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Turbulent chimeras in large semiconductor laser arrays

Outline

- The model
- Effect of system parameters
- Chimeras states
- Quantify the chimeras states
- The influence of initial conditions and the system size
- Conclusions and open problems

The minimal model of rate equations

$$\frac{d\varepsilon_j}{dt} = (1 - ia)\varepsilon_j N_j + i\eta(\varepsilon_{j+1} + \varepsilon_{j-1}) + i\omega_j\varepsilon_j$$

$$T\frac{dN_j}{dt} = p - N_j - (1 + 2N_j)|\varepsilon_j|^2 \qquad \text{j} = 1 \ldots M$$

a: Linewidth enhancement factor

η: The coupling strength

ω_j: Optical frequency detuning

T: Carrier photon lifetime / photons in the laser cavity lifetime.

p: Pump rate

Polar coordinates

$$\varepsilon_j = E_j e^{i\varphi_j}$$

$$\frac{dE_j}{dt} = E_j N_j - \eta[E_{j+1}\sin(\varphi_{j+1} - \varphi_j) + E_{j-1}\sin(\varphi_{j-1} - \varphi_j)]$$

$$\frac{d\varphi_j}{dt} = \omega_j - aN_j - \eta[\frac{E_{j+1}}{E_j}\cos(\varphi_{j+1} - \varphi_j) + \frac{E_{j-1}}{E_j}\cos(\varphi_{j-1} - \varphi_j)]$$

$$T\frac{dN_j}{dt} = p - N_j - (1 + 2N_j)|\varepsilon_j|^2$$

Without coupling

$$\frac{dE_j}{dt} = E_j N_j$$

$$T\frac{dN_j}{dt} = p - N_j - (1 + 2N_j)\,E_j^2$$

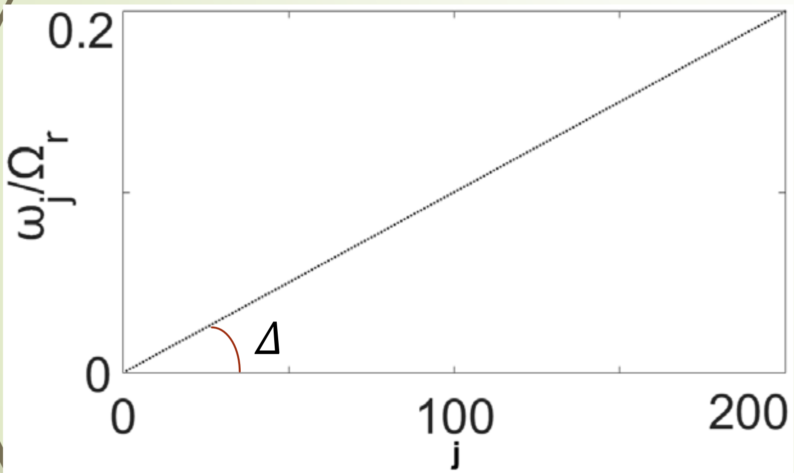
$$\frac{d\varphi_j}{dt} = \omega_j - aN_j$$

