Towards a physics of complex networks

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Padova, 25 October 2024

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Networks Days

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THE NOBEL PRIZE

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Ilya Prigogine
Facts

1977

Photo from the Nobel Foundation archive.

Ilya Romanovich Prigogine
The Nobel Prize in Chemistry 1977

Born: 25 January 1917, Moscow, Russia

Died: 28 May 2003, Brussels, Belgium

Affiliation at the time of the award: Université Libre de Bruxelles, Brussels, Belgium; University of Texas, Austin, TX, USA

Prize motivation: "for his contributions to non-equilibrium thermodynamics, particularly the theory of dissipative structures"

WHAT IS PHYSICS?

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Why the Physics Nobel Honored Climate Science and Complex Systems

The prestigious award finally recognizes work that helped scientists understand climate change and, more broadly, find order in disorder

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WHAT IS PHYSICS?

2024

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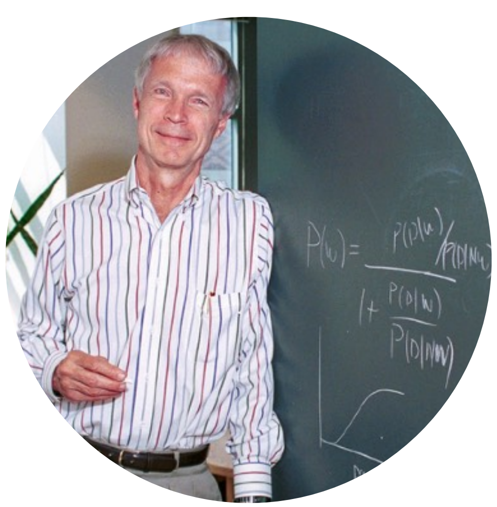
NEWS | 08 October 2024

Physics Nobel scooped by machine-learning pioneers

John Hopfield and Geoffrey Hinton pioneered computational methods that enabled the development of neural networks.



REVIEWS OF MODERN PHYSICS

Brain, neural networks, and computation

J. J. Hopfield

Department of Molecular Biology, Princeton University, Princeton, New Jersey 08544

[S0034-6861(99)04102-1]

I. INTRODUCTION

The method by which brain produces mind has for centuries been discussed in terms of the most complex engineering and science metaphors of the day. Descartes described mind in terms of interacting vortices. Psychologists have metaphorized memory in terms of paths or traces worn in a landscape, a geological record of our experiences. To McCulloch and Pitts (1943) and von Neumann (1958), the appropriate metaphor was the digital computer, then in its infancy. The field of "neural networks" is the study of the computational properties and behavior of networks of "neuronlike" elements. It lies somewhere between a model of neurobiology and a metaphor for how the brain computes. It is inspired by two goals: to understand how neurobiology works, and to understand how to solve problems which neurobiology solves rapidly and effortlessly and which are very hard on present digital machines.

Most physicists will find it obvious that understanding biology might help in engineering. The obverse ... the actuators of a robot for a desired motion is a problem in classical mechanics that can be solved on a computer. While we may not know how to write efficient algorithms for these tasks, such examples do illustrate that what the nervous system does might be described as computation.

For present purposes, a computer can be viewed as an input-output device, with input and output signals that are in the same format (Hopfield, 1994). Thus in a very simple digital computer, the input is a string of bits (in time), and the output is another string of bits. A million axons carry electrochemical pulses from the eye to the brain. Similar signaling pulses are used to drive the muscles of the vocal tract. When we look at a person and say, "Hello, Jessica," our brain is producing a complicated transformation from one (parallel) input pulse sequence coming from the eye to another (parallel) output pulse sequence which results in sound waves being generated. The idea of *composition* is important in this definition. The output of one computer can be used as the input for another computer of the same general

Hopfield, Rev Mod Phys (1999)

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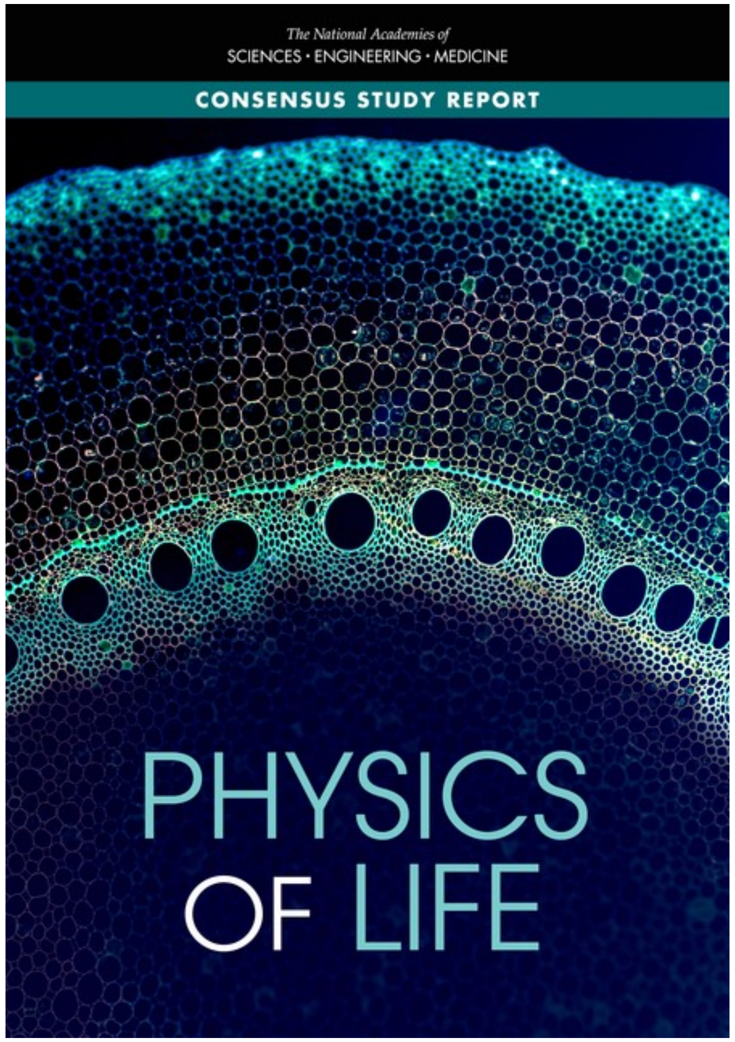
2022



