Lecture 28

Partial synchrony in complex networks: interplay of structure, noise, and delay

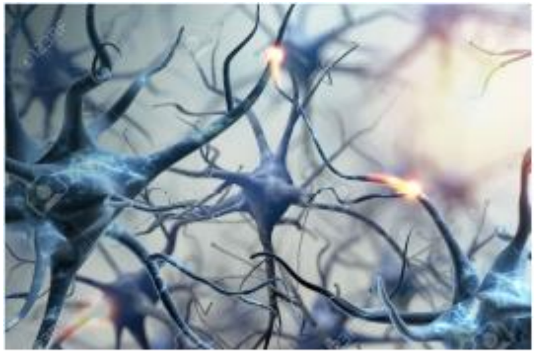
Anna Zakharova

Winter Term 2019/20 “Non-equilibrium Statistical Physics”

synchrony

Is synchrony always good?

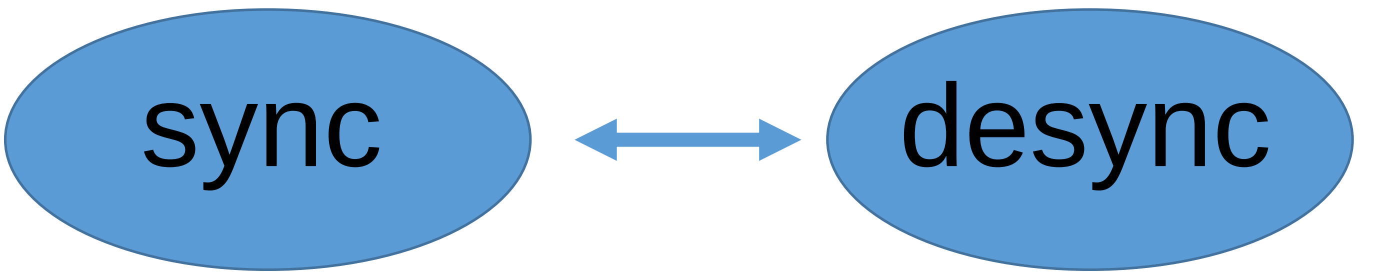
Is synchrony always good?



- neural networks

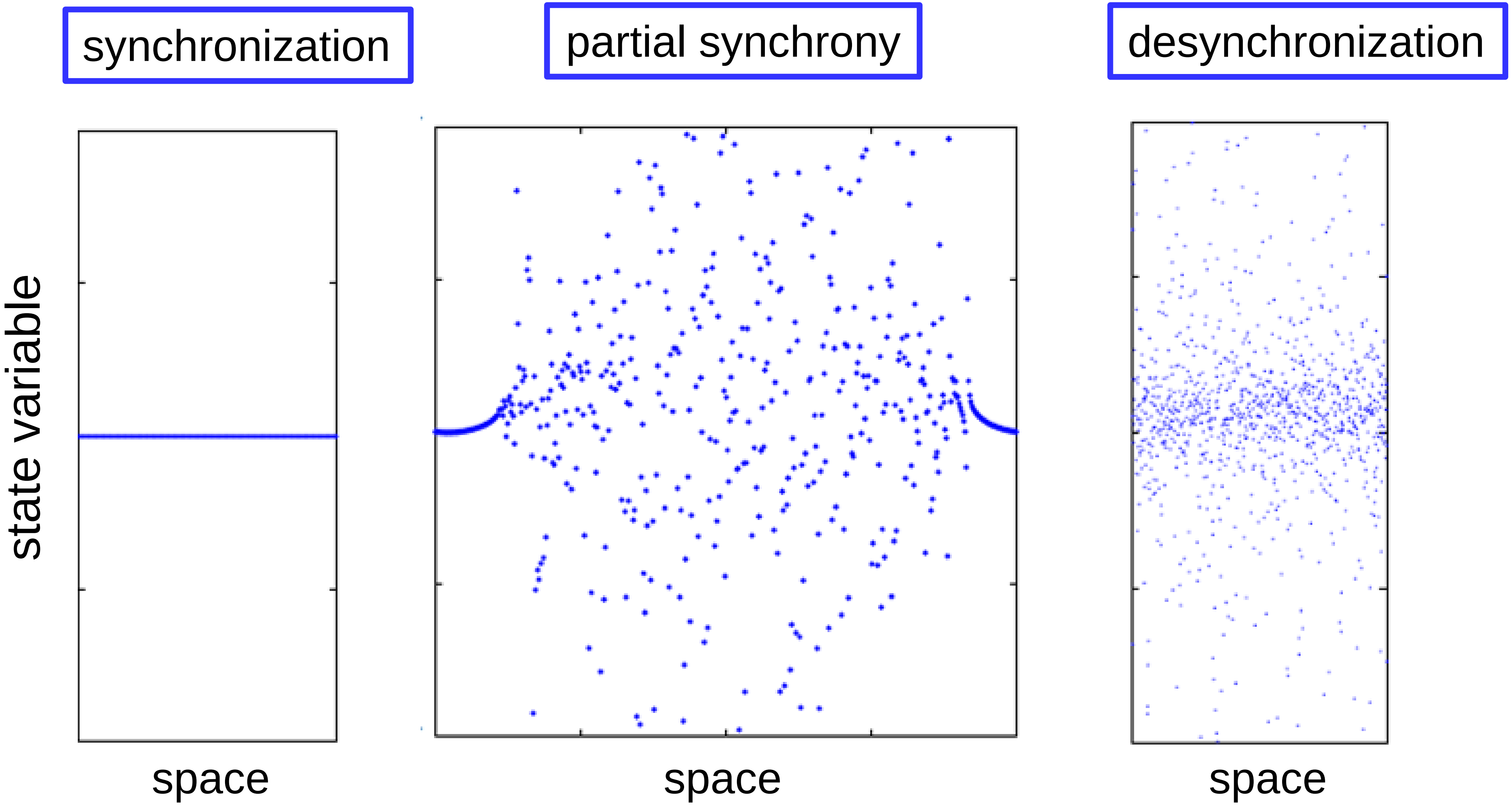
- power grid networks

Transitions



partial synchronization patterns

What is partial synchrony?



Chimera states

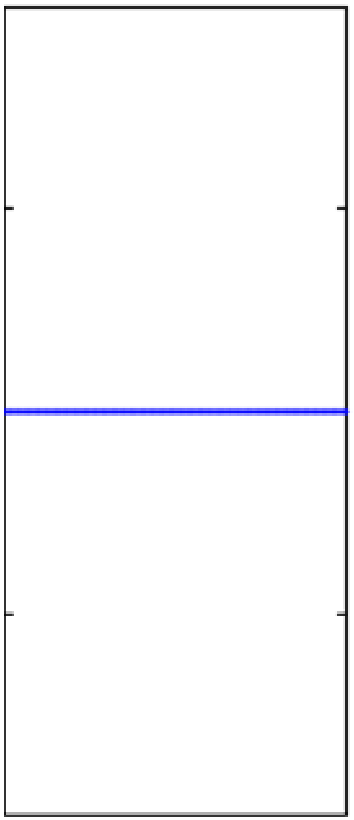
What is partial synchrony?

synchronization

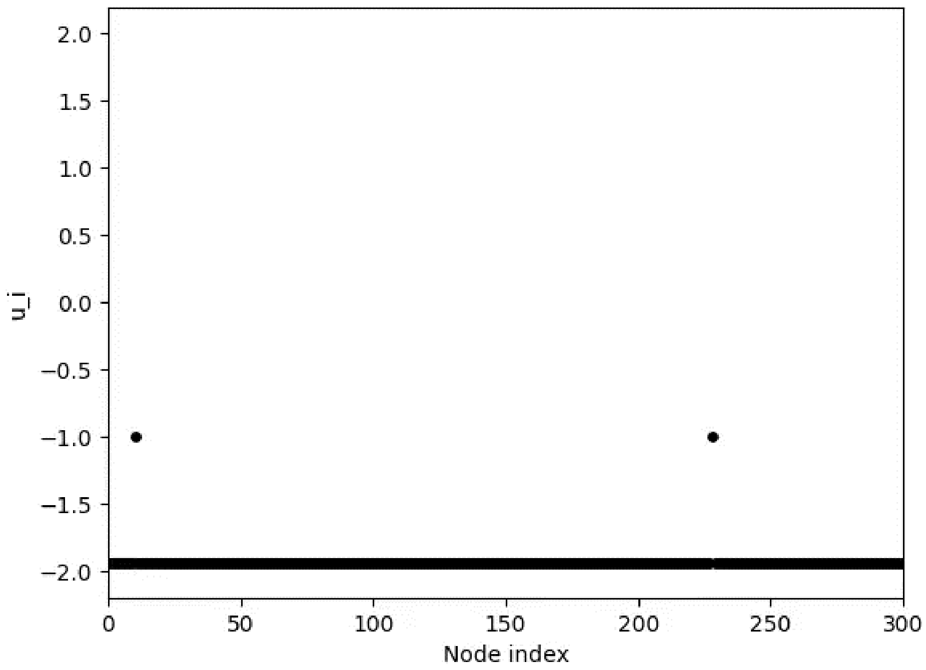
partial synchrony

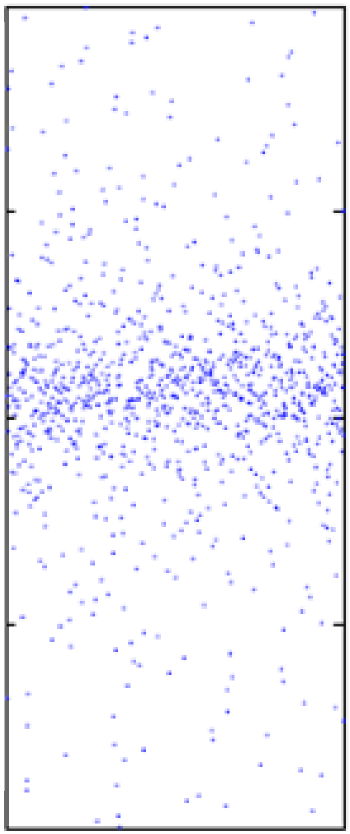
desynchronization

state variable



space



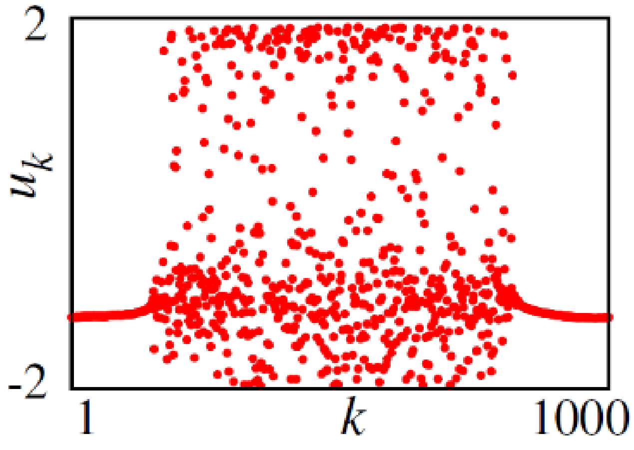


space

Solitary states

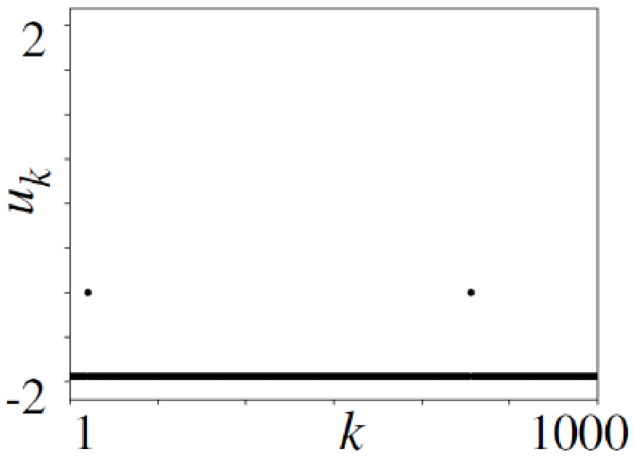
What is the difference?

chimera states



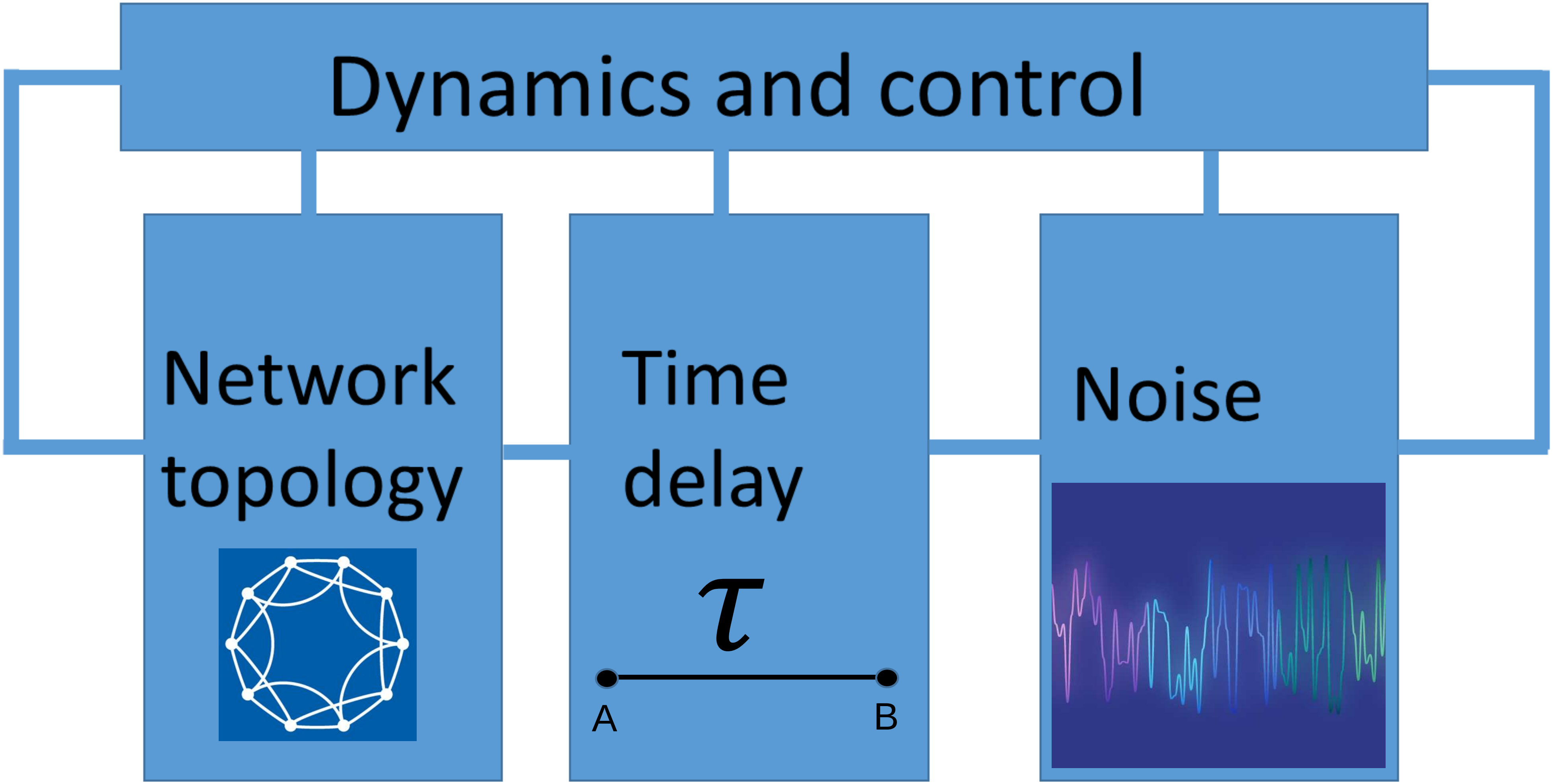
Localized in space incoherent domain

solitary states



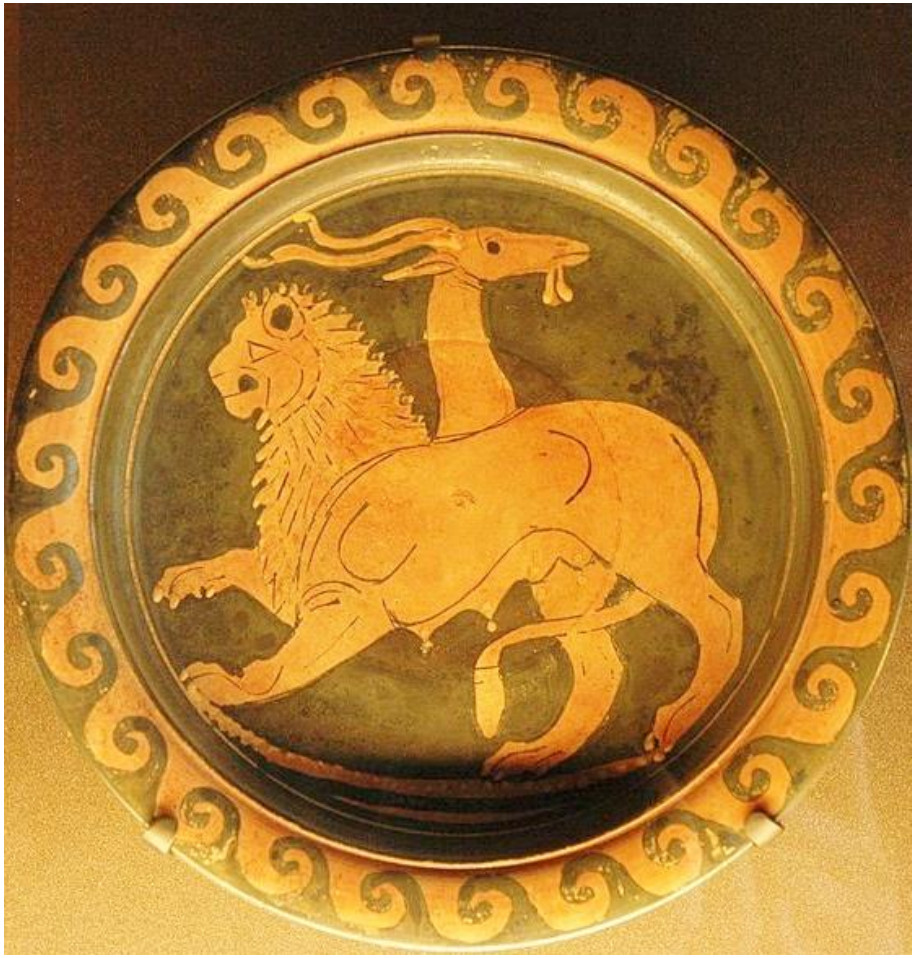
Randomly distributed solitary nodes

Structure, delay and noise

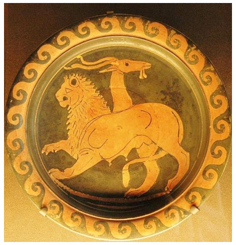


Dynamics and control
Network topology
Time delay
τ
A
B
Noise

Partial sync pattern: chimera state

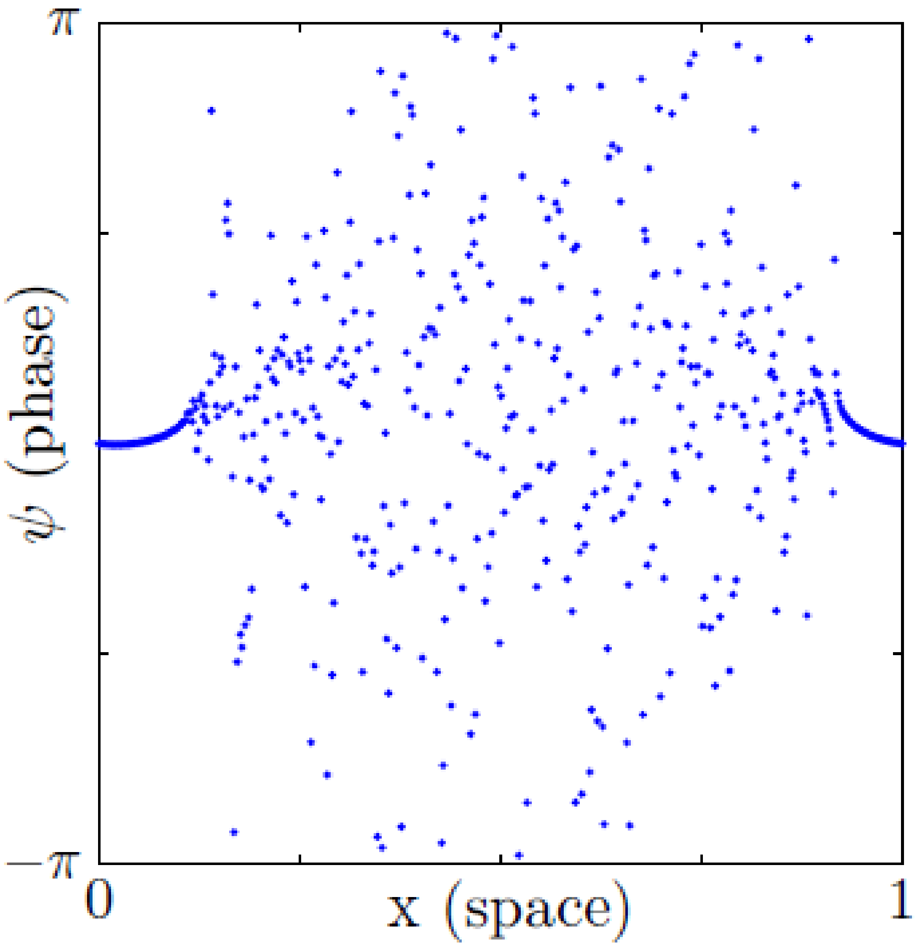


What is a chimera state?



