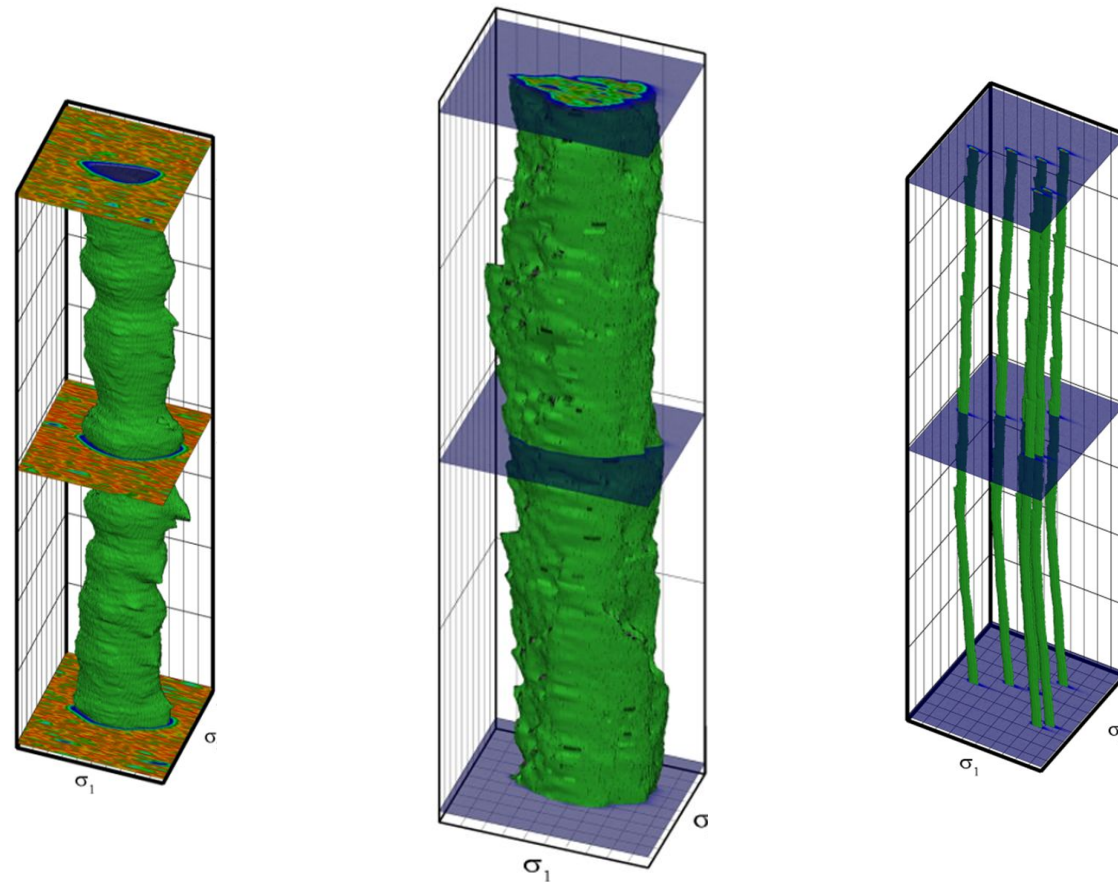


Chimera States in Nonlinear Systems with Multiple Delayed Feedbacks



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FEMTO-ST Institute, France

in collaboration with

D. Brunner R. Levchenko E. Schöll L. Larger Y. Maistrenko

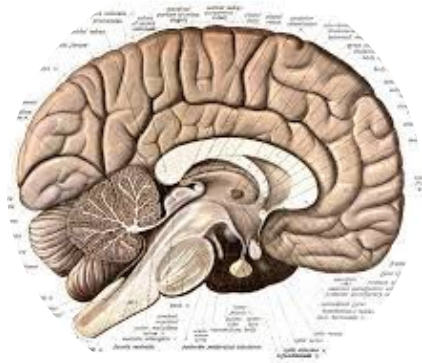


Delays affect your life in a number of ways

Long-distance light propagation



Propagation delays in the brain

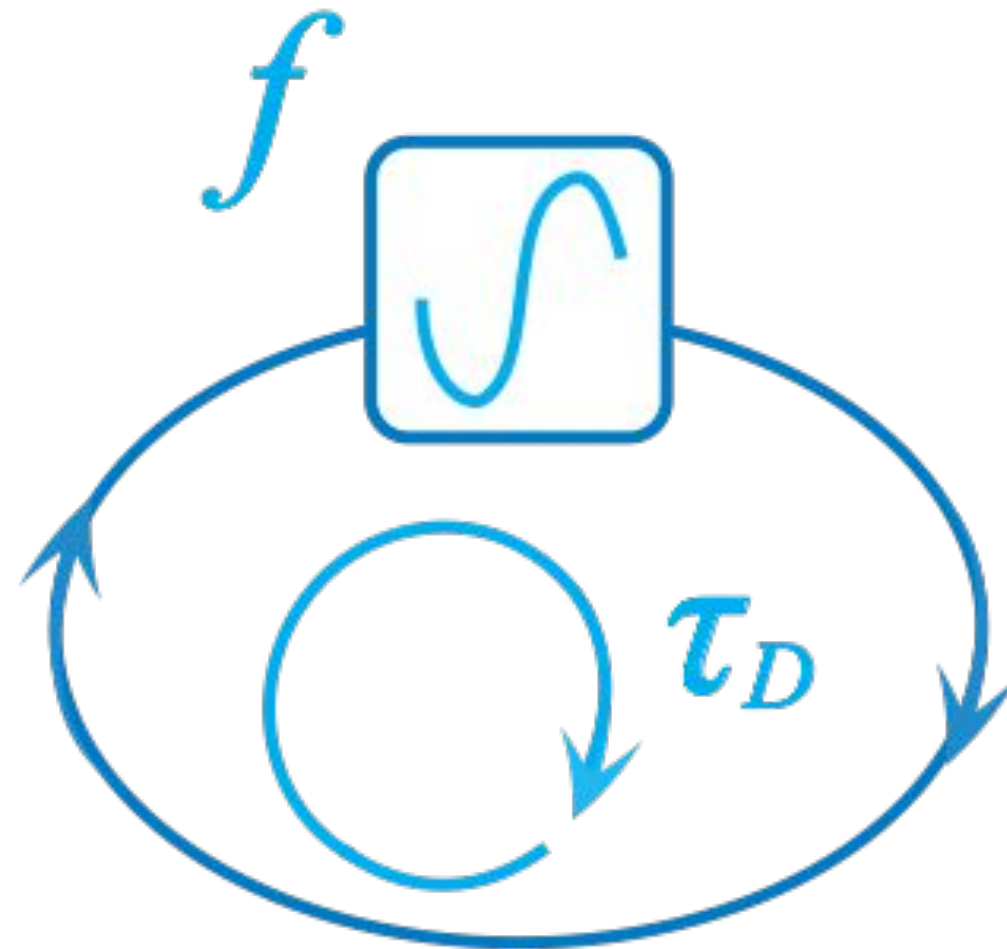


Traffic jams

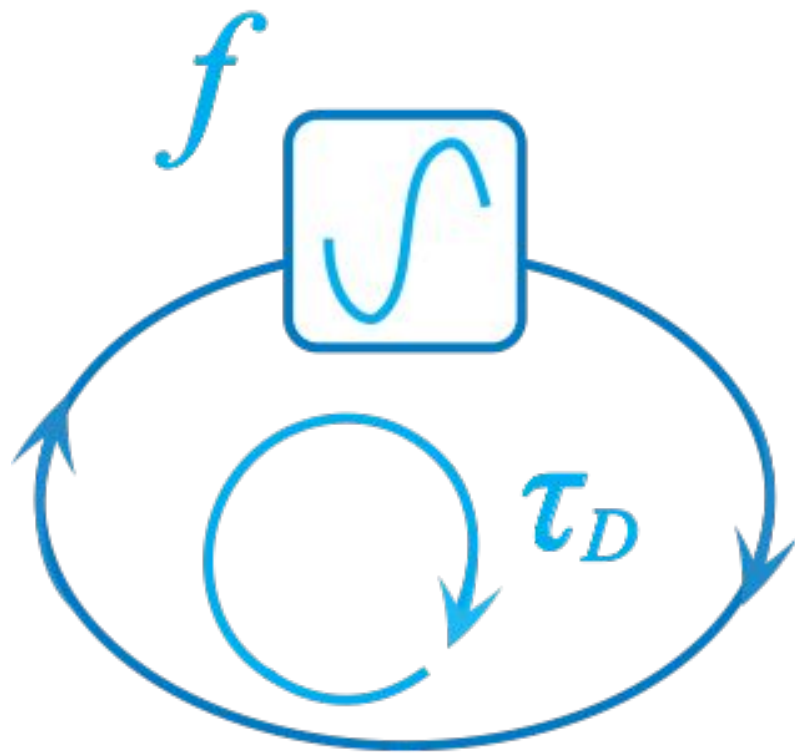


Hot-cold water control in a shower!

Delayed-feedback Systems



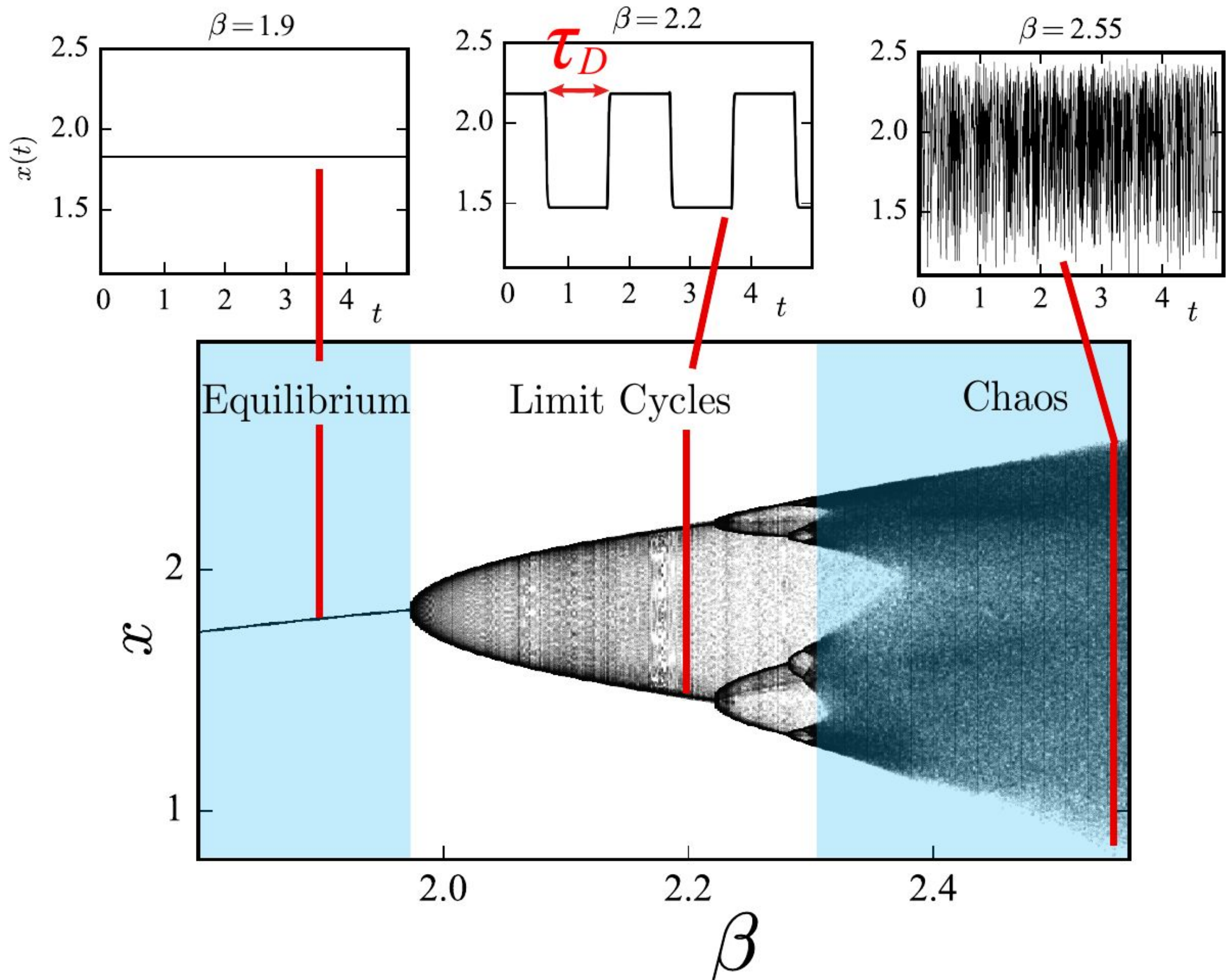
Delay Differential Equations (DDEs)



$$\tau \dot{x}(t) + x(t) = \beta f(x(t - \tau_D))$$

- $x(t)$ is dynamical variable
- τ_D is delay time
- $\tau \ll \tau_D$ is system response time
- $f(x)$ is nonlinear transformation
- β is feedback gain

