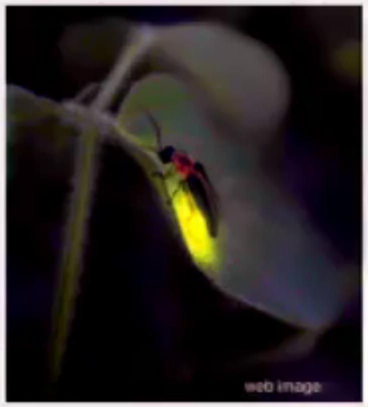
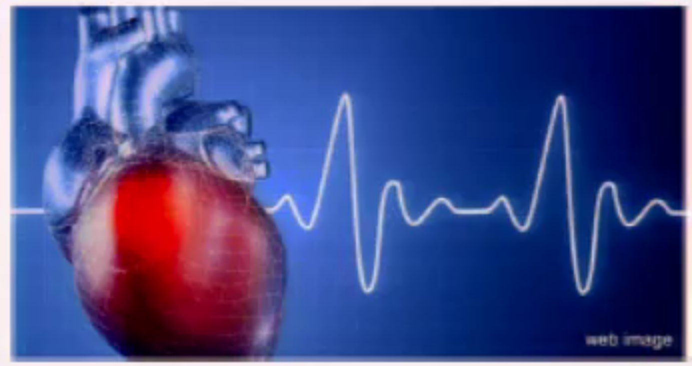
Synchronization

