OIST

Simone Pigolotti (OIST)

Pattern formation and the physics of growing surfaces

YITP workshop “Frontiers in Nonequilibrium Physics”, 14/5/26

Physics of development

Egg

From larva to adult

© P. Salis, JE Randal

Physics of development

Egg

From larva to adult

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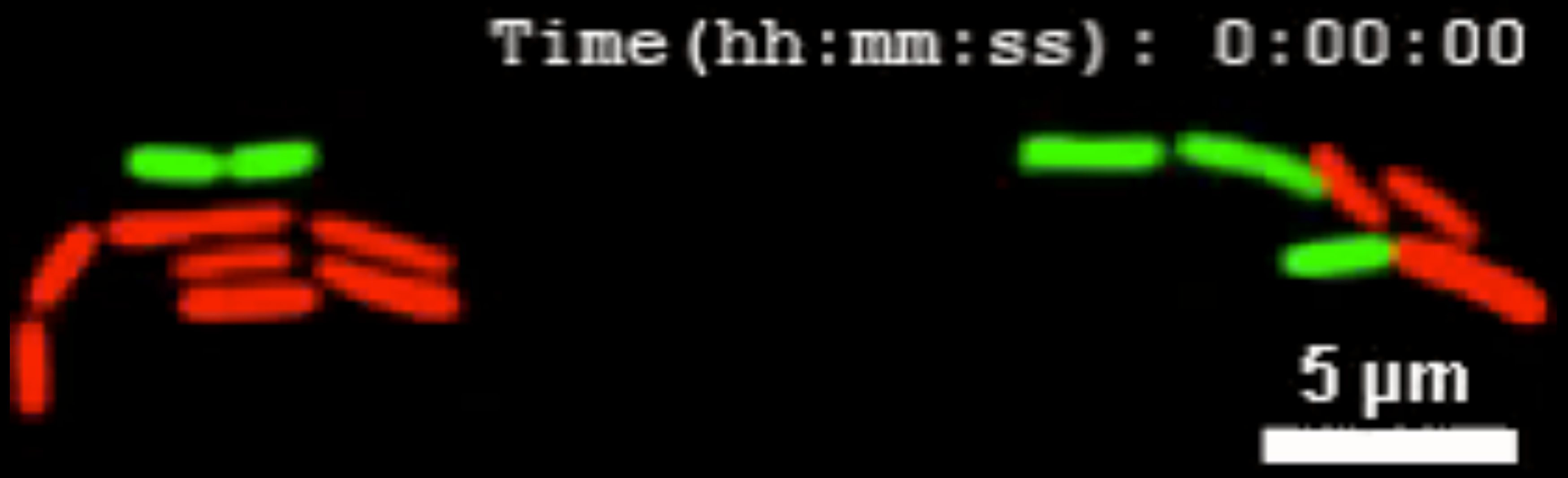
- Can growth unlock new mechanisms for pattern formation?
- How are patterns maintained during growth?

Outline

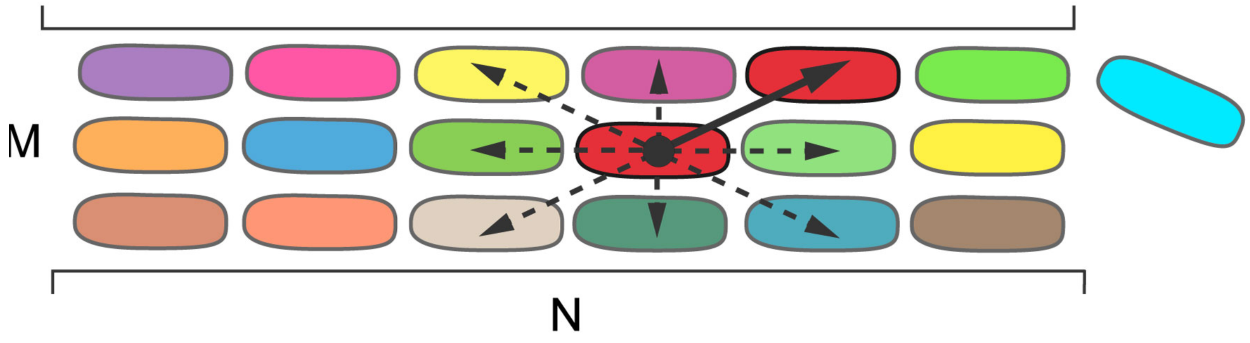
- Pattern formation in microchannels
- Disordered packing on growing surfaces
- Clownfish patterns as an interface problem

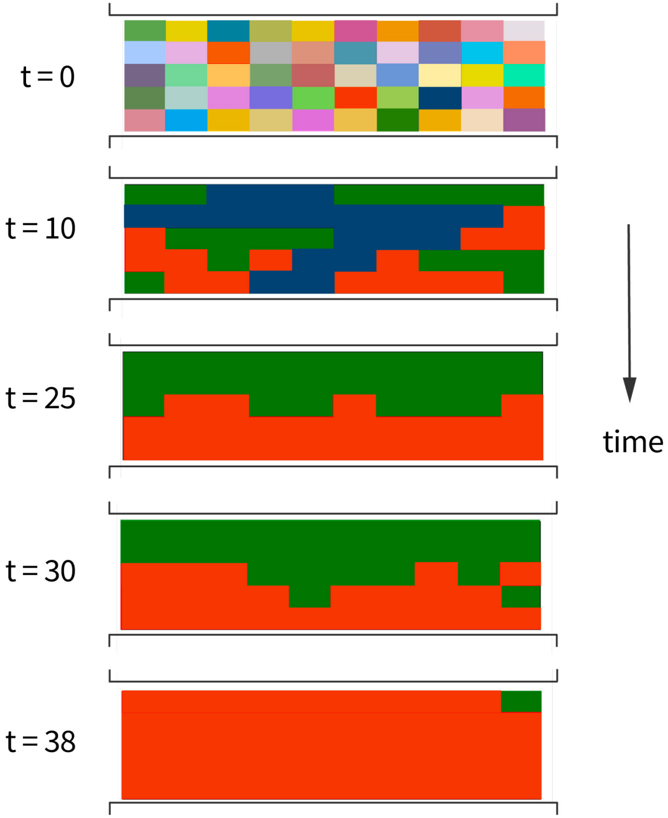
Competition in microchannels



A. Koldaeva, P. Tsai, A. Shen, SP, Proc. Natl. Acad. Sci. (2022)

Model



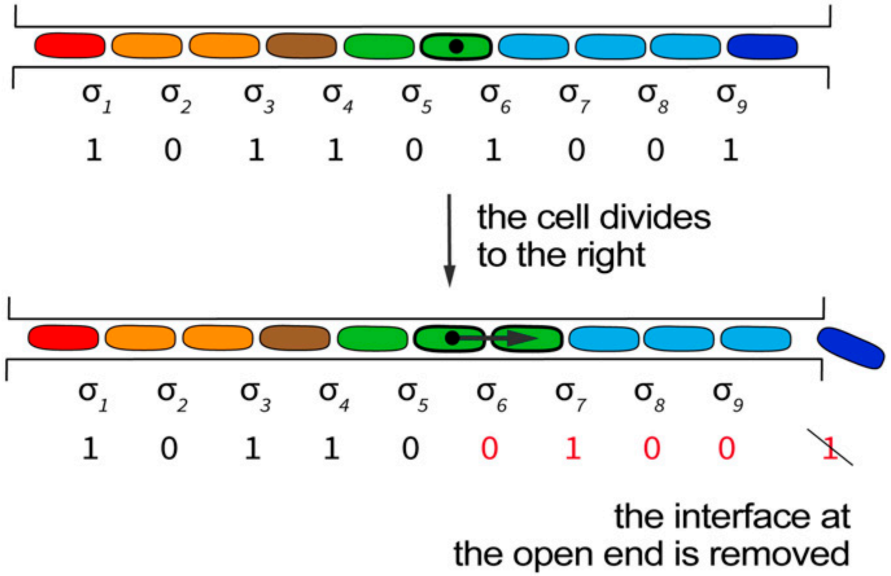


- Cells reproduce into neighboring sites with non-uniform rates.

- Each reproduction event pushes an entire lane of other cells, leading to an expulsion of another cell

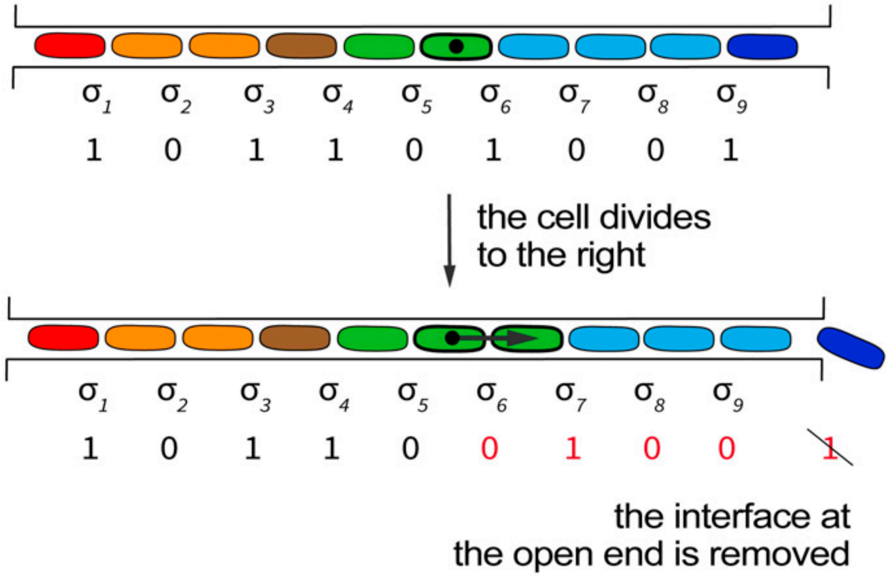
A. Koldaeva, P. Tsai, A. Shen, SP, Proc. Natl. Acad. Sci. (2022)

