DINCON 2019 – USP São Carlos, SP, Brazil November 27, 2019

Control of neural networks by weak multiplexing

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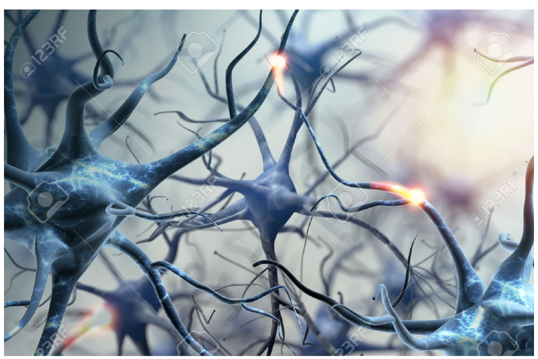
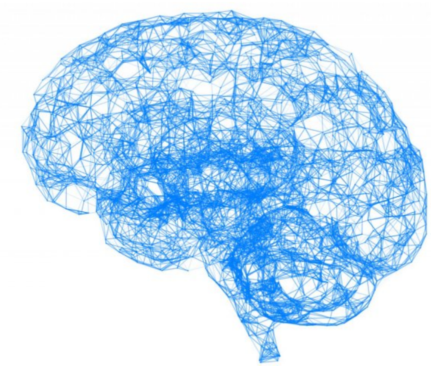
Multilayer networks

Why multilayer?

Better representation of real-world systems





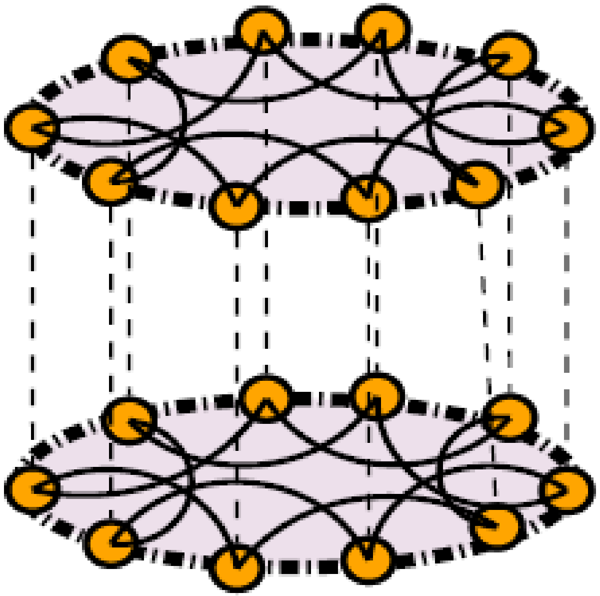
Reviews:

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.

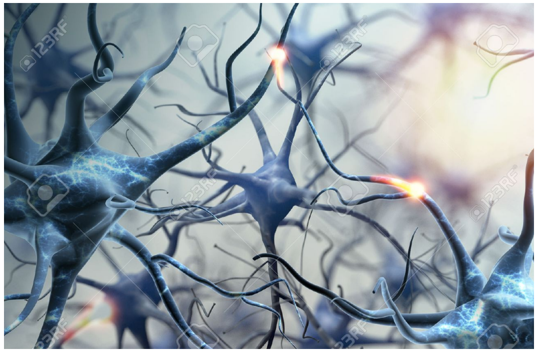


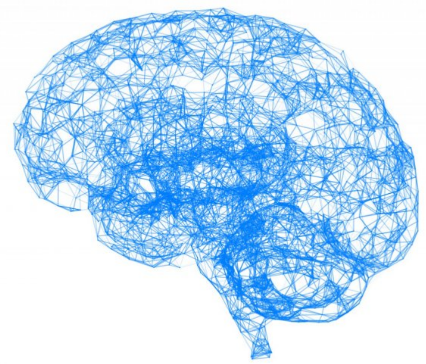
Examples

- **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

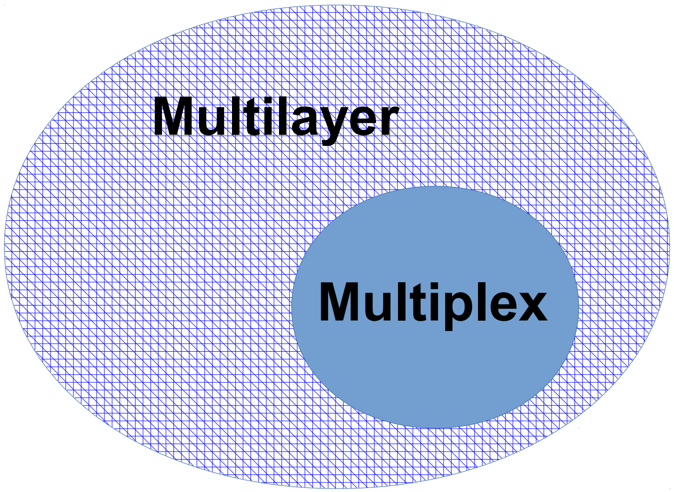
Multilayer or multiplex?

Multilayer

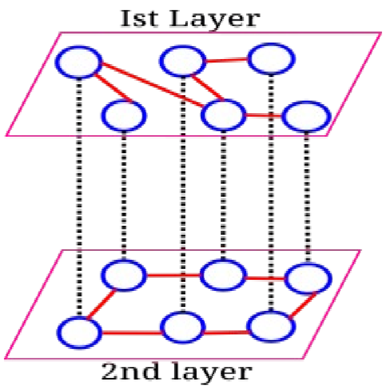
the same set of nodes in different layers and cross links are allowed

Multiplex

the same set of nodes in different layers and cross links are not allowed: one-to-one correspondence between the nodes in different layers



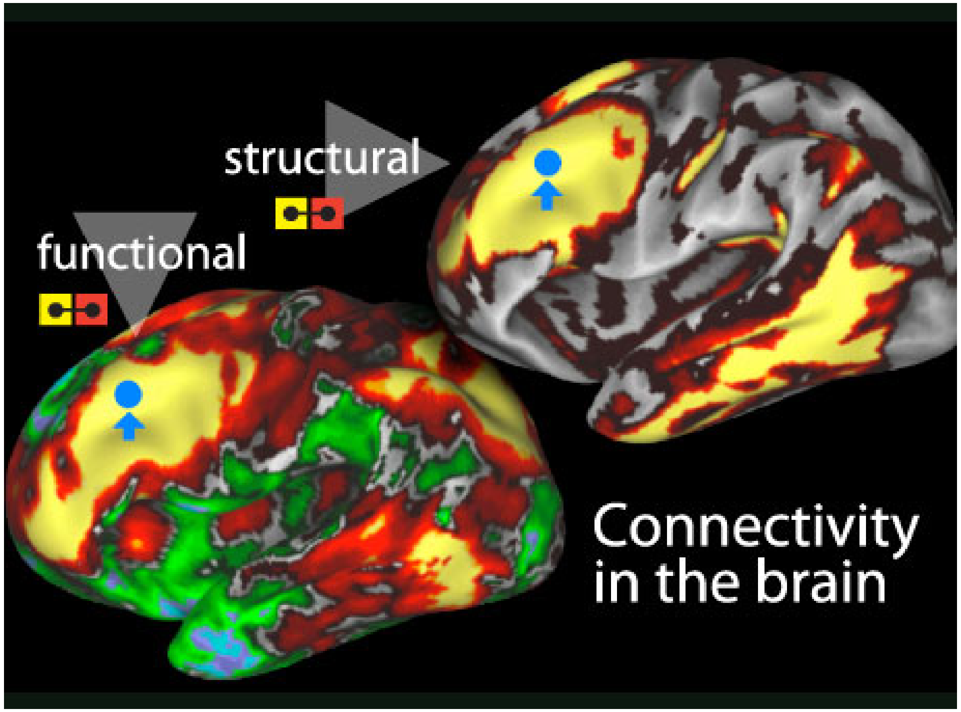
What if we neglect multiplexing?

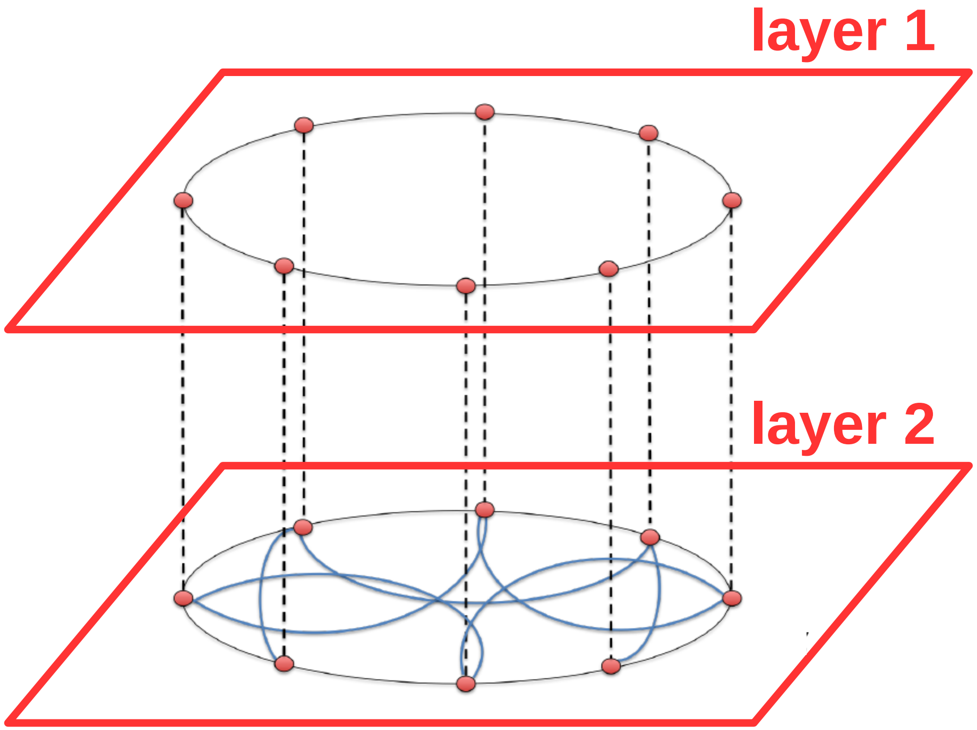


Ignoring impact of multipexing may result in wrong prediction for the behavior of a system

Example
A strike of the bus service may result in overloading the rail and air traffic routes

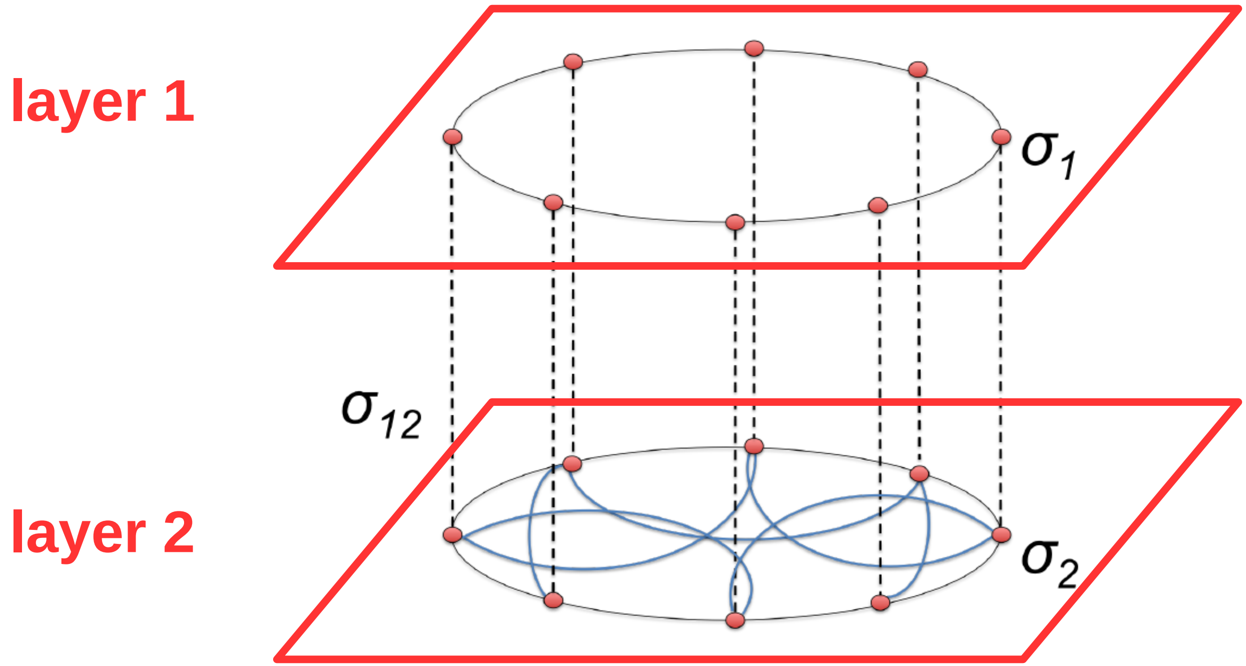
Multilayer modeling of brain networks

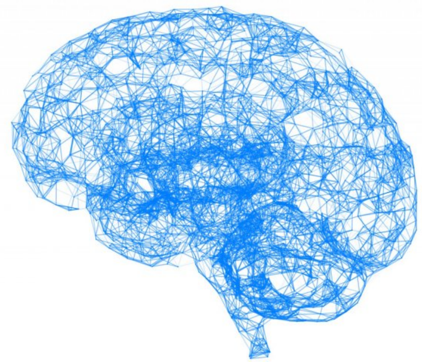




M. De Domenico, Multilayer modeling and analysis of human brain networks, Gigascience 6, 1 (2017)

Control by multiplexing

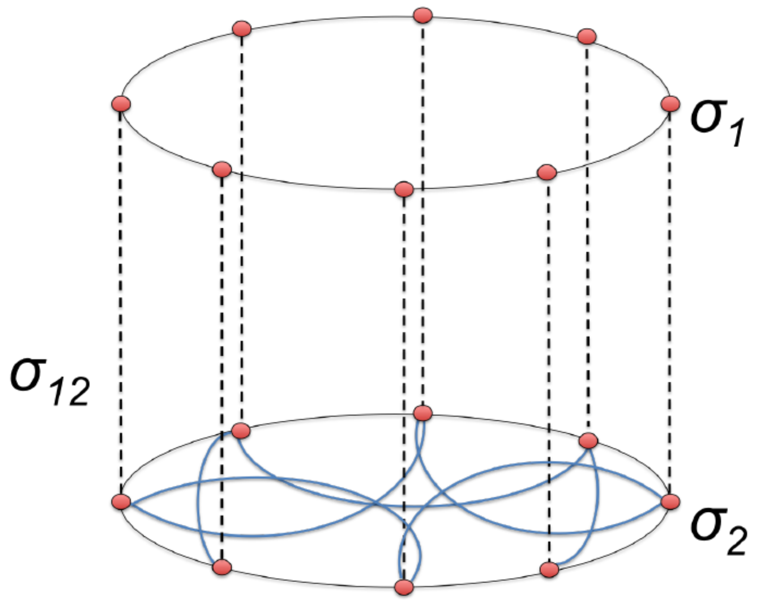




Controlling one layer by manipulating the parameters of the other layer

Strong and weak multiplexing

Multiplex network



weak multiplexing
$\sigma_{12} < \sigma_1, \sigma_{12} < \sigma_2$

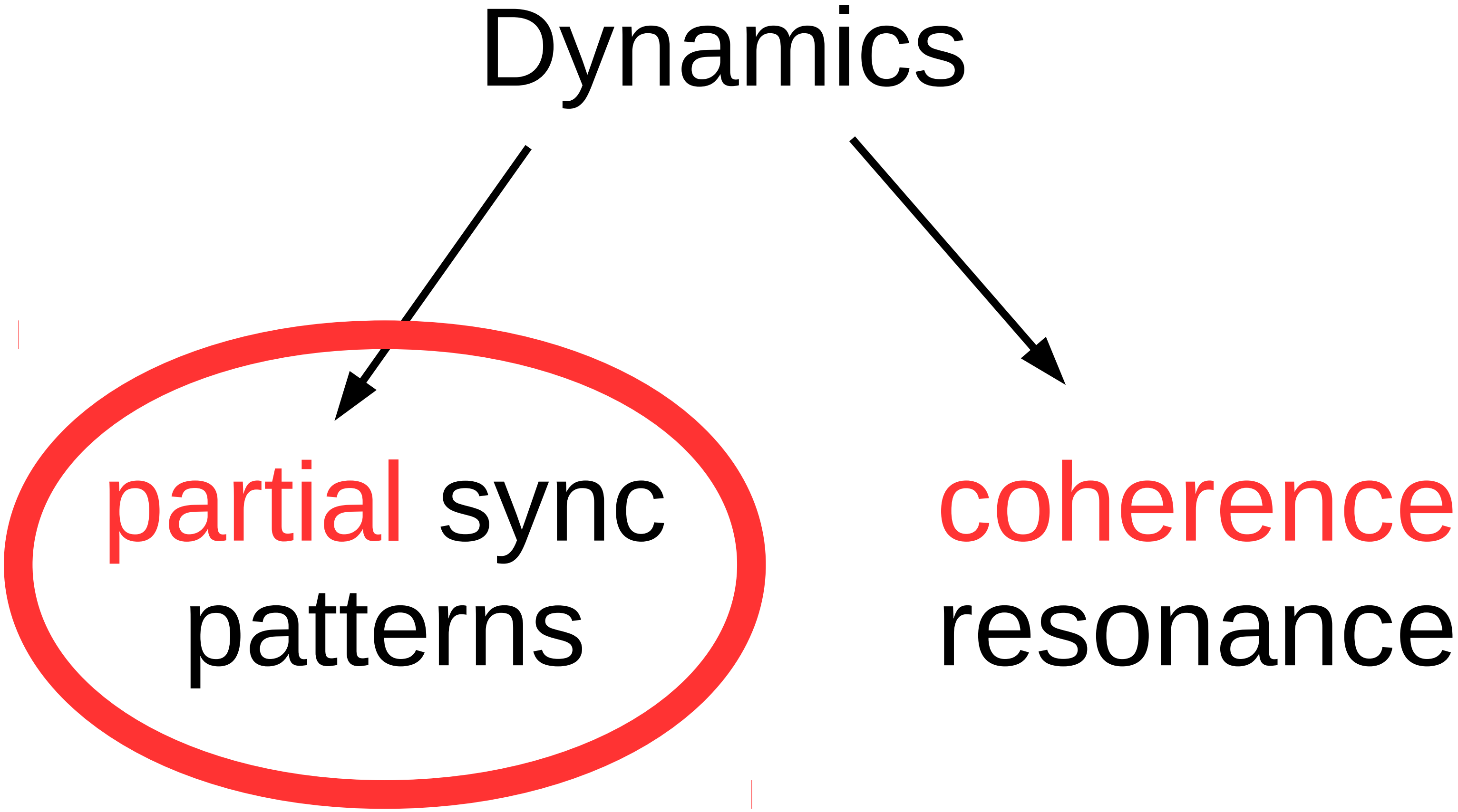
strong multiplexing
$\sigma_{12} \geq \sigma_1, \sigma_{12} \geq \sigma_2$

Strong multiplexing:

S. Ghosh, A. Kumar, A. Zakharova, S. Jalan, Birth and death of chimera: interplay of delay and multiplexing, EPL 115, 60005 (2016)

S. Ghosh, A. Zakharova, S. Jalan, Non-identical multiplexing promotes chimera states, Chaos, Solitons and Fractals 106, 56-60 (2018)

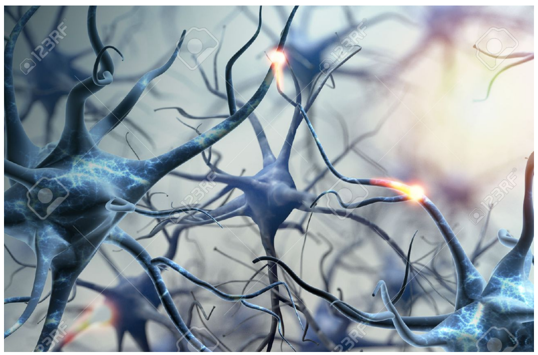
Can weak multiplexing have a strong impact on the dynamics?


Dynamics
partial sync patterns
coherence resonance

synchronization

Is synchrony always good?

