Learning the space-time phase diagram of bacterial swarm expansion

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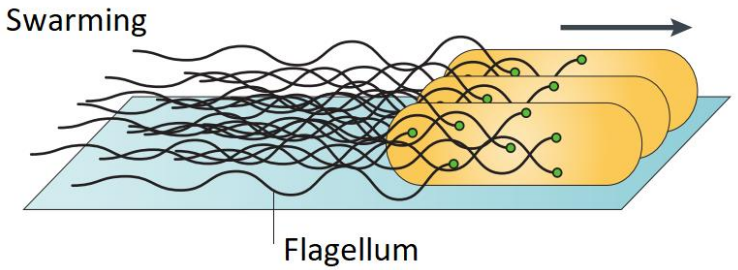
Fundamentals of Growing Active Matter

25.03.2021

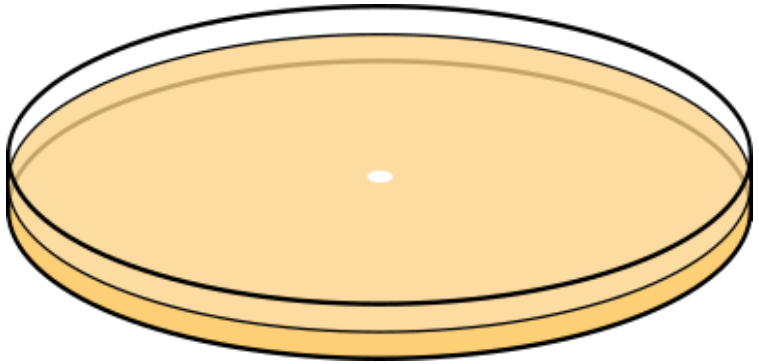
Bacterial swarming & cell-cell interactions

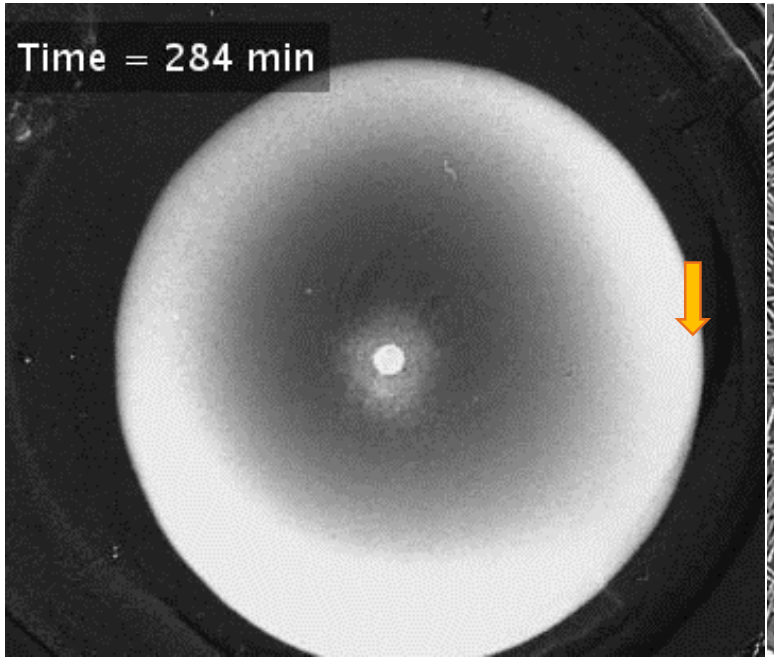
Bacterial swarming is an **active** movement across **surfaces**.

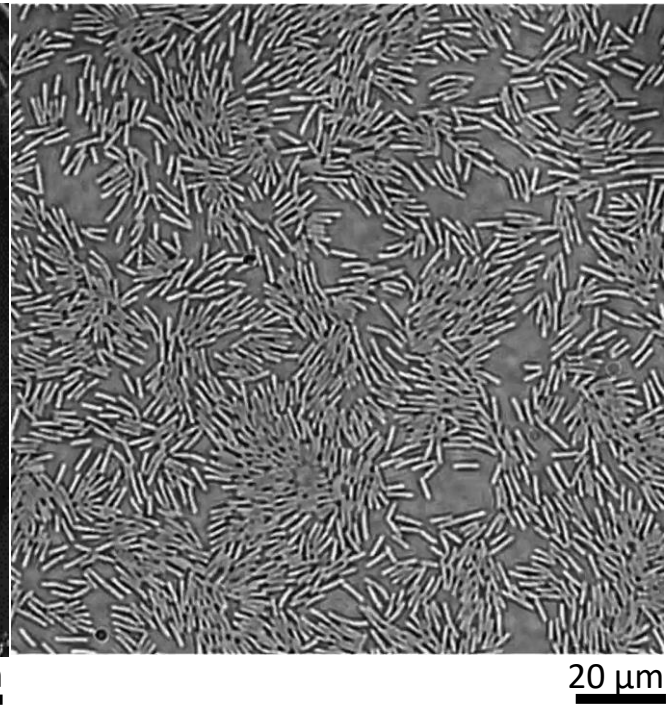
Bacillus subtilis



Patrick & Kearns, *Mol. Microbiol.* 2012







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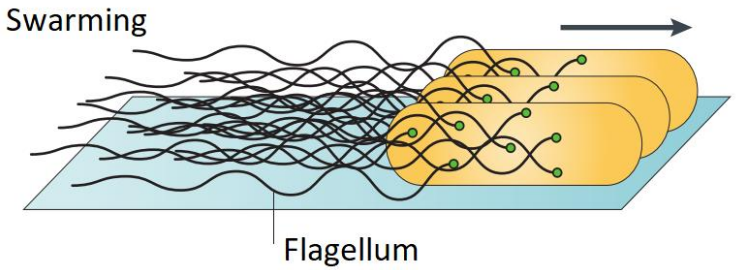