Interface density



A. Koldaeva, P. Tsai, A. Shen, SP, PNAS (2022)

Interface density



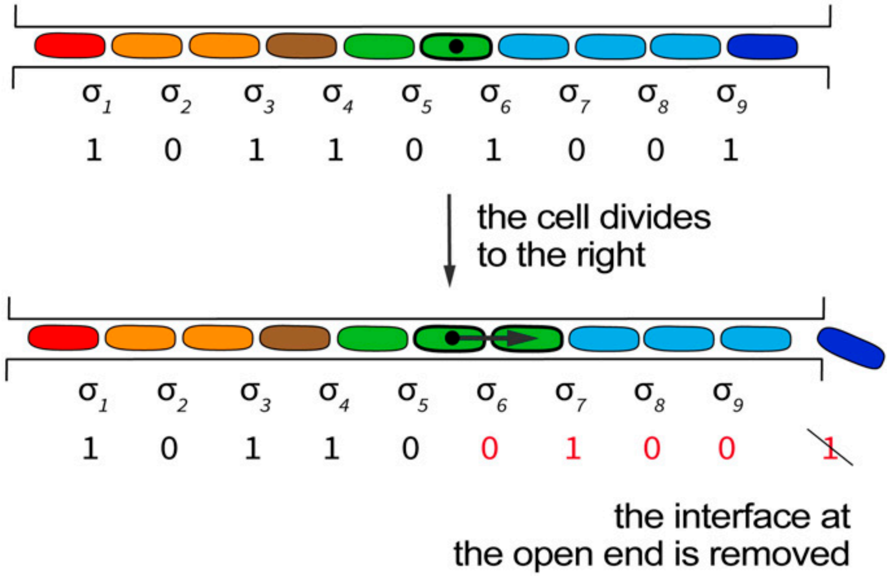
$$\hat{b}_r^i \vec{\sigma} = (\sigma_1, \sigma_2, \ldots, \sigma_{i-1}, \sigma_{i+1}, \ldots, \sigma_{N-1}, 0),$$
$$\hat{b}_l^i \vec{\sigma} = (0, \sigma_1, \sigma_2, \ldots, \sigma_{i-1}, \sigma_{i+1}, \ldots, \sigma_{N-1}),$$
$$\hat{c}_r^i \vec{\sigma} = (\sigma_1, \sigma_2, \ldots, \sigma_{i-1}, \sigma_{i+1}, \ldots, \sigma_{N-1}, 1),$$
$$\hat{c}_l^i \vec{\sigma} = (1, \sigma_1, \sigma_2, \ldots, \sigma_{i-1}, \sigma_{i+1}, \ldots, \sigma_{N-1}).$$

Master equation for the interfaces:

$$\frac{dP_{\vec{\sigma}}}{dt} = -b \sum_{i=1}^{N-1} [q(i) + p(i+1)] P_{\vec{\sigma}}(t) +$$
$$+ b \sum_{i=1}^{N-1} \delta_{\sigma_i,0} [q(i)(P_{\hat{b}_r^i \vec{\sigma}} + P_{\hat{c}_r^i \vec{\sigma}}) + p(i+1)(P_{\hat{b}_l^i \vec{\sigma}} + P_{\hat{c}_l^i \vec{\sigma}})],$$

A. Koldaeva, P. Tsai, A. Shen, SP, PNAS (2022)

Interface density

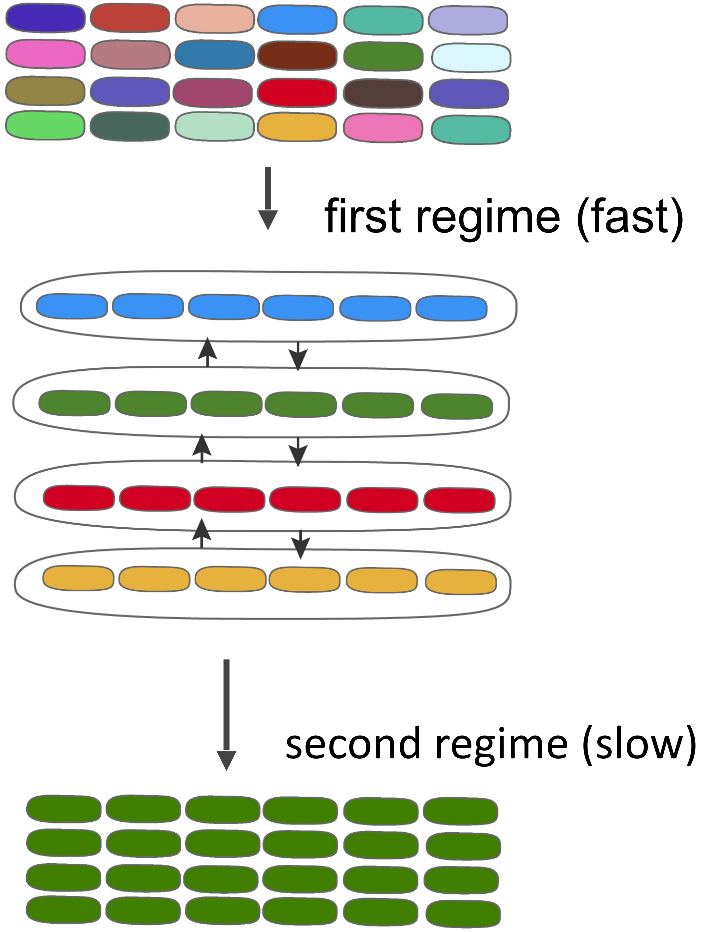


Results:

- $\{\sigma_i\}$ are i.i.d. with: $P(\sigma_i(t) = 1) = e^{-bt}$
- Diversity loss: $\langle A(t) \rangle = (N-1)e^{-bt} + 1$
- Fixation time: $T_{N\to 1} = b^{-1} \sum_{A=2}^{N} \frac{1}{A-1} \approx b^{-1}[\log(N-1) + \gamma]$
- Fixation probabilities: approx. Gaussian with $\sigma \approx \sqrt{N}$

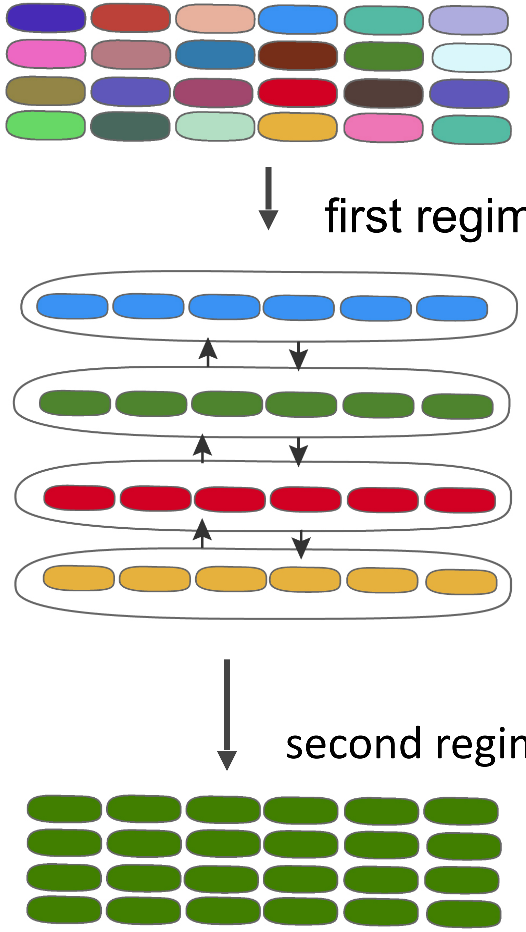
A. Koldaeva, P. Tsai, A. Shen, SP, PNAS (2022)

Fixation dynamics



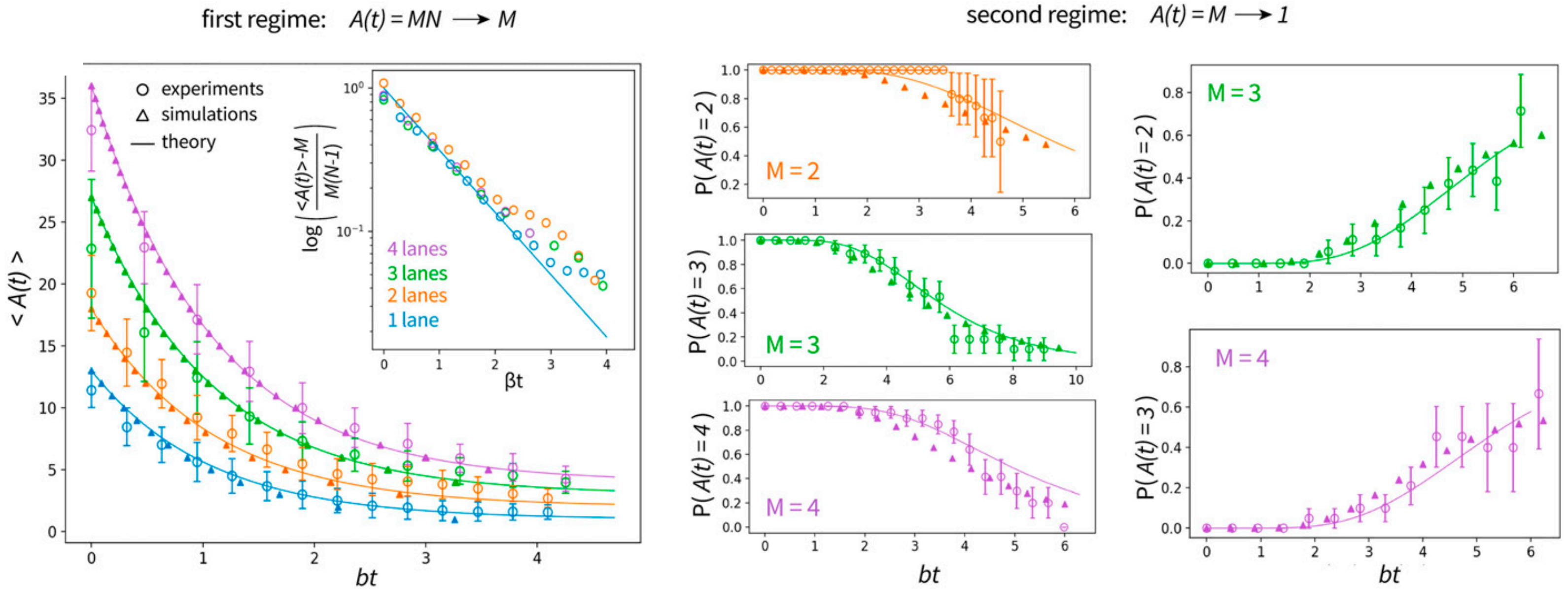
A. Koldaeva, P. Tsai, A. Shen, SP, PNAS (2022)

