From bacteria to collective motion in heterogeneous media.

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In collaboration with:

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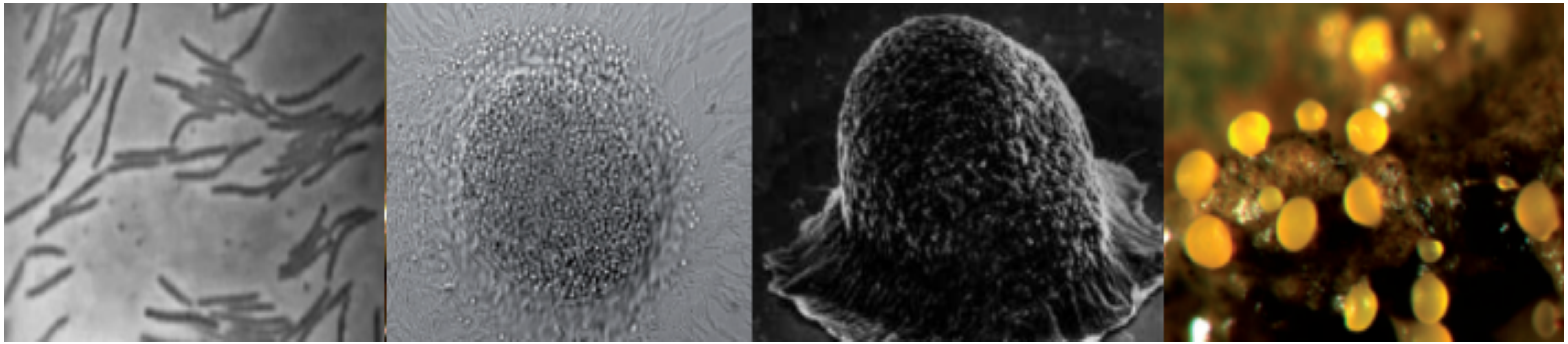
Journées de la physique nicoise - Nice – Dec. 2012



-- first part --

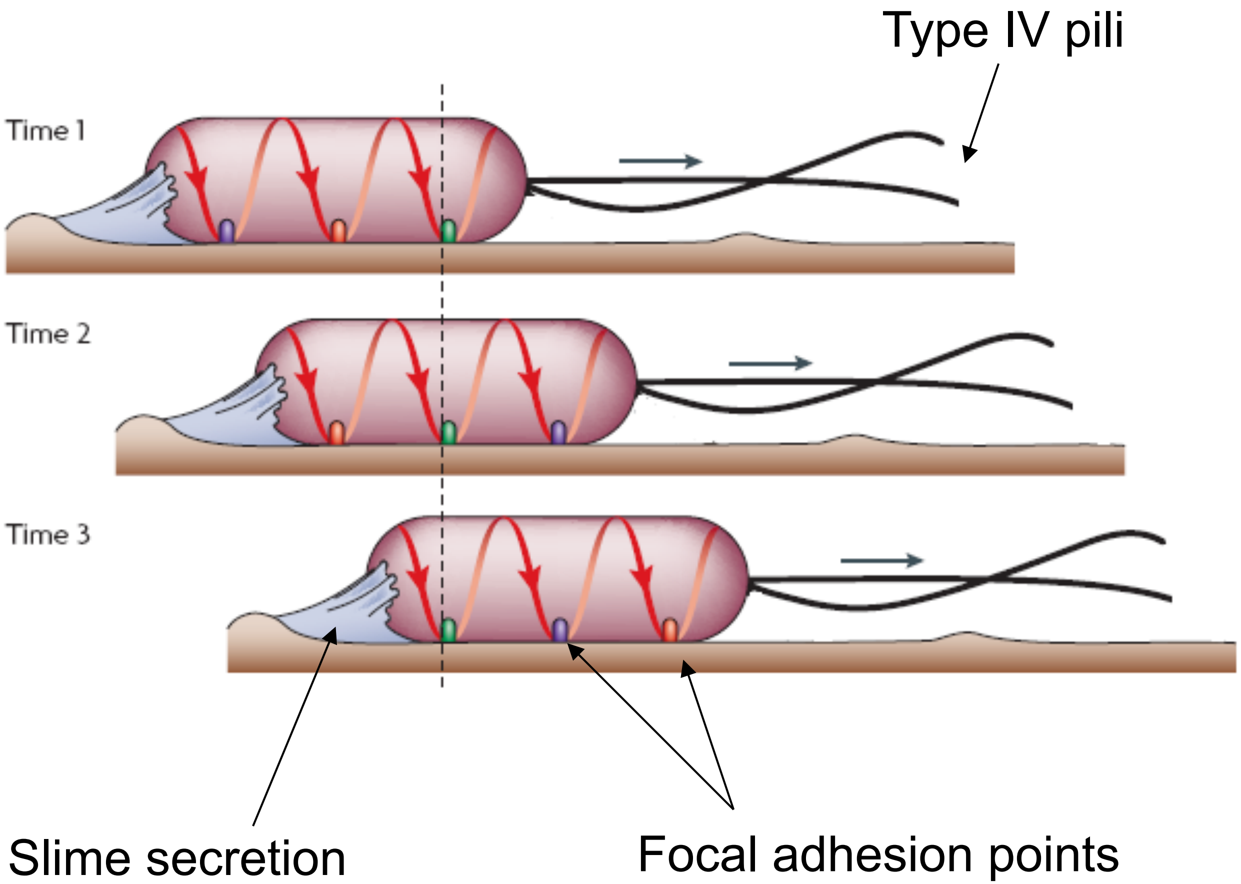
Motivation: collective macroscopic behavior in myxobacteria

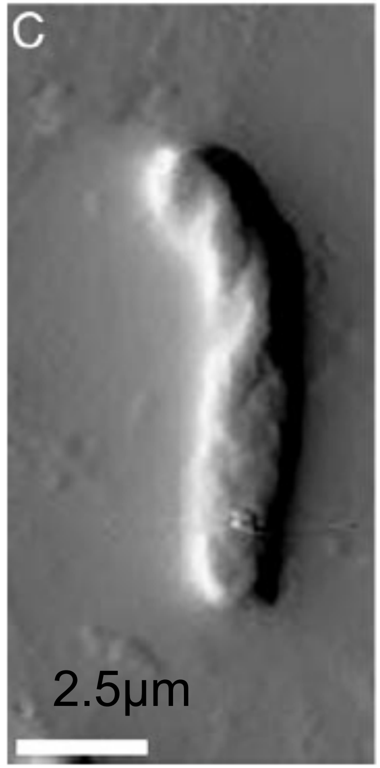
Myxobacteria as self-propelled rods

Spatial self-organization of myxobacteria

Motivation: collective macroscopic behavior in myxobacteria

- **<u>Motility engines in M. xanthus:</u>**





Pelling 05

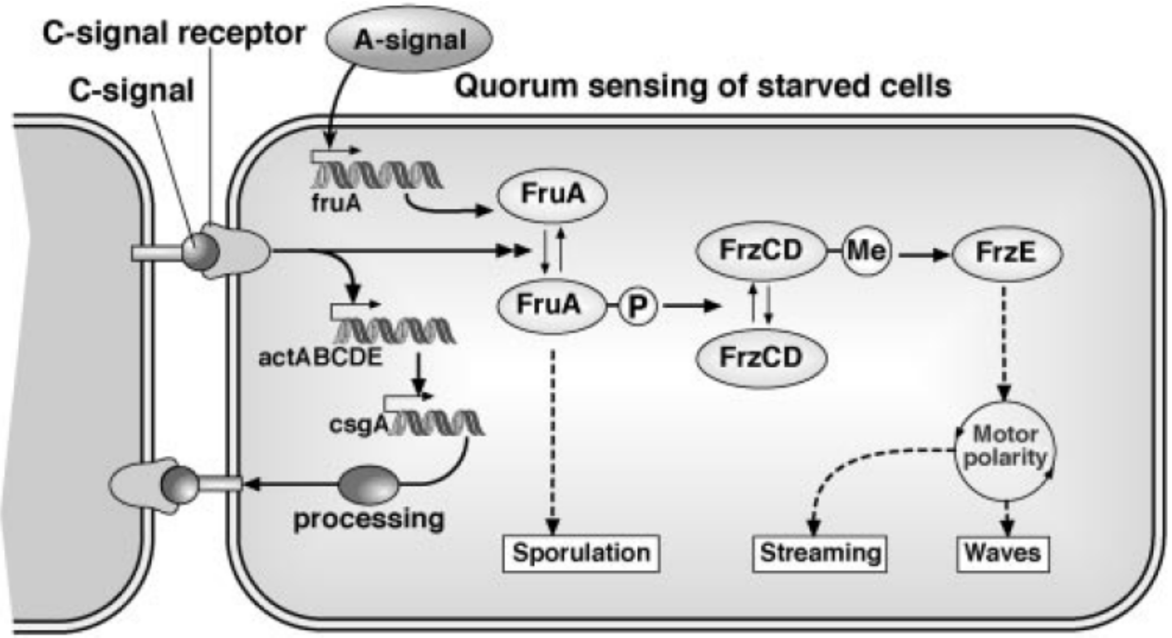
Myxobacteria (speed = 0.025 to 0.1 μm/s)
Cyanobacteria (speed =10 μm/s)
Cytophaga-Flavobacterium (speed = 2 to 4 μm/s)

Motivation: collective macroscopic behavior in myxobacteria

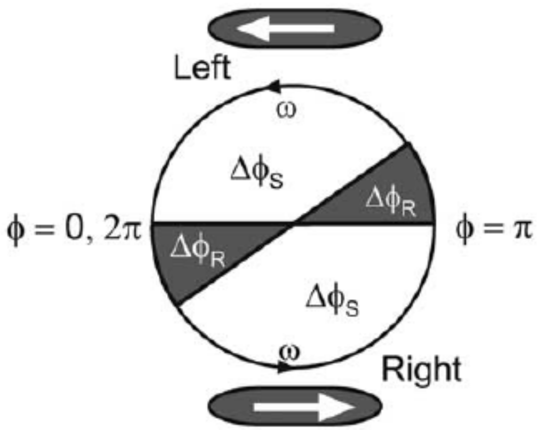
- **<u>How do M. xanthus cells communicate?</u>**

  - A quorum sensing diffusive mechanism to trigger the life cycle.
  - There is no evidence of a <u>guiding chemotactic signals</u> involved in <u>collective motion</u>.
  - Cells exchange C-signal which controls cell reversal (it requires cell-cell contact).