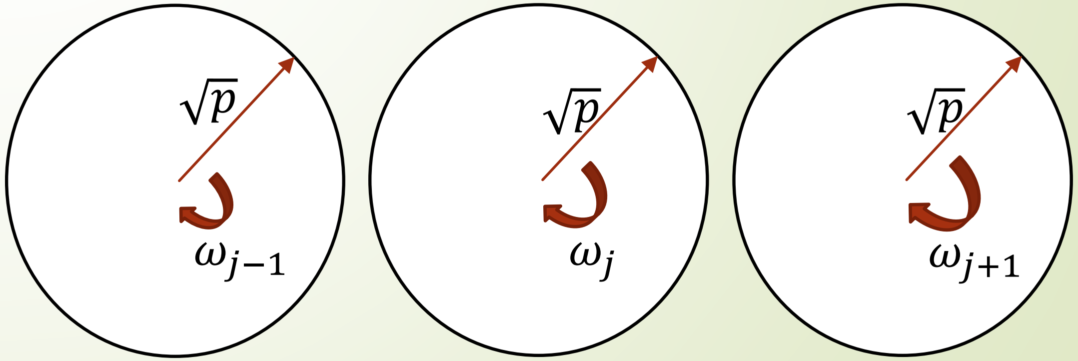
$$(N_j, E_j) \to (0, \sqrt{p})$$

stable

$$\lambda_{1,2} = -\frac{1}{2T} \pm i\sqrt{\frac{2p}{T}}$$

$\Omega_r \to$ relaxation oscillation frequency





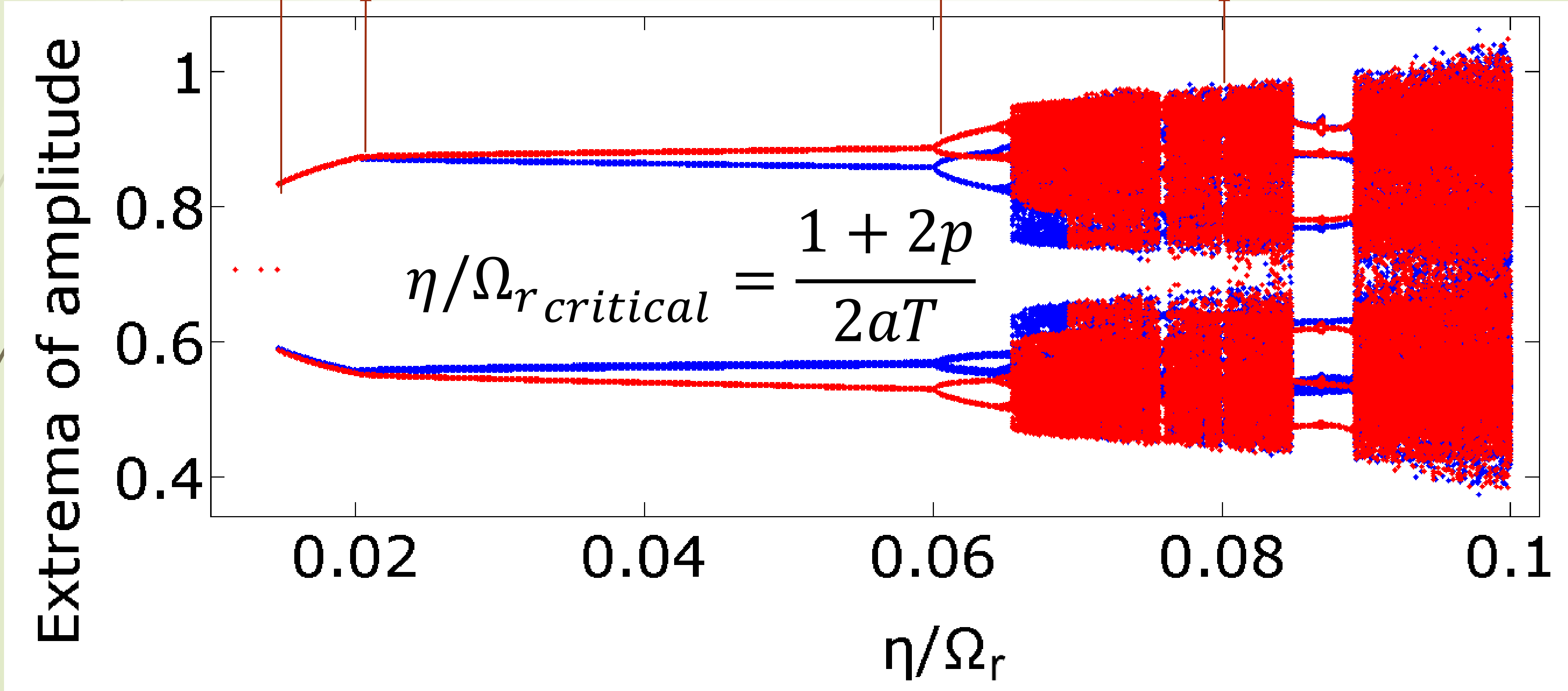
