Informational and topological signatures of individuality and age

Giovanni Petri
IPAM MAC-2024

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at Northeastern University

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Higher-order signatures of individuality and age

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Higher-order signatures of individuality ~~and age~~

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What is topology?

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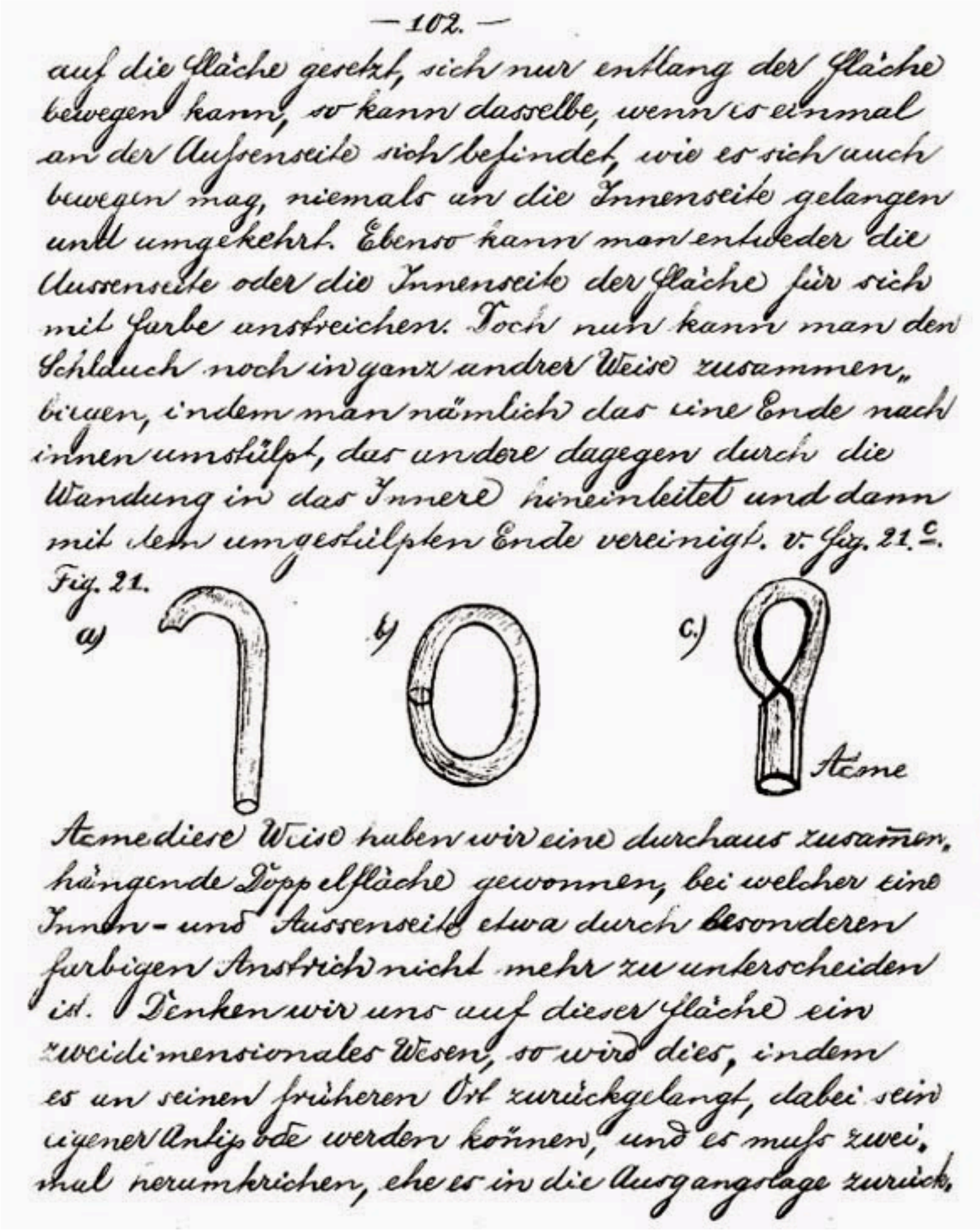
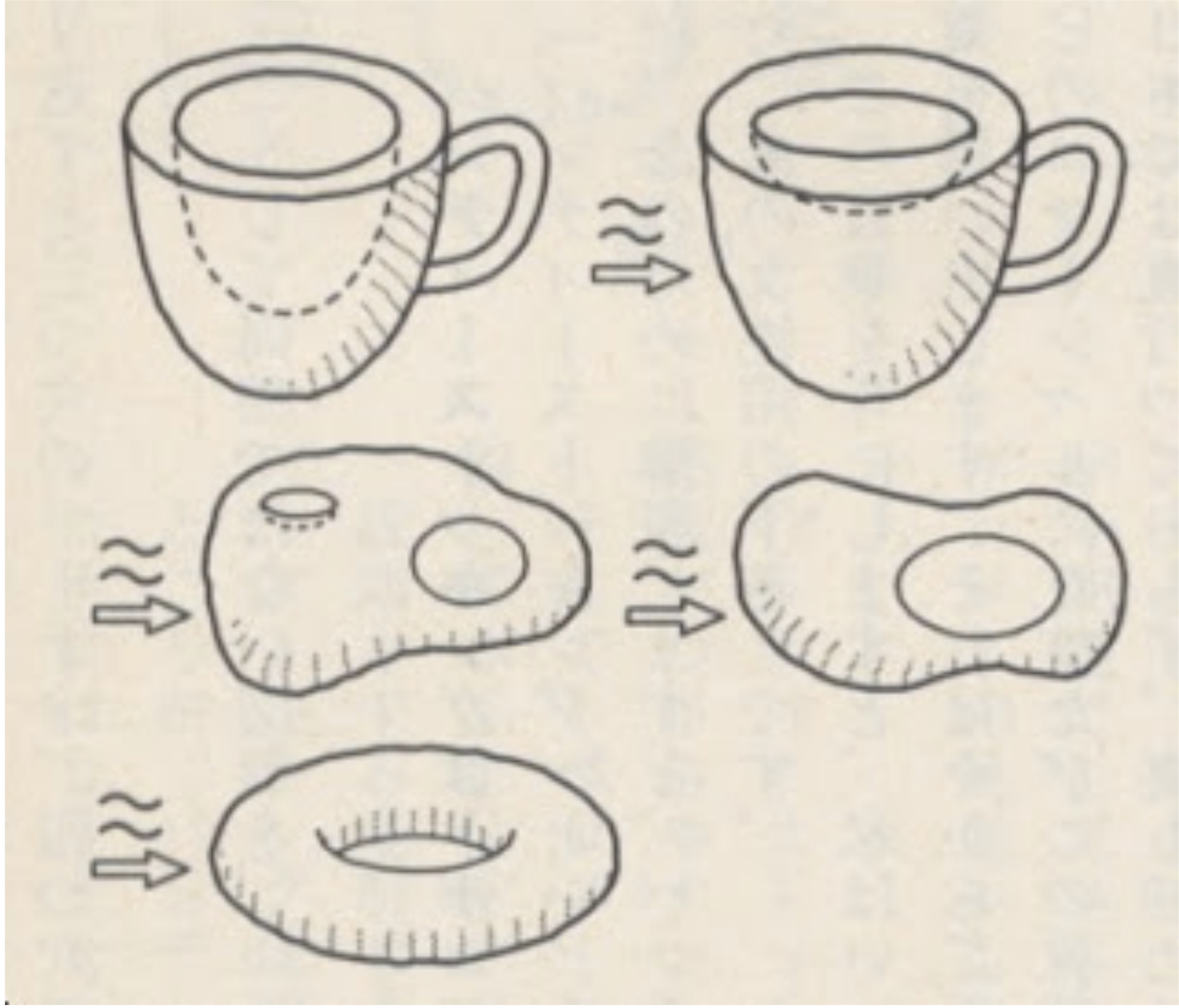


— 102. —

auf die Fläche gesetzt, sich nur entlang der Fläche bewegen kann, so kann dasselbe, wenn es einmal an der Außenseite sich befindet, wie es sich auch bewegen mag, niemals an die Innenseite gelangen und umgekehrt. Ebenso kann man entweder die Aussenseite oder die Innenseite der Fläche für sich mit Farbe anstreichen. Doch nun kann man den Schlauch noch in ganz andrer Weise zusammenbiegen, indem man nämlich das eine Ende nach innen umstülpt, das andere dagegen durch die Wandung in das Innere hineinleitet und dann mit dem umgestülpten Ende vereinigt. v. Fig. 21.c.

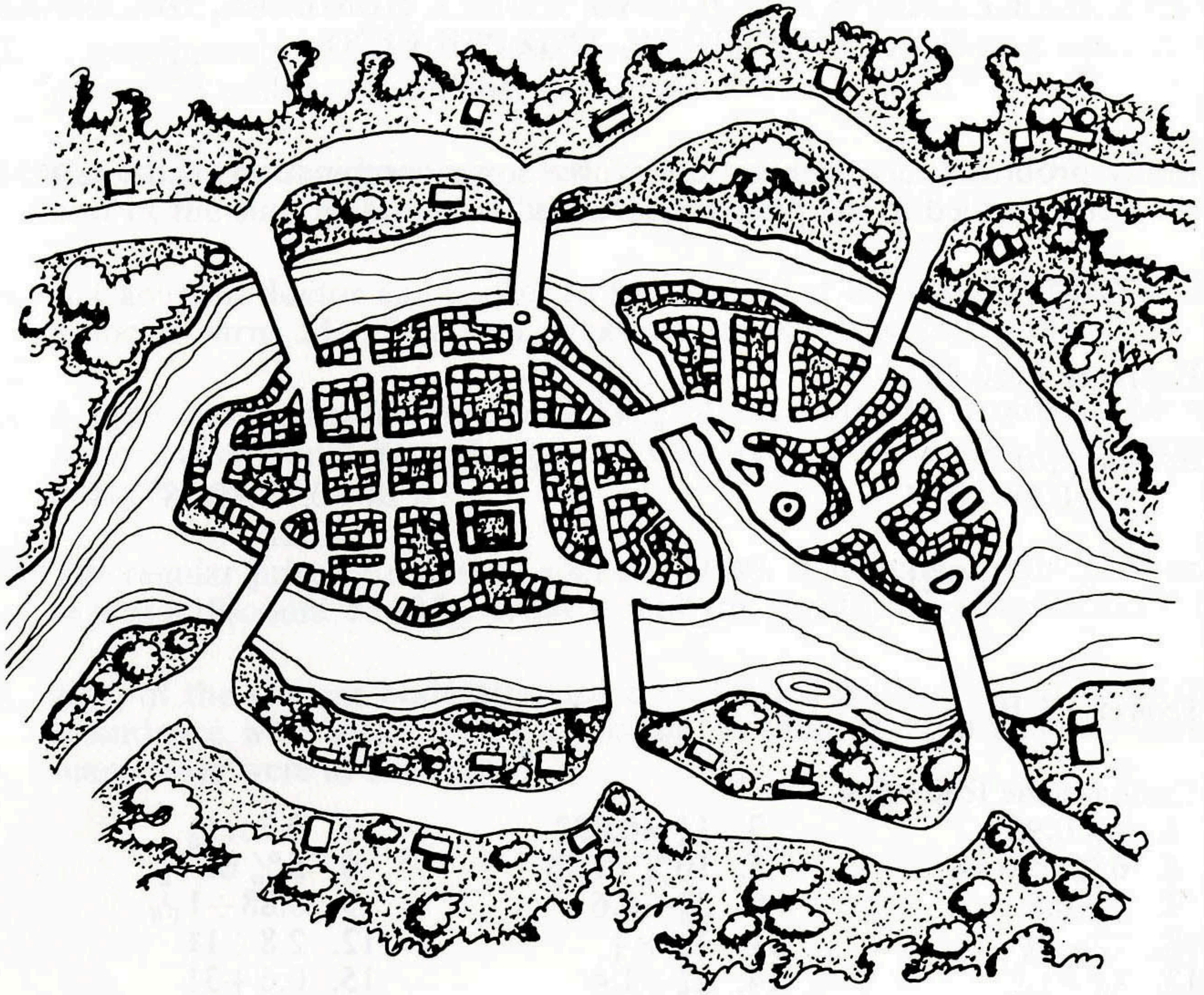
Fig. 21. a) b) c)

Auf diese Weise haben wir eine durchaus zusammenhängende Doppelfläche gewonnen, bei welcher eine Innen- und Aussenseite etwa durch besonderen farbigen Anstrich nicht mehr zu unterscheiden ist. Denken wir uns auf dieser Fläche ein zweidimensionales Wesen, so wird dies, indem es an seinen früheren Ort zurückgelangt, dabei sein eigenes Antipode werden können, und es muß zweimal herumkriechen, ehe es in die Ausgangslage zurück.



What is topology?

THE BRIDGES OF KONIGSBERG



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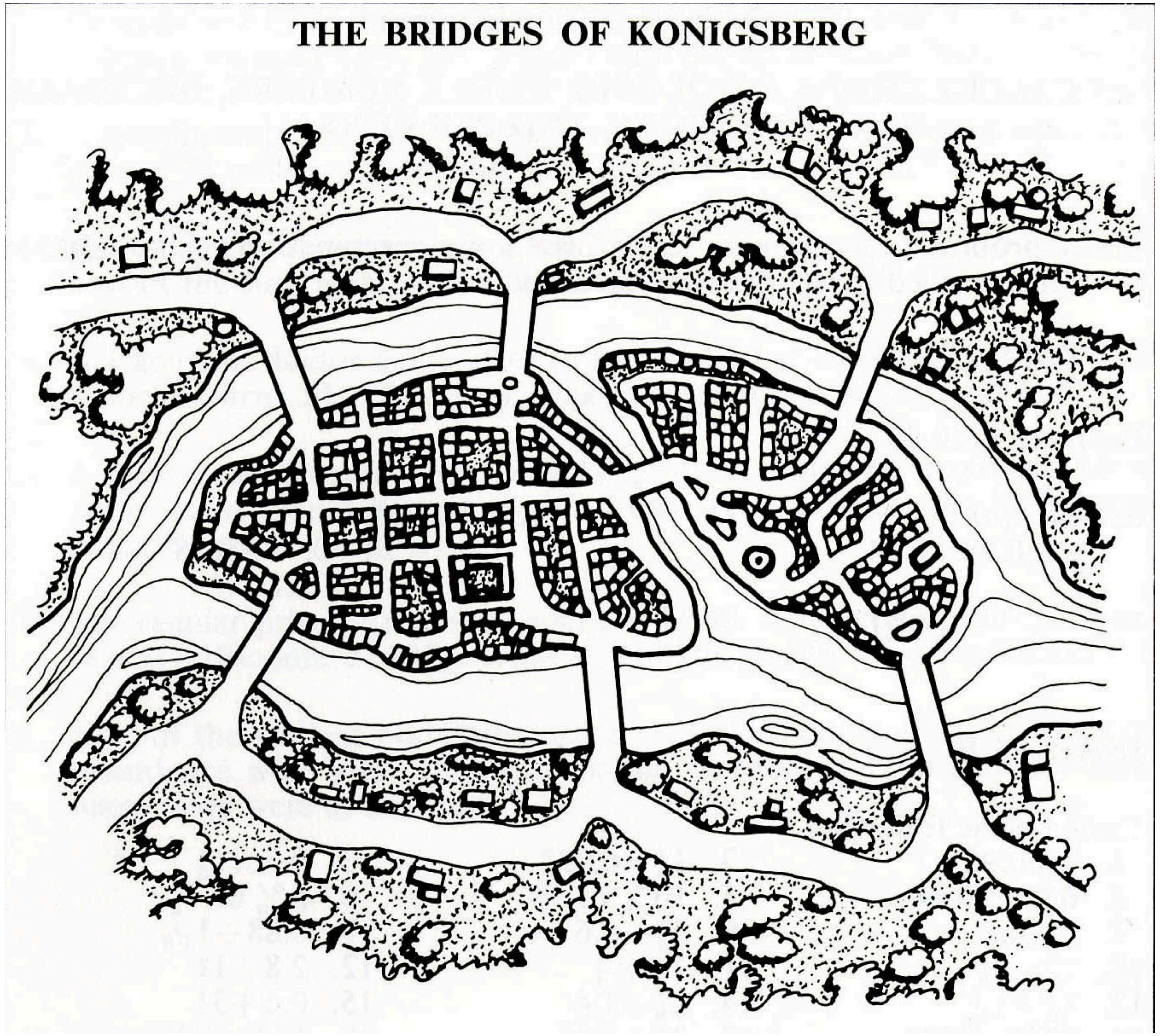

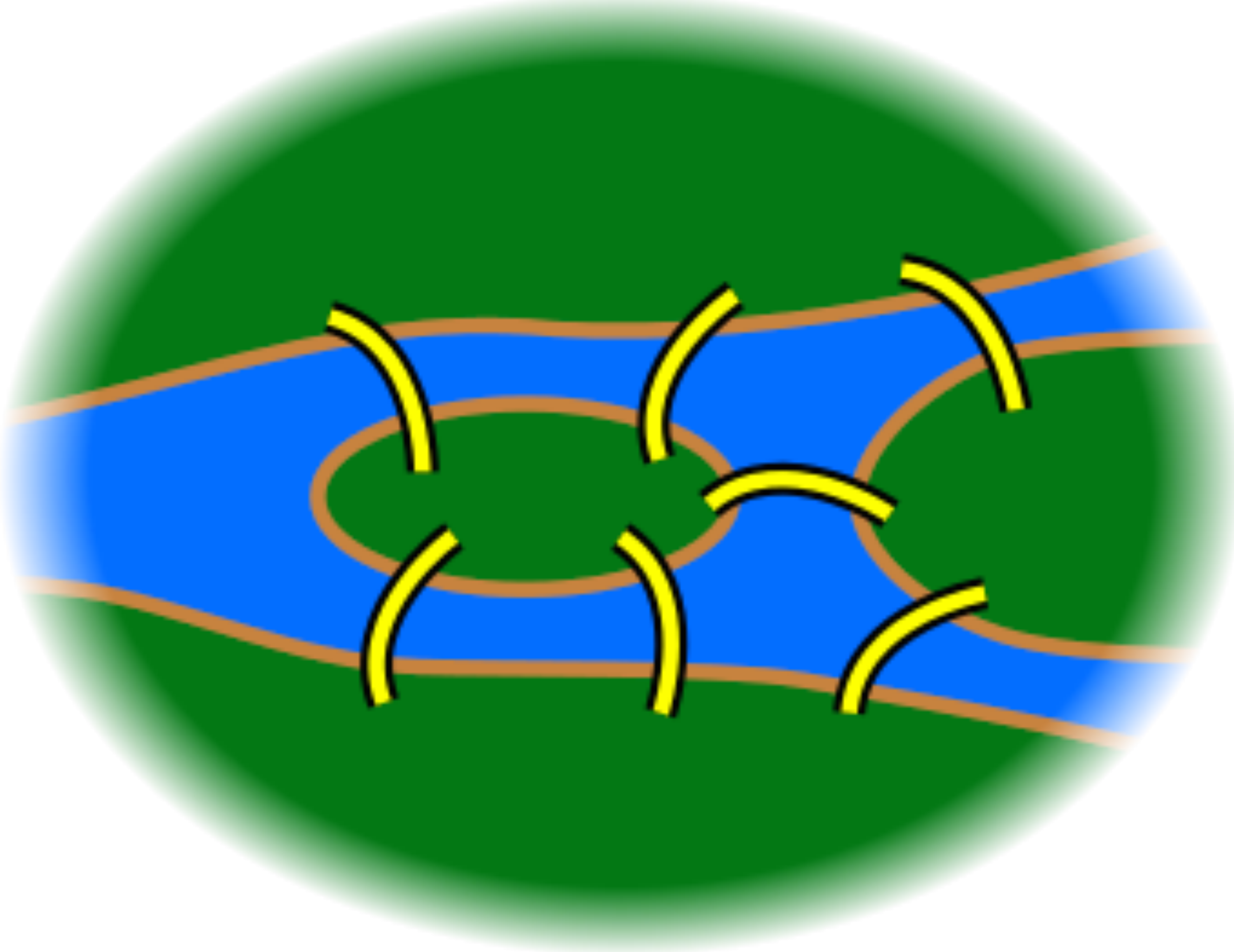

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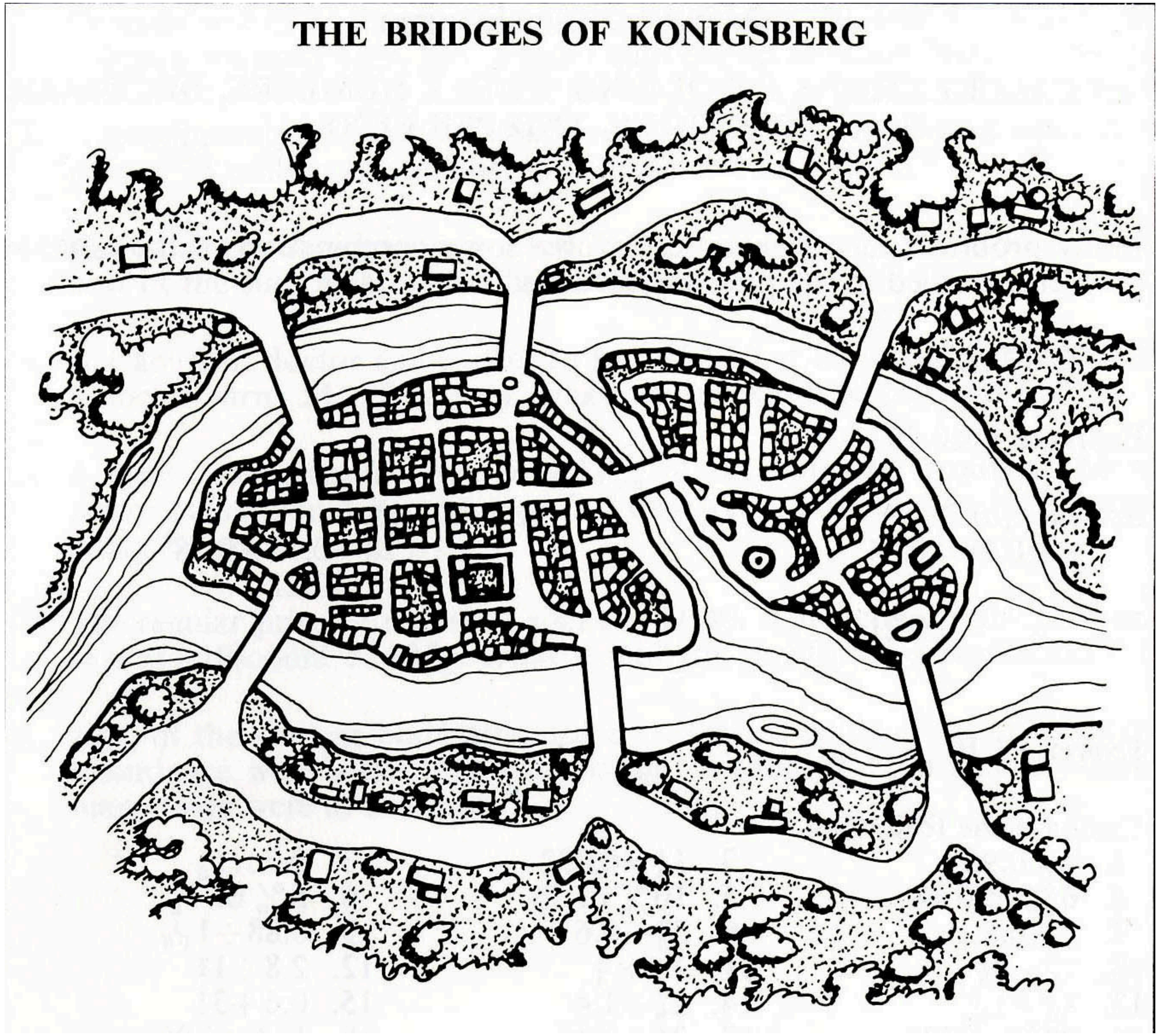

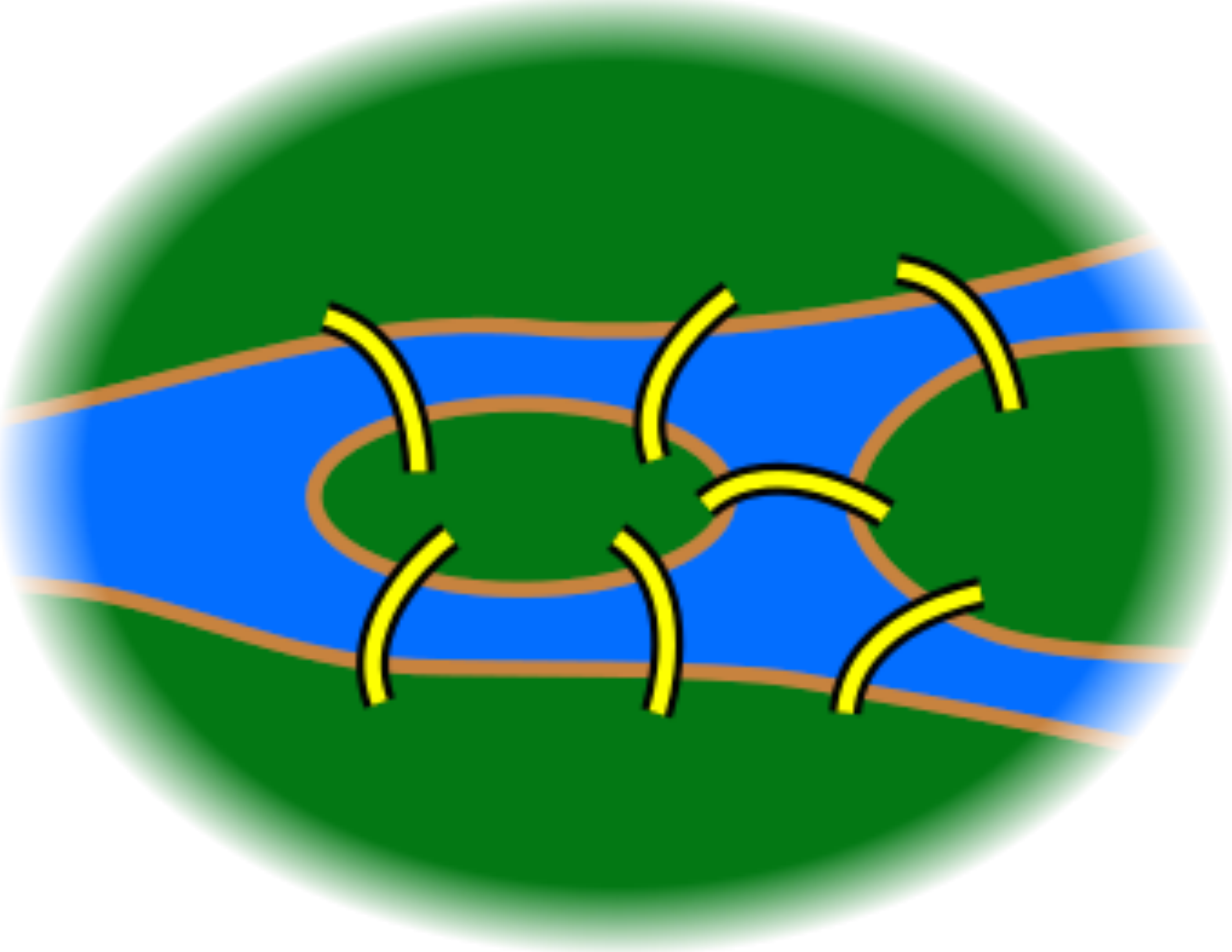

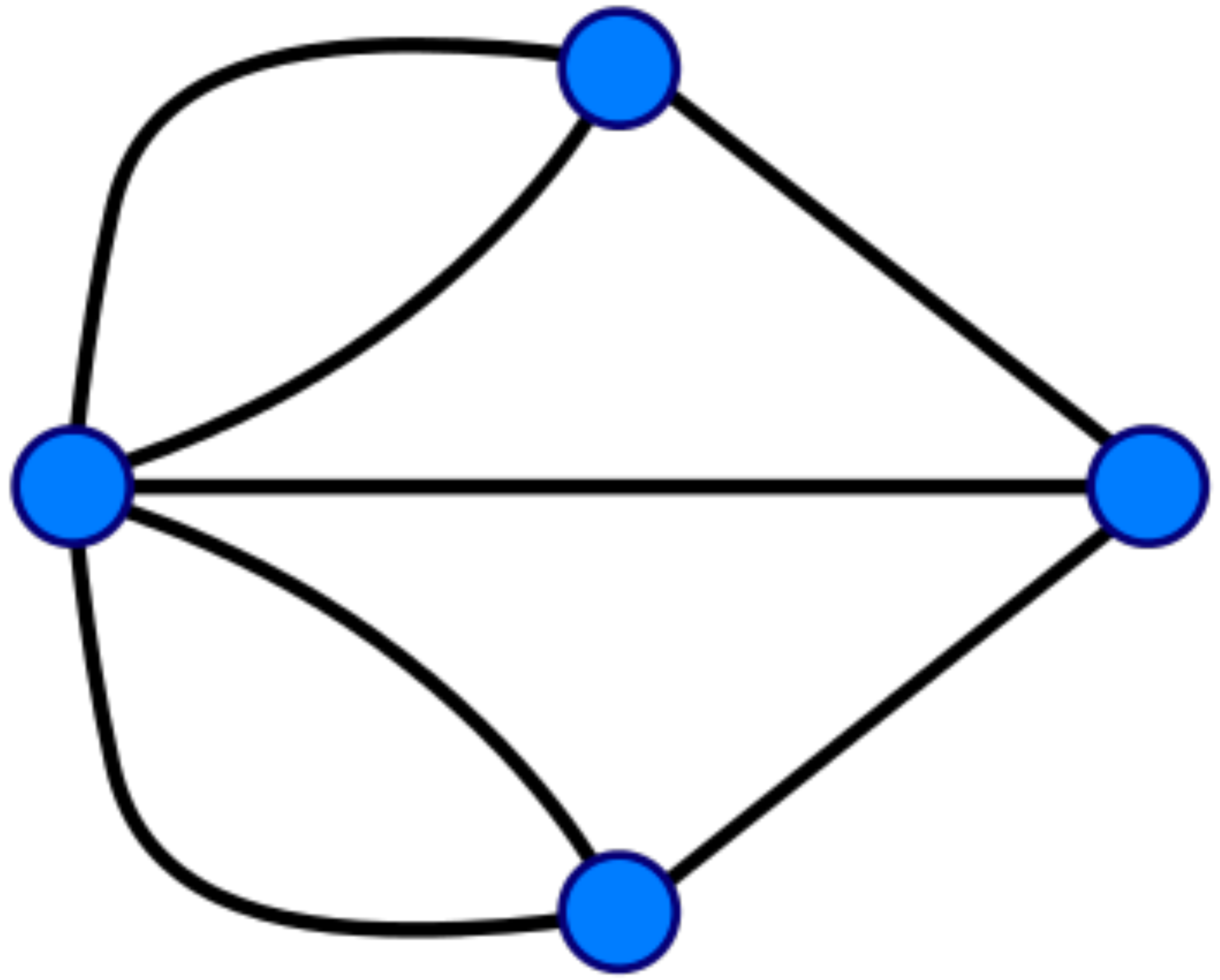

Why topology?

DOT
= 0-simplex

EDGE =
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Ghrist, R. (2008). Barcodes: The persistent topology of data. *Bulletin-American Mathematical Society*, *45*(1), 61.