Evolution

Communication & Language

Ecosystems

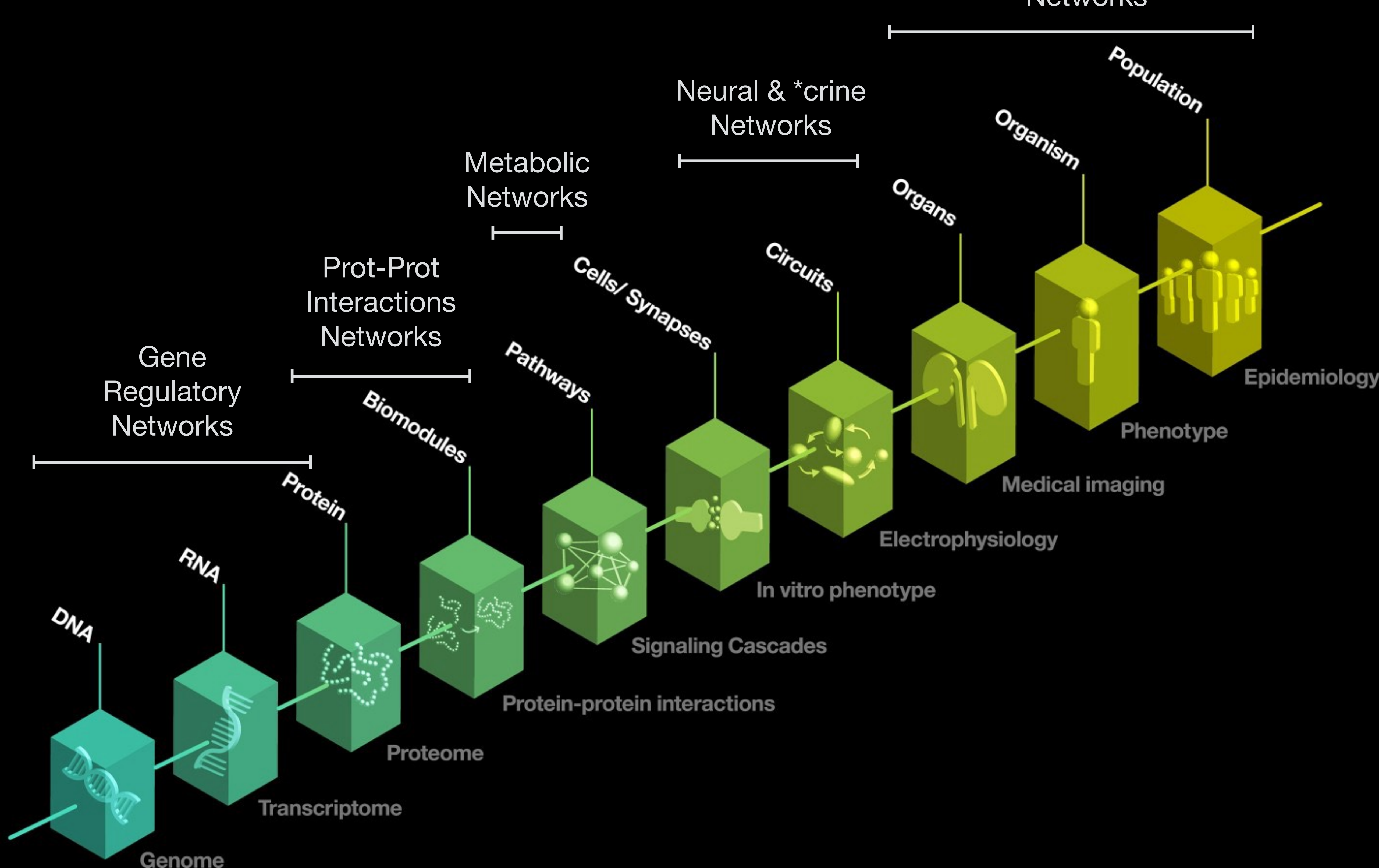
Active matter

Cells

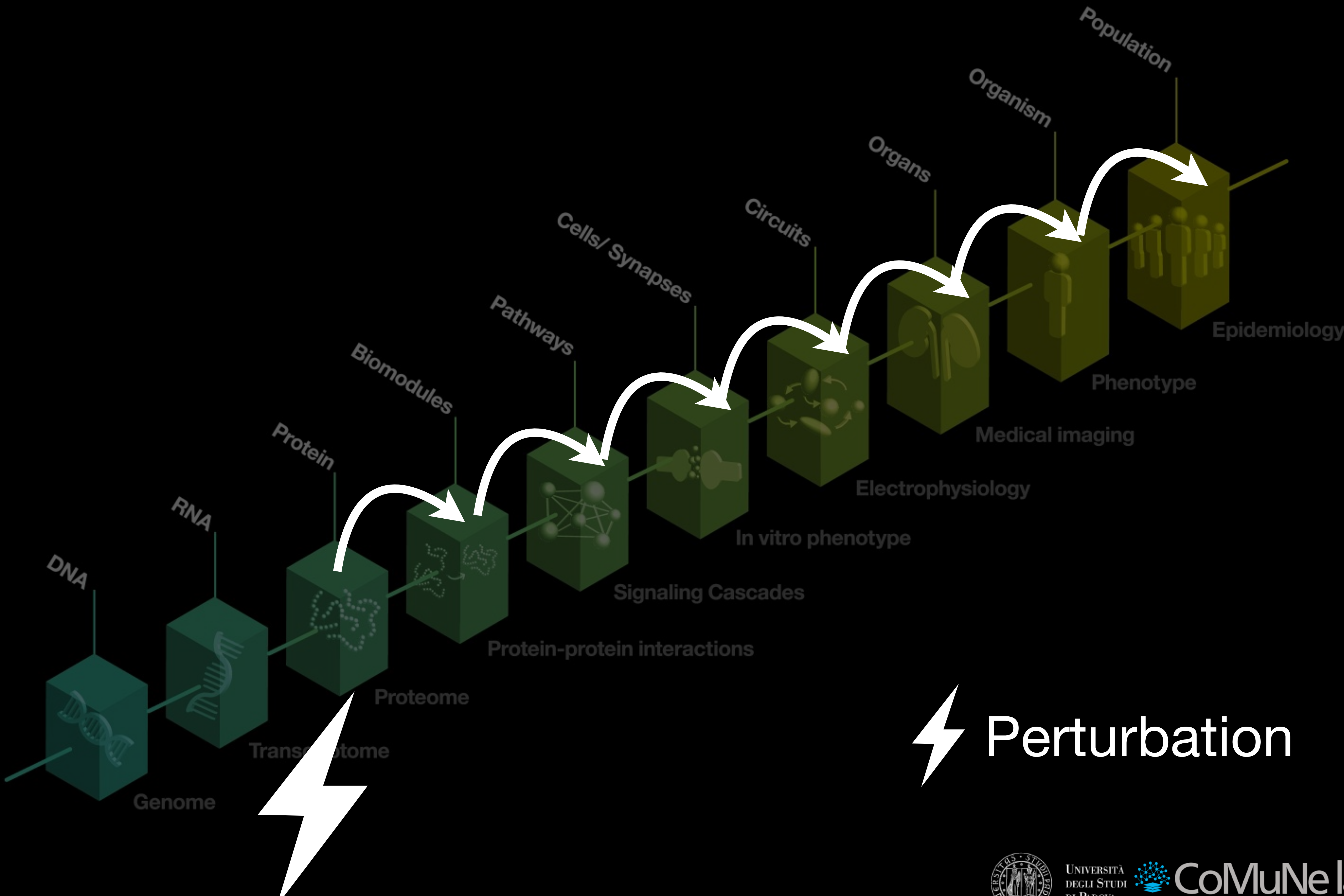
Networks

Information

Complex Networks: Multiscale view of systems biology & systems medicine



Complex Networks: Multiscale view of systems biology & systems medicine



Perturbation

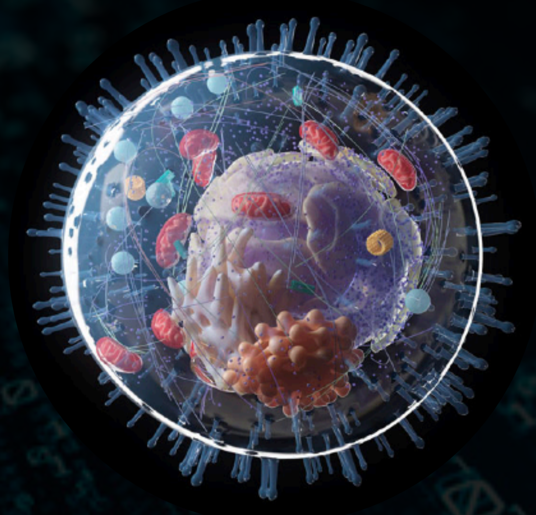
Fix one component…

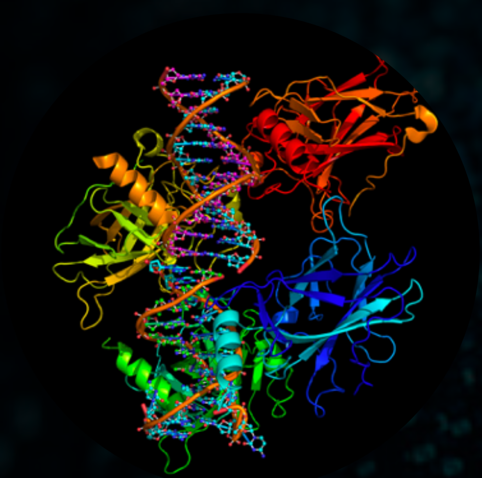
… and something else will change

The risk of breaking something else

is far from negligible

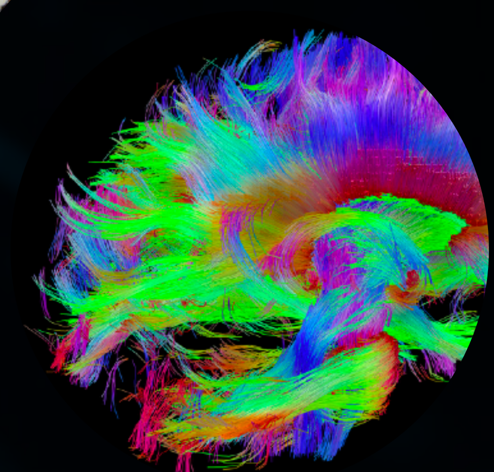
10^{-4} **m** $\approx 100\ \mu m$





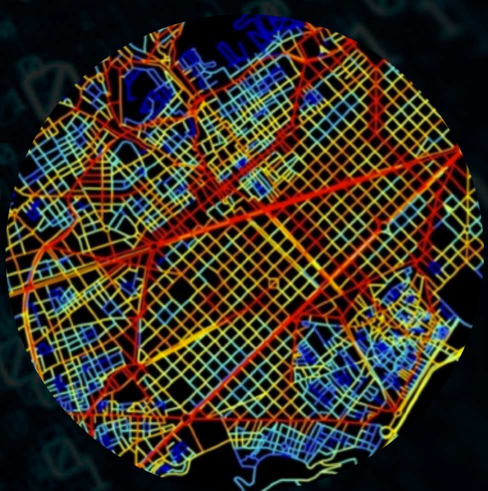
10^{-2} **m** $\approx 1\ cm$

10^{-8} **m** $\approx 10\ nm$



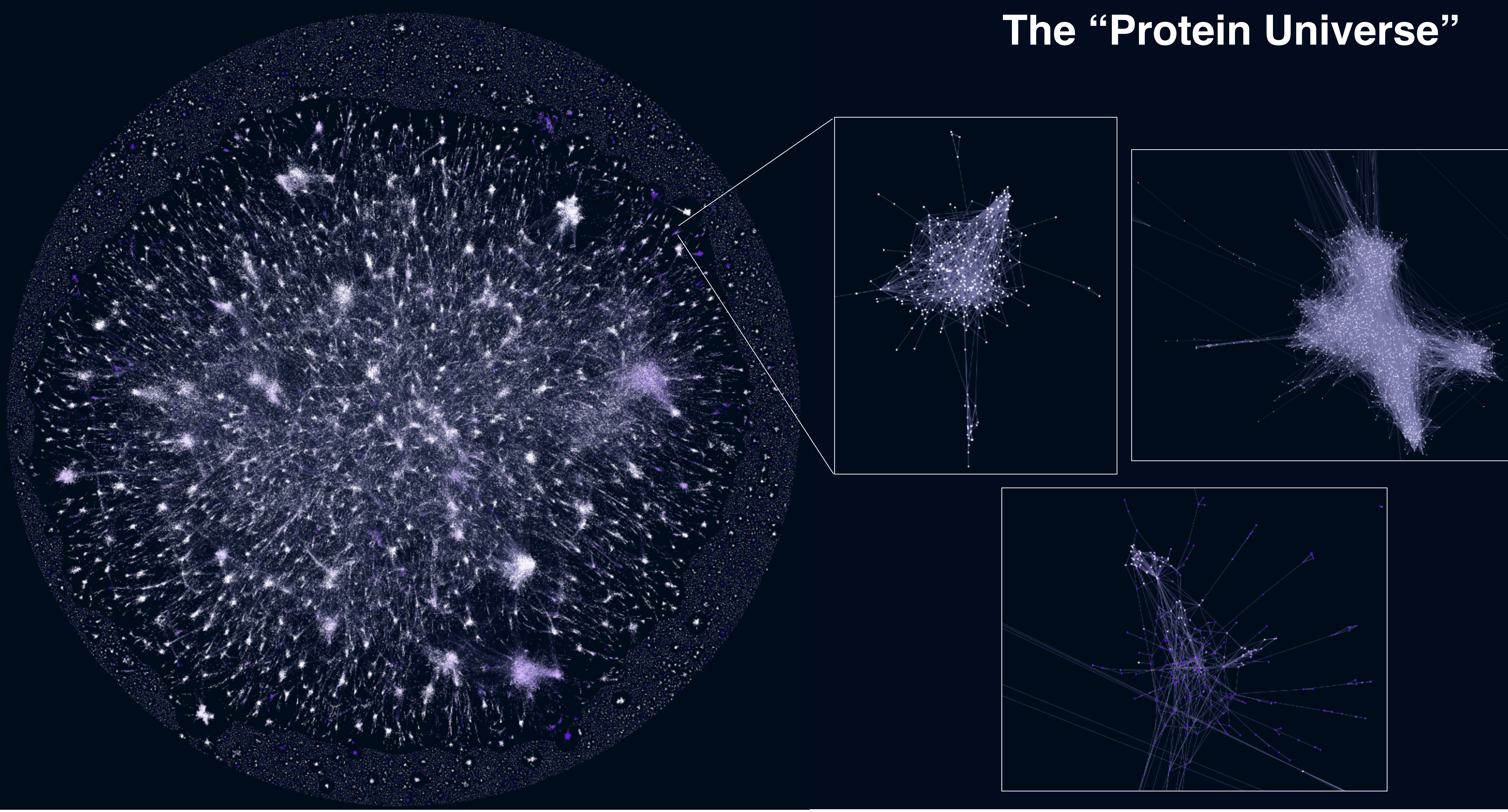
10^{4} **m** $\approx 10\ km$

10^{-1} **m** $\approx 10\ cm$



10^{6} **m** $\approx 1000\ km$

The “Protein Universe”



nature https://doi.org/10.1038/s41586-023-06622-3

Accelerated Article Preview

Uncovering new families and folds in the natural protein universe

Received: 24 March 2023

Accepted: 7 September 2023

Accelerated Article Preview

Cite this article as: Durairaj, J. et al. Uncovering new families and folds in the natural protein universe. *Nature* https://doi.org/10.1038/s41586-023-06622-3 (2023)

Janani Durairaj, Andrew M. Waterhouse, Toomas Mets, Tetiana Brodiazhenko, Minhal Abdullah, Gabriel Studer, Gerardo Tauriello, Mehmet Akdel, Antonina Andreeva, Alex Bateman, Tanel Tenson, Vasili Hauryliuk, Torsten Schwede & Joana Pereira

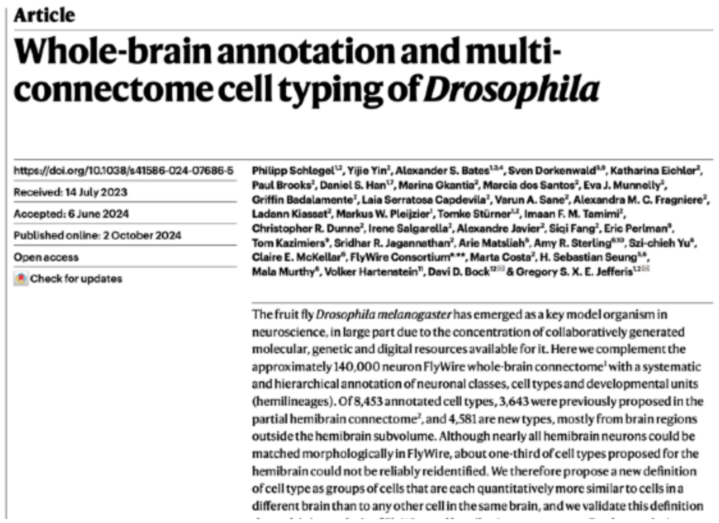
Sequence Similarity Network

UniRef50 clusters with at least one member with a high predicted accuracy model (avg. pLDDT > 90) in the AlphaFold database. It represents 11% of all UniRef50

