Bacterial collective swarming and navigation

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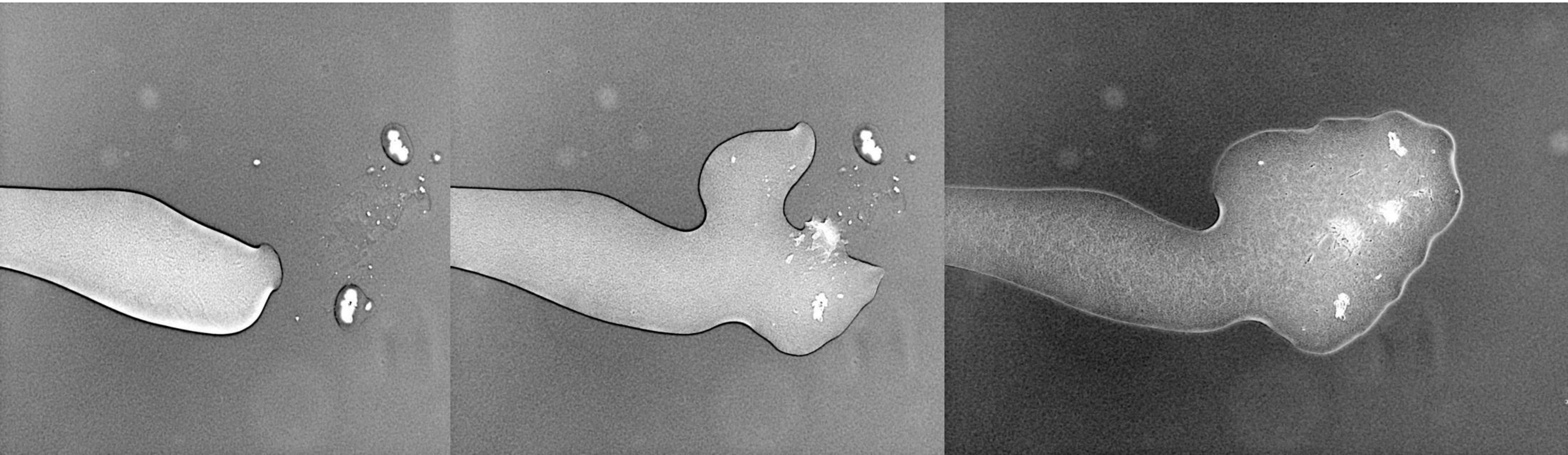
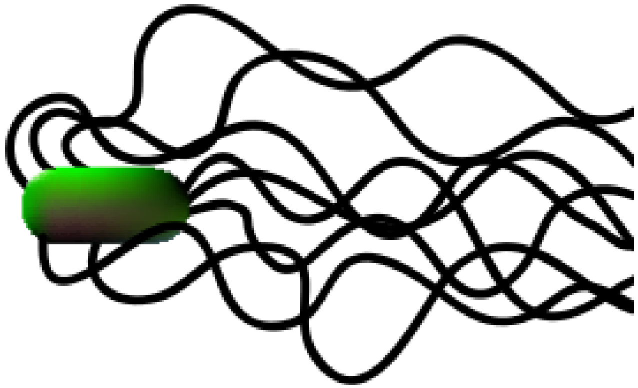


What is swarming of bacteria

[Kearns '10]



A mode of motion

- Movement using flagella – mechanical motors.
- High density
- Above surfaces
- Extracellular matrix - hydration layer, surfactants.
- Approximately 2D

Swarming of *P. dendritiformis* by Avraham Be'er – Ben Gurion U

movie with flow

Swarming as a selfish herd

Individuals benefit by being part of a group but otherwise compete

- Minimally cooperation - decide whether to swarm, quorum sensing, assessment of surfaces and nutrients
- Competition on location - occupy the colony periphery. Uncoordinated expansion.

[Darnton et al 10; Wu and Berg ’12; Kearns ‘10…]

Requires communication

Swarming as a selfish herd

The dynamics inside a swarm

- Rapid mixing of cells
- Many length scales
- Chemotaxis – run and tumble

[Chen et al ‘12; Sokolov et al ’07; Zhang et al ‘12]

