TIPPING POINTS IN THE EARTH SYSTEM

Co-financed by the Connecting Europe Facility of the European Union

Tipping in Spatially Extended Systems

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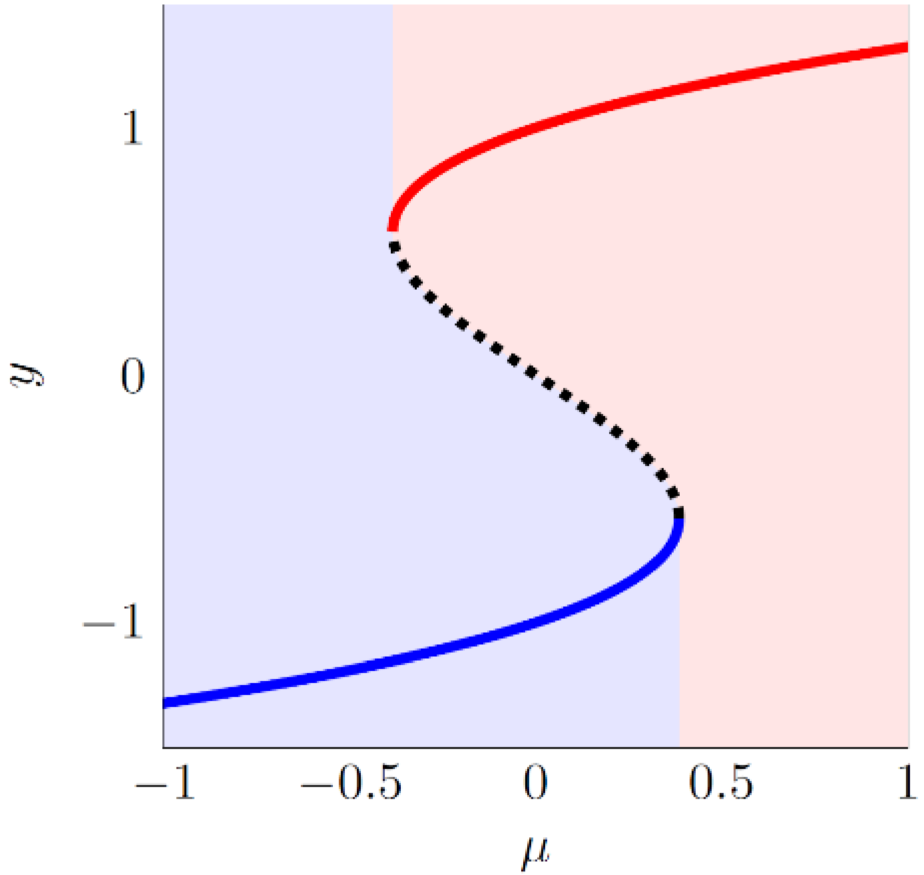
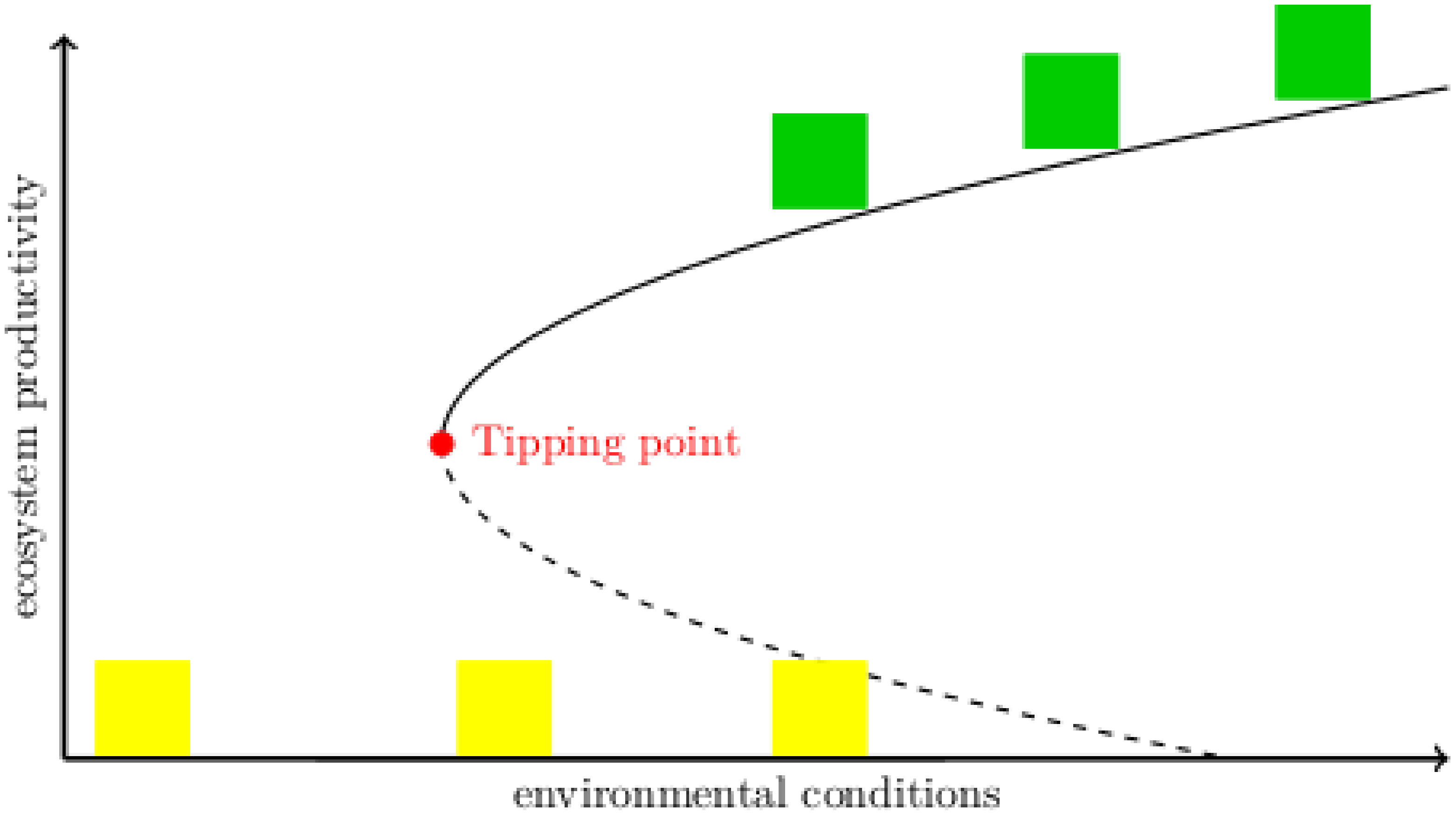
Classic Theory of Tipping





Canonical example:

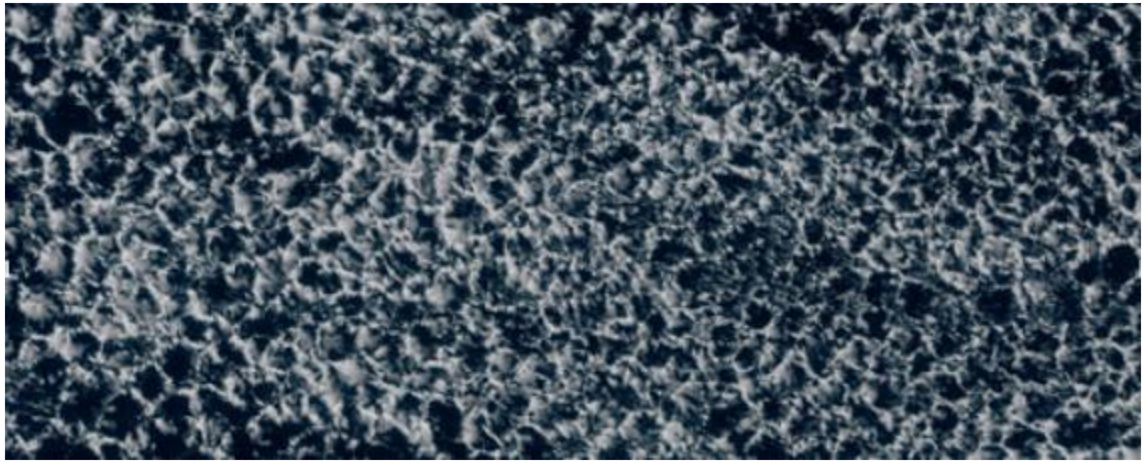
$$\frac{dy}{dt} = y(1 - y^2) + \mu$$

$$\frac{d\vec{y}}{dt} = f(\vec{y}; \mu)$$

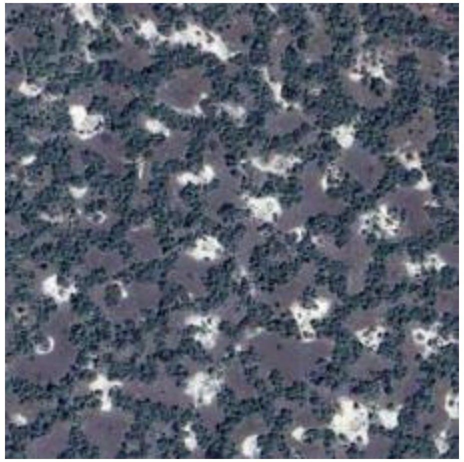
$$\begin{cases} \frac{du}{dt} = f(u, v; \mu) \\ \frac{dv}{dt} = g(u, v; \mu) \end{cases}$$

Examples of spatial patterning – regular patterns

mussel beds

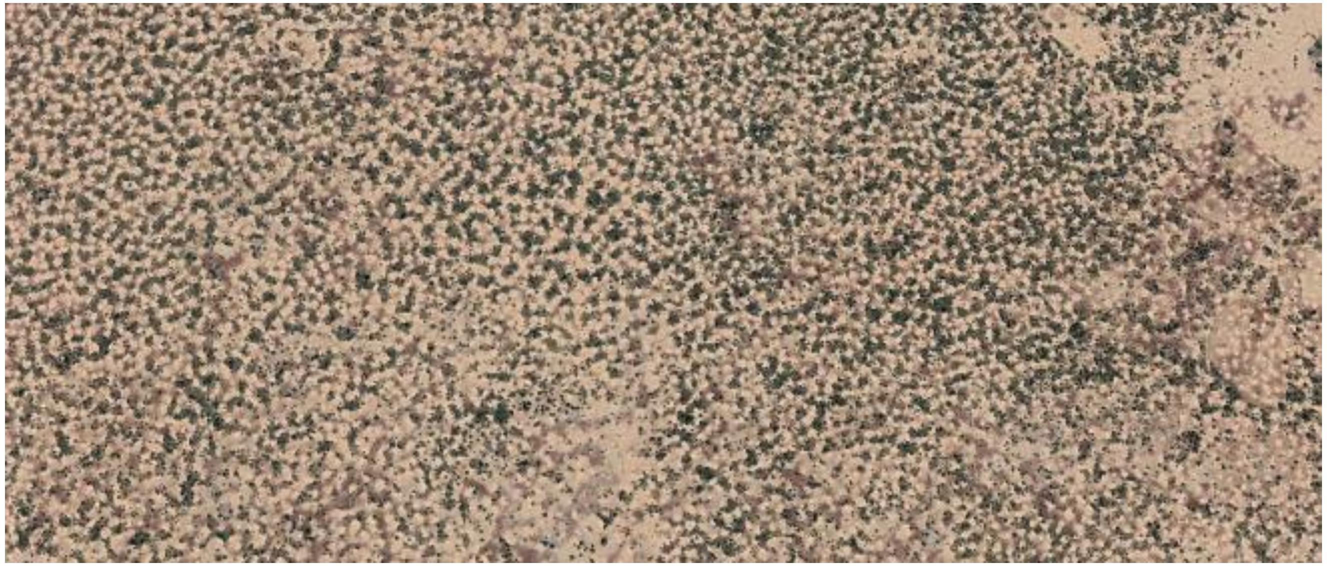


clouds



savannas

melt ponds

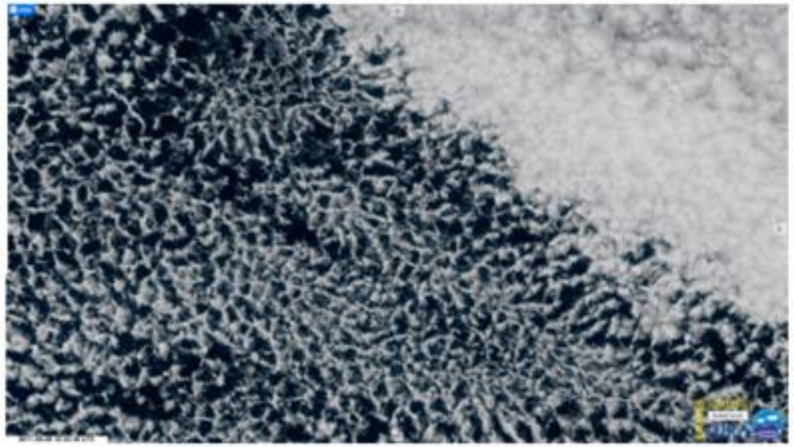


drylands

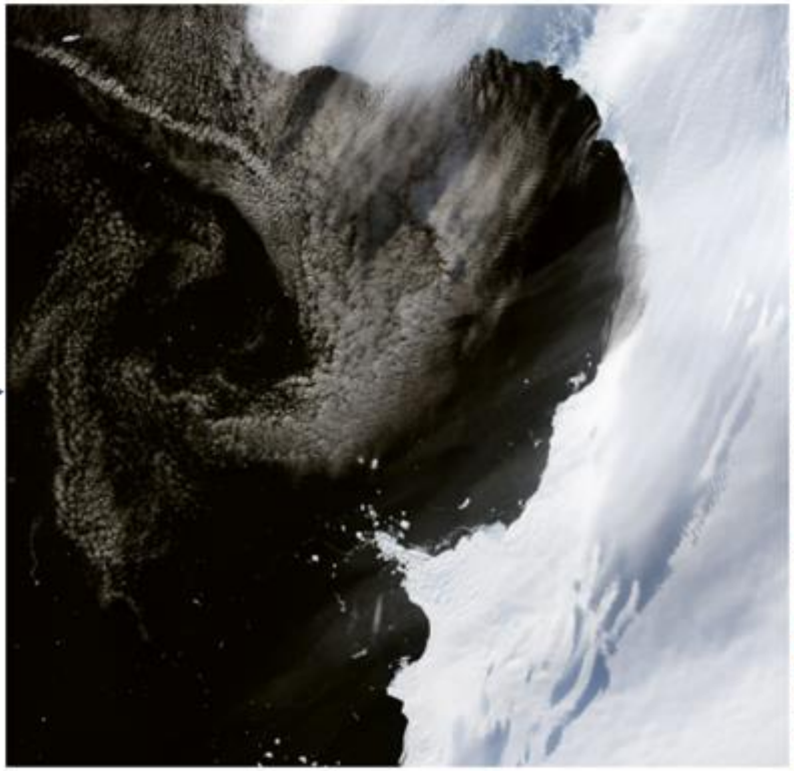
Examples of spatial patterning – spatial interfaces

tropical forest
& savanna
ecosystems
[Google Earth]

types of
stratocumulus
clouds
[RAMMB/CIRA SLIDER]



sea-ice & water
at Eltanin Bay
[NASA's Earth observatory]



algae bloom
in Lake St. Clair
[NASA's Earth observatory]