Fixation dynamics



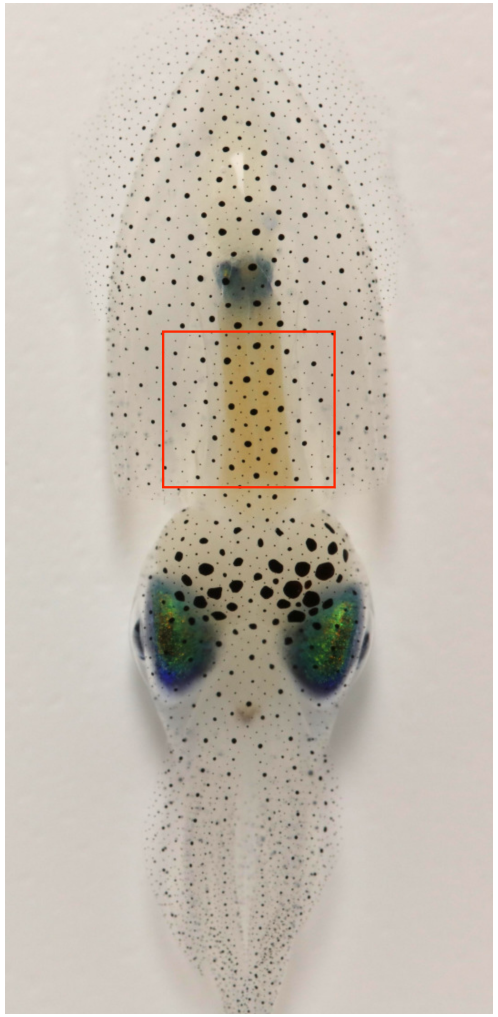
first regime (fast)

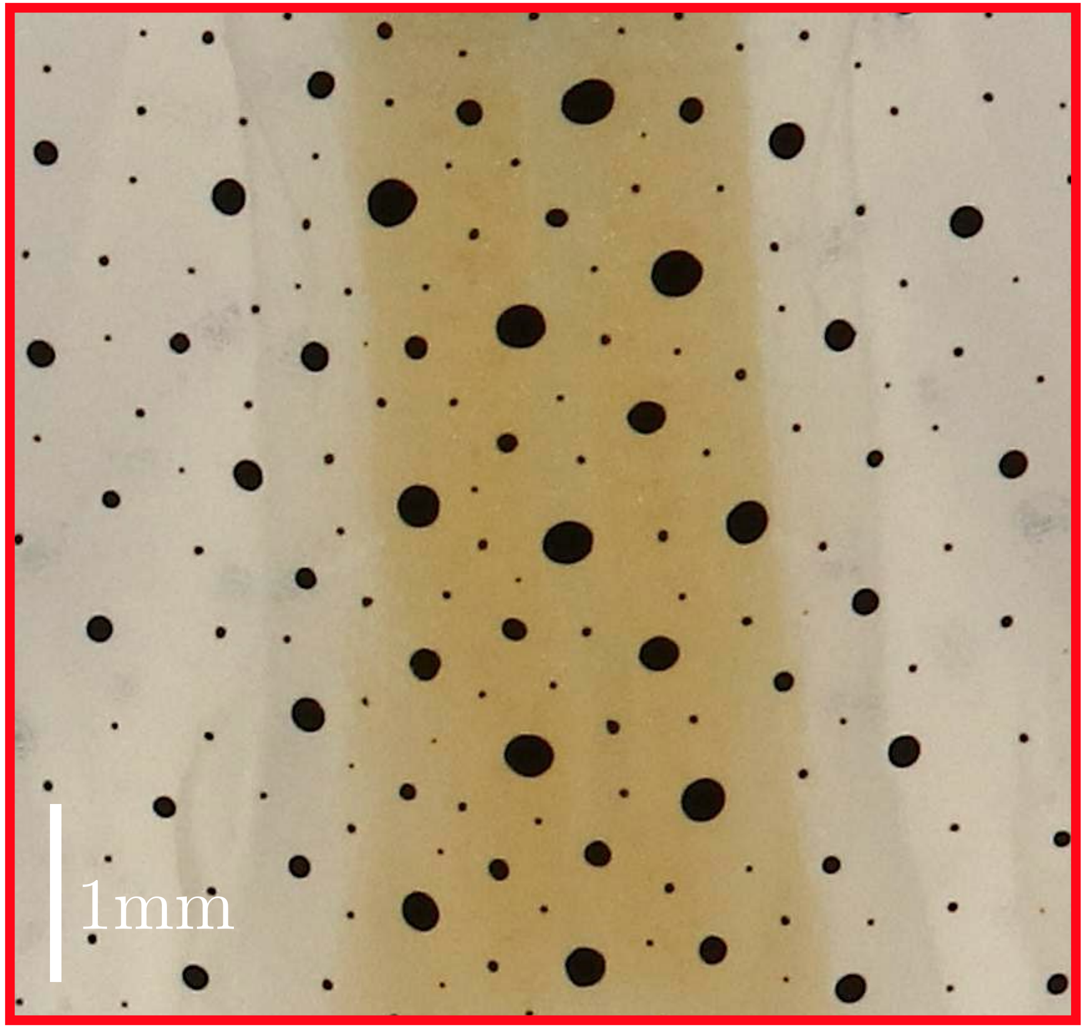
second regime (slow)



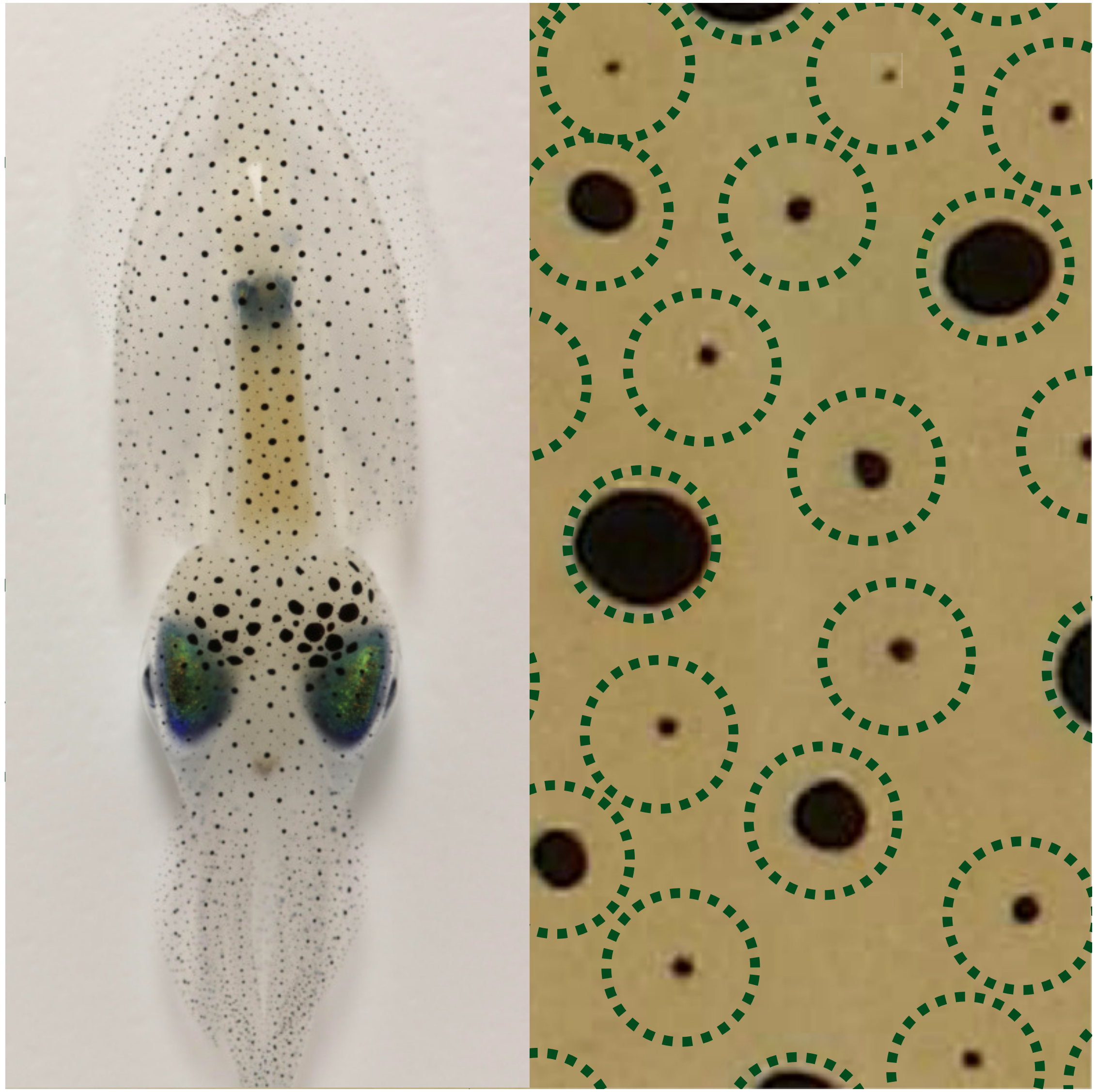
A. Koldaeva, P. Tsai, A. Shen, SP, PNAS (2022)

Ok, what about multicellular organisms?