- **<u>Cell reversal and C-signal:</u>**



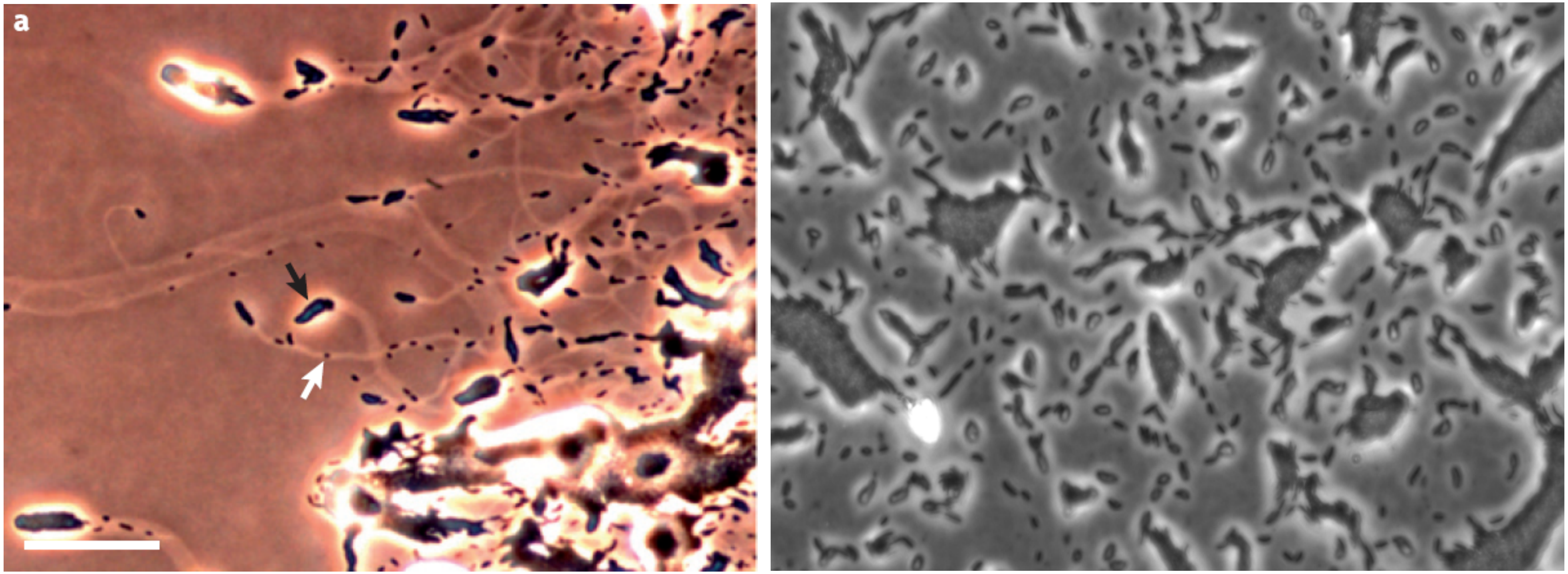
Igoshin & Oster 2003



Internal clock

Motivation: collective macroscopic behavior in myxobacteria

Which mechanism is used by the cells to coordinate their motion?



(Collective motion and clustering in the wild type during the vegetative growth)

- Is there a hidden guiding chemotactic signal?
- Can slime trail following cause these effects?
- Is there a cell-density sensing mechanism that controls cell speed causing of these effects?
- What is the minimal mechanism that can produce these effects?

Motivation: collective macroscopic behavior in myxobacteria

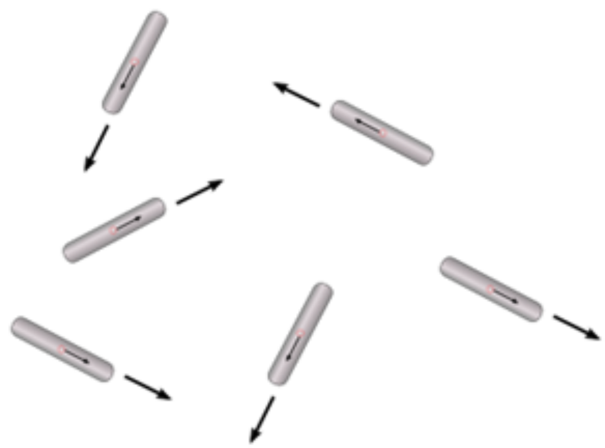
Self-propulsion of bacteria + elongated shape

= collective behavior ?

↓

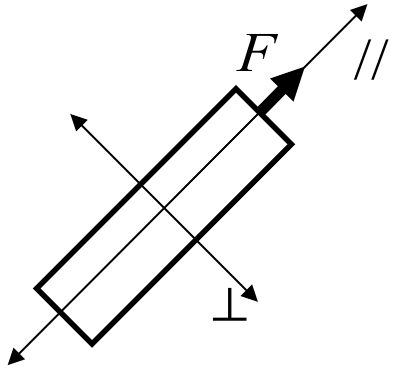
What macroscopic effects emerge

in a system of self-propelled rods ?



Myxobacteria as self-propelled rods

• A simple model for self-propelled rods

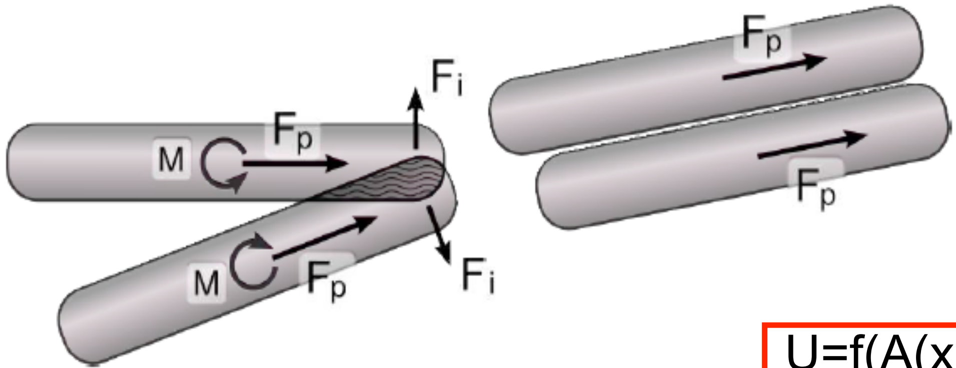


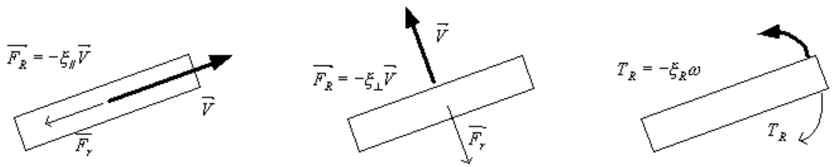
We consider the over-damped situation in which we have:

Self-Propelling force

$$\begin{cases} (v_{\parallel}^{(i)}, v_{\perp}^{(i)}) = \left(\frac{1}{\zeta_{\parallel}} (R_{\parallel}^{(i)} + F - \frac{\partial U^{(i)}}{\partial x_{\parallel}}), \frac{1}{\zeta_{\perp}} \left(R_{\perp}^{(i)} - \frac{\partial U^{(i)}}{\partial x_{\perp}} \right) \right) \\ \dot{\theta}^{(i)} = \frac{1}{\zeta_{\theta}} \left(R_{\theta}^{(i)} - \frac{\partial U^{(i)}}{\partial \theta} \right) \end{cases}$$

$R_{//}, R_{\perp}, \widetilde{R}$ **are white noises!**





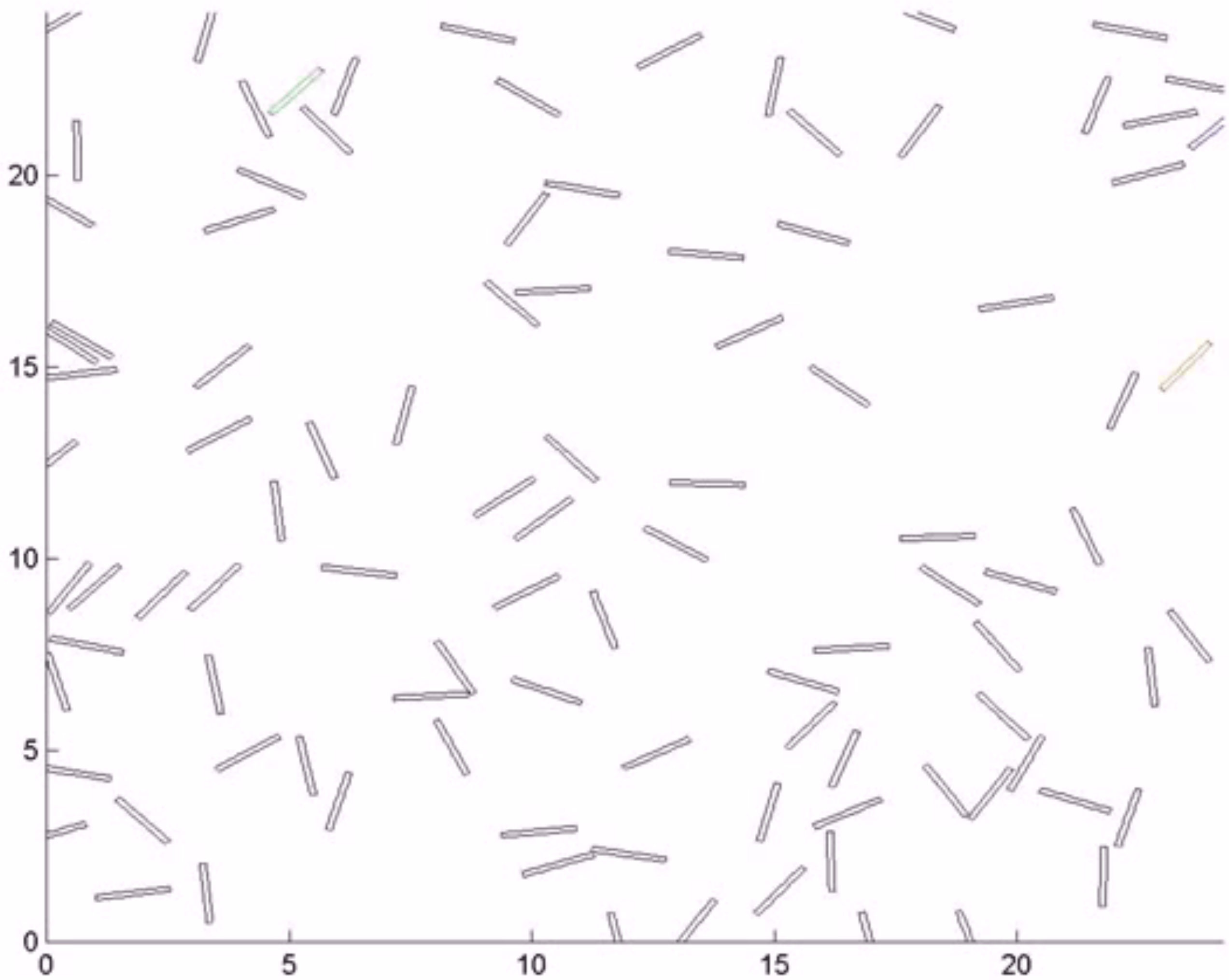
Interactions are due to overlapping of particles :

U=f(A(xi, θi, xj, θj)) where A is the overlapping area between particle i and j.

Peruani, Deutsch, and Bär, PRE (2006)