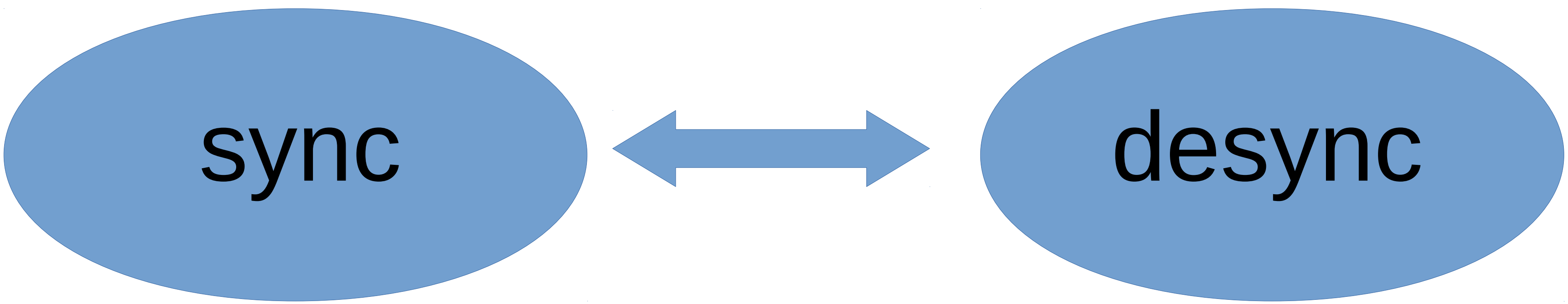
Is synchrony always good?



- neural networks

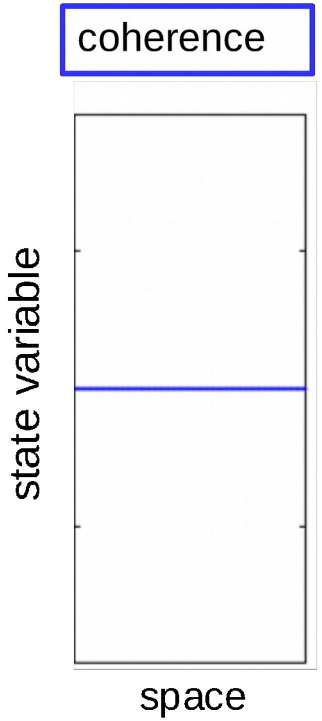
- power grid networks

Transitions

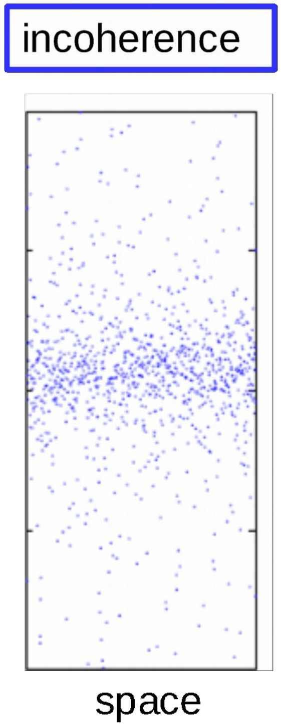


partial synchronization patterns

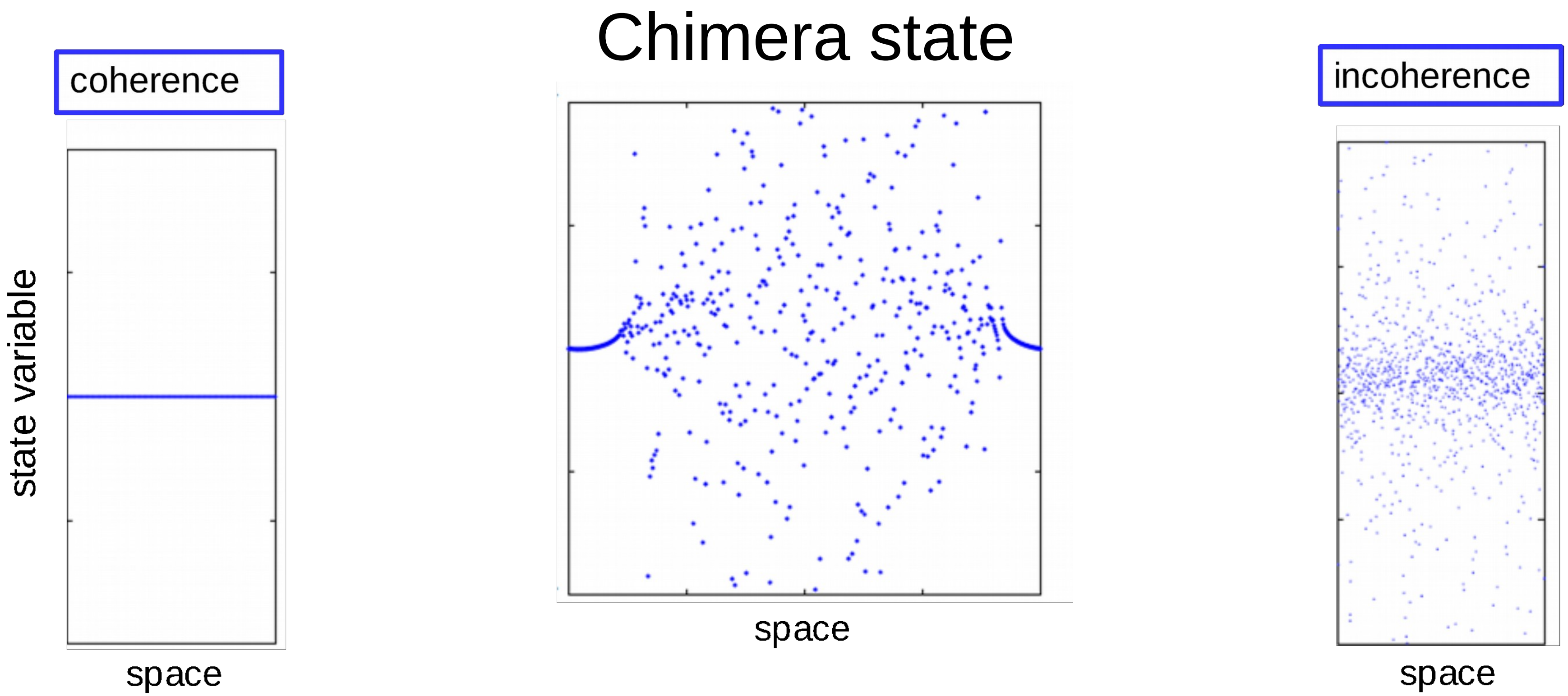
Transition from sync/coherence to desync/incoherence



?



Transition from sync/coherence to desync/incoherence



Chimera state – spatial coexistence of synchronized/coherent and desynchronized/incoherent domains in a dynamical network

Examples of chimera states

- Classical chimeras:

  discovered in 2002 by Kuramoto and Battogtokh

  called *chimeras* by Abrams and Strogatz in 2004

- Amplitude chimeras

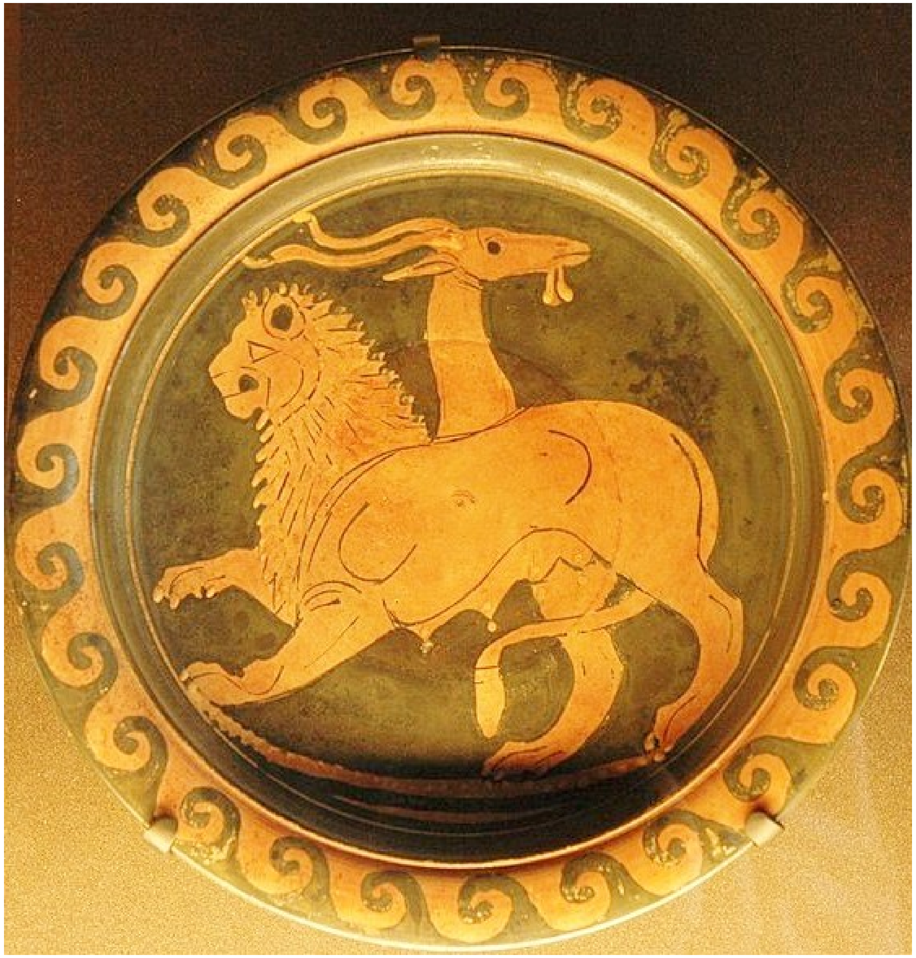
  2014

- Coherence-resonance

  chimeras

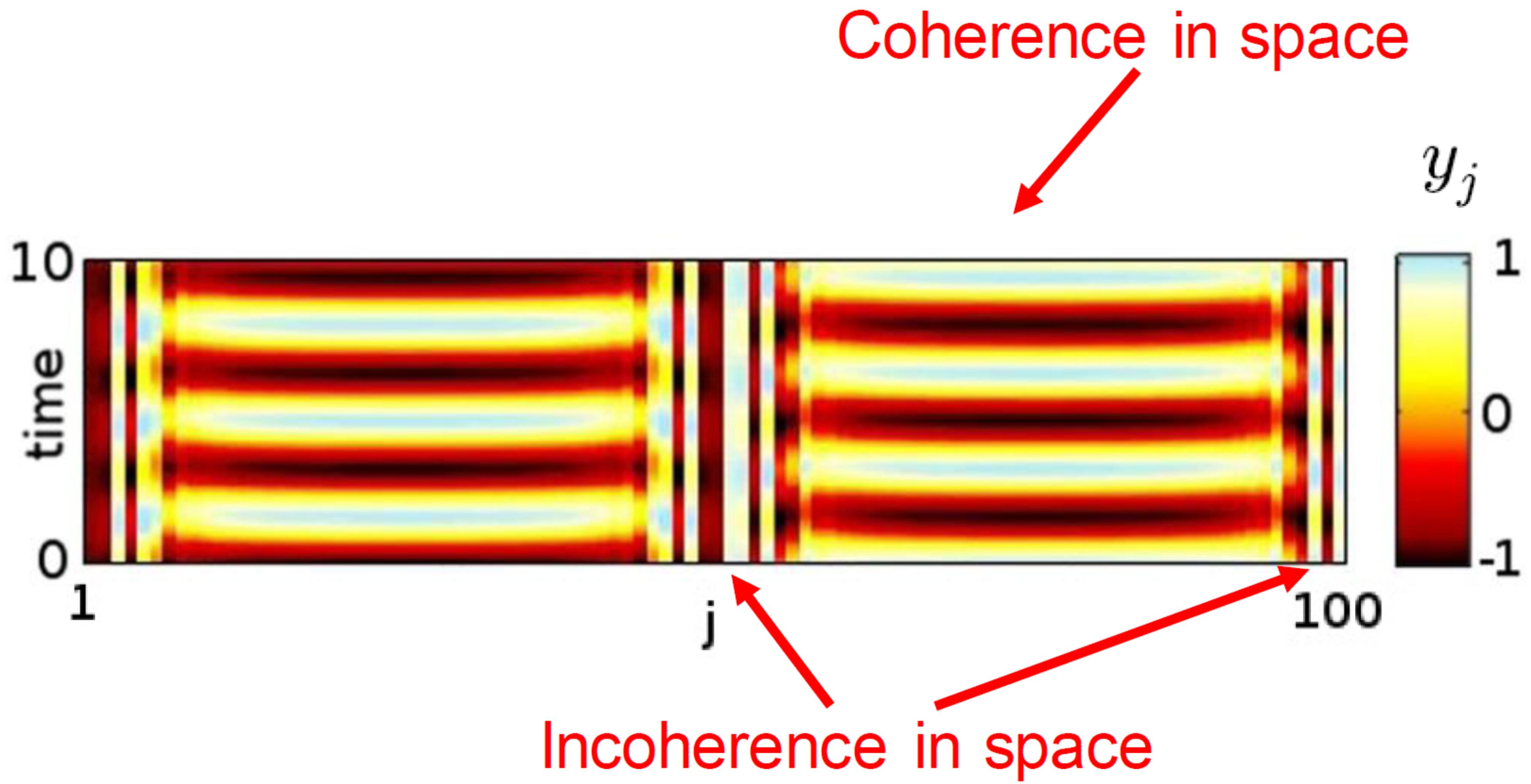
  2016

- …



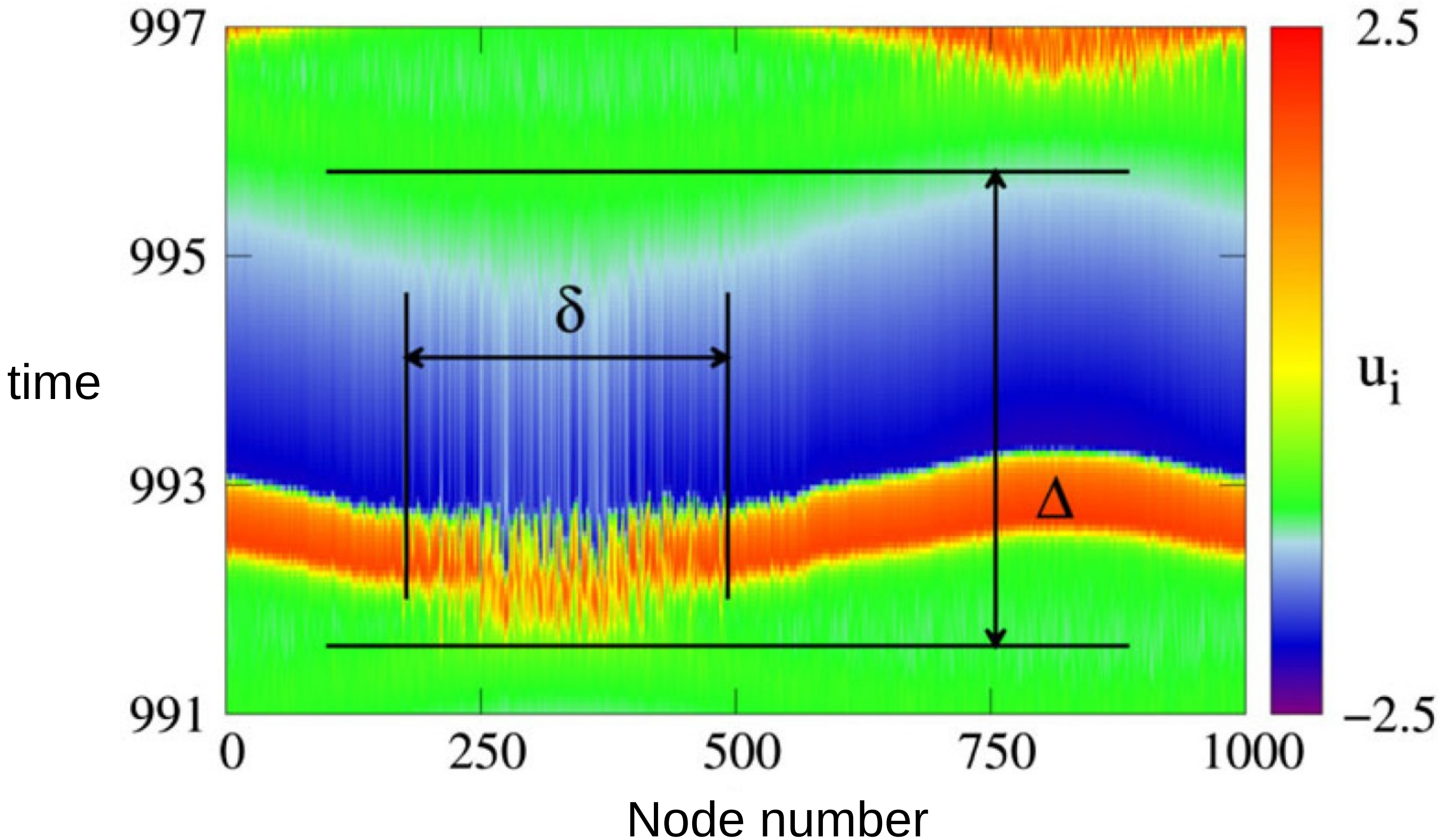
A. Zakharova, Chimera Patterns in Networks: Interplay between Dynamics, Structure, Noise, and Delay, ISBN 978-3-030-21714-3, Springer (2020)

Amplitude chimera



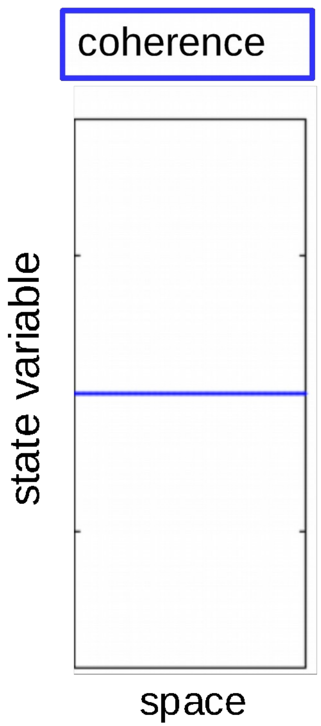
A. Zakharova, M. Kapeller, E. Schöll, Phys. Rev. Lett. 112, 154101 (2014)

Coherence-resonance chimera

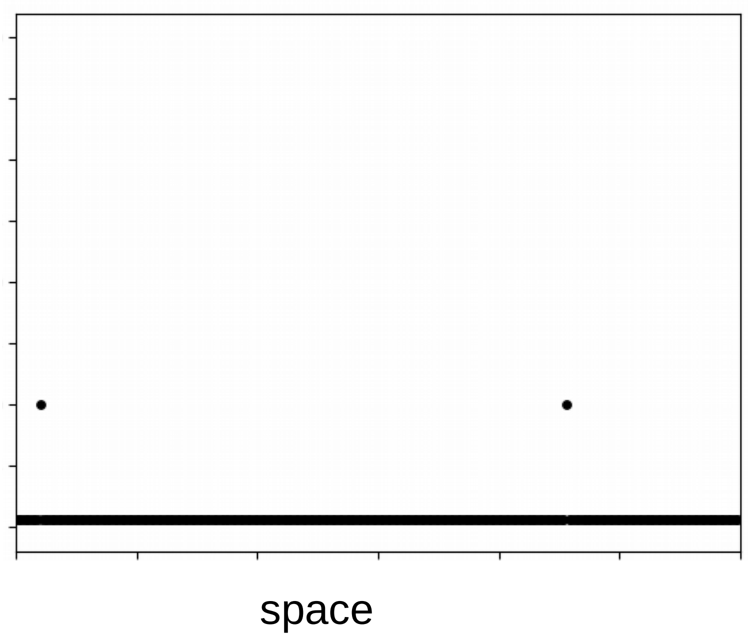


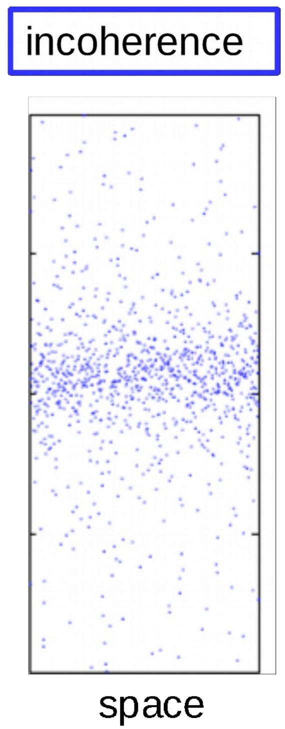
N. Semenova, A. Zakharova, V. Anishchenko, E. Schöll, Phys. Rev. Lett. 117, 014102 (2016)