Spatial coexistence of coherent/synchronized and incoherent/desynchronized domains in a dynamical network

- discovered by Kuramoto and Battogtokh in 2002
- named ***chimera states*** by Abrams and Strogatz in 2004
- identical elements, symmetric topology



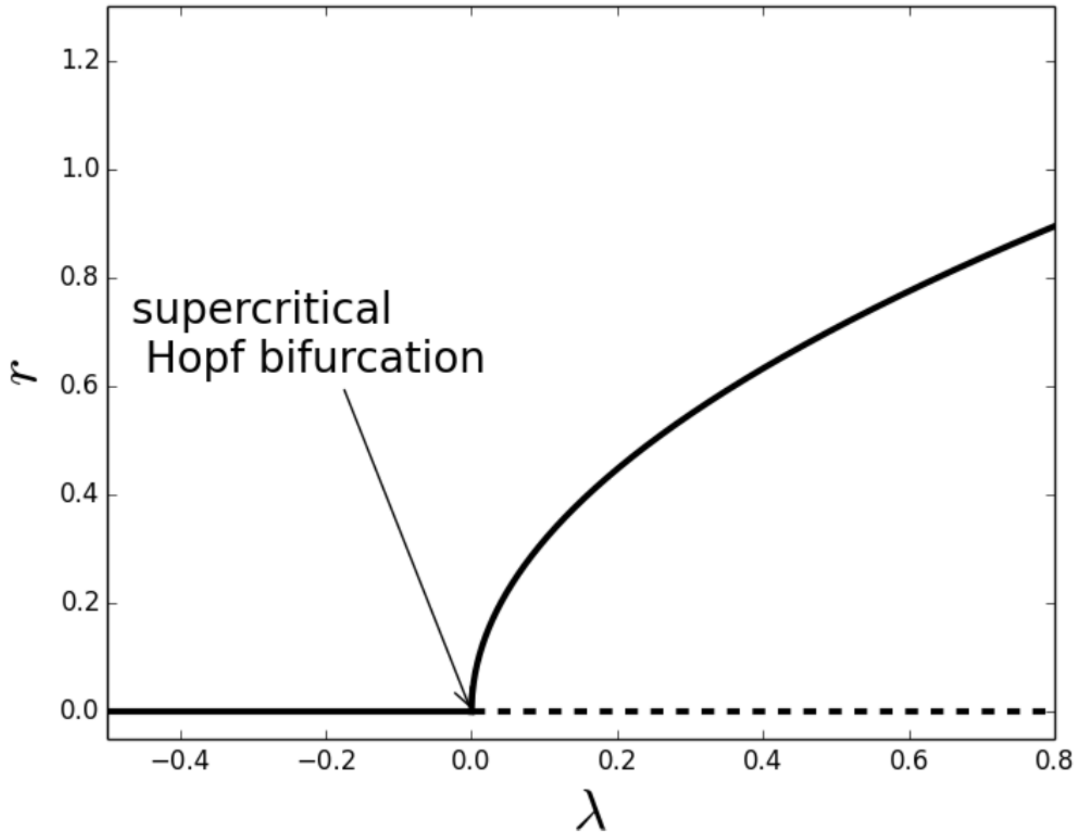
Amplitude chimeras and chimera death

Model: Stuart-Landau oscillator

Single node dynamics

$$\boxed{\dot{z} = f(z) \equiv (\lambda + i\omega - |z|^2)z}$$

$$z(t) = x(t) + iy(t)$$



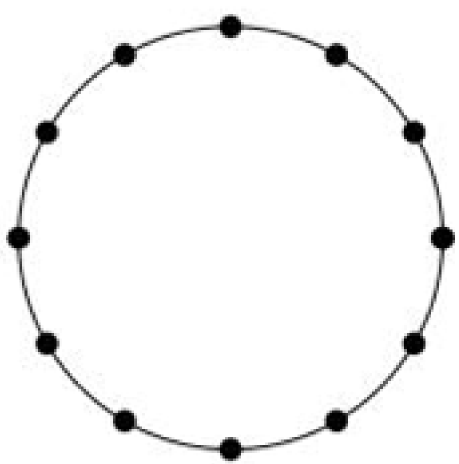
Model: Stuart-Landau oscillator

Single node dynamics

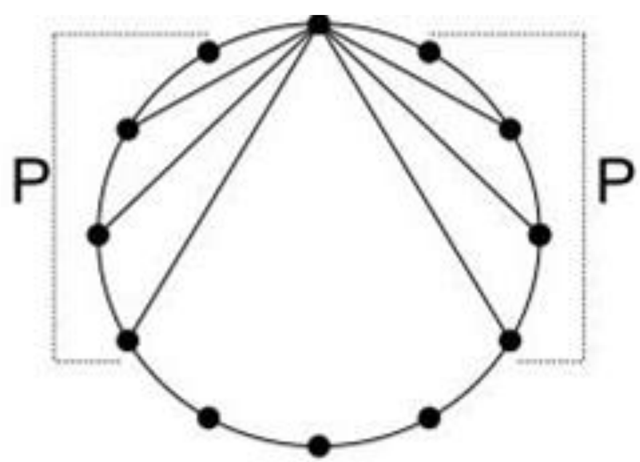
$$\boxed{\dot{z} = f(z) \equiv (\lambda + i\omega - |z|^2) z}$$

$$z(t) = x(t) + iy(t)$$

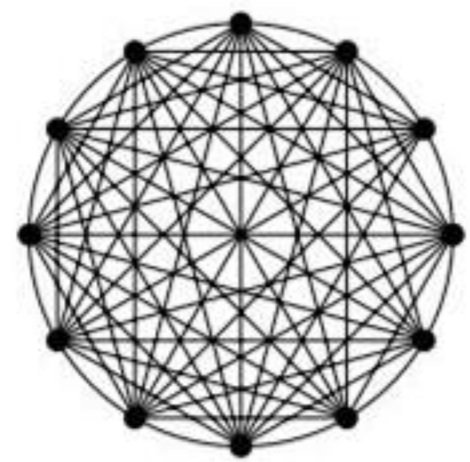
How to couple the oscillators?



local



nonlocal



global

Model: network of coupled Stuart-Landau oscillators

$$\dot{z}_j = f(z_j) + \frac{\sigma}{2P} \sum_{k=j-P}^{j+P} (\mathrm{Re}\, z_k - \mathrm{Re}\, z_j)$$

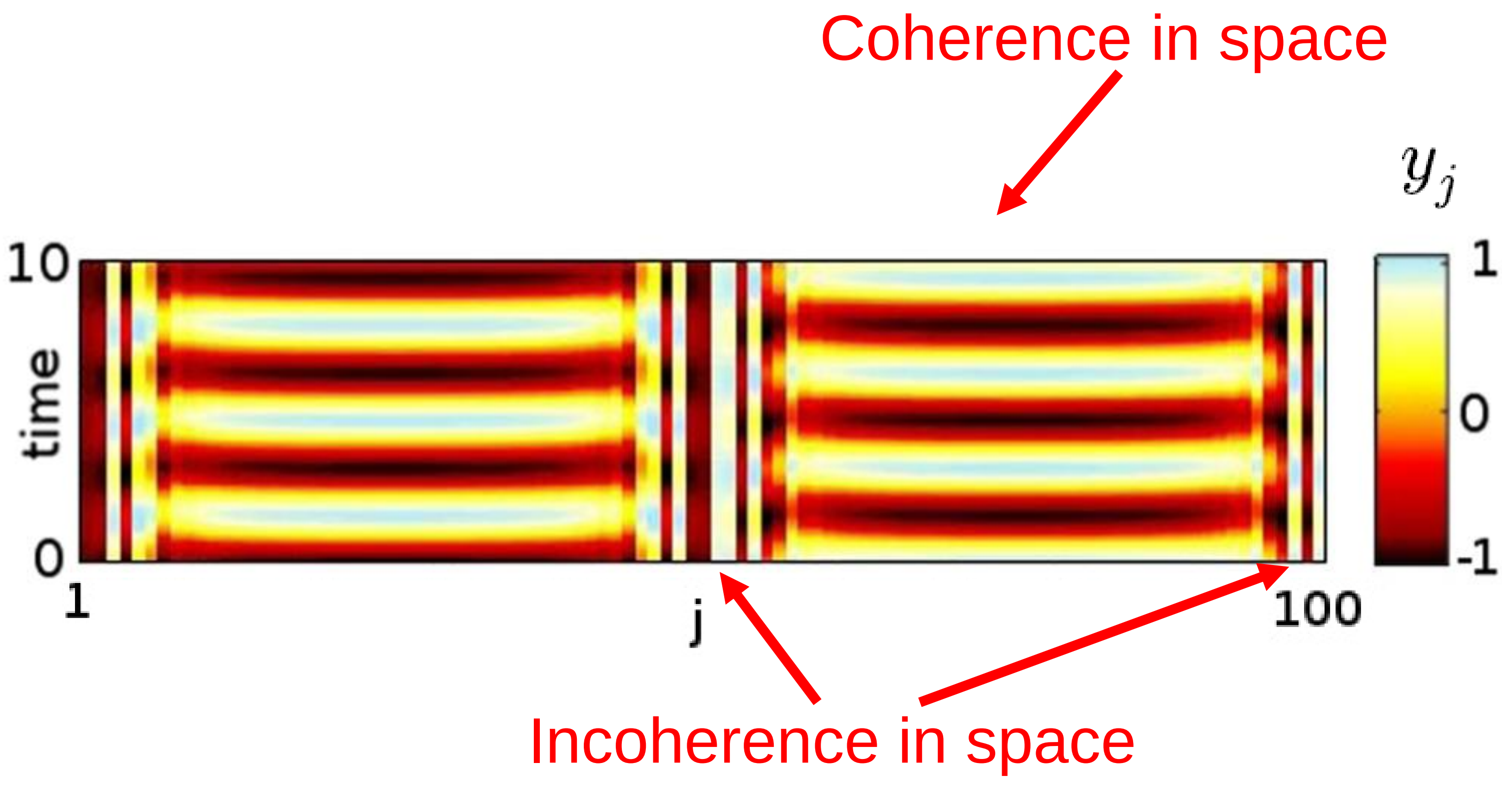
Symmetry-breaking coupling

amplitude chimeras

chimera death

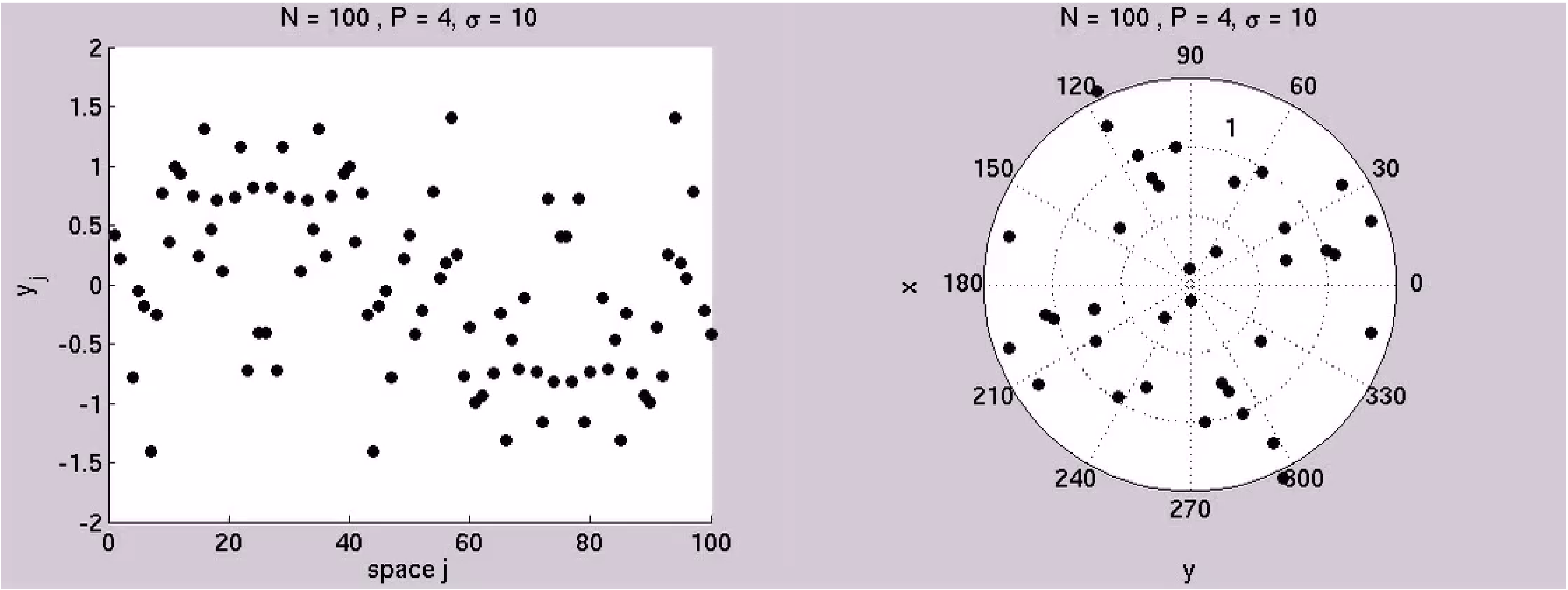
A. Zakharova, M. Kapeller, E. Schöll, *Phys. Rev. Lett.* 112, 154101 (2014)

Amplitude chimera



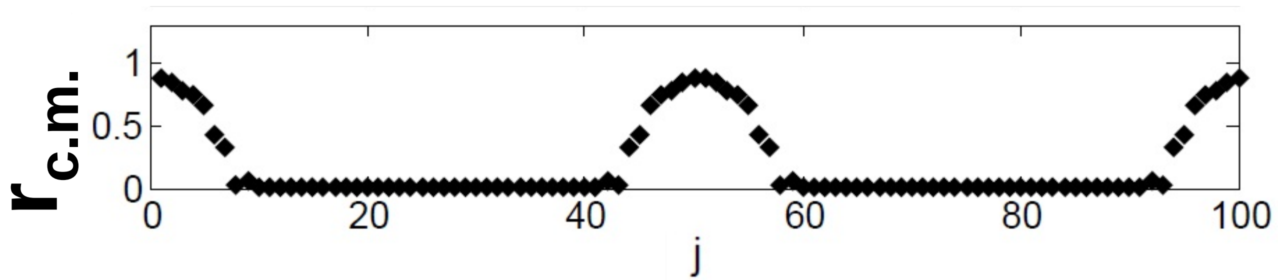
A. Zakharova, M. Kapeller, E. Schöll, *Phys. Rev. Lett.* 112, 154101 (2014)