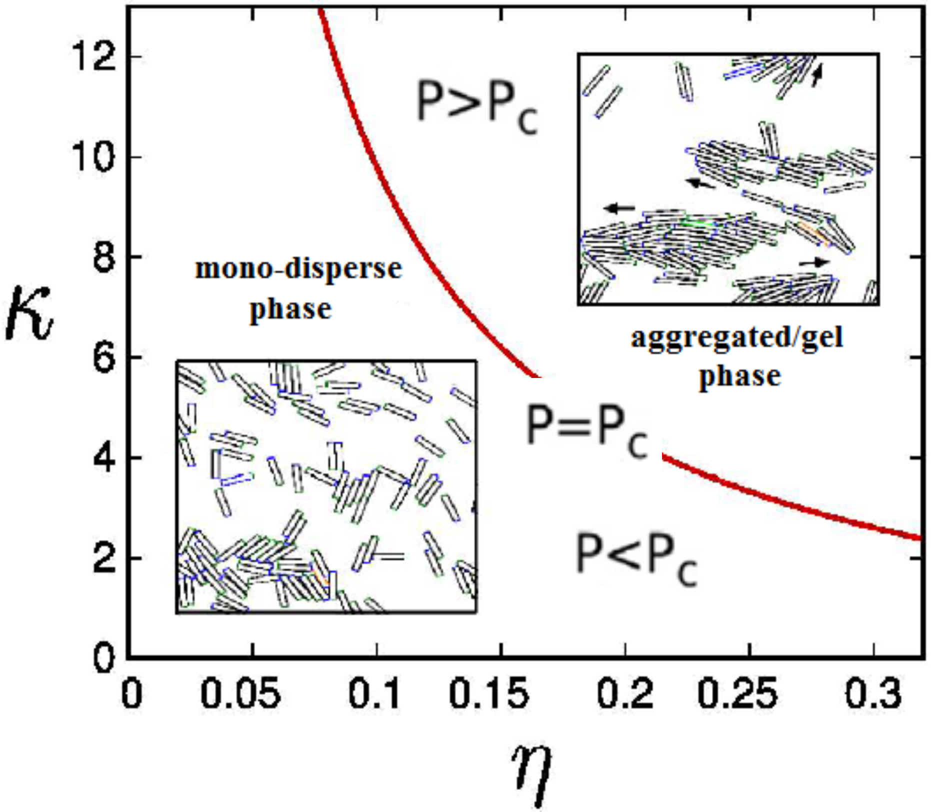
Myxobacteria as self-propelled rods

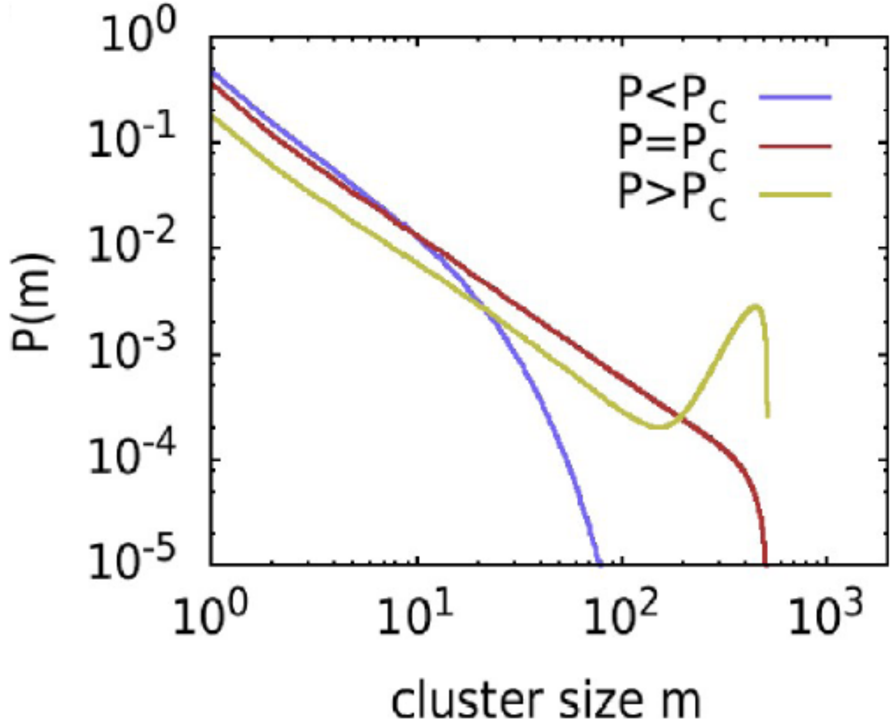
• **How is the behavior in the bulk? -** Simulate with periodic boundary conditions



Myxobacteria as self-propelled rods

Clustering properties of a system of SP rods

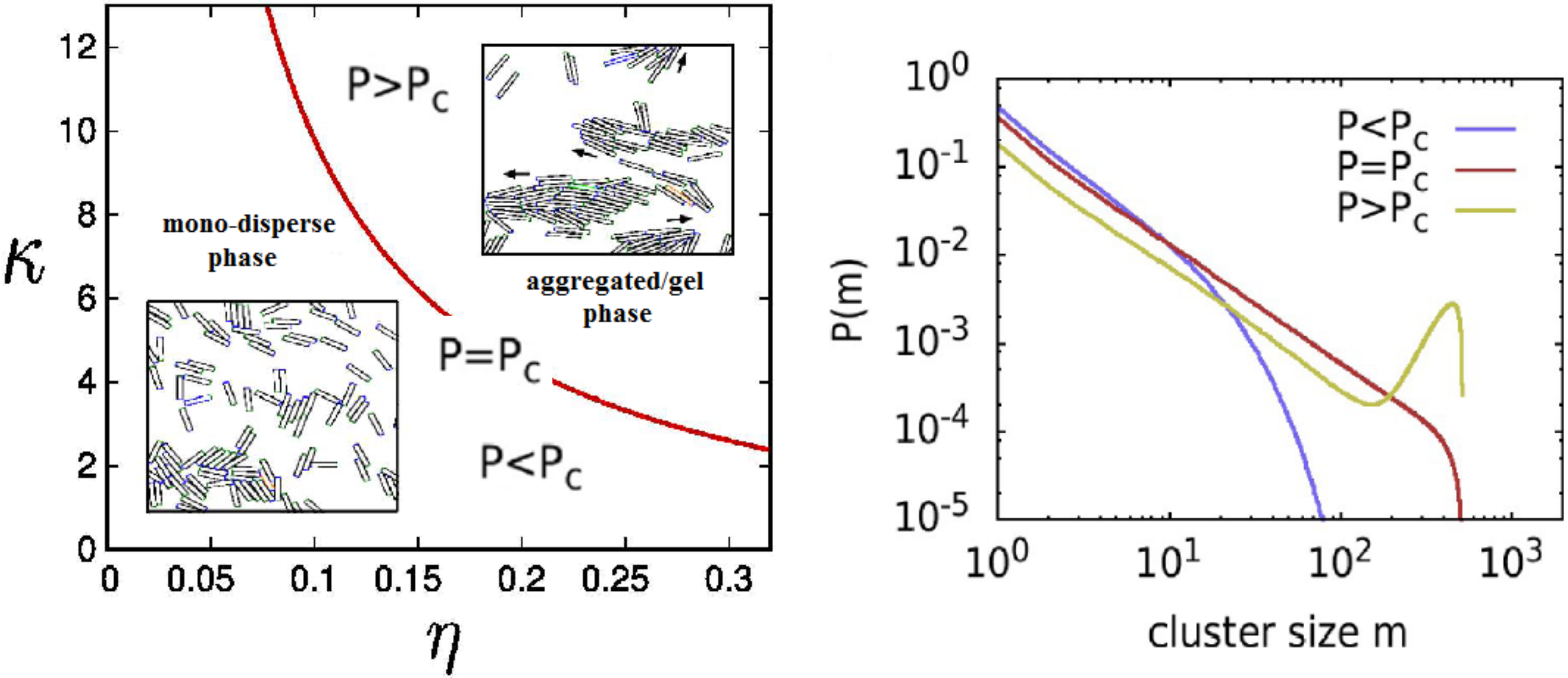




There is a dramatic change in the clustering properties of the system!
The cluster size distribution p(m) encodes this information.

Myxobacteria as self-propelled rods

Clustering properties of a system of SP rods



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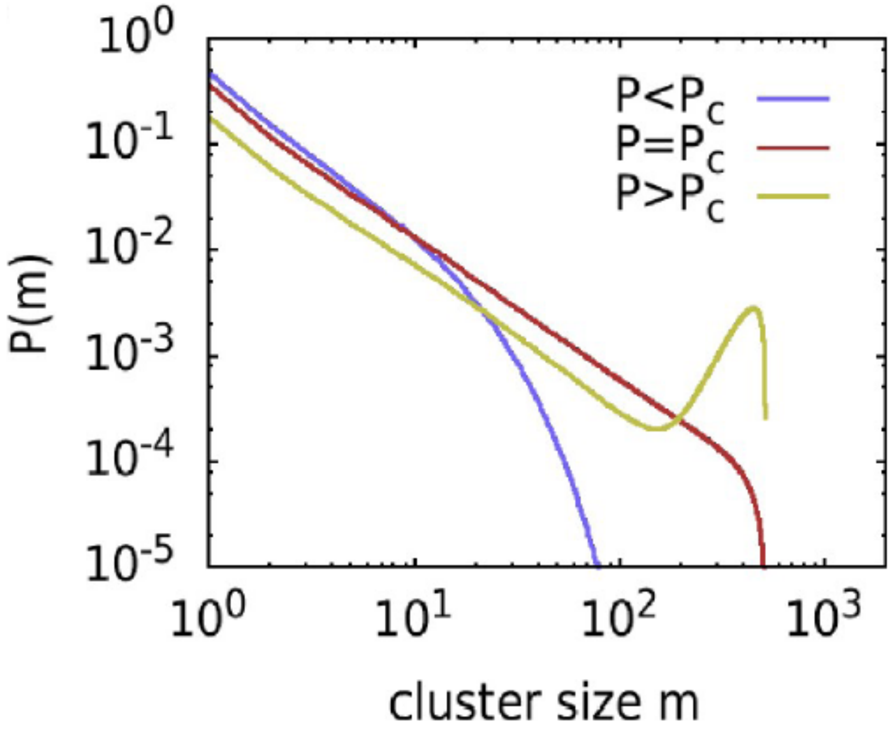
Myxobacteria as self-propelled rods

Clustering properties of a system of SP rods

Summary:

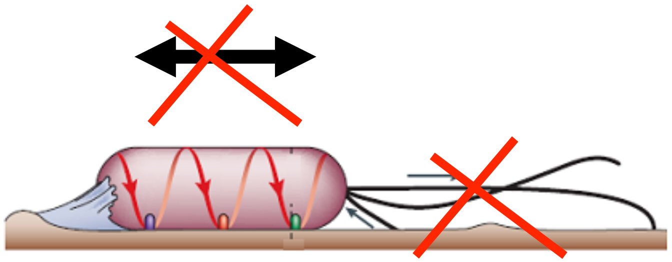
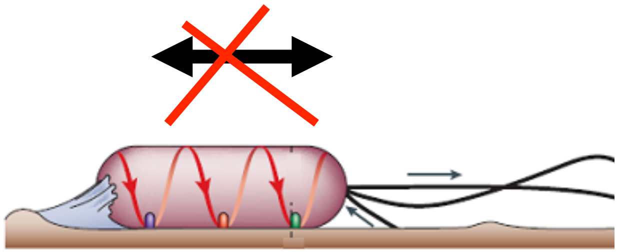
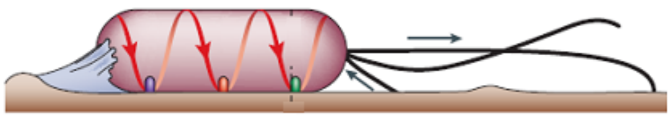


- low density – exponential (*mono-dispersed phase*)
- at critical density – power-law
- large density – peak at large m (*collect. mot. phase*)

Spatial self-organization of myxobacteria

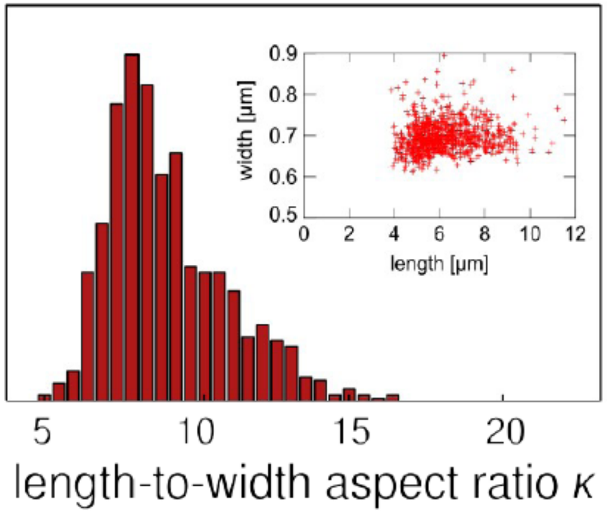
What kind of clustering properties exhibit real myxobacteria ?