Swarming in coherent groups

Swarming of *P. vortex* – single branch

streams with flow

Swarming in coherent groups

Swarming of *P. vortex*

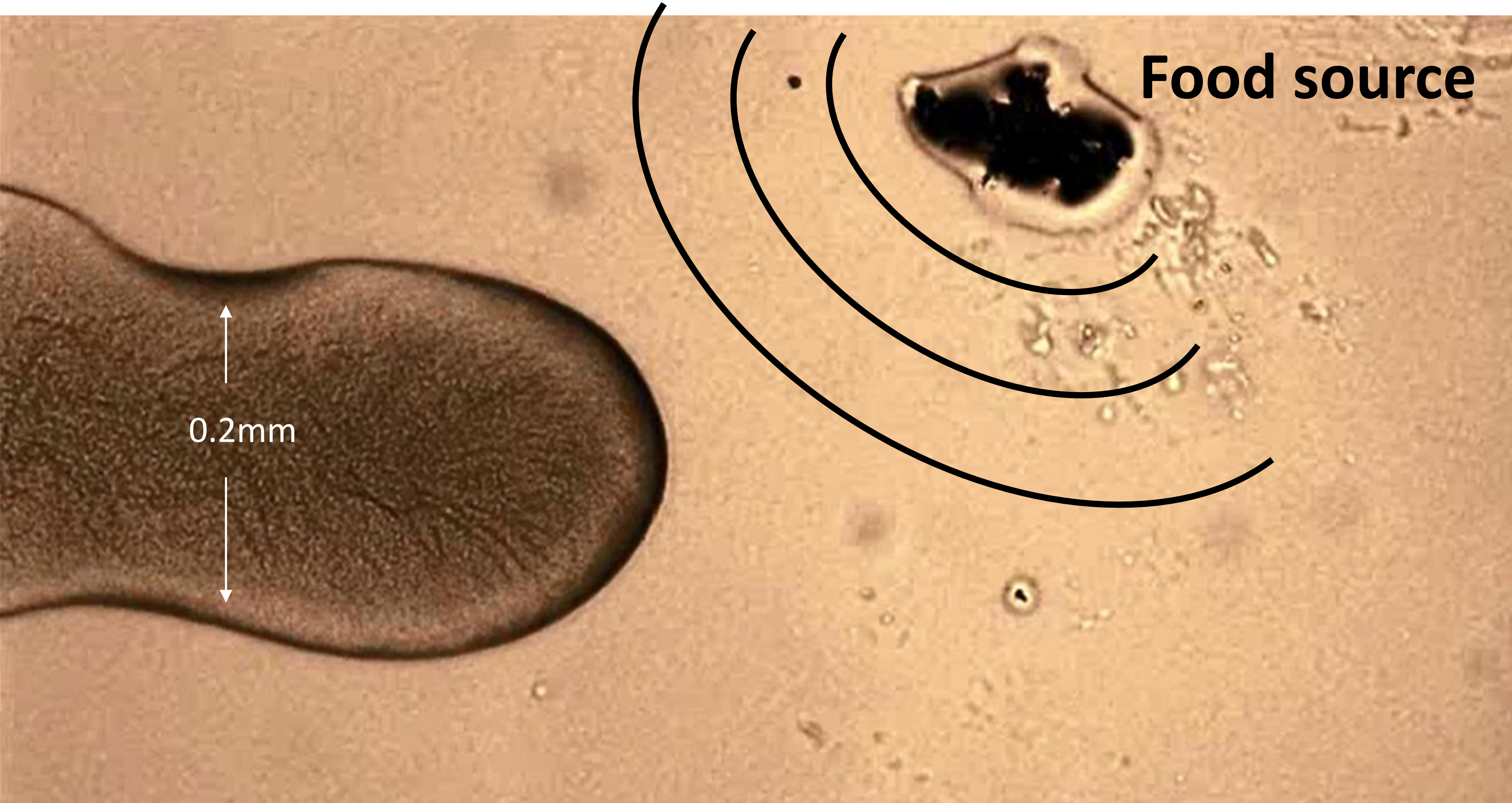
Challenges the classical view of swarming

- Movement in organized groups
- Stable streams and vortices – traffic lanes
- Collective maneuvers
- Cooperation instead of competition
- Sharing of resources

[Ingham and Ben-Jacob '08; Ingham et al '11]