Transition from sync/coherence to desync/incoherence



Solitary state





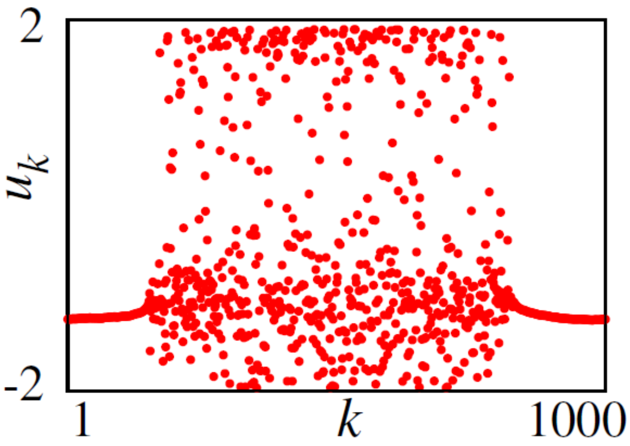
Solitary state – coexistence of a synchronized cluster and solitary nodes randomly distributed along the network

Solitary states

video

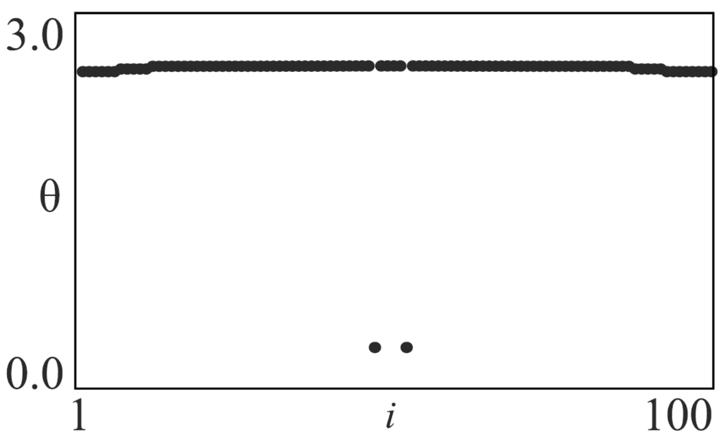
What is the difference?

chimera states



Localized in space
incoherent domain

solitary states



Randomly distributed
solitary nodes

Partial sync patterns in a multiplex network of coupled neurons

Previous studies on one-layer network

Network of nonlocally coupled FitzHugh-Nagumo systems

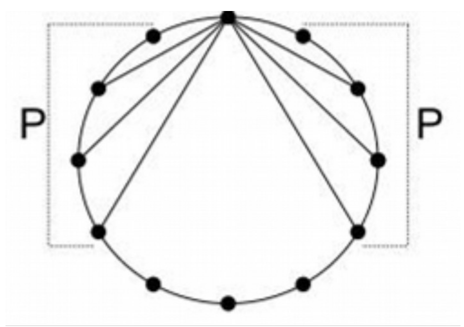
$$\varepsilon \dot{u}_i = u_i - \frac{u_i^3}{3} - v_i + \frac{\sigma}{2P} \sum_{j=i-P}^{i+P} \left[b_{uu}(u_j - u_i) + b_{uv}(v_j - v_i) \right],$$

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

$$\begin{pmatrix} b_{uu} & b_{uv} \\ b_{vu} & b_{vv} \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{pmatrix}$$

$|a_i| < 1$
oscillatory

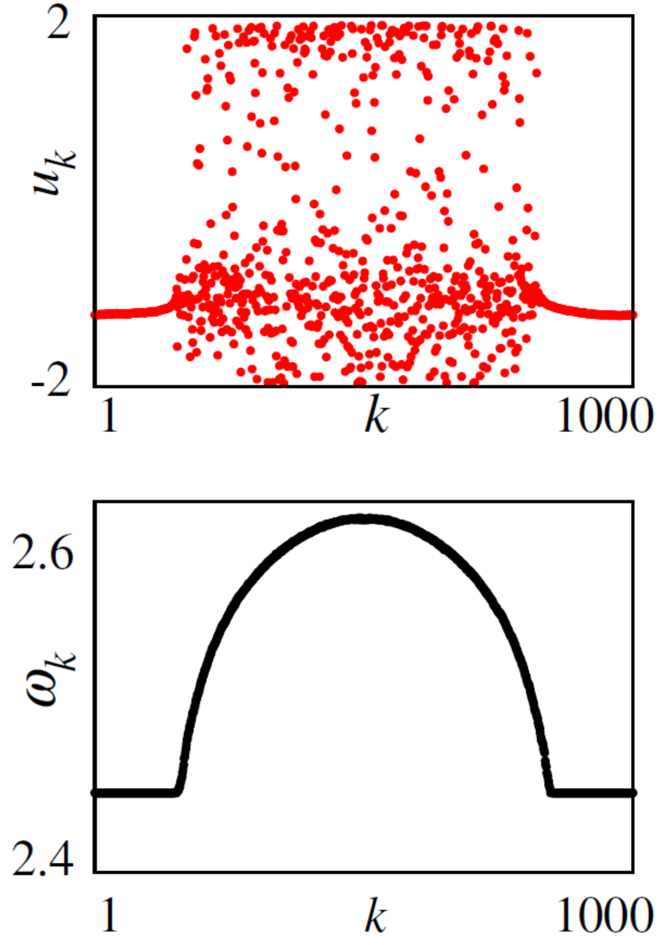
$$\phi = \frac{\pi}{2} - 0.1$$

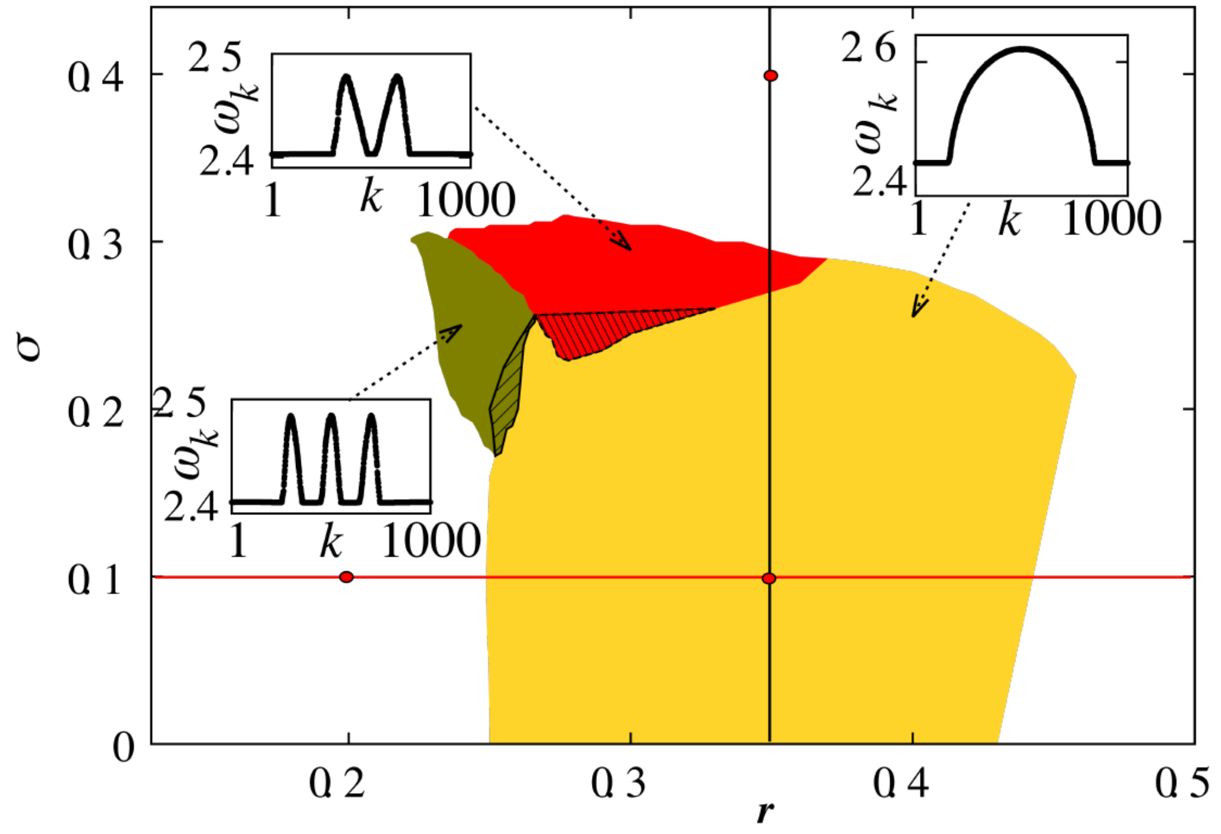


nonlocal

I. Omelchenko, O. Omel'chenko, P. Hövel, E. Schöll, Phys. Rev. Lett. 110, 224101 (2013)

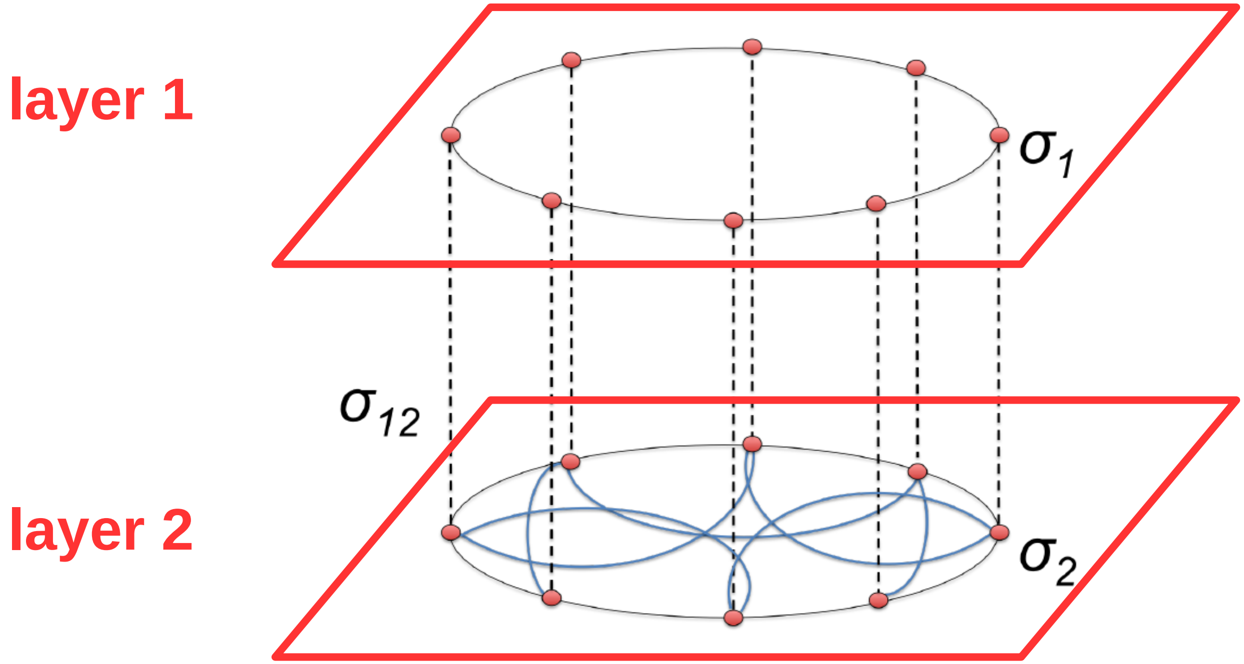
Chimera states in one-layer network





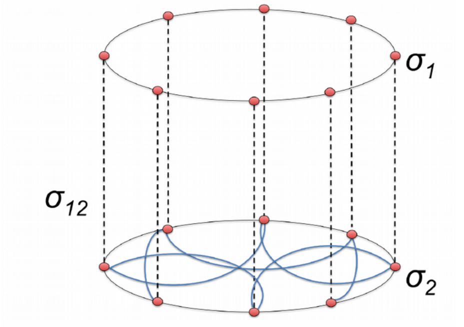
Multiplex network

Can we control the dynamics in the presence of weak multiplexing?



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

Multiplex network



Layer 1

$$\varepsilon \frac{du_{1i}}{dt} = u_{1i} - \frac{u_{1i}^3}{3} - v_{1i} + \frac{\sigma_1}{2R_1} \sum_{j=i-R_1}^{i+R_1} [b_{uu}(u_{1j} - u_{1i}) + b_{uv}(v_{1j} - v_{1i})] + \sigma_{12}(u_{2i} - u_{1i}),$$

$$\frac{dv_{1i}}{dt} = u_{1i} + a_i + \frac{\sigma_1}{2R_1} \sum_{j=i-R_1}^{i+R_1} [b_{vu}(u_{1j} - u_{1i}) + b_{vv}(v_{1j} - v_{1i})],$$

Layer 2

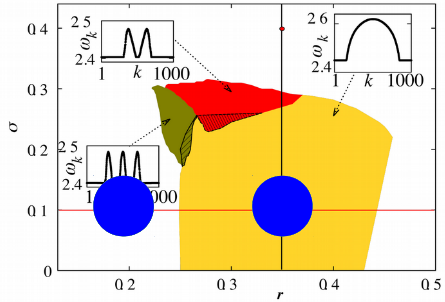
$$\varepsilon \frac{du_{2i}}{dt} = u_{2i} - \frac{u_{2i}^3}{3} - v_{2i} + \frac{\sigma_2}{2R_2} \sum_{j=i-R_2}^{i+R_2} [b_{uu}(u_{2j} - u_{2i}) + b_{uv}(v_{2j} - v_{2i})] + \sigma_{12}(u_{1i} - u_{2i}),$$

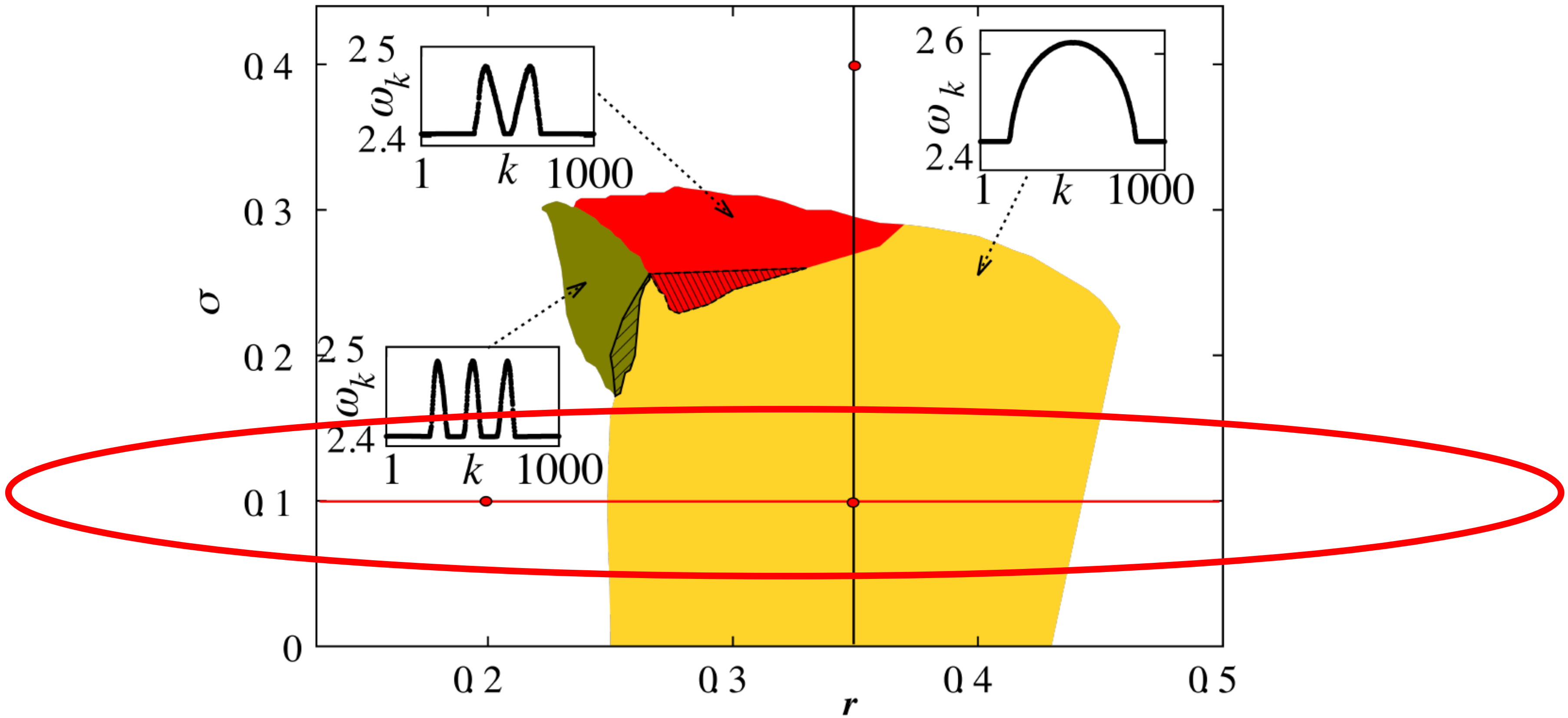
$$\frac{dv_{2i}}{dt} = u_{2i} + a_i + \frac{\sigma_2}{2R_2} \sum_{j=i-R_2}^{i+R_2} [b_{vu}(u_{2j} - u_{2i}) + b_{vv}(v_{2j} - v_{2i})],$$

M. Mikhaylenko, L. Ramlow, S. Jalan, A. Zakharova, Weak multiplexing in neural networks: Switching between chimera and solitary states, Chaos 29, 023122 (2019)

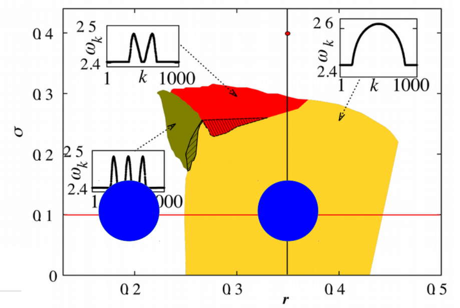
Multiplex network:
coupling range mismatch

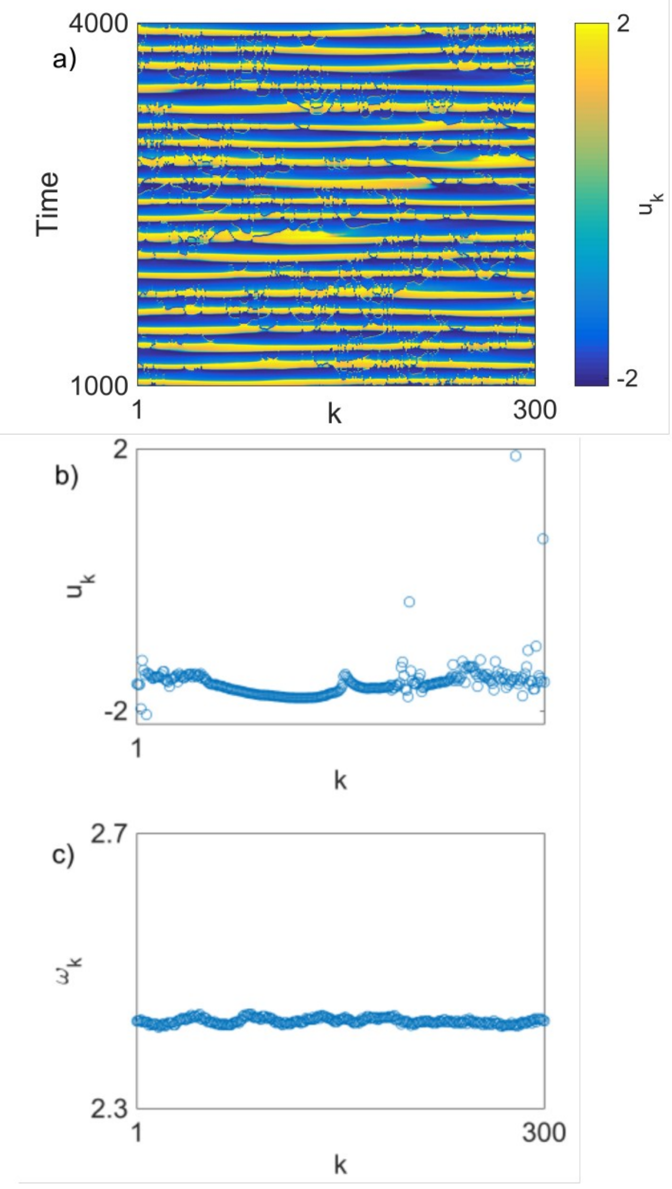
Chimeras in isolated layers: different coupling range

