Network GPS: Navigating network dynamics

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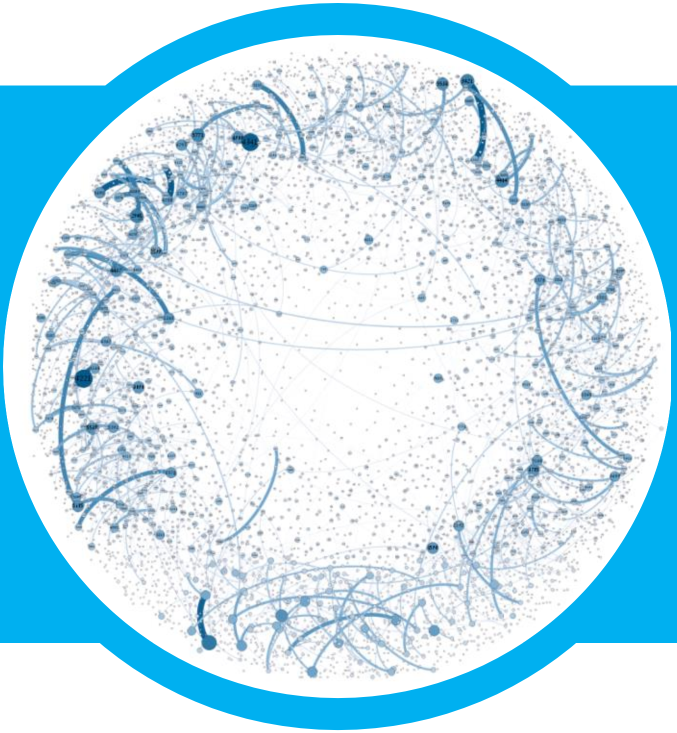
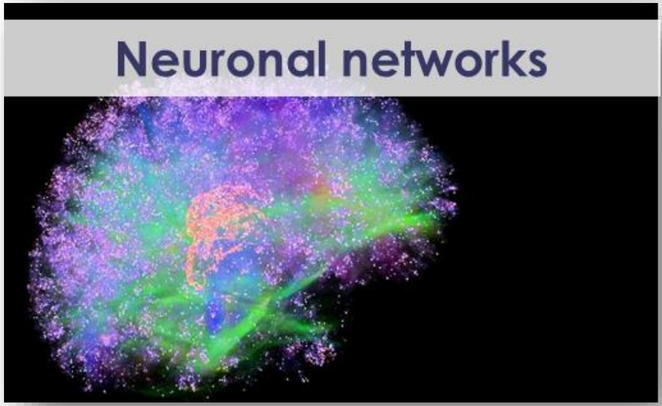
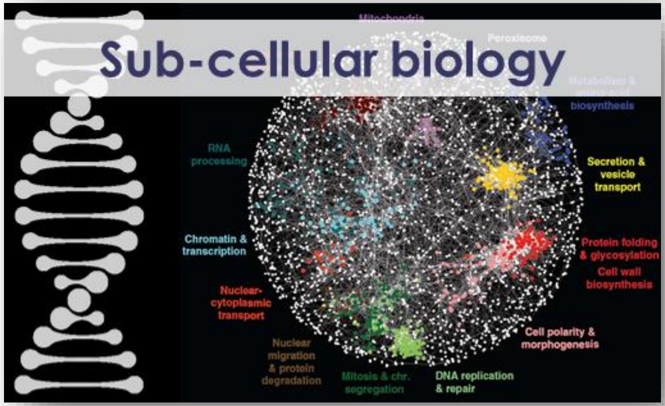


Going beyond mapping

Going beyond mapping

Network dynamics



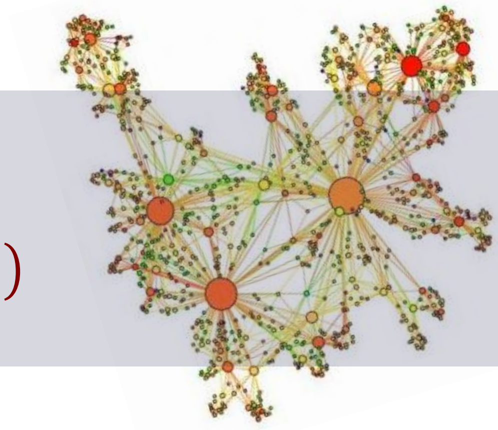


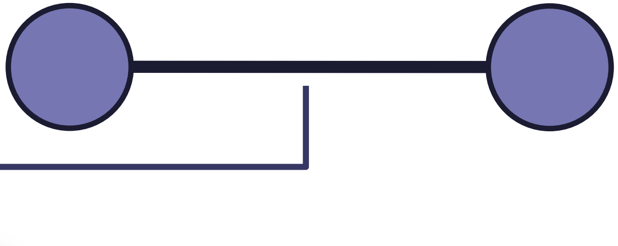
UNDERSTAND → PREDICT → INFLUENCE

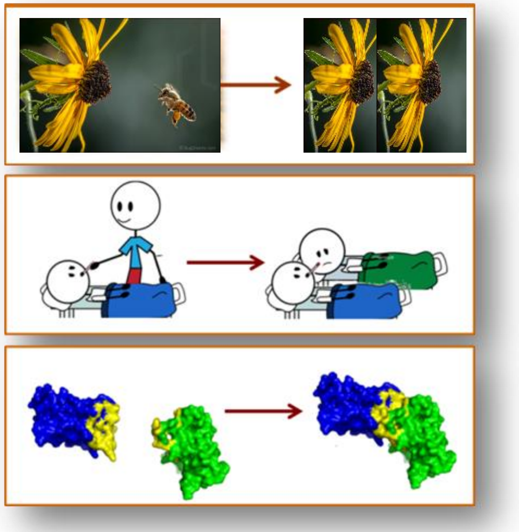
Dynamics layer

$\boldsymbol{x_i(t)}$ → Activity

$$\frac{dx_i}{dt} = M_0(x_i) + \sum_{j=1}^{N} A_{ij} M_1(x_i)\, M_2(x_j)$$





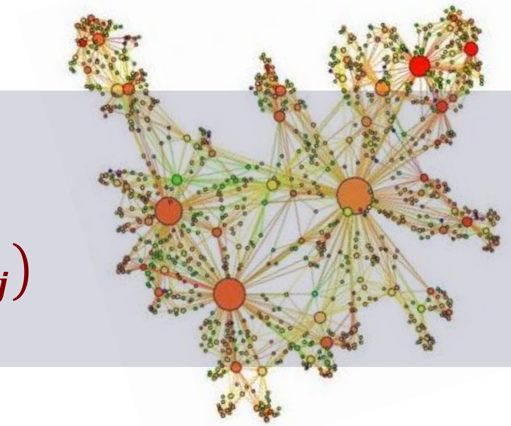


A_{ij} Weighted, directed topology

M_0, M_1, M_2 Intrinsic nonlinear interaction mechanisms

Gao, Barzel, Barabási. *Nature* **530**, 307 (2016) • Barzel, Barabási. *Nature Physics* **9**, 673 (2013)

Dynamics layer



$x_i(t) \rightarrow$ Activity

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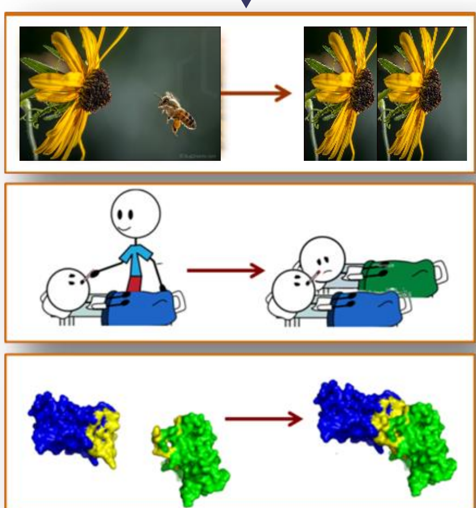

$$\frac{dx_i}{dt} = Bx_i\ (1 - x_i) + \sum_{j=1}^{N} A_{ij} \frac{x_i x_j^a}{1 + x_j^a}$$

$$\frac{dx_i}{dt} = -Bx_i + \sum_{j=1}^{N} A_{ij}(1 - x_i)x_j$$

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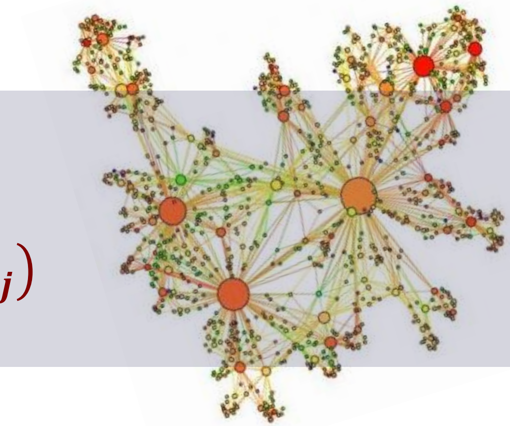

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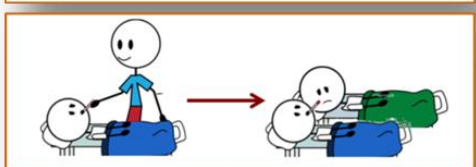

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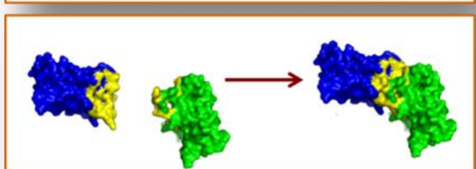

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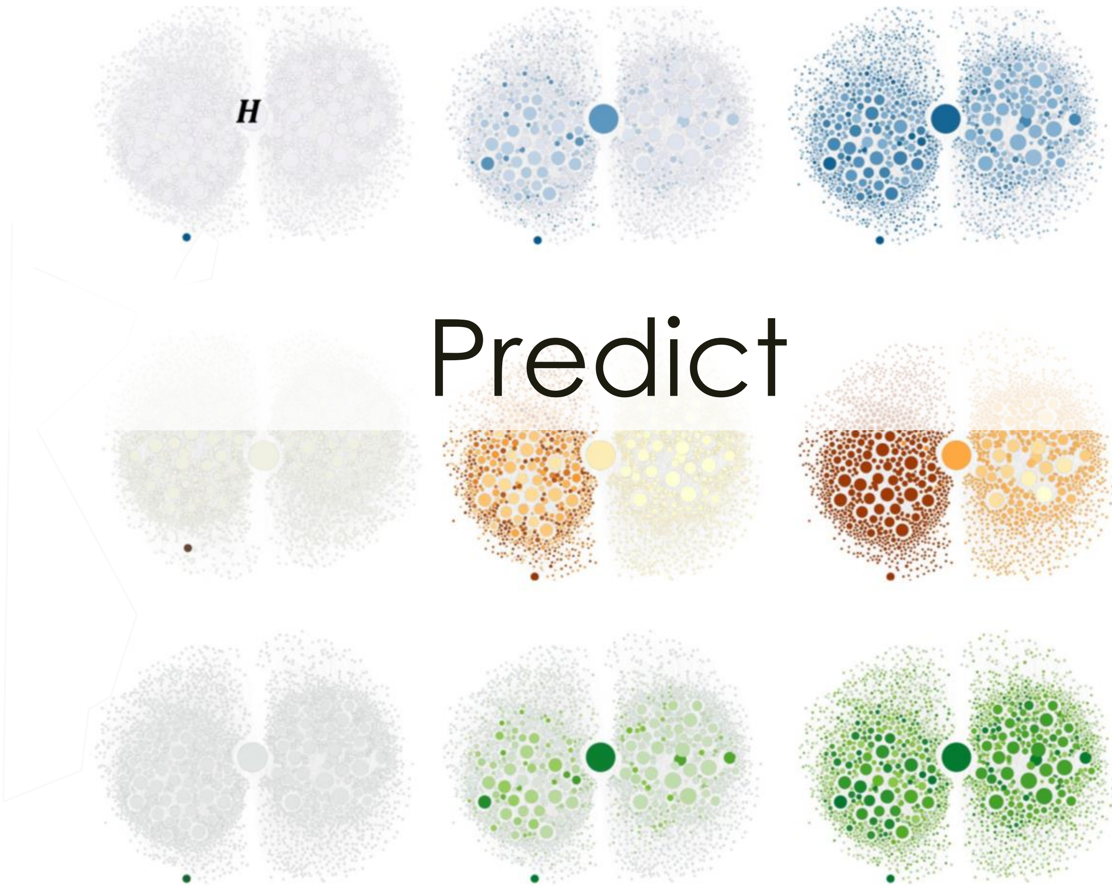
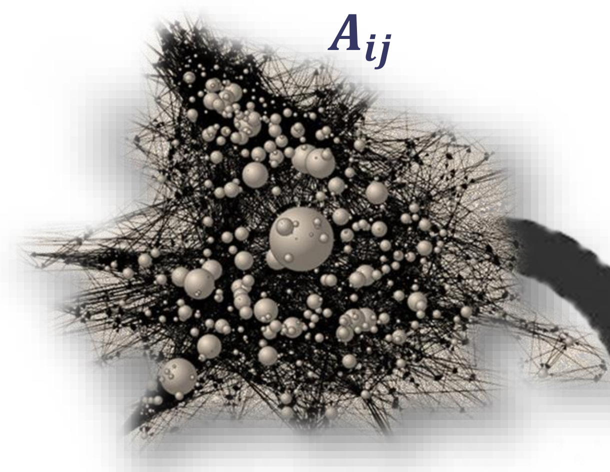


Predict

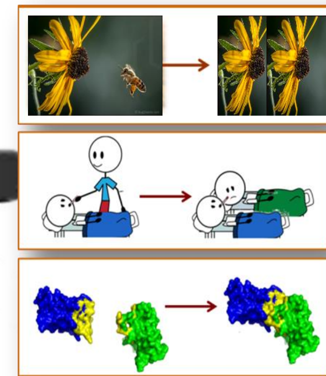
Figure from: Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

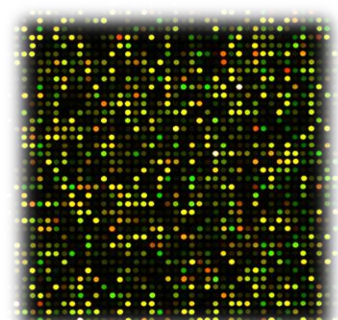
Bringing networks to life

A_{ij}



$M_0(x), M_1(x), M_2(x)$



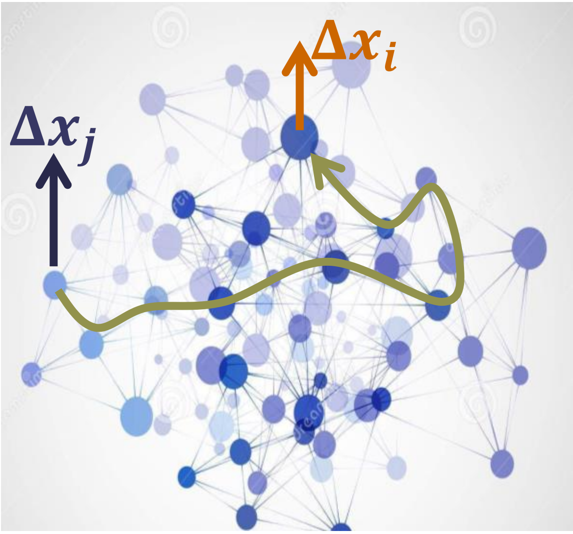


patterns of information spread

Information flow in complex networks

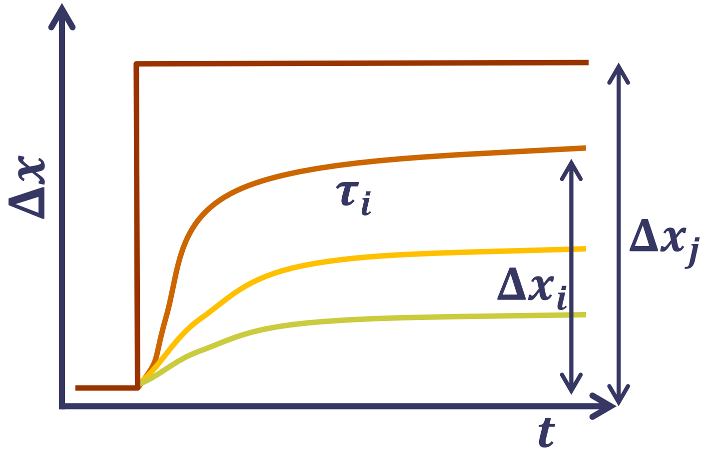
$$\boldsymbol{x_j} \to \boldsymbol{x_j} + \boldsymbol{\Delta x_j} \longrightarrow \boldsymbol{x_i} + \boldsymbol{\Delta x_i(t)}$$

signal response



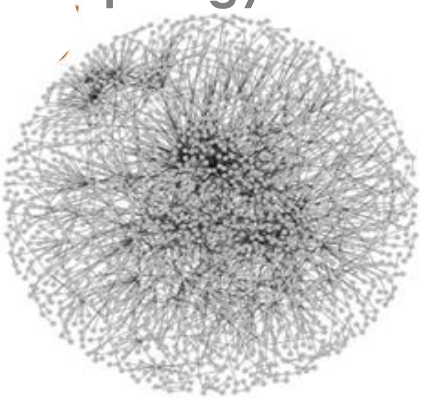
Information flow in complex networks

- When (τ_i)
- Where (l_{ij})
- How strongly (Δx_i)
- How $\left(\mathcal{F}_i, \mathcal{F}_{ij}\right)$

