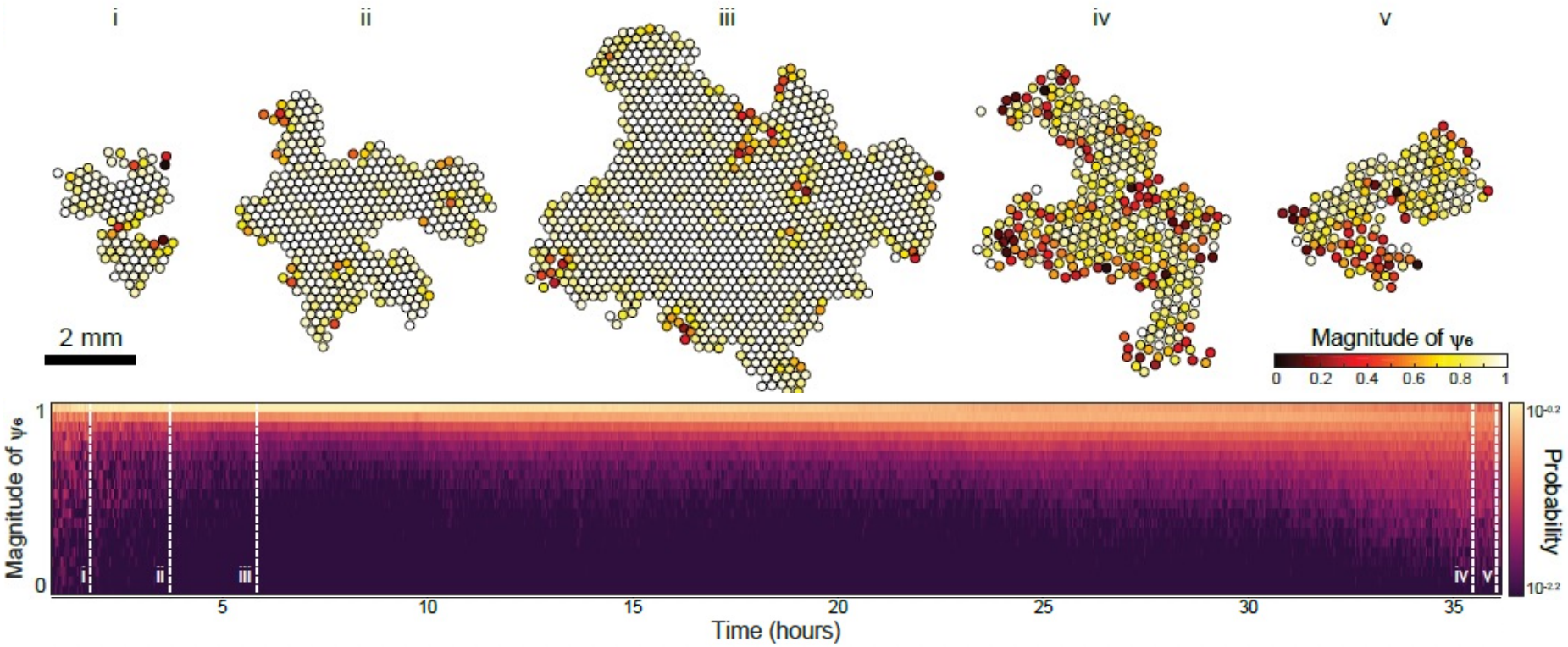
$\boldsymbol{A_i}$: magnitude of ψ_6
(quantifies local hexagonal order)

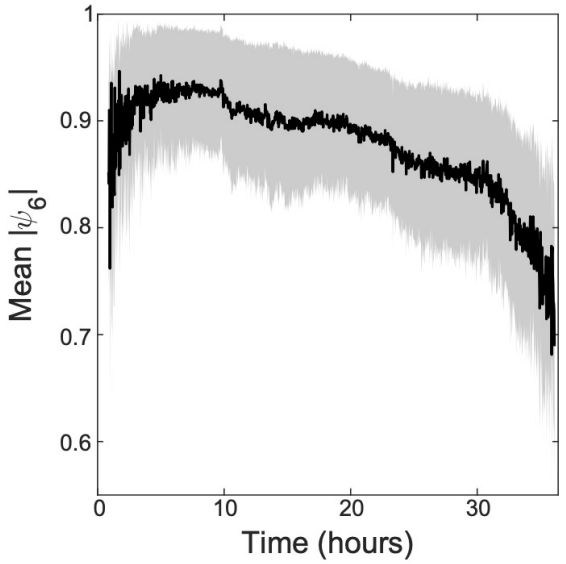


$\boldsymbol{\phi_i}$: phase of ψ_6
(indicates orientation of hexagonal order)

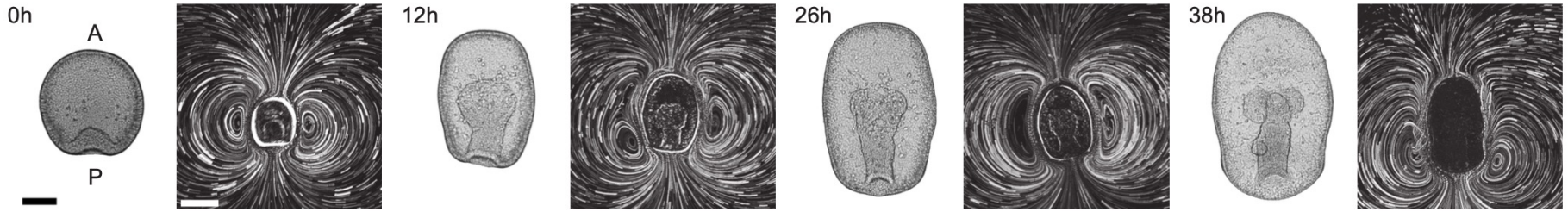


Autonomous order-disorder transition in living chiral crystal





Probability-time kymograph of A_i (magnitude of ψ_6)



Acknowledgement

Odd dynamics living chiral crystal

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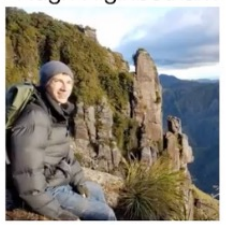
Hugh Higinbotham



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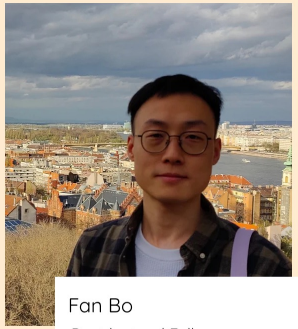
Nikta Fakhri

Odd dynamics of living chiral crystal
Tan TH*, Mietke A*, Li J, Chen Y, Higinbotham H, Foster PJ, Gokhale S, Dunkel J and Fakhri N,
Nature (2022).

Group members



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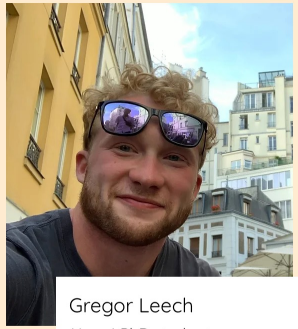
Postdoctoral Fellow



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