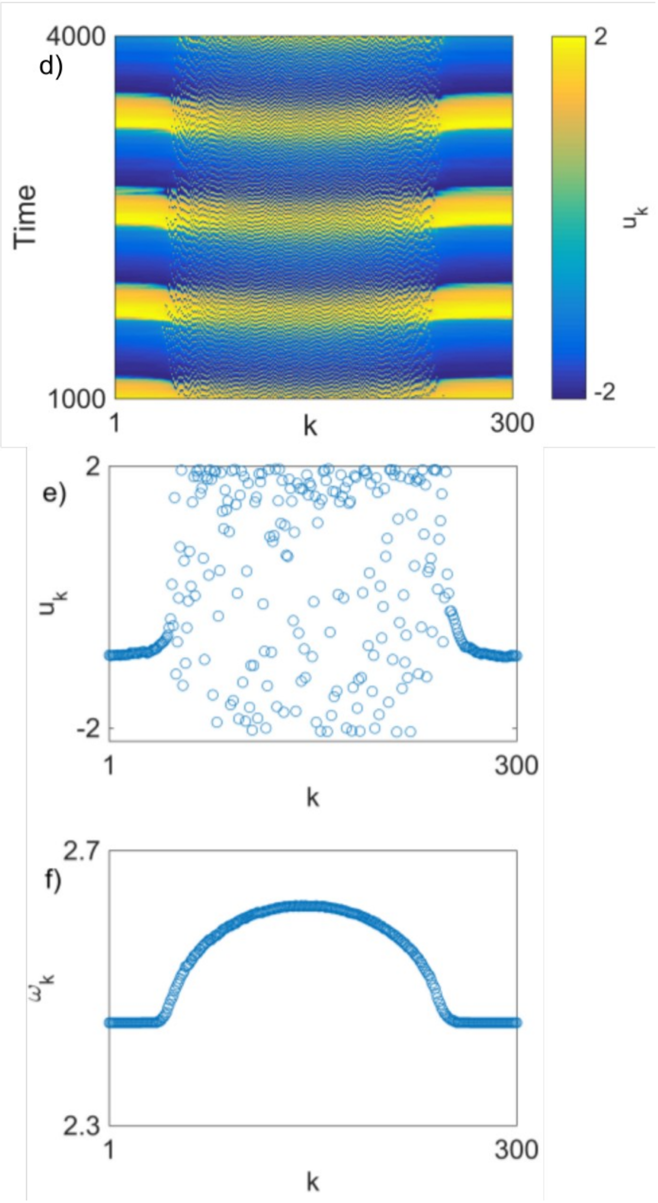




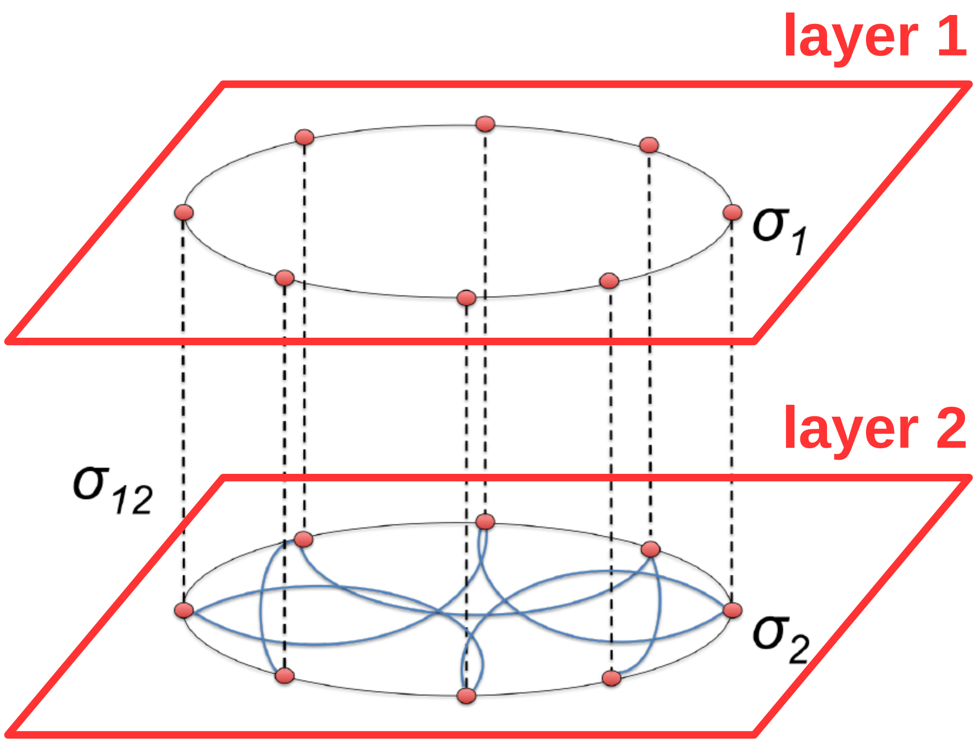
Isolated layers: different coupling range







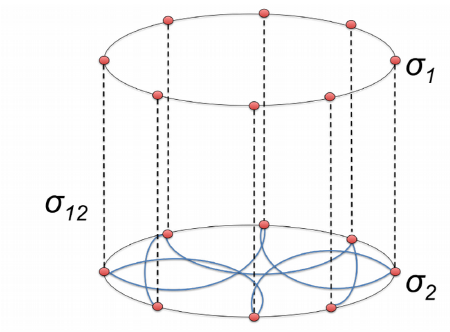
Multiplex network



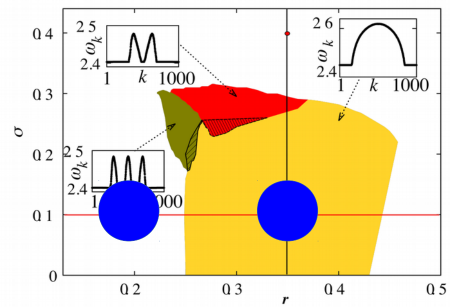
weak multiplexing
$\sigma_{12} = 0.01$

$\sigma_1 = \sigma_2 = 0.1$

$r_1 = 0.2, r_2 = 0.35$

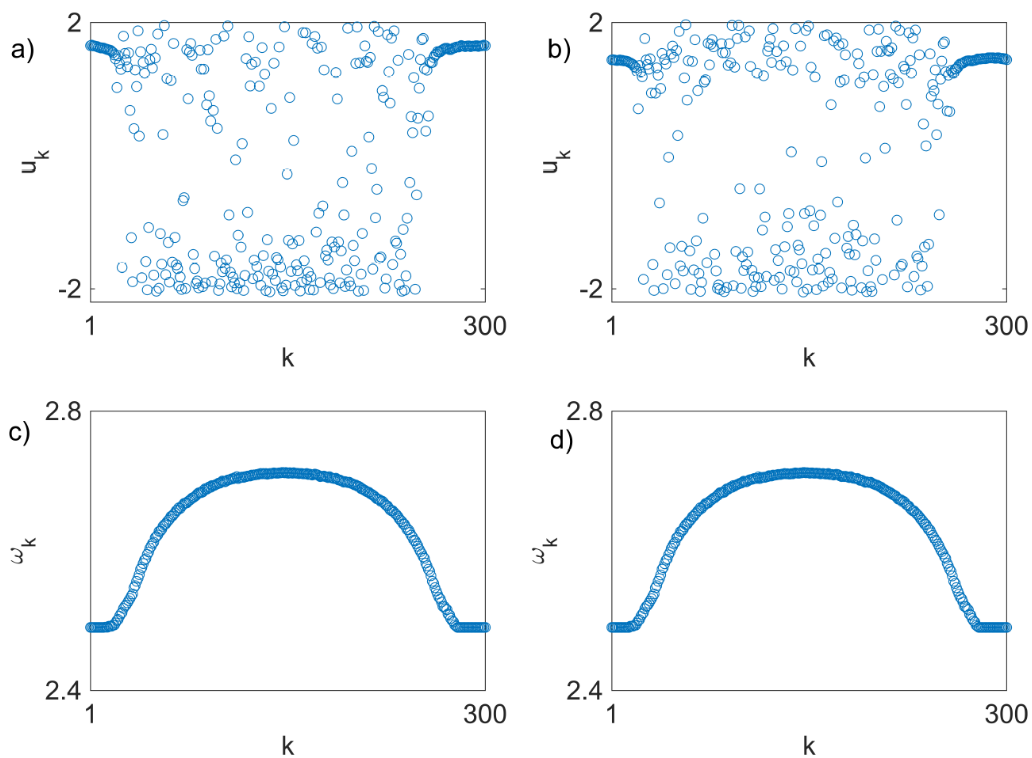


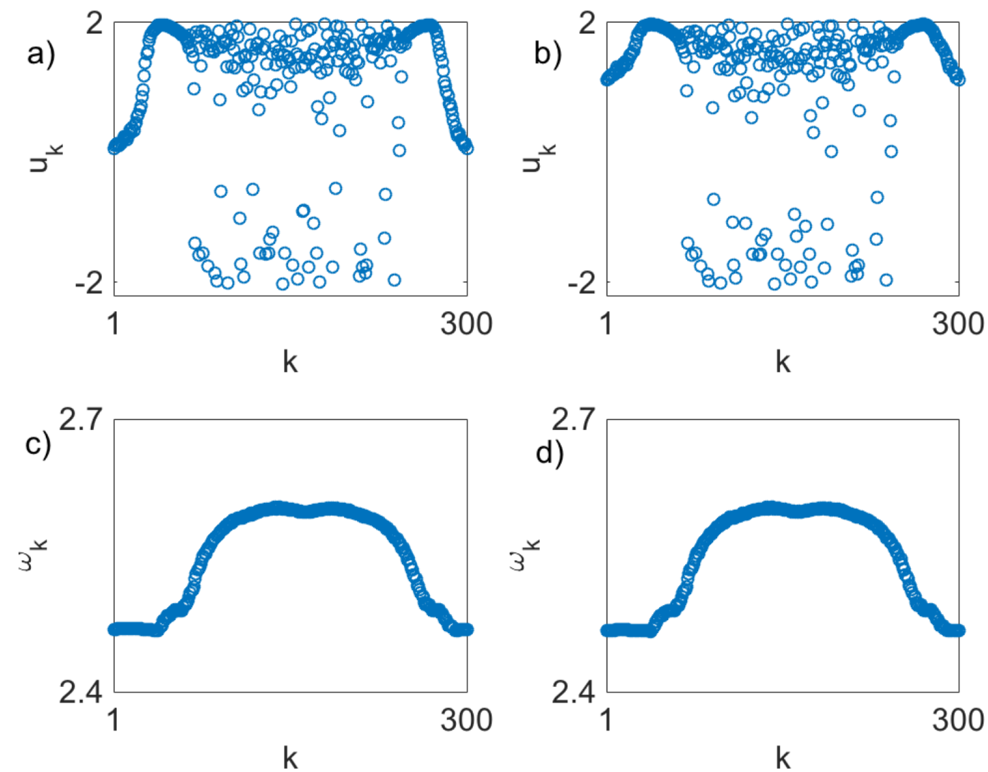
Multiplex network



weak multiplexing
$\sigma_{12} = 0.01$

strong multiplexing
$\sigma_{12} = 0.1$

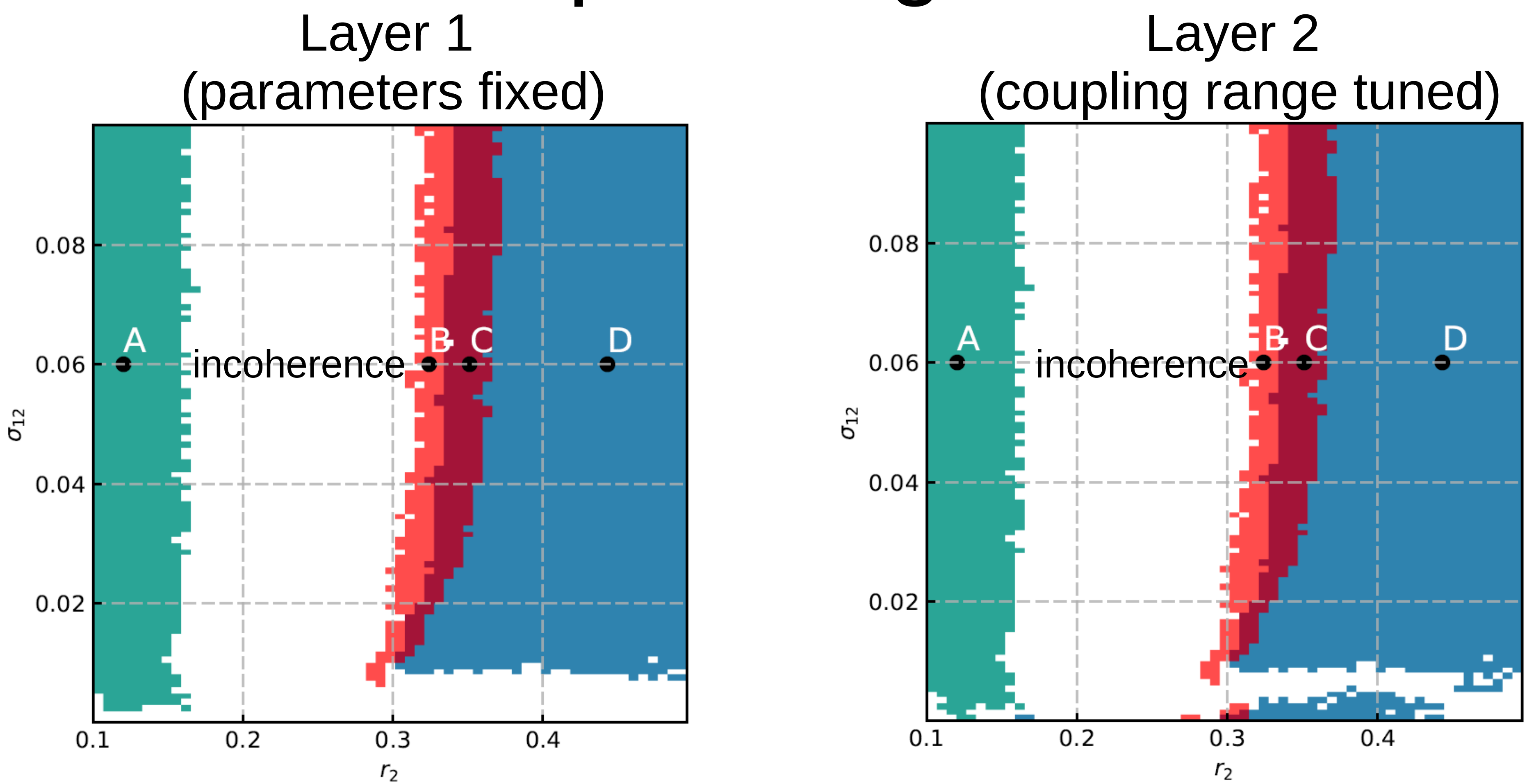




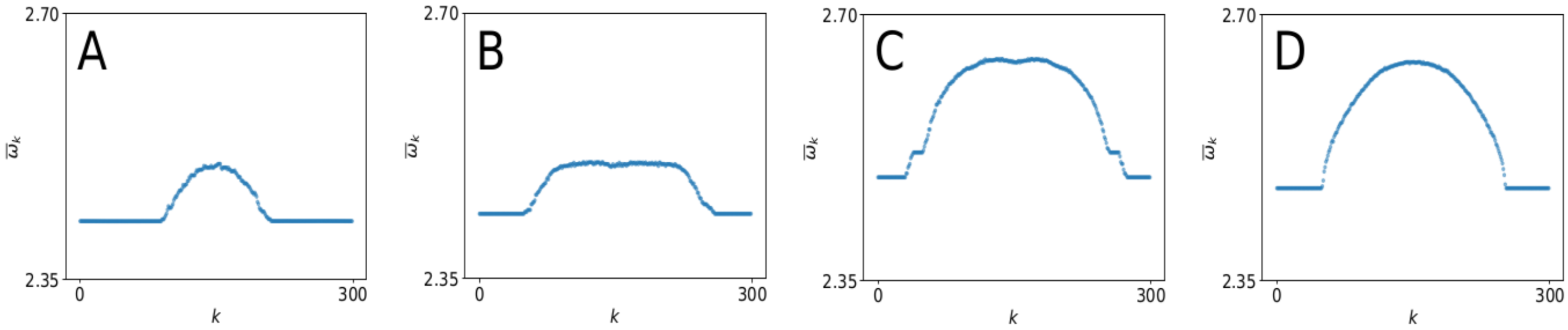
Weak multiplexing induces chimeras

M. Mikhaylenko, L. Ramlow, S. Jalan, A. Zakharova, Weak multiplexing in neural networks: Switching between chimera and solitary states, Chaos 29, 023122 (2019)

Maps of regimes

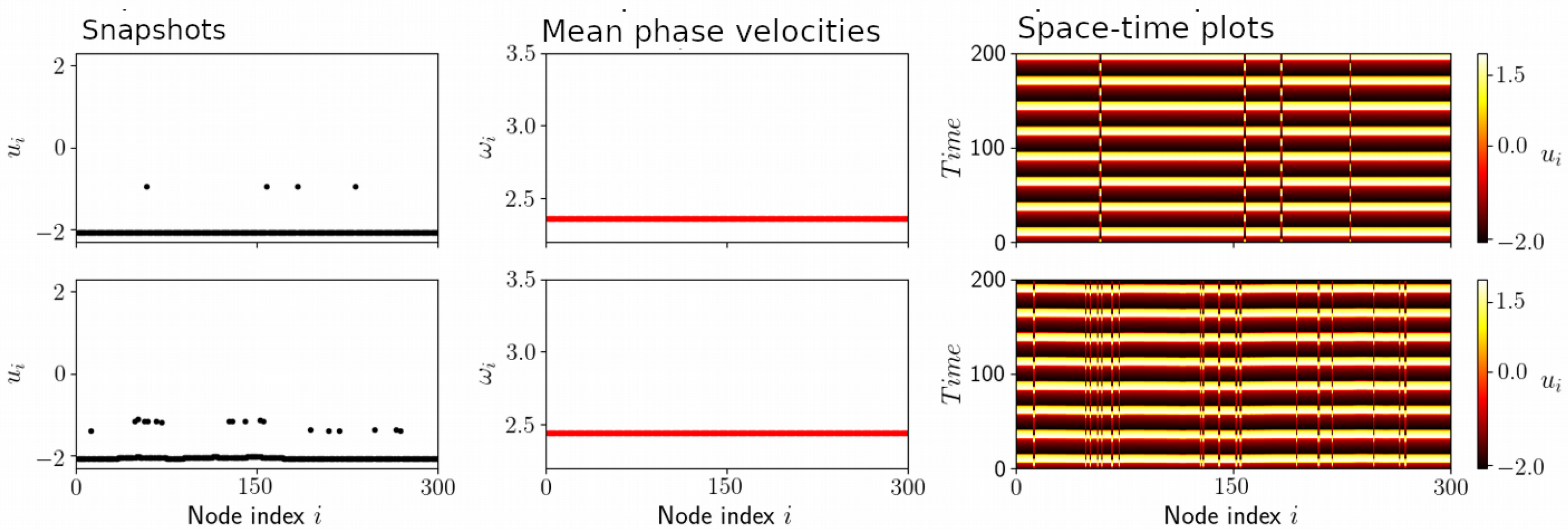


We can induce chimeras with different profiles in layer 1 by multiplexing it with layer 2.