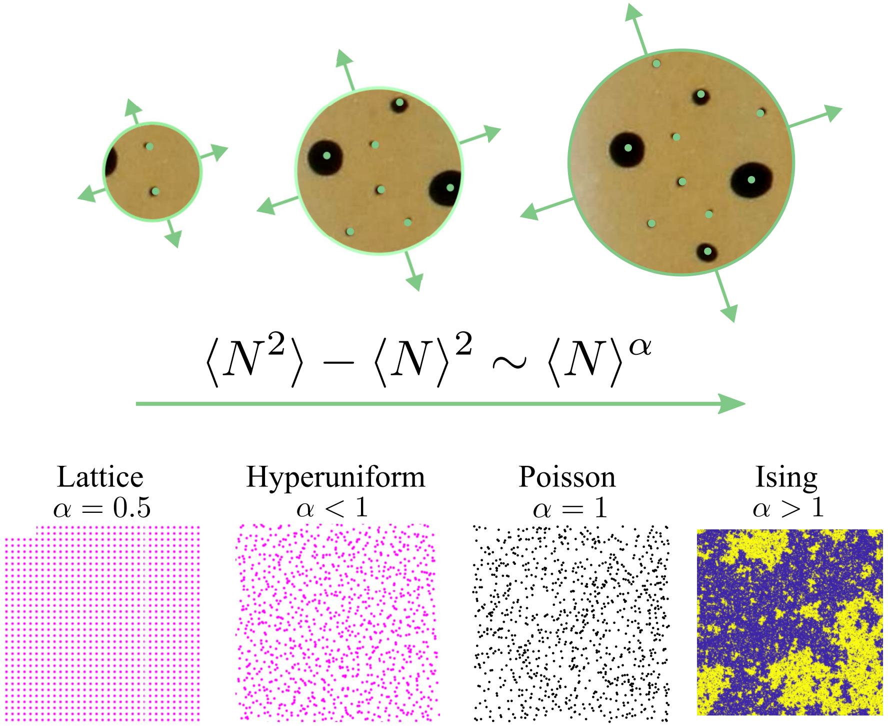


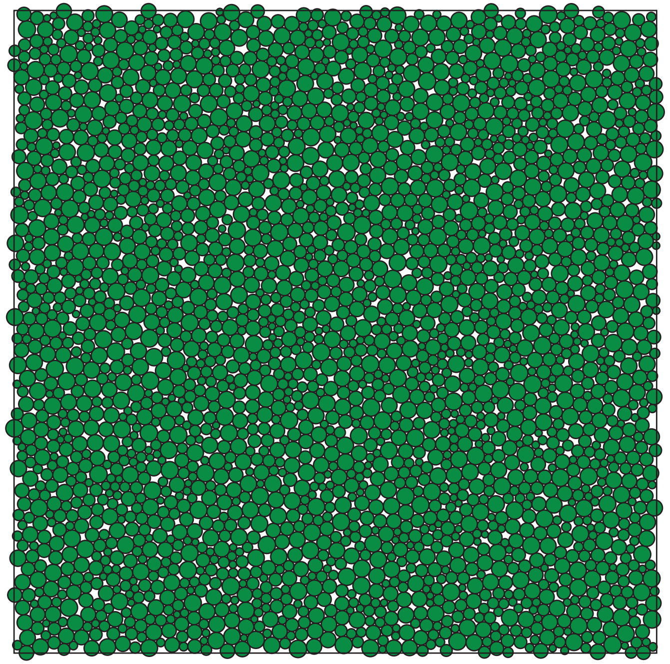


R. Ross …. SP, Phys. Rev. X (2025)



Hyperuniformity?



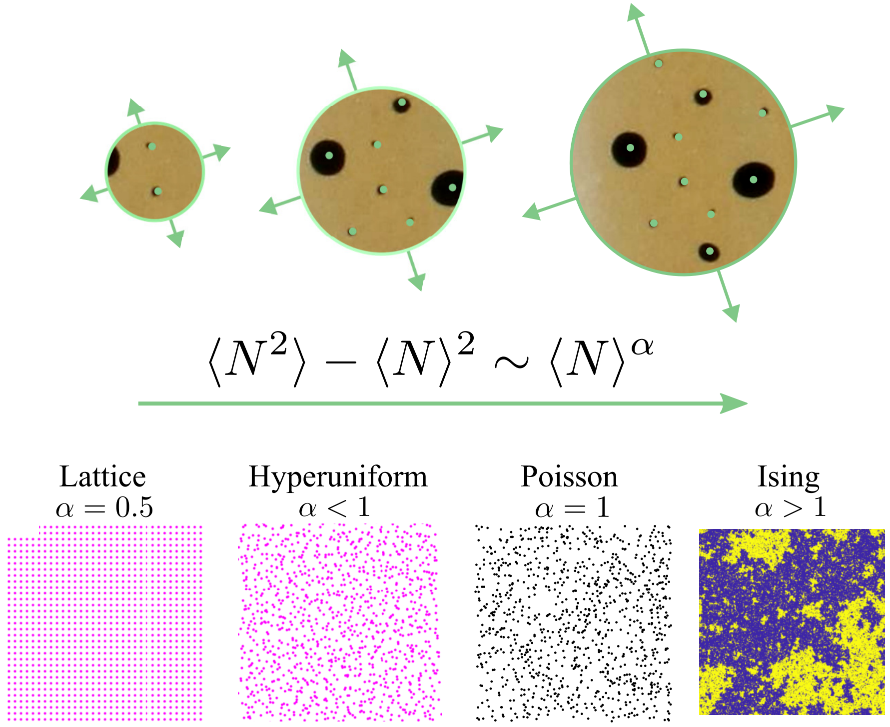


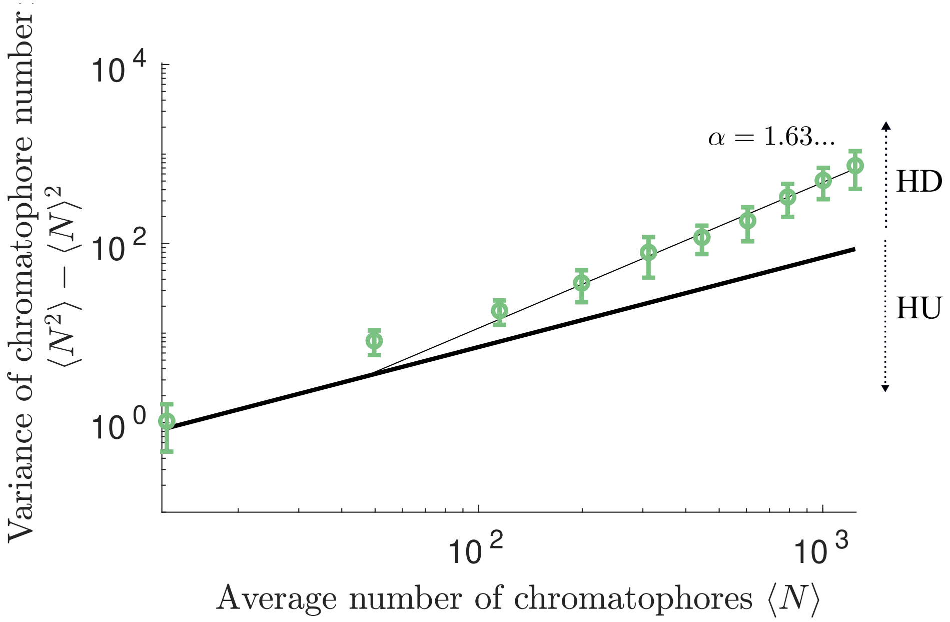
Zachary, Jiao, Torquato, PRE (2011)