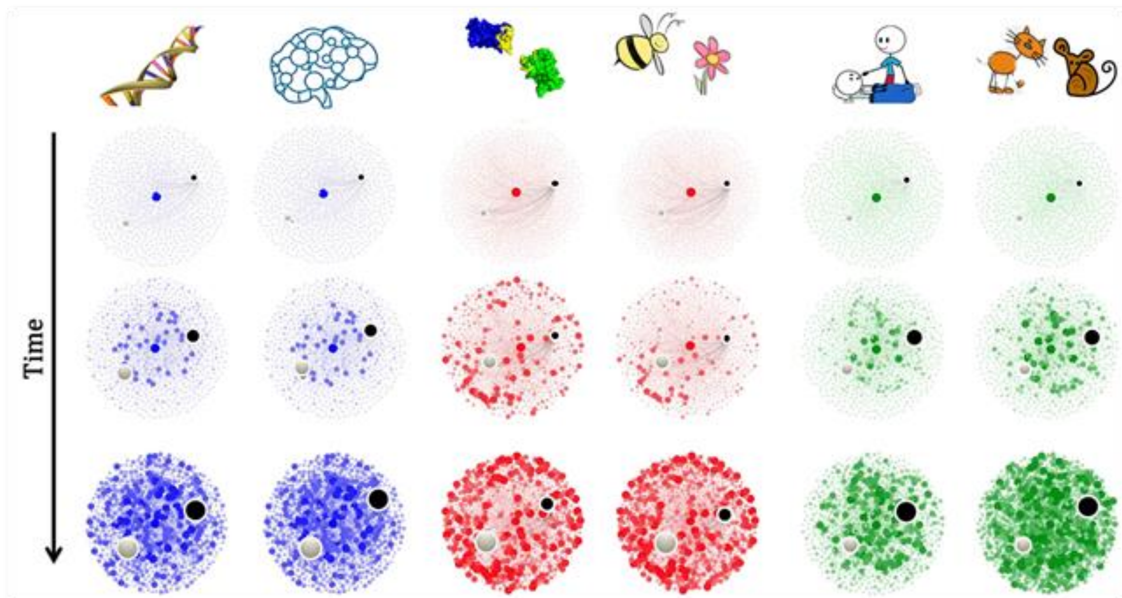


The zoo of propagation patterns

Topology



Interaction mechanisms



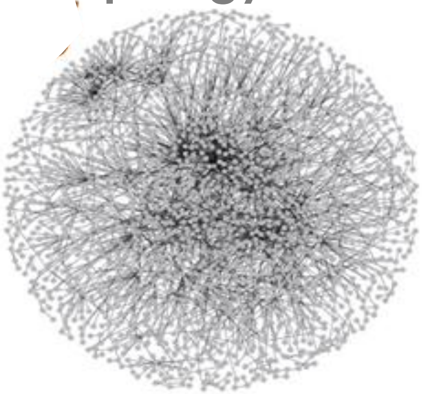
$t \sim 10^{1}$ $t \sim 10^{4}$ $t \sim 10^{-2}$

Identical networks yield visibly distinct propagation patterns

Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

The zoo of propagation patterns

Topology



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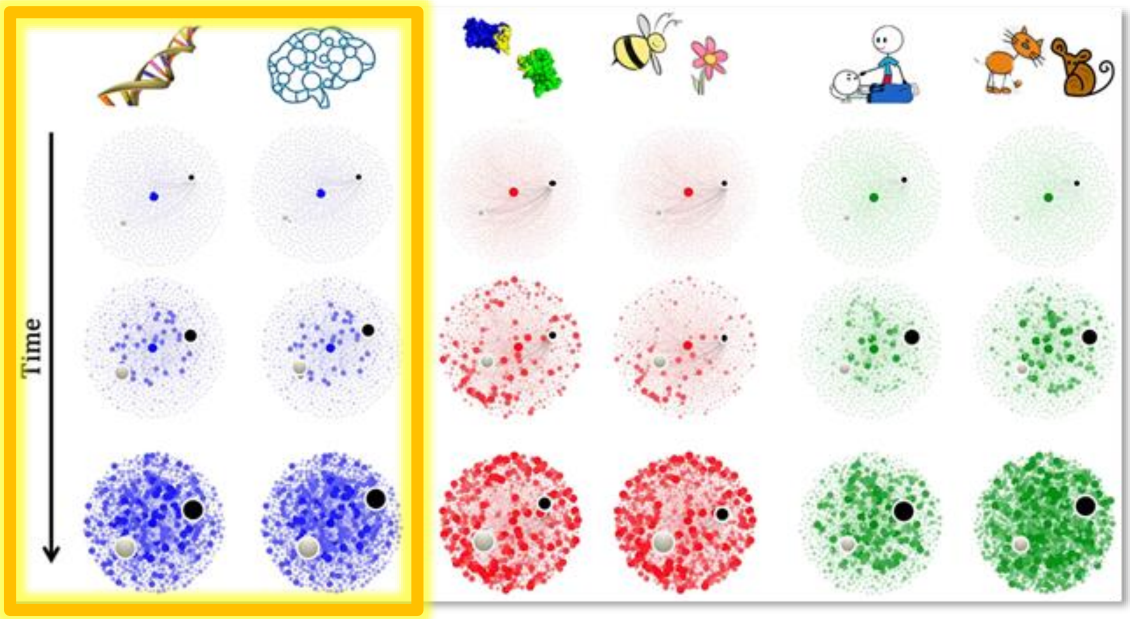

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The zoo of propagation patterns

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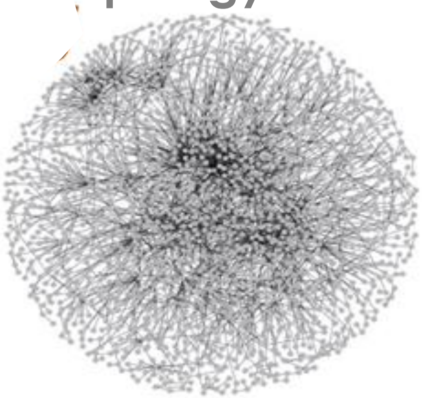

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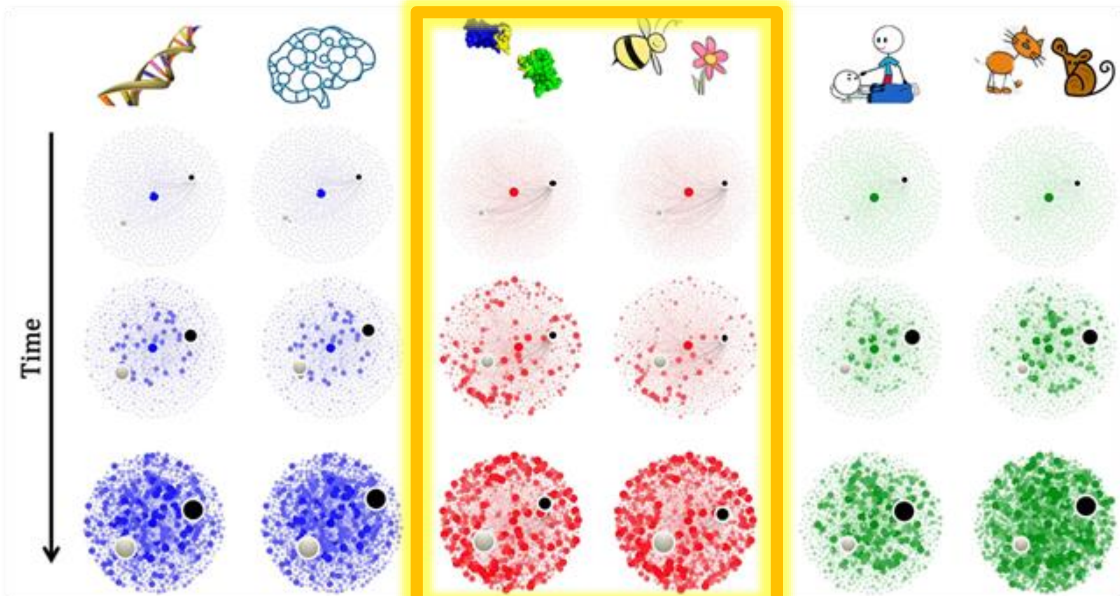

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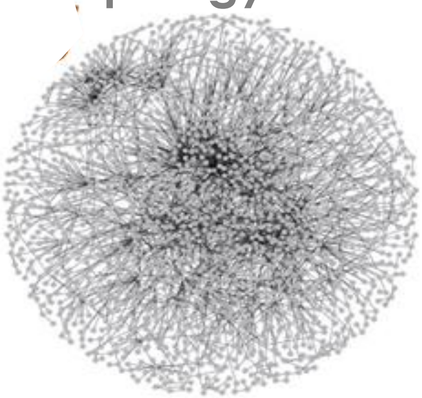

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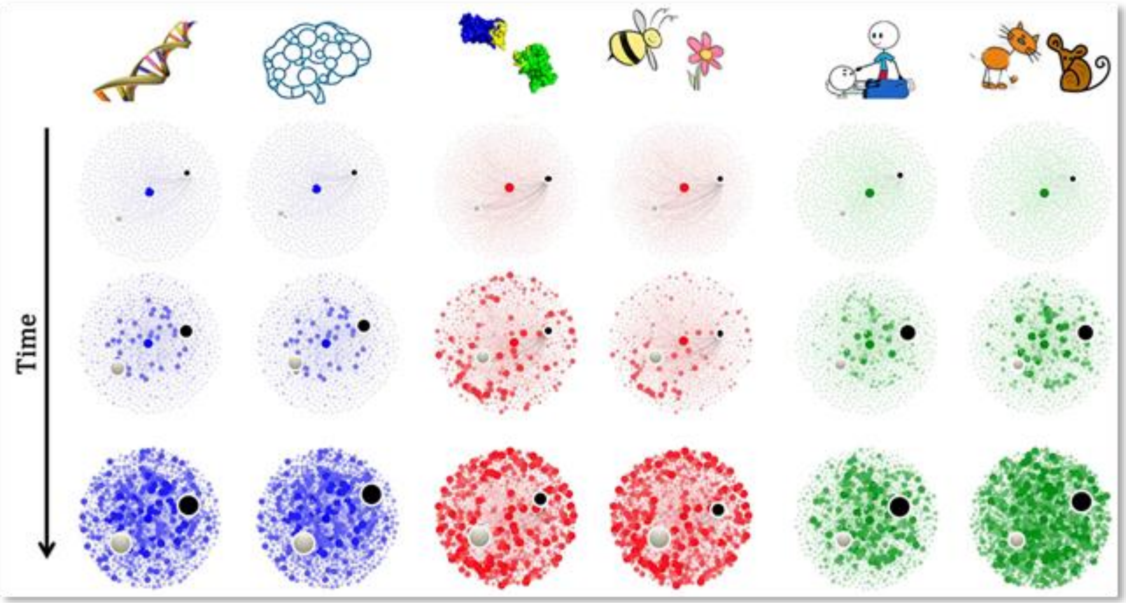

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The zoo of propagation patterns

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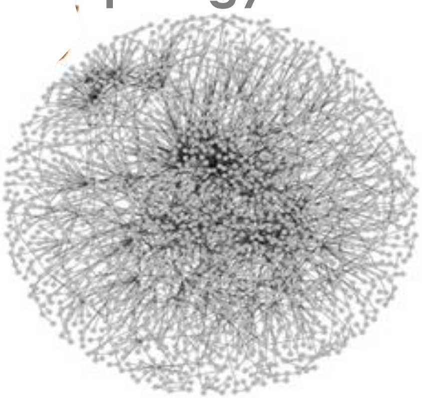

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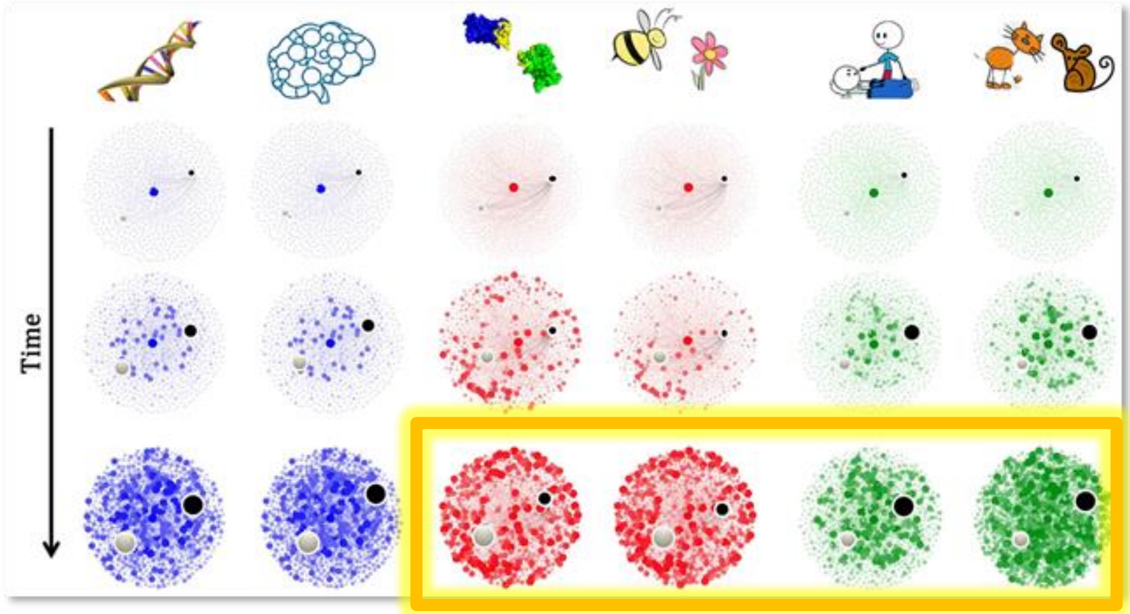

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The zoo of propagation patterns

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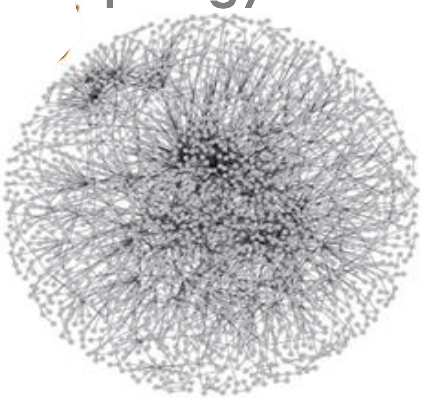