*“We are now **entering a new era in protein sequence** and structure annotation, with hundreds of millions of predicted protein structures made available through the AlphaFold database”*

Durairaj et al, Nature (2023)

The “Neural Circuitry”



Article

Whole-brain annotation and multi-connectome cell typing of *Drosophila*

https://doi.org/10.1038/s41586-024-07686-5
Received: 14 July 2023
Accepted: 6 June 2024
Published online: 2 October 2024
Open access
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Philipp Schlegel[1,2], Yijie Yin[2], Alexander S. Bates[1,3,4], Sven Dorkenwald[5,6], Katharina Eichler[2], Paul Brooks[2], Daniel S. Han[1,7], Marina Gkantia[2], Marcia dos Santos[2], Eva J. Munnelly[2], Griffin Badalamente[2], Laia Serratosa Capdevila[2], Varun A. Sane[2], Alexandra M. C. Fragniere[2], Ladann Kiassat[2], Markus W. Pleijzier[1], Tomke Stürner[1,2], Imaan F. M. Tamimi[2], Christopher R. Dunne[2], Irene Salgarella[2], Alexandre Javier[2], Siqi Fang[2], Eric Perlman[8], Tom Kazimiers[9], Sridhar R. Jagannathan[2], Arie Matsliah[6], Amy R. Sterling[6,10], Szi-chieh Yu[6], Claire E. McKellar[6], FlyWire Consortium[*,**], Marta Costa[2], H. Sebastian Seung[5,6], Mala Murthy[6], Volker Hartenstein[11], Davi D. Bock[12] & Gregory S. X. E. Jefferis[1,2]

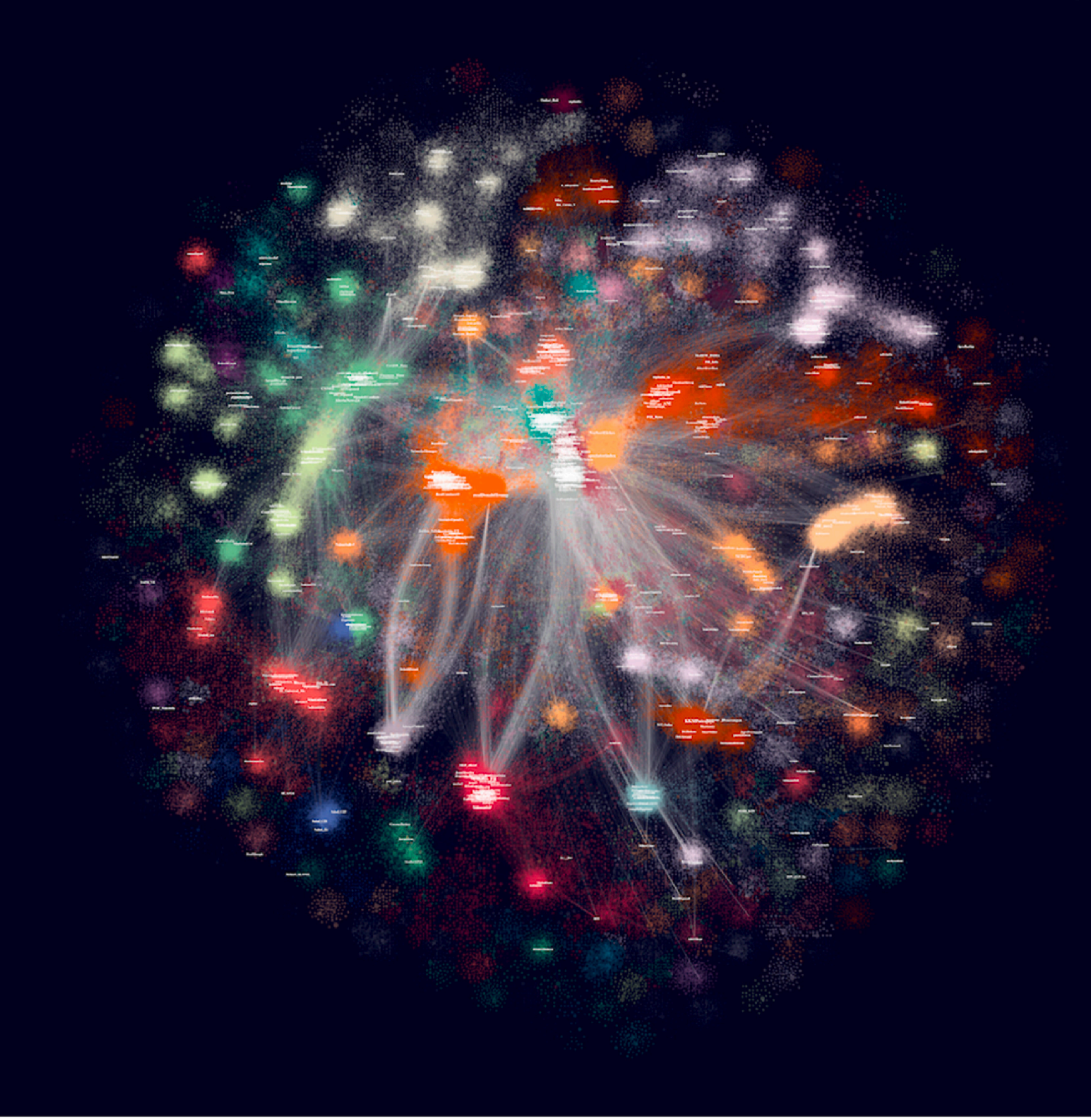
The fruit fly *Drosophila melanogaster* has emerged as a key model organism in neuroscience, in large part due to the concentration of collaboratively generated molecular, genetic and digital resources available for it. Here we complement the approximately 140,000 neuron FlyWire whole-brain connectome[1] with a systematic and hierarchical annotation of neuronal classes, cell types and developmental units (hemilineages). Of 8,453 annotated cell types, 3,643 were previously proposed in the partial hemibrain connectome[2], and 4,581 are new types, mostly from brain regions outside the hemibrain subvolume. Although nearly all hemibrain neurons could be matched morphologically in FlyWire, about one-third of cell types proposed for the hemibrain could not be reliably reidentified. We therefore propose a new definition of cell type as groups of cells that are each quantitatively more similar to cells in a different brain than to any other cell in the same brain, and we validate this definition

140,000 neurons
15.1 million connections

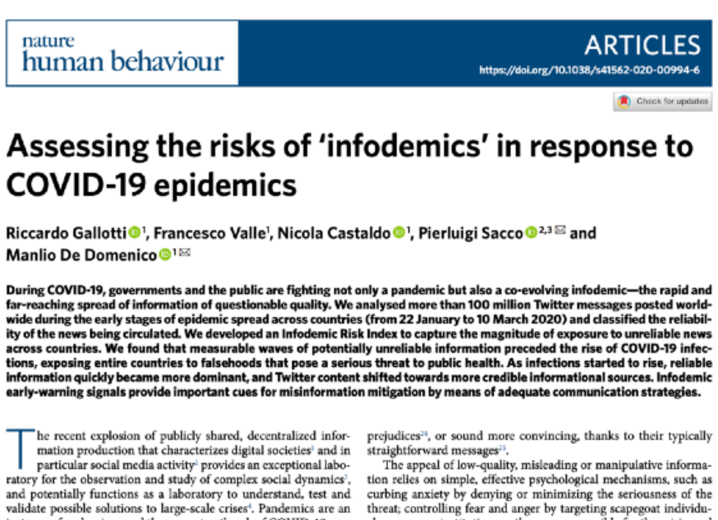
Leaky Integrate and Fire model by Philip Shiu et al.
Simulations of 3x Mi1 optic cells. Credits: Tyler Sloan

Schlegel et al, Nature (2024)

The “Online Sociosphere”



Social interactions in Jan-Apr 2020 among users writing about COVID-19 in the online platform Twitter.



nature human behaviour

ARTICLES

https://doi.org/10.1038/s41562-020-00994-6

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Assessing the risks of ‘infodemics’ in response to COVID-19 epidemics

Riccardo Gallotti[1], Francesco Valle[1], Nicola Castaldo[1], Pierluigi Sacco[2,3] and Manlio De Domenico[1]

During COVID-19, governments and the public are fighting not only a pandemic but also a co-evolving infodemic—the rapid and far-reaching spread of information of questionable quality. We analysed more than 100 million Twitter messages posted worldwide during the early stages of epidemic spread across countries (from 22 January to 10 March 2020) and classified the reliability of the news being circulated. We developed an Infodemic Risk Index to capture the magnitude of exposure to unreliable news across countries. We found that measurable waves of potentially unreliable information preceded the rise of COVID-19 infections, exposing entire countries to falsehoods that pose a serious threat to public health. As infections started to rise, reliable information quickly became more dominant, and Twitter content shifted towards more credible informational sources. Infodemic early-warning signals provide important cues for misinformation mitigation by means of adequate communication strategies.

The recent explosion of publicly shared, decentralized information production that characterizes digital societies[1] and in particular social media activity[2] provides an exceptional laboratory for the observation and study of complex social dynamics[3], and potentially functions as a laboratory to understand, test and validate possible solutions to large-scale crises[4]. Pandemics are an instance of such crises, and the current outbreak of COVID-19 may prejudices[24], or sound more convincing, thanks to their typically straightforward messages[25].

