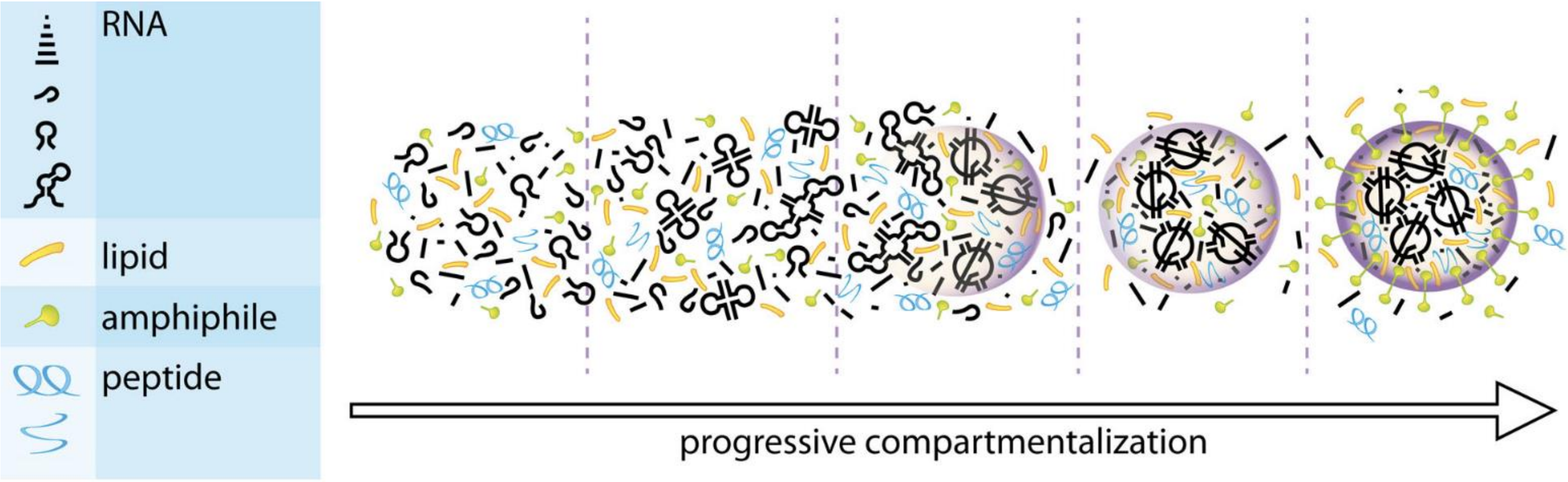
Compositional memory matters for early molecular systems

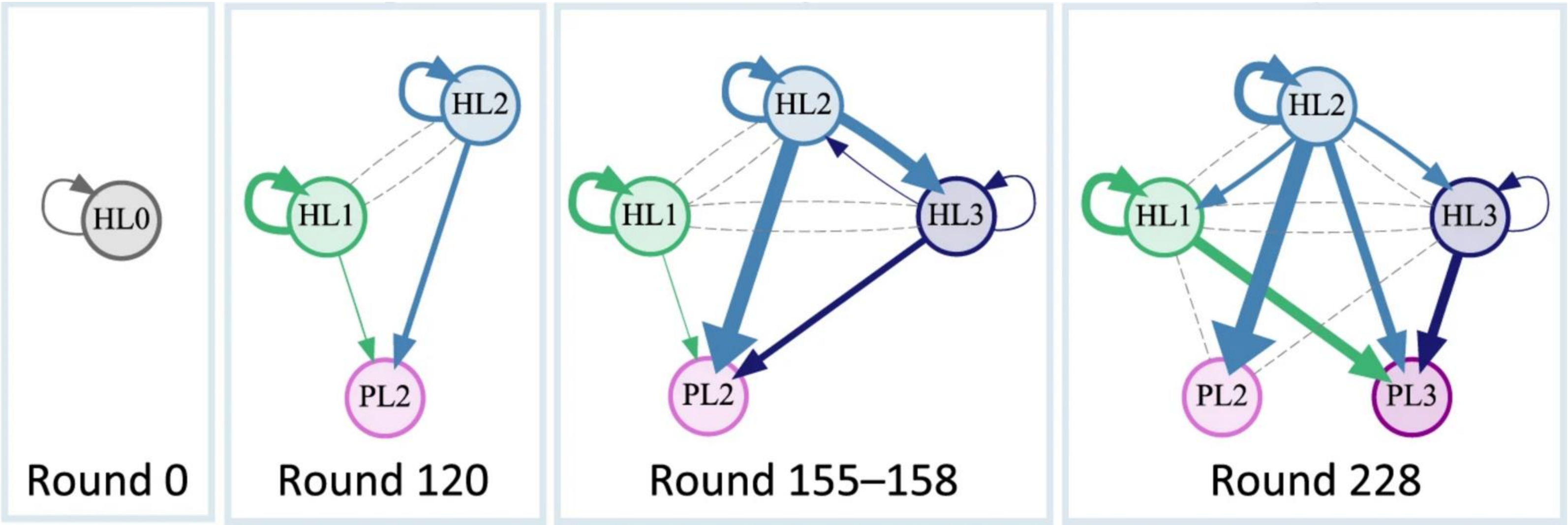
Barnabe Ledoux

Evolution of complexity

[1]



[2]