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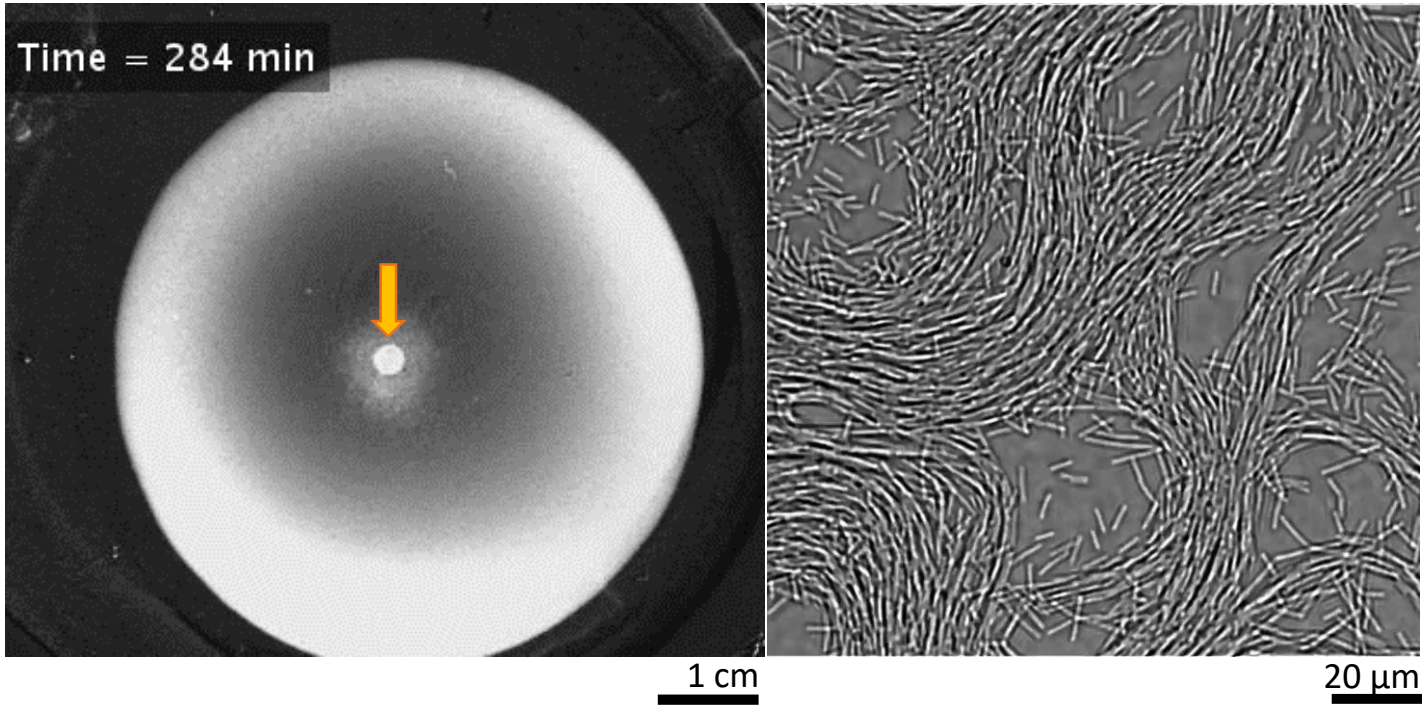


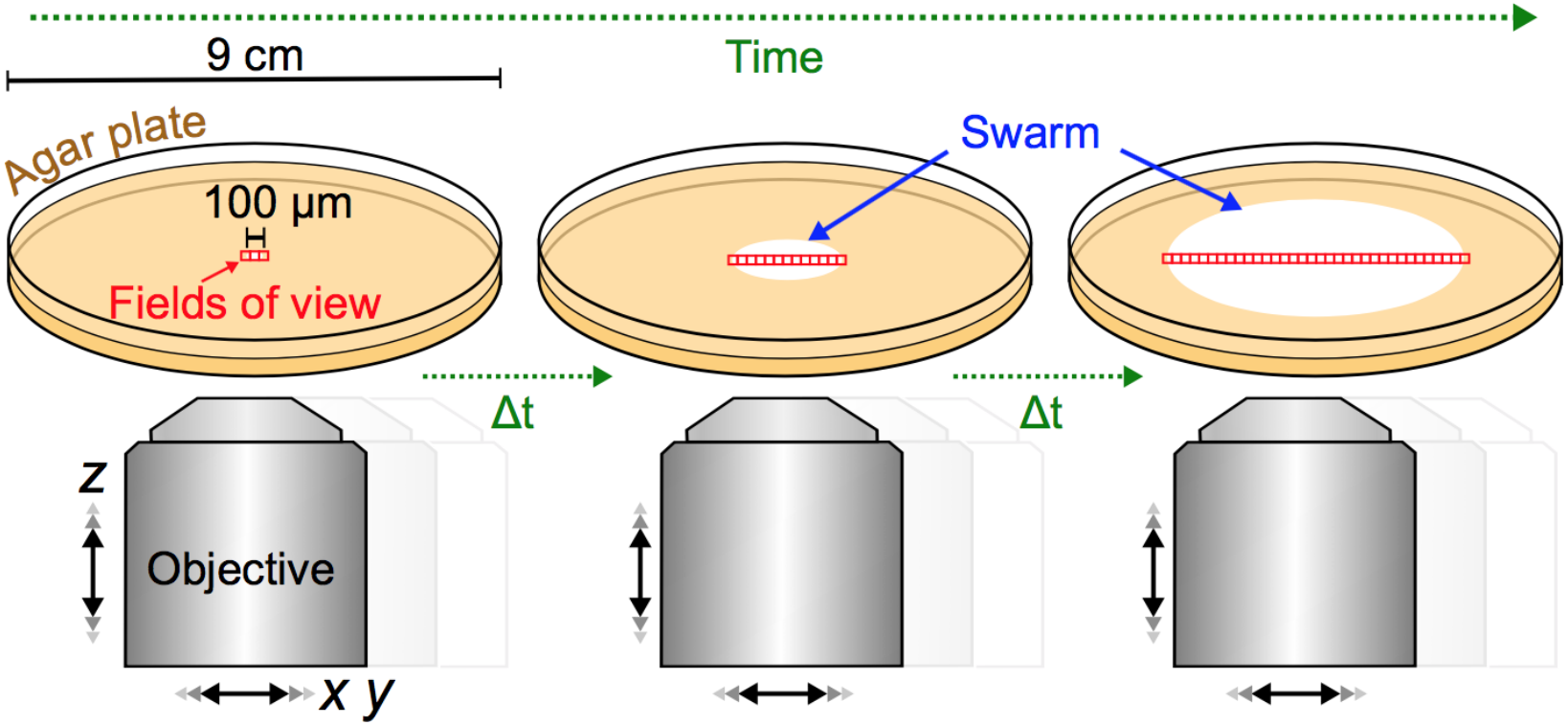
Microscopic dynamics are **diverse** spanning **several orders of magnitude**