Amplitude chimera

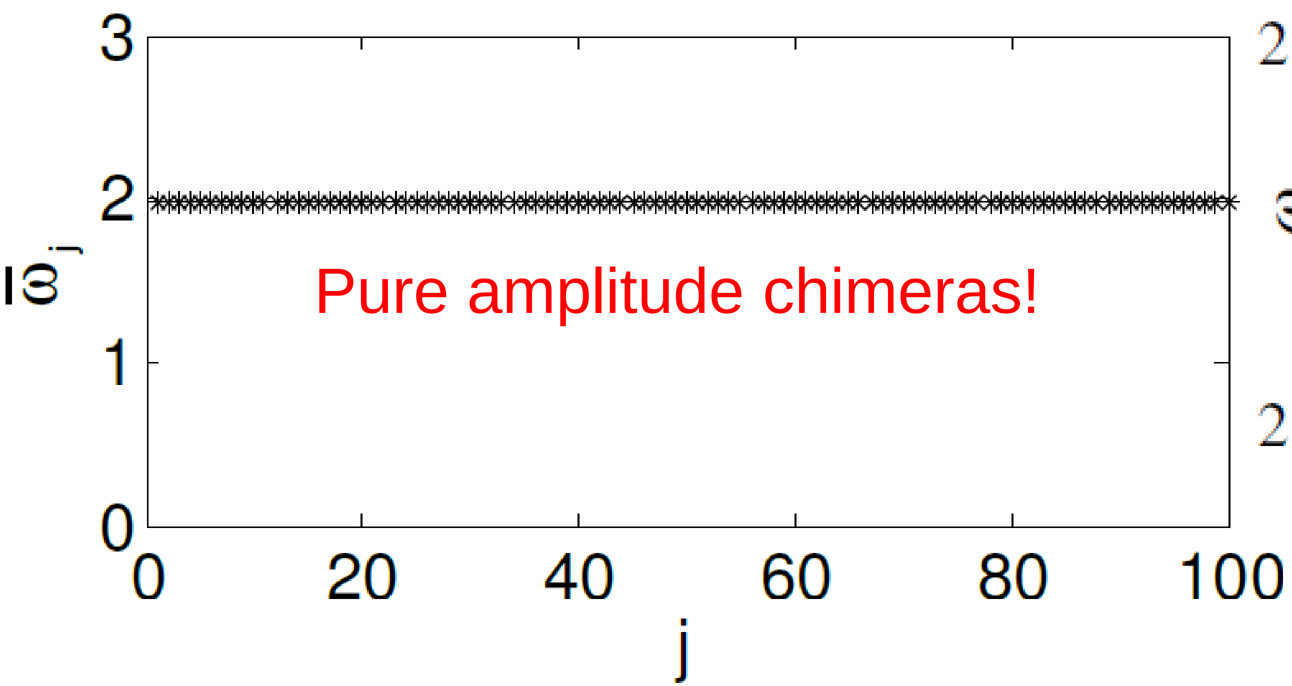


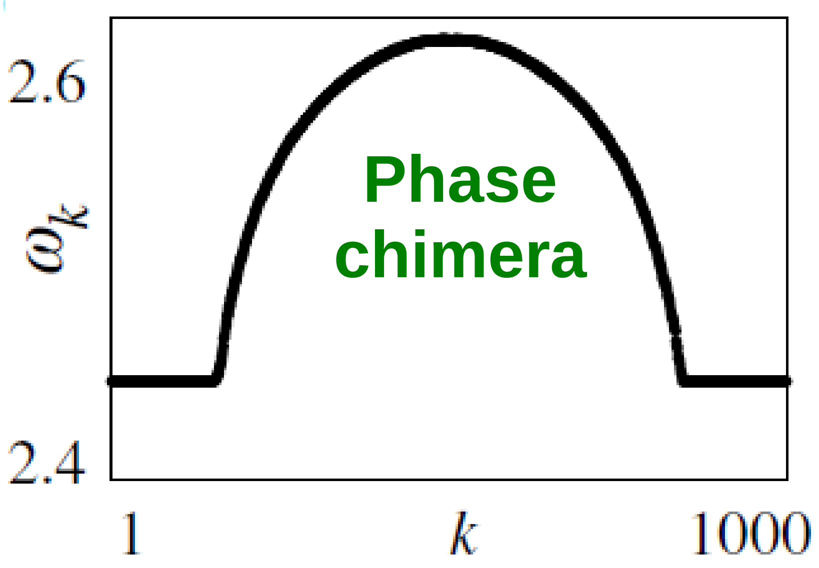
A. Zakharova, M. Kapeller, E. Schöll, *Phys. Rev. Lett.* 112, 154101 (2014)

Amplitude chimera



$r_{c.m.}$ is the shift of the center of mass from the origin



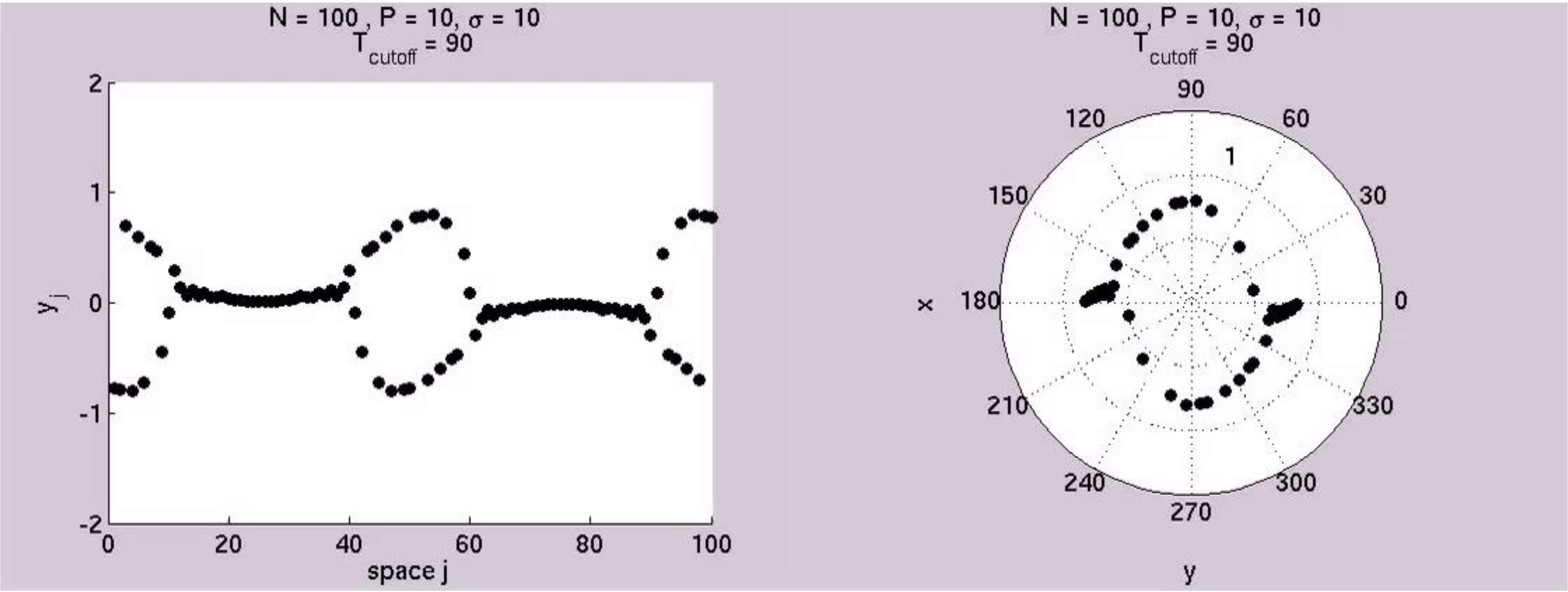


A. Zakharova, M. Kapeller, E. Schöll, *Phys. Rev. Lett.* 112, 154101 (2014)

Amplitude chimera

	Amplitude	Phase
◦**Classical chimeras** Kuramoto and Battogtokh (2002), Abrams and Strogatz (2004)	**no amplitude dynamics**	✓
◦**Amplitude-mediated chimeras** Sethia and Sen (2014)	✓	✓
◦**Amplitude chimeras** Zakharova, Kapeller, Schöll (2014)	✓	✗

Amplitude chimera



A. Zakharova, M. Kapeller, E. Schöll, *Phys. Rev. Lett.* 112, 154101 (2014)

Classical chimeras:

the dynamics is chaotic in time

M. Wolfrum and O. Omel’chenko, Chimera states are chaotic transients, *Phys Rev E 84*, 015201 (2011)

Amplitude chimeras:

the dynamics is periodic in time!

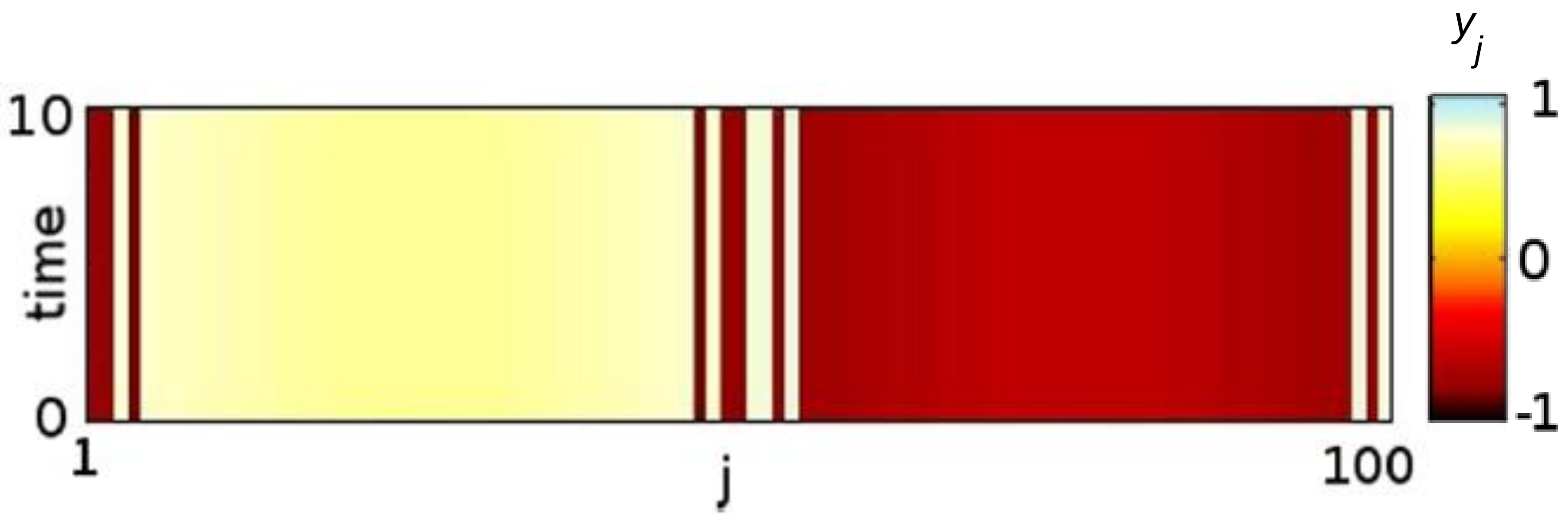
Amplitude chimeras are long-living transients!

A. Zakharova, M. Kapeller, E. Schöll, *J. Phys. Conf. Series* 727, 012018 (2016)

Chimera death

Chimera death

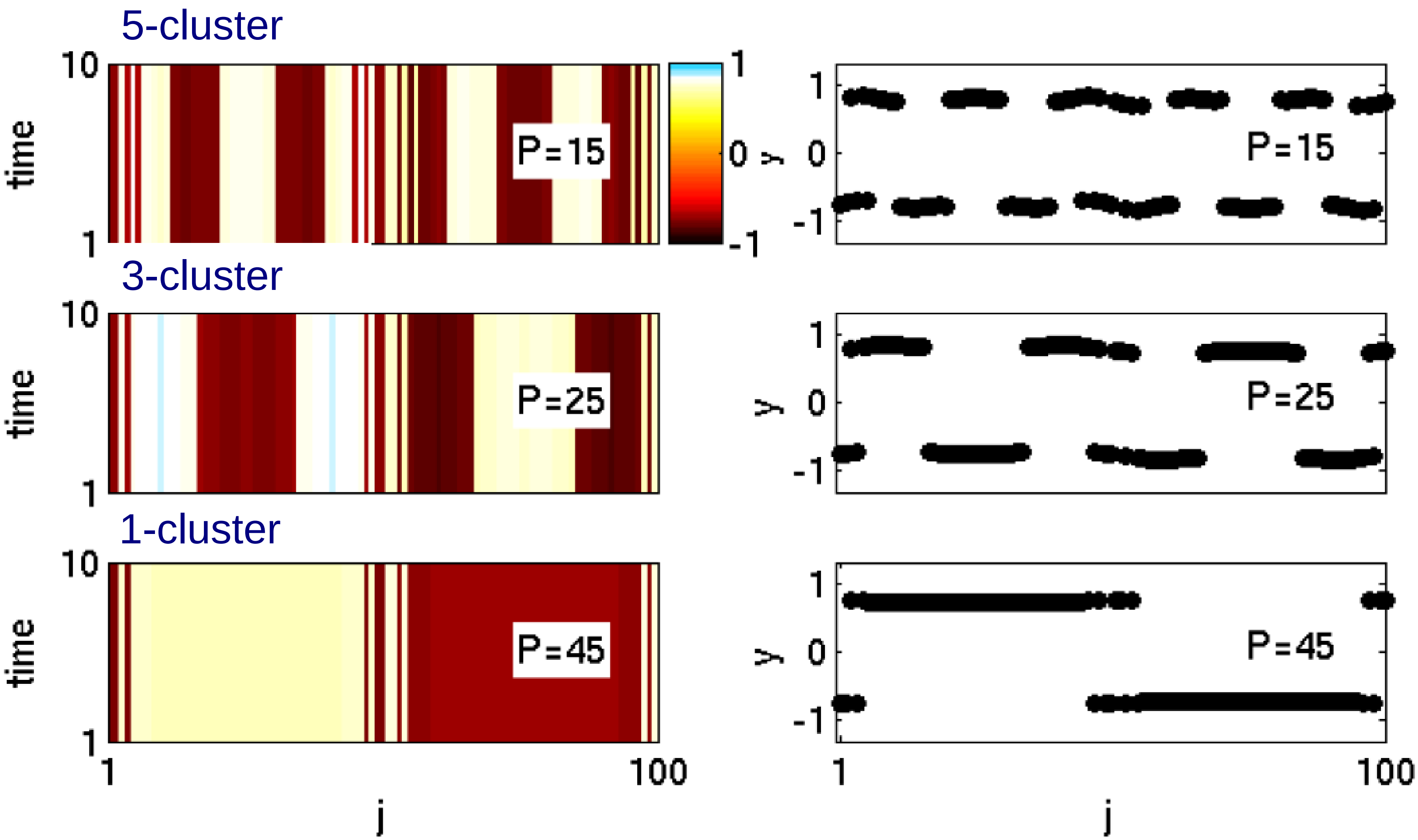
coexisting domains of spatially coherent and spatially incoherent oscillation death



Chimera of steady states!

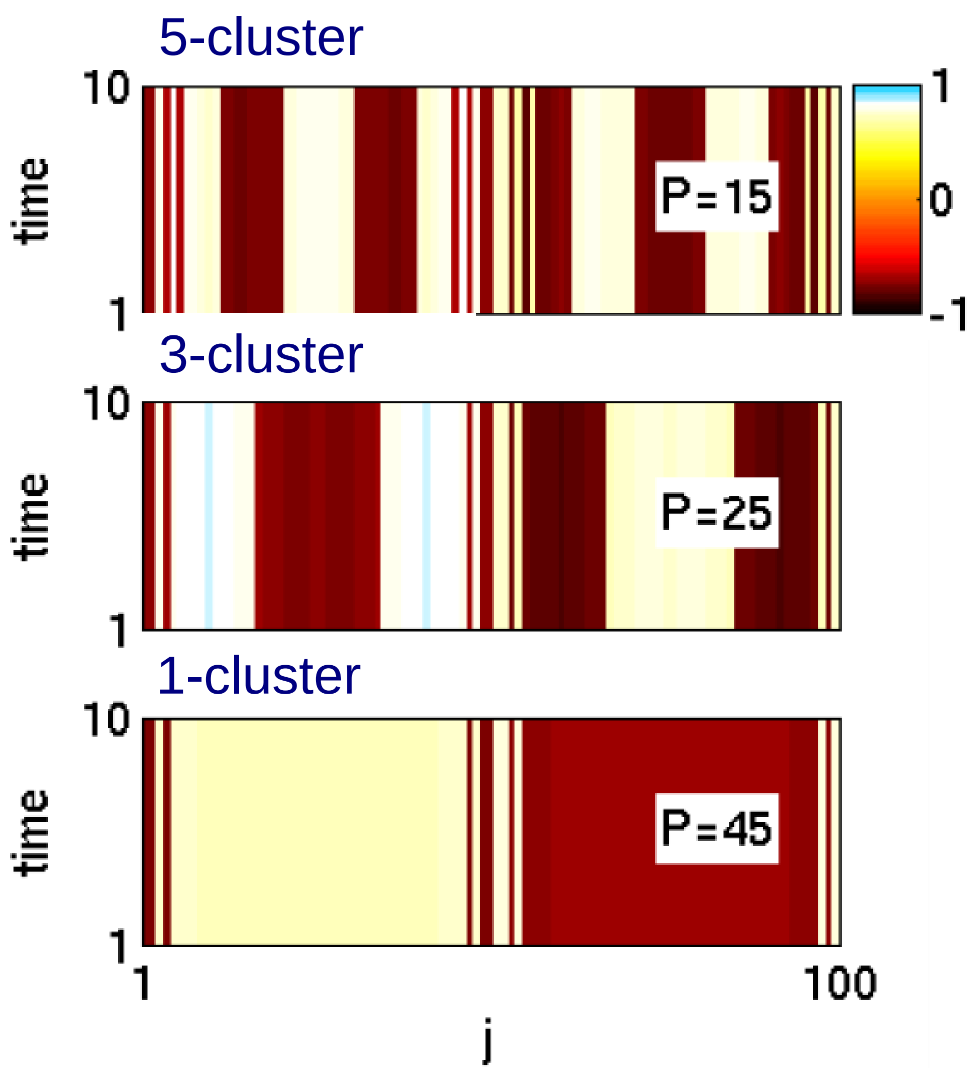
A. Zakharova, M. Kapeller, E. Schöll, *Phys. Rev. Lett.* 112, 154101 (2014)