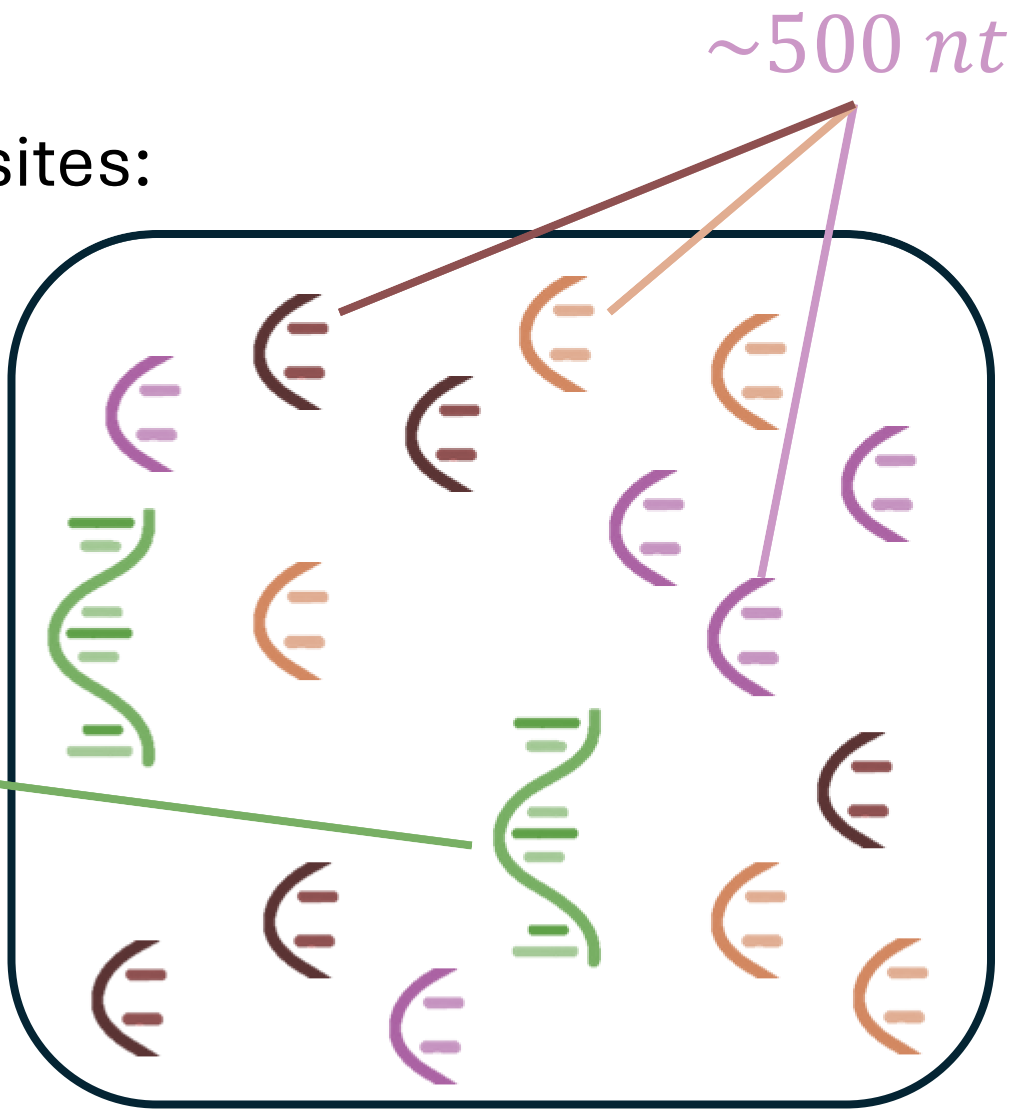


[1] P.Nghe, *A stepwise emergence of evolution in the RNA world*, FEBS Letters, 10.1002/1873-3468.70065 (2025)
[2] R Mizuuchi, T Furubayashi, N Ichihashi, *Evolutionary transition from a single RNA replicator to a multiple replicator network*. Nat. Commun. 13, 1460 (2022)

The need for compartments

In a **pool** with replicases and parasites:

- Parasite replication (**fast**)
- Self replication (**slow**)