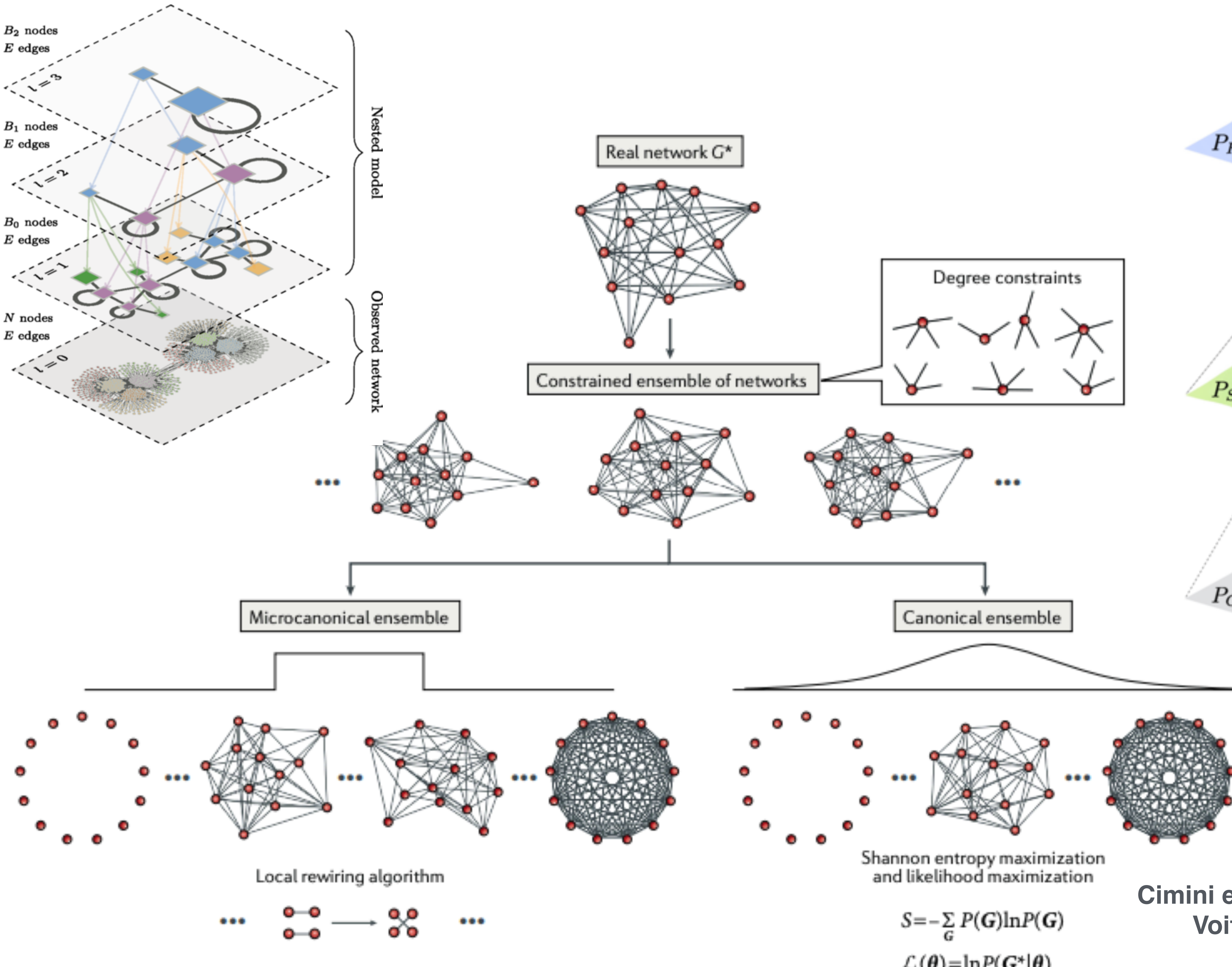
The appeal of low-quality, misleading or manipulative information relies on simple, effective psychological mechanisms, such as curbing anxiety by denying or minimizing the seriousness of the threat; controlling fear and anger by targeting scapegoat individuals, groups or institutions as the ones responsible for the crisis; and

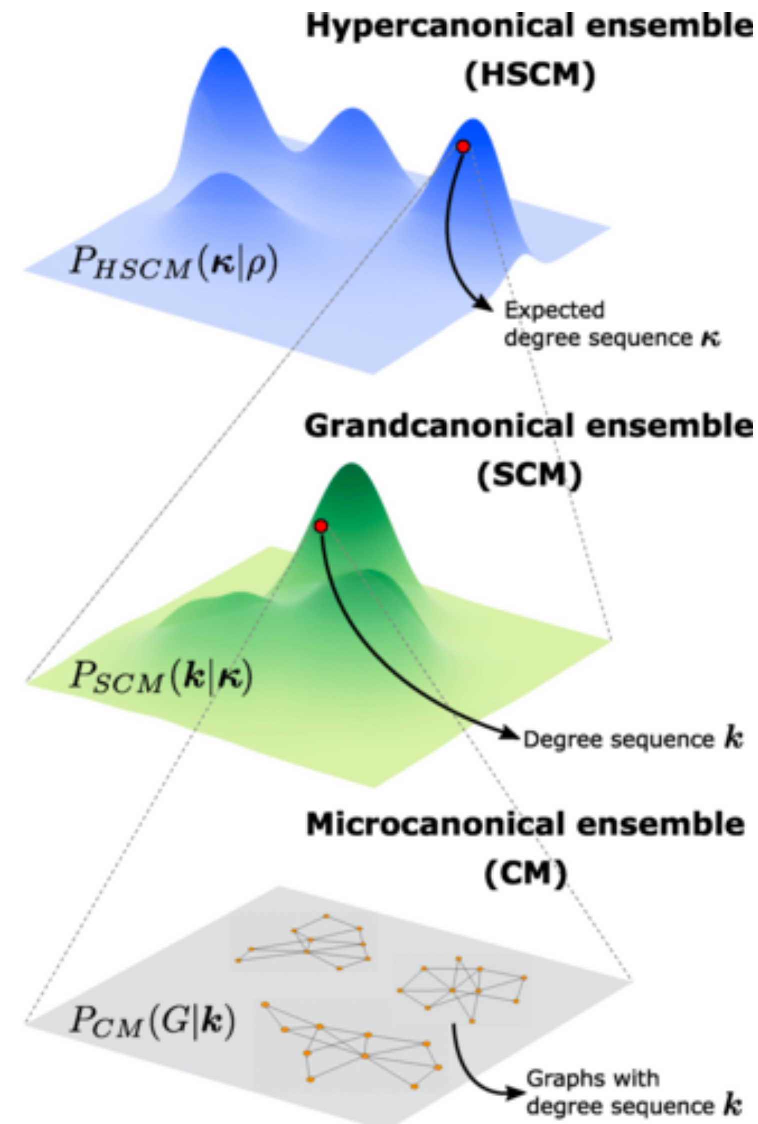
“*We found that measurable waves of potentially unreliable information preceded the rise of COVID-19 infections, exposing entire countries to falsehoods that* ***pose a serious threat to public health***”

Gallotti et al, Nature Human Behavior (2020)

Are data enough?

Making sense of complex data



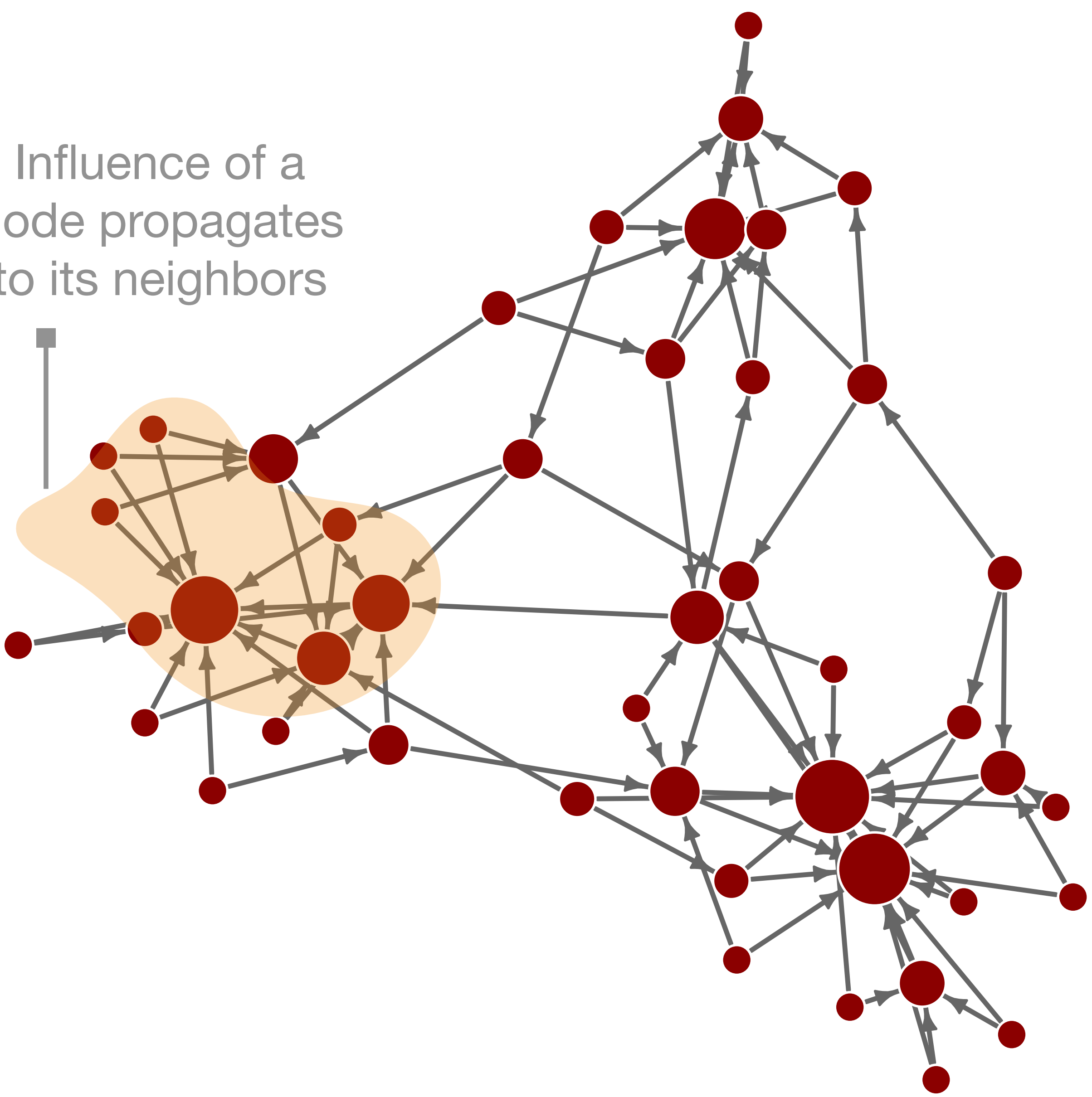


Peixoto, Phys. Rev. X (2014)
Cimini et al, Nature Rev. Physics (2019)
Voitalov et al, Phys Rev Res (2020)