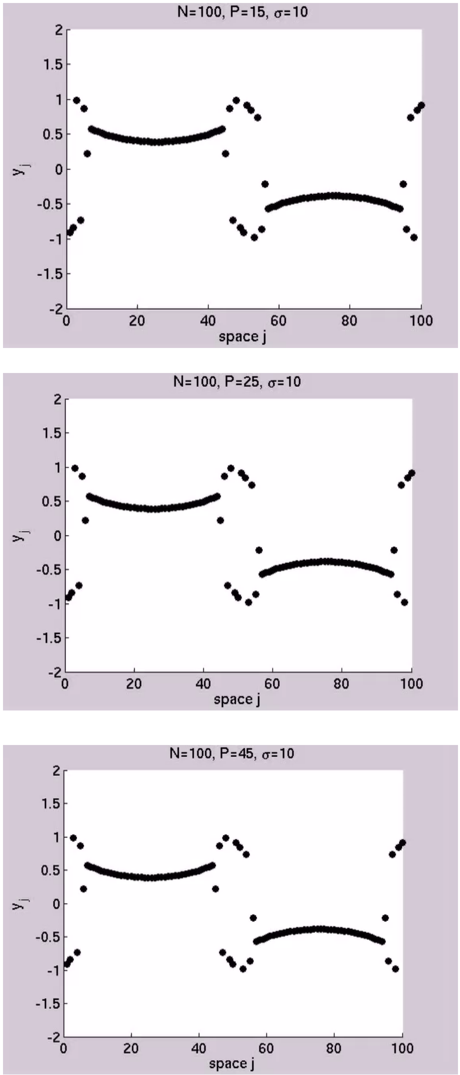
Chimera death: formation of clusters



A. Zakharova, M. Kapeller, E. Schöll, *Phys. Rev. Lett.* 112, 154101 (2014)

Chimera death: formation of clusters

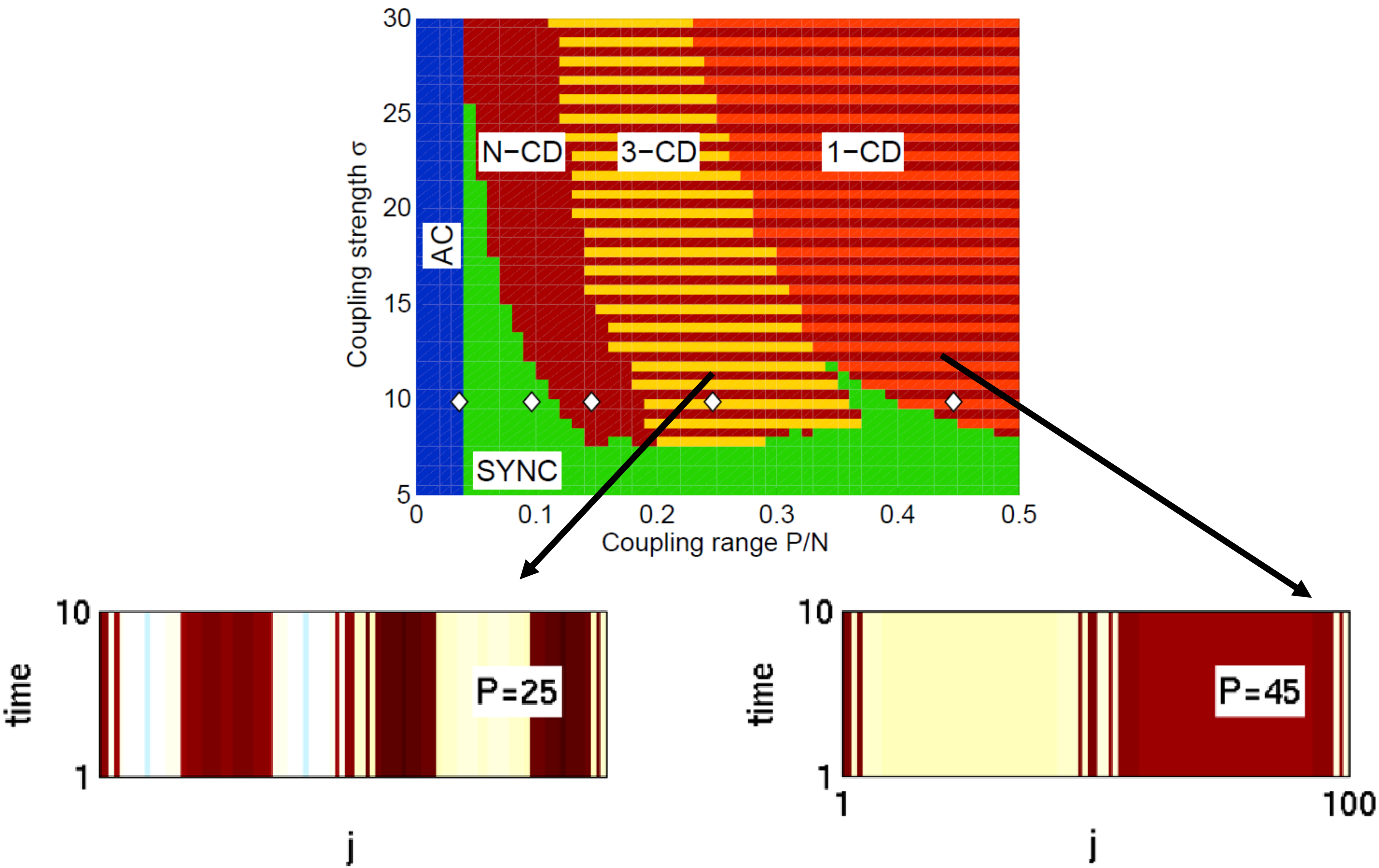




A. Zakharova, M. Kapeller, E. Schöll, *Phys. Rev. Lett.* 112, 154101 (2014)

What is the impact of the interaction range?

Chimera death



Chimeras in nature?

Unihemispheric sleep: one half of the brain is highly synchronized (sleeping) while the other half remains desynchronized (awake).

- birds: sleeping during the flight

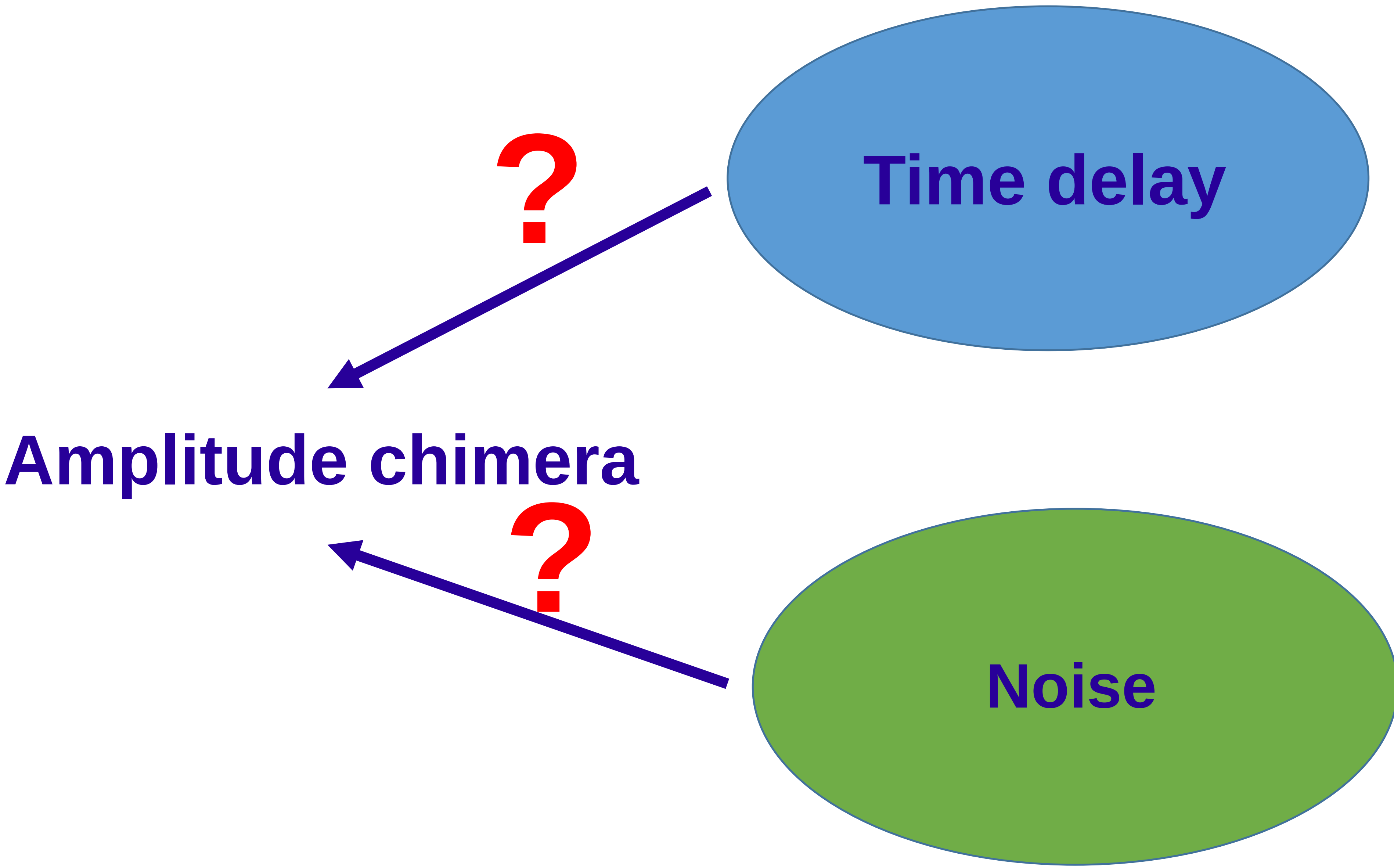
Rattenborg, N.C., Voirin, B., Cruz, S. M., Tisdale, R., Dell'Omo, G., Lipp, H.-P., Wikelski, M. and Vyssotski, A. L., Evidence that birds sleep in mid-flight, Nature Comm. 7, 12468 (2016)

Chimeras in nature?

- humans: first-night effect – our brain stays alert to protect against unknown danger.

M. Tamaki, J. W. Bang, T. Watanabe, Y. Sasaki, Night Watch in One Brain Hemisphere during Sleep Associated with the First-Night Effect in Humans, Curr Biol. 26, 5 (2016)

Robustness of amplitude chimeras



Amplitude chimeras: impact of delay and noise

Network of Stuart-Landau oscillators

$$\dot{z}_j = f(z_j) + \frac{\sigma}{2P} \sum_{k=j-P}^{j+P} \left[Re(z_k) - Re(z_j)\right]$$

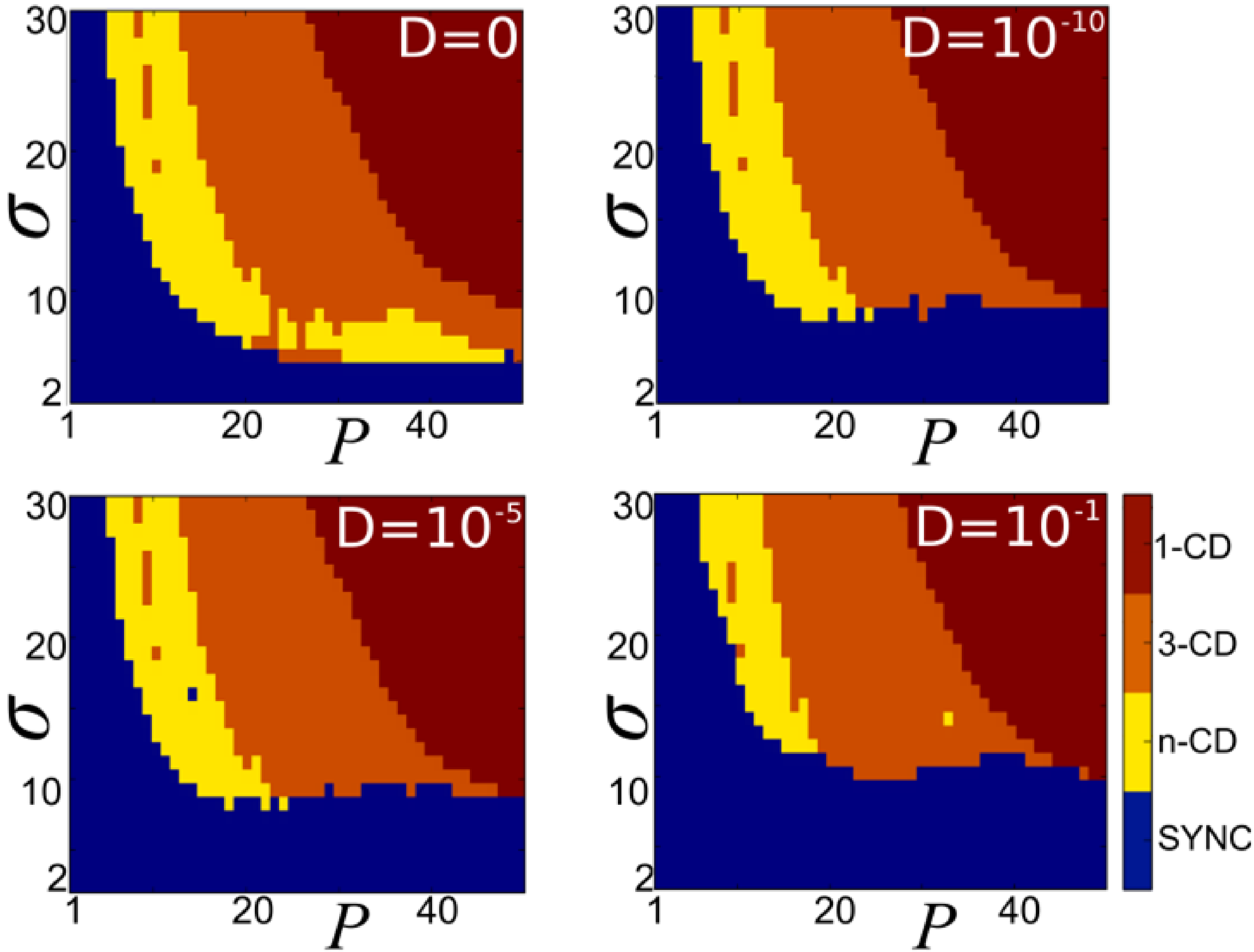
Network of Stuart-Landau oscillators with delay

$$\dot{z}_j = f(z_j) + \frac{\sigma}{2P} \sum_{k=j-P}^{j+P} \left[Re\left(z_k(t - \boldsymbol{\tau})\right) - Re(z_j(t))\right]$$

Network of Stuart-Landau oscillators with noise

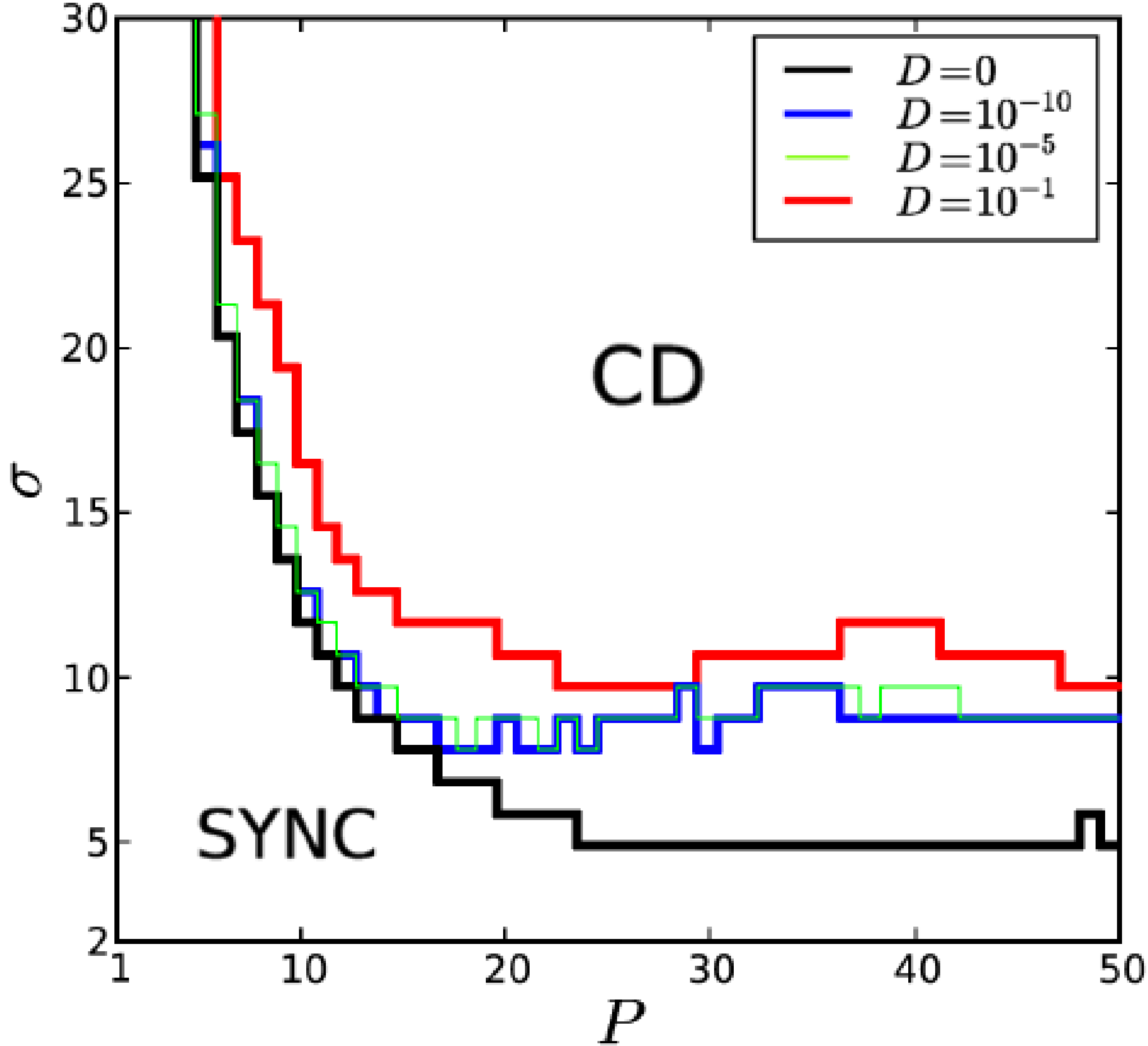
$$\dot{z}_j = f(z_j) + \frac{\sigma}{2P} \sum_{k=j-P}^{j+P} \left[Re(z_k) - Re(z_j)\right] + \sqrt{\mathbf{2D}}\, \boldsymbol{\xi_j(t)}$$

Impact of noise



S. Loos, J. C. Claussen, E. Schöll, and A. Zakharova, *Phys. Rev. E* 93, 012209 (2016)

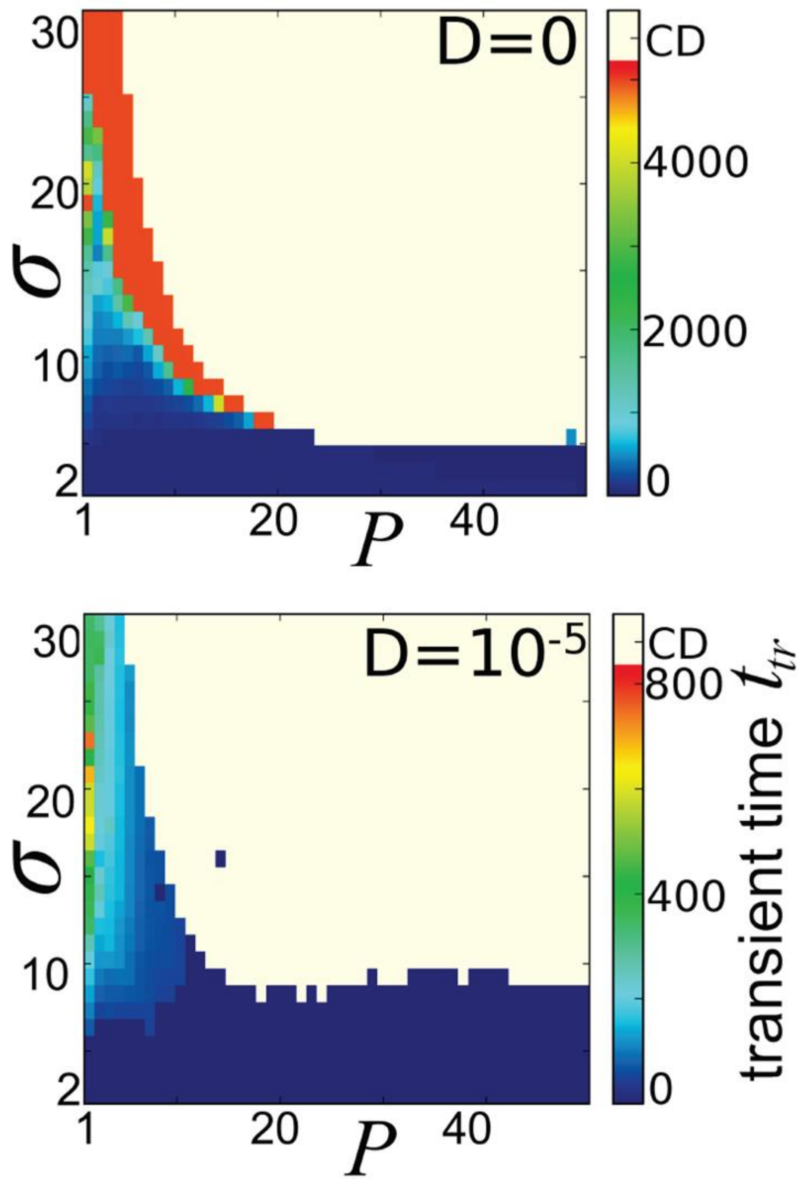
Impact of noise



The stronger the noise, the larger the oscillatory regime (SYNC).

