

Cooperation, cheating and collapse in biological populations

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SIAM Conference on Dynamical Systems

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How do interactions between individuals determine the evolutionary and ecological dynamics of populations?

Where we are heading:



Can we tell that a population is about to collapse?

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Can we tell that a population is about to collapse?

How can evolution lead to cooperation?



Where we are heading:



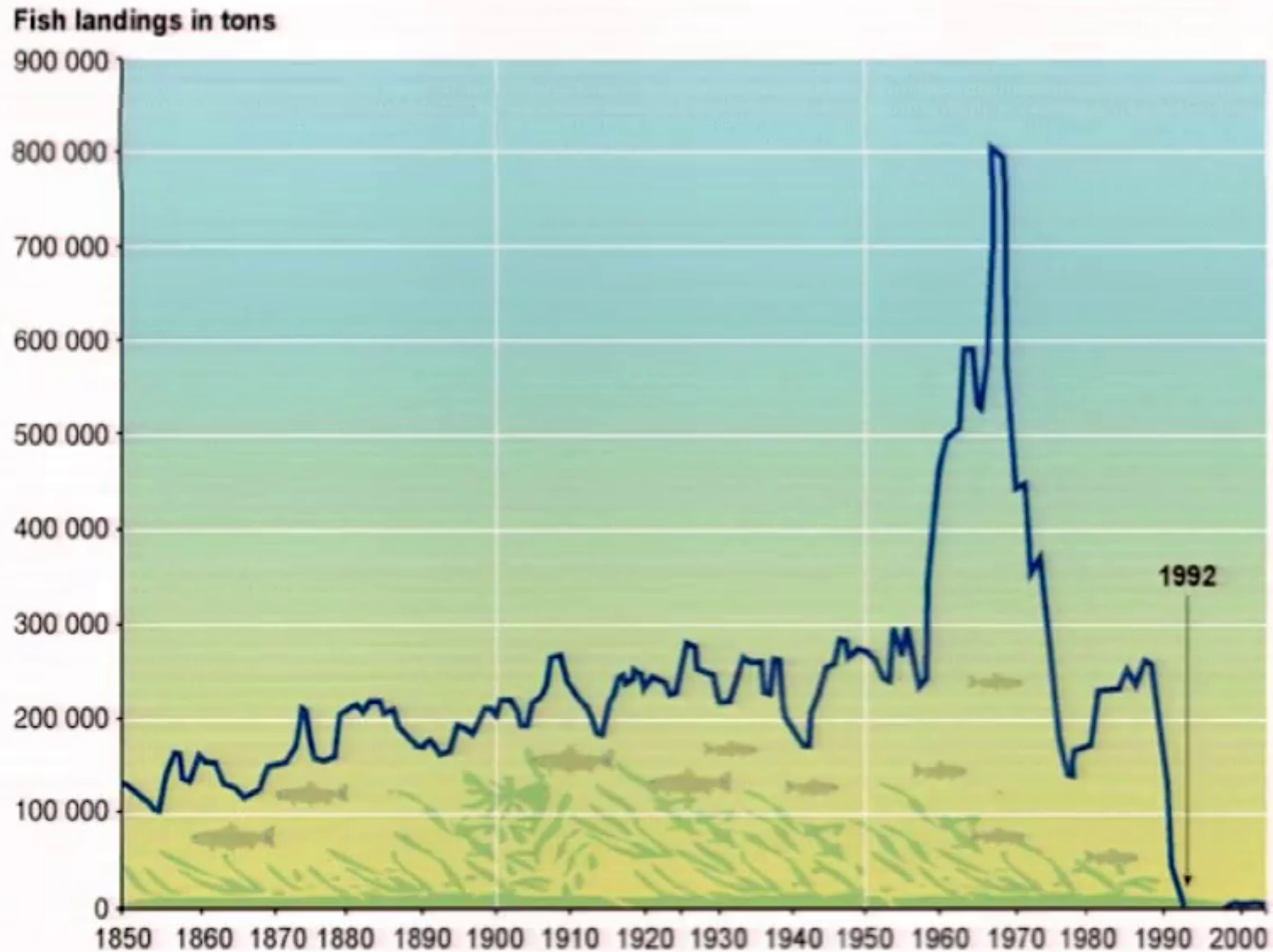
Can we tell that a population is about to collapse?

How can evolution lead to cooperation?



What are the consequences of cheaters in the population?

Collapse of cod population in Newfoundland



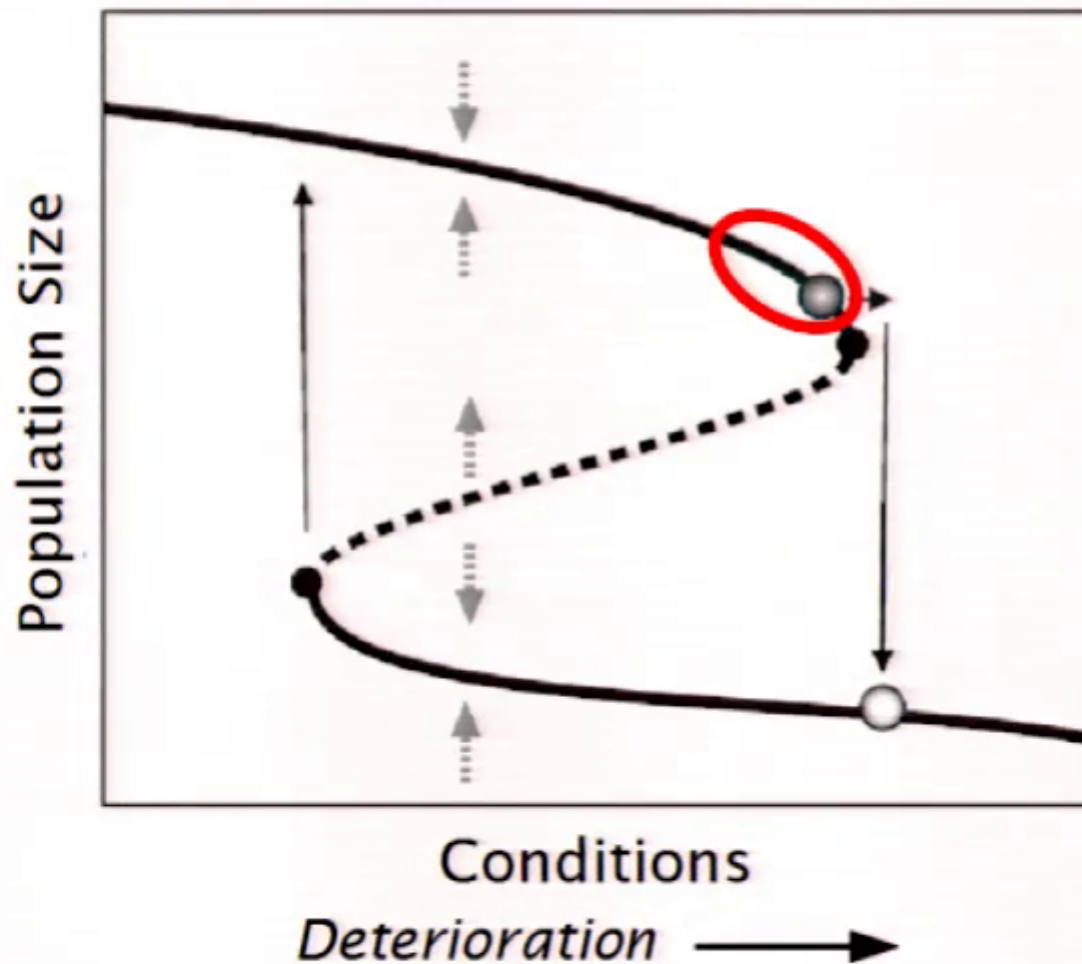
Source: Millennium Ecosystem Assessment





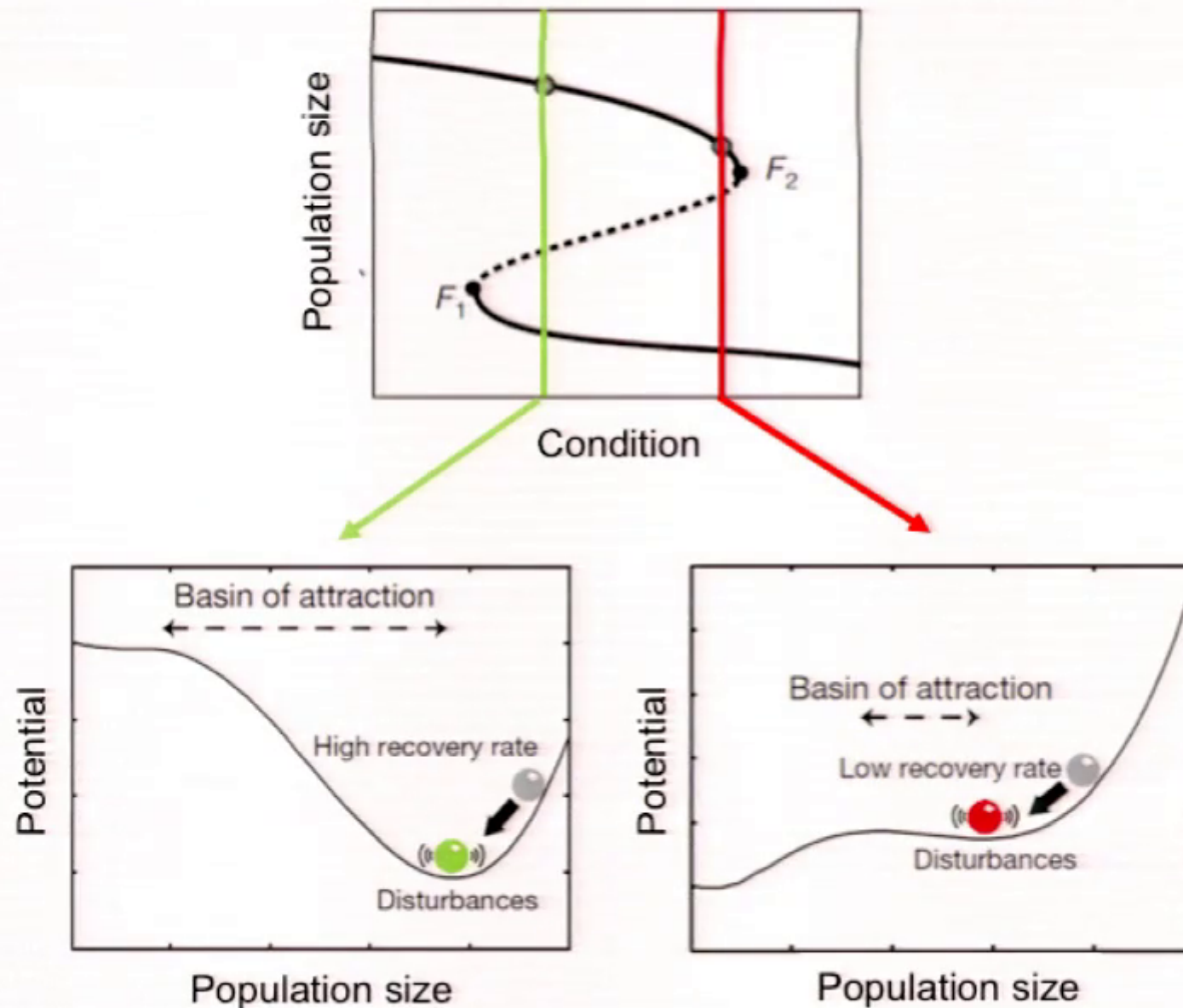
Morne Hardenberg

Positive interactions between individuals → Sudden collapse in deteriorating environments



Scheffer *et al.*, *Nature* (2009)

Change in stability landscape may provide advance warning of population collapse



Scheffer *et al.*, *Nature* (2009)

Predicted universal behavior near tipping point

Loss of **resilience** to perturbations

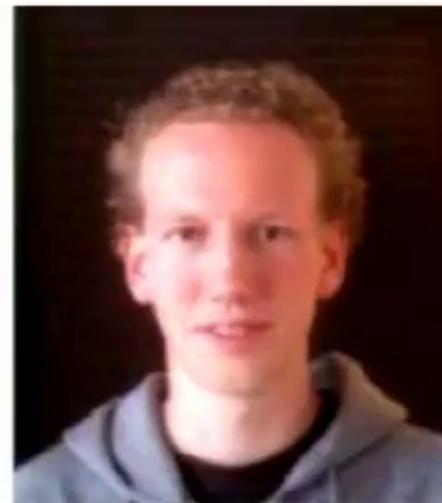
Possible **early warning** signals:

- 1) Increase in **recovery time** after a perturbation
- 2) **Fluctuations** get larger and slower

“Can these universal behaviors be measured experimentally?”



Lei Dai
Physics Grad



Daan Vorselen
Visiting student

Laboratory microbial populations as a bridge between theoretical ecology and natural populations

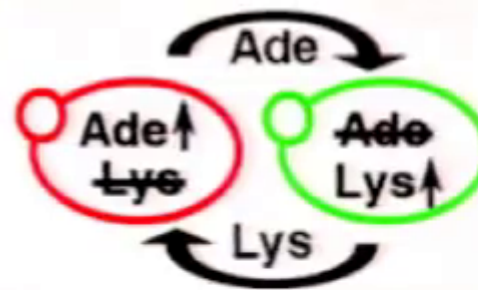
Natural systems



Simplified natural systems

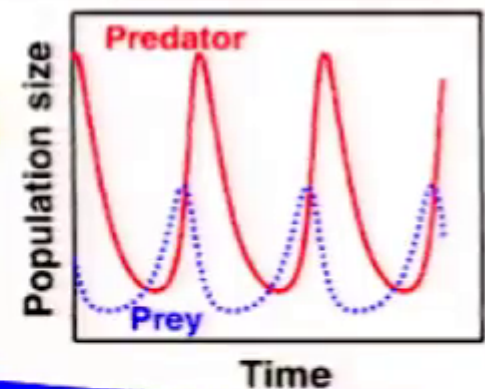


Engineered living systems



Controllability

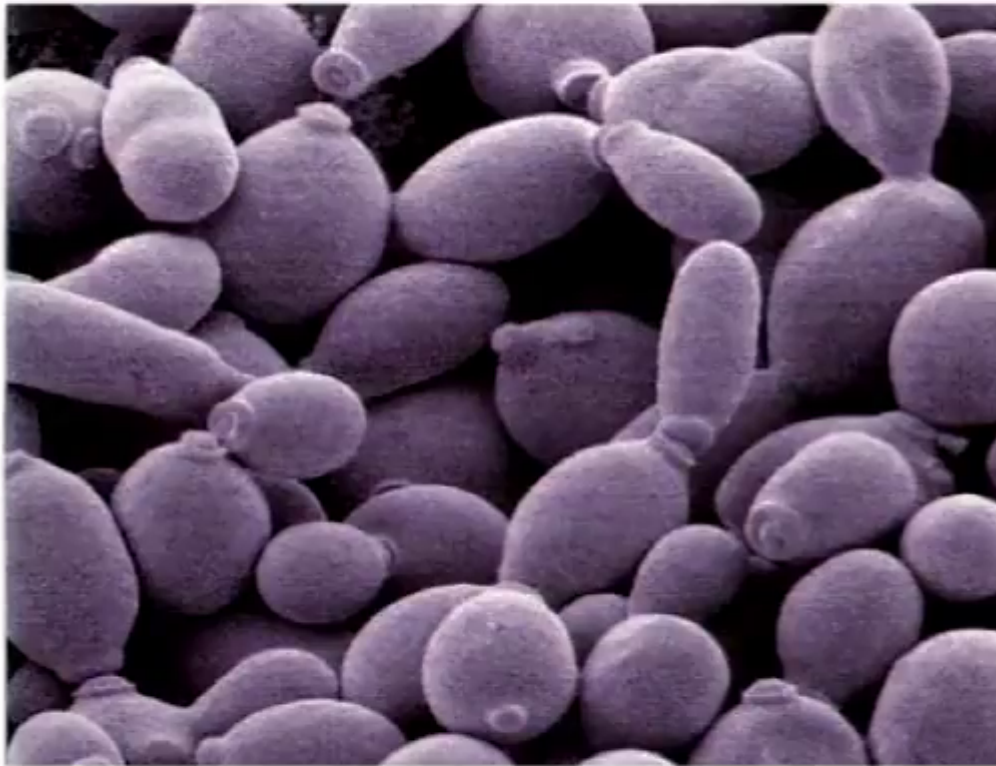
Mathematical models



Complexity

Wenying Shou

Laboratory microbial populations as a bridge between theoretical ecology and natural populations