• **Experiments with:**

A+S-Frz- mutants	*A+S+Frz-* mutants	*Wild-type*
		
* Cells do not reverse * Social motility engine – off * Advent. motility engine - on	* Cells do not reverse * Social motility engine – on * Advent. motility engine - on	* Cells do reverse * Social motility engine – on * Advent. motility engine - on

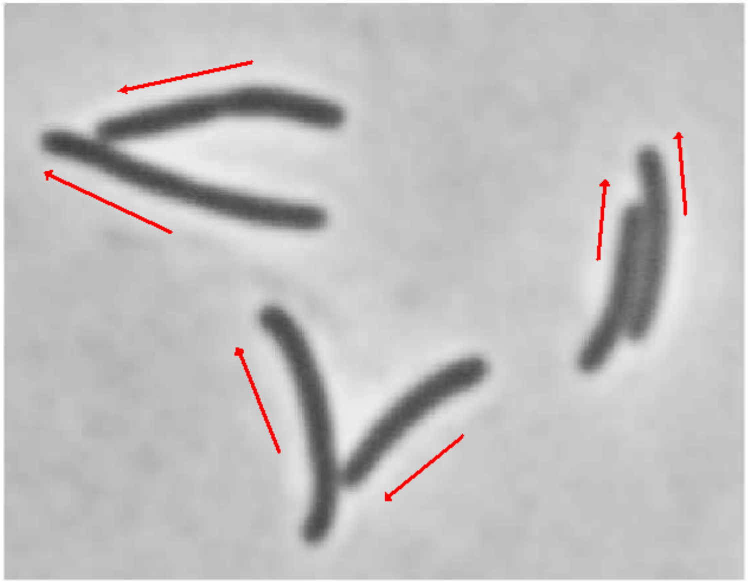
Spatial self-organization of myxobacteria

- **Alignment and clustering (A+S-Frz- & A+S+Frz-)**

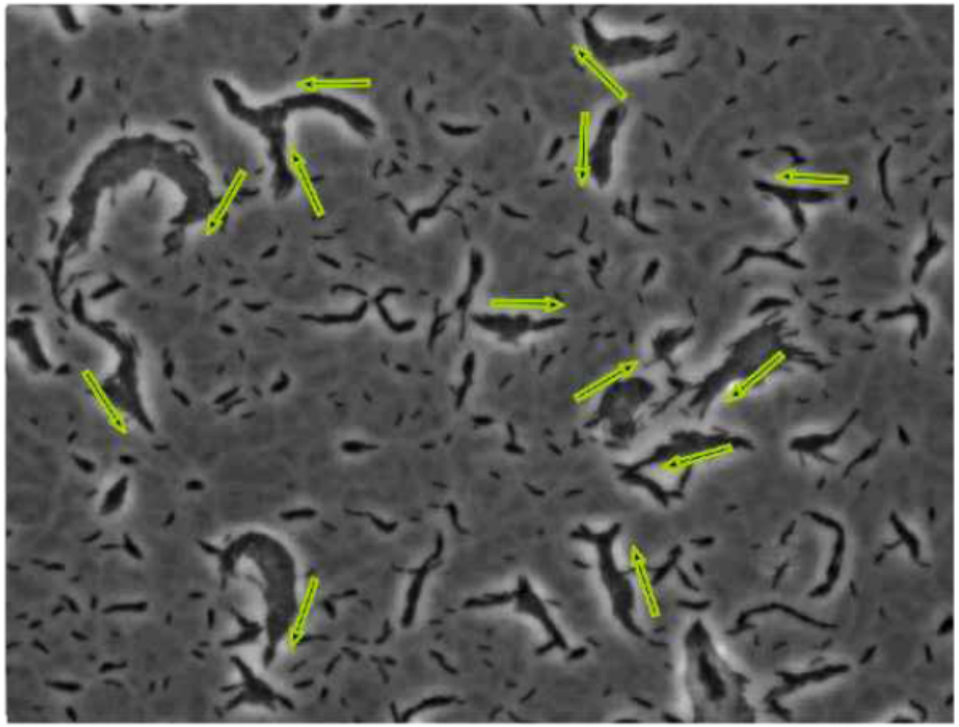


- Gliding speed = 3.10 ± 0.35 µm/min
- W=0.7 µm, L=6.3 µm, a=4.4 µm
- κ=8.9 ± 1.95

Cell collision leads to alignment:

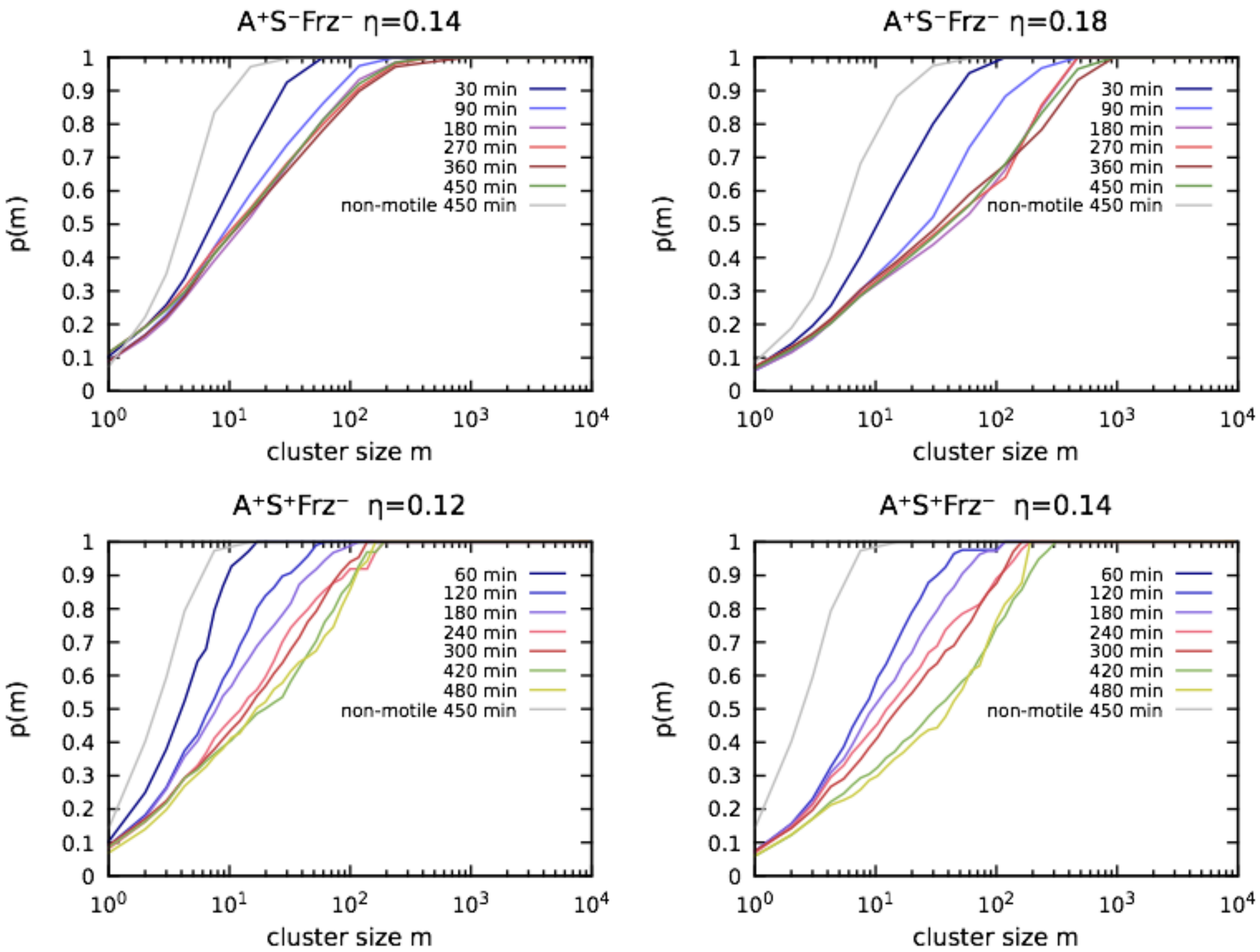


Moving clusters of bacteria are formed:



Spatial self-organization of myxobacteria

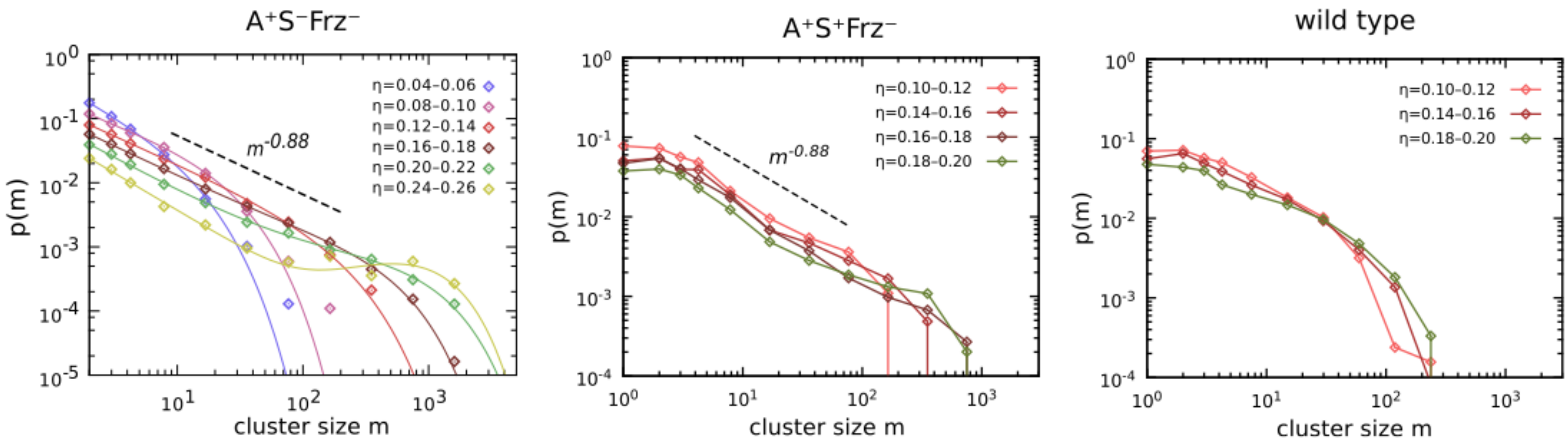
- **Convergence with time:**



There is a steady state cluster size distribution

Spatial self-organization of myxobacteria

- **Steady state cluster size distribution is a function of the density**



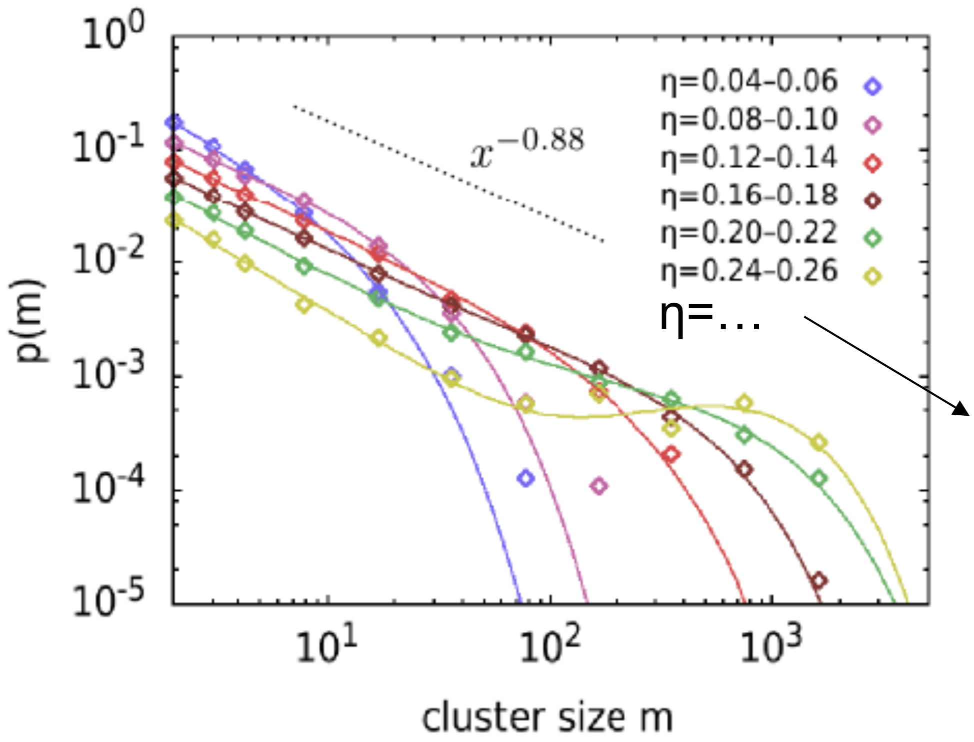
CSD in non-reversing mutants:

