Topological edge states in bacterial collective motion - results and open problems -

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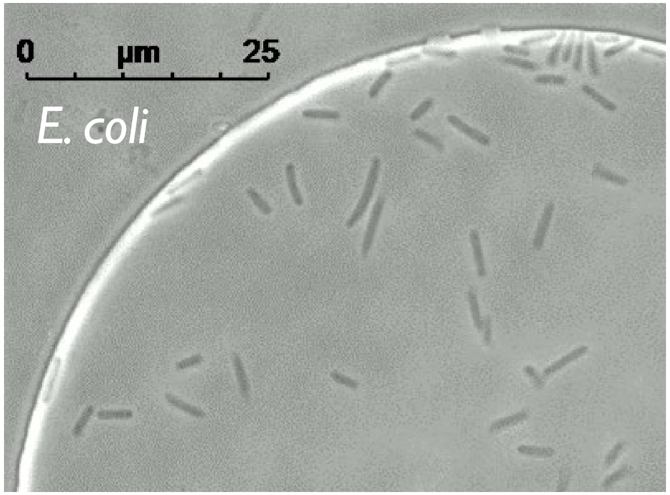
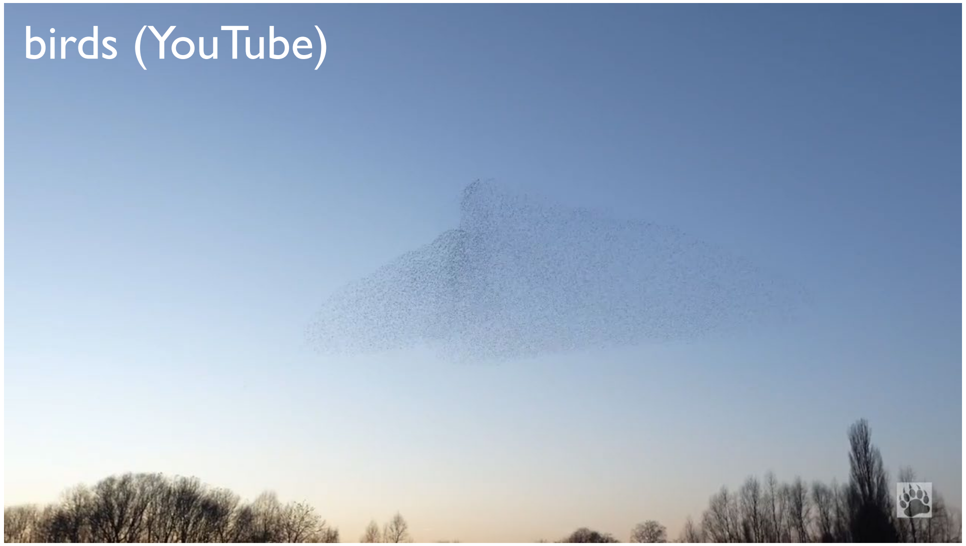
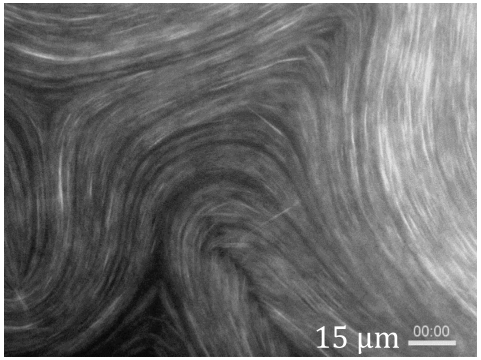
Reference
arXiv:2601.08243

Funding:
科研費 KAKENHI
Dynamical Materials Science
創発
INFO PHYS BIO Information physics of living matters
Active Matter c2c

Active Matter

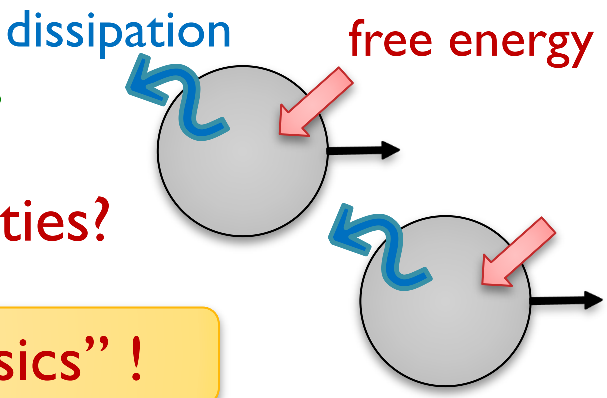






biofilaments
+ motor proteins
[Sanchez et al. 2012]

- Various examples over different scales
- Non-equilibrium at particle scale.
  "Material" made of "non-eq molecules"

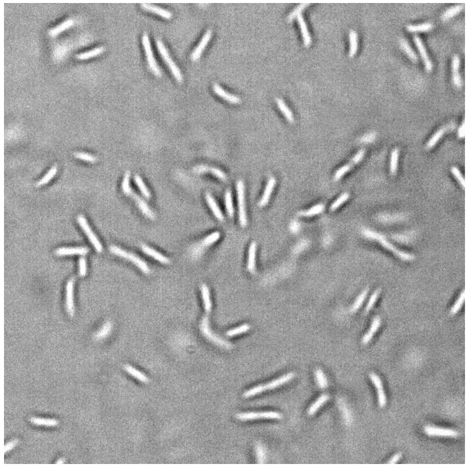


phases? equations? material properties?

To study & answer in "active matter physics" !

Phases of Active Matter...? — in the case of bacteria

Bacteria swimming randomly
(disordered, “gaseous”)



Bacillus subtilis

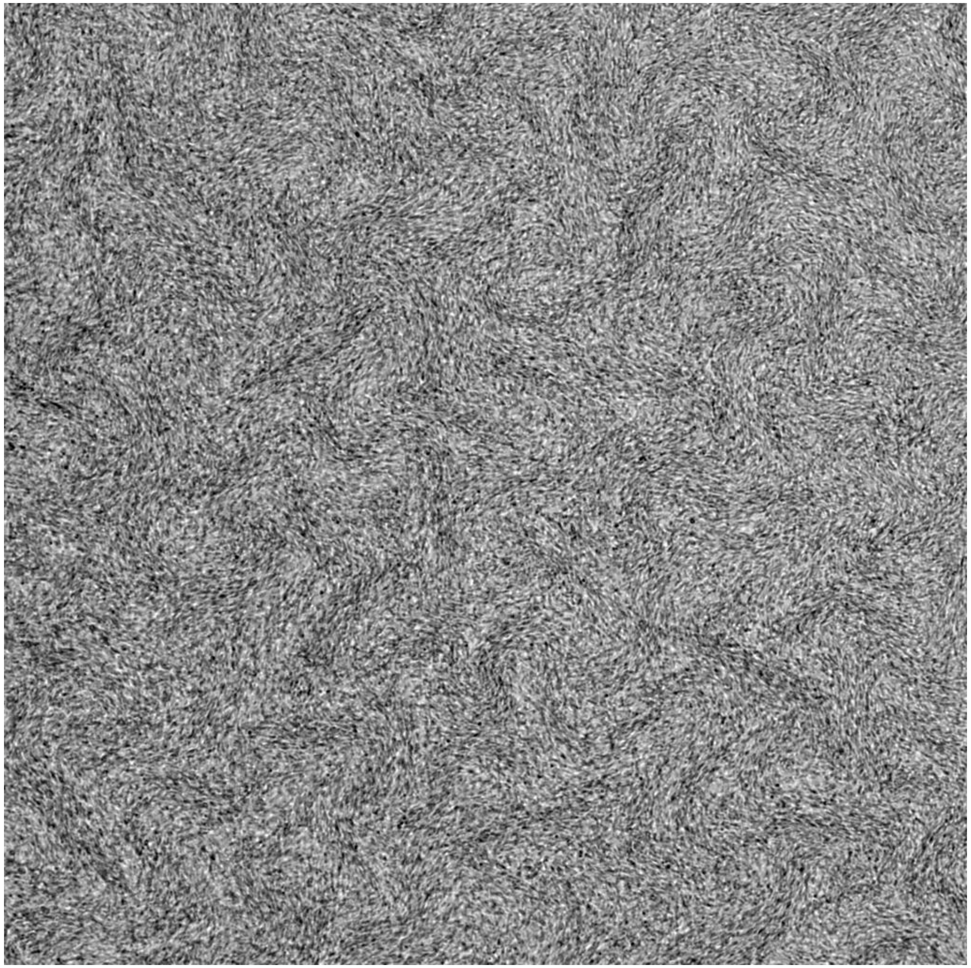
10 μm

[video credit:
D. Nishiguchi]

culturing

centrifuge

Became a “liquid” state
with strongly correlated motion



100 μm

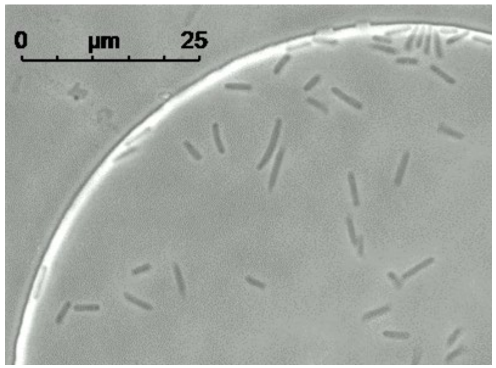
Bacterial Active Matter

Takeuchi Lab

[see our perspective at arXiv:2604.13575]