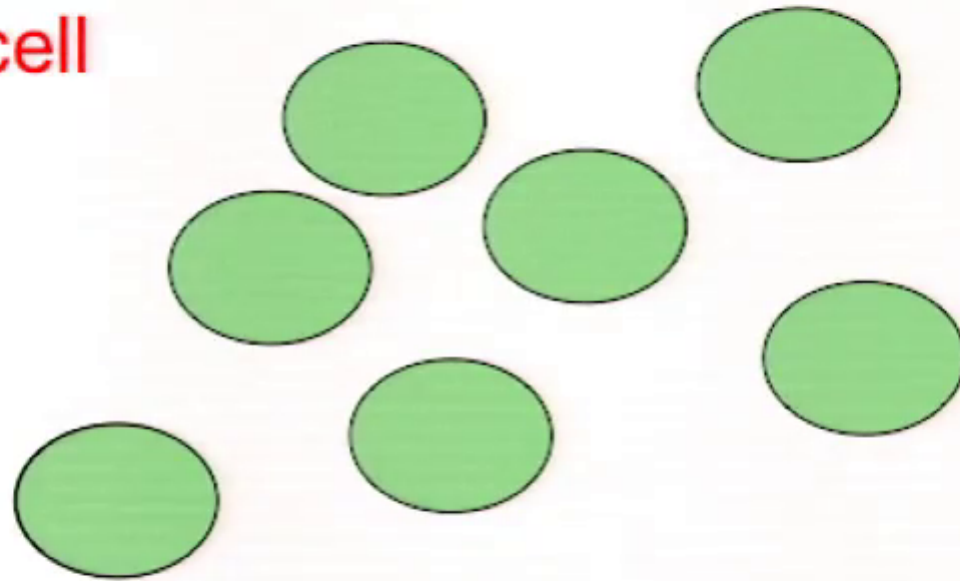
Budding yeast (*S. cerevisiae*)

Experimentally tractable:

- Small and simple
 - Short generation time
 - Quantitative measurements
 - Environmental control
 - Genetic manipulations
- Control strategies

Yeast benefit from other yeast in the population

Sucrose is broken down
outside of the cell

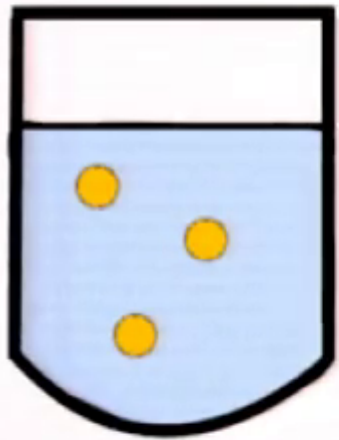


Yeast divide more rapidly
at higher cell density



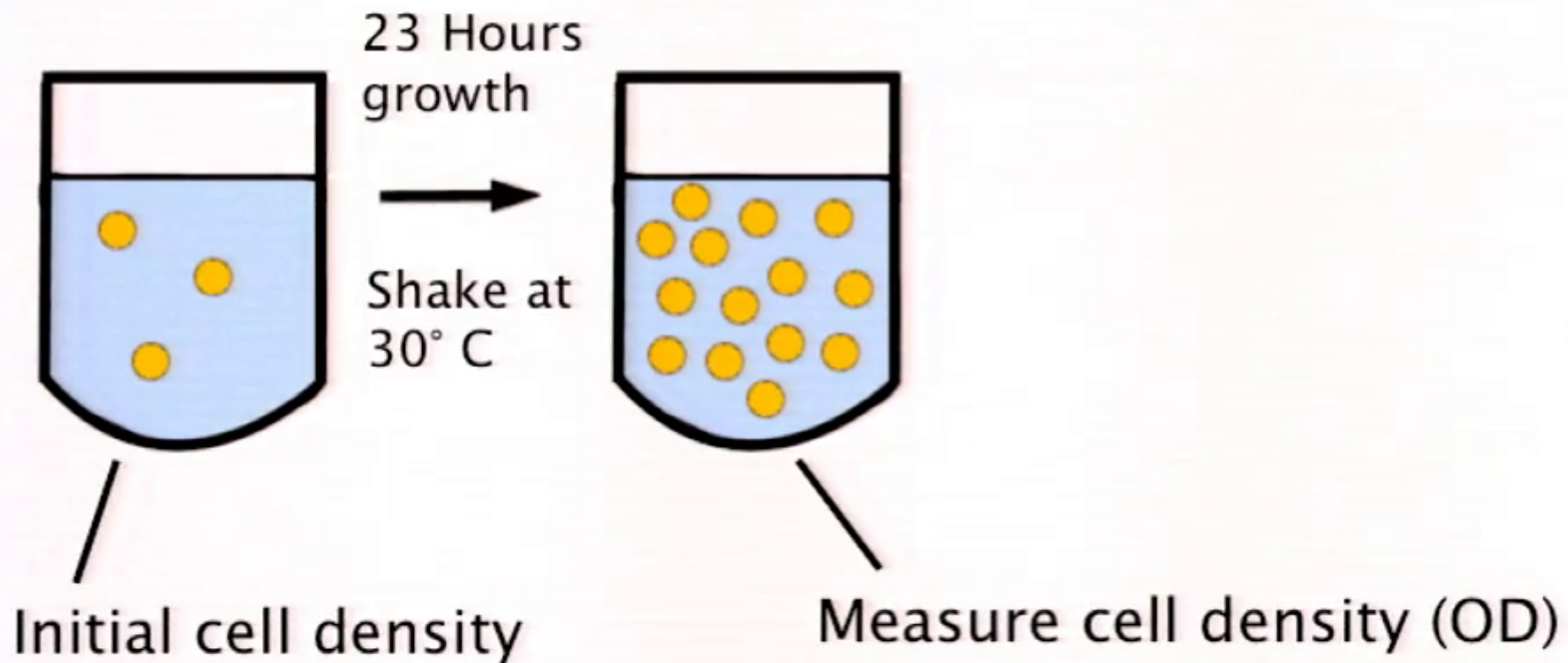
Possibility of
sudden collapse!