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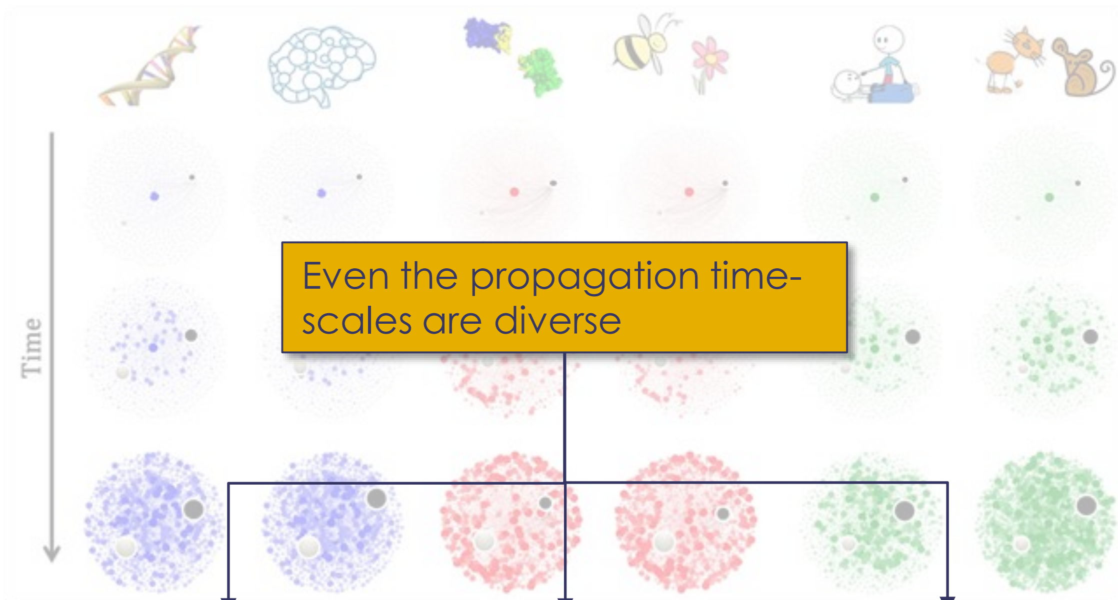


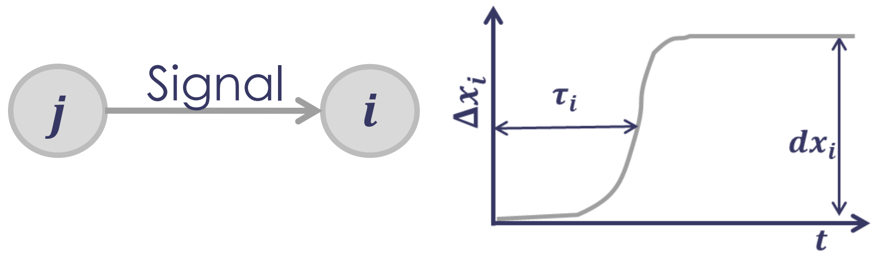
Even the propagation time-scales are diverse

$t \sim 10^{1}$ $t \sim 10^{4}$ $t \sim 10^{-2}$

Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

Taming the zoo of propagation patterns

Individual node response time



k_i Node i's weighted degree
τ_i Node i's individual response time

$$\tau_i \sim k_i^{\theta}$$

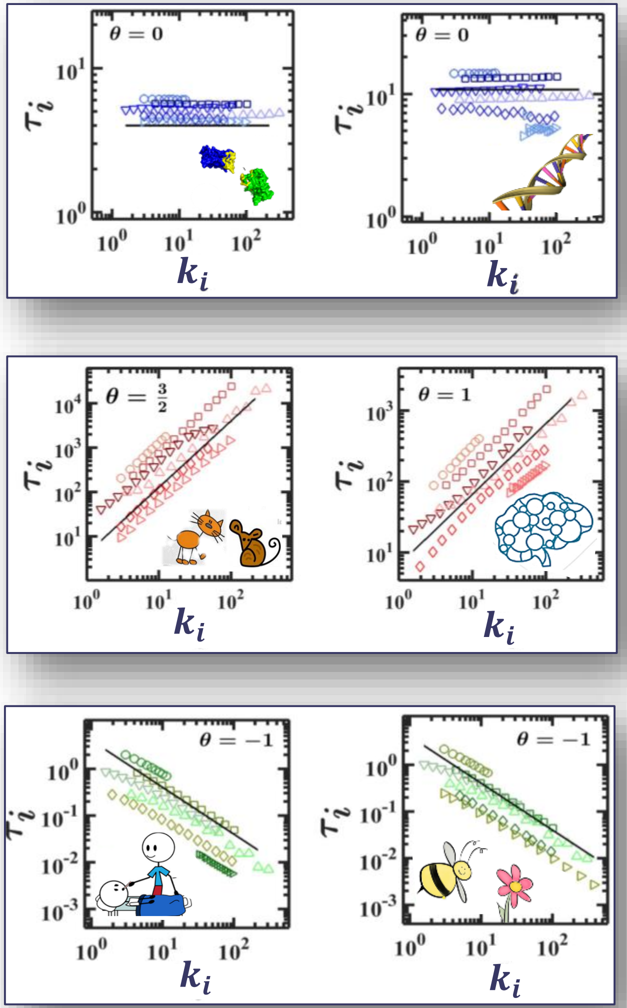
A node's intrinsic response time scales with its weighted degree

Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

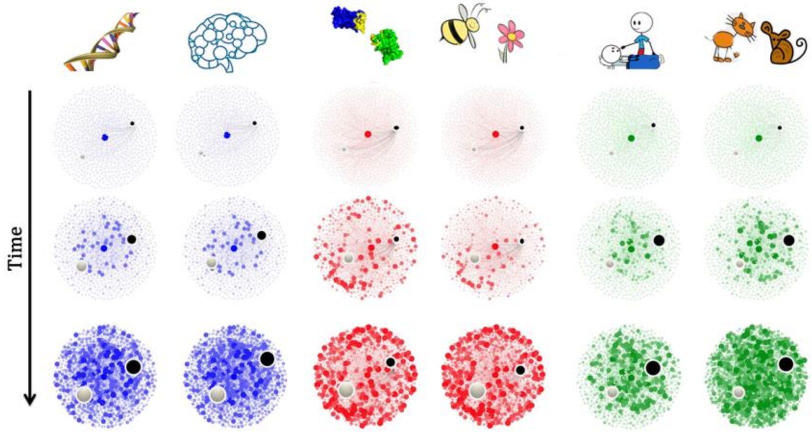
Why should you care?

Universal

$$\tau_i \sim k_i^{\theta}$$



Diverse & unpredictable



Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

Dynamic insight

$$\tau_i \sim k_i^{\theta}$$

Response time
Dynamic observable of interest.

Dynamic determinant
Mapping topology into dynamics

Weighted degree
Known topological element

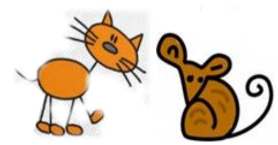
Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

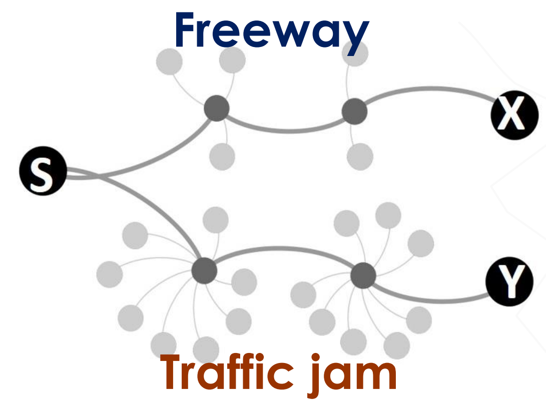
Network GPS – how signals navigate the network

$$\tau_i \sim k_i^{\theta}$$

$\theta > 0$

Hubs
=
Bottlenecks





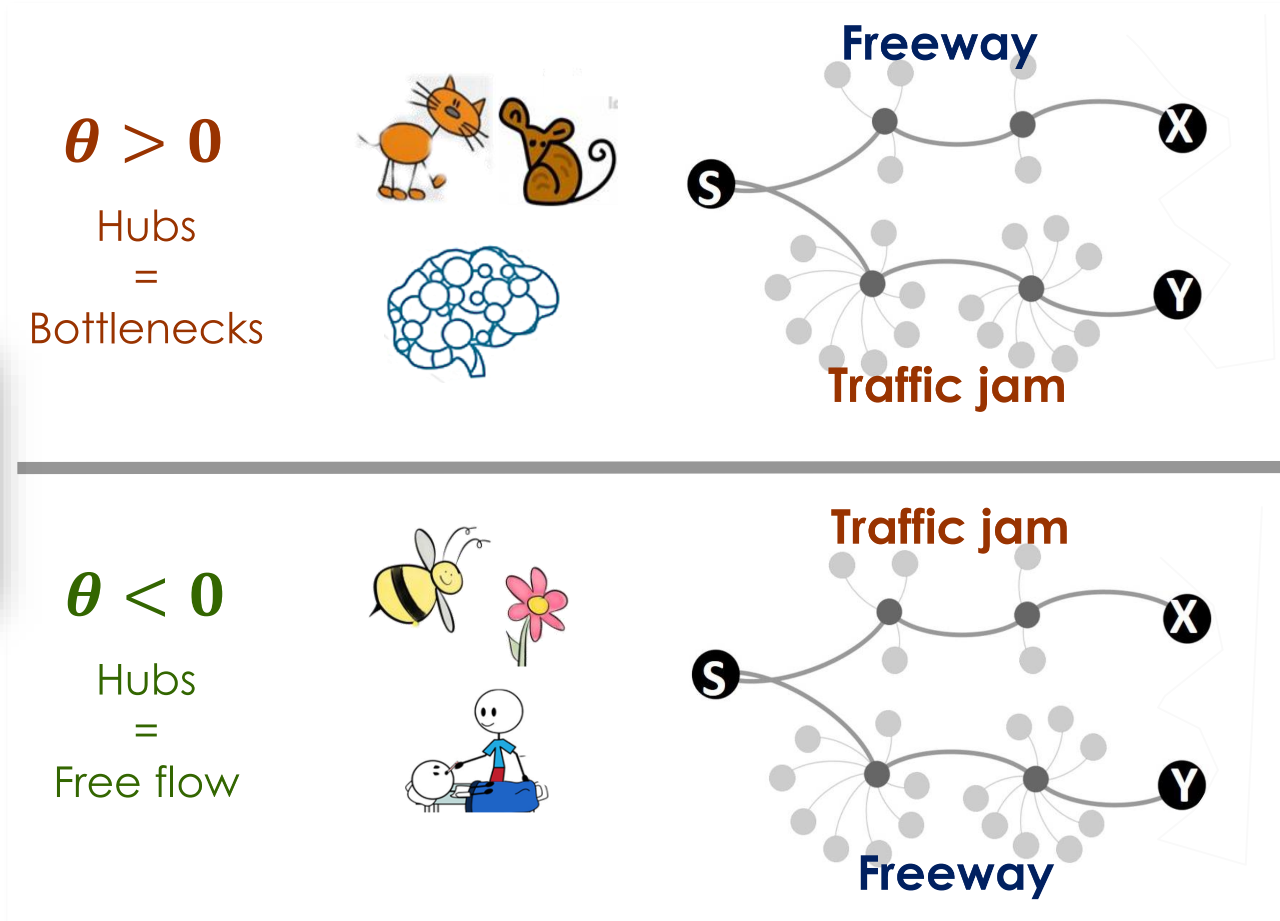
$\theta < 0$

Hubs
=
Free flow

Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

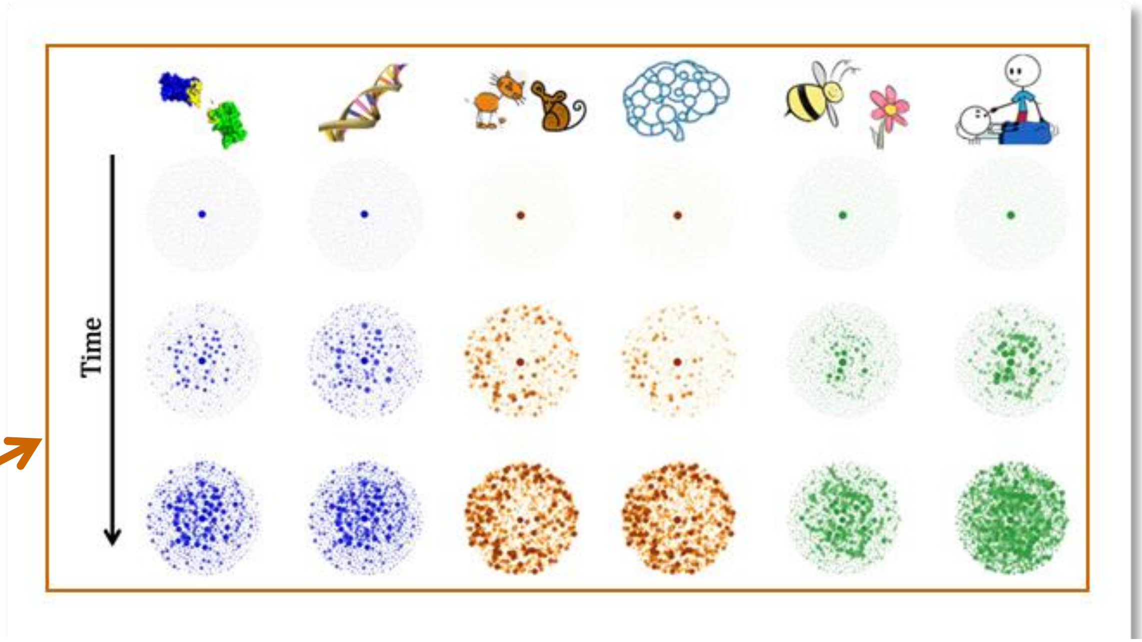
Network GPS – how signals navigate the network