Which interactions determine different dynamics and their transition?

Imaging swarm development

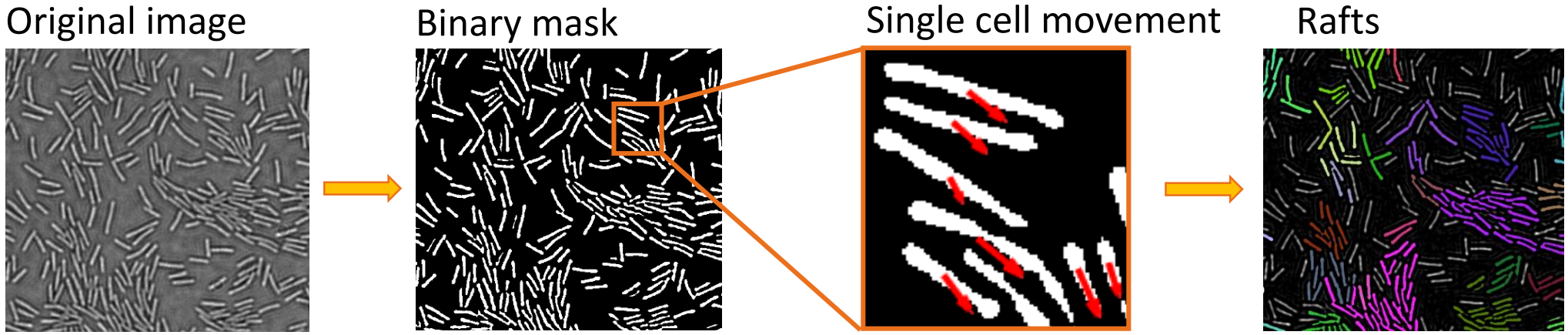
Adaptive microscopy: feedback between image acquisition & analysis

- Follow swarm from 10^0 cell to 10^9 cells
- Single-cell resolution



Quantifying swarm development

Image analysis



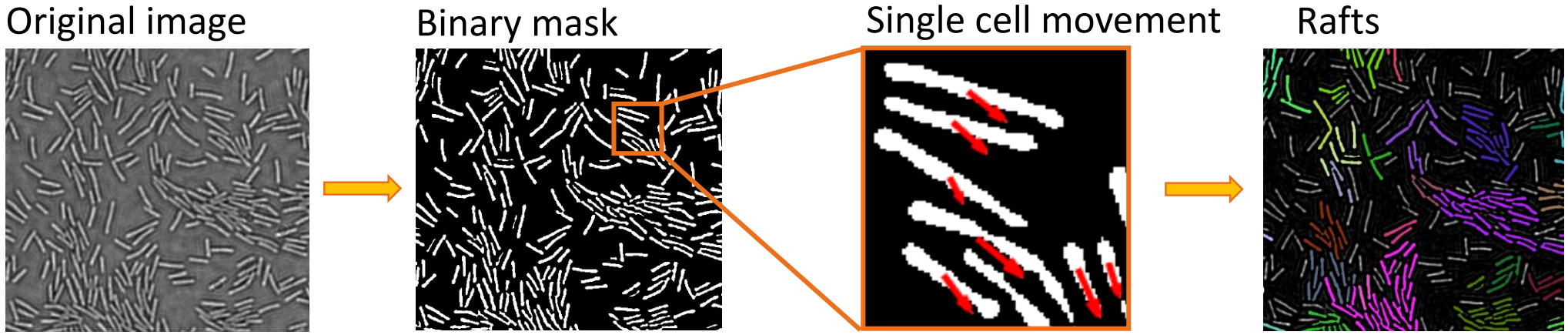
Basic parameters
- Speed
- Cell length
- (Biomass) density
- Number of cells

Emergent parameters
- Ratio of cells within rafts to all cells
- Average size of raft
- Velocity correlation measures
- Number of non-motile cell clumps

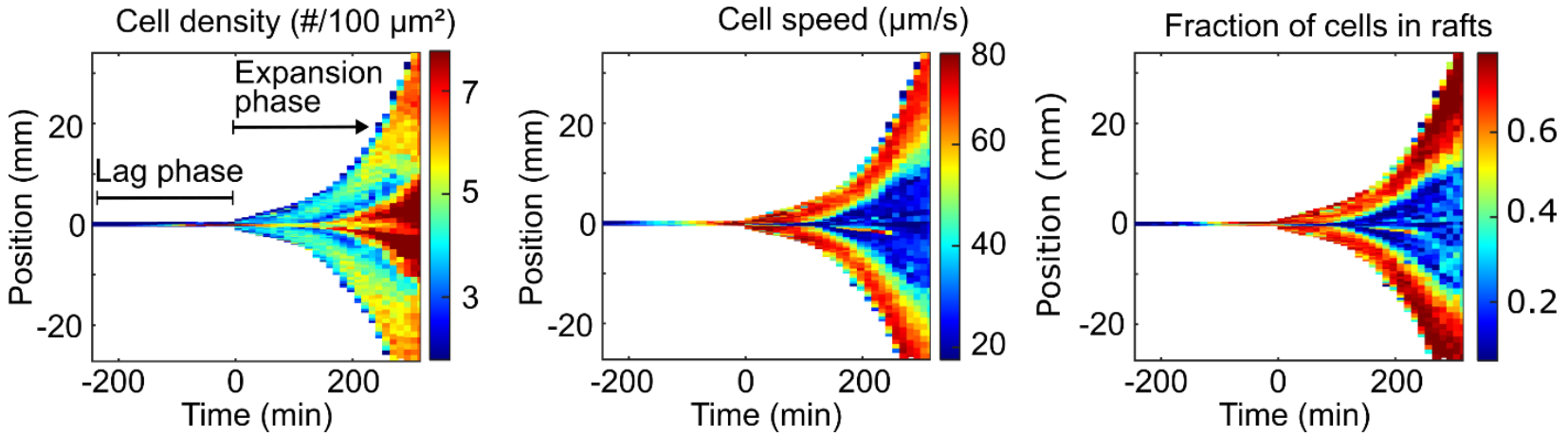
...