Experimental procedure: Serial batch culture

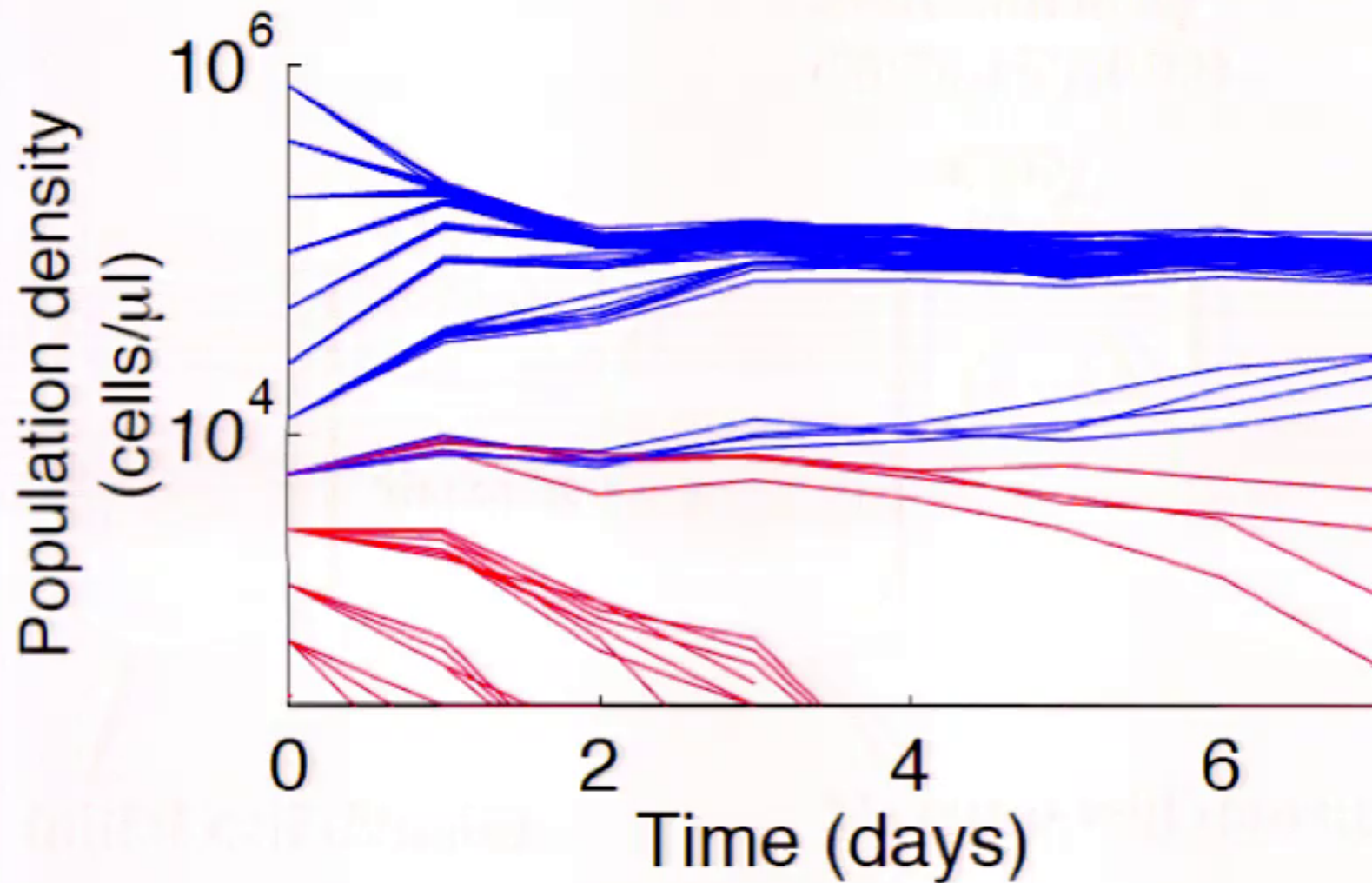


Initial cell density

Experimental procedure: Serial batch culture

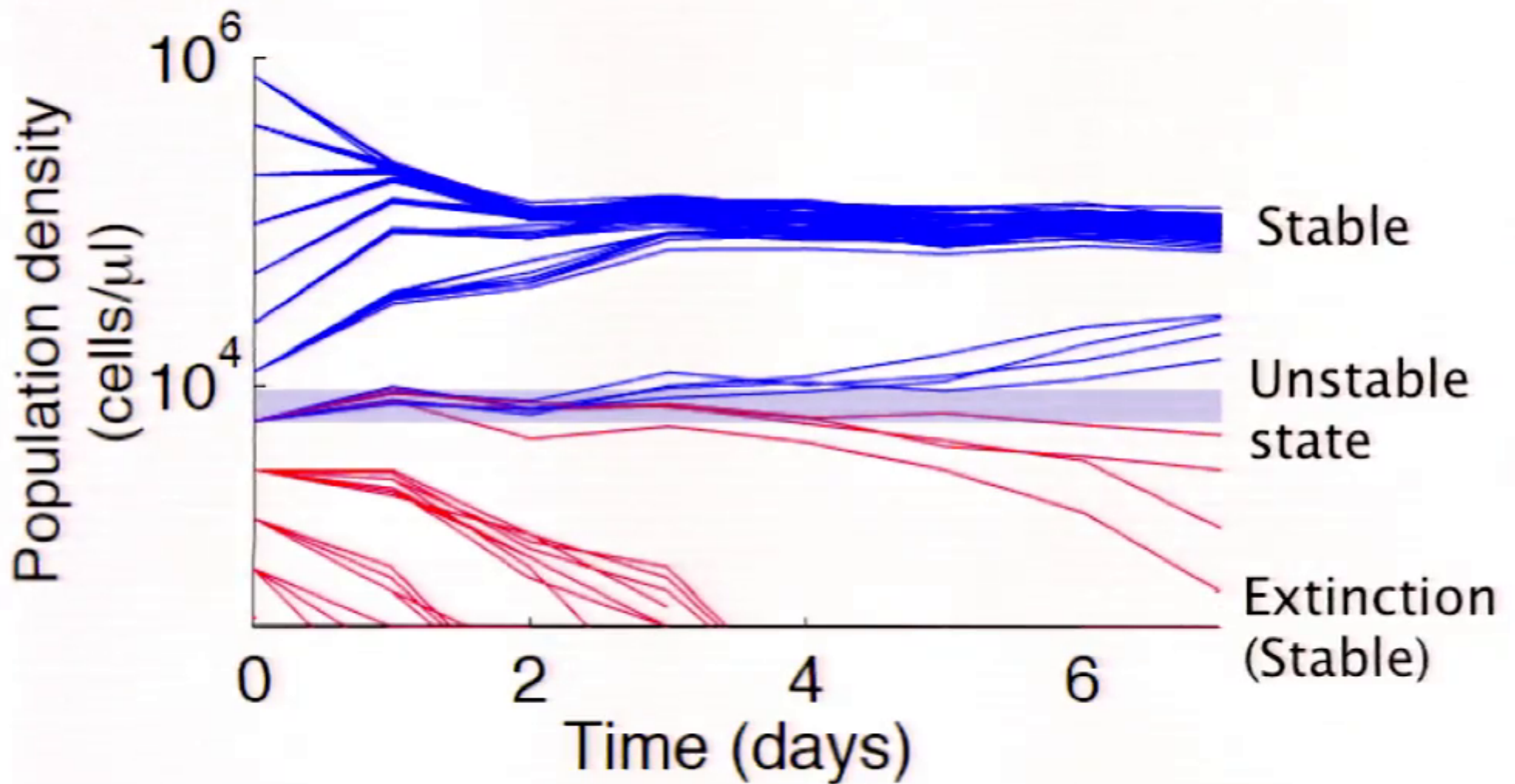


Yeast population size is bistable



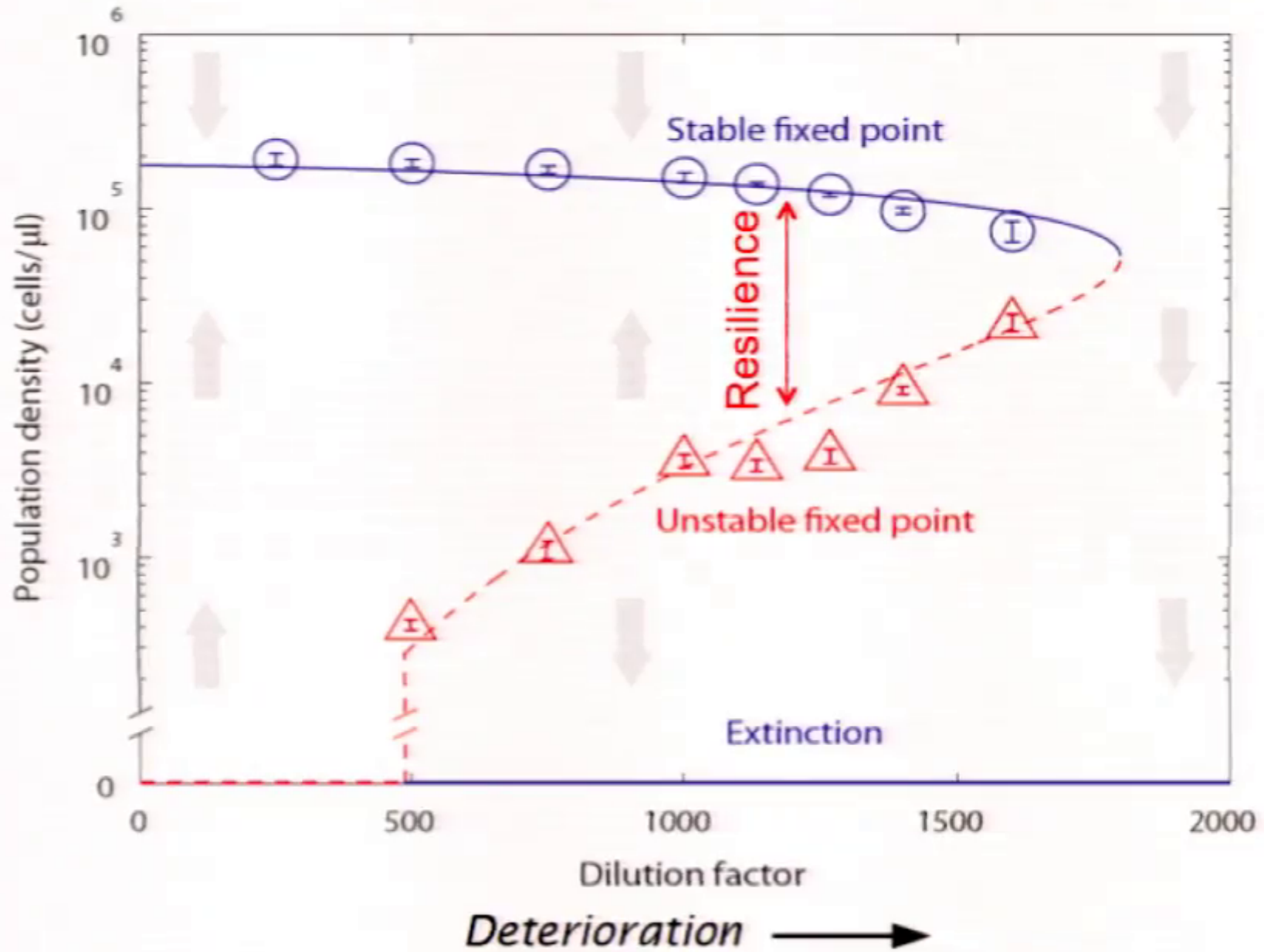
Dilution Factor = 1400

Yeast population size is bistable

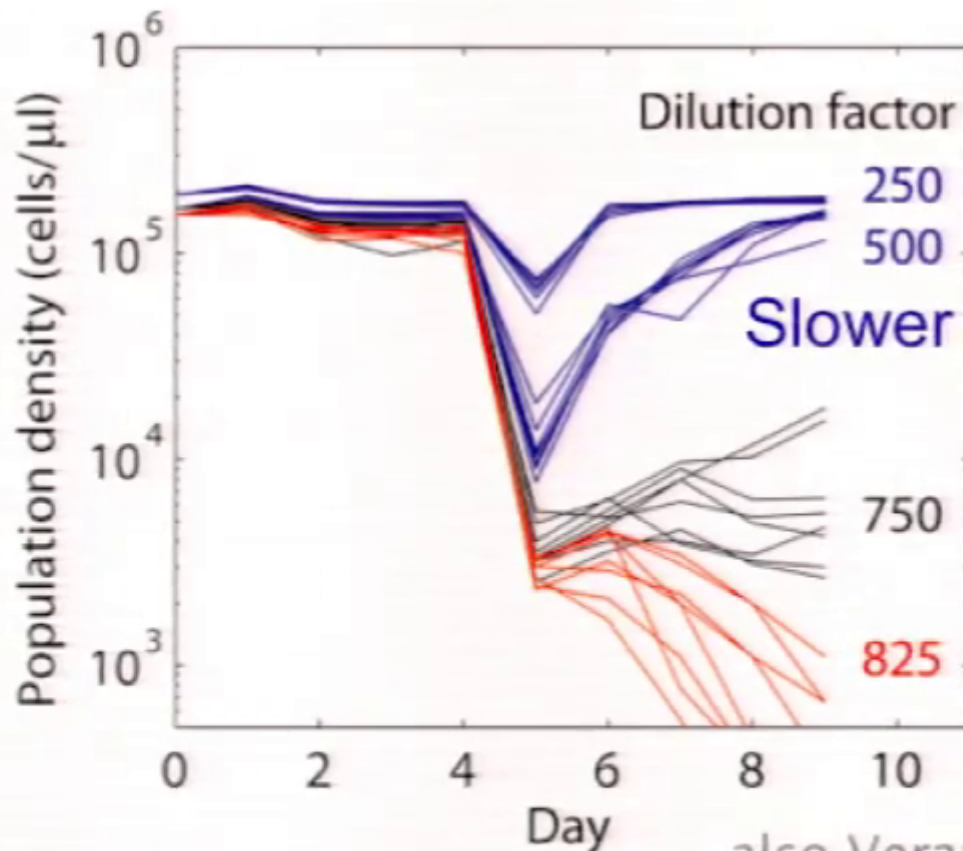
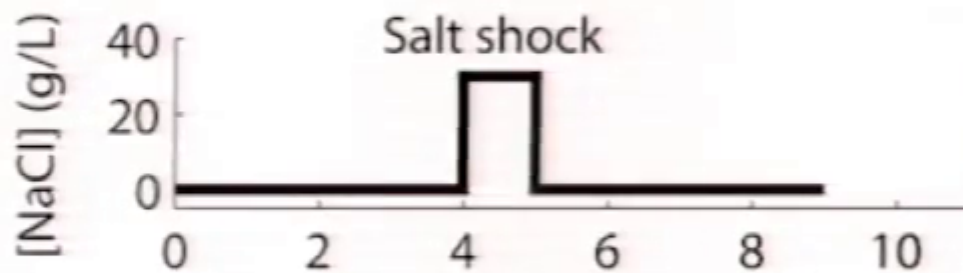


Dilution Factor = 1400

Yeast populations experience a fold bifurcation



Population less resilient near tipping point



Benign conditions
→ Rapid recovery

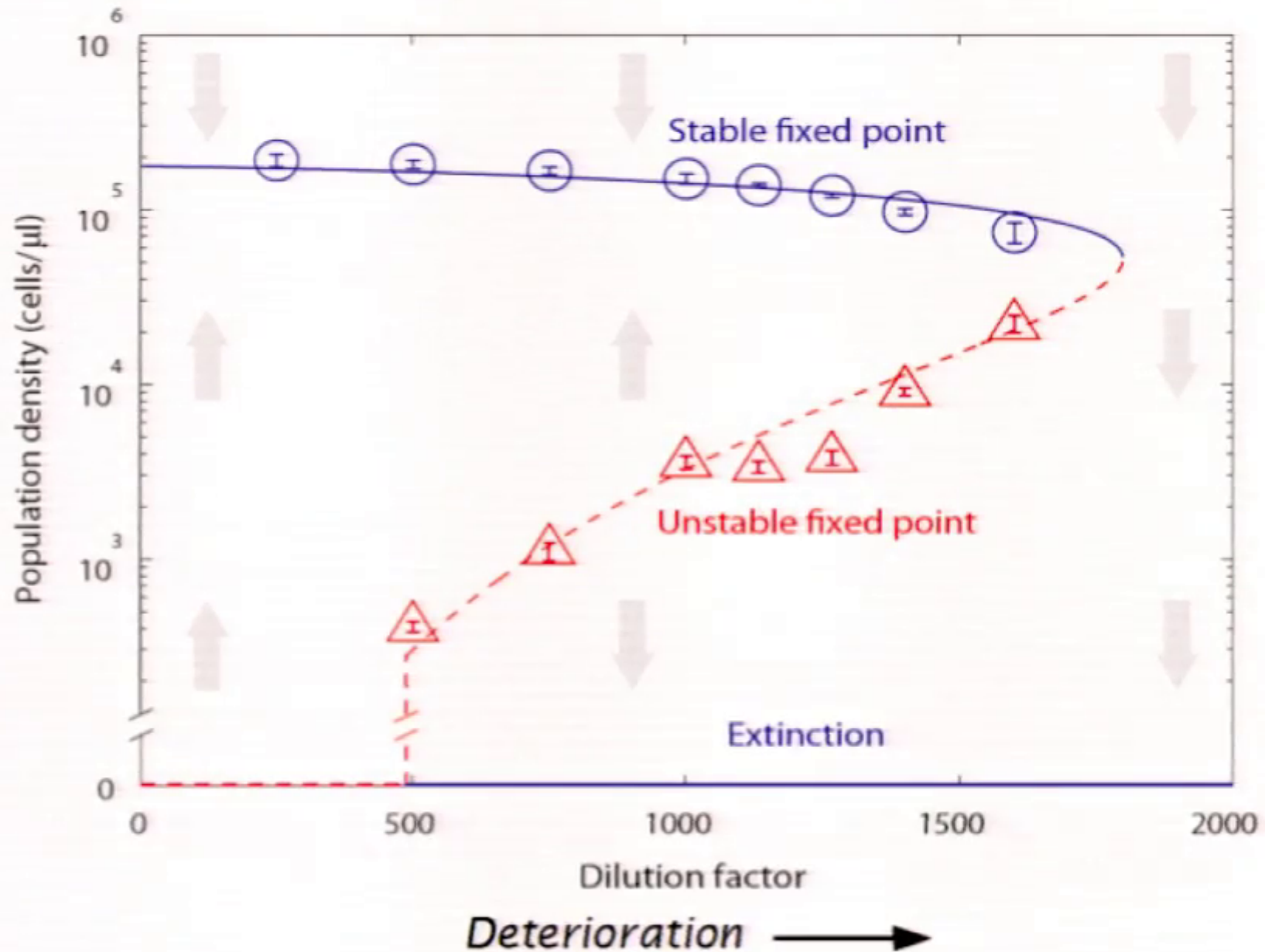
Slower recovery

Poor conditions
→ collapse

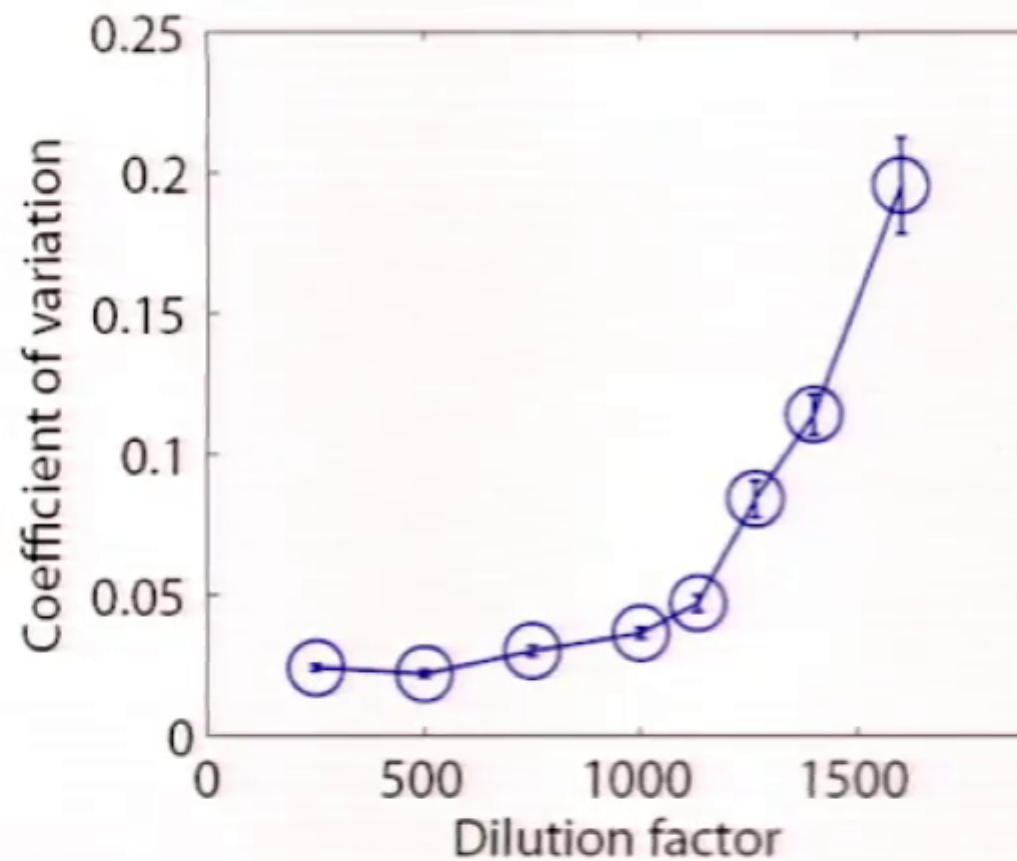
also Veraart, ...Scheffer, *Nature* (2012)

Dai, Vorselen, Korolev, Gore, *Science* (2012)

Can indicators be observed before tipping point?