$$\tau_i \sim k_i^{\theta}$$



Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

Network GPS – how signals navigate the network

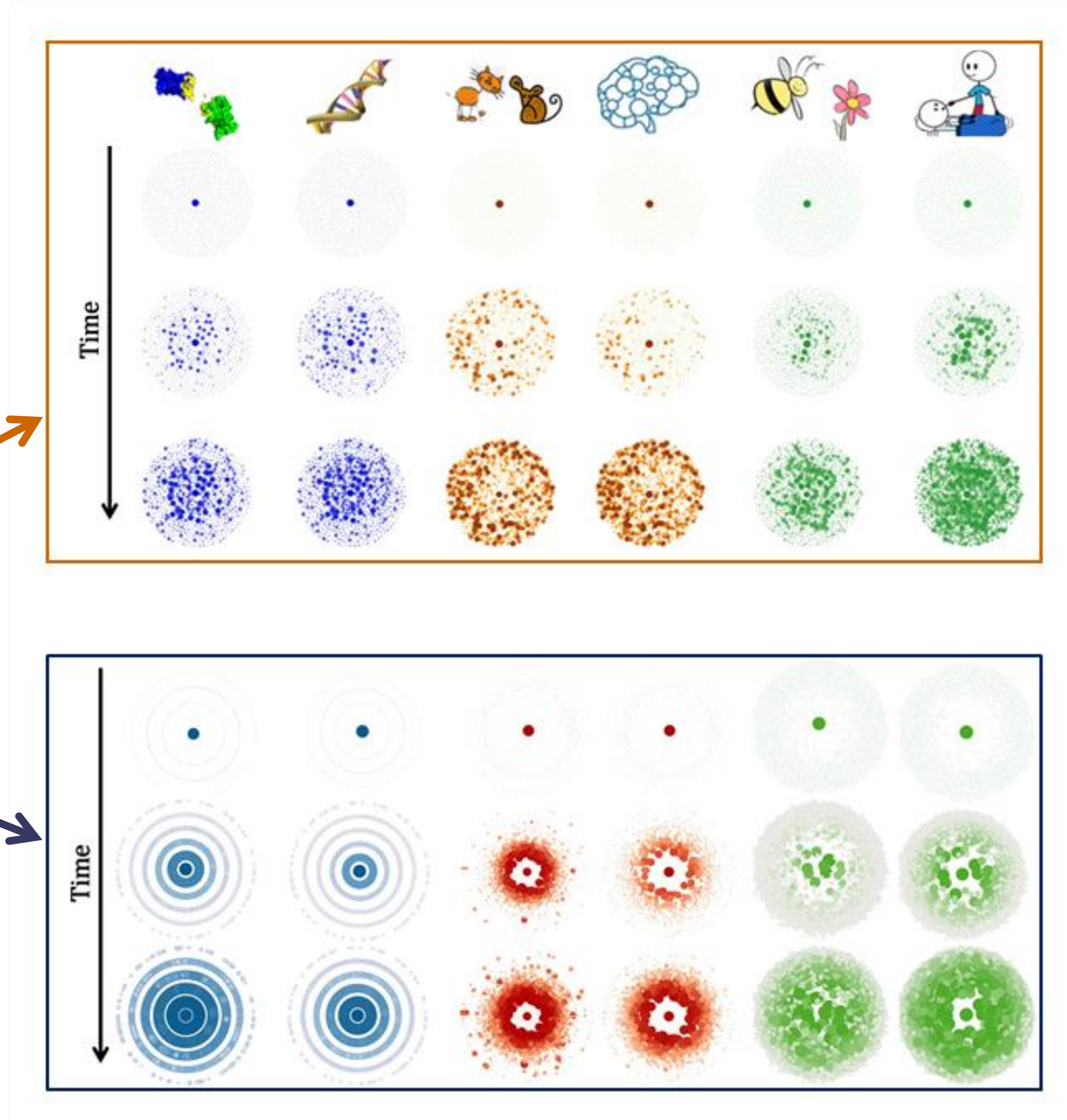


Naïve
layout

Network GPS – how signals navigate the network

Naïve layout

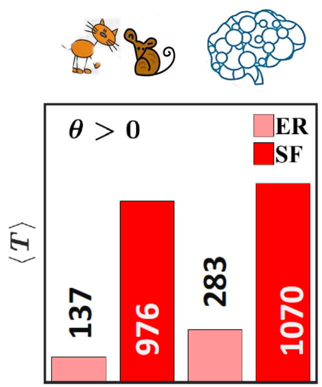
Our GPS prediction



Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

Same topology – different spreading rules

$\theta > 0$
Hubs dramatically slow down propagation



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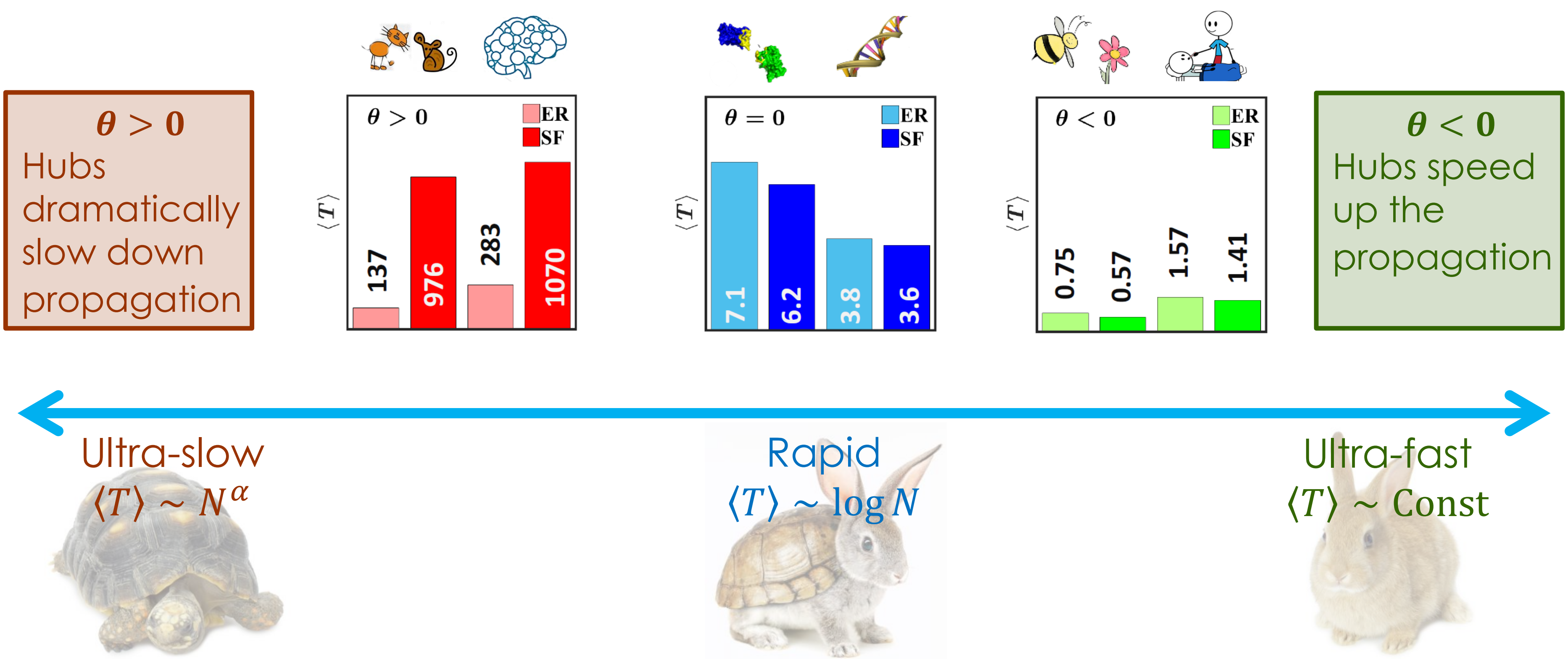

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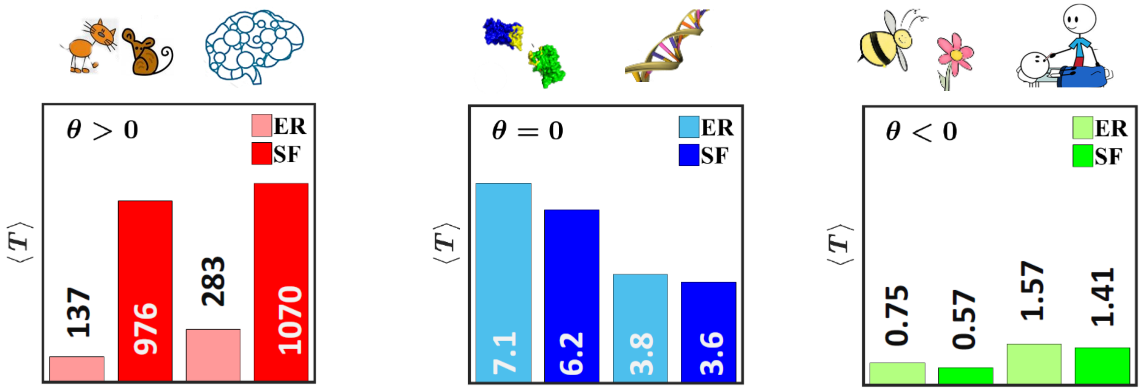
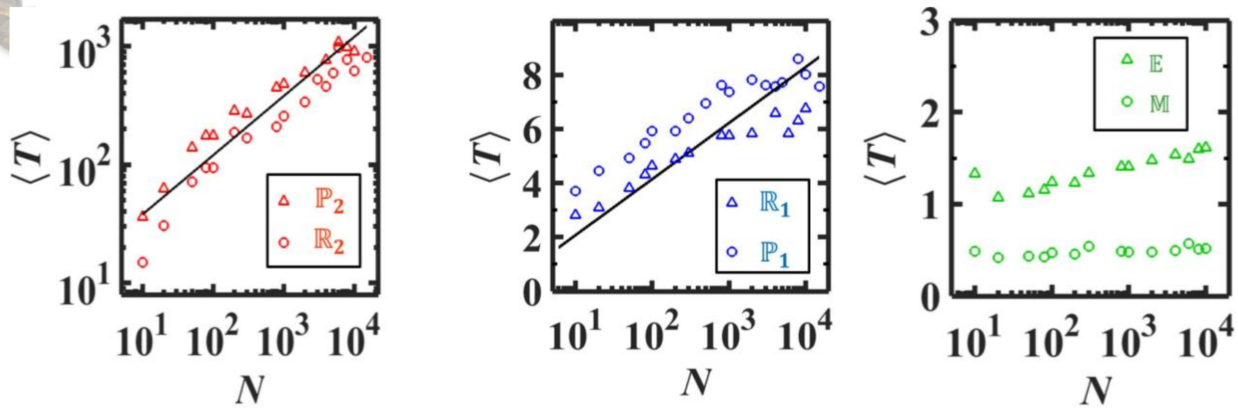


$\theta < 0$
Hubs speed up the propagation

Ultra-slow
$\langle T \rangle \sim N^{\alpha}$

Rapid
$\langle T \rangle \sim \log N$

Ultra-fast
$\langle T \rangle \sim \text{Const}$



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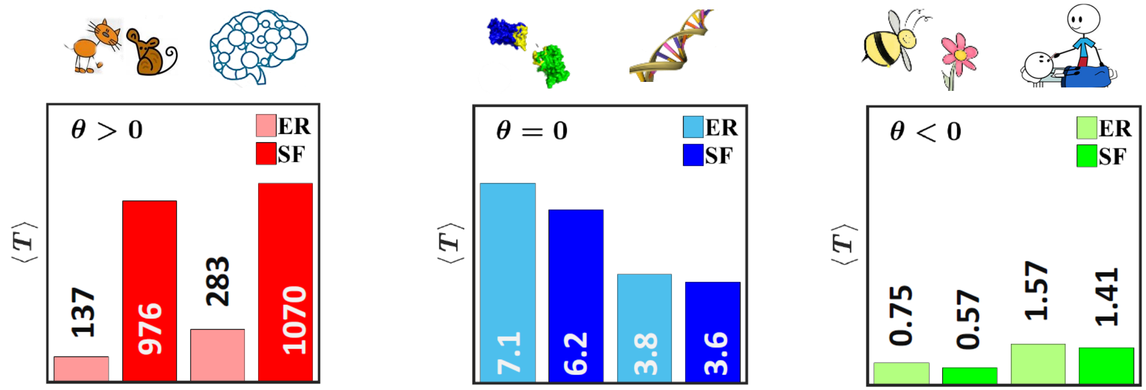

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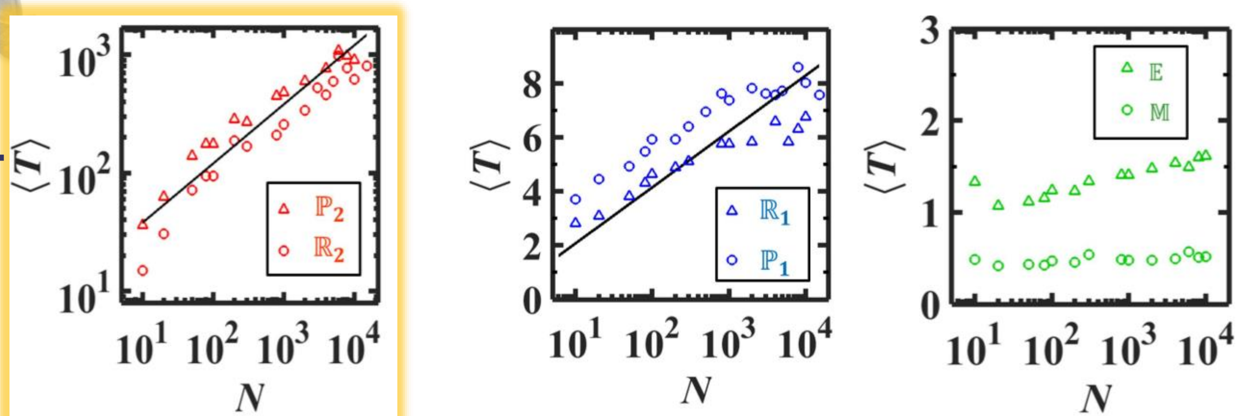
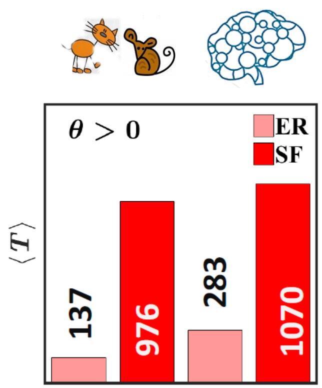


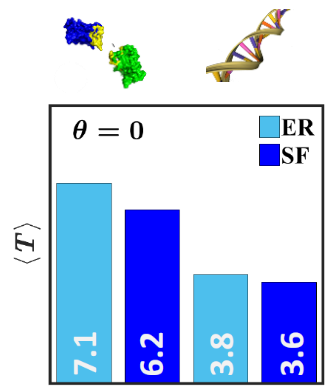
Lattice-like propagation

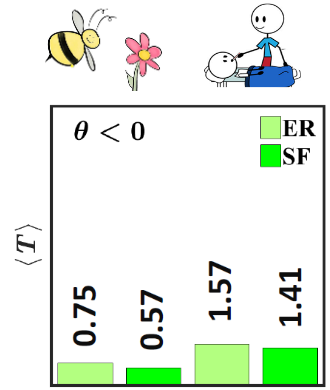
Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

Same topology – different spreading rules

$\theta > 0$
Hubs dramatically slow down propagation







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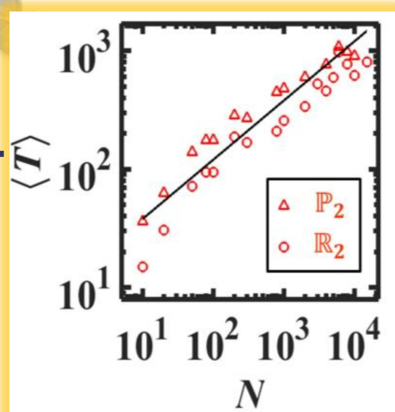
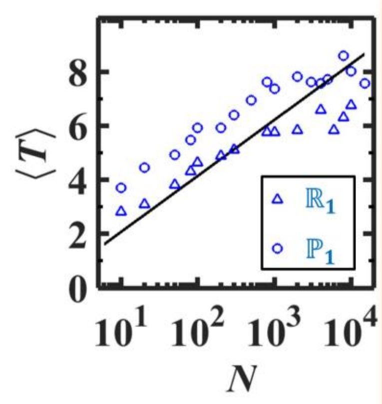
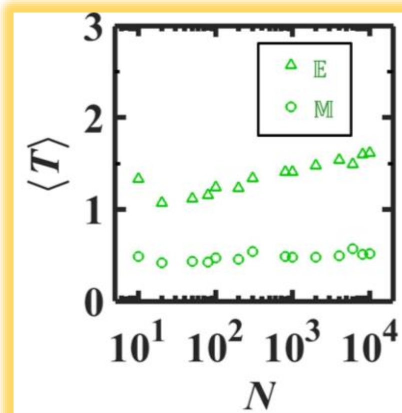






Lattice-like propagation

Single-node propagation

Hens, Harush, Haber, Cohen & Barzel. *Nature Physics* **15**, 403 (2019)

Same topology – different spreading rules

Different interpretations of scale-freeness. All boils down to a single analytically predictable parameter θ

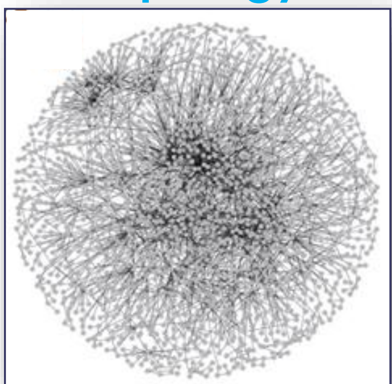
Ultra-slow
$\langle T \rangle \sim N^{\alpha}$

Rapid
$\langle T \rangle \sim \log N$

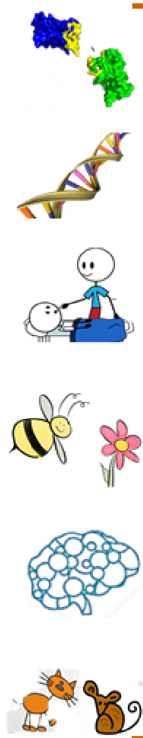
Ultra-fast
$\langle T \rangle \sim \text{Const}$