Dynamical regimes. Bifurcations



Applications of NL Delay Dynamics



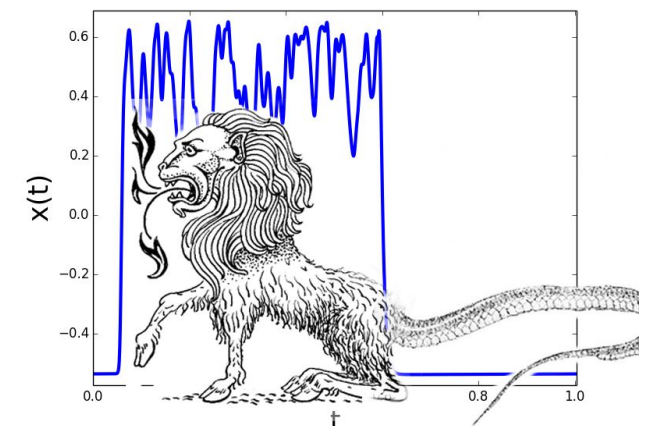
Chaos communications, 1995

High spectral purity microwave oscillators, 1994



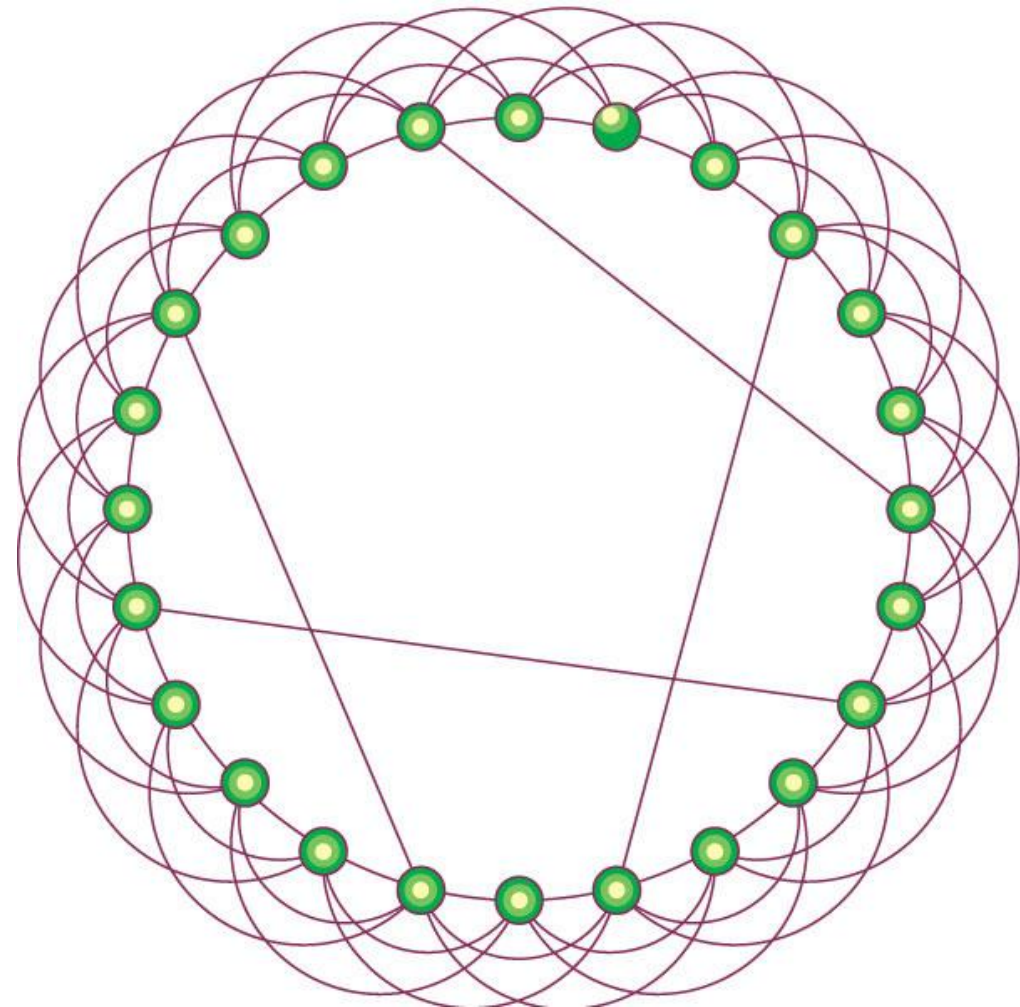
Photonic Reservoir Computing, 2012

Chimera study in networks of virtual oscillators, 2013



Understanding NL Dynamical Networks is Crucial

- . Power grids
- . Internet
- . Social networks
- . Bird swarms
- . Brain



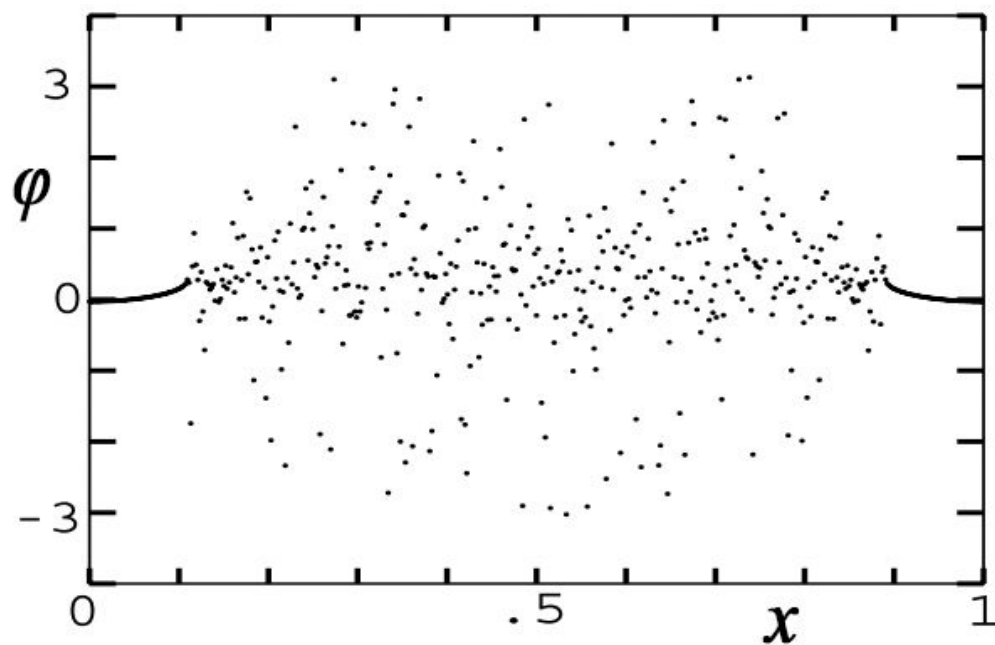
* Image from S. H. Strogatz (Nature, 2001.)



What are chimeras?
...monstrous fire-breathing creatures

Chimeras: Kuramoto and Delay Networks

- Chimera is a network state consisting of incongruent parts: coherent and chaotic.



- Symmetric Kuramoto network
- Long-range coupling to obtain a chimera state

Chimera states can arise in many real-world networks

- Power grids
- Networks of neurons in the human heart

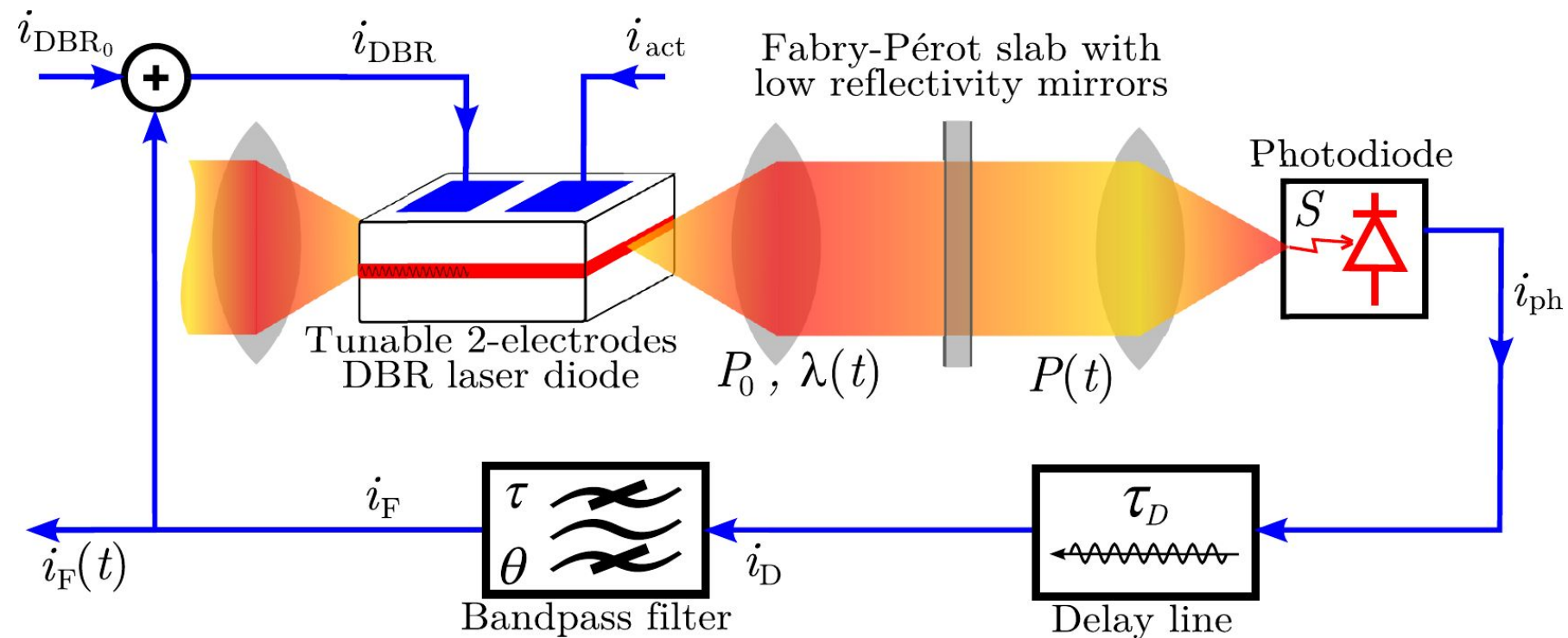
Leading to failure of the system.

Are chimeras possible in delay systems?

*Y. Kuramoto (Nonlin. Phenomena in Complex Sys., 2002.)