Part 1: Turing Patterns

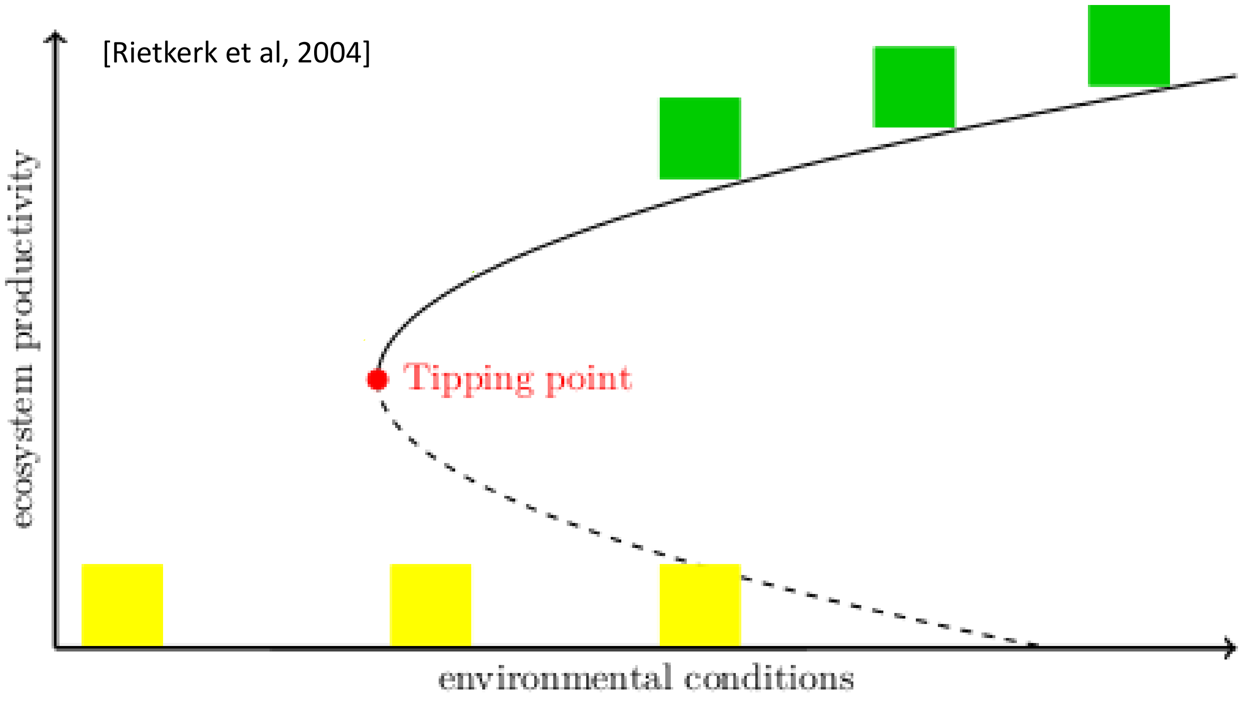
image courtesy: National Science Foundation

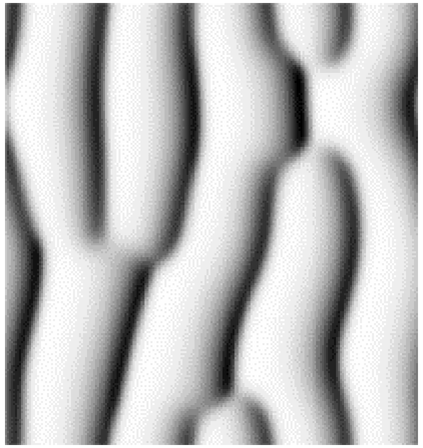
Patterns in models

Add spatial transport:

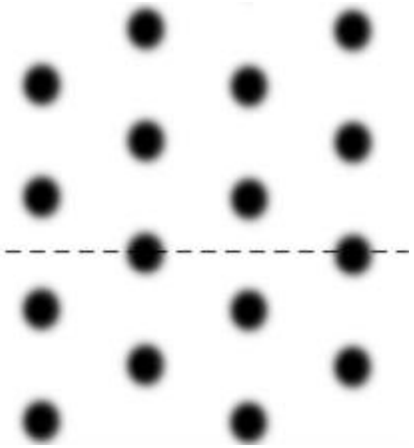
Reaction-Diffusion equations:

$$\begin{cases} \dfrac{du}{dt} = f(u,v) + D_u\,\Delta u \\ \dfrac{dv}{dt} = g(u,v) + D_v\,\Delta v \end{cases}$$



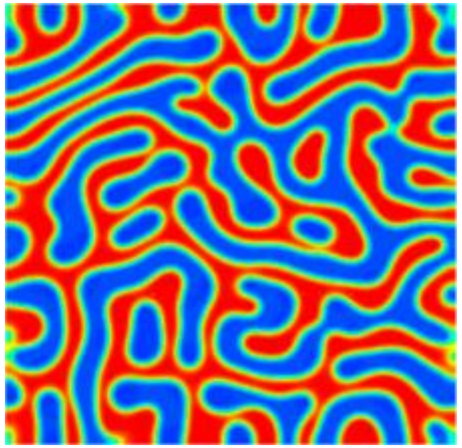


[Klausmeier, 1999]



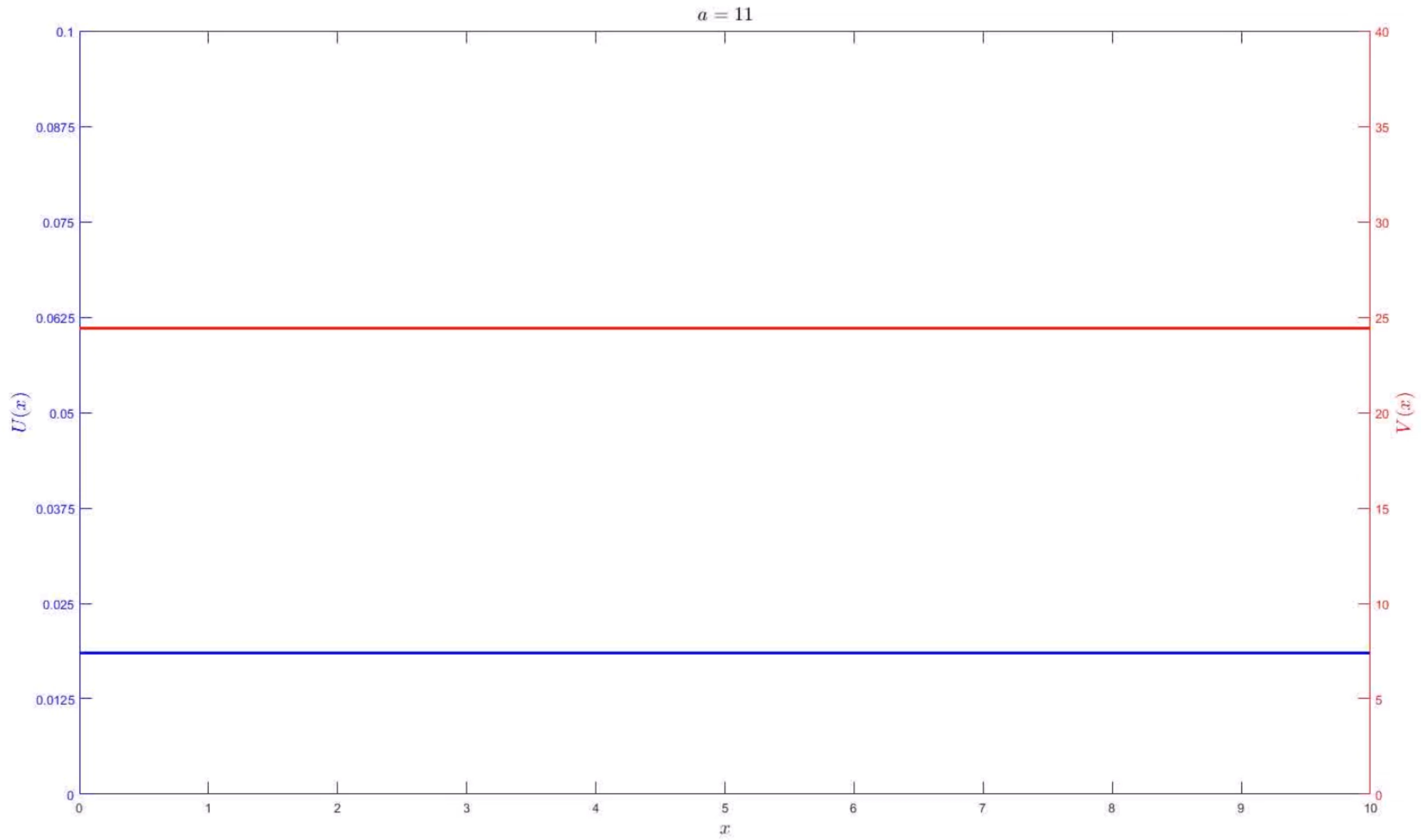
[Gilad et al, 2004]

[Rietkerk et al, 2002]



[Liu et al, 2013]

Behaviour of PDEs



Turing patterns

$$\begin{cases} \frac{du}{dt} = f(u,v) + D_u \Delta u \\ \frac{dv}{dt} = g(u,v) + D_v \Delta v \end{cases}$$

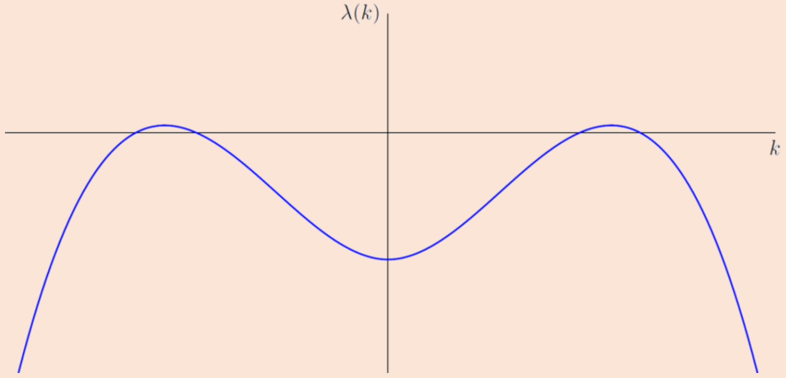
Turing bifurcation

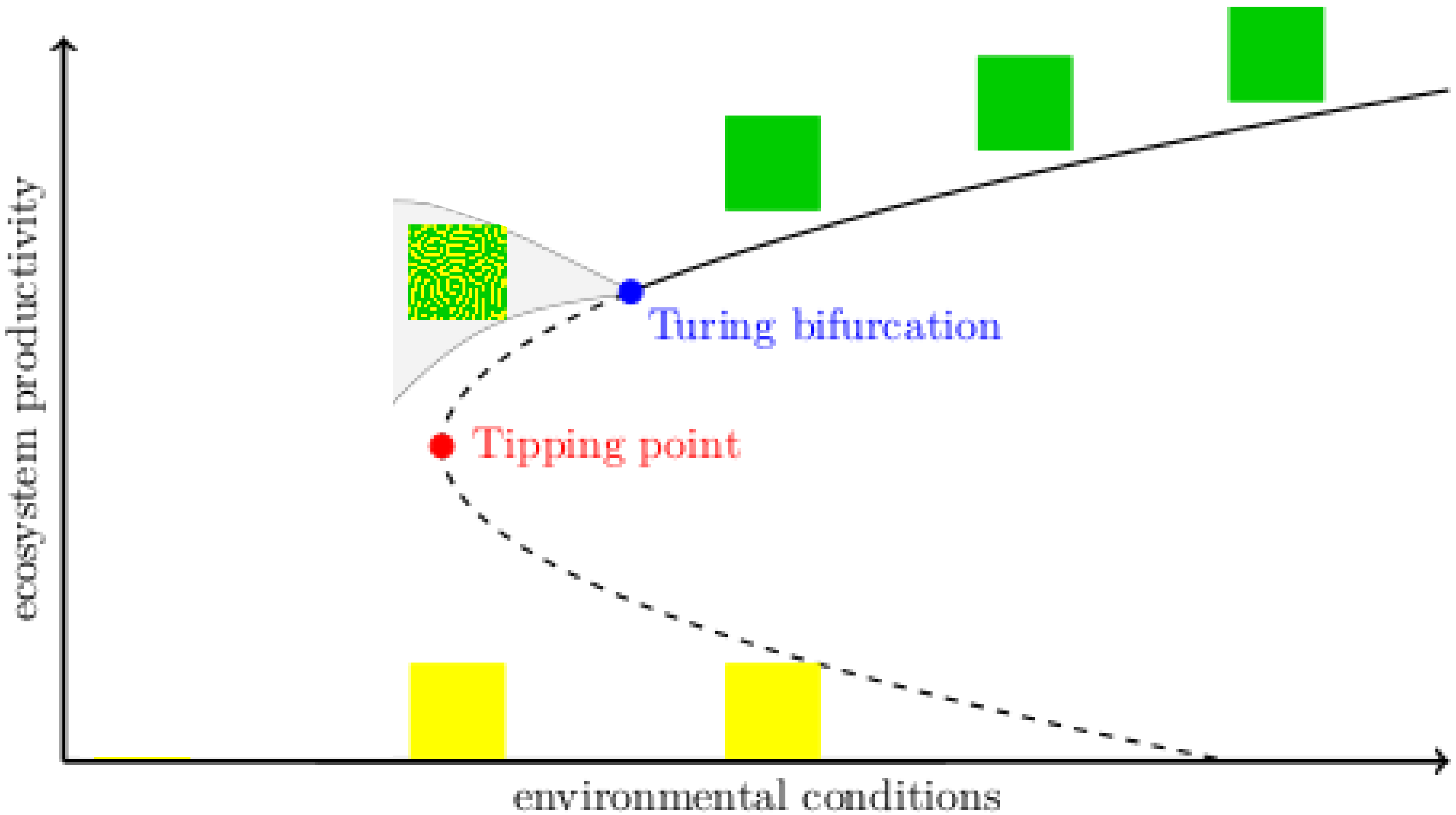
Instability to non-uniform perturbations

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} u_* \\ v_* \end{pmatrix} + e^{\lambda t} e^{ikx} \begin{pmatrix} \bar{u} \\ \bar{v} \end{pmatrix}$$

→ Dispersion relation

$$\lambda(k) = \cdots$$





Weakly non-linear analysis

Ginzburg-Landau equation / Amplitude Equation

& Eckhaus/Benjamin-Feir-Newel criterion

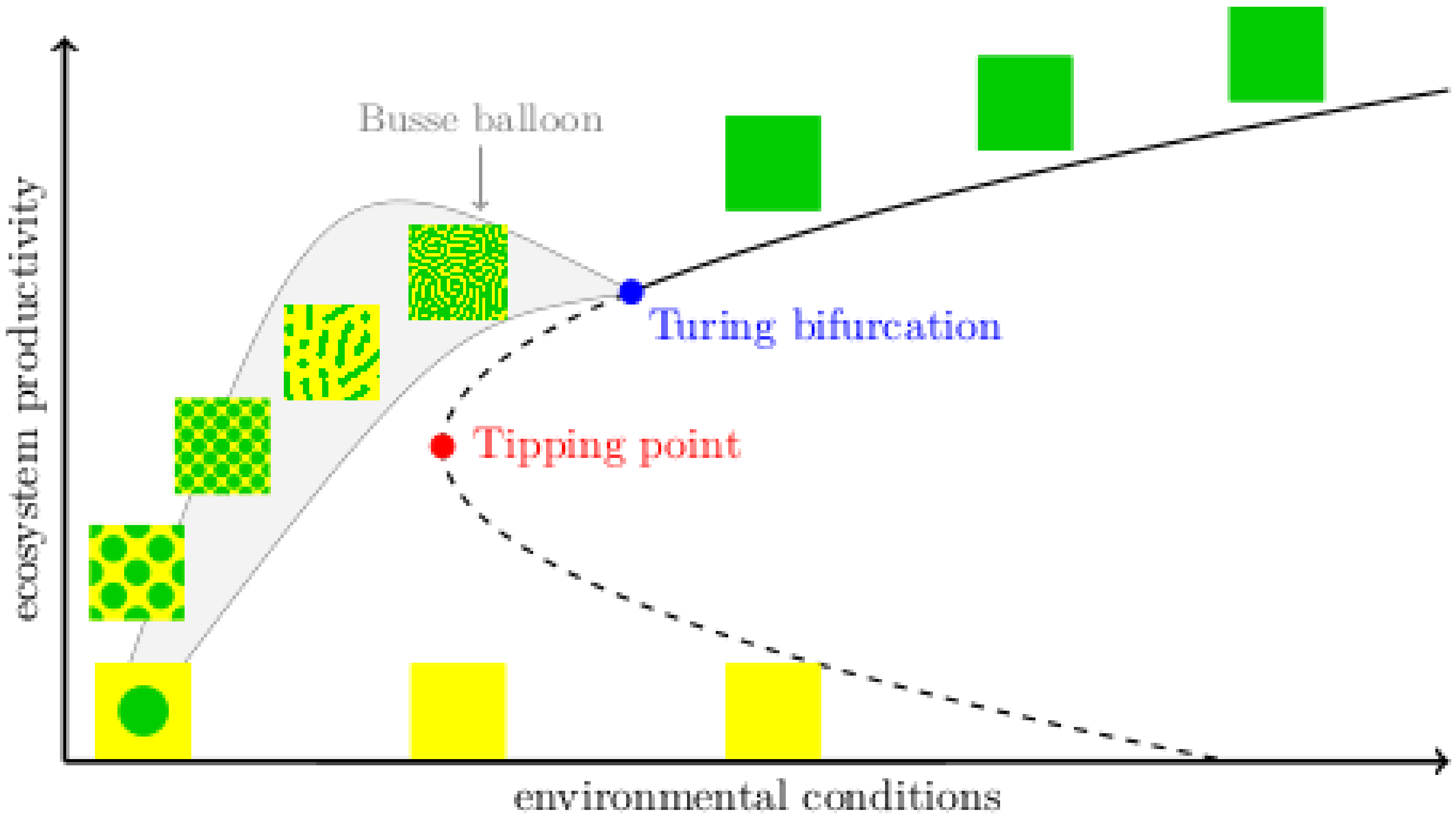
[Eckhaus, 1965; Benjamin & Feir, 1967; Newell, 1974]

Busse balloon

$$\begin{cases} \frac{du}{dt} = f(u,v) + D_u \Delta u \\ \frac{dv}{dt} = g(u,v) + D_v \Delta v \end{cases}$$

Busse balloon

A model-dependent shape in *(parameter, observable)* space that indicates all stable patterned solutions to the PDE.