Dictionary of network dynamics

Topology



Interaction mechanisms
M_0, M_1, M_2



Dynamic determinants

$$\tau_i \sim k_i^{\theta}$$

$$I_i \sim k_i^{\varphi}$$

$$Q_i \sim k_i^{\delta}$$

$$\Gamma(l) = e^{-\beta \alpha l}$$

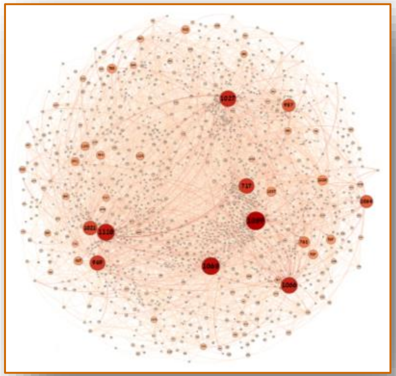
$$C_i \sim k_i^{\omega}$$

$$\beta_{\mathrm{eff}} = \frac{\mathbf{1}^{\top} A^2 \mathbf{1}}{\mathbf{1}^{\top} A \mathbf{1}}$$

$$\mathcal{F}_i \sim S_{i,\mathrm{out}} S_{i,\mathrm{in}}^{\xi}$$

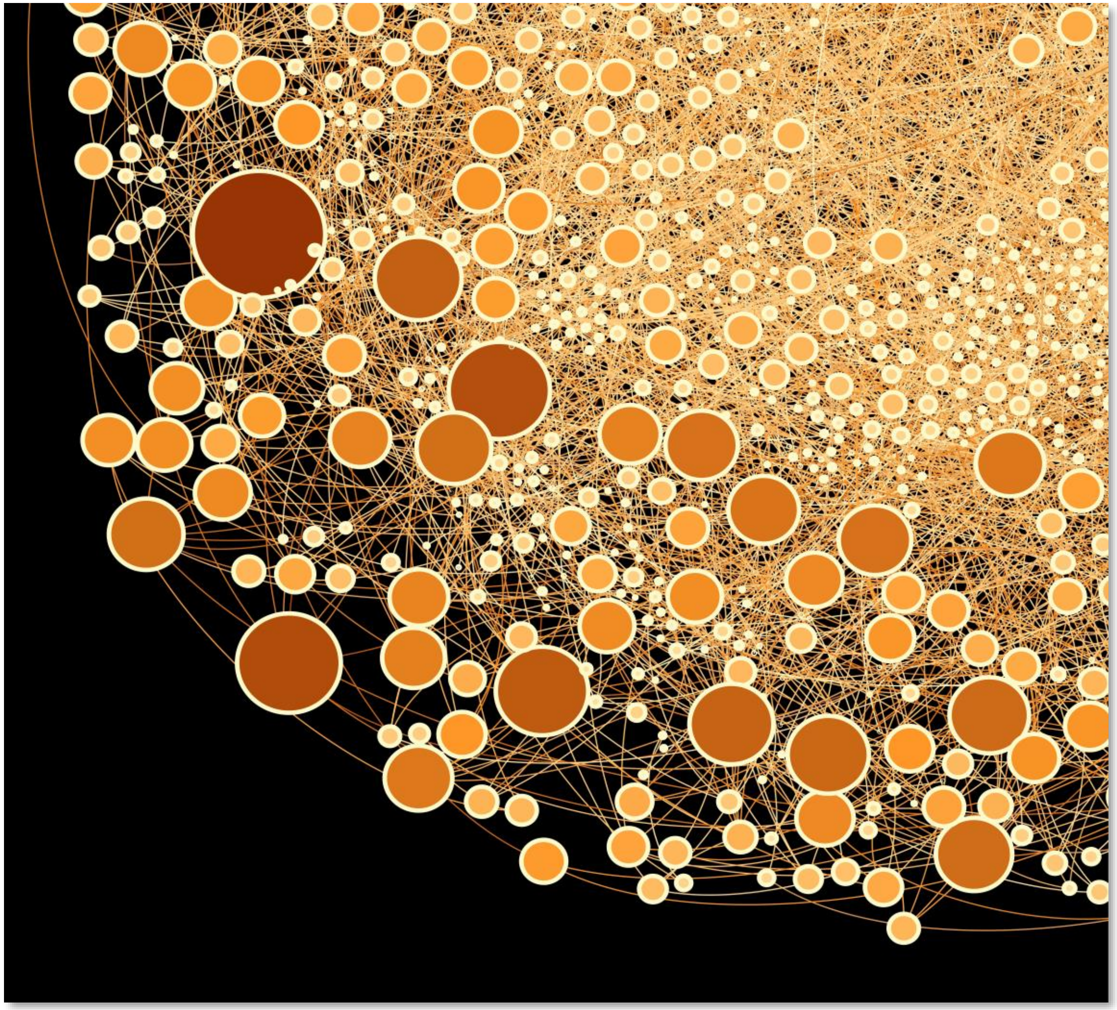
$$\mathcal{F}_{ij} \sim S_{i,out} S_{i,in}^{\xi-1} S_{j,\mathrm{in}}^{\xi-2}$$

Observable dynamics



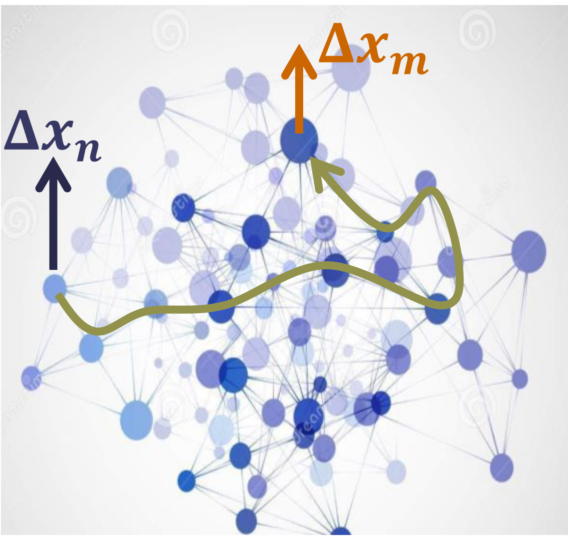
Microscopic Diversity condenses into a discrete set of Universality classes that determine how Topology translates into observable Dynamics

Understand



B. Barzel *et al*. *Nature Communications* **7186** (2015), *Nature Biotechnology* **31** (2013).

Information flow



$x_n + \Delta x_n \longrightarrow x_i + \Delta x_i(t) \longrightarrow x_m + \Delta x_m(t)$

signal mediation response

Node flow $\mathcal{F}_i$: how effective is each node in *transferring* information?

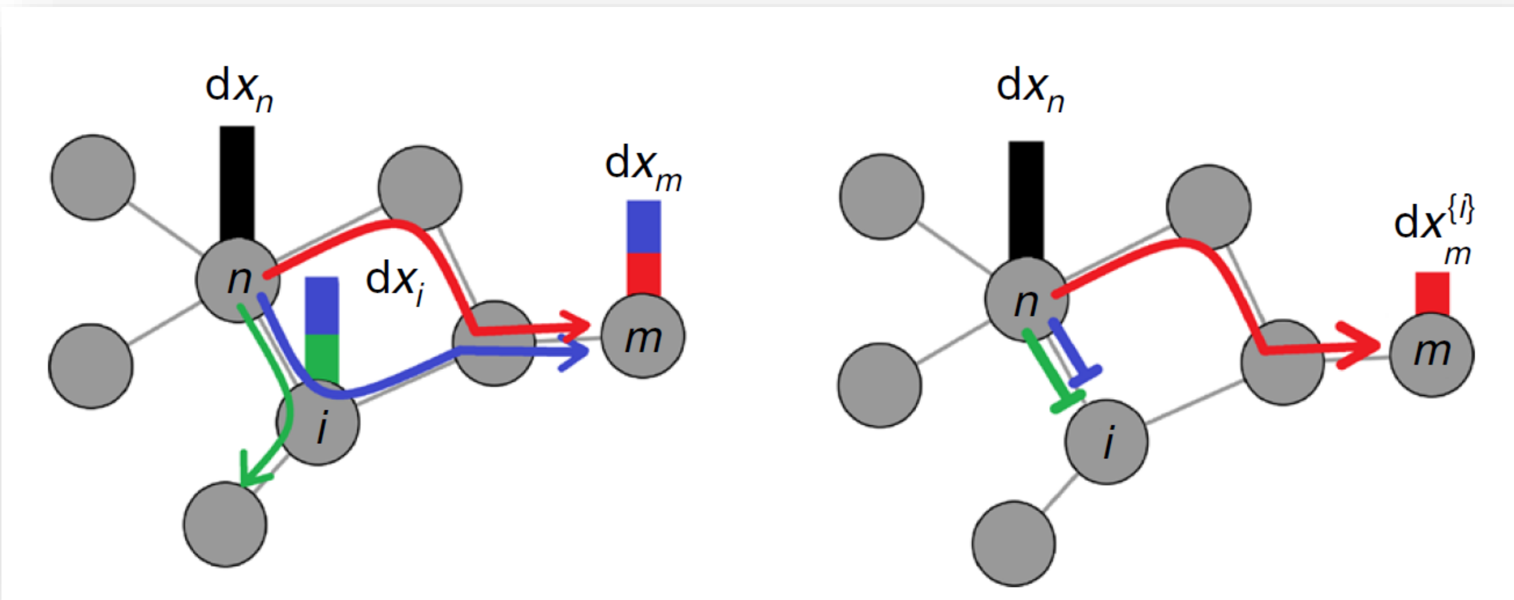
Link flow $\mathcal{F}_{ij}$: How effective is each link, pathway?

U. Harush and B. Barzel. *Nature Communications* **2181** (2017)

Information flow

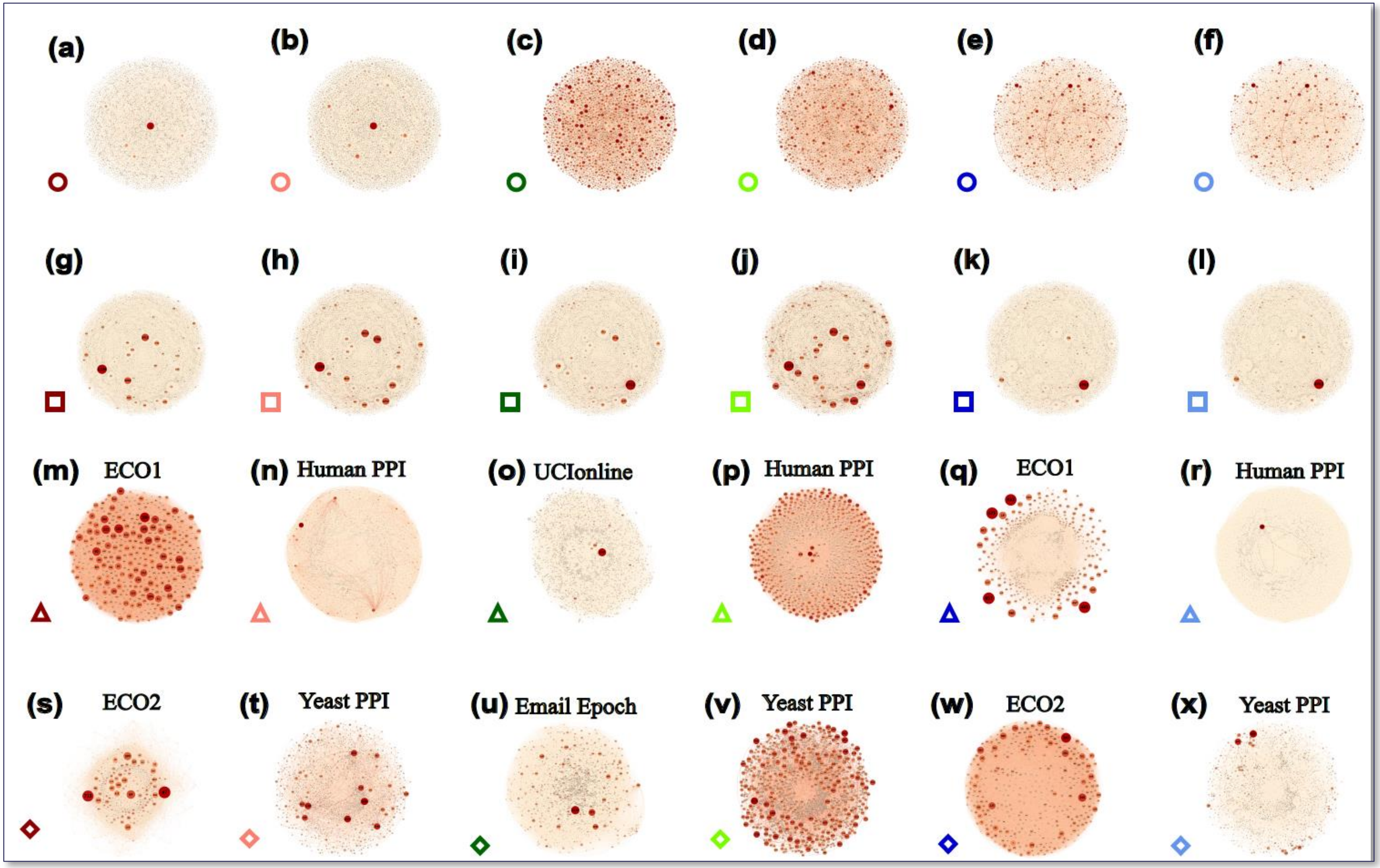
$$x_n + \Delta x_n \longrightarrow x_i + \Delta x_i(t) \longrightarrow x_m + \Delta x_m^{\{i\}}(t)$$

signal — mediation — response



U. Harush and B. Barzel. *Nature Communications* **2181** (2017)

The zoo of information flow patterns



U. Harush and B. Barzel. *Nature Communications* **2181** (2017)

Taming the zoo of information flow patterns

$$\mathcal{F}_i \sim k_{i,\mathrm{out}} k_{i,\mathrm{in}}^{\omega-1}$$

$$\mathcal{F}_{ij} \sim A_{ij} k_{i,out} k_{i,in}^{\xi-1} k_{j,\mathrm{in}}^{\xi}$$

Node/link flow
Dynamic function of interest.