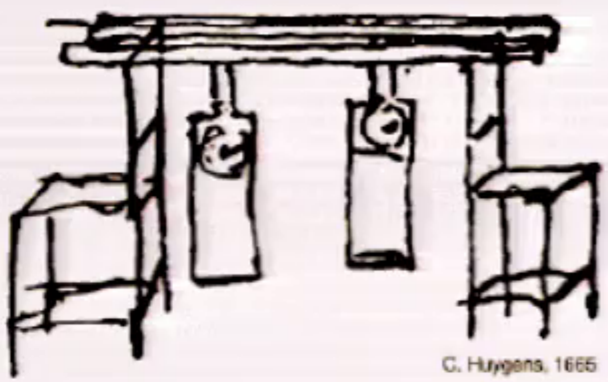
Common rhythms of interacting systems



Fireflies in Sync

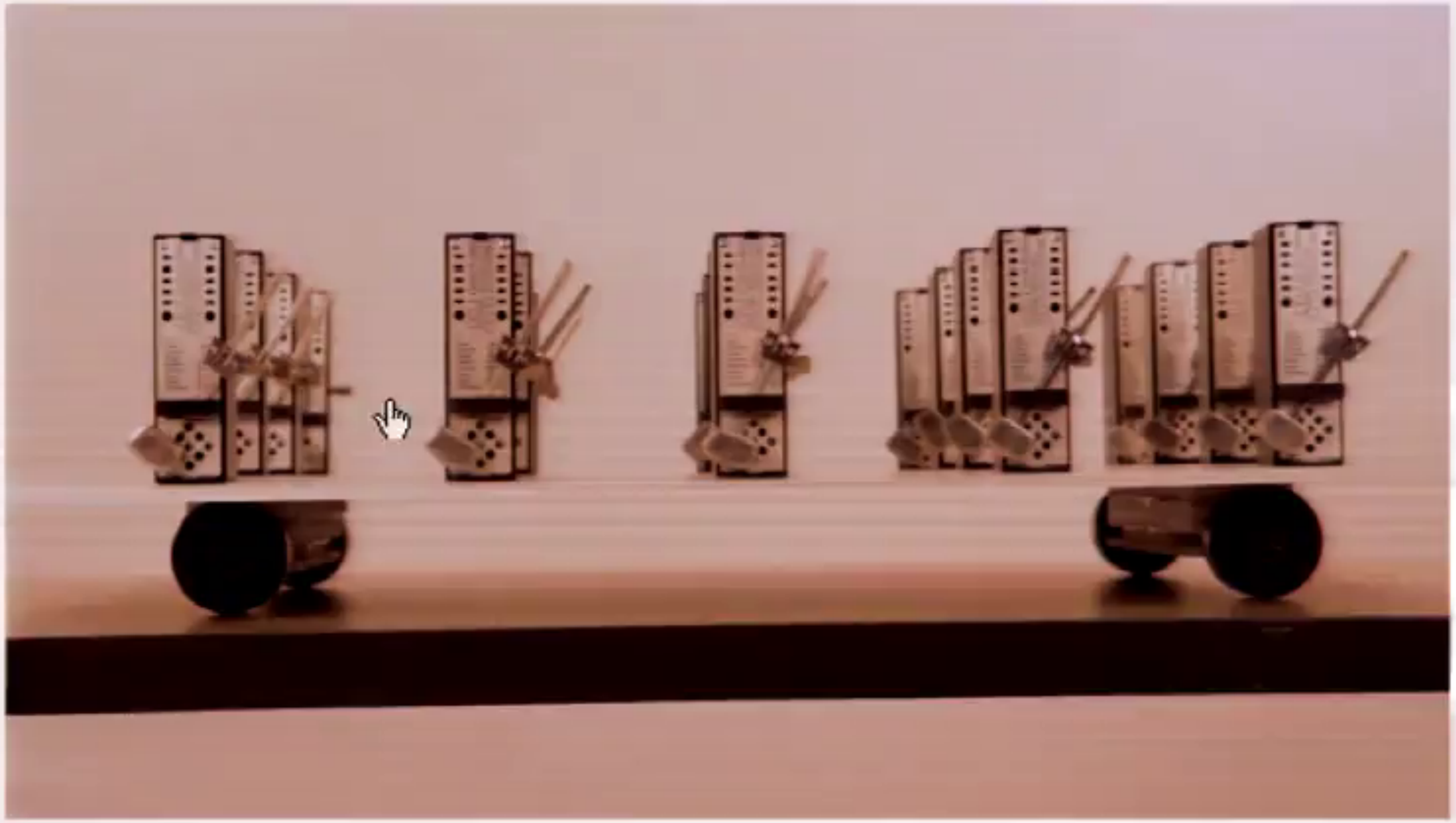


Beating of the heart

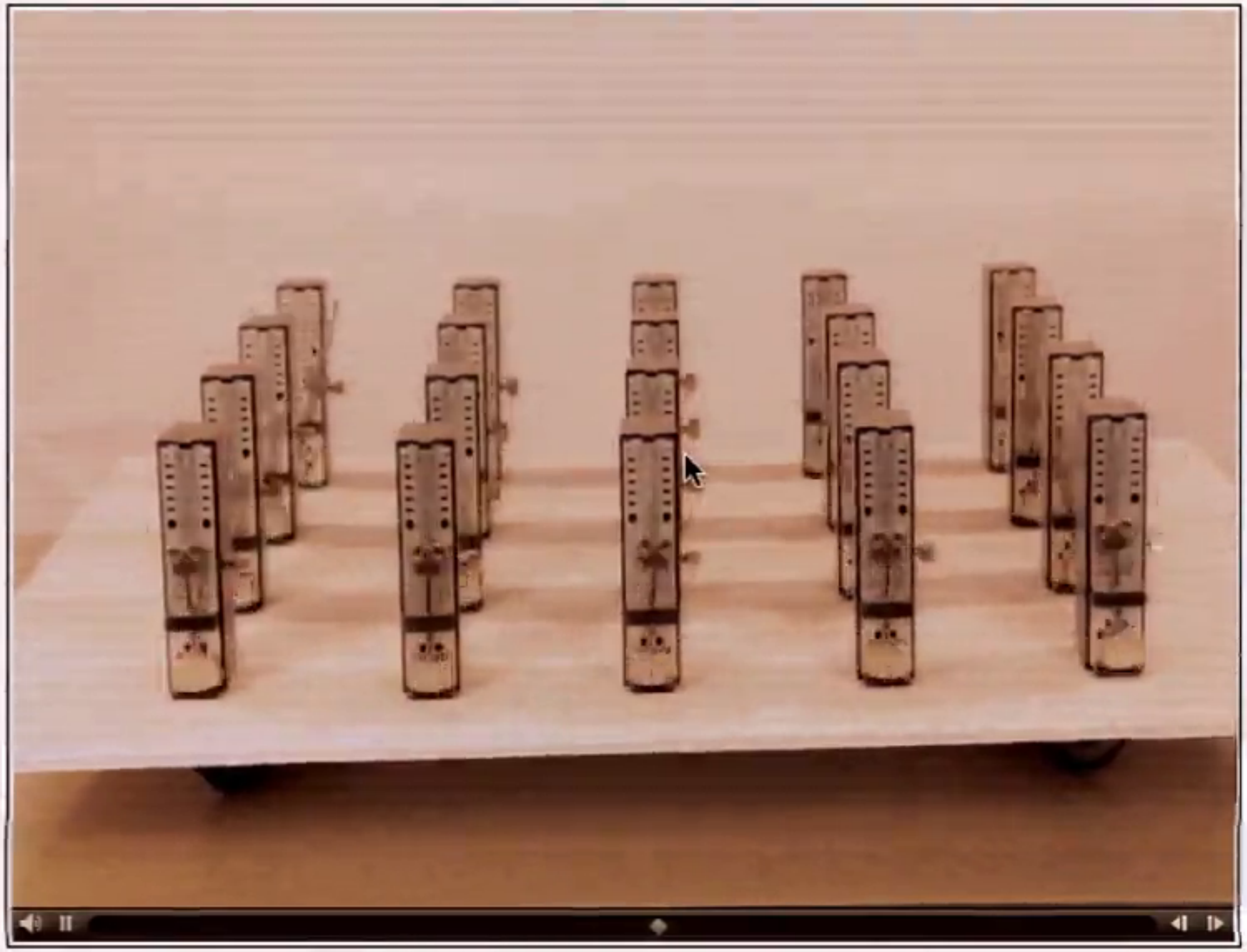


Pendulum clocks

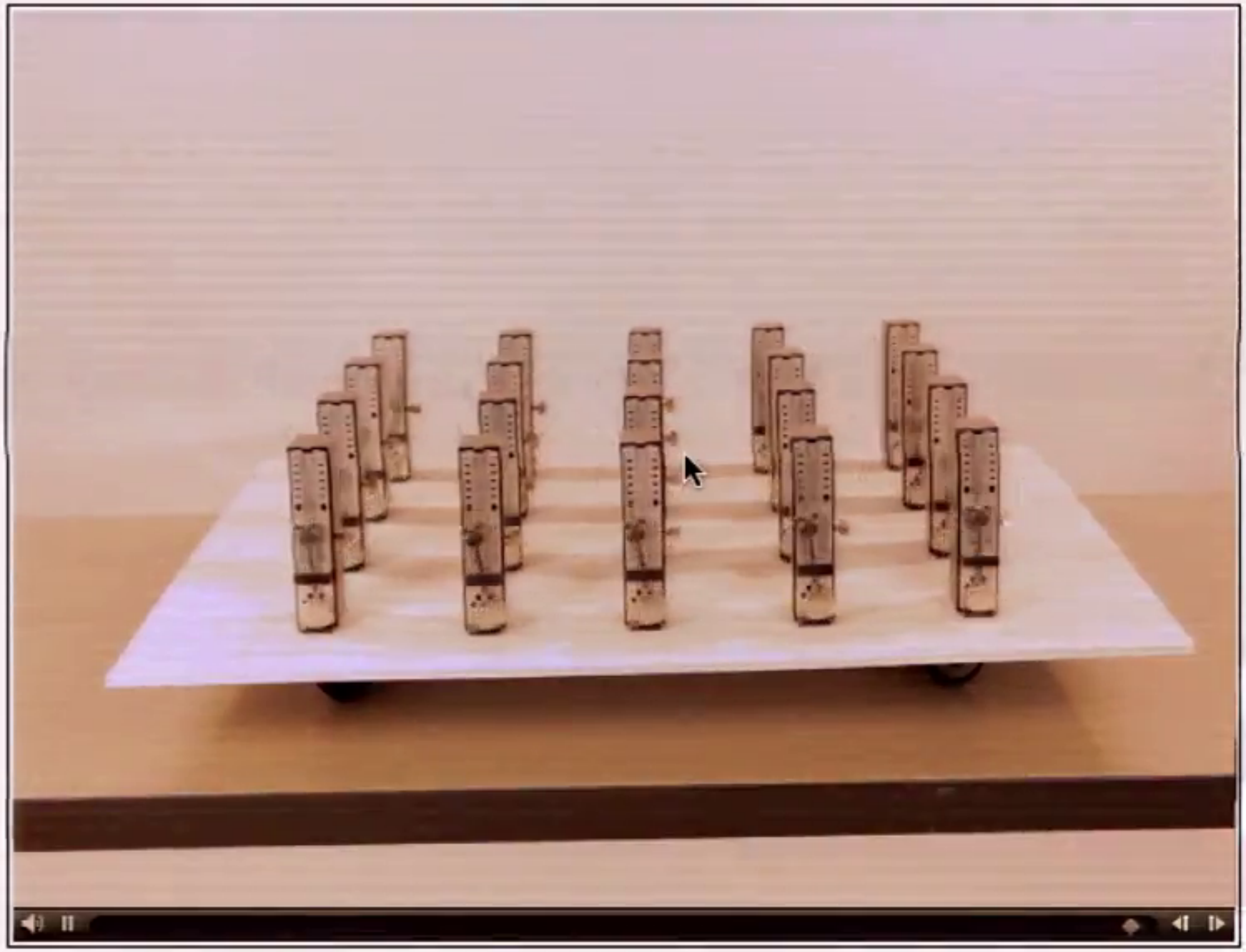
Mechanical Oscillators: Metronomes



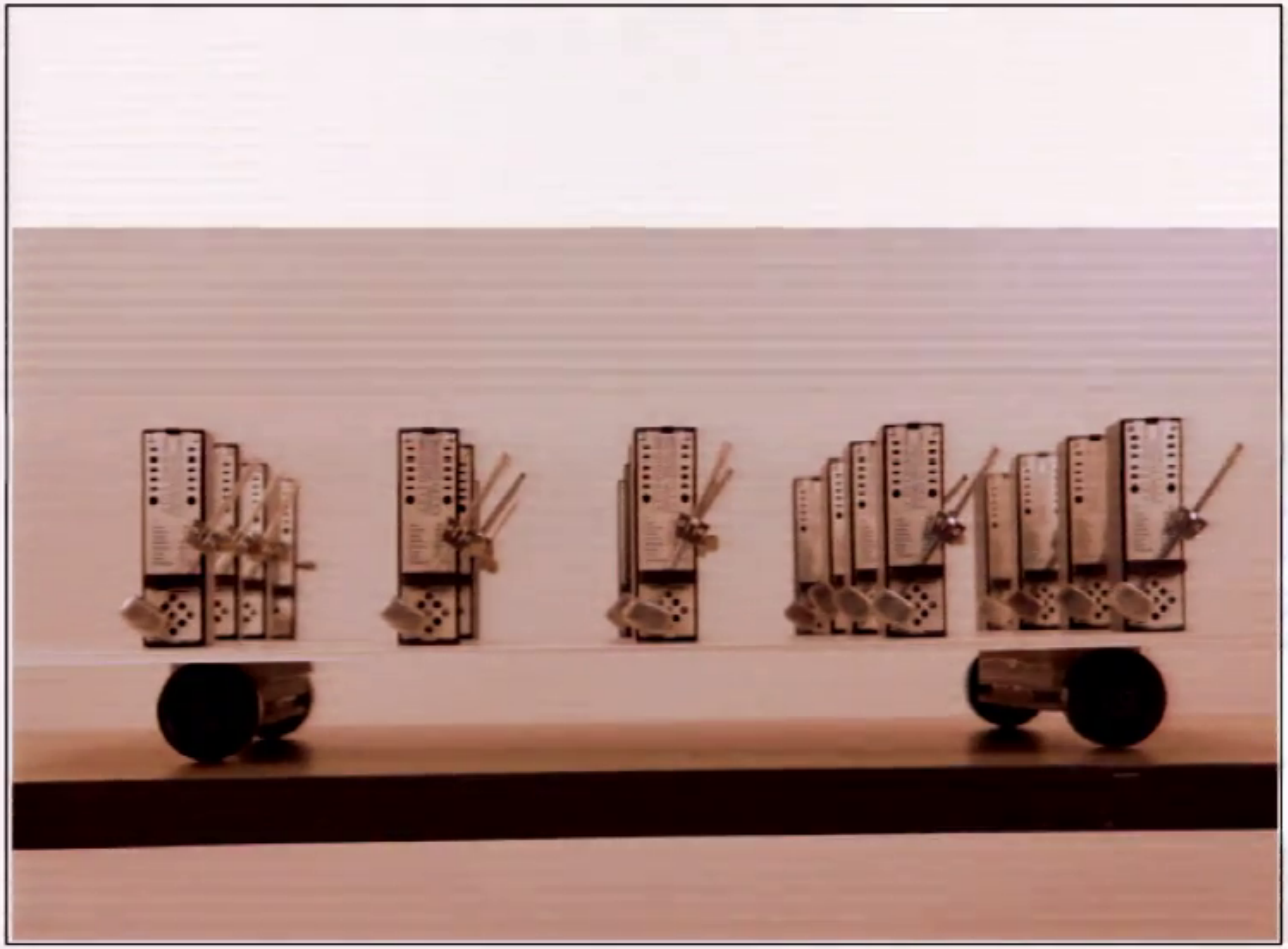
Mechanical Oscillators: Metronomes



Mechanical Oscillators: Metronomes



Mechanical Oscillators: Metronomes



Chimera States

Coexistence of synchronous and incoherent domains in arrays of identical oscillators

- Y. Kuramoto & D. Battogtokh (2002)
  Array of nonlocally coupled Complex Ginzburg-Landau equation
- D.M Abrams & S.H. Strogatz (2004)
  Exact solution for ring of phase oscillators coupled by a cosine kernel

Phase pattern of a typical chimera

Abrams & Strogatz, PRL (2004)

Theoretical studies characterizing chimera states

1. Y. Kuramoto and D. Battogtokh, *Coexistence of coherence and incoherence in nonlocally coupled phase oscillators*, Nonlinear Phenom. Complex Syst, 5, 380 (2002).
2. D.M Abrams and S.H. Strogatz, *Chimera states for coupled oscillators*, Phys. Rev. Lett. 93, 174102, (2004)
3. D. M. Abrams, R. Mirollo, S. H. Strogatz, and D. A. Wiley, *Solvable Model for Chimera States of Coupled Oscillators*, Phys. Rev. Lett., 101 (2008).
4. C. R. Laing, *Chimera states in heterogeneous networks*, Chaos, 19, 013113 (2009)
5. G. C. Sethia and A. Sen, *Clustered Chimera States in Delay-Coupled Oscillator Systems*, Phys. Rev. Lett. 100, 144102 (2008)
6. G. Bordyugov, A. Pikovsky and M. Rosenblum, *Self-emerging and turbulent chimeras in oscillator chains*, Phys. Rev. E 82, 035205 (2010)
7. G. C. Sethia, A. Sen and G.L. Johnston, *Amplitude-mediated chimera states*, Phys. Rev. E 88, 042917 (2013)