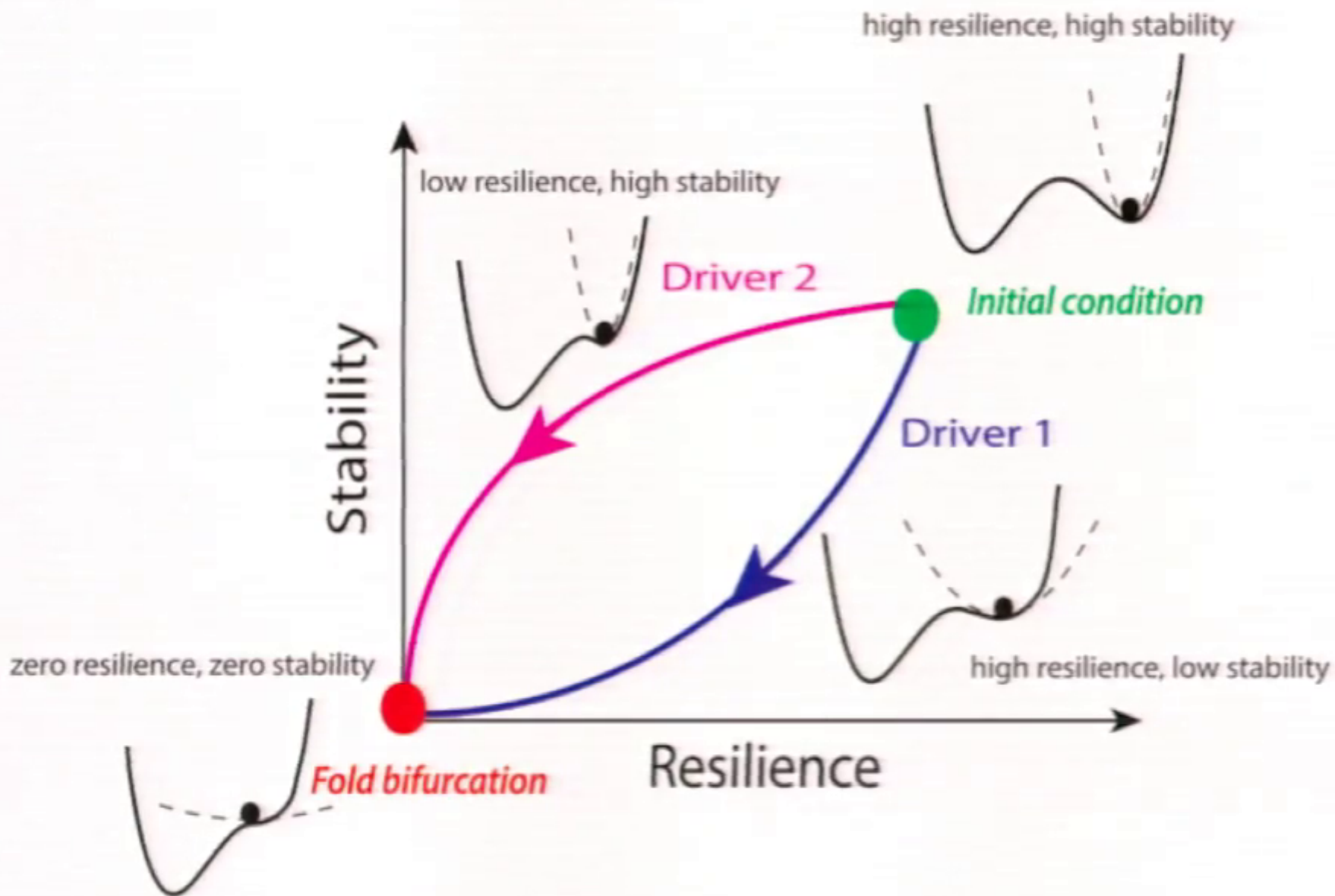


Population fluctuations increase near the tipping point

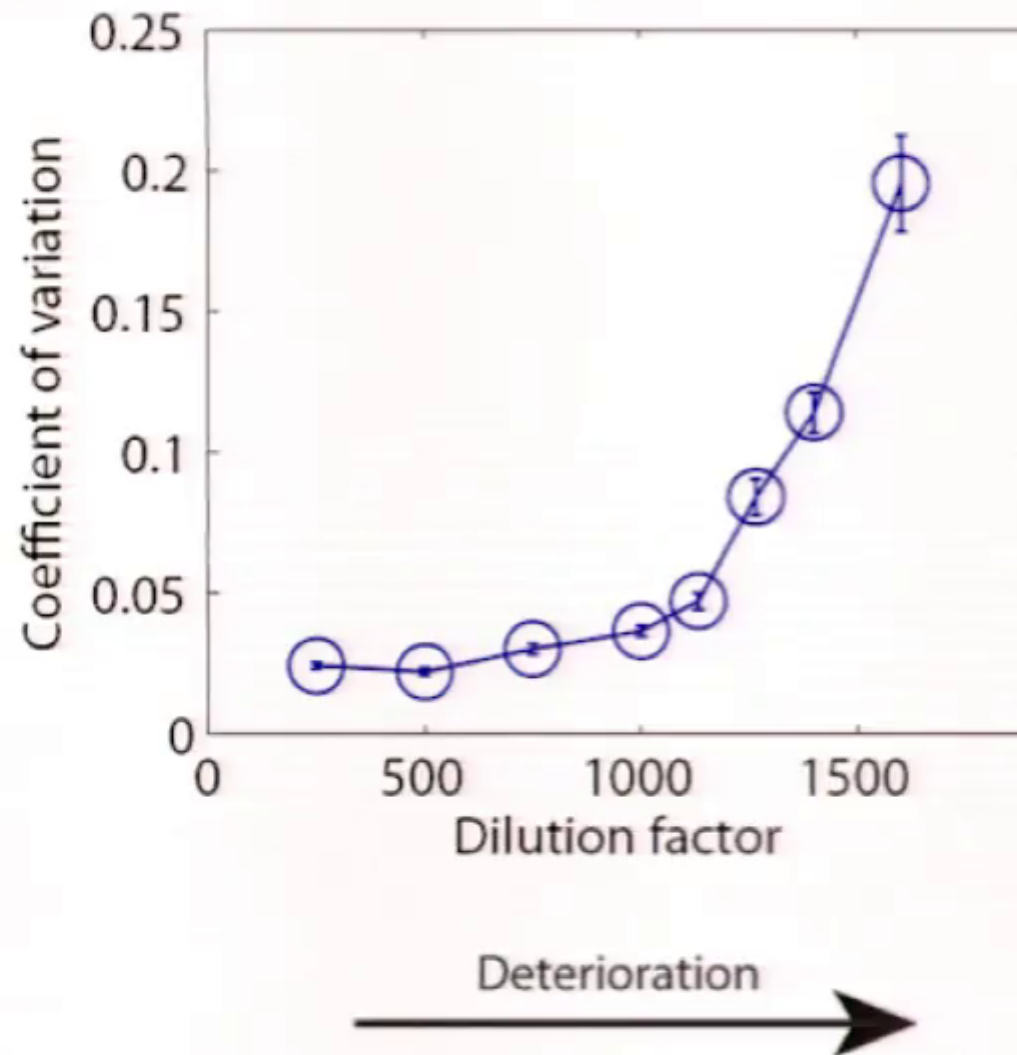


Deterioration
→

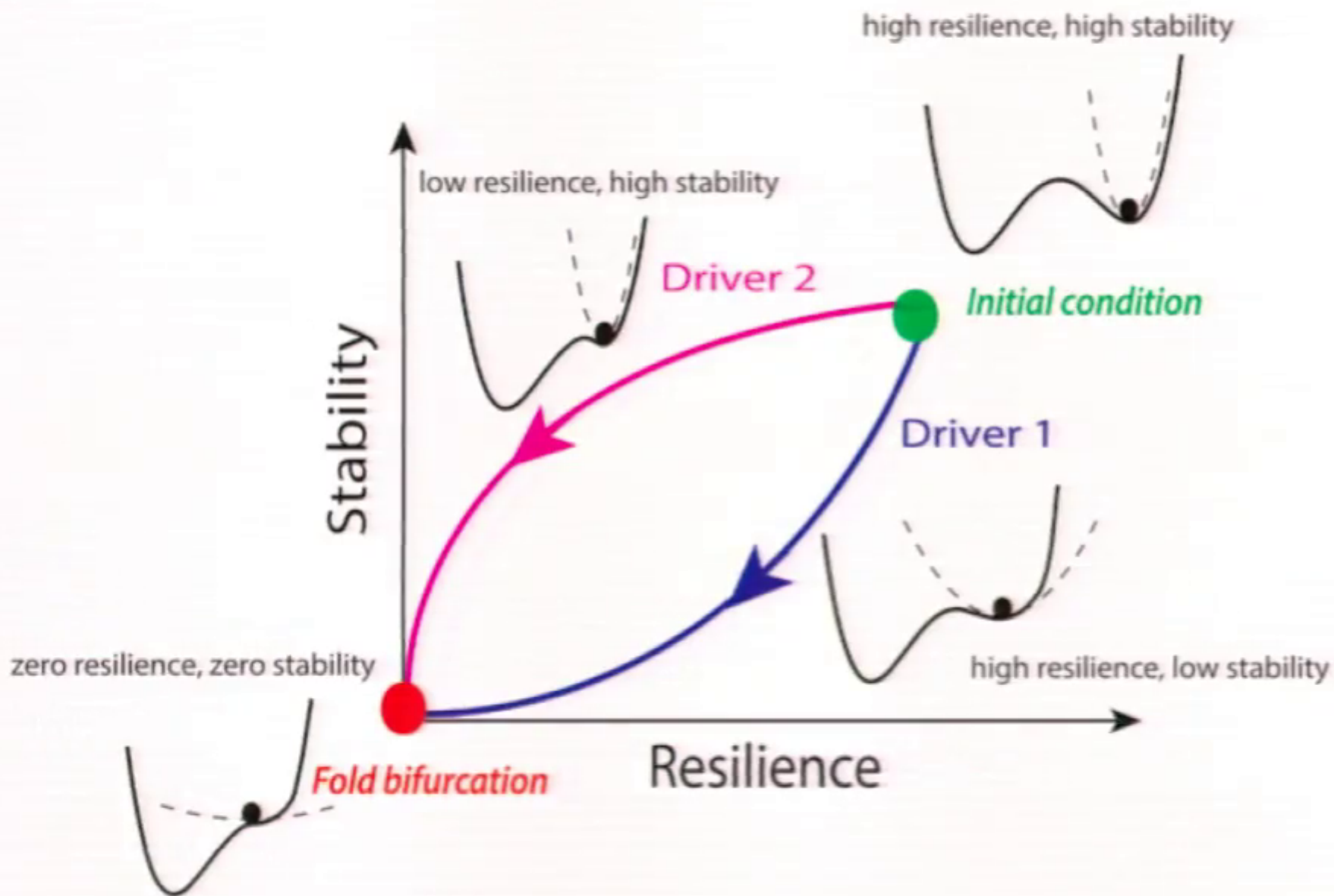
Stability vs resilience determines indicator performance



Population fluctuations increase near the tipping point



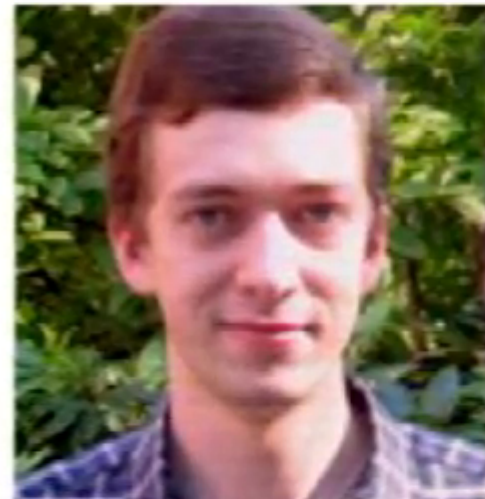
Stability vs resilience determines indicator performance



“How do these early warning indicators behave in spatially connected populations?”

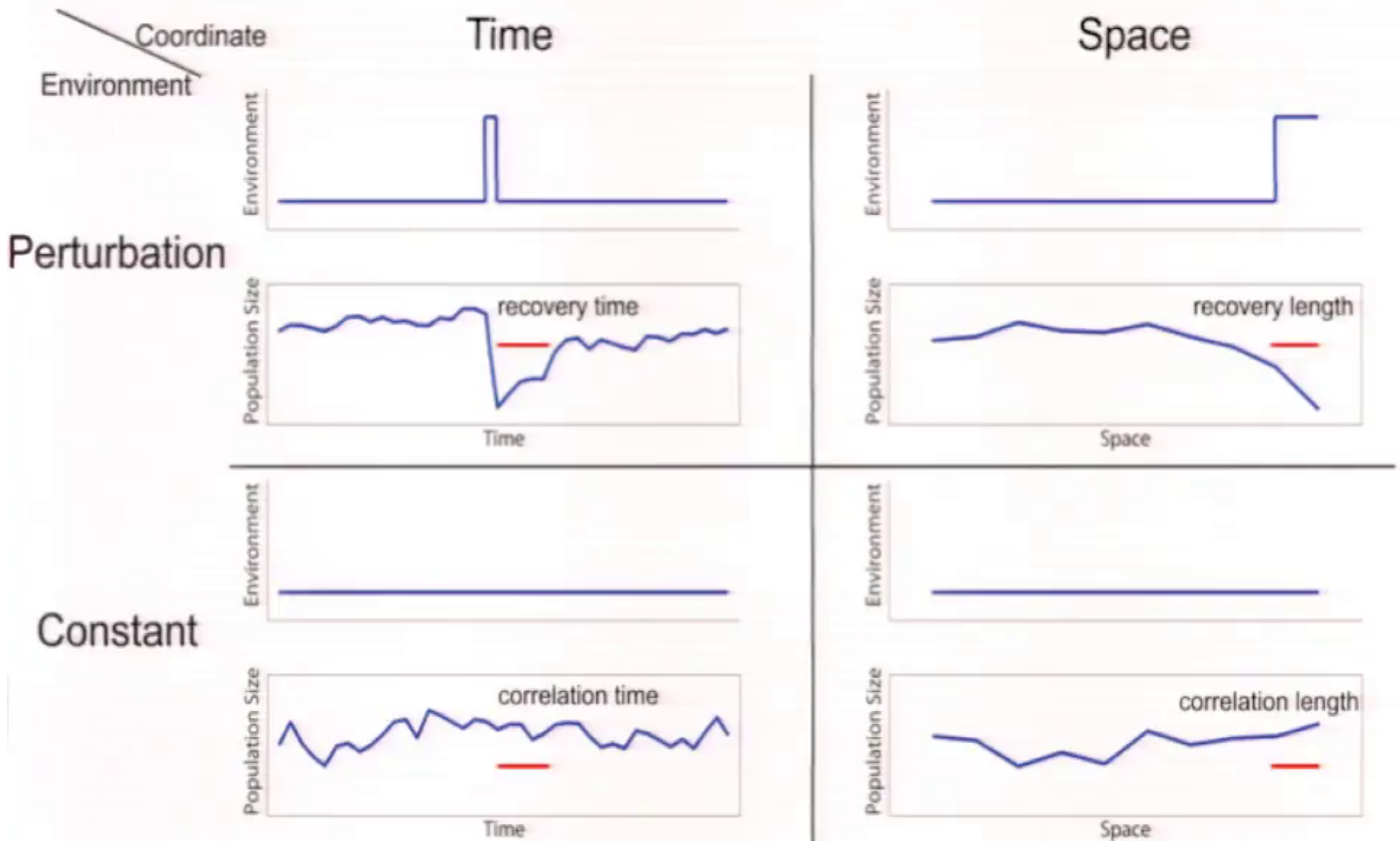


Lei Dai
Physics student
→ Viral evolution @
UCLA

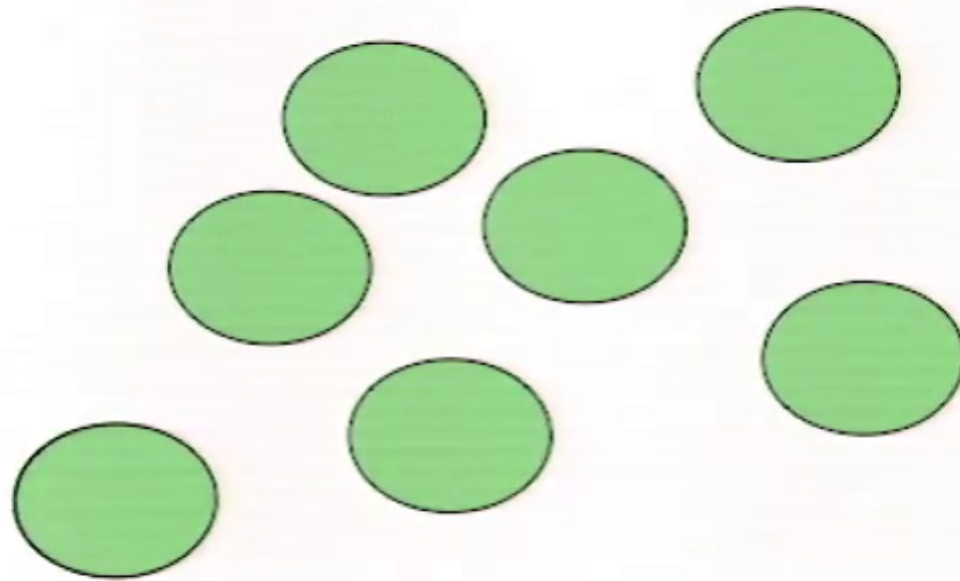


Kirill Korolev
Pappalardo Postdoc Fellow
→ Boston Univ Physics Dept

Recovery length is the spatial analogue to recovery time

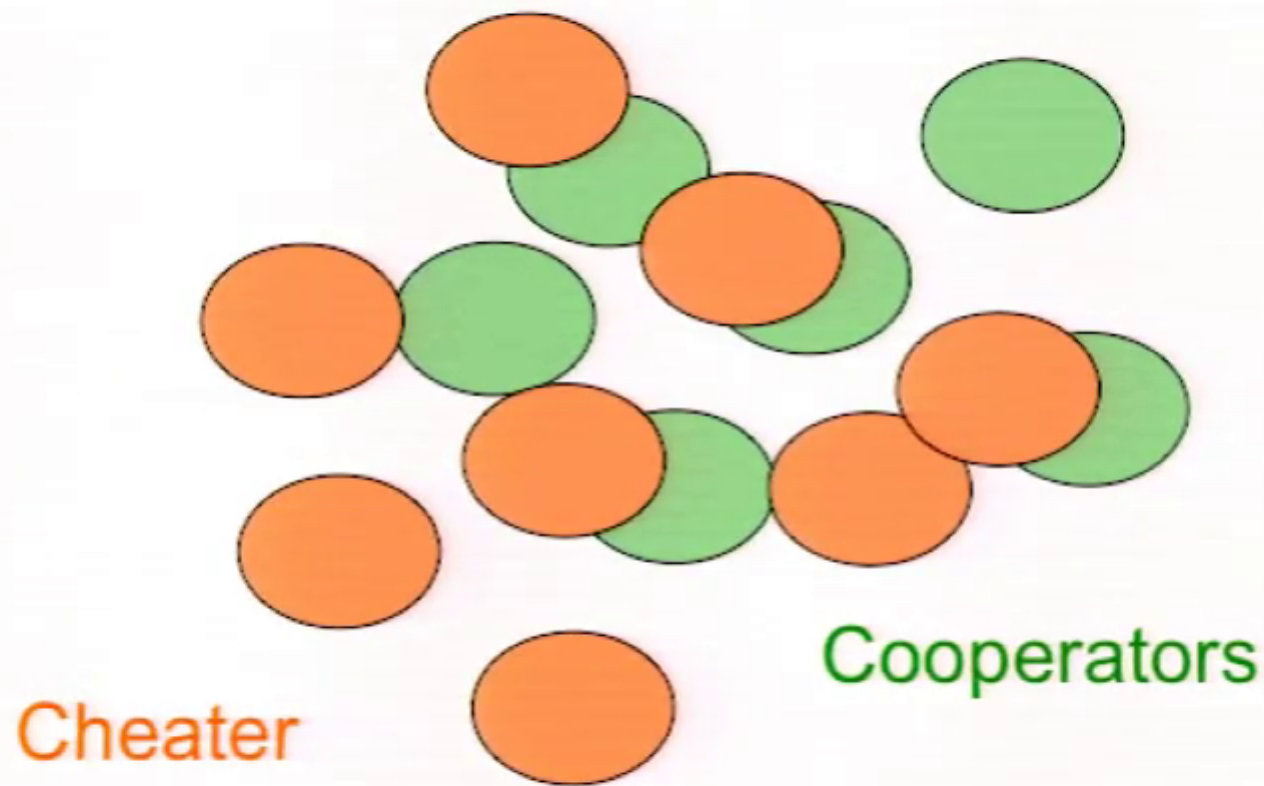


Cooperation not always stable



Yeast growing on sucrose

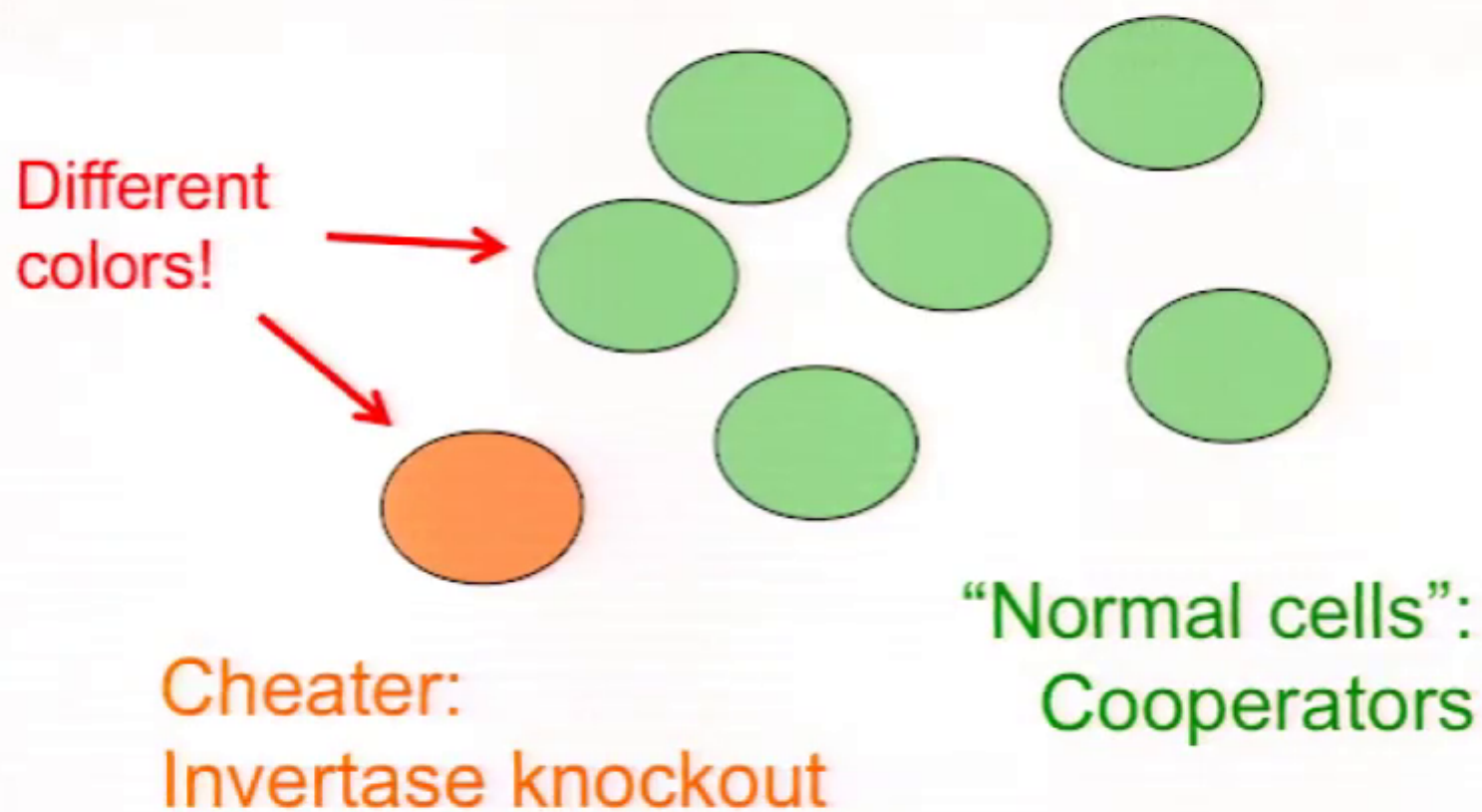
Cheaters can often take advantage of cooperators



