How distributed is „distributed information“ in complex systems?

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in collaboration with Christoph Kirst and Demian Battaglia

Network Dynamics
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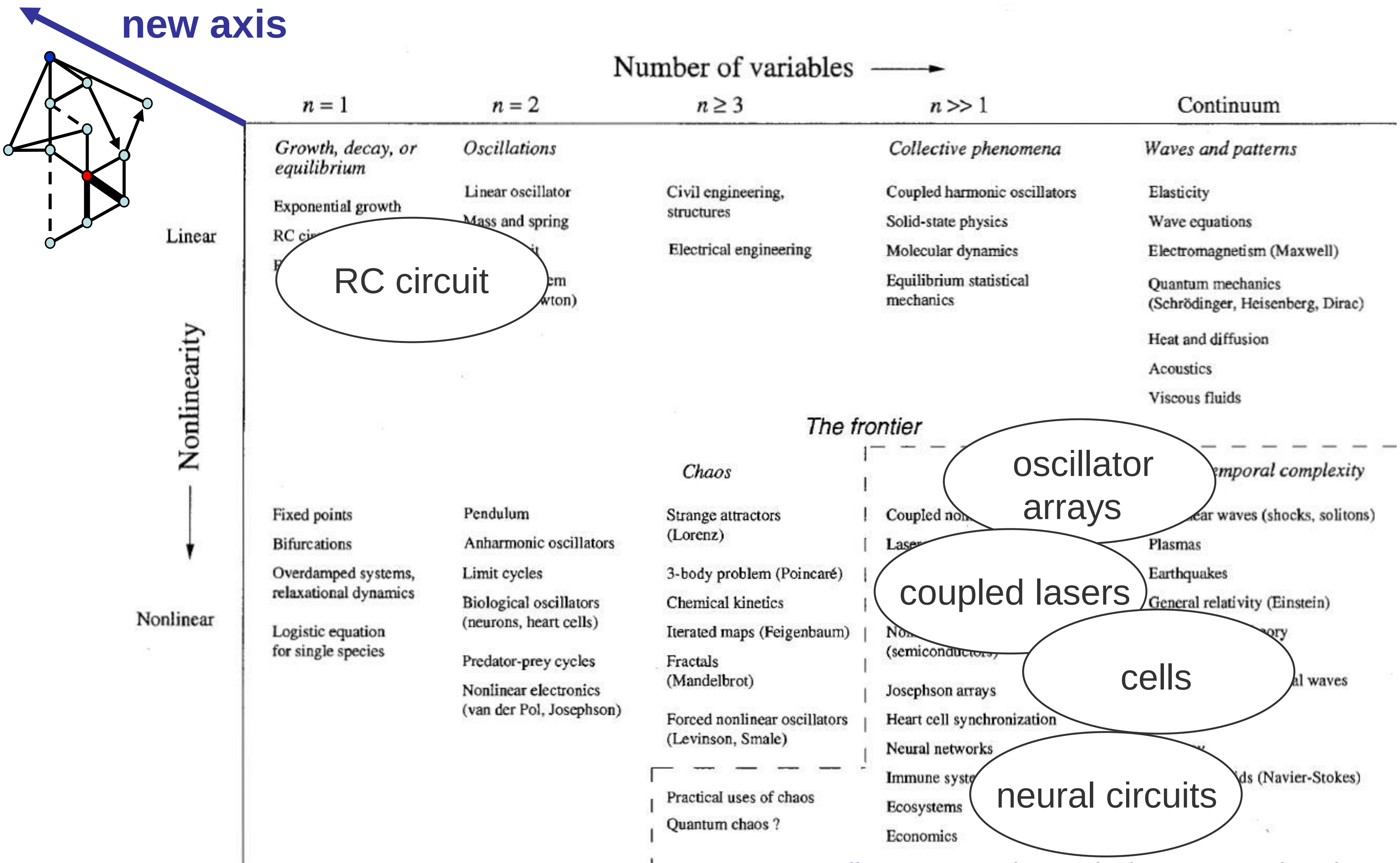
Networks are everywhere - most are dynamic

Social Networks
Neural Circuits
Gene Regulatory Networks
Traffic Networks
Communication Networks
‚Smart' Power Grids
...

All these systems are essential in everyday life!

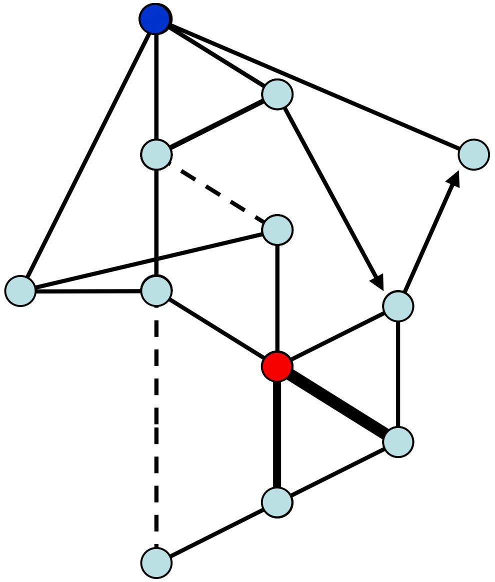
From simple & low-dimensional to complex systems



Strogatz, *Nonlinear Dynamics and Chaos*, Westview (1994)

… to complex *networked* systems

Graph/**connectivity as new axis**: complex networks



linear:
Kirchhoff's law,
Random walks,…

In general
no continuum limit

nonlinear

?

Limited knowledge,
Few general methods

Network Topology co-acts with nonlinearities:
Topological Speed Limits, Remote Action, …

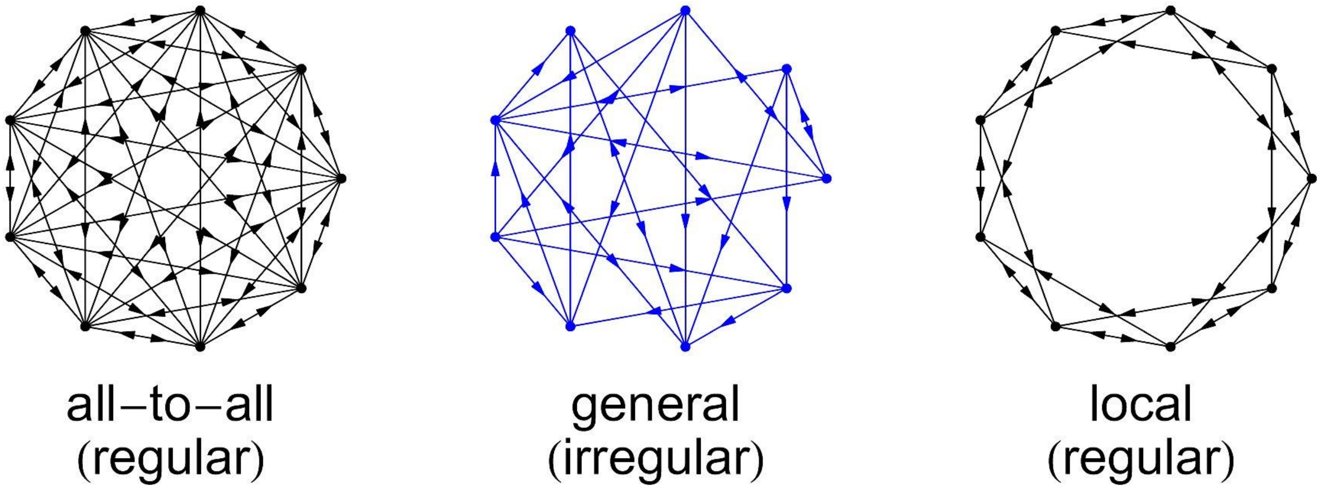
Mathematical challenges for theory

Simultaneous occurrence of:

- **Nonlinearity**
- **High dimensionality**
- Complicated Network **Connectivity**
- Interaction **Delays**
- Strong **Heterogeneities**
- **Stochasticity**

common approach:

Mean Field Theories, Statistical Description, e.g. averaging over network

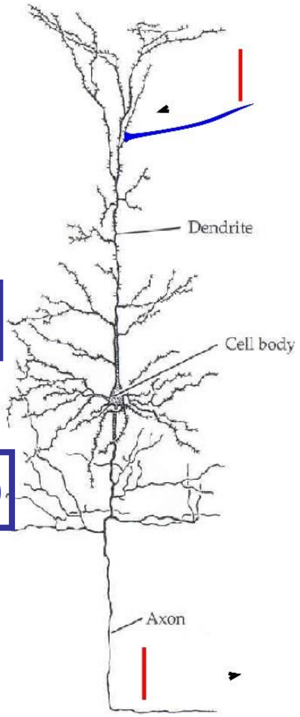


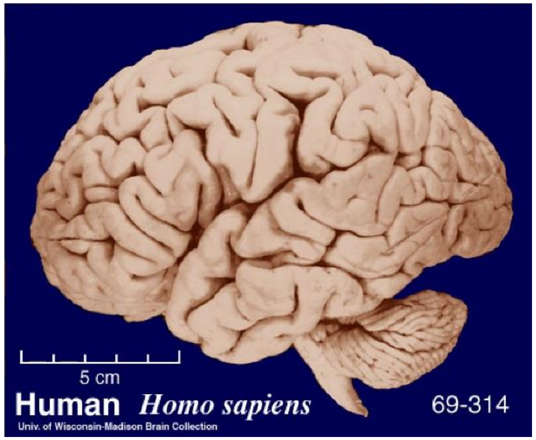
Mind the specifics (links, events, realizations, …) !