8. A. Yeldesbay, A. Pikovsky, and M. Rosenblum, *Chimeralike States in an Ensemble of Globally Coupled Oscillators*, Phys. Rev. Lett., 112, 144103 (2014).
9. M. J. Panaggio and D. M. Abrams, *Chimera states: coexistence of coherence and incoherence in networks of coupled oscillators*, Nonlinearity 28 (2015)

Experimental demonstration of chimera states

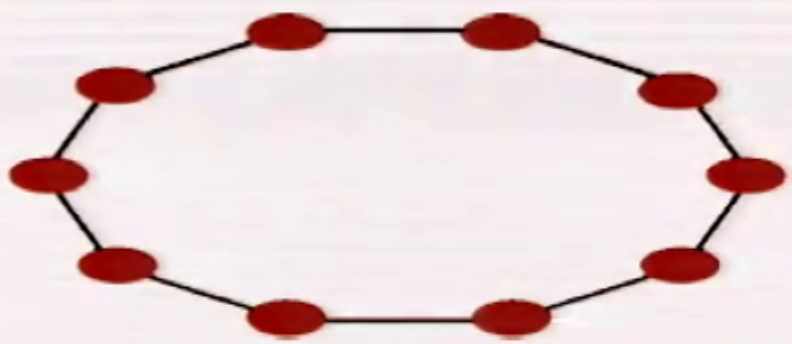
10. M. R. Tinsley, S. Nkomo and K. Showalter, *Chimera and phase-cluster states in populations of coupled chemical oscillators*, Nature Phys. 8, 662-5 (2012)
11. A.M. Hagerstrom, T.E. Murphy, R. Roy, P. Hövel, I. Omelchenko and E. Schöll, *Experimental observation of chimeras in coupled-map lattices*, Nature Phys. 8, 658-61(2012)
12. S. Nkomo, M. Tinsley and K. Showalter, *Chimera states in populations of nonlocally coupled chemical oscillators*, Phys. Rev. Lett. 110 244102 (2013)
13. E. A. Martens, S. Thutupalli, A. Fourrire and O. Hallatschek,*Chimera states in mechanical oscillator networks*, Proc. Natl Acad. Sci. USA 110 10563-7 (2013)
14. D. P. Rosin, D. Rontani, N. D. Haynes, E. Schöll, and D. J. Gauthier, *Transient scaling and resurgence of chimera states in networks of Boolean phase oscillators*, Phys. Rev. E 90, 030902 (2014).
15. M. Wickramasinghe and I. Z. Kiss, *Spatially Organized Dynamical States in Chemical Oscillator Networks: Synchronization, Dynamical Differentiation, and Chimera Patterns*, PloS one, 8, e80586 (2013).
16. L. Larger, B. Penkovsky, and Y. Maistrenko, *Virtual Chimera States for Delayed-Feedback Systems*, Phys. Rev. Lett., 111, 054103 (2013).
17. E. A. Viktorov, T. Habruseva, S. P. Hegarty, G. Huyet, and B. Kelleher, *Coherence and Incoherence in an Optical Comb*, Phys. Rev. Lett., 112, 224101 (2014).

In this work

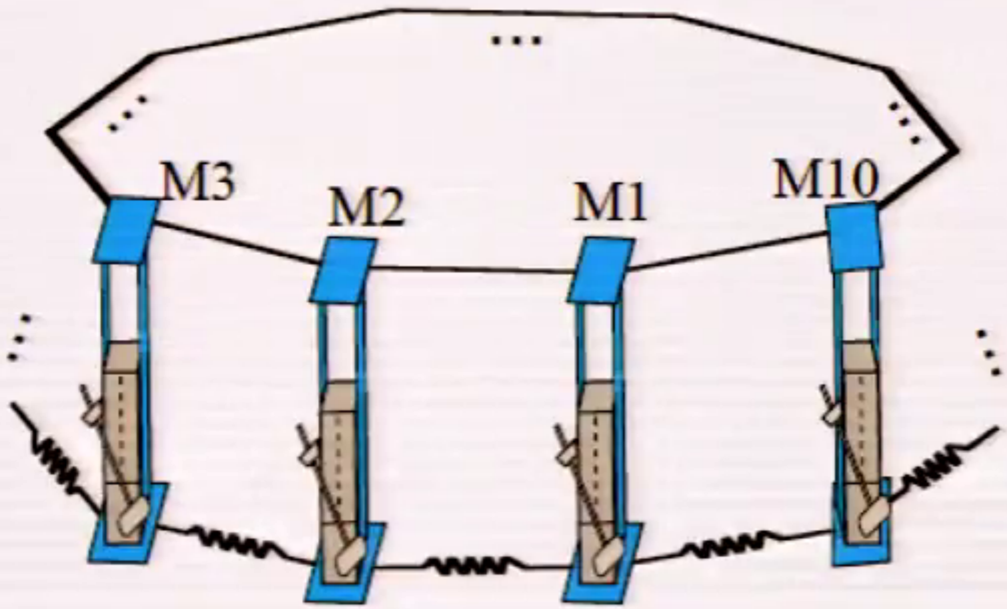
Numerical simulations and experimental demonstration of chimera states in homogeneous networks.