S. Loos, J. C. Claussen, E. Schöll, and A. Zakharova, *Phys. Rev. E* 93, 012209 (2016)

Impact of noise

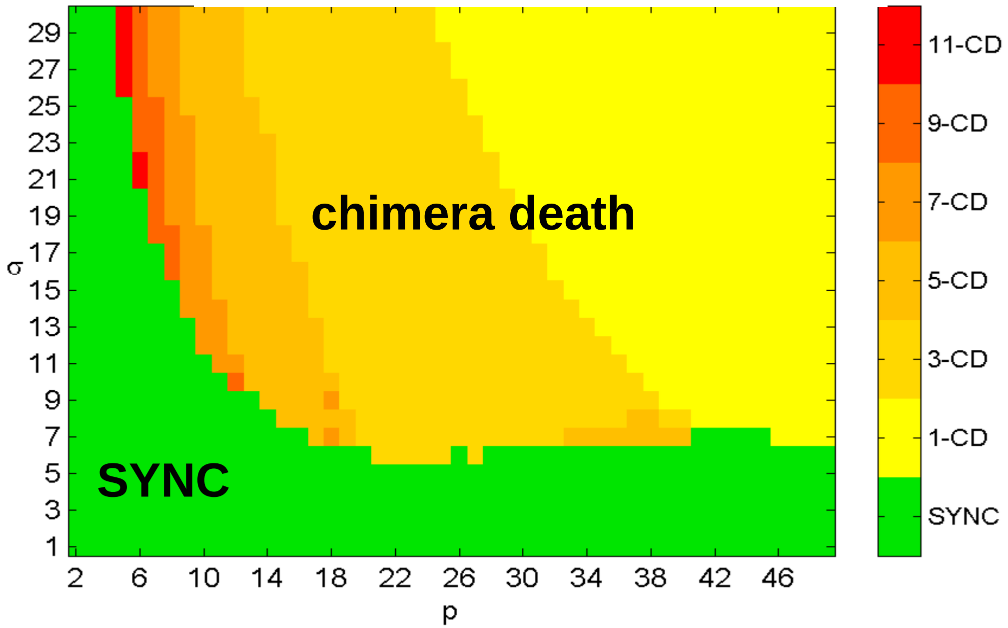


Noise decreases the lifetime of amplitude chimera.

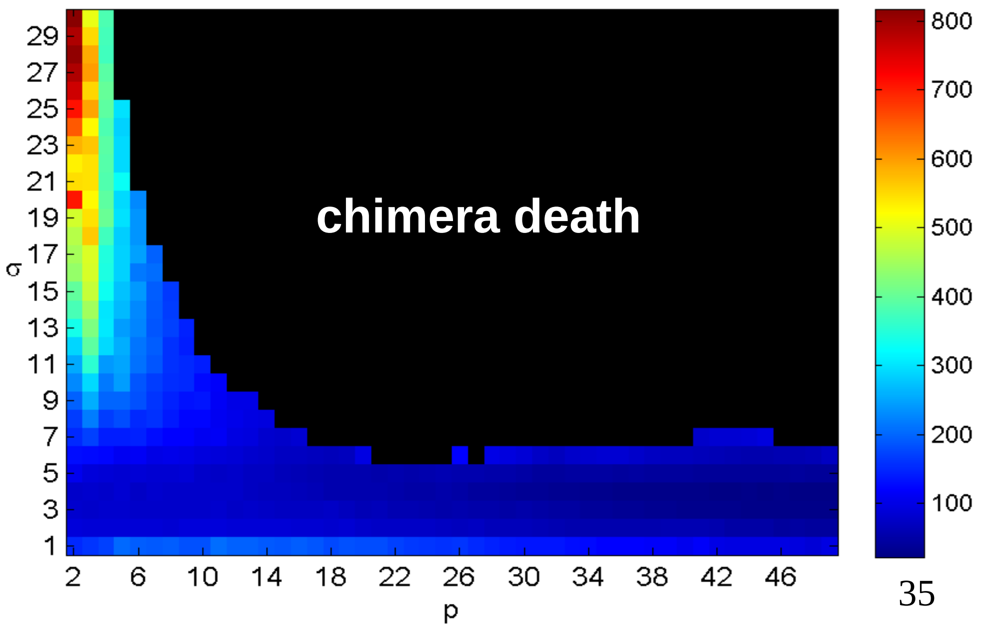
S. Loos, J. C. Claussen, E. Schöll, and A. Zakharova, *Phys. Rev. E* 93, 012209 (2016)

Amplitude chimeras: no time delay

Map of regimes



Lifetime of amplitude chimera

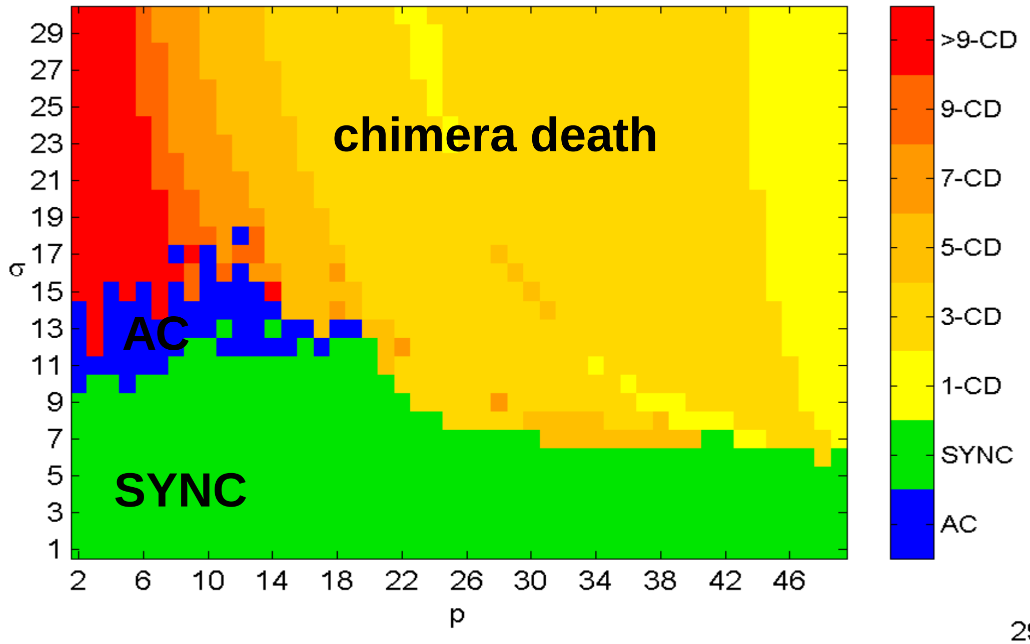


No amplitude chimeras beyond t=900!

A. Gjurchinovski, E. Schöll, and A. Zakharova, *Phys. Rev. E* 95, 042218 (2017)

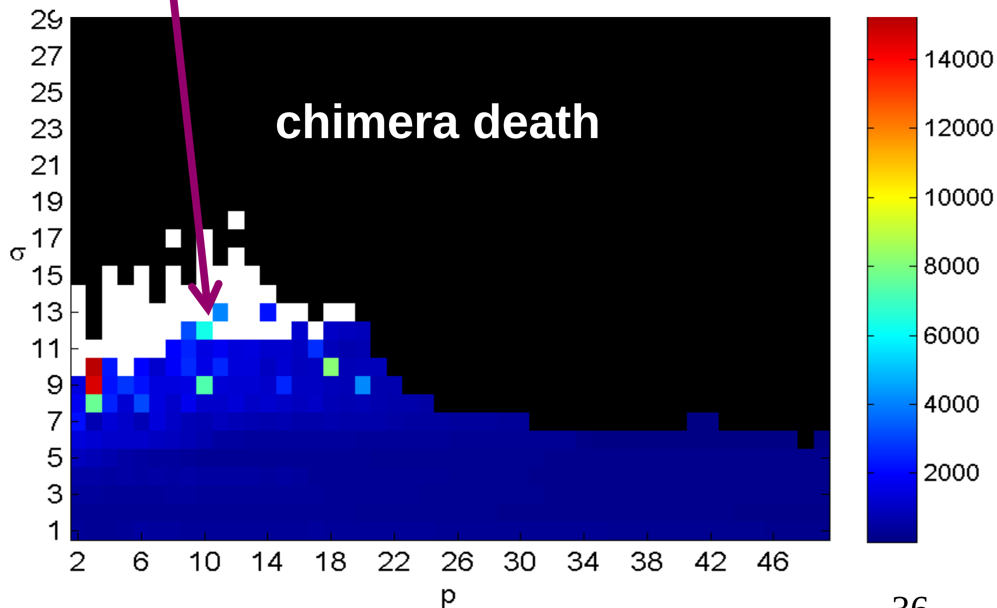
Impact of time delay ($\tau=\pi$)

Map of regimes



Amplitude chimera lifetime t=20000

Lifetime of amplitude chimera



Time delay enlarges the lifetime of amplitude chimeras!

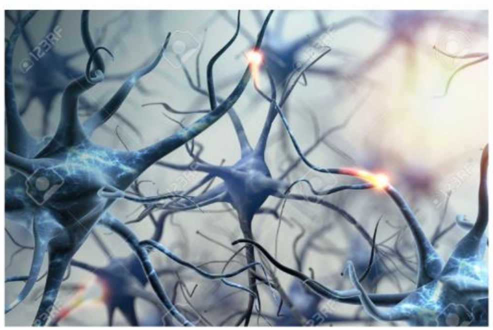
A. Gjurchinovski, E. Schöll, and A. Zakharova, *Phys. Rev. E* 95, 042218 (2017)

partial synchrony
in multilayer networks

Why multilayer?

facebook

Better representation of real-world systems



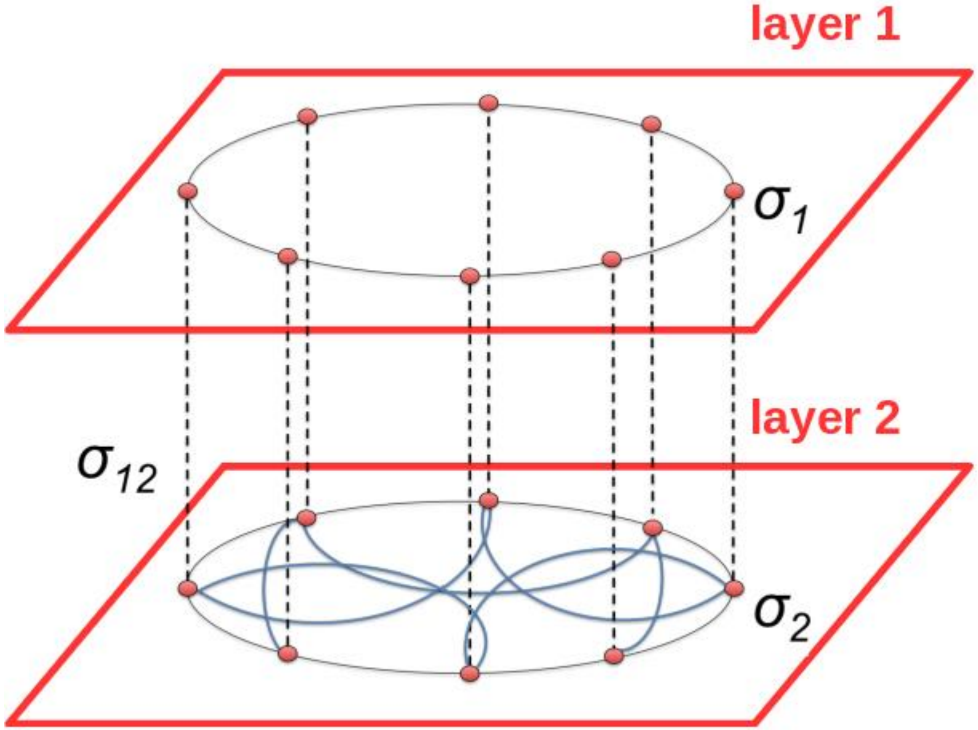
Reviews:

S. Boccaletti et al.,The structure and dynamics of multilayer networks, Physics Reports 544, 1 (2014)

M. Kivelä, A. Arenas et al., Multilayer networks, Journal of Complex Networks 2, 3, 203 (2014)

What is a multilayer network?

A set of nodes interacting in layers,
each reflecting a distinct type of interaction.

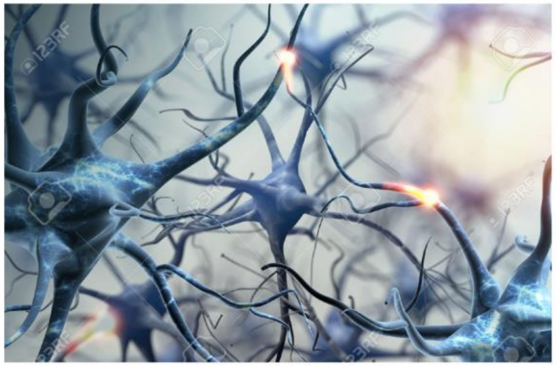


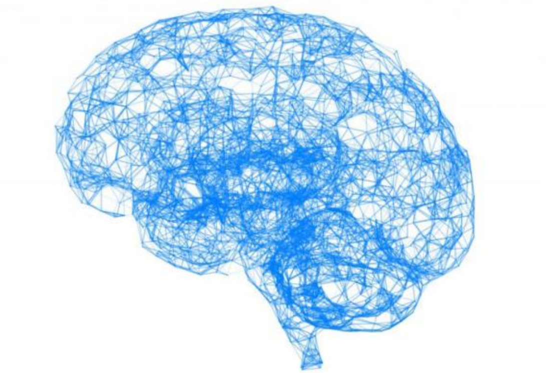
Examples

- **Social networks:** friendships in Facebook: family, friends, coworkers

- **Transportation networks:** air, train and bus transportation networks

- **Neural networks:** chemical link or ionic channel

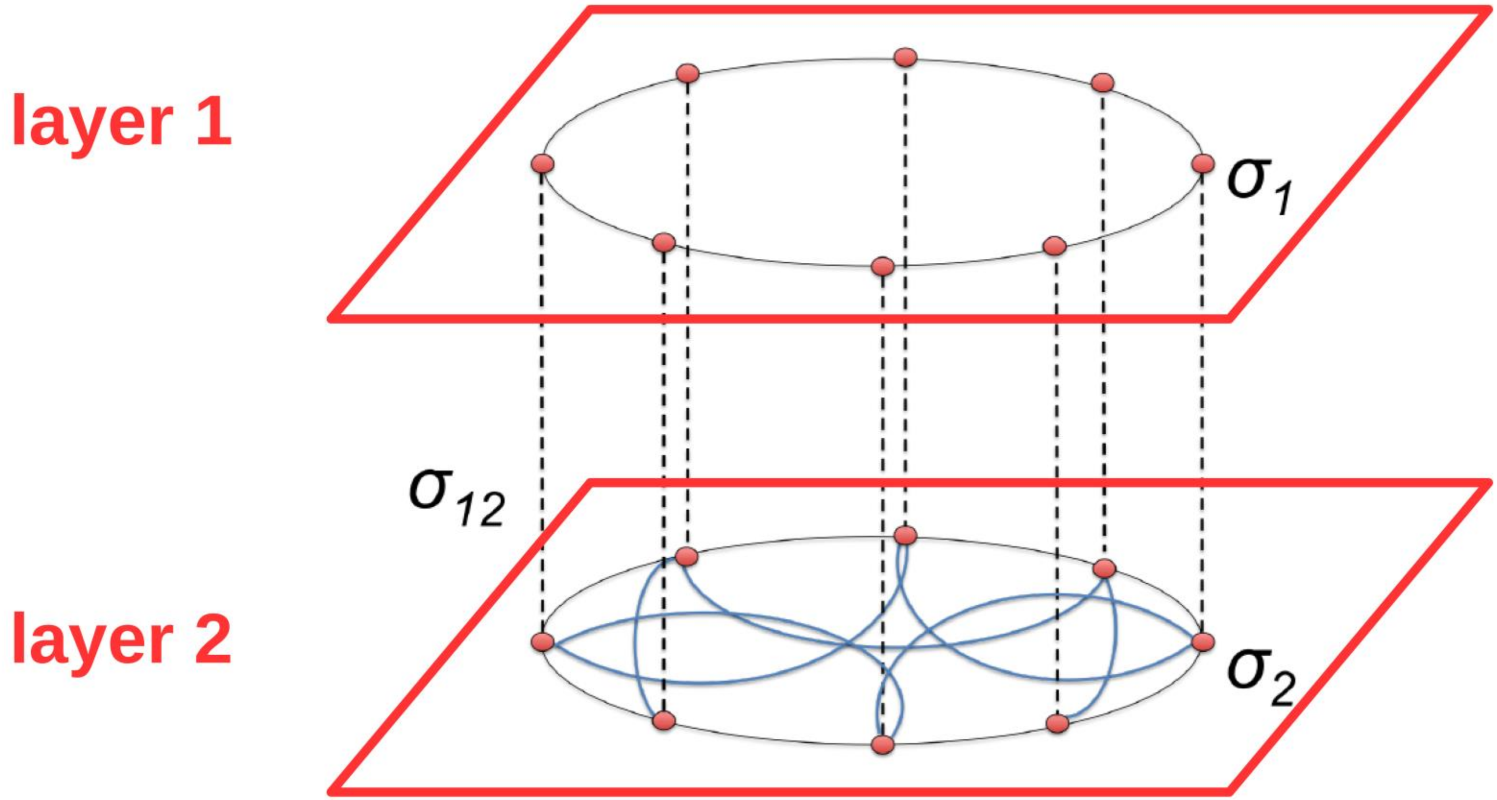




- **Brain networks:** different regions can be seen connected by functional and structural neural networks