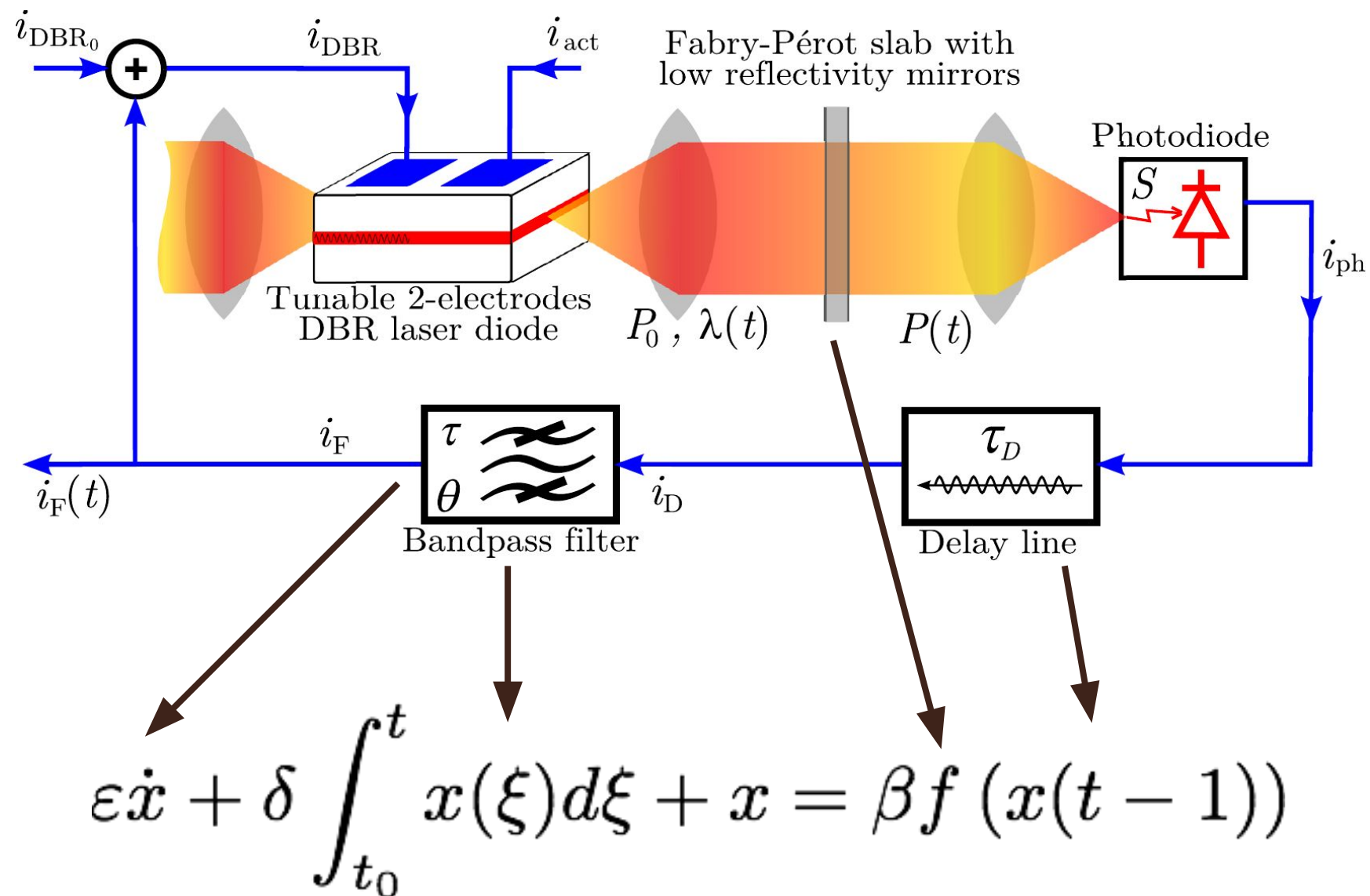
Chimeras in single delay systems

Experimental Setup For Delay Chimeras

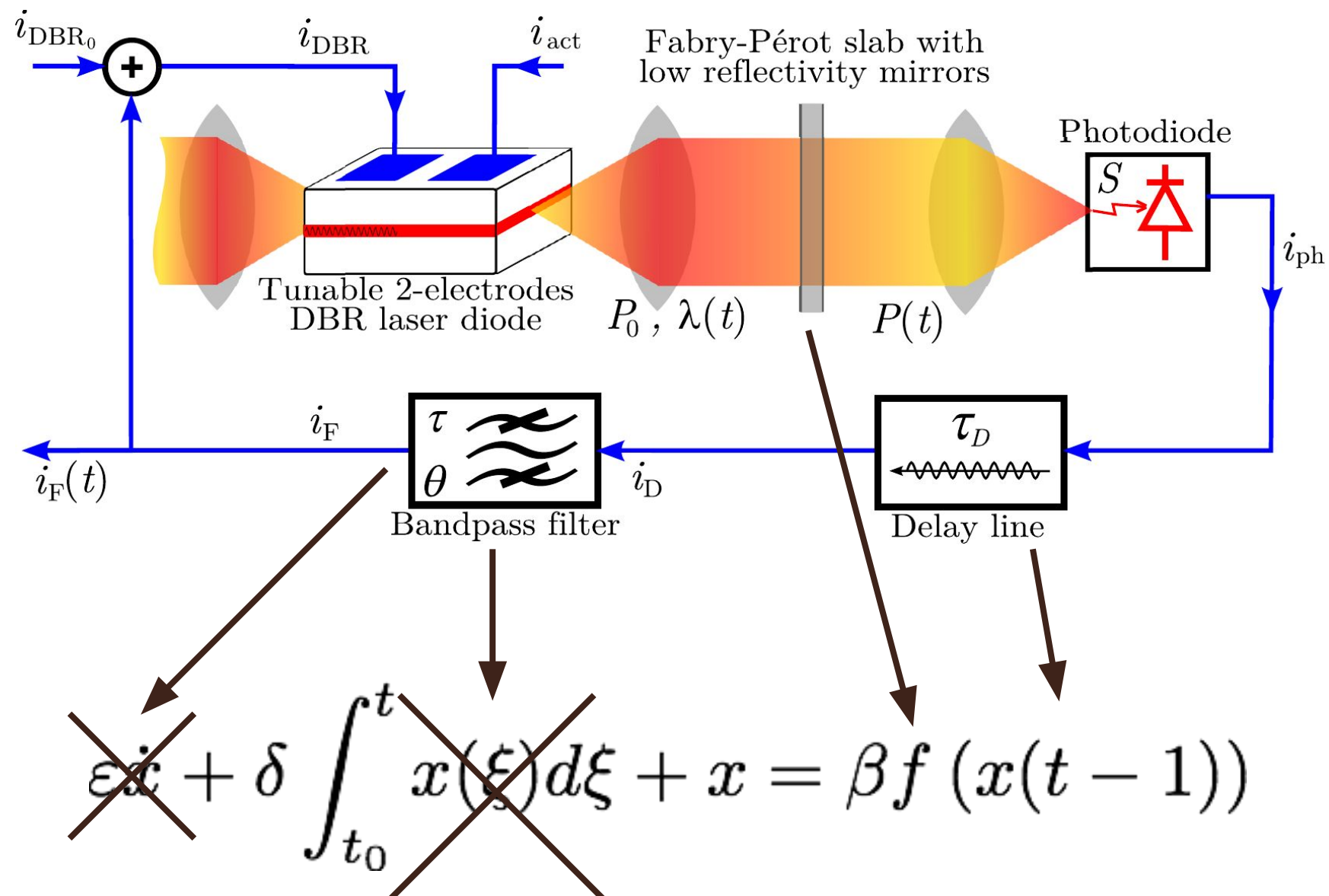


- Laser light is NL transformed
- The signal is delayed, filtered
- The signal is modulating the wavelength of the laser

Experimental Setup For Delay Chimeras

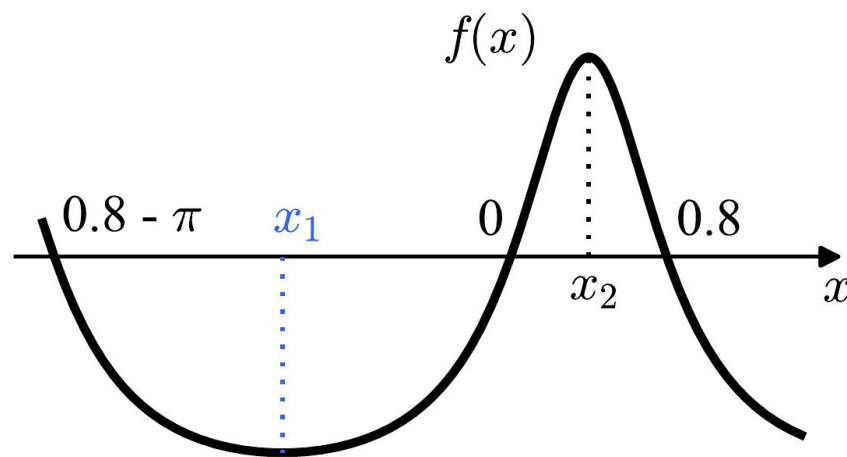


Experimental Setup For Delay Chimeras



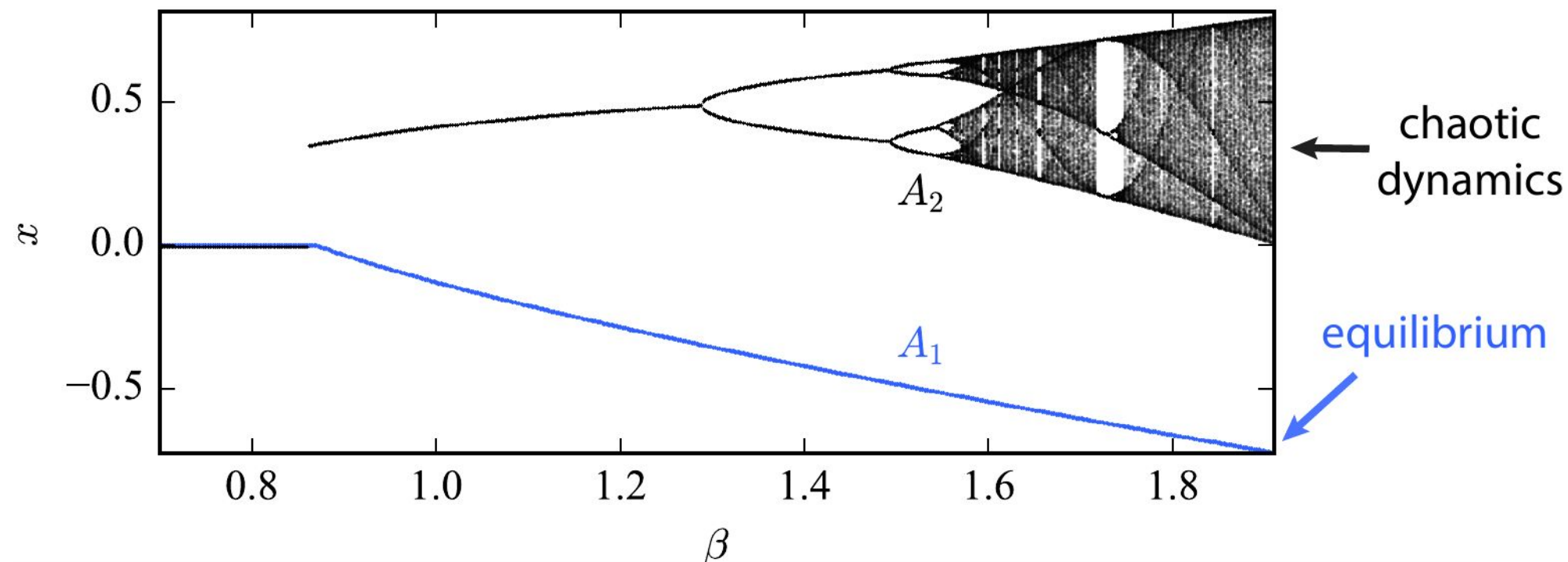
System Properties

NL function asymmetry

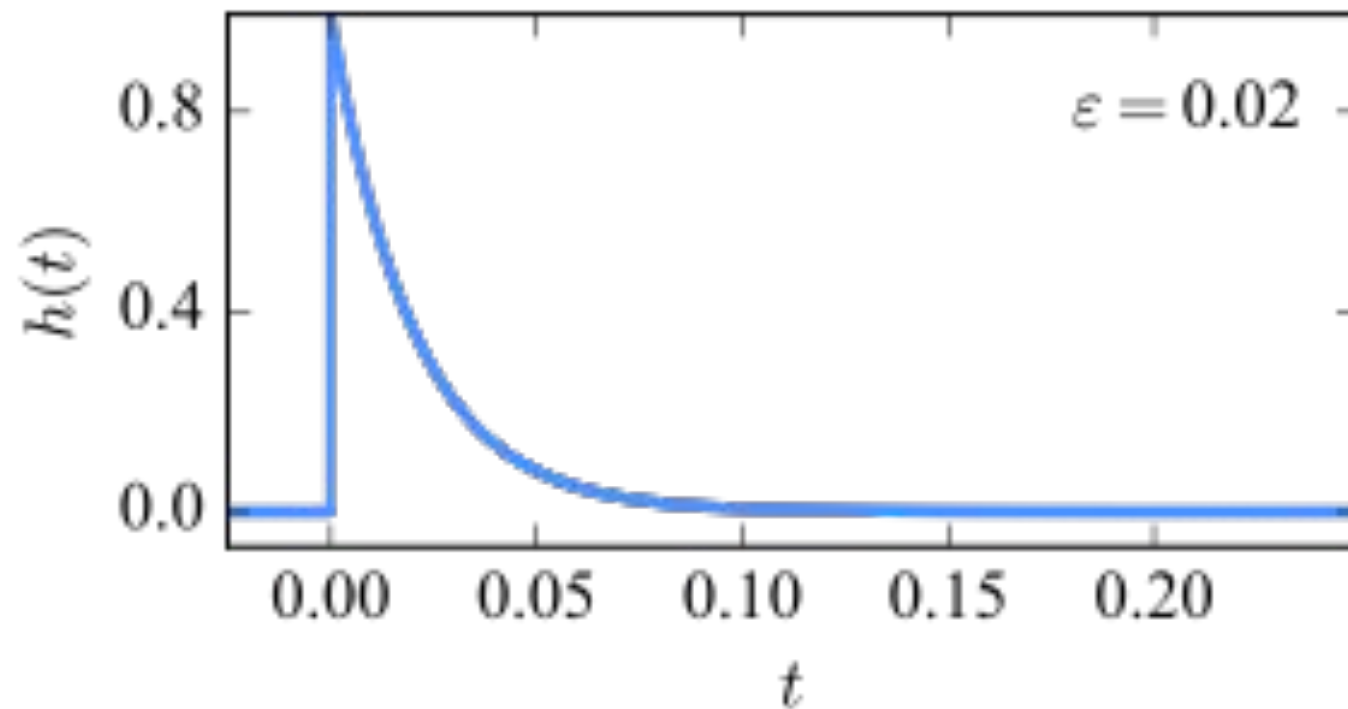


Bistability:
low gradient and large gradient

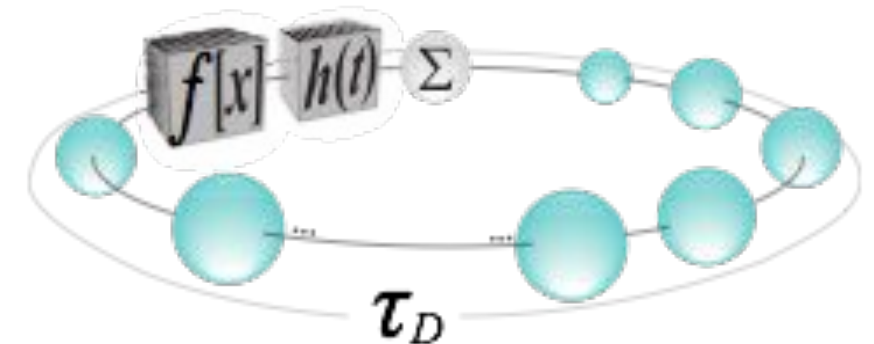
Singular limit map $x_n = \beta f(x_{n-1})$