Mapping interactions & reproducing behaviors

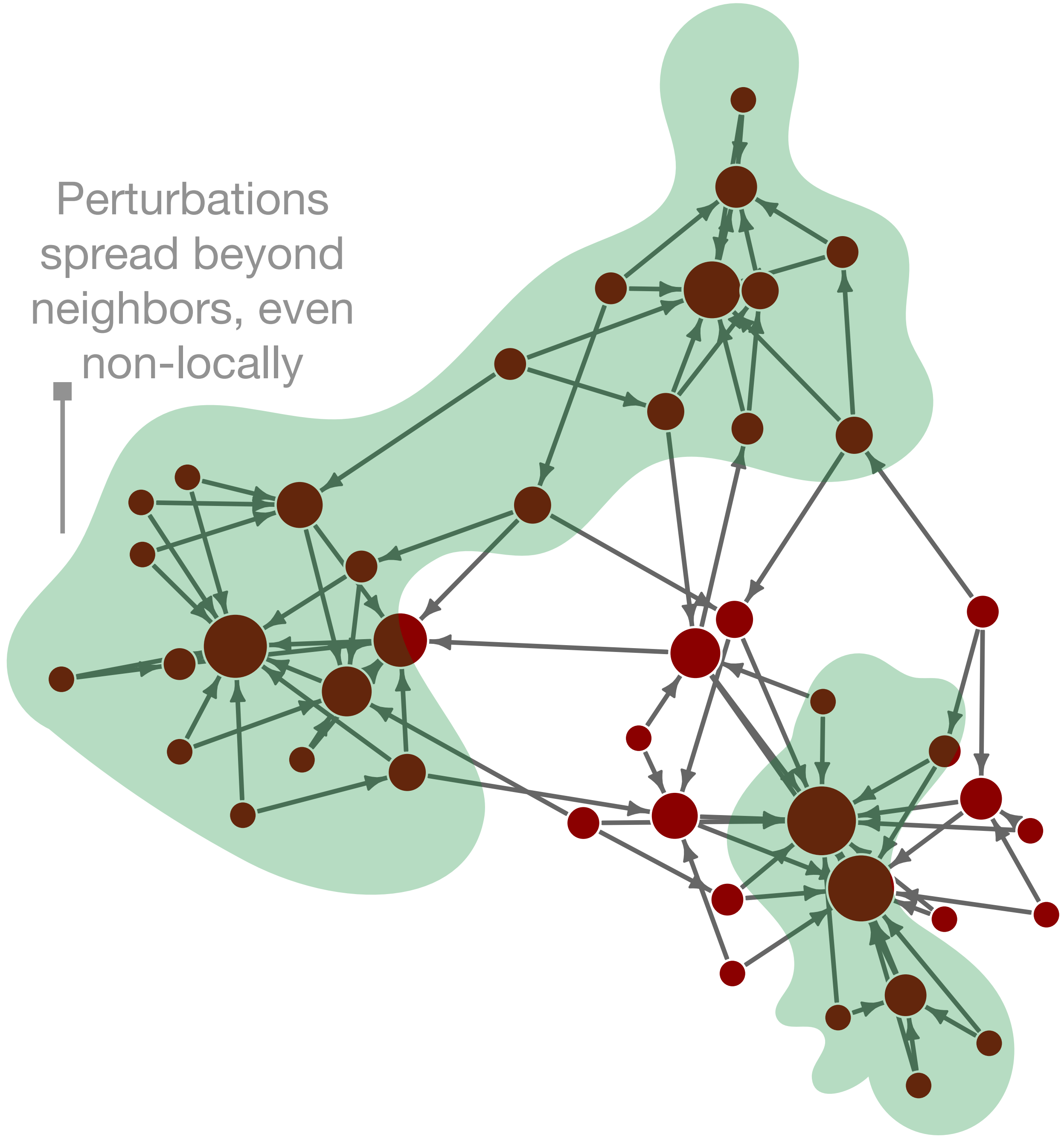
Topology

Influence of a node propagates to its neighbors

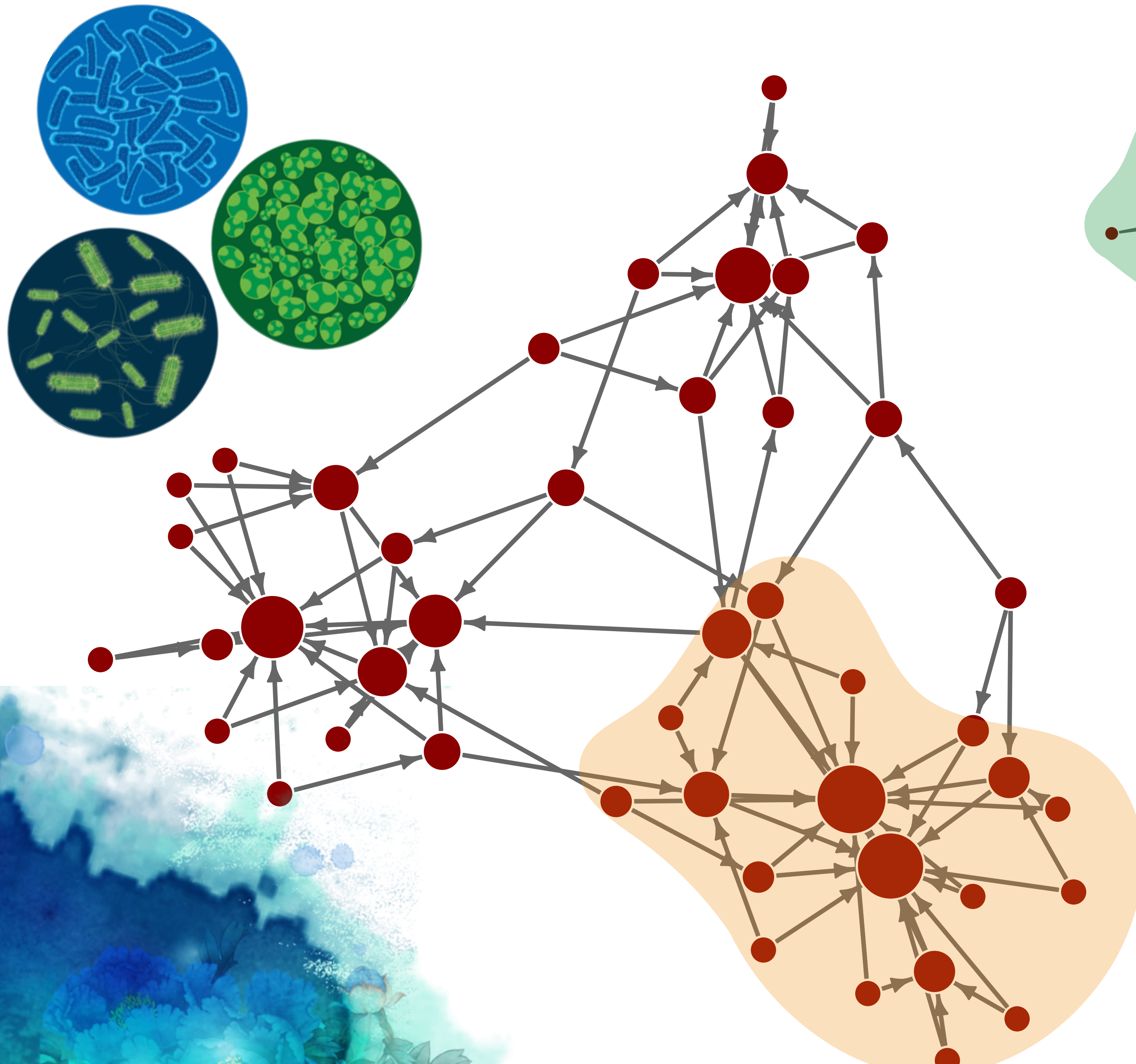


Dynamics

Perturbations spread beyond neighbors, even non-locally

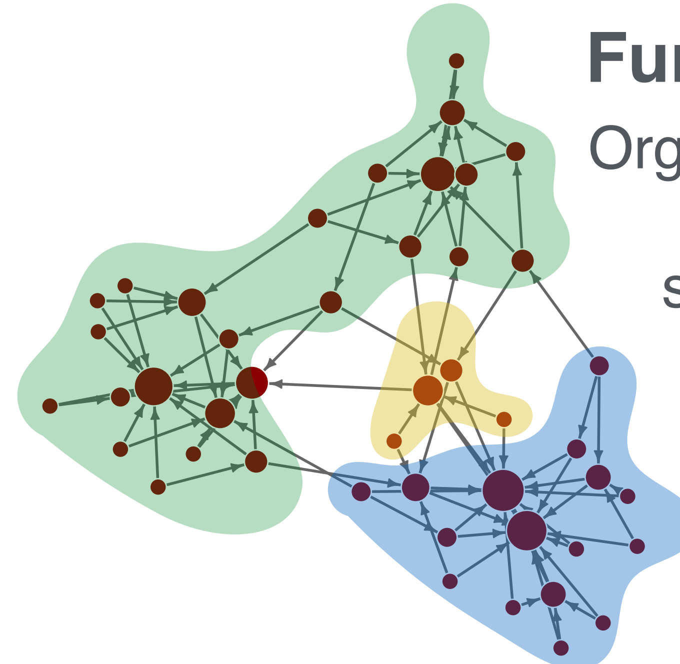


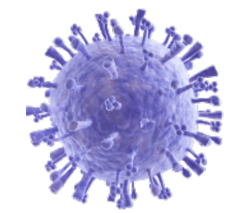
Structural & functional organization

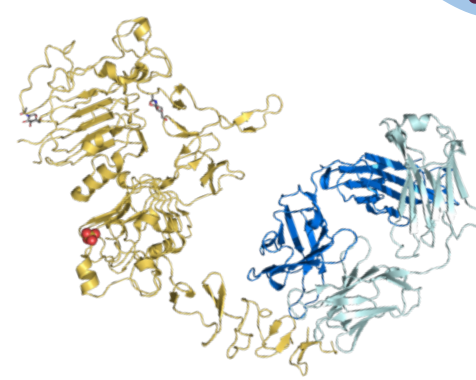


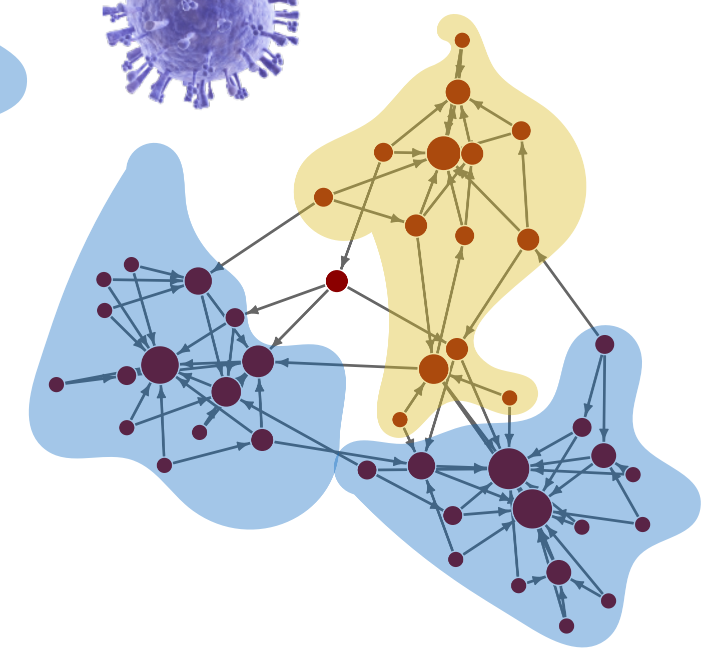
Functional Perspective

Organization depends on the interplay between structure and dynamics





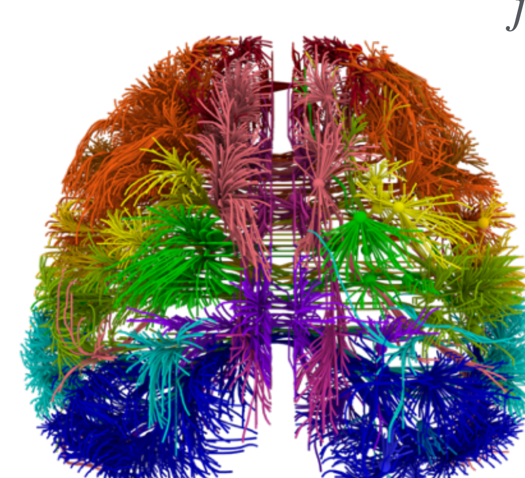


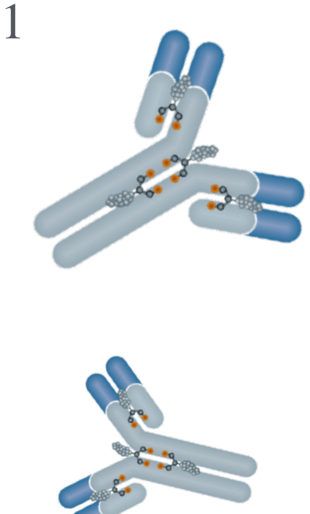


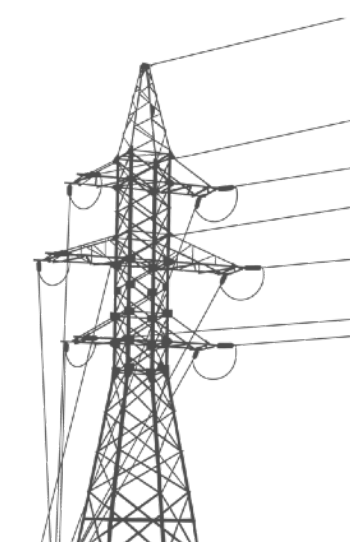
$$\dot{x}_i(t) = f_i(x_i) + \sigma \sum_{j=1}^{N} A_{ij}(t) g(x_i, x_j) + \eta_i(t)$$