Distributed collective dynamics of networks

<u>Dynamics of biological networks</u>
($10^{-3} - 10^{10}$ *s*; $10^{-5} - 10^{-1}$ *m*)

- Selective links support sensing
- Connectomics from dynamics
- model- free network inference
- information transfer Nature Comm. (2016)
- protein scaling laws from geometry



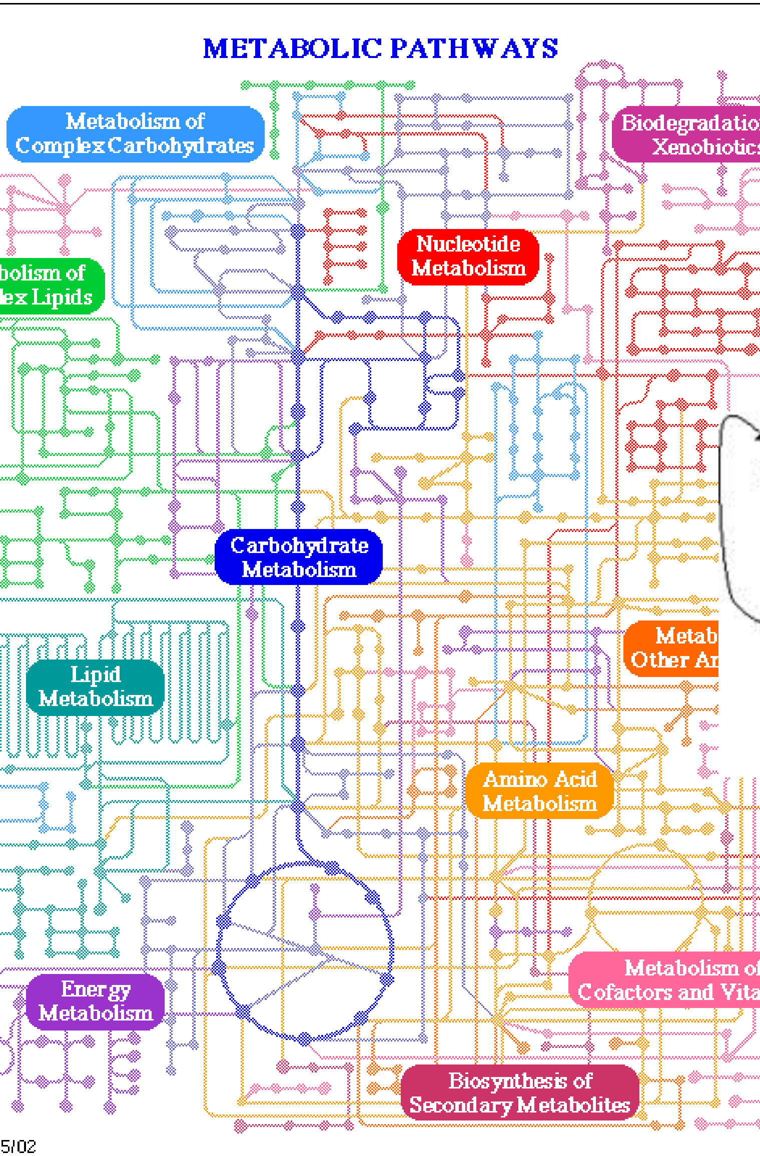


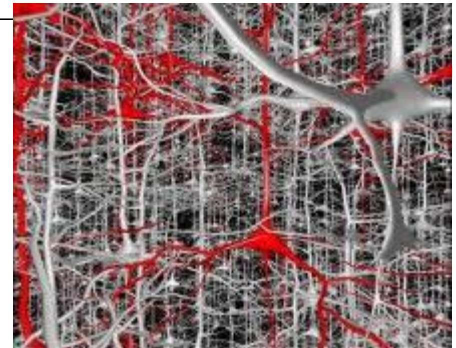
<u>Dynamics of physical networks</u>
($10^{-2} - 10^{10}$ *s*; $10^{-9} - 10^{6}$ *m*)

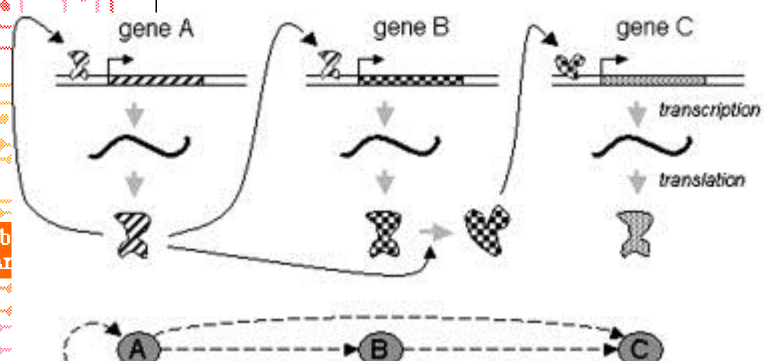
- Network growth & disordered media
- Dynamical system‘s computation & network control
- Nonlocal rerouting and dynamically smart grids
- Flexible networked mobility

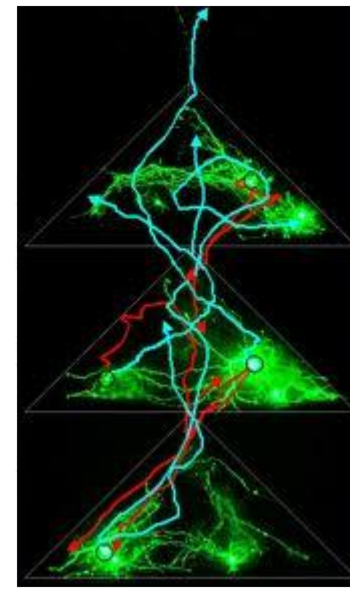
Information routing essential for function

How does it work?