"Coupling" Induced By Filters



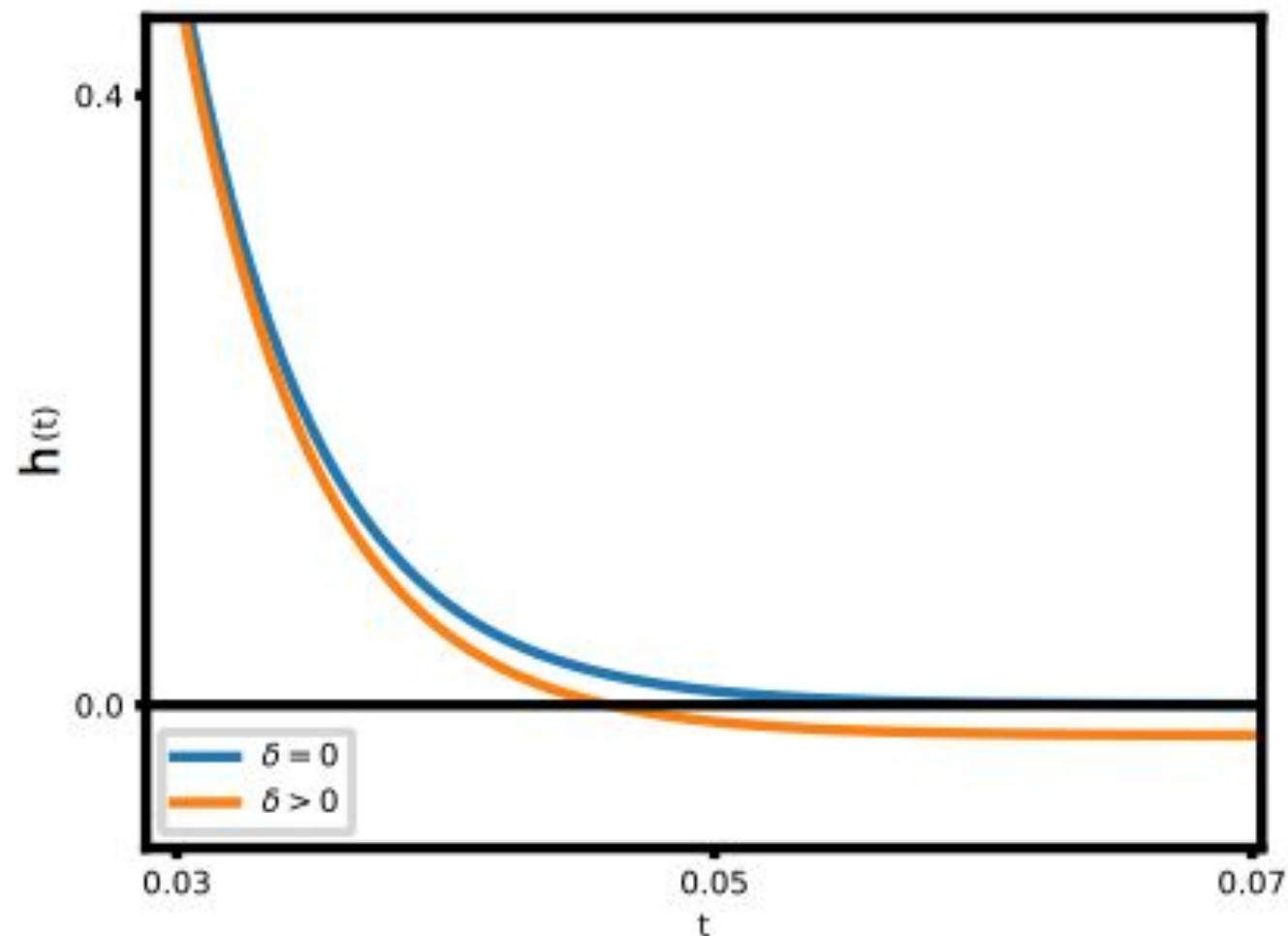
Impulse response function $h(t)$



$$\varepsilon \dot{x} + \delta \int_{t_0}^t x(\xi) d\xi + x = \beta f(x(t-1))$$

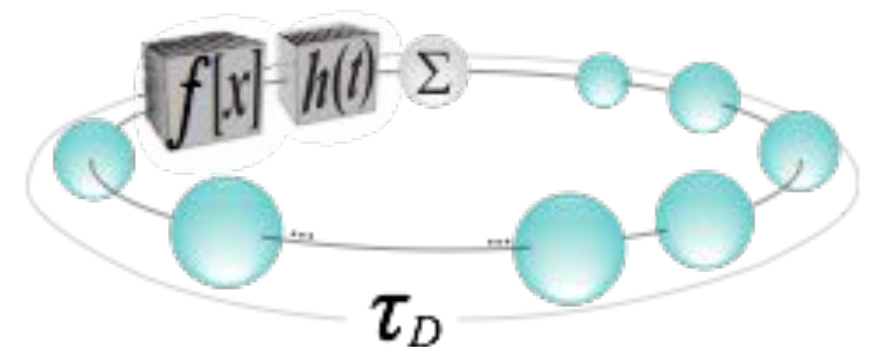
$$x_{\sigma}(n') = \underbrace{x_{\sigma}(n' - 1)}_{\text{Discrete coupling}} + \underbrace{\int_{\sigma-1}^{\sigma} \overbrace{h(\sigma - \xi')}^{\text{Impulse response}} \cdot \overbrace{f[x_{\xi'}(n' - 1)]}^{\text{Nonlinearity}} d\xi'}_{\text{Continuous coupling}}$$

DDE "Coupling": Impulse Response Function



Long-range coupling thanks to the integral term

$$\delta \int_{t_0}^t x(\xi) d\xi$$



$$x_{\sigma}(n') = \underbrace{x_{\sigma}(n' - 1)}_{\text{Discrete coupling}} + \underbrace{\int_{\sigma-1}^{\sigma} \overbrace{h(\sigma - \xi')}^{\text{Impulse response}} \cdot \overbrace{f[x_{\xi'}(n' - 1)]}_{\text{Nonlinearity}} d\xi'}_{\text{Continuous coupling}}.$$

Network Analogy. Space-Time Representation

PHYSICAL REVIEW A

VOLUME 45, NUMBER 7

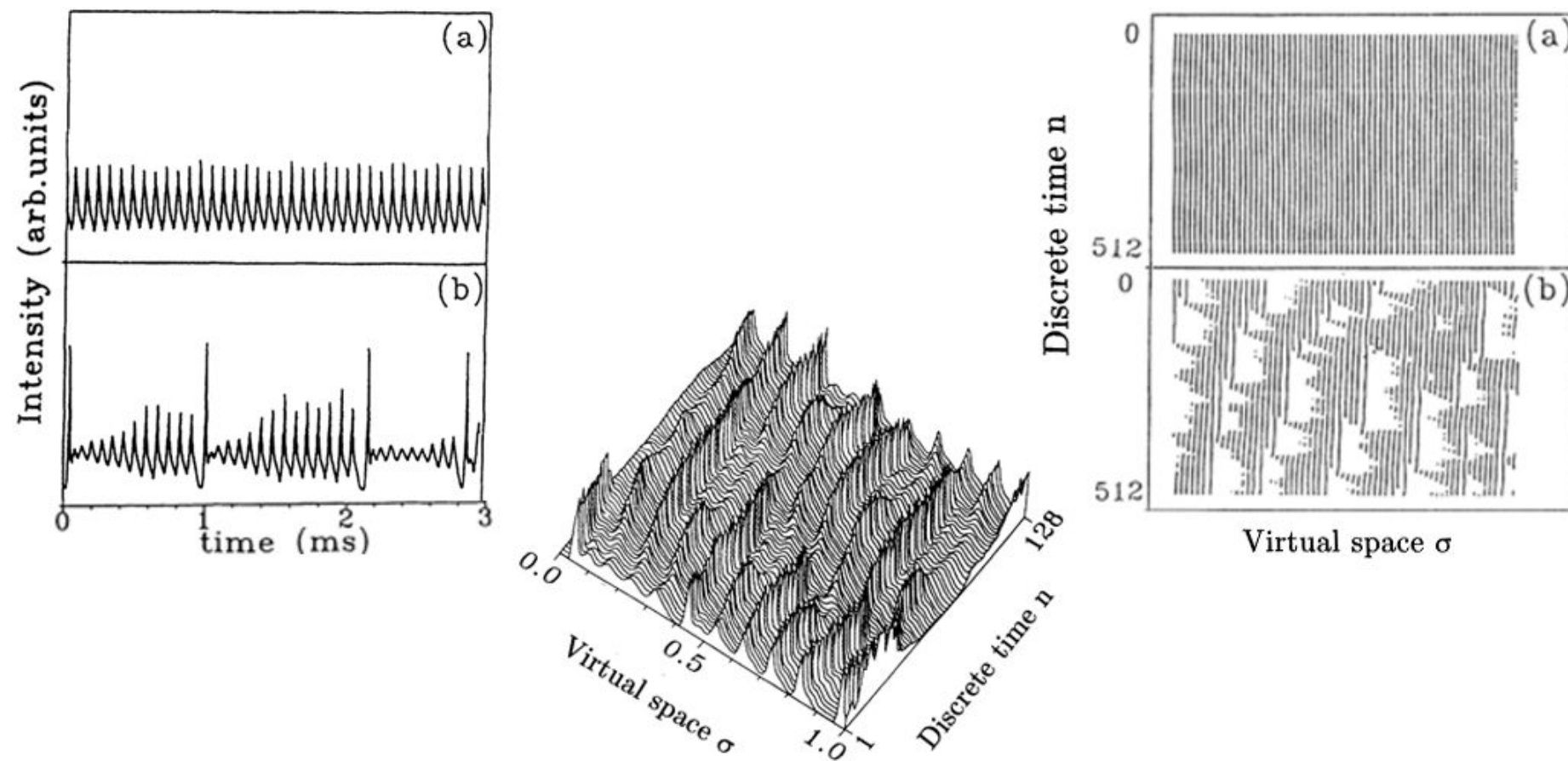
1 APRIL 1992

Two-dimensional representation of a delayed dynamical system

F. T. Arecchi,* G. Giacomelli, A. Lapucci, and R. Meucci

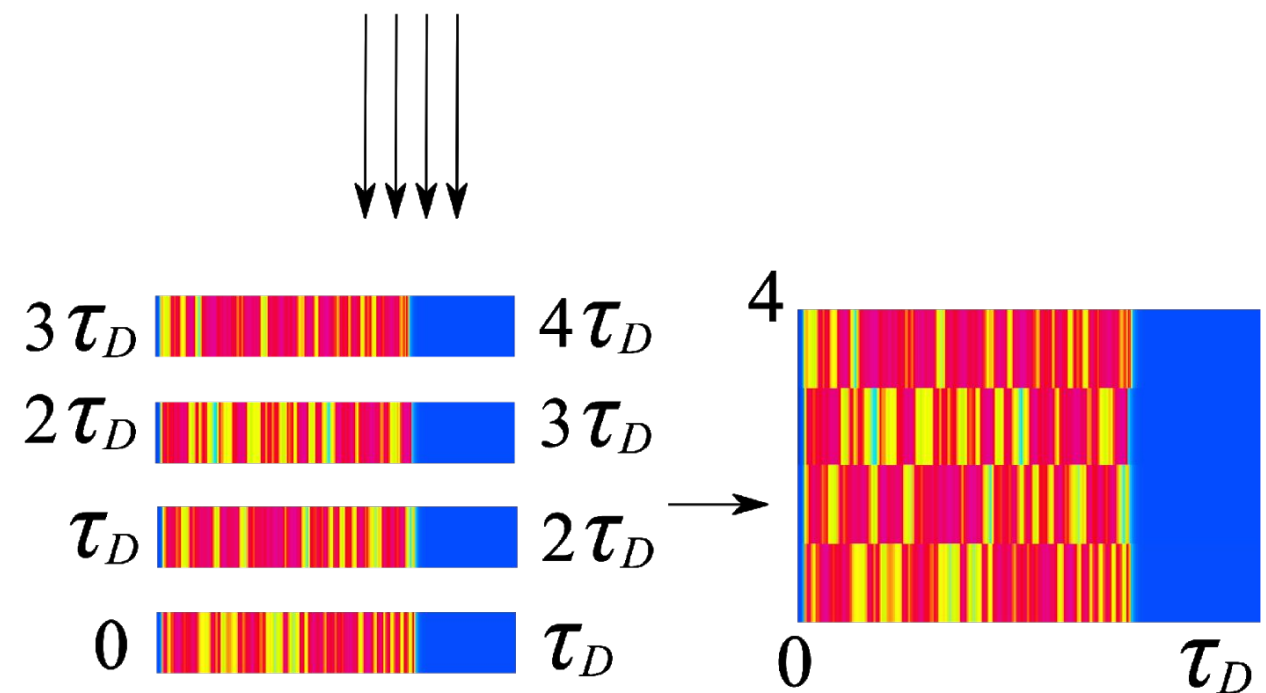
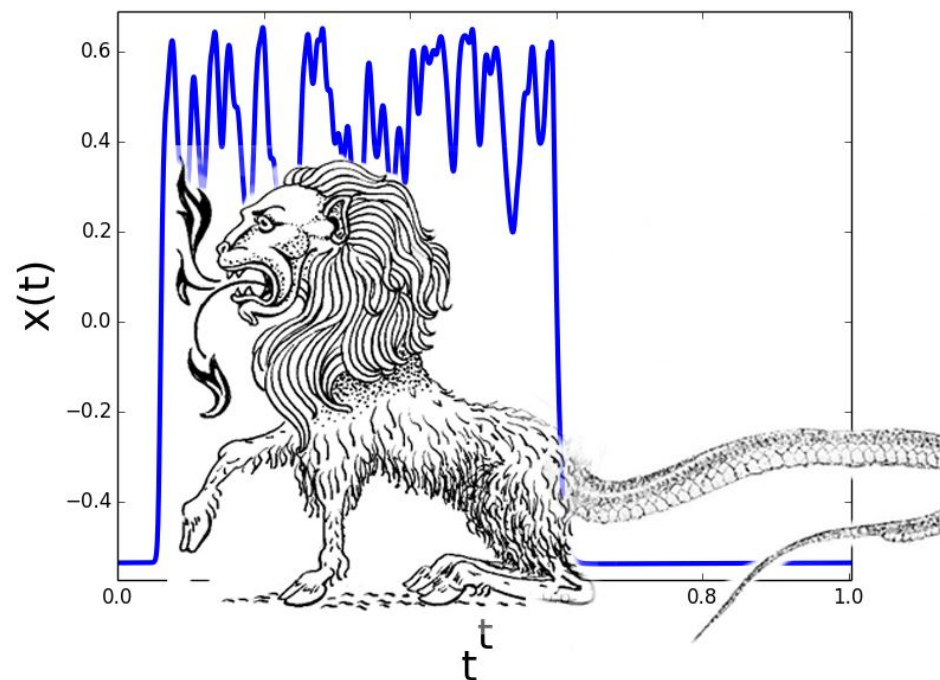
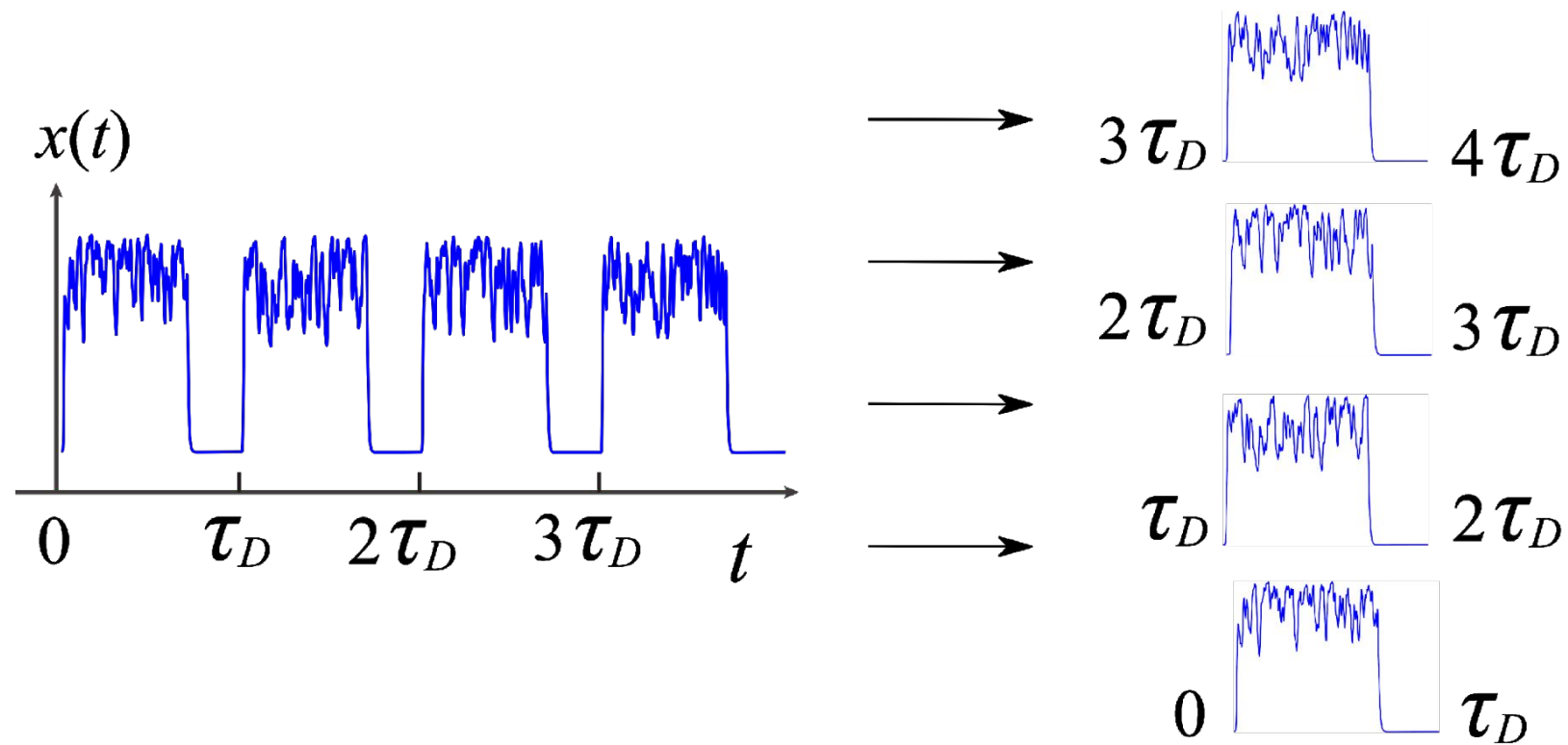
Istituto Nazionale di Ottica, Largo E. Fermi 6, 50125 Firenze, Italy