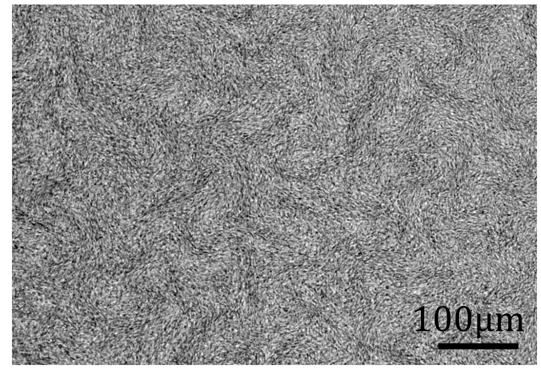
Various phases of active matter can be explored with bacteria!

active gas



[Shimaya, ..., Takeuchi, Comm Phys 2021]

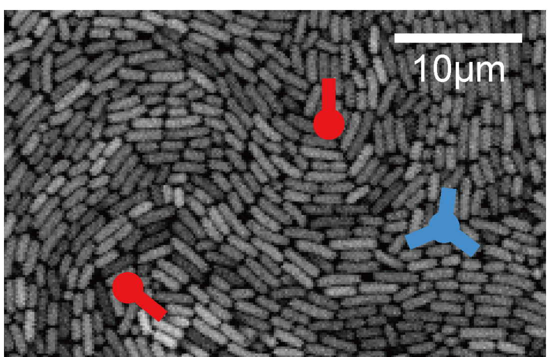
active liquid



[e.g., Nishiguchi, ..., PNAS 2025]

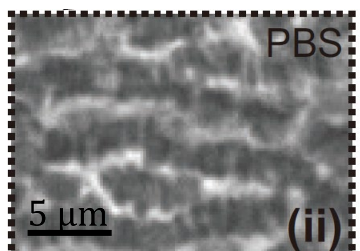
Let's focus.

active liquid crystal



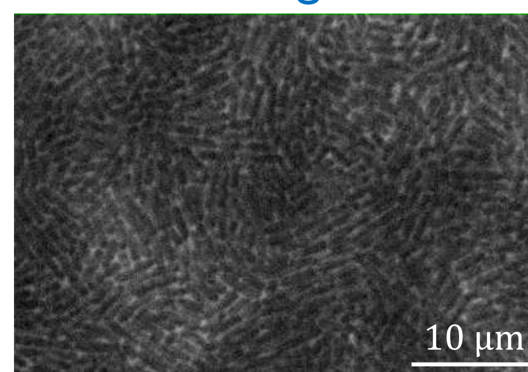
[Shimaya & Takeuchi, PNAS Nexus 2022]

even smectics!



[Shimaya, Yokoyama, Takeuchi, Soft Matter 2025]

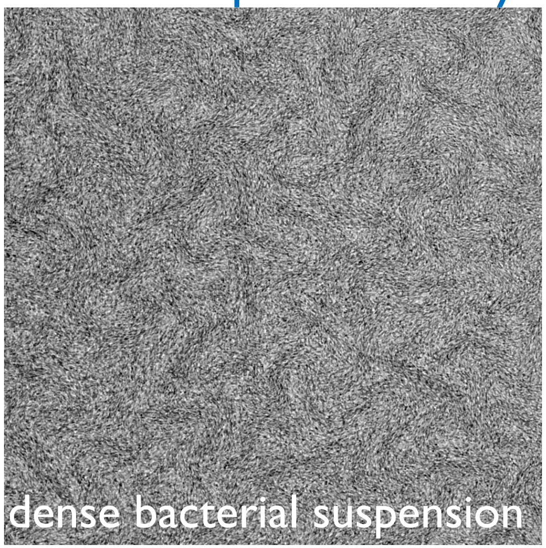
active glass



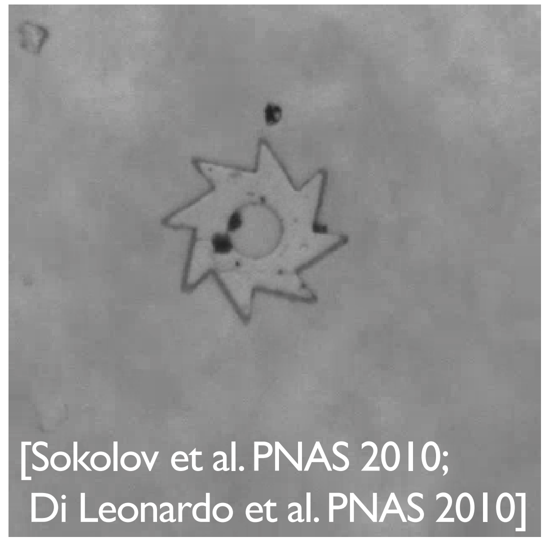
[Lama, ..., Takeuchi, PNAS Nexus 2024]

Some Features of Bacterial Active Liquid

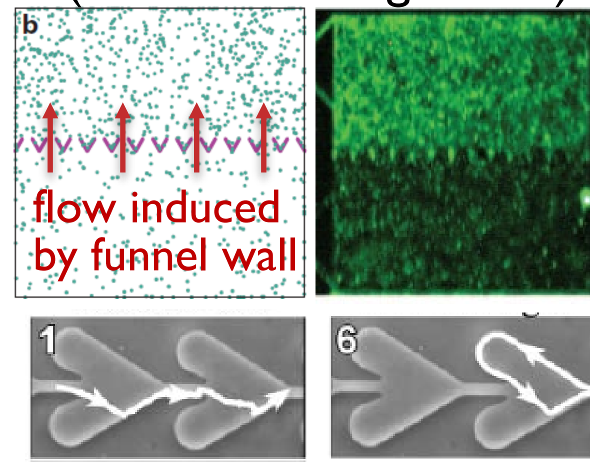
turbulence
formed spontaneously



turns a gear!



spontaneous rectification
(at least for single cells)



[Reichhardt 2017 (review);
Galajda et al. 2007; Hulme et al. 2008]

active fluid mechanics?
route to turbulence?
[cf., Nishiguchi et al., PNAS 2025]

intrinsically broken time-reversal symmetry allows
- work extraction
- unusual transport

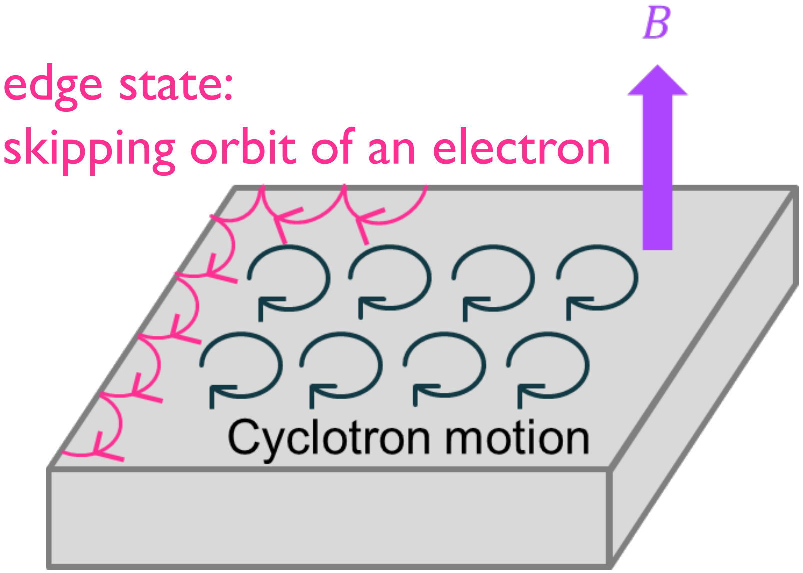
We can explore exotic phenomena
that would be thermodynamically forbidden for passive matter

Exotic Transport in Condensed Matter Physics

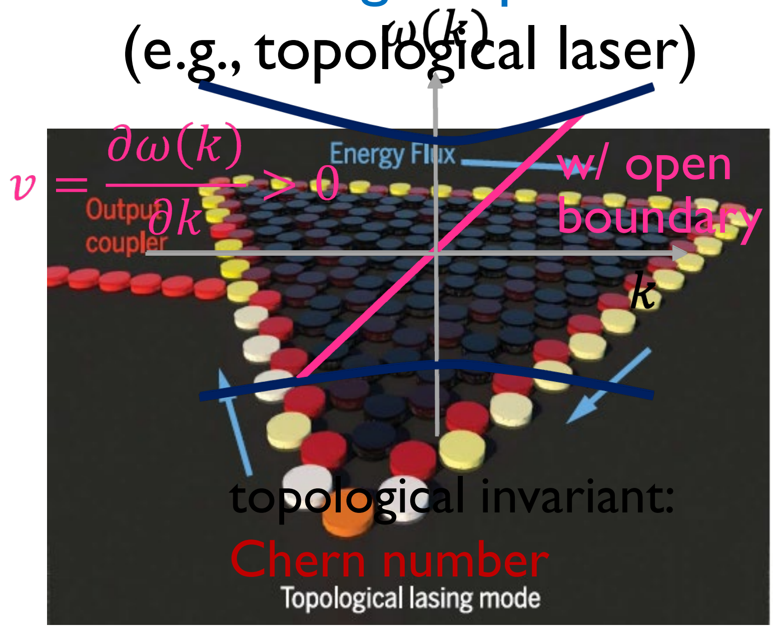
Topological transport

[cf; Huber & Neupert's lecture notes on Topological Condensed Matter Physics]

e.g.) quantum Hall effect



various analogous phenomena
(e.g., topological laser)



[Harari+ Science 2018 & Brandes+ Science 2018]

- Characterized by topology of bulk band structure.
- Nontrivial topology in bulk → edge states (non-vanishing Chern number)

Topological Active Matter?