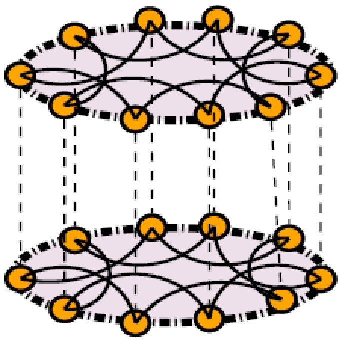
Control of solitary states

Solitary states in one-layer networks

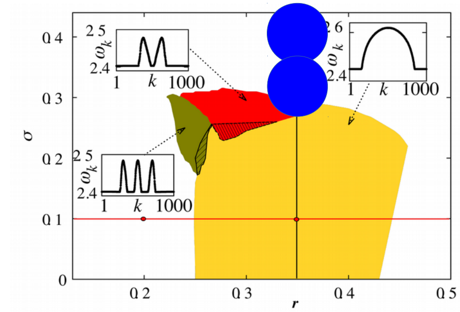


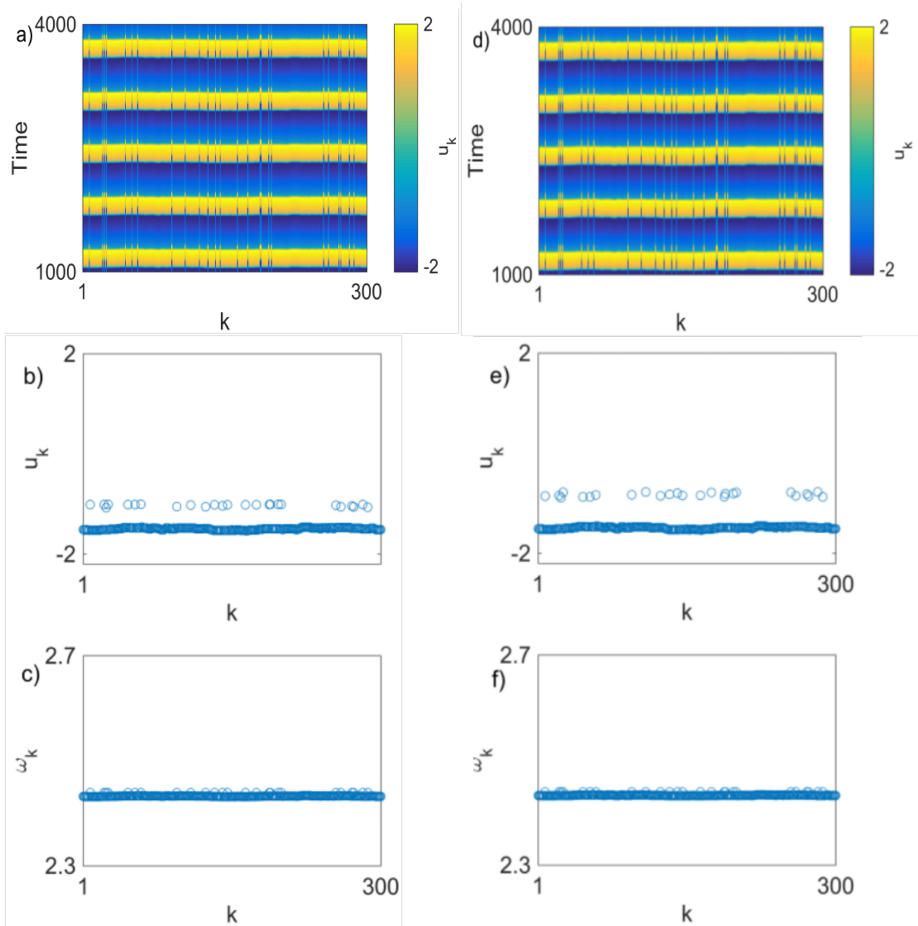
E. Rybalova, V.S. Anishchenko, G.I. Strelkova, A. Zakharova, Solitary states and solitary states chimera in neural networks, Chaos Fast Track 29, 071106 (2019)

L. Schülen, S. Ghosh, A. D. Kachhvah, A. Zakharova, S. Jalan, Delay engineered solitary states in complex networks, Chaos, Solitons and Fractals 128, 290 (2019)



Solitary states in a two-layer network





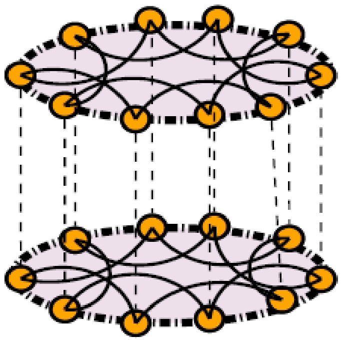
Small coupling strength mismatch

and

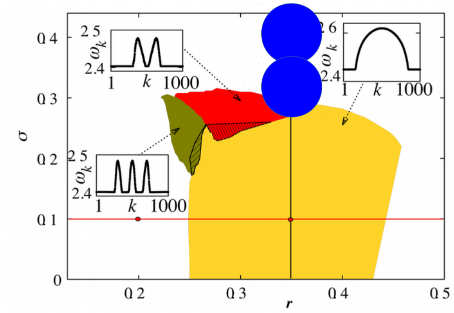
weak multiplexing $\sigma_{12} = 0.05$

Weak multiplexing induces solitary states in both layers

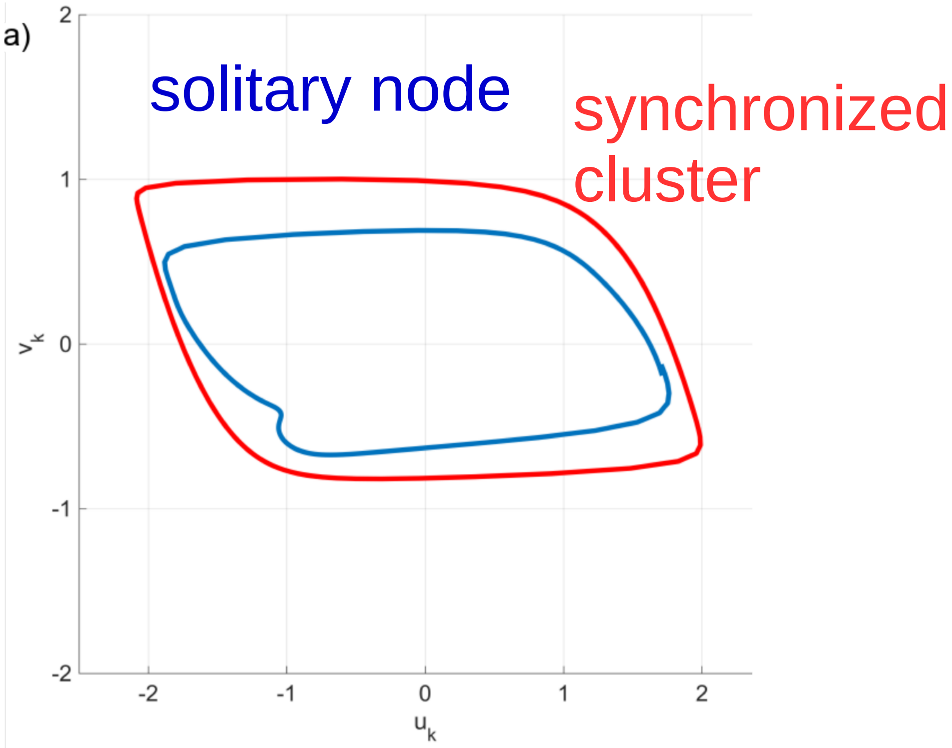
M. Mikhaylenko, L. Ramlow, S. Jalan, A. Zakharova, Weak multiplexing in neural networks: Switching between chimera and solitary states, Chaos 29, 023122 (2019)

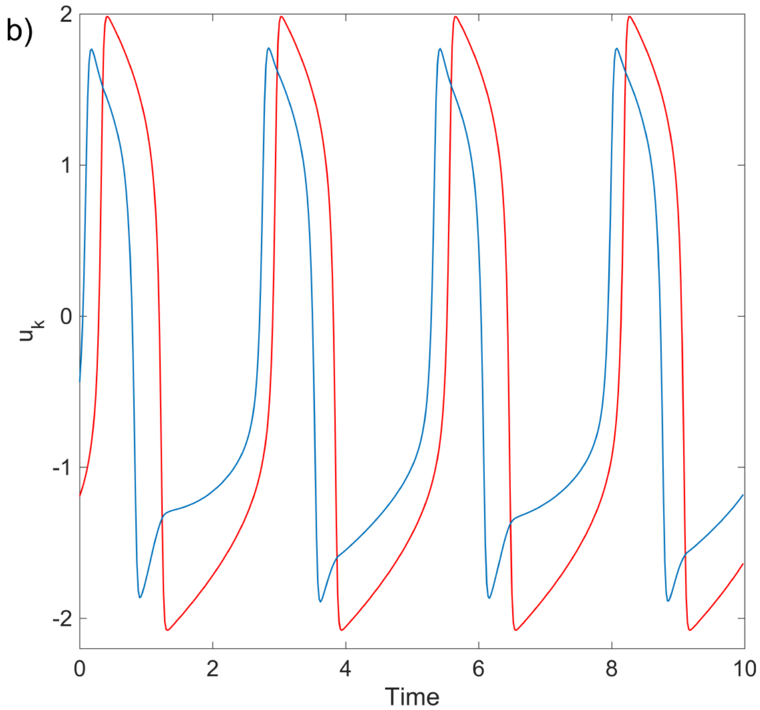


Solitary states in a two-layer network



weak multiplexing
$\sigma_{12} = 0.05$

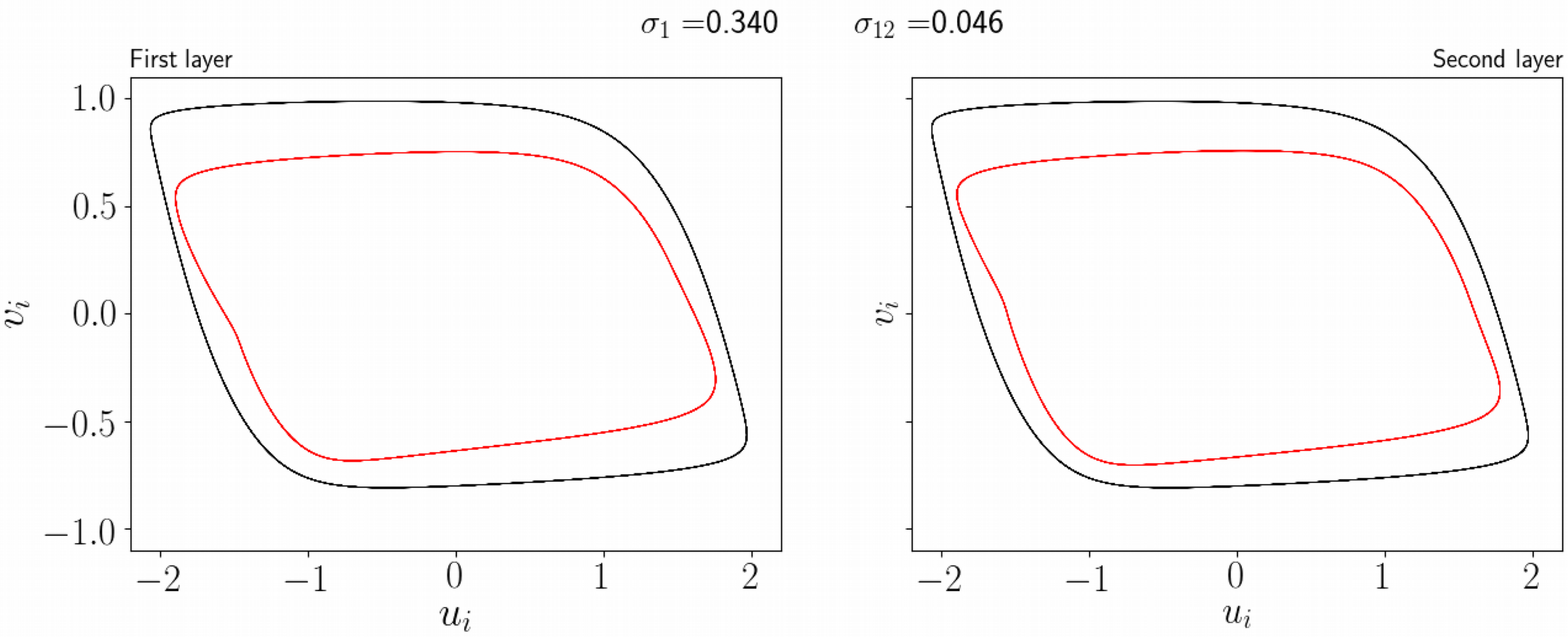




Are the layers synchronized?

M. Mikhaylenko, L. Ramlow, S. Jalan, A. Zakharova, Weak multiplexing in neural networks: Switching between chimera and solitary states, Chaos 29, 023122 (2019)

Solitary states in a two-layer network

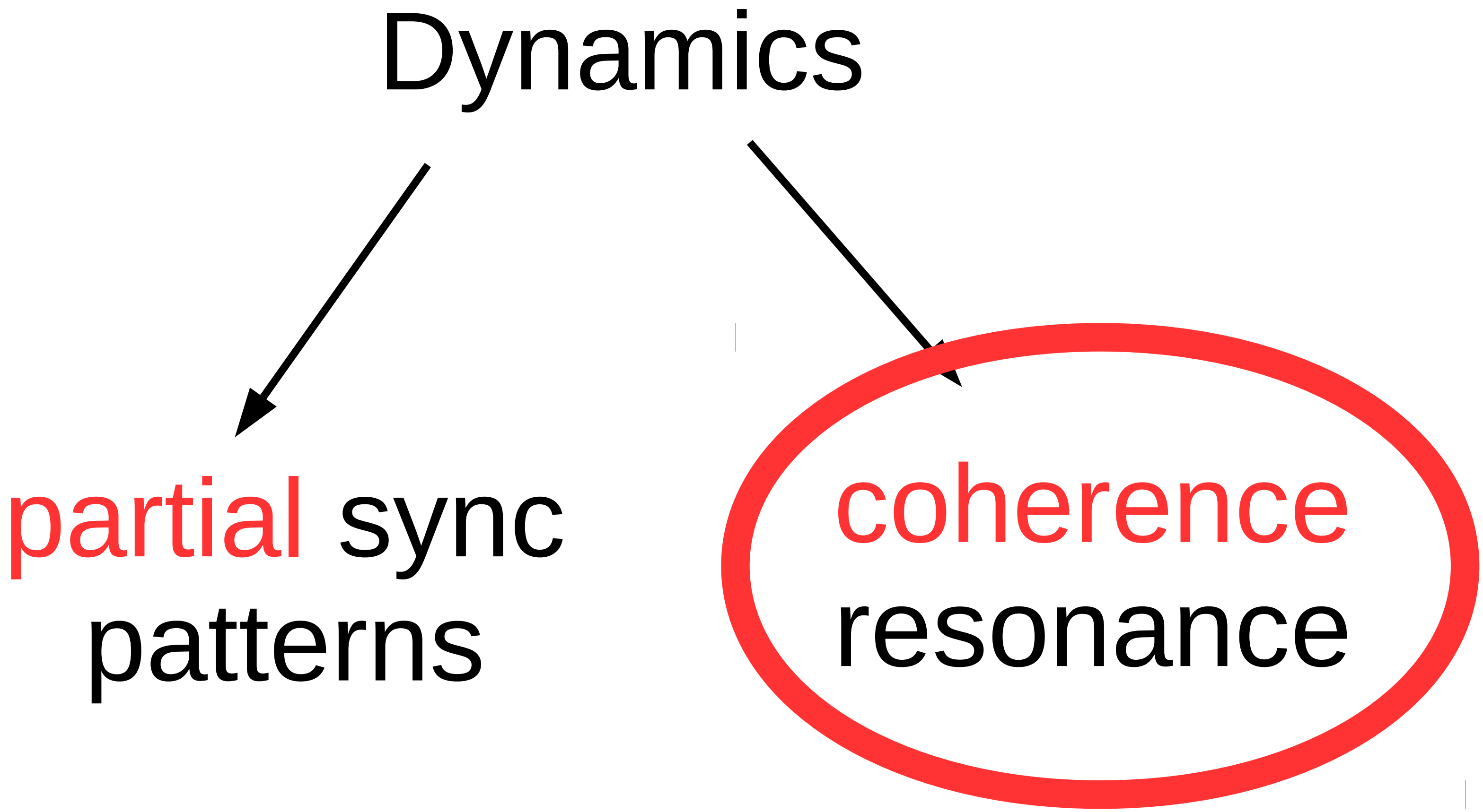


Solitary nodes and **synchronized cluster** follow different trajectories

We consider a multiplex network of two non-locally coupled rings:
$N_1 = N_2 = N/2 = 500,\ r_1 = r_2 = r = 0.35,\ a_i = a = 0.5,\ \varepsilon = 0.05.$

Solitary states in two-layer network

Video!

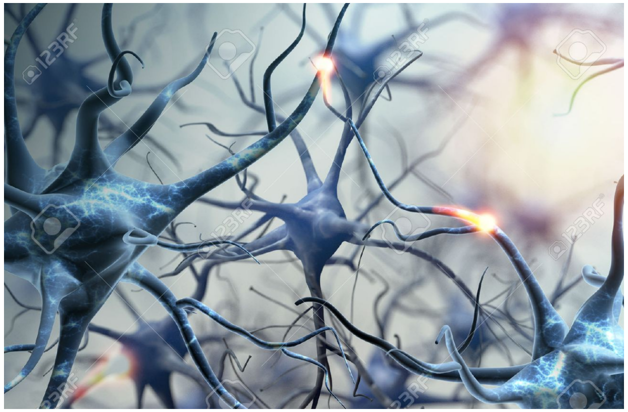

Dynamics
partial sync
patterns
coherence
resonance

Coherence resonance

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
- analytical treatment by Lindner and Schimansky-Geier in 1999