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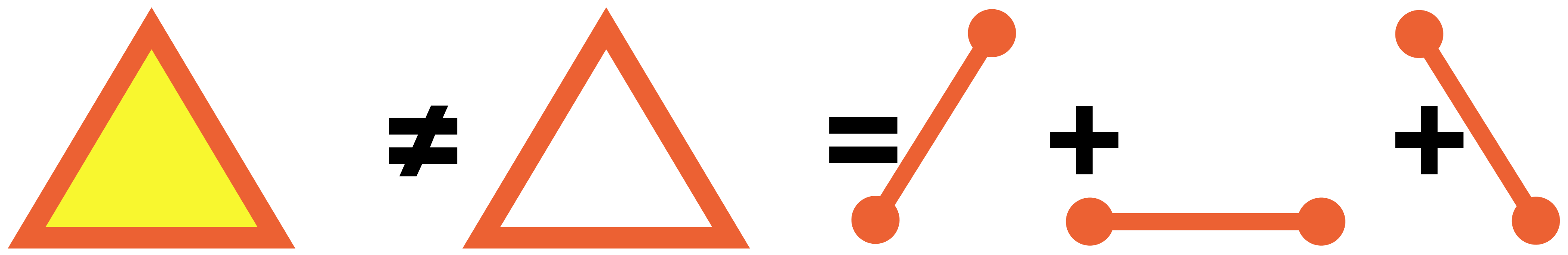

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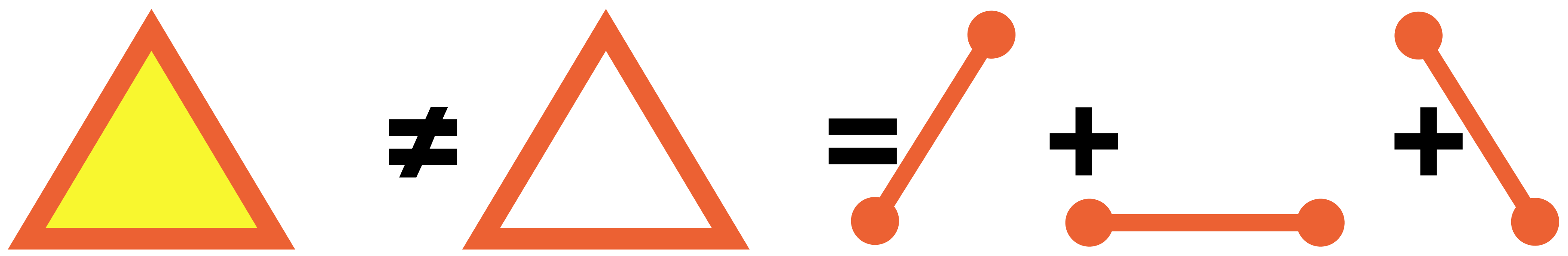

Definition of k-simplex

$$\sigma = [p_0, p_1, p_2, \ldots, p_k]$$

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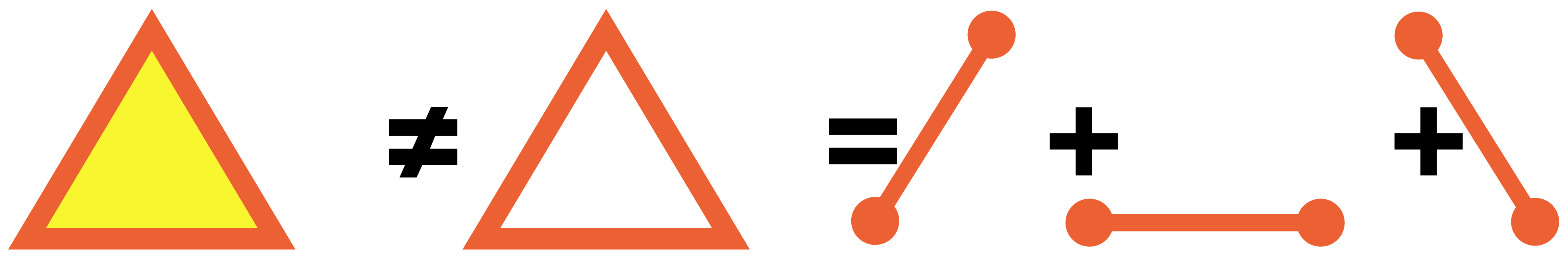

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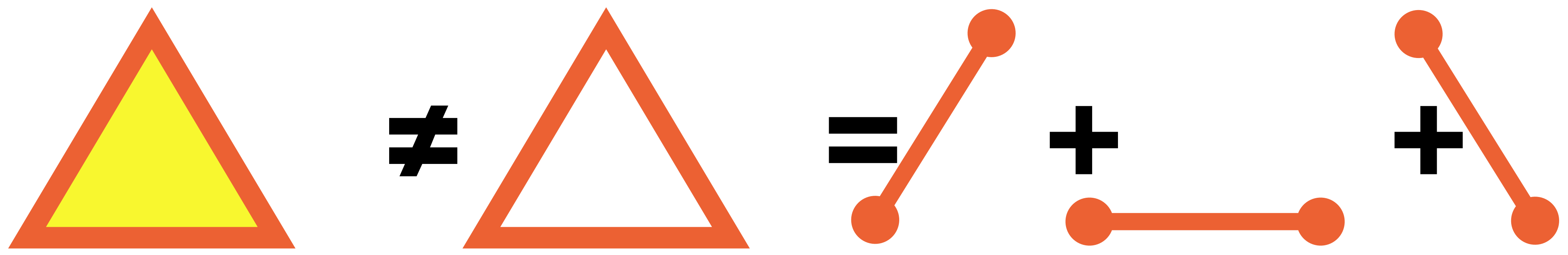

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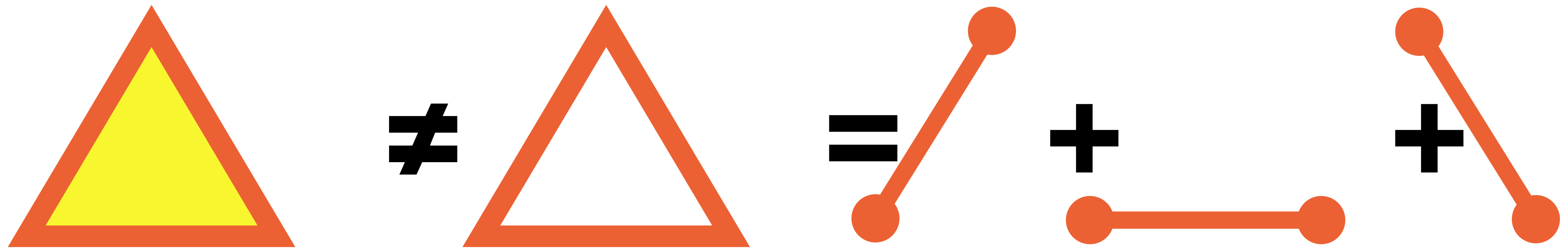
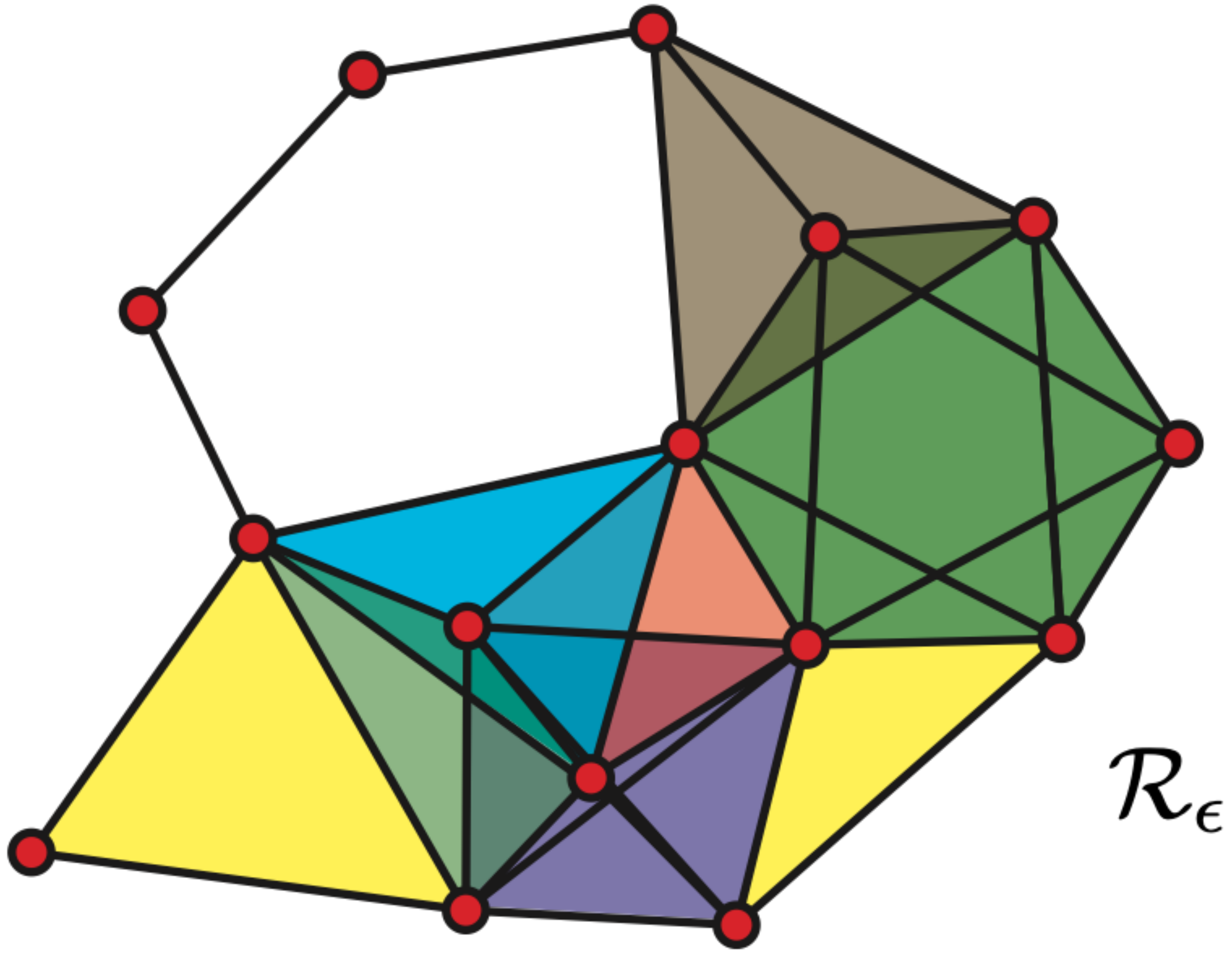


Simplicial Complex



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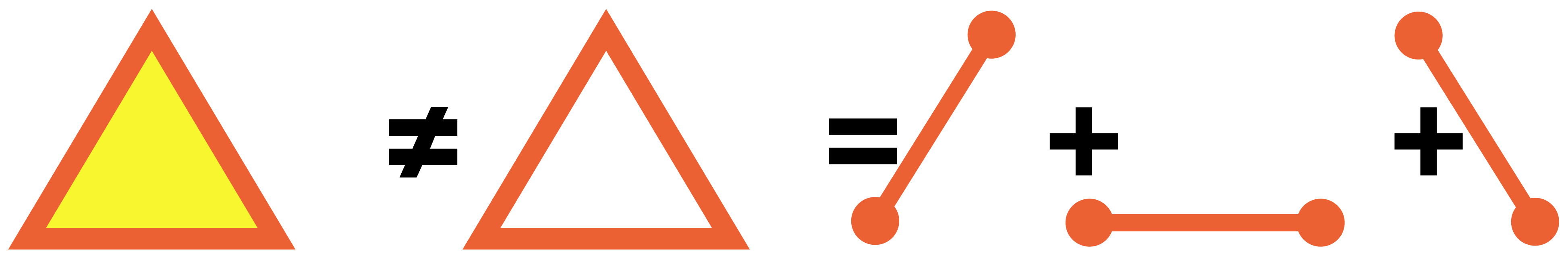
TRIANGLE = 2-simplex 

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Topology in the wild

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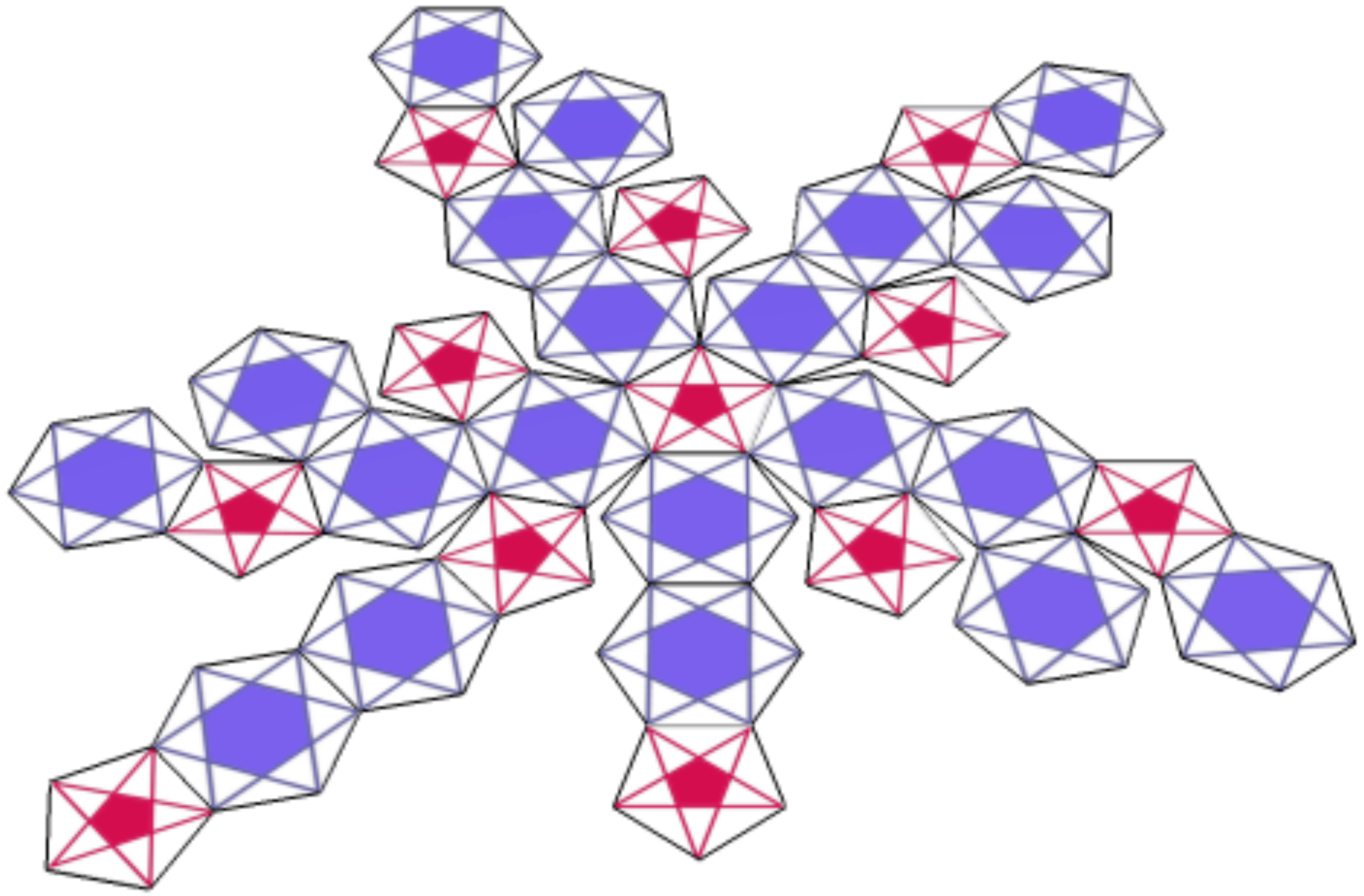

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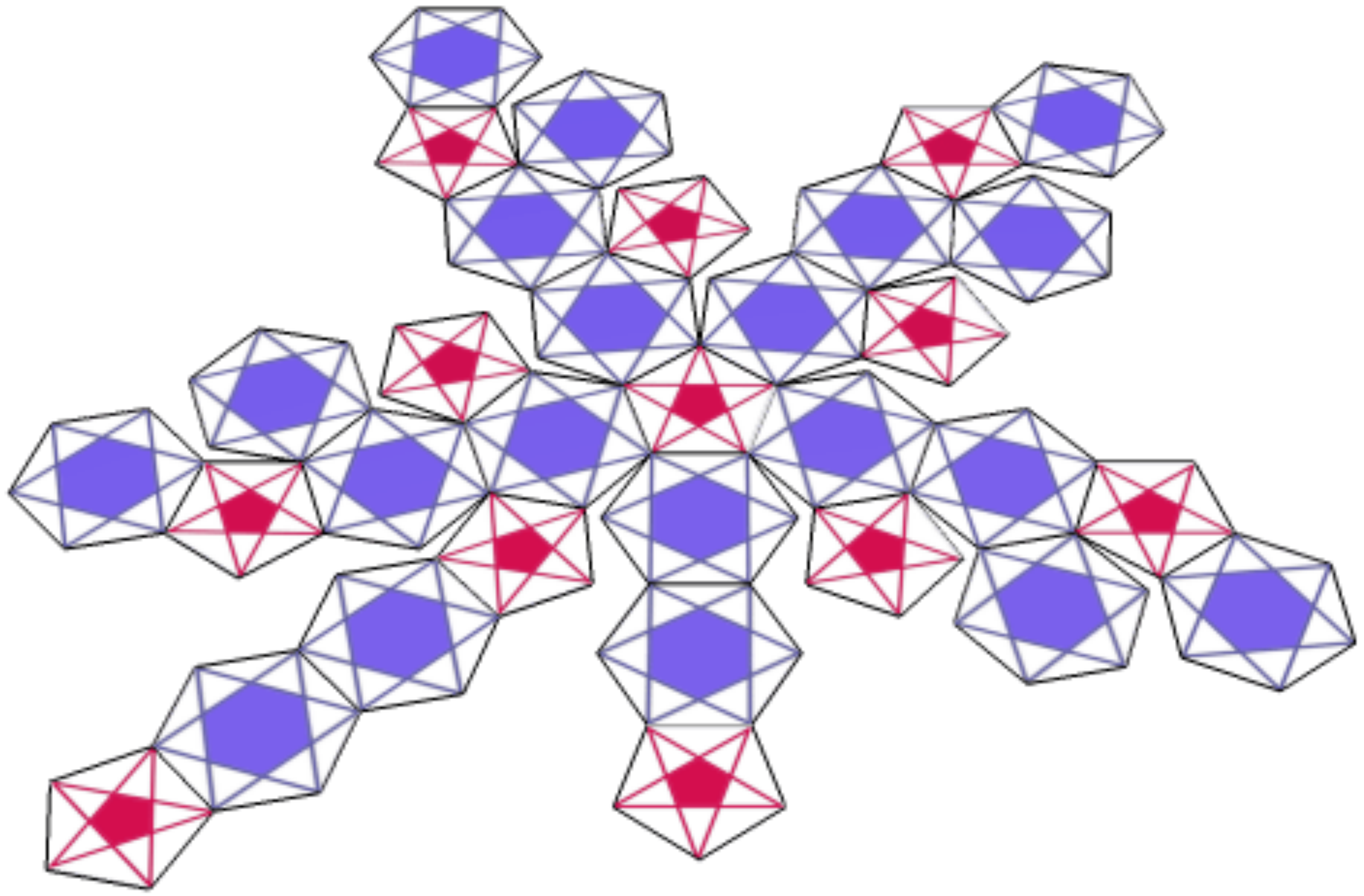

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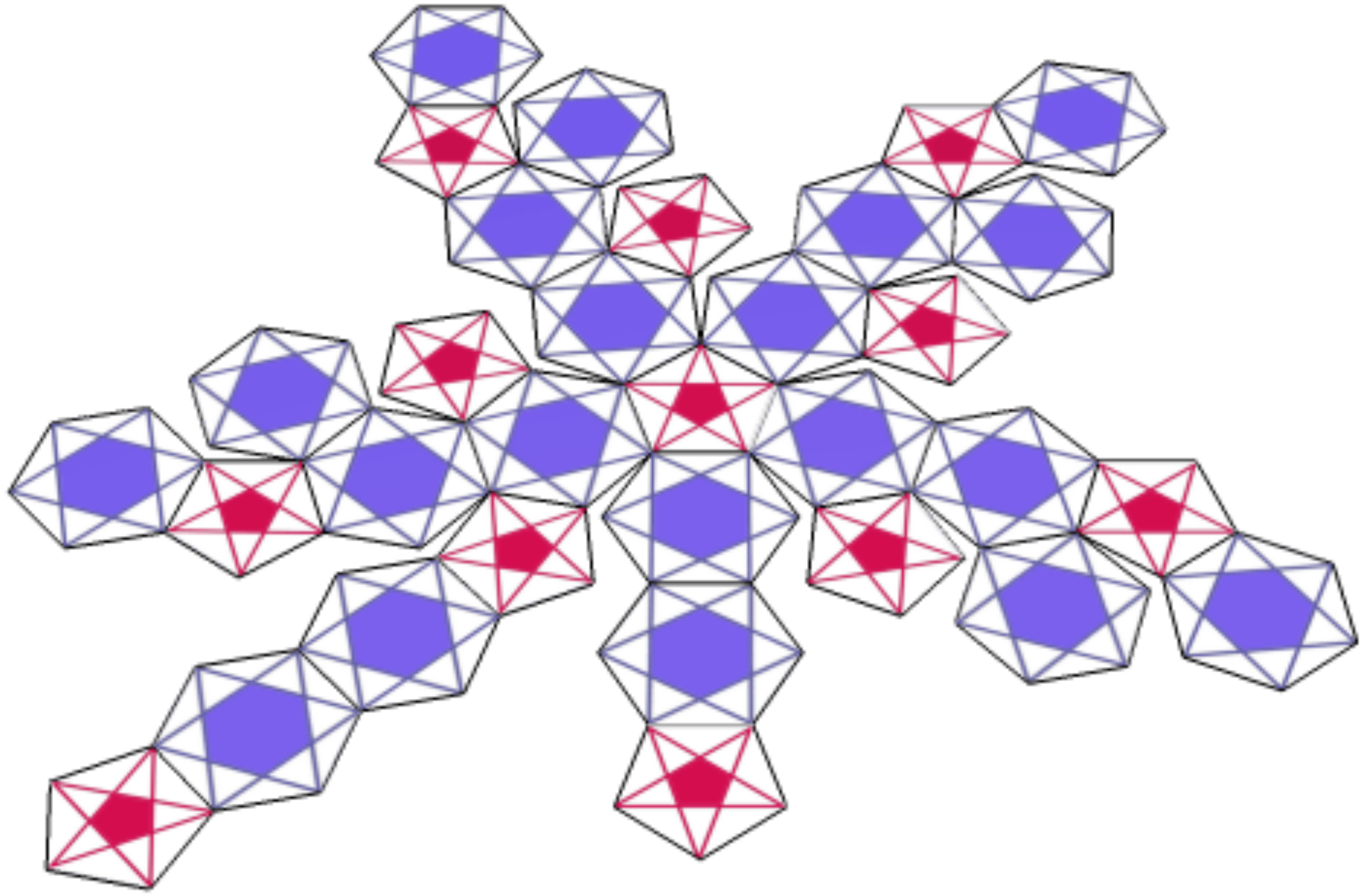

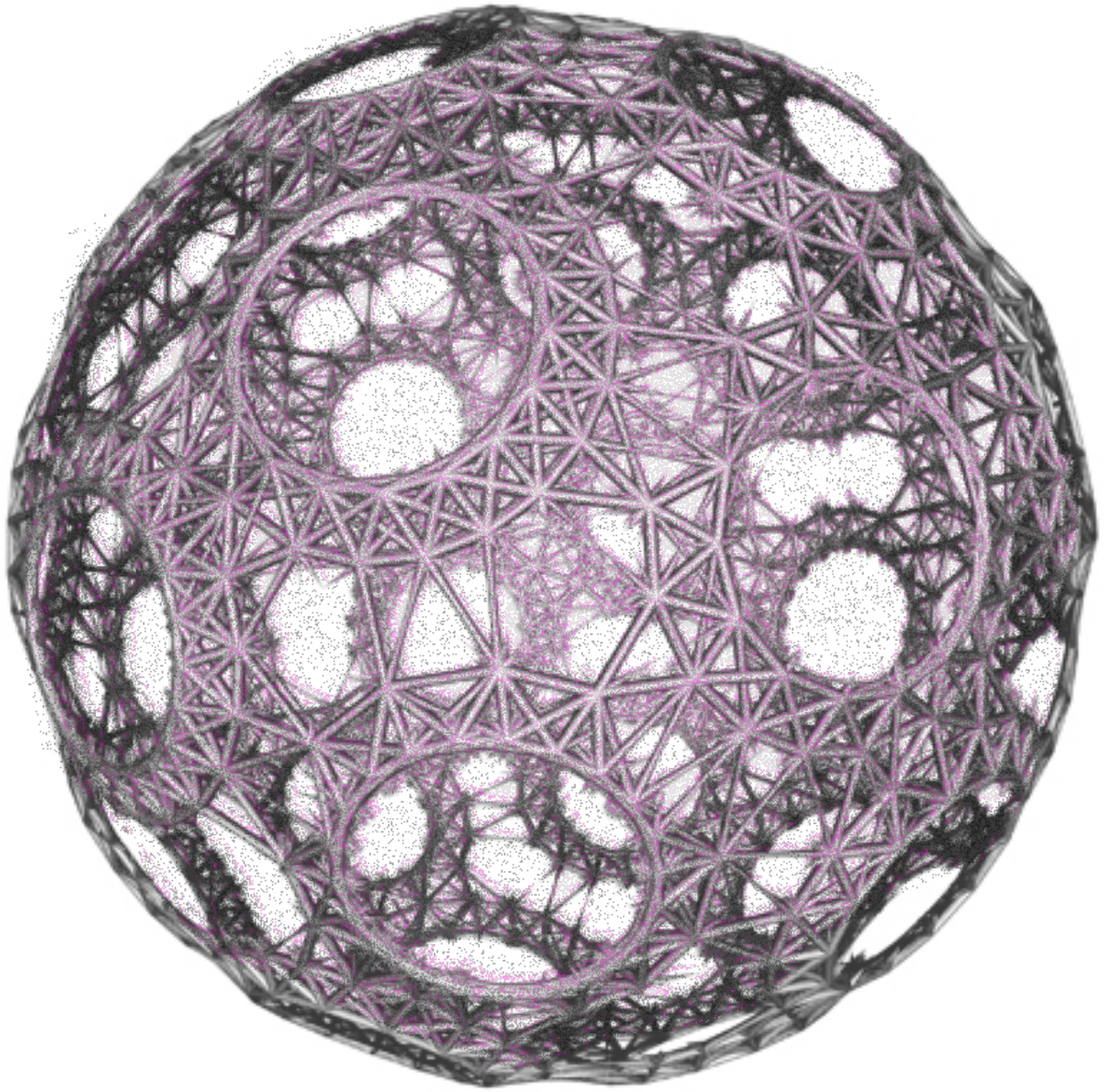

From data to simplices

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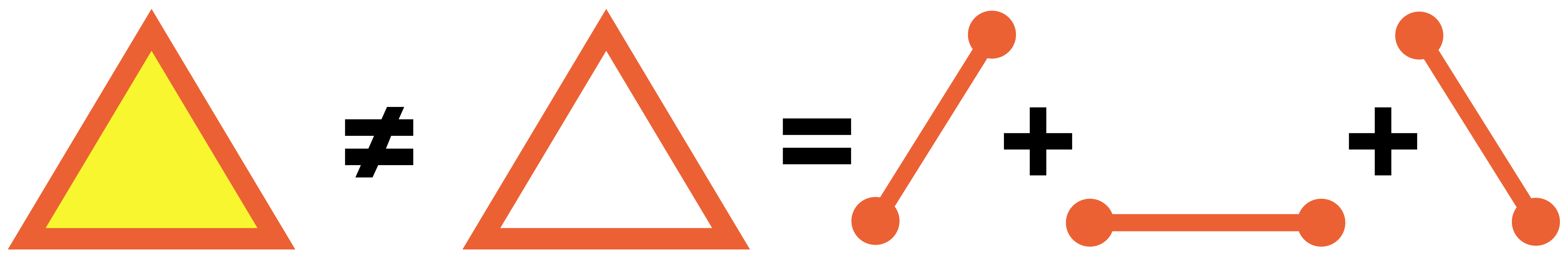

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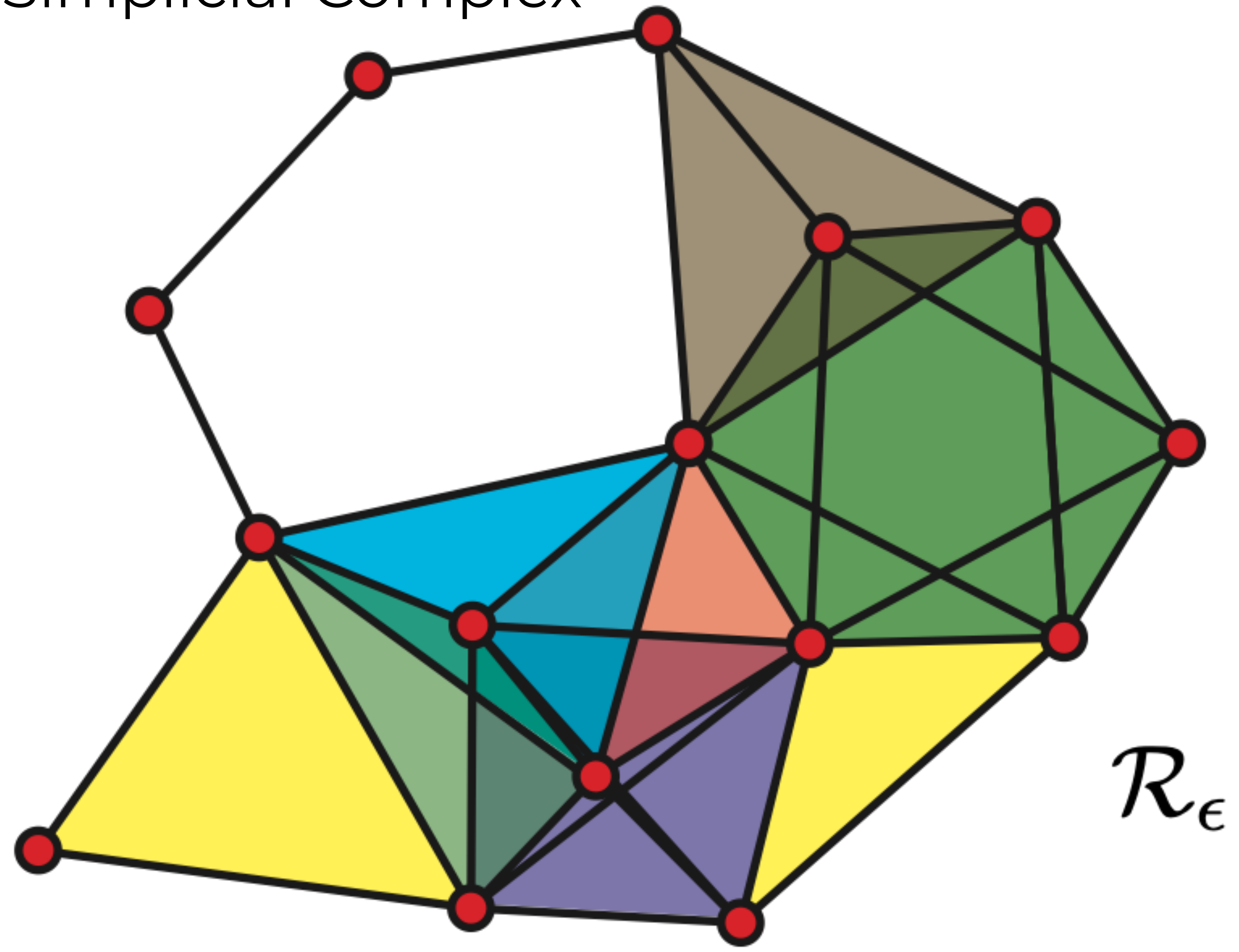