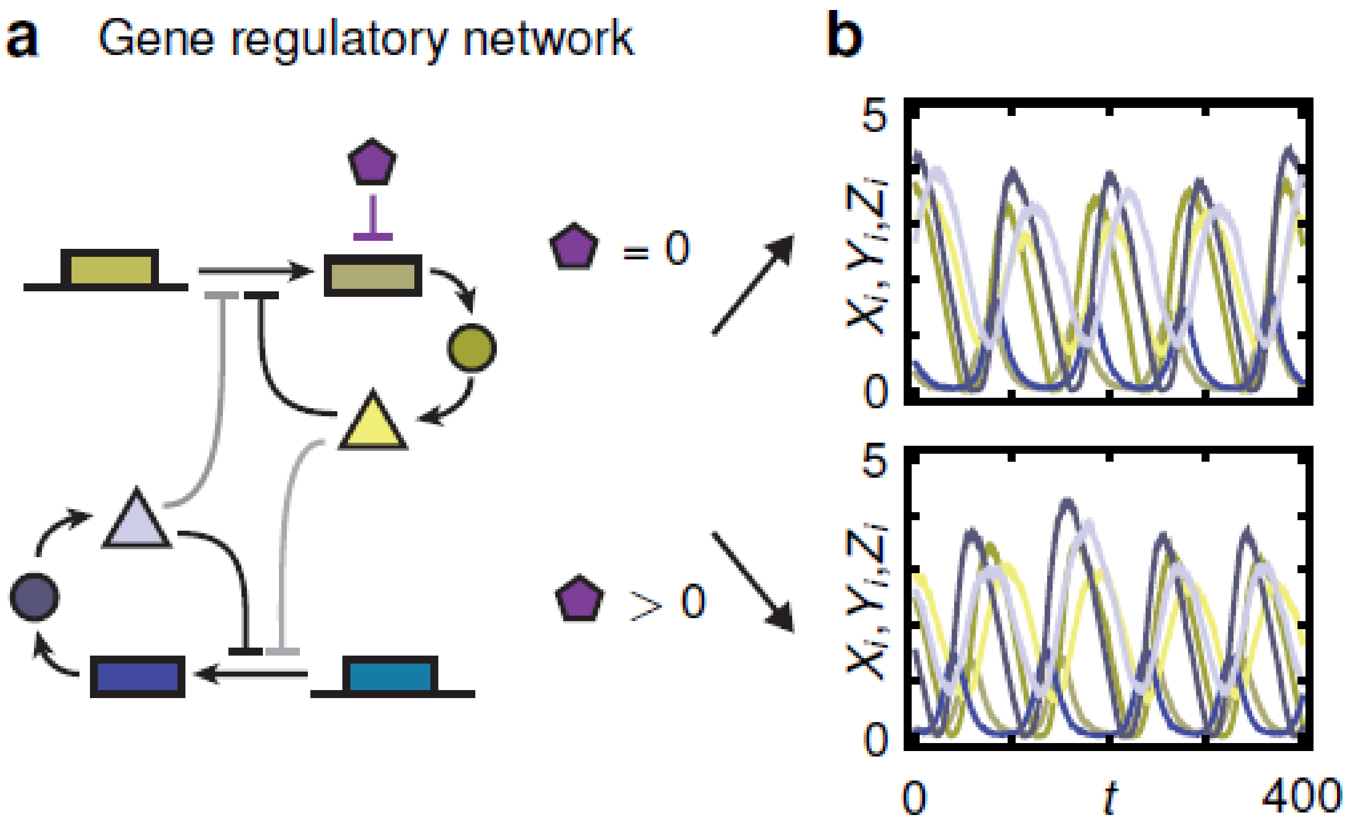




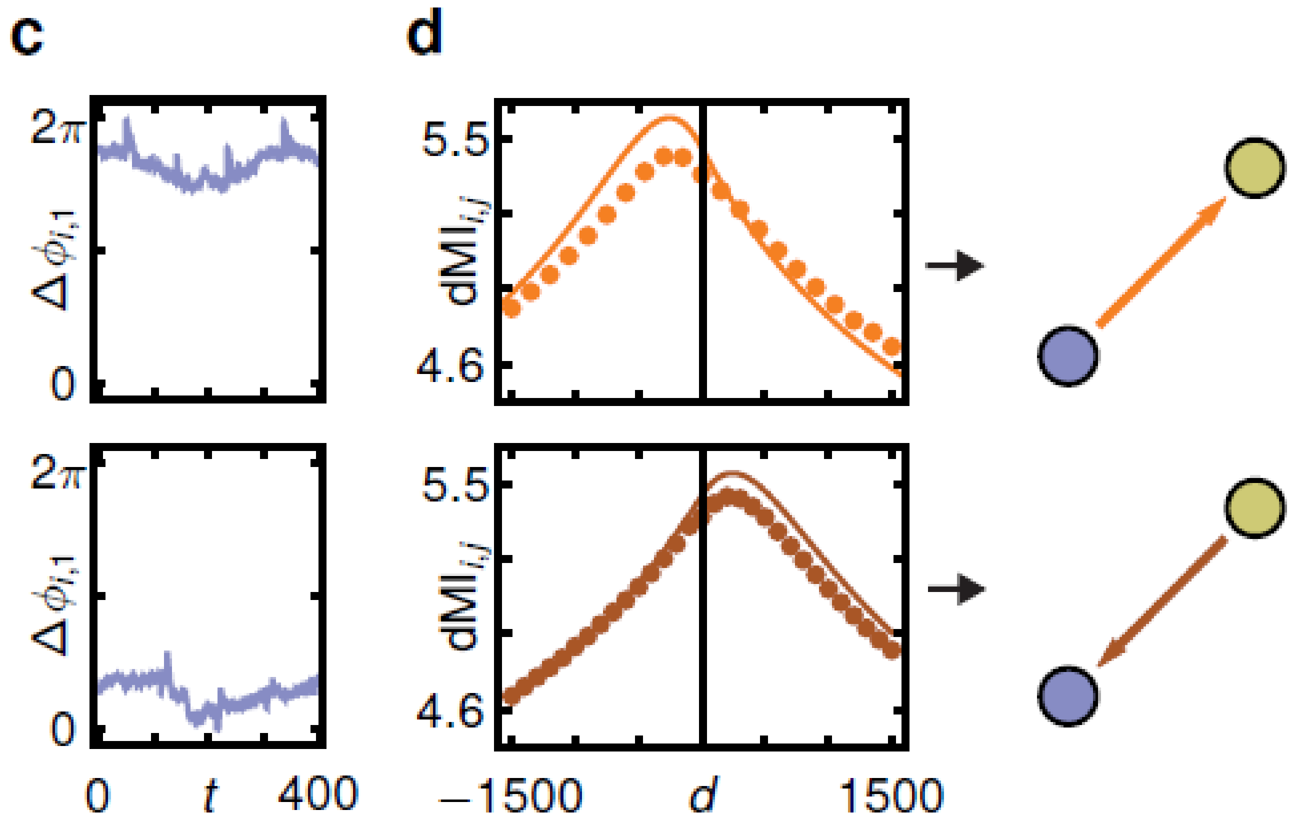


Biosystems, 96:86 (2009);
Brockmann et al, *Nature* (2006)
Google Inc. (2010)
Feinerman et al,
Nature Phys. (2008)

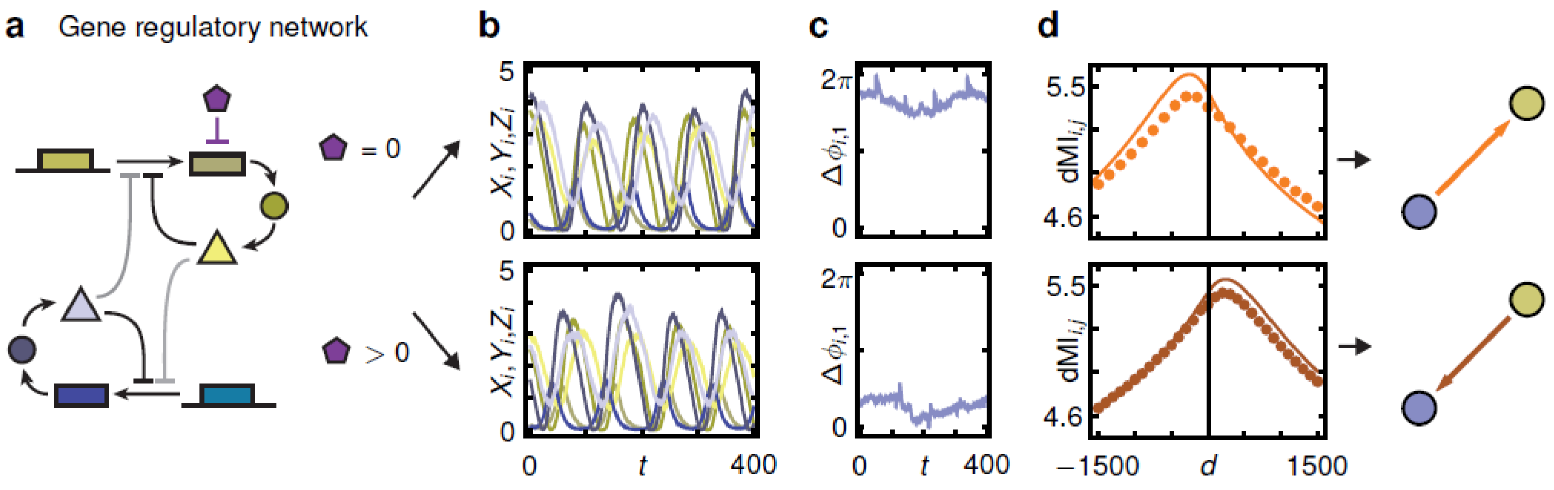
Collective Dynamics ➔ Information Routing Patterns I