(Received 31 July 1991; revised manuscript received 10 December 1991)



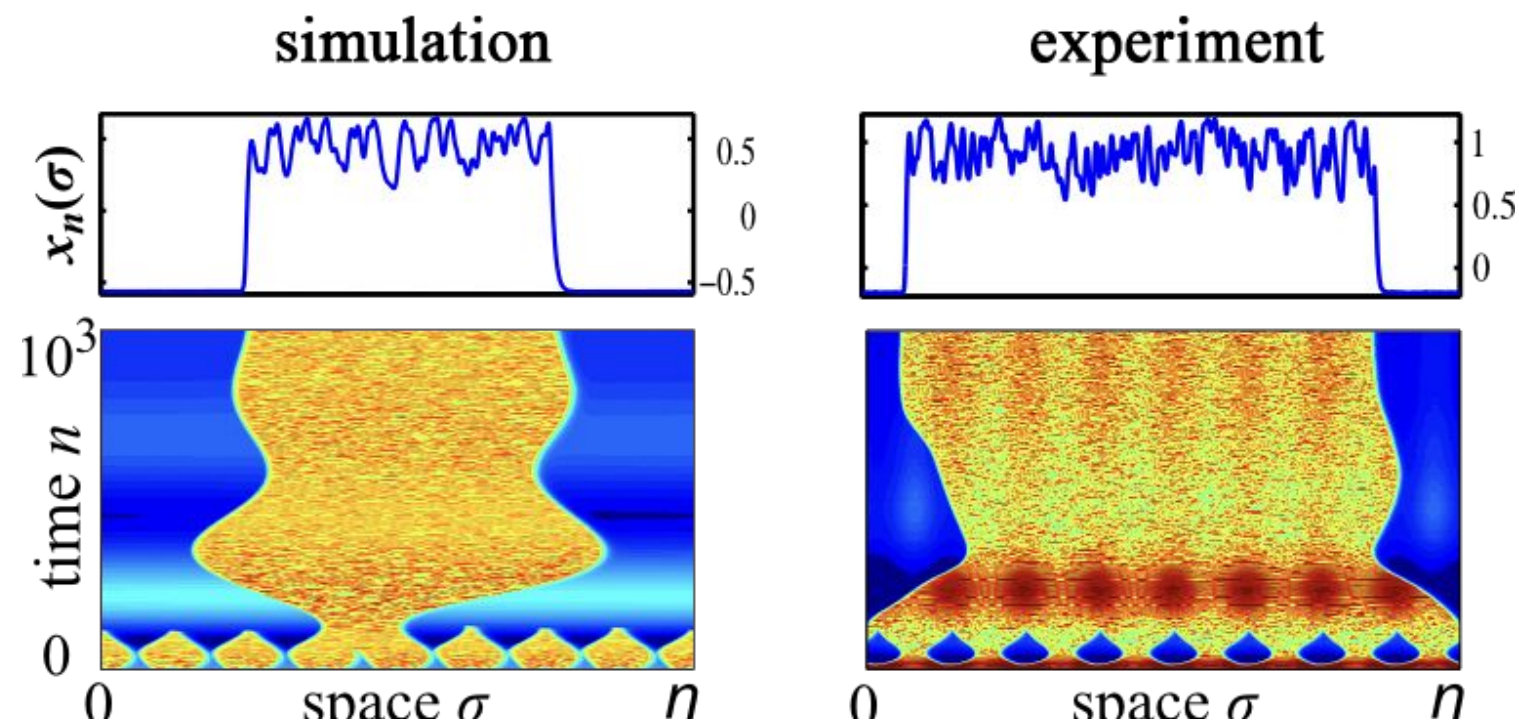
- Stacking temporal coordinates
- Virtual space

Network Analogy. Space-Time Representation



Theory vs Experiment

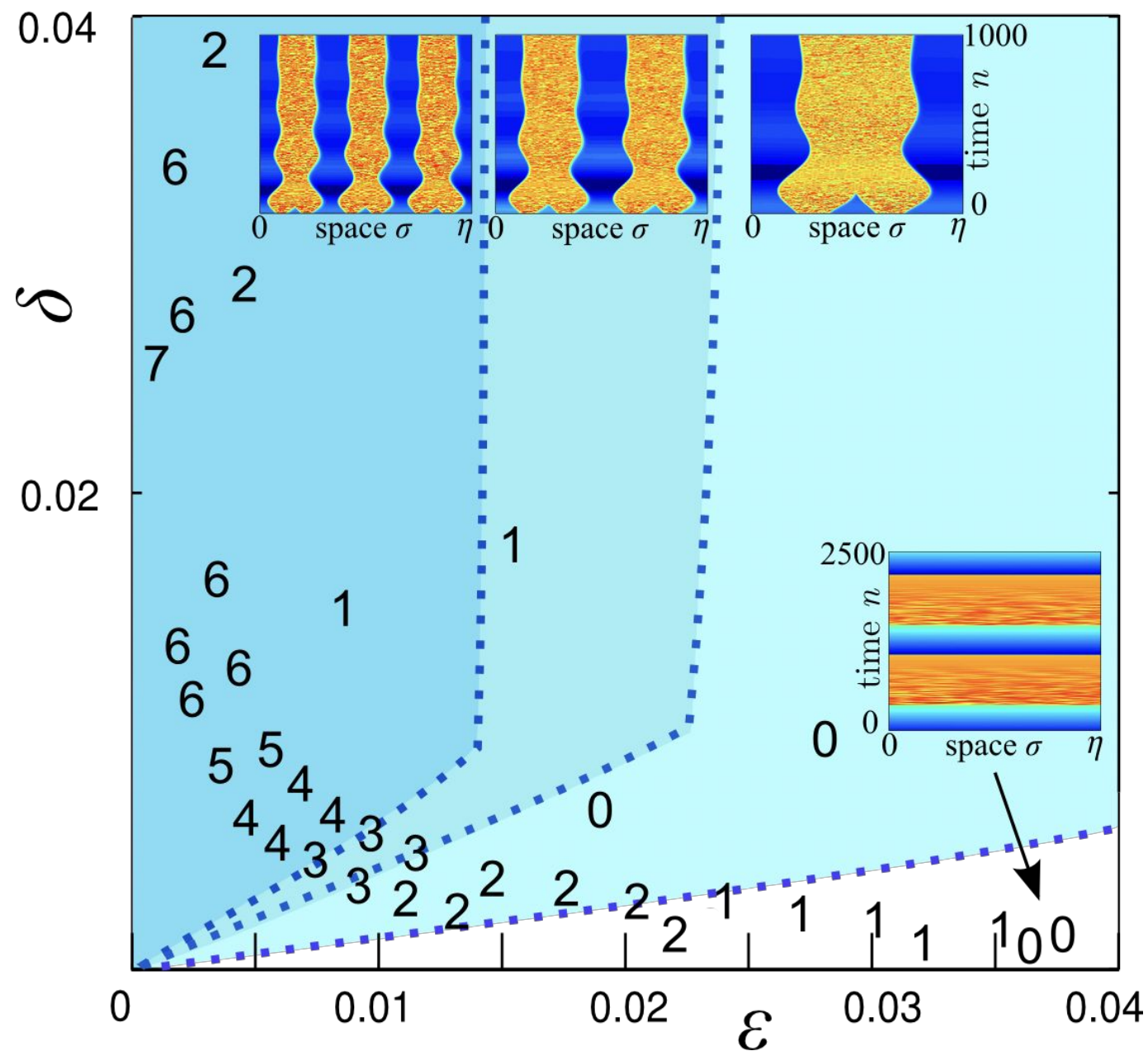
- First demonstration of chimeras in delay systems