Topological Perspective

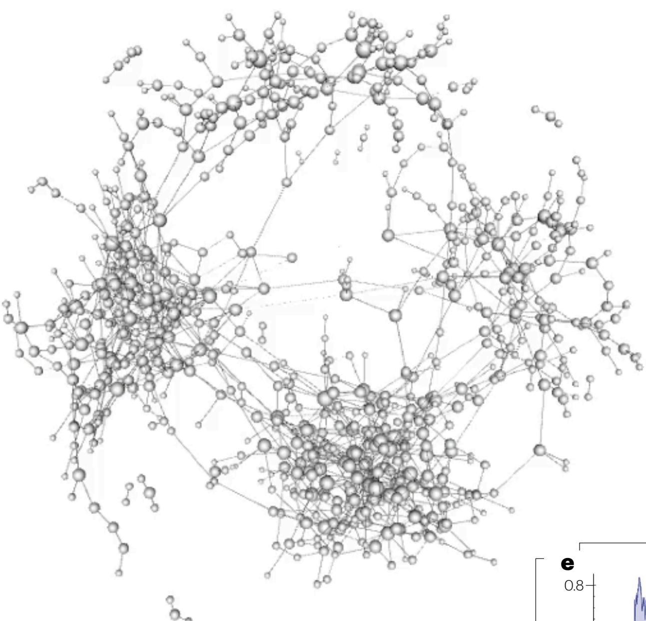
Organization depends only on structure

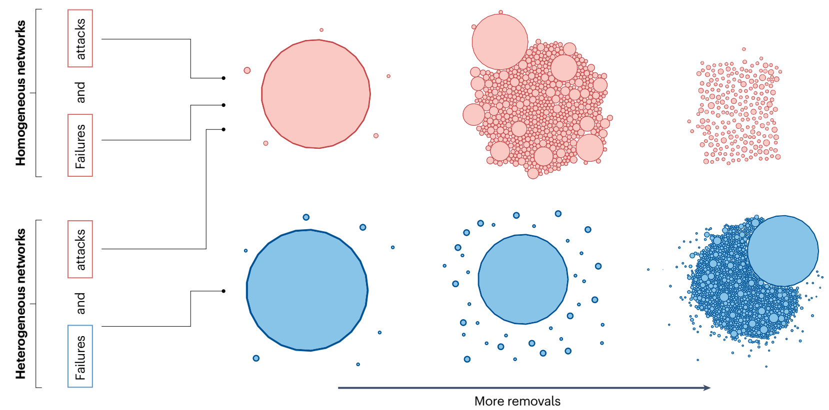


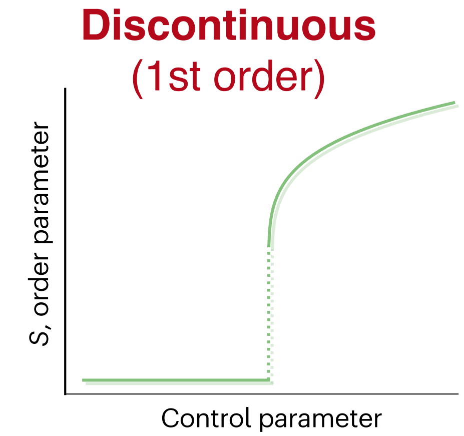


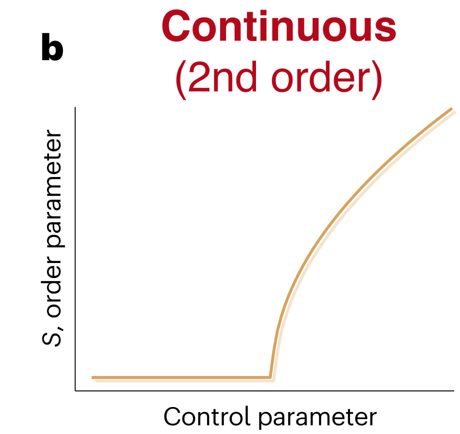


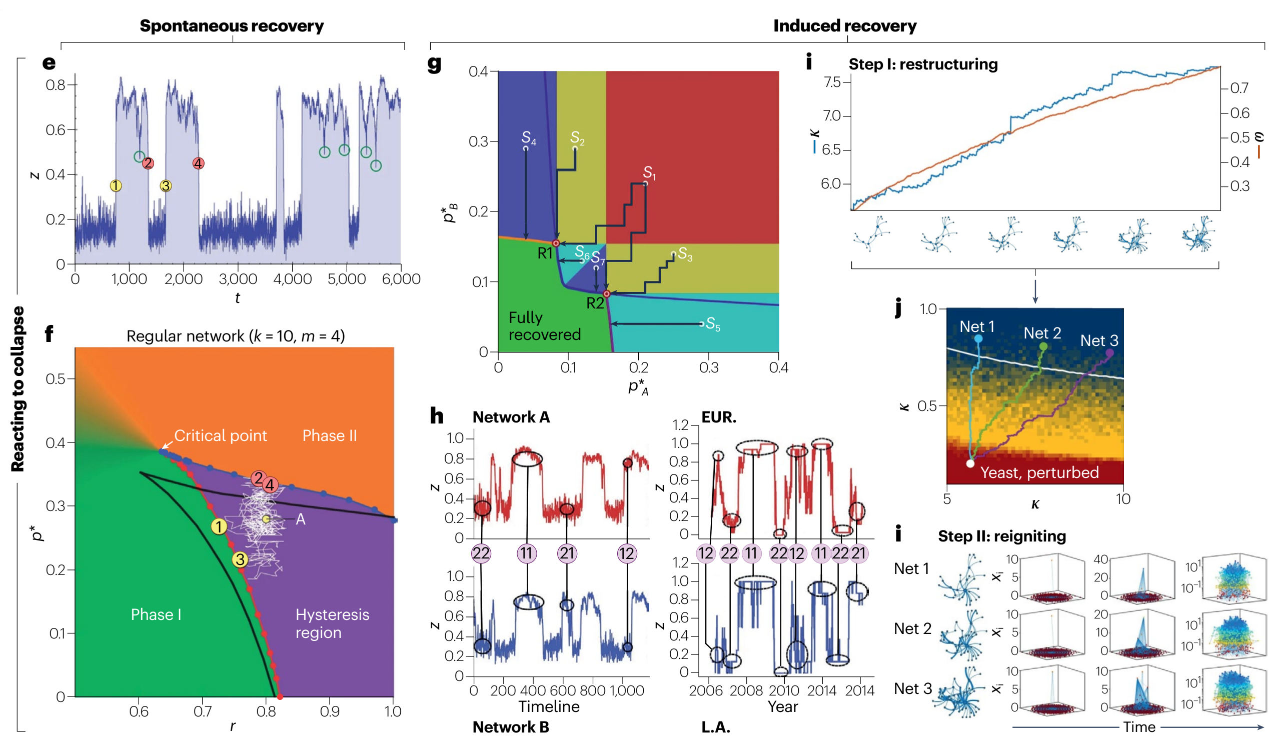
Robustness & resilience to perturbations

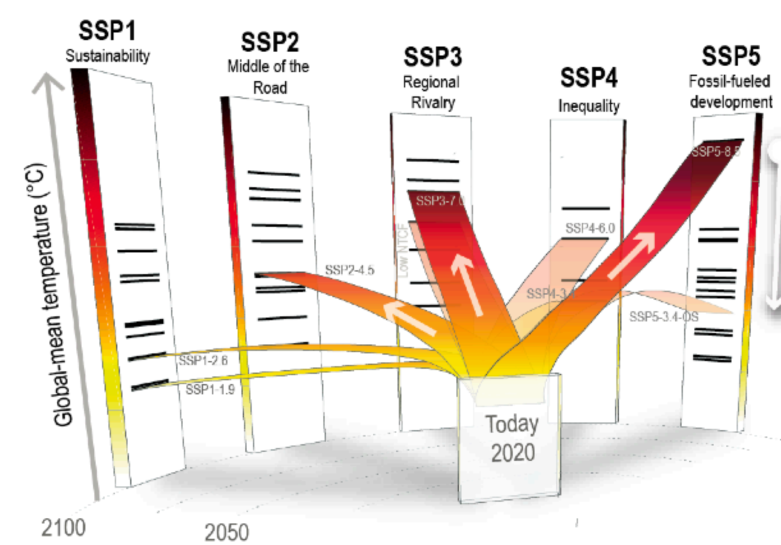






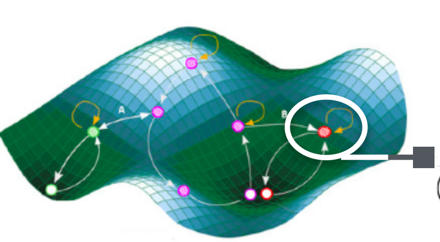


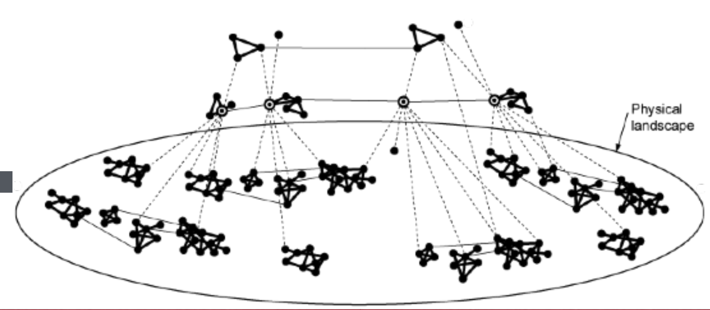




Majdandzic et al, Nature Phys (2014)
Nature Comms (2016)

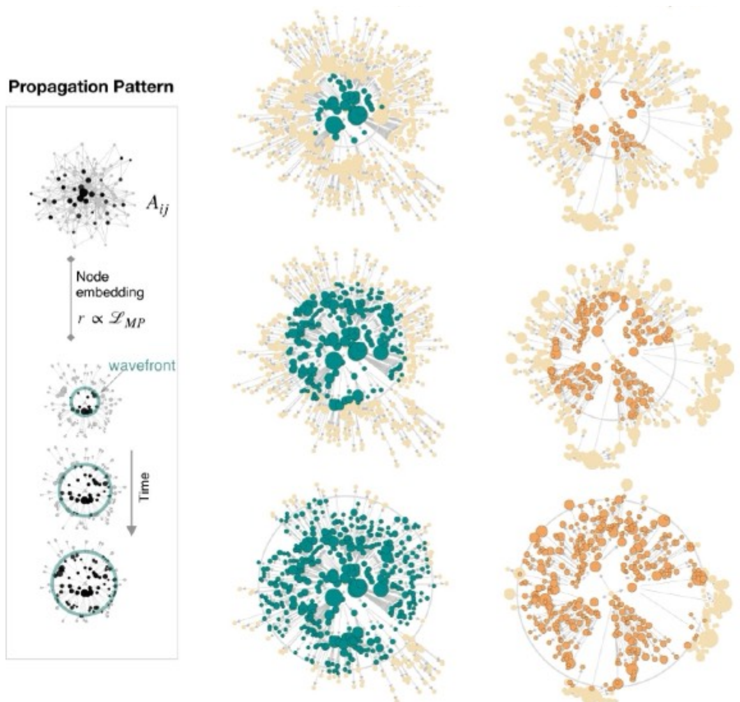
Sanhedrai et al, Nature Phys (2022)