Collective Dynamics ➔ Information Routing Patterns I



Collective Dynamics ➔ Information Routing Patterns I

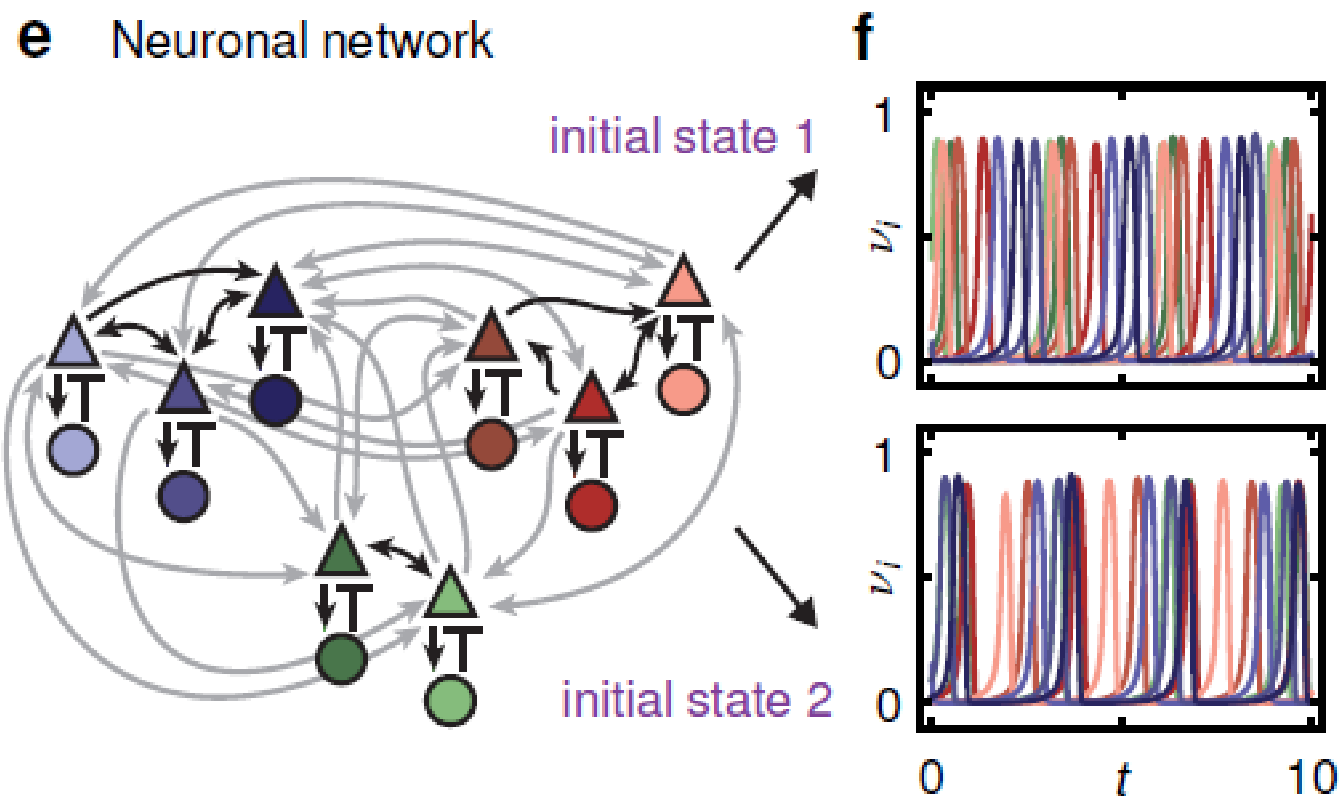


External signals change information routing pattern

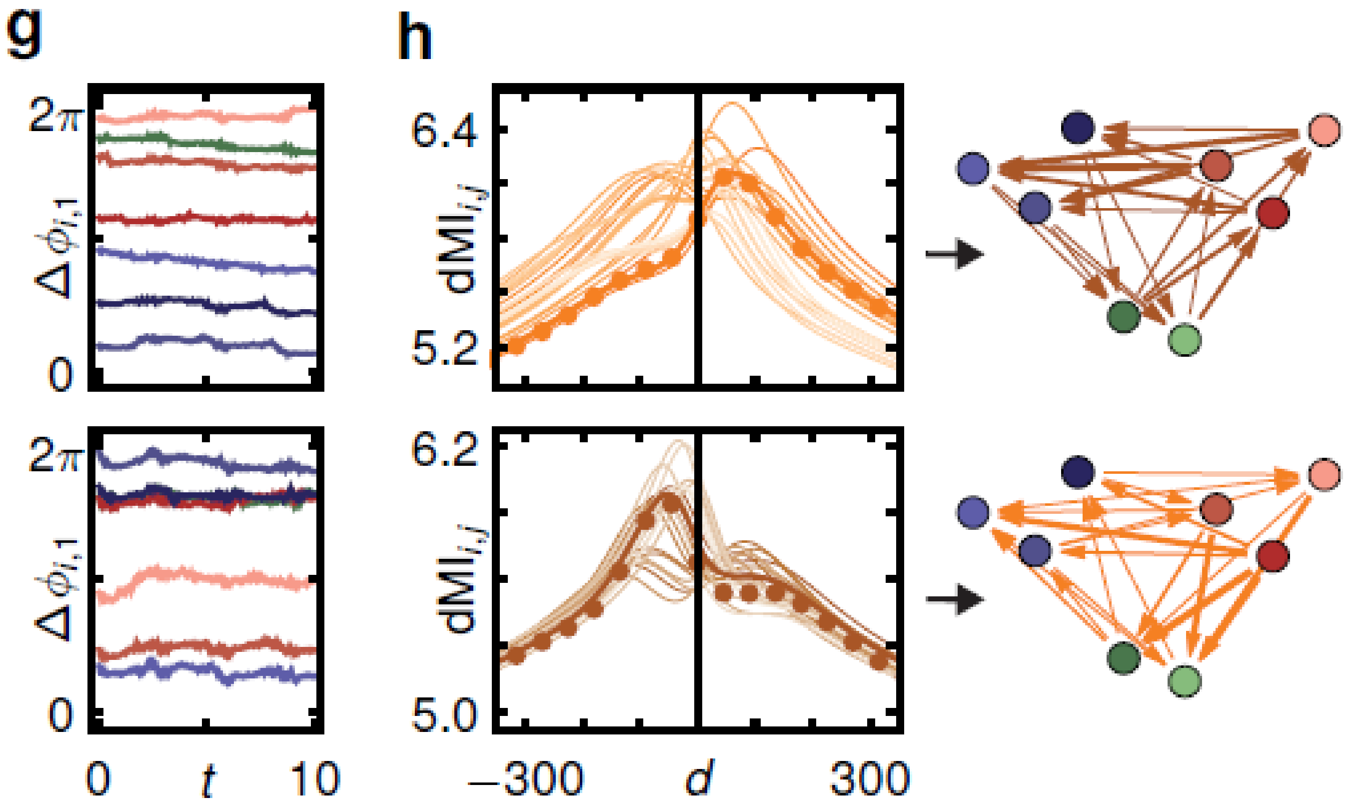
<u>Information sharing, quantified by delayed mutual information (dMI)</u>

$$\mathrm{dMI}_{i,j}\left(d\right) = \int p\left(\phi_{i,t}, \phi_{j,t+d}\right) \log\left(\frac{p\left(\phi_{i,t}, \phi_{j,t+d}\right)}{p\left(\phi_{i,t}\right) p\left(\phi_{j,t+d}\right)}\right) \mathrm{d}\phi_{i,t} \mathrm{d}\phi_{j,t+d}$$

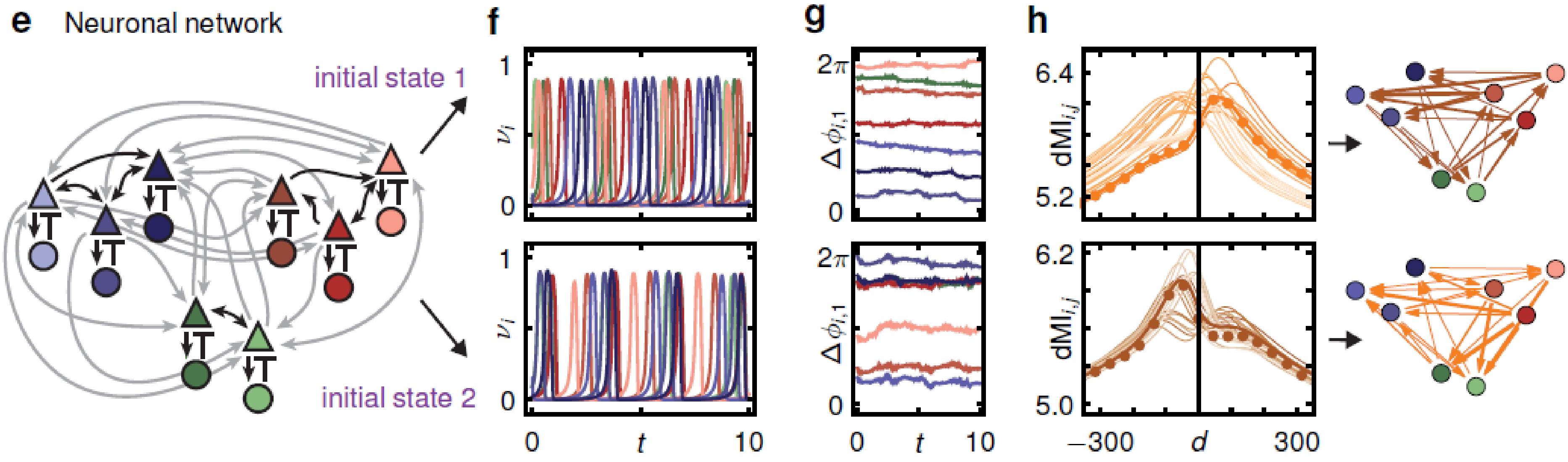
Collective Dynamics ➔ Information Routing Patterns II