Two coupled lasers without detuning

(a) Hopf bifurcation

(b) Limit cycle

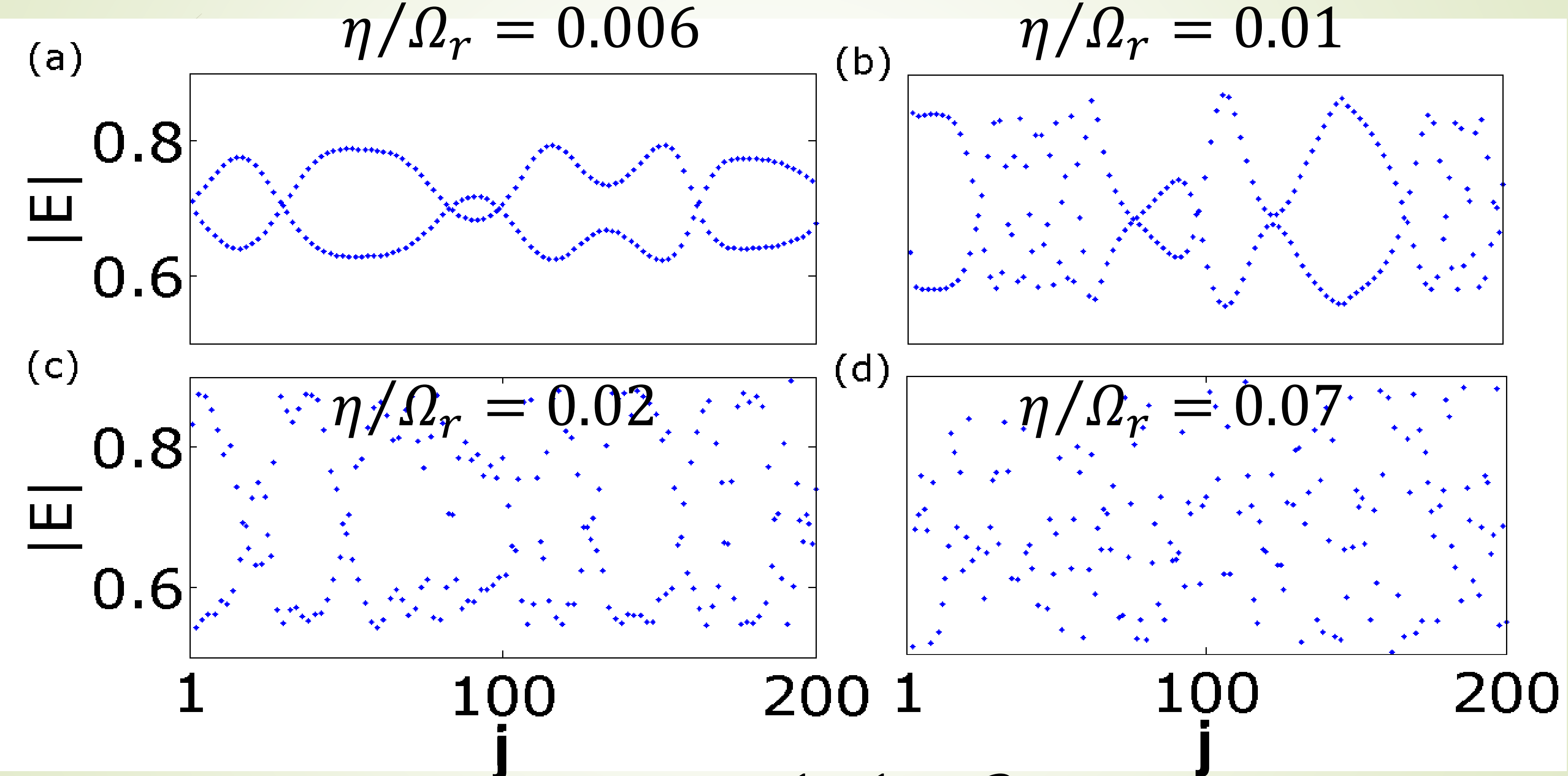
(c) Period doubling

(d) Chaotic region



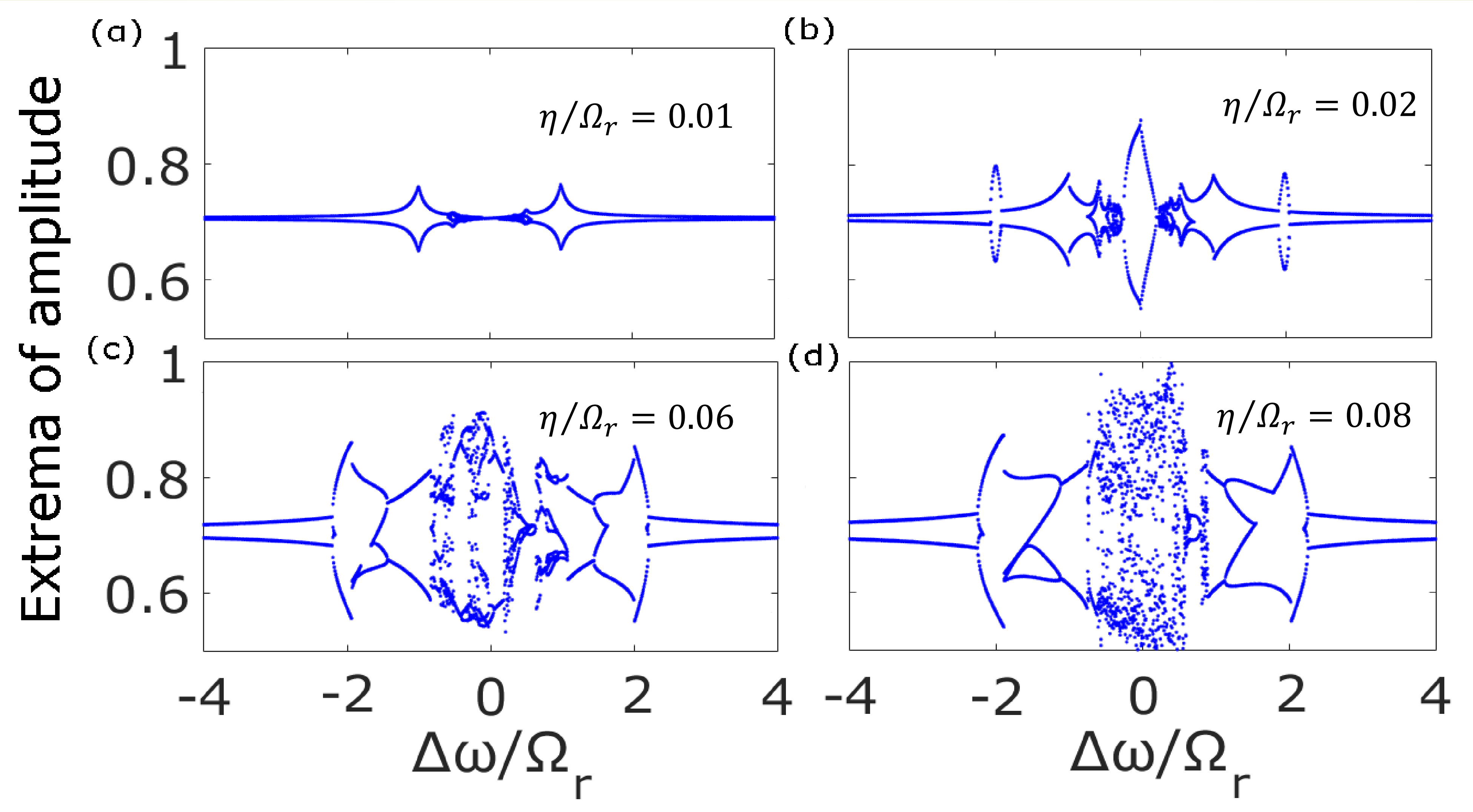
$$\eta/\Omega_{r\,critical} = \frac{1+2p}{2aT}$$