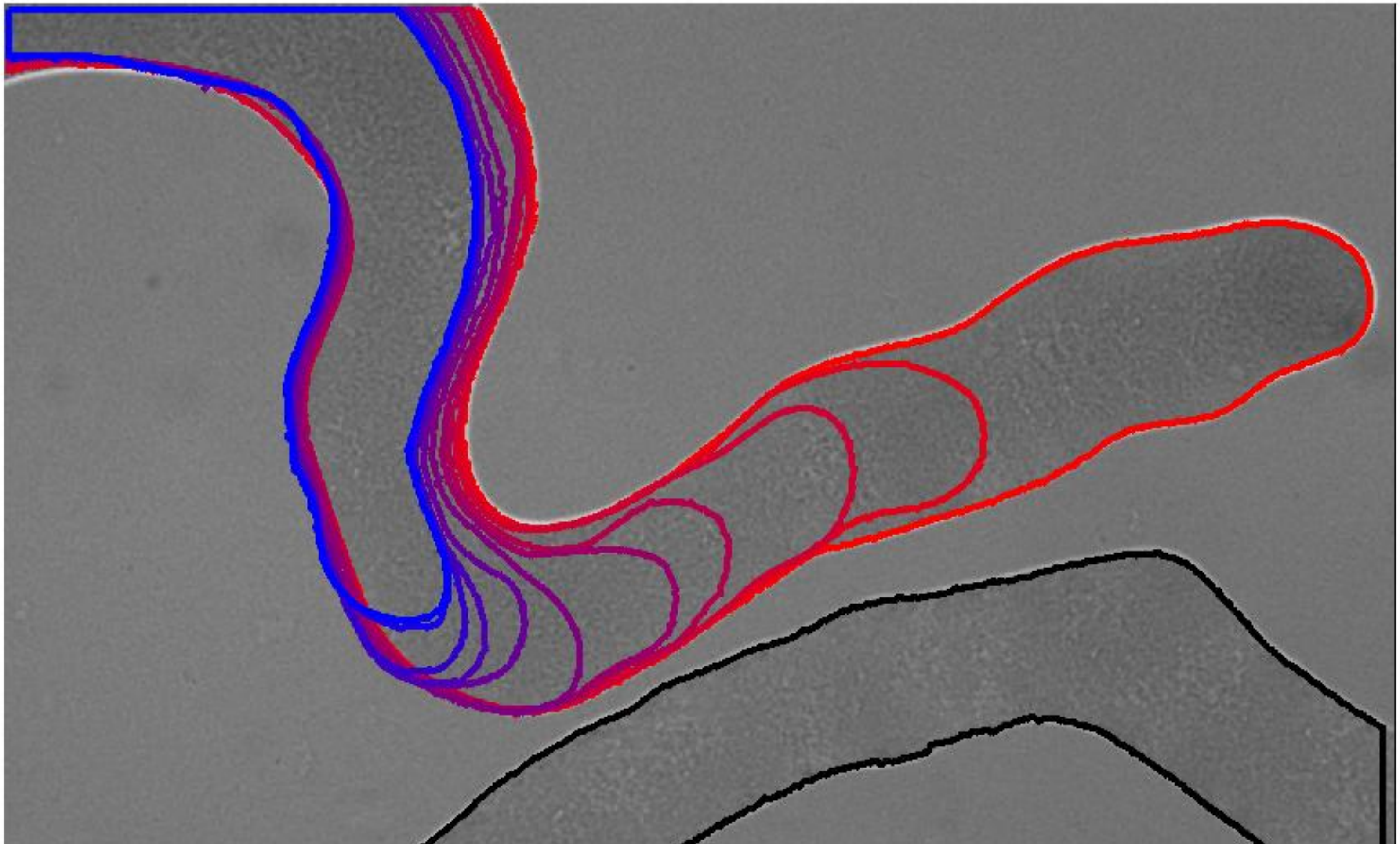
Collective navigation

Navigation toward a source [1source] [2sources]



Collective navigation

Collision avoidance movie

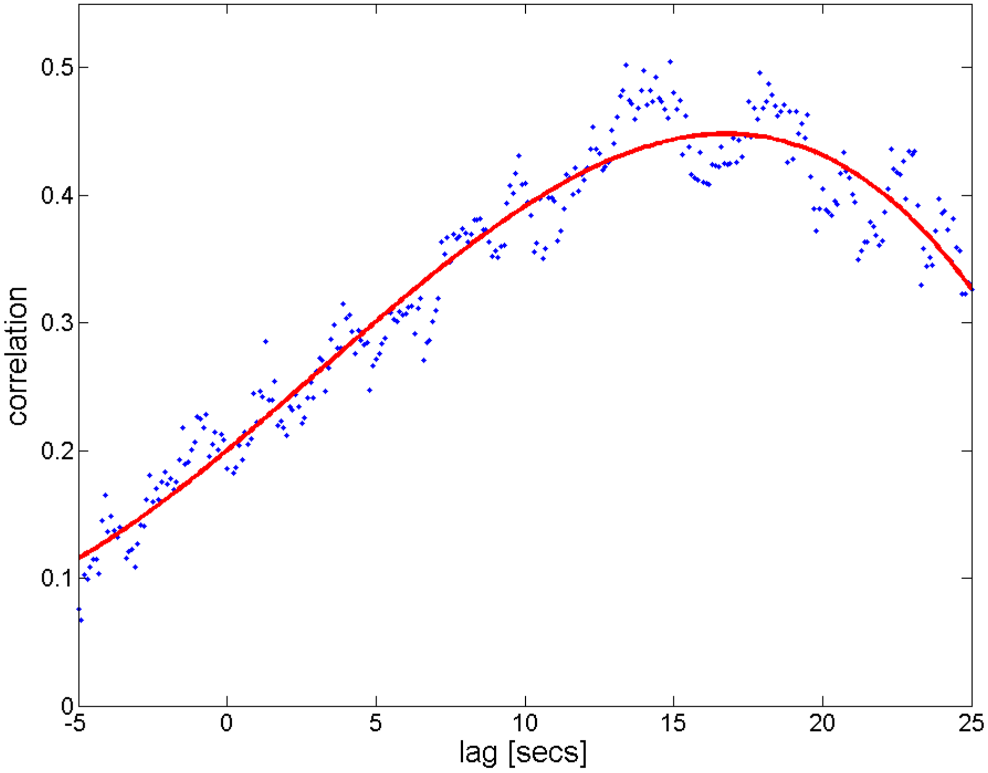


Swarming in coherent groups

Collective navigation

Optical flow analysis:

The turning point predicts direction



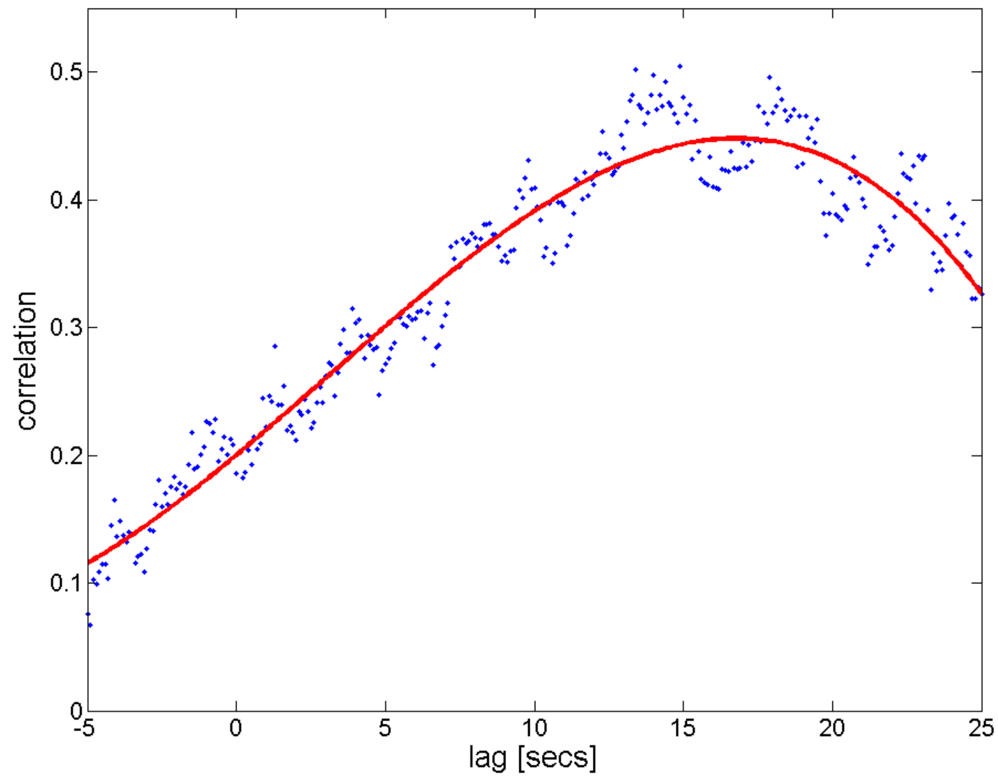
Swarming in coherent groups

Collective navigation

Optical flow analysis:

The turning point predicts direction

Bacteria use the internal organization to navigate the tip.



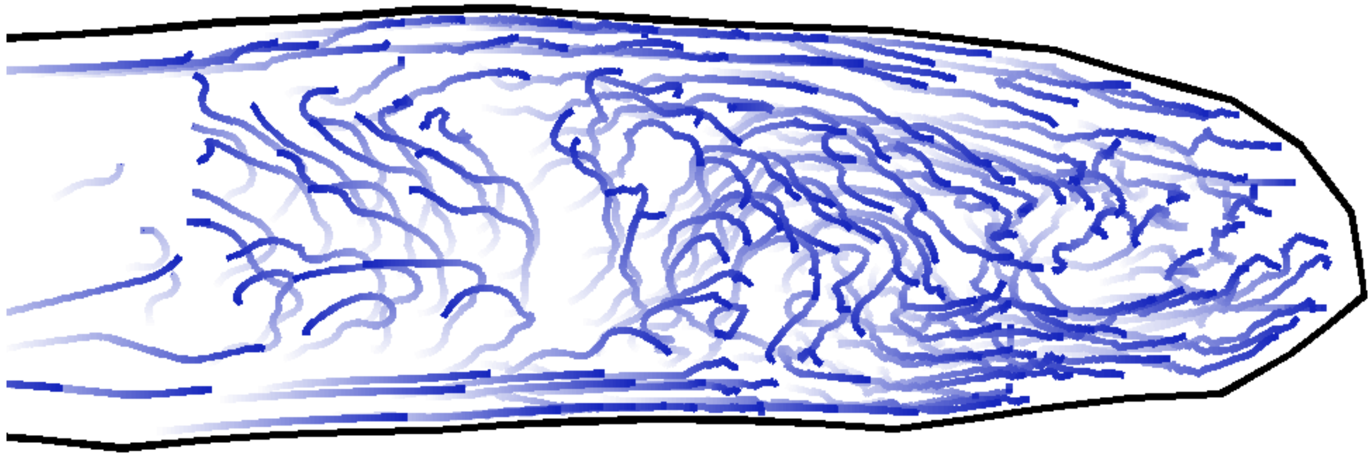
Modeling

- Biological perspective: Identify the key interactions and communication mechanisms bacteria use for cooperation and strategy selection.

- Mathematical perspective:
  - A bottom-up approach.
  - Study the interaction between the internal flow and a dynamic boundary.
  - A non- standard fluid model - sheer flow.