$$\mathcal{F}_i, \mathcal{F}_{ij}, k_{in/out}, \omega, \xi$$

Dynamic determinants
Mapping topology into dynamics

Weighted in/out degrees
Known topological elements

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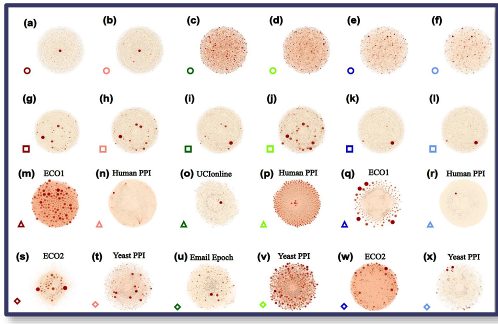
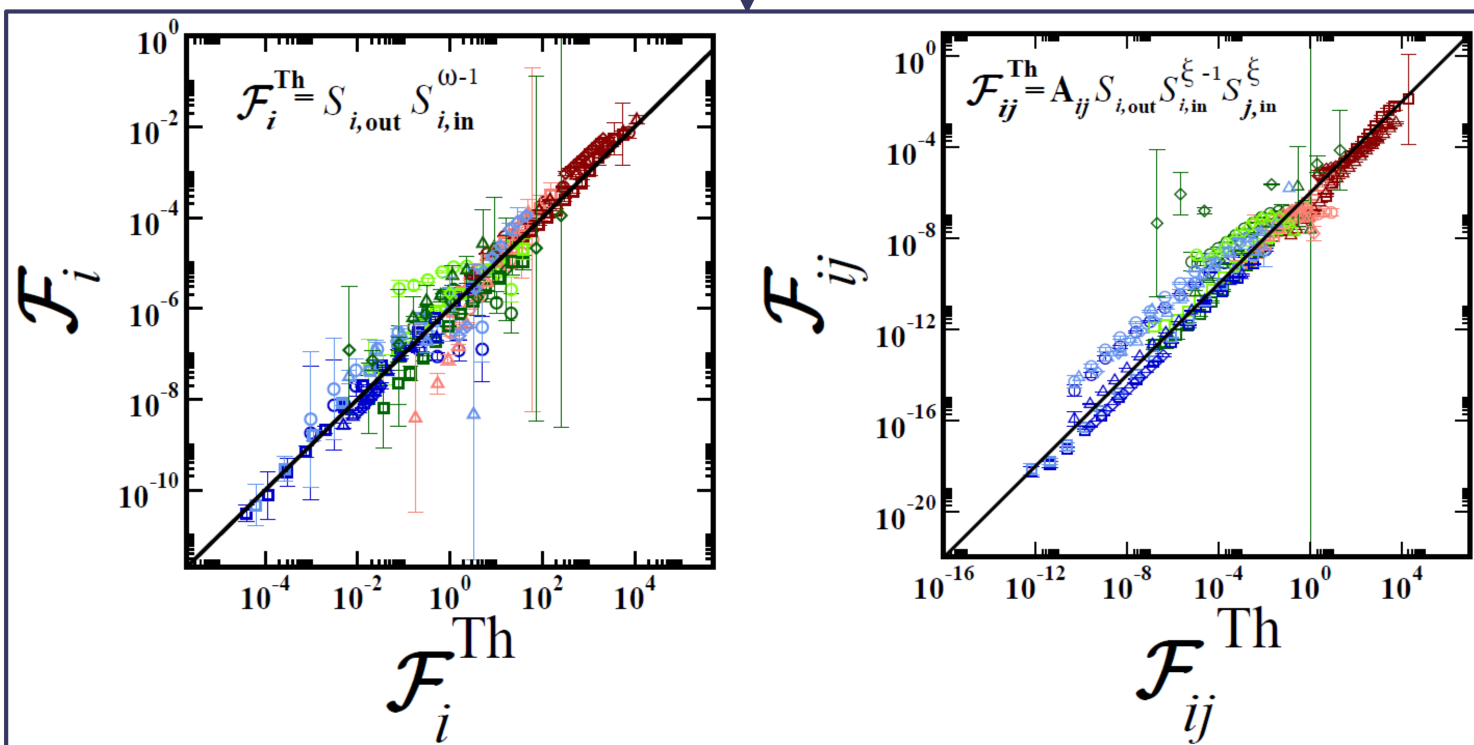
~~The zoo~~ universal information flow patterns



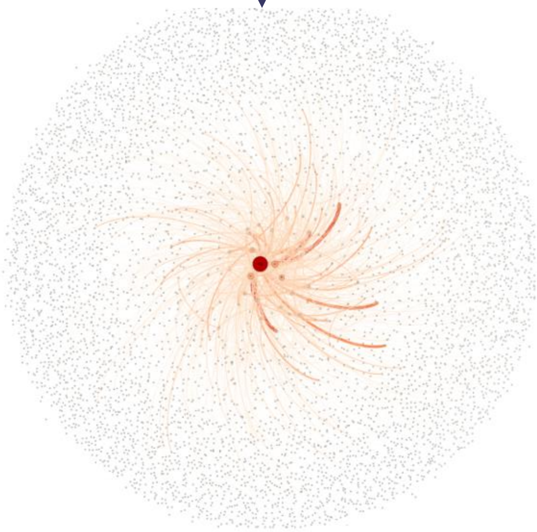


U. Harush and B. Barzel. *Nature Communications* **2181** (2017)

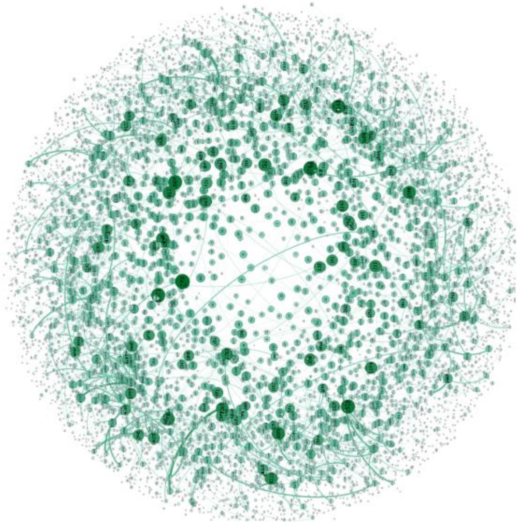
Universal classes of information flow patterns

$$\mathcal{F}_i \sim k_{i,\text{out}} k_{i,\text{in}}^{\omega-1}$$

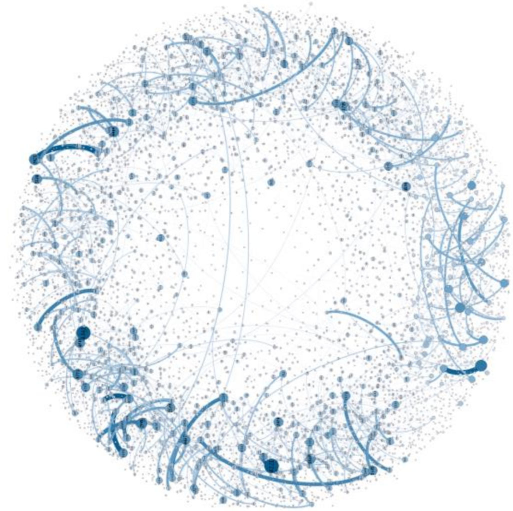
$$\mathcal{F}_{ij} \sim A_{ij} k_{i,out} k_{i,in}^{\xi-1} k_{j,\text{in}}^{\xi}$$



Hub centric



Egalitarian



Peripheral

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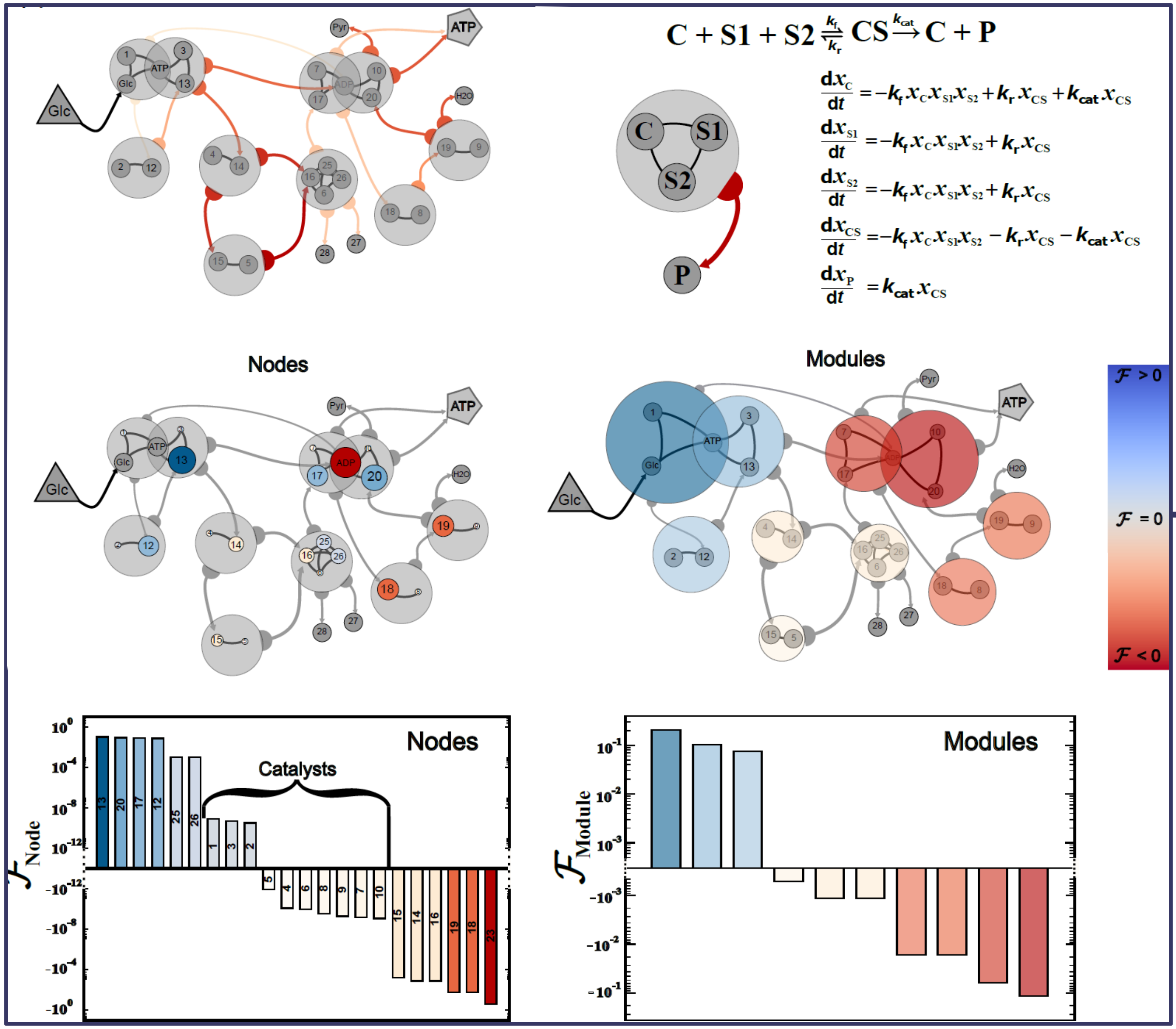
Glycolysis: do cells prefer traffic jams?



Metabolism: Designed to push the mean information flow towards zero.

Output (response) independent of Input (perturbation)

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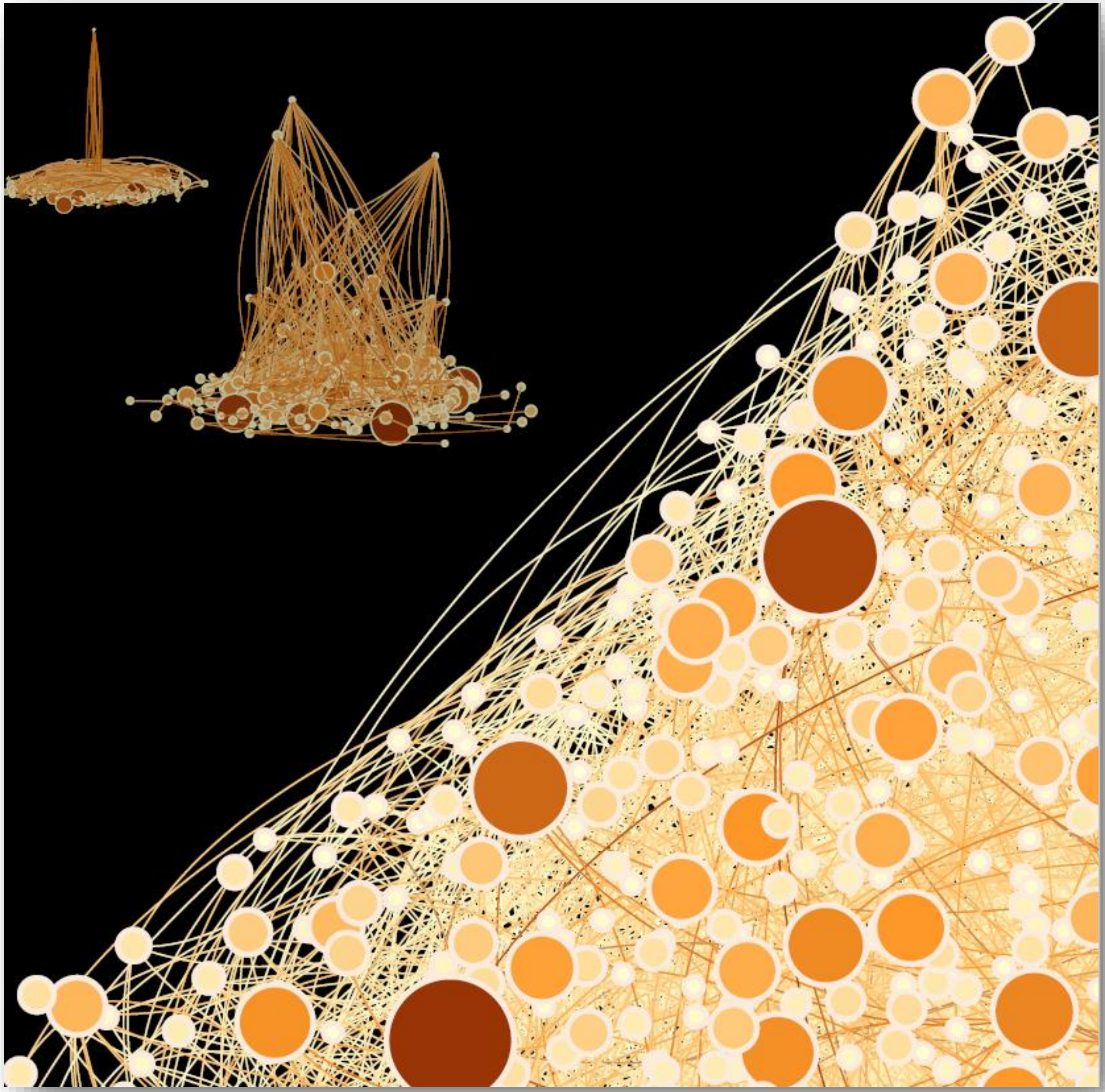
Control



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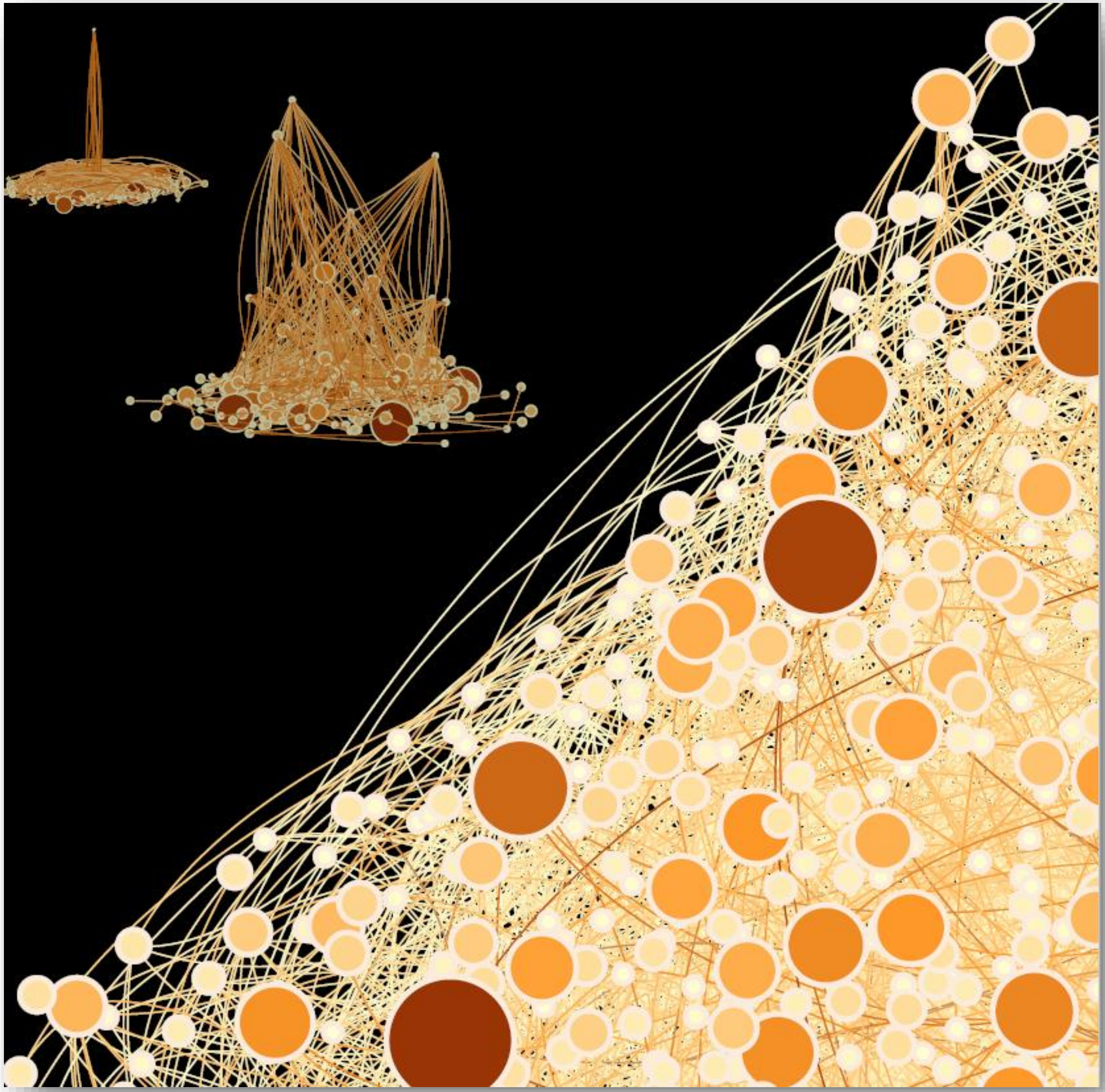
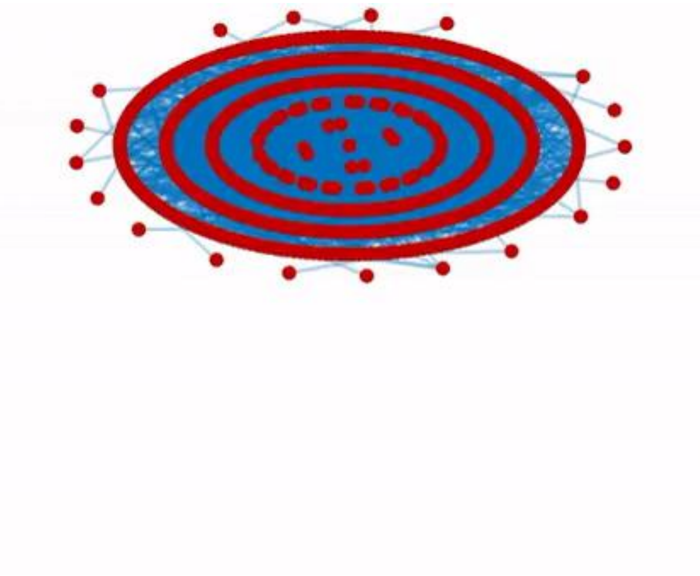
Inaugural meeting on network dynamics
& networks of networks
January 29 – February 1, 2024 | Yehuda Hotel, Jerusalem