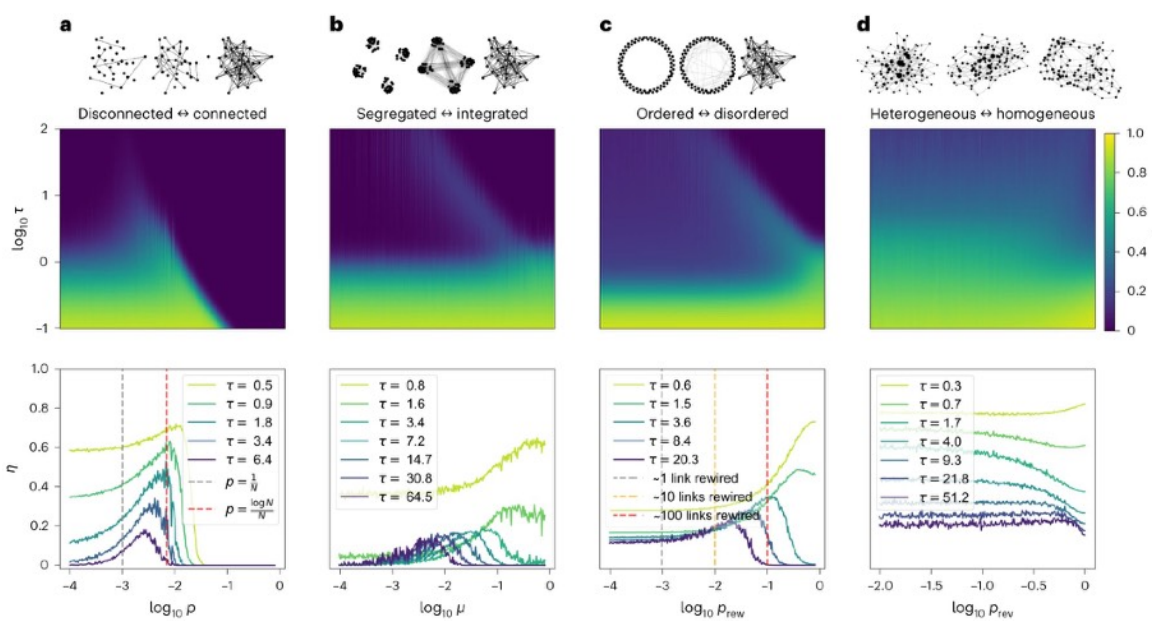


Artime et al, Nature Rev. Phys. (2024)
Cohen, Erez, ben-Avraham & Havlin, Phys. Rev. Lett. (2001)

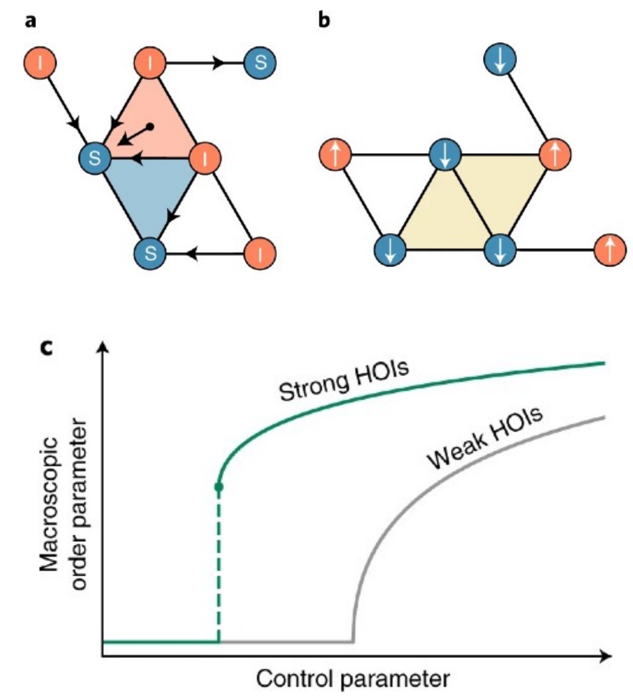
Geometry, field theories, RG, gen. thermodynamics, quantum information, HOI



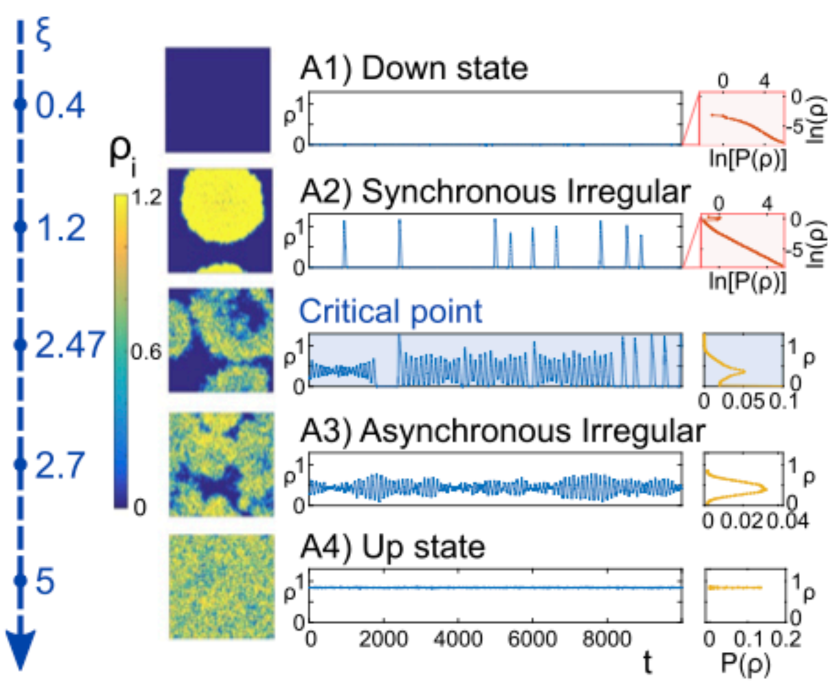
Hens et al, Nature Phys. (2019)
Bontorin & MDD, Comm. Phys. (2023)
Boguña et al, Nature Rev. Phys. (2021)



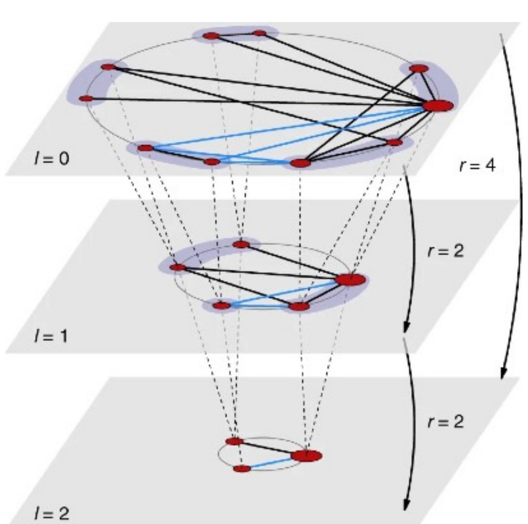
MDD & Biamonte, Phys. Rev. X (2016)
Ghavasieh & MDD, Nature Phys. (2024)

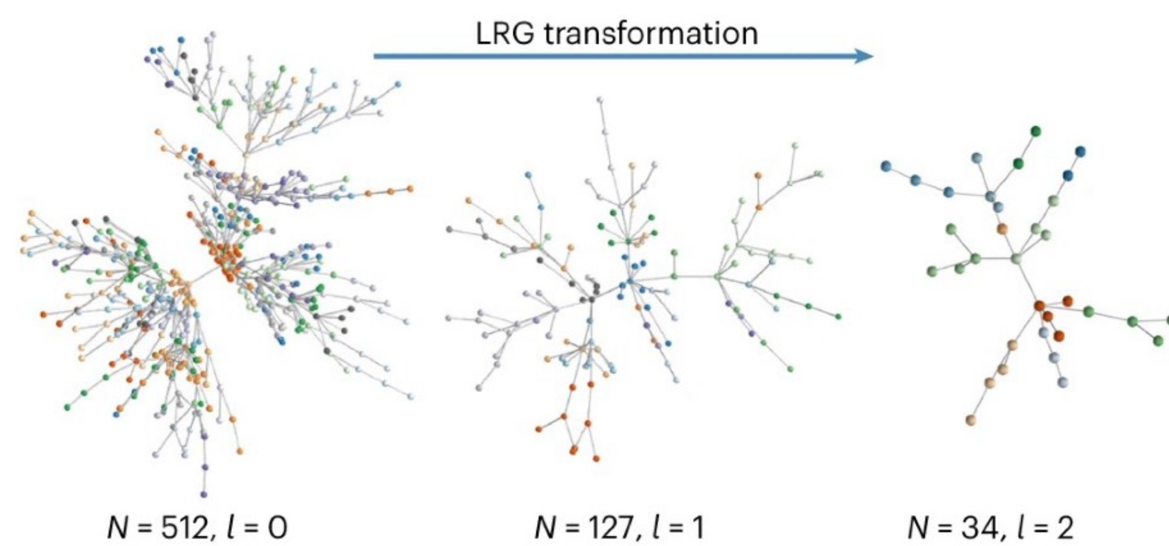


Battiston et al, Nature Phys. (2021)



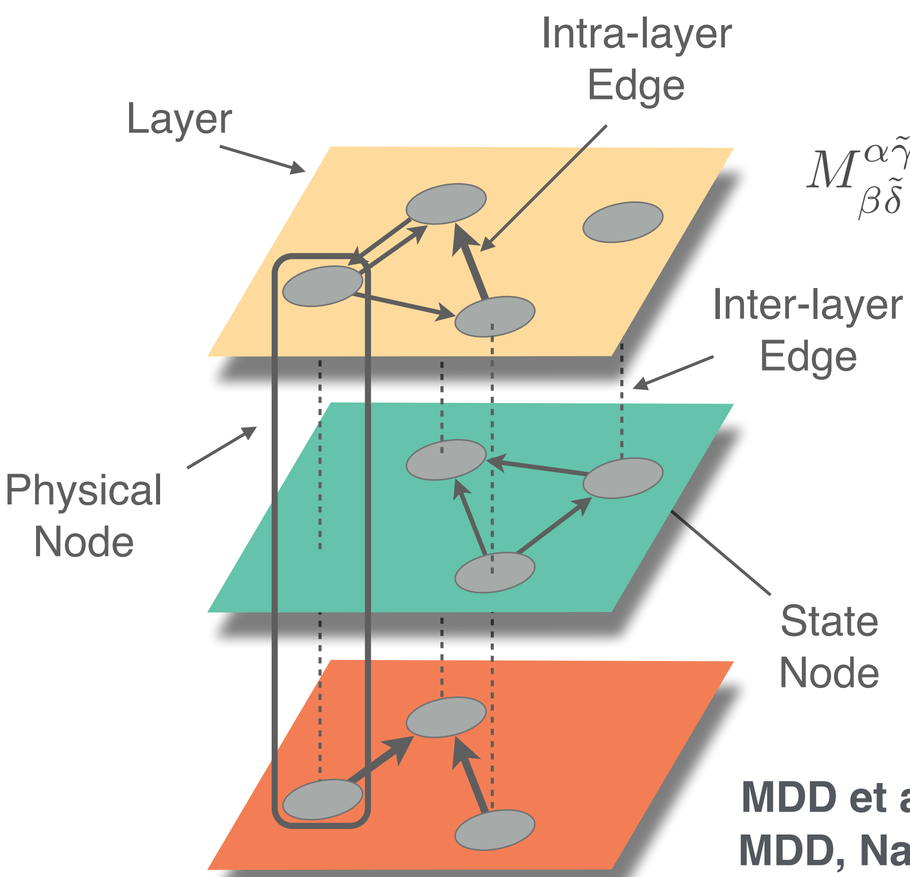
Di Santo, Villegas, Burioni & Muñoz, PNAS (2017)