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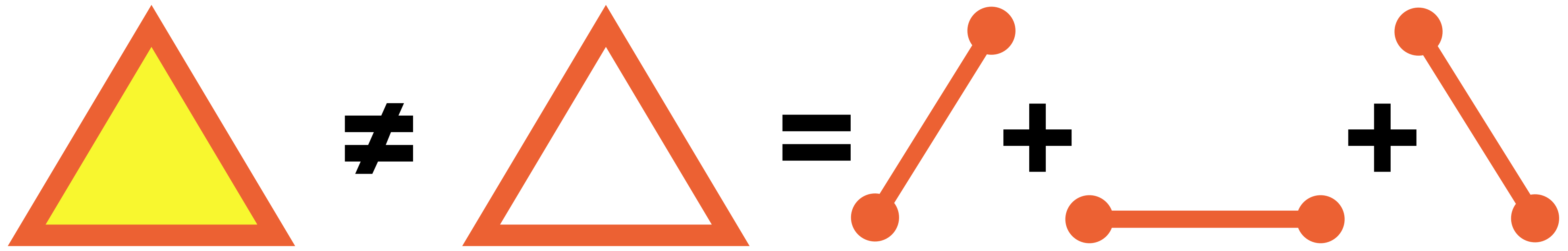

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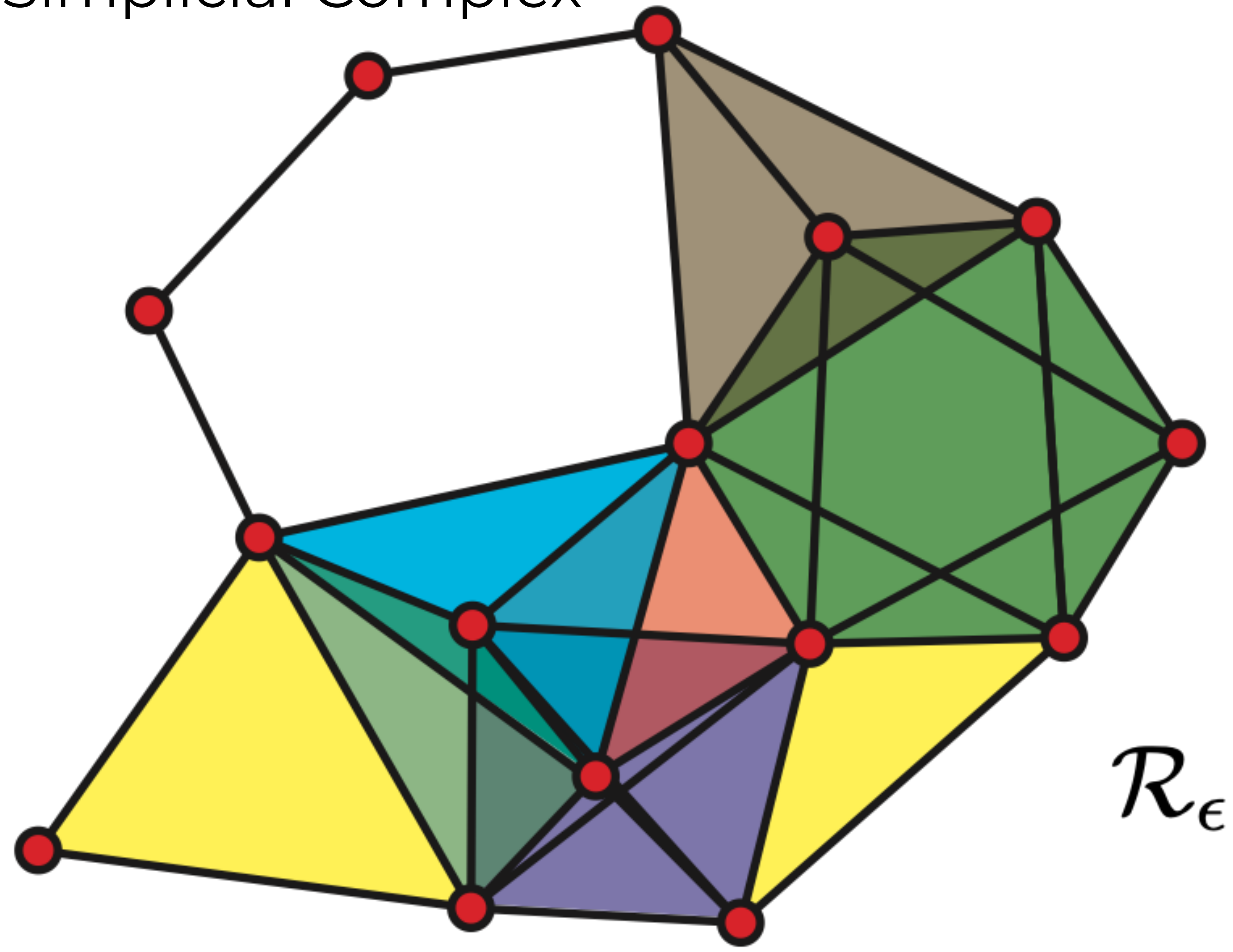

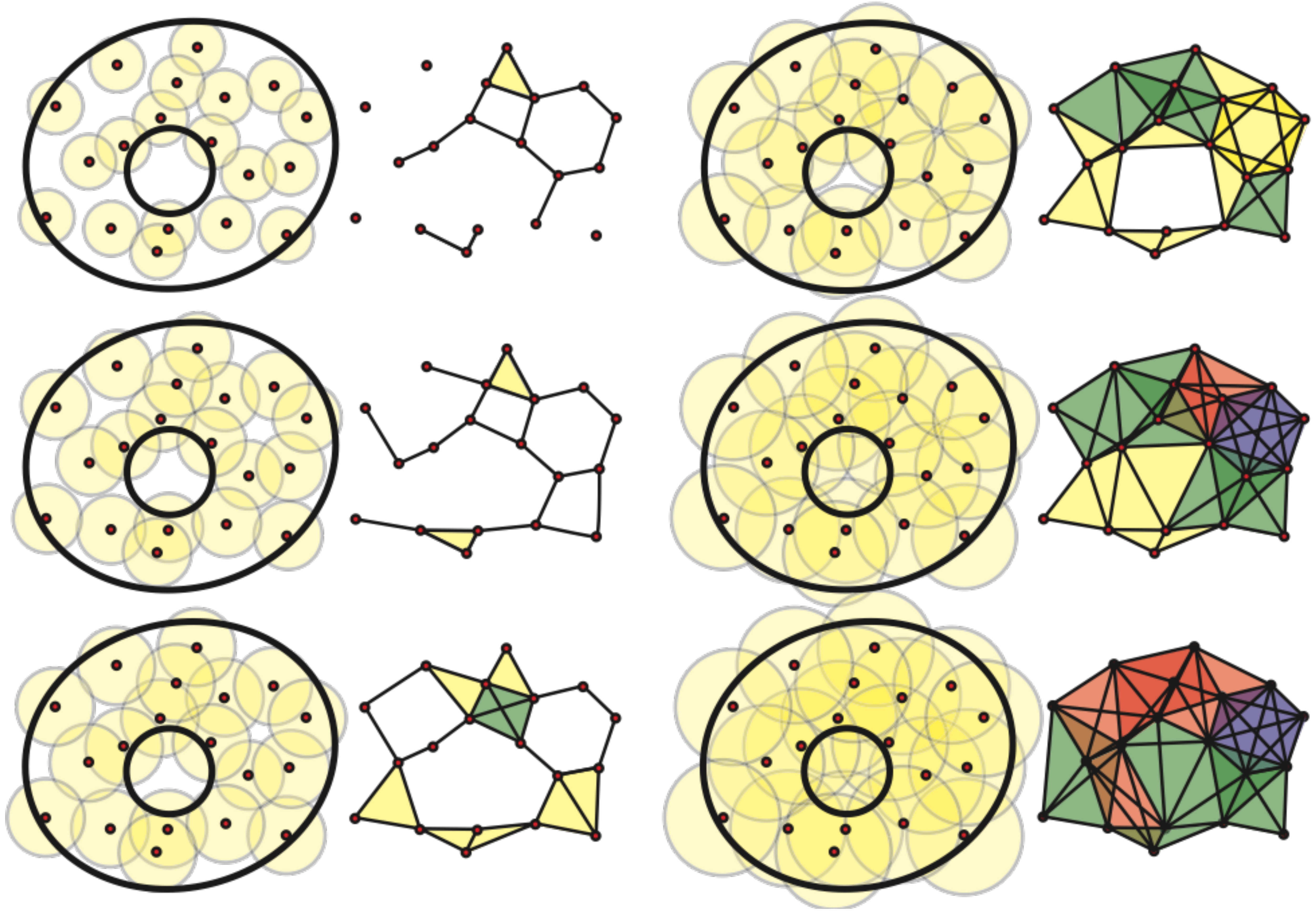

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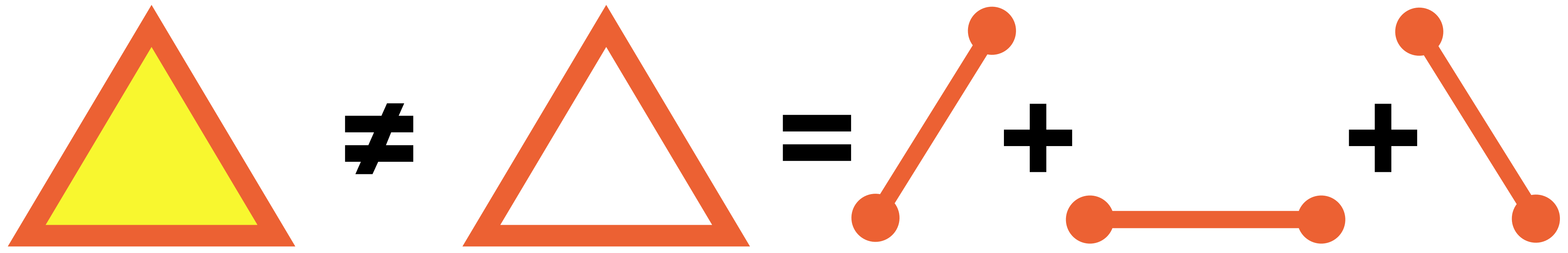

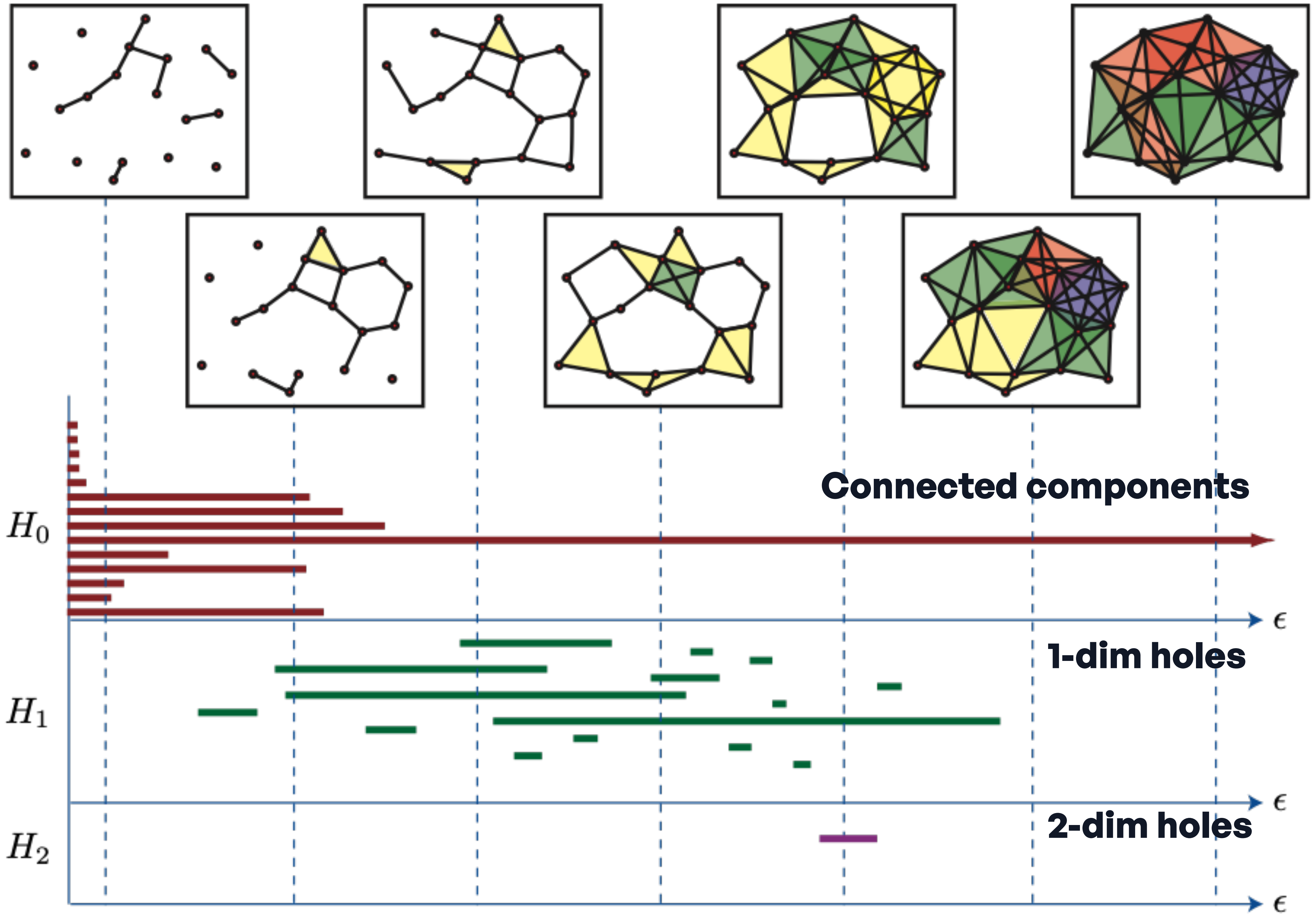

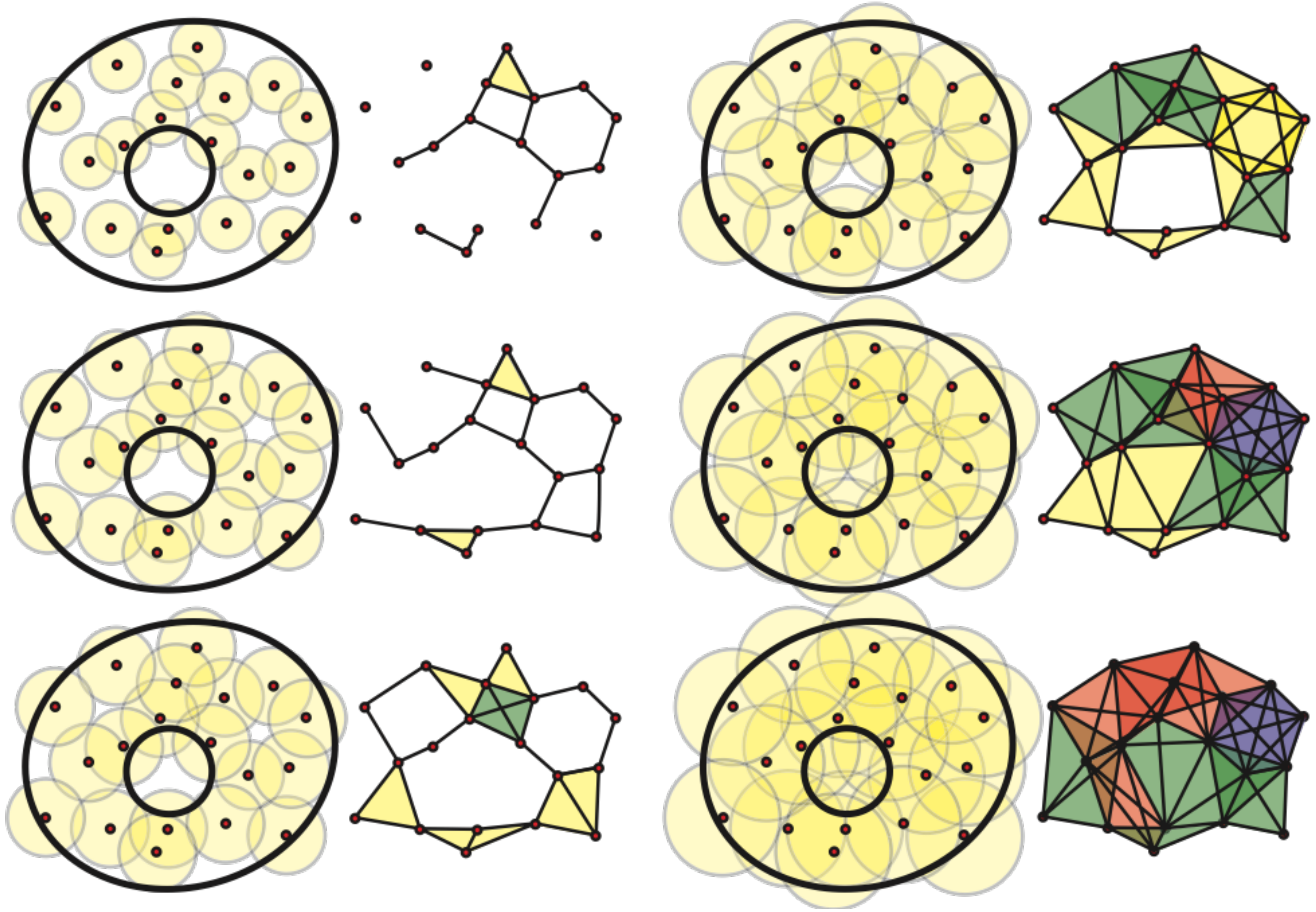

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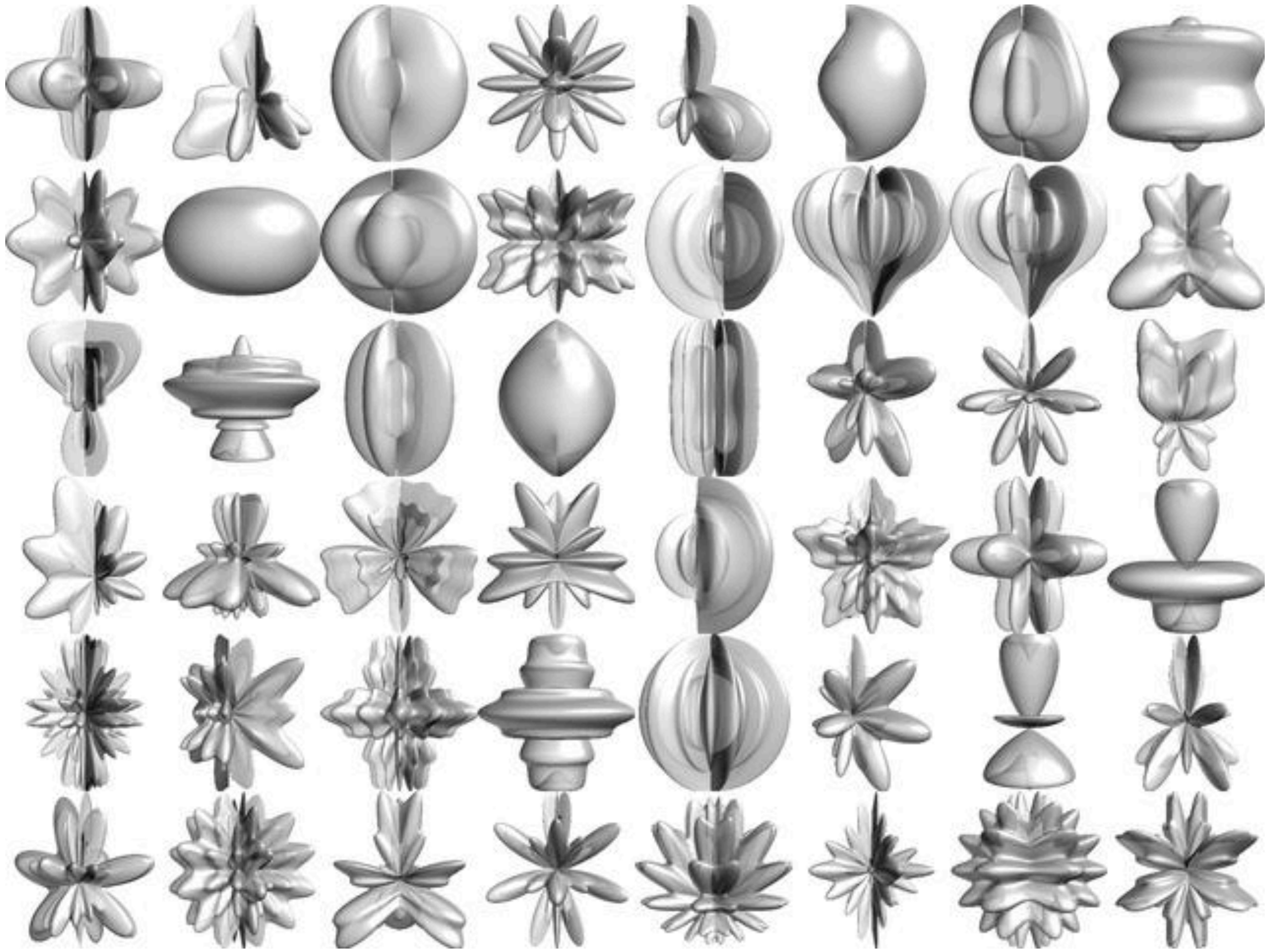
Quantitative comparison

Quantitative topological comparison



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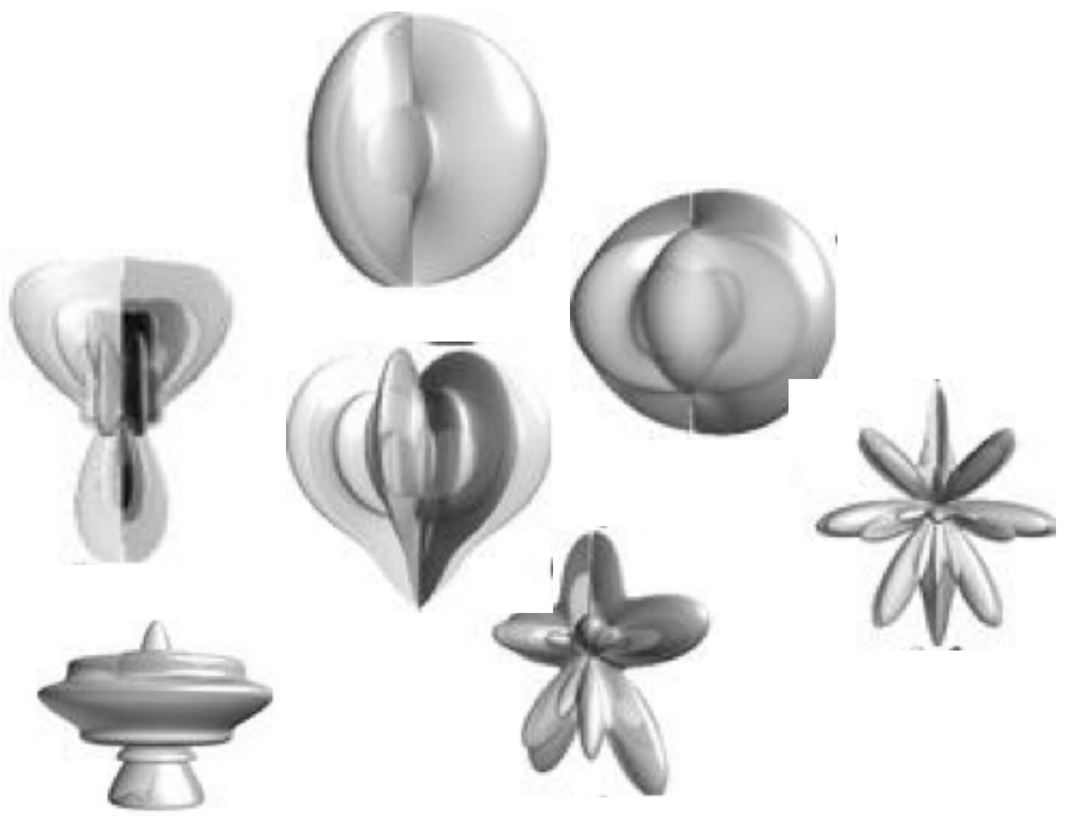

Quantitative comparison

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Aktas, Mehmet E., Esra Akbas, and Ahmed El Fatmaoui. "Persistence homology of networks: methods and applications." *Applied Network Science* 4.1 (2019): 1-28.
Fasy, Brittany, et al. "Comparing distance metrics on vectorized persistence summaries." *TDA {\&} Beyond*. 2020.
Chung, Moo K., et al. "Topological distances between brain networks." *Connectomics in NeuroImaging: First International Workshop, CNI 2017, Held in Conjunction with MICCAI 2017, Quebec City, QC, Canada, September 14, 2017, Proceedings 1*. Springer International Publishing, 2017.

Quantitative comparison

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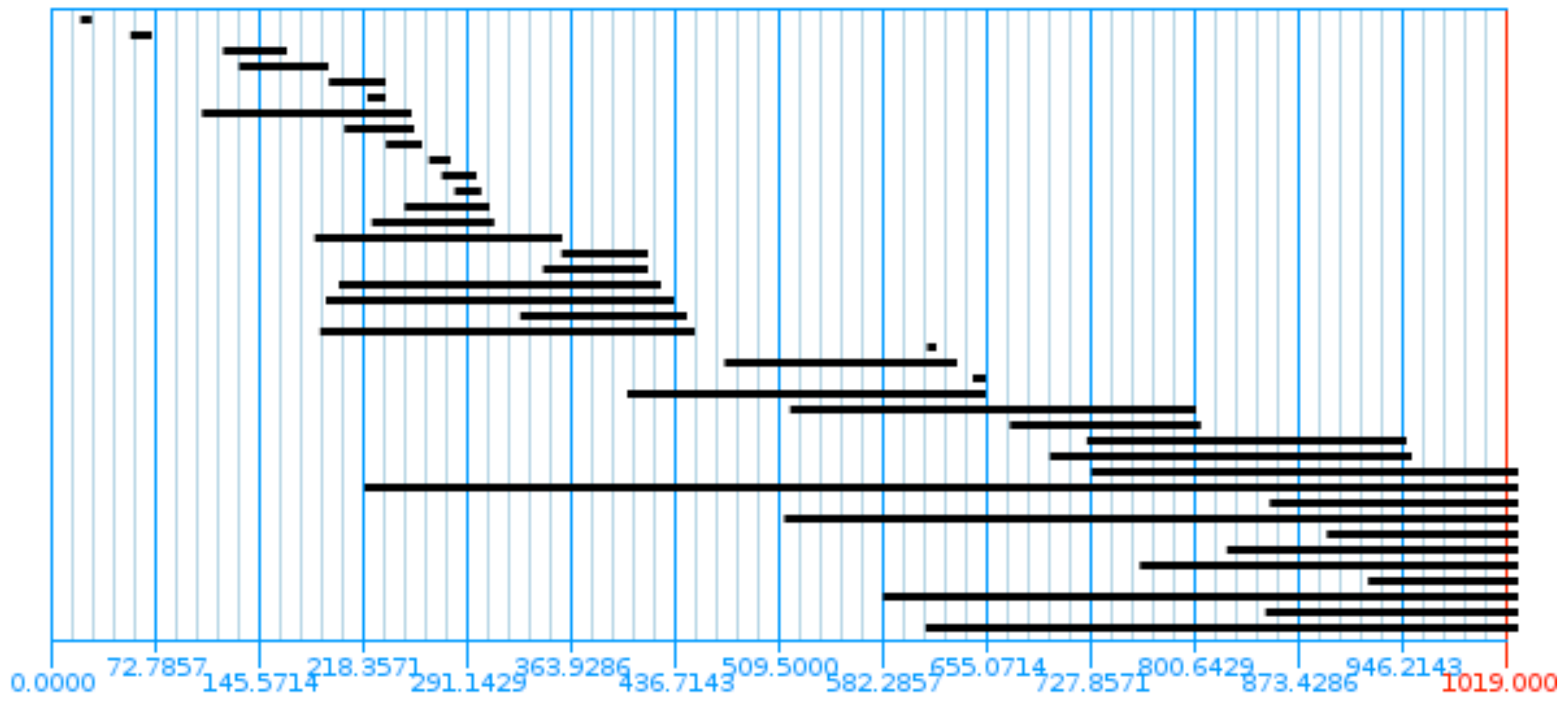

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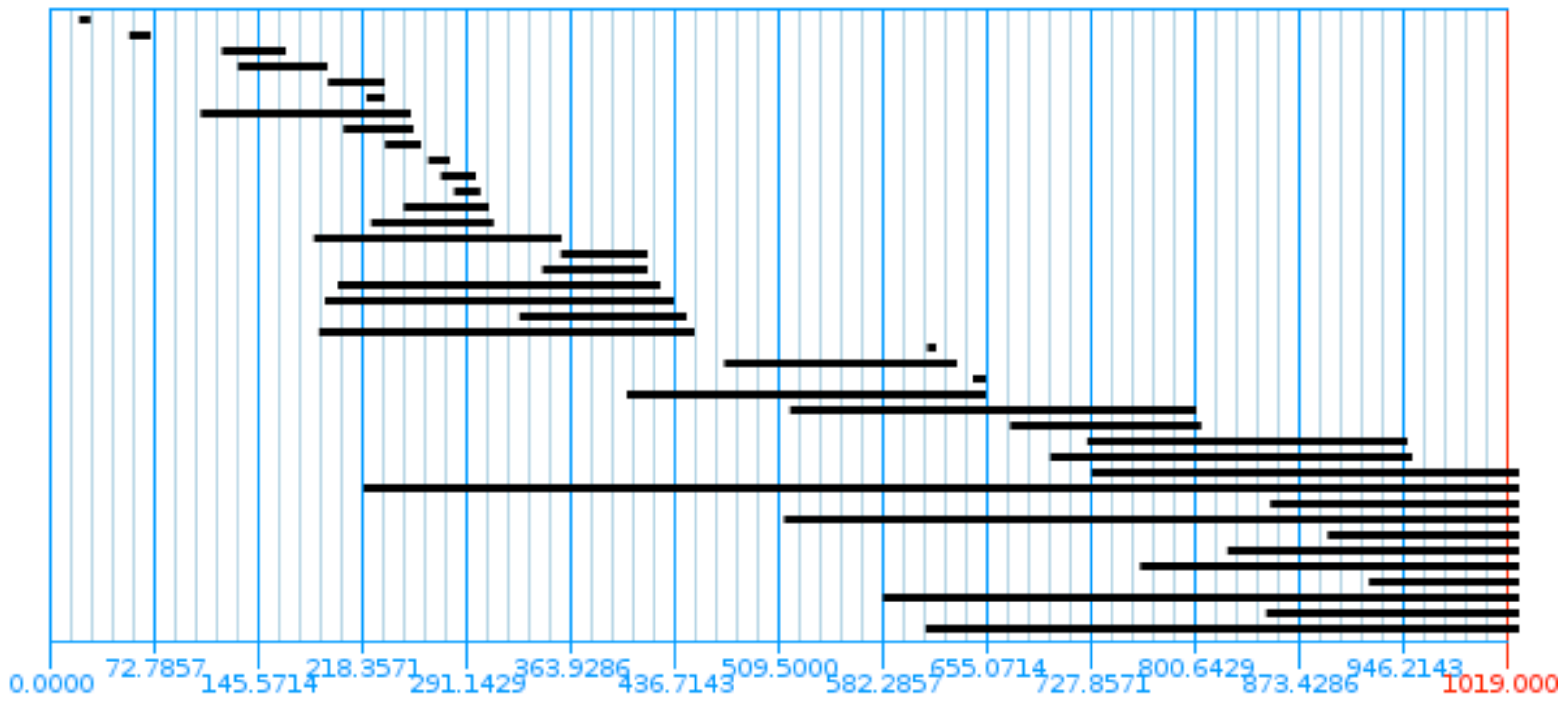