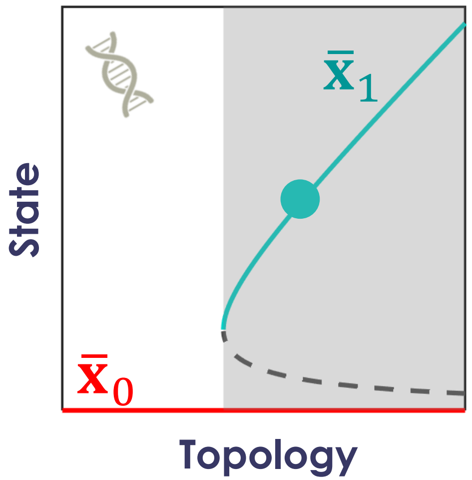
Control

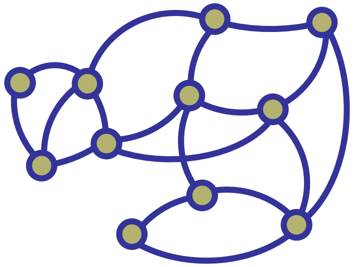


H. Sanhedrai, J. Gao, M. Schwartz, S. Havlin and B. Barzel. *Nature Physics* **18**, 338 (2022)

Dynamic transitions

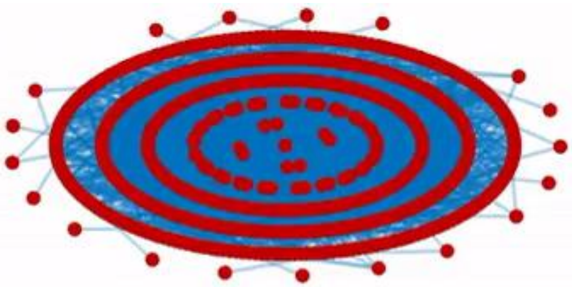


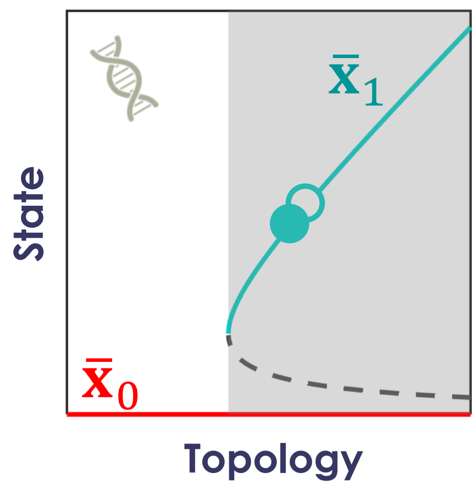


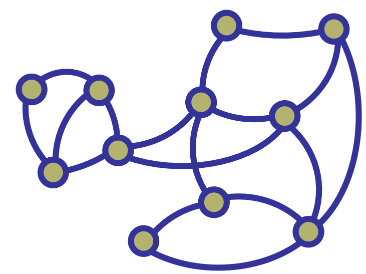


J. Gao, B. Barzel and A.-L. Barabási. *Nature* **530**, 307 (2016)

Dynamic transitions

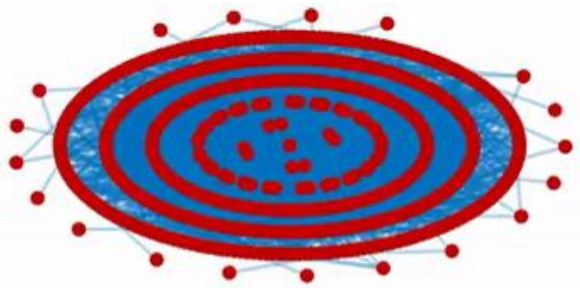


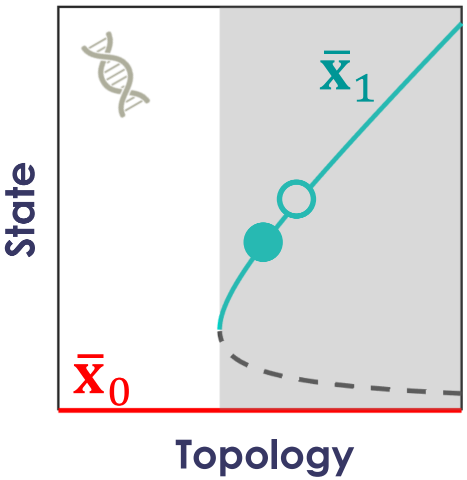


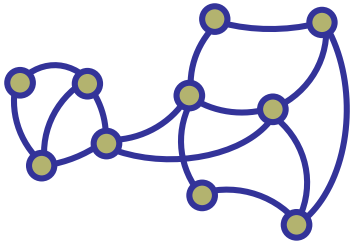


J. Gao, B. Barzel and A.-L. Barabási. *Nature* **530**, 307 (2016)

Dynamic transitions







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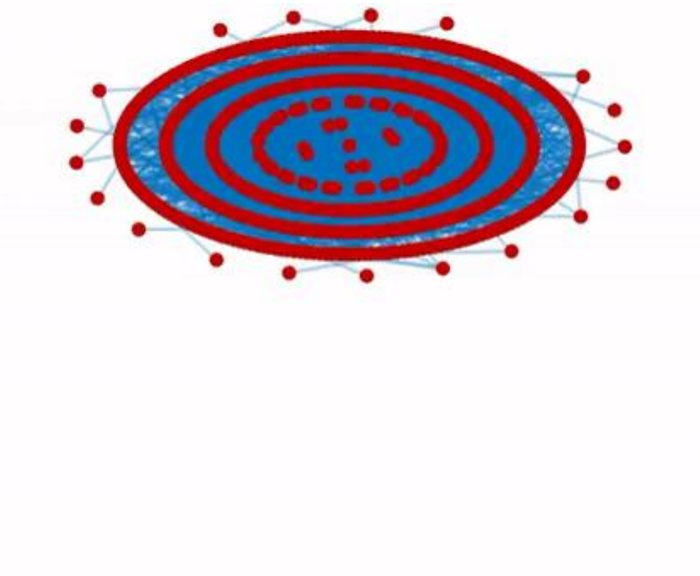
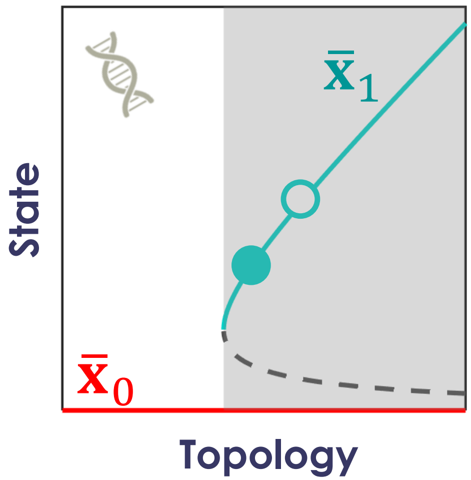
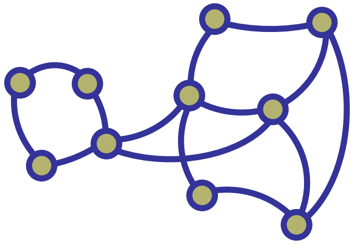
Dynamic transitions







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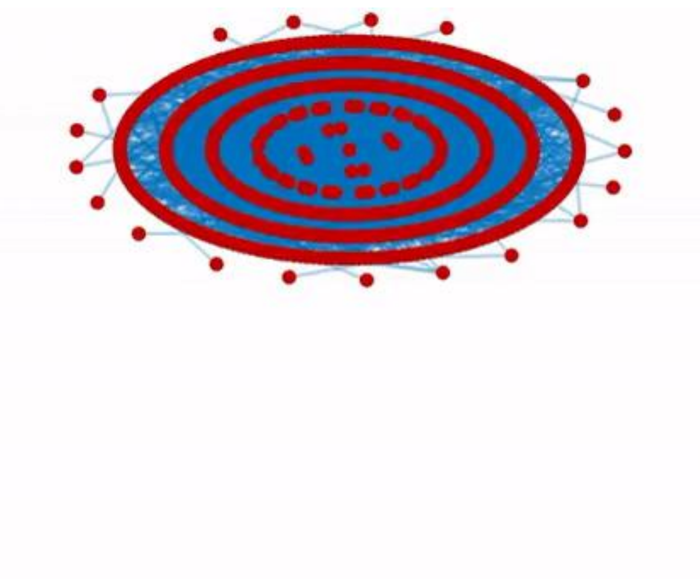
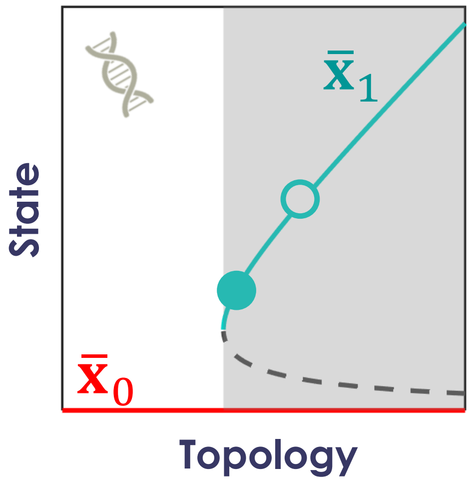
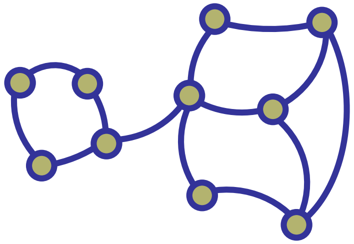
Dynamic transitions







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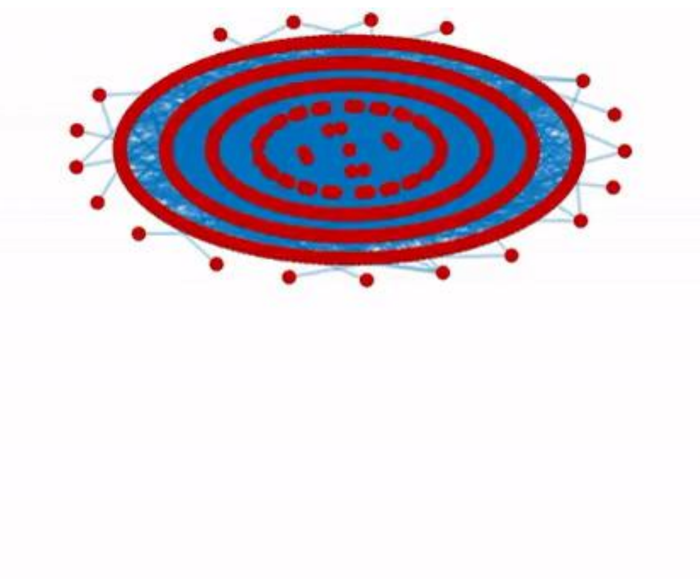
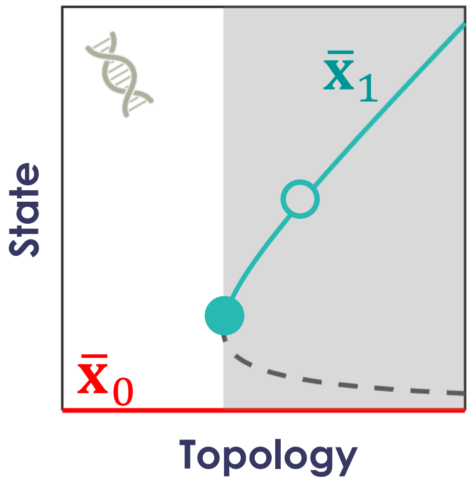
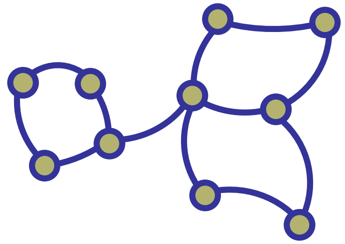
Dynamic transitions







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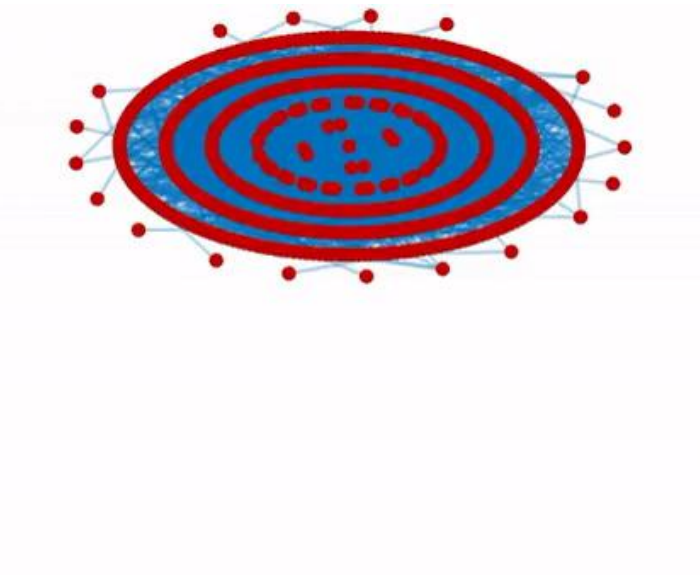
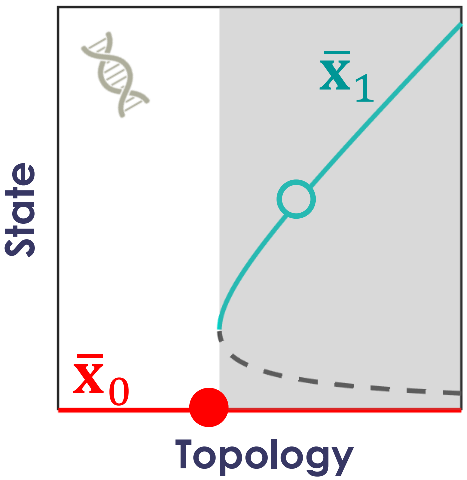
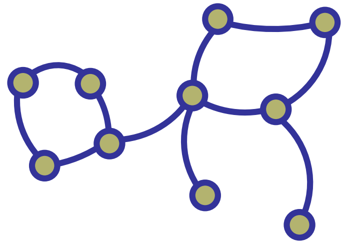
Dynamic transitions