REVIEWS
Nat. Rev. Phys. 2022
Check for updates

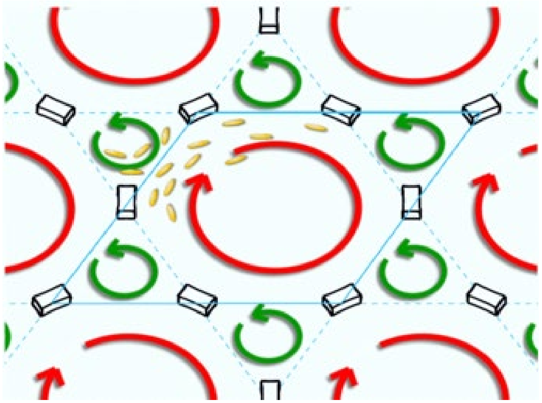
Topological active matter

Suraj Shankar[1], Anton Souslov[2], Mark J. Bowick[3], M. Cristina Marchetti[4] and Vincenzo Vitelli[5,6,7]

theoretical proposals

experiments

by spatial design
(e.g., kagome network)

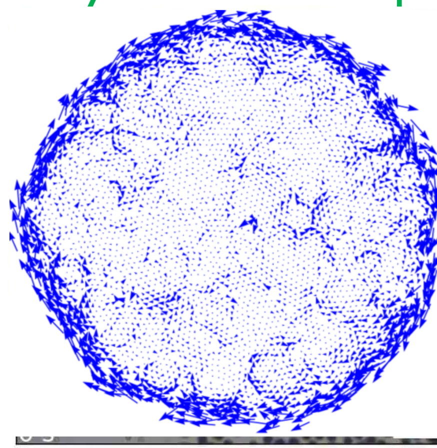


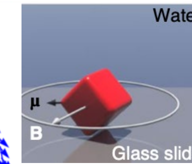
[Sone & Ashida, PRL 2019]

by chiral active particles

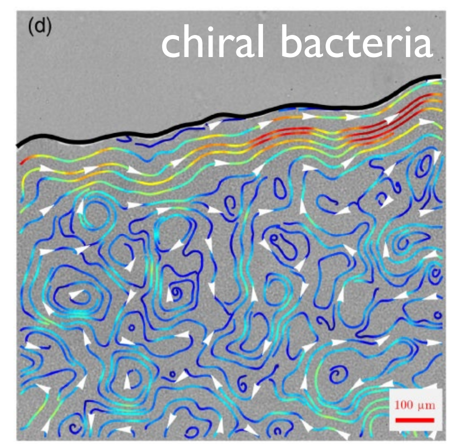
[Souslov et al., PRL 2019]

by chiral active particles





Soni et al., Nat. Phys. 2019



Li et al., PRX 2024

no experiment so far

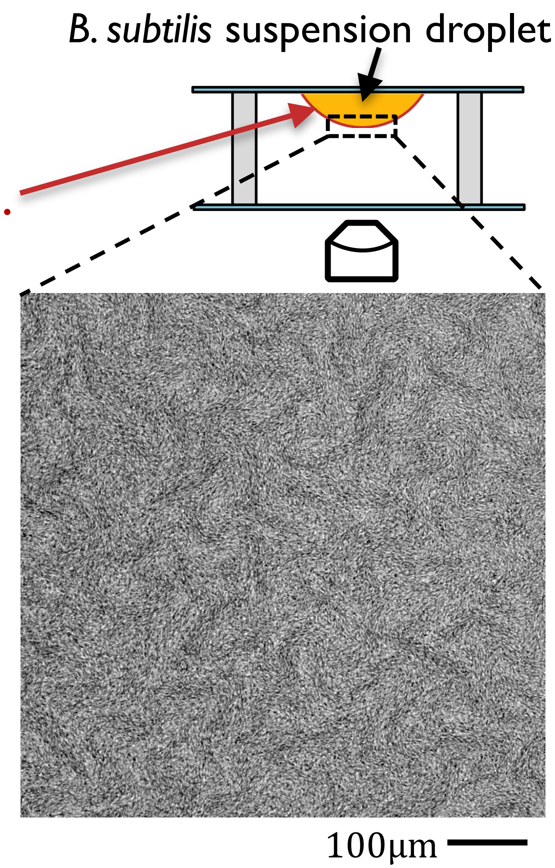
some advantages
- no need of chiral particles
- topology controlled by geometry design

Let’s try with bacterial active matter!

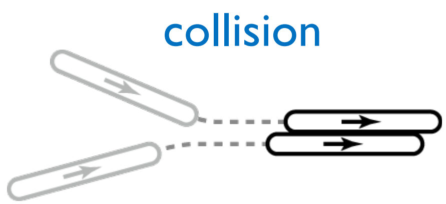
Our System: Dense Bacterial Suspension

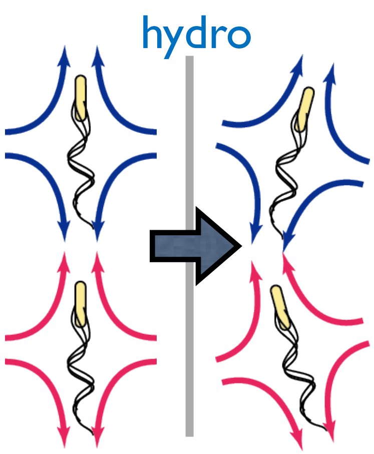
[review: Aranson, Rep. Prog. Phys. 2022]

- Common setup:
  inverted suspension droplet
  - *B. subtilis* cells tend to be near air-liquid interface.



- Turbulence formed spontaneously there
  - Driving mechanism:
    Collisions ➜ alignment at short distances
    Hydro interaction ➜ instabilities at long distances



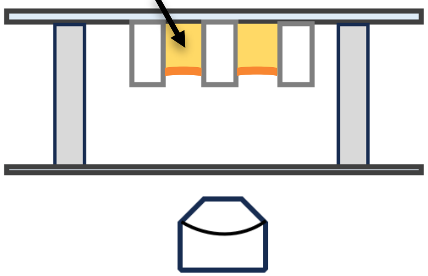


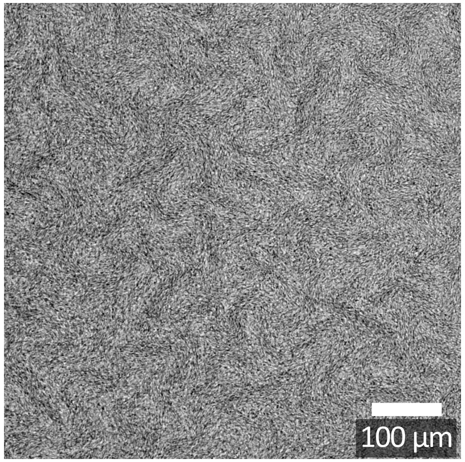
  - Characteristic length
    = vortex size (~ 70 µm)

➜ We can design flow pattern
by device's geometric structures

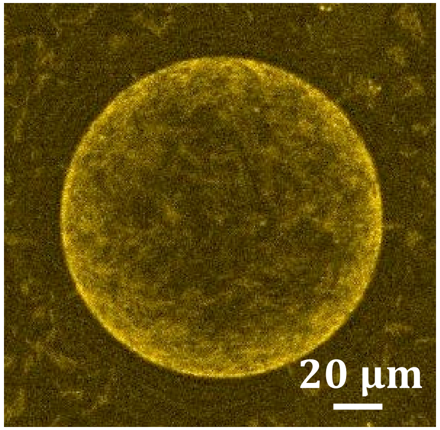
[e.g., Wioland+ PRL 2013, Nishiguchi+ Nat Comm 2018, Nishiguchi...Takeuchi... PNAS 2025]