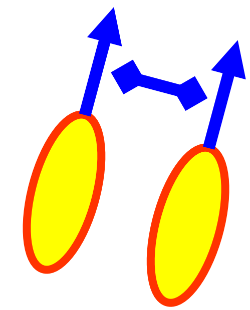
Modeling

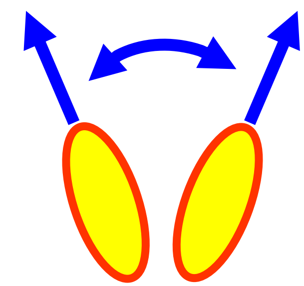
- **2D**
- **Agent based modeling –**
  coarse graining, groups of bacteria.
- **Dynamic envelope**



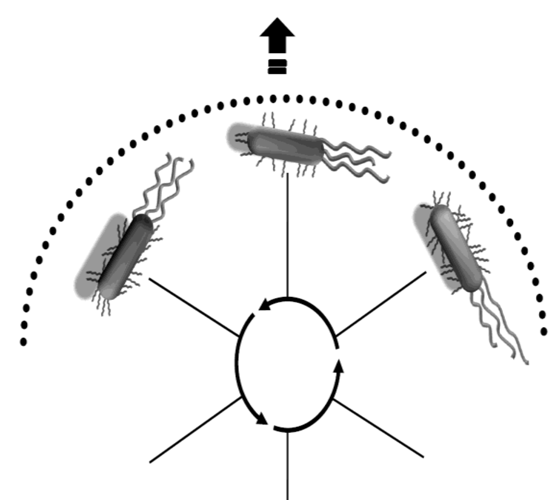
Modeling

- **Self propelled particles**
  Acceleration depends on food,
  Inelastic collisions
  Alignment b/w agents and boundary,
  Repulsion from neighbors.





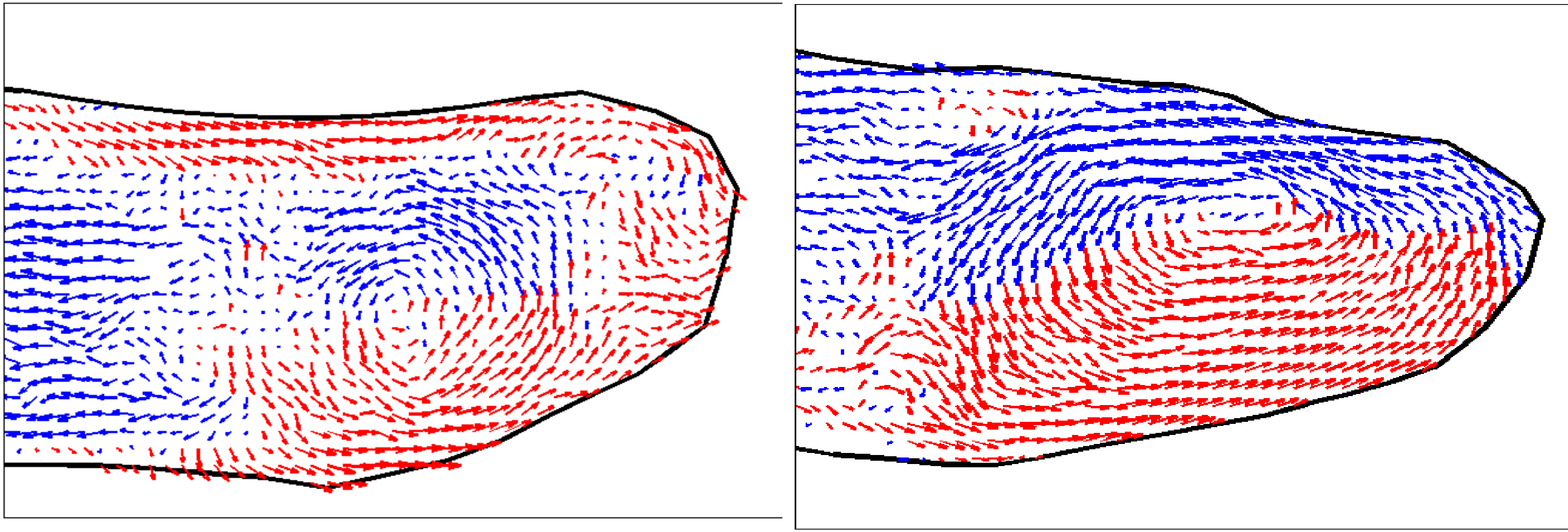
- **Dynamic envelope**
  Surface tension,
  A phenomenological expression
  for the normal speed of the
  boundary $v \times \hat{v} \times \nabla n$.