Construction Busse balloon

Via numerical continuation

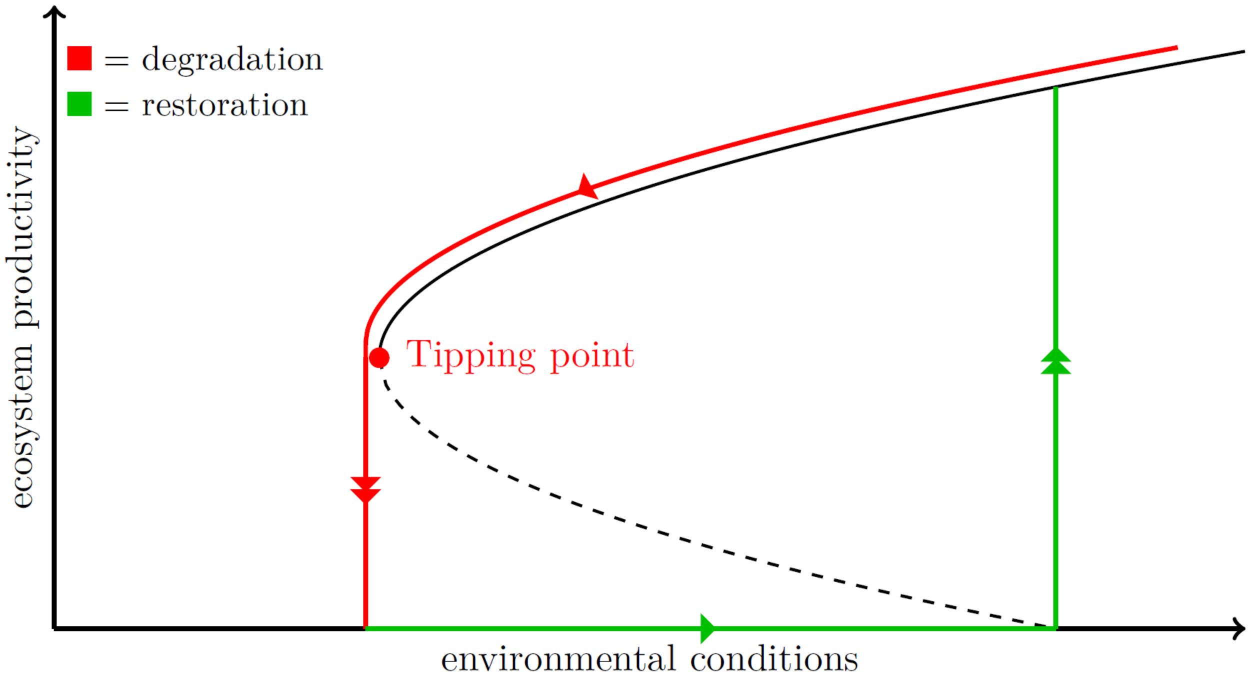
few general results on the shape of Busse balloon

Busse balloon

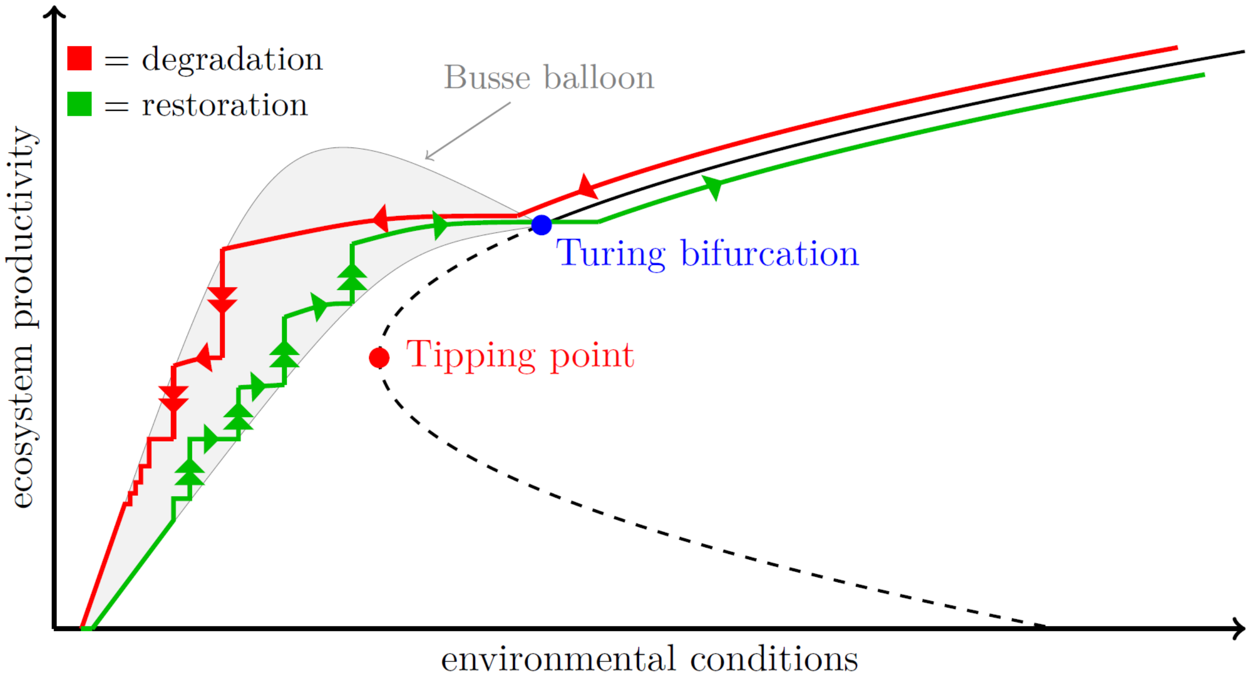
Idea originates from thermal convection

[Busse, 1978]

Tipping of (Turing) patterns

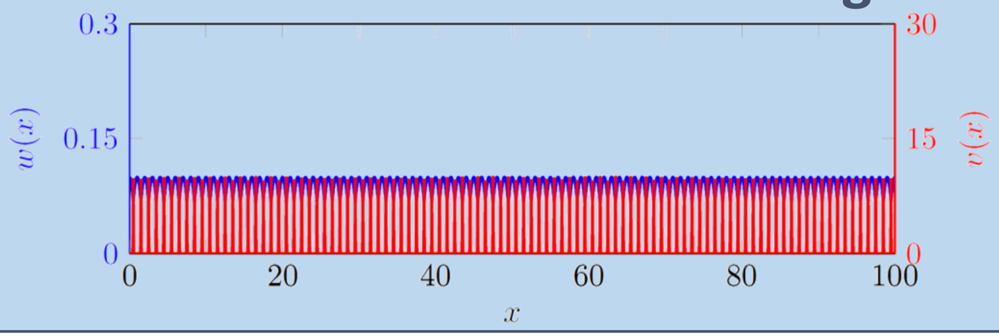


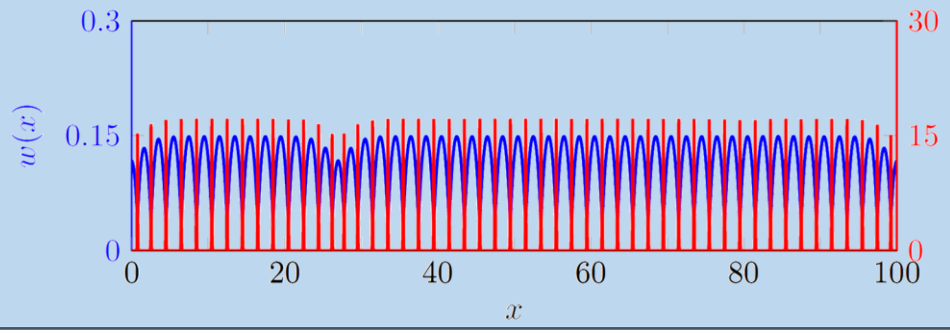
Classic tipping



Tipping of patterns

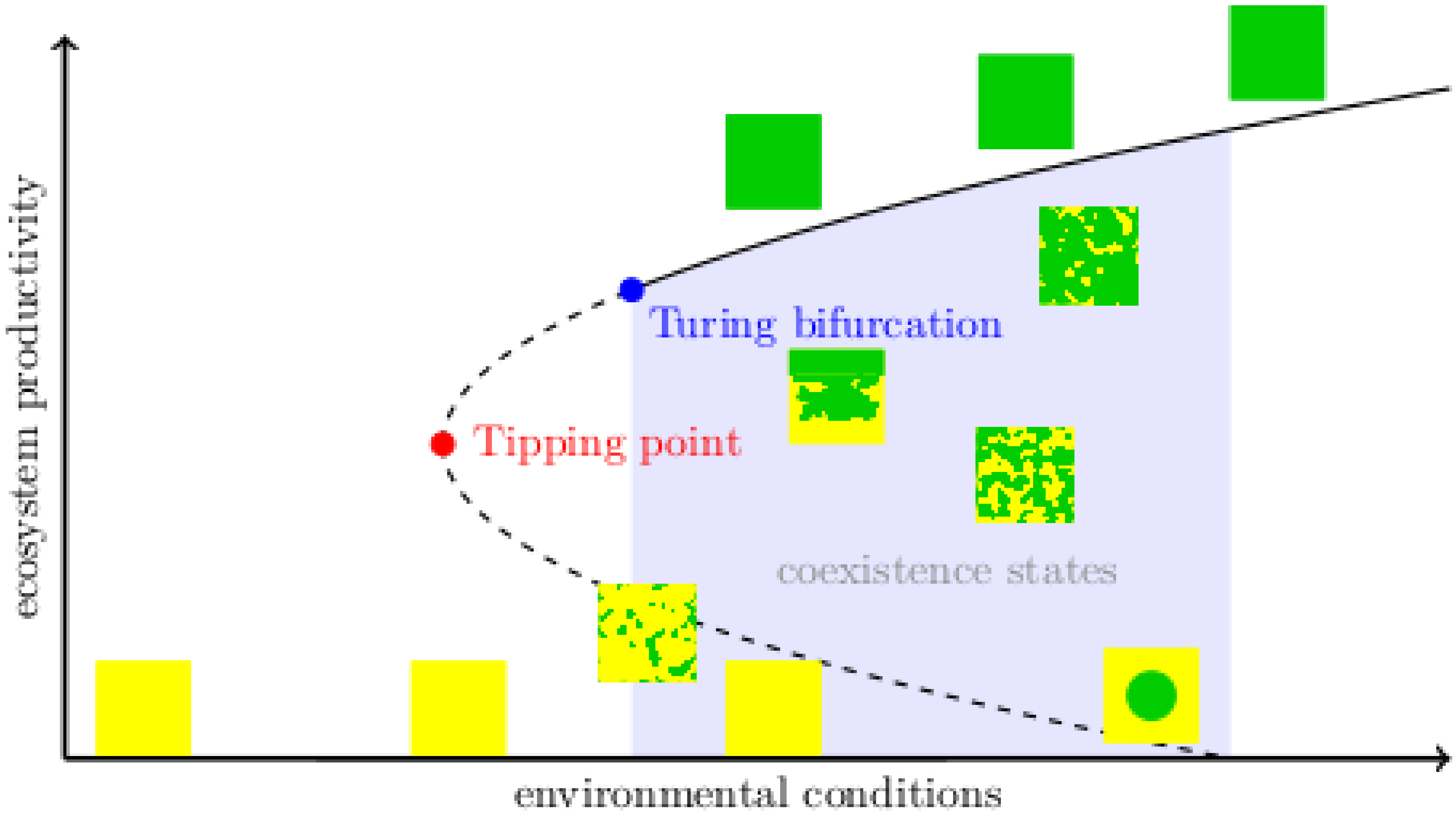
Degradation of patterns





Part 2:
Coexistence States
and spatial heterogeneities

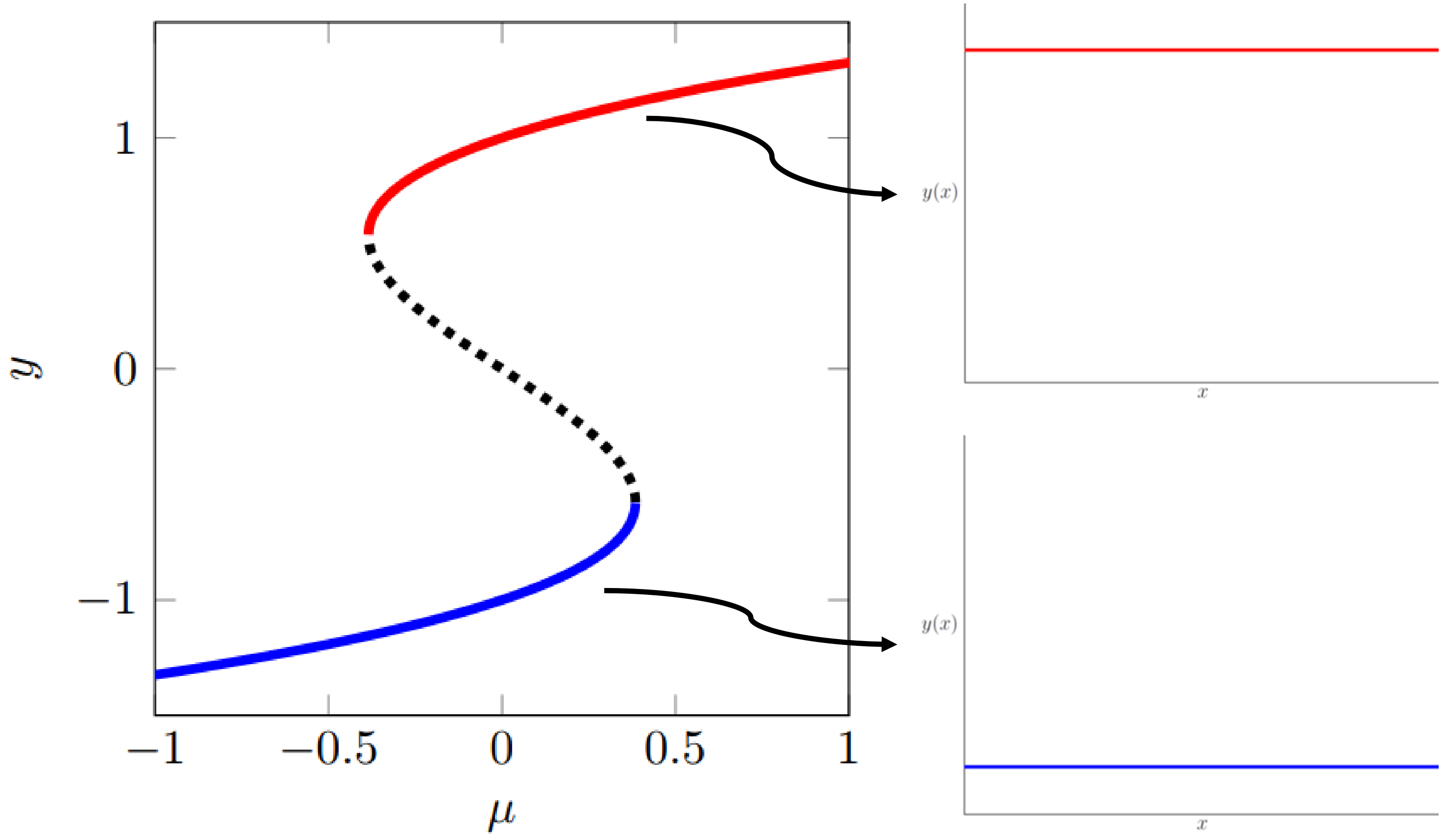
Coexistence states in bifurcation diagram