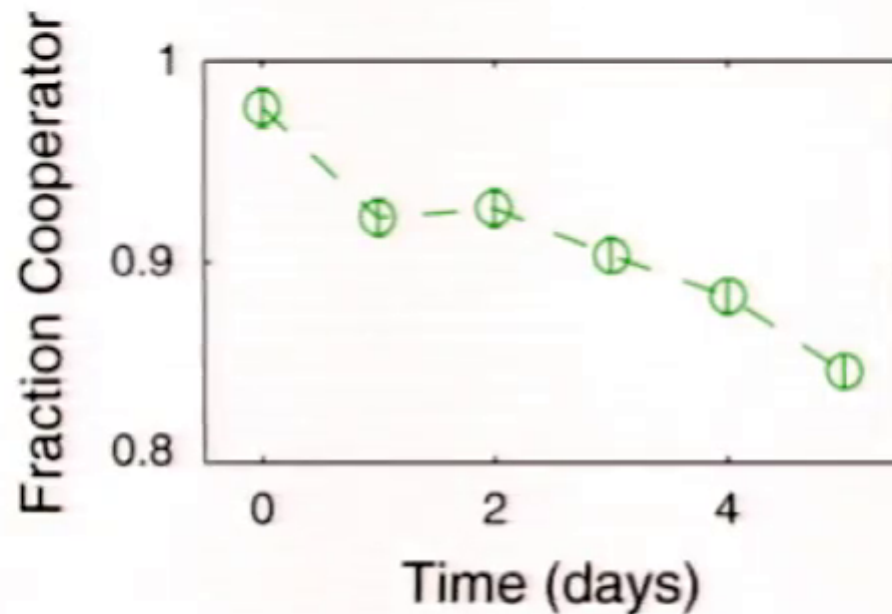
Greig & Travisano, *Proc Royal Soc B* (2004)

Gore et al, *Nature* (2009)

Gene knockout is a “cheater”

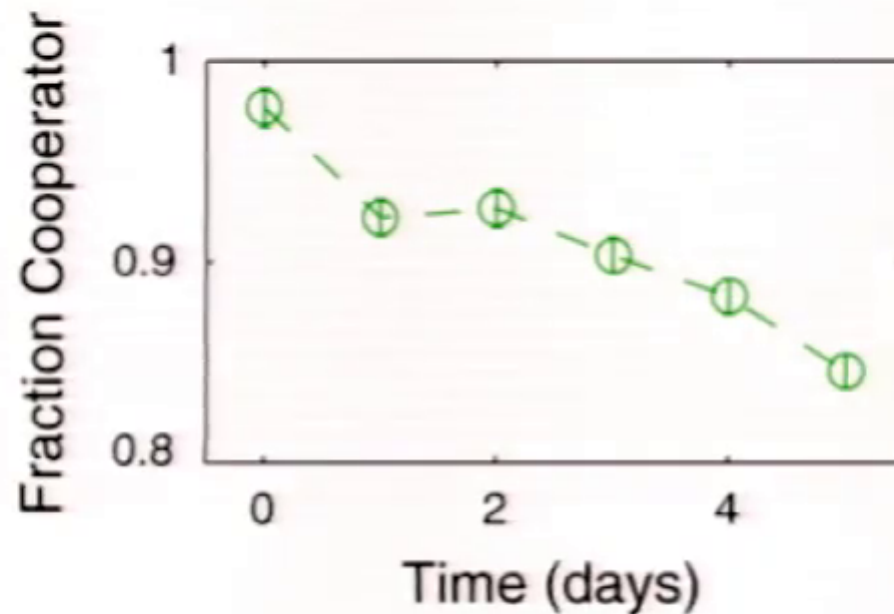


Cheater can spread in a population of cooperators



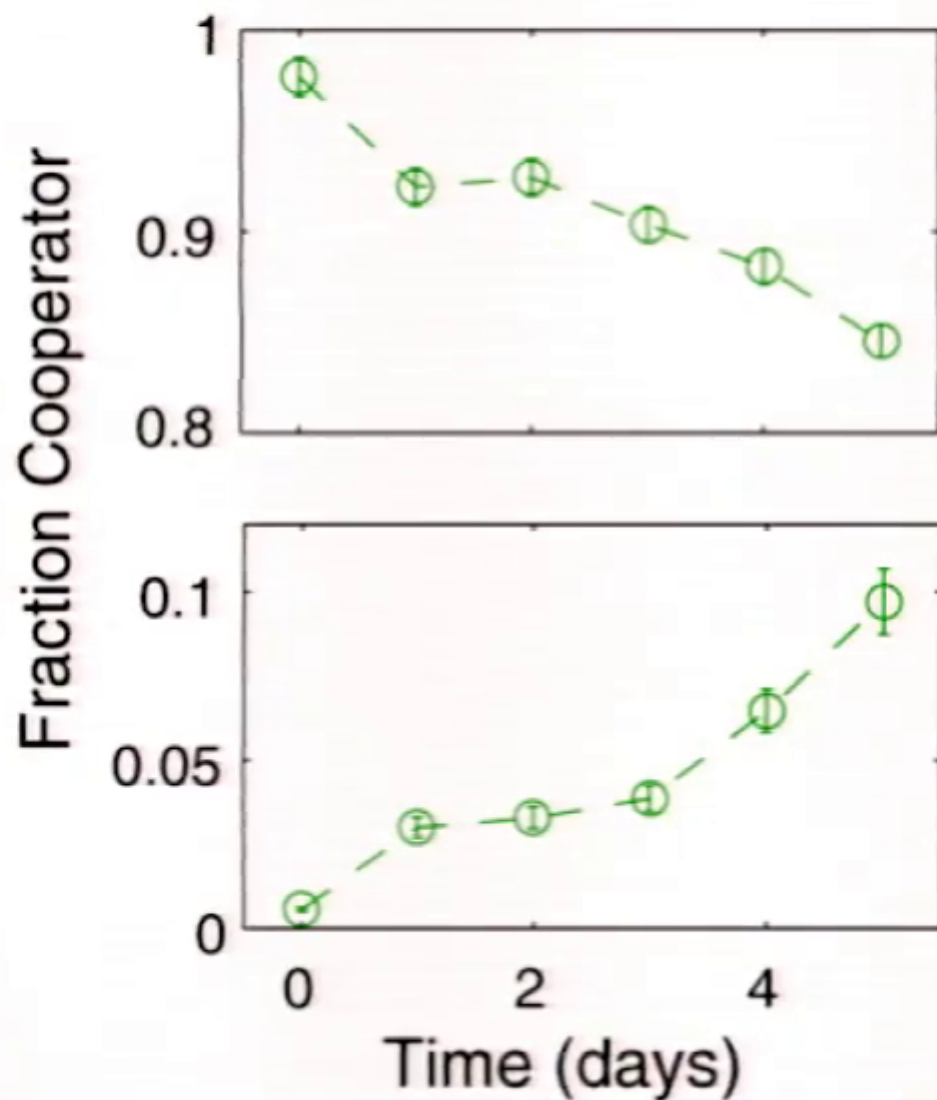
Growth rate
decreasing!

Cheater can spread in a population of cooperators



Growth rate
decreasing!

Cheater can spread in a population of cooperators, Cooperator can spread in a population of cheaters

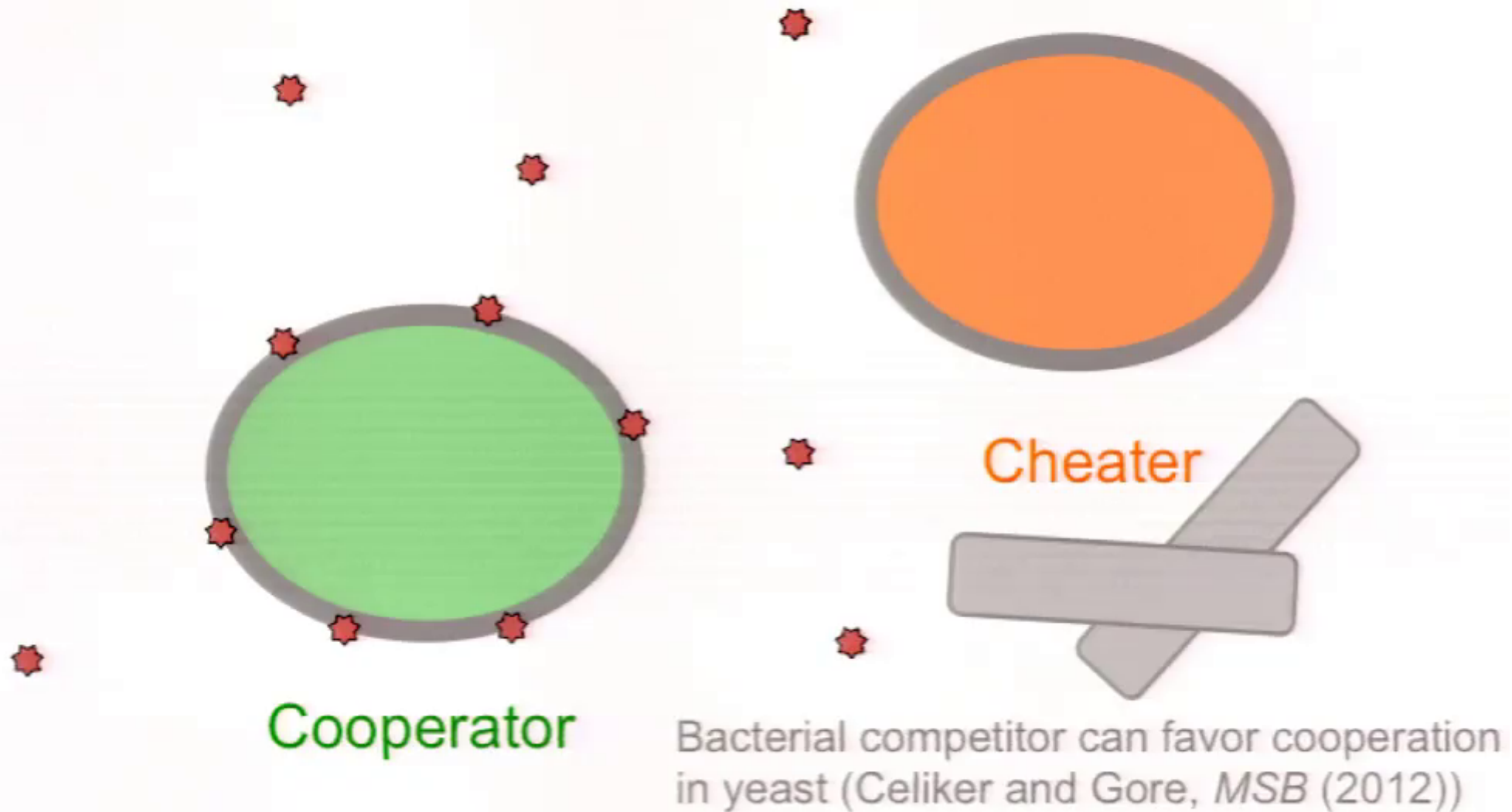


Coexistence!

Snowdrift game: Cheat if your opponent cooperates Cooperate if your opponent cheats



Cooperators have preferential access to benefits



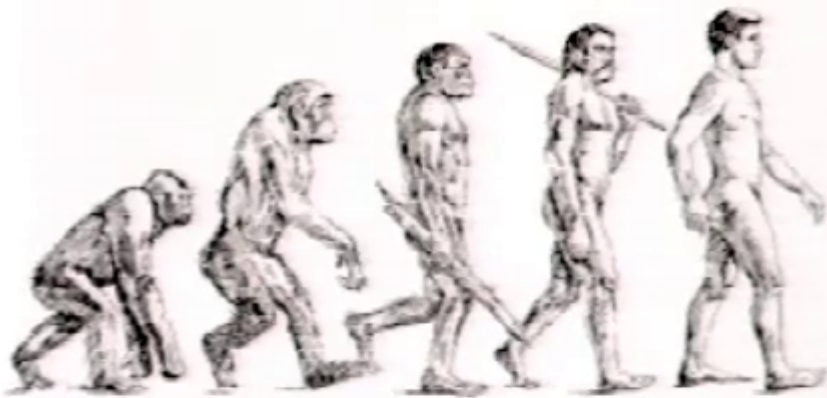


“How might feedback between population dynamics and evolutionary dynamics determine the fate of populations?”

Alvaro Sanchez
Postdoctoral Fellow
→ Rowland Institute
of Harvard

Evolution and population dynamics: Different timescales?

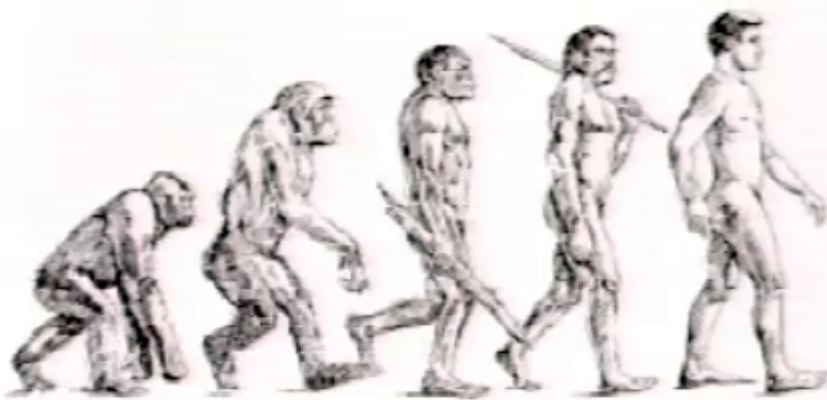
Evolution



~ 1 Million Years

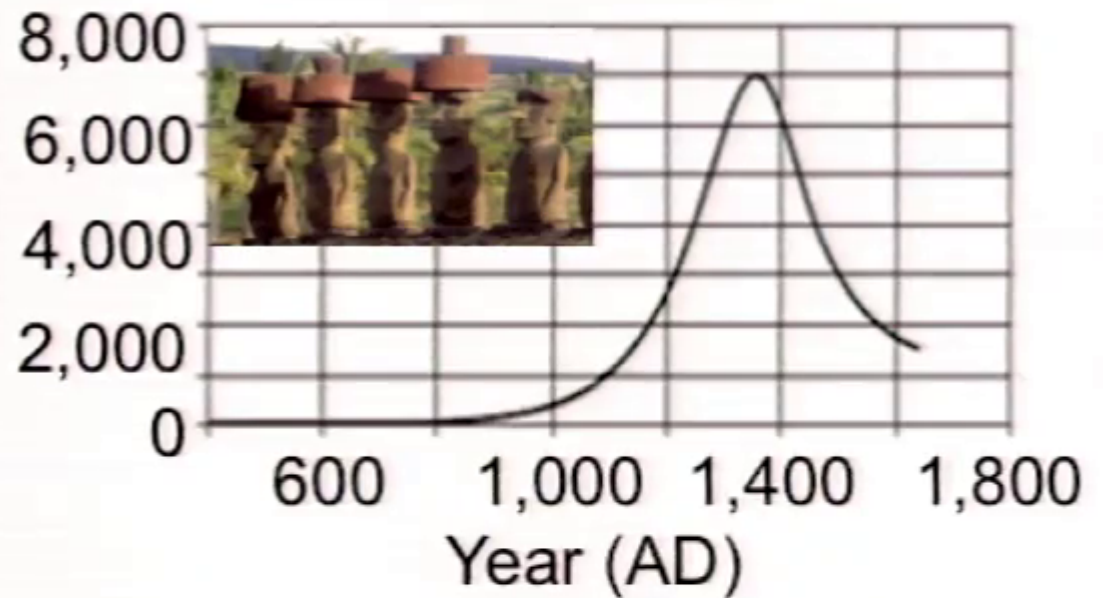
Evolution and population dynamics: Different timescales?