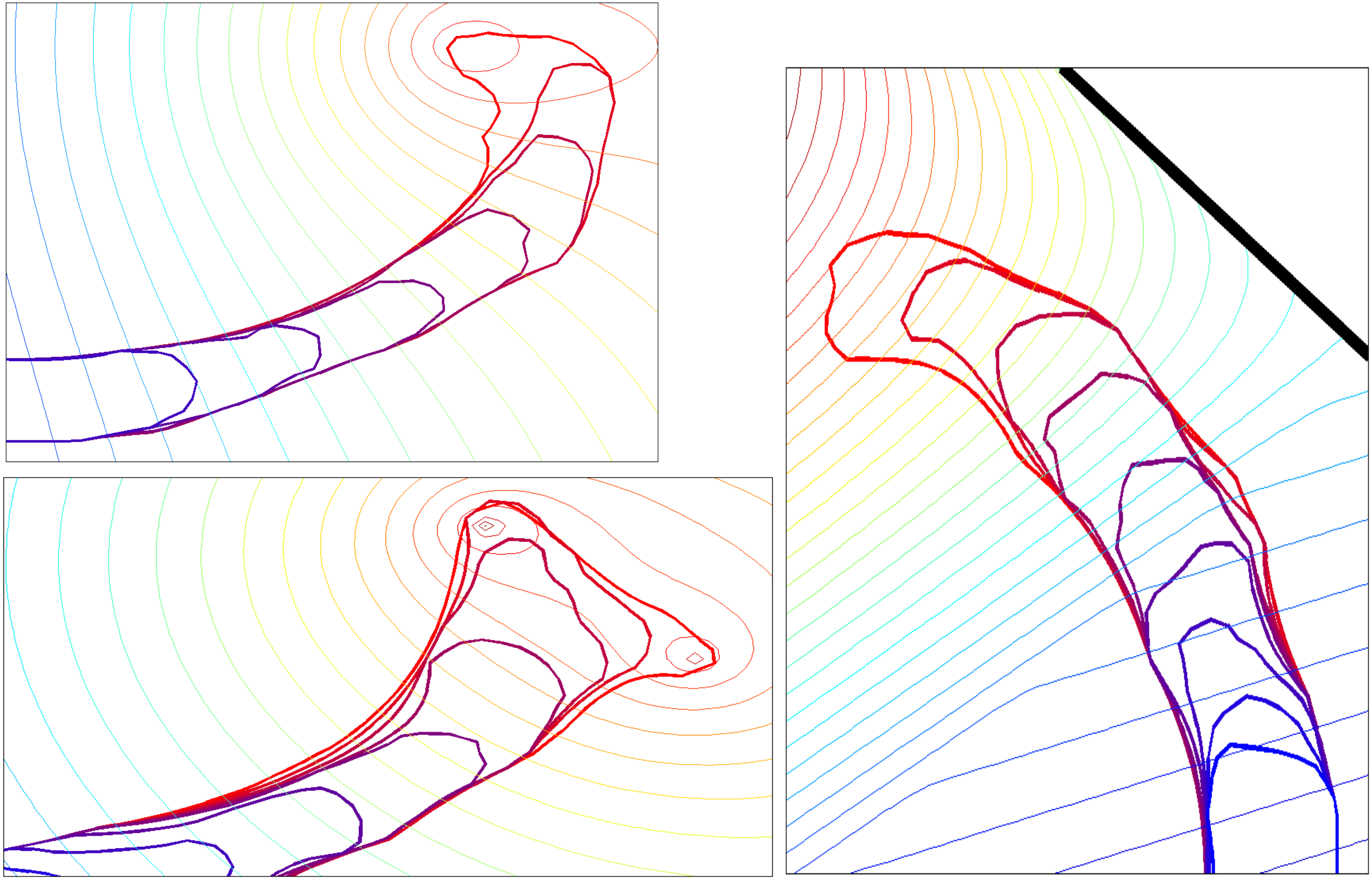
Modeling Results

Two stable dynamical states

- Standing tip with 2 lanes. movie
- Advancing tip with 3 lanes. movie



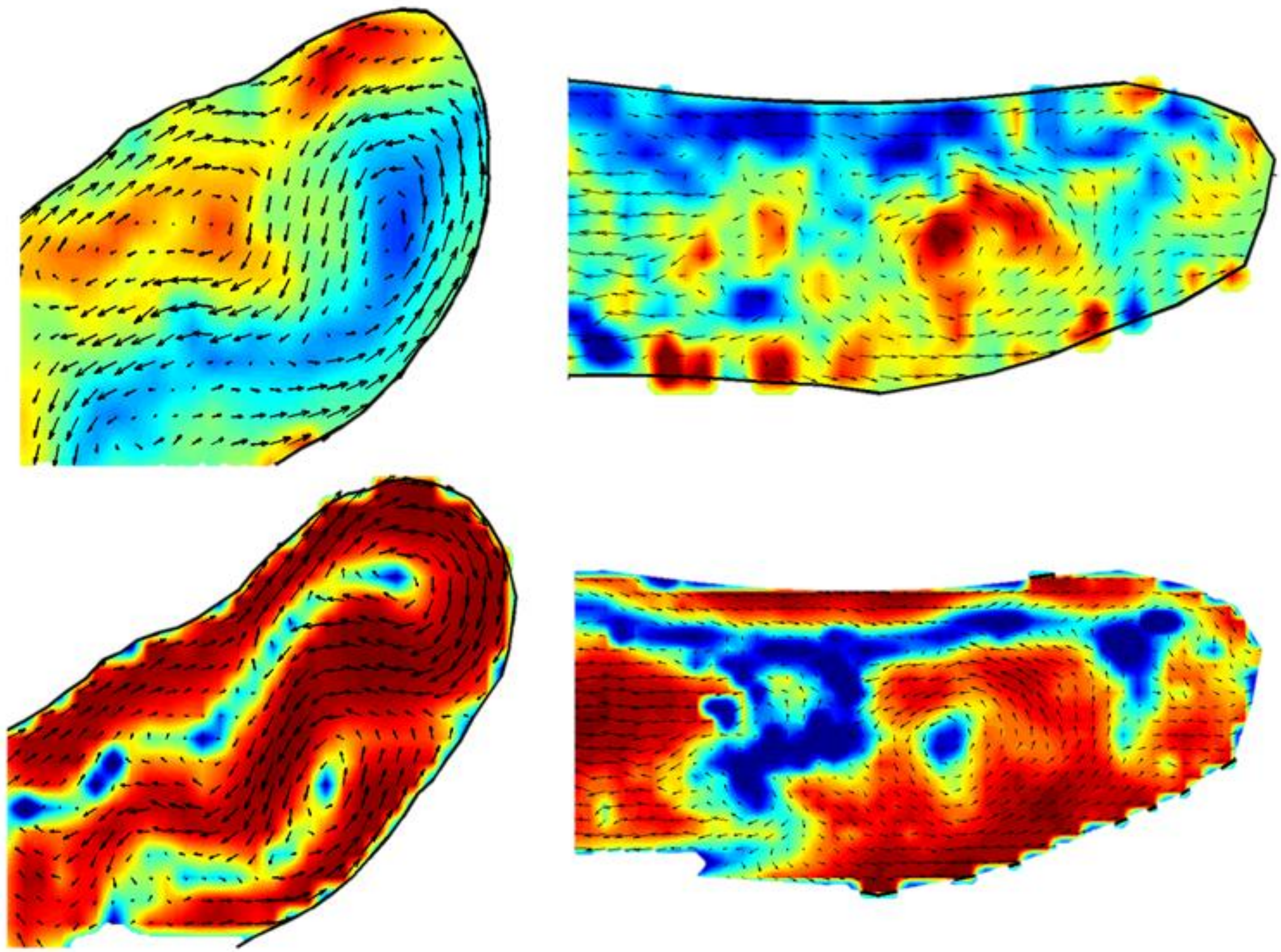
Modeling Results



Analysis of the flow

vorticity

order parameter