200 coupled lasers without detuning



$$\eta/\Omega_{r\,critical} = \frac{1}{2}\left(\frac{1+2p}{2aT}\right) = 0.005$$

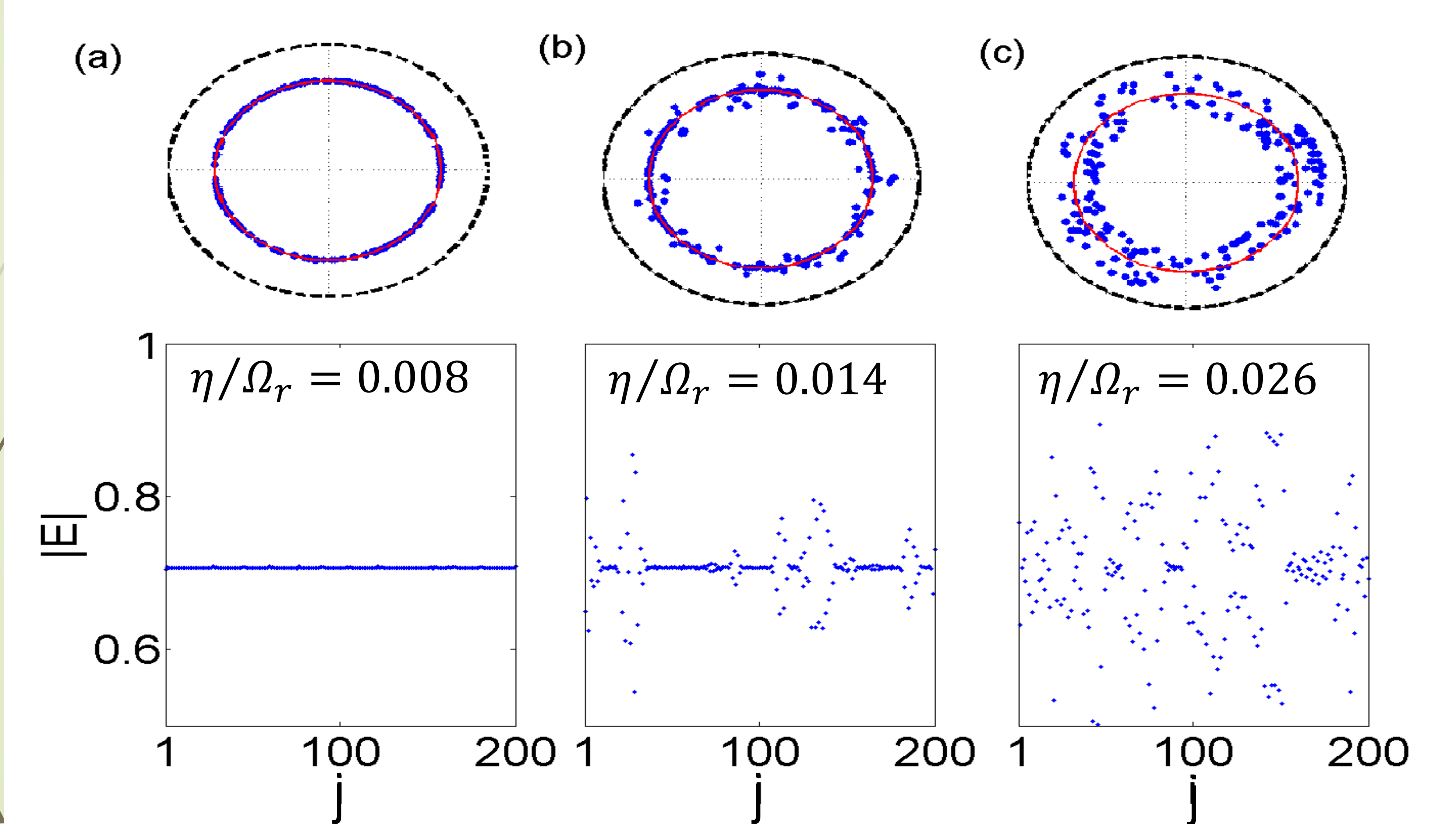
Two coupled lasers with detuning



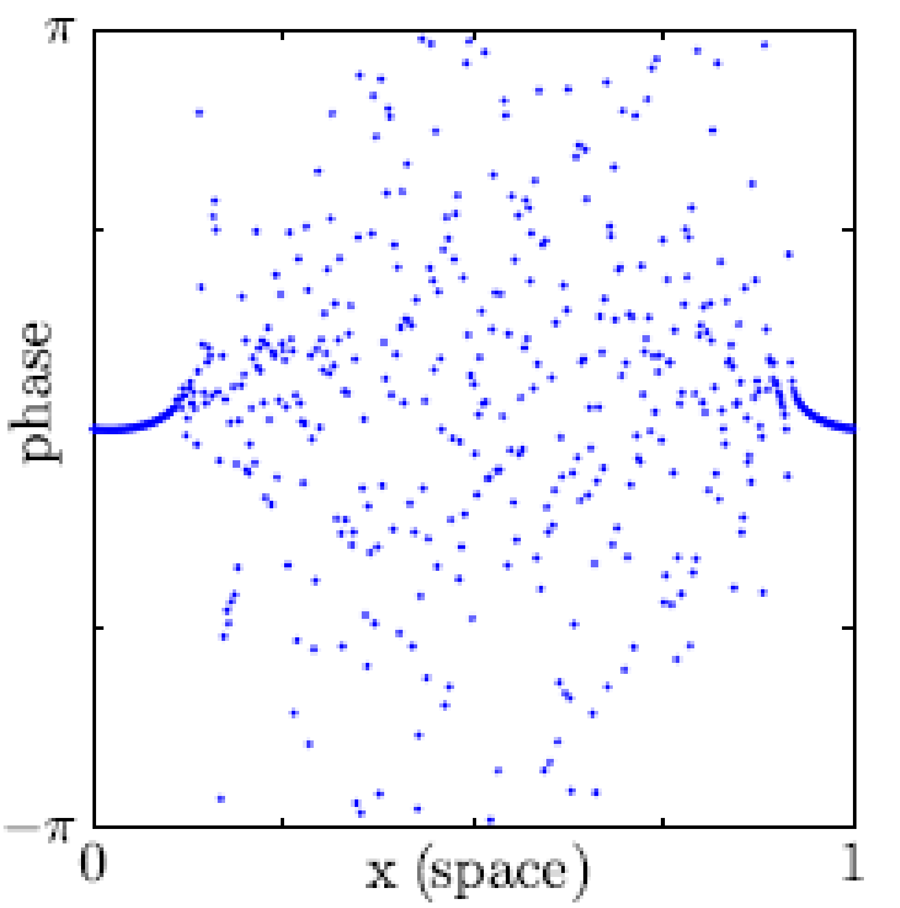
$$\Delta\omega = \omega_2 - \omega_1$$

200 coupled lasers with detuning

$\Delta = 0.01$



Kuramoto model



Chimeras in a one-dimensional periodic space

Coexistence of Coherence and Incoherence in Nonlocally Coupled Phase Oscillators

2002

Y. Kuramoto[1] and D. Battogtokh[2]

$$\frac{d\theta_j}{dt} = \omega + \frac{k}{2R}\sum_{l=j-R}^{j+R}\sin(\theta_l - \theta_j + a)$$

k = The coupling

ω = The frequency

R = The range of coupling

a = phase lag parameter

Chimeras in laser systems

ARTICLE

Received 28 Nov 2014 | Accepted 5 Jun 2015 | Published 14 Jul 2015

DOI: 10.1038/ncomms8752 OPEN

Laser chimeras as a paradigm for multistable patterns in complex systems

Laurent Larger[1], Bogdan Penkovsky[1] & Yuri Maistrenko[1,2]

Experiment based on an **optoelectronic delayed feedback** applied to a semiconductor laser

2014

PHYSICAL REVIEW E 91, 040901(R) (2015)

Amplitude-phase coupling drives chimera states in globally coupled laser networks

Fabian Böhm,[1] Anna Zakharova,[1] Eckehard Schöll,[1] and Kathy Lüdge[2]

[1]Institut für Theoretische Physik, Technische Universität Berlin, 10623 Berlin, Germany

[2]Institut für Theoretische Physik, Freie Universität Berlin, 14195 Berlin, Germany

(Received 28 November 2014; published 22 April 2015)

Globally coupled network of semiconductor lasers with delay feedback

2015

PHYSICAL REVIEW E 94, 042204 (2016)

Small chimera states without multistability in a globally delay-coupled network of four lasers

André Röhm, Fabian Böhm, and Kathy Lüdge

Institut für Theoretische Physik, Technische Universität Berlin, 10623 Berlin, Germany

(Received 24 June 2016; published 5 October 2016)

A network of **four** delay-coupling class B lasers

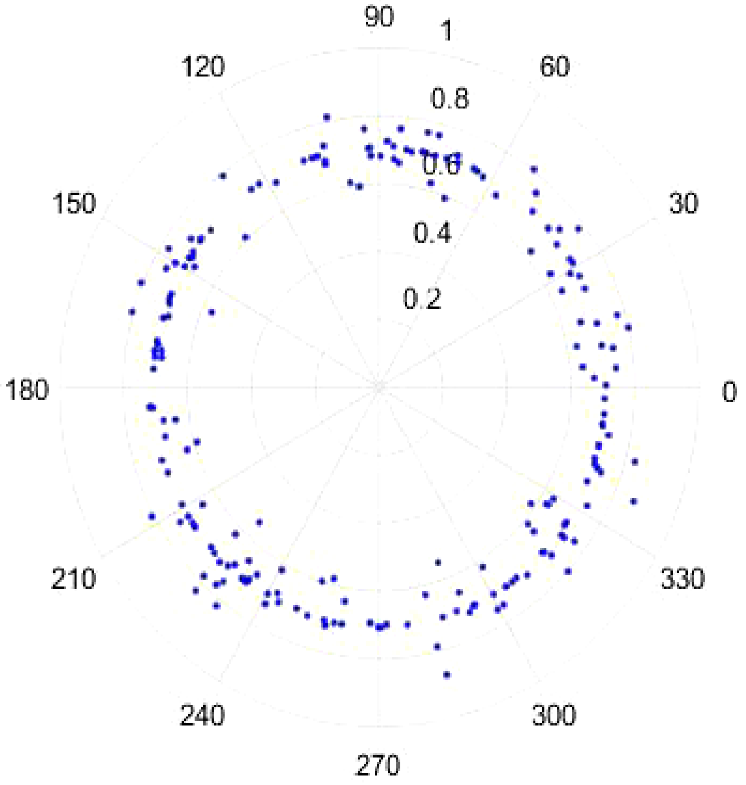
2017

Large arrays

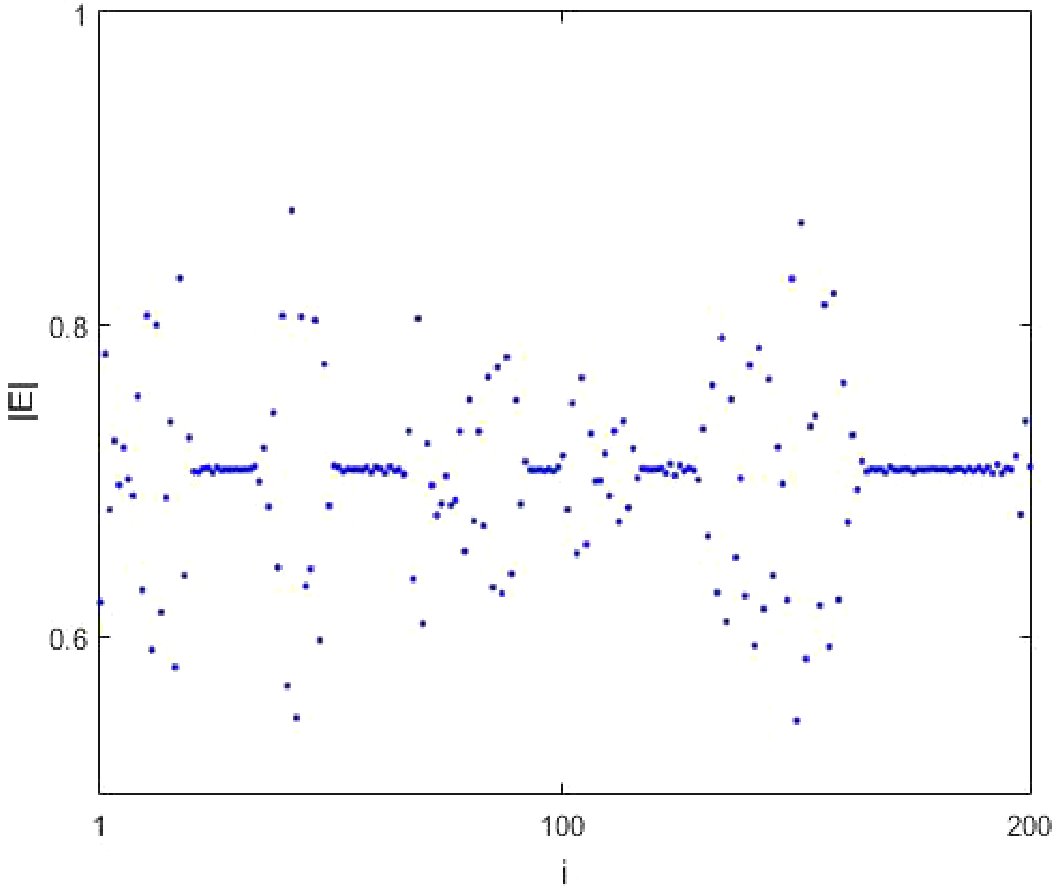
Local coupling

Detuning

Videos



90
120
60
150
30
180
0
210
330
240
300
270
1
0.8
0.6
0.4
0.2



1
0.8
0.6
|E|
1
100
200
i

Local curvature

For measuring spatial coherence

$$DE_j(t) = E_{j+1}(t) + E_{j-1}(t) - 2E_j$$

Discrete Laplacian

Synchronization regime $\longrightarrow$ $DE_j(t) \approx 0$

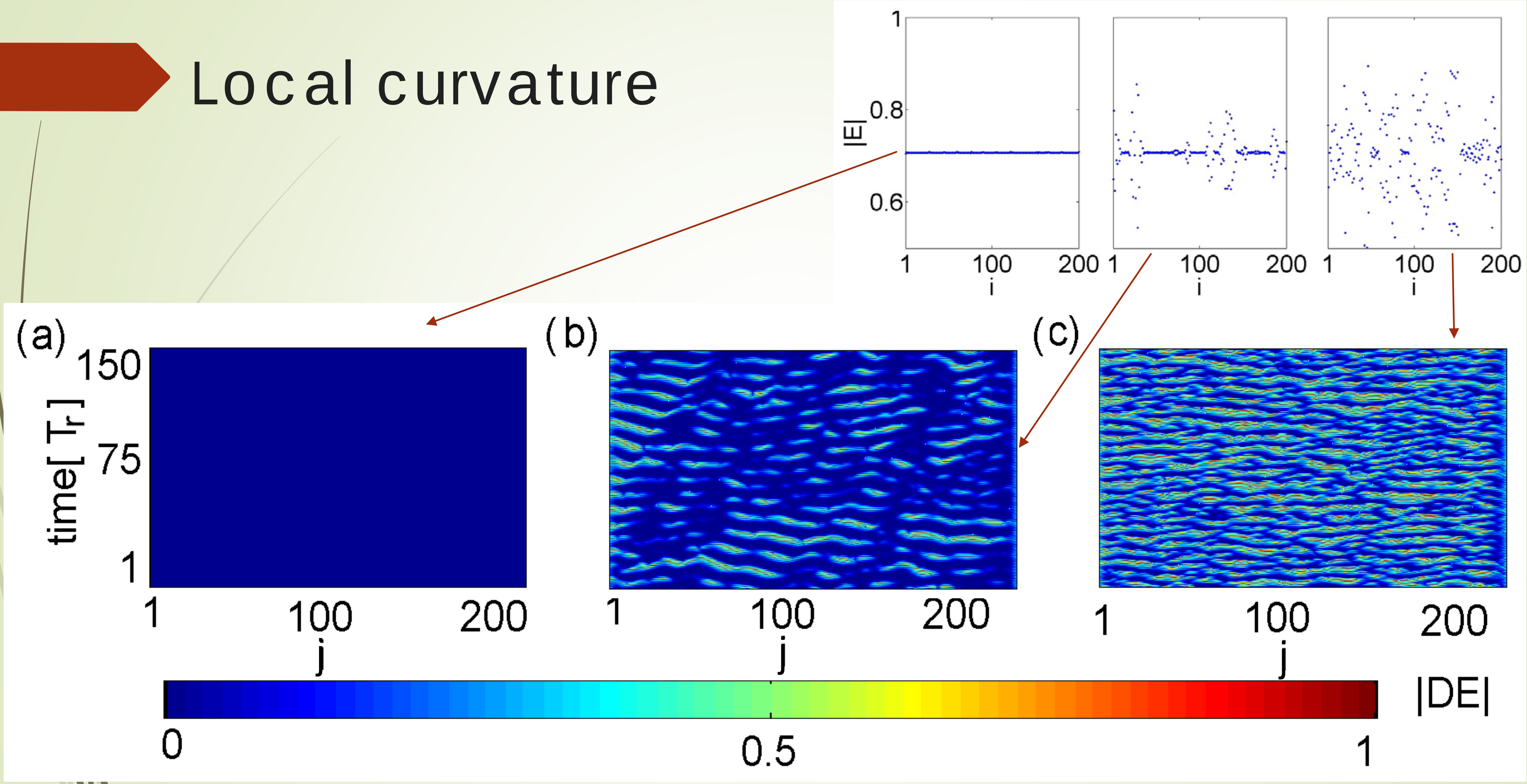
Asynchronous regime $\longrightarrow$ $DE_j(t) \approx 1$

CHAOS 26, 094815 (2016)

A classification scheme for chimera states

Felix P. Kemeth,[1,2,3] Sindre W. Haugland,[1,2] Lennart Schmidt,[1] Ioannis G. Kevrekidis,[2,3] and Katharina Krischer[1,a)]

Local curvature



$T_r =$ is the period of the relaxation oscillation

Probability density function

If g is the normalized probability density function of $|DE|$ then

$$g(|DE| = 0) = g_0$$

measures the spatially coherent region in each temporal realization

Fully synchronized system $\longrightarrow$ $g_0 = 1$

Totally incoherent system $\longrightarrow$ $g_0 = 0$

CHAOS 26, 094815 (2016)

A classification scheme for chimera states

Felix P. Kemeth,[1,2,3] Sindre W. Haugland,[1,2] Lennart Schmidt,[1] Ioannis G. Kevrekidis,[2,3] and Katharina Krischer[1,a)]

If $0 < g_0 < 1$ then we have chimera states

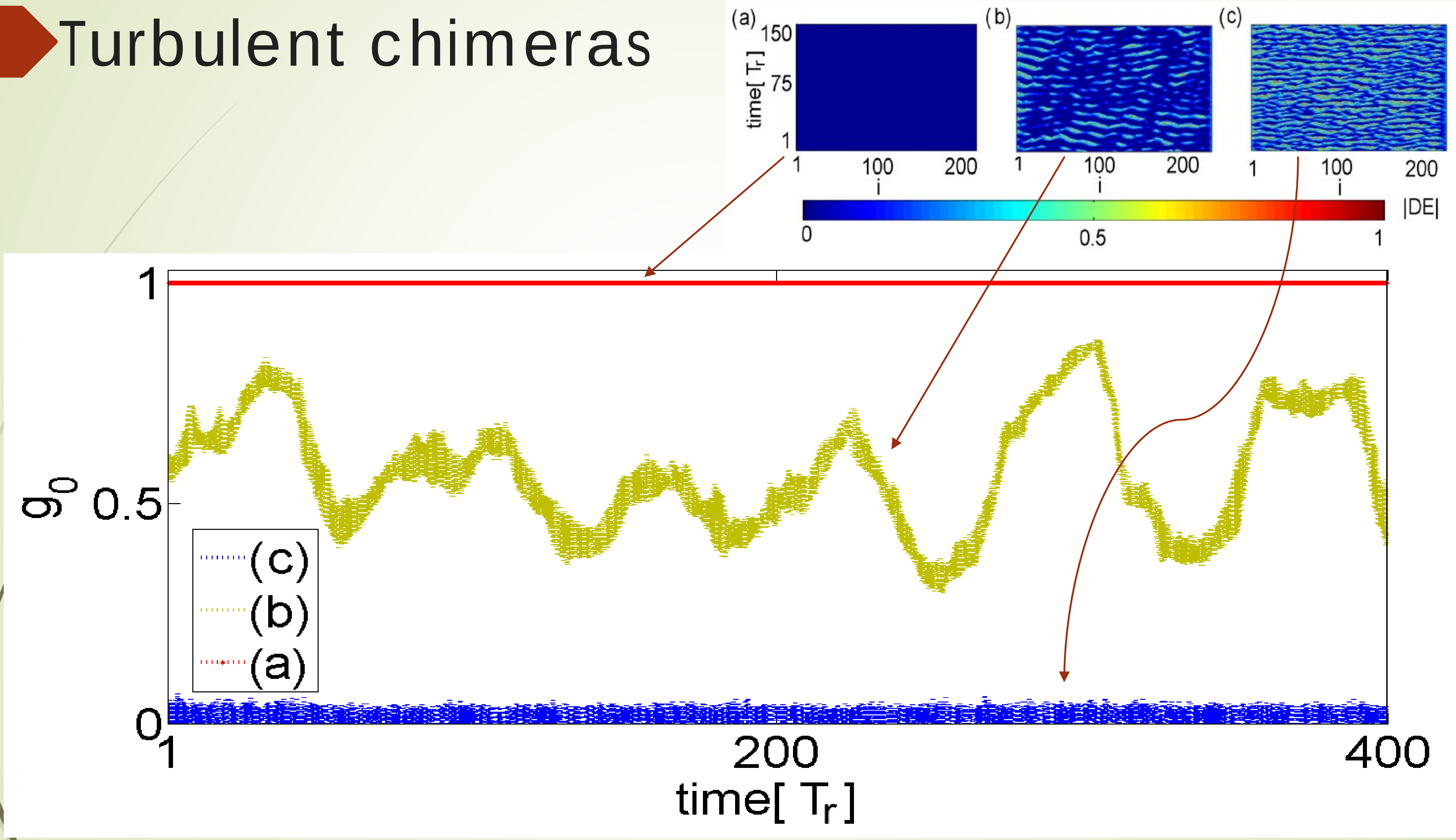
Constant

Stationary chimeras

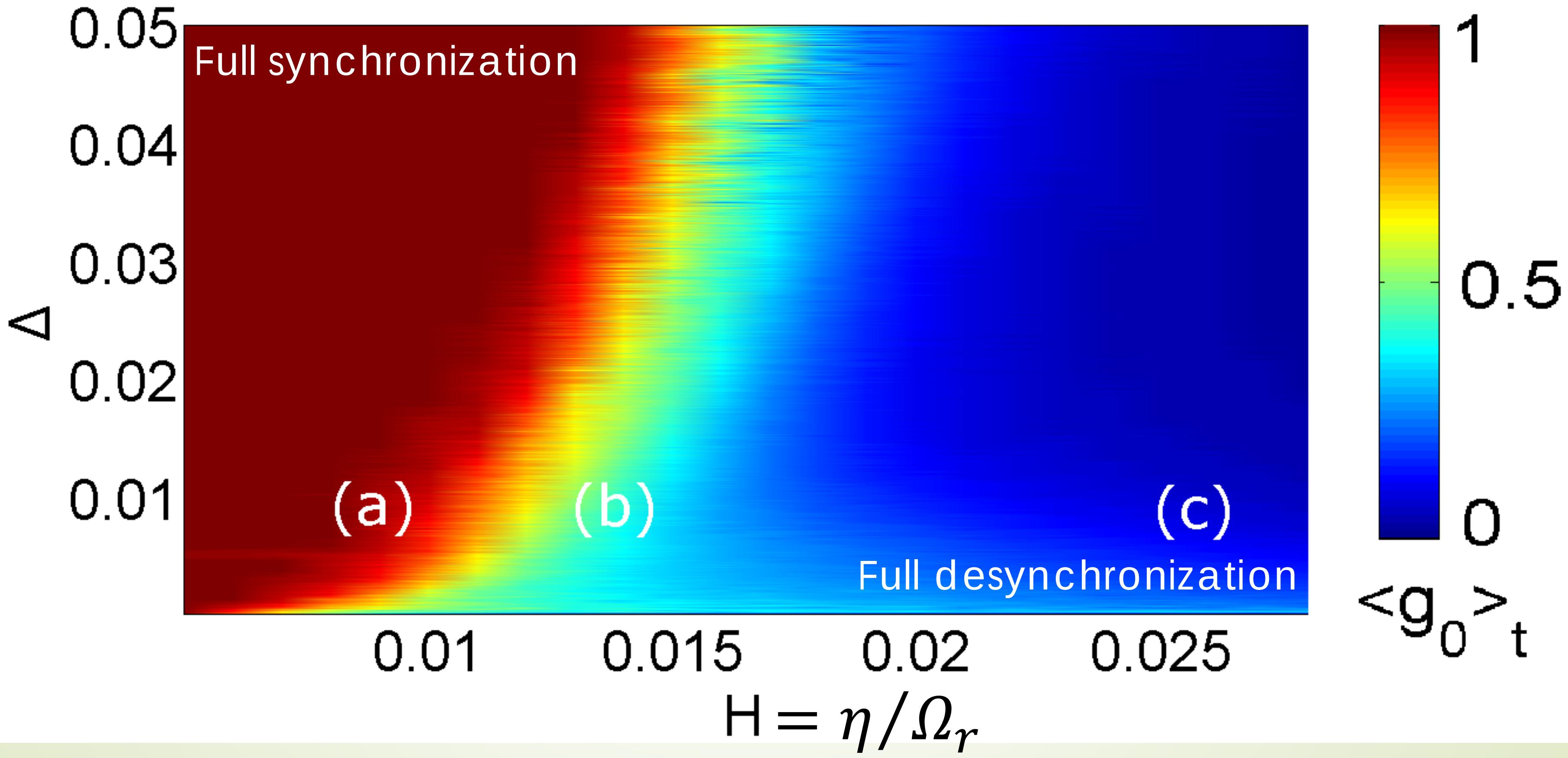
Irregular oscillatory

Turbulent chimera

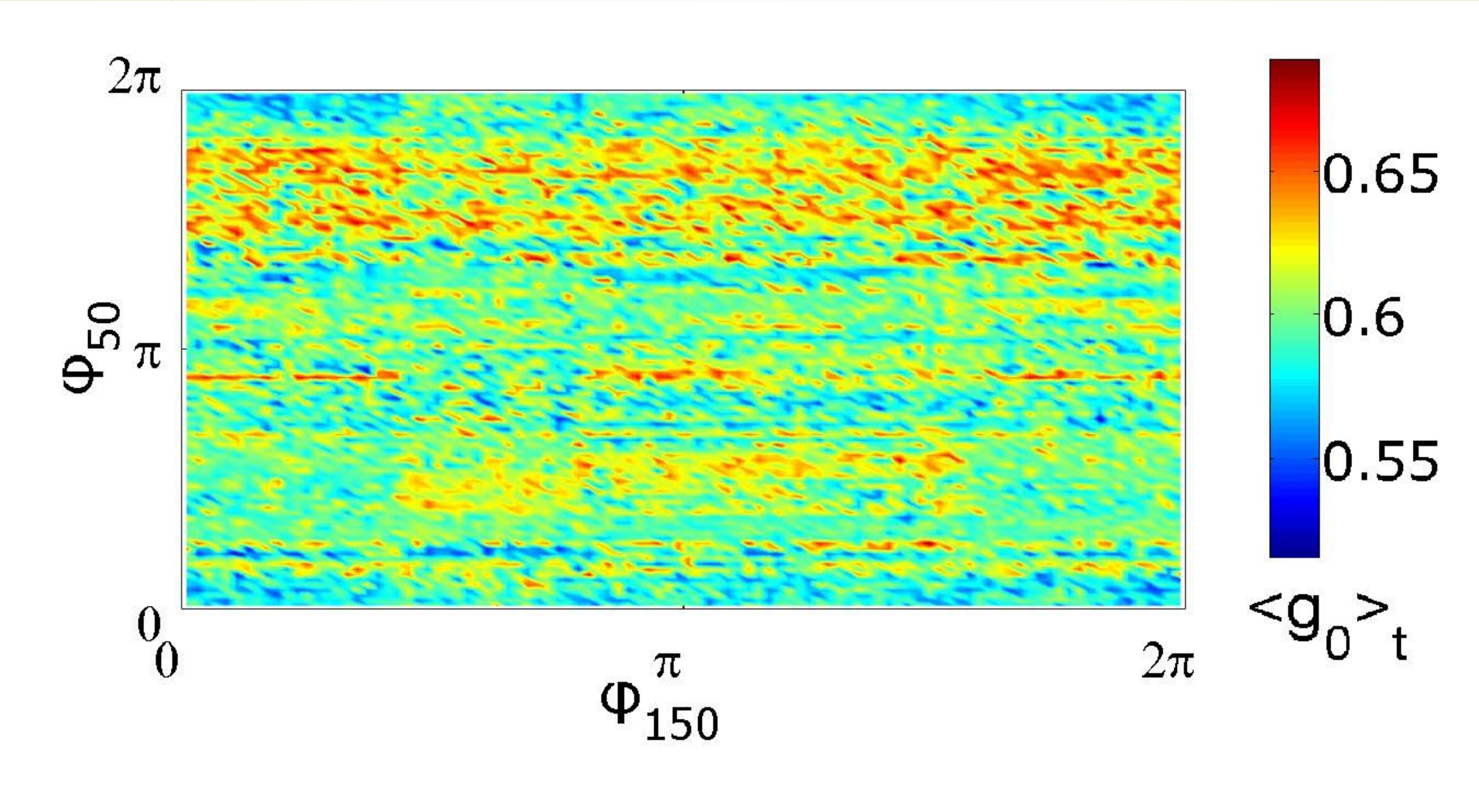
Turbulent chimeras



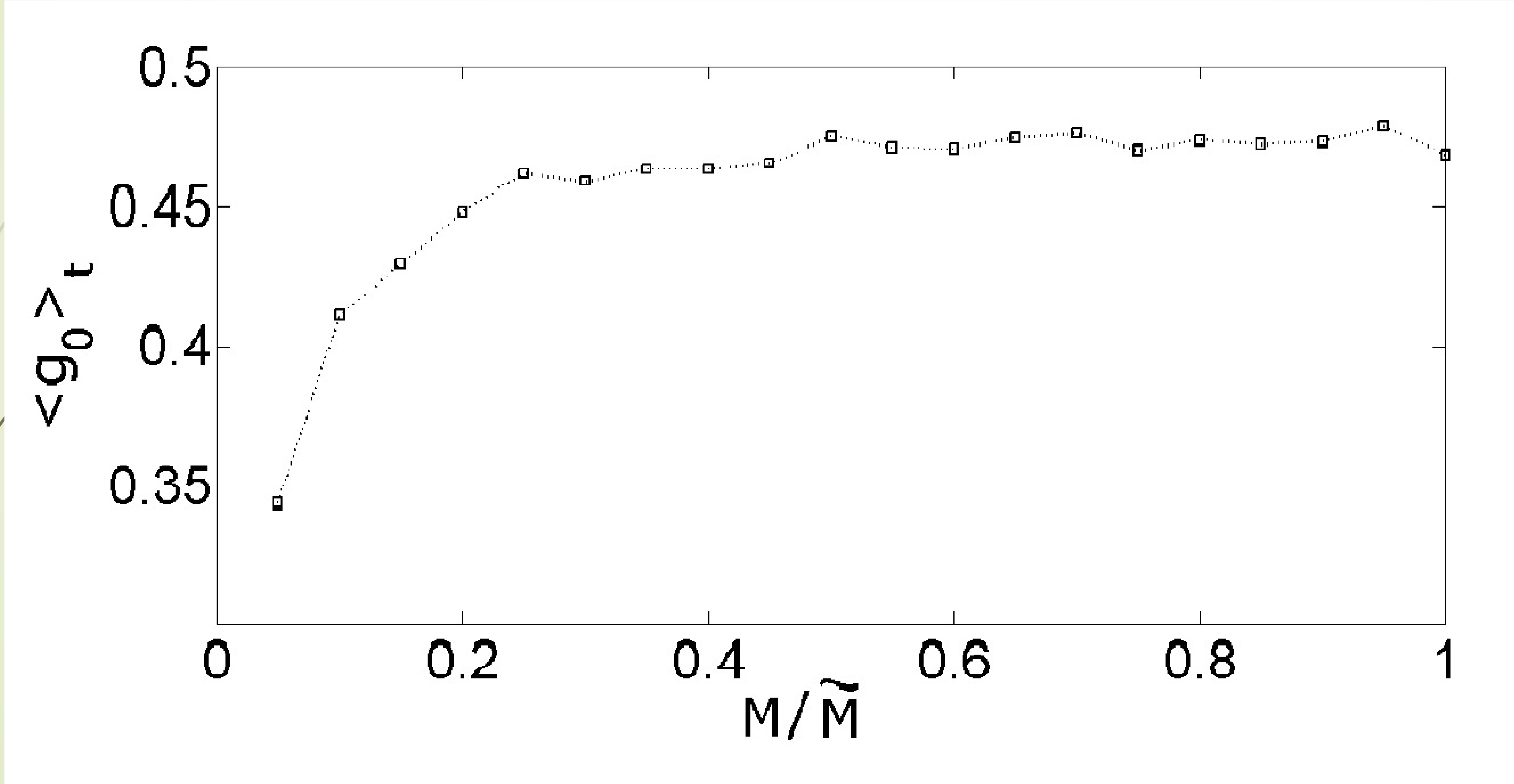
The region of turbulent chimeras



Initial conditions



System size



Normalized to $\widetilde{M} = 1000$

Conclusions

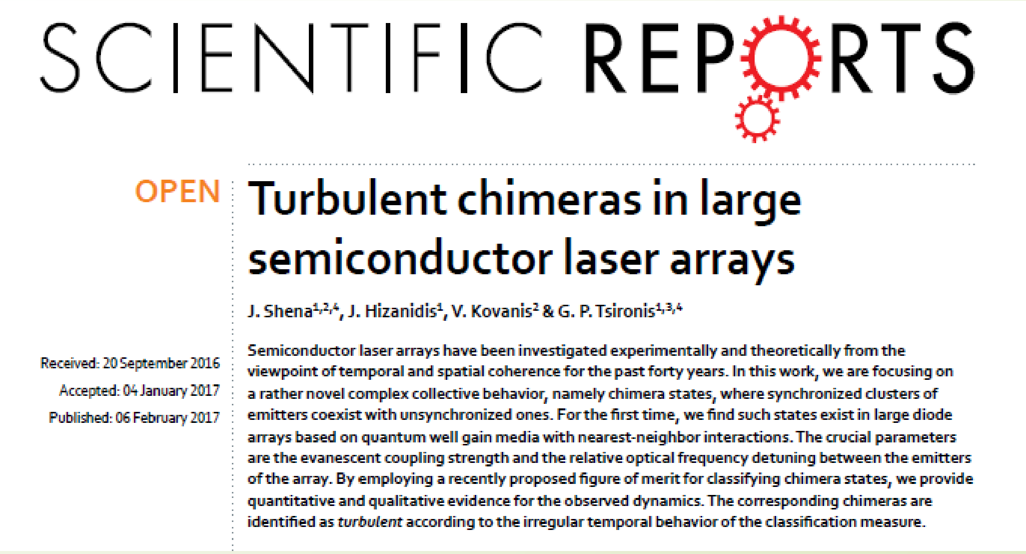
- ❑ Amplitude chimeras in a large network of semiconductor lasers with detuning
- ❑ The nature of the chimeras is turbulent
- ❑ Chimera states exist for locally coupled emitters
- ❑ The region of chimeras states lies between full synchronization and desynchronization
- ❑ Any initial conditions ensures the existence of chimeras state
- ❑ The system size also has an effect which saturates for arrays with more that 200 emitters.

For future studies

- Explore the effects introduced by noise
- The effects of the laser pump power which is the most accessible control parameter

J.Hizanidis
V.Kovanis
G.P.Tsironis

06/12/2017


SCIENTIFIC REPORTS

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Turbulent chimeras in large semiconductor laser arrays

J. Shena[1,2,4], J. Hizanidis[1], V. Kovanis[2] & G. P. Tsironis[1,3,4]

Received: 20 September 2016
Accepted: 04 January 2017
Published: 06 February 2017

Semiconductor laser arrays have been investigated experimentally and theoretically from the viewpoint of temporal and spatial coherence for the past forty years. In this work, we are focusing on a rather novel complex collective behavior, namely chimera states, where synchronized clusters of emitters coexist with unsynchronized ones. For the first time, we find such states exist in large diode arrays based on quantum well gain media with nearest-neighbor interactions. The crucial parameters are the evanescent coupling strength and the relative optical frequency detuning between the emitters of the array. By employing a recently proposed figure of merit for classifying chimera states, we provide quantitative and qualitative evidence for the observed dynamics. The corresponding chimeras are identified as *turbulent* according to the irregular temporal behavior of the classification measure.


THANK YOU