Random jammed systems are hyperuniform $(\alpha < 1)$

R. Ross …. SP, Phys. Rev. X (2025)
S. Torquato, Phys. Rep. (2018)

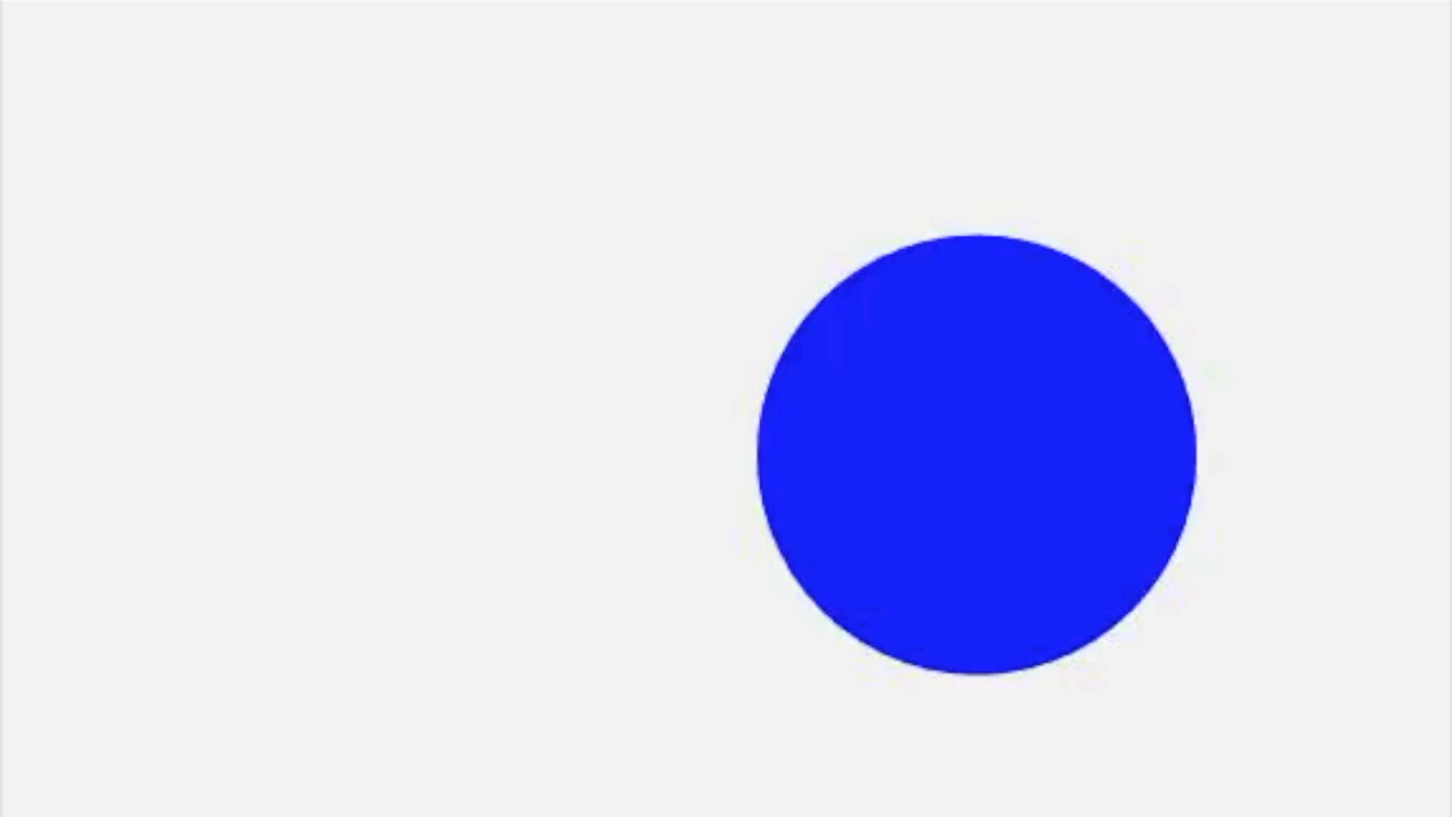
Hyperdisordered behavior





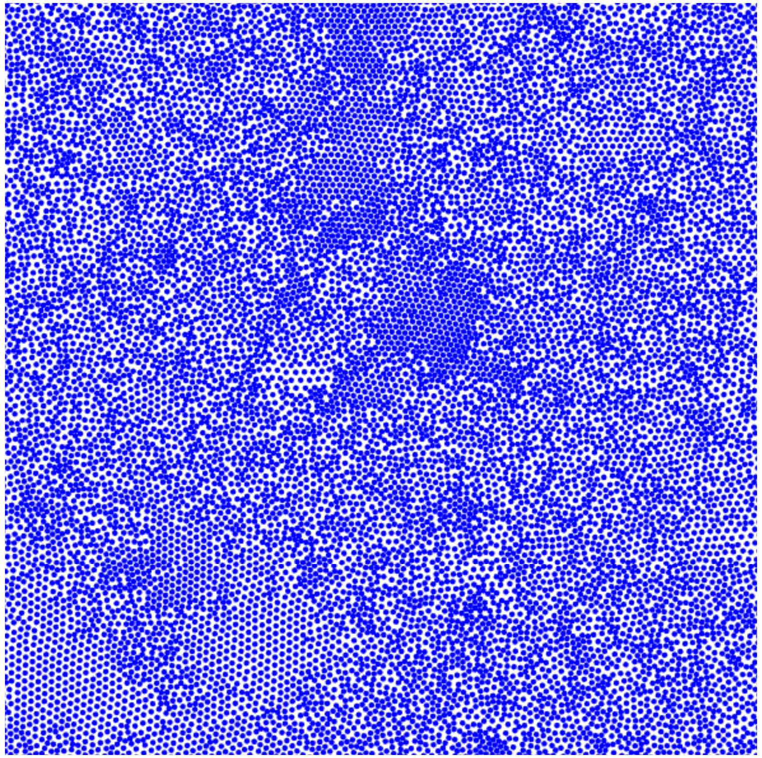
R. Ross …. SP, Phys. Rev. X (2025)

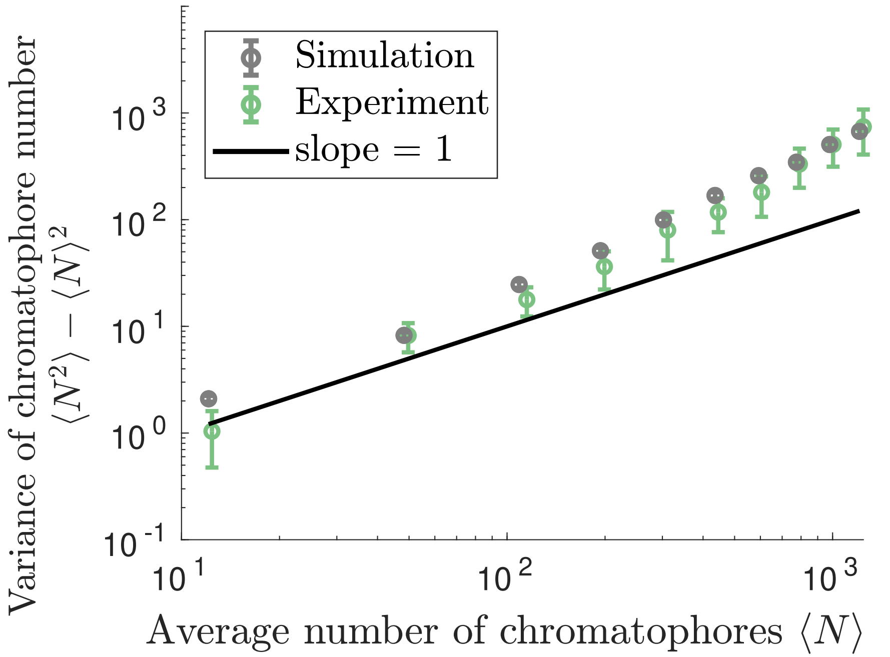
Packed disks on growing domains



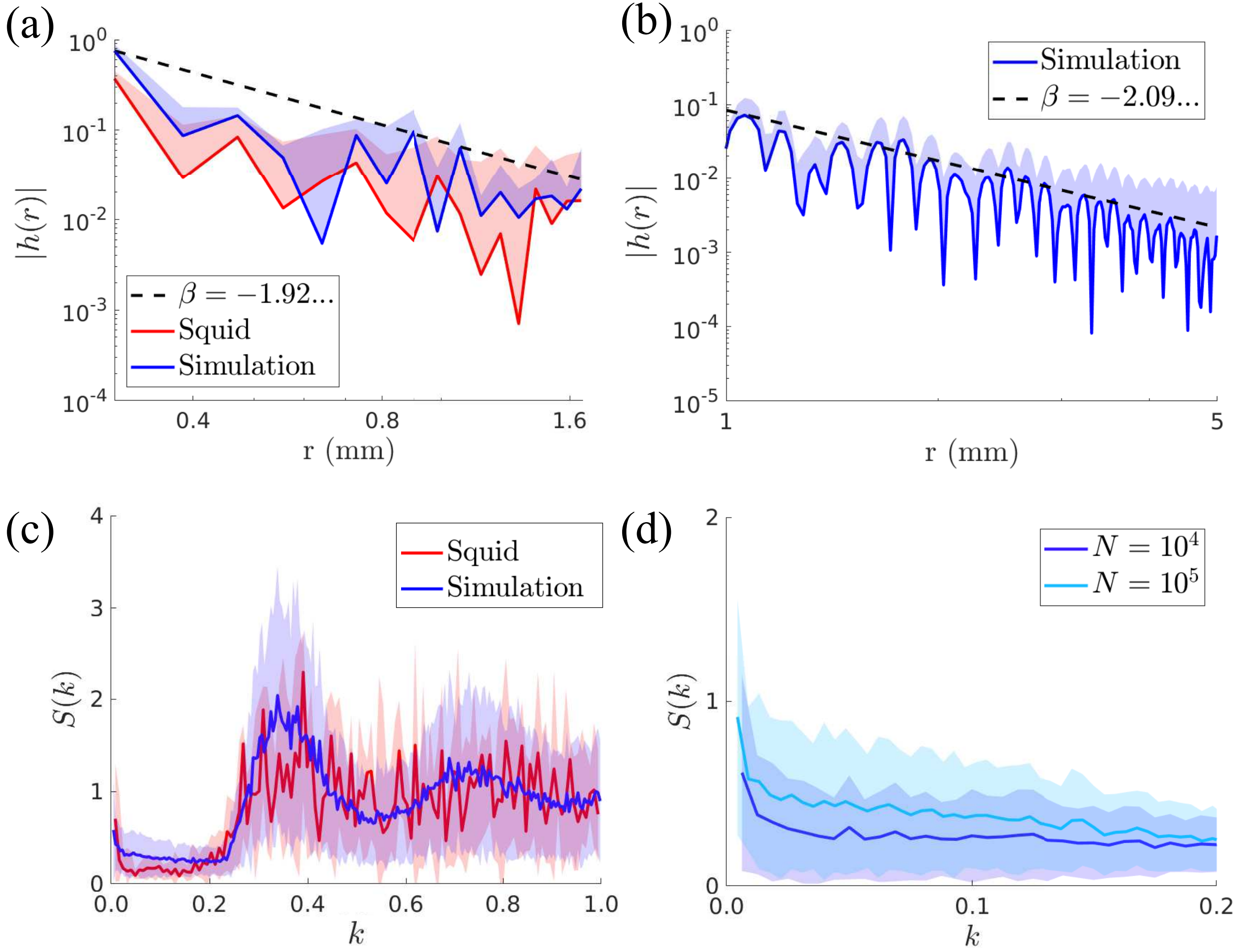
R. Ross …. SP, Phys. Rev. X (2025)