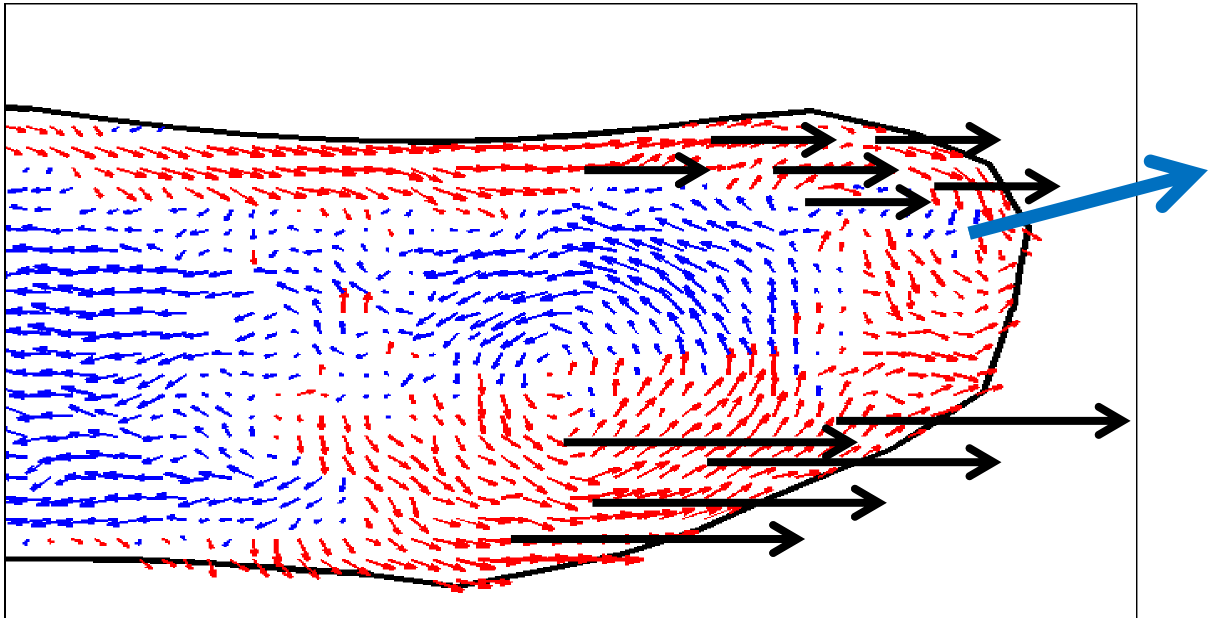


experiment

simulation

What we learn from simulations

- **Interaction depend on velocity.** alignment and speed matching dominate over collisions.
- **Strong coupling between flow and boundary** – bacteria use the internal organization to navigate the tip.