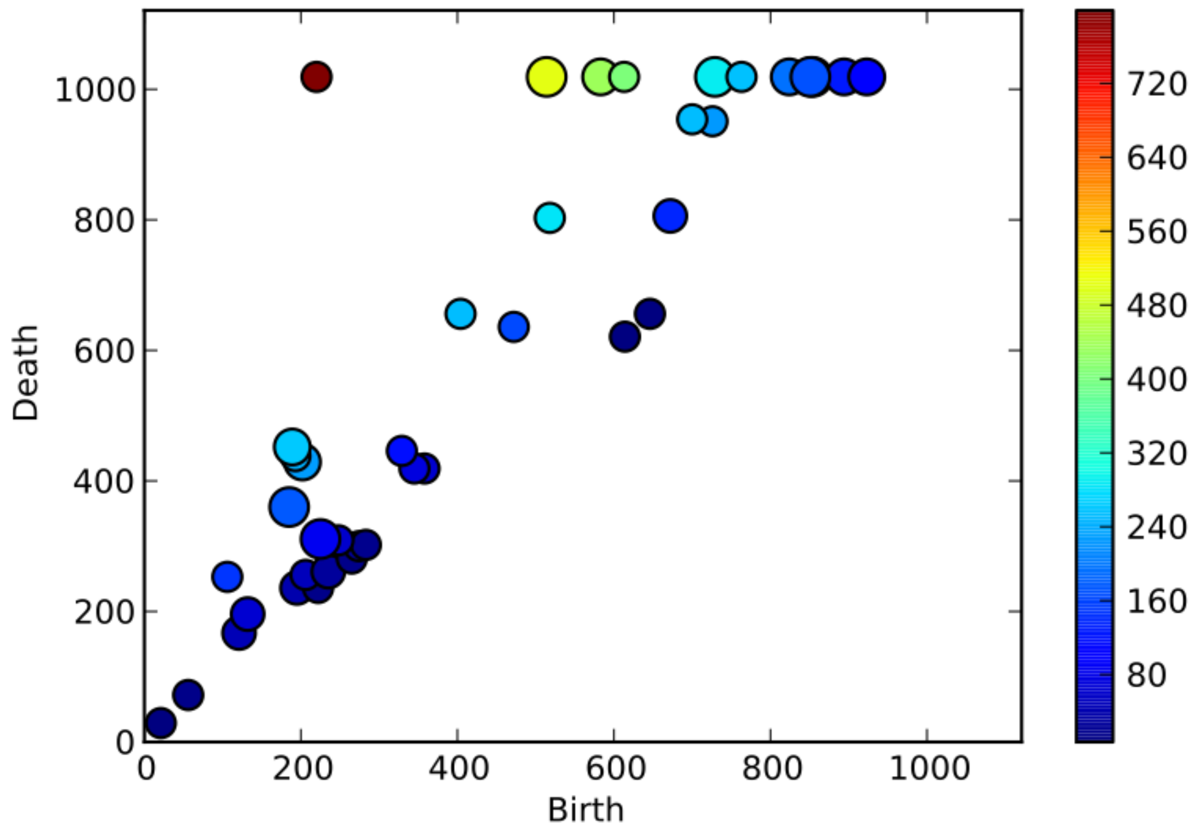

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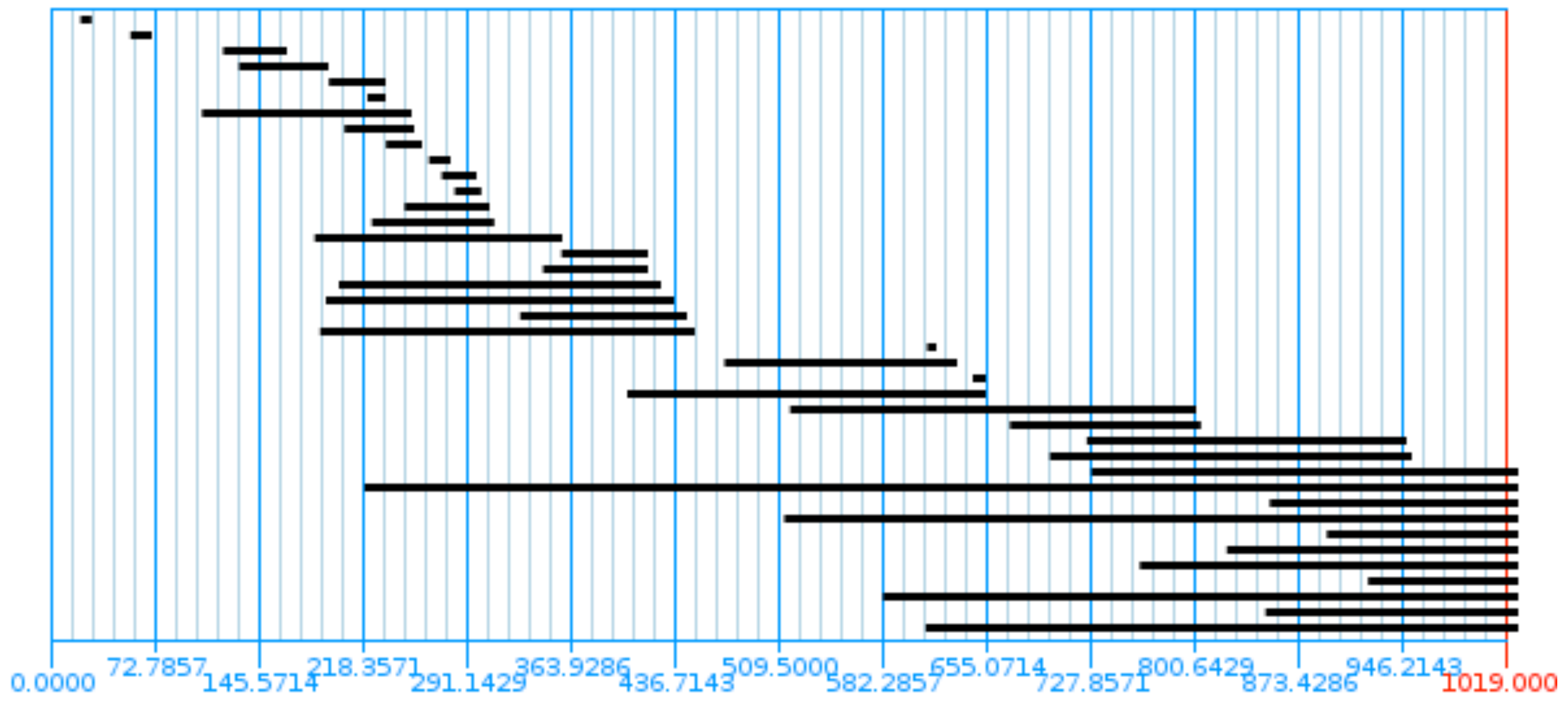

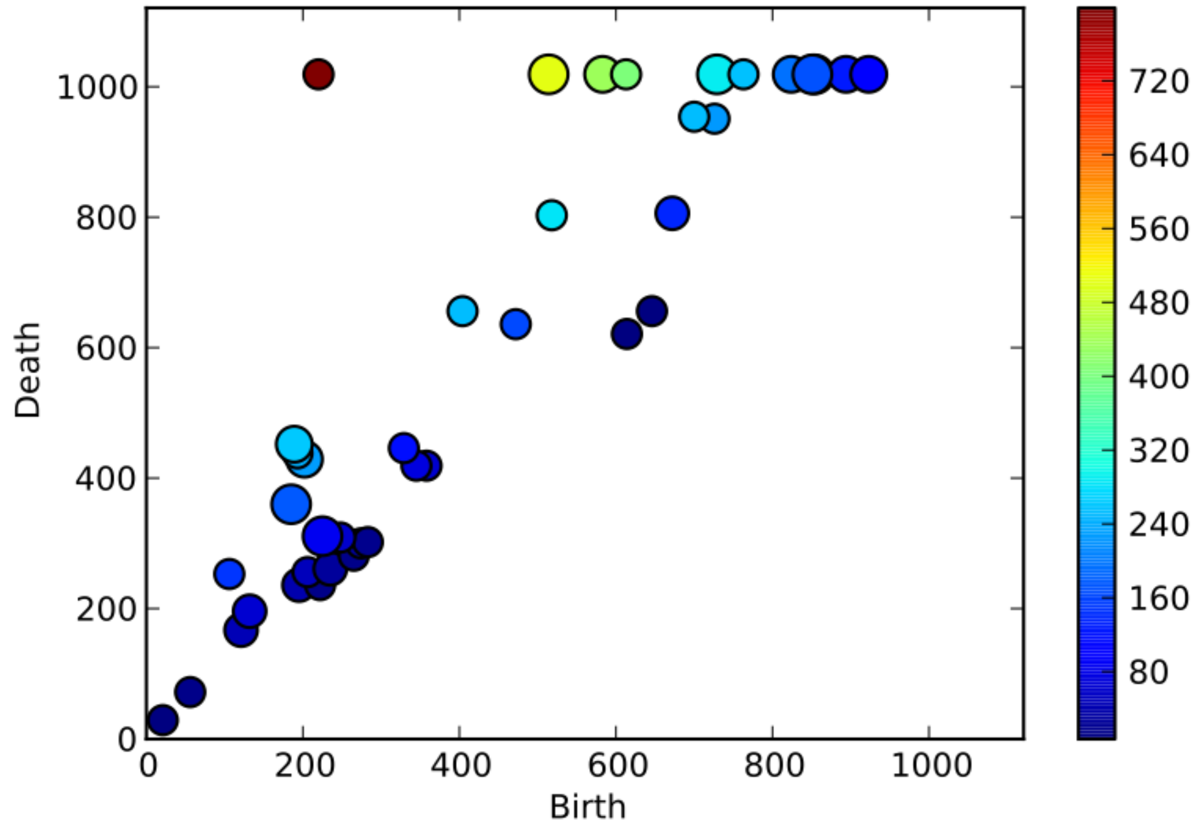

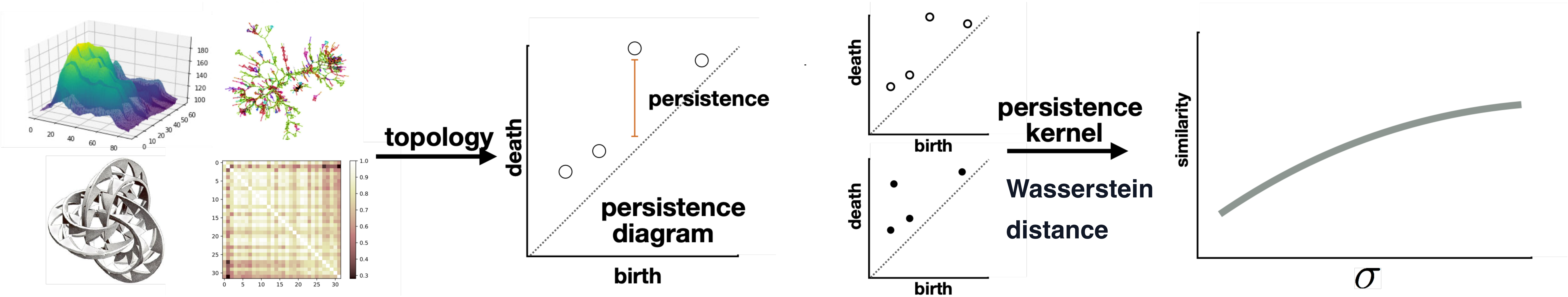


BrainZ

Altered functional topology

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rs-fMRI,
15 subjects,
2 sessions
1 recording condition

Carhart-Harris, Robin L., et al. "Neural correlates of the psychedelic state as determined by fMRI studies with psilocybin." Proceedings of the National Academy of Sciences 109.6 (2012): 2138-2143.

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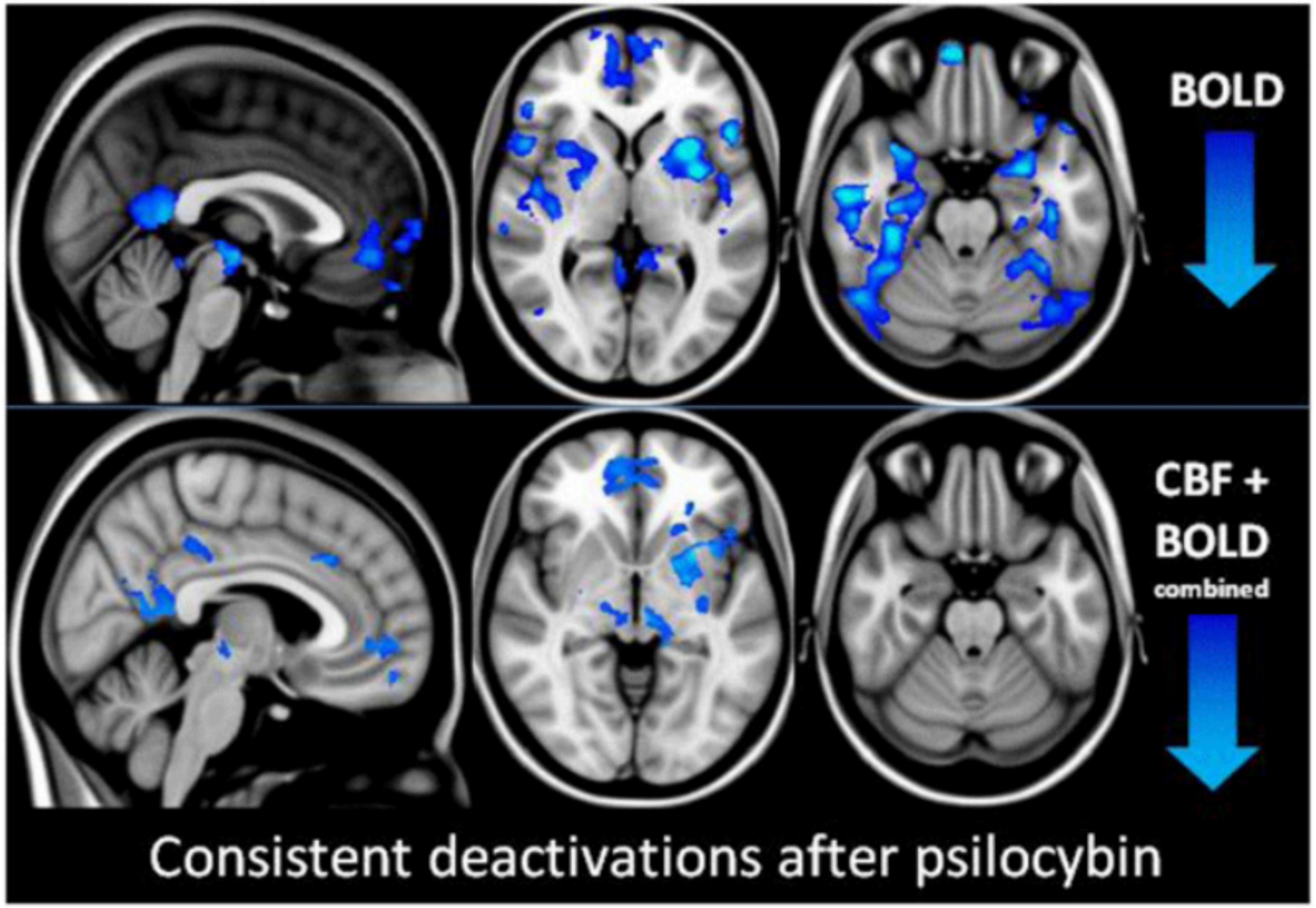

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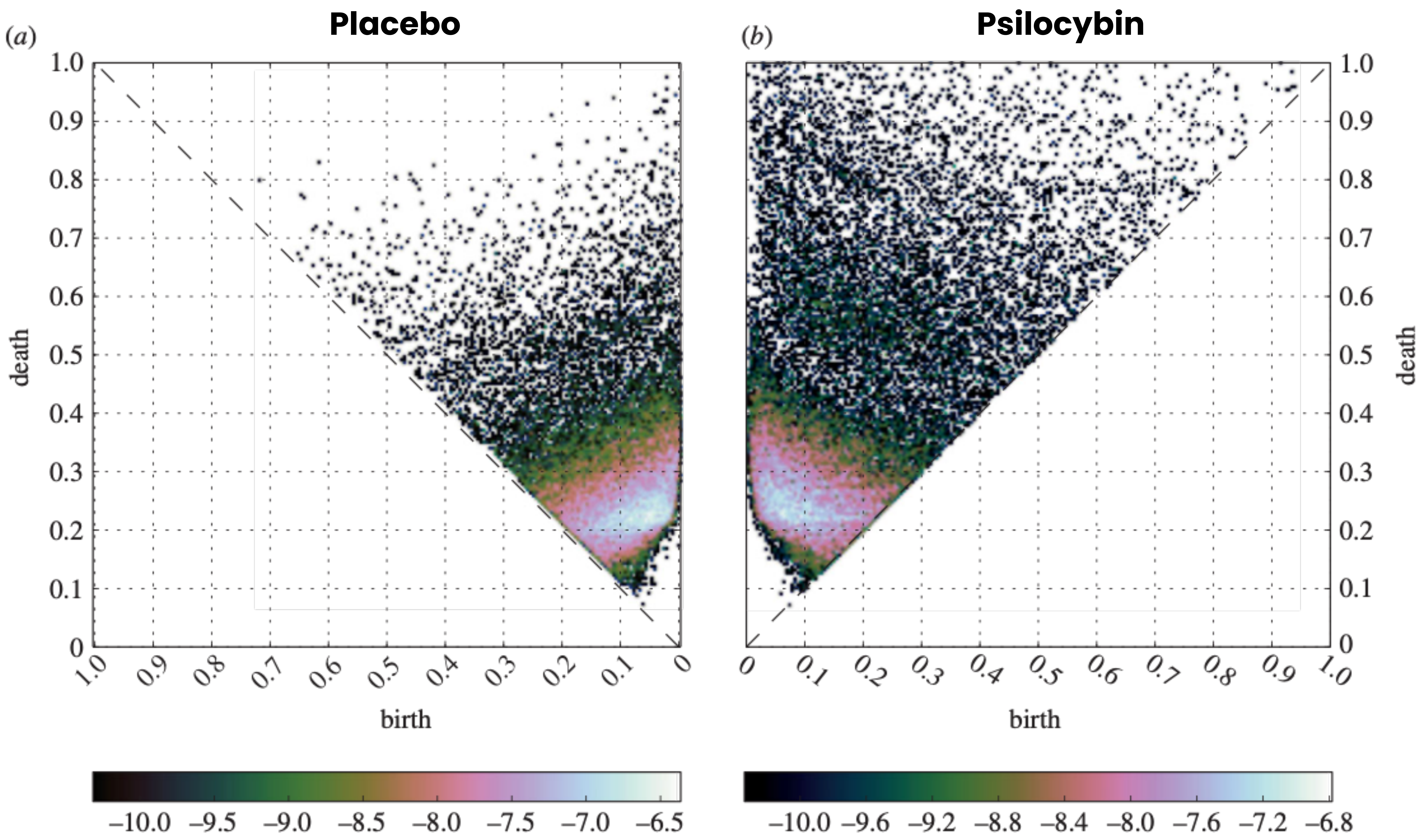

Group level persistence diagrams

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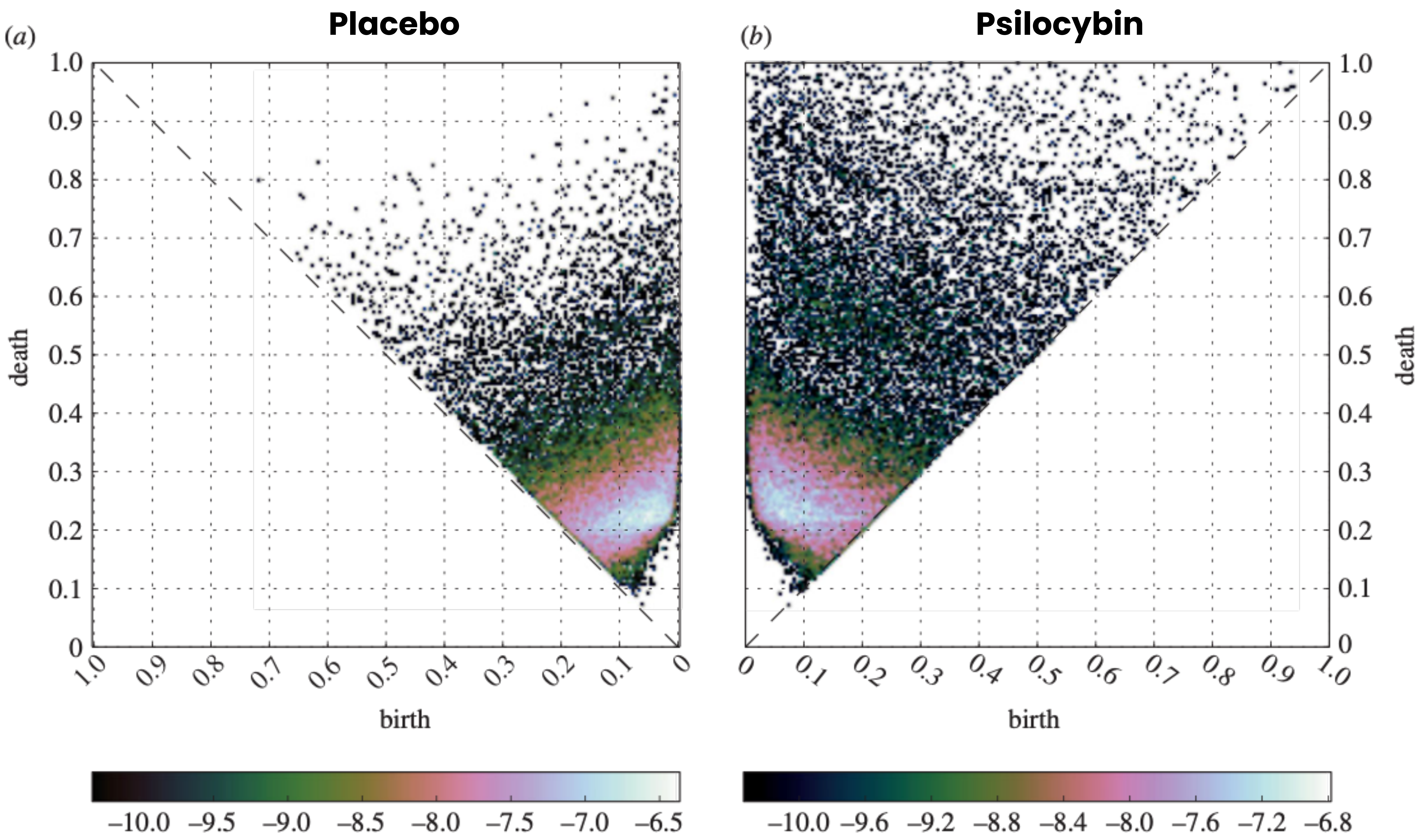

Group level persistence diagrams

Localisation of information?

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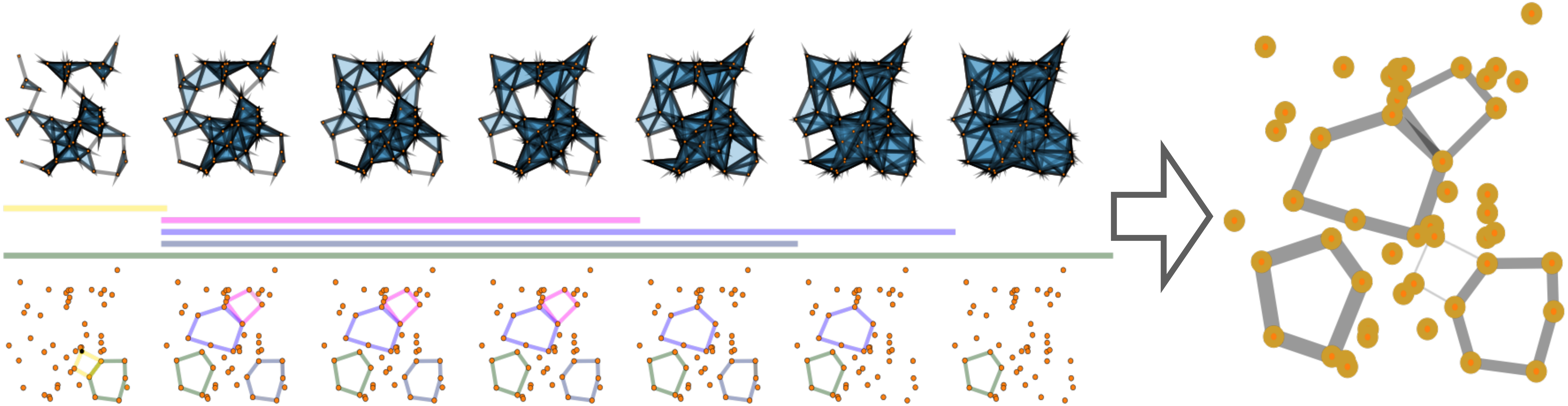
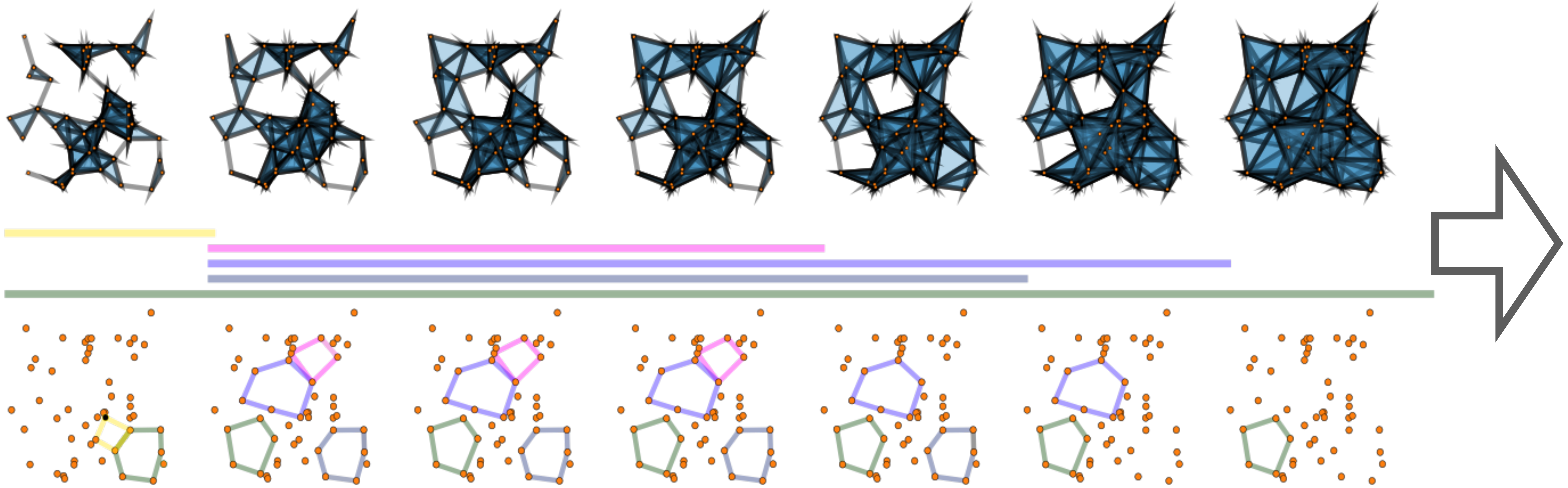
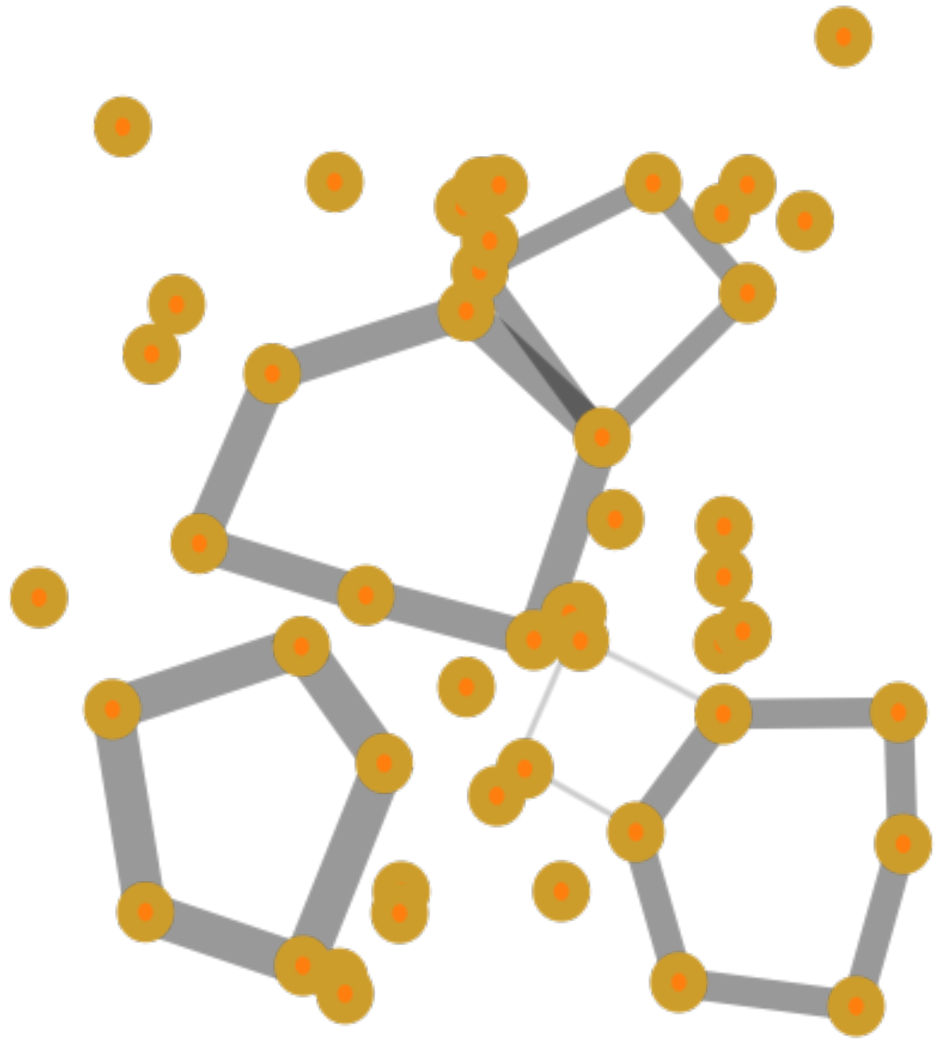
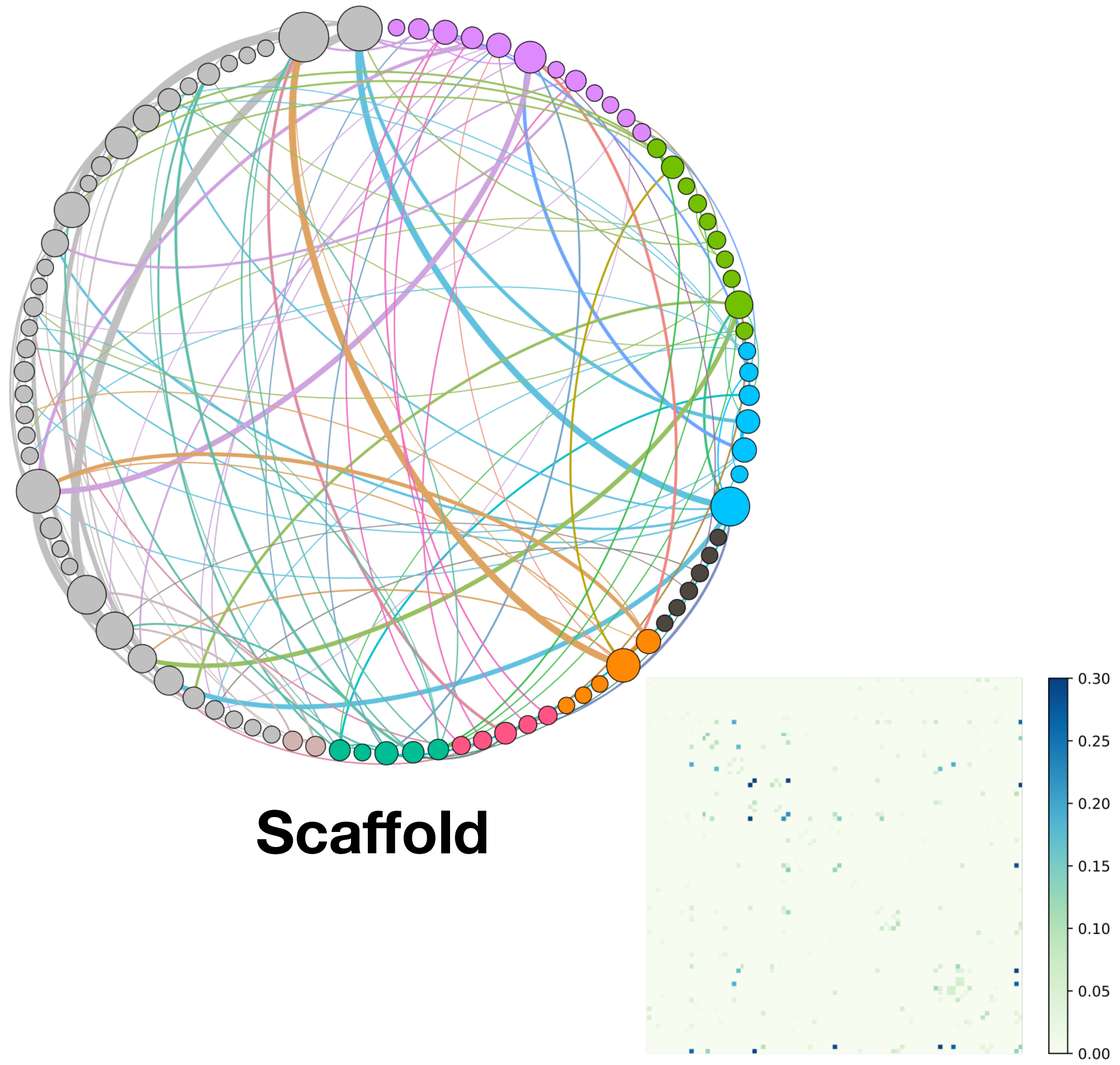
Scaffolds in one slide