Collective Dynamics ➔ Information Routing Patterns II

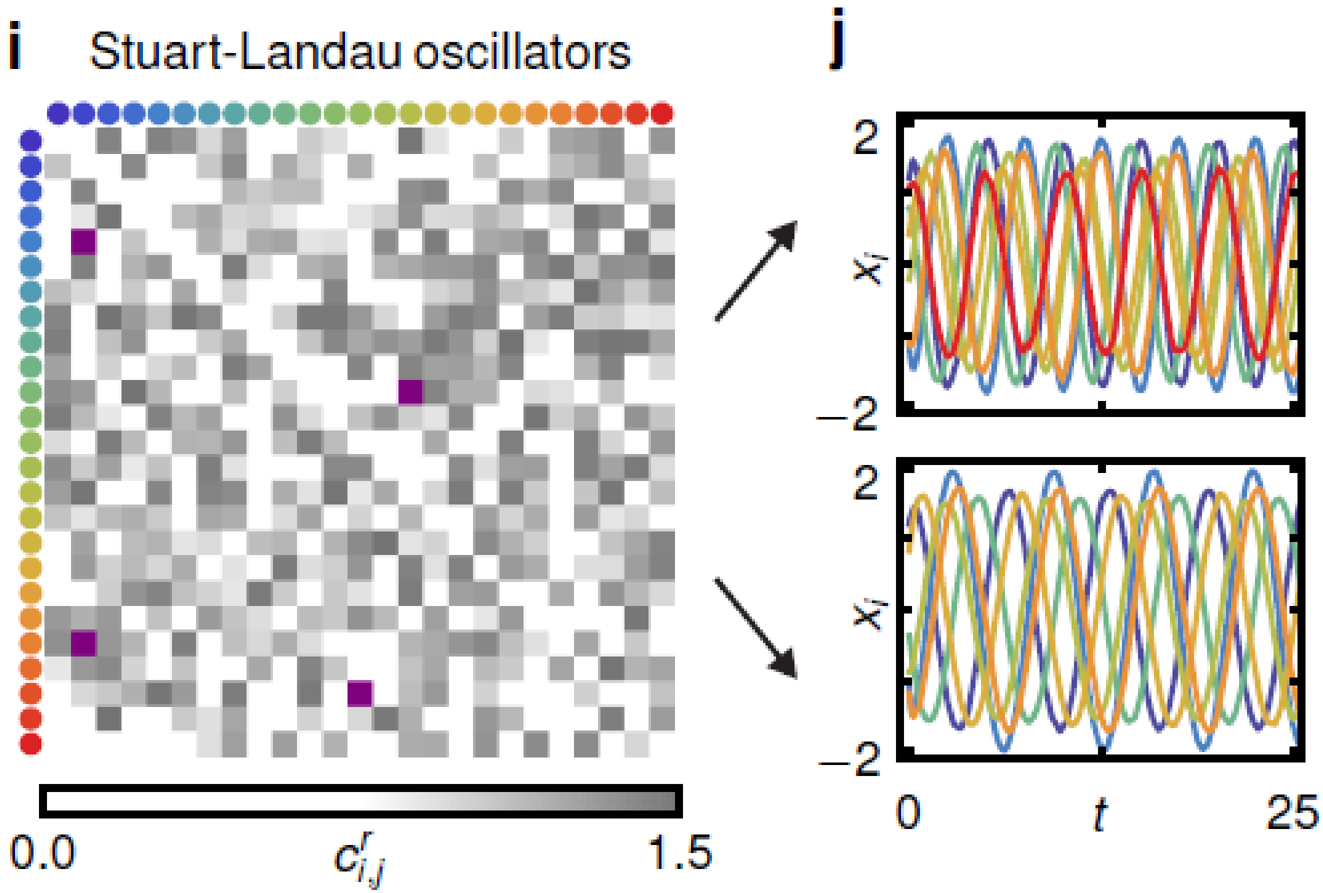


Collective Dynamics ➔ Information Routing Patterns II

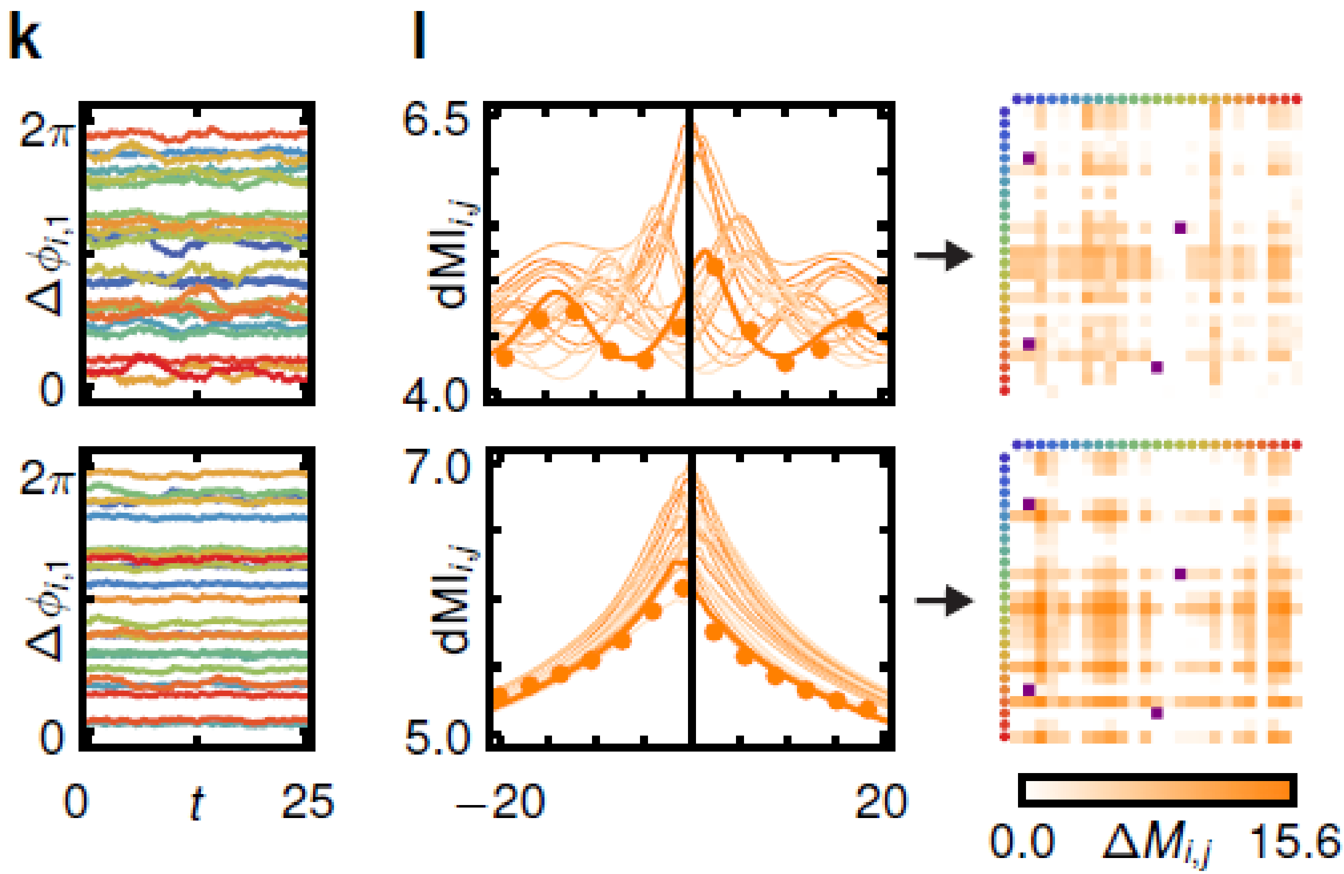


Initial states determine information routing pattern

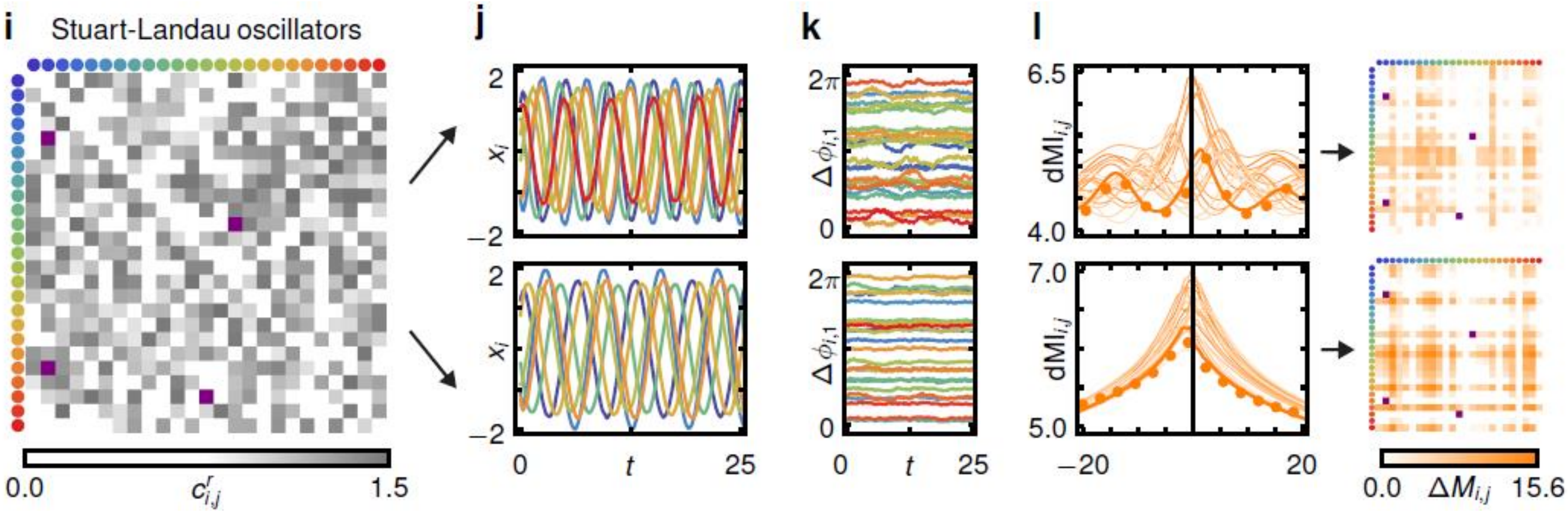
Collective Dynamics ➔ Information Routing III