A homogeneous network would require a breaking a continuous symmetry, while a clustered network would involve the breaking of a discrete symmetry.

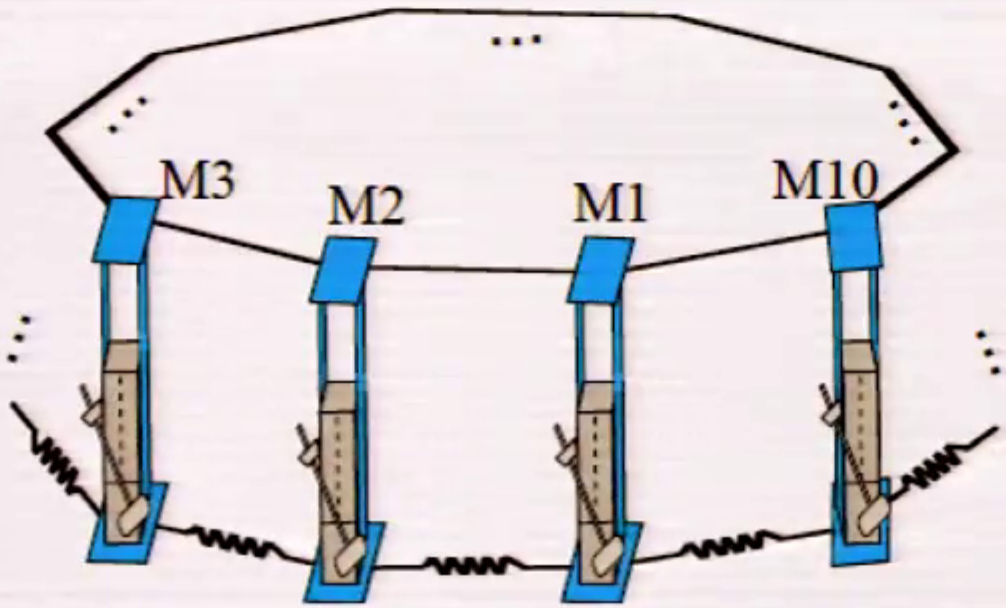
One dimensional translationally invariant network of identically coupled mechanical oscillators

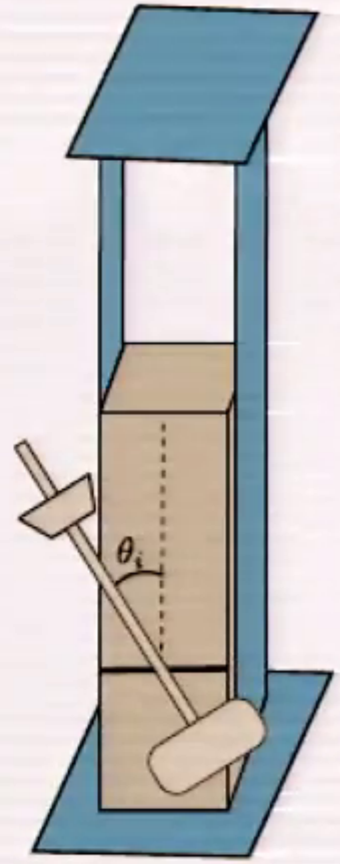


Metronome-swing oscillator network setup



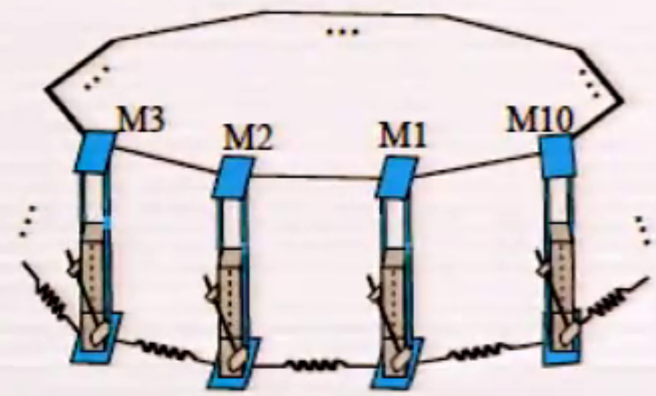
Metronome-swing oscillator network setup





Data acquisition system

- Piezoelectric contact microphone
- NI-USB multifunction card
- Matlab data acquisition software
- Sample rate 15,000 S/s



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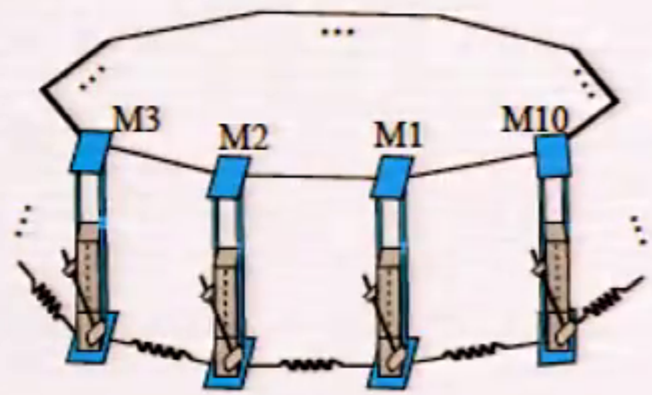
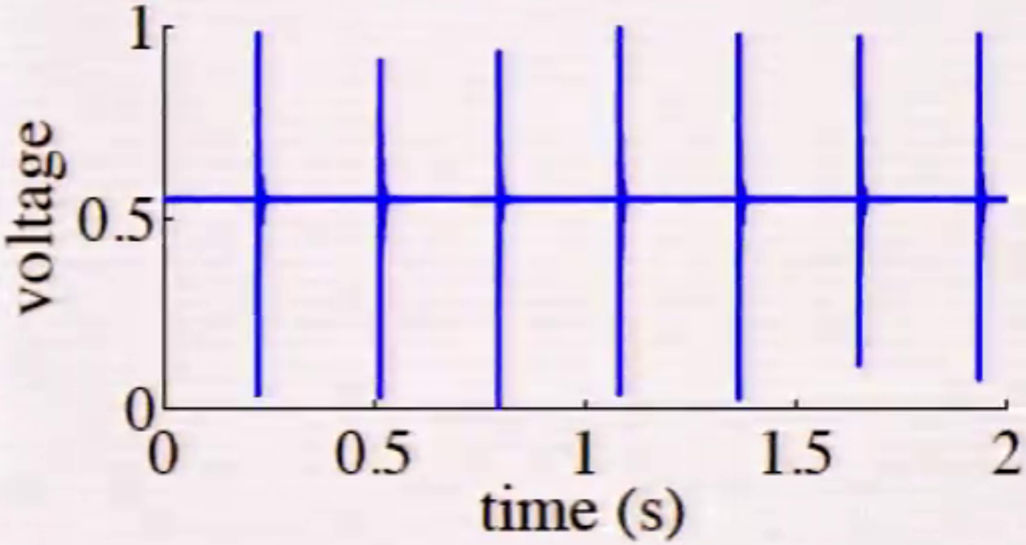