Evolution



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Population Dynamics

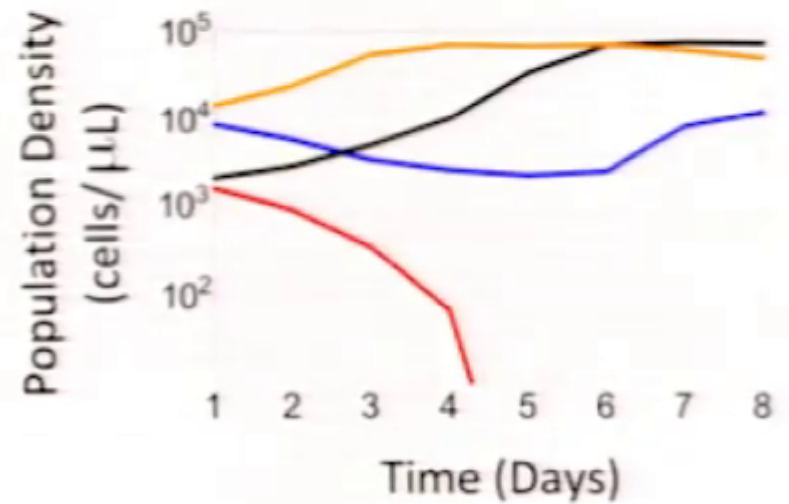
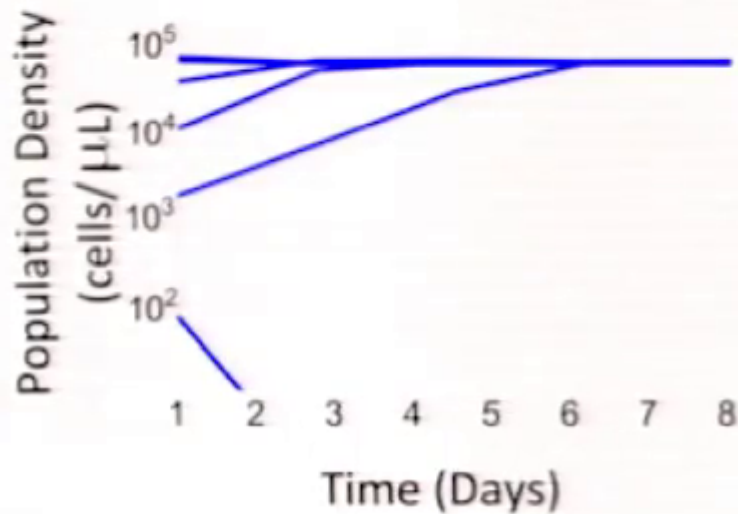


Bologna & Flores, EPL (2008)

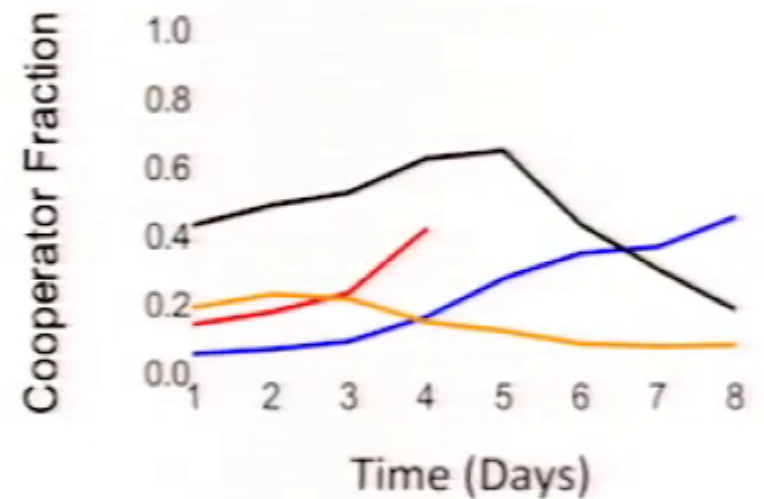
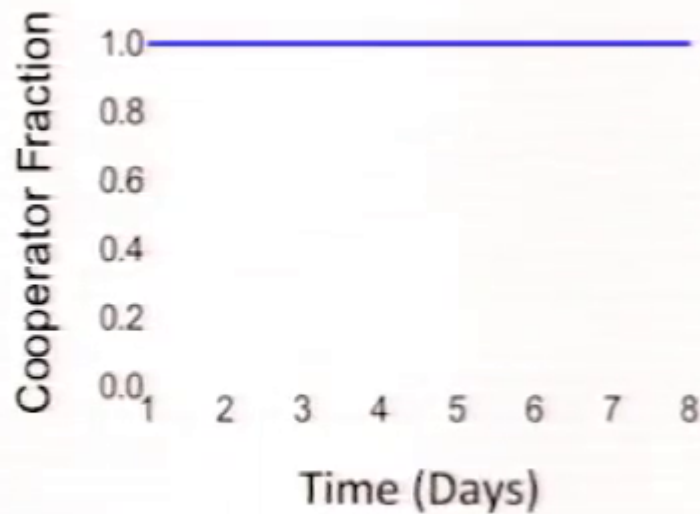
Sanchez and Gore, *PLOS Biology* (2013)

Seemingly erratic behavior of individual populations

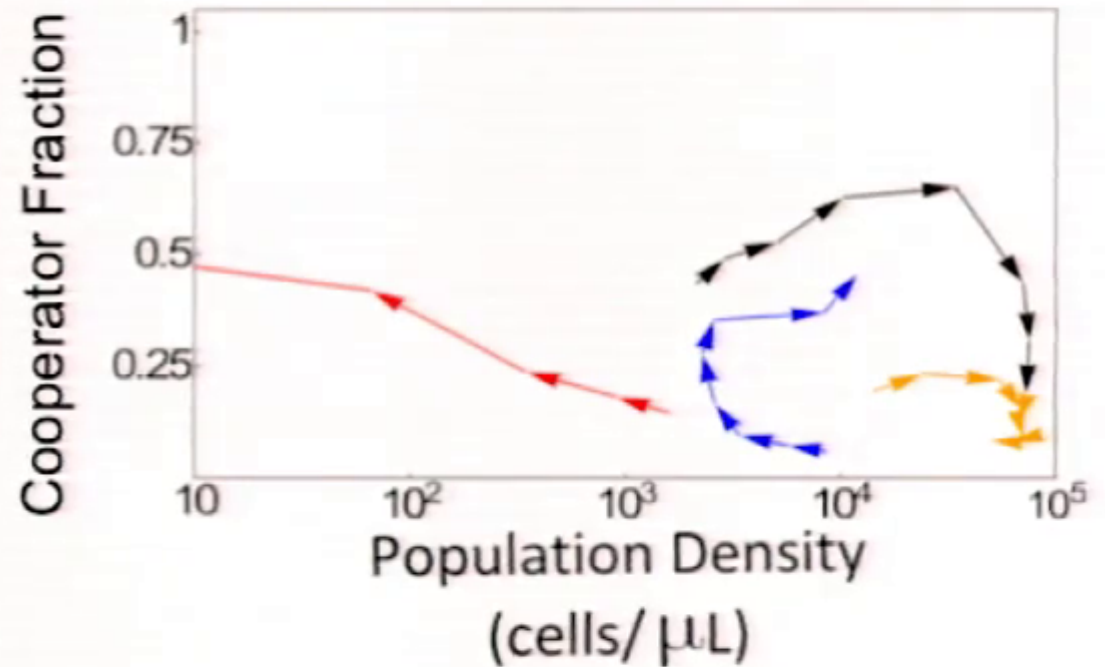
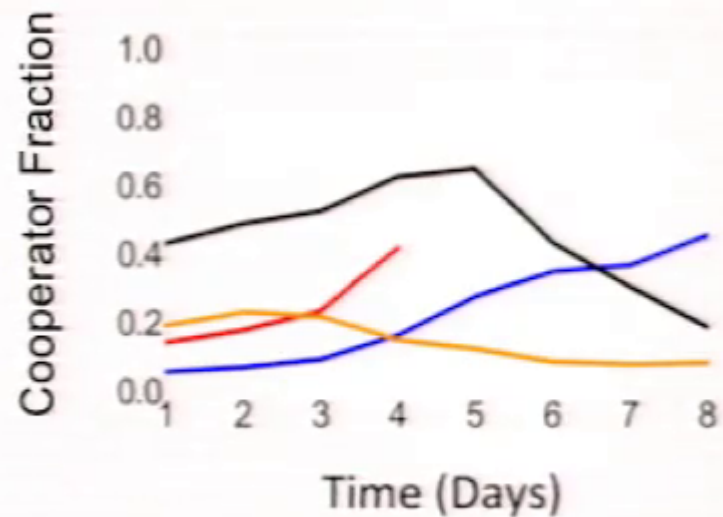
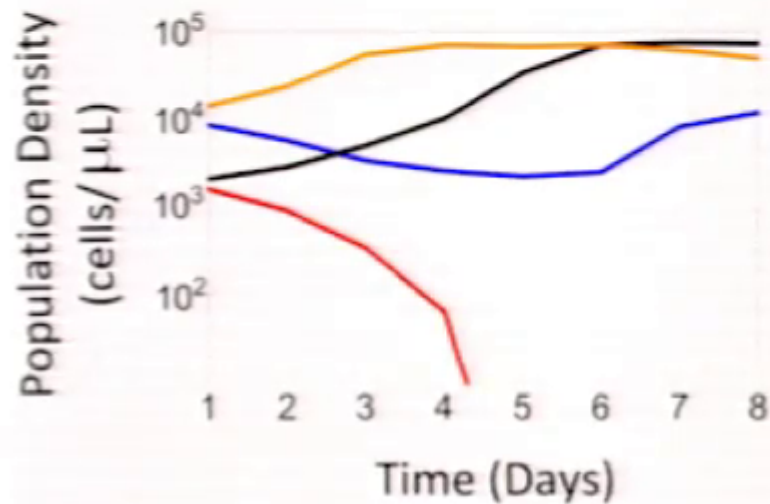
Population
Dynamics



Evolutionary
Dynamics



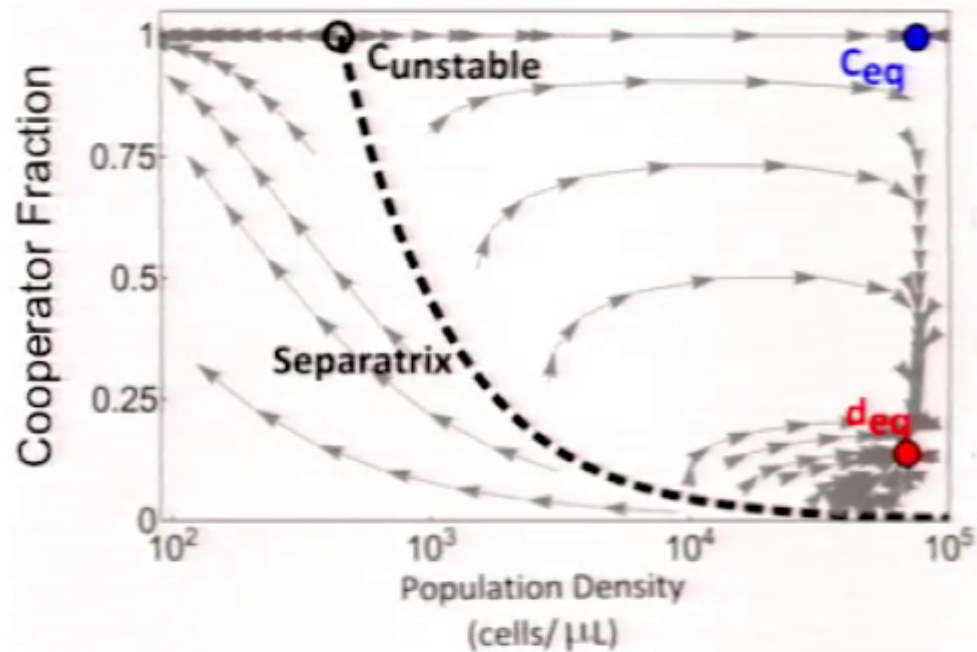
Patterns revealed by the eco-evolutionary trajectory



“Spirals” are eco-evolutionary feedback!

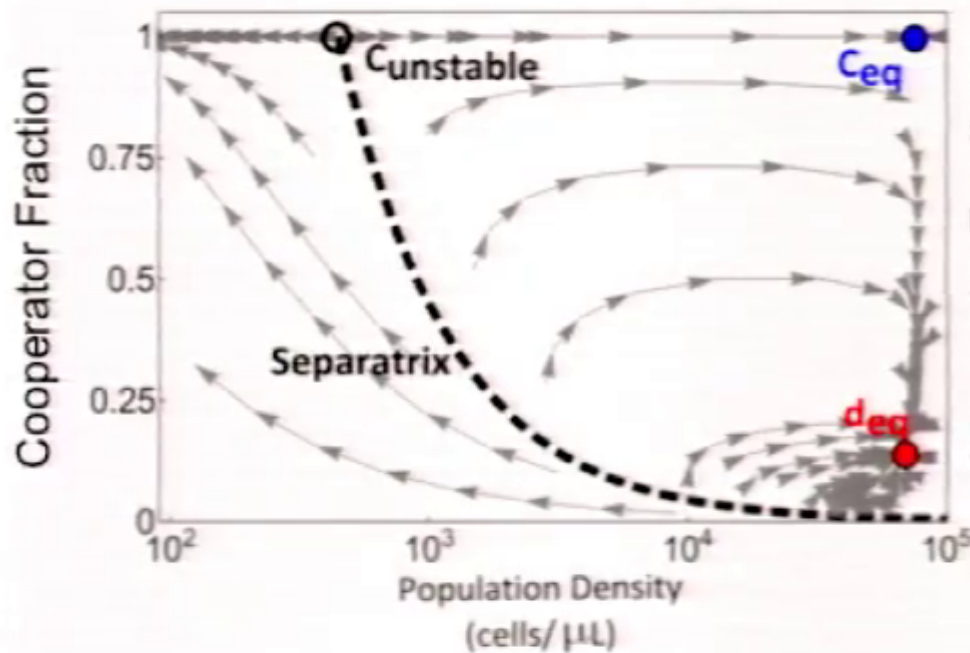
Tracking of trajectories in eco-evolutionary space

Model

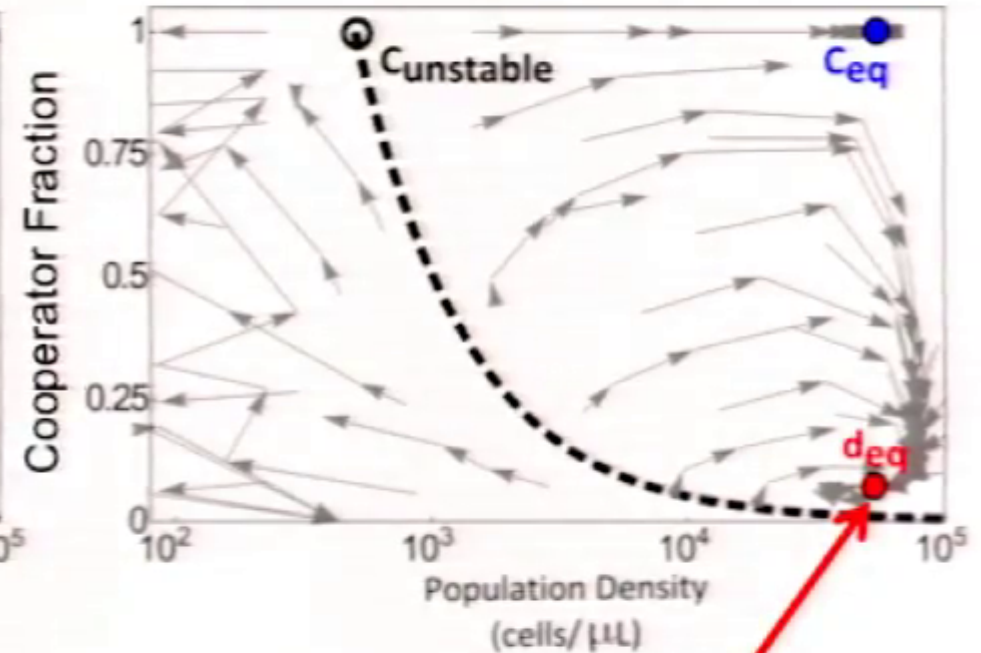


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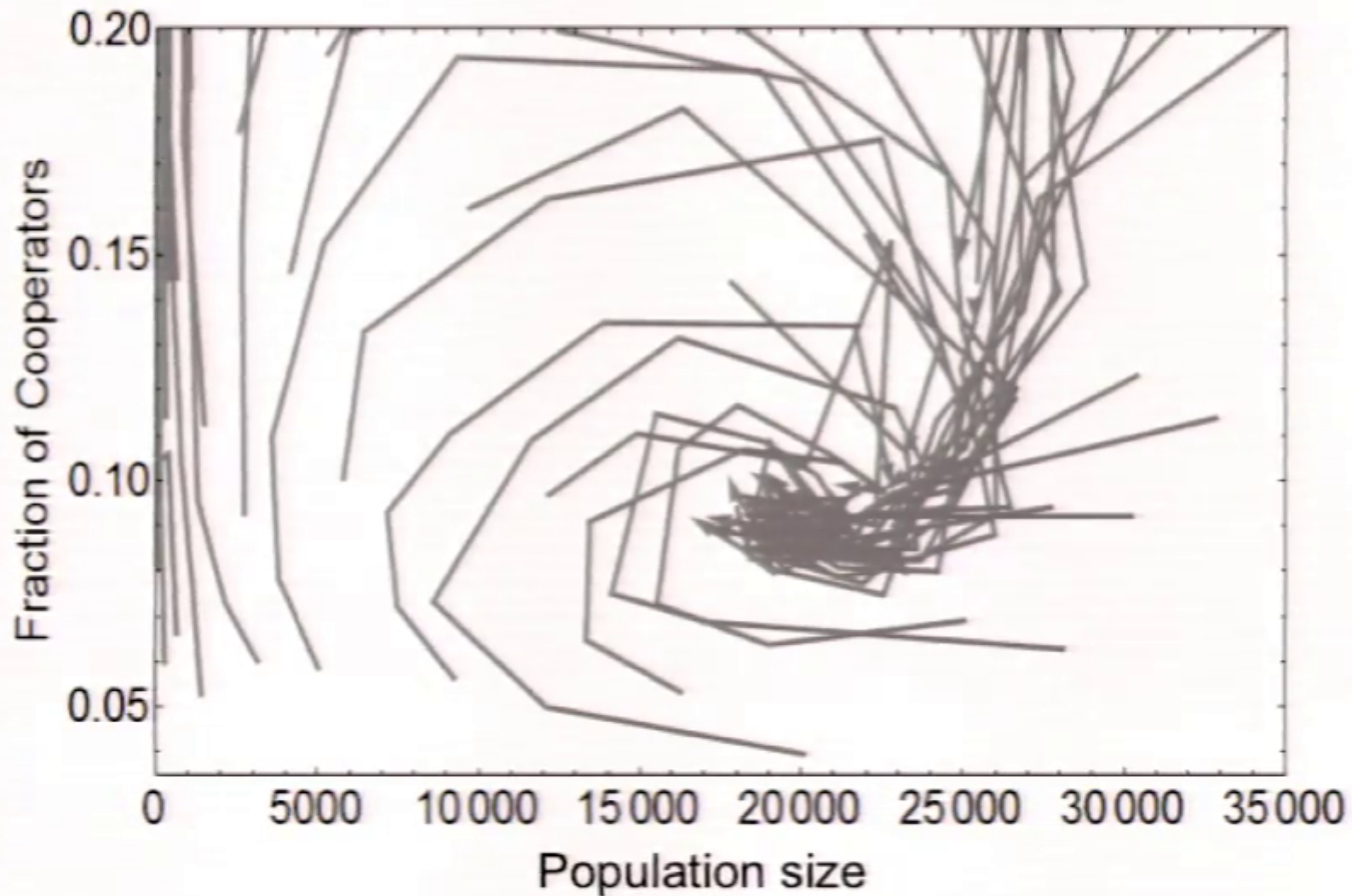