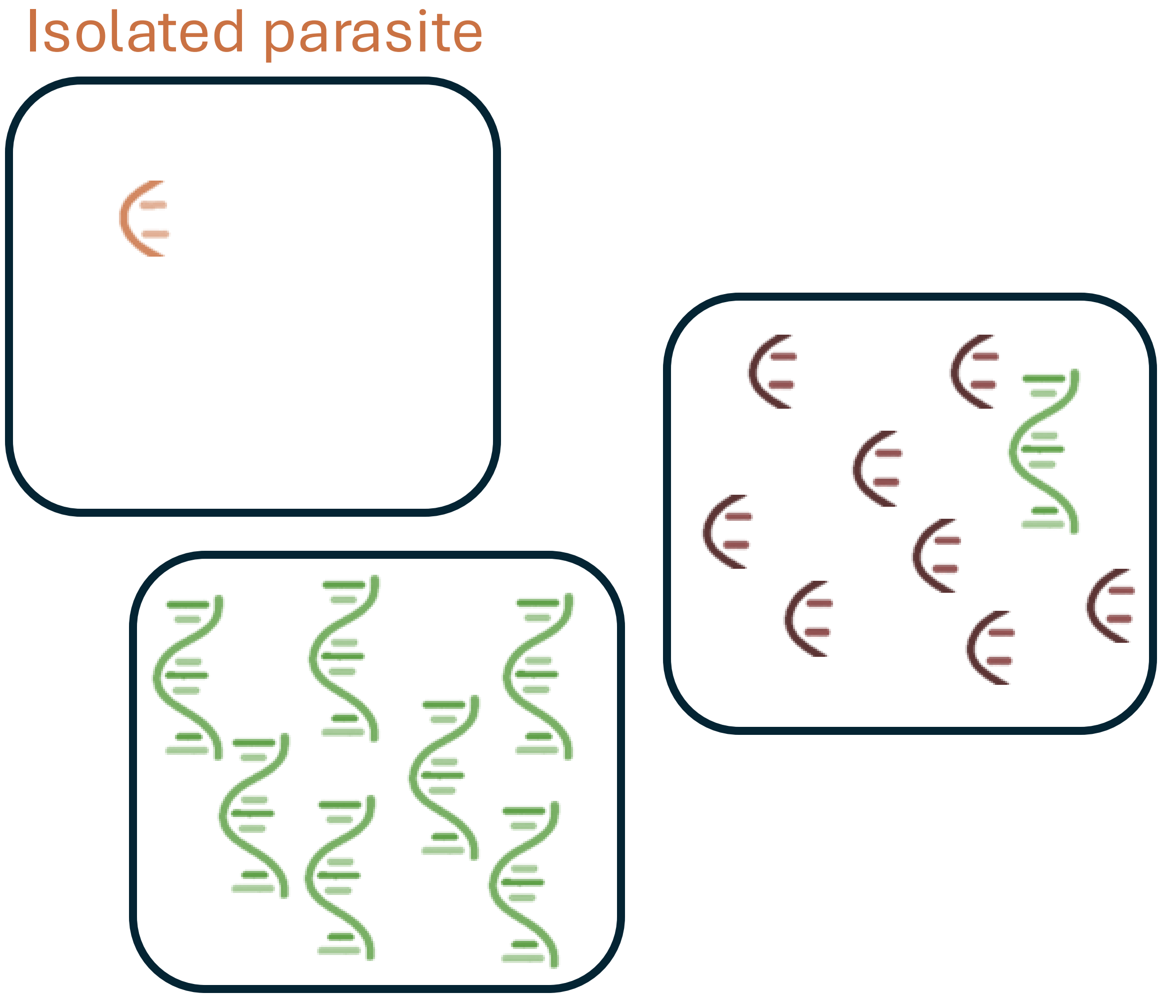


$\Rightarrow$ Parasites invade the system

The need for compartments

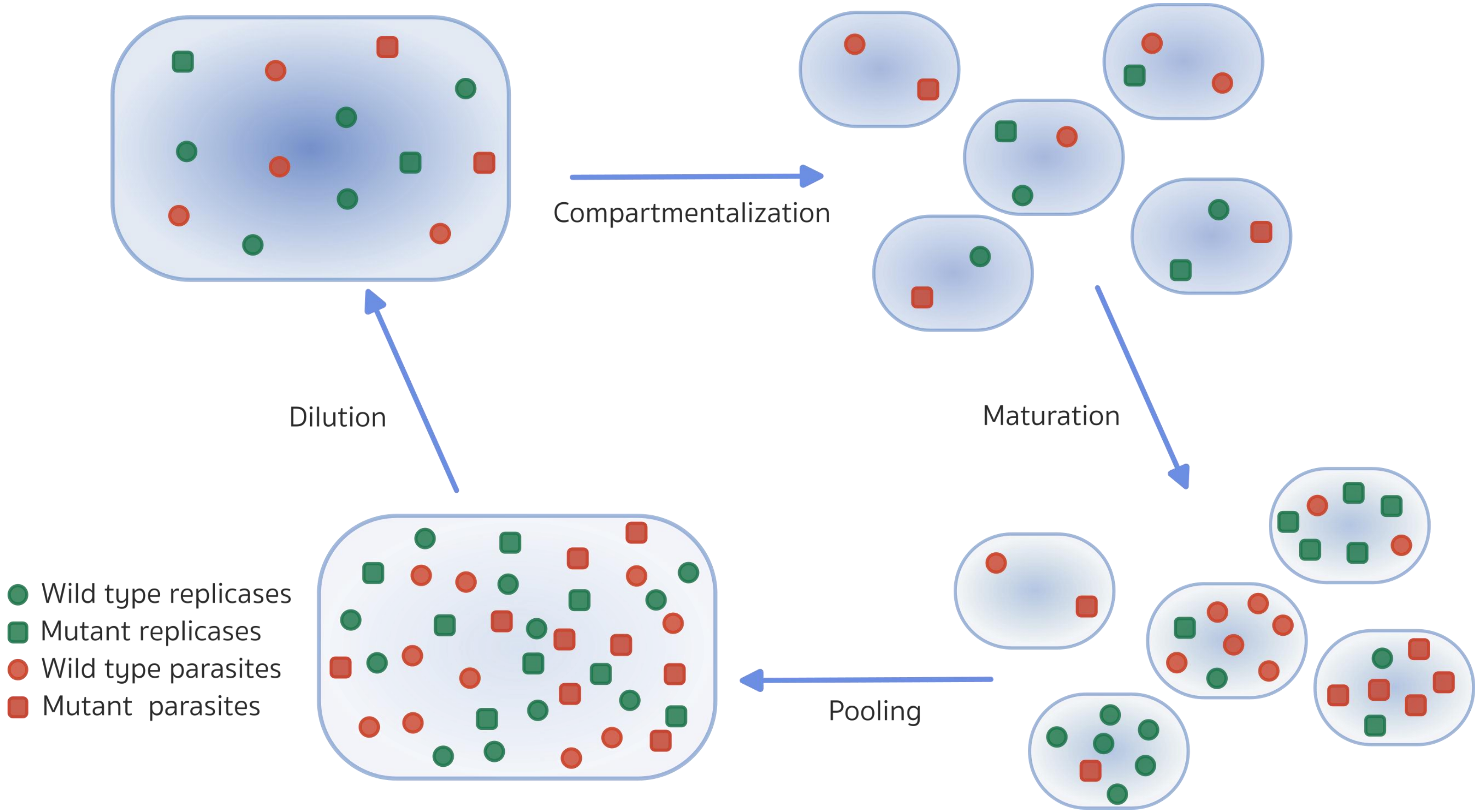
With compartments:

- Parasite replication (**fast**)
- Self replication (**slow**)
- Parasites alone cannot replicate



Modeling dynamics

Transient compartmentalization with natural selection and mutations



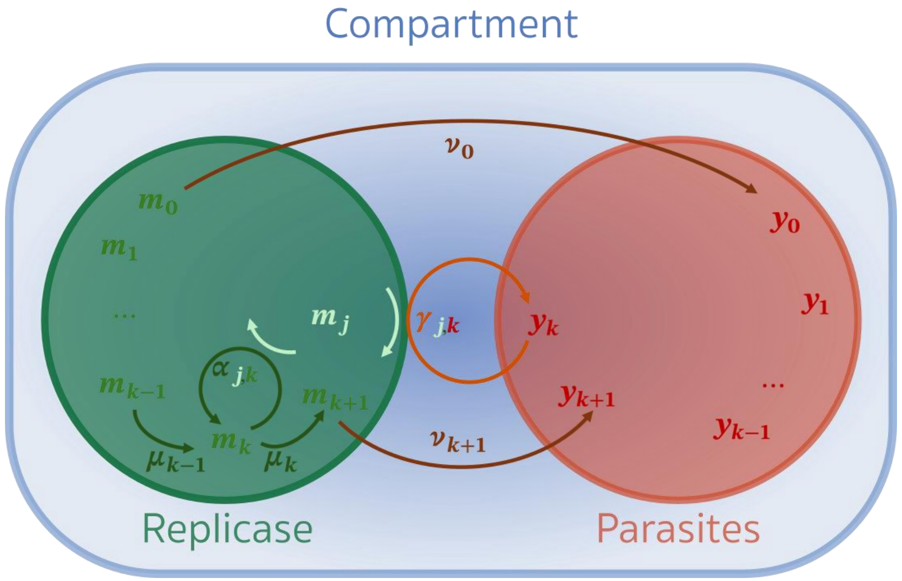
Evolution equations

$$\lambda = \frac{m_0 + m_1 + y_0 + y_1}{d}$$

Compartmentalization

$$P(m_0, m_1, y_0, y_1 | x_0, x_1, z_0, z_1, \lambda) = \sum \frac{\lambda^n}{n!} e^{-\lambda} \frac{n!}{m_0!\, m_1!\, y_0!\, y_1!} x_0^{m_0} x_1^{m_1}\, z_0^{y_0}\, z_1^{y_1}$$