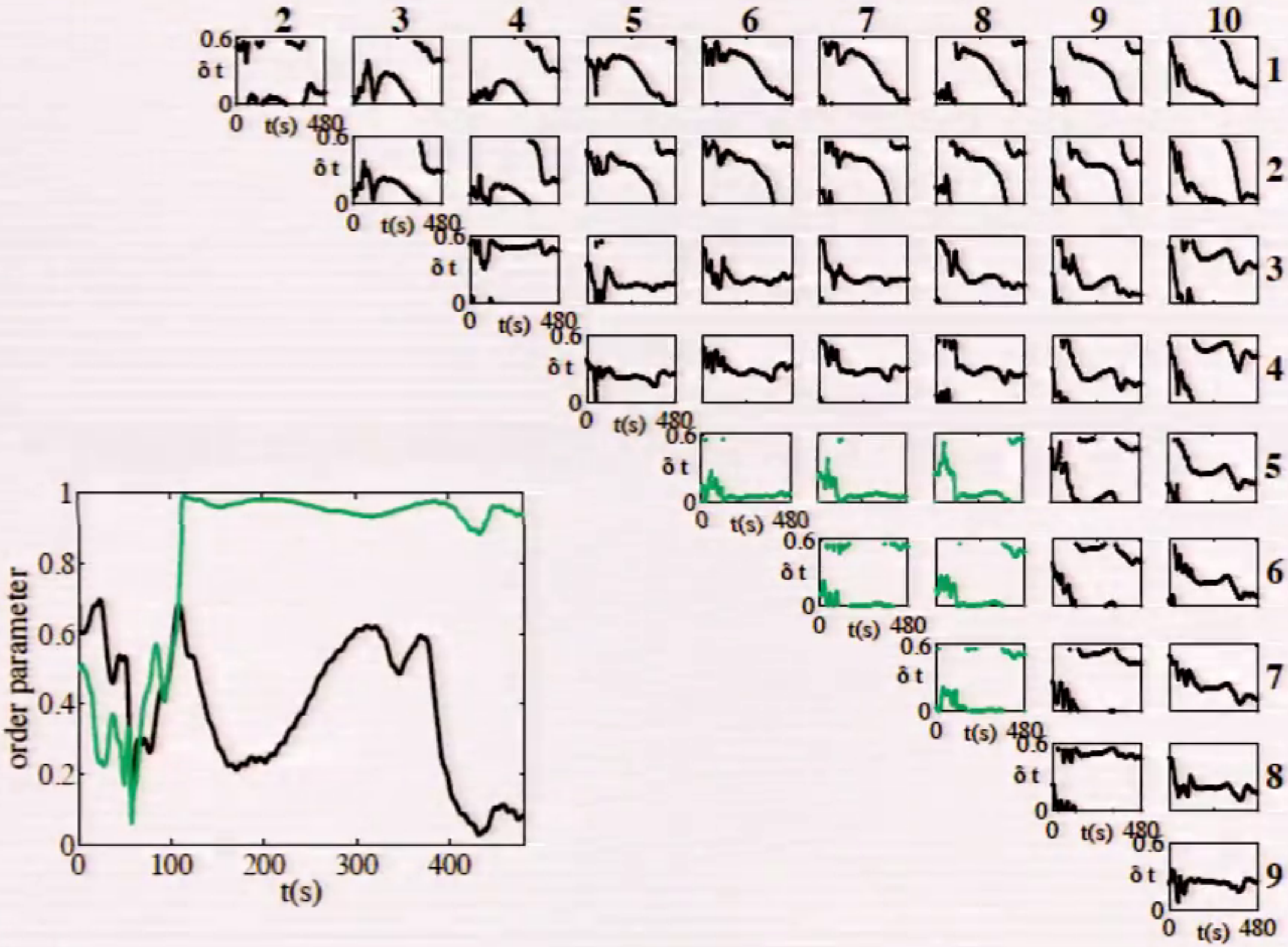
- Frequency ω_i
- Time lag, δt, between metronomes $M(i, j)$, $i, j = 1, 2, ..., 10$, $j > i$
- Oscillation phases $\psi_i(t) = 2\pi + \frac{t - t_n}{t_{n+1} - t_n} 2\pi$,
- Order parameter $R_S(t) = \frac{1}{N_S} \sum_{k=1}^{N_S} e^{i\psi_k(t)}$