Control

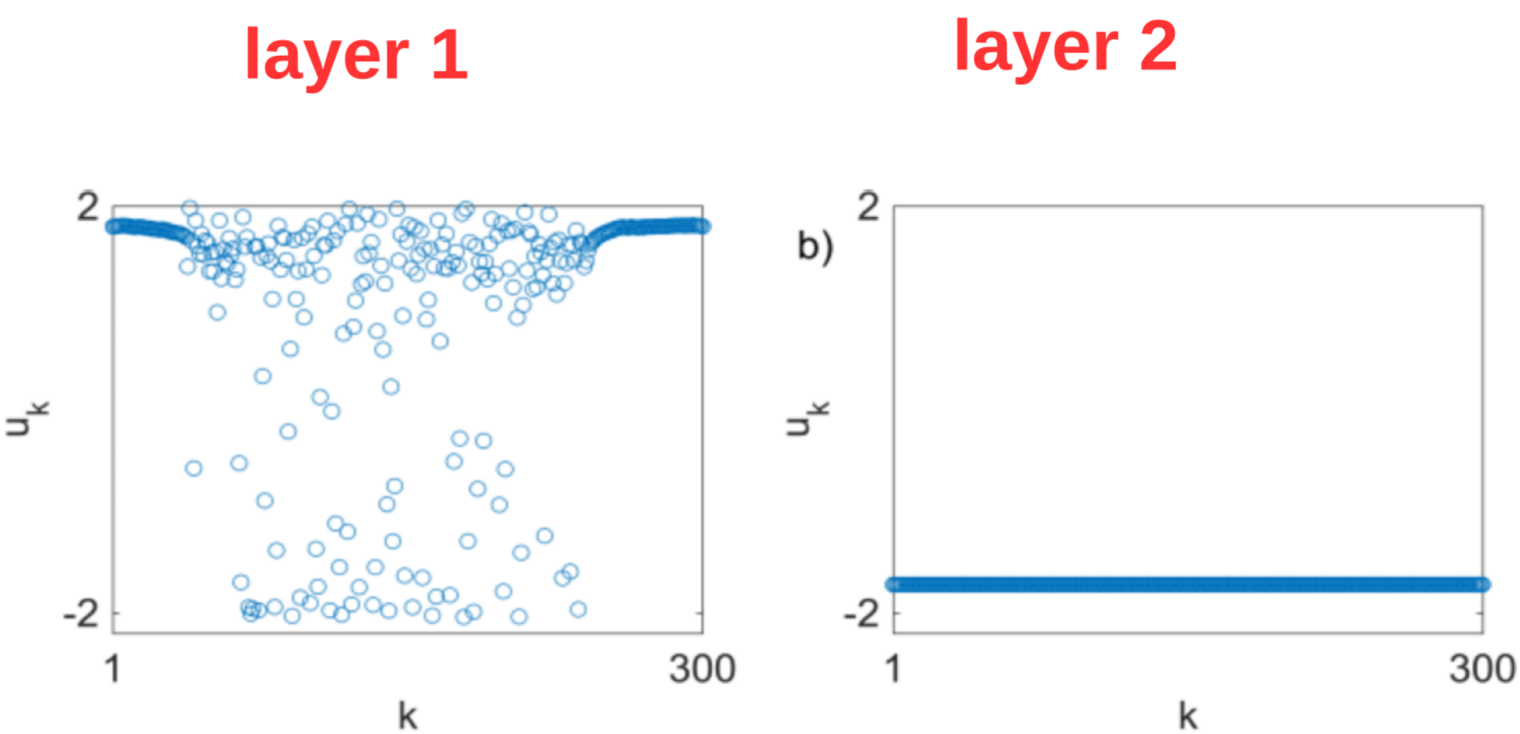
Control



Can we control one layer by manipulating the parameters of the other layer?

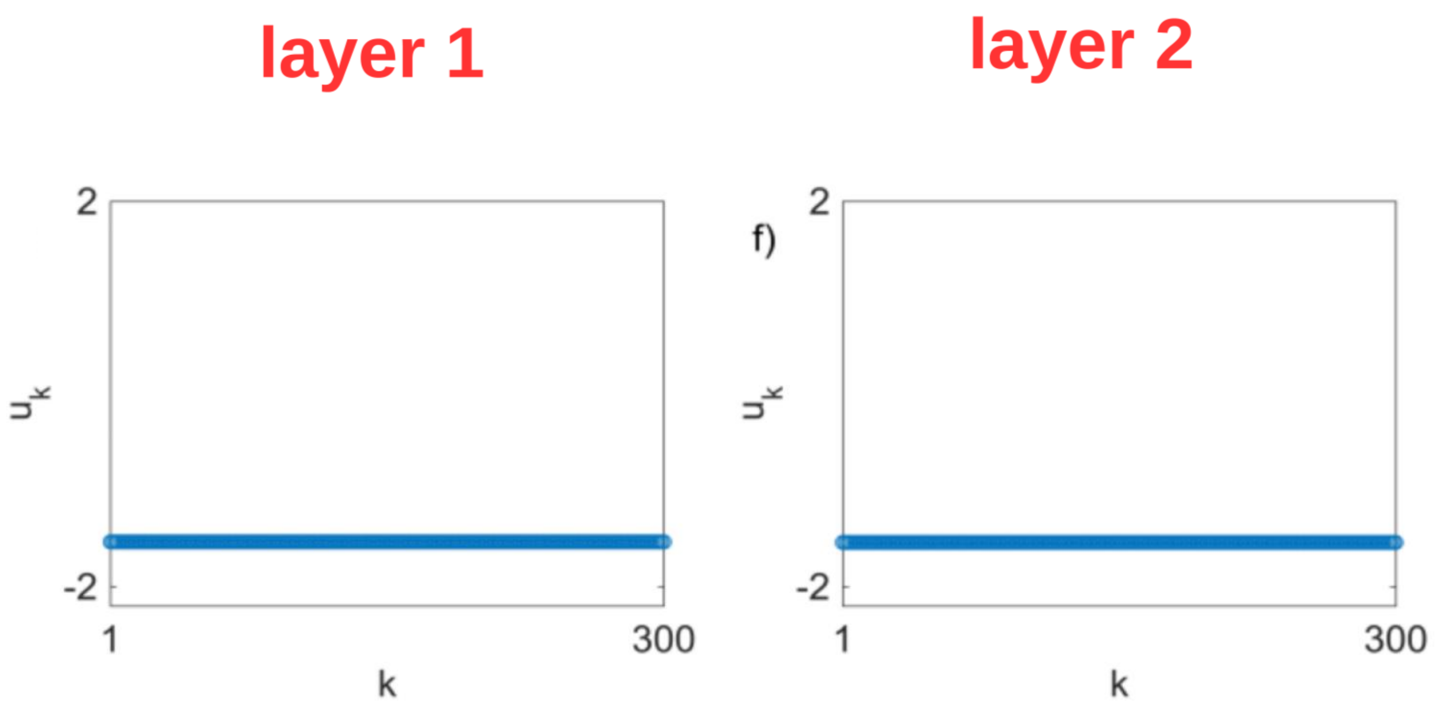
Control of chimera states

Isolated layers: different coupling strength



M. Mikhaylenko, L. Ramlow, S. Jalan, A. Zakharova, *Chaos* 29, 023122 (2019)

Coupled layers: chimera is suppressed in layer 1

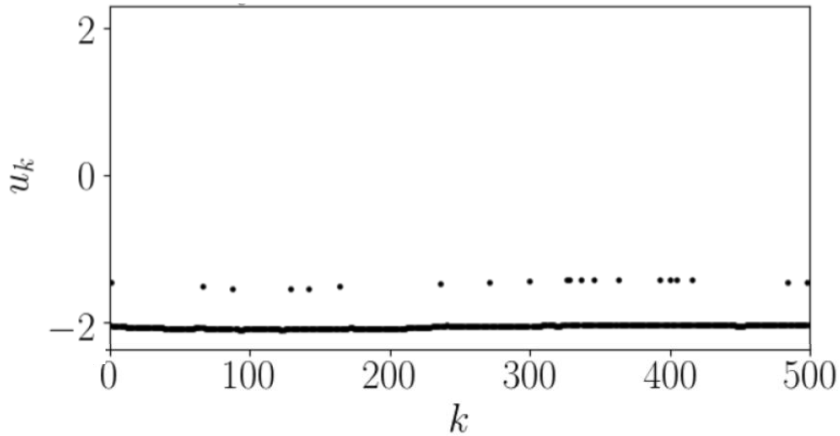


M. Mikhaylenko, L. Ramlow, S. Jalan, A. Zakharova, *Chaos* 29, 023122 (2019)

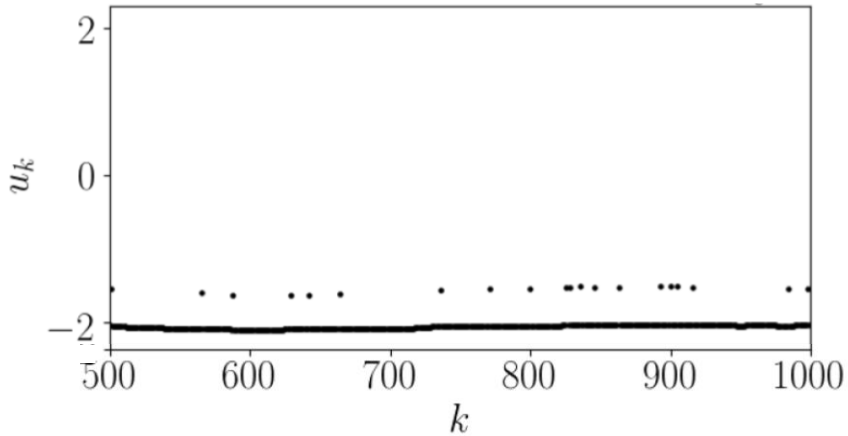
Control of solitary states

Coupled layers:
solitary states are induced

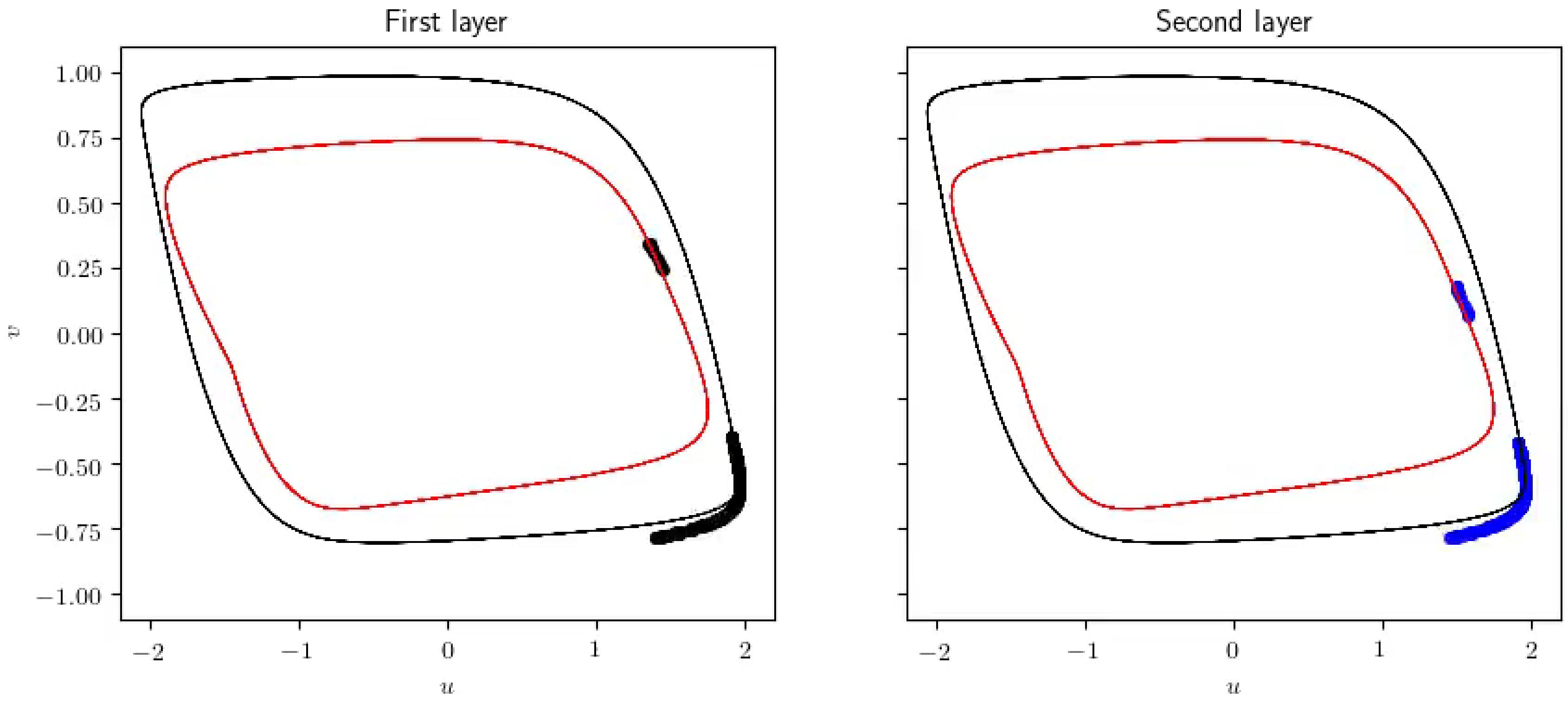
layer 1



layer 2



Coupled layers: solitary states are induced



Constructive role of noise?

Coherence-resonance chimeras

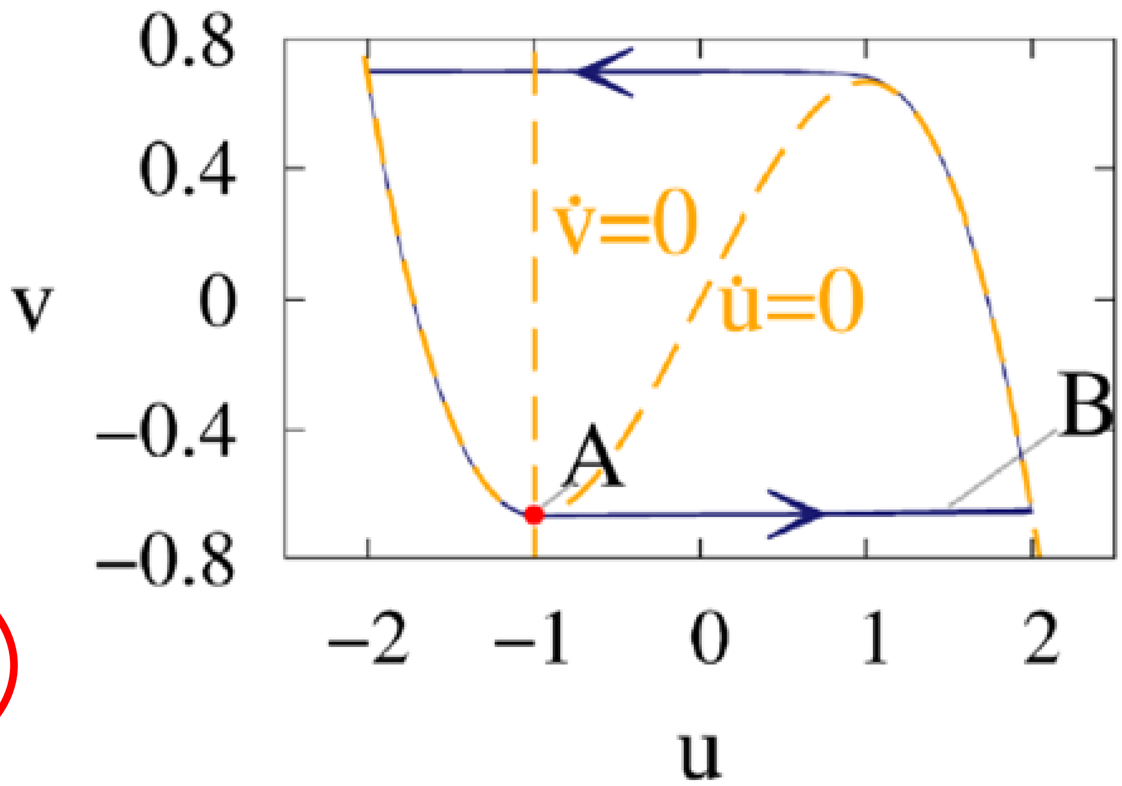
Model: FitzHugh-Nagumo system in excitable regime

Single node dynamics

$$\varepsilon\dot{u} = u - \frac{u^3}{3} - v,$$
$$\dot{v} = u + a + \sqrt{2D}\xi(t)$$

$|a_i| < 1$
oscillatory

$|a_i| > 1$
excitable



Model: network of coupled FitzHugh-Nagumo systems

Nonlocally coupled ring

$$\varepsilon \dot{u}_i = u_i - \frac{u_i^3}{3} - v_i + \frac{\sigma}{2P} \ldots (v_j - v_i)\Big],$$

$$\dot{v}_i = u_i + a_i + \frac{\sigma}{2P} \sum_{j=i-P}^{i+P} \Big[\ldots)\Big] + \sqrt{2D}\,\xi_i(t)$$

$|a_i| > 1$
excitable

noise

coherence-resonance chimeras

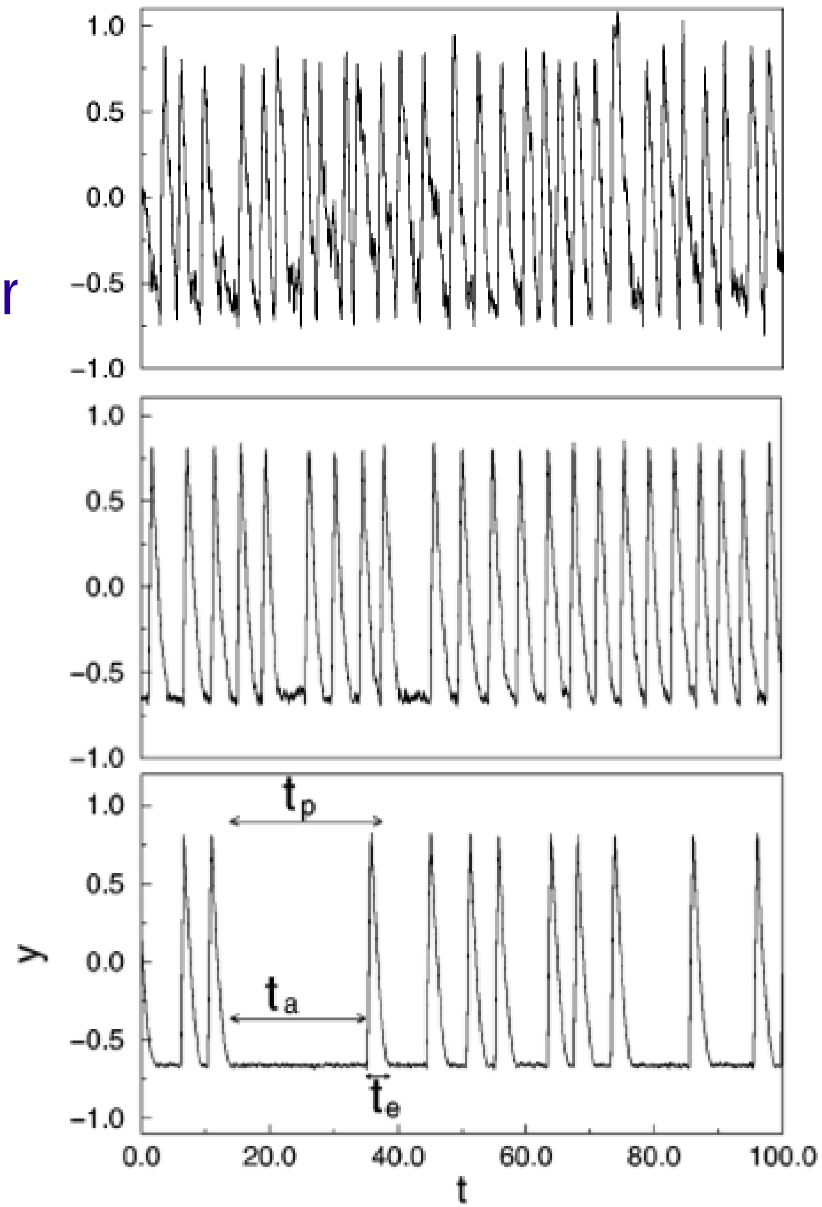
N. Semenova, A. Zakharova, V. Anishchenko, E. Schöll, *Phys. Rev. Lett.* 117, 014102 (2016)

What is coherence resonance?