- Exist over long time
- Excellent agreement between the model and experiment

L. Larger, B. Penkovsky, Y. Maistrenko (PRL 2013; Nature Comm. 2015)

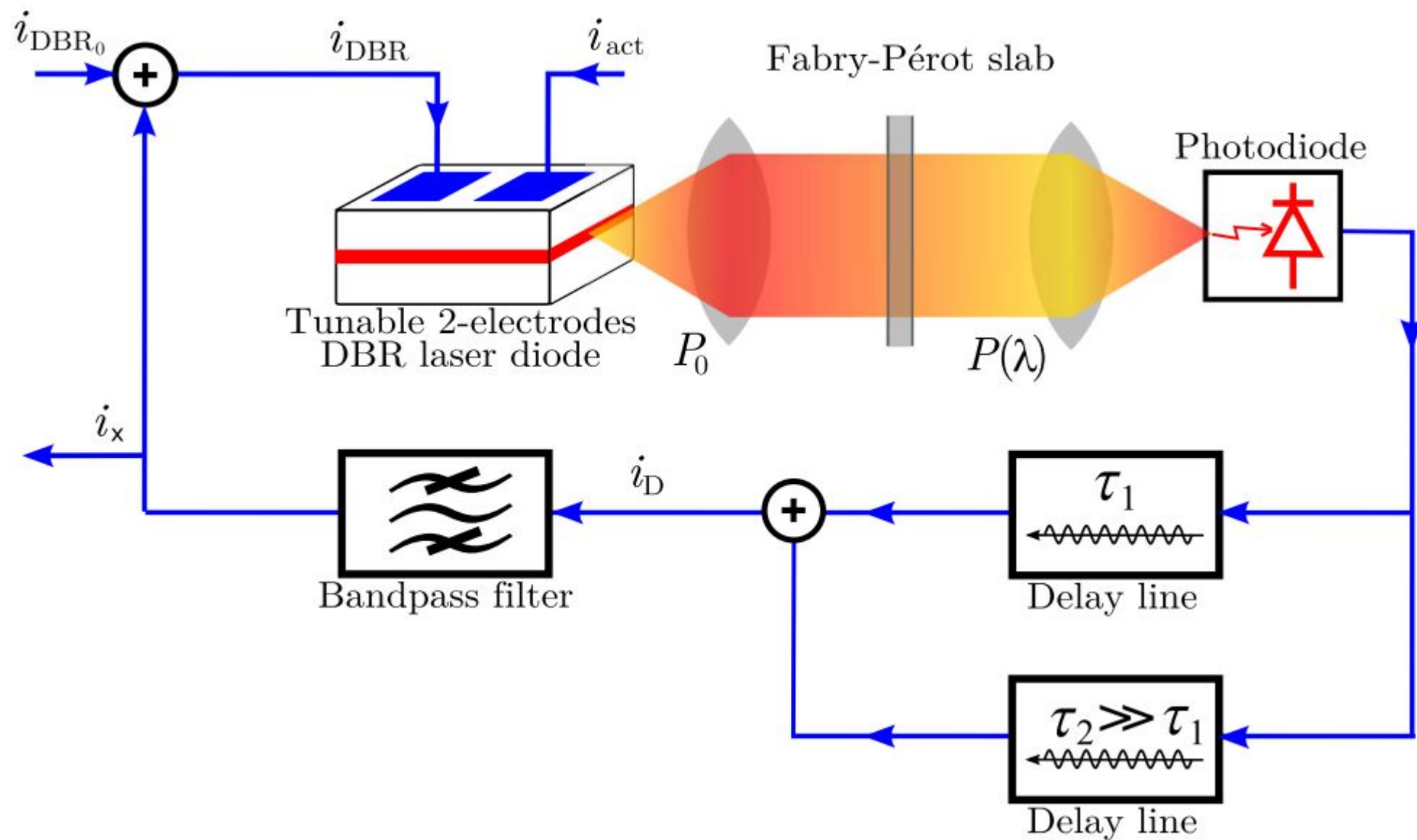
Multiheaded Chimeras



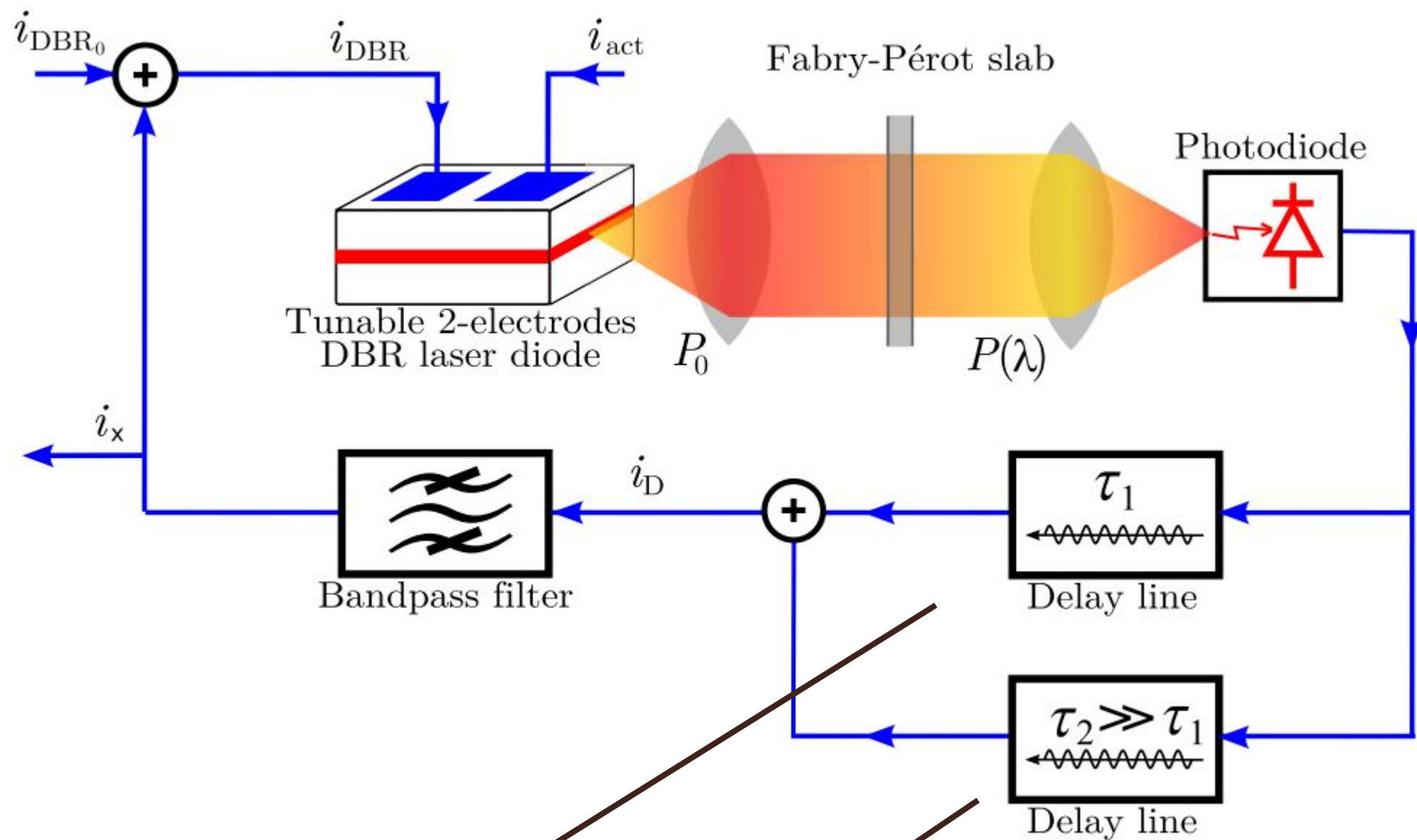
- Tunable number of heads
- Increased system complexity
- Coexistence of chimeras with different number of heads
- Can be possibly used in applications

Double delay systems

System with two delays



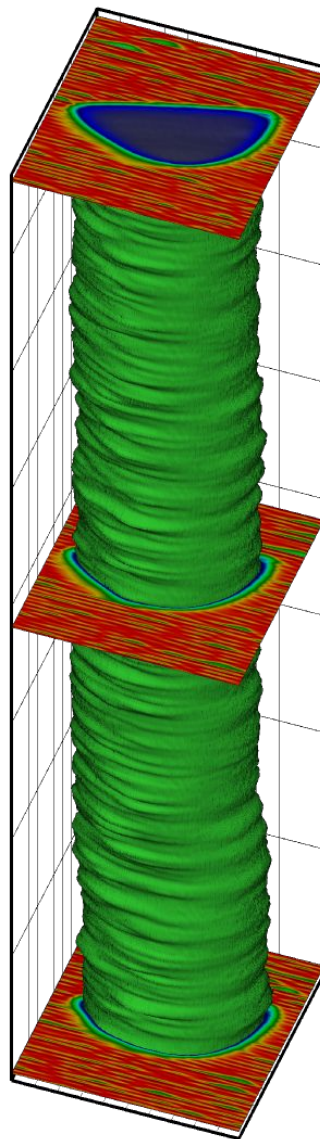
System with two delays



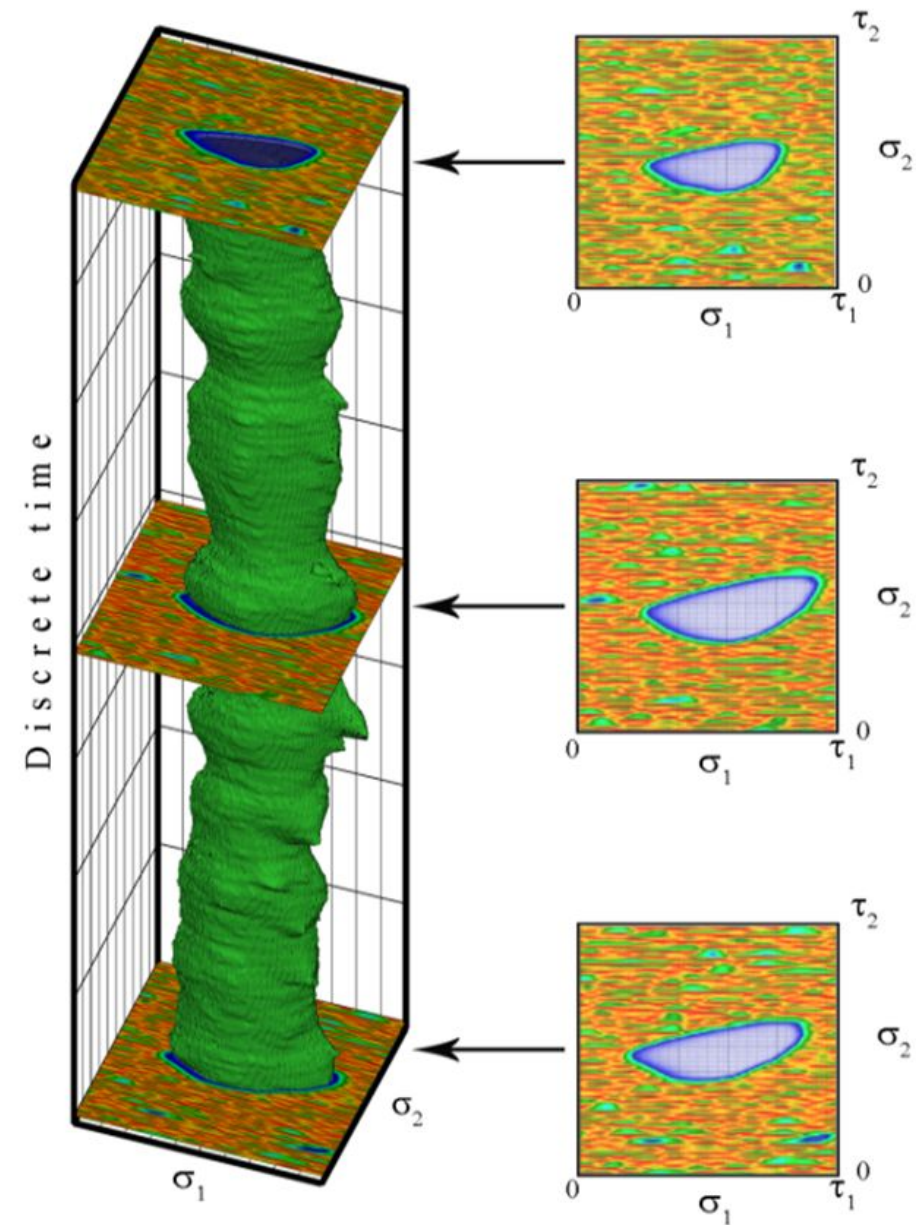
$$\varepsilon \dot{x} + \delta \int_{t_0}^t x(\xi) d\xi + x = (1 - \gamma) f(x(t - 1)) + \gamma f(x(t - 100))$$