Sample of acquired data

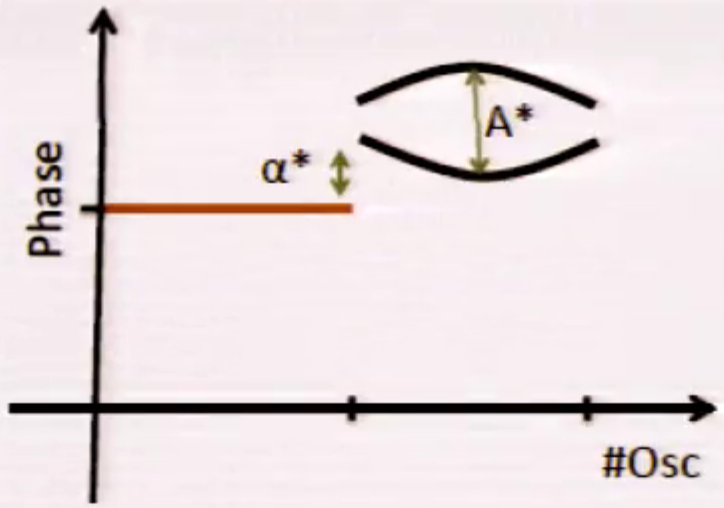


Experimental realization, F=208bpm

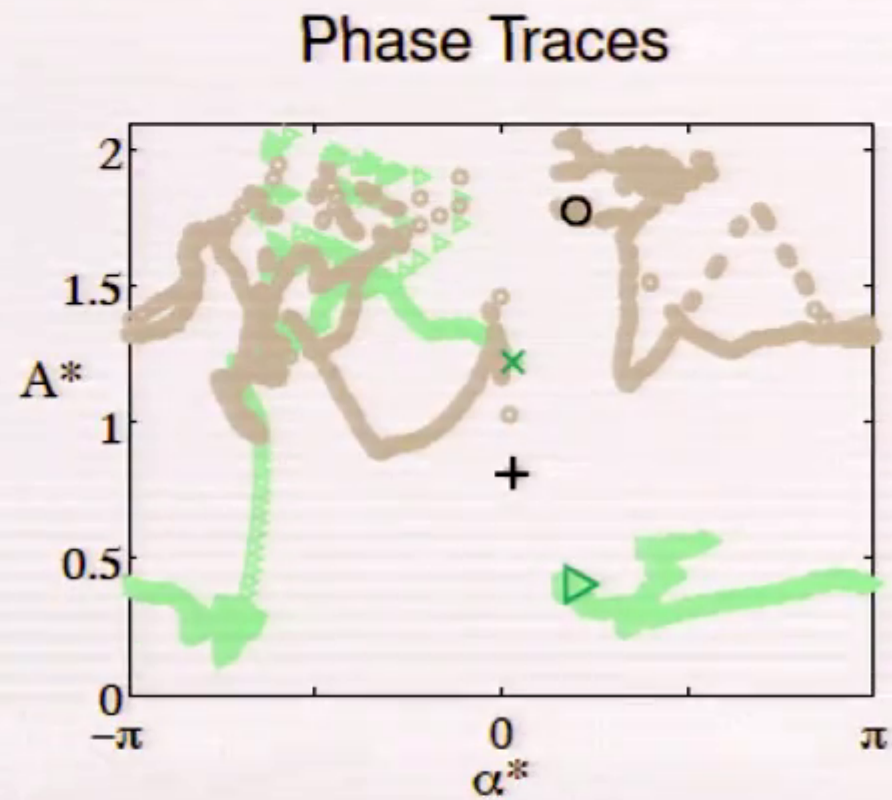
Experimental realization, F=208bpm



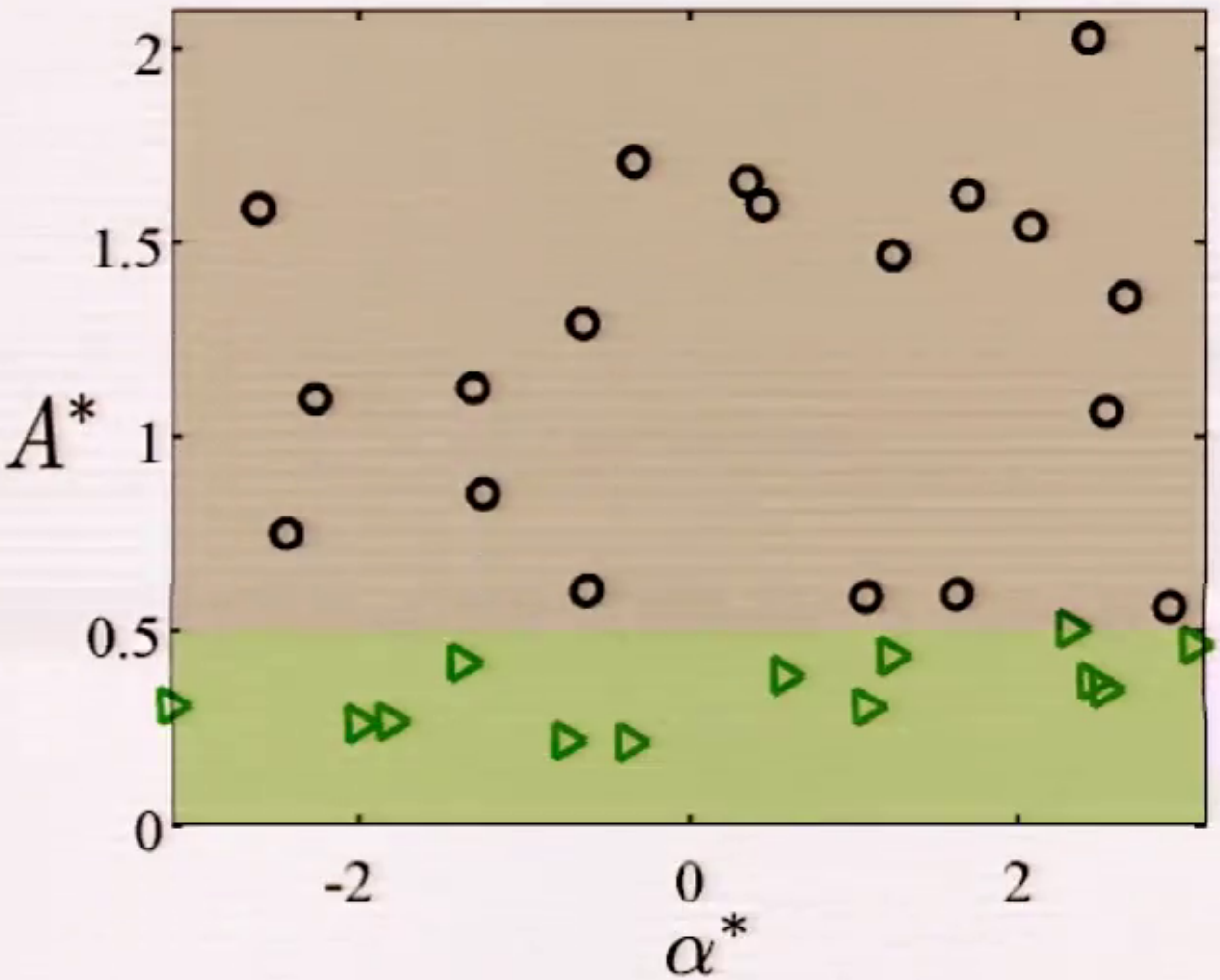
Two dimensional phase space projection



- A^* standard deviation of the phases
- α^* mean phase difference between the synchronous and incoherent groups

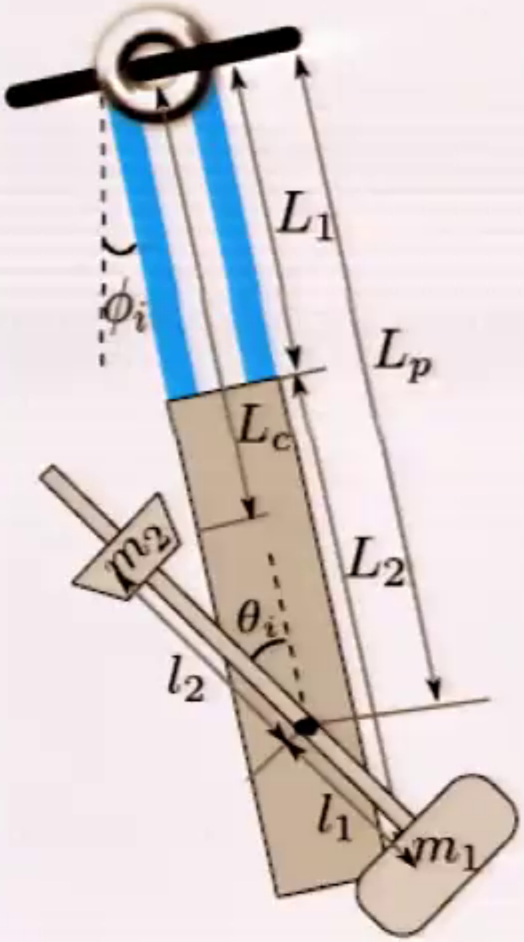


Snapshot of Phase Traces



F=208 bpm, 32 data files

Metronome-Swing Dynamics



Equations of Motion

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\phi}_i}\right) - \frac{\partial \mathcal{L}}{\partial \phi_i} = -\beta \dot{\phi}_i$$

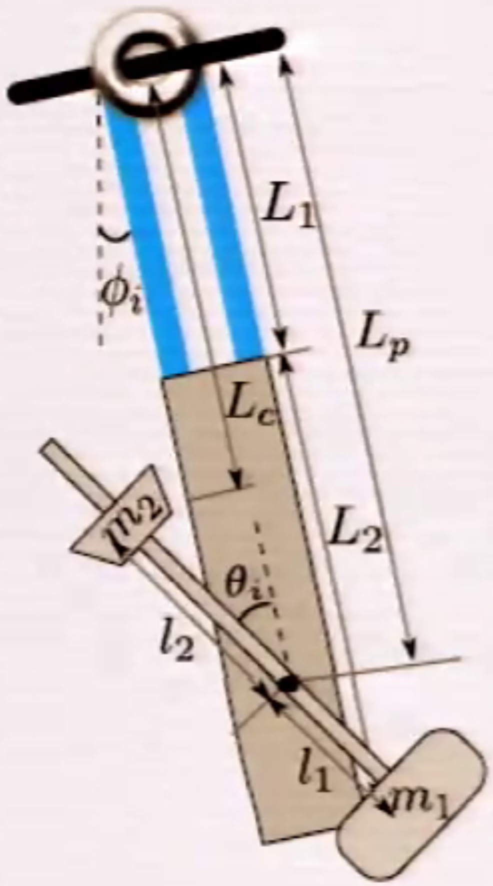
$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{\theta}_i}\right) - \frac{\partial \mathcal{L}}{\partial \theta_i} = -\mu \left[\left(\frac{\theta_i}{\theta_0}\right)^2 - 1\right] \dot{\theta}_i$$

β: energy dissipation in the swing

μ: damping/driving of the metronome escapement and for the air resistance of the bob motion. It is of van der Pol type, the angular velocity increases for $\theta_i < \theta_0$ and decreases for $\theta_i > \theta_0$.