Quantifying swarm development

Image analysis



Spatio-temporal swarm development



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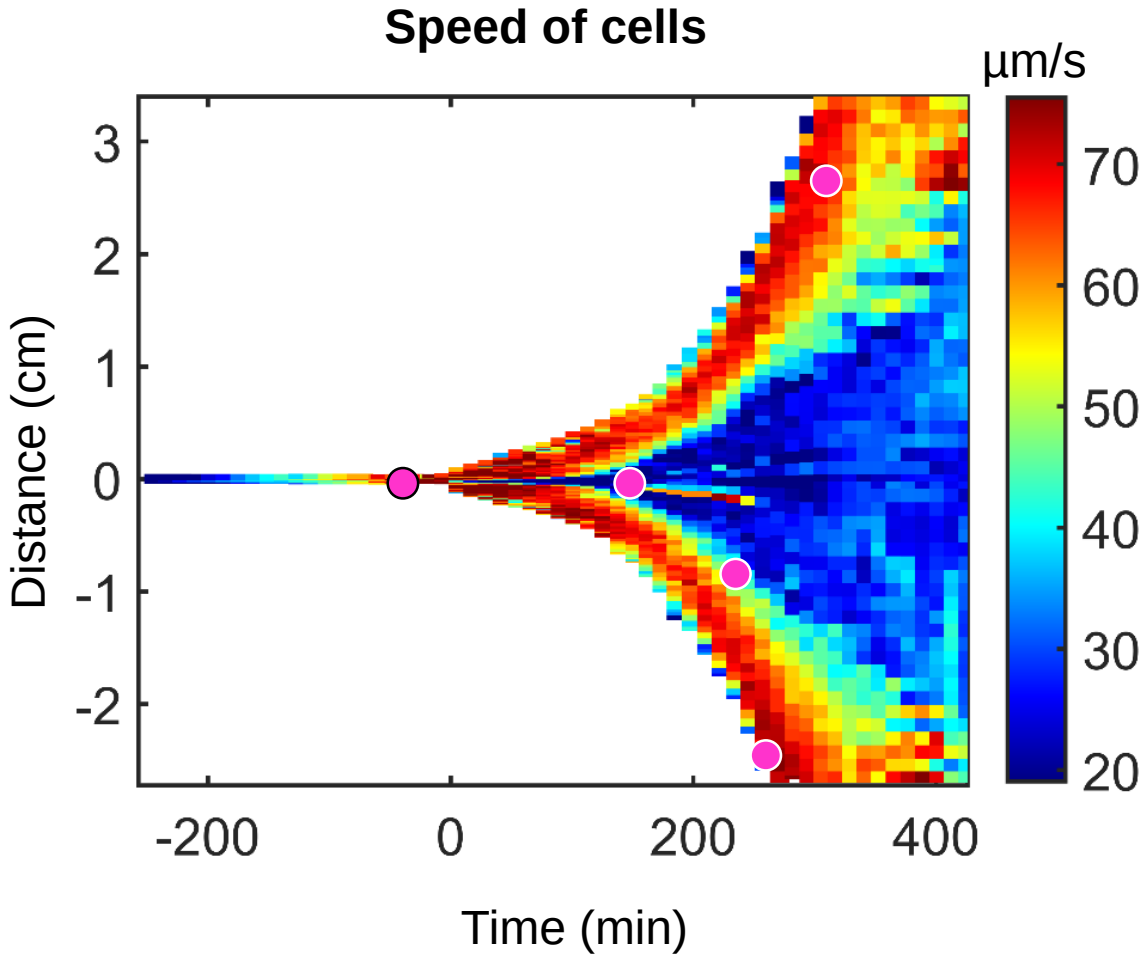
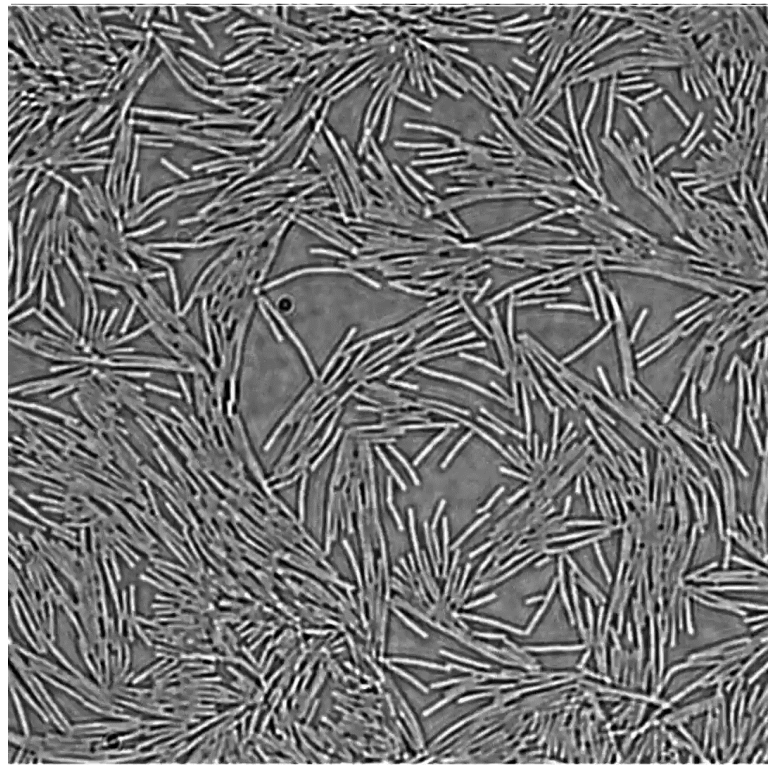
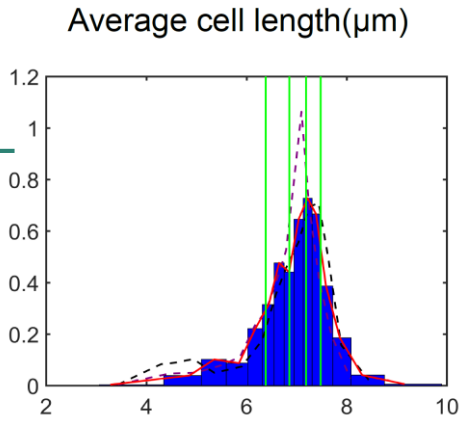
Visualizing swarm *micro* & *macro* development