Coherent core

Simulation

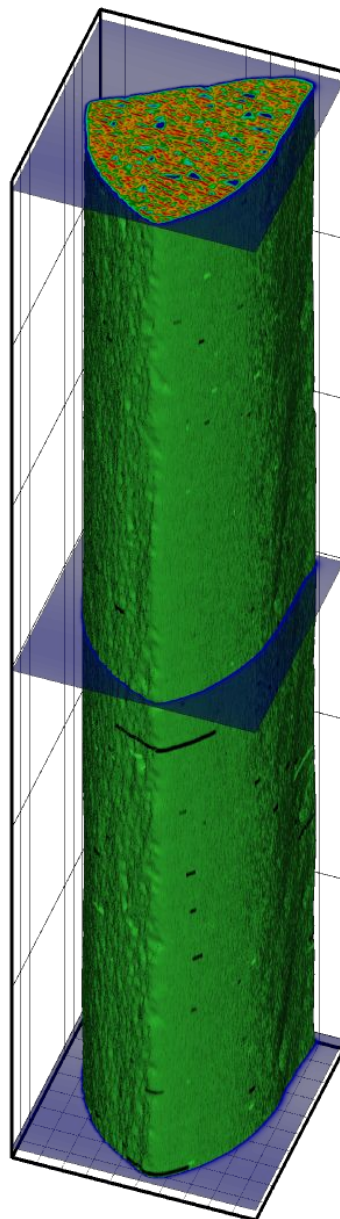


Experiment

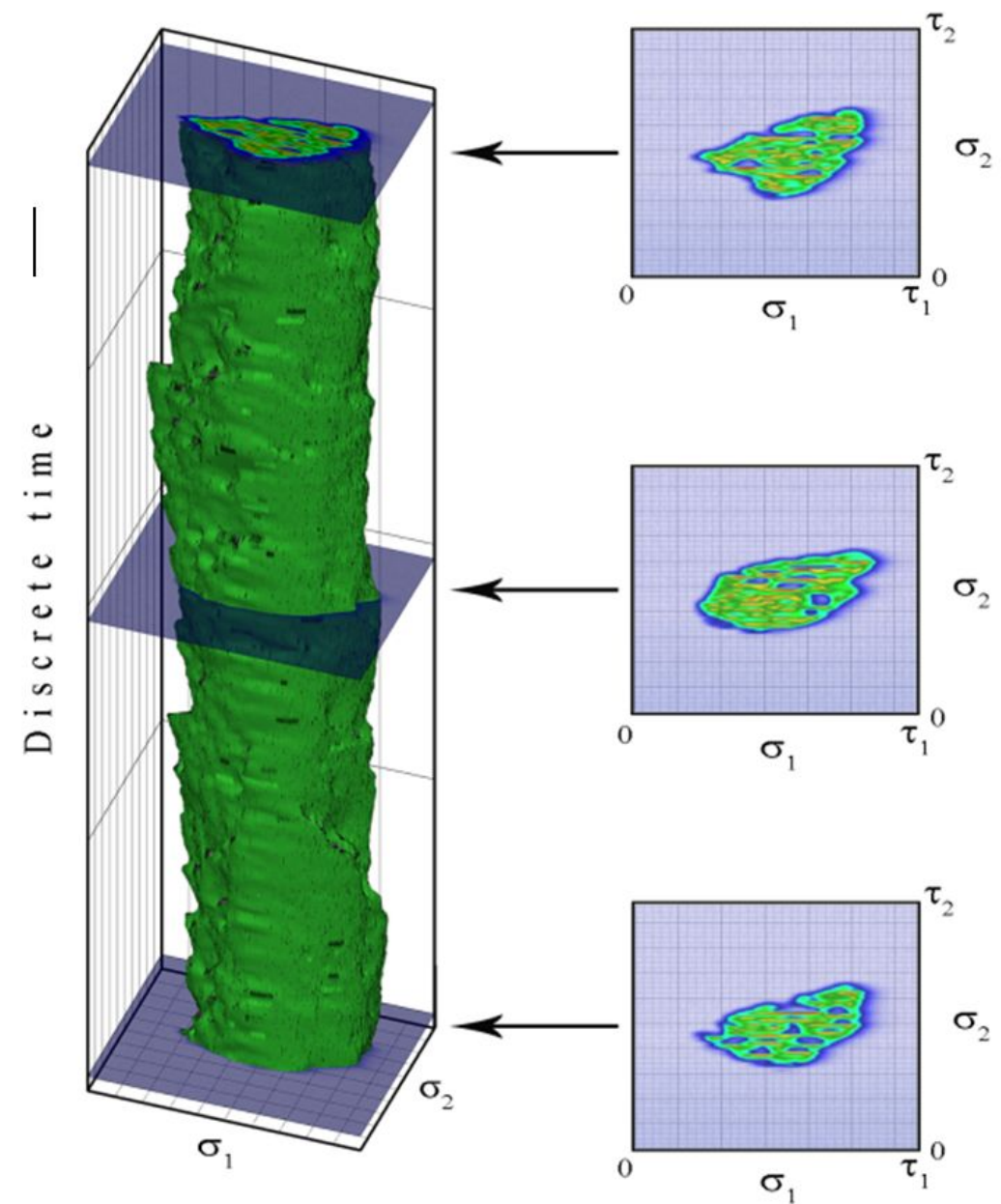


Incoherent core

Simulation



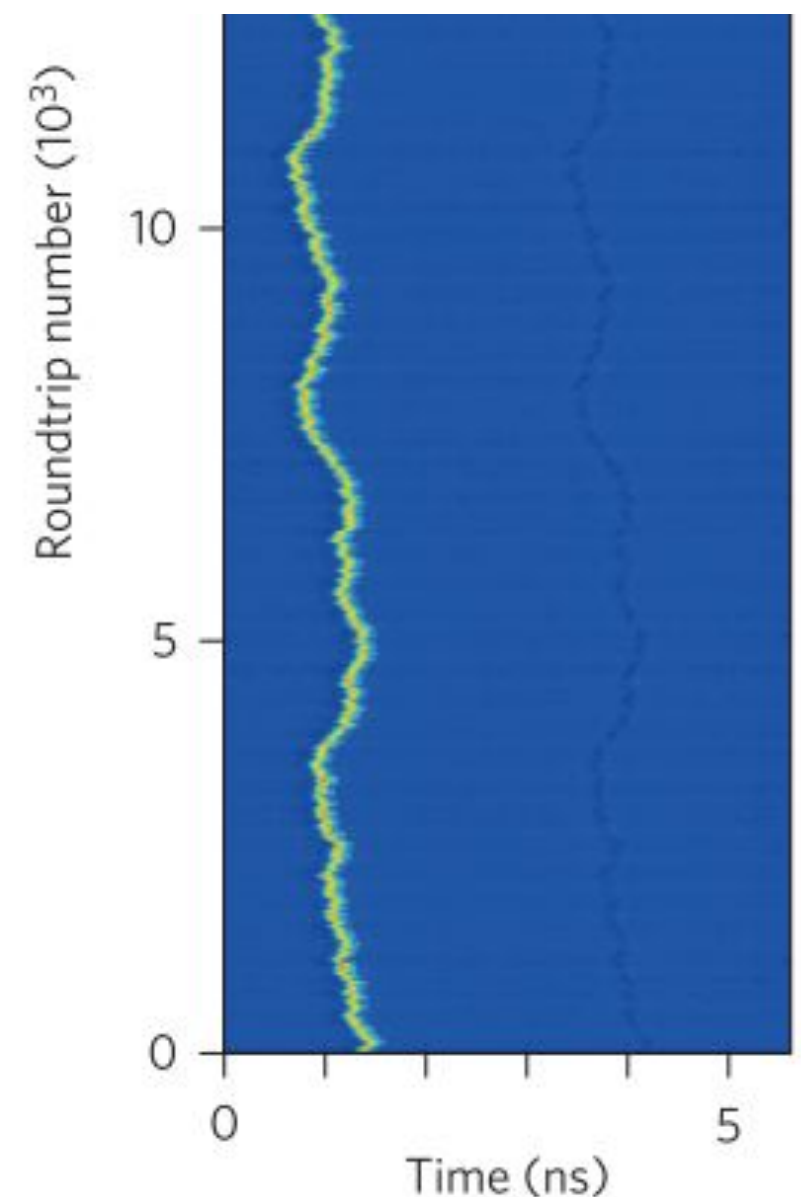
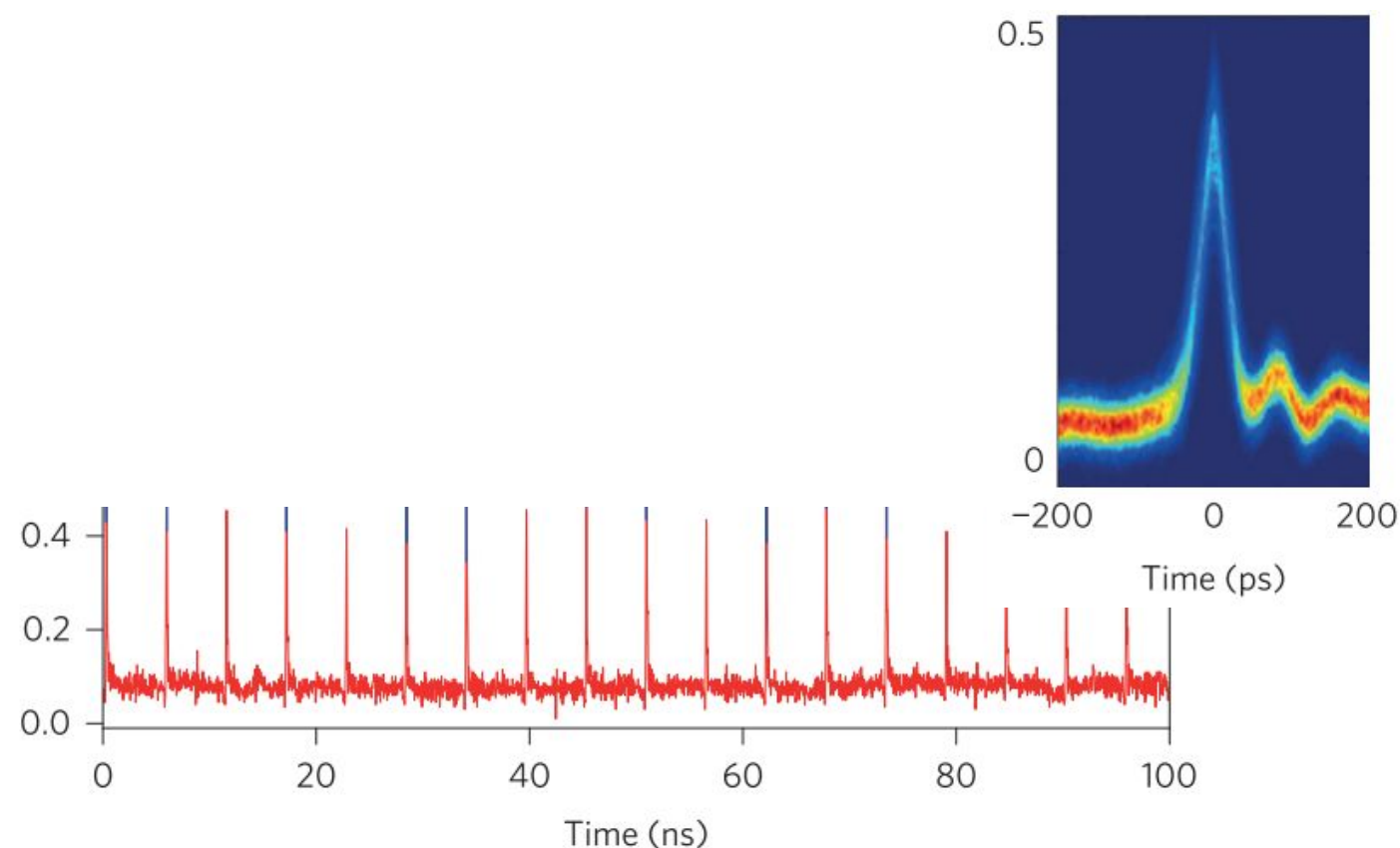
Experiment



Dissipative solitons:
optical memory medium?

Vectorial dissipative solitons in vertical-cavity surface-emitting lasers with delays

M. Marconi¹, J. Javaloyes², S. Barland¹, S. Balle³ and M. Giudici^{1*}

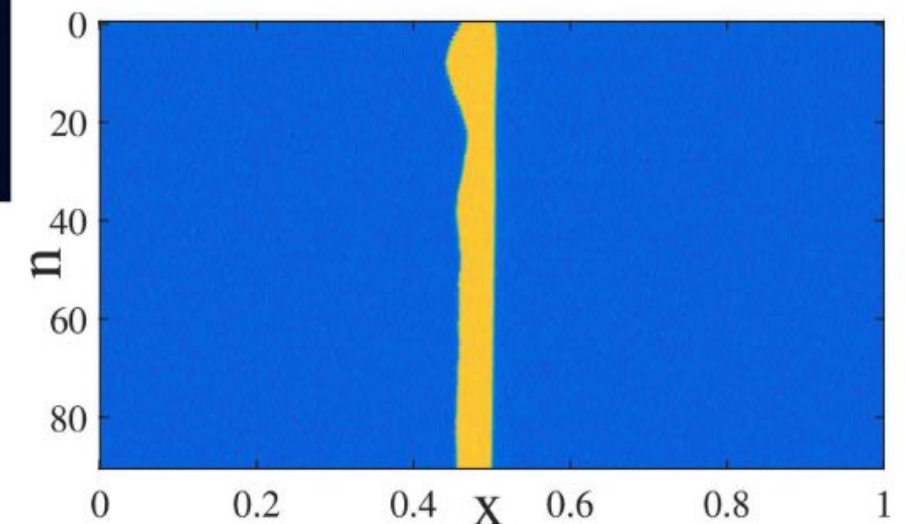
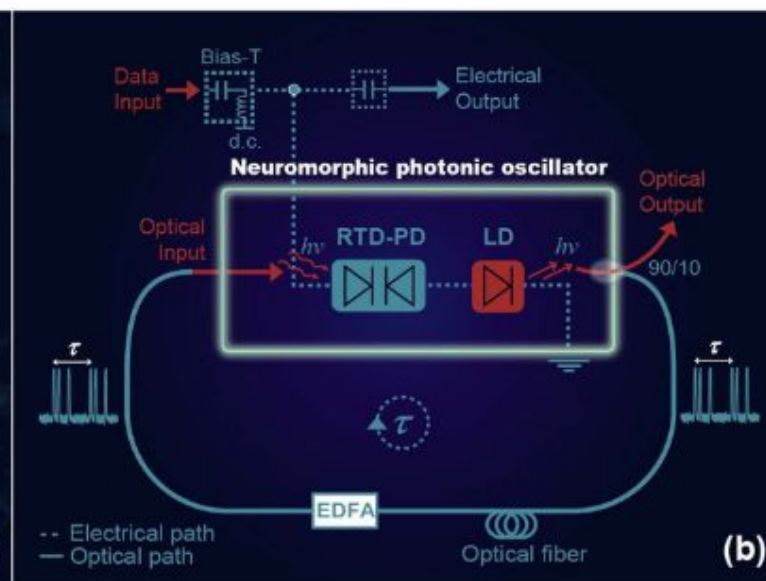
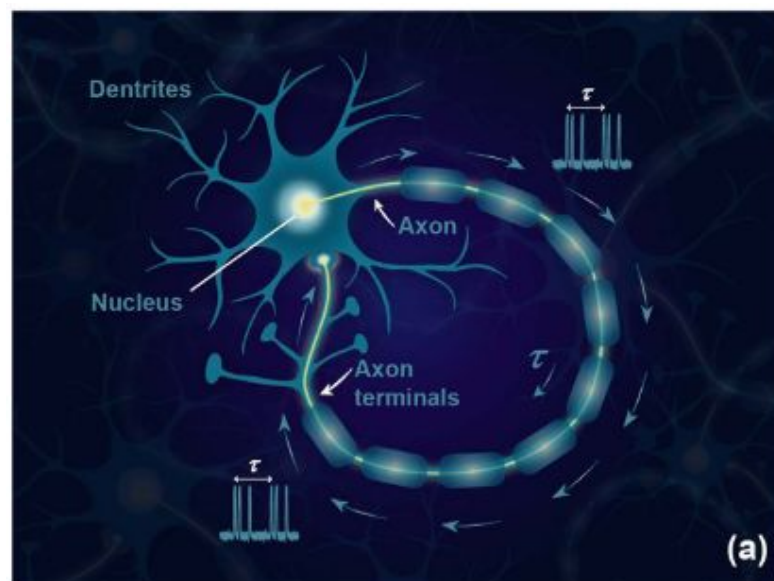