Packed disks on growing domains



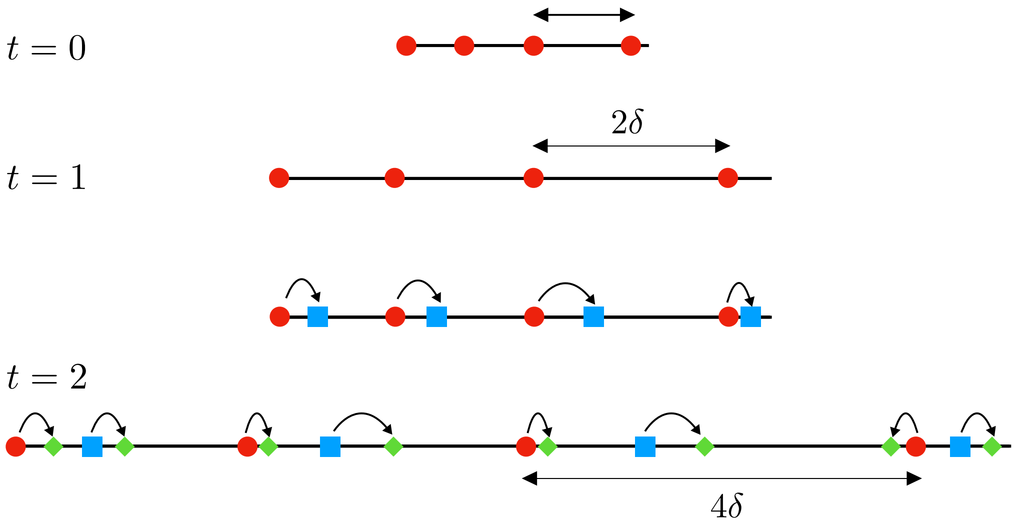


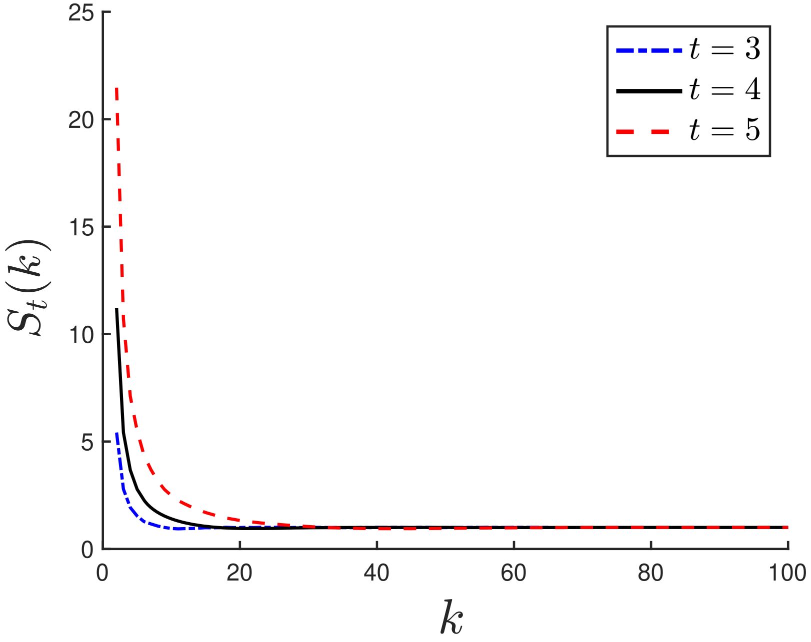
R. Ross …. SP, Phys. Rev. X (2025)



R. Ross …. SP, Phys. Rev. X (2025)

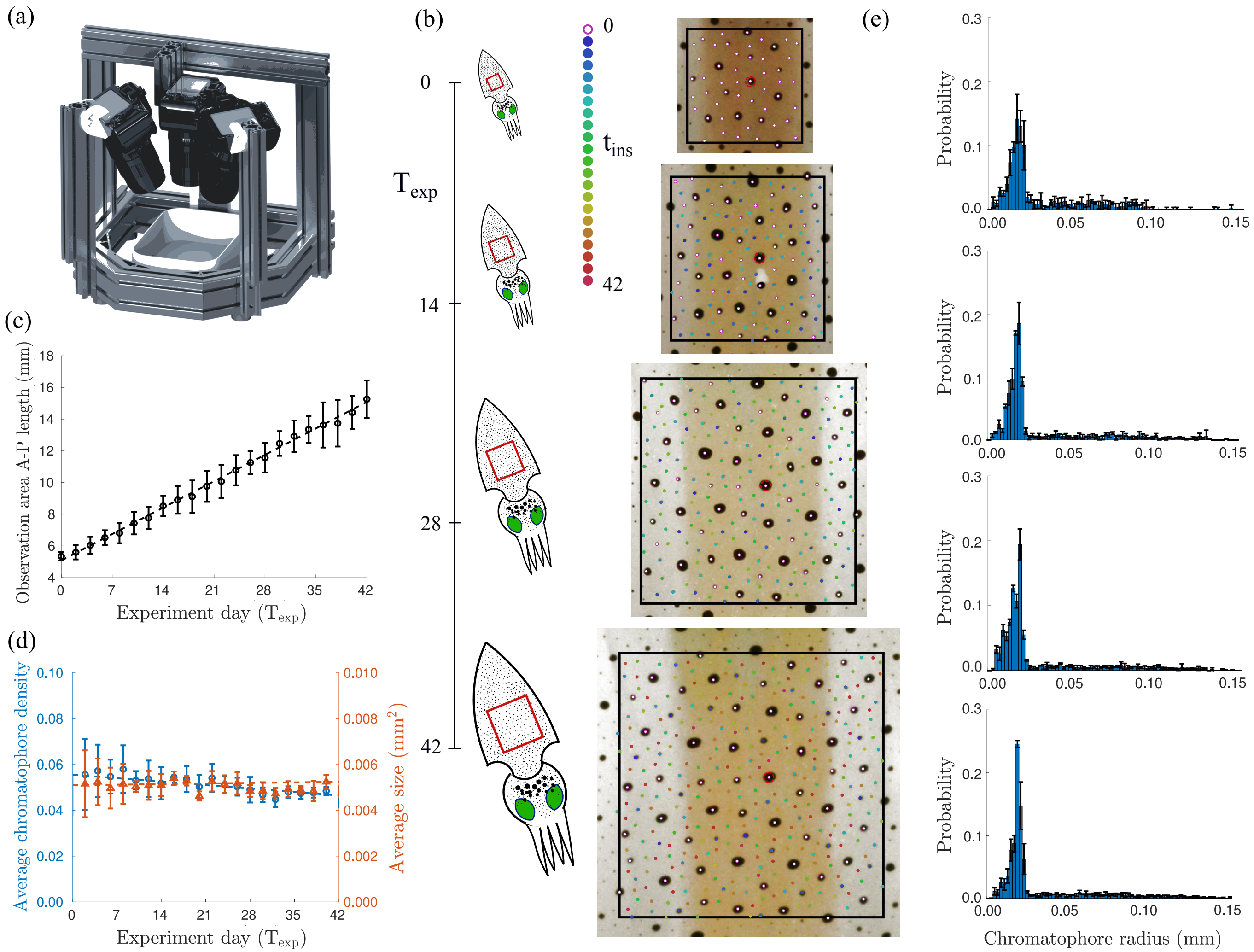
Hierarchical toy model (1D)





Density fluctuations are exported to larger and larger scales

Stationary distribution of chromatophore sizes

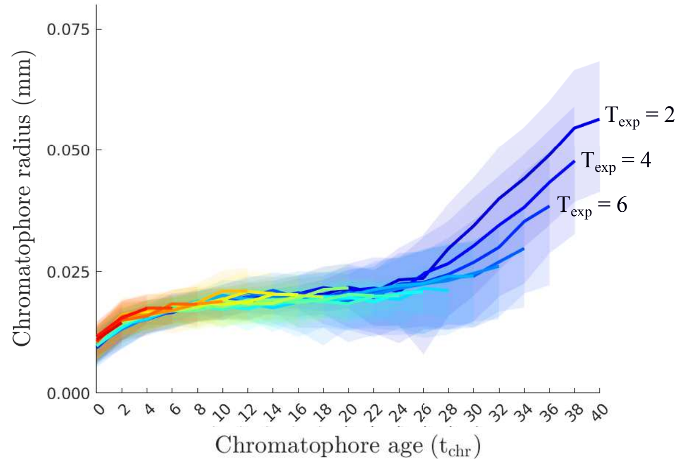


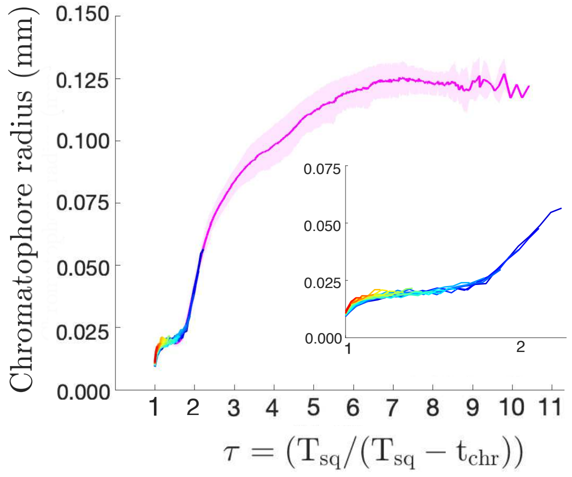
R. Ross …. SP, Phys. Rev. X (2025)

Stationary distribution of chromatophore sizes

$$p(R) = \int_0^\infty dt_{\mathrm{chr}}\, p(R|t_{\mathrm{chr}}, T_{\mathrm{squid}}) \frac{2(T_{\mathrm{squid}} - t_{\mathrm{chr}})}{T_{\mathrm{squid}}^2}$$