Dense Bacterial Suspension + Geometric Confinement



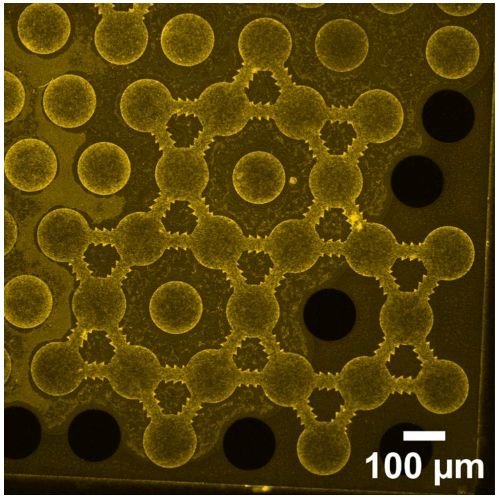


circular well

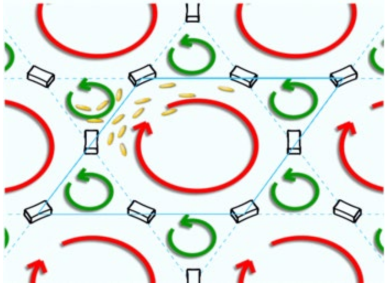


e.g., Nishiguchi et al., PNAS 2025

kagome network with directional channels

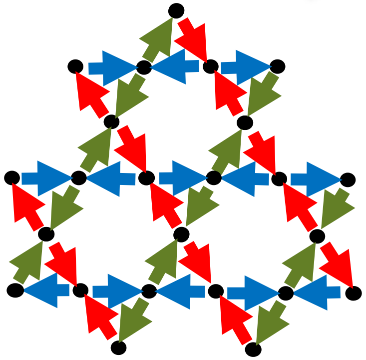


theory



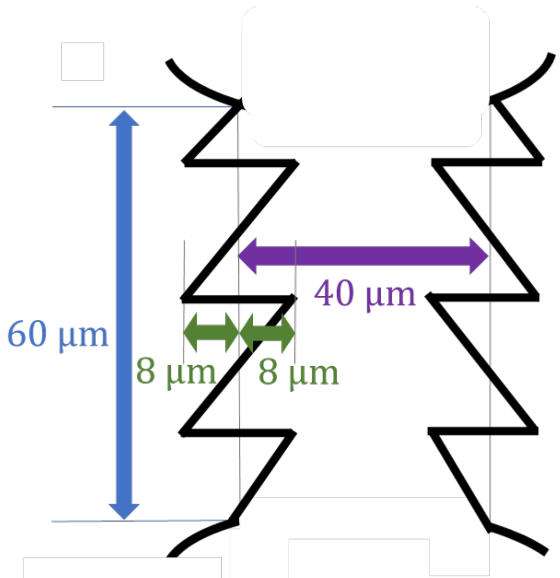
Sone & Ashida, PRL 2019

≈



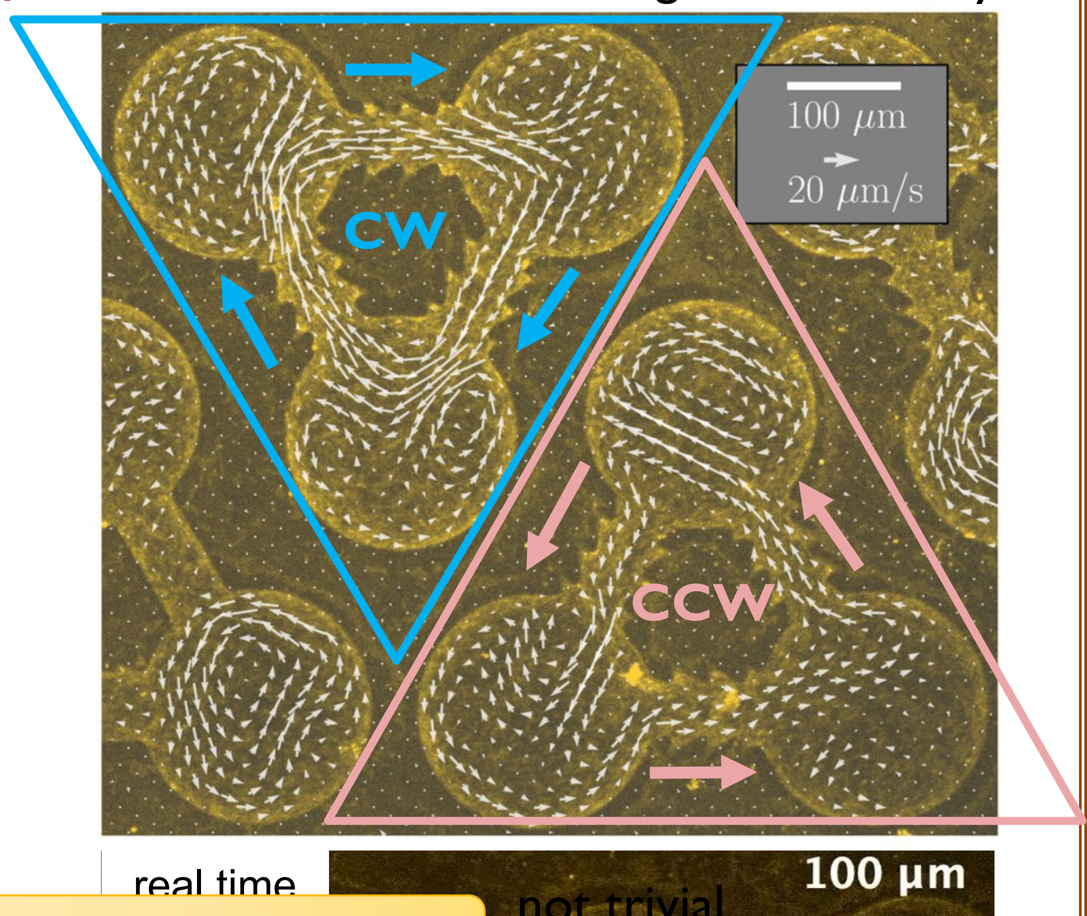
How to Generate Directional Flow?

An answer: ratchet-shaped channels



※ not to scale

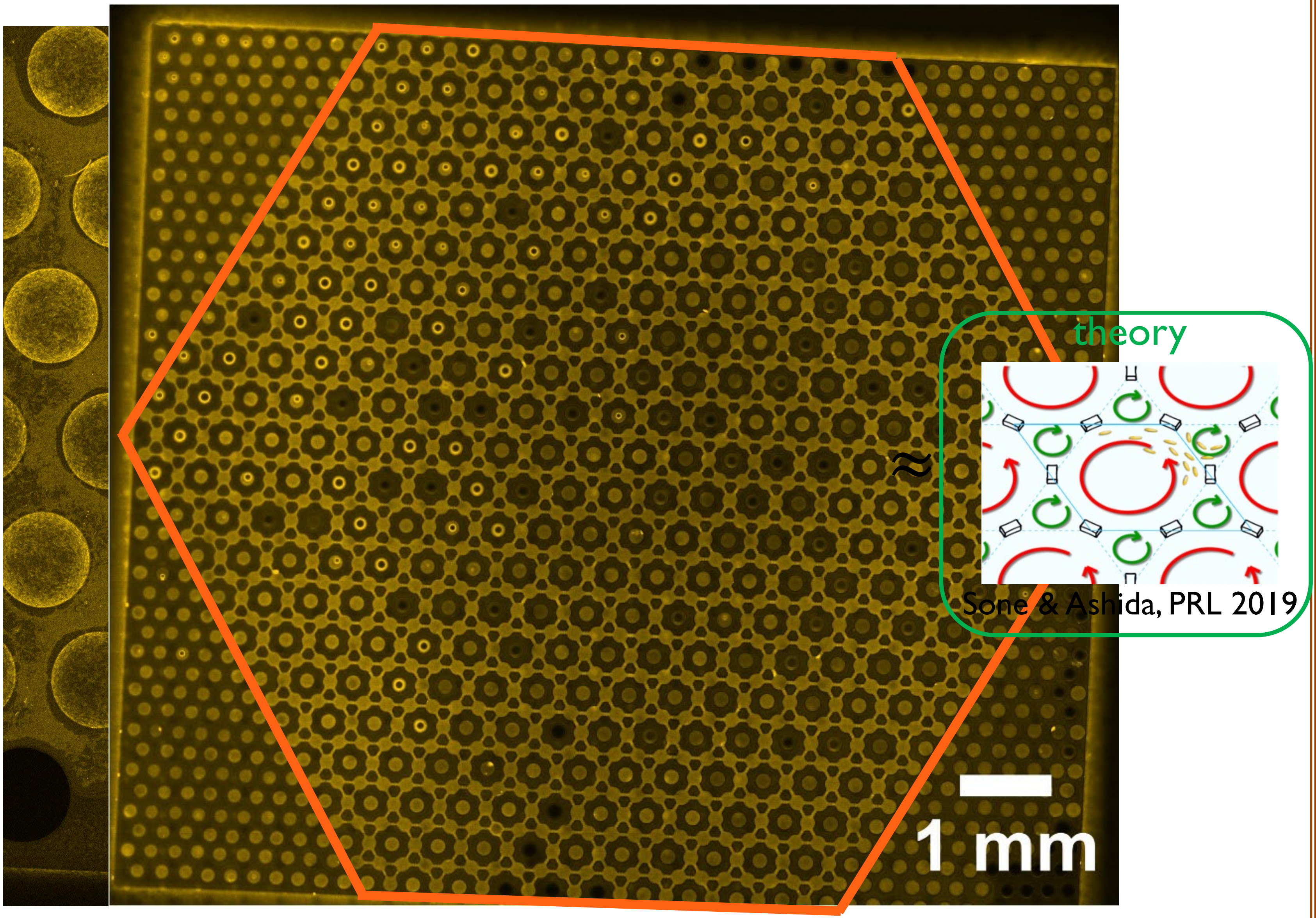
time-averaged PIV velocity



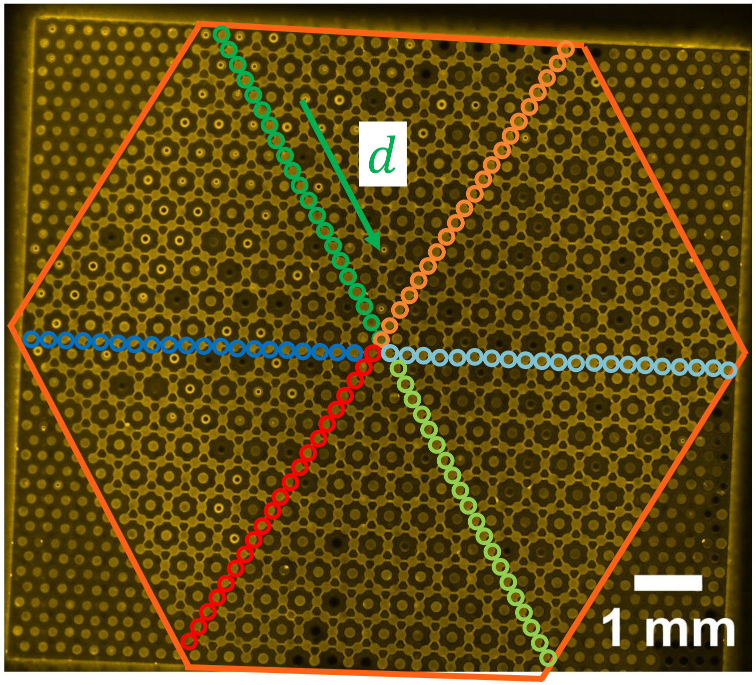
Ratchet channels rectify bacterial flow!