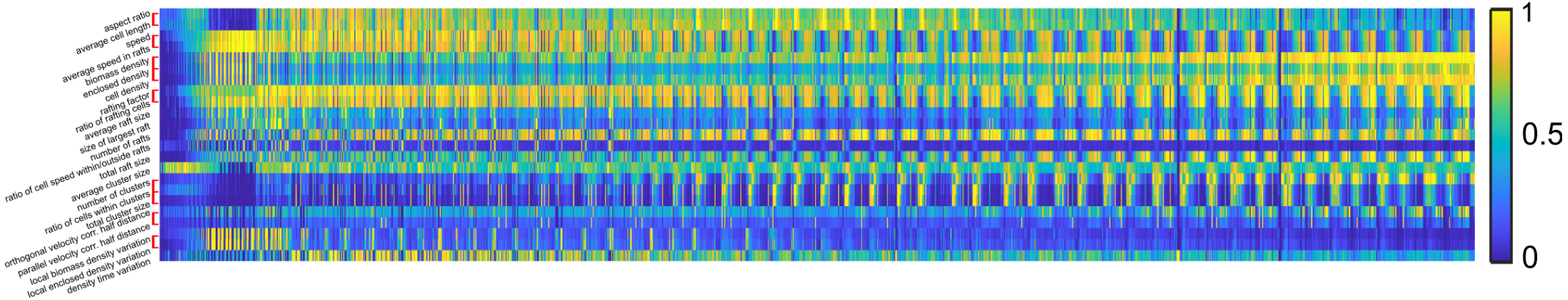
Jeckel et al., *PNAS* 2019
interactive: drescherlab.org/data/swarm

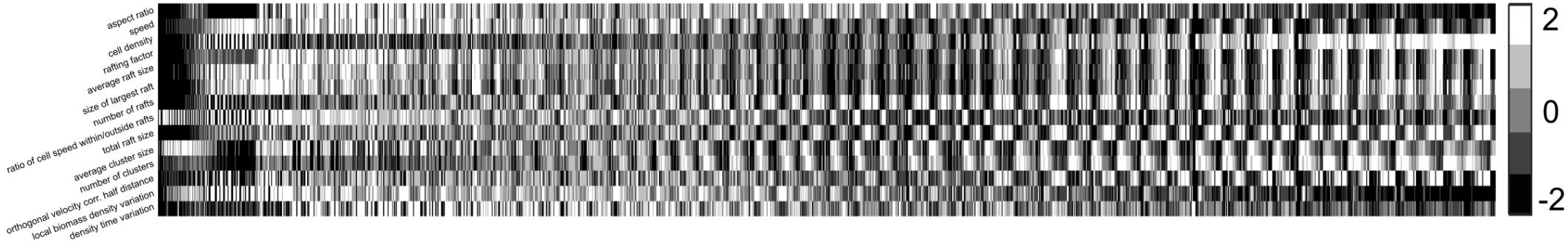
Interpretation of data



Step 1: Remove rendundancies

Step 2: Simplify data (continuous spectrum → integers)



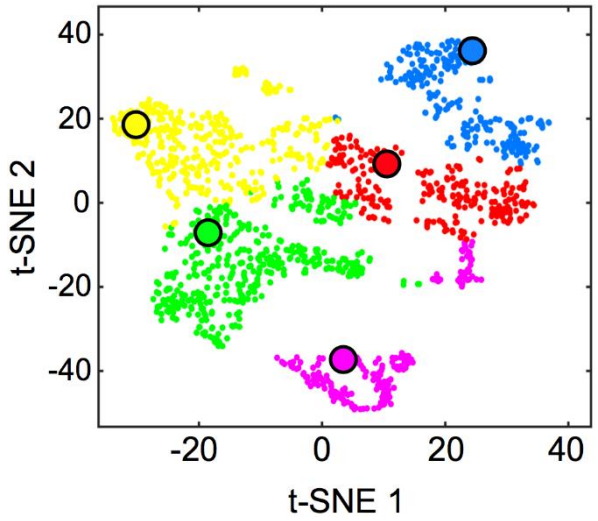


Machine learning the phase diagram of swarm behavior

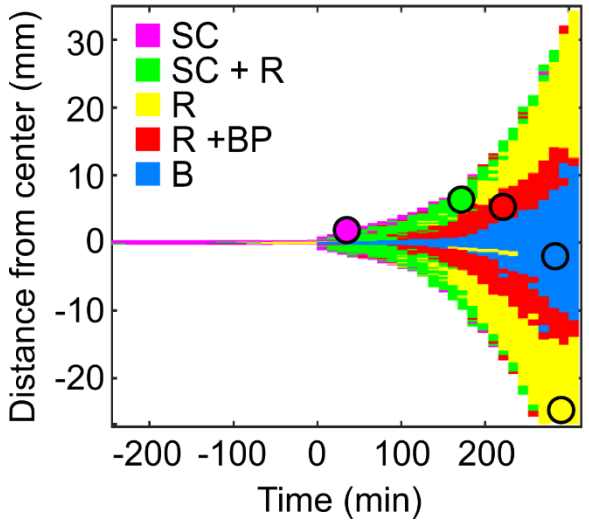
Step 3: Use t-SNE for 2-dimensional representation