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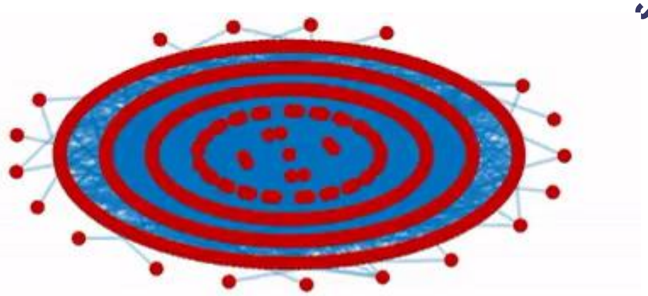
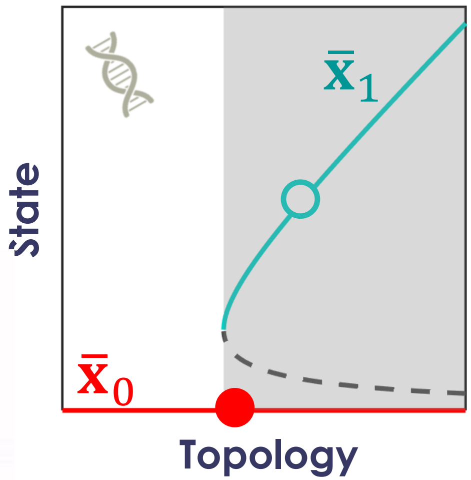
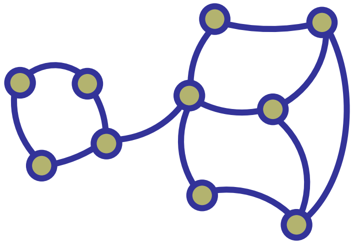
Dynamic transitions - irreversible







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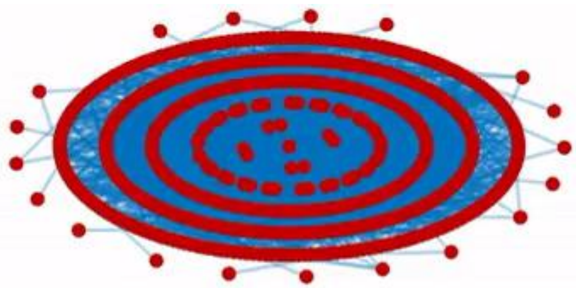
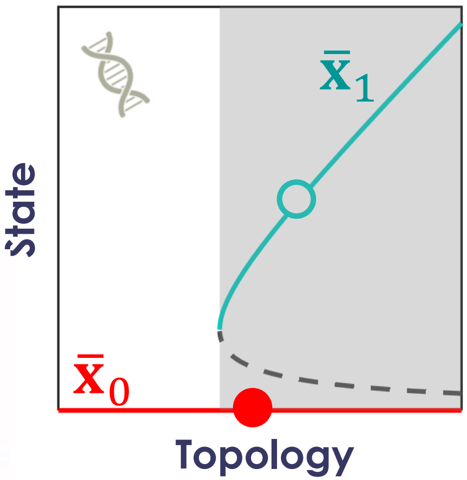
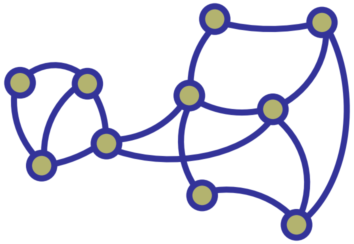
Dynamic transitions - irreversible







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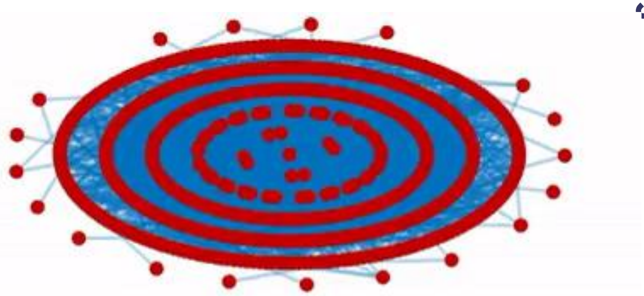
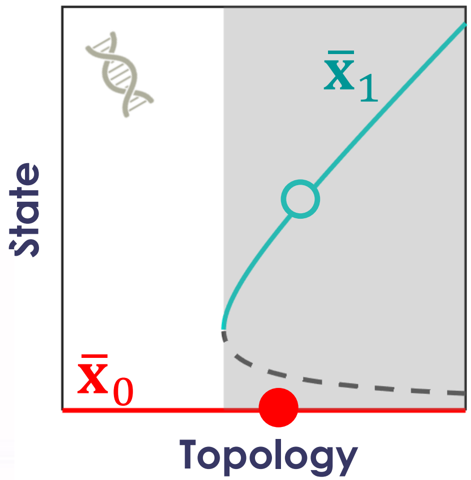
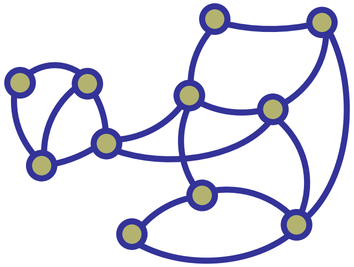
Dynamic transitions - irreversible







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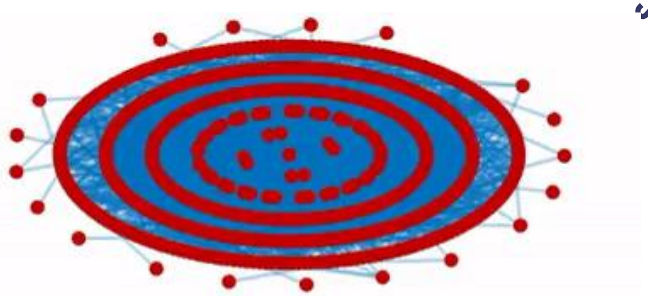
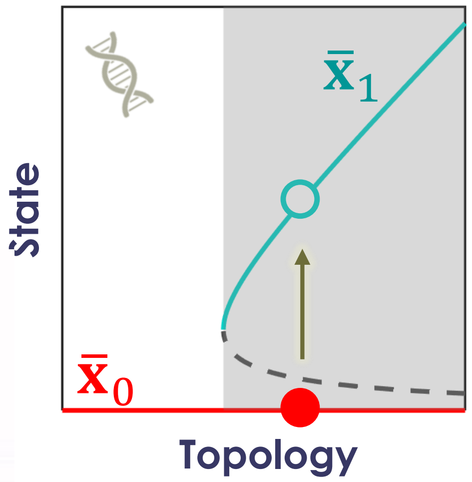
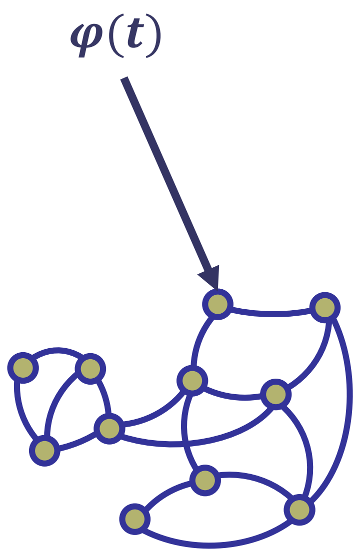
Reigniting the network activity

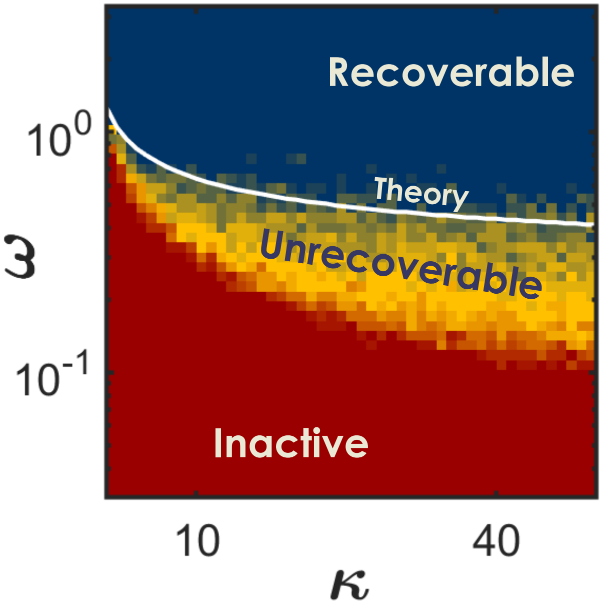






H. Sanhedrai, J. Gao, M. Schwartz, S. Havlin and B. Barzel. *Nature Physics* (In press)

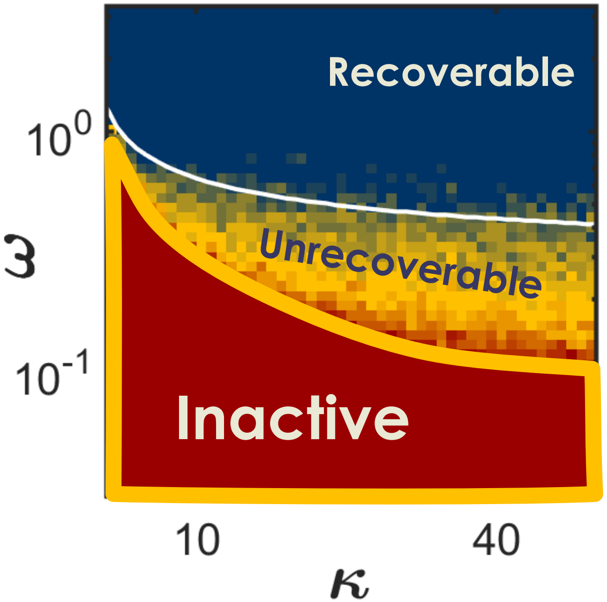
The recoverable phase

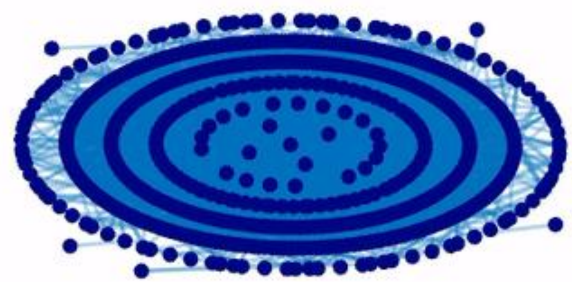


Can you reignite a failed system by controlling just one node?

H. Sanhedrai, J. Gao, M. Schwartz, S. Havlin and B. Barzel. *Nature Physics* (In press)

The recoverable phase





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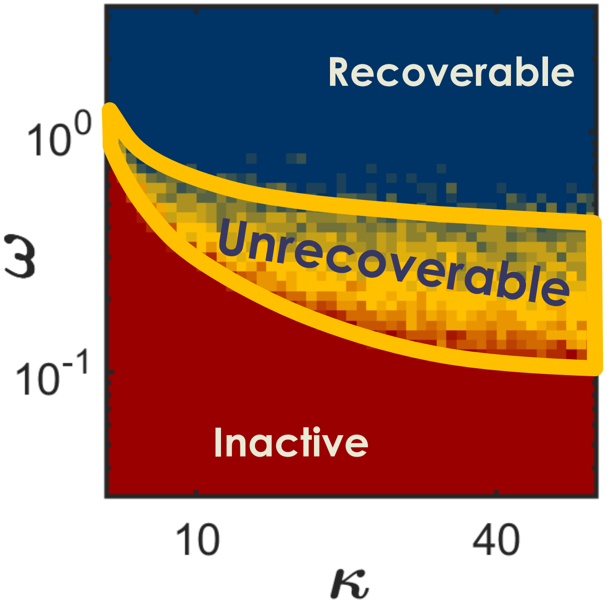

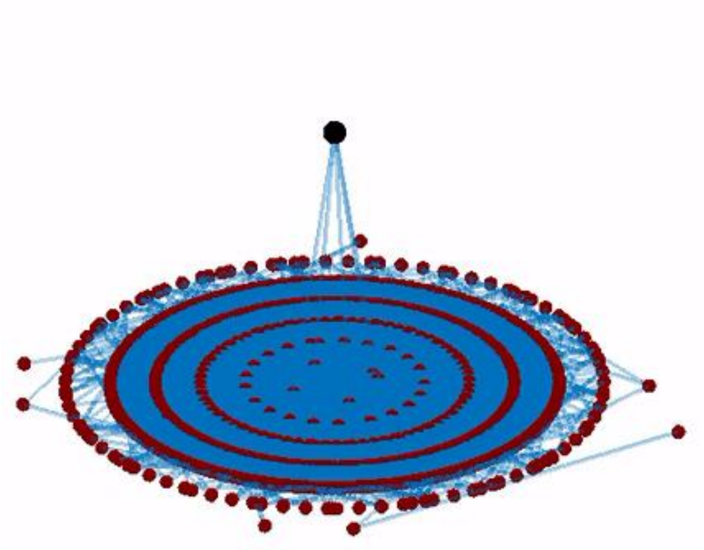

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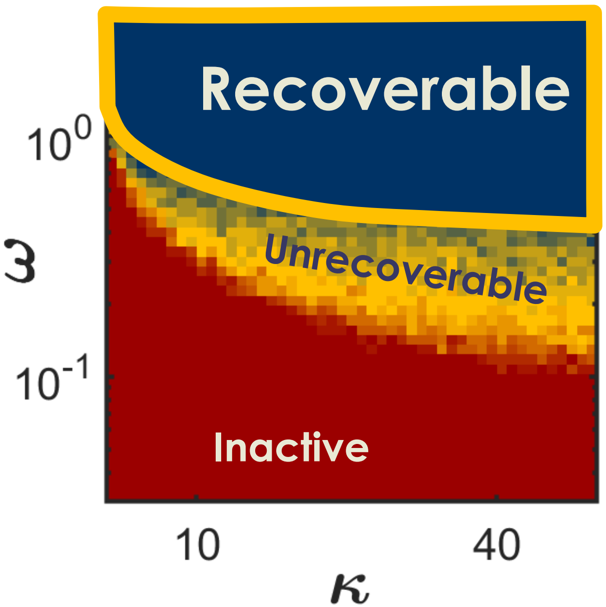
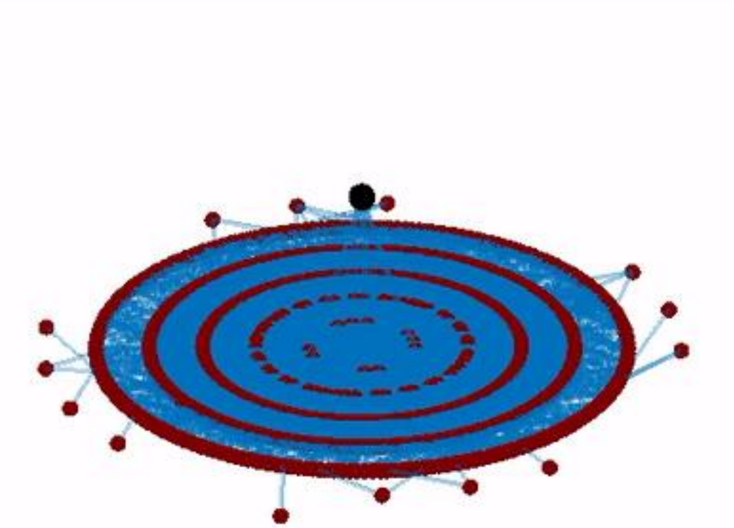


Single node reigniting – reviving the failed system by activating one node



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Theory of network dynamics was brought to you by

Guy Berger

Dr. Chitta-ranjan Hens

Dr. Chan-drakala Meena

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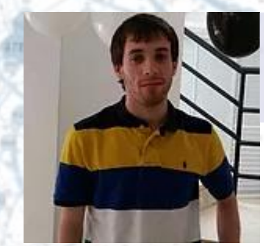
Hillel Sanhedrai

Adar Hacohen

Gil Tankus



Eran Reches

See more at: *https://www.barzellab.com/*