Collective Dynamics ➔ Information Routing III



Collective Dynamics ➔ Information Routing III



Local changes modify information routing patterns

Dynamic & flexibly controllable patterns of IRPs in large networks

Analytical Prediction of Information Routing Patterns

1. Phase reduction of oscillators
2. Averaging coupling (over cycle)

$$\frac{\mathrm{d}}{\mathrm{d}t}\phi_i = \omega_i + \sum_{j=1}^{N} \gamma_{ij}(\phi_i - \phi_j) + \sum_{k=1}^{N} \varsigma_{ik}\xi_k$$

3. Joint probabilities
4. Integration of dMI

$$\mathrm{dMI}_{ij}(d) = \frac{k_{ij(d)}\, I_1\left(k_{ij(d)}\right)}{I_0\left(k_{ij(d)}\right)} - \log\left(I_0\left(k_{ij(d)}\right)\right)$$

$I_n\left(k\right)$: n-th modified Bessel function

$k_{ij(d)}$: inverse of variance of von Mises distribution „Gaussian on circle“

Information Routing Patterns (IRPs) **between subnetworks**

$$\frac{\mathrm{d}}{\mathrm{d}t}\phi_i = \omega_i + \sum_{j=1}^{N} \gamma_{ij}(\phi_i - \phi_j) + \sum_{k=1}^{N} \varsigma_{ik}\xi_k$$

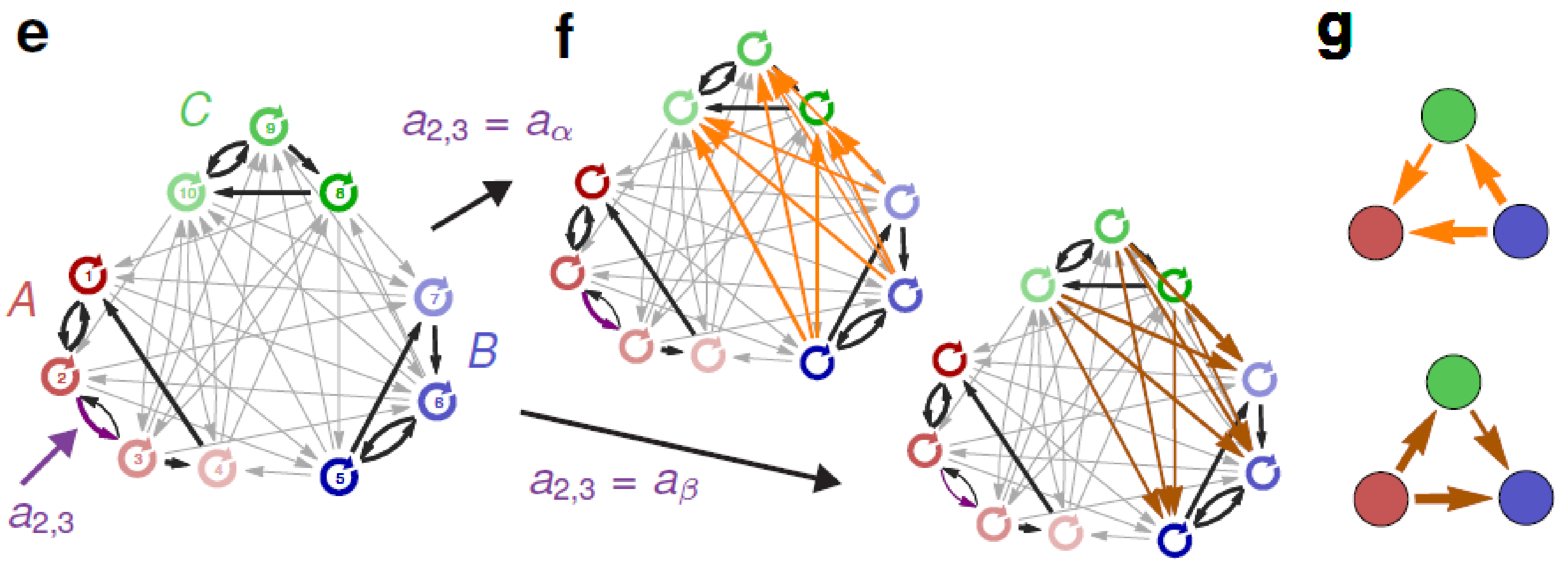
Φ_X : effective phase of subnetwork X

… other effective quantities …

$$\frac{\mathrm{d}}{\mathrm{d}t}\Phi_X = \Omega_X + \sum_{Y=1}^{M} \Gamma_{X,Y}(\Phi_X - \Phi_Y) + \sum_{Y=1}^{M} \Sigma_{X,Y}\Xi_Y$$

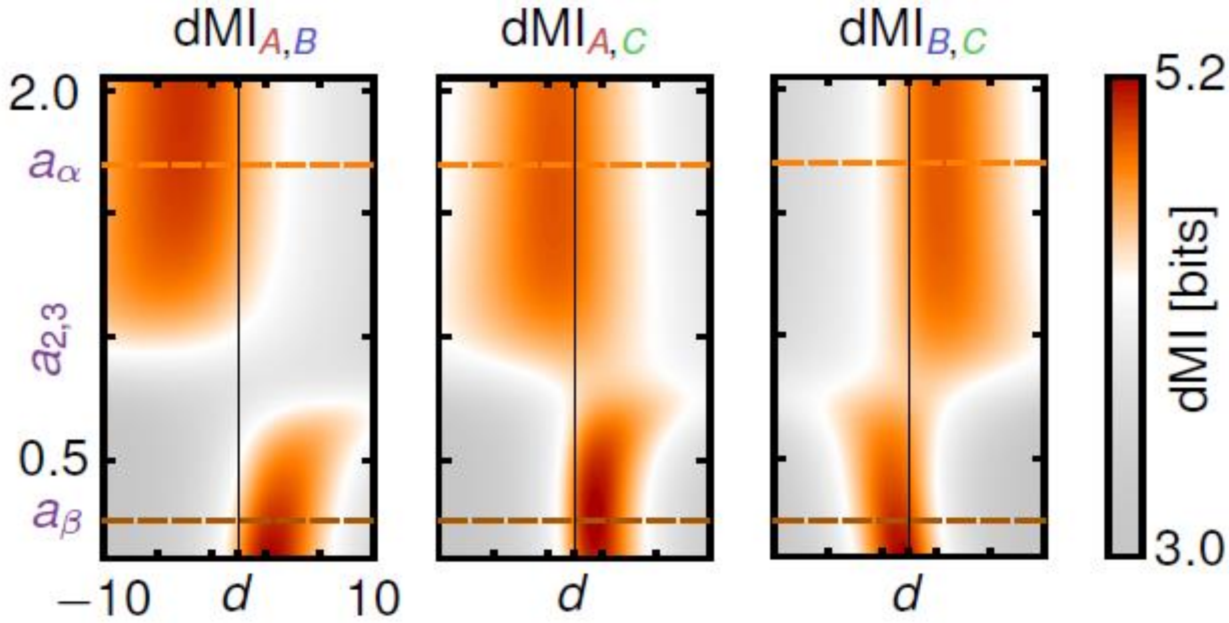
Theory naturally generalizes to predict IRPs between entire subnetworks