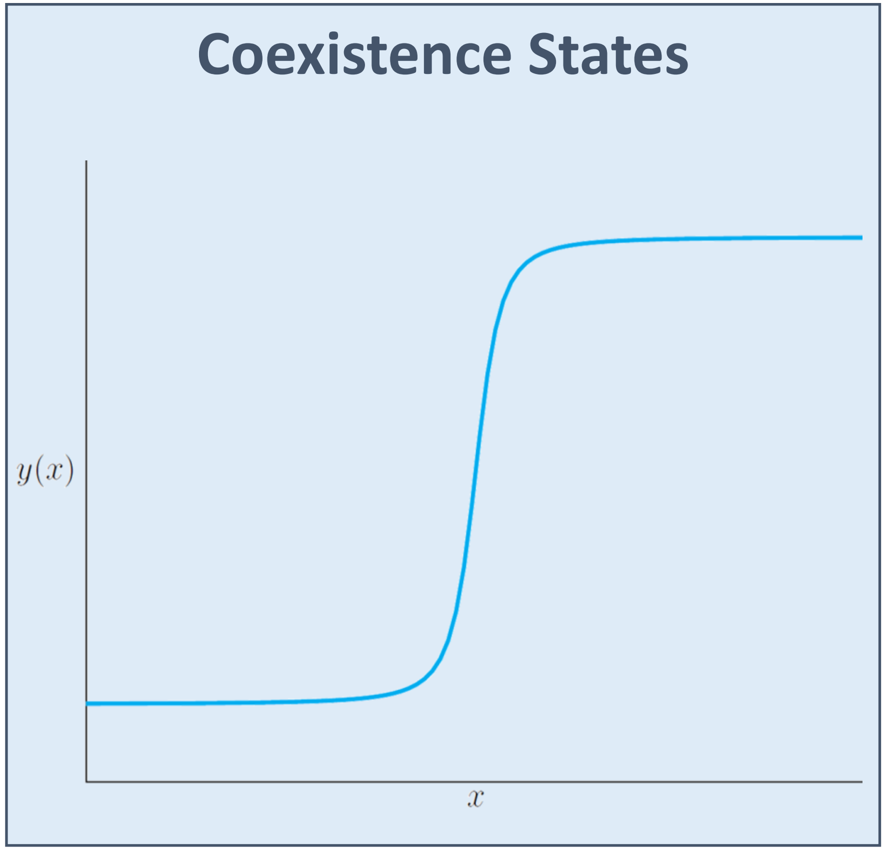


Coexistence states

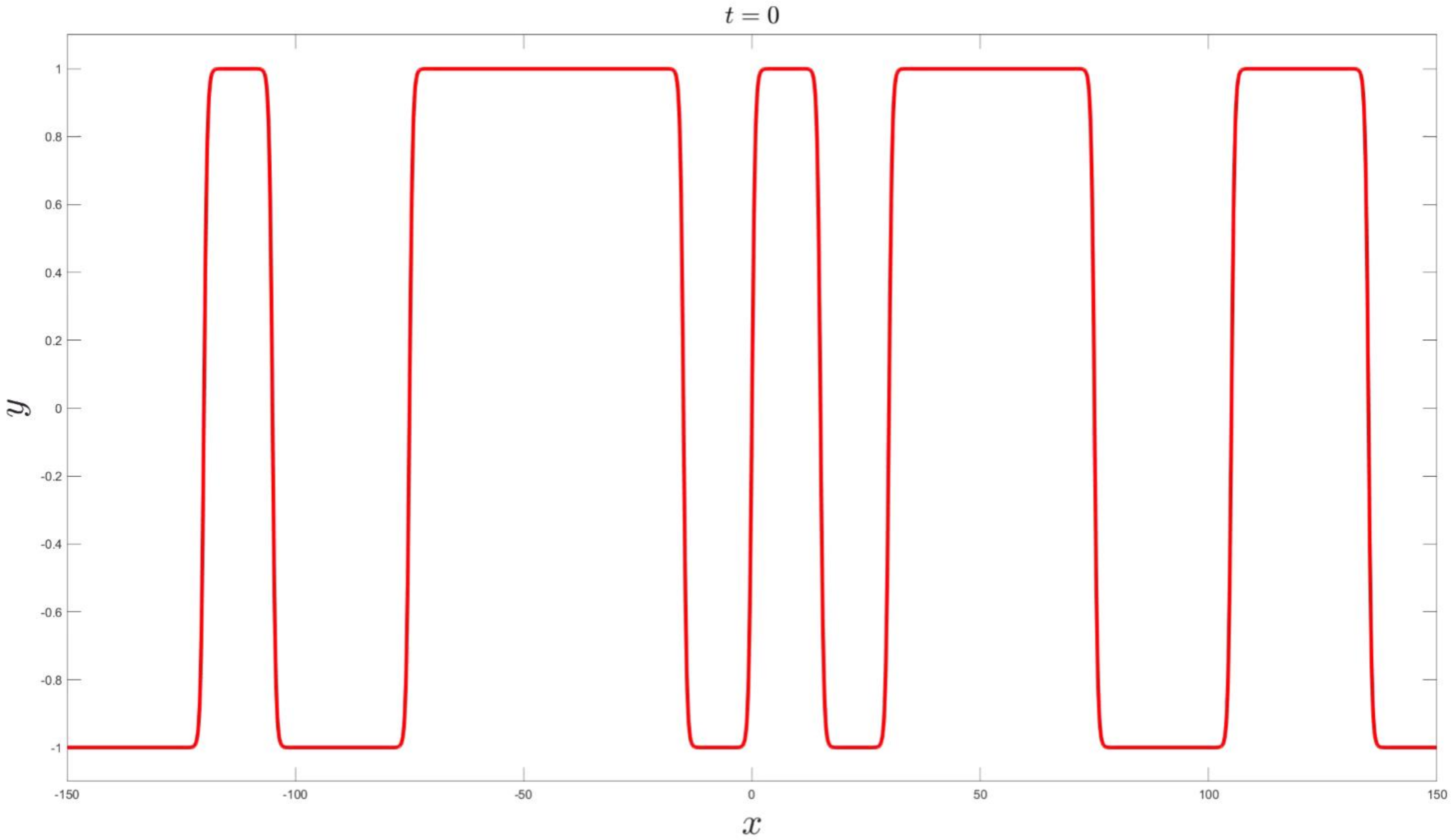
Bistable (Allen-Cahn/Nagumo) equation:

$$\frac{\partial y}{\partial t} = y(1 - y^2) + \mu + D\,\frac{\partial^2 y}{\partial x^2}$$





Dynamics of $\frac{\partial y}{\partial t} = D\ \frac{\partial^2 y}{\partial x^2} + y(1 - y^2) + \mu$

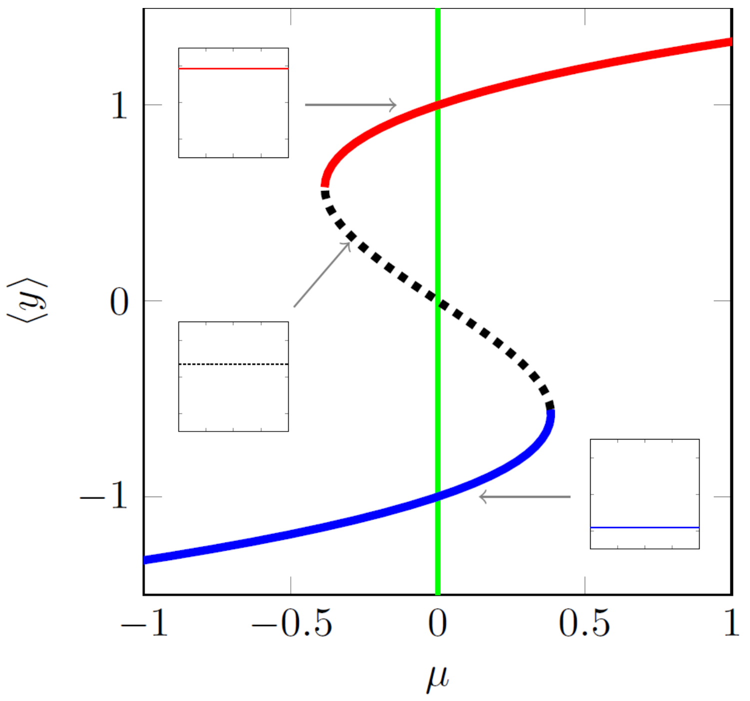


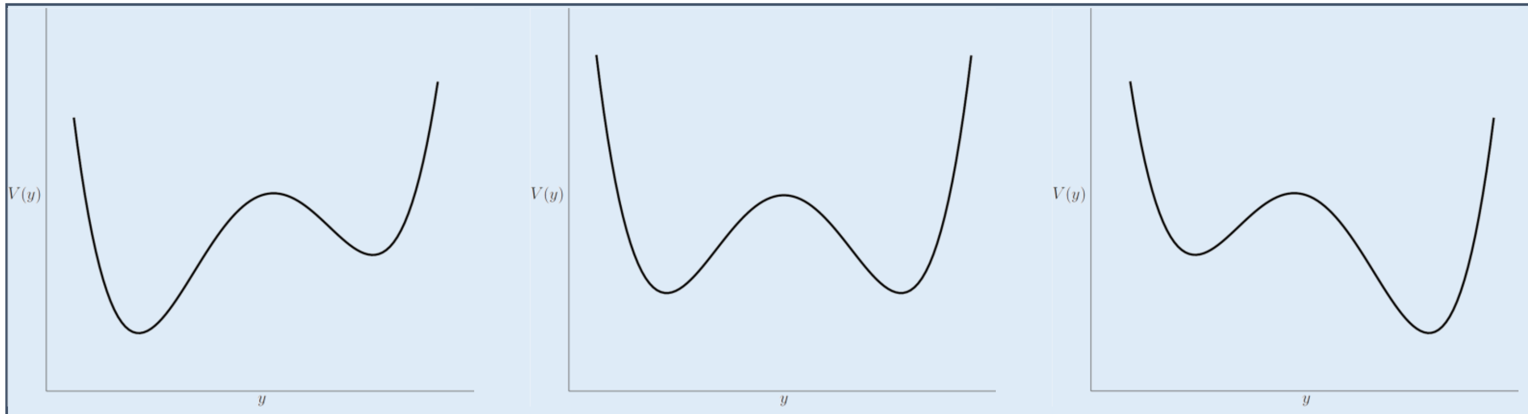
Front Dynamics

$$\frac{\partial y}{\partial t} = D\,\frac{\partial^2 y}{\partial x^2} + f(y;\mu)$$

Potential function $V(y;\mu)$:

$$\frac{\partial V}{\partial y}(y;\mu) = -f(y;\mu)$$



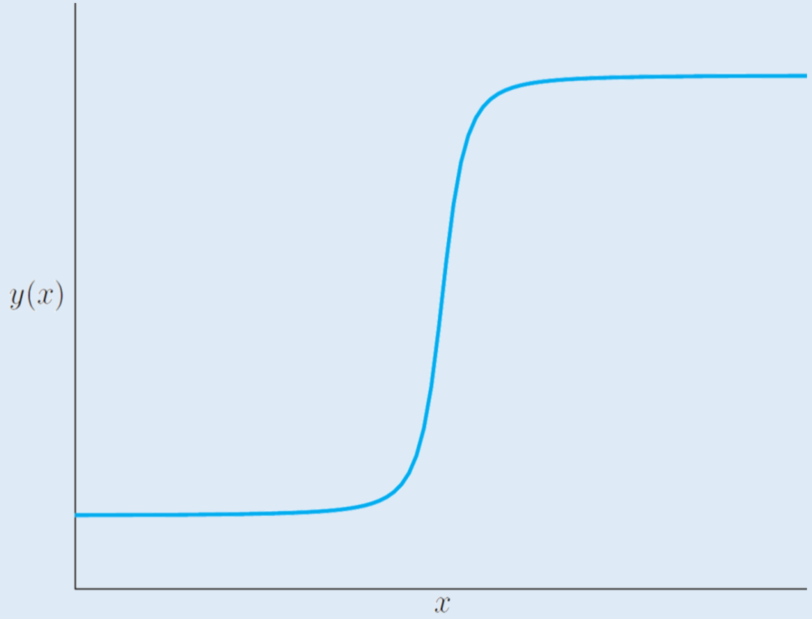


moves right

stationary

moves left

Maxwell Point $\mu_{maxwell}$



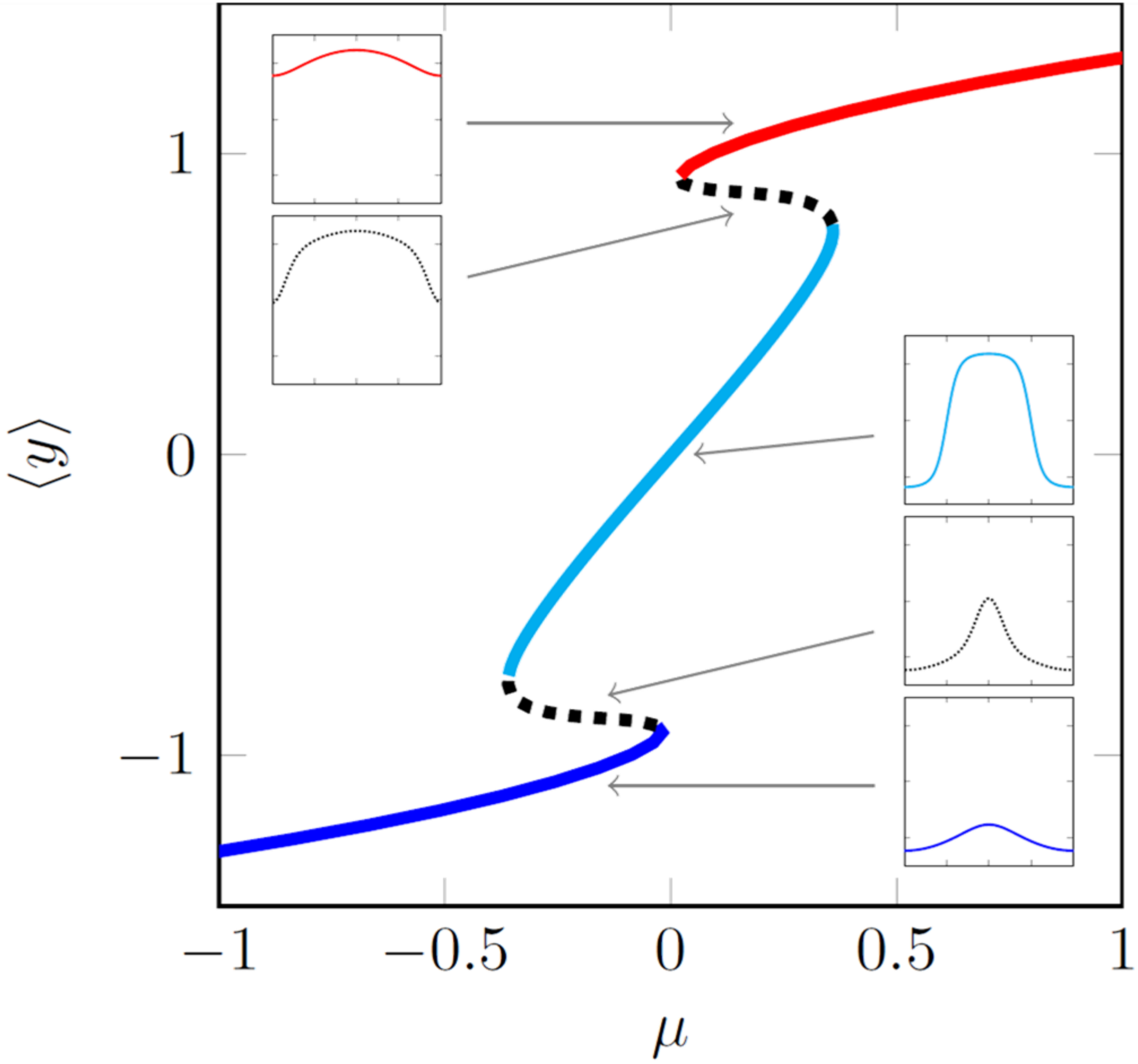
Adding Spatial Heterogeneity

$$\frac{\partial y}{\partial t} = D\frac{\partial^2 y}{\partial x^2} + f(y, x; \mu)$$