Scaffold

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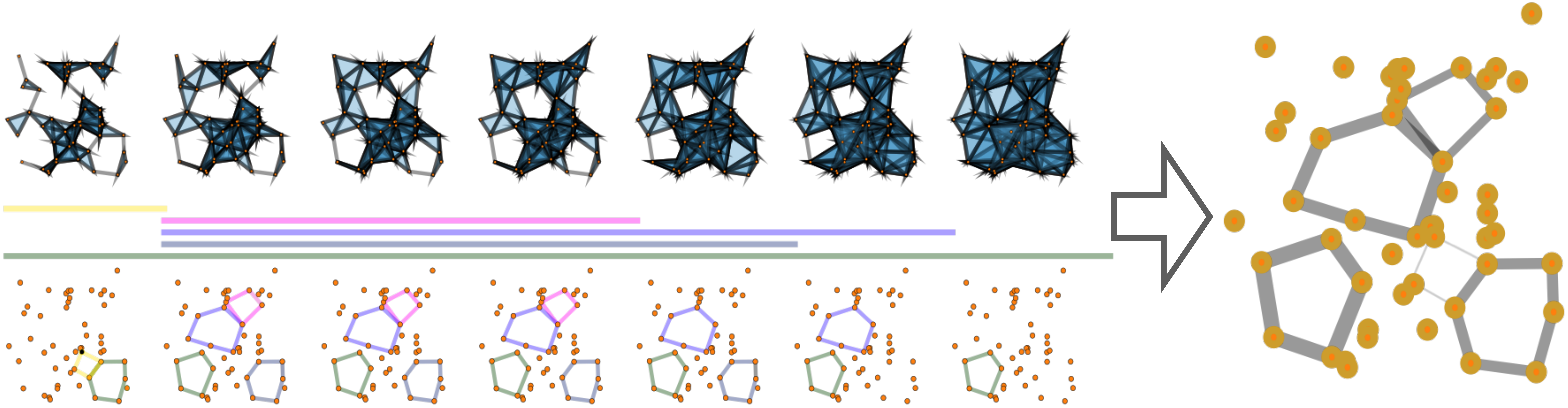

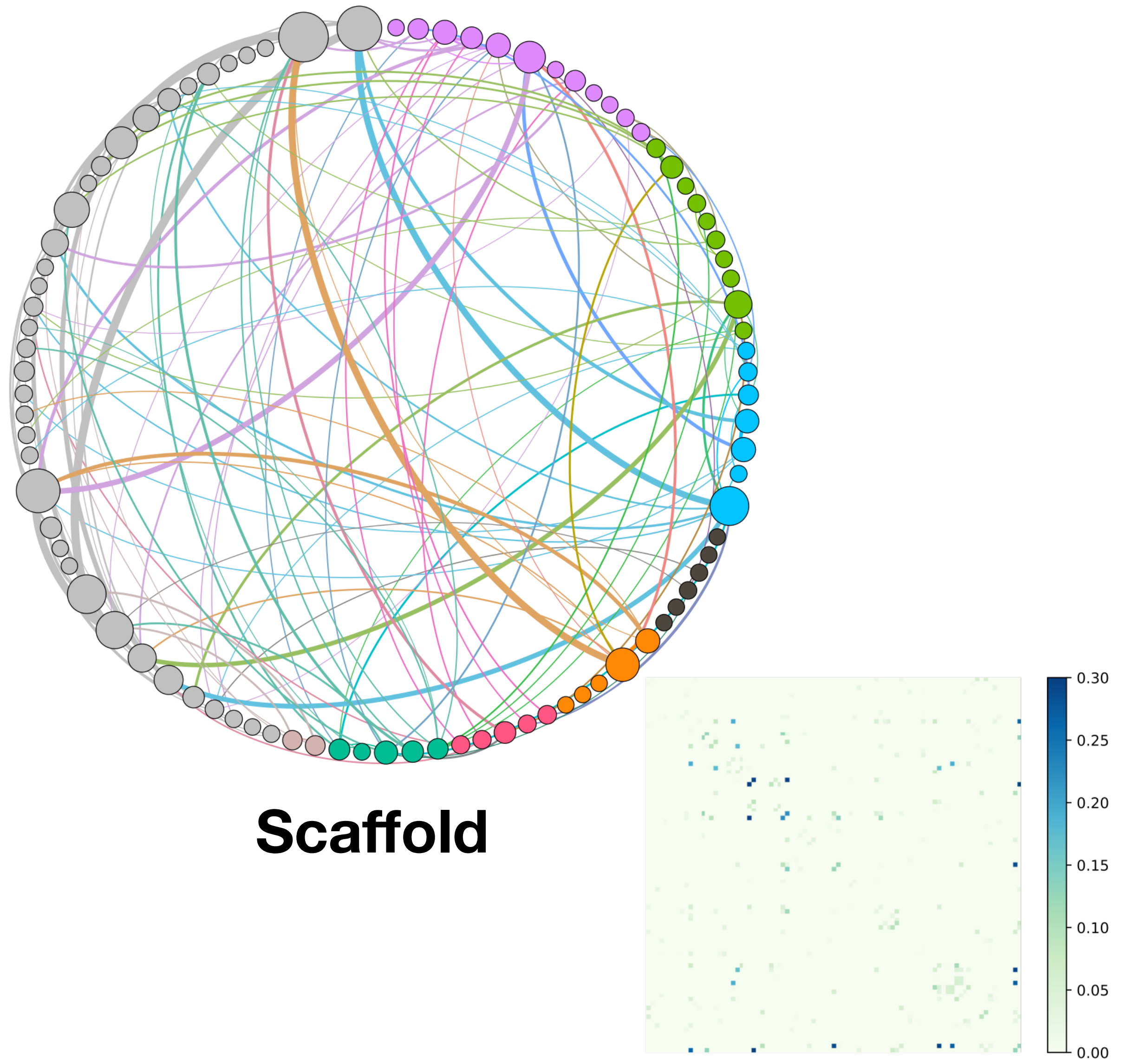

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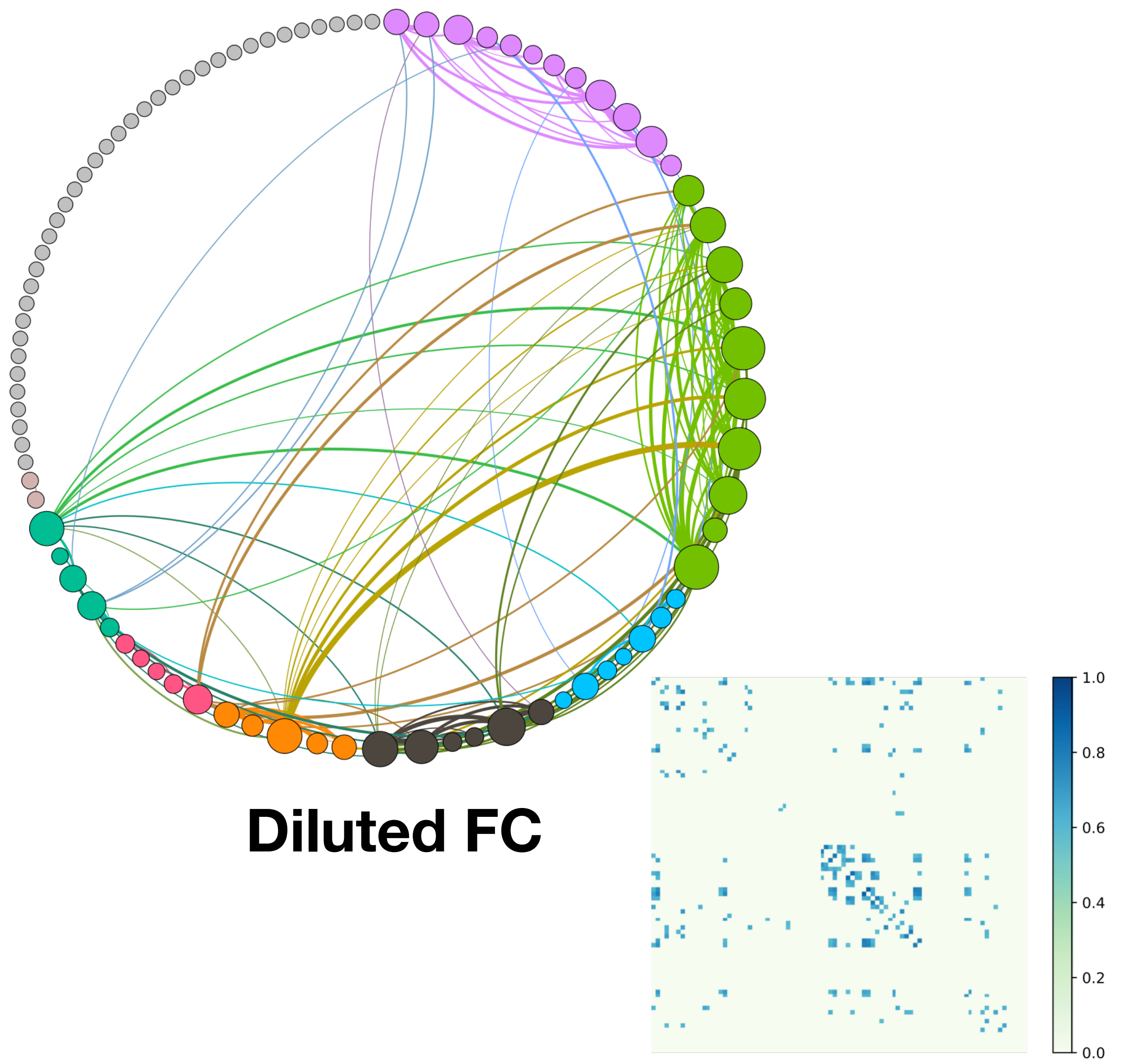

Diluted FC

Scaffolds in one slide

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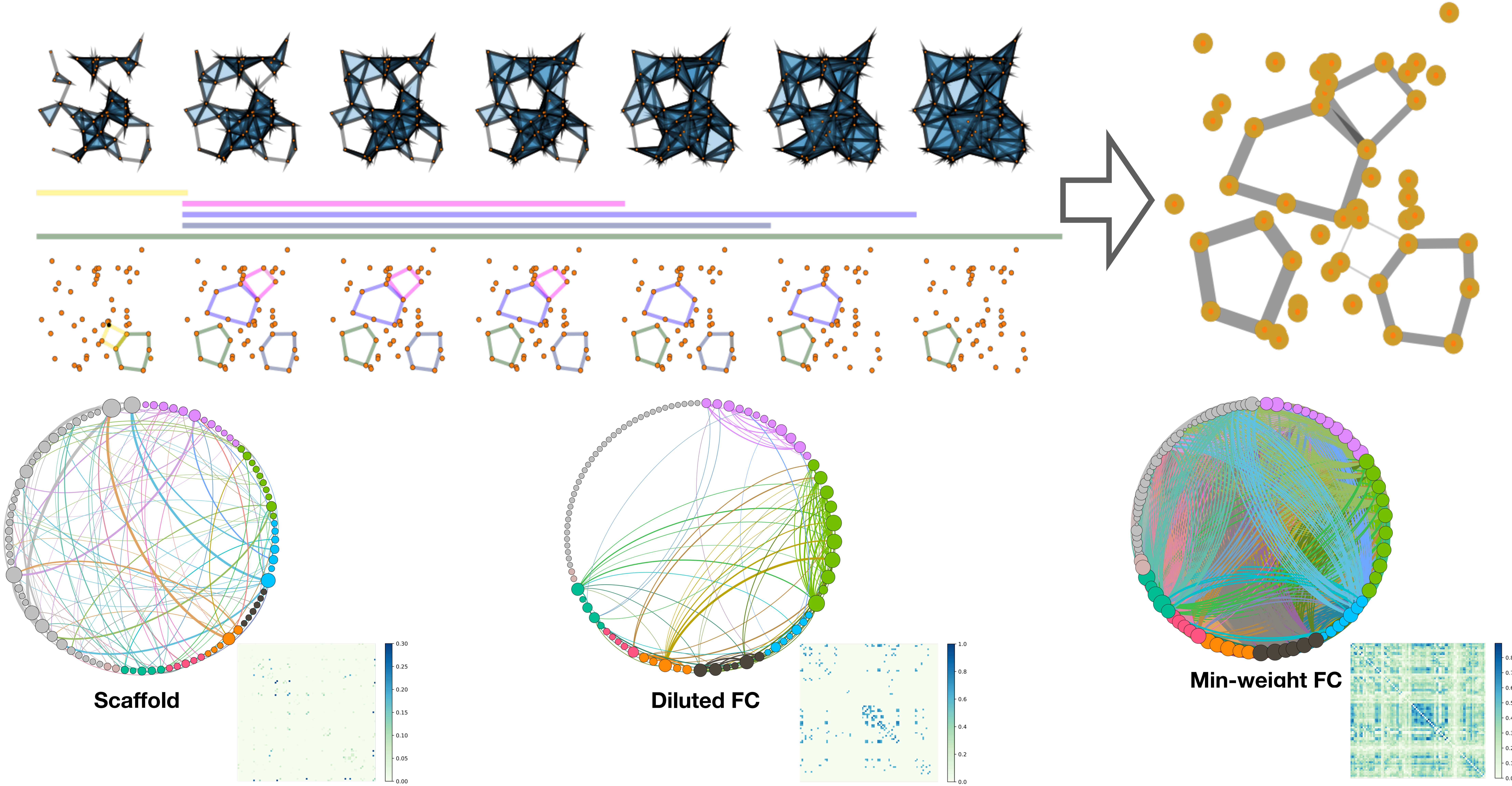
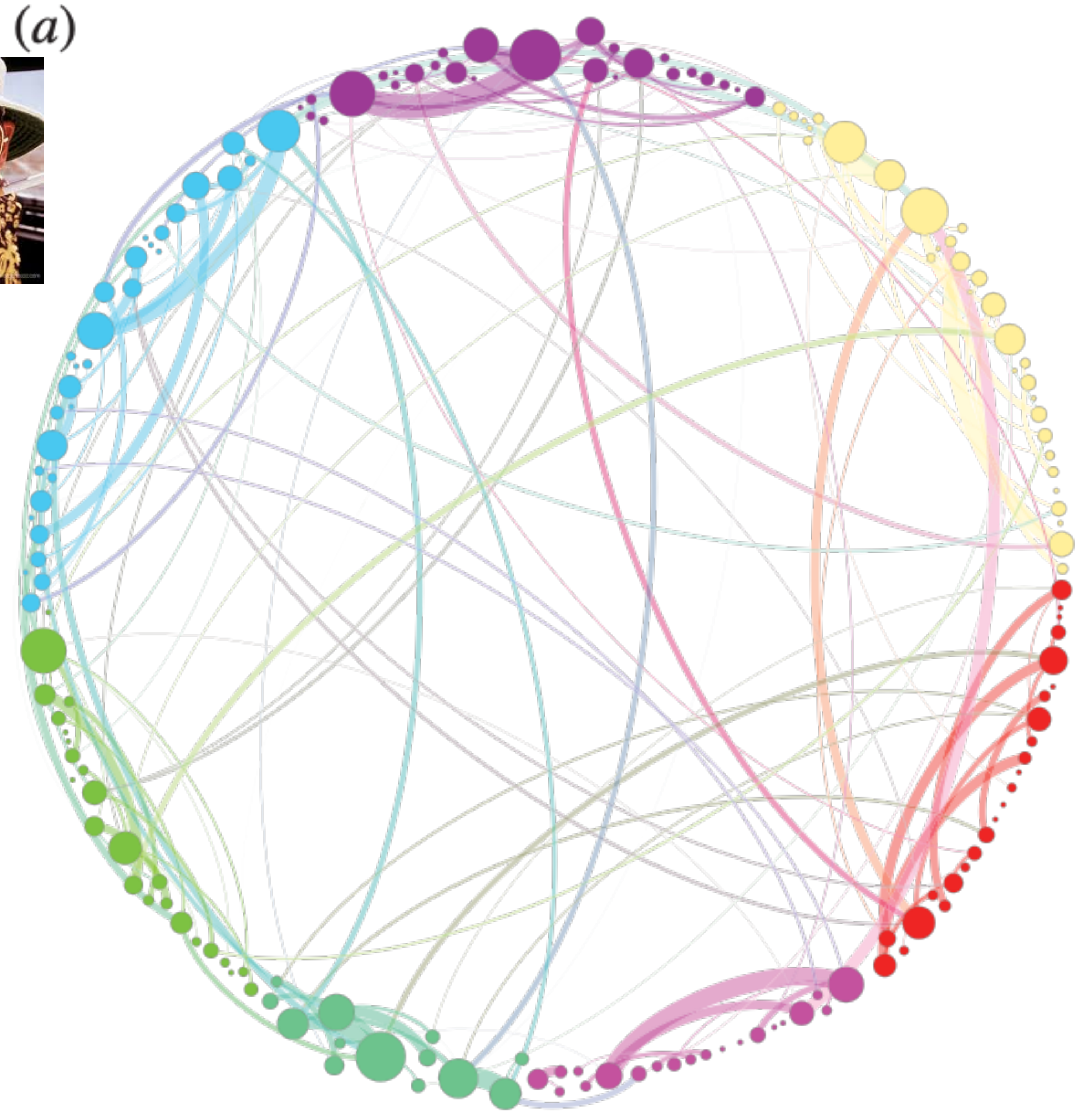
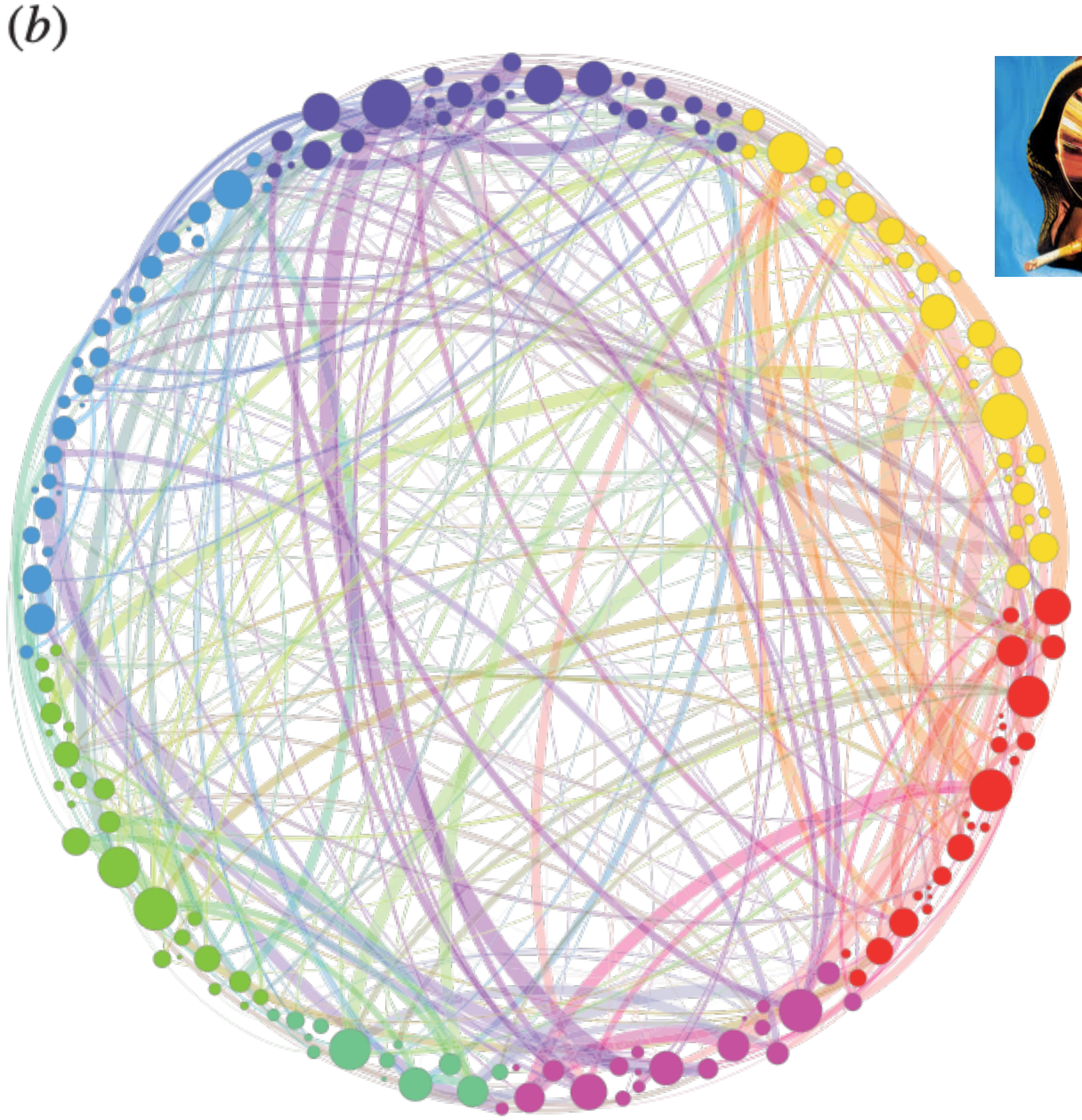


Scaffolds: local alterations





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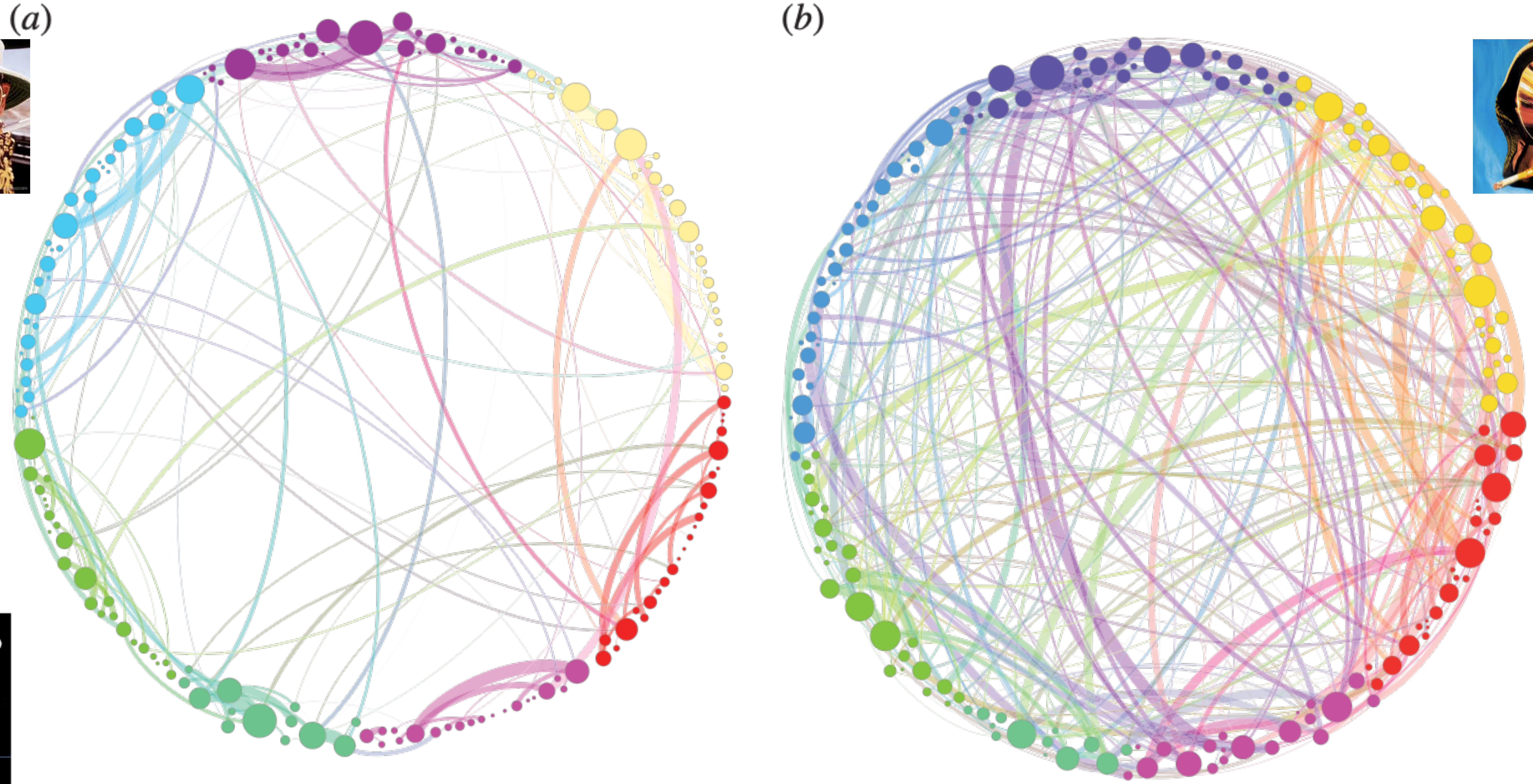