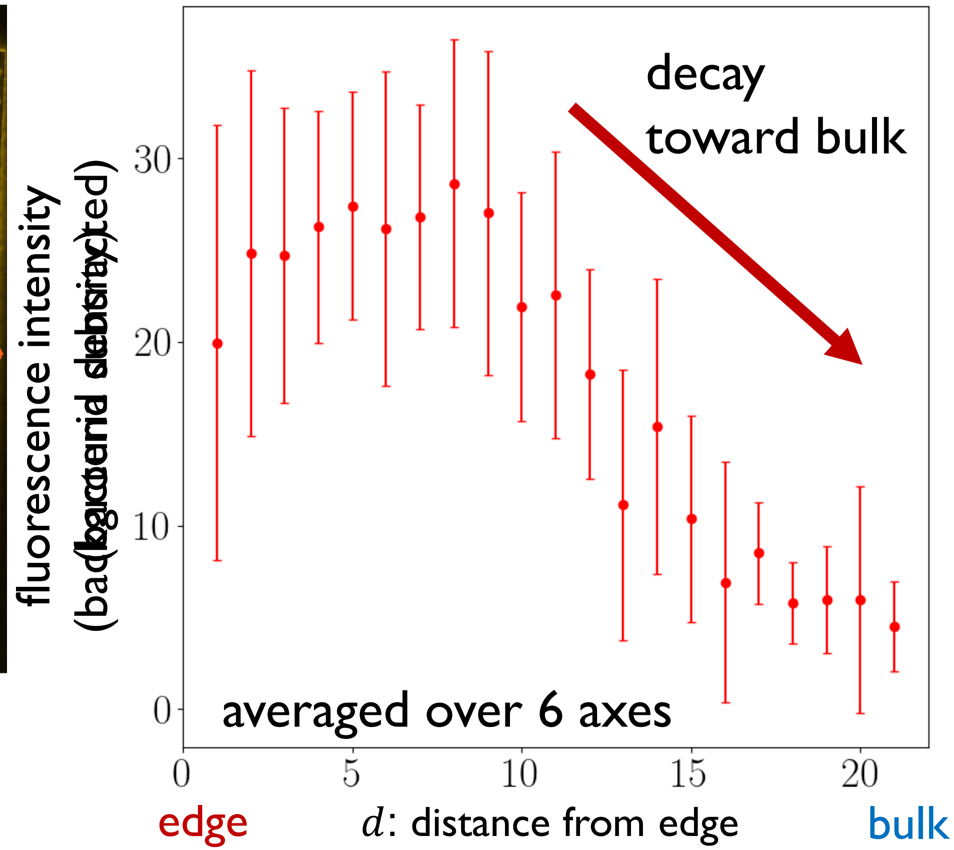
Ref.) Uchida, Nishiguchi, Takeuchi, arXiv:2601.08243

Kagome Network with Directional Channels



Kagome Network with Directional Channels





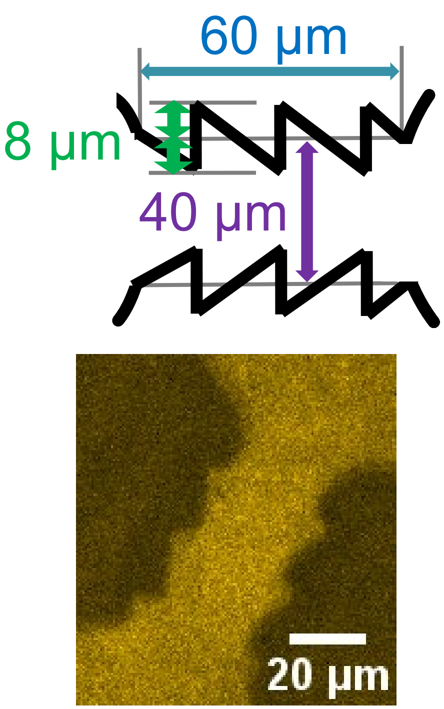
Bacteria tend to localize near the edge!

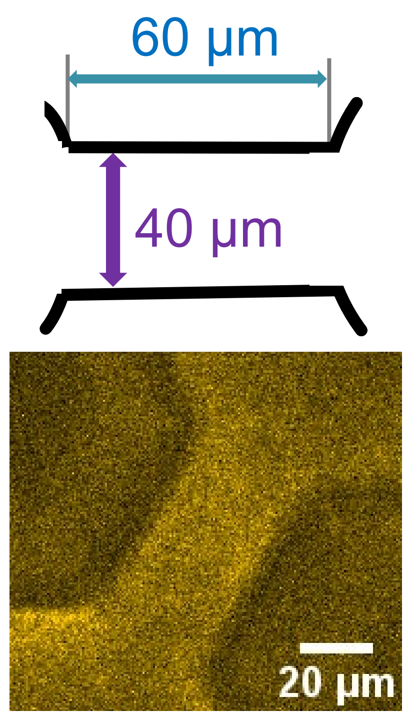
Is Network Structure Related?

We compare kagome networks with

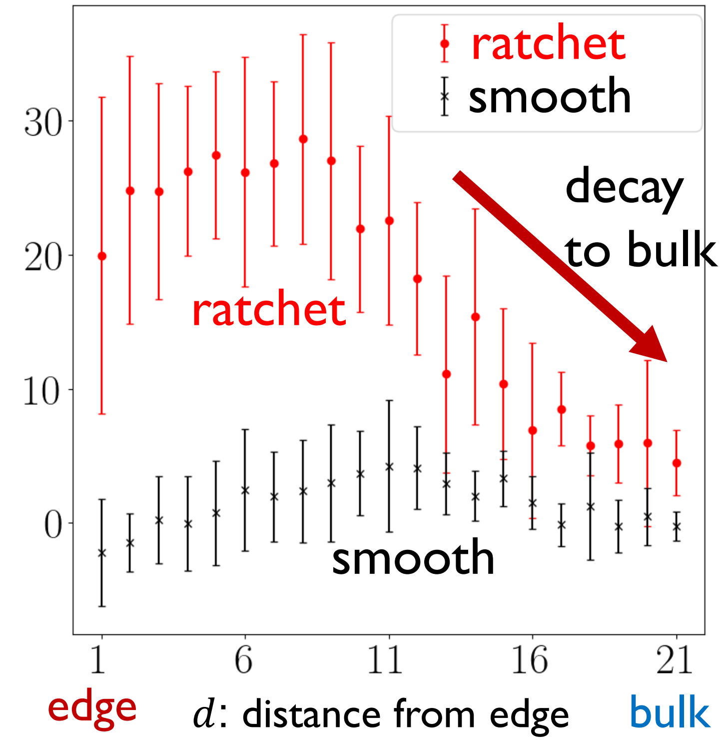
ratchet channels (directional)

smooth channels (non-directional)



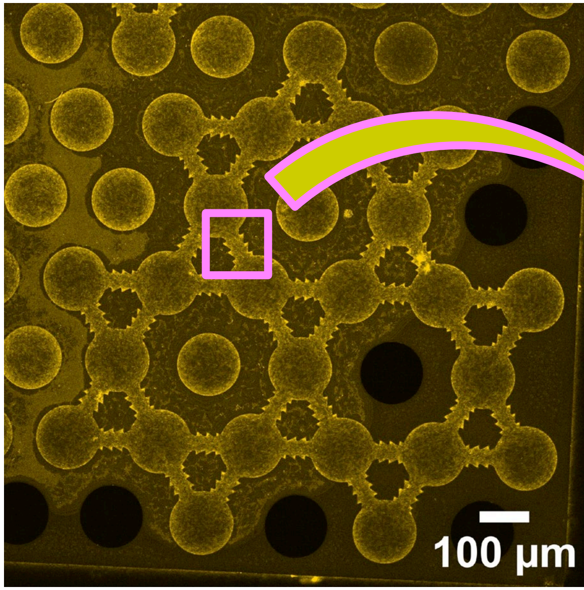


fluorescence intensity
(bacteria density)
(background subtracted)

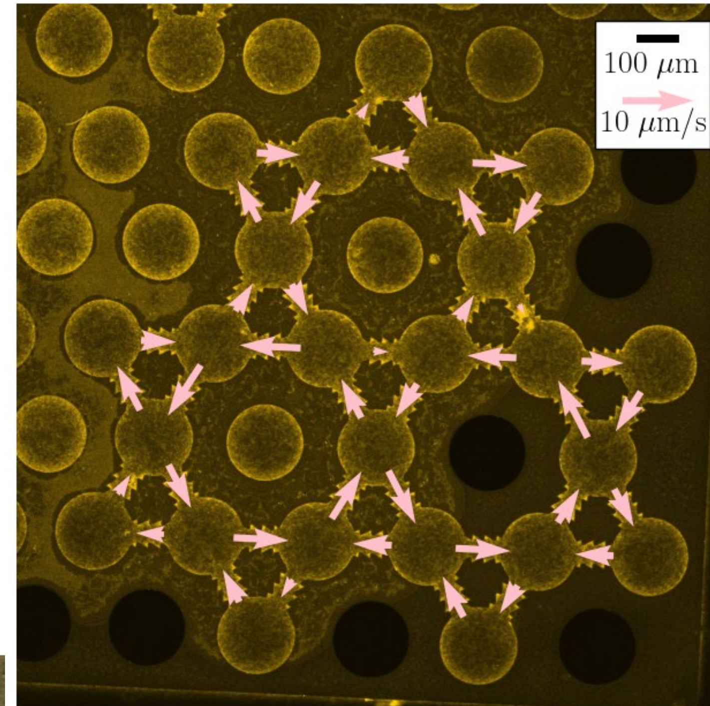


Edge localization for ratchet channels only!