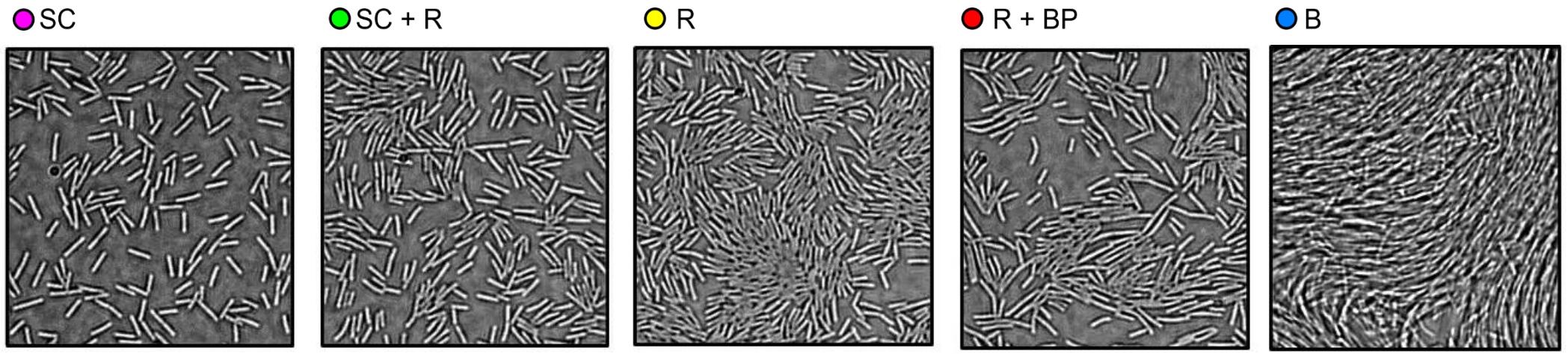
Step 4: Cluster 2D data points

Phase identification:



Phases during swarming:





Jeckel, et al., *PNAS* (2019)

Which cell-cell interactions dominate each phase?

Individual-based simulations

Inertia

Hydrodynamics

Steric interation

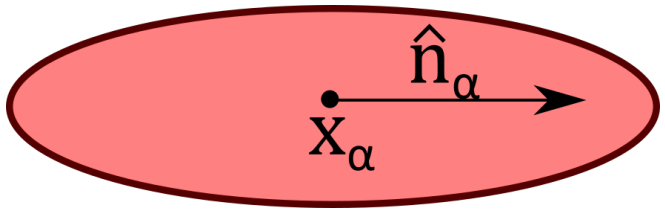
$$m_\alpha \frac{\mathrm{d}^2\mathbf{x}_\alpha}{\mathrm{d}t^2} = \mathbf{\Gamma}_\alpha \left(v_\alpha \hat{\mathbf{n}}_\alpha + \mathbf{U}_\alpha - \frac{\mathrm{d}\mathbf{x}_\alpha}{\mathrm{d}t} \right) - \frac{\partial}{\partial \mathbf{x}_\alpha} V_\alpha$$

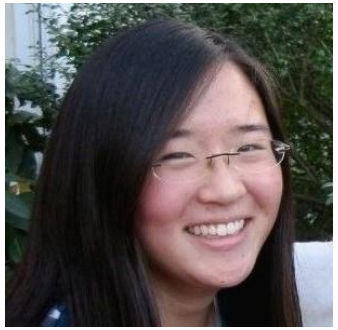
Self propulsion

Friction

+ Biochemical interactions

$$\frac{\mathrm{d}\mathbf{x}_\alpha}{\mathrm{d}t} = v_\alpha \hat{\mathbf{n}}_\alpha - \mathbf{\Gamma}_\alpha^{-1} \frac{\partial V_\alpha}{\partial \mathbf{x}_\alpha}$$





Rachel Mok, MIT

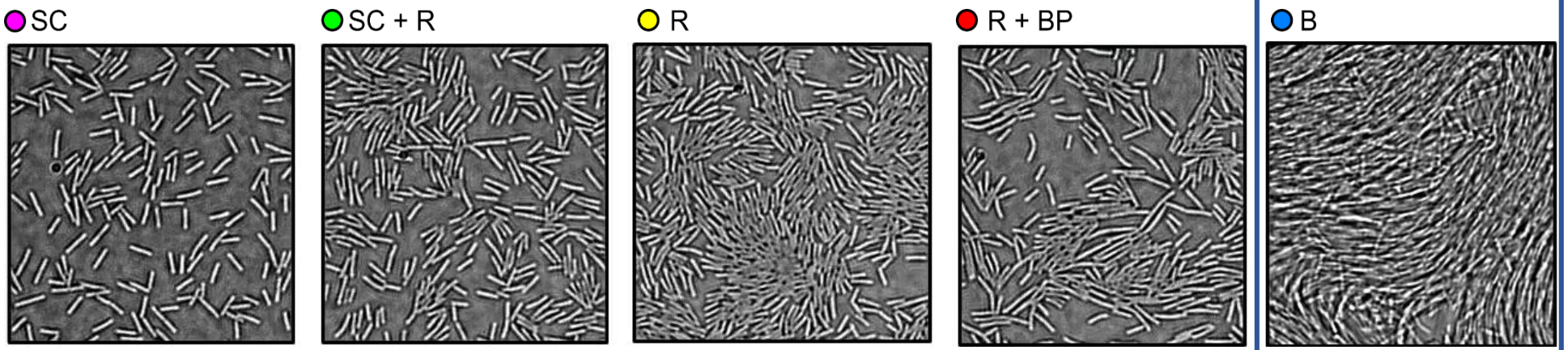
Obtain input parameters from experiment : Cell density, speed, shape for each phase.