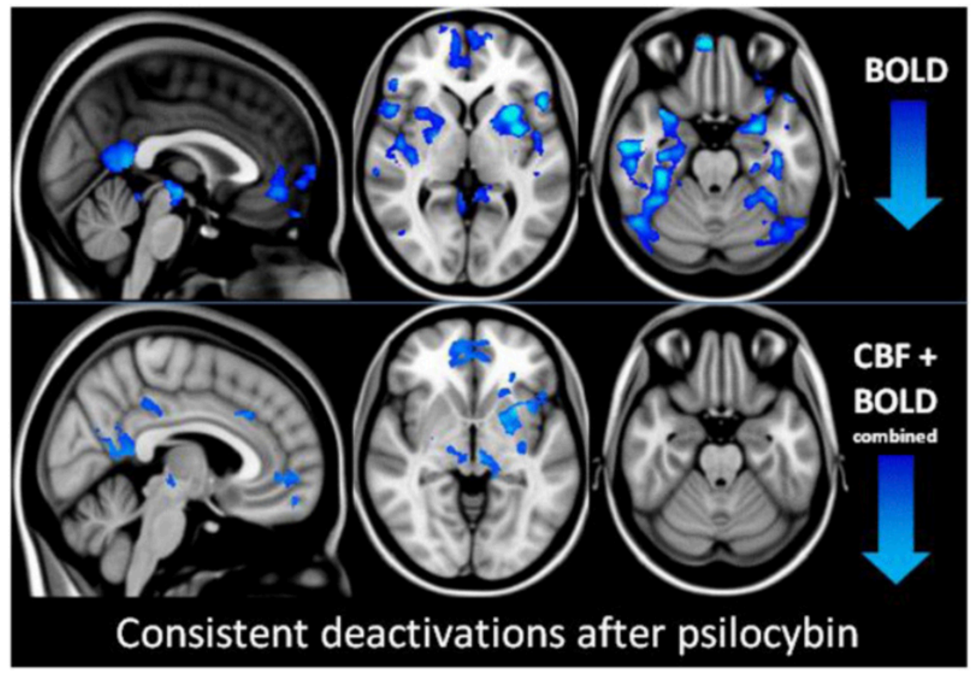

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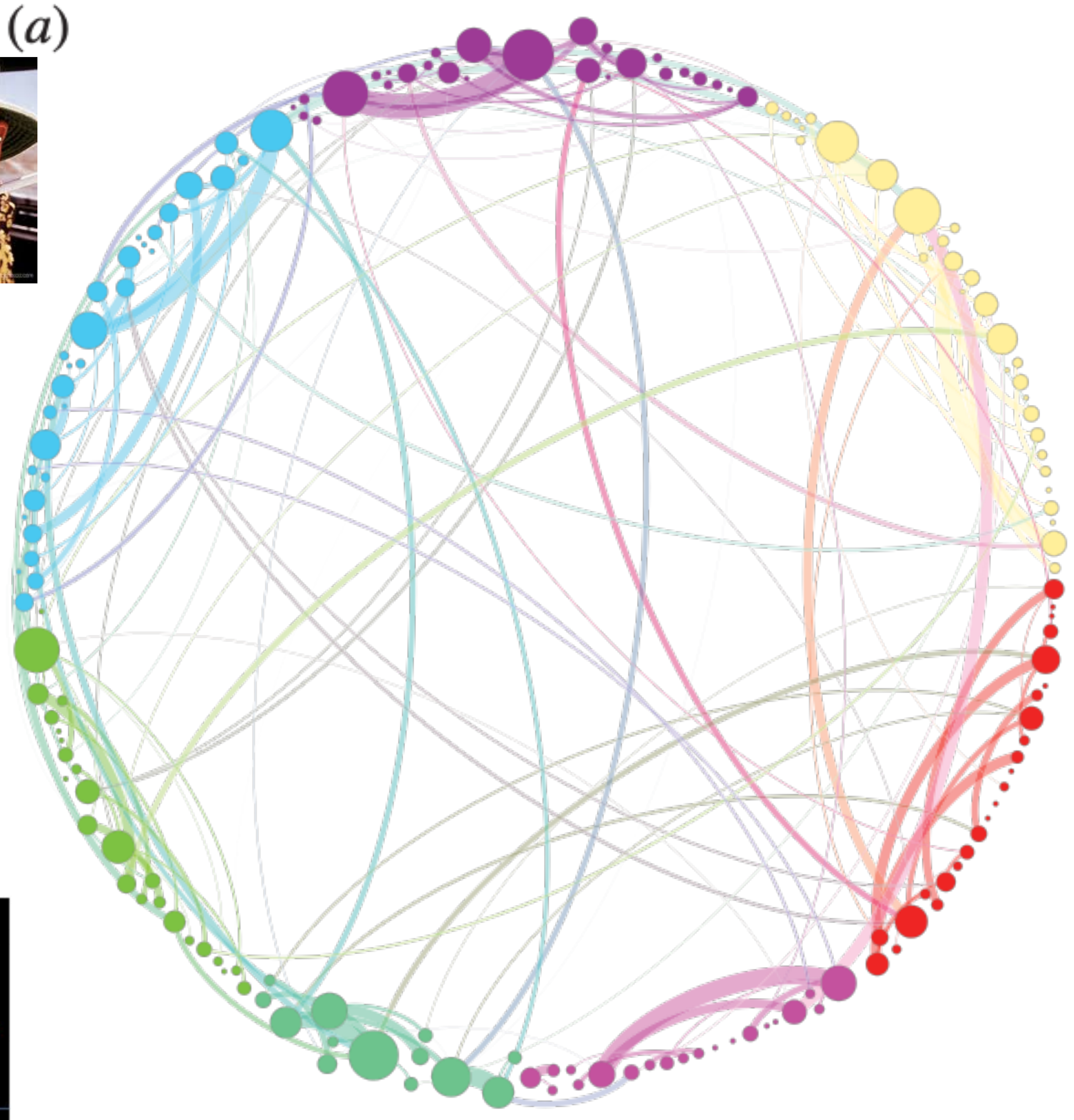
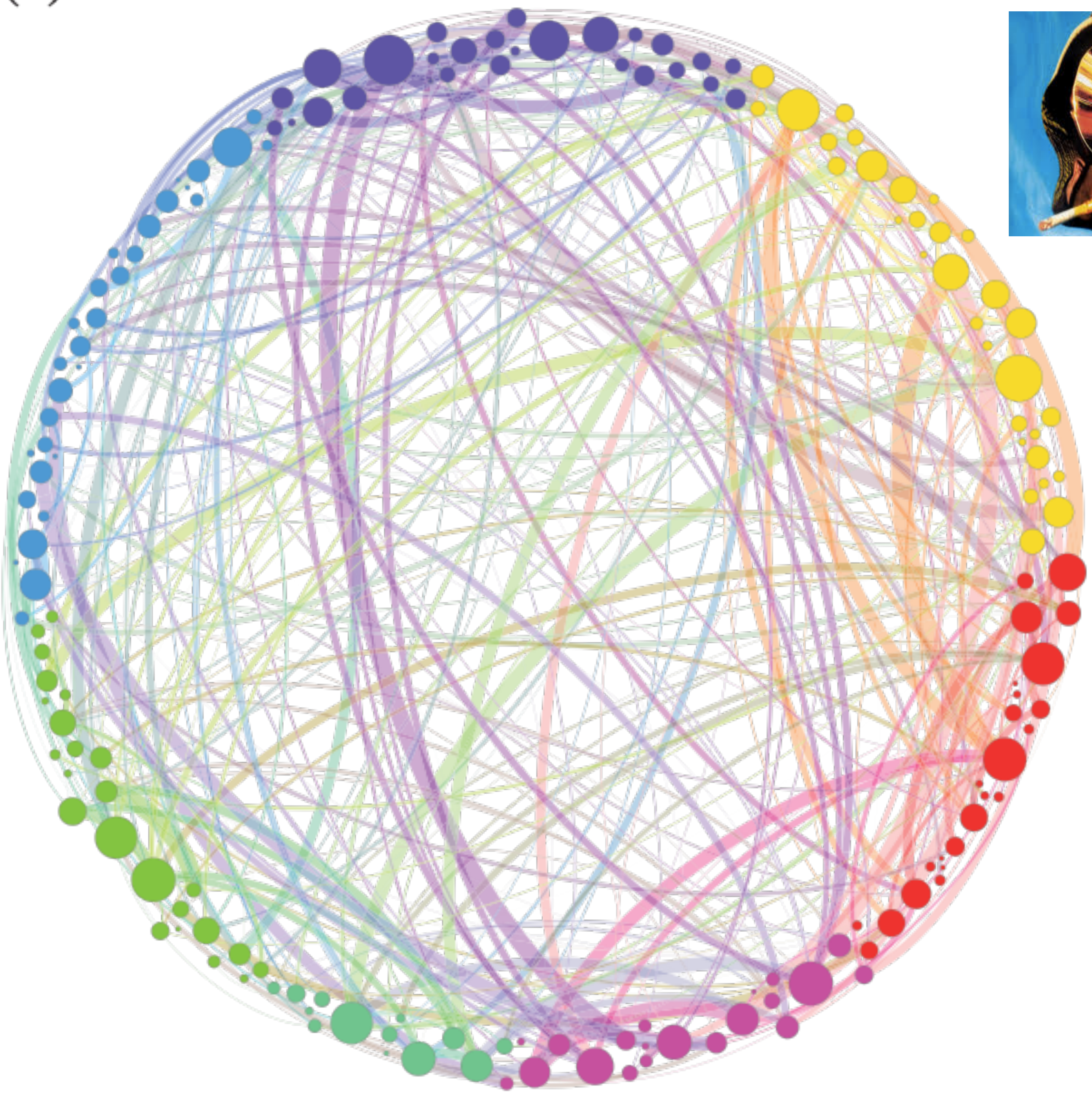
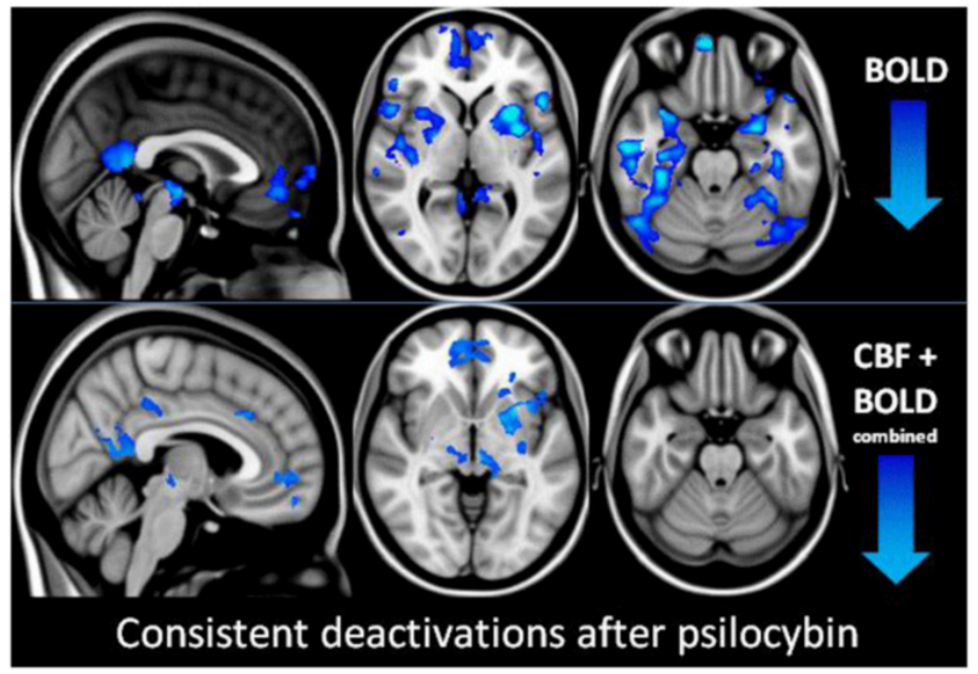


(b)

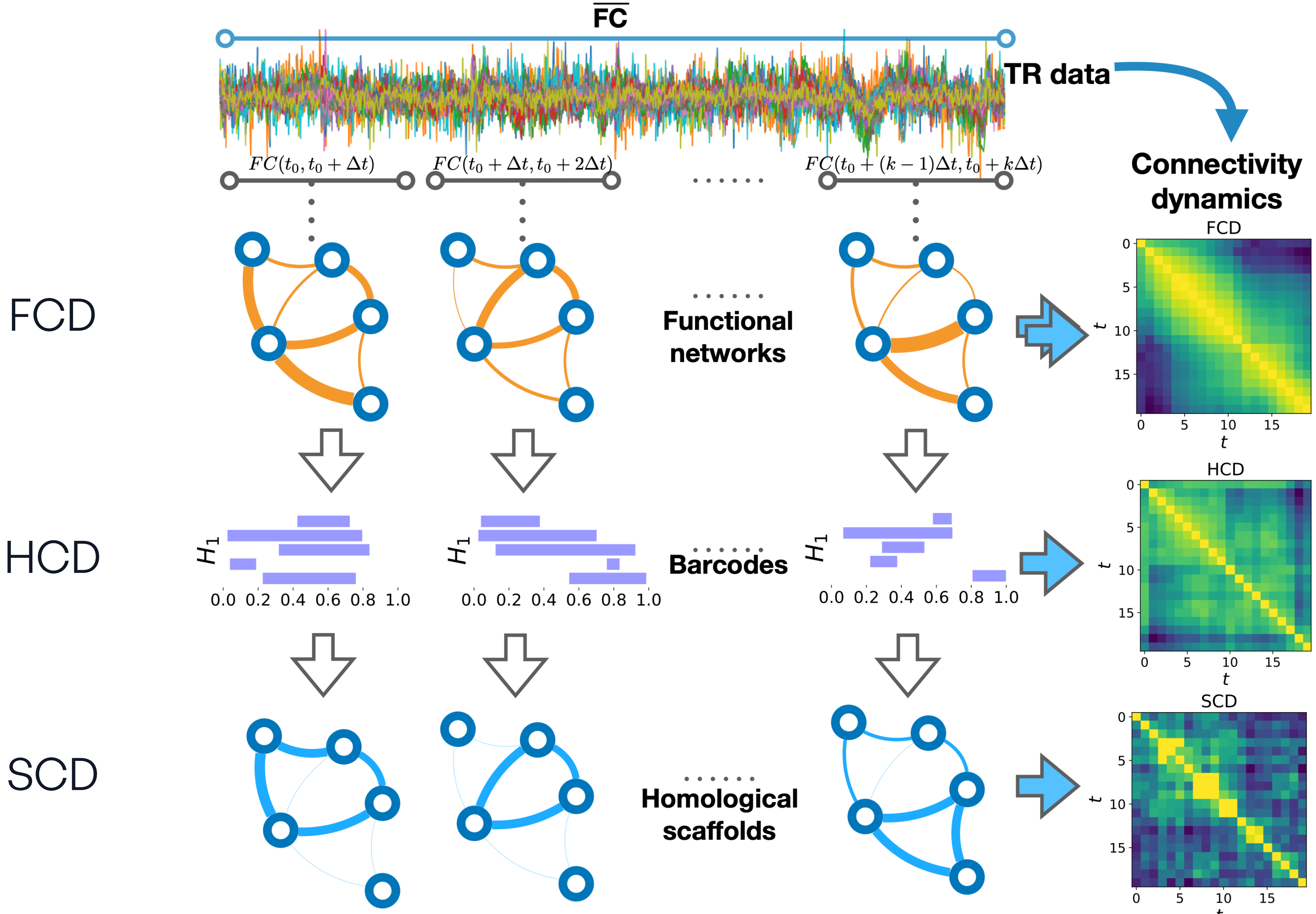




Distributed reorganisation of the hierarchy of functional circuits

Petri, Giovanni, et al. "Homological scaffolds of brain functional networks." Journal of The Royal Society Interface 11.101 (2014): 20140873.

Scaffold fingerprinting



Poetto, Saggar, Battaglia, Vaccarino, Rabuffo, Petri in prep

Scaffold fingerprinting

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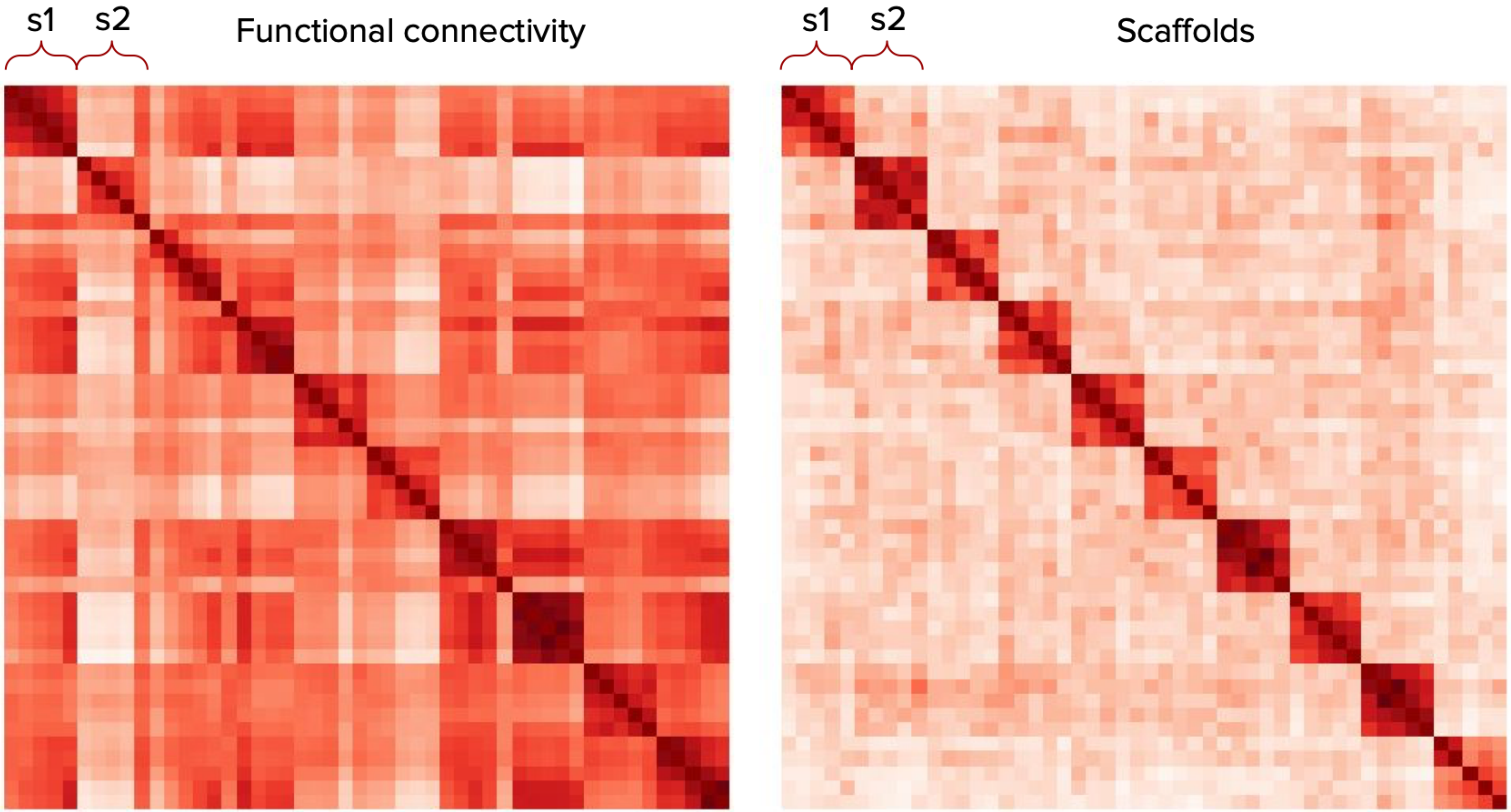
100 subjects (HCP), rs-fMRI, test+retest



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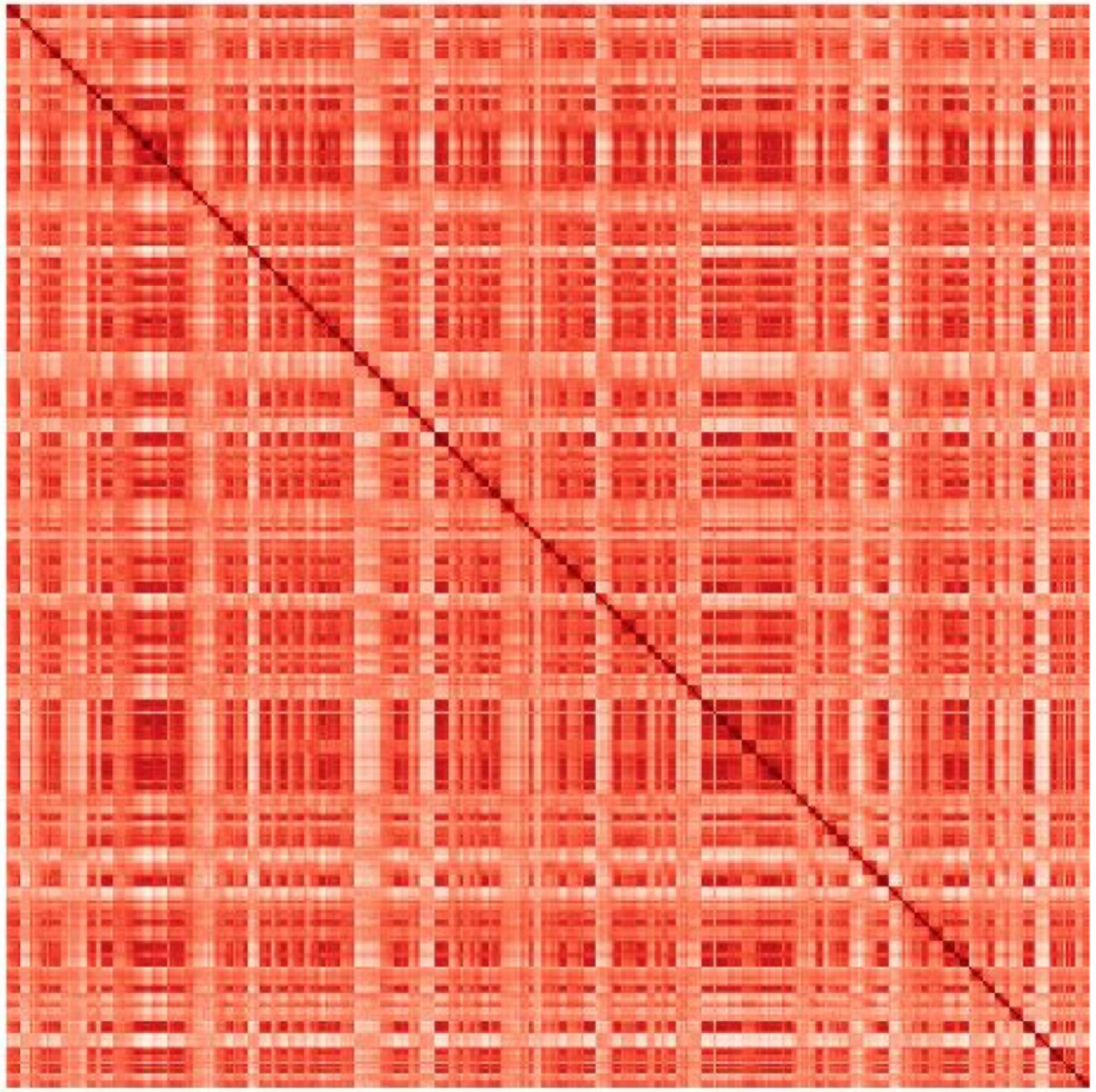
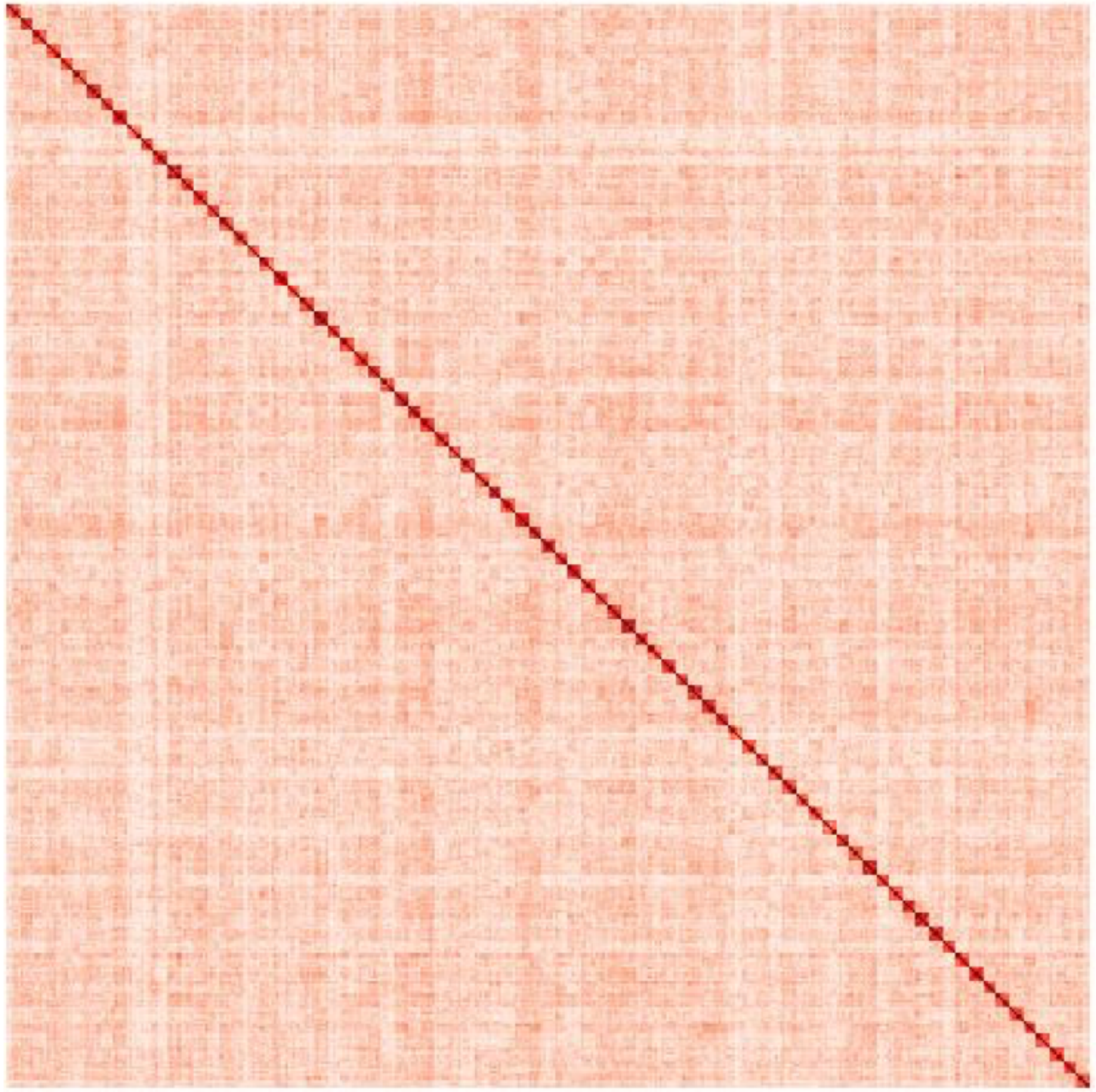
Functional connectivity



Scaffolds



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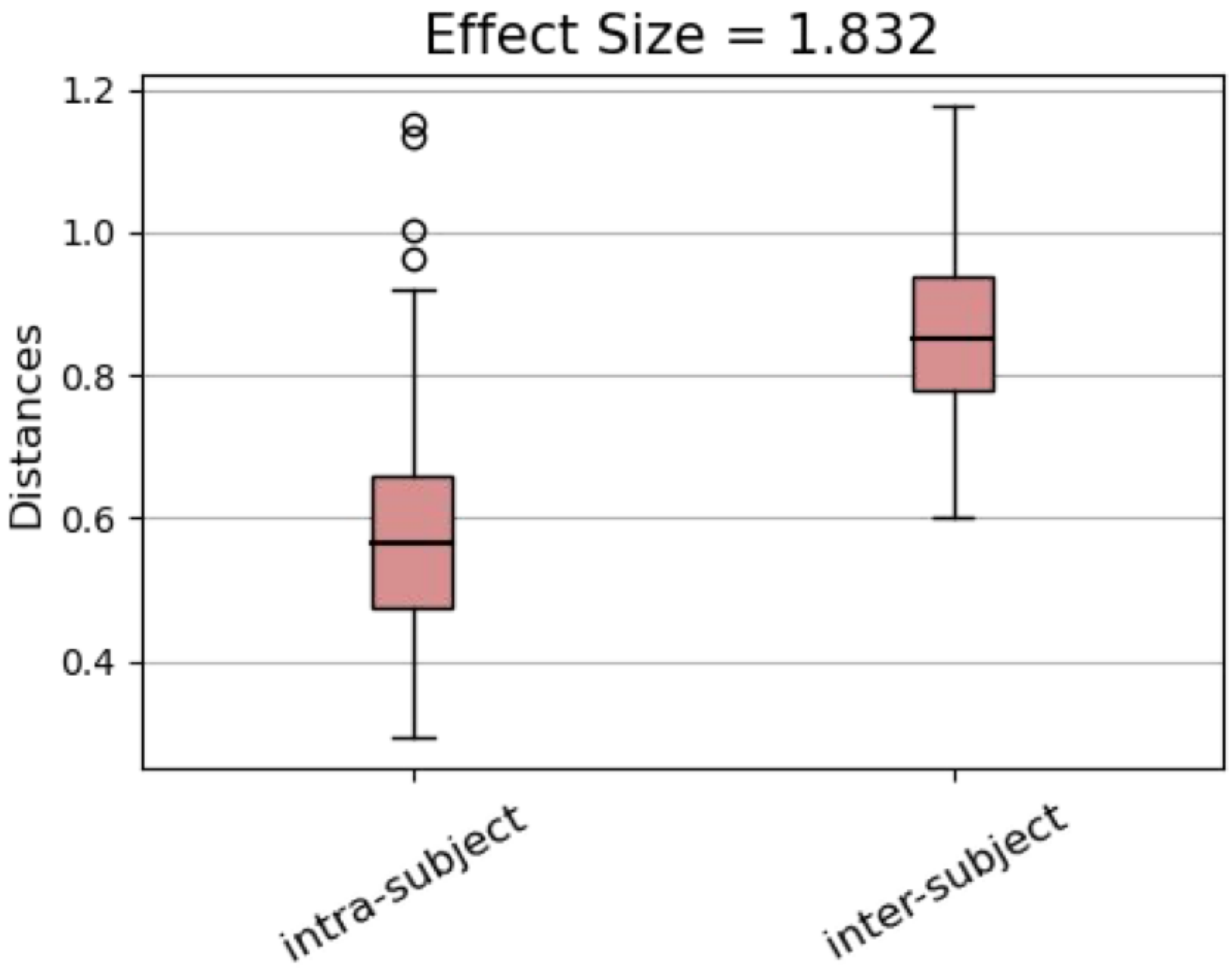

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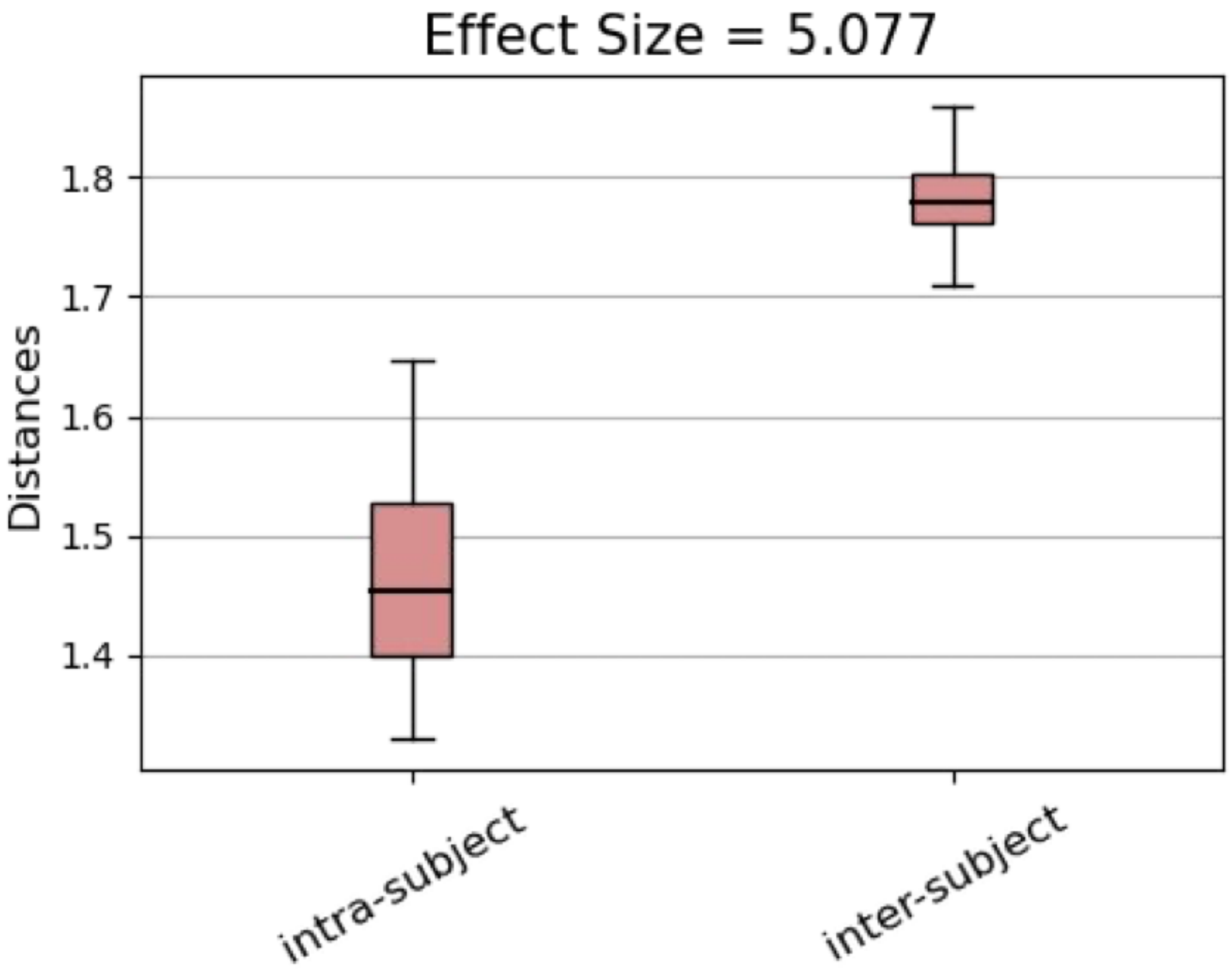