Dilution



Maturation

$$\frac{dm_0}{dt} = -(\mu_0 + \nu_0)m_0 + \alpha_{0,0} m_0^2$$

$$\frac{dm_1}{dt} = -(\mu_1 + \nu_1)m_1 + \mu_0 m_0 + \alpha_{1,1} m_1^2$$

$$\vdots$$

$$\frac{dy_0}{dt} = \nu_0 m_0 + \gamma_{0,0} m_0 y_0$$

$$\frac{dy_1}{dt} = \nu_1 m_1 + \gamma_{1,1} m_1 y_1$$

$$\vdots$$

Mutations

Replication

Variation

Pooling

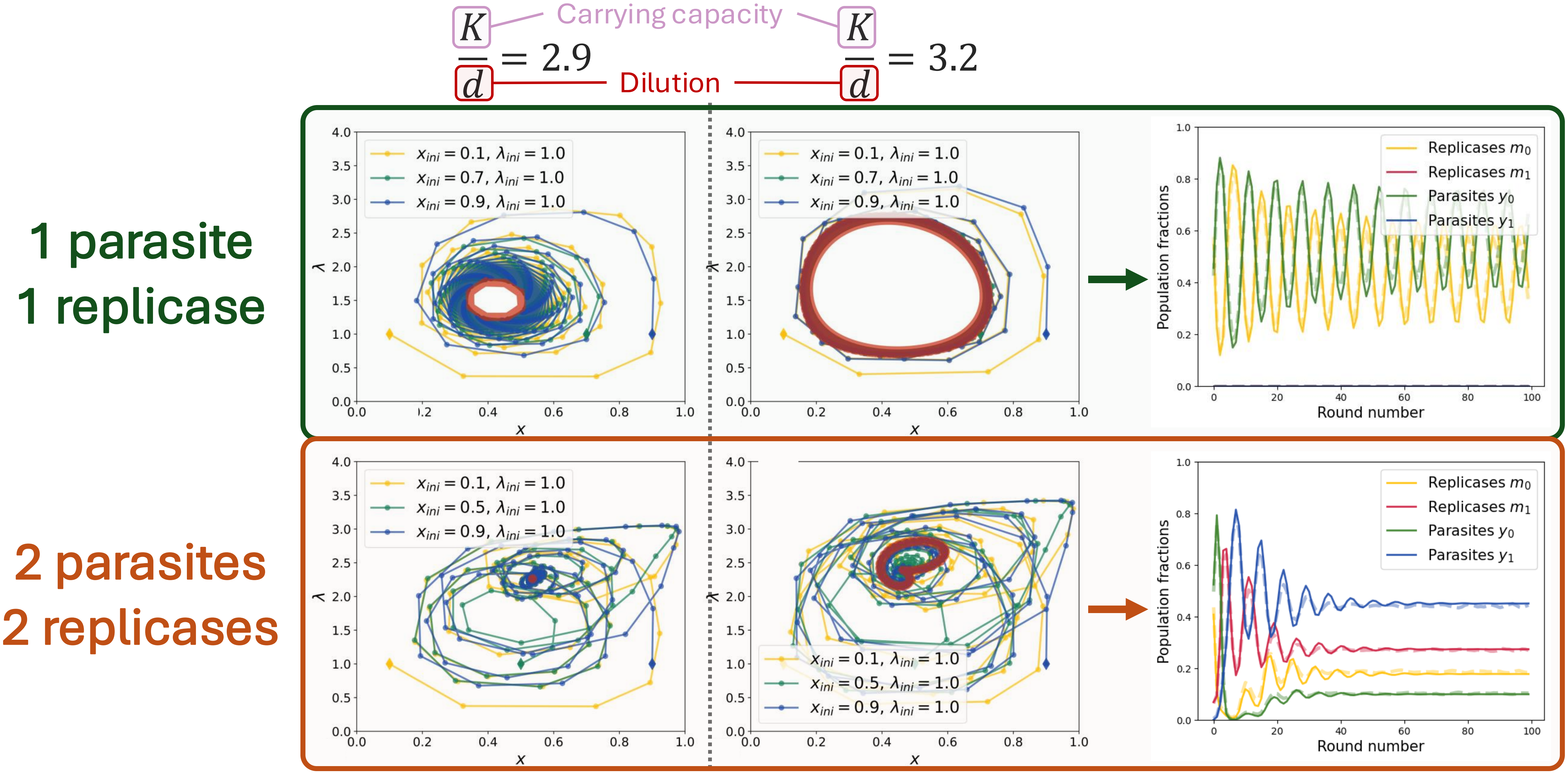
$$x_0 = \frac{m_0}{m_0 + m_1 + y_0 + y_1}$$

$$x_1 = \frac{m_1}{m_0 + m_1 + y_0 + y_1}$$

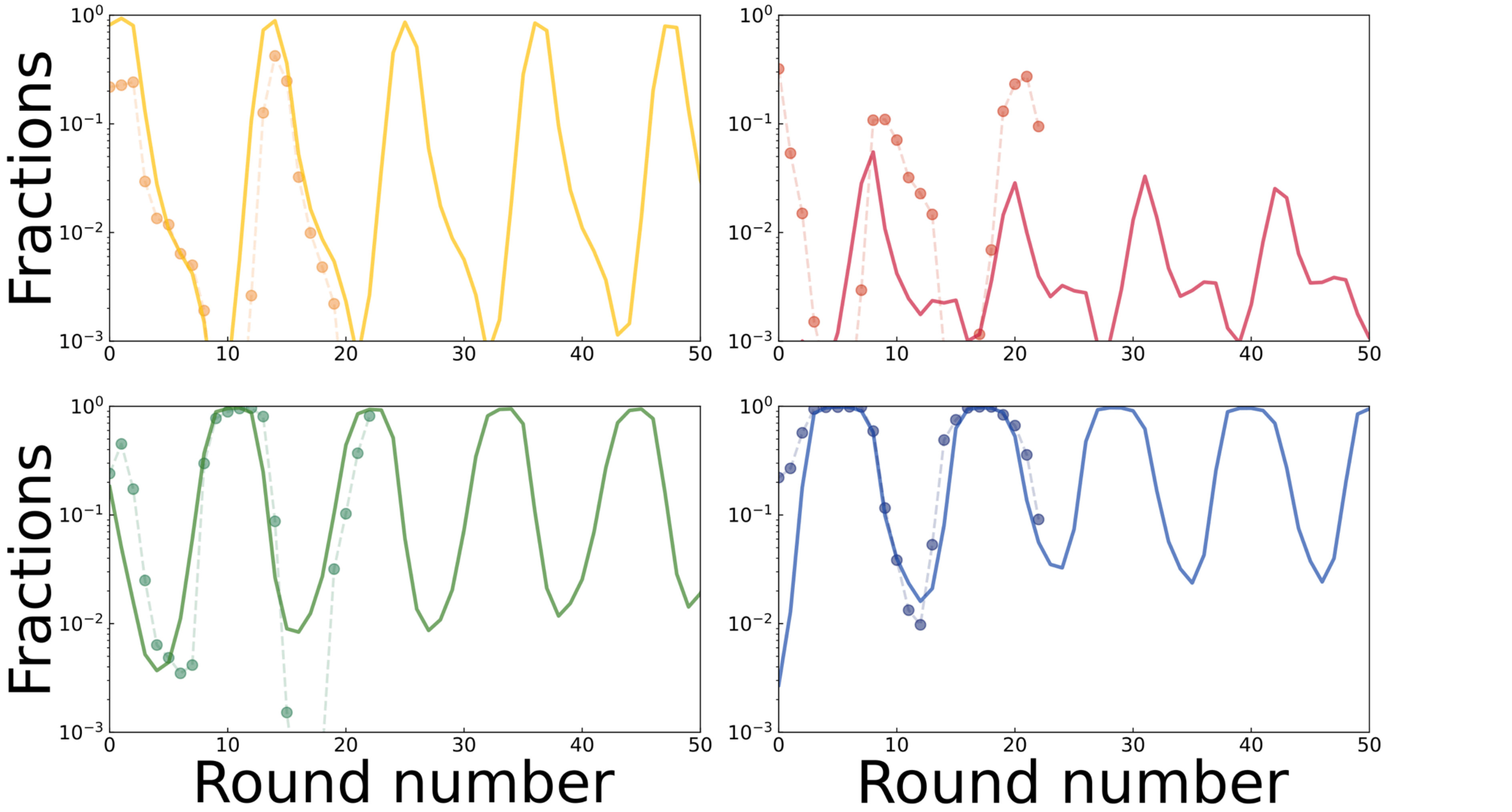
$$z_0 = \frac{y_0}{m_0 + m_1 + y_0 + y_1}$$