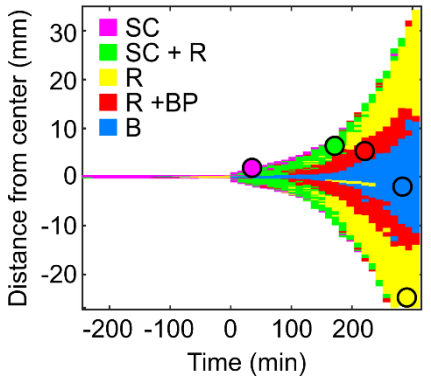
Jeckel, et al., *PNAS* (2019)

Steric cell-cell interactions dominate each phase

Jeckel, et al., *PNAS* (2019)

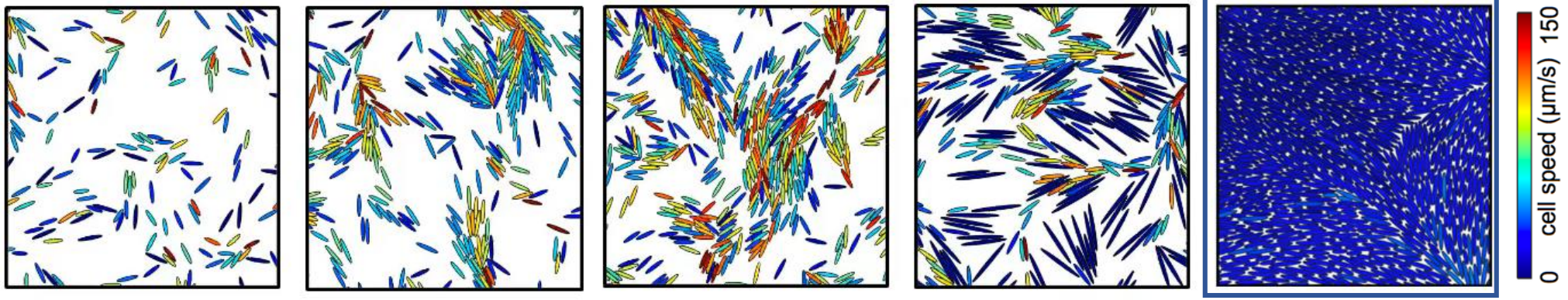
Examples of behavioral phases:





+ growth

Simulations of behavioral phases:

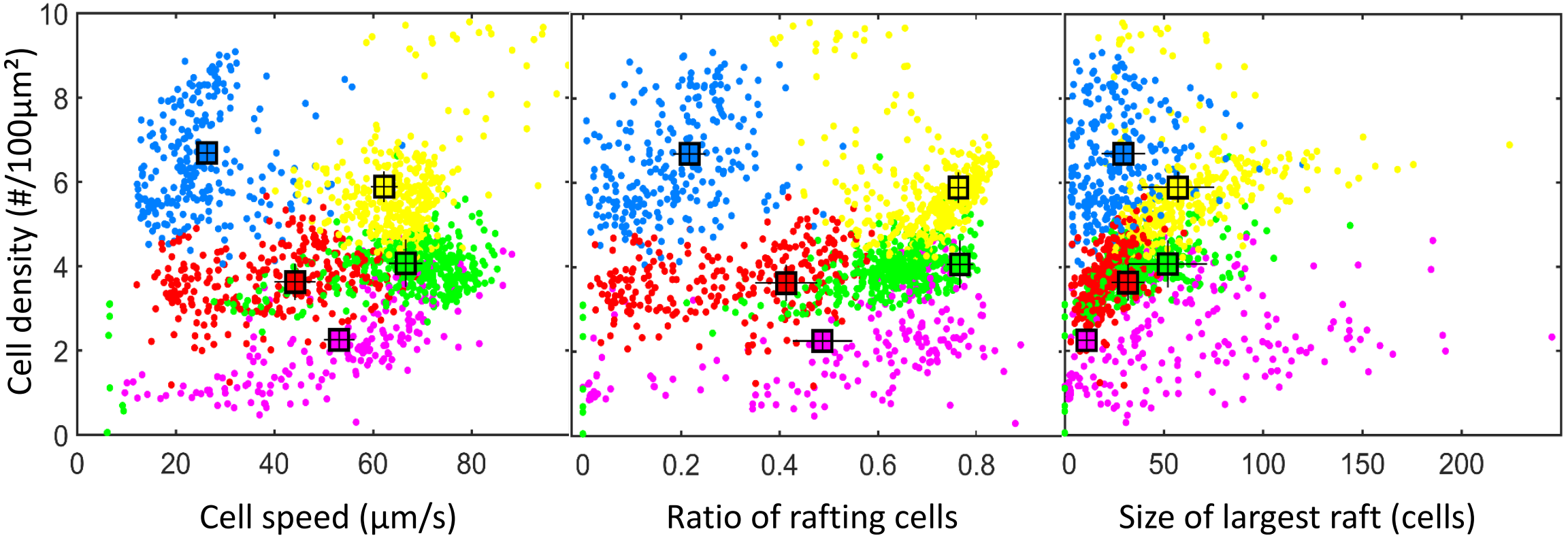


20 μm

All phases can be described by mechanical simulations

Quantiative agreement

Compare emergent parameters:



Quantitative agreement between experiment and simulation.

What determines macroscopic swarm expansion?