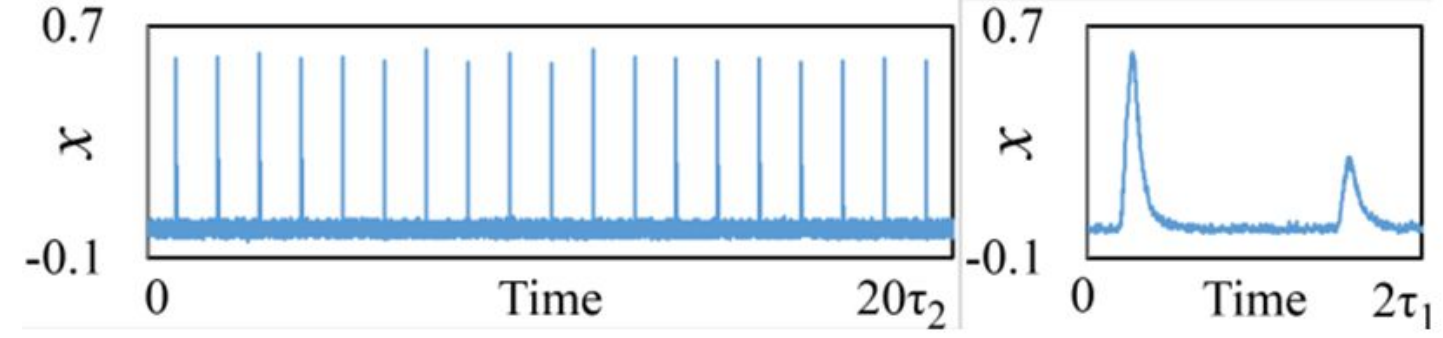
OPEN

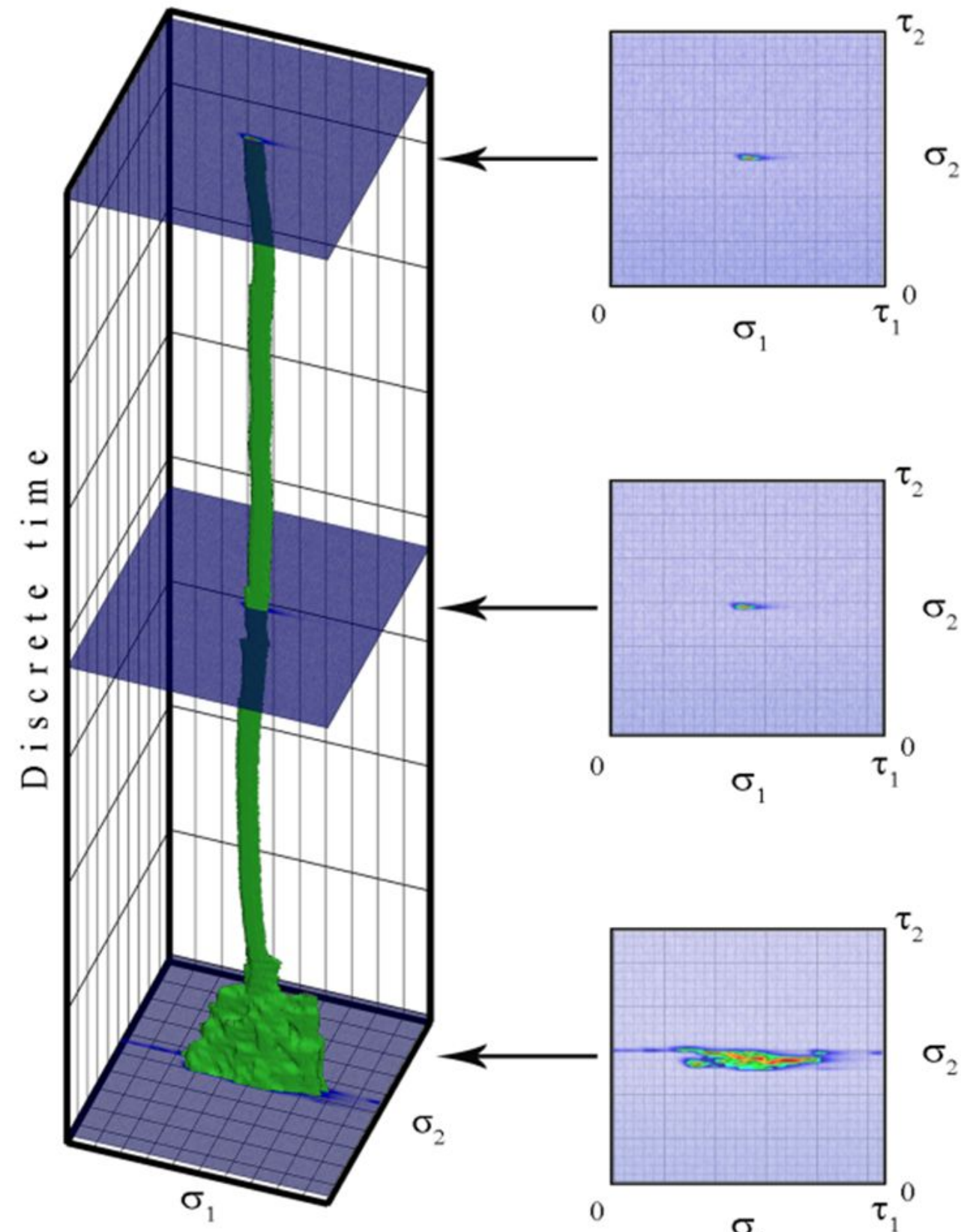
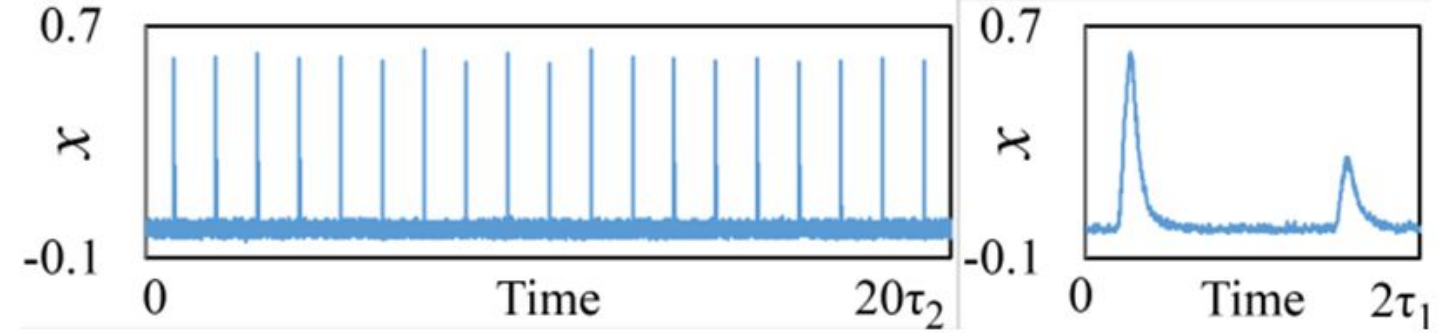
Regenerative memory in time-delayed neuromorphic photonic resonators

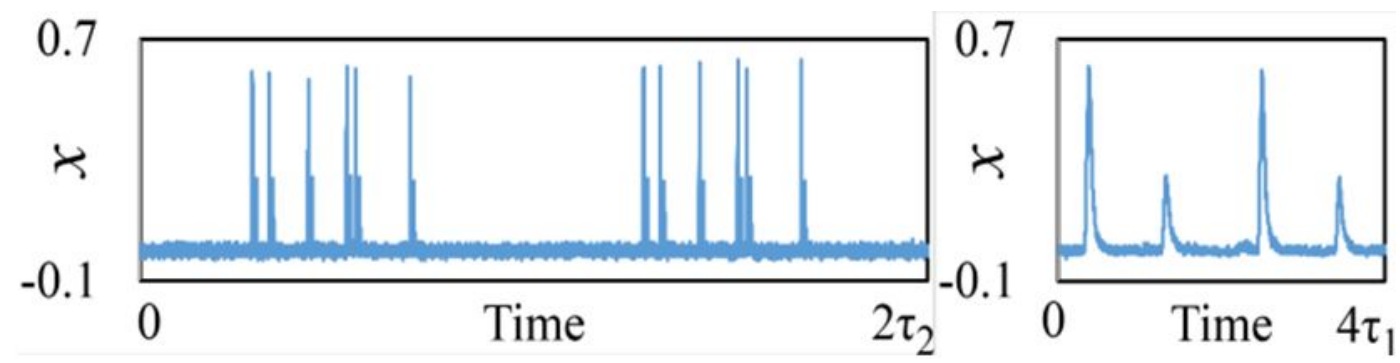
Received: 25 September 2015

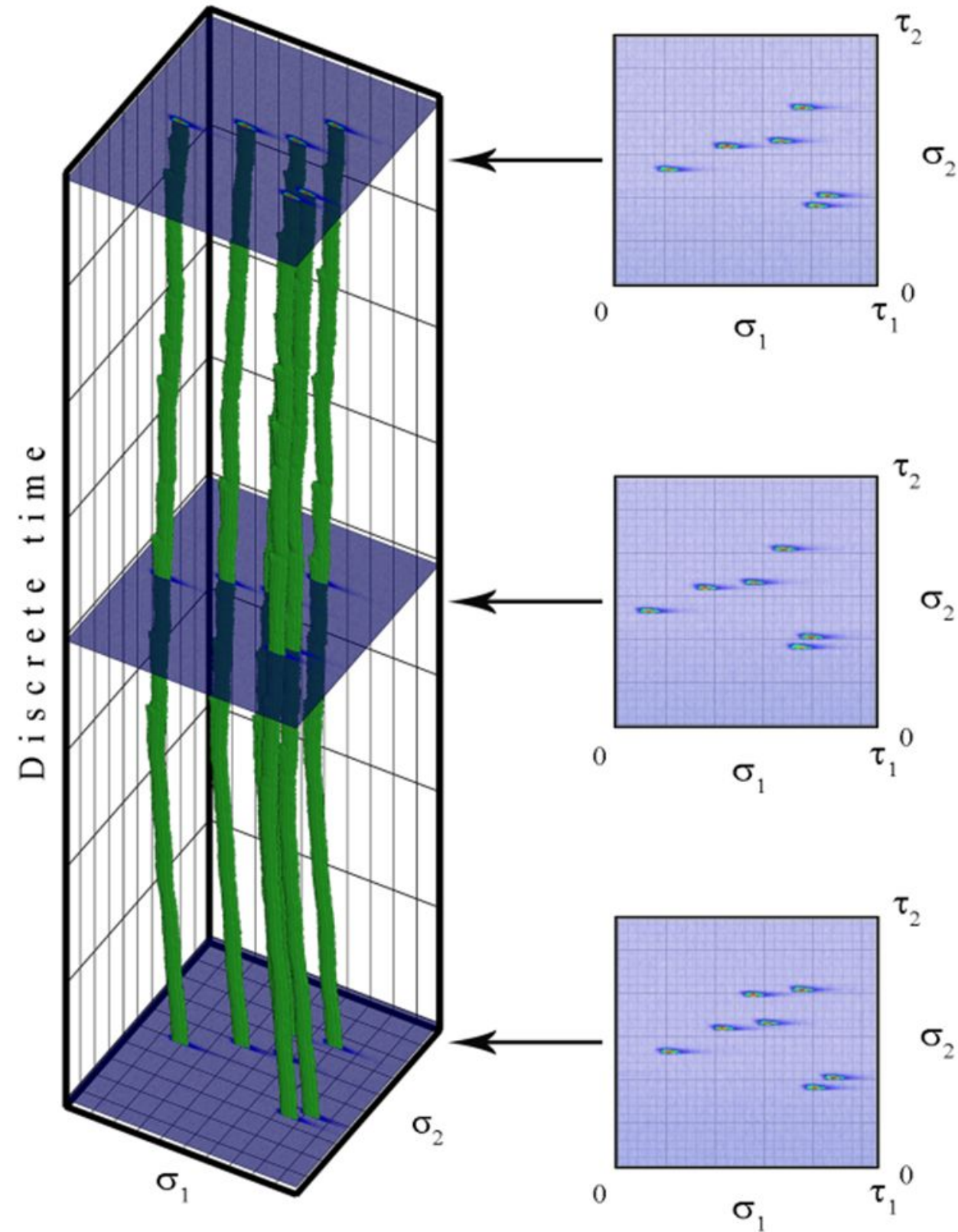
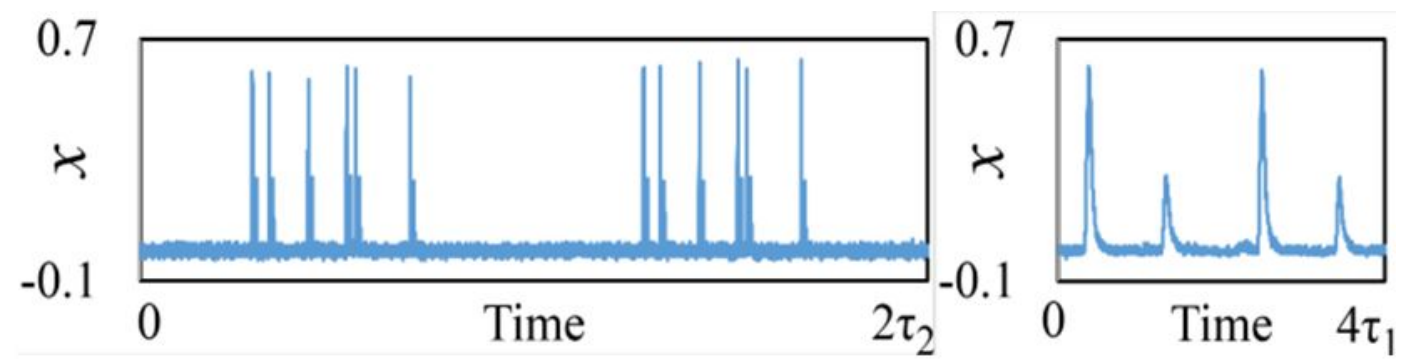
B. Romeira^{1,*}, R. Avó¹, José M. L. Figueiredo¹, S. Barland² & J. Javaloyes³



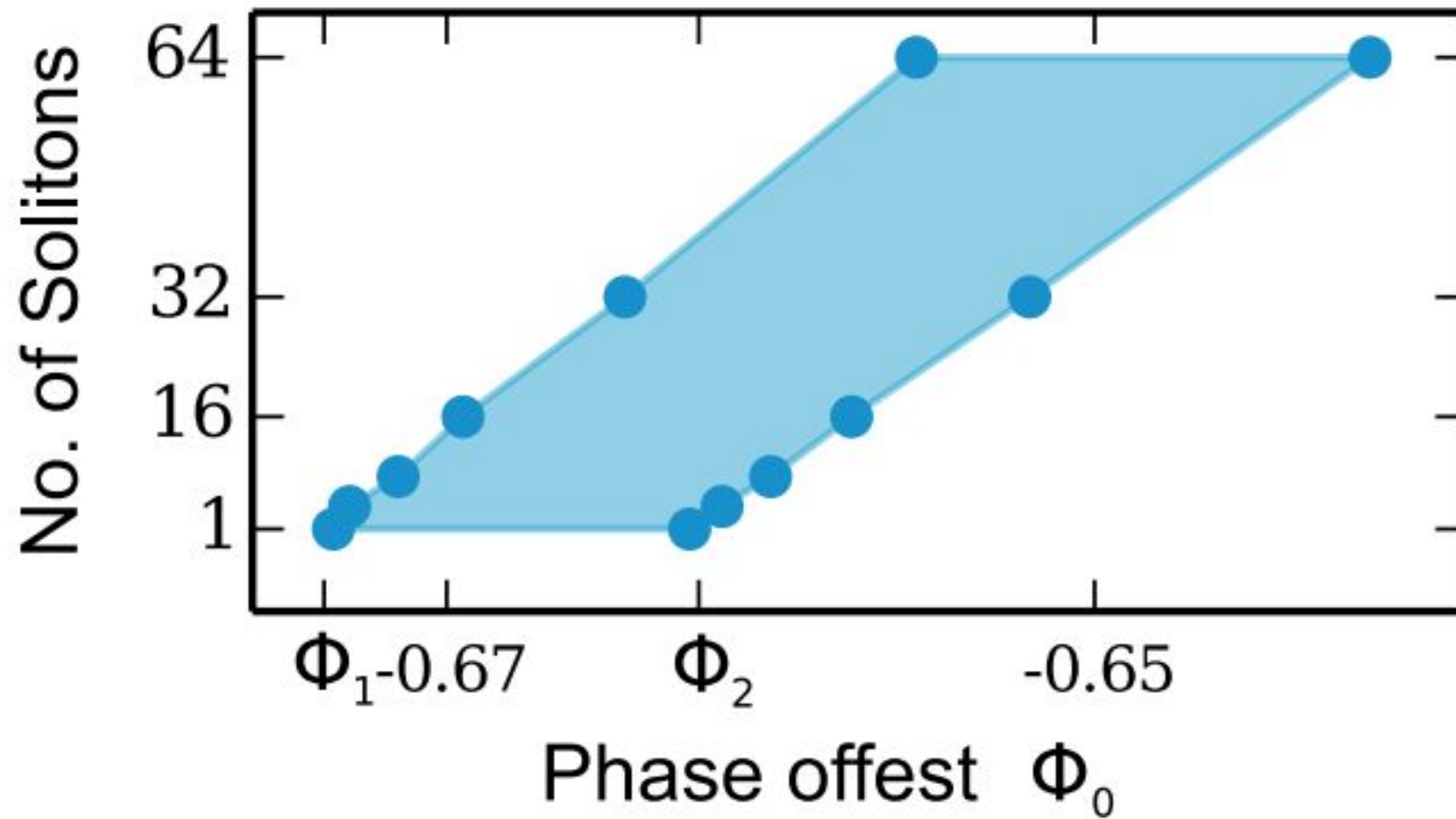








Multistability





Network



Take-away message

The dynamical behavior on the delay interval can be translated to a network.

Those networks allow observation of chimera states and dissipative solitons.



Network



Applications of Chimera States/Dissipative solitons

Study of synchronization in complex networks:

- . Power grids
- . Networks of neurons in the human heart

Neuromorphic computing

- . Optical memory

Thank You

www.penkovsky.com