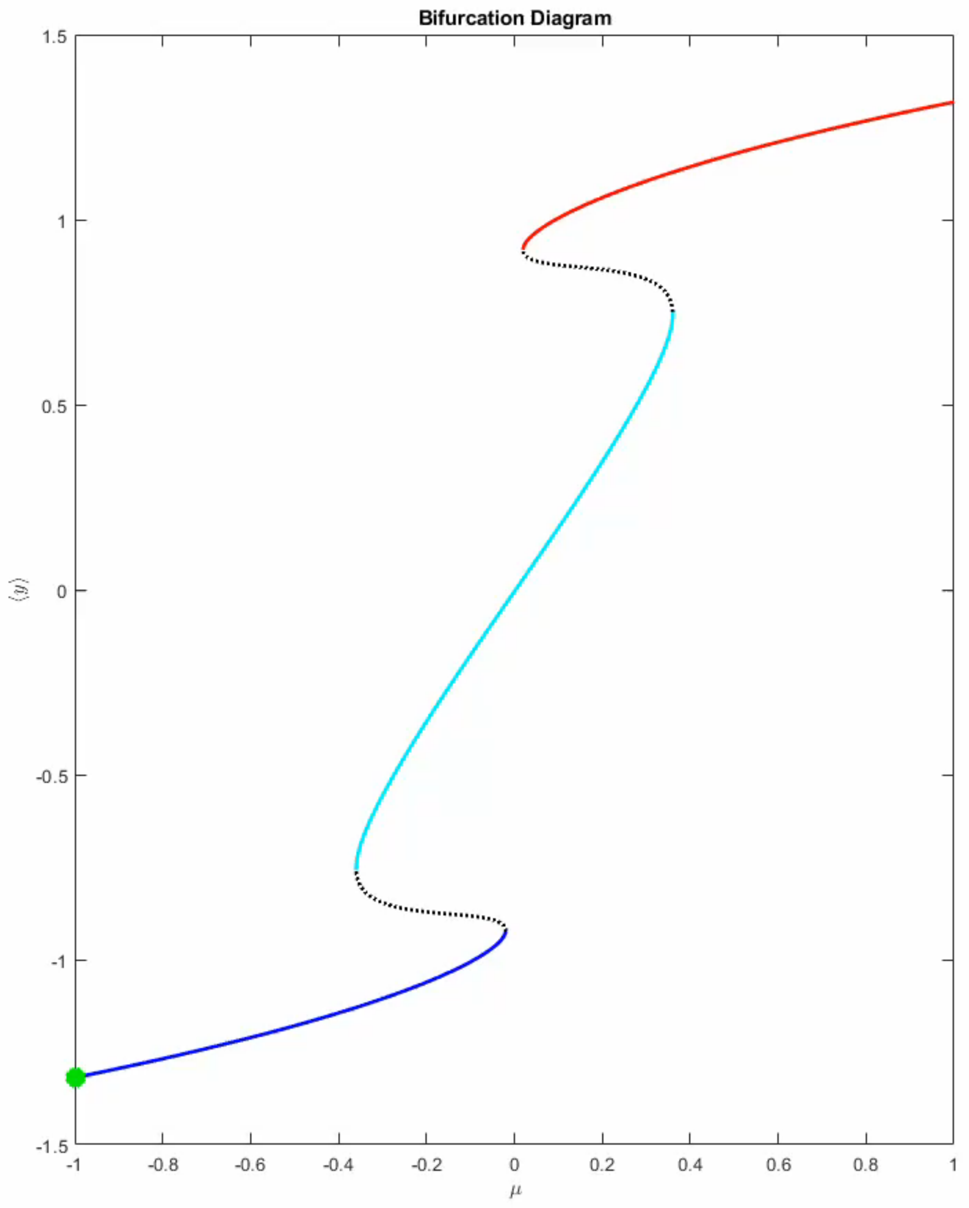
Now, the **local** difference in potentials determines the front movement

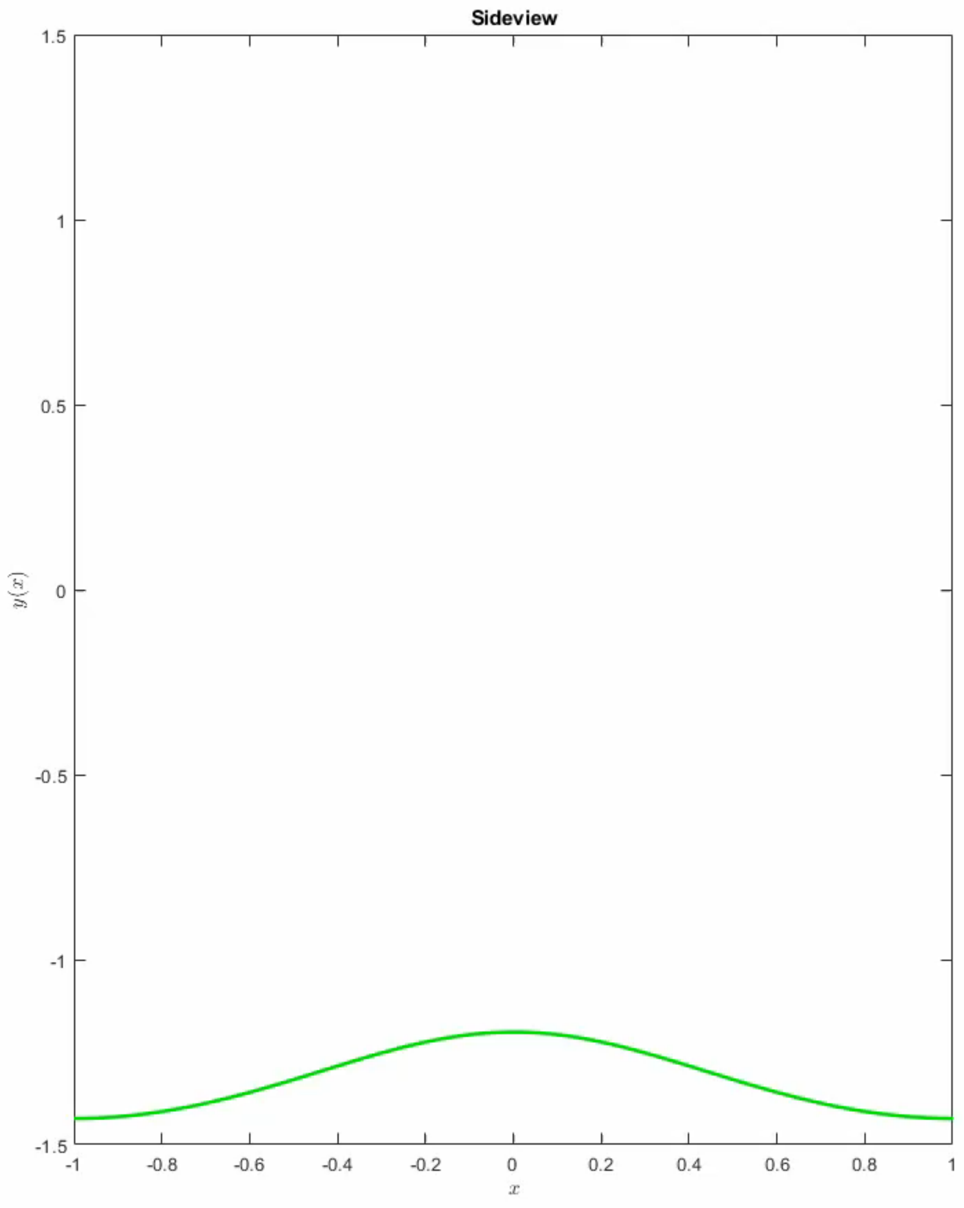
New behaviour:

- Multi-fronts can be stationary
- Maxwell point is smeared out



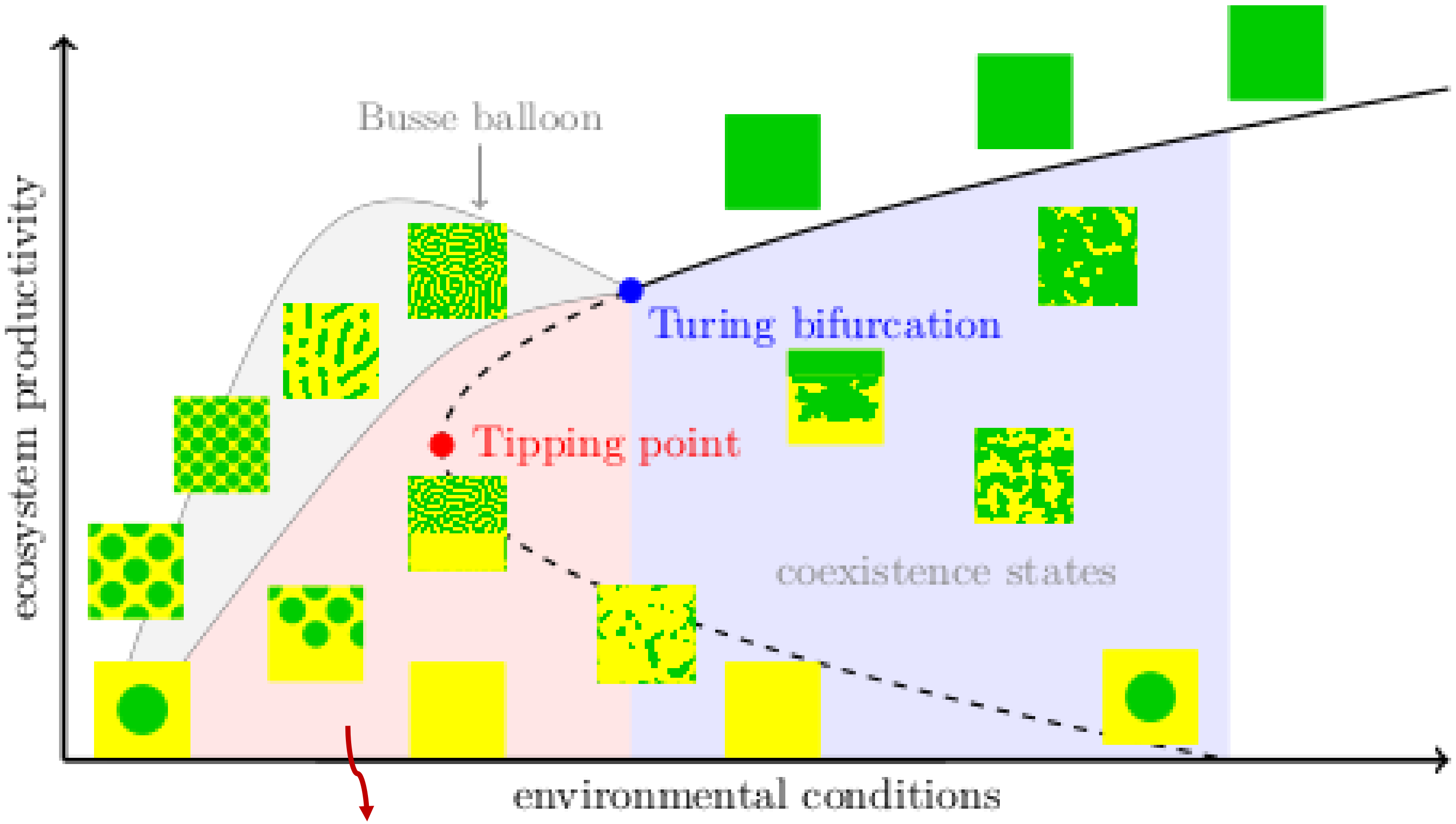
Fragmented Tipping



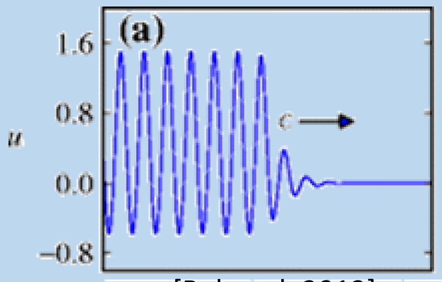


Part 3:
Tipping in Spatially Extended Systems?

“Bifurcation Diagram” for spatially extended systems



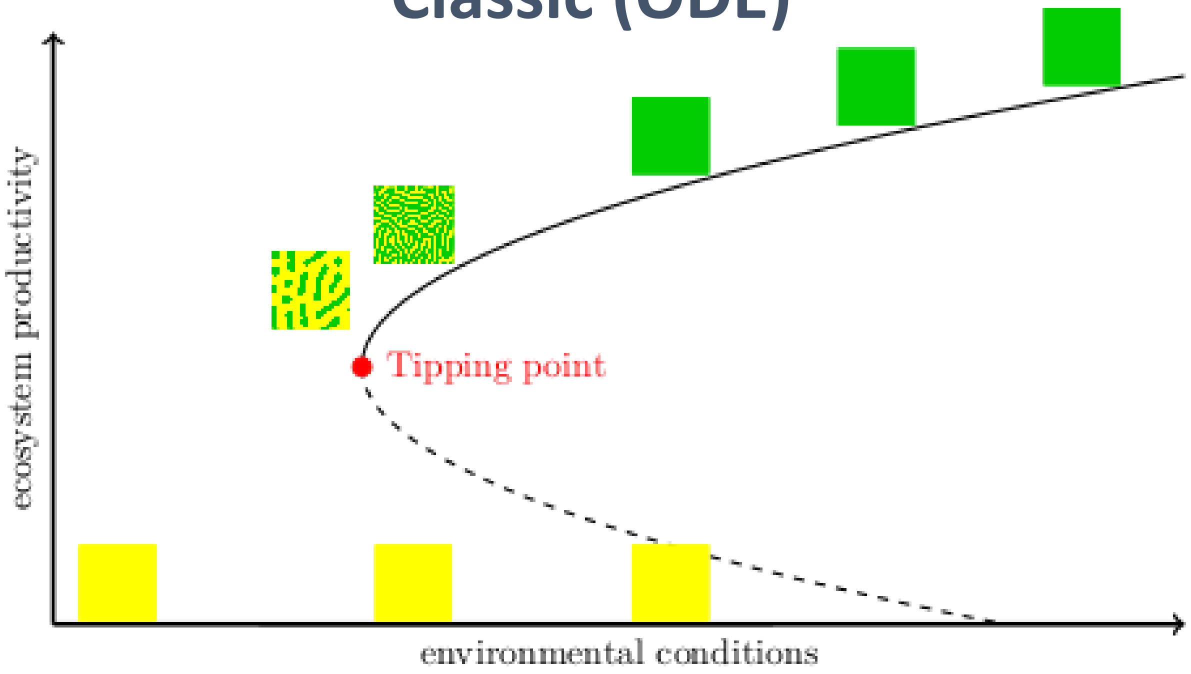
Coexistence states between patterned and uniform states also exist



[Bel et al, 2012]

What if the system tips?