Is There Edge Flow too?

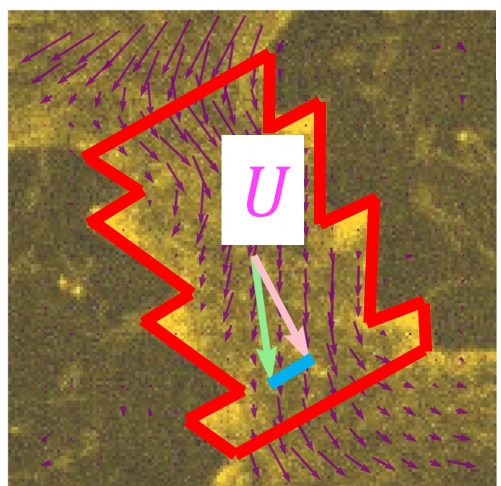


flow structure obtained!

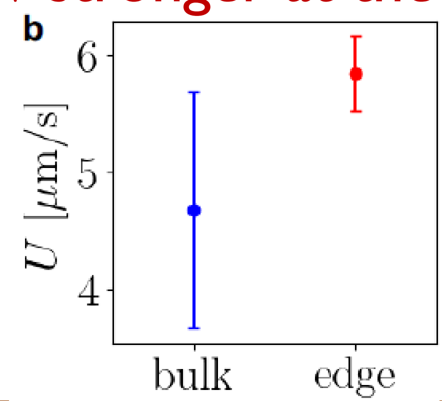


channel flow *U*

PIV velocity
↓ time-averaged
purple arrows
↓ space-averaged
green arrow
↓ projected
channel flow *U*



flow stronger at the edge

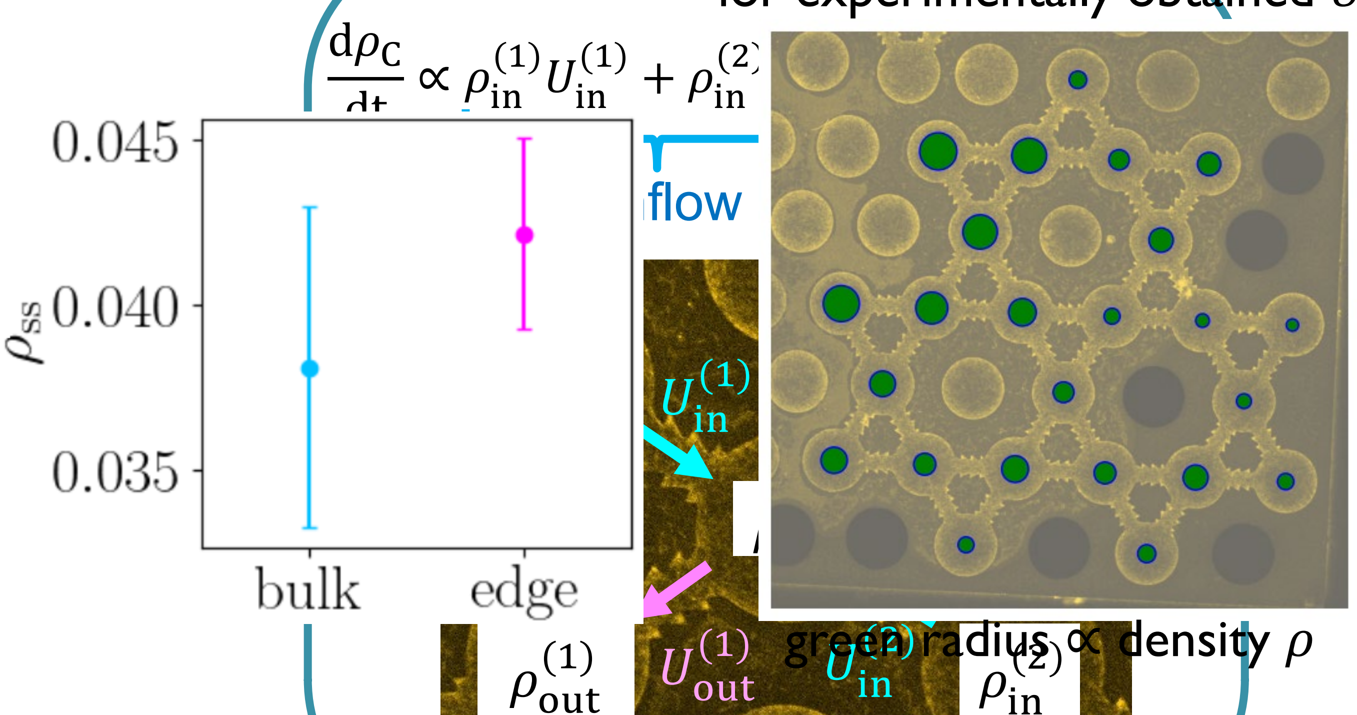


How are Flow & Edge Localization Related?

Let's assume $$\frac{\partial \rho_I}{\partial t} = \sum_{J \in \mathrm{in}} \rho_J U_{J \to I} - \sum_{J \in \mathrm{out}} \rho_I U_{I \to J}$$ (I, J: wells)

steady state

for experimentally obtained U's



green radius ∝ density ρ

Observed flow seems to favor edge localization.

Is Topology Related? ➜ Let's do Modelling!

- Same time-evolution rule:

$$\frac{\partial \rho_I}{\partial t} = \sum_{J \in \mathrm{in}} \rho_J U_{J \to I} - \sum_{J \in \mathrm{out}} \rho_I U_{I \to J}$$

- Now we assume:

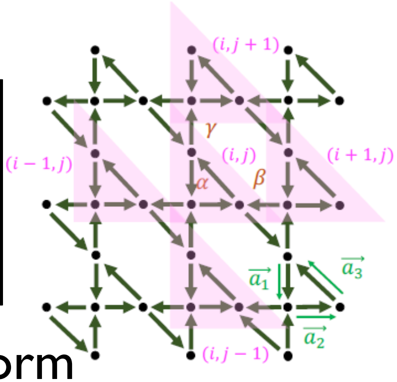
$$U_{I \to J}(t) = U_0 + c\left(\frac{\rho_I(t) + \rho_J(t)}{2} - \rho_0\right)$$

- For kagome network…

$$\frac{\partial \rho_{(i,j)\alpha}}{\partial t} = -\rho_{(i,j)\alpha}\left(U_{(i,j)\alpha\to(i,j)\beta} + U_{(i,j)\alpha\to(i-1,j)\beta}\right) + \rho_{(i,j)\gamma}U_{(i,j)\gamma\to(i,j)\alpha} + \rho_{(i,j-1)\gamma}U_{(i,j-1)\gamma\to(i,j)\alpha}$$

$$\frac{\partial \rho_{(i,j)\beta}}{\partial t} = -\rho_{(i,j)\beta}\left(U_{(i,j)\beta\to(i,j)\gamma} + U_{(i,j)\beta\to(i+1,j-1)\gamma}\right) + \rho_{(i,j)\alpha}U_{(i,j)\alpha\to(i,j)\beta} + \rho_{(i+1,j)\alpha}U_{(i+1,j)\alpha\to(i,j)\beta}$$

$$\frac{\partial \rho_{(i,j)\gamma}}{\partial t} = -\rho_{(i,j)\gamma}\left(U_{(i,j)\gamma\to(i,j)\alpha} + U_{(i,j)\gamma\to(i,j+1)\alpha}\right) + \rho_{(i,j)\beta}U_{(i,j)\beta\to(i,j)\gamma} + \rho_{(i-1,j+1)\beta}U_{(i-1,j+1)\beta\to(i,j)\gamma}$$



⇩ linearization $\rho_I(t) = \rho_0 + \delta\rho_I(t)$ & Fourier transform

$$\frac{\partial}{\partial t}\boldsymbol{\delta\rho}(\boldsymbol{k}) = -\mathrm{i}\mathcal{H}(\boldsymbol{k})\boldsymbol{\delta\rho}(\boldsymbol{k})$$

Schrödinger-like equation
(non-Hermitian)

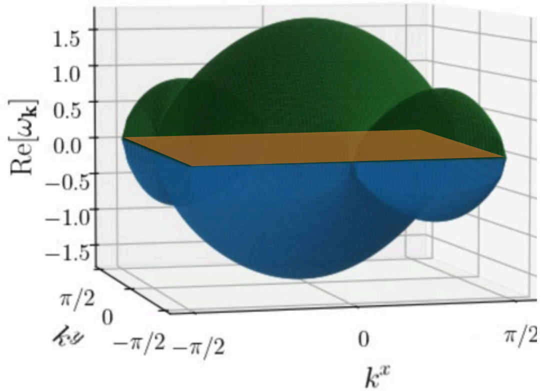
Band structure (dispersion relation)
& its topology can be analyzed!