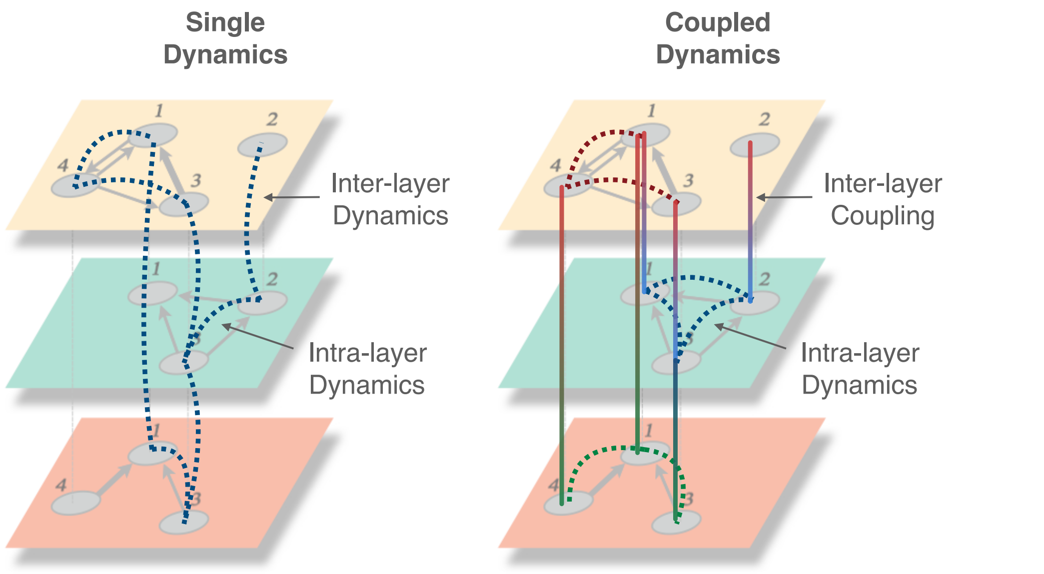
Garcia-Perez, Boguña & Serrano, Nature Phys. (2018)
Villegas et al, Nature Phys. (2023)

Mapping interdependency: systems of systems



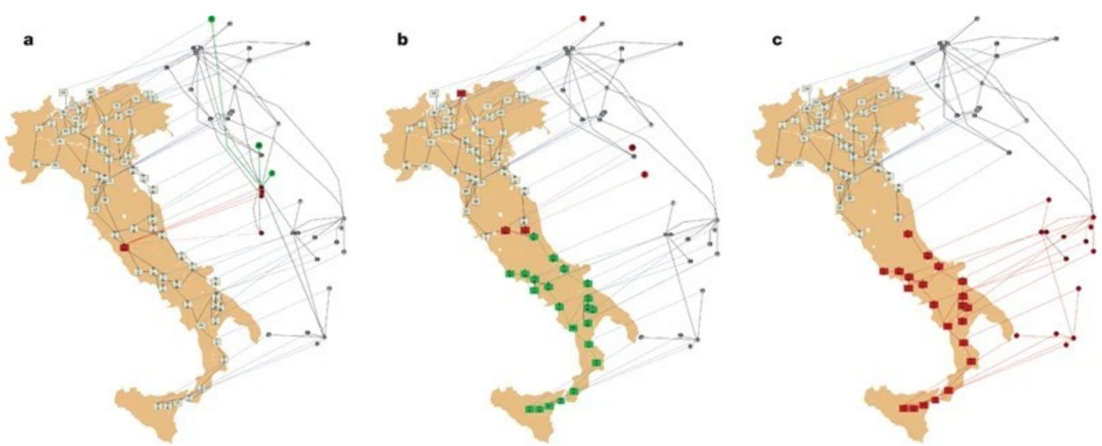
$$M^{\alpha\tilde{\gamma}}_{\beta\tilde{\delta}} = \sum_{\tilde{h},\tilde{k}=1}^{L} C^{\alpha}_{\beta}(\tilde{h}\tilde{k}) E^{\tilde{\gamma}}_{\tilde{\delta}}(\tilde{h}\tilde{k})$$

MDD et al, Phys Rev X (2013)
MDD, Nature Physics (2023)

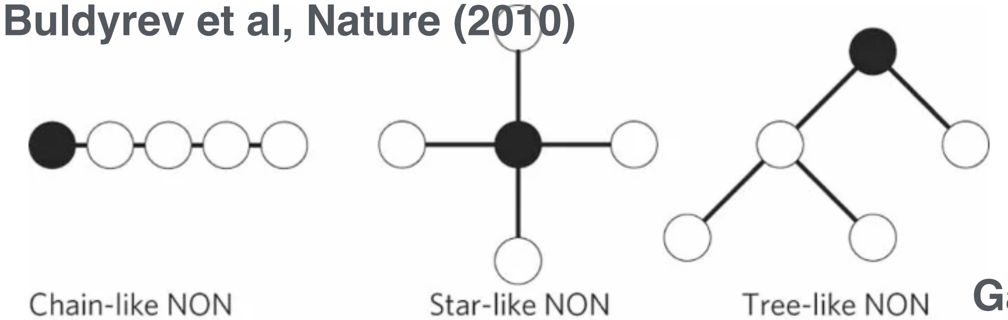


MDD, C. Granell, M. Porter, A. Arenas, Nature Physics (2016)

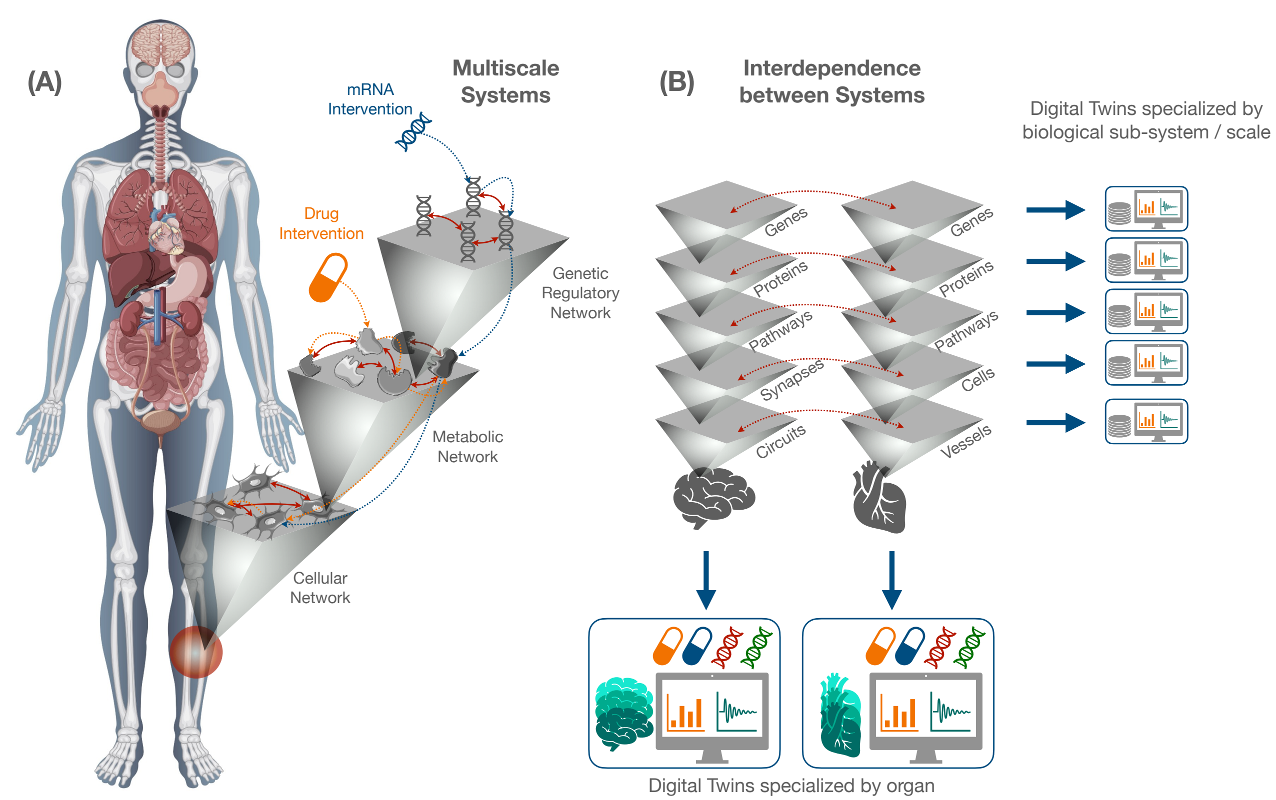
$$\dot{x}_{i,\alpha}(t) = f^{i\alpha}_{i\alpha}(X(t)) + \sum_{j\neq i} f^{j\alpha}_{i\alpha}(X(t)) + \sum_{\beta\neq\alpha}\sum_{j\neq i} f^{j\beta}_{i\alpha}(X(t)) + \sum_{\beta\neq\alpha} f^{i\beta}_{i\alpha}(X(t))$$



Buldyrev et al, Nature (2010)

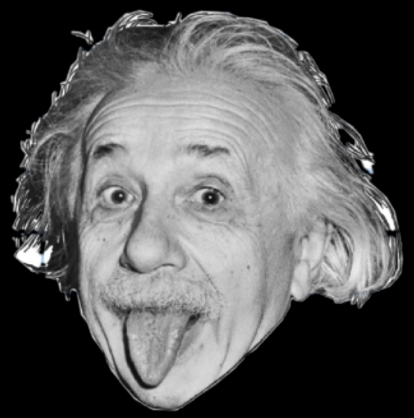


Gao et al, Nature Phys (2011)



WHAT
IS
PHYSICS?

Whatever physicists do.



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Networks Days: a collaborative platform for advancing network science

Manifesto

Do you feel there are plenty of opportunities for large, global events, but not enough small, local workshops dedicated to complex networks? Then you might want to organize your own local Networks Days!

"Networks Days" is a delocalized scientific workshop aimed at bringing together researchers, students, and professionals in the field of network science. The aim of these events is to foster open discussions about the latest advances and future directions of network research, with a strong focus on collective knowledge-building in an informal, yet academically rigorous, environment.

"Networks Days" promotes small-scale, interactive gatherings where every participant contributes to and benefits from in-depth exchanges of ideas. Anyone can organize a "Networks Days" event: the only requirement is to keep the minimum required format and gather the materials for this repository.

Key Features

- **Small, focused groups**: often "less is more". There are many venues for large meetings, in "Networks Days" the participation should be limited to 20-30 individuals to ensure that all attendees engage in meaningful discussions, fostering a close-knit environment for collaboration.
- **Autonomy in organization**: each "Networks Days" event is independently organized, but they all share a common goal of advancing network science and contributing to a collective knowledge repository. Workshops will be named `Networks Days - City MM/YYYY` to reflect their location and date.
- **International accessibility**: the entire workshop will be held in English to accommodate international participants and ensure that shared materials are accessible to a global audience. Each event will have its own repository named following the format `YYYY-MM-City`.
- **Flexible format**: the workshop is designed to unfold over a whole day. As a general recommendation, consider to include a night between two consecutive sessions: this is expected to promote more informal interaction and enhance collaboration. At least one session should be fully open to local students and network enthusiasts.
- **Closed-door session**: a part of the workshop might be reserved for invited speakers to engage in closed-door discussions focused on potential collaborations and research synergies. This private session is essential for generating practical ideas for future work.

Building collective knowledge

HFSP International Human Frontier Science Program Organization

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