Classic (ODE)



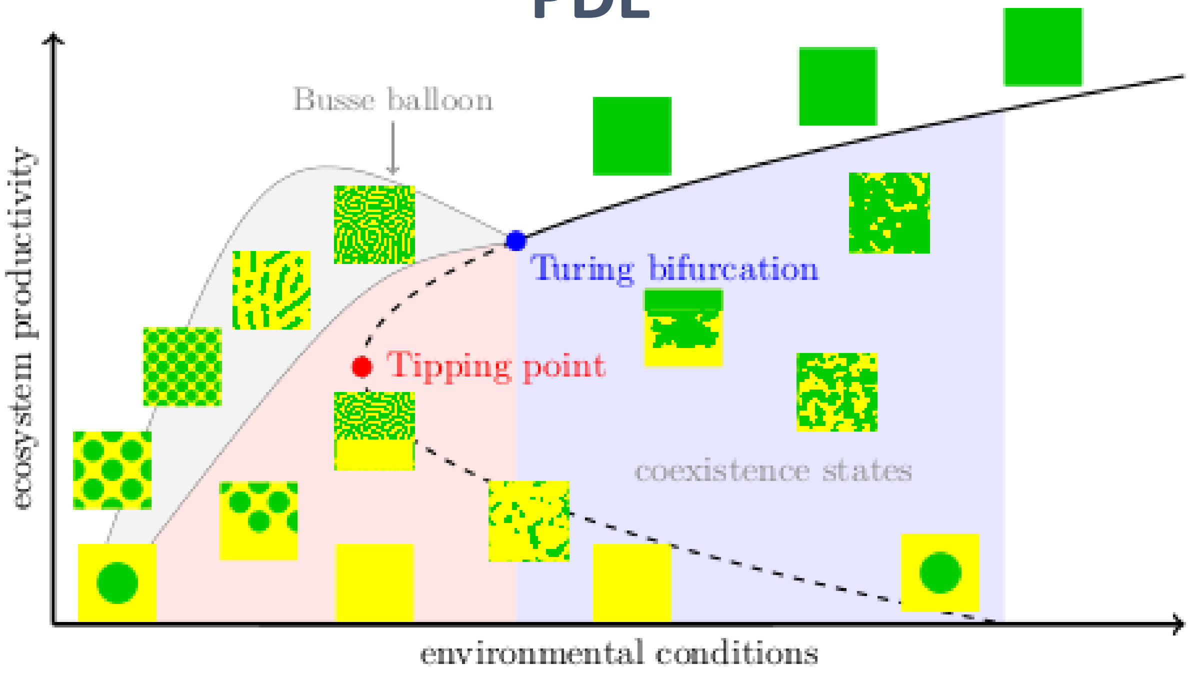
Crossing a Tipping Point:

→ Always full reorganization

Early Warning Signals

signal for <u>WHEN</u>

PDE



Crossing a bifurcation:

Now also possible:

→ Spatial reorganization (Turing patterns)

→ Fragmented tipping (coexistence states)

Early Warning Signals

need to signal <u>WHEN</u> & <u>WHAT</u>

Part 4:

Mathematical Differences Between ODEs & PDEs

Differences between ODEs and PDEs

	ODE $y_t = f(y;\mu)$	**PDE** $y_t = y_{xx} + f(y;\mu)$
Stationary States	$0 = f(y^*;\mu)$	$0 = y^*_{xx} + f(y^*;\mu)$
Linear Stability	$\lambda\,\bar{y} = f_y(y^*;\mu)\,\bar{y}$	$\lambda\,\bar{y} = \bar{y}_{xx} + f_y(y^*(x);\mu)\,\bar{y}$

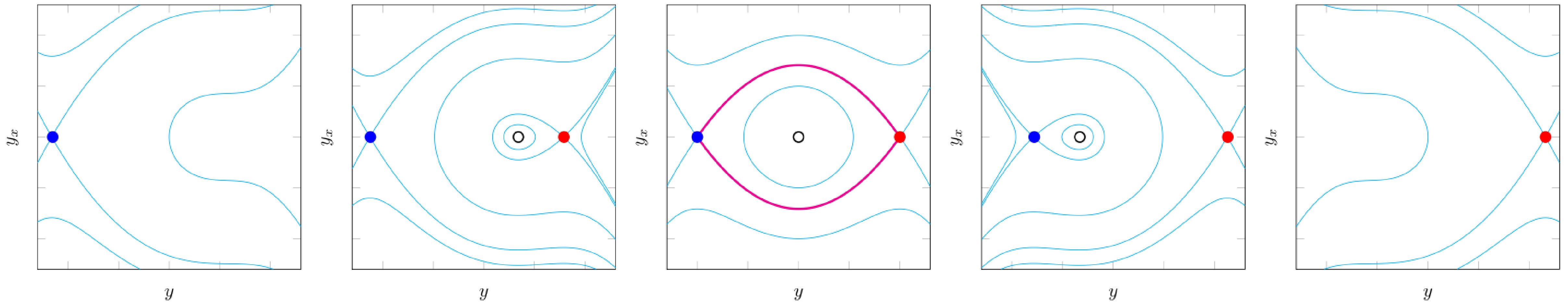
Stationary States

$$y_t = y_{xx} + f(y;\mu)$$

Stationary states

$$0 = y_{xx} + f(y;\mu)$$

$$\begin{cases} y_x = p \\ p_x = -f(y;\mu) \end{cases}$$

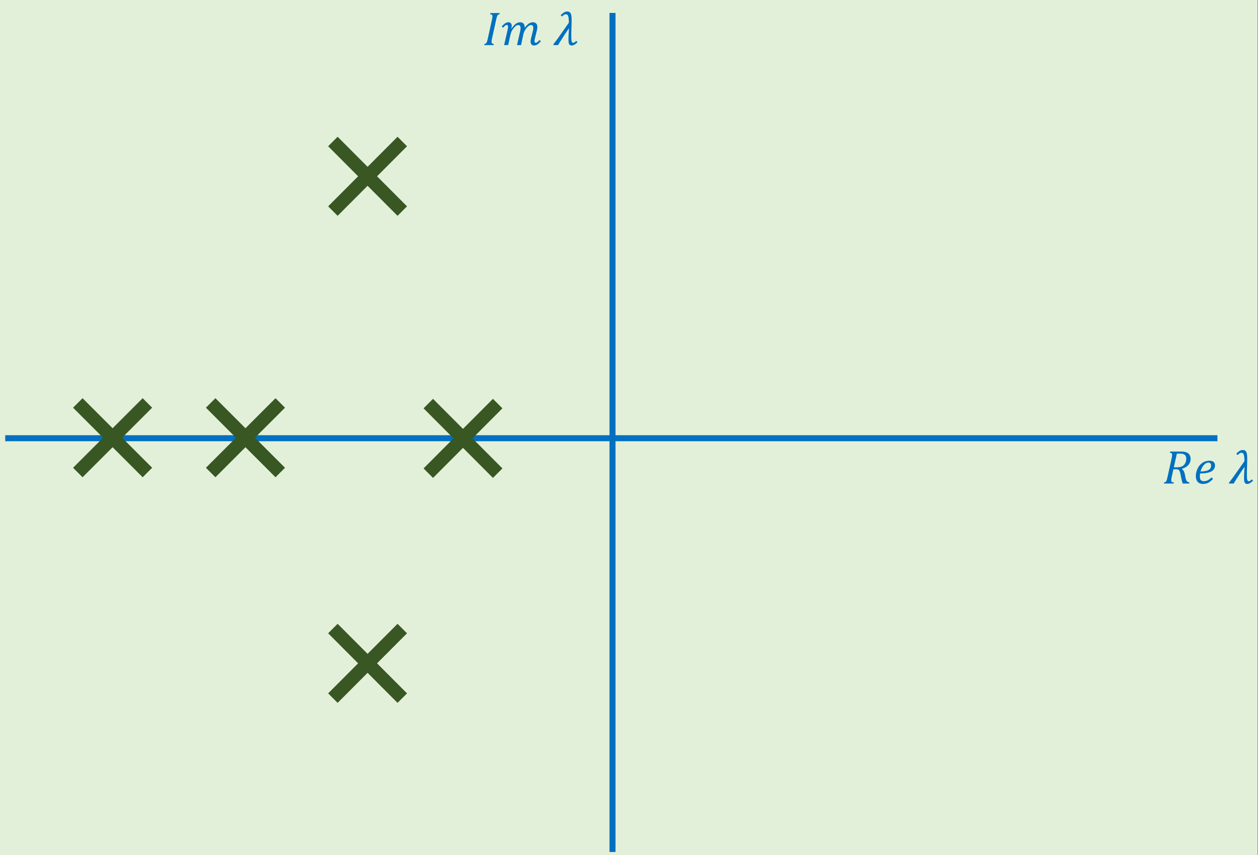


(a) $\mu < \mu_B$ (b) $\mu_B < \mu < \mu_M$ (c) $\mu = \mu_M$ (d) $\mu_M < \mu < \mu_A$ (e) $\mu > \mu_A$

Stability of Stationary States

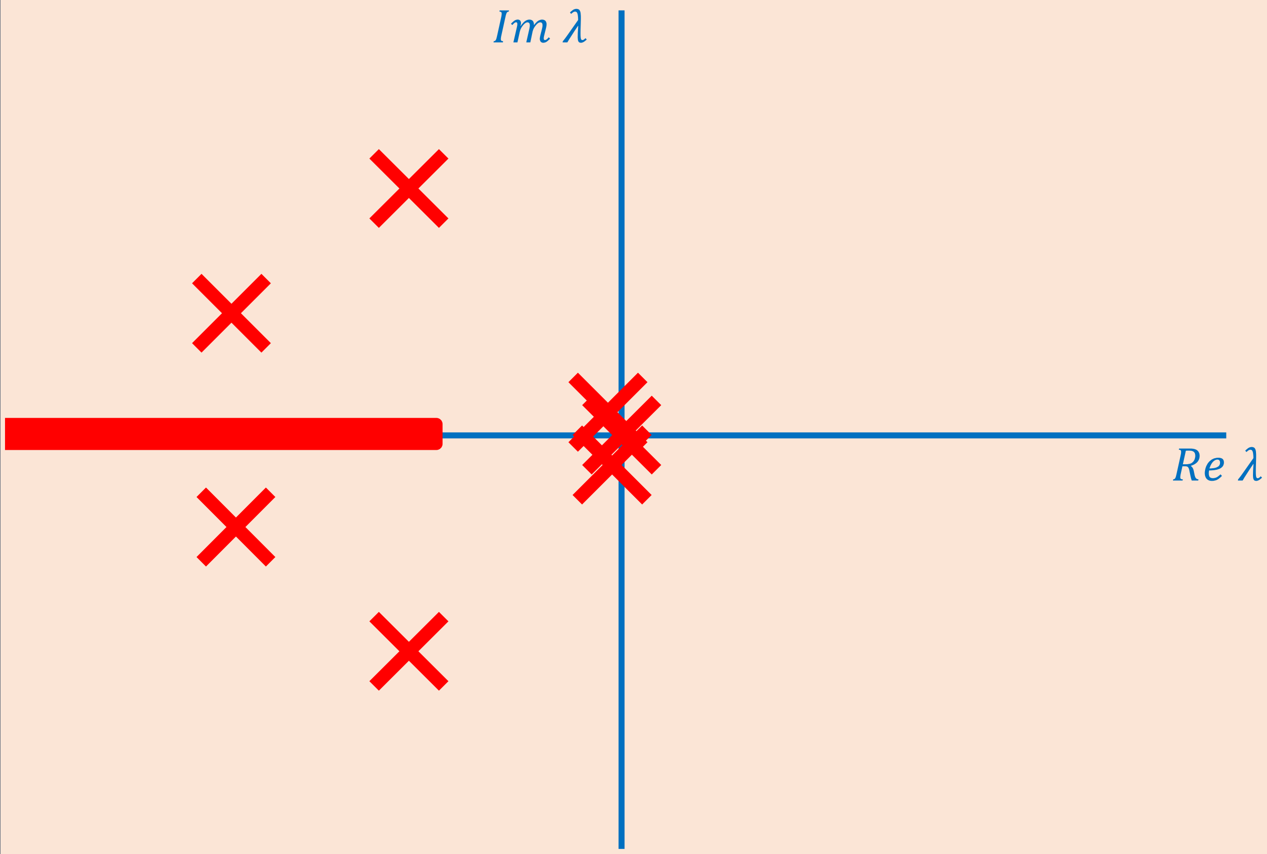
ODE

$$\lambda\,\bar{y} = f_y(y^*;\mu)\,\bar{y}$$



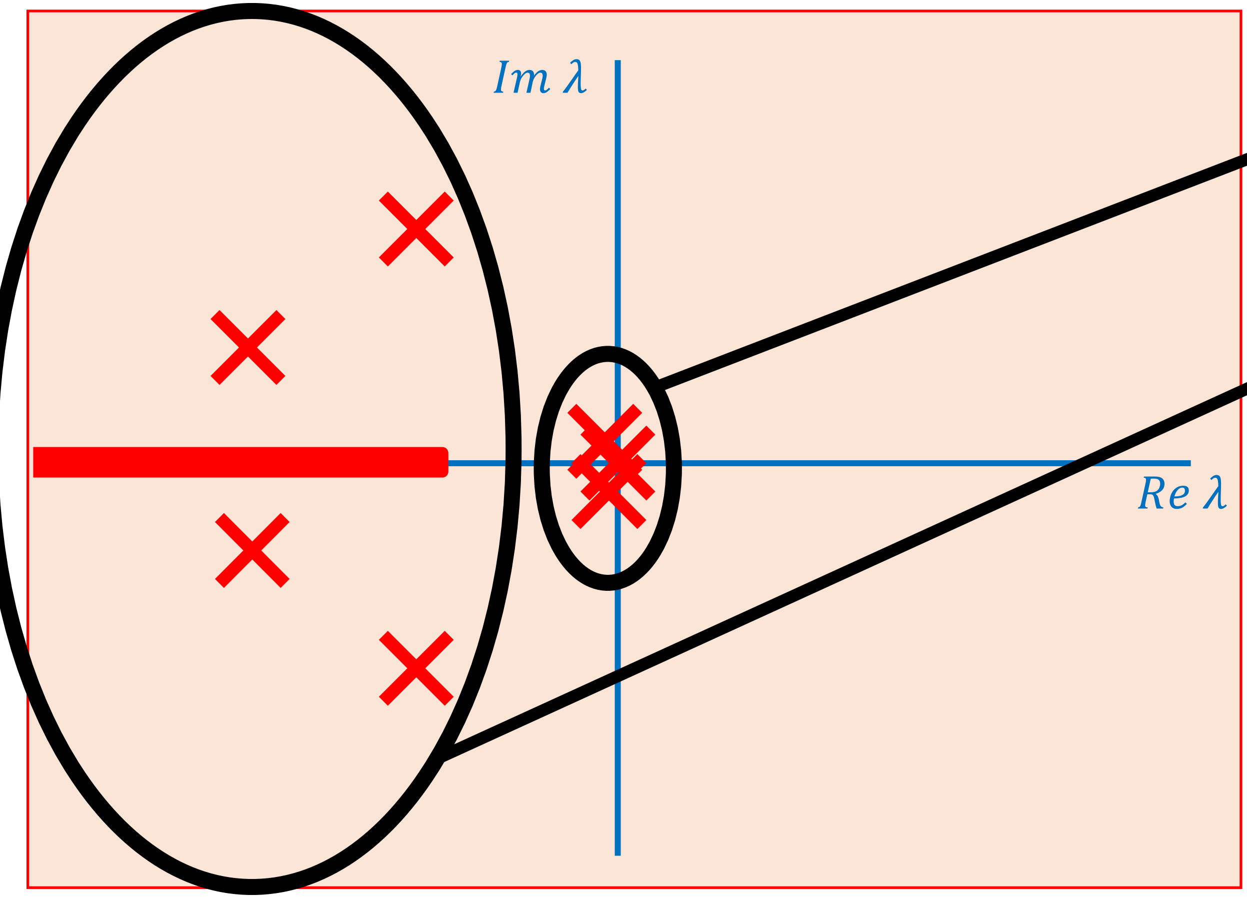
PDE

$$\lambda\,\bar{y} = \bar{y}_{xx} + f_y(y^*(x);\mu)\,\bar{y}$$



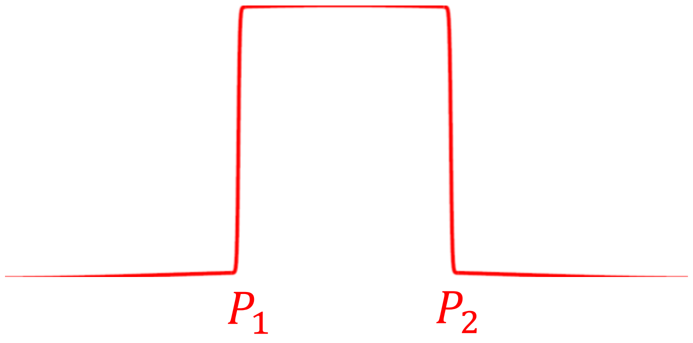
Part 5: Dynamics & Bifurcations of Patterned States