Remote Control of Information Routing



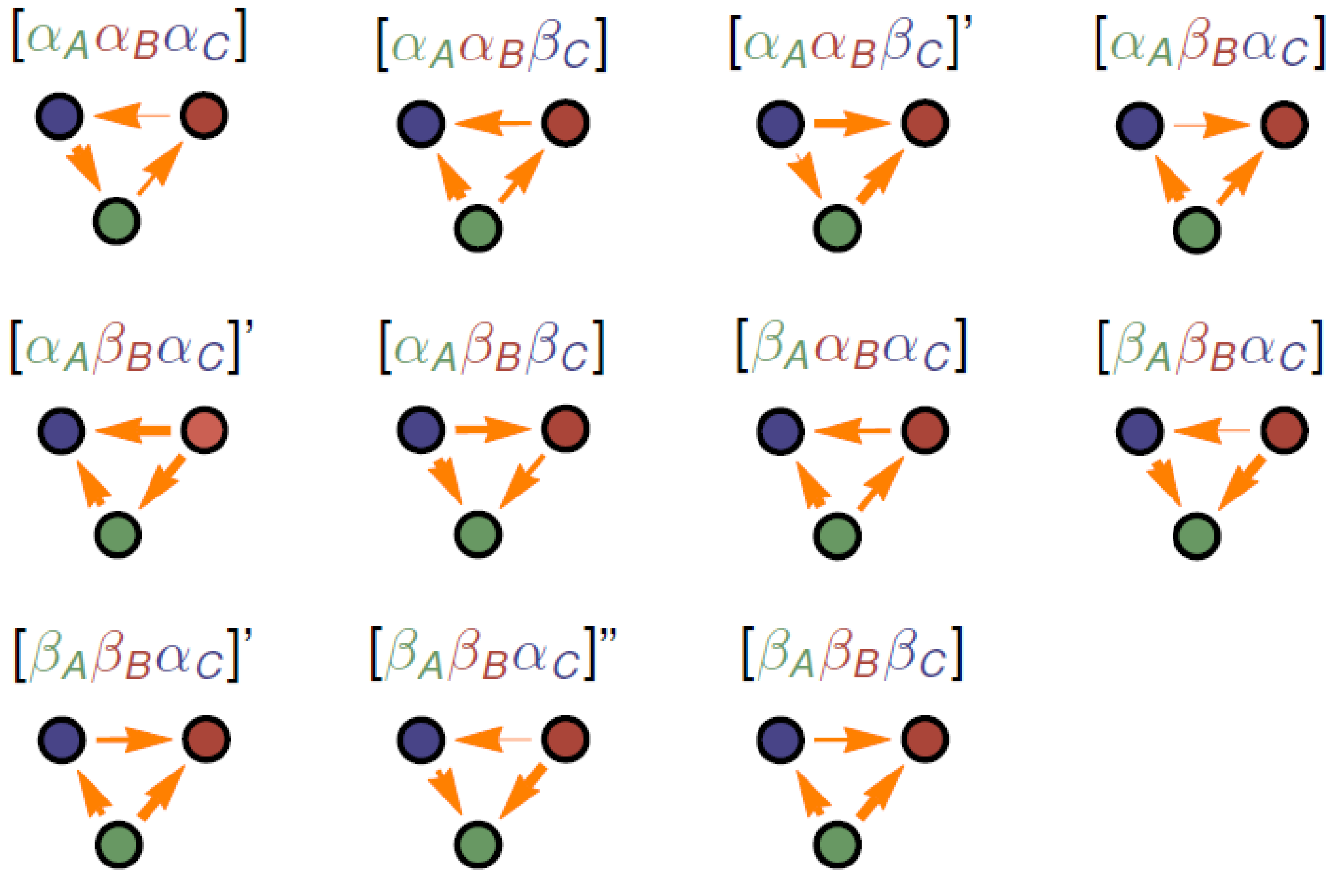
Local Structural Changes ➔ Nonlocal Changes in IRP

Remote Control of Information Routing

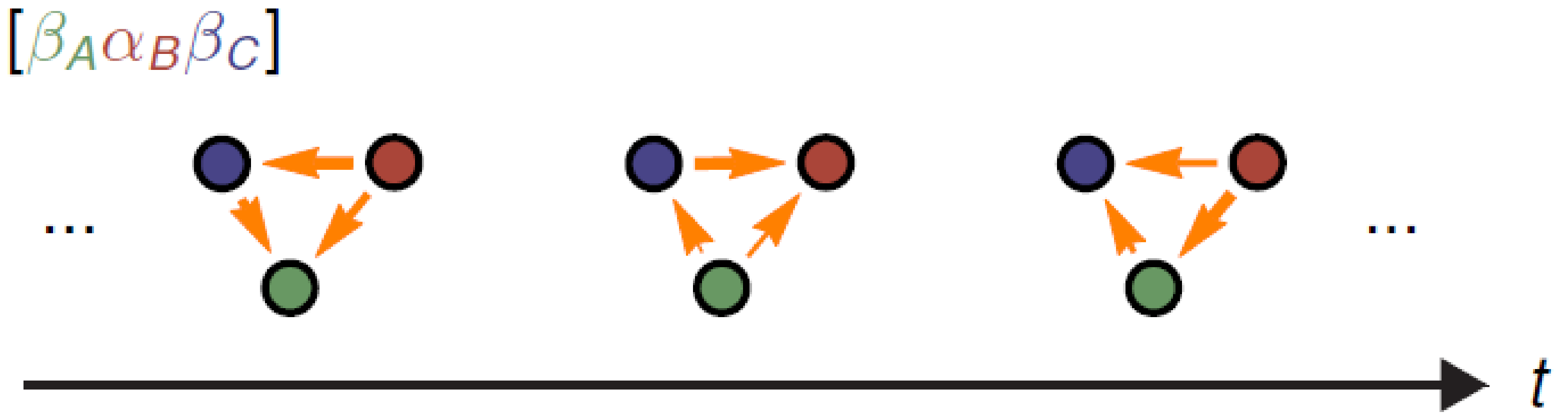


Local Structural Changes → Nonlocal Changes in IRP

Combinatorial #IRPs possible

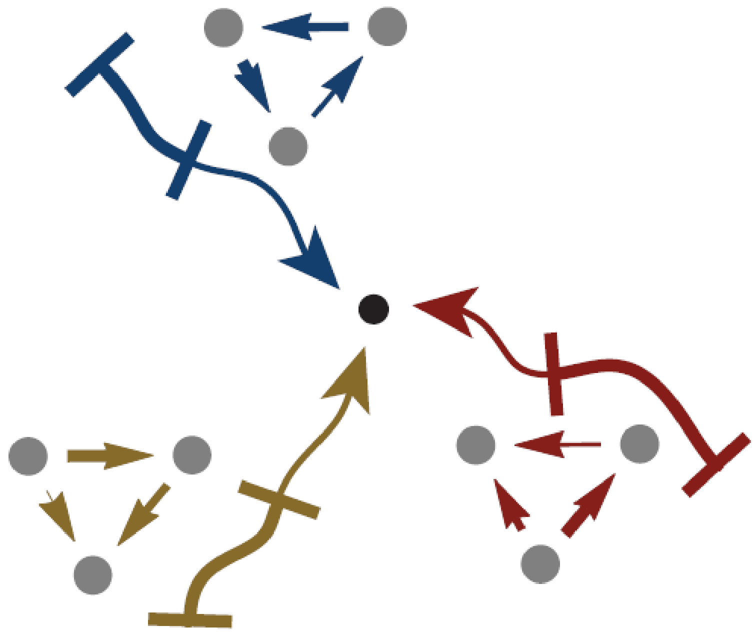


Temporally Changing Routing



Collective dynamics close to complex periodic orbit
➔ temporally changing phase order
➔ tempotally changing IRPs

Flexible Routing via Transients



Each transient may exhibit **individual IRP**
despite the fixed point („ground state“) exhibits one IRP

Summary

Collective states determine information routing patterns (IRP)

IRP selected by:

- **local unit/coupling features**
- **network connectivity**
- **initial condition**
- **external driving signals**

Analytic description for phase oscillator networks
Coarse-graining: theory generalizes to IRP between entire subsystems

Possible features of network dynamics:
Remote control
Combinatorial #IRPs
Temporally changing IRPs

Theory of **Dynamic Information Routing in Networks**

Network Dynamics

Dynamics of Biological (& Bioinspired) Networks:

distributed processing & self-organized control

Nature Phys. (2010);
***Nature Comm.* (2016);**
J. Neurosci. (2015);
Phys. Rev. Lett. (2012c);
PLoS Comput. Biol. (2011, 2012, 2013, 2015)*;*
New J. Phys. (2011);
Frontiers Neurosci.(2011, 2012, 2013)
Phys. Rev. X (2013, 2014);

spike-based processing & non-additive neural circuits:
2 BMBF + 1 DFG grants (2004-2016)

Dynamics of Networks in Engineering:

communication, power grids & flexible mobility

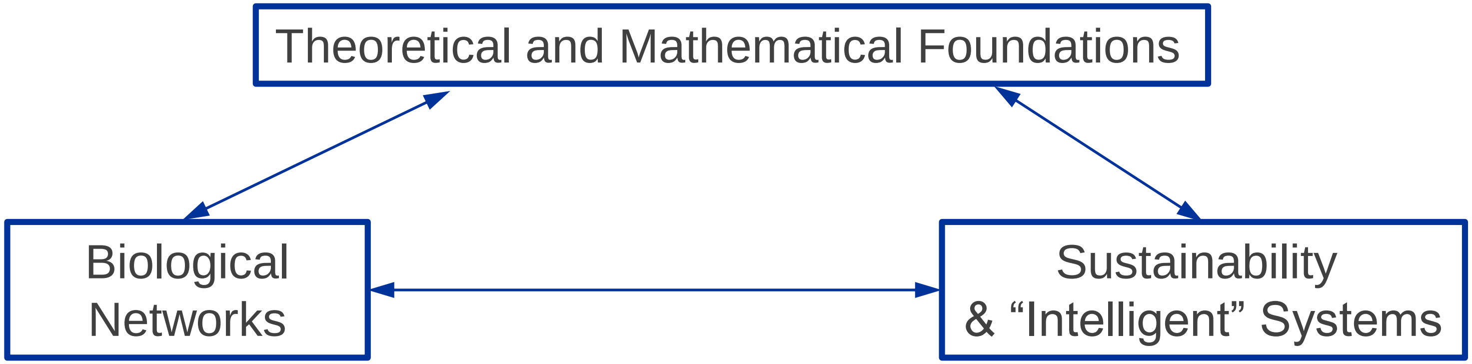
Phys. Rev. Lett. (2016, 2012b); New J. Phys. (2012, 2015); Chaos (2014); EPJST (2013); EPJB (2014); IEEE Trans. Power Syst. & IEEE Trans. Mobile Comput. (tbp, 2016)

power grids: BMBF grant 2.71 Mio Euros (2014-2017)
patent* WO** 2013178237 (2013); ***patent reg. 16184441.6-1955 (2016)
flexible mobility: EFRE grant 2.96 Mio Euros (pending, 2016-2018)