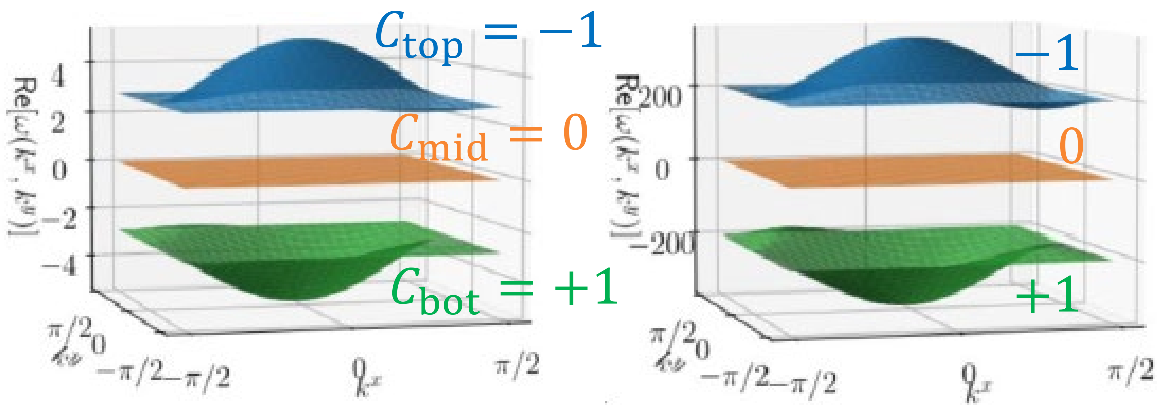
Band Topology

$$U_{I\to J}(t) = U_0 + c\left(\frac{\rho_I(t)+\rho_J(t)}{2} - \rho_0\right)$$

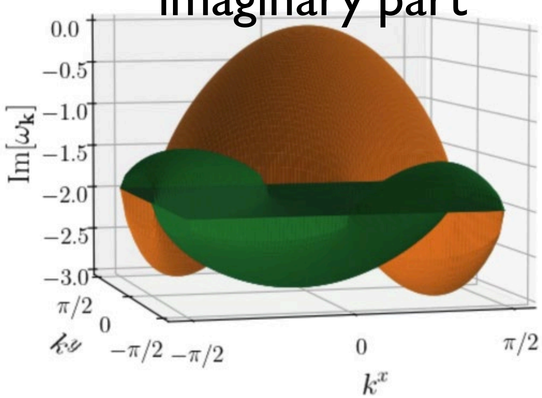
(periodic boundary condition)

real part





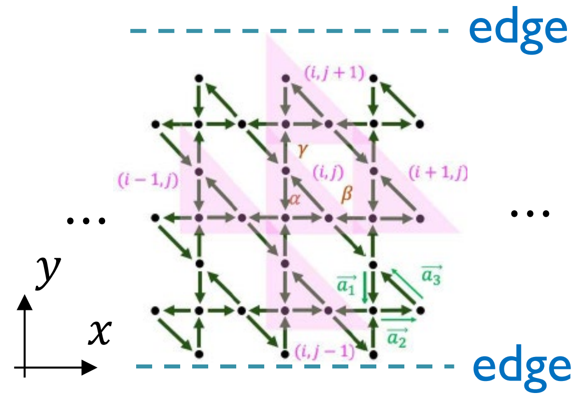
imaginary part



- $c = 0$: gapless, $\mathrm{Im}[\omega] \le 0$ (=0 only for uniform $\delta\rho$)
- $c > 0$: $\mathrm{Re}[\omega]$ gapped, $\mathrm{Im}[\omega] \le 0$
- Top & bottom bands have nonvanishing Chern numbers (∴ nontrivial topology!)

NB) Chern number $C_n = \frac{1}{2\pi \mathrm{i}} \int d^2\boldsymbol{k}\, \nabla_{\boldsymbol{k}} \times \langle u_n(\boldsymbol{k}) | \nabla_{\boldsymbol{k}} u_n(\boldsymbol{k}) \rangle$

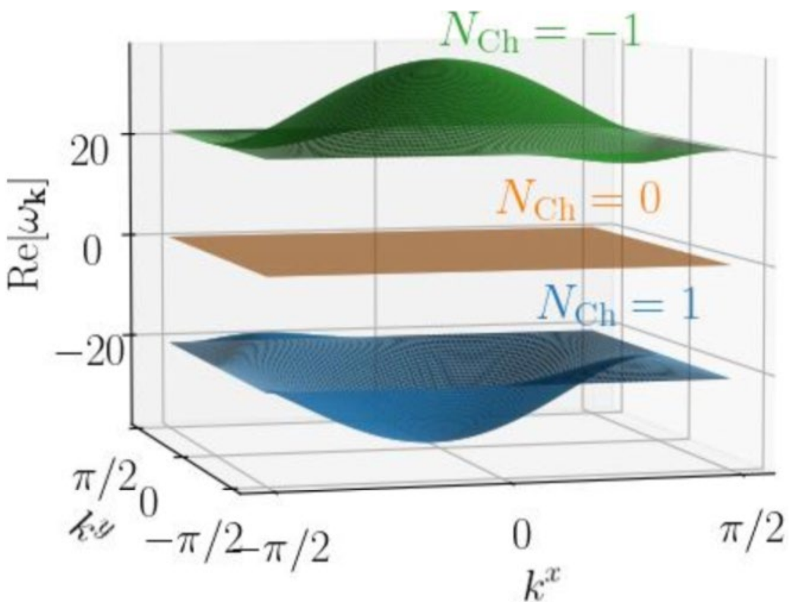
Relation to Edge State



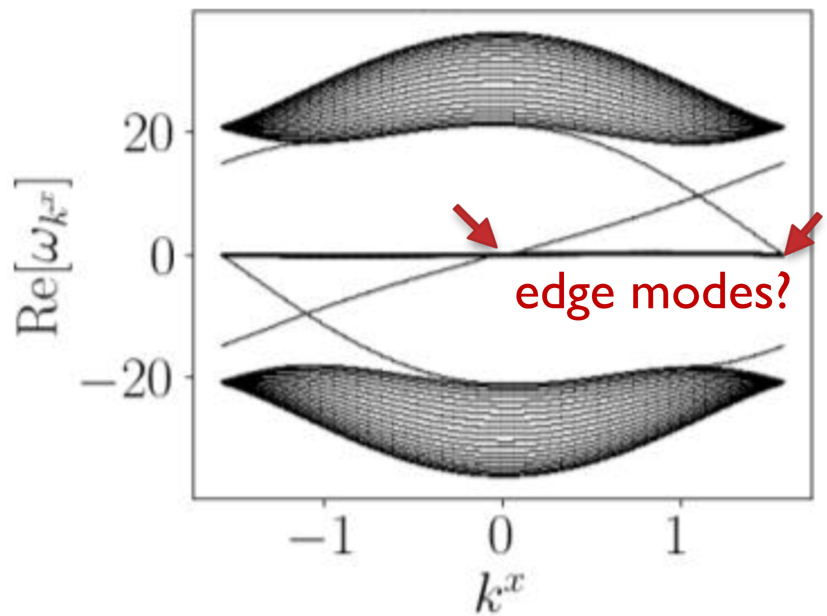
Let's introduce an edge

fully periodic boundary

open boundary (edge) in *y*

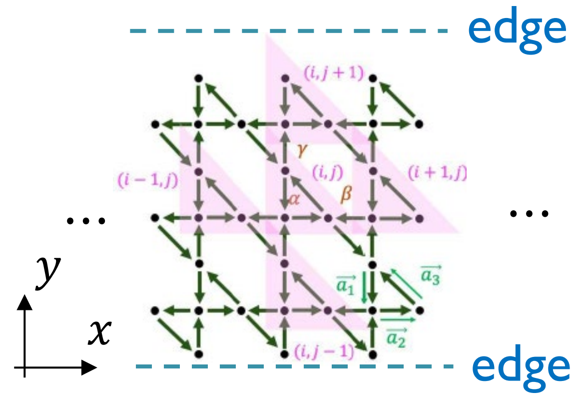


$\left(\frac{\rho_0}{2U_0}c = 10\right)$

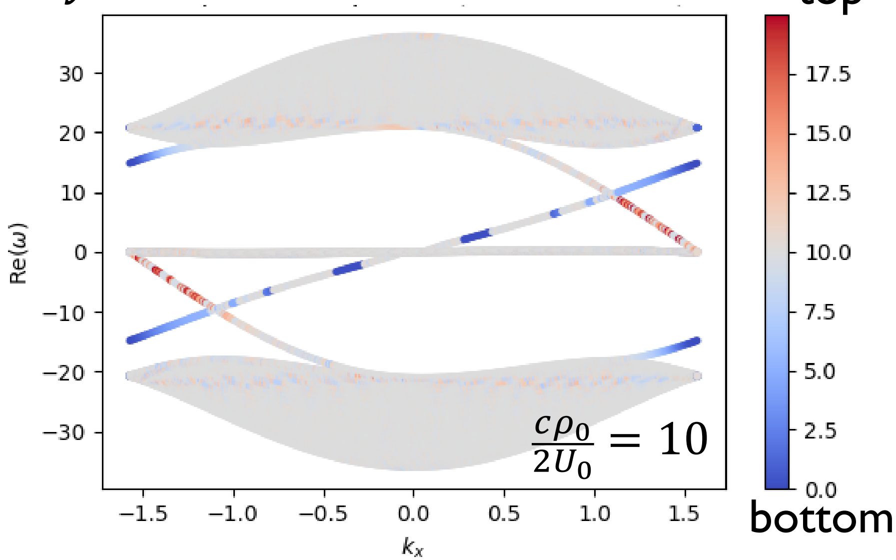


Topological edge-like modes emerge for $c > 0$!