Experiments

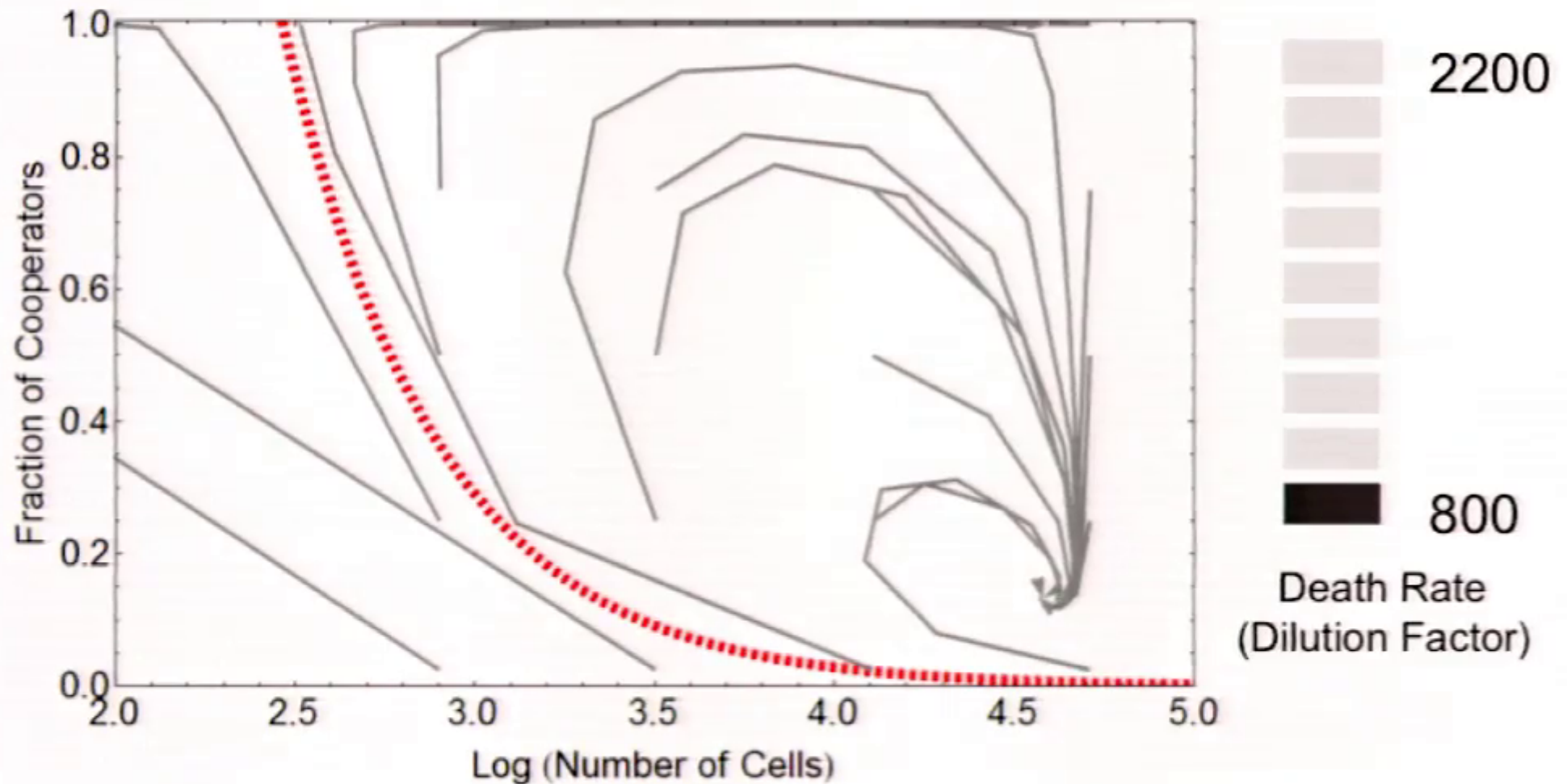


Cheaters don't significantly reduce population size, but do reduce resilience

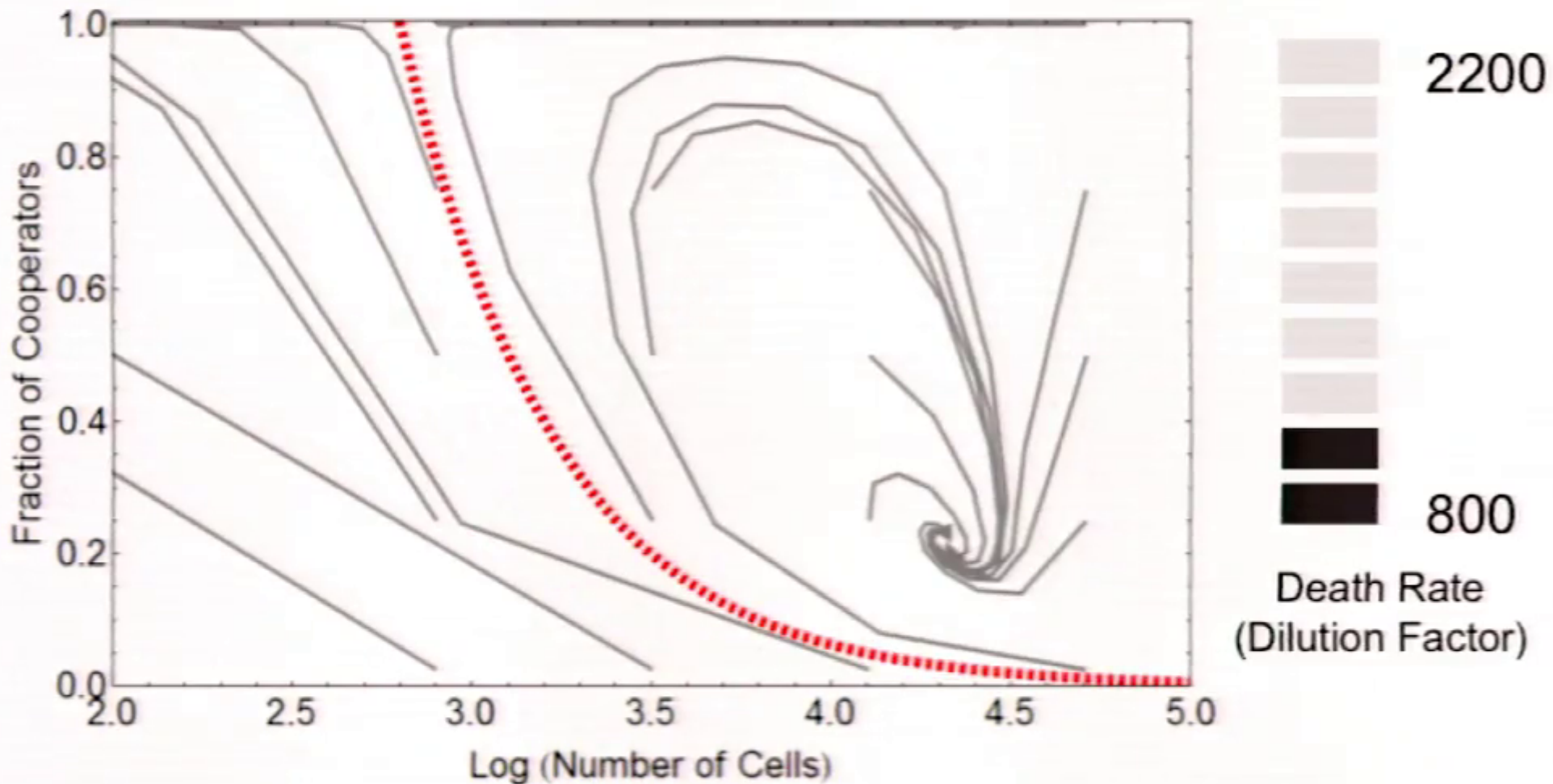
How do spirals change near collapse?



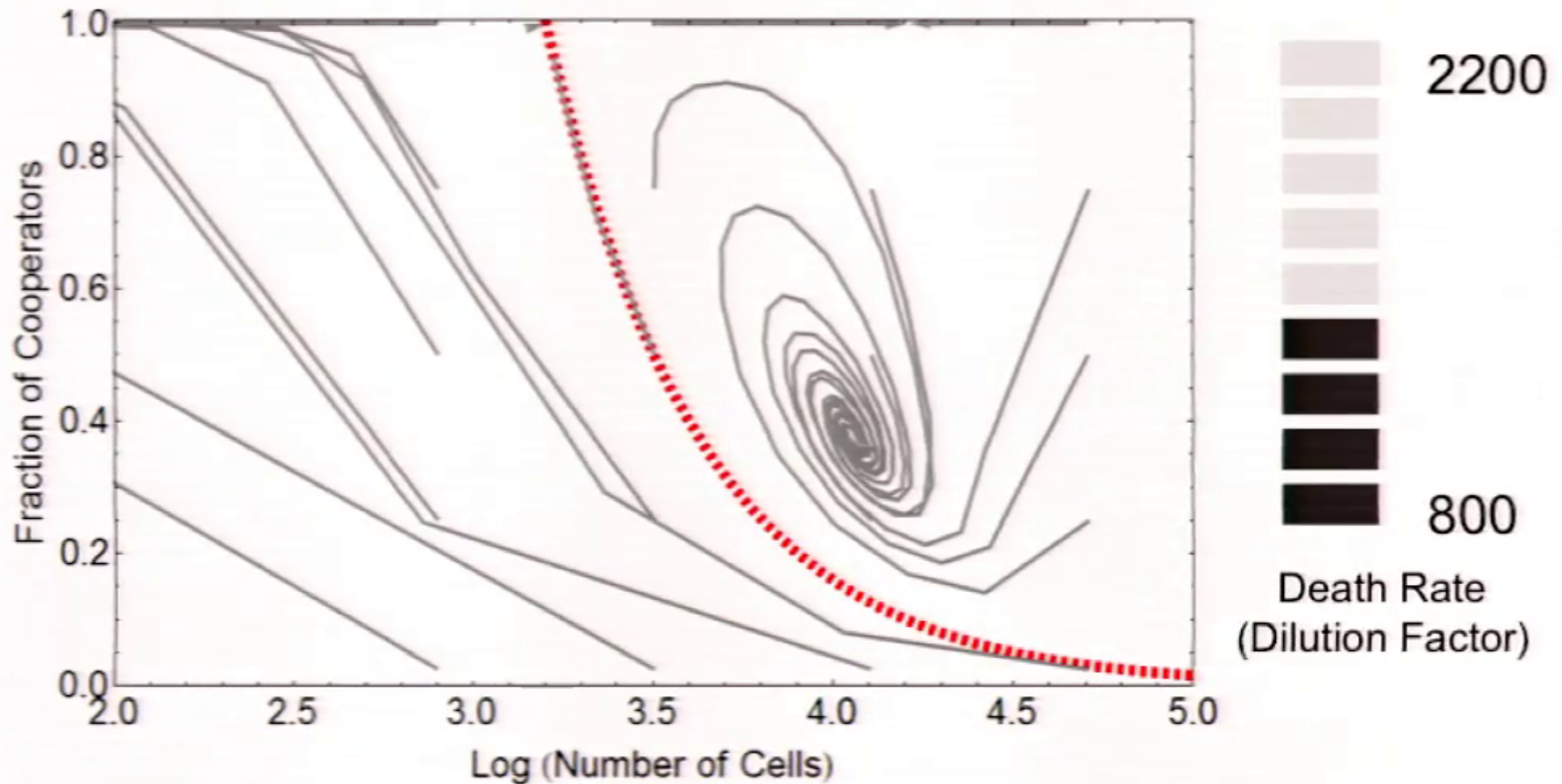
A simple model of yeast growth yields spirals



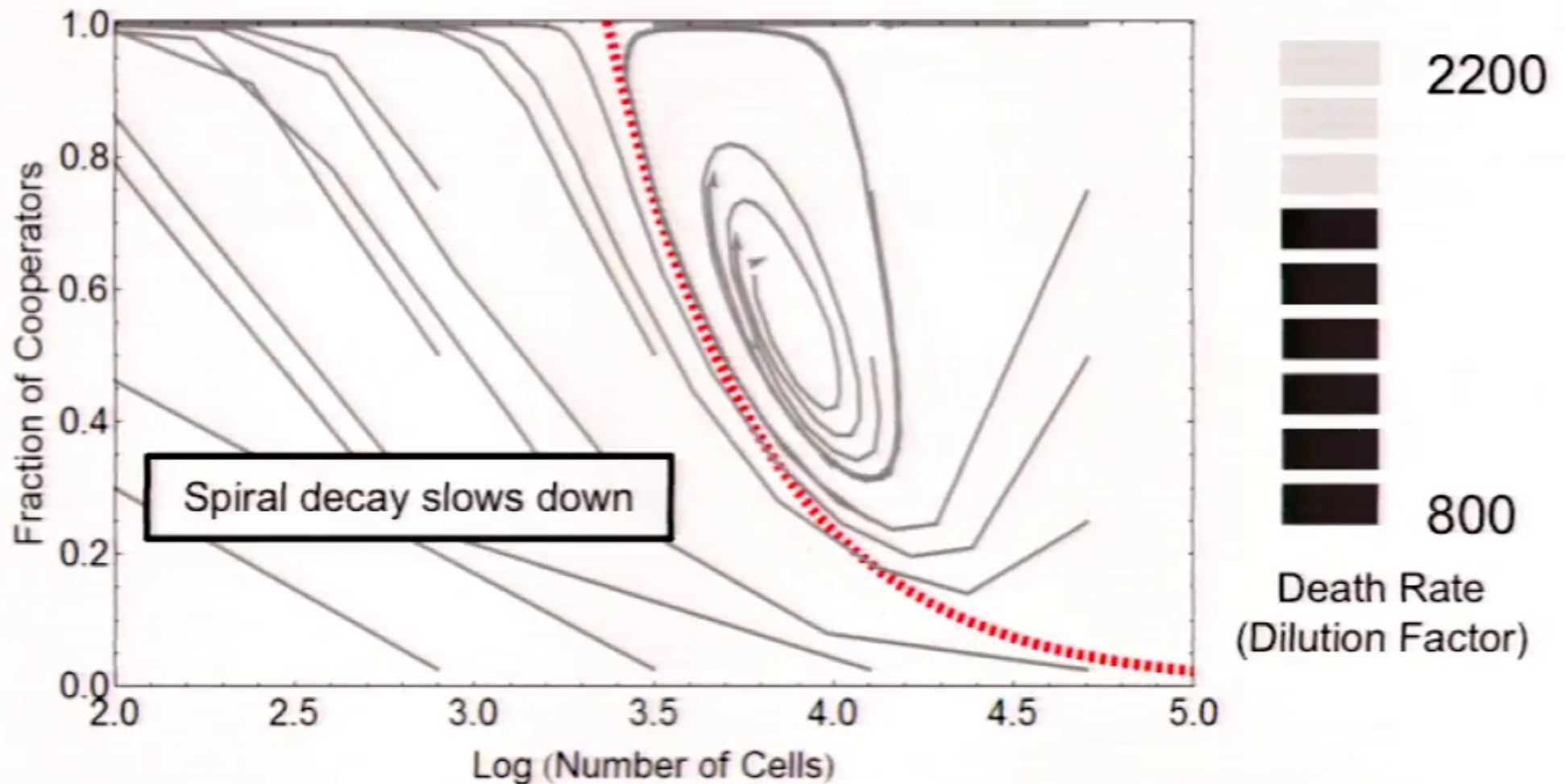
Spiral changes as environment deteriorates