J. Pantaleone, Am. J. Phys. (2002)

Metronome-Swing Dynamics



Equations of Motion

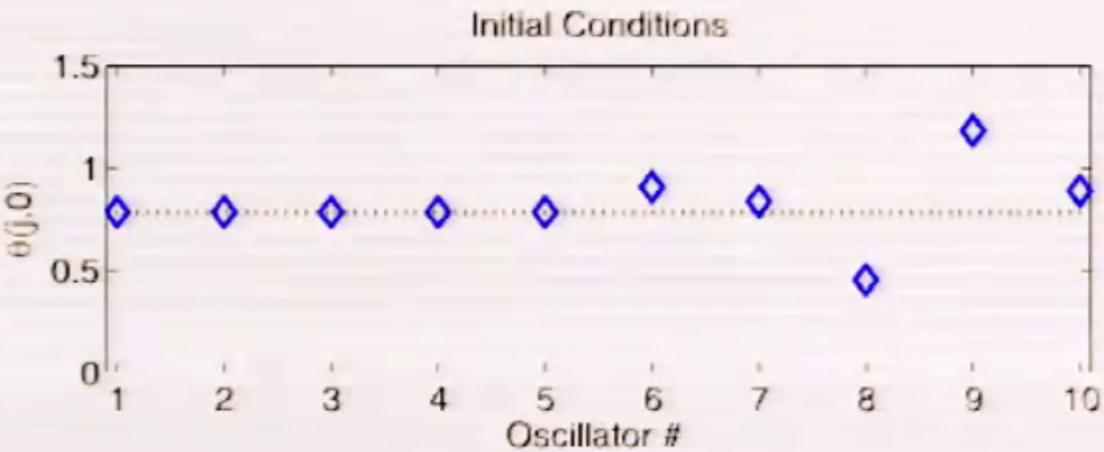
$$\ddot{\phi}_i + \frac{D}{A}\sin\phi_i + \frac{C}{A}\ddot{\theta}_i\cos(\phi_i - \theta_i) + \frac{C}{A}\dot{\theta}_i^2\sin(\phi_i - \theta_i) - \frac{\kappa}{A}(\sin\phi_{i-1} - 2\sin\phi_i - \sin\phi_{i+1})L_s^2\cos\phi_i = -\frac{\beta}{A}\dot{\phi}_i$$

$$\ddot{\theta}_i + \frac{E}{B}\sin\theta_i + \frac{C}{B}\ddot{\phi}_i\cos(\phi_i - \theta_i) - \frac{C}{B}\dot{\phi}_i^2\sin(\phi_i - \theta_i) = -\mu_\theta\left[\left(\frac{\theta_i}{\theta_0}\right)^2 - 1\right]\dot{\theta}_i.$$

$A = (I_s + (m_1 + m_2)L_p^2)$, $B = (m_1 l_1^2 + m_2 l_2^2)$, $C = (m_1 l_1 - m_2 l_2)L_p$,
$D = (M_s L_c + (m_1 + m_2)L_p)g$, $E = (m_1 l_1 - m_2 l_2)g$ and $\mu_\theta = \frac{\mu}{B}$

Simulations: Initial conditions

- Velocities zero, $\dot{\phi}_i(0) = 0$ and $\dot{\theta}_i(0) = 0$
- Swing starts in equilibrium position, $\phi_i(0) = 0$

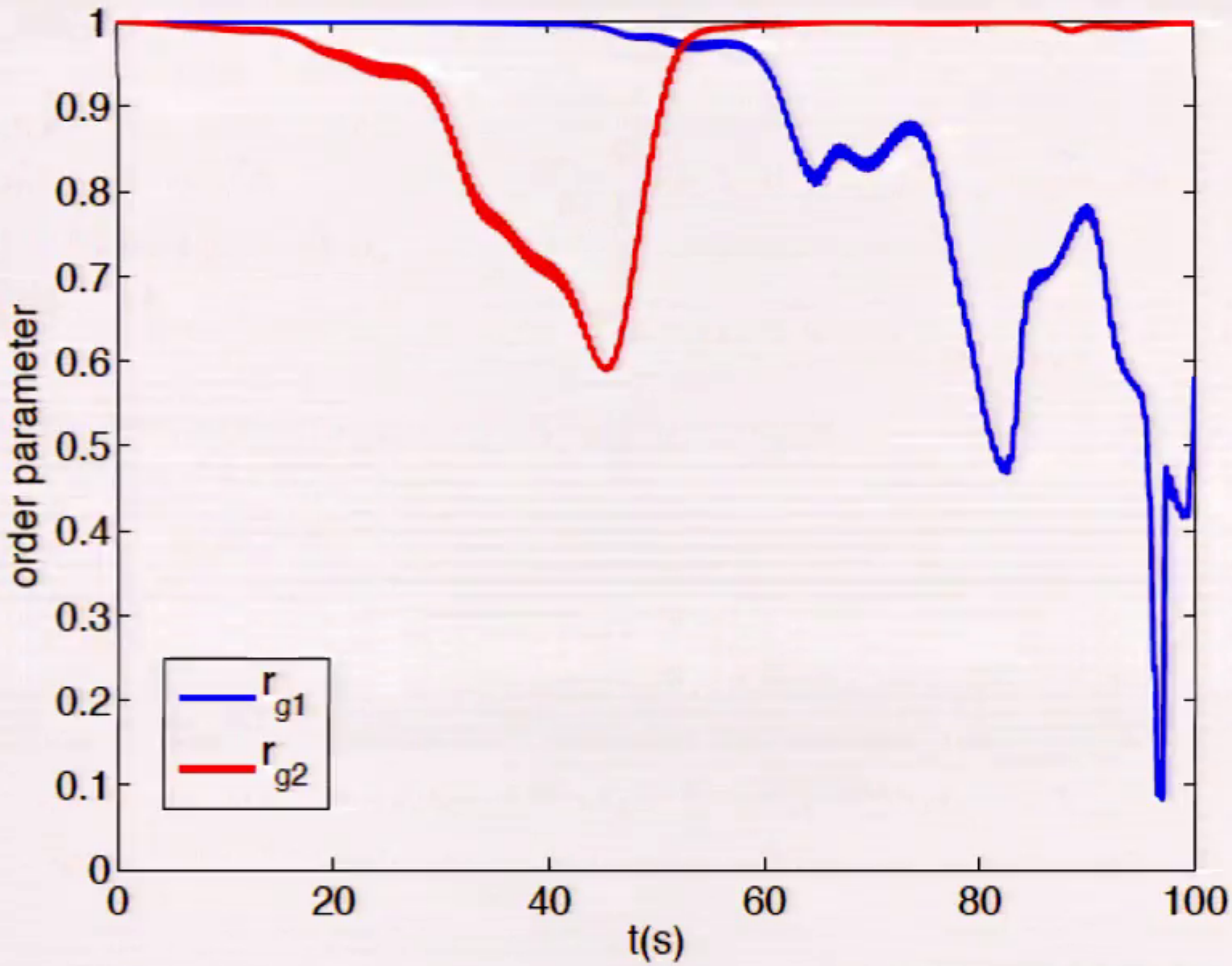


- Metronomes pendulum initial angles
  - $\theta_i(0)_{g1} = 2\theta_0$
  - $\theta_i(0)_{g2} = A\exp(-30(x-.5)^2)r(x) + \alpha$, where $r(x)$ is a uniform random number in the interval $-0.5 < r < 0.5$.