$$z_1 = \frac{y_1}{m_0 + m_1 + y_0 + y_1}$$

Oscillatory dynamics



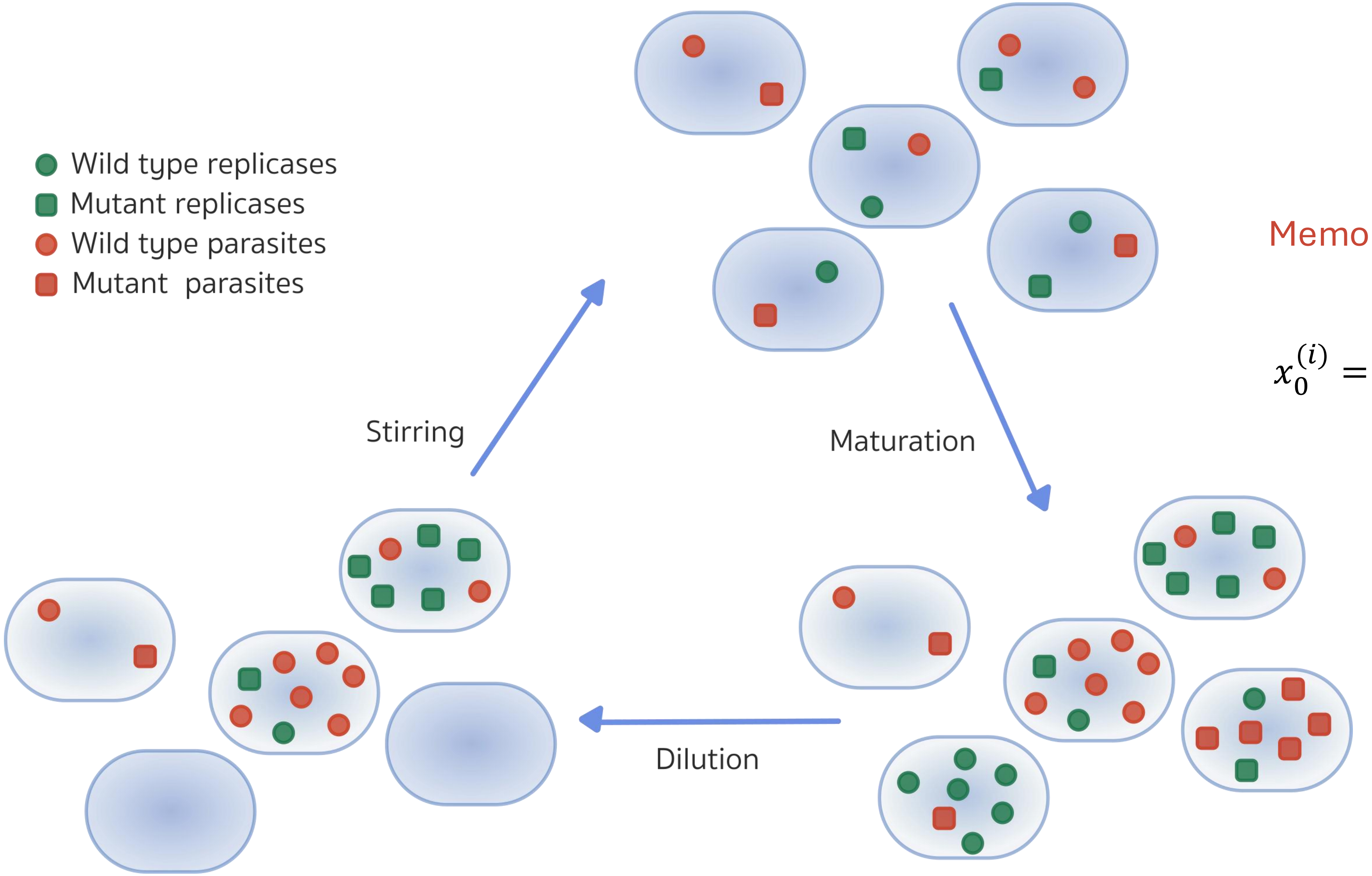
Comparison to experiments



[1] R Mizuuchi, T Furubayashi, N Ichihashi, *Evolutionary transition from a single RNA replicator to a multiple replicator network.* Nat. Commun. 13, 1460 (2022)

Stirring

Stirring in serial transfer



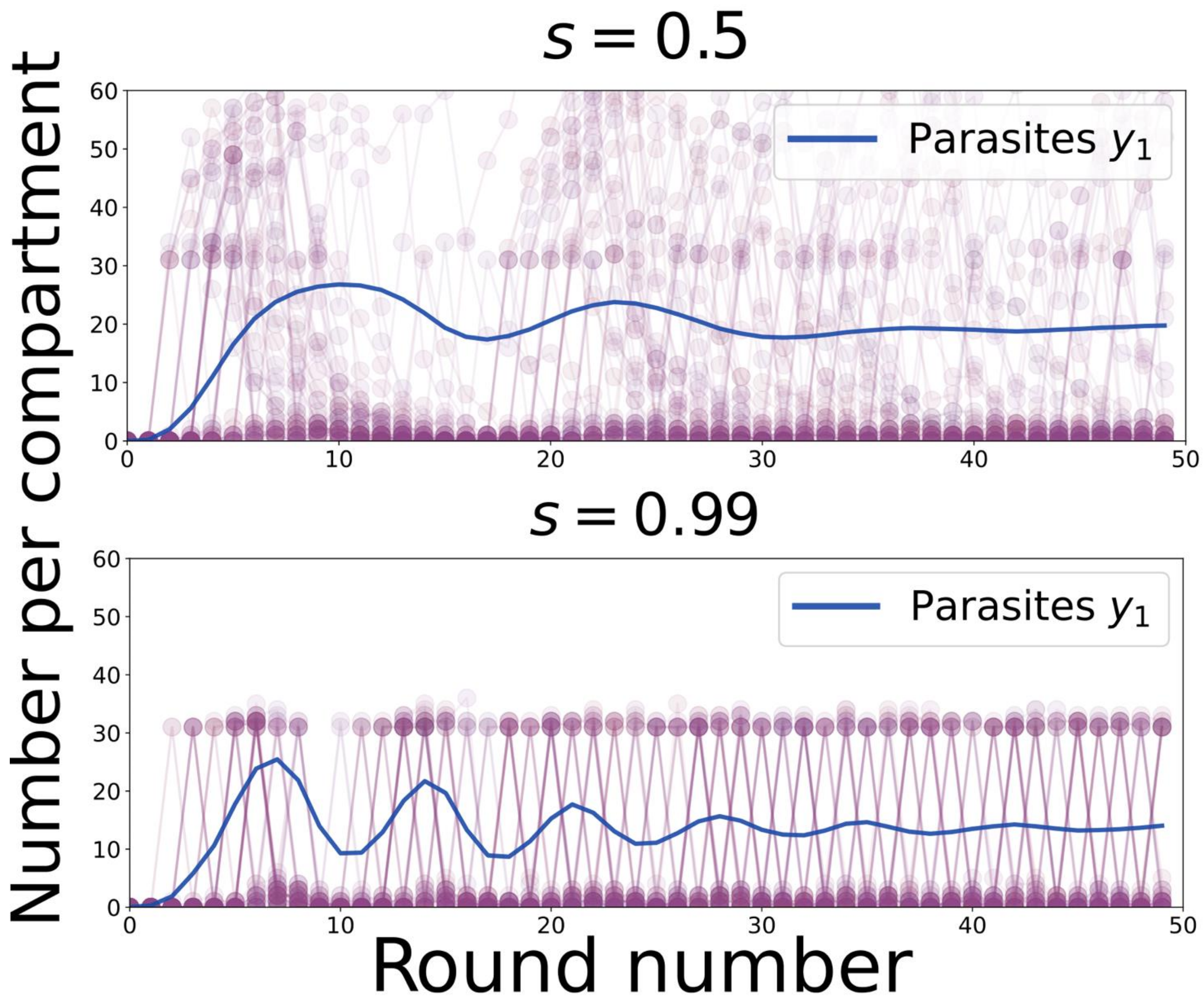
Memory of the compartment

$$x_0^{(i)} = \frac{(1-s)m_0^{(i)} + \frac{s}{n_{cell}-1}\sum_j m_0^{(j)}}{(1-s)n^{(i)} + \frac{s}{n_{cell}-1}\sum_j n^{(j)}}$$