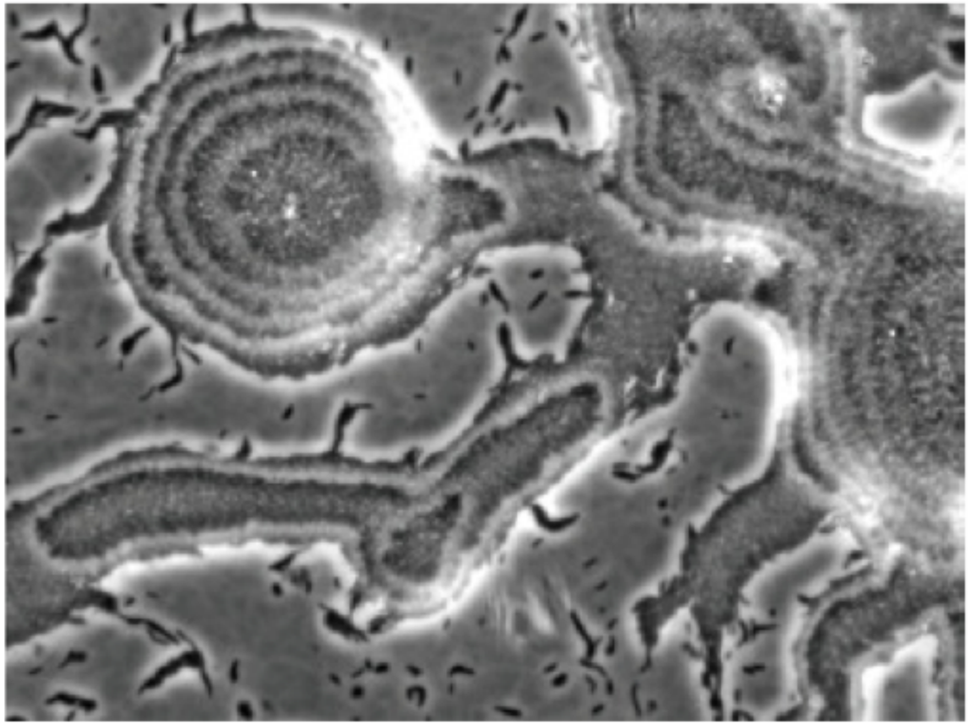
- low density – exponential (*mono-dispersed phase*)
- at critical density – power-law
- large density – peak at large m (*collective m. phase*)

- Always exponential
- Here there is a percolation transition at high densities.

Spatial self-organization of myxobacteria

- <u>Steady state cluster size distribution is a function of the density</u>

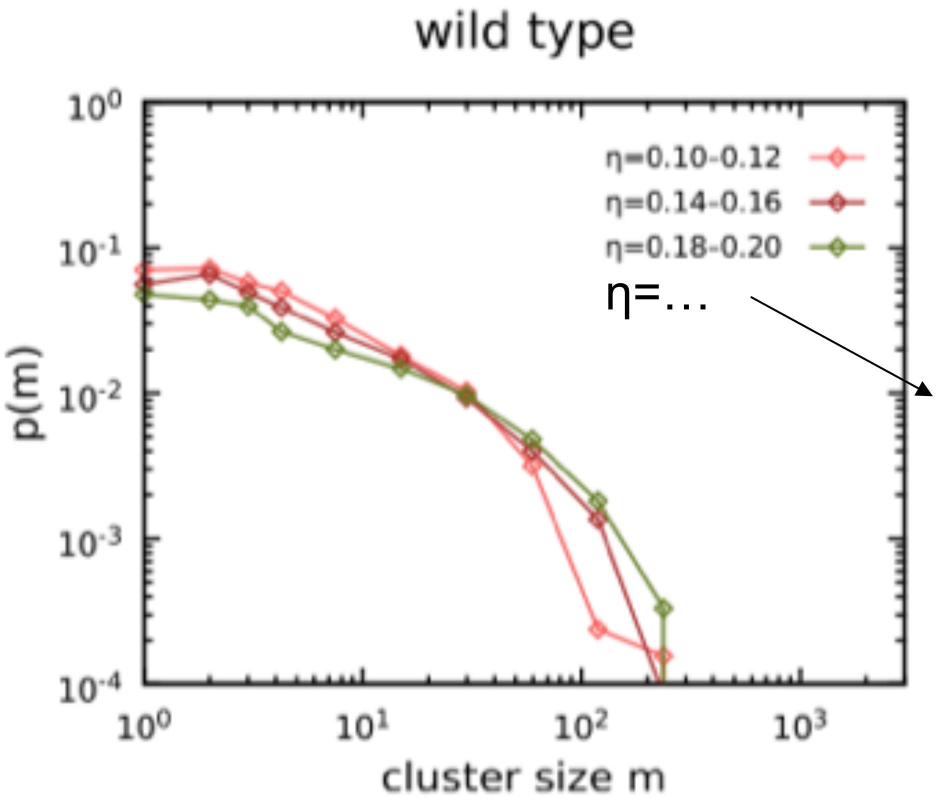


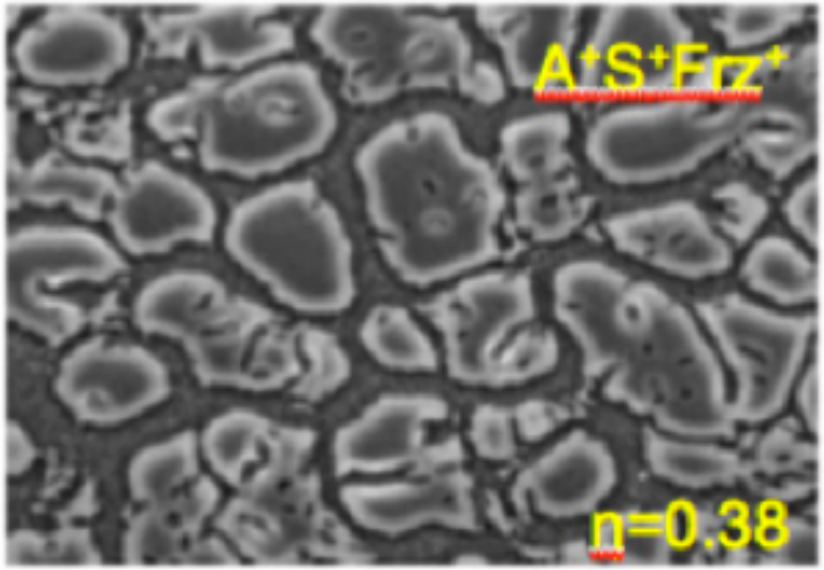


At very high densities we observe vortex formation in A+S-Frz- & A+S+Frz-

Spatial self-organization of myxobacteria

- **Steady state cluster size distribution is a function of the density**



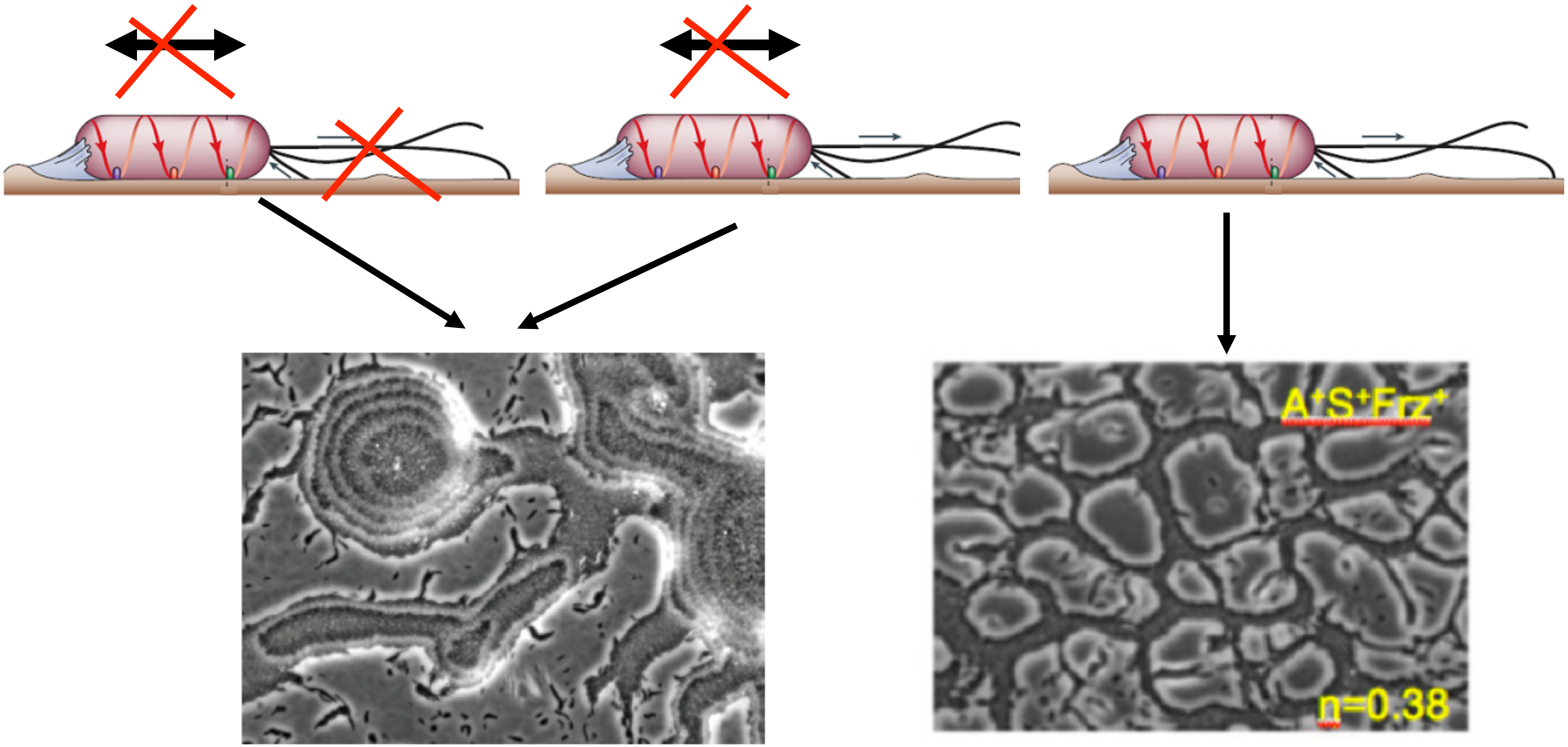


At very high densities we observe formation of mesh-like structures in the (reversing) wild-type