constructive role of noise, counter-intuitive phenomenon

Model: FitzHugh-Nagumo system in excitable regime

$$\varepsilon \dot{u} = u - \frac{u^3}{3} - v,$$

$$\dot{v} = u + a + \sqrt{2D}\xi(t)$$

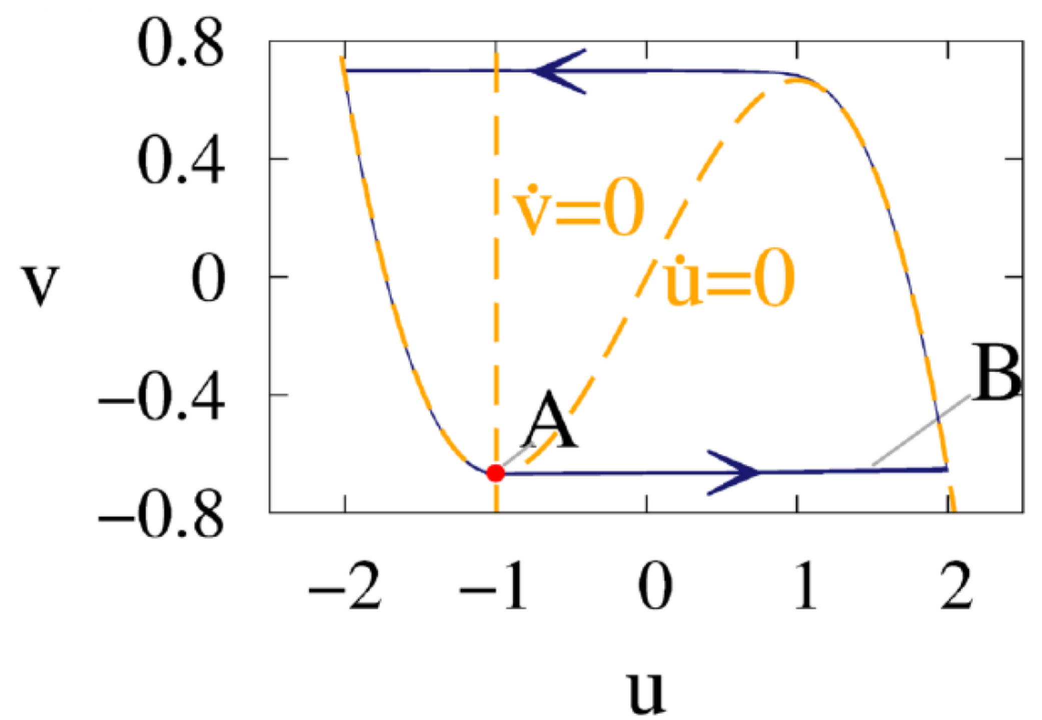
single node dynamics

u – activator

v – inhibitor

$|a_i| < 1$ oscillatory

$|a_i| > 1$ excitable

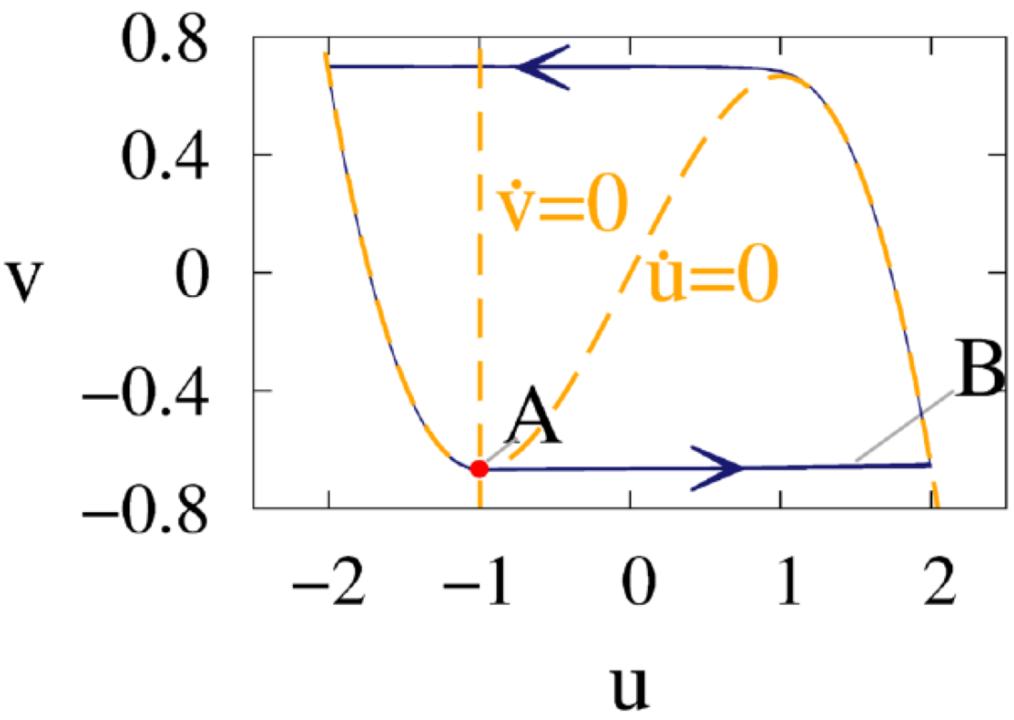


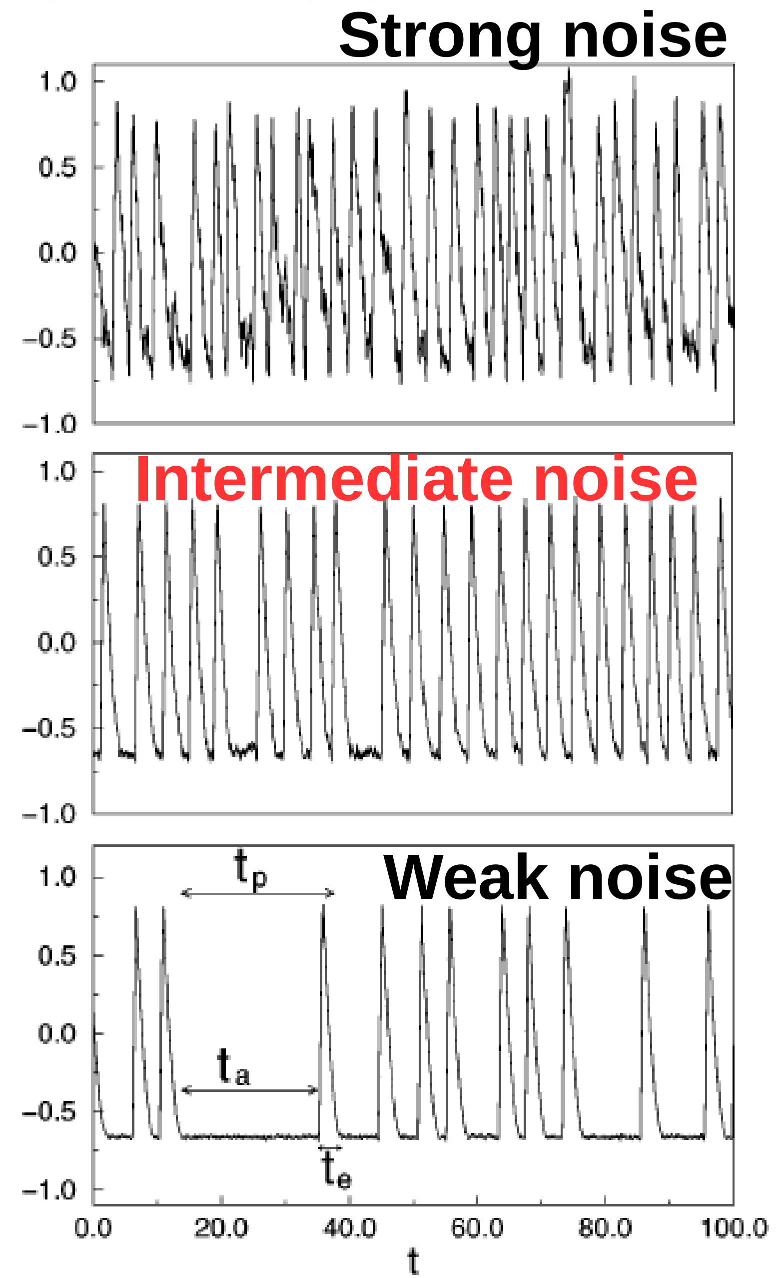
System parameters: $\varepsilon = 0.01$, a=1.001, $D = 0.0001$

Coherence resonance

$$\varepsilon\dot{u} = u - \frac{u^3}{3} - v,$$

$$\dot{v} = u + a + \sqrt{2D}\,\xi(t)$$





Model: FitzHugh-Nagumo system in excitable regime

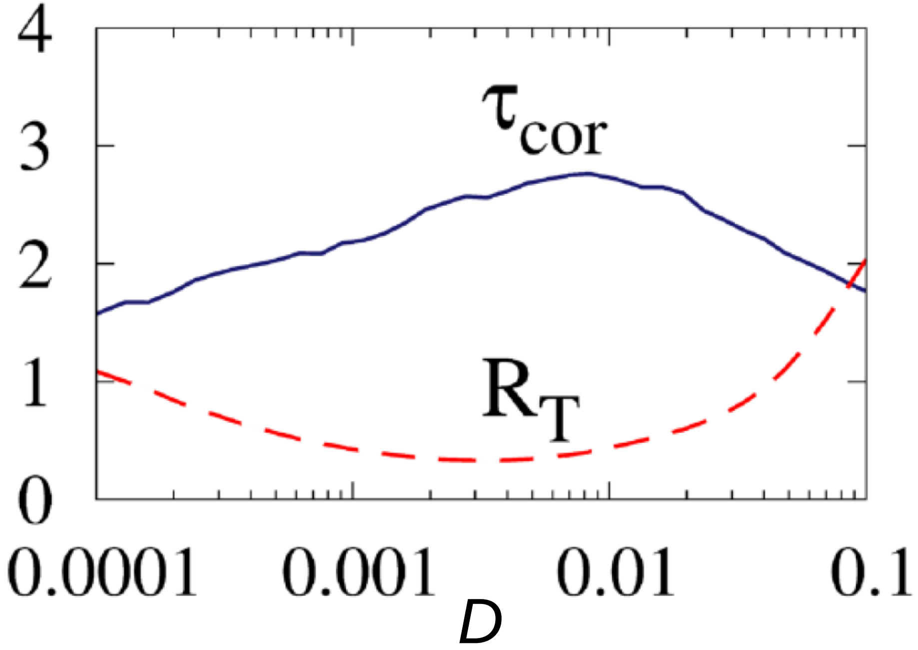
$$\varepsilon \dot{u} = u - \frac{u^3}{3} - v,$$

$$\dot{v} = u + a + \sqrt{2D}\xi(t)$$

$|a_i| > 1$

excitable

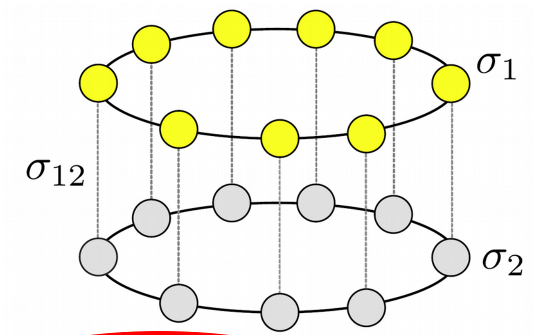
Coherence resonance



System parameters: $\varepsilon = 0.01$, a=1.001

Can we control coherence resonance
by weak multiplexing?

Multiplex network of excitable FHN neurons



$$\varepsilon \frac{du_{1i}}{dt} = u_{1i} - \frac{u_{1i}^3}{3} - v_{1i} + \frac{\sigma_1}{2}\sum_{j=i-1}^{i+1}(u_{1j} - u_{1i}) + \sigma_{12}(u_{2i} - u_{1i}),$$

$$\frac{dv_{1i}}{dt} = u_{1i} + a + \sqrt{2D_1}\xi_i(t),$$

$$\varepsilon \frac{du_{2i}}{dt} = u_{2i} - \frac{u_{2i}^3}{3} - v_{2i} + \frac{\sigma_2}{2}\sum_{j=i-1}^{i+1}(u_{2j} - u_{2i}) + \sigma_{12}(u_{1i} - u_{2i}),$$

$$\frac{dv_{2i}}{dt} = u_{2i} + a + \sqrt{2D_2}\eta_i(t),$$

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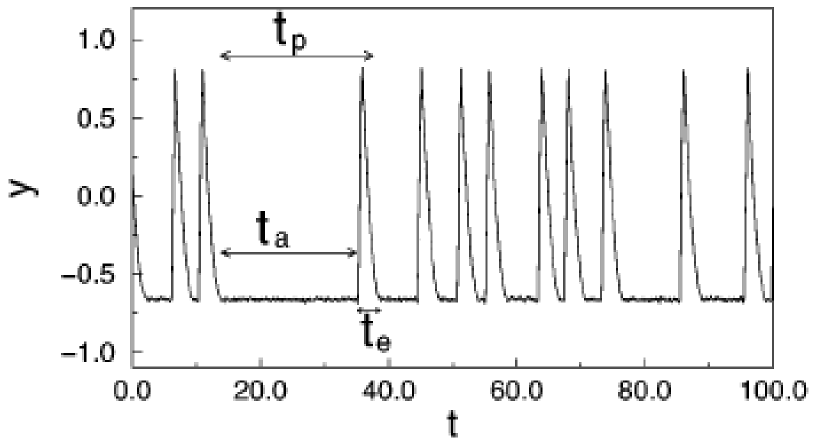
Coherence resonance: measures

Normalized standard deviation of the interspike interval

single node

$$R_T = \frac{\sqrt{\langle t_{ISI}^2 \rangle - \langle t_{ISI} \rangle^2}}{\langle t_{ISI} \rangle}$$



network

$$R_T = \frac{\sqrt{\langle \overline{t_{ISI}^2} \rangle - \langle \overline{t_{ISI}} \rangle^2}}{\langle \overline{t_{ISI}} \rangle}$$

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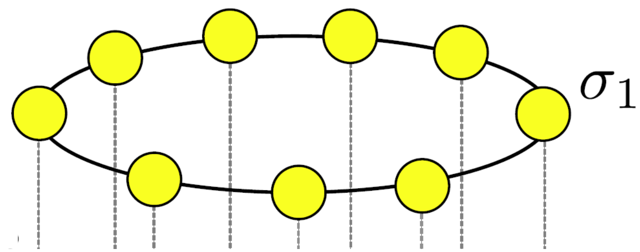
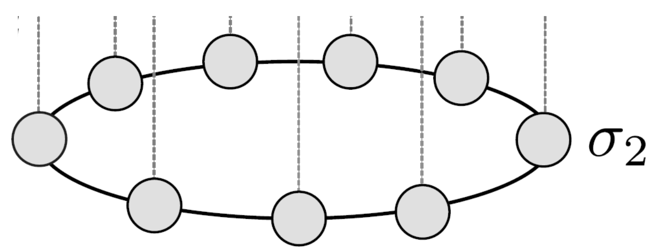
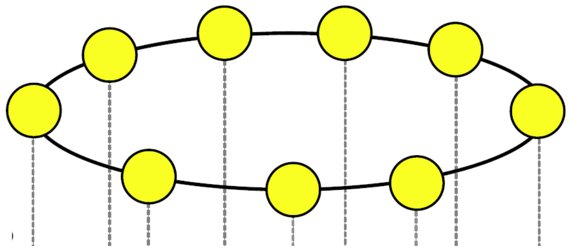
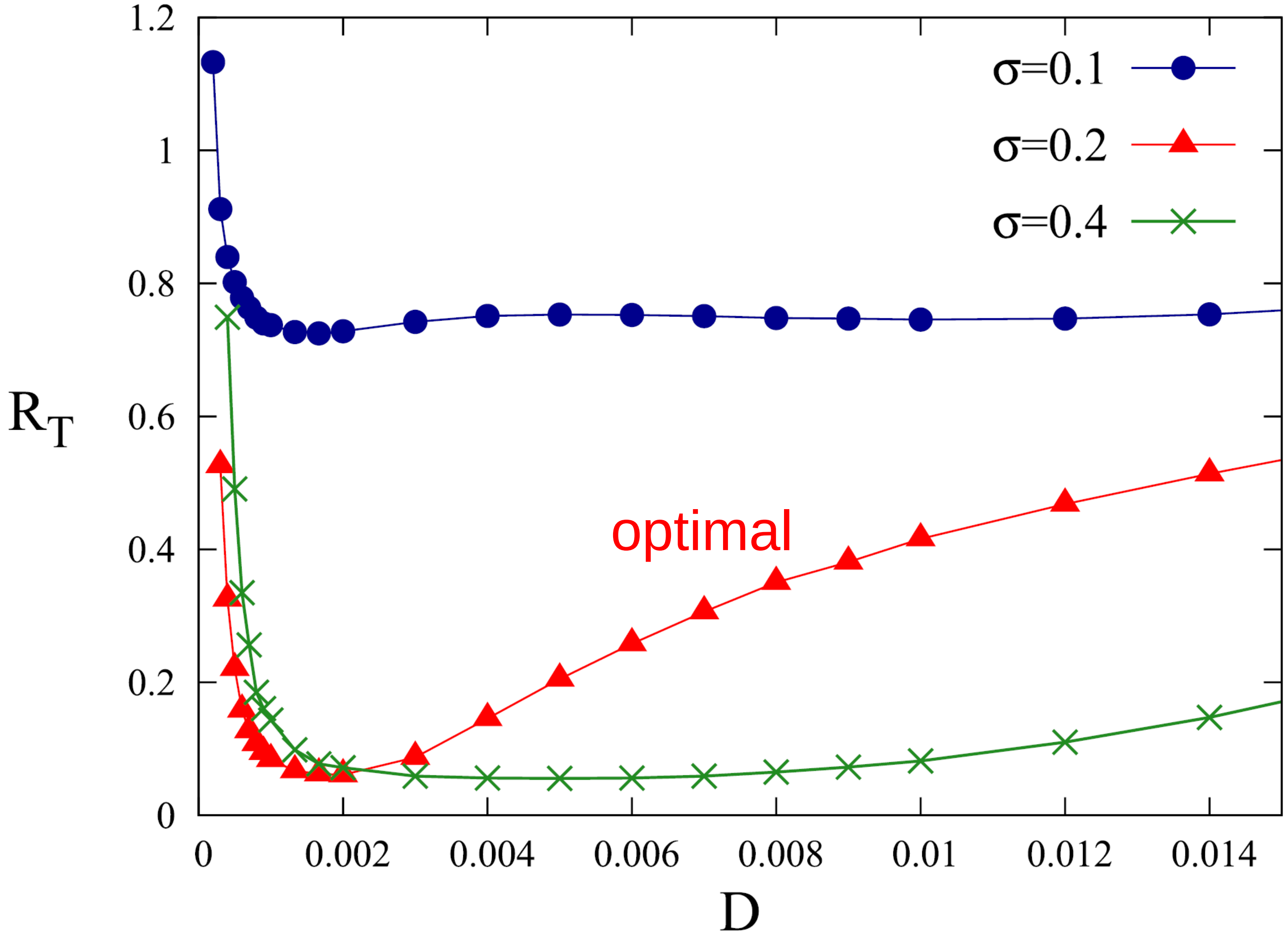