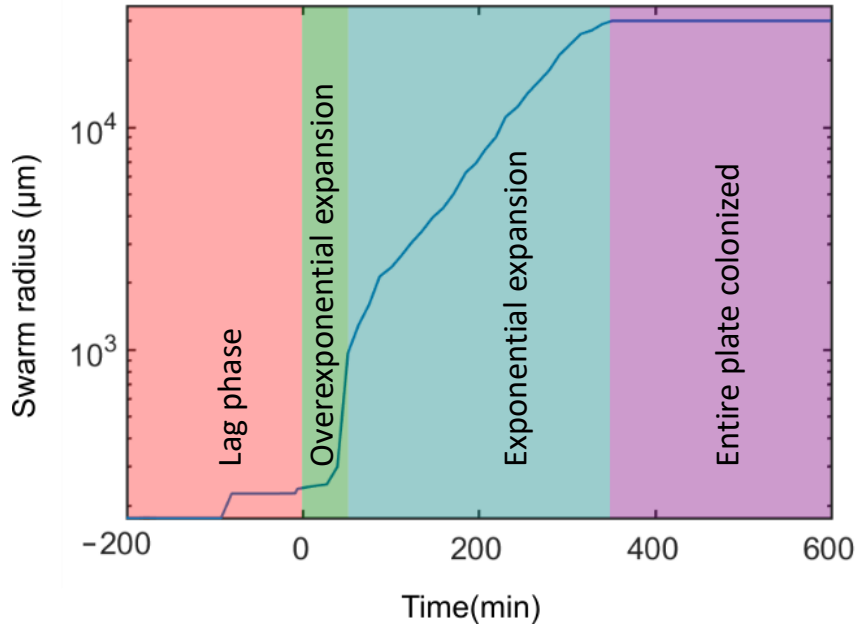

Jan Totz

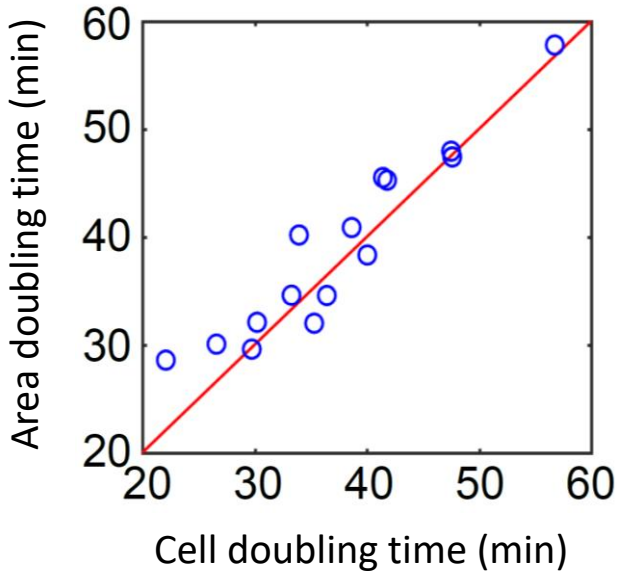
B. Subtilis swarm expansion dynamics:

Lag phase of several hours

Short overexpoential expansion

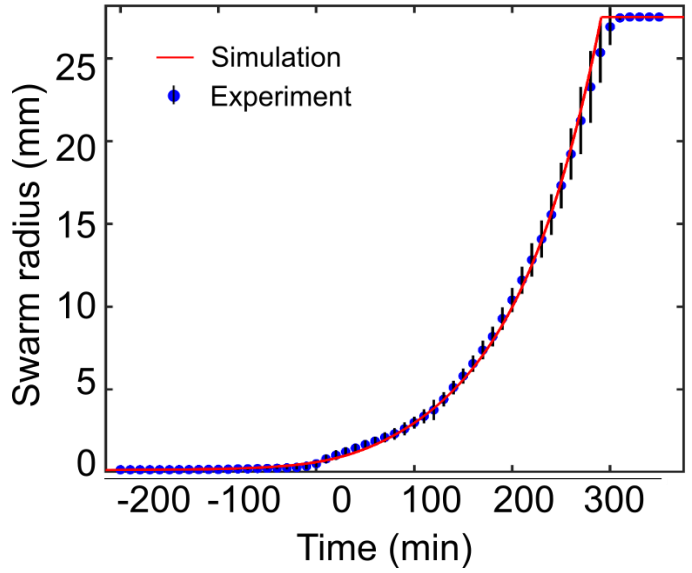
Exponential expansion



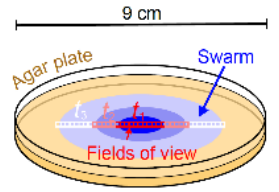


Continuum model

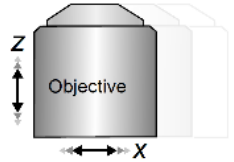
Growth
+ diffusion
+ activity
+ front slip condition



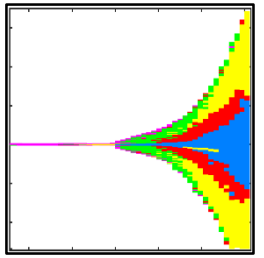
Summary



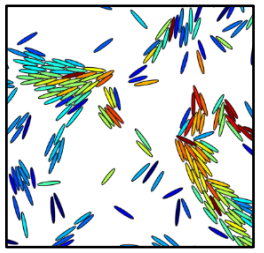
1. Quantified swarm development at cellular resolution



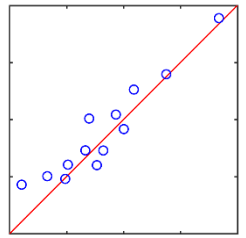
2. Meachine learning reveals 5 dynamical phases



3. Microscopic - Mechanical interactions dominate



4. Macroscopic - Swarm expansion is exponential, set by growth



Jeckel et al., *PNAS* 2019

YouTube

Raw data: drescherlab.org/data/swarm

Thank you!


Jörn Dunkel


Jan Totz


Rachel Mok

Knut Drescher
Jörn Dunkel

Eric Jelli
Ramo Hartmann
Praveen Singh
Rachel Mok
Jan Totz
Lucia Vidakovic
Bruno Eckhardt

Drescher Lab
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Philipps Universität Marburg