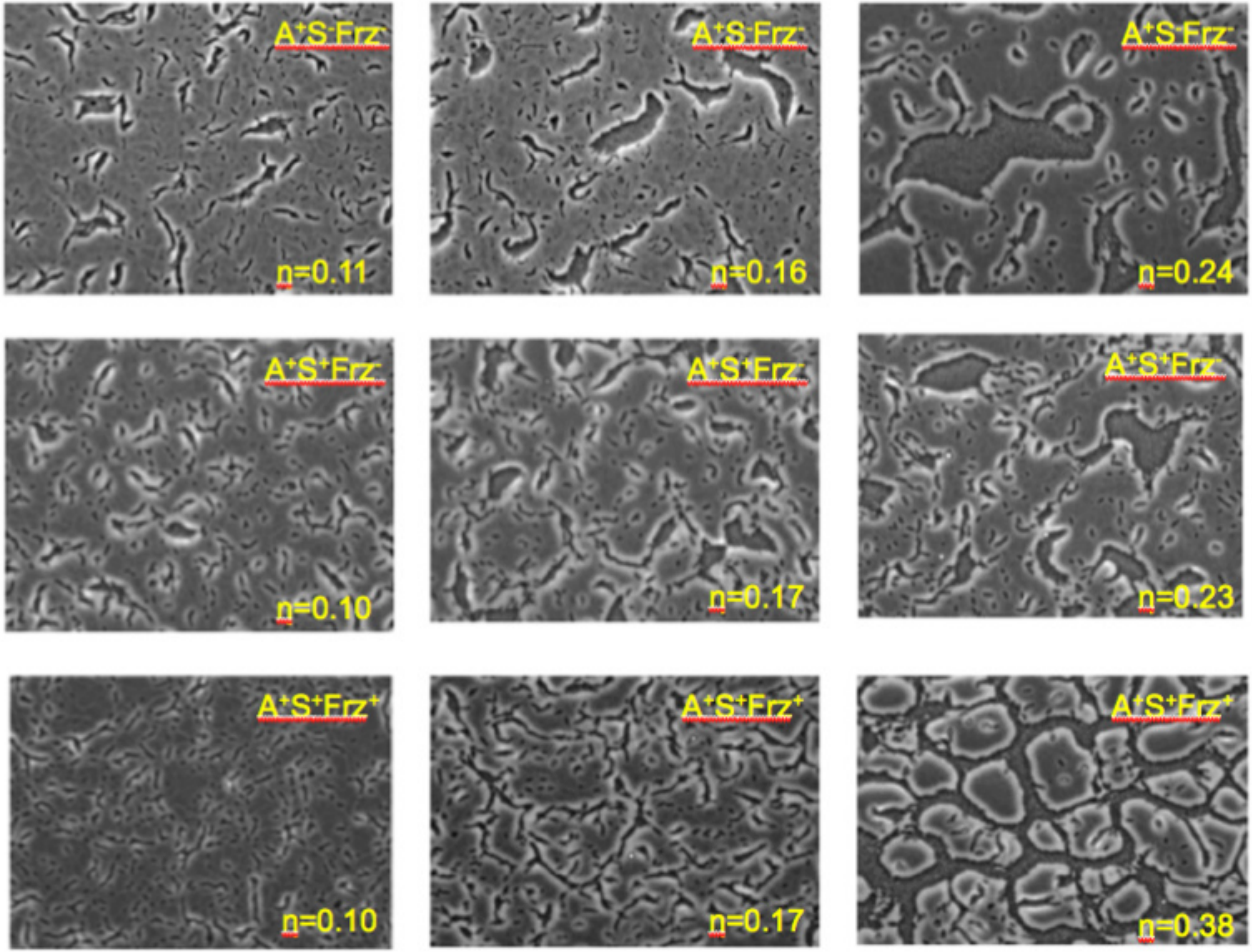
Spatial self-organization of myxobacteria

- **Experiments with:**

A+S-Frz- mutants | *A+S+Frz-* mutants | *Wild-type*

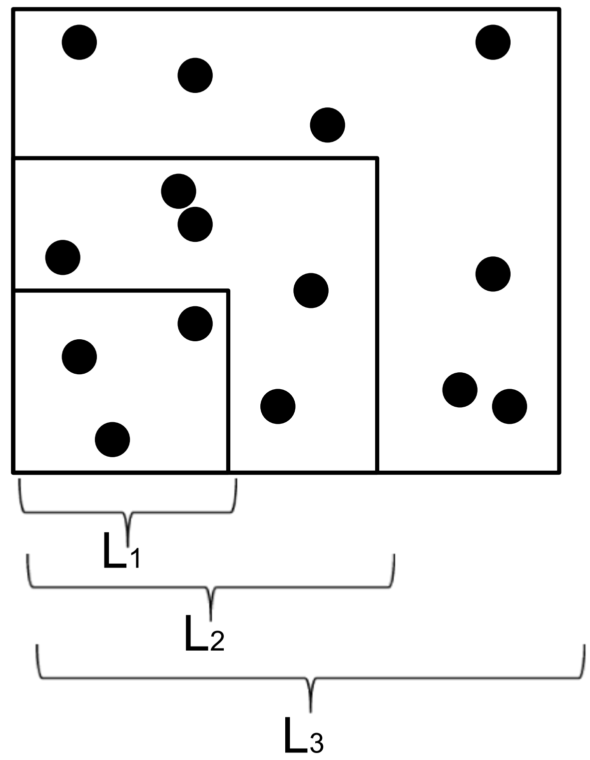


Spatial self-organization of myxobacteria



Spatial self-organization of myxobacteria

Number fluctuations



n(L) = number of particles in box of size L

Average number:

$$\langle n(L)\rangle = \rho L^2$$

Average square number:

$$\Delta n^2 = \langle [\, n(L) - \langle n(L)\rangle]^2 \rangle$$

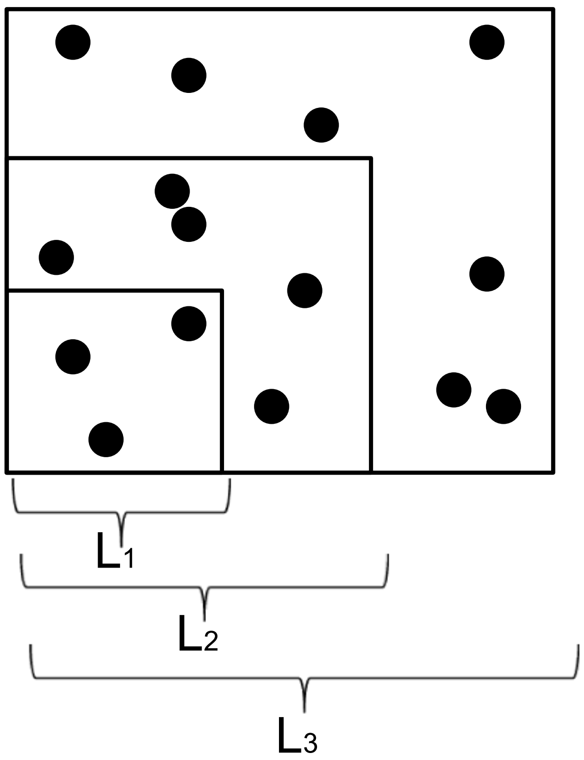
$$\Delta n = \left(\langle [\, n(L) - \langle n(L)\rangle]^2 \rangle\right)^{1/2} = \langle n(L)\rangle^{\beta}$$

Normal number fluctuations

$$\Delta n = \langle n(L)\rangle^{1/2}$$!

Spatial self-organization of myxobacteria

Number fluctuations



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$$\Delta n = (\langle [\, n(L) - \langle n(L)\rangle]^2 \rangle)^{1/2} = \langle n(L)\rangle^{\beta}$$

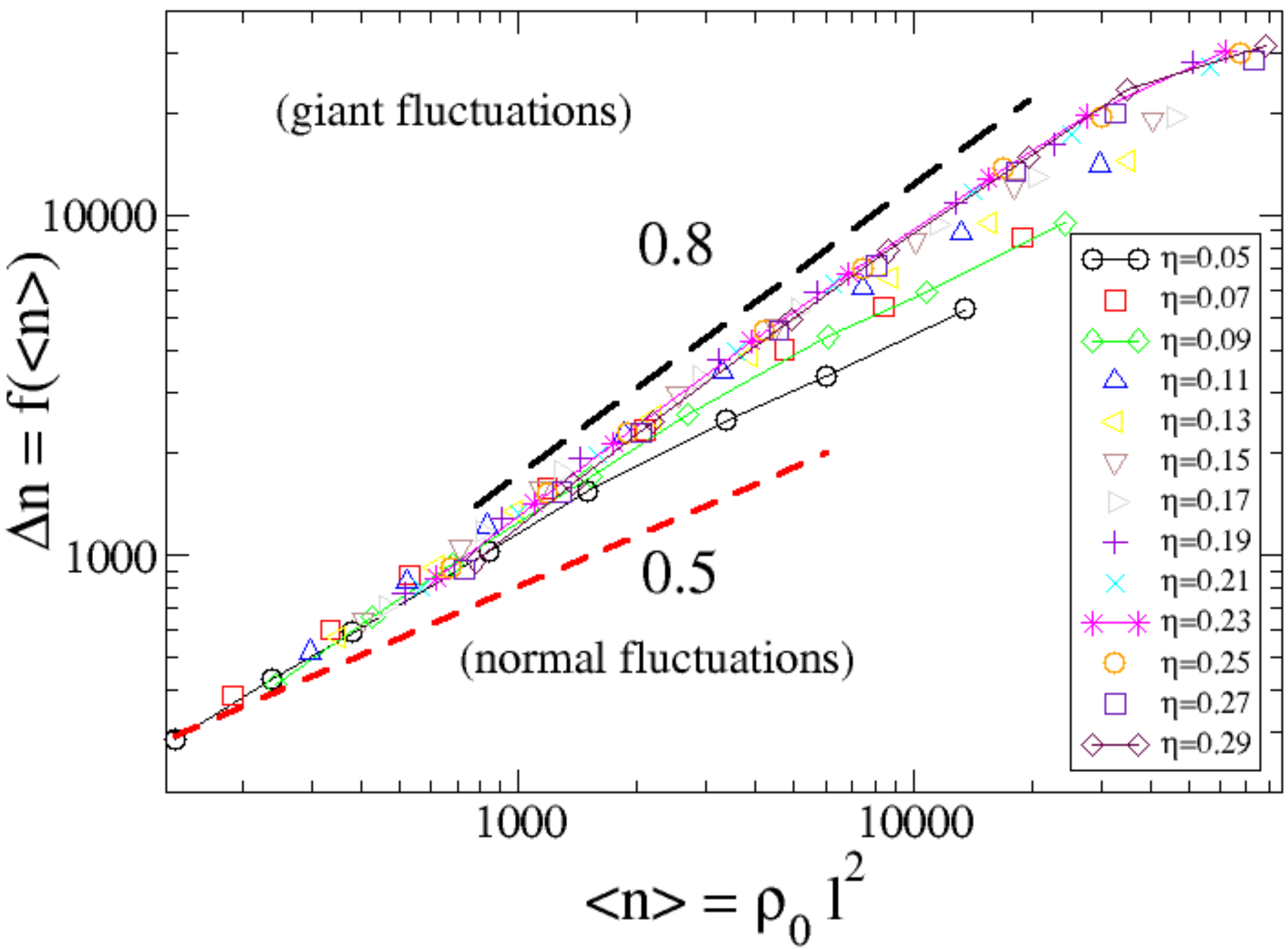
Giant number fluctuations

$$\Delta n = \langle n(L)\rangle^{\beta}$$

$\beta > 1/2$!