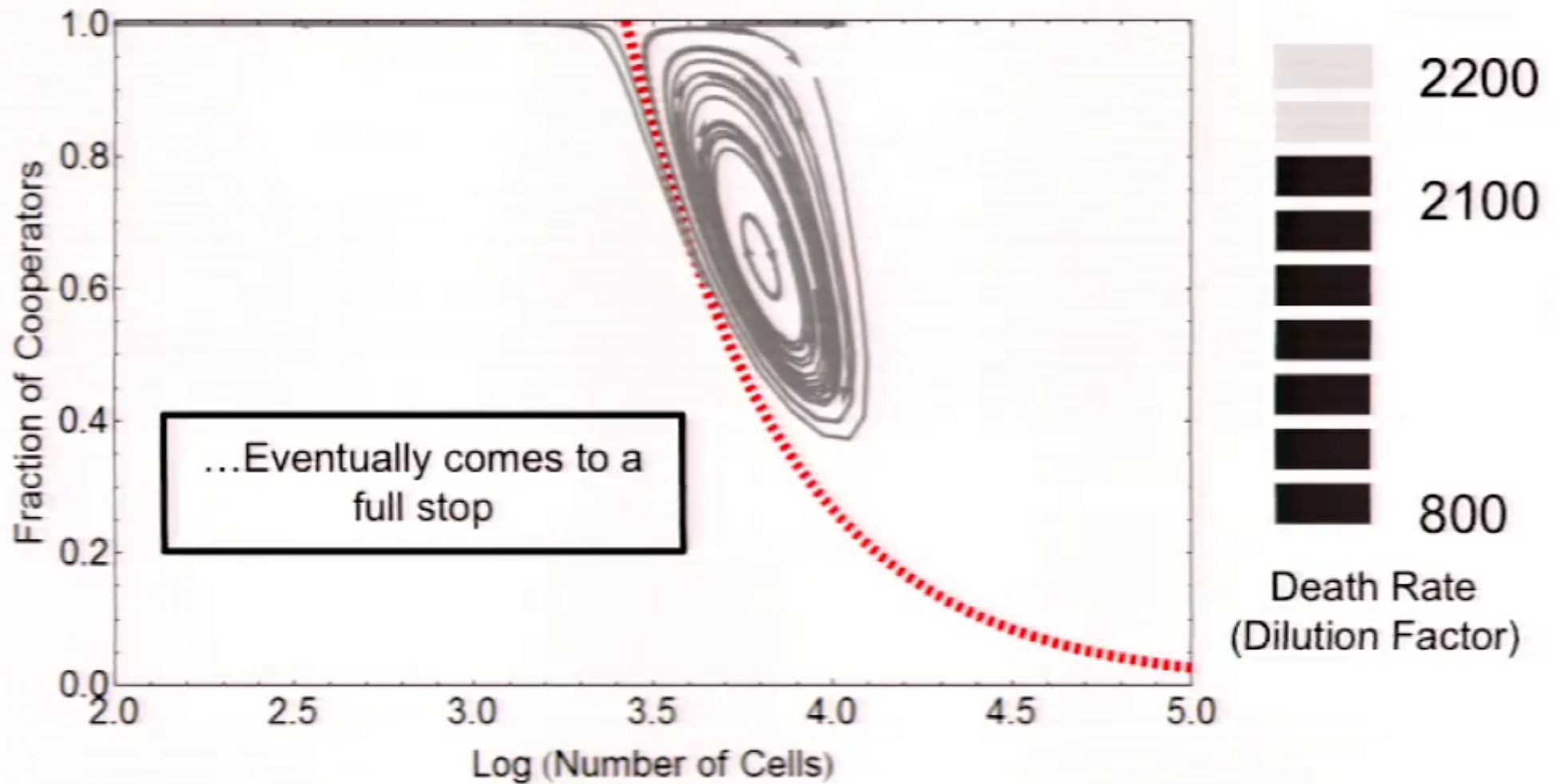
Spiral changes as environment deteriorates



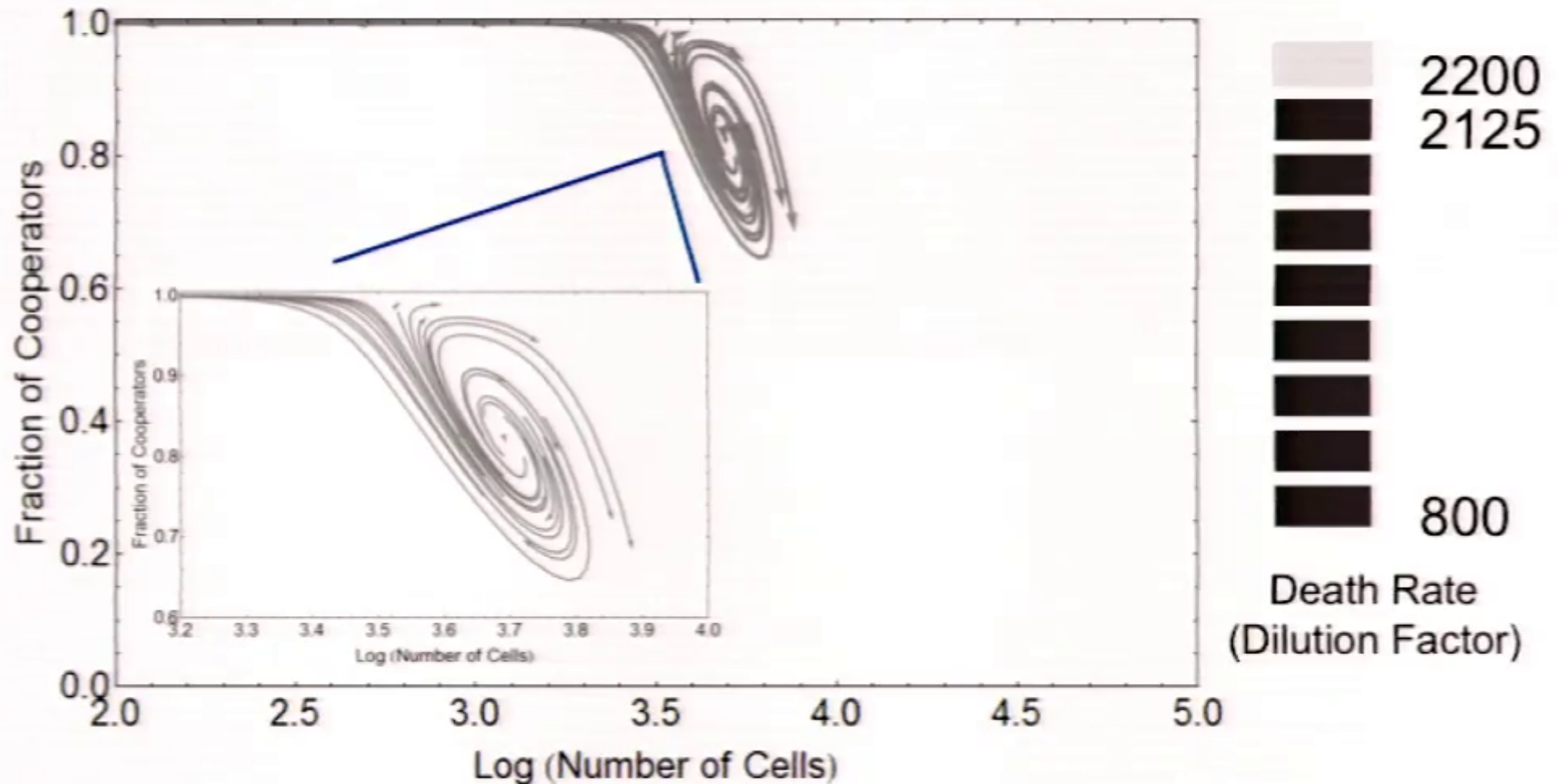
Fixed point loses stability as environment deteriorates



Fixed point loses stability as environment deteriorates

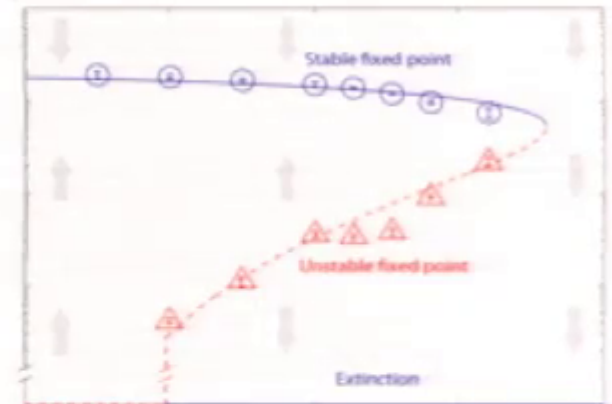


Eventually the fixed point becomes unstable



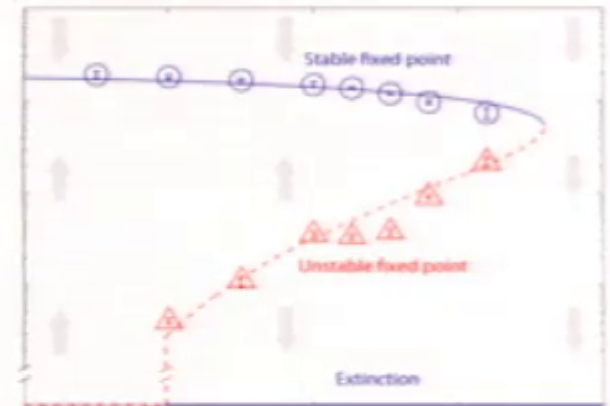
Summary

Cooperative populations can **collapse** when environment deteriorates



Summary

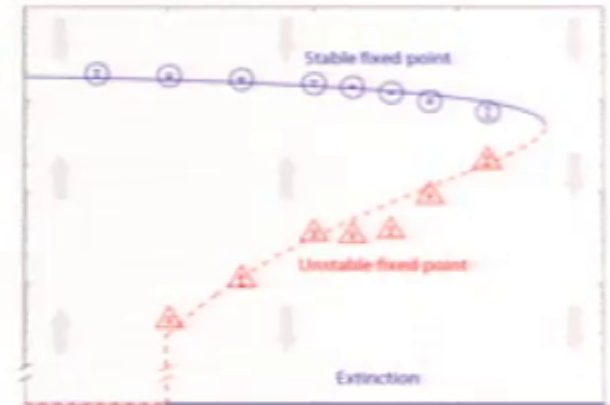
Cooperative populations can **collapse** when environment deteriorates



Cheater strategies invade, but there is often coexistence and survival

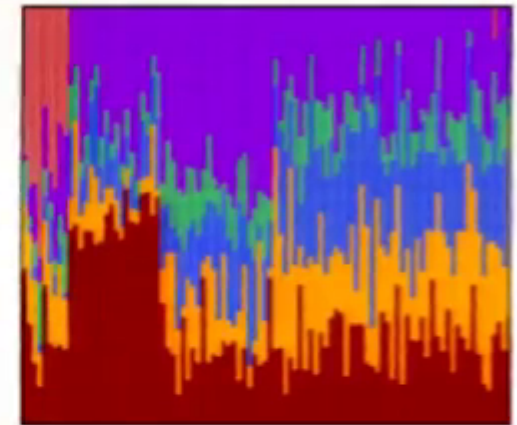
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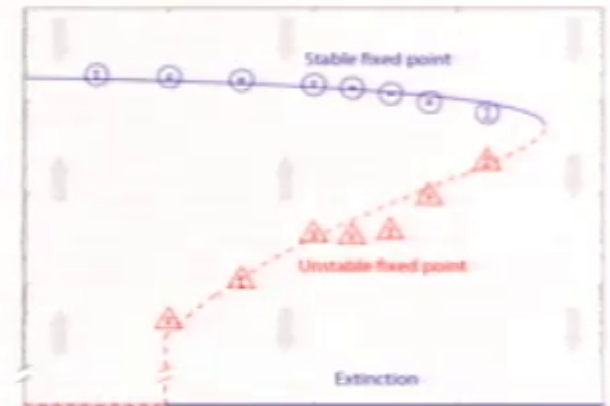
Multi-species experiments may illuminate rules of community assembly



Nature Comm (2014)

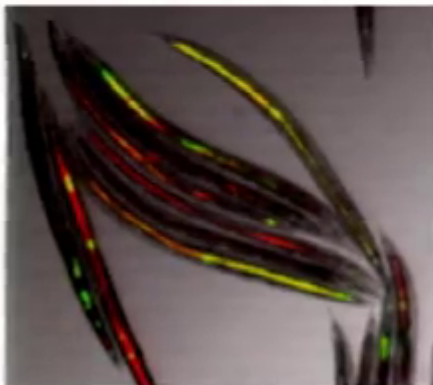
Summary

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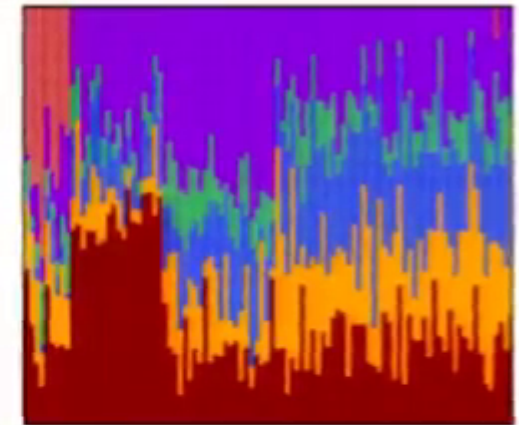


Cheater strategies invade, but there is often coexistence and survival

Multi-species experiments may illuminate rules of community assembly



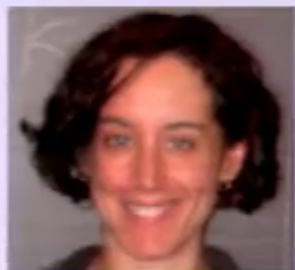
Laboratory microcosms are a powerful window into theoretical ecology



Nature Comm (2014)

Acknowledgements

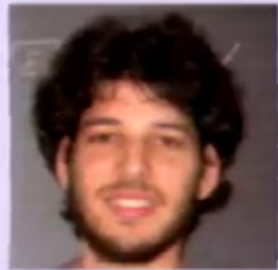
Postdocs



Nic Vega



Christoph Ratzke



Jonathan Friedman



Avihu Yona



Barrett Deris



Alfonso Perez Escudero

Graduate Students



Saurabh Gandhi



Manoshi Datta



Kevin Axelrod



Tanya Artemova



Hasan Celiker



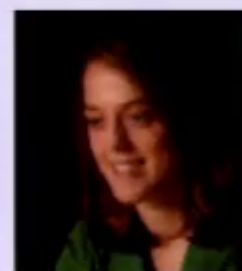
Logan Higgins



Eugene Yurtsev

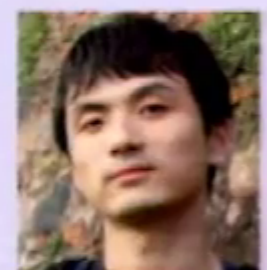


David Healey



Arolyn Conwill

Former



Lei Dai



Kirill Korolev



Alvaro Sanchez



NIH DIRECTOR'S
NEW INNOVATOR
AWARD



THE PAUL G. ALLEN
FAMILY foundation



THE
PEW
CHARITABLE TRUSTS



Largest Human Spiral Wave @ SIAMDS15?

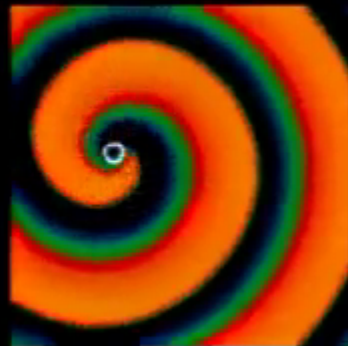
1. Your basic state is standing with your hands down (deactivation).
2. If your nearest neighbors is standing, stand up (activation).
3. After standing for a few seconds, sit back down (deactivation).
4. Continually monitor your neighbors to activate or deactivate.
5. **Only stand when your nearest neighbors do, not before!**

Georgia Tech, March 2014, ~500 student, staff and faculty:



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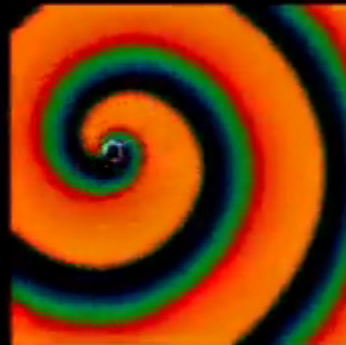


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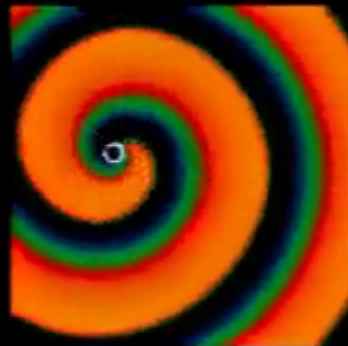


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