Mean field effect

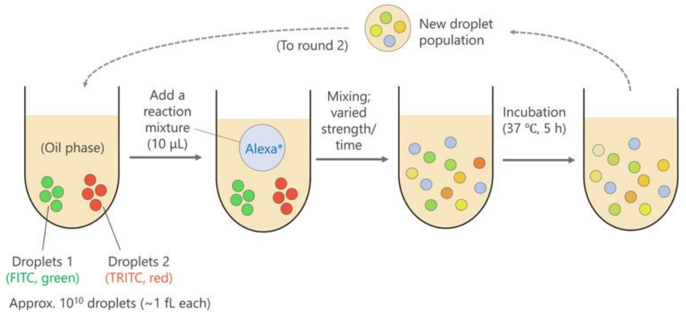
Single compartment evolution

Increasing stirring

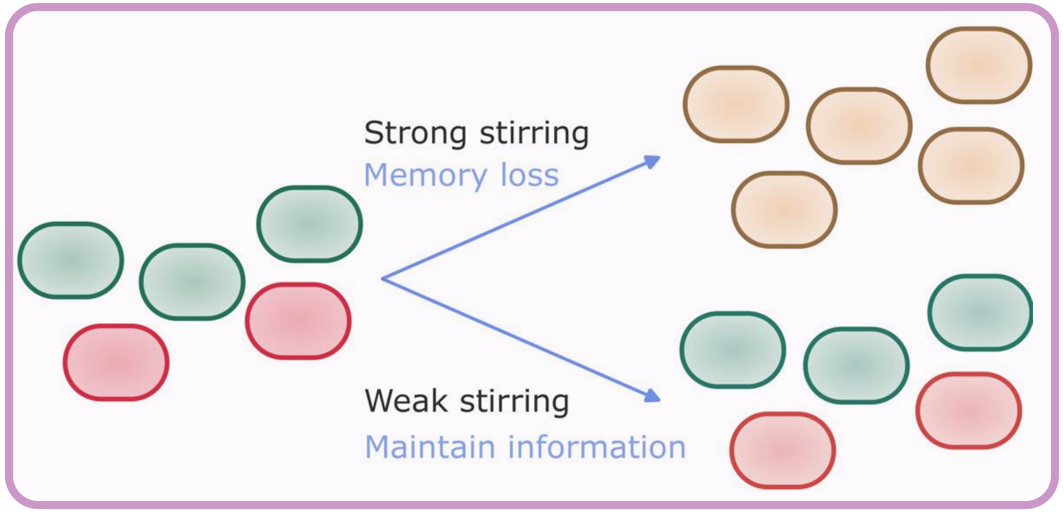


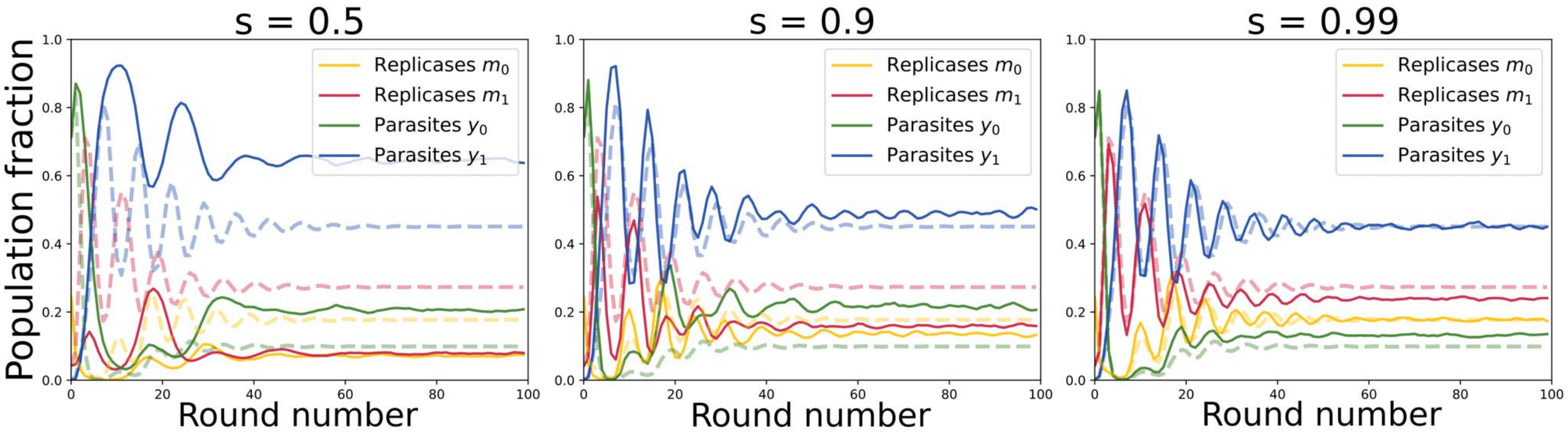
Increasing heterogeneity

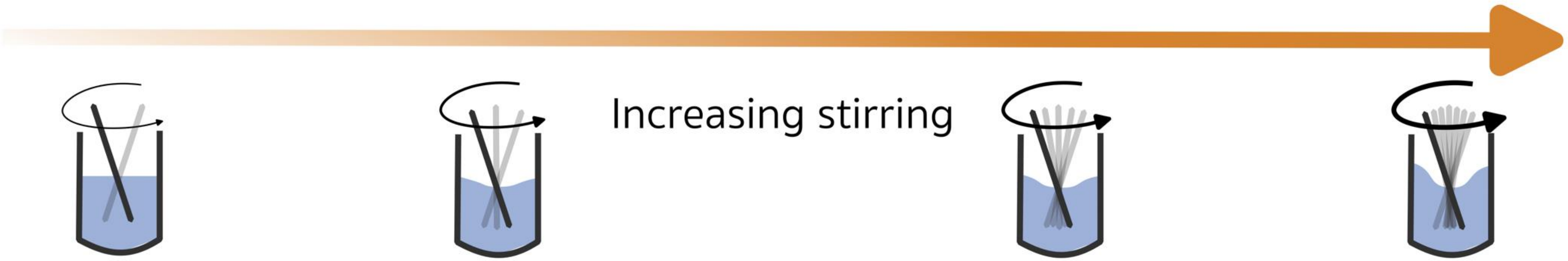
Stirring in serial transfer



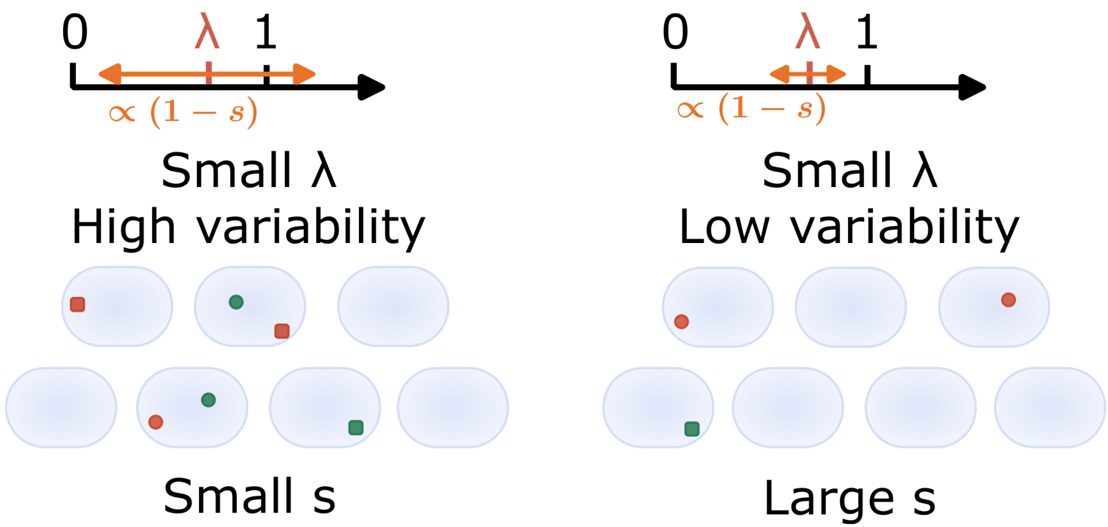
Tested experimentally



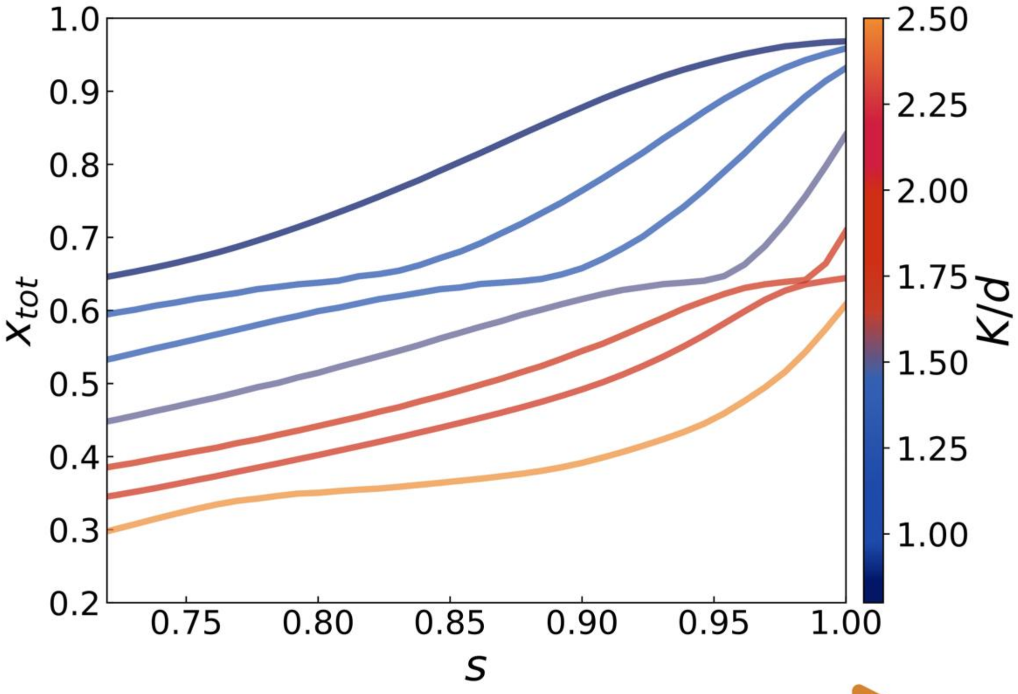


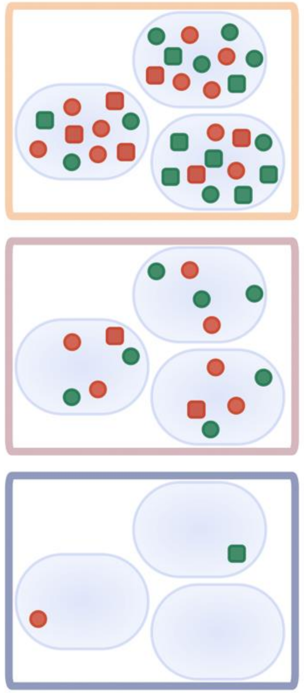