Spatial self-organization of myxobacteria

Apparent giant number fluctuations



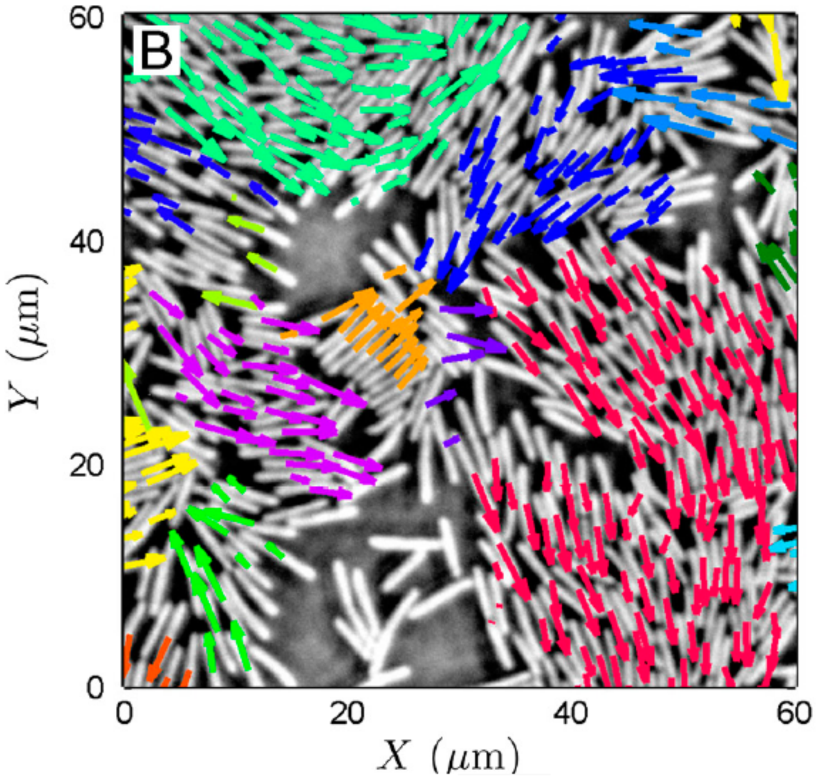
critical NF exponent: **0.8**

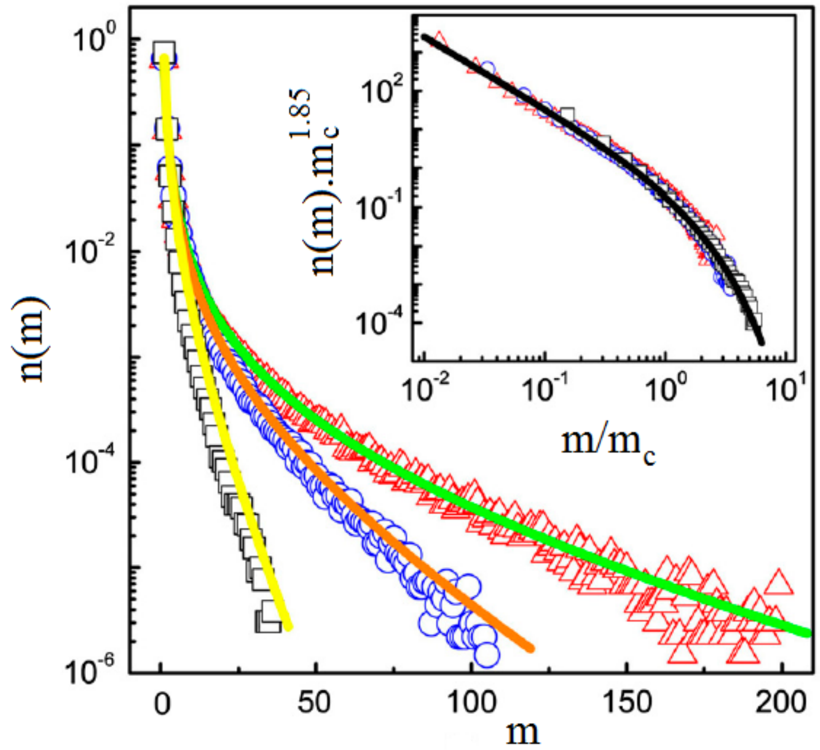
(Measurements performed with the A+S-Frz- cells)

Spatial self-organization of myxobacteria

Can the combination of self-propulsion and volume exclusion be a "general" mechanism for spatial self-organization in bacteria ?

Experiments with *Bacillus subtilis* – motion in a 2D thin film of flagellated cells





$$n(m) \sim m^{-1}\, p(m) \longrightarrow$$ critical exponent: **0.85**

H. P. Zhang et al., PNAS 107, 13626 (2010)

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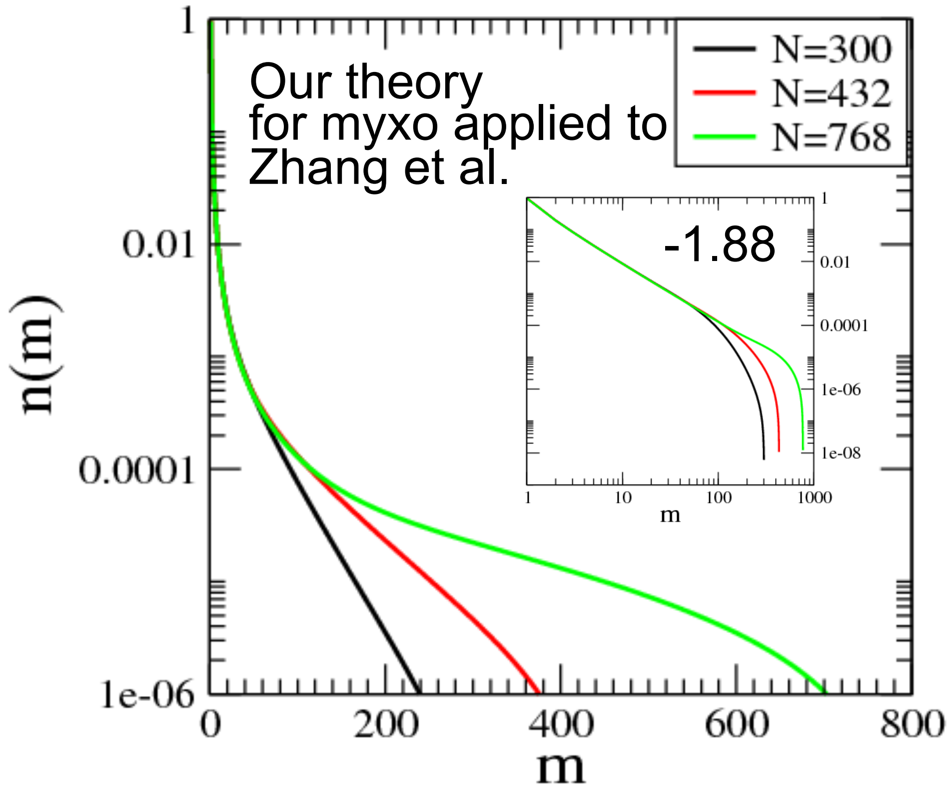

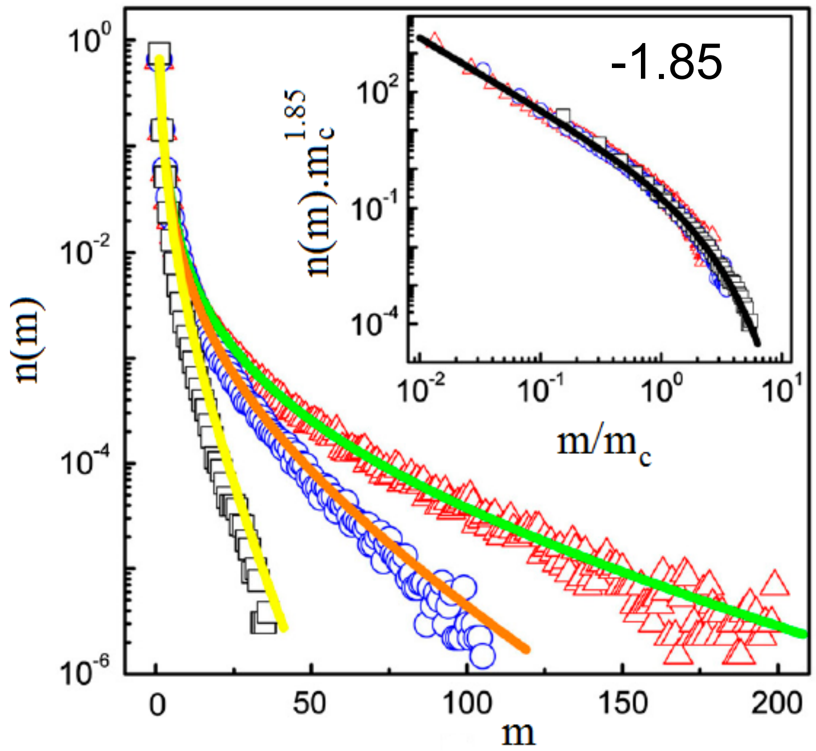

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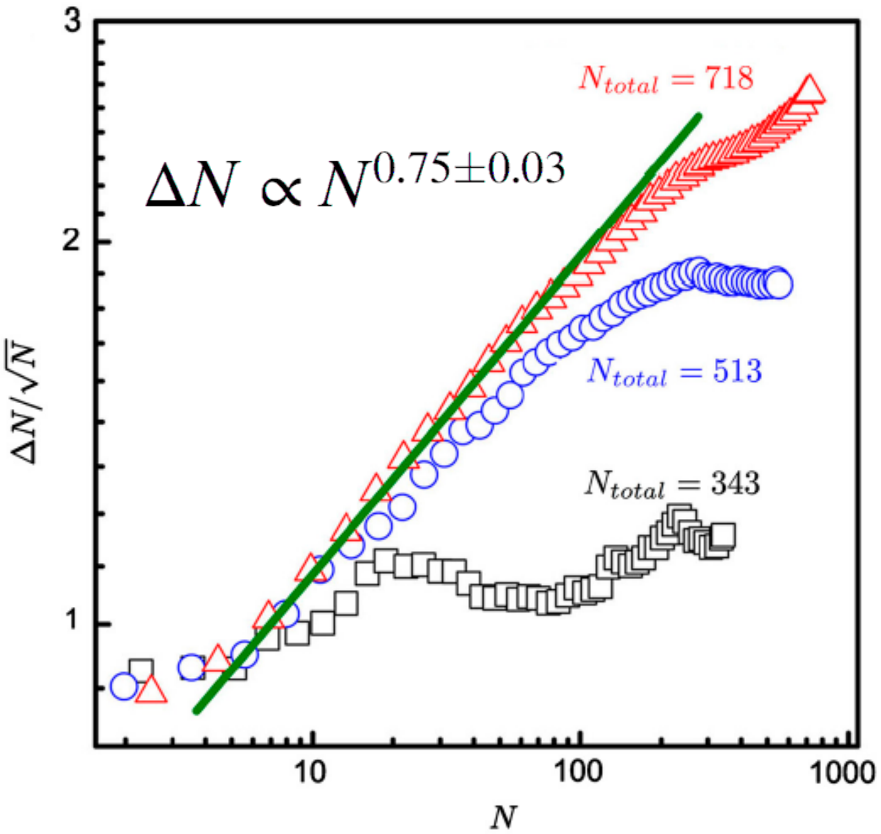


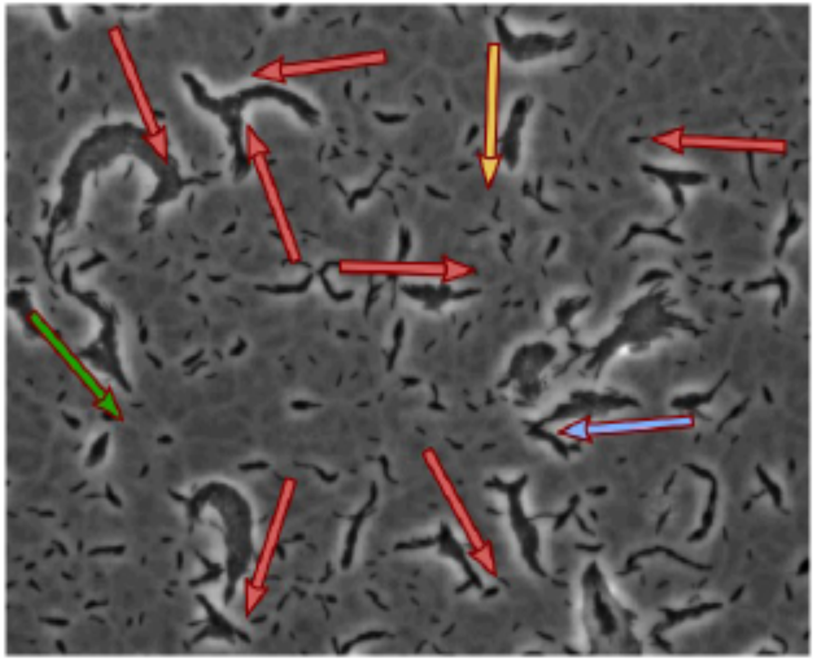
Measurement of number fluctuations:

- Giant number fluctuations reported!
- Critical NF exponent: **0.75 +/- 0.03**

H. P. Zhang et al., PNAS 107, 13626 (2010)

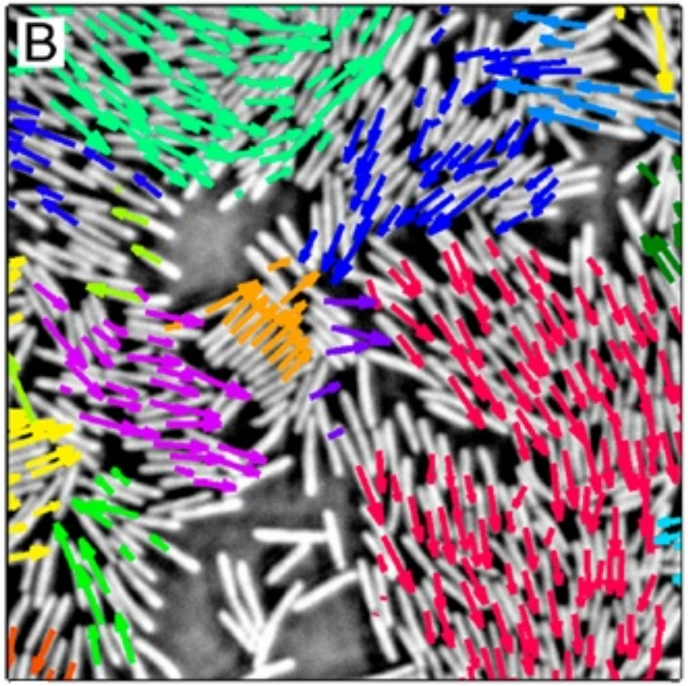
Spatial self-organization of myxobacteria

Myxococcus xanthus



- no flagella
- no swimming, no fluid – just gliding
- speed 3.1 μm/min
- L=6.3μm; W=0.7μm
- T=480 min (8hs)

Bacillus subtilis



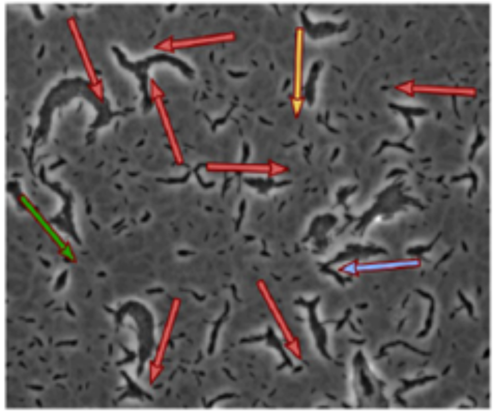
- flagella
- swimming ?
- speed 900 μm/min ?
- L =3μm; W=0.6μm
- T=1.6 min

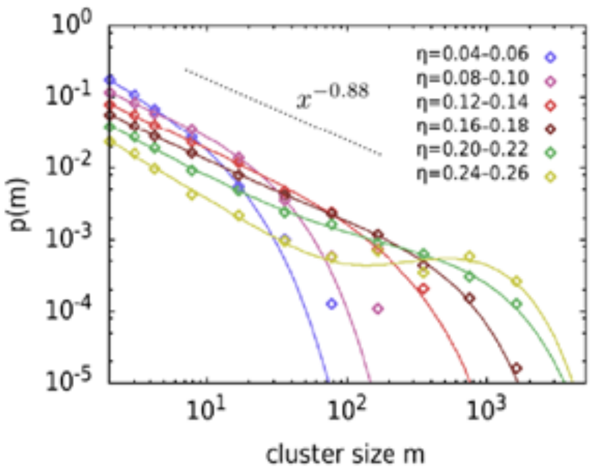
Common features: **2D motion, self-propulsion, volume exclusion effects**

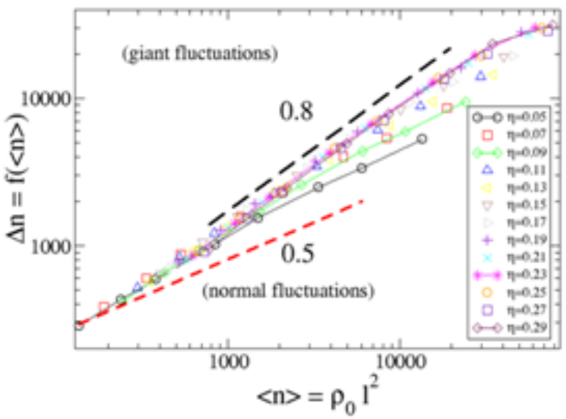
Critical clustering exponent: **0.88 (myxo)** and **0.85 (B. subt.)!**
Critical NF exponent: **0.8 (myxo)** and **0.75 (B. subt.)!**

evidence of a general mechanism for the spatial self-organization in bacteria ?

Spatial self-organization of myxobacteria







Gliding bacteria – in absence of biochemical signal regulation or hydrodynamical interactions – exhibit a Collective Motion (CM) phase!

Measured statistical features of this CM phase:

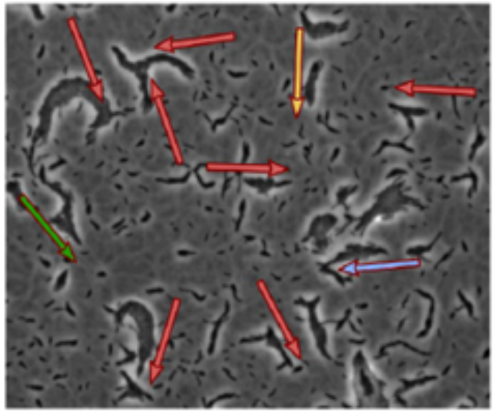
- Non-monotonic CSD – existence of arbitrary large cluster sizes
- Giant number fluctuations

Onset of collective motion:

- Power-law CSD with exponent 0.88
- Apparent giant num. fluctuations with exponent 0.8

FP et al., PRL (2012) & Starruss et al. Interface focus (2012)

Spatial self-organization of myxobacteria



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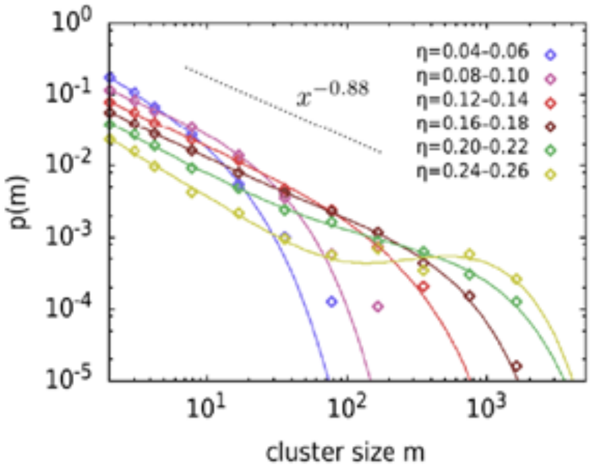

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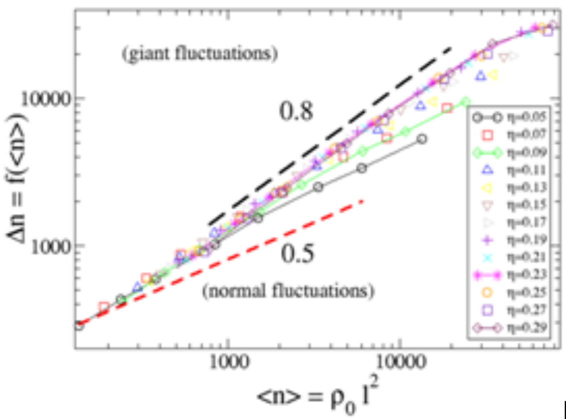
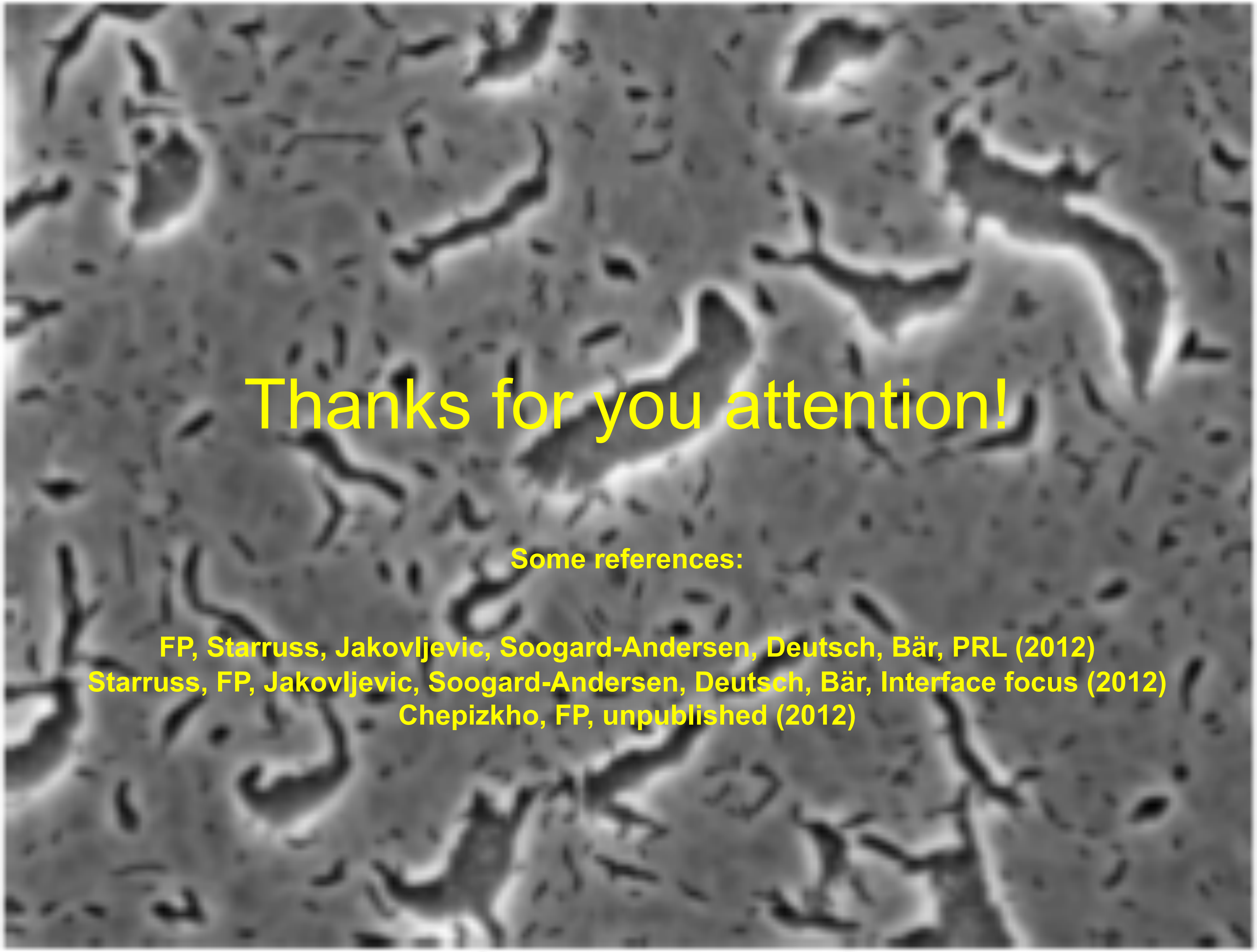


Similar statistical features observed in *B. Subtilis*!

SP + volume exclusion candidate to be a general mechanism in the spatial self-organization of bacteria moving in 2D

FP et al., PRL (2012) & Starruss et al. Interface focus (2012)


Thanks for you attention!
Some references:
FP, Starruss, Jakovljevic, Soogard-Andersen, Deutsch, Bär, PRL (2012)
Starruss, FP, Jakovljevic, Soogard-Andersen, Deutsch, Bär, Interface focus (2012)
Chepizkho, FP, unpublished (2012)