Theoretical & Mathematical Foundations:

Phys. Rev. Lett. (2015, 2012a);
Nature Phys. (2011);
SIAM J. Appl. Math, (2010);
Chaos (2014)
Discr. Cont. Dyn. Syst. (2010)
SIAM J. Appl Dyn. Syst. (2012);
New J Phys. (2012)

Current Topics in Network Dynamics



Selected recent publications

physics

Nature Phys. *(2010 + 2011)*
Phys. Rev. Lett.
(2010, 2011, 2012a,b,c, 2015, 2016)
Phys. Rev. X (2013 + 2014)
New J. Phys. (2012a,b, 2015);

bio- & neuro-science

Nature Comm. *(2016)*
Frontiers in Comput. Neurosci.
(2009a,b, 2011, 2012, 2013)
PLoS Comput. Biol.
(2011, 2013, 2014, 2015)
J. Neurosci. (2015)

appl. mathem.

Discr. Cont. Dyn. Syst. (2010)
SIAM J. Appl Dyn. Syst. (2012)
SIAM J. Appl. Math, (2010)

engineering

patent WO 2013178237 (2013)
patent registration 16154441.6-1955 (2016)
IEEE Trans. Mobile Comput. (tbp 2016);
IEEE Trans. Power Syst. (tbp 2016)*;* ***Chaos*** *(2014);*
Eur. Phys. J. Special Topics *(2014);*
Eur. Phys. J. B *(2013);*

Collaboration & Support

Network Dynamics

Jose Casadiego, Wen-Chuang Chou, Hauke Haehne
Dimitra Maoutsa, Debsankha Manik, Nora Molkenthin
Florencia Noriega, Diemut Regel, Benjamin Schaefer
Malte Schroeder, Nahal Sharafi, Xiaozhu Zhang

S. Herminghaus (**MPIDS**) A. Fiala, F. Wörgötter (**Göttingen**) J. Nagler (**ETH Zurich**)

Christoph Kirst (**Rockefeller**) Demian Battaglia (**Marseille**) Martin Greiner (**Aarhus**)

R.-M. Memmesheimer (**Columbia**) Mor Nitzan (**Hebrew U**) S. G. Shandilya (**Yale**)

Dirk Witthaut (**FZ Julich**) Martin Rohden (**JU Bremen**) S. Hallerberg (**IBM Dublin**)

Rudolf Sollacher (**Siemens**) Th. Walter (**EasySmartGrid**) Joh. Klinglmayr (**LCM**)

Thank you to

my colleagues, collaborators,
my research group **Network Dynamics,**

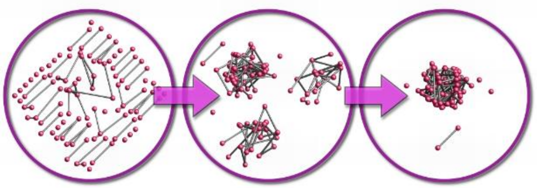
www.networkdynamics.info

and you all for your attention & interest

Questions and comments welcome!

Recent Progress

Theoretical and Mathematical Foundations



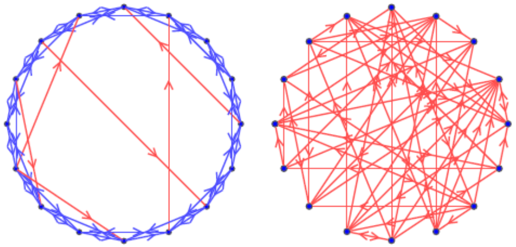
Explosive Transition in Network Growth

competition → transition between 1st & 2nd order

single link matters!

Nature Phys. (2011);

see also Nagler & Co, *Nature Comm.* (2013), *Phys. Rev. X* (2013)

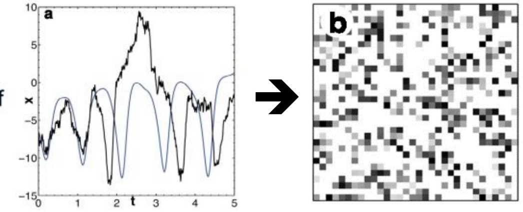


Small World Networks

structure: Watts & Strogatz, *Nature* (1998), >21000 citations

now relaxation **dynamics**

Phys. Rev. Lett. (2012a)



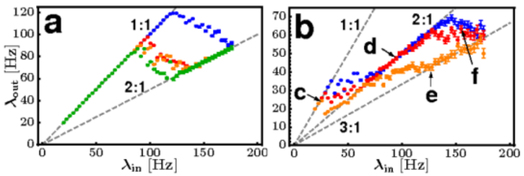
Network Inverse Problem: Structure from Dynamics

Methods for **inference** and **design**

Front. Comput. Neurosci. (2011); *New. J. Phys.* (2011);

Invited Topical Review: *J. Phys. A (2014)*

Recent Progress
Neuro- and Biophysics

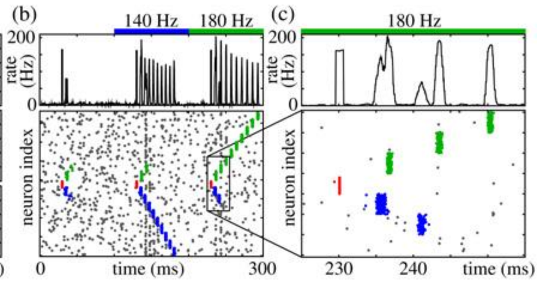


Spike Sequence Processing in Neurons

Resource limitations

➔ **generic non-monotonic response**

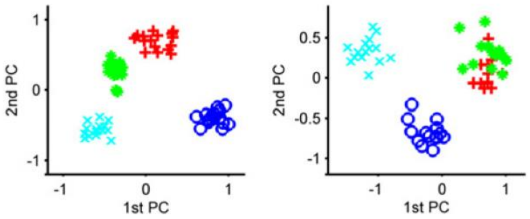
BMC Neurosci. (2013); *PLoS Comput. Biol.* (under review)



Non-additive Coupling & Plasticity

→ **spike patterns** & **memory**

PLoS Comput Biol. (2012, 2013); *Phys. Rev. X* (2012)

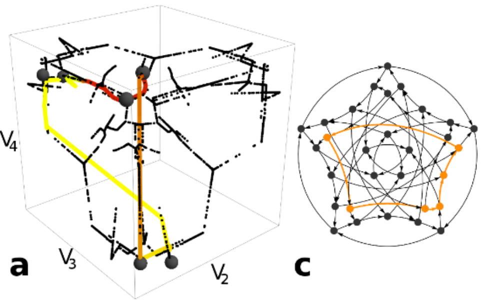


Combinatorial Neural Processing

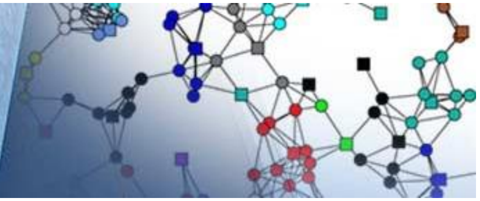
exploiting network heterogeneities

joint PhD students with A. Fiala (Uni-Bio); *PLoS ONE* (2011);

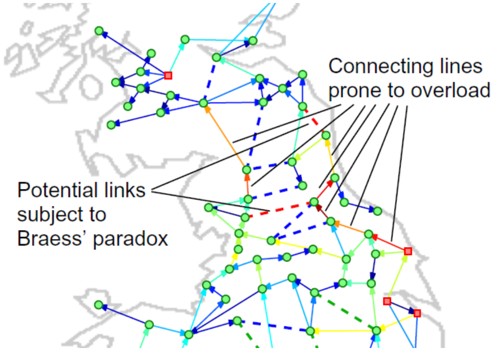
Recent Progress –
Intelligent Dynamical Systems f. Computation & Engineering



Intelligent Dynamical Systems
universal **heteroclinic computing**
with exponential capacity
Phys. Rev. Lett. (2012b)



Communication Networks & Robotics
distributed, stochastic & adaptive control
➔**self-organize versatile functions**
Nature Phys. (2010); *New J. Phys.* (2012a); ***patent*** (2013)



Dynamically Smart Power Grids
decentralization helps**, Braess' paradox** hinders
Phys. Rev. Lett. (2012c), *New J. Phys.* (2012b)