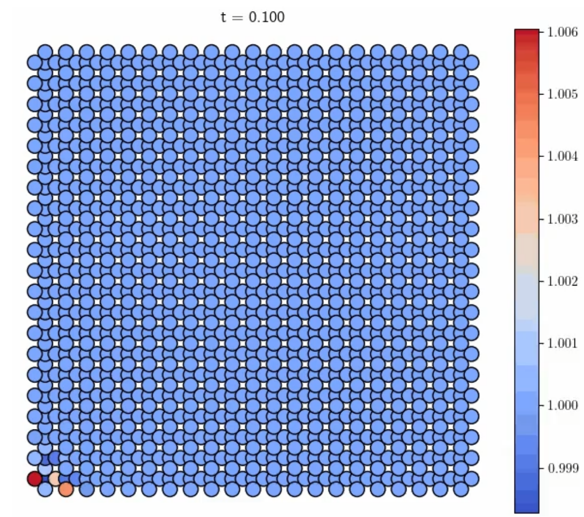
Are These Edge Modes?



y-coordinate of "center of mass"



simulations w/ fully open boundary

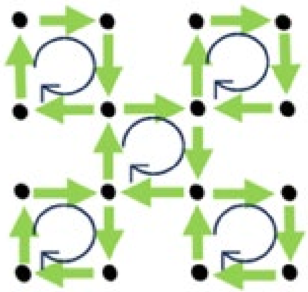


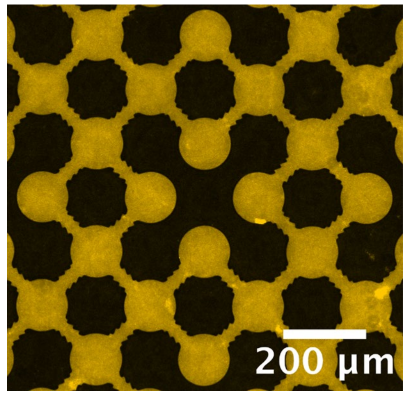
- Crossing modes turned out to be edge modes (edge-localized)
- Edge-localized initial state
  → edge transport at the velocity consistent with band slope.

Confirmation of topological edge modes!

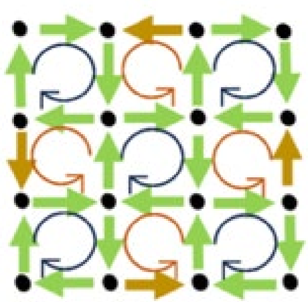
Controlling the Emergence of Topological Modes

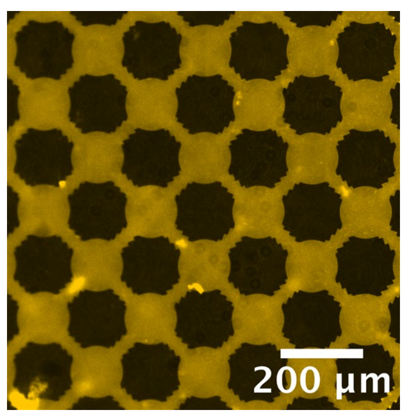
chiral square network



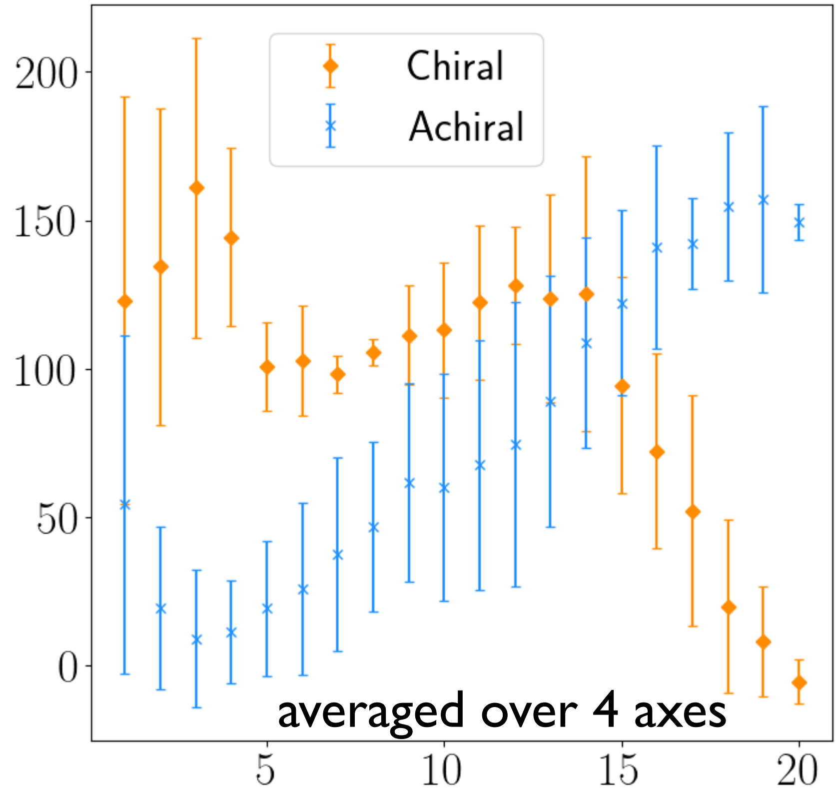


achiral square network





fluorescence intensity
(bacteria density)



d: distance from edge

Edge localization for
the chiral network only!

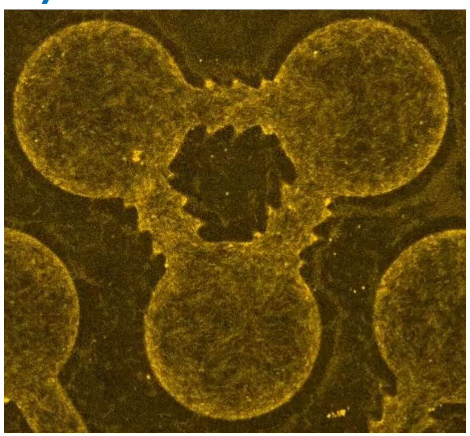
Summary

Reference

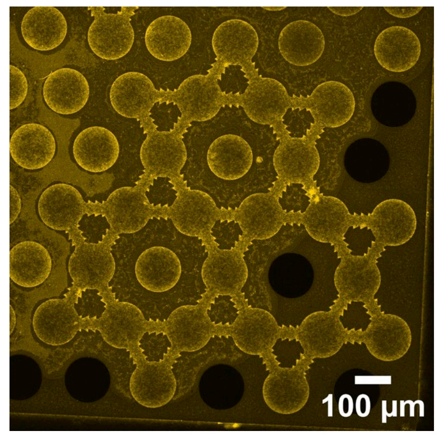
Uchida, Nishiguchi, Takeuchi, arXiv:2601.08243

We realized geometry-induced (hence tunable) topological edge states in bacterial active matter!

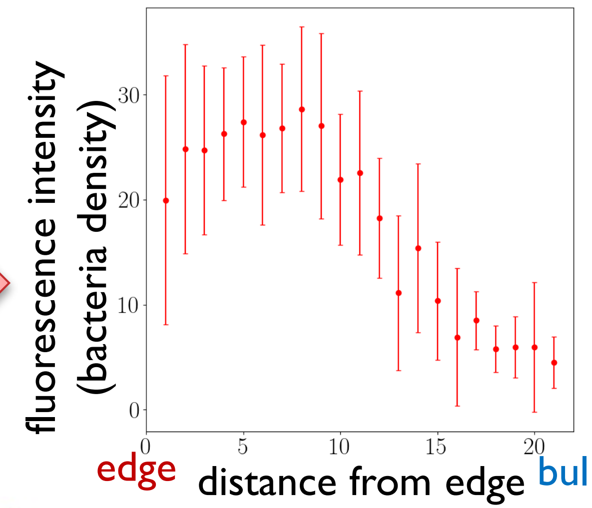
rectified bacterial flow by ratchet channels



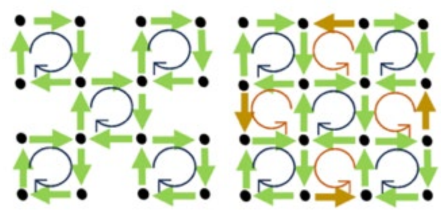
nontrivial topology of kagome network

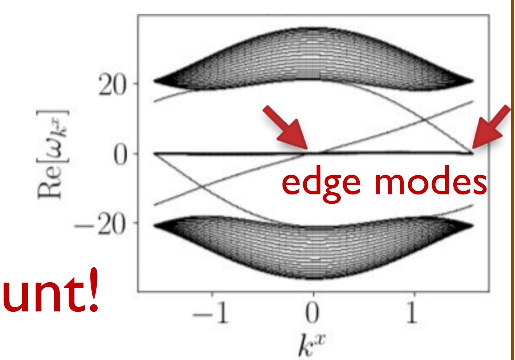


edge localization!



- We can switch the emergence of edge states!





- Linear theory tells nontrivial topology behind but nonlinear topology is needed for full account!