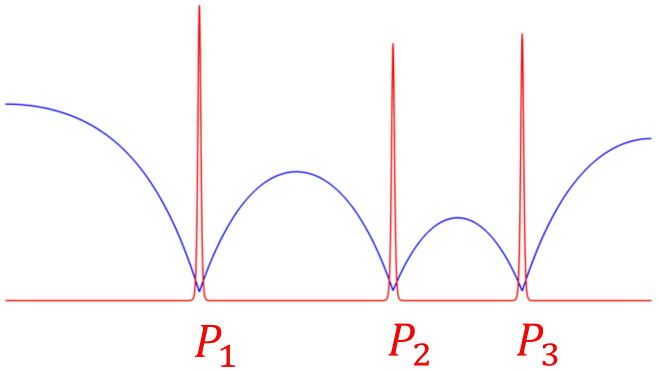
Dynamics of Patterned States

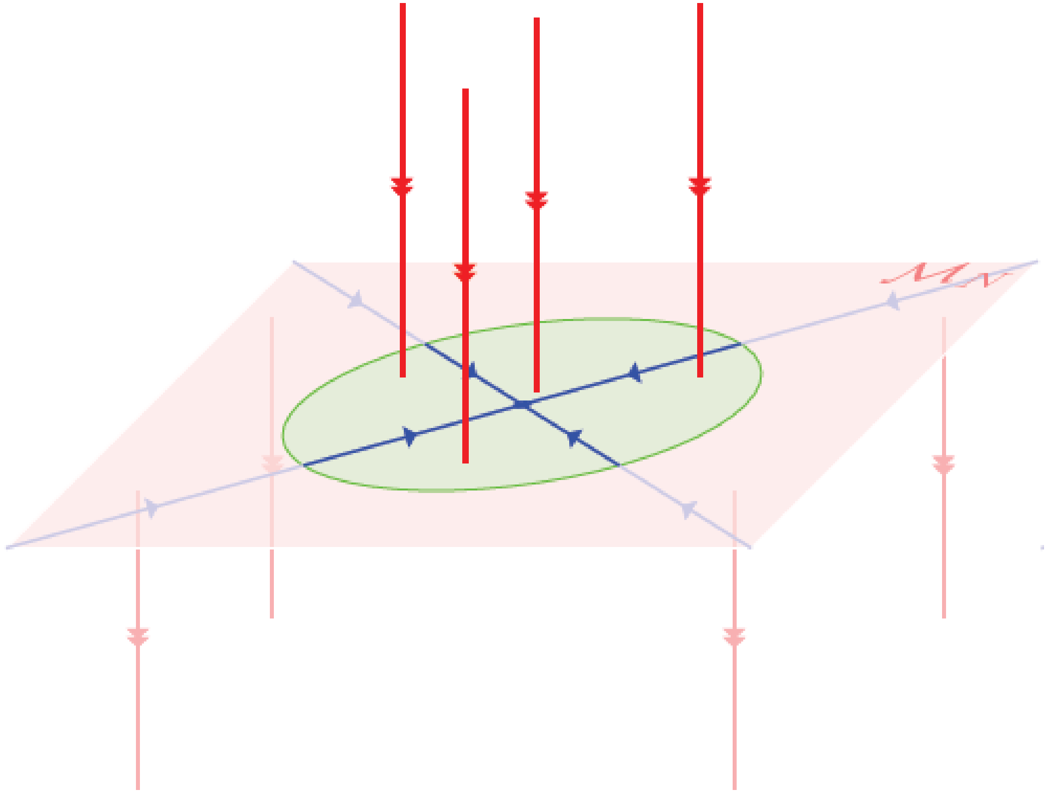


1. SLOW Pattern Adaptation

2. FAST Pattern Degradation





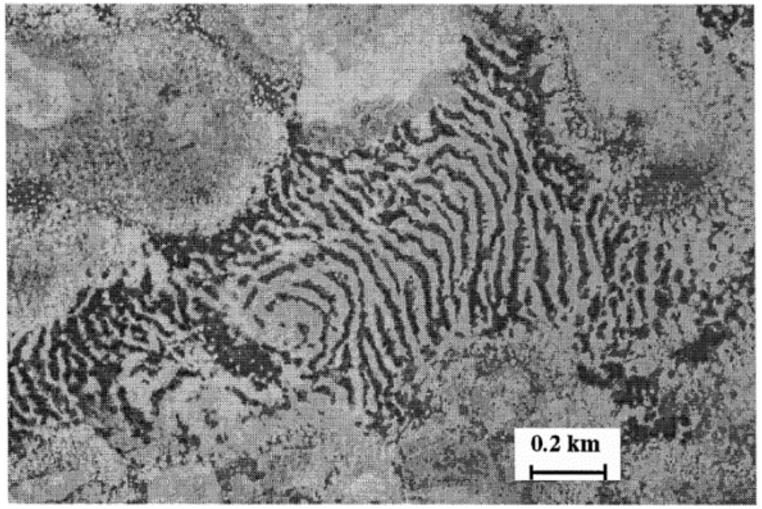


1. SLOW pattern adaptation

Somaliland, 1948 [Macfadyen, 1950]

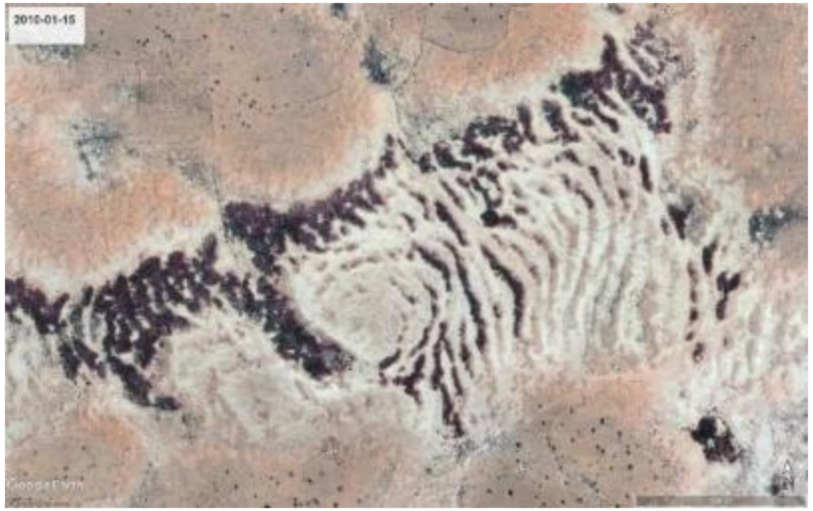
Somaliland, 2008

2. FAST Pattern Degradation

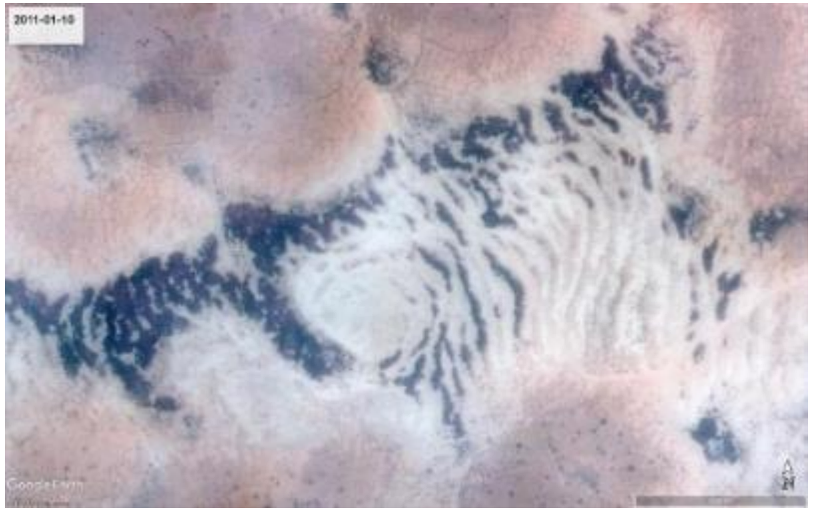


Niger, 1950 [Valentin, 1999]

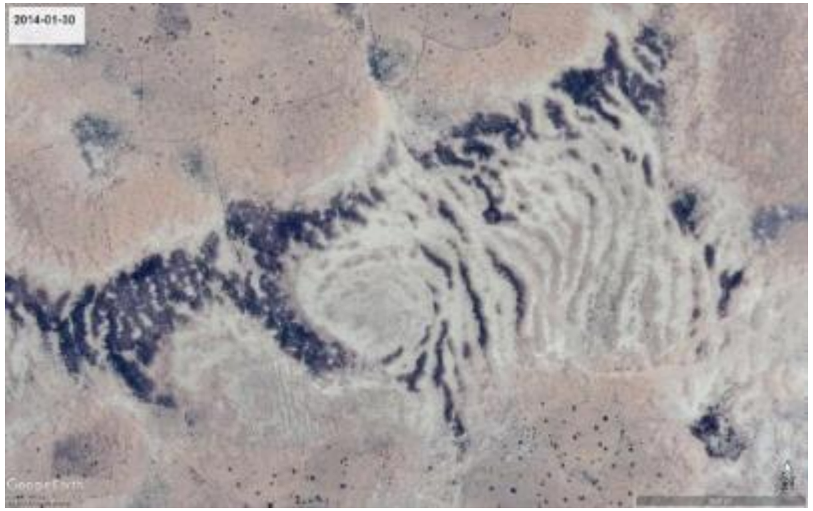
Niger, 2008



Niger, 2010



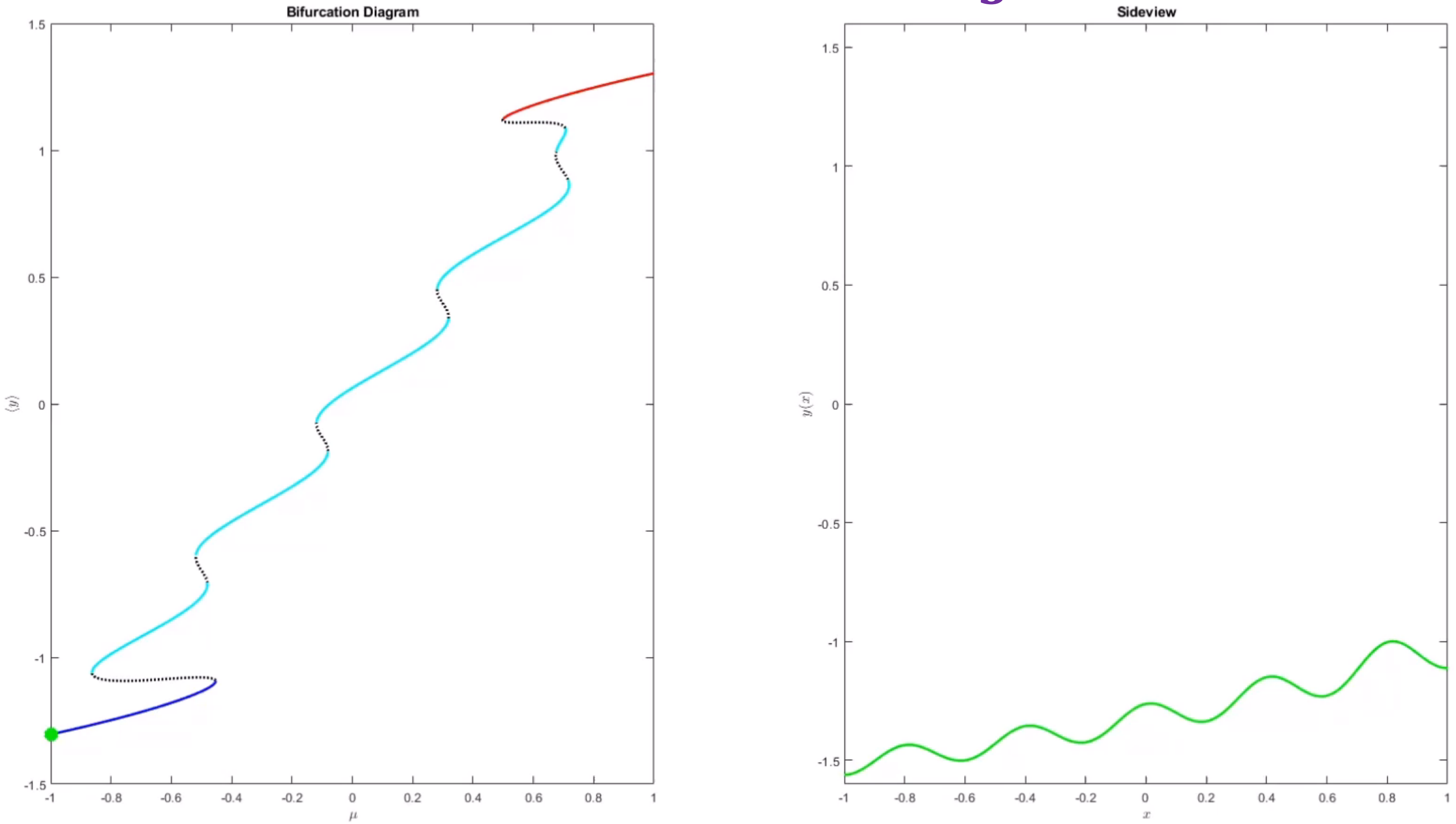
Niger, 2011



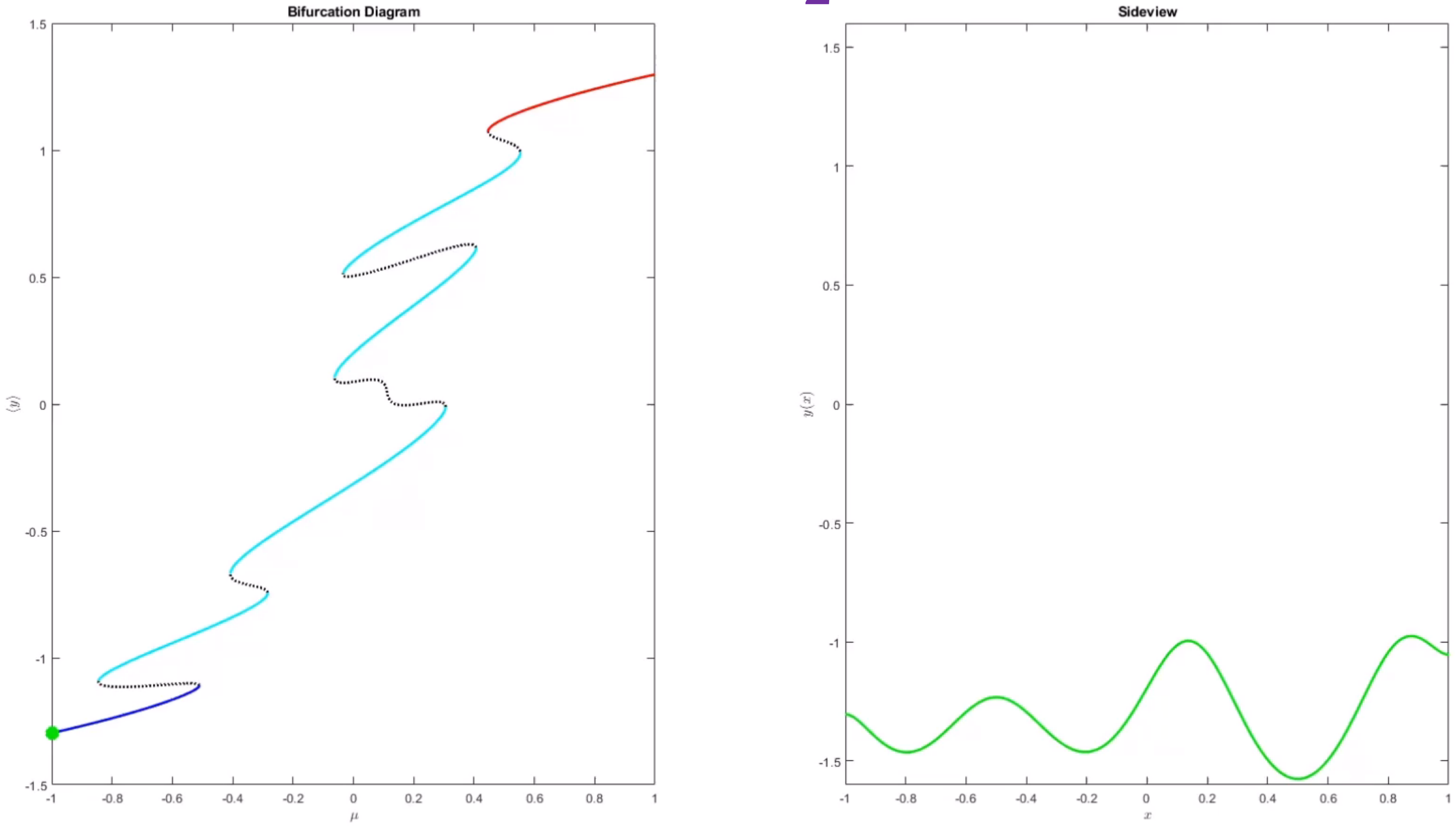
Niger, 2014

Niger, 2016

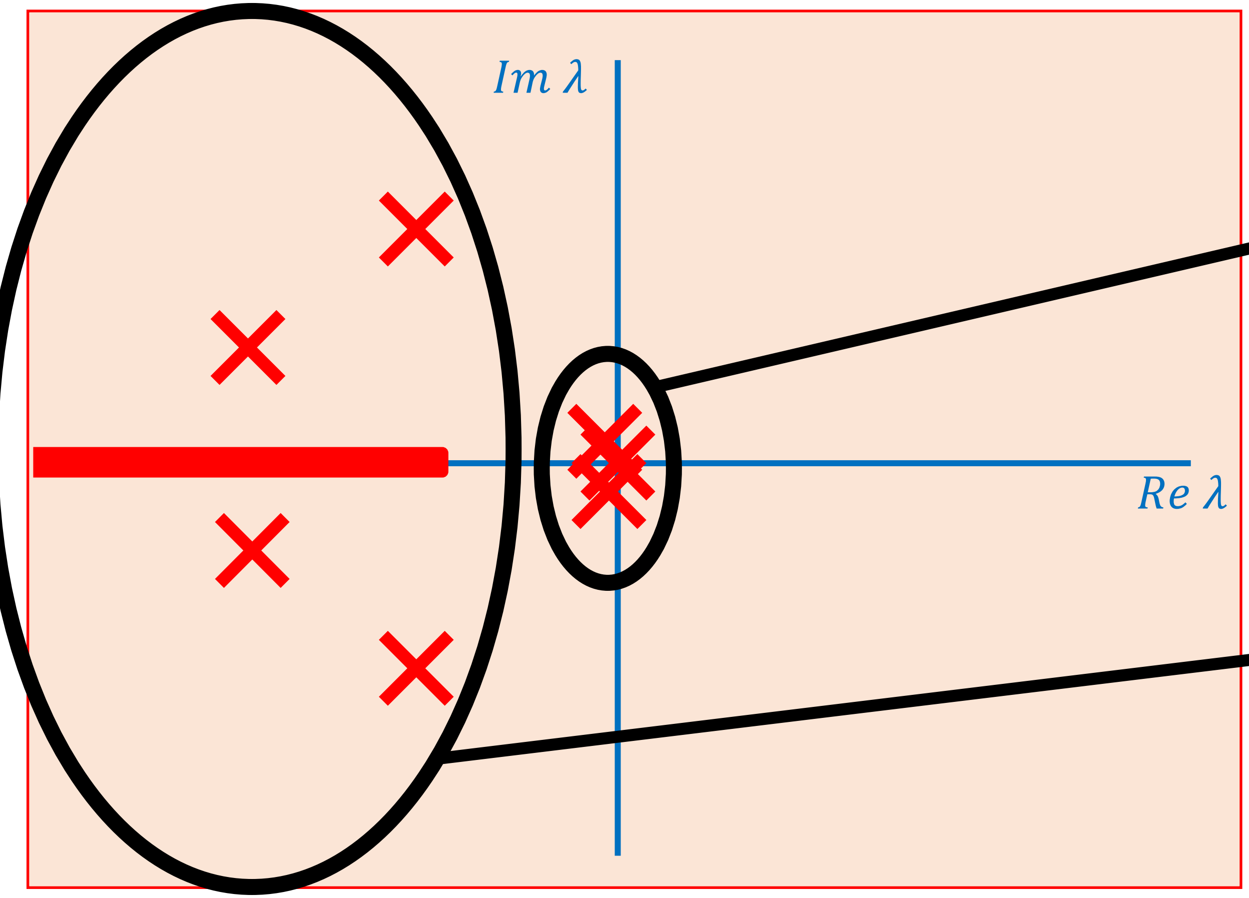
$$y_t = D\, y_{xx} + y(1 - y^2) + \mu + x + \frac{2}{5}\cos(5\pi x)$$



$$y_t = D\, y_{xx} + y(1 - y^2) + \mu + \frac{1}{2}\left(\cos(2\pi x) + \sin(3\pi x)\right)$$



Bifurcations



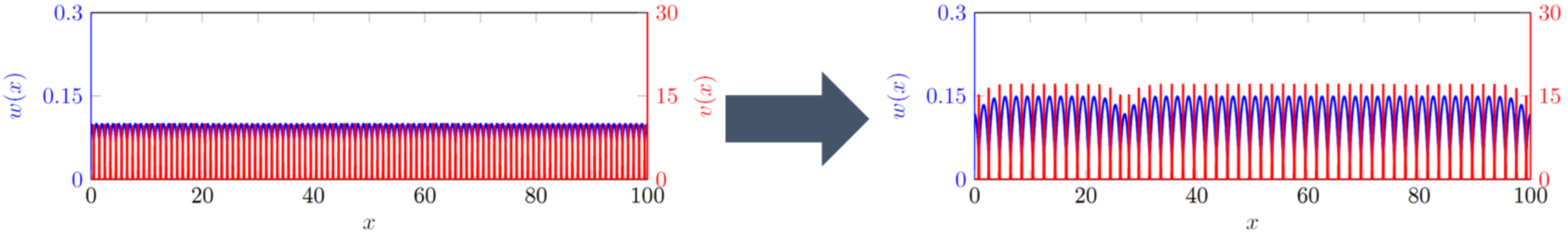
What happens at bifurcation?

1. SLOW Pattern Adaptation

At bifurcation:
→ Location of structure changes

2. FAST Pattern Degradation

At bifurcation:
→ Structures created or destroyed

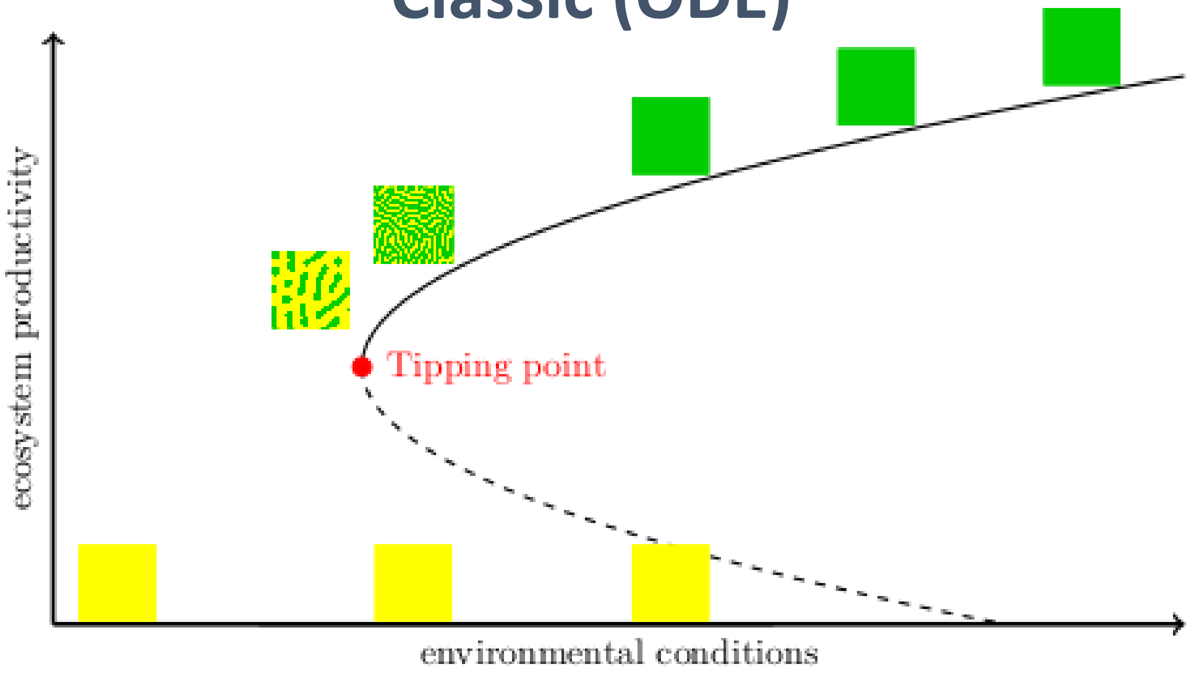


Summary

Tipping in Spatially Extended Systems

What if the system tips?

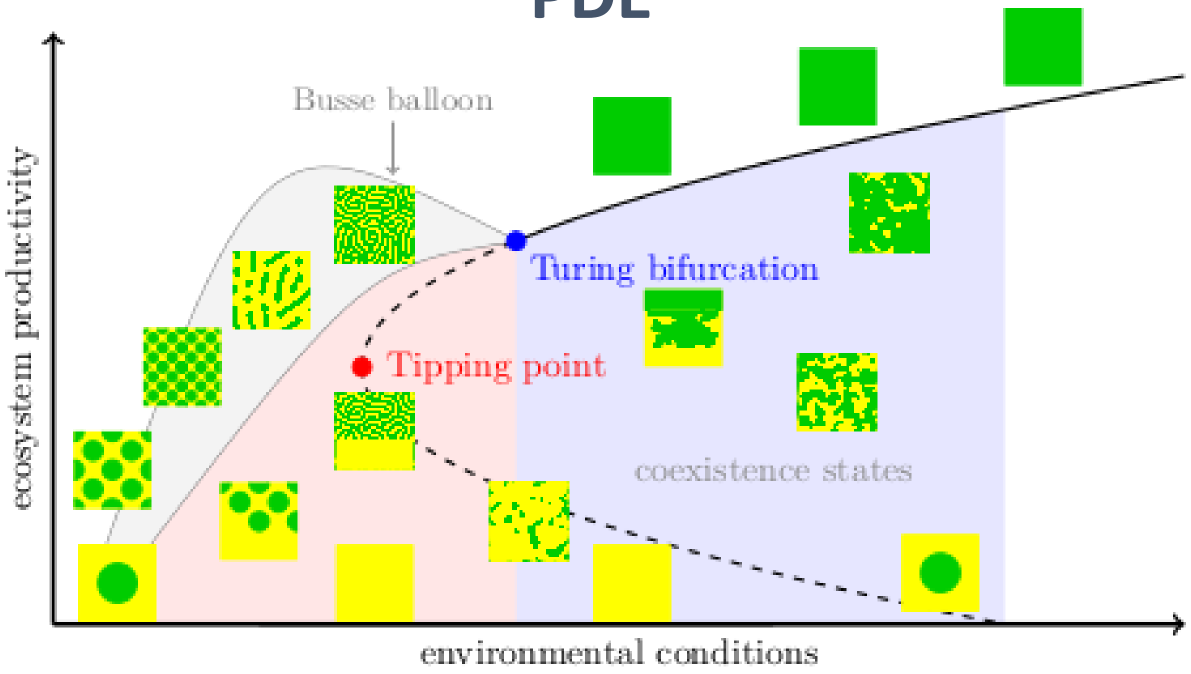
Classic (ODE)



Crossing a Tipping Point:
→ Always full reorganization

Early Warning Signals
signal for <u>WHEN</u>

PDE



Crossing a bifurcation:
Now also possible:
→ Spatial reorganization (Turing patterns)
→ Fragmented tipping (coexistence states)

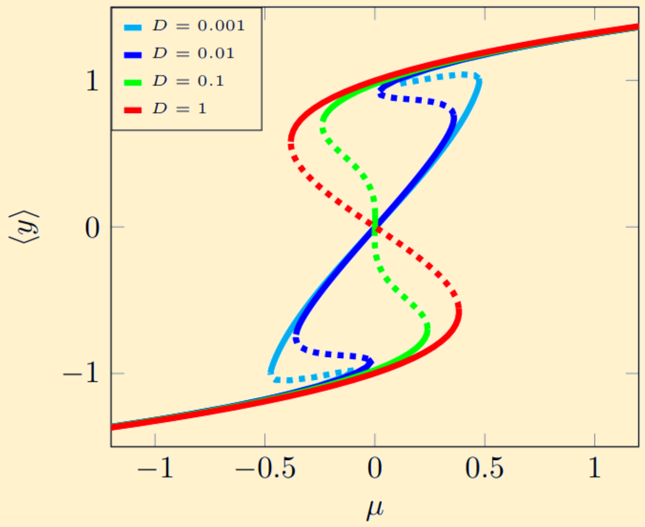
Early Warning Signals
need to signal <u>WHEN</u> & <u>WHAT</u>

Do systems always behave like this? (a.k.a. the small print)

No.

Well-mixed systems

Spatially confined systems



→ Such systems (again) behave like ODEs ←

But even in other systems terms & conditions apply:
System-specific knowledge is required!

Summary

Spatial Patterns:

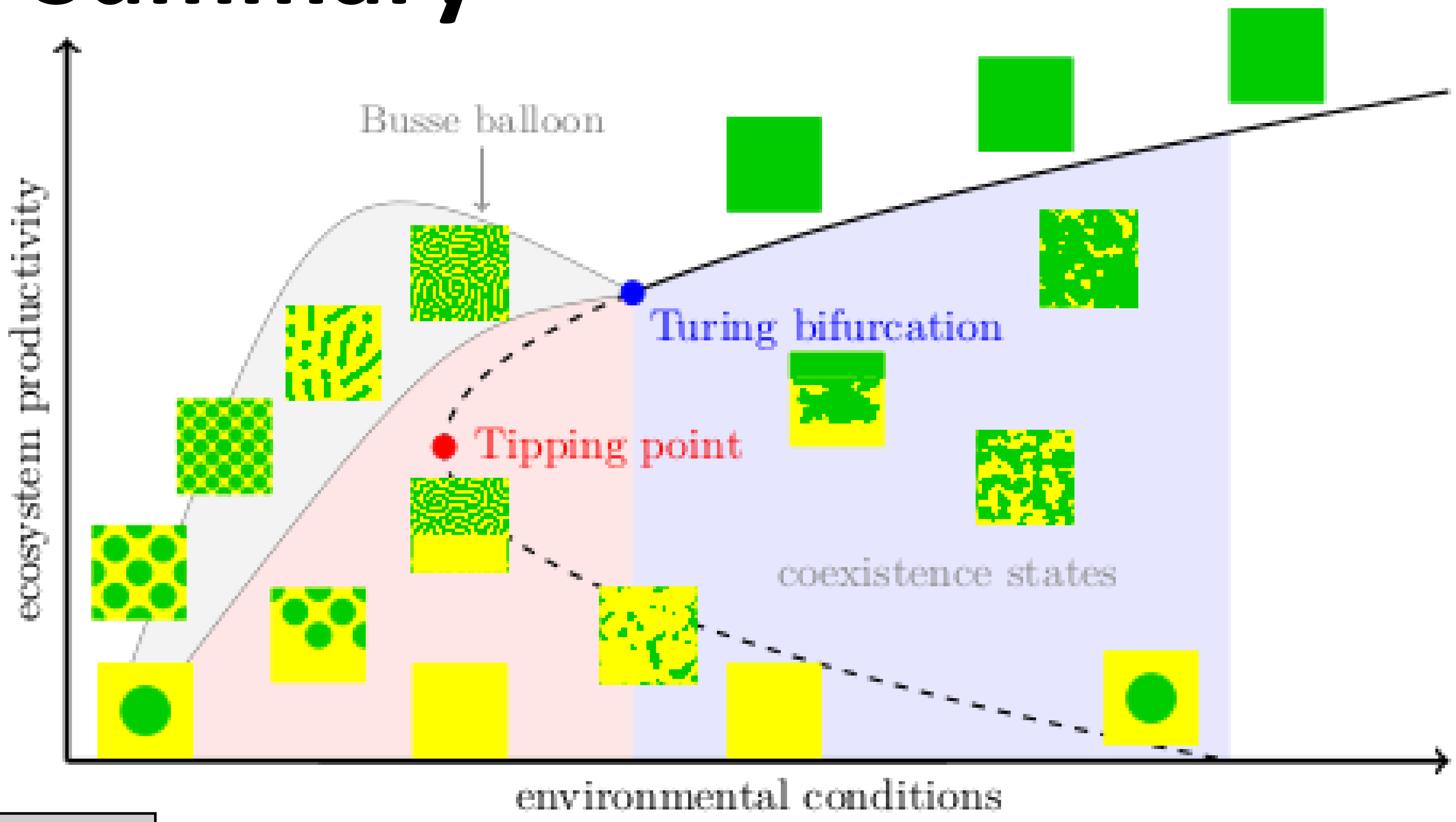
- Turing Patterns
- Coexistence States

Tipping can be more subtle:

- Spatial reorganization
- Fragmented Tipping

Dynamics of Patterns is:

- Slow Pattern Adaptation
- Fast Pattern Degradation



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Bastiaansen, R., Dijkstra, H. A., & von der Heydt, A. S. (2021). Fragmented Tipping in a spatially heterogeneous world. *Environmental Research Letters, 17, 045006*