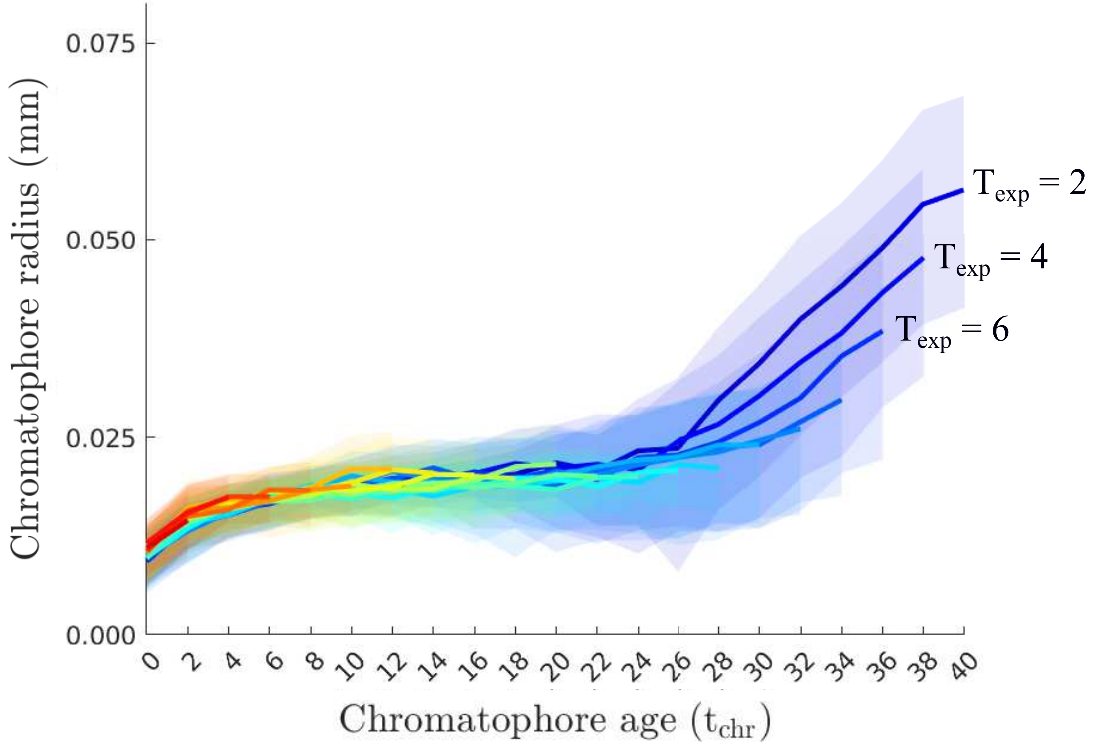
Chromatophore dynamics must depend on the “absolute” time