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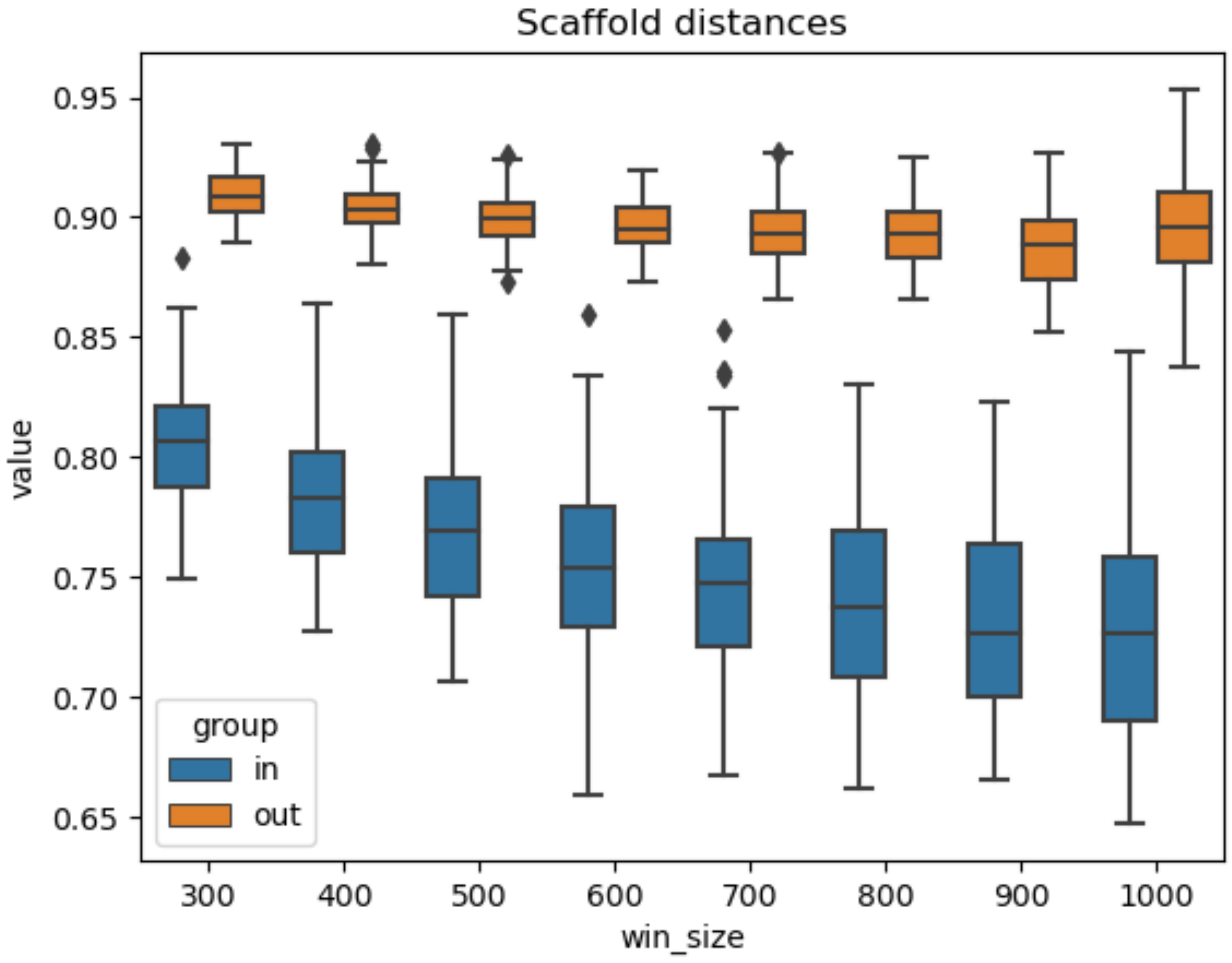

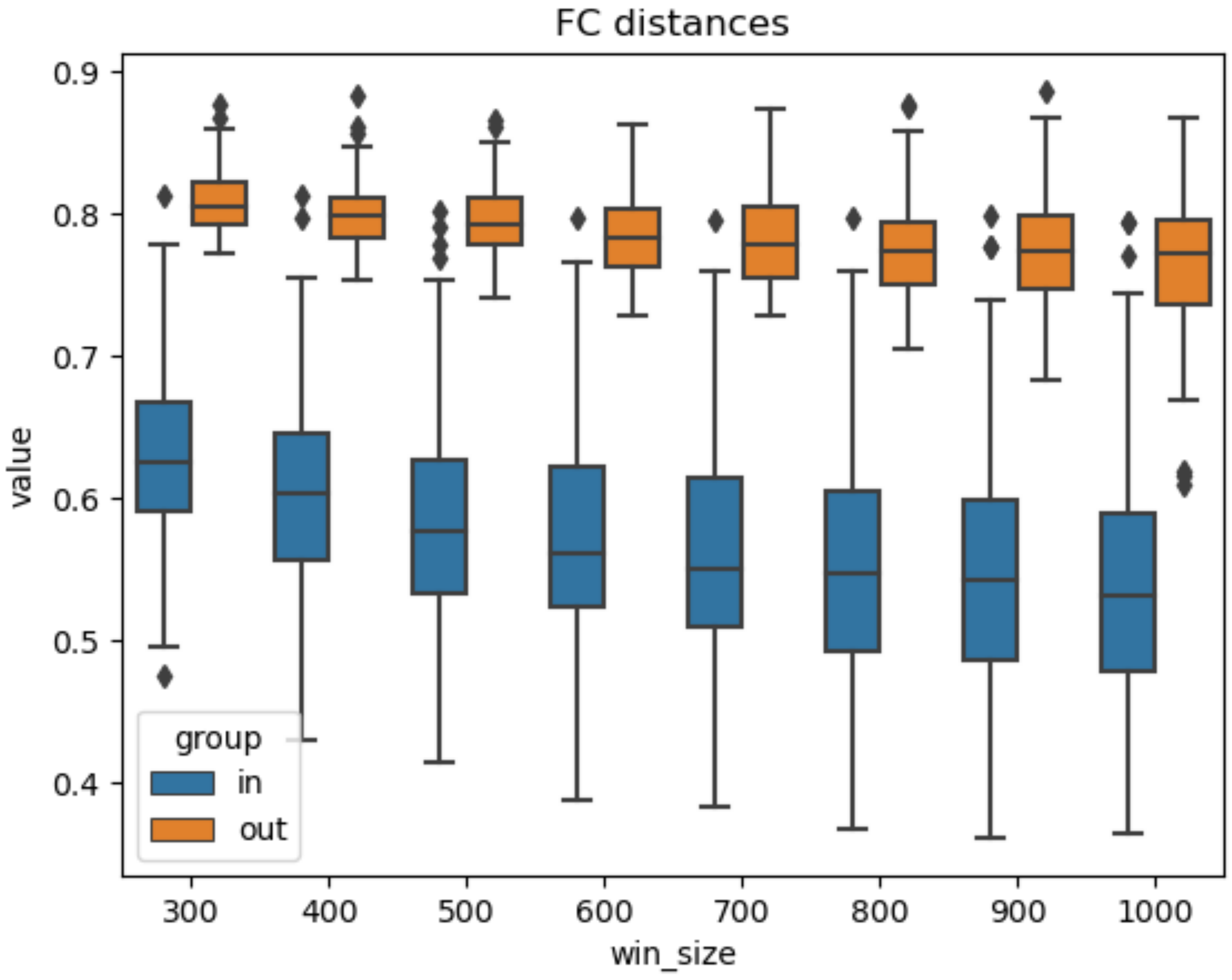

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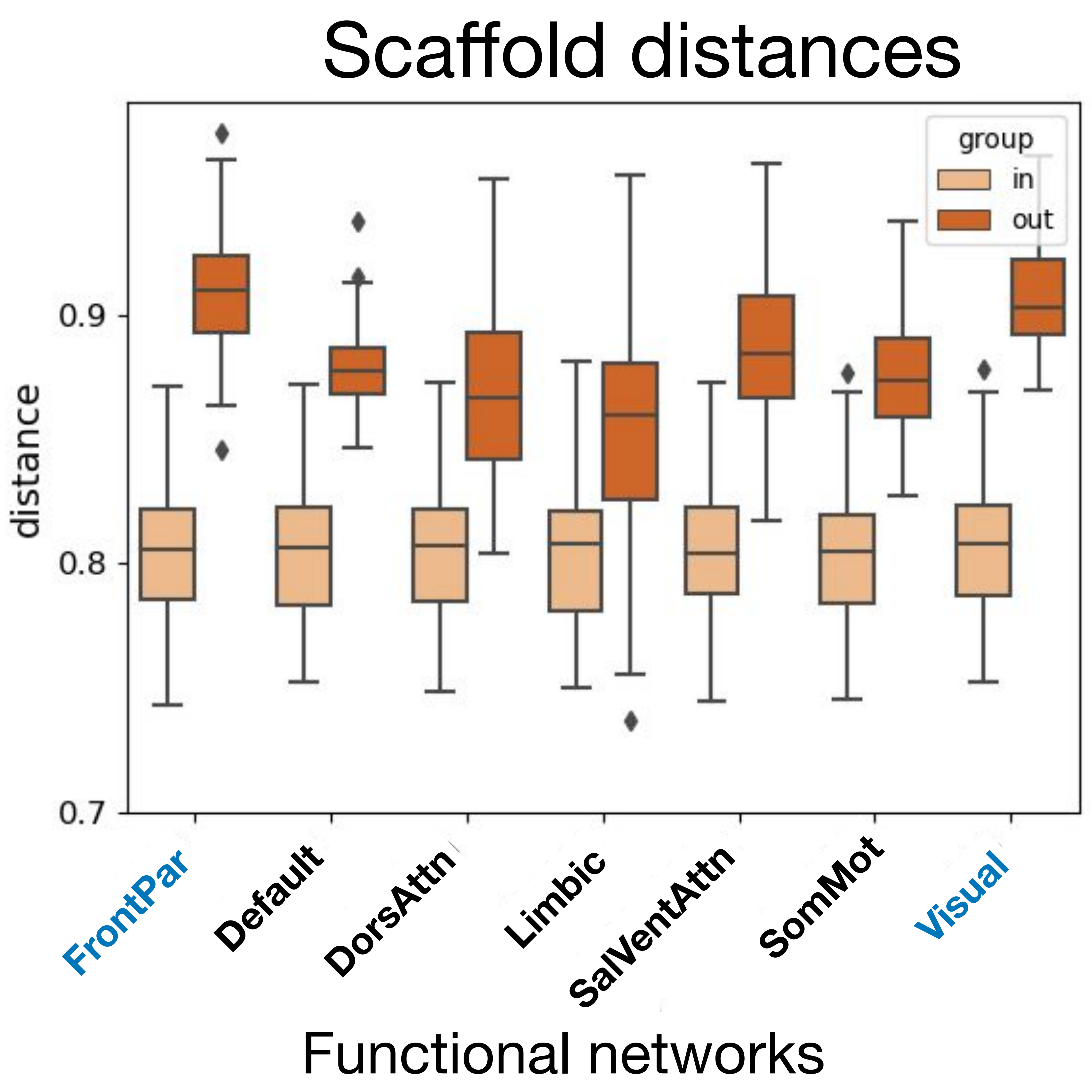

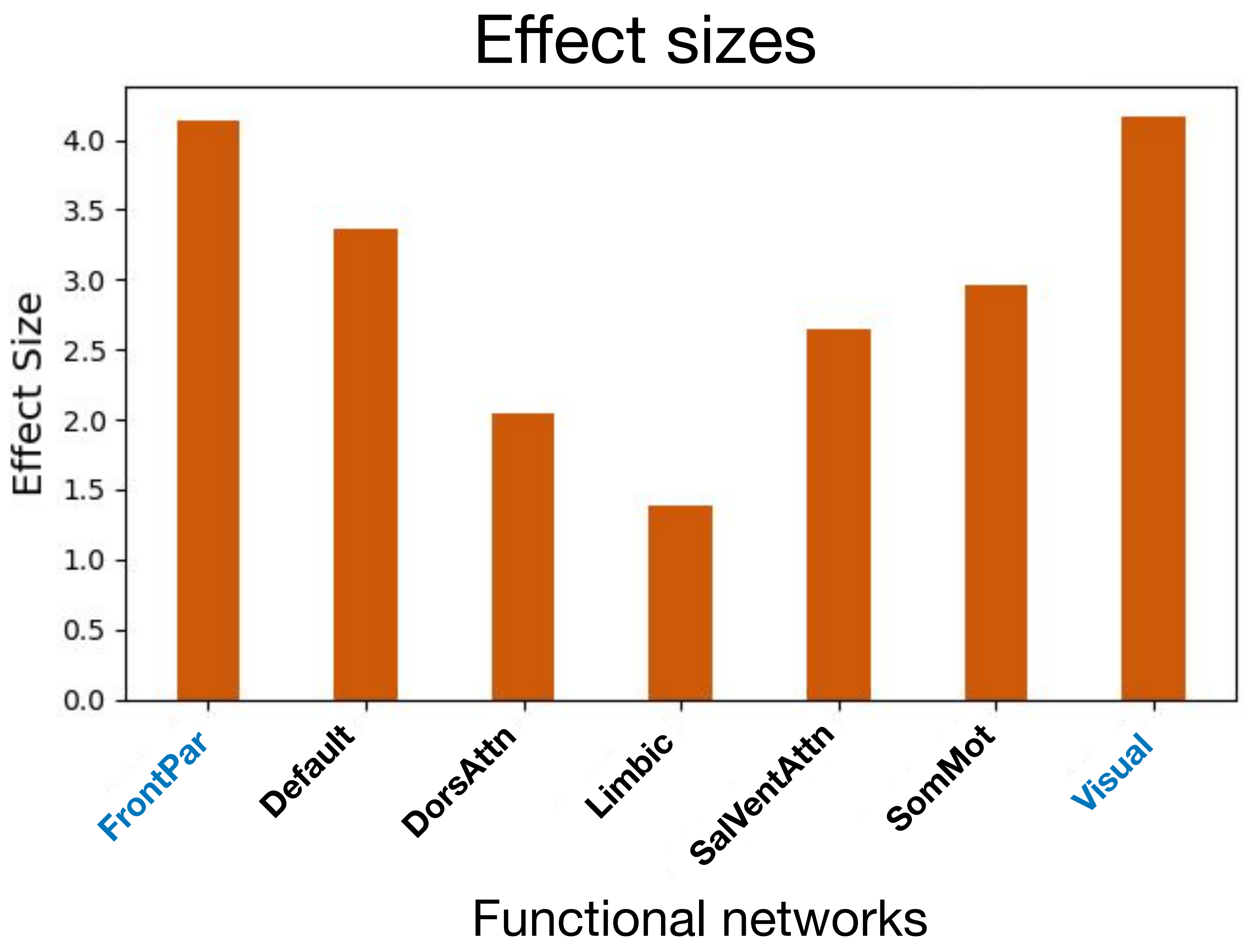

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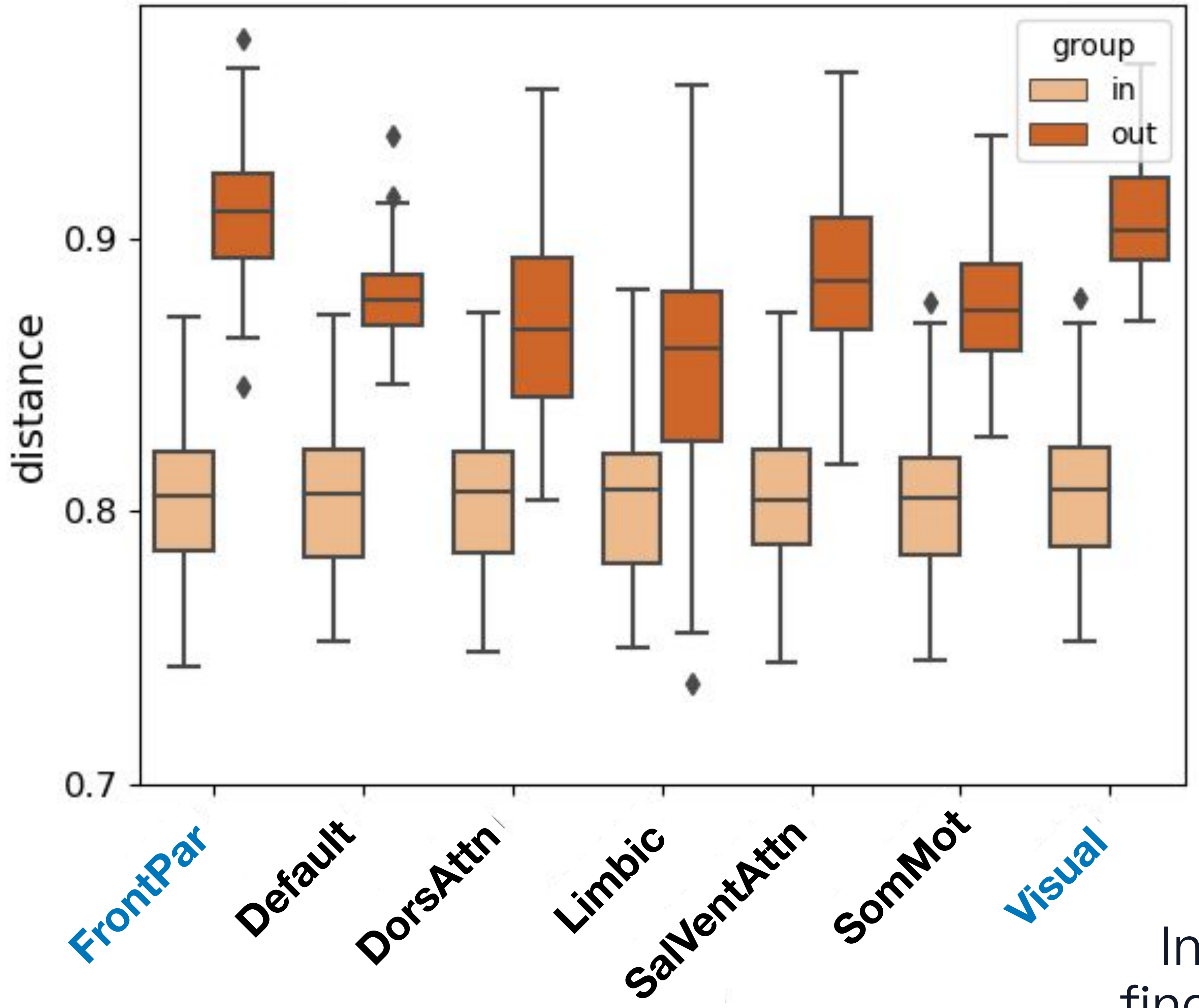
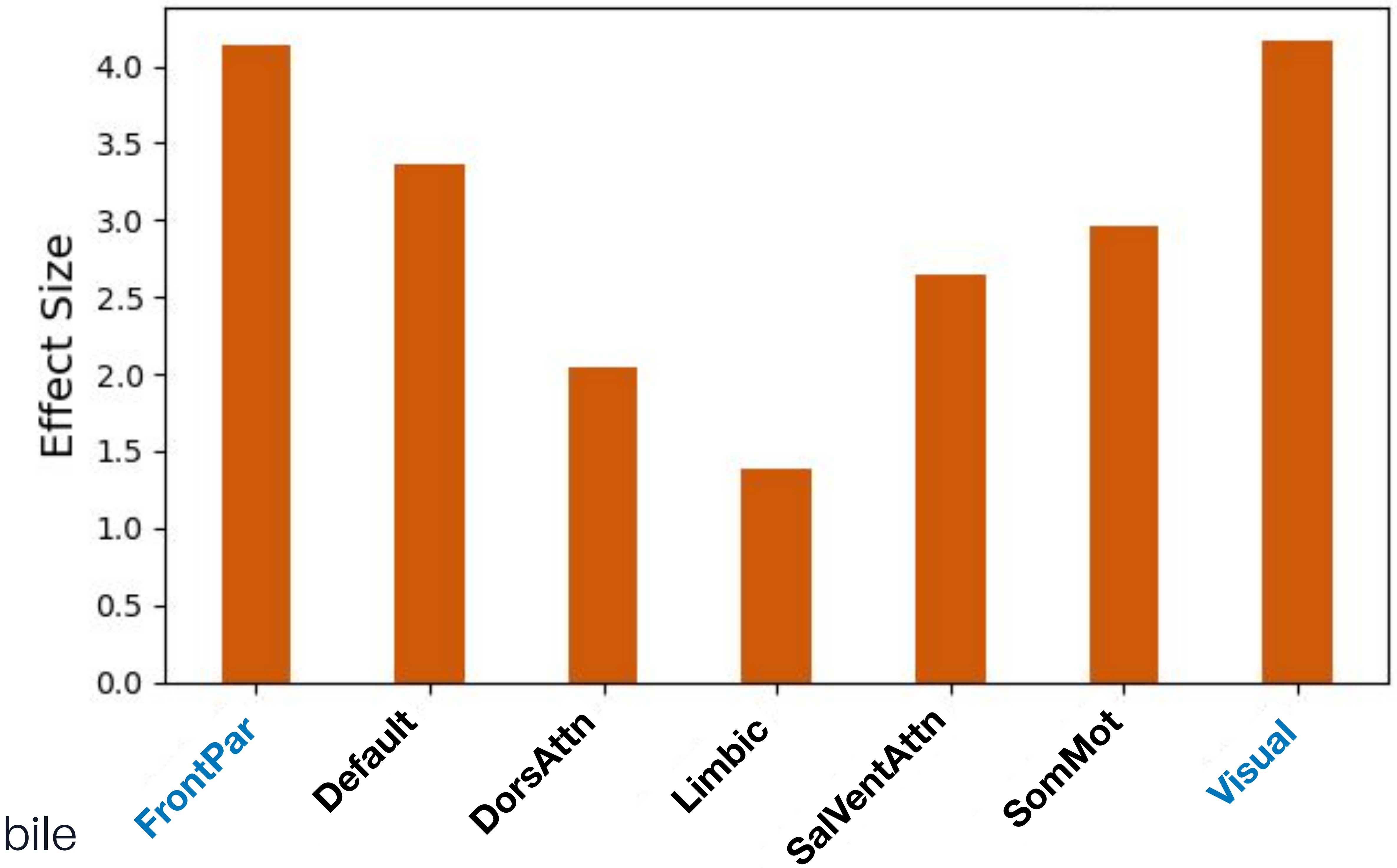
Scaffold fingerprinting

Scaffold distances



Functional networks

Effect sizes



Functional networks

Incredibile fingerprinting capacity!

No idea on the origin!

Poetto, Saggar, Battaglia, Vaccarino, Rabuffo, Petri in prep

Scaffold fingerprinting

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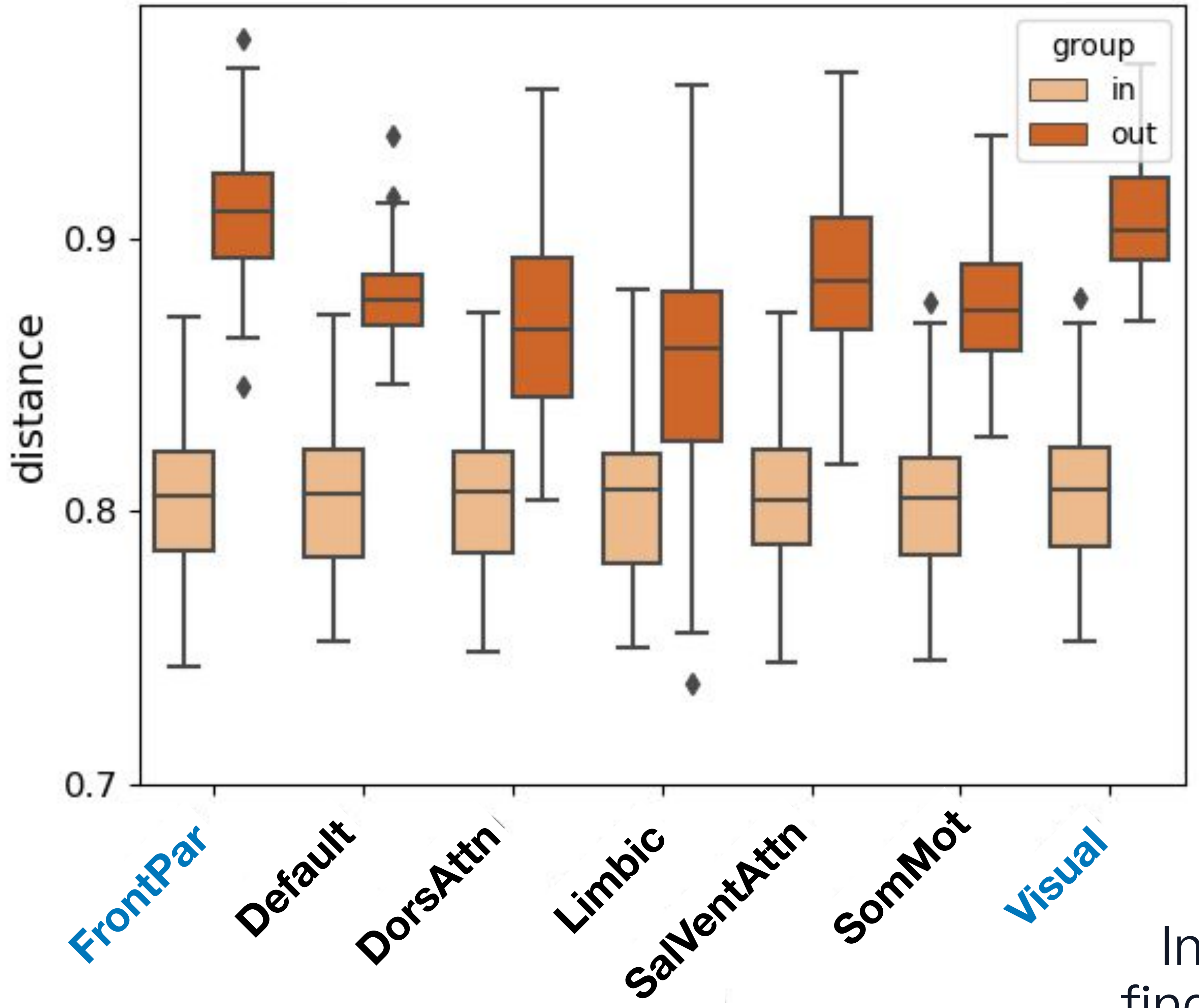

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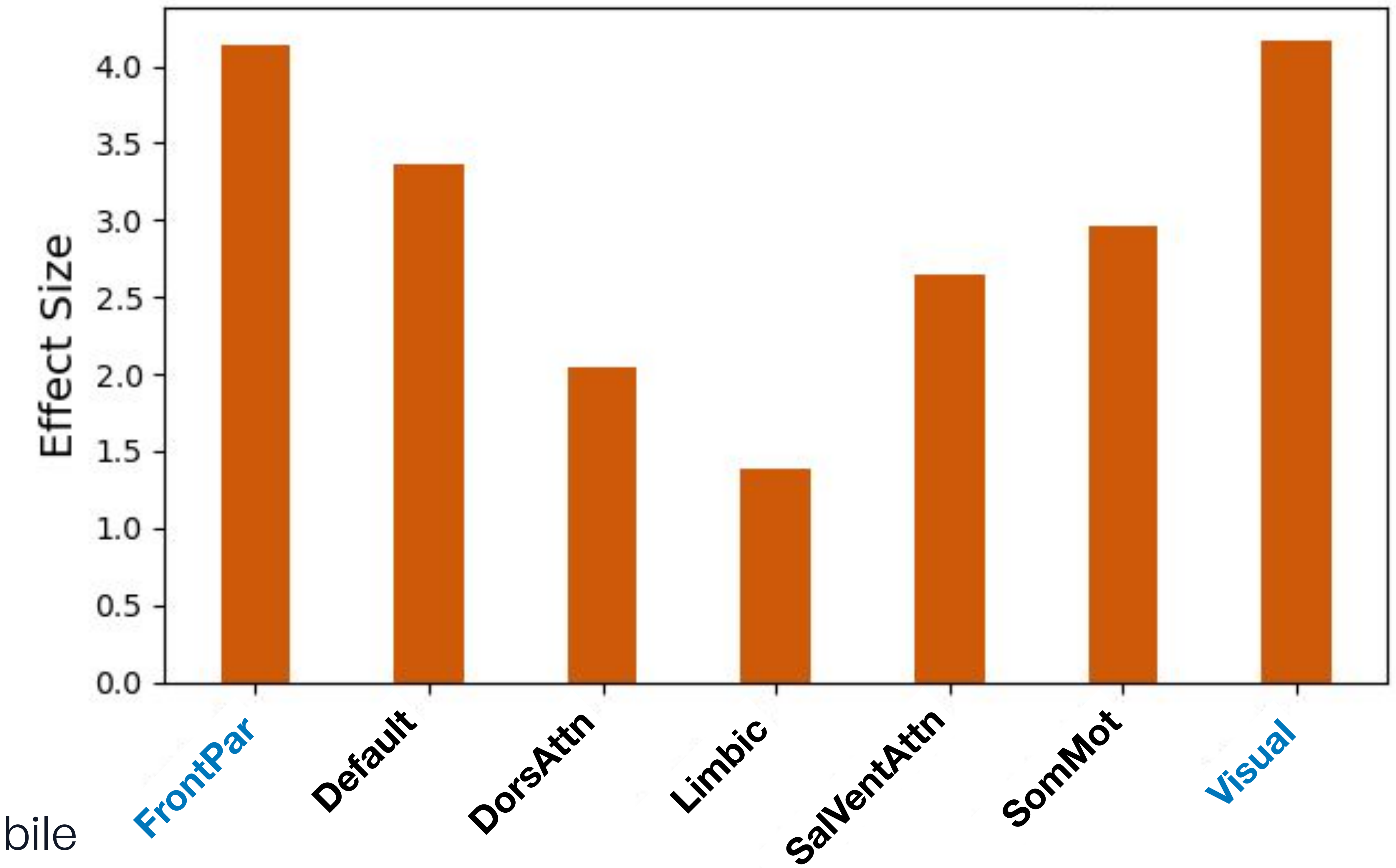