The best temporal regularity of the noise-induced oscillations occurs for an intermediate value of noise intensity

- discovered by Haken et al. in 1993

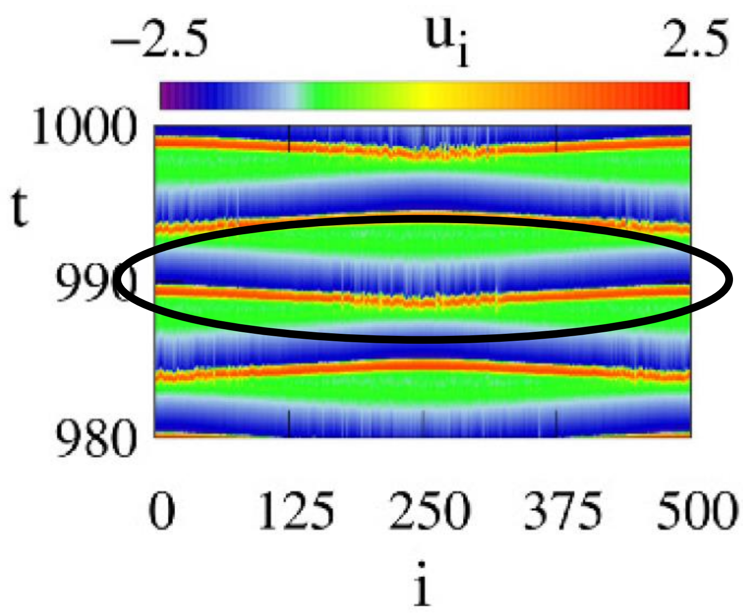
- named ***coherence resonance*** by Pikovsky and Kurths in 1997

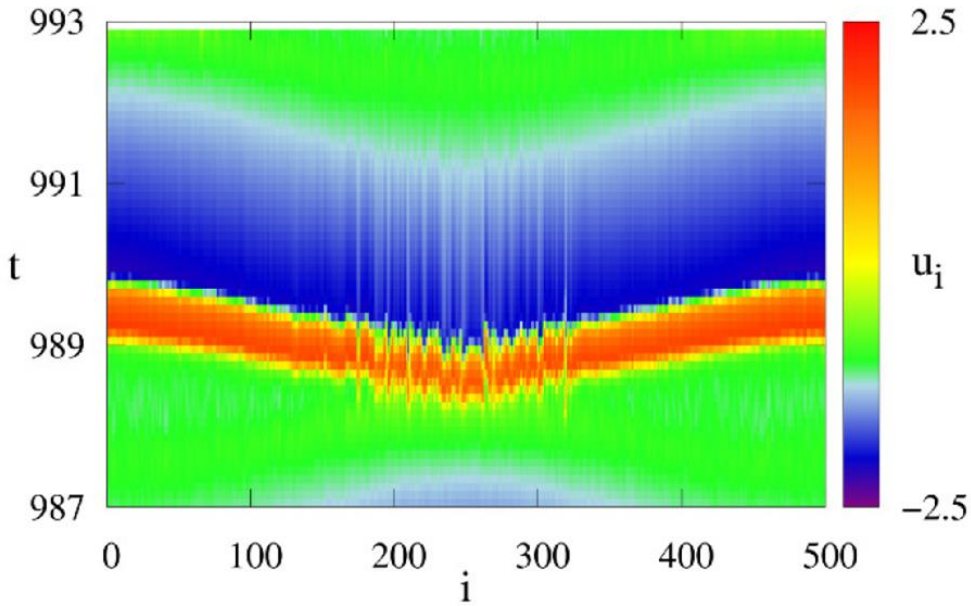


constructive role of noise, counter-intuitive phenomenon

Coherence-resonance chimeras

domains of coherent and incoherent spiking



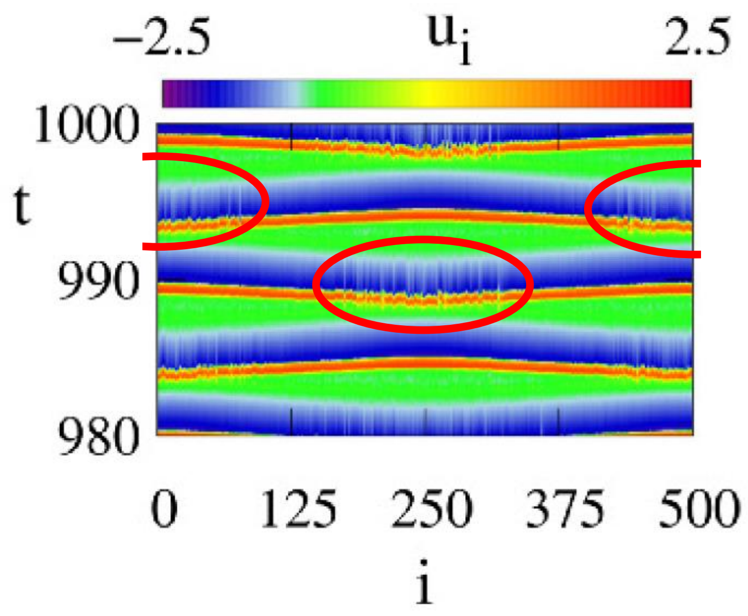


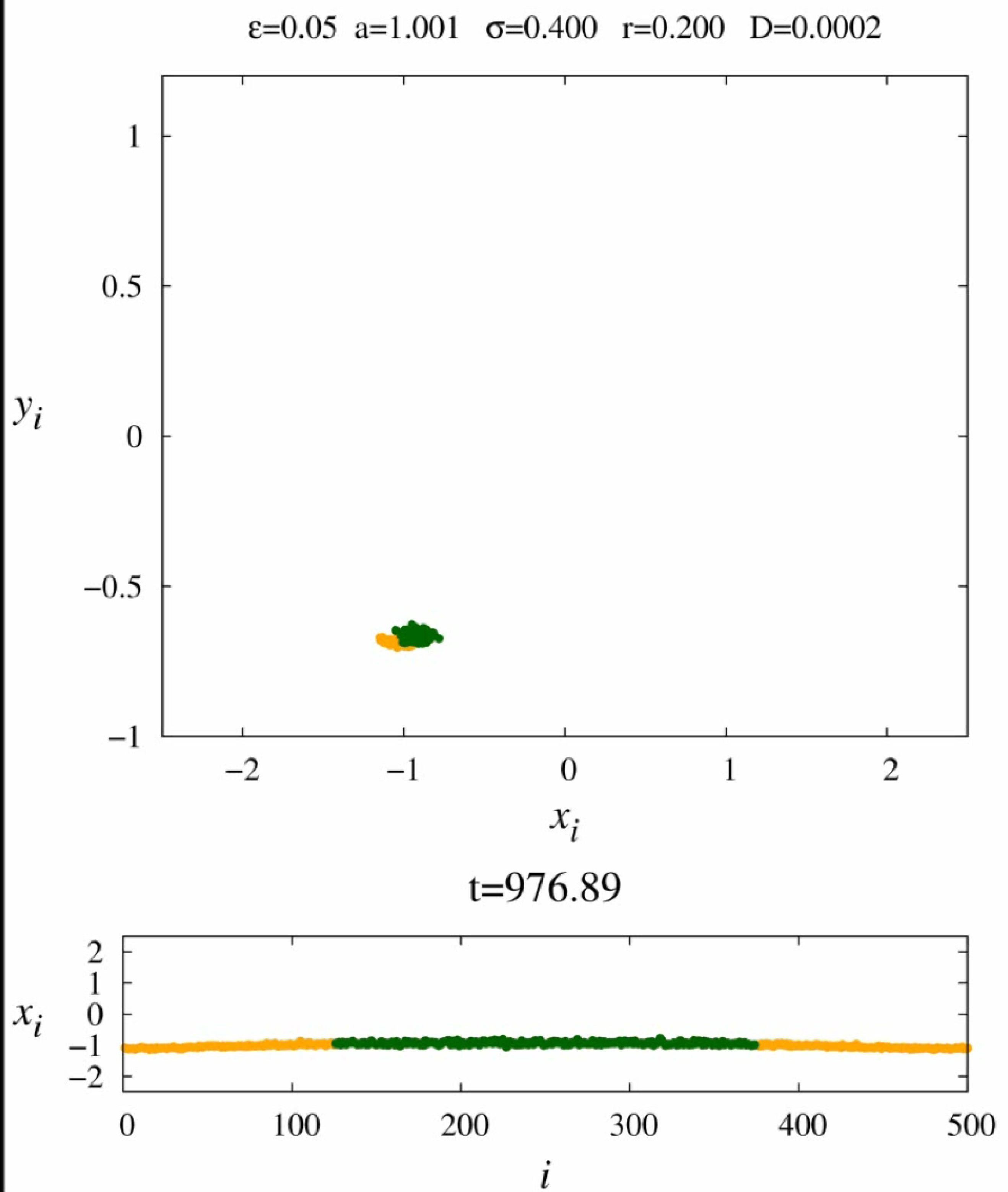
Intermediate noise intensities 0.000062≤D≤0.000325!

N. Semenova, A. Zakharova, V. Anishchenko, E. Schöll, *Phys. Rev. Lett.* 117, 014102 (2016)

Coherence-resonance chimeras

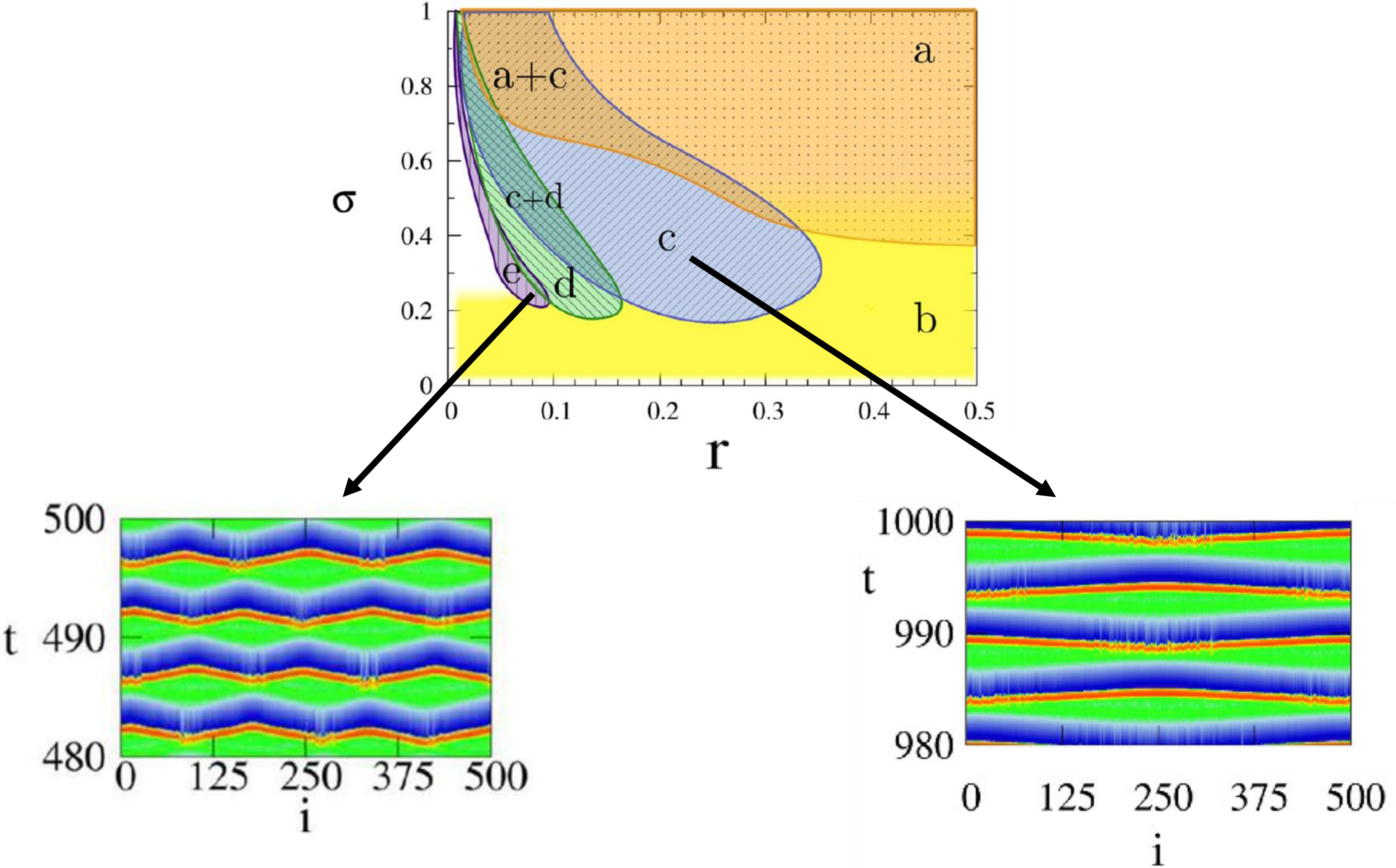
- noise-induced
- coherence resonance + chimera state
- alternating behavior




ε=0.05 a=1.001 σ=0.400 r=0.200 D=0.0002
1
0.5
0
−0.5
−1
y_i
−2
−1
0
1
2
x_i
t=976.89
2
1
0
−1
−2
x_i
0
100
200
300
400
500
i

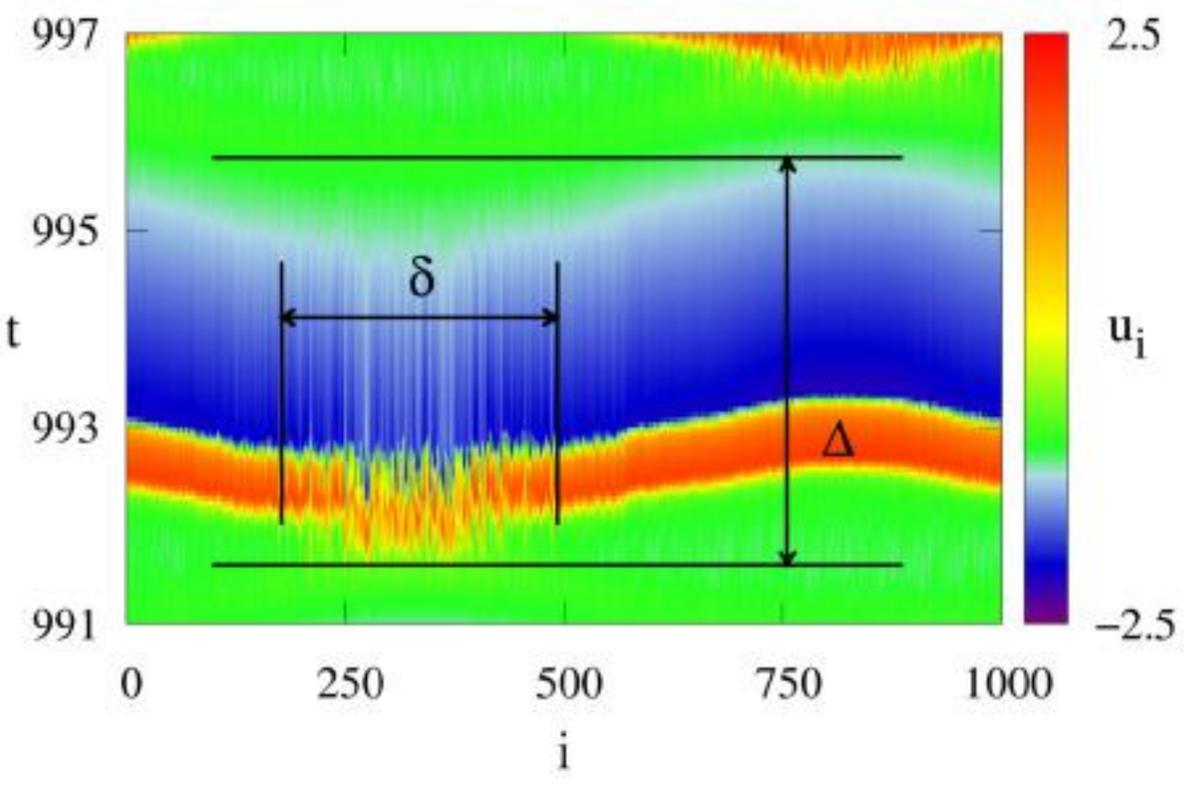
What is the impact of the interaction range?