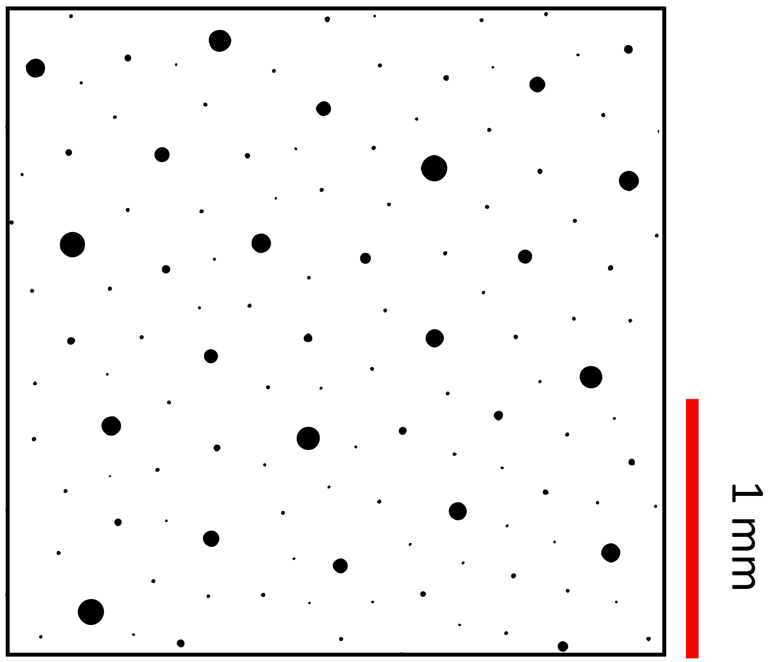




R. Ross …. SP, Phys. Rev. X (2025)

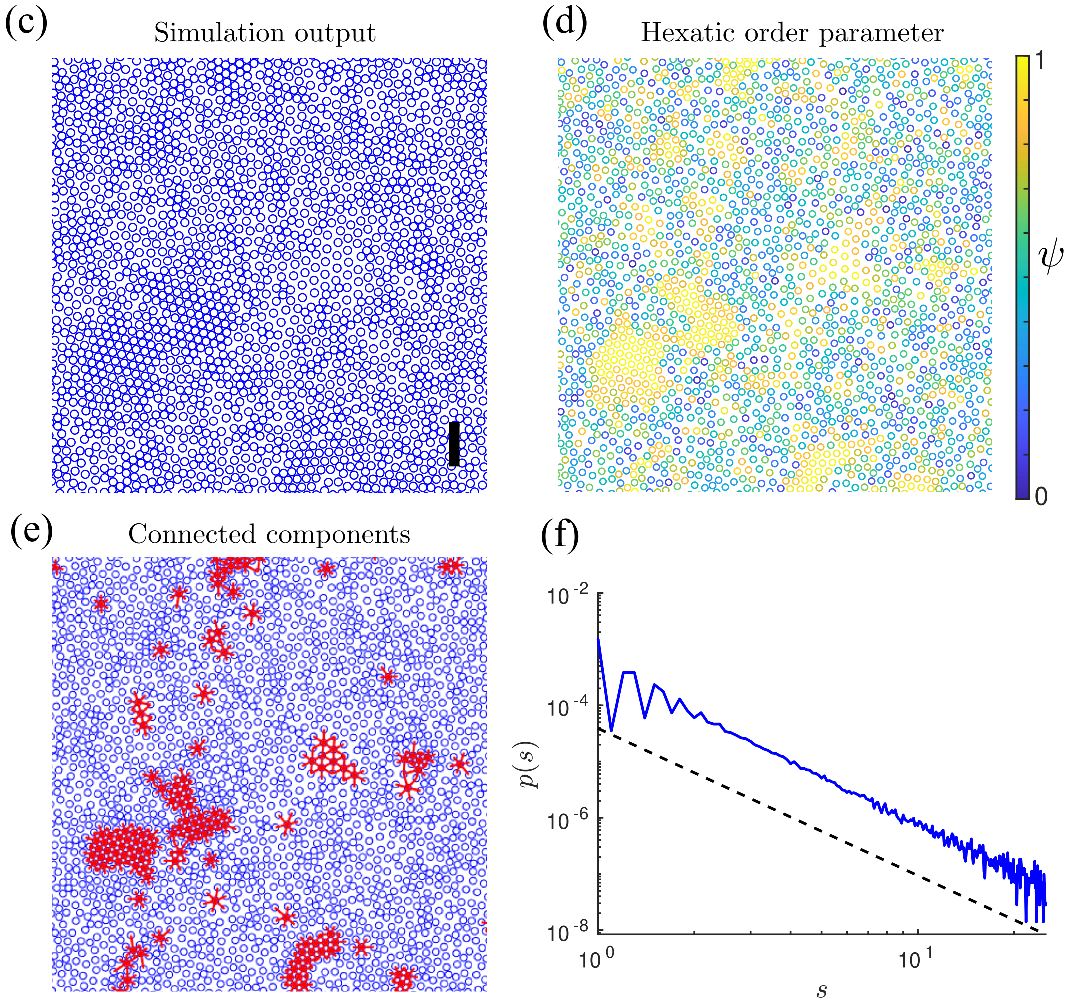
Chromatophore sizes



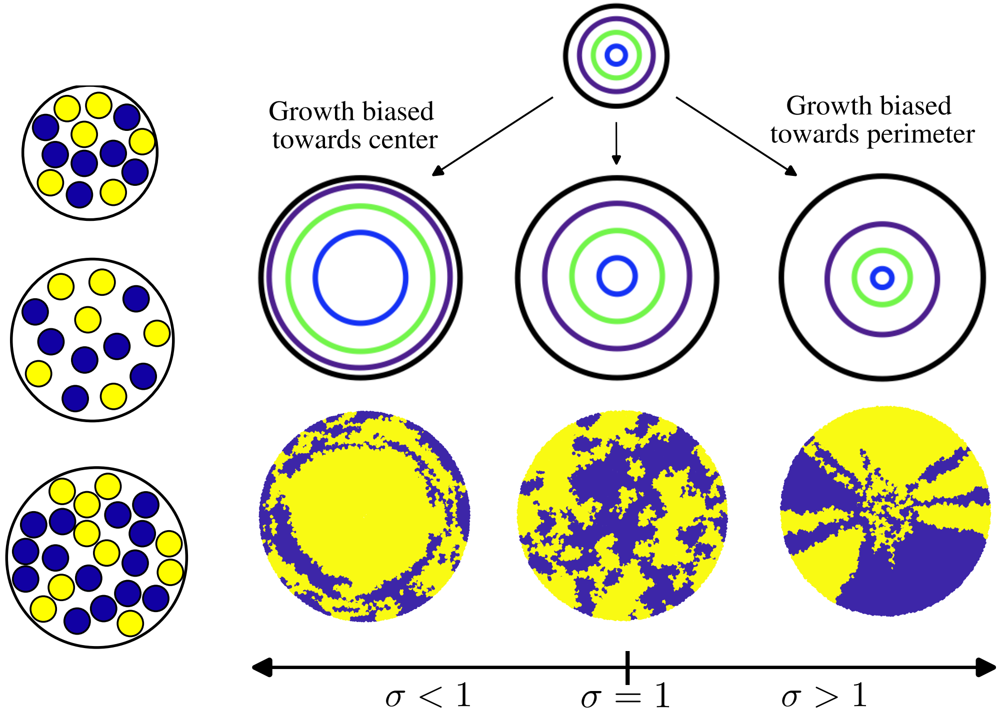


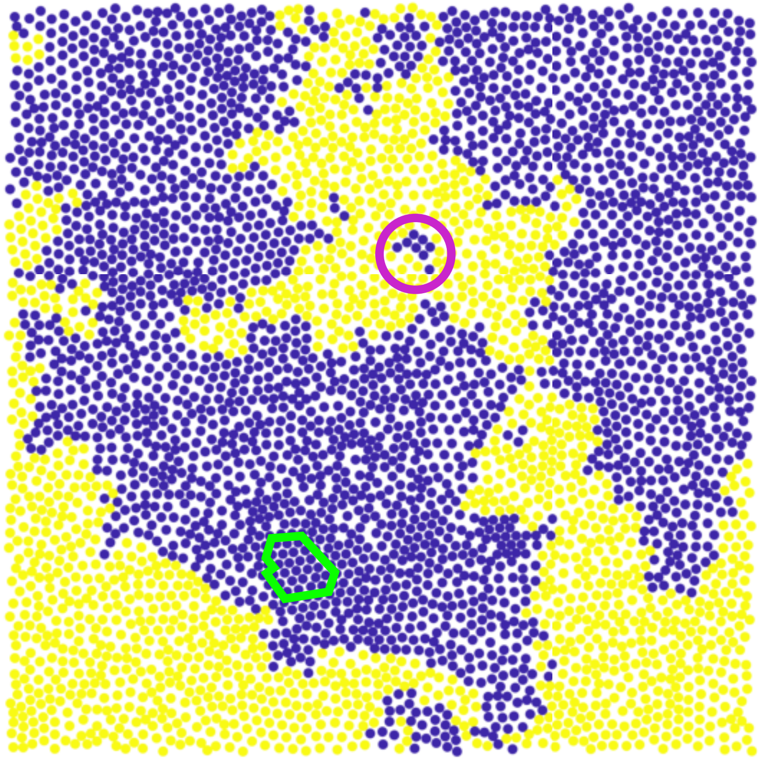
R. Ross …. SP, Phys. Rev. X (2025)

A critical growing state?



The growing voter model



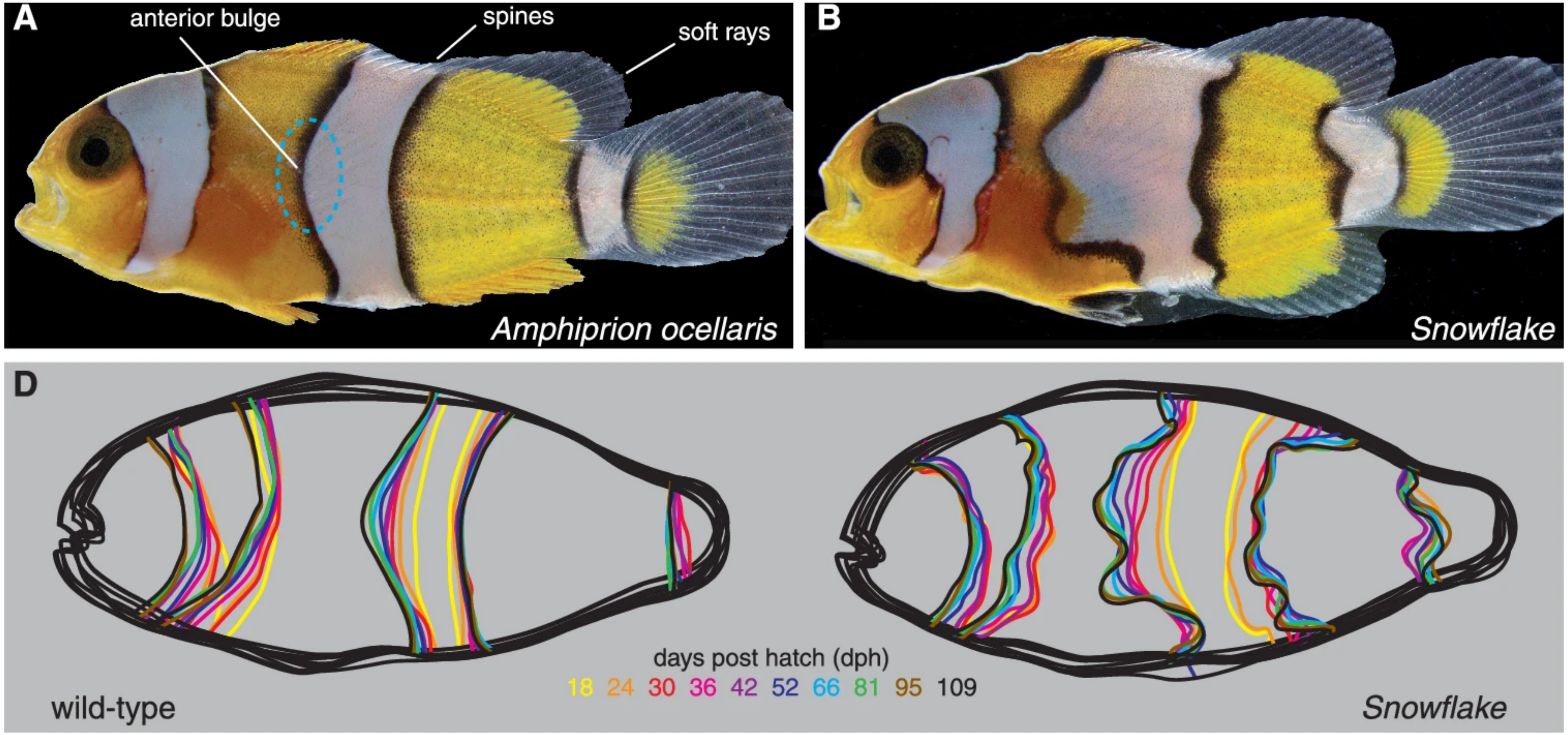


Displacement field $\lambda = [r/R(t)]^{\sigma}$

Phenomenological theory for the critical exponents

R. Ross, SP, arXiv:2411.09172

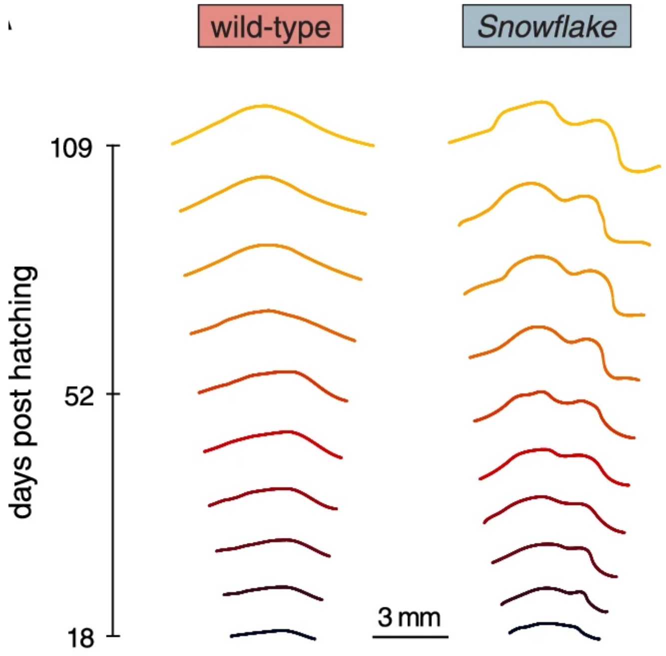
The snowflake mutation of clownfish



M. Klann … SP … V Laudet, Nature Communications (2026)

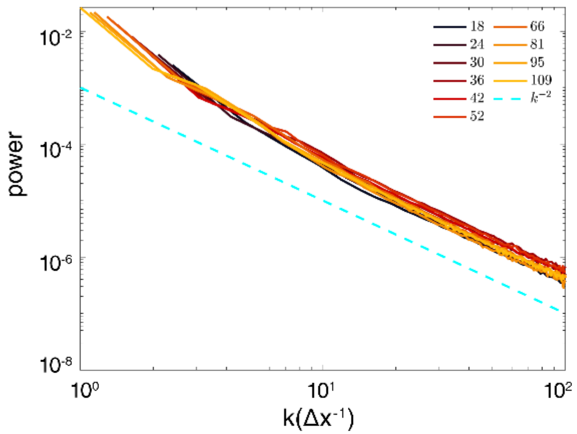
Edwards-Wilkinson model

$$\partial_t h(x,t) = D\nabla^2 h + \sigma\xi(x,t)$$

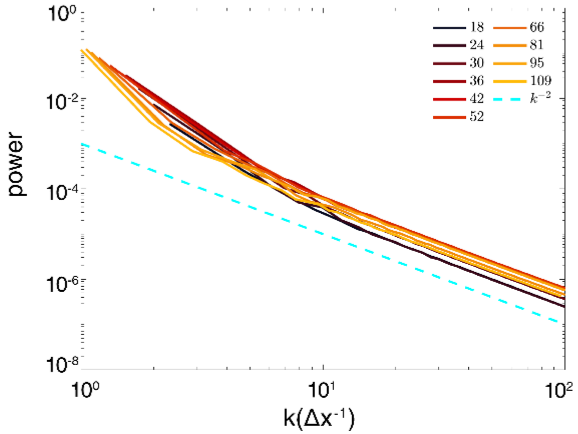


Band-pass filter

Wild type



Snowflake



- Spectrum compatible with EW model for both wild type and Snowflake
- Either larger noise amplitude or smaller surface tension in Snowflake

M. Klann … SP … V Laudet, Nature Communications (2026)

Conclusions

- Growth is ubiquitous in biological development
- It gives rise to new physics
- New universality classes?

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Reiter Unit (Squids)
Laudet Unit (Clownfish)

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