Functional networks

Poetto, Saggar, Battaglia, Vaccarino, Rabuffo, Petri in prep

Topo+Info brain fingerprinting

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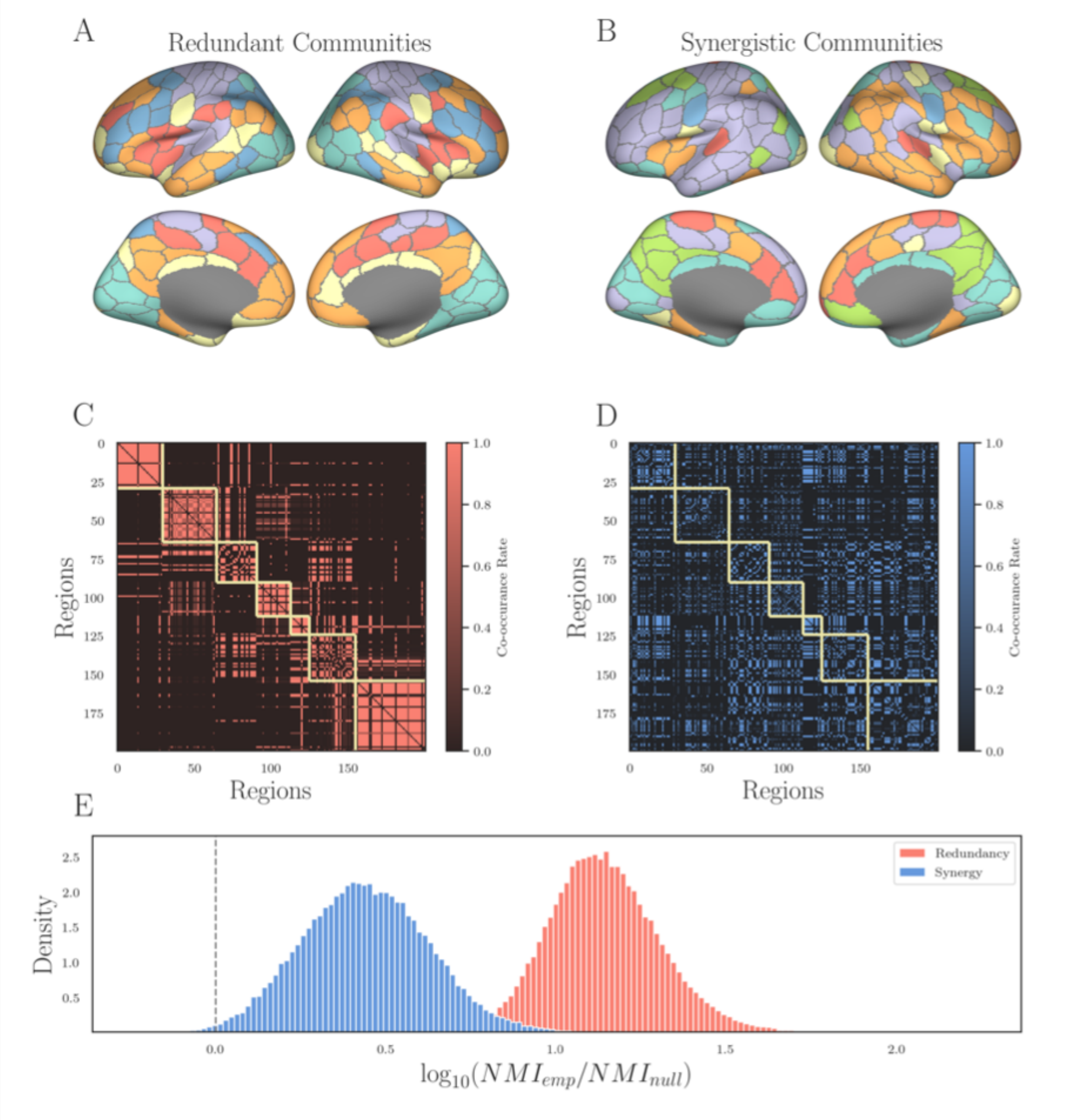

Varley, Thomas F., et al. *arXiv preprint*

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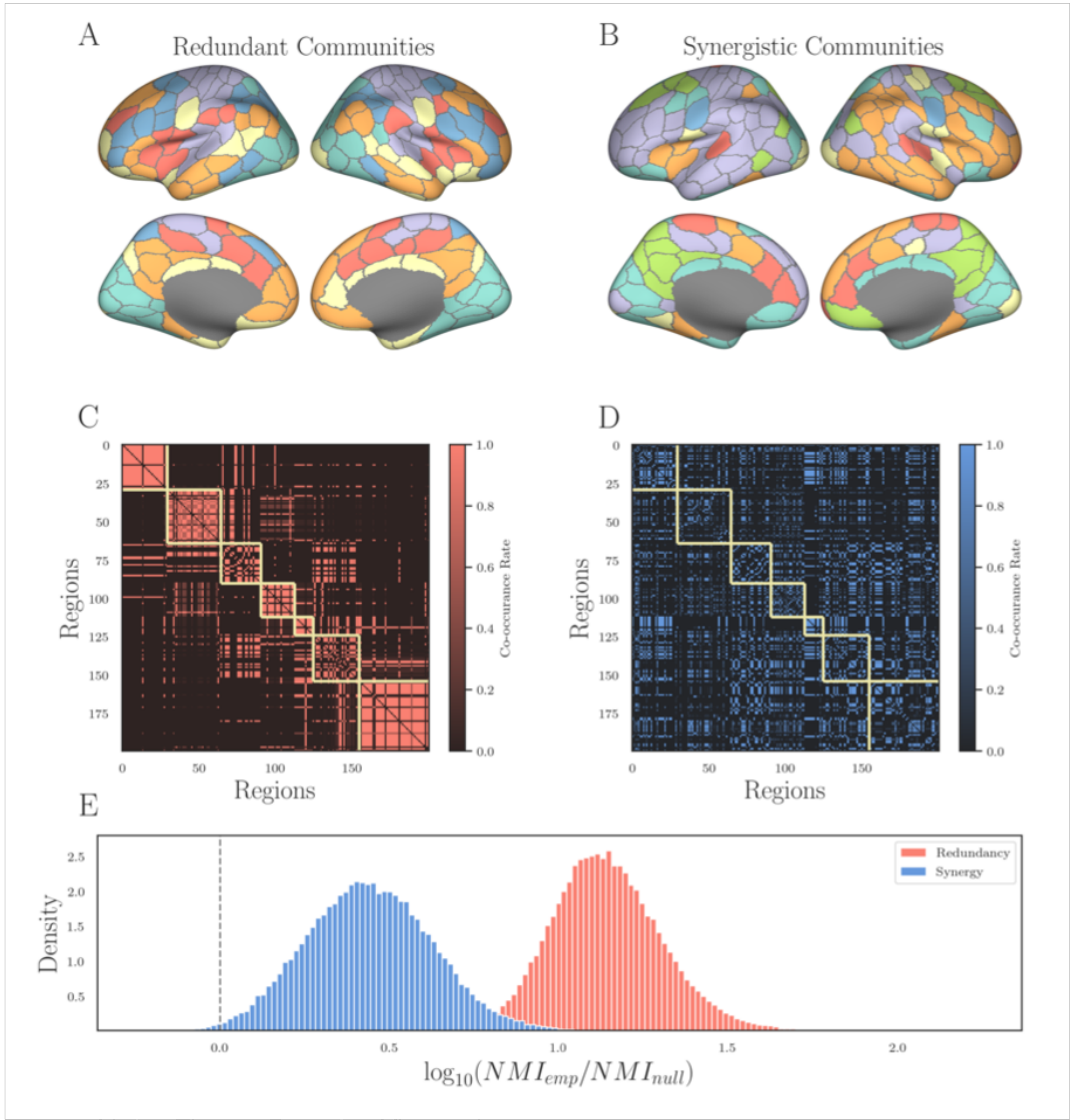

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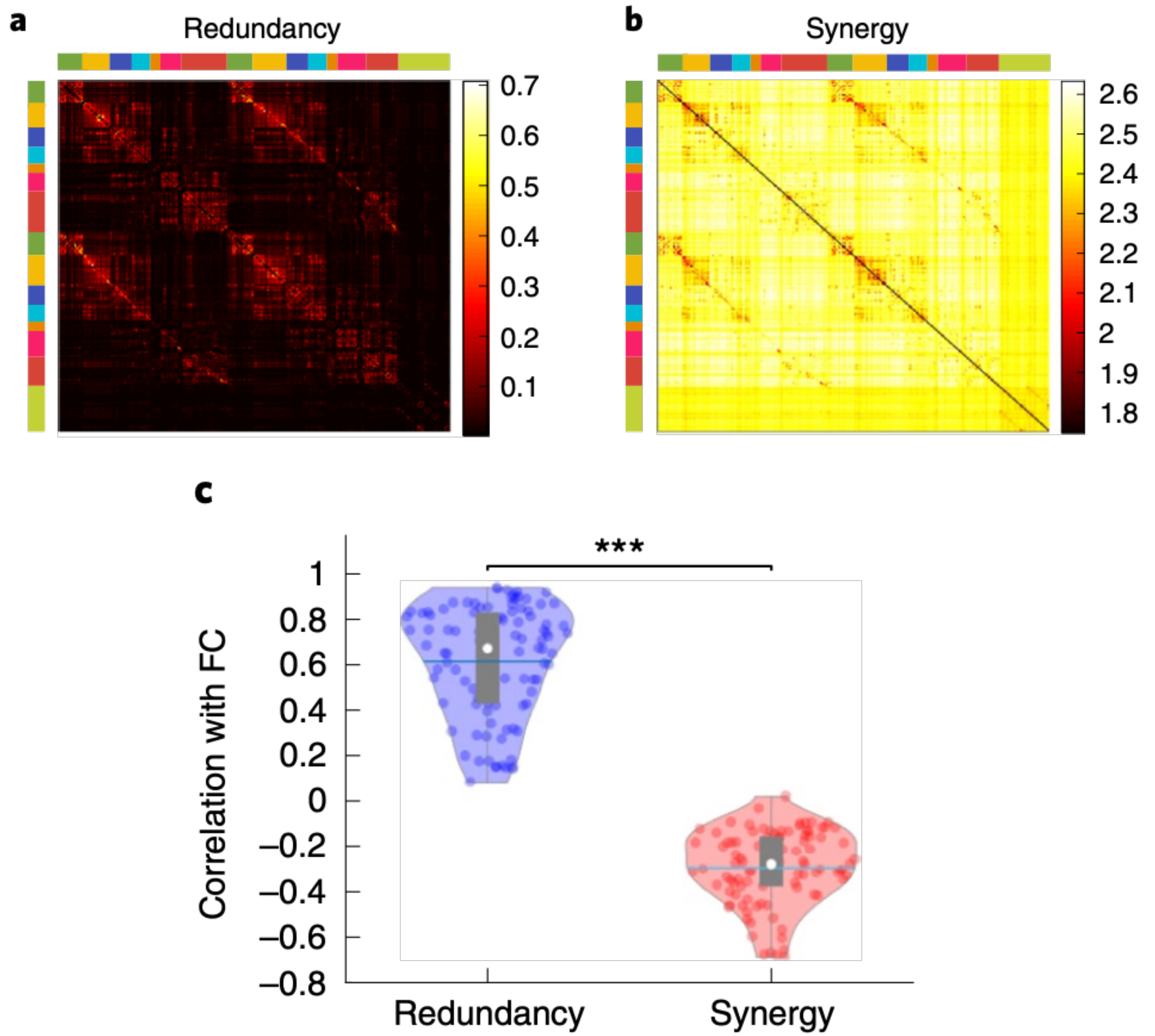


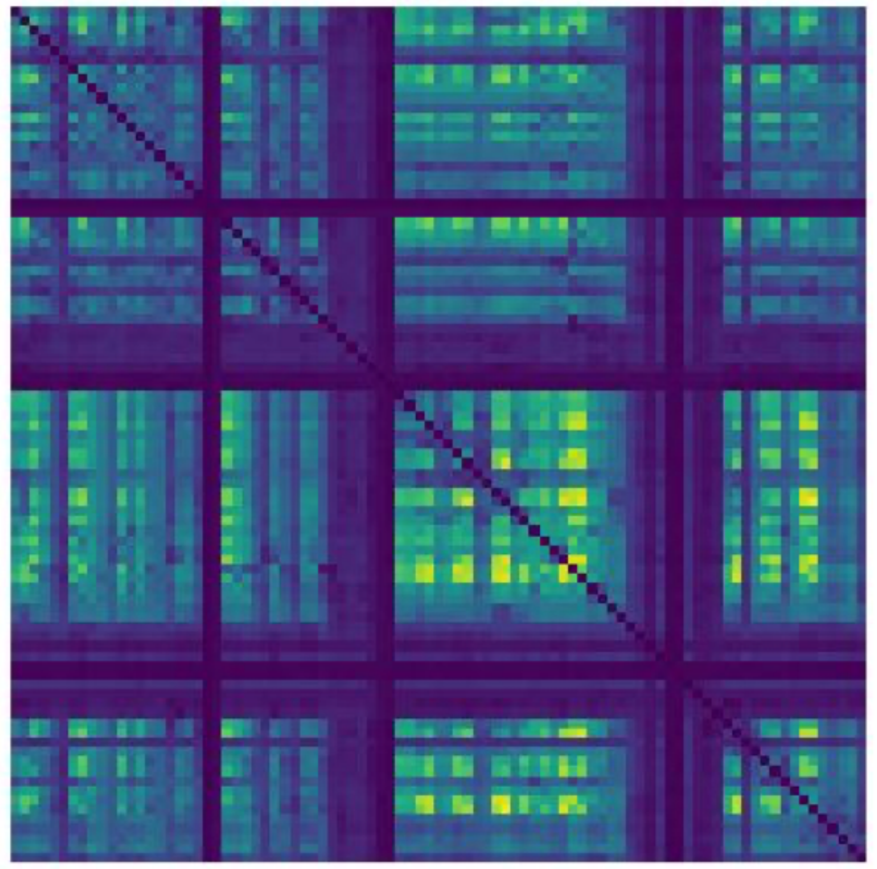
Luppi, Andrea I., et al. *Nature Neuroscience* 25.6 (2022):

Topo+Info brain fingerprinting

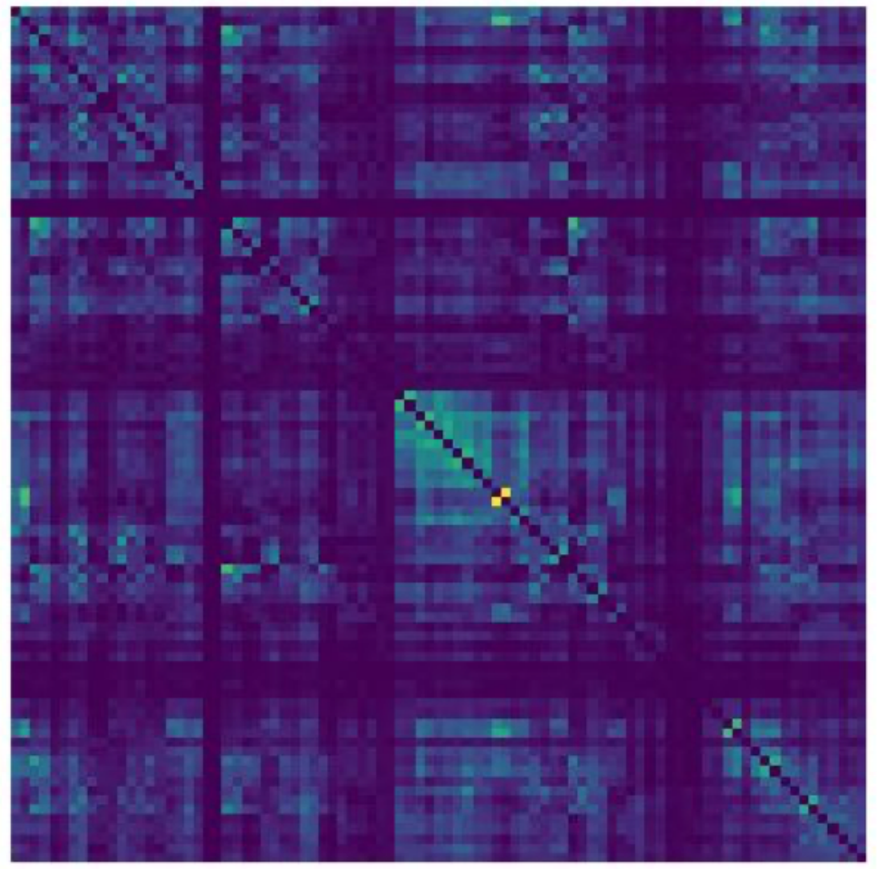
Poetto, Saggar, Battaglia, Vaccarino, Rabuffo, Petri in prep

Topo+Info brain fingerprinting

Synergy



Redundancy



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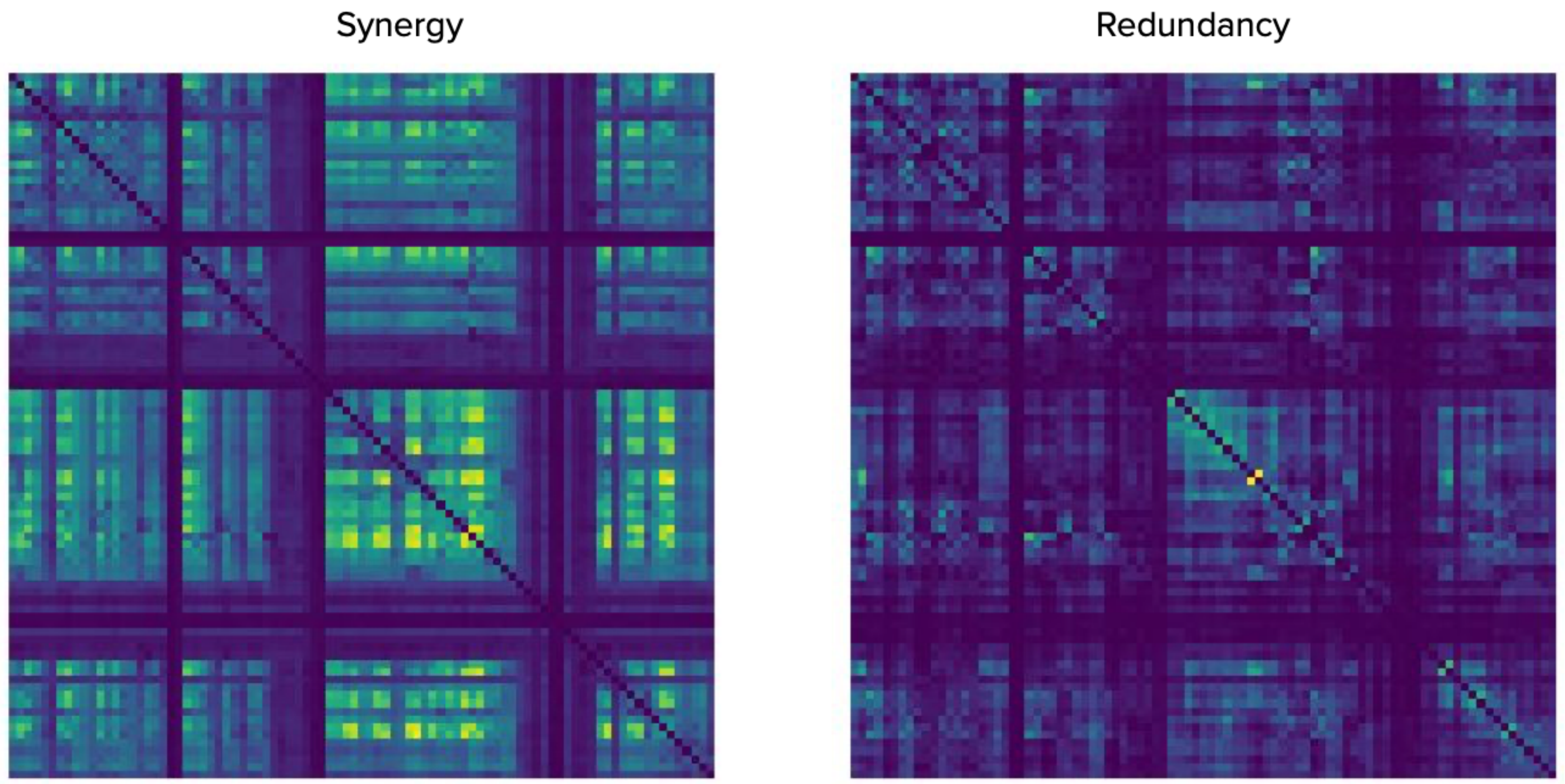

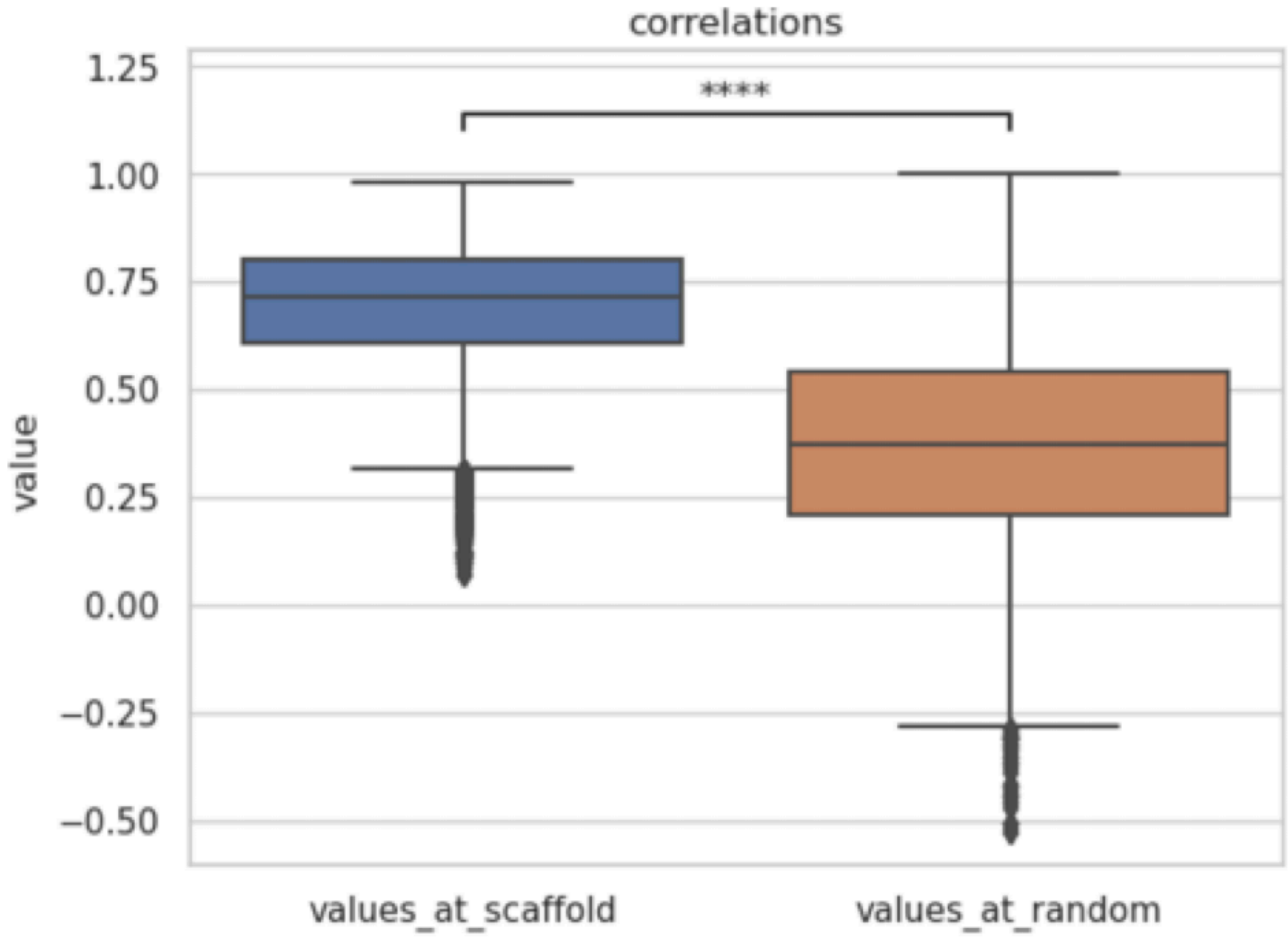

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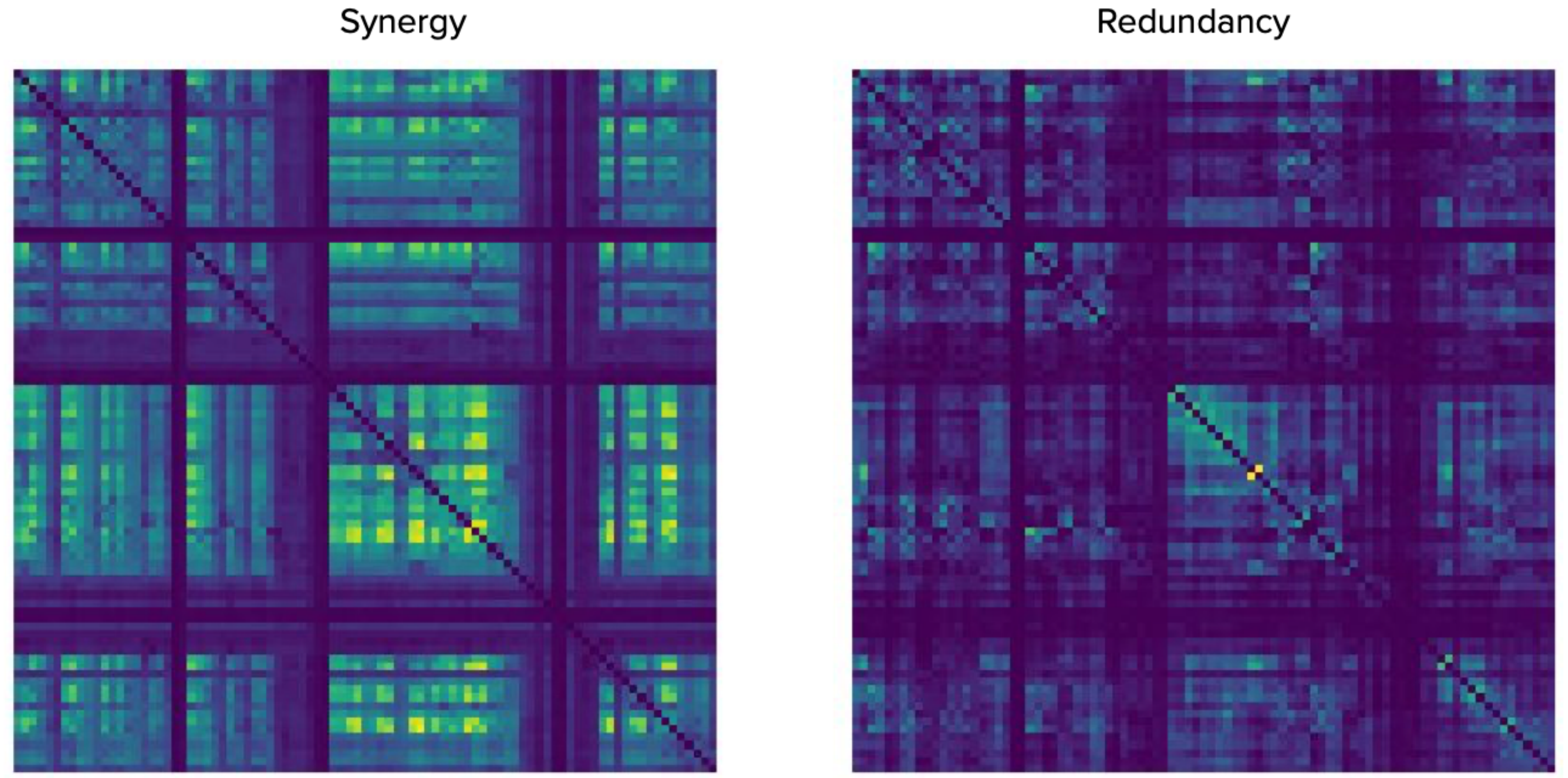

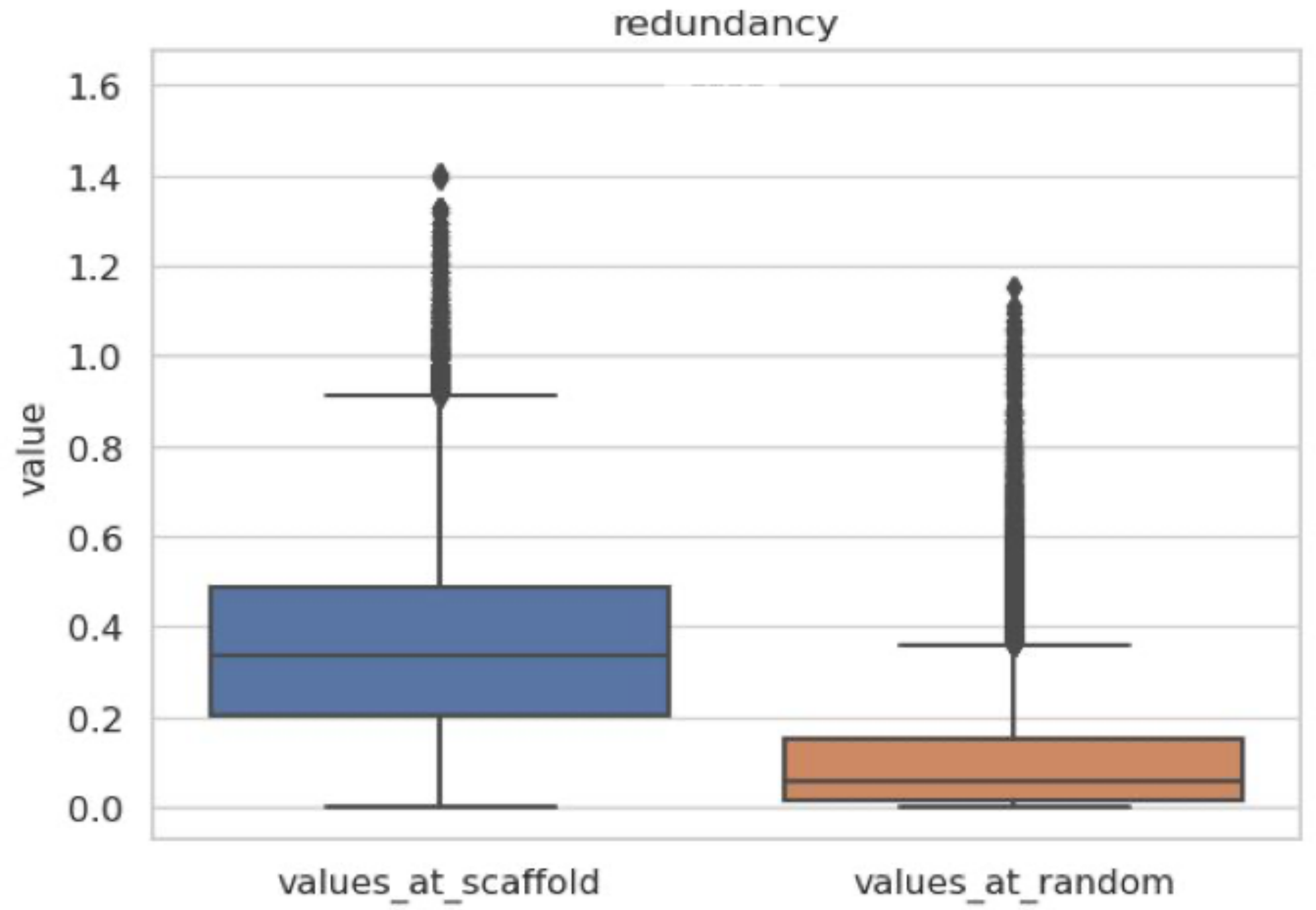