Dynamics of isolated layers

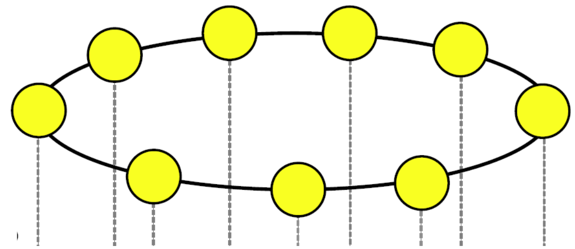


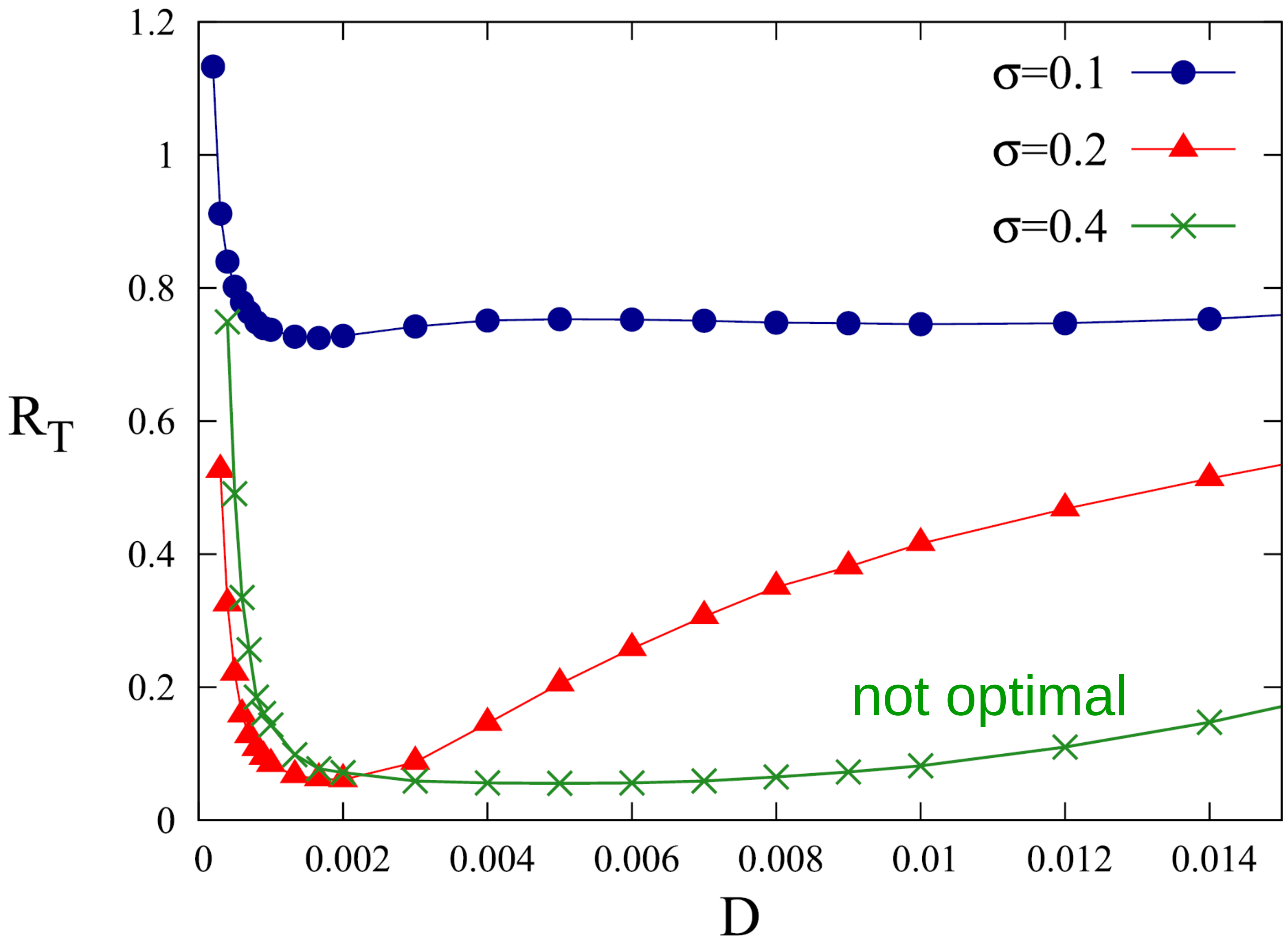
Isolated ring network



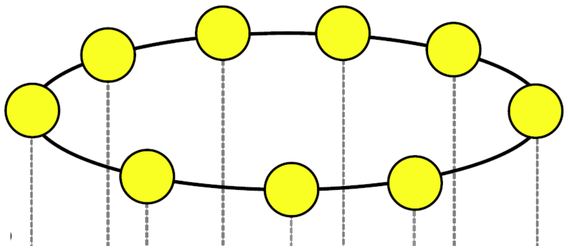


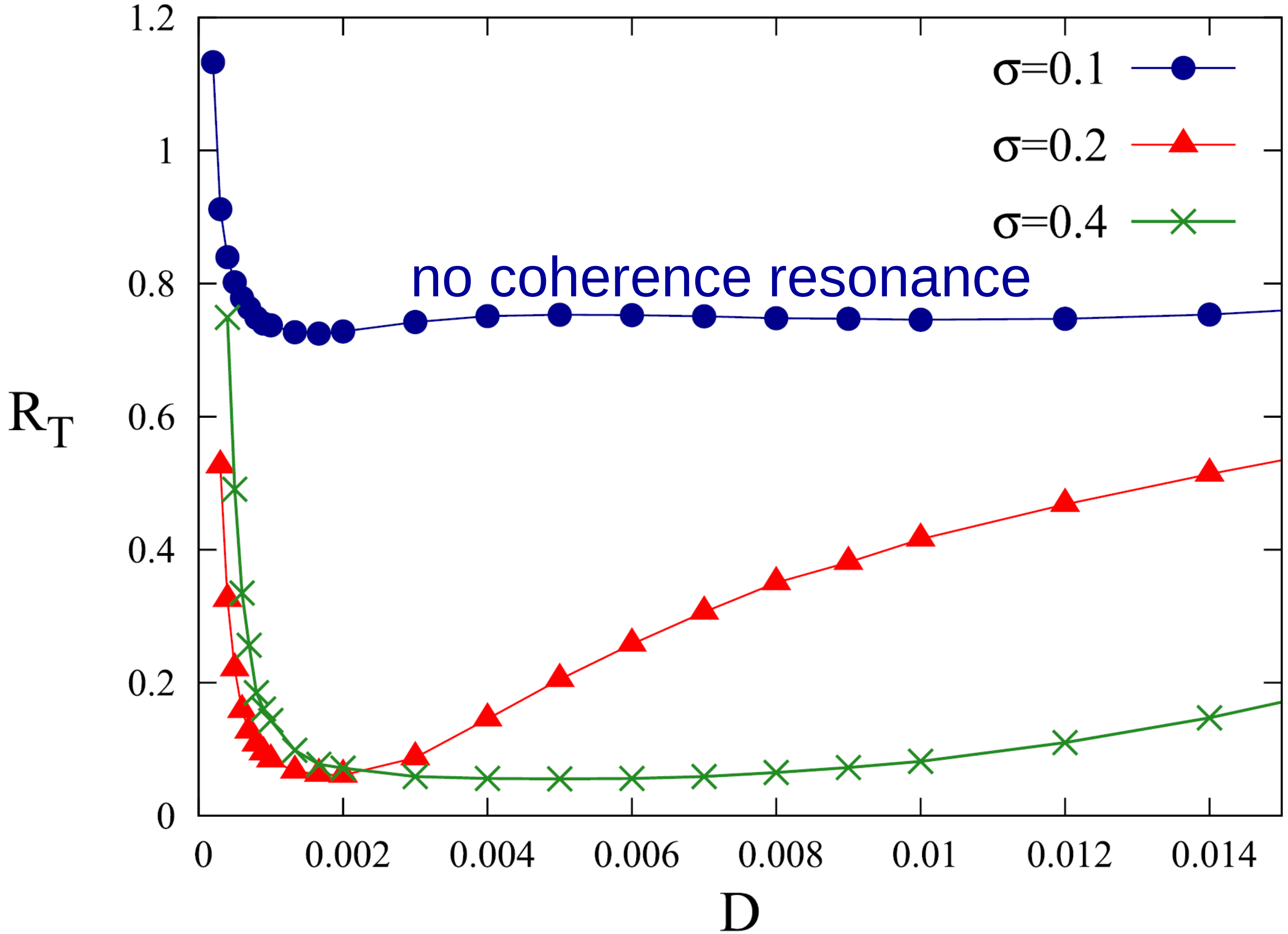
Isolated ring network



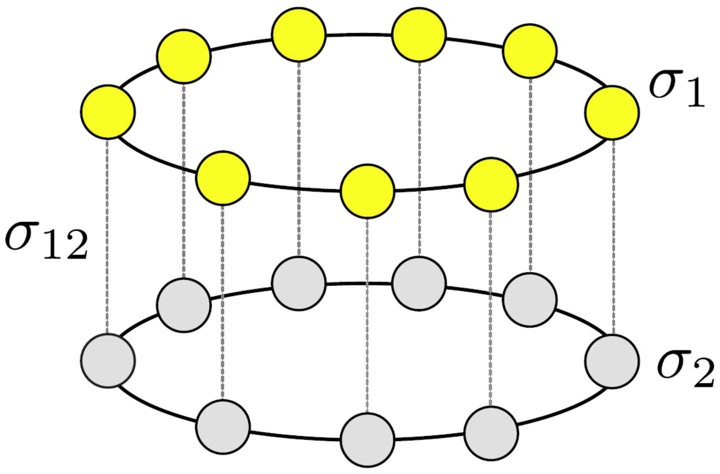


Isolated ring network

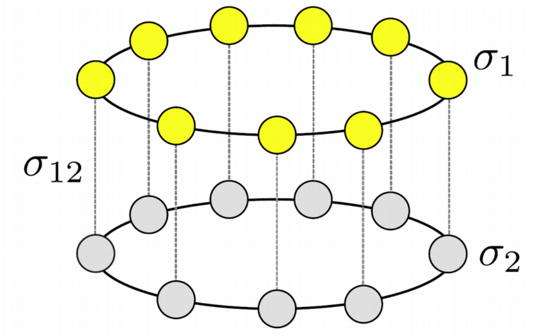


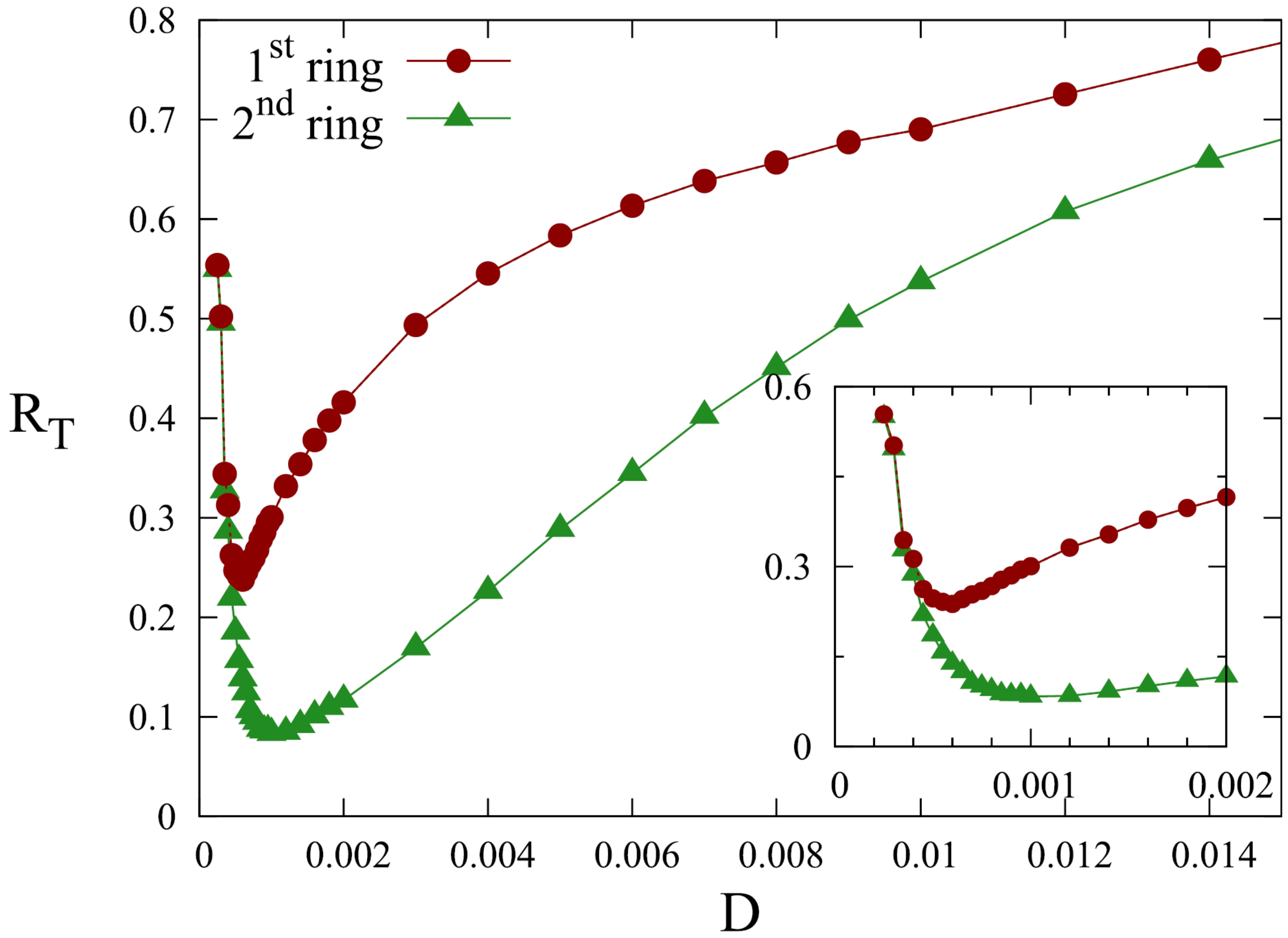


Multiplex network: coupling strength mismatch



Coupling strength mismatch





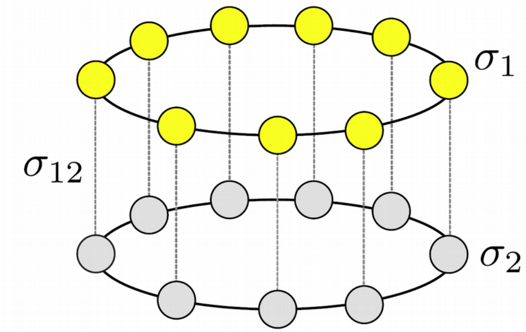
weak multiplexing
$\sigma_{12} = 0.04$

$\sigma_1 = 0.1$ (no CR in isolation)

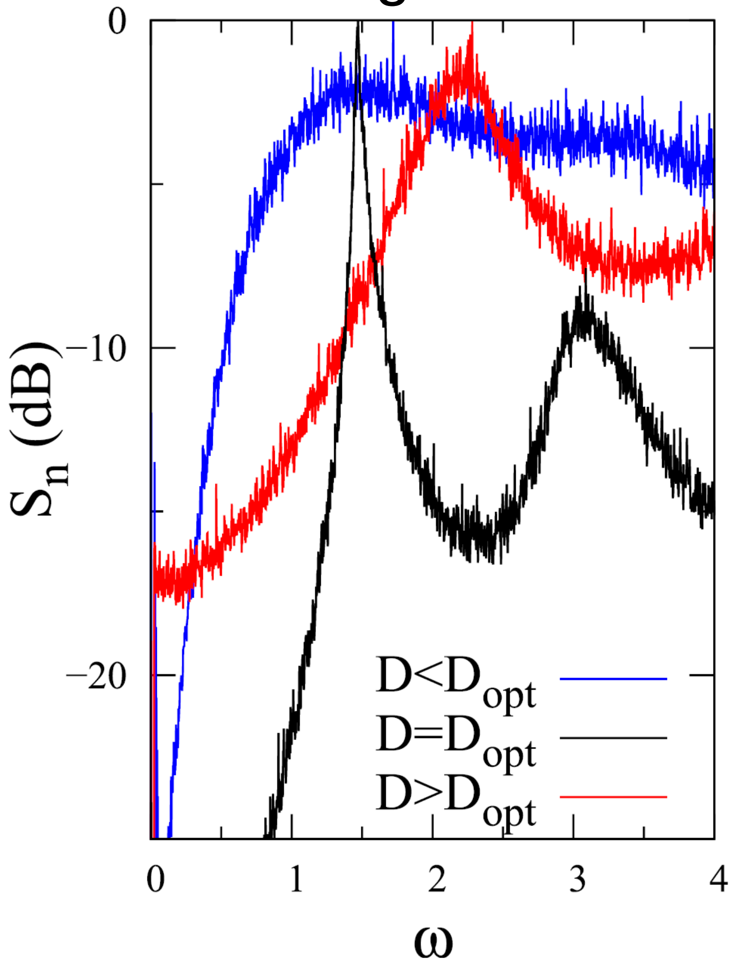
$\sigma_2 = 0.2$ (optimal)

- Weak multiplexing induces coherence resonance

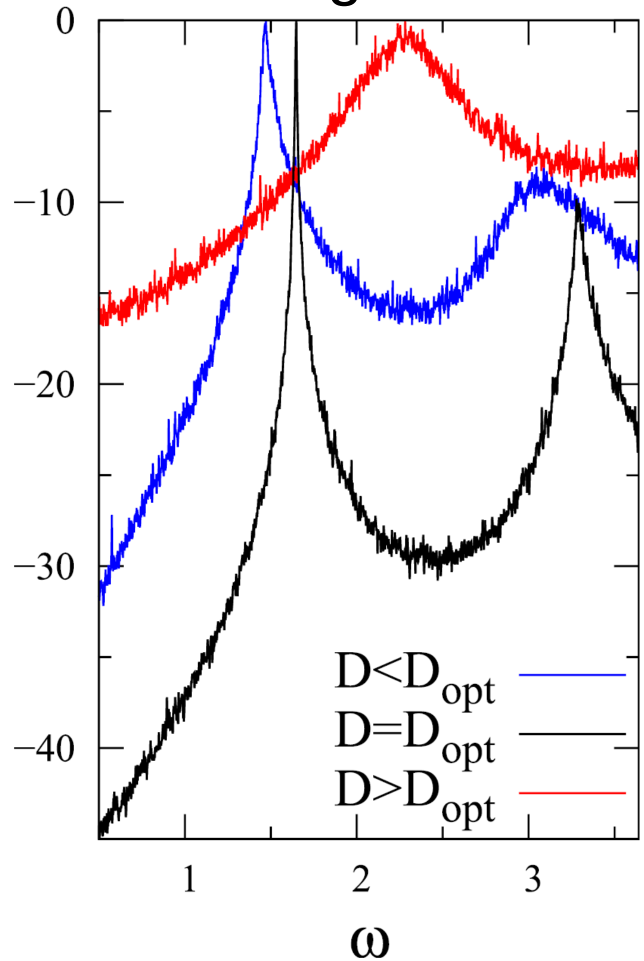
Coupling strength mismatch



1st ring



2nd ring



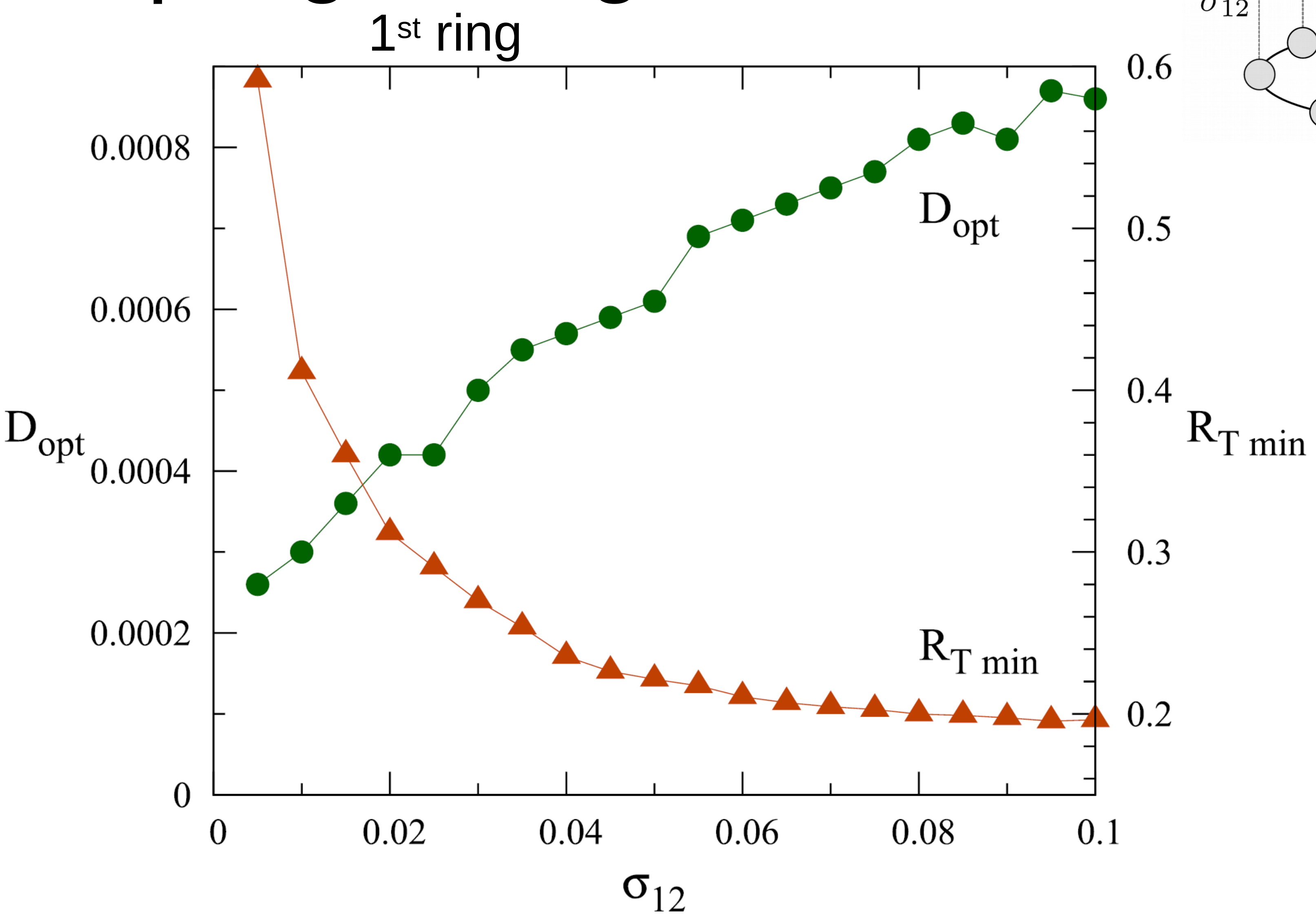
weak multiplexing
σ_{12} = 0.04

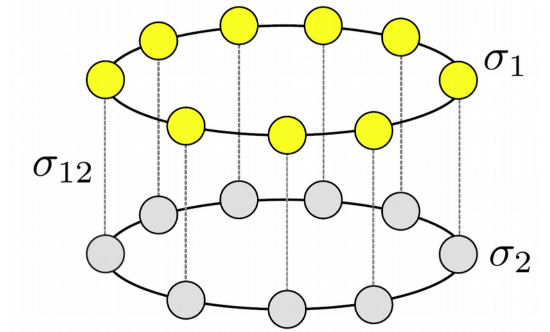
σ_1 = 0.1 (no CR in isolation)

σ_2 = 0.2 (optimal)