PDE models

- **High density** (crowd dynamics)
- **Free boundary**
- **Director fields** (liquid crystals)
- **Sheer flow – the velocity field is discontinuous**

movie

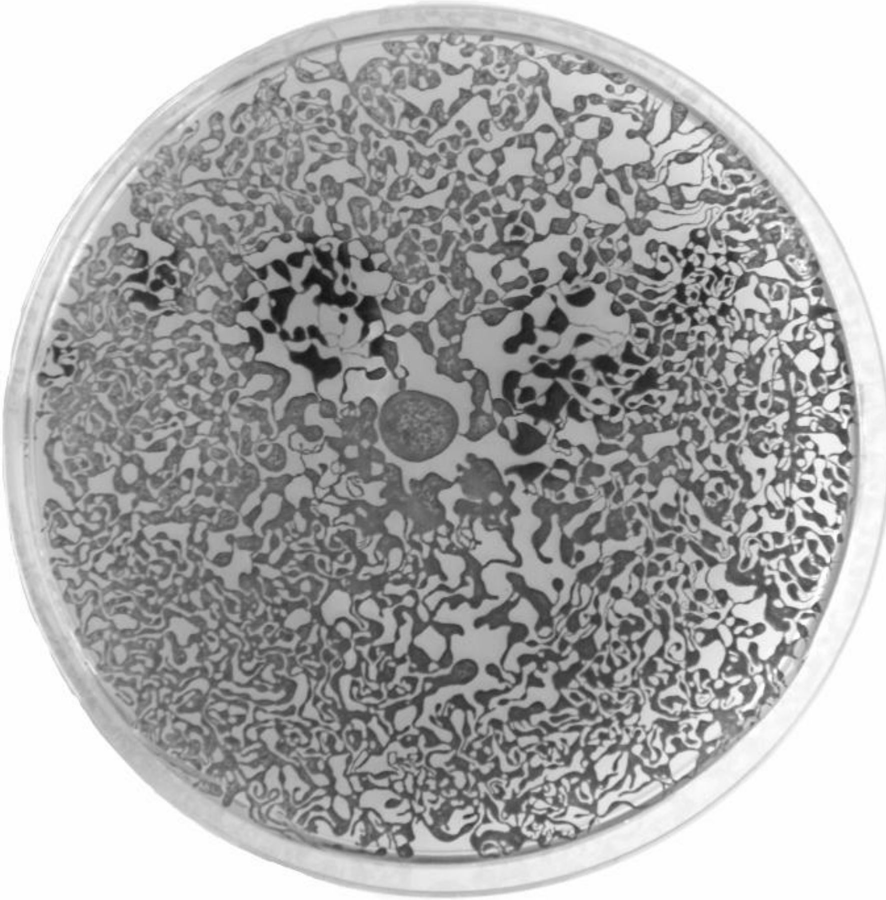
Previous approaches fail

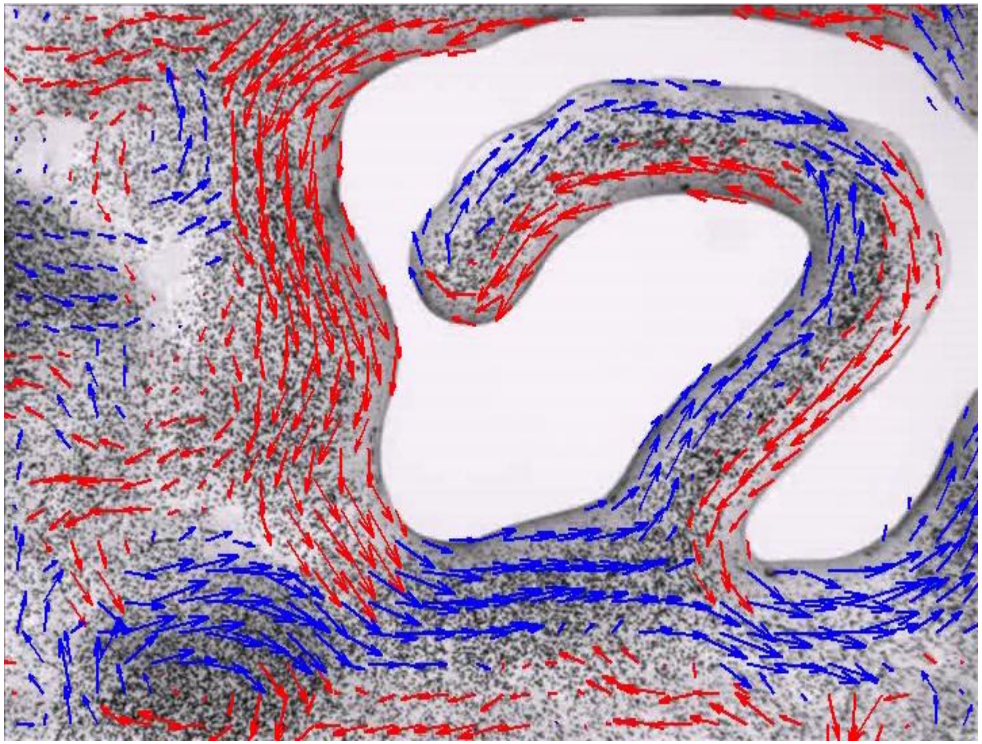
Non-linear diffusion [Ben-Jacob et al '96 '00]

Non-local kinetic equation [Mogilner and Edelshtein-Keshet et al '99, Topaz and Bertozzi '04]

and more …

Swarming logistics





multiscale approach


Animal swarms:
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