Stirring favors replicases

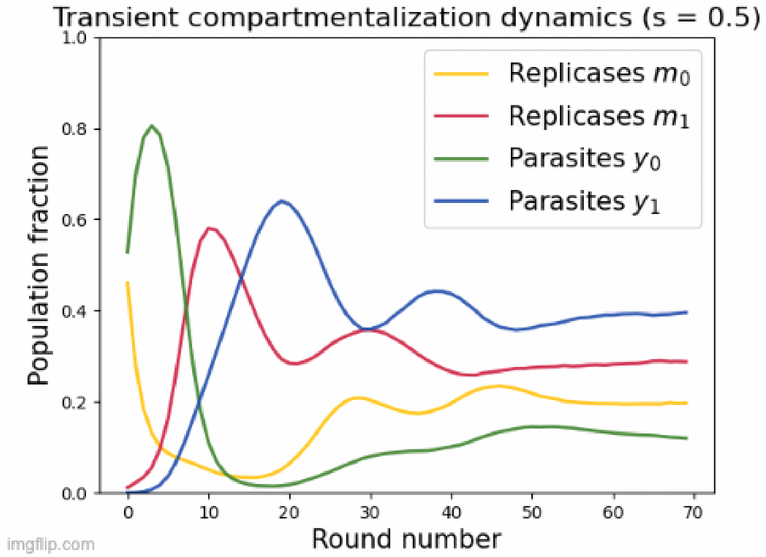


Tested experimentally





Increasing stirring



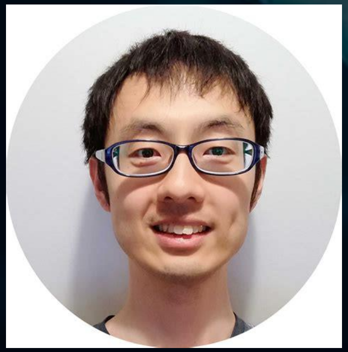
Conclusion

- **Compartments** along with **stirring** are a way to ensure **coevolution** and appearance of **complexity**.
- More species and strong dilution **stabilizes** the system.
- **Stirring** homogenizes the system, which tend to **isolate parasites** and favors **replicases**.