- Coherence resonance is better pronounced in the 2nd ring

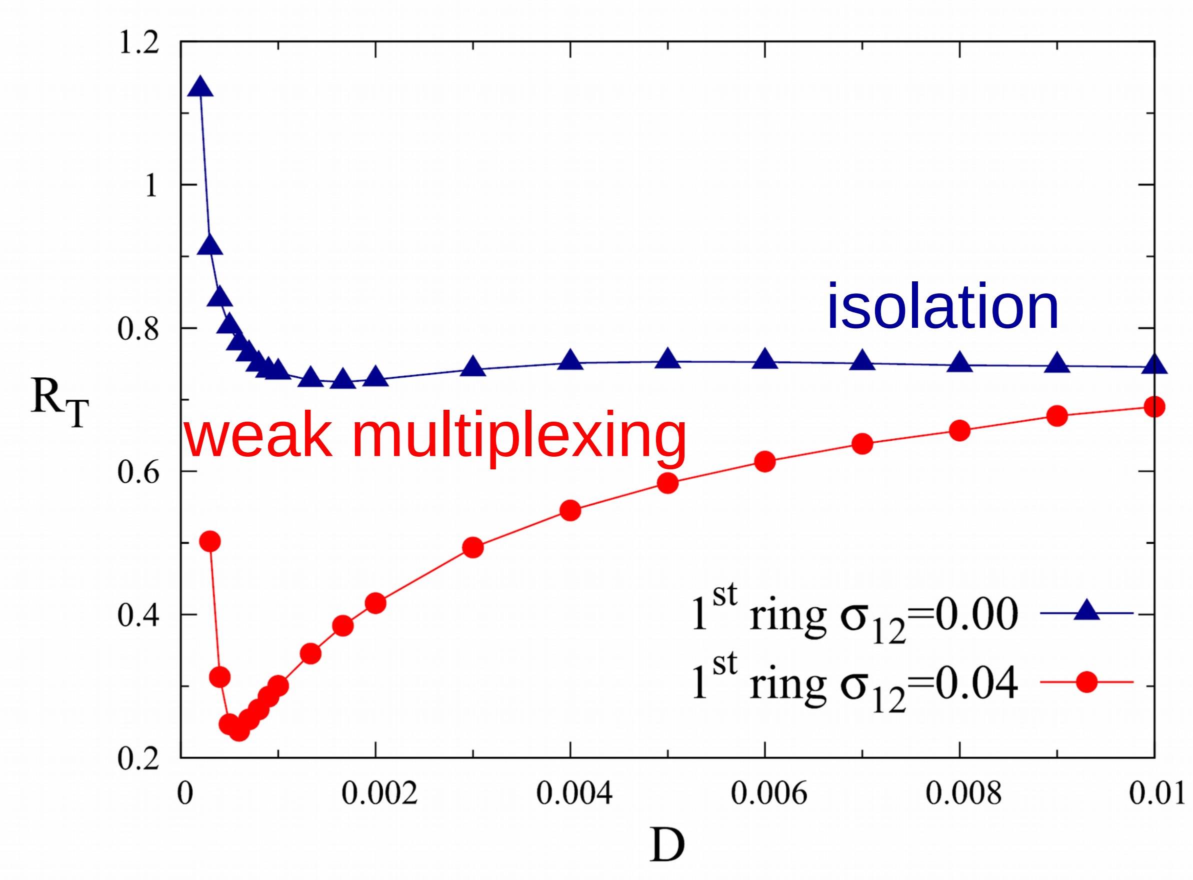
Coupling strength mismatch

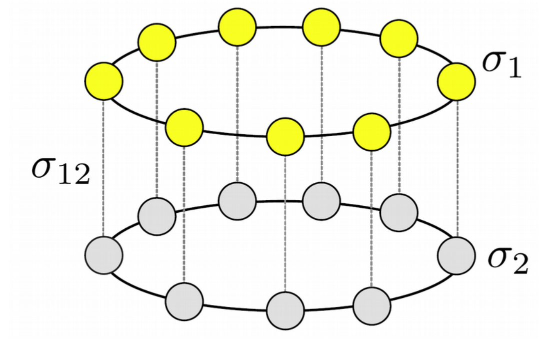




- Stronger multiplexing increases the coherence of oscillations in the 1st ring

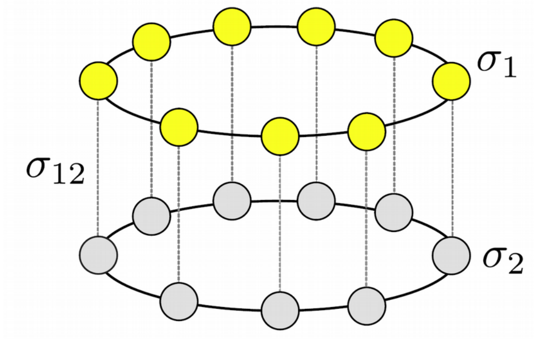
Coupling strength mismatch





- Weak multiplexing induces coherence resonance

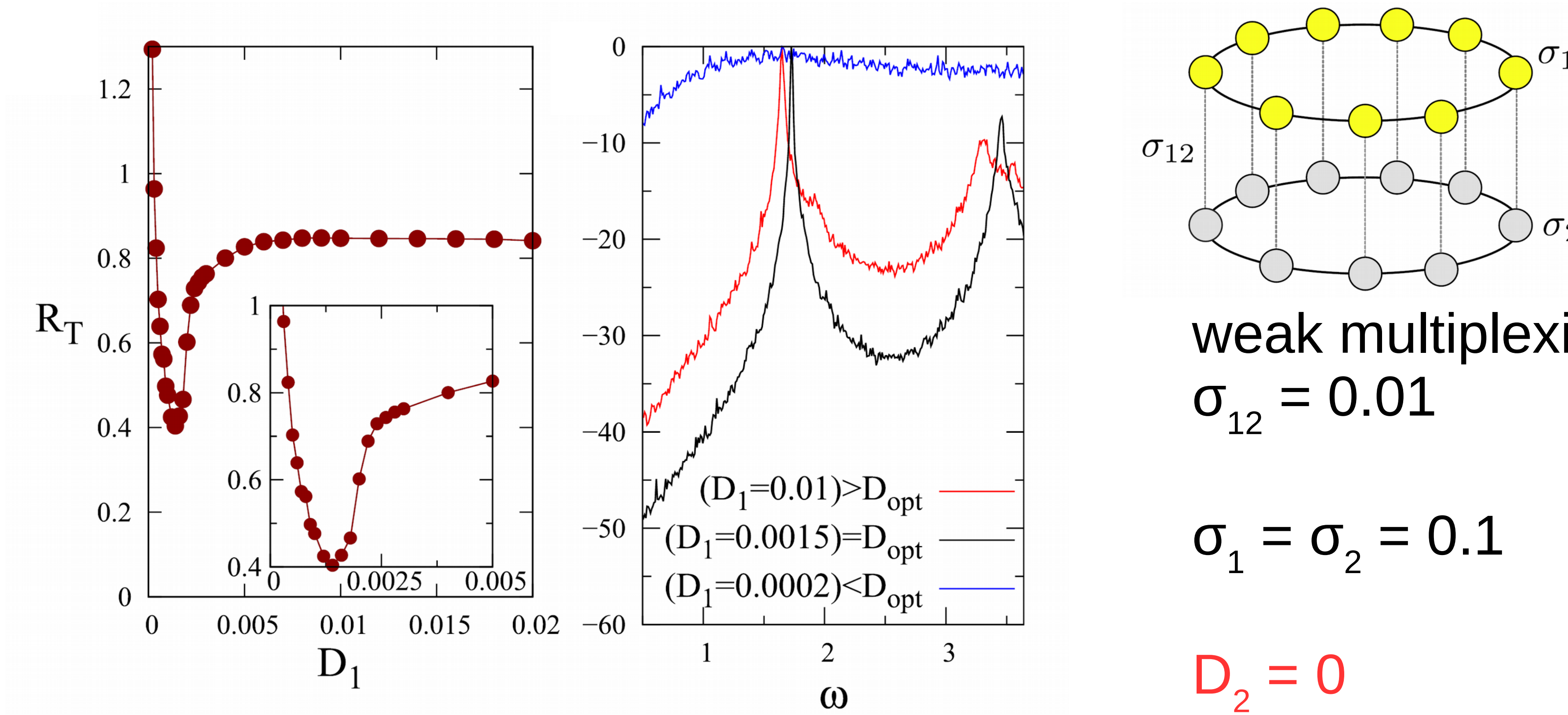
N. Semenova and A. Zakharova, Weak multiplexing induces coherence resonance, Chaos Fast Track 28, 5, 051104 (2018) *Selected as Editor's Pick



Deterministic layer multiplexed with a noisy layer

Deterministic layer multiplexed with a noisy layer

2nd ring



weak multiplexing
$\sigma_{12} = 0.01$

$\sigma_1 = \sigma_2 = 0.1$

$D_2 = 0$

- Weak multiplexing induces coherence resonance in the deterministic layer

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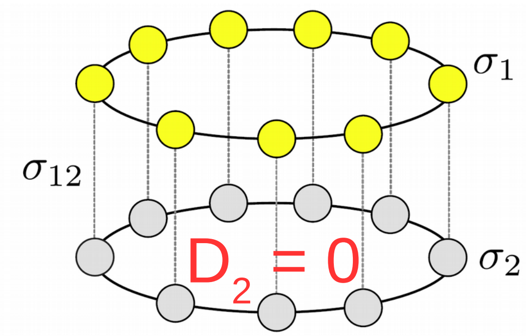
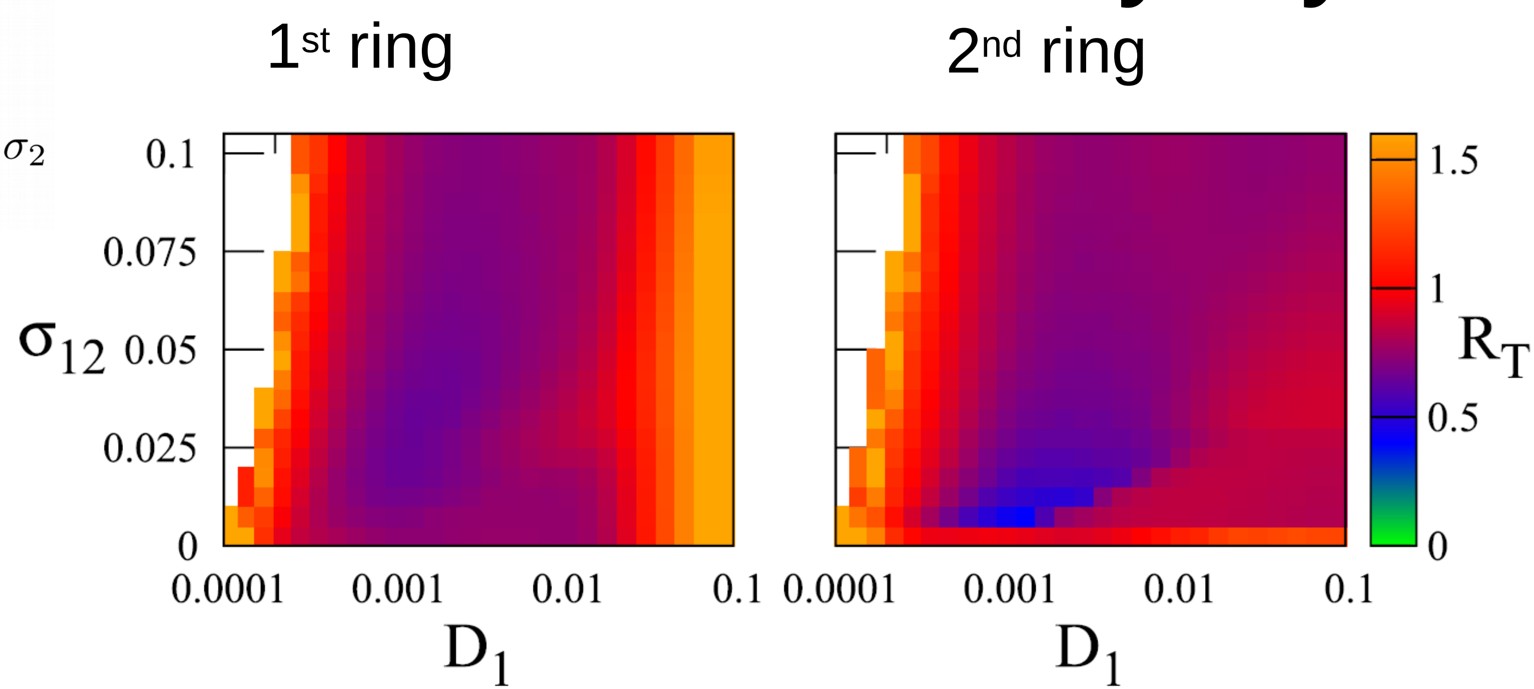
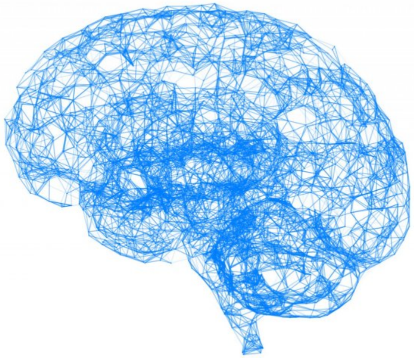
Deterministic layer multiplexed with a noisy layer

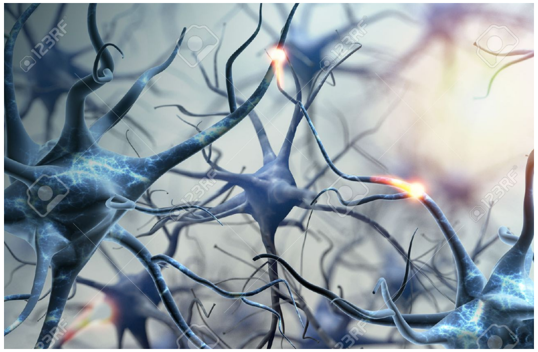




- Coherence resonance is more pronounced in the 2nd layer
- Stronger multiplexing shifts the minimum of R_T to larger values of noise
- Multiplexing induces coherence resonance for rather small values of σ_{12}

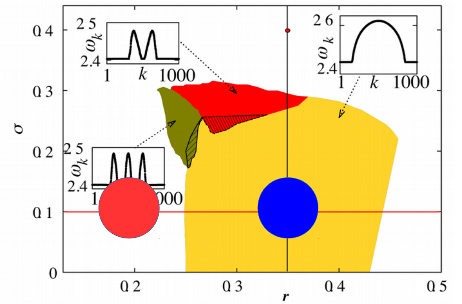


Conclusions

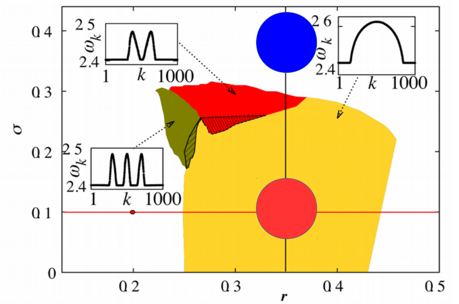


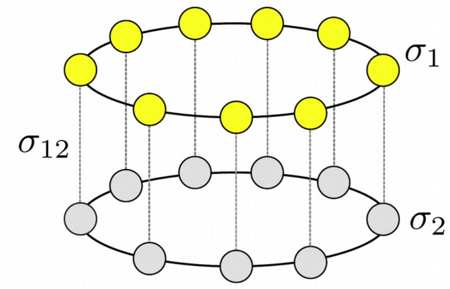
Multiplexing is a powerful method to control neural networks in both oscillatory and excitable regimes:

- induces chimeras with desired properties in the parameter regime where they do not occur in isolation

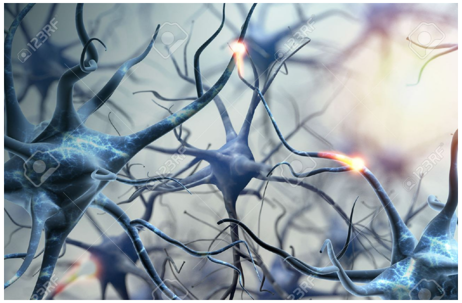


- suppresses chimeras in the parameter regimes where they occur in isolation and induces in-pase sync, two-headed chimeras, **solitary states**



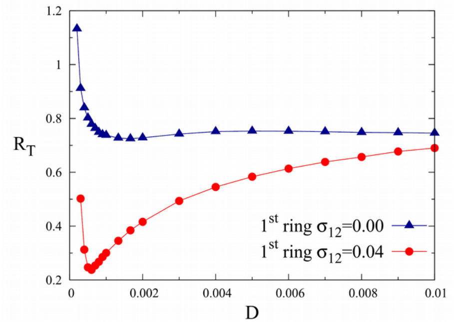


Conclusions

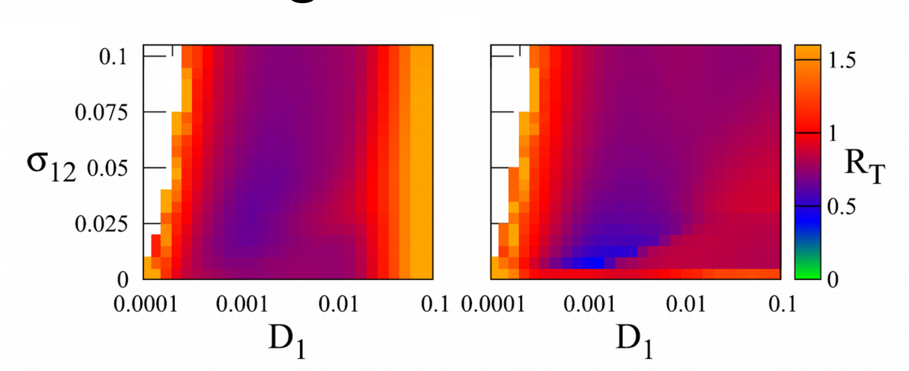


Weak multiplexing induces **coherence resonance** in the parameter regimes where it is absent for isolated networks

the coupling strength is not optimal

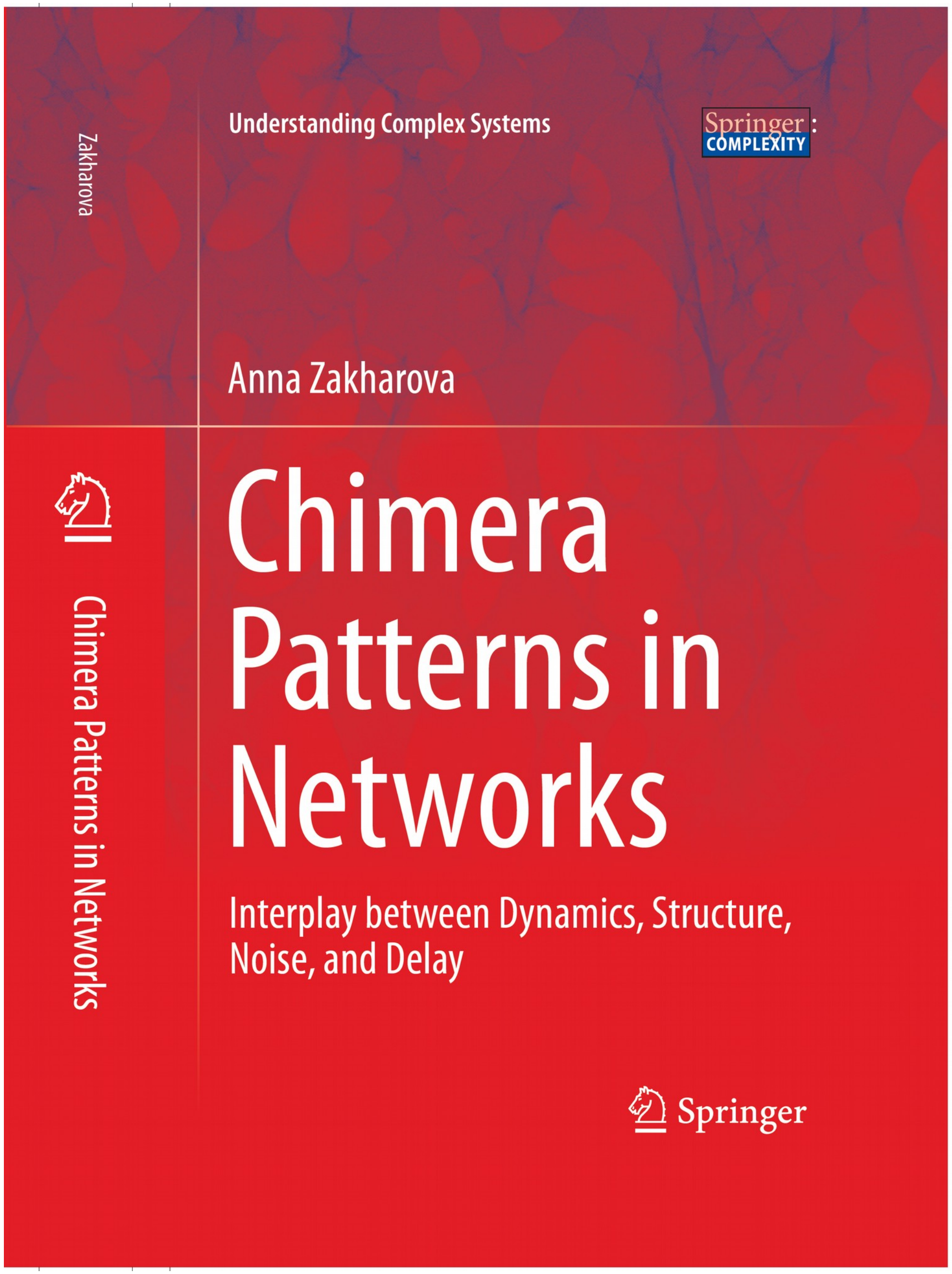


there is **no noise** noise exciting the elements



First book on chimera states

- To appear in 2020



Thanks to my collaborators

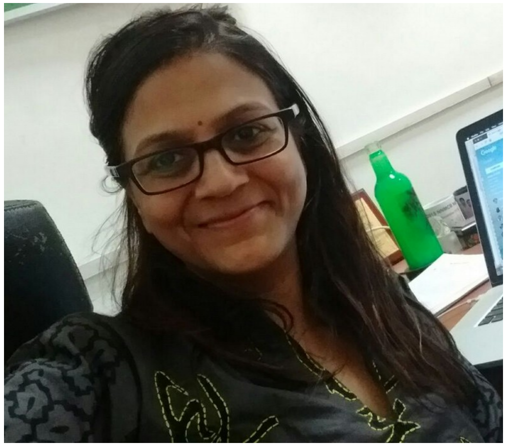
Leonhard Schülen

Maria Mikhailenko

Lukas Ramlow

Nadezhda Semenova

Sarika Jalan



Vadim Anishchenko

Galina Strelkova

Elena Rybalova

Thank you!