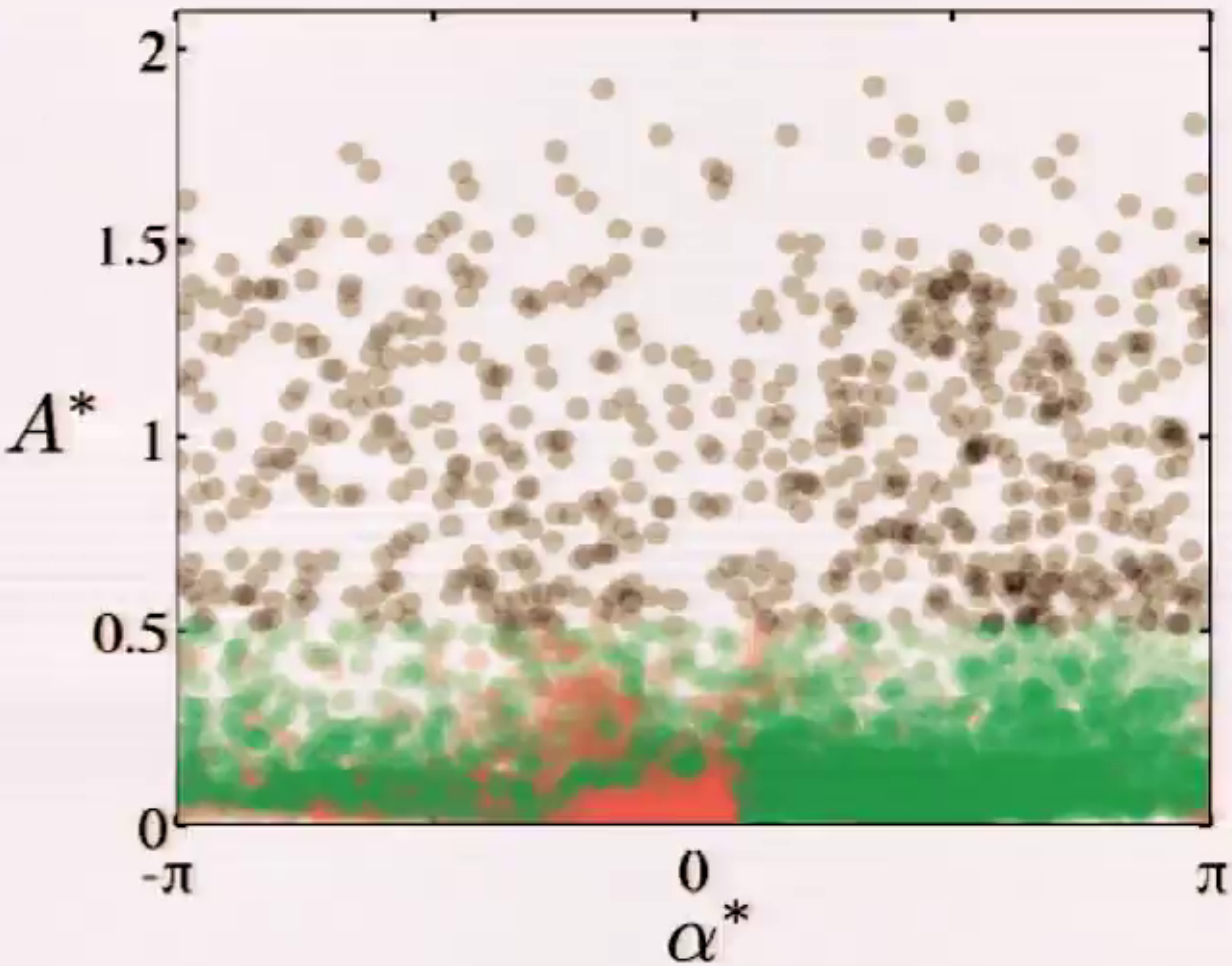
  Kuramoto & Battogtokh NPCS (2002)

- Parameters used in the simulations: $F = 208$ bpm, $m_1 = 0.023$ m, $m_2 = 0.0056$ m, $l_1 = 0.01$ m, $l_2 = 0.0734 - 0.000227 \times F$, $L_1 = 0.09$ m, $L_2 = 0.11$ m, $L_p = 0.17$ m, $L_c = 0.15$ m, $I_s = 0.0018$ kg.m^2, $M_s = 0.082$ kg, $g = 9.81$ m/s, $\kappa = 17.51$ N/m, $\mu = 0.5$, $\theta_0 = \pi/8$ and $\beta = 0.001$.

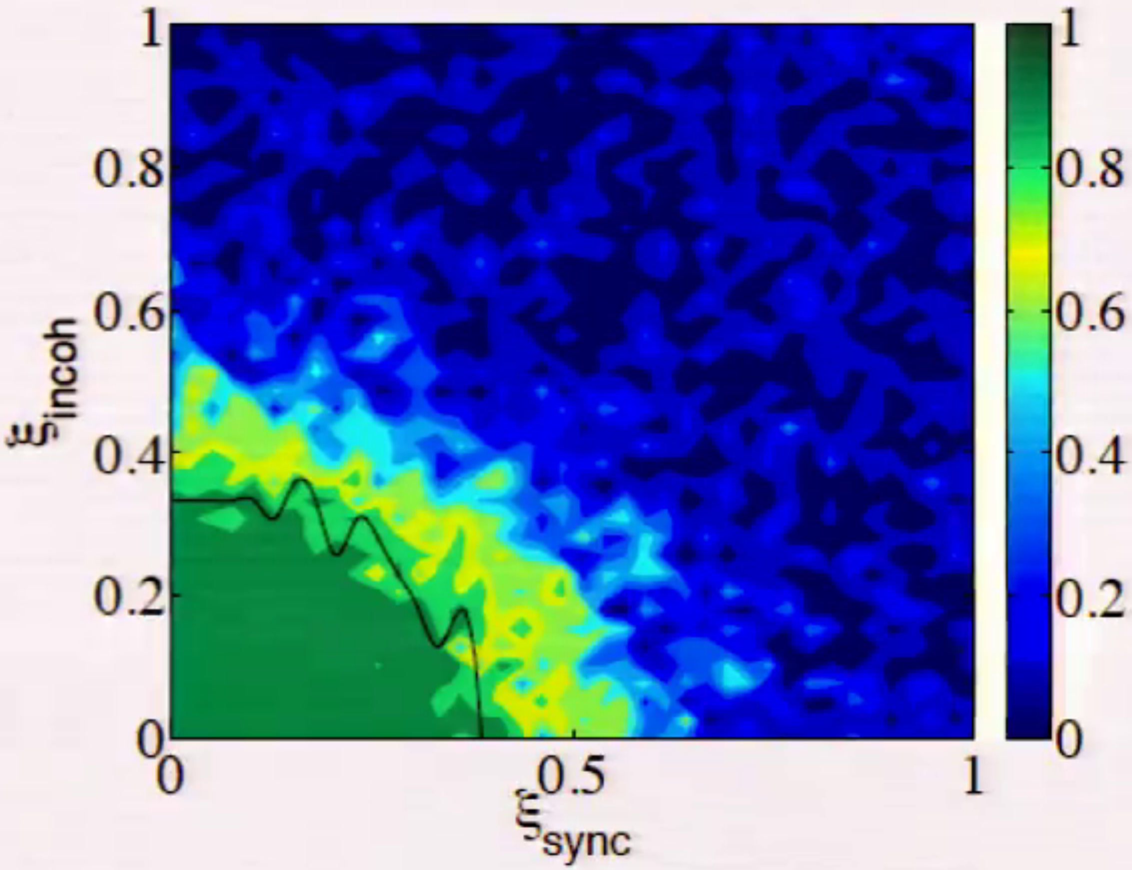
Evolution of the order parameter for each group



Numerical simulations: Snapshot of the phase traces



Basin of attraction of a typical chimera state



Relative difference between the coefficient of variation of the incoherent and synchronous groups, $\Delta CV = (\frac{\sigma_I}{\mu_I} - \frac{\sigma_S}{\mu_S}) / \max[\frac{\sigma_I}{\mu_I}, \frac{\sigma_S}{\mu_S}]$.

In conclusion

- Addressed an experimental observation of spontaneous emergence of chimeras in a one-dimensional network of identically coupled identical mechanical oscillators