David Lacoste

Ryo Mizuuchi

Ryoka Kuwabara



Taro Furubayashi

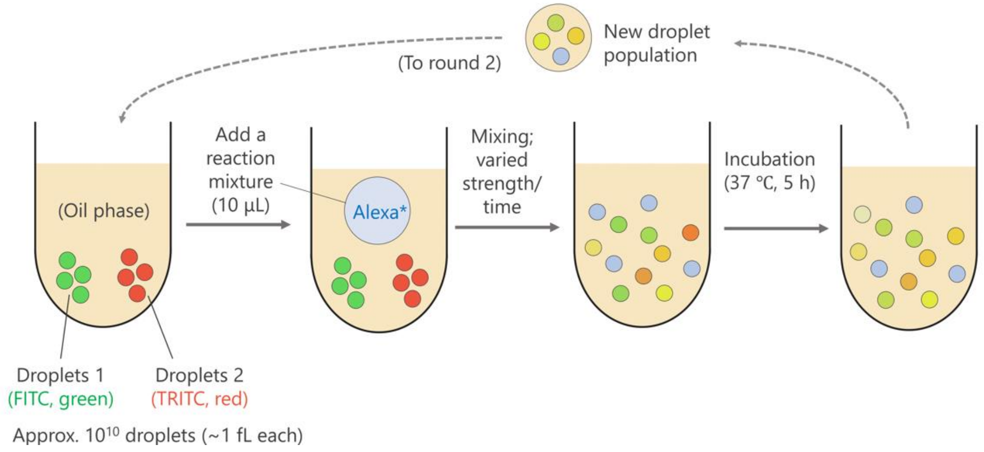
Philippe Nghe

Additional content

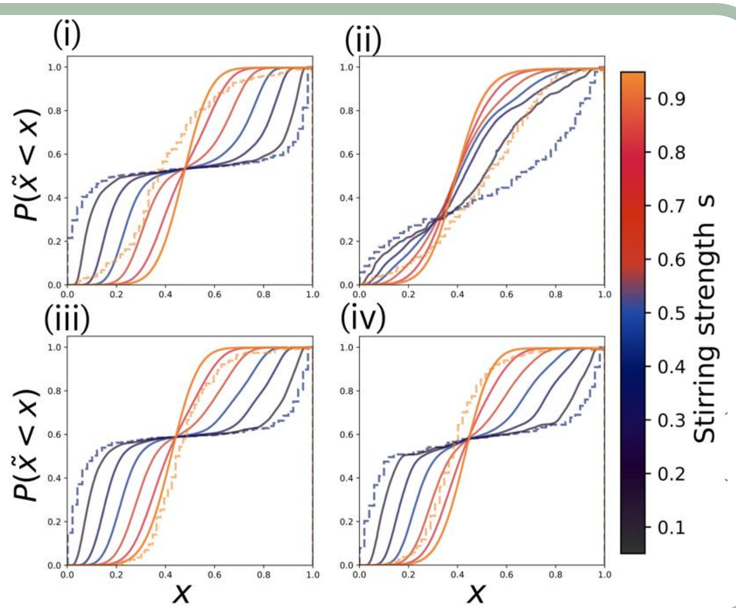
Experimental tests

With 2 species :

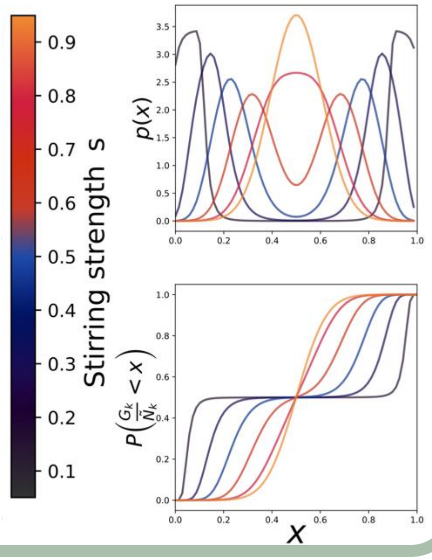
- From bimodal to monomodal distribution
- Depends on stirring process



(i). Quick, strong stirring
(ii). Long, weak stirring
(iii). Medium length, strong stirring
(iv). Long, strong stirring

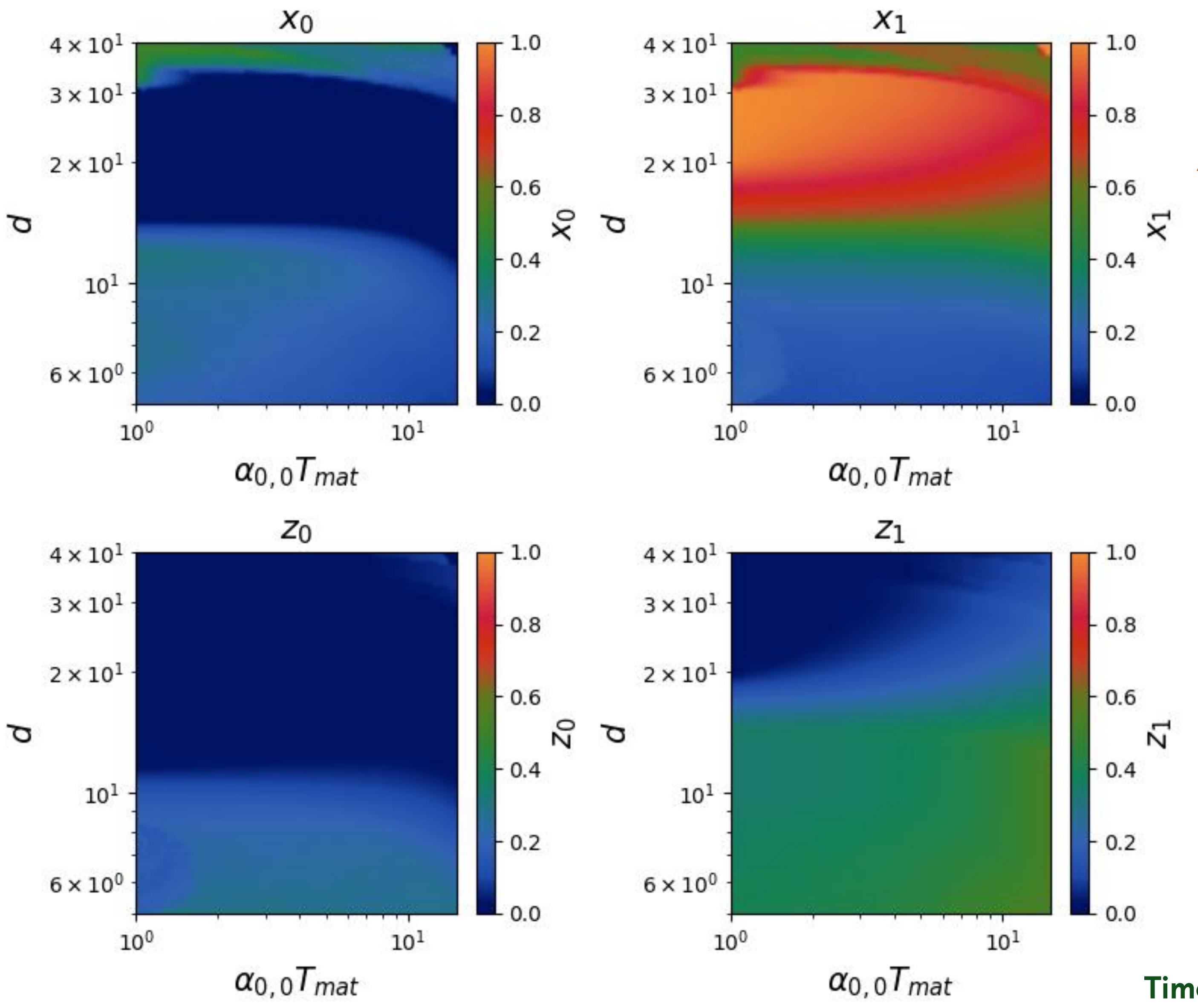


Distribution starting from 2 Dirac peaks.



Influence of dilution factor and maturation time

Very strong dilution:
$\lambda \lesssim 1 \Rightarrow$ No competition



Strong dilution:
$\lambda \sim 1 \Rightarrow$ Isolate parasites

Time for maturation:
Mutations towards parasites