Coherence-resonance chimeras



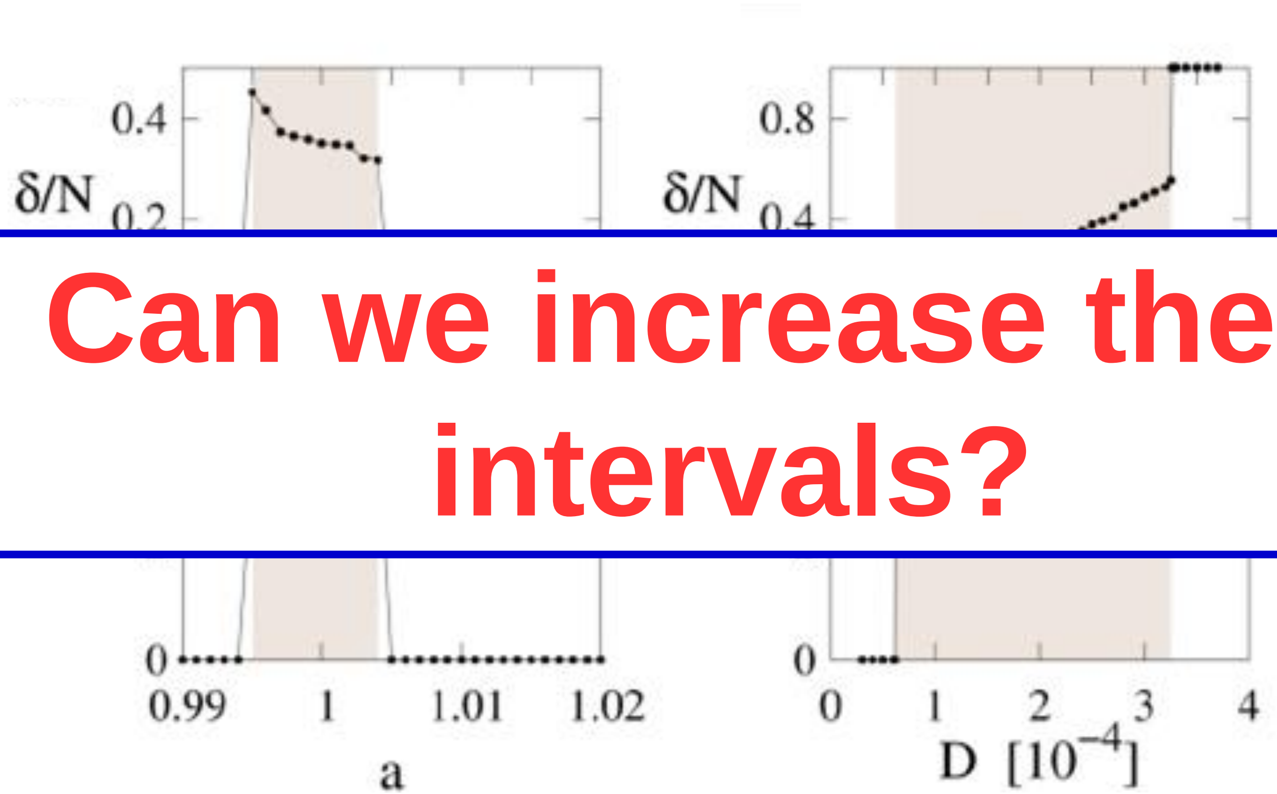
Coherence resonance chimera:

- active time span
- size of the incoherent domain



Coherence resonance chimera: interval of existence

- Threshold parameter a
- Noise intensity D



Can we increase these intervals?

Time-delayed feedback

Model: network of coupled FitzHugh-Nagumo systems

Time-delayed feedback

$$\varepsilon \dot{u}_i = u_i - \frac{u_i^3}{3} - v_i + \frac{\sigma}{2P} \sum_{j=i-P}^{i+P} \left[b_{uu}(u_j - u_i) + b_{uv}(v_j - v_i) \right] + \gamma(u_i(t) - u_i(t-\tau)),$$

$$\dot{v}_i = u_i + a_i + \frac{\sigma}{2P} \sum_{j=i-P}^{i+P} \left[b_{vu}(u_j - u_i) + b_{vv}(v_j - v_i) \right] + \sqrt{2D}\xi_i(t)$$

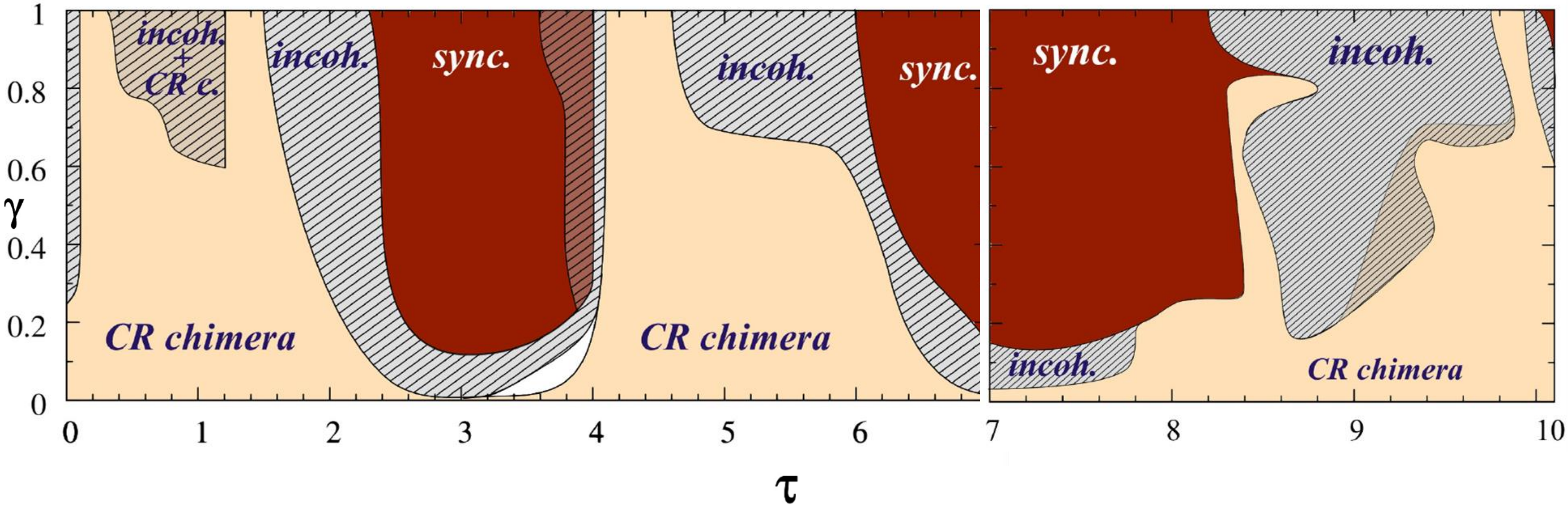
feedback

Parameters -> coherence resonance chimera

A. Zakharova, N. Semenova, V. Anishchenko, E. Schöll, *Chaos* 27, 114320 (2017)

Map of regimes

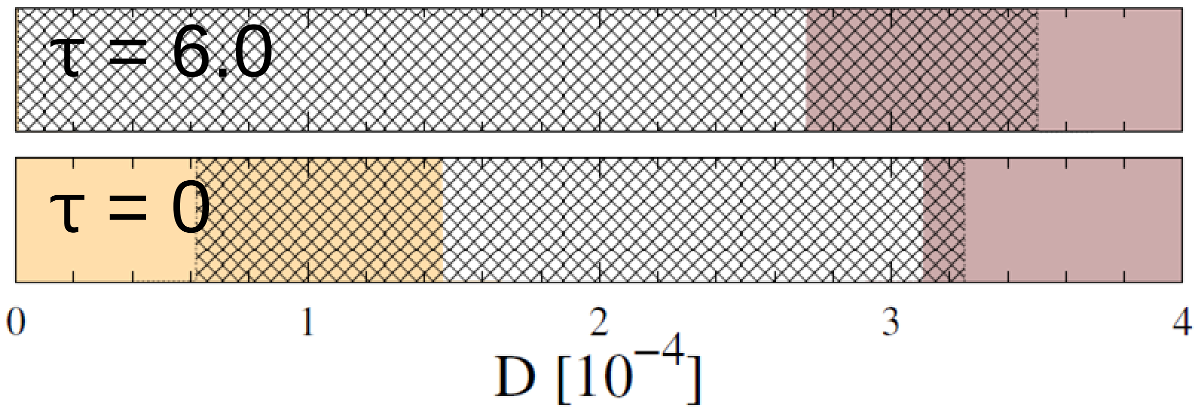
- Feedback: strength and time delay
- “Synchronization tongues”



A. Zakharova, N. Semenova, V. Anishchenko, E. Schöll, *Chaos* 27, 114320 (2017)

Impact of time delay

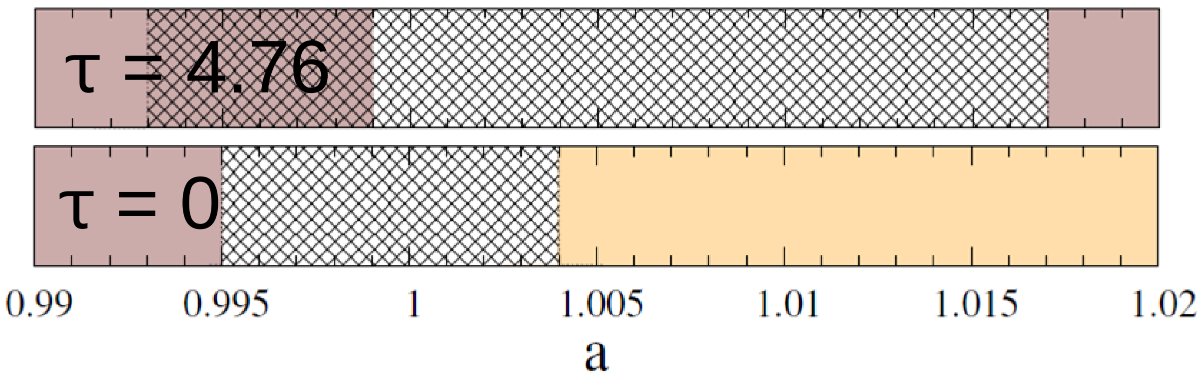
Noise intensity interval



Enlargement of the interval: 33%

Impact of time delay

Threshold parameter interval

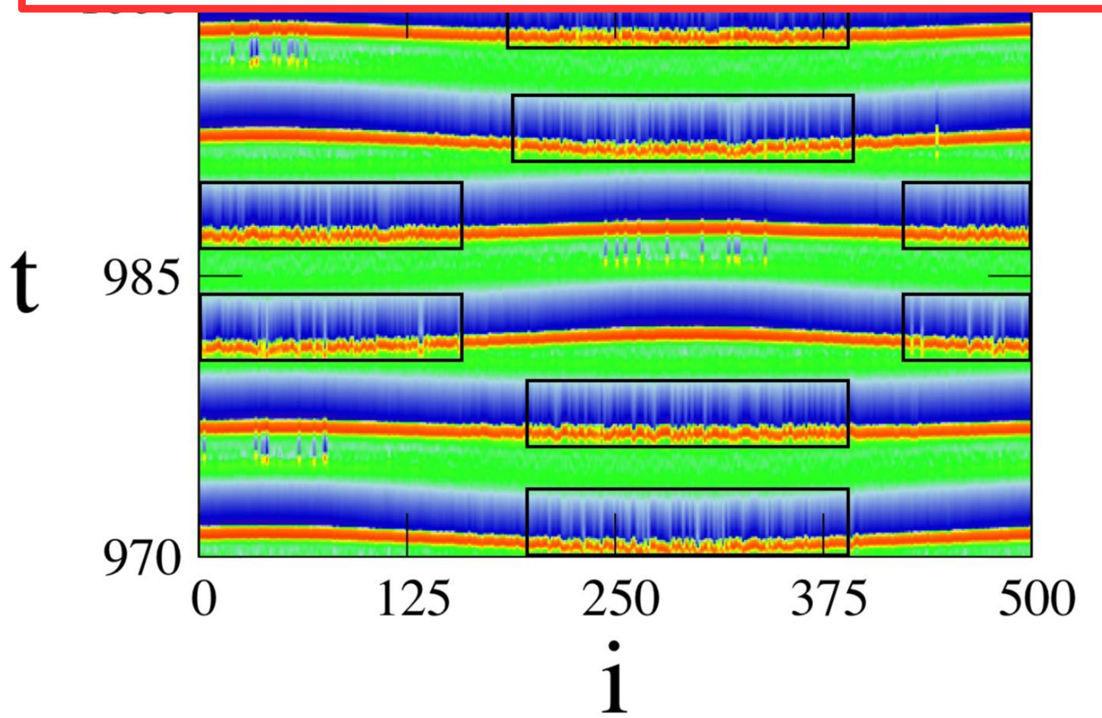


Enlargement of the interval: more than doubled

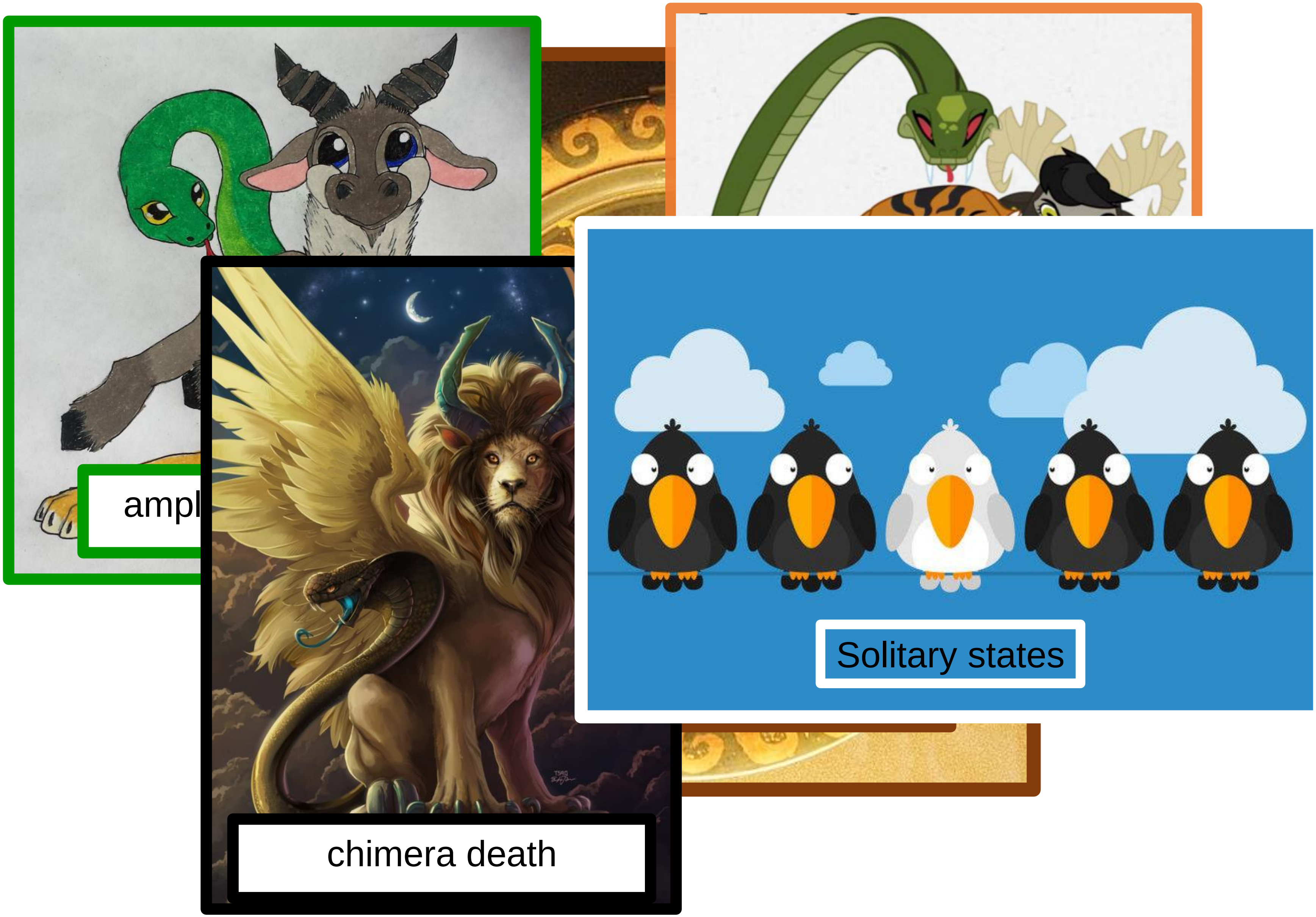
Delay-induced chimeras

- Switching for every second spiking event

Period-two coherence resonance chimeras

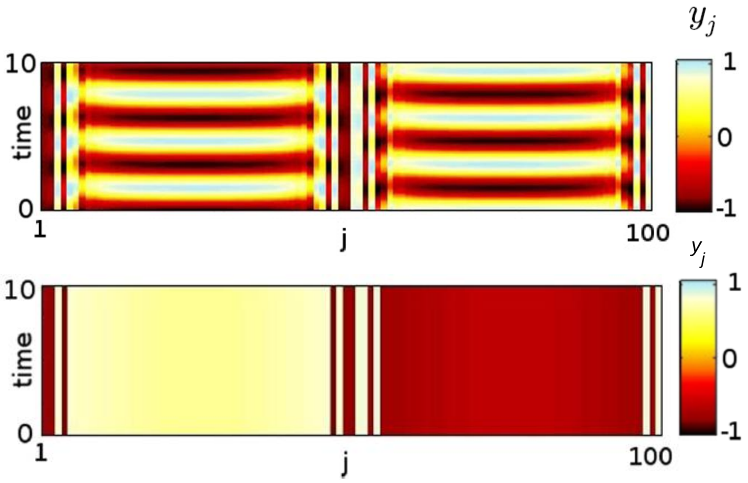


A. Zakharova, N. Semenova, V. Anishchenko, E. Schöll, *Chaos* 27, 114320 (2017)


ampl
chimera death
Solitary states

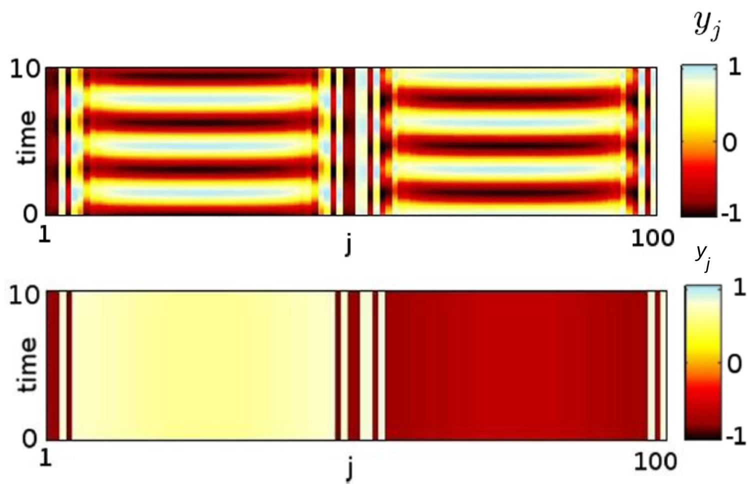
Different types of chimeras

Amplitude chimeras and
chimera death in ring networks
(Stuart-Landau oscillator)

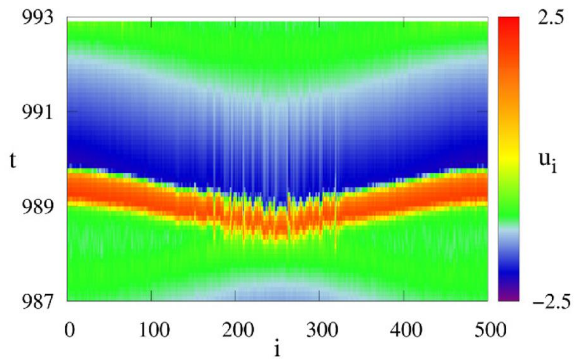


Different types of chimeras

Amplitude chimeras and chimera death in ring networks (Stuart-Landau oscillator)



Noise-induced chimera states – coherence-resonance chimeras (FitzHugh-Nagumo system)



Common trend:

decreasing coupling rage → formation of clusters

What is the impact of delay and noise?

- Time delay and noise can induce new dynamical regimes (coherence-resonance chimeras, delay-induced period-two chimeras)

- Time delay allows to control chimera states (delay increases chimera lifetime)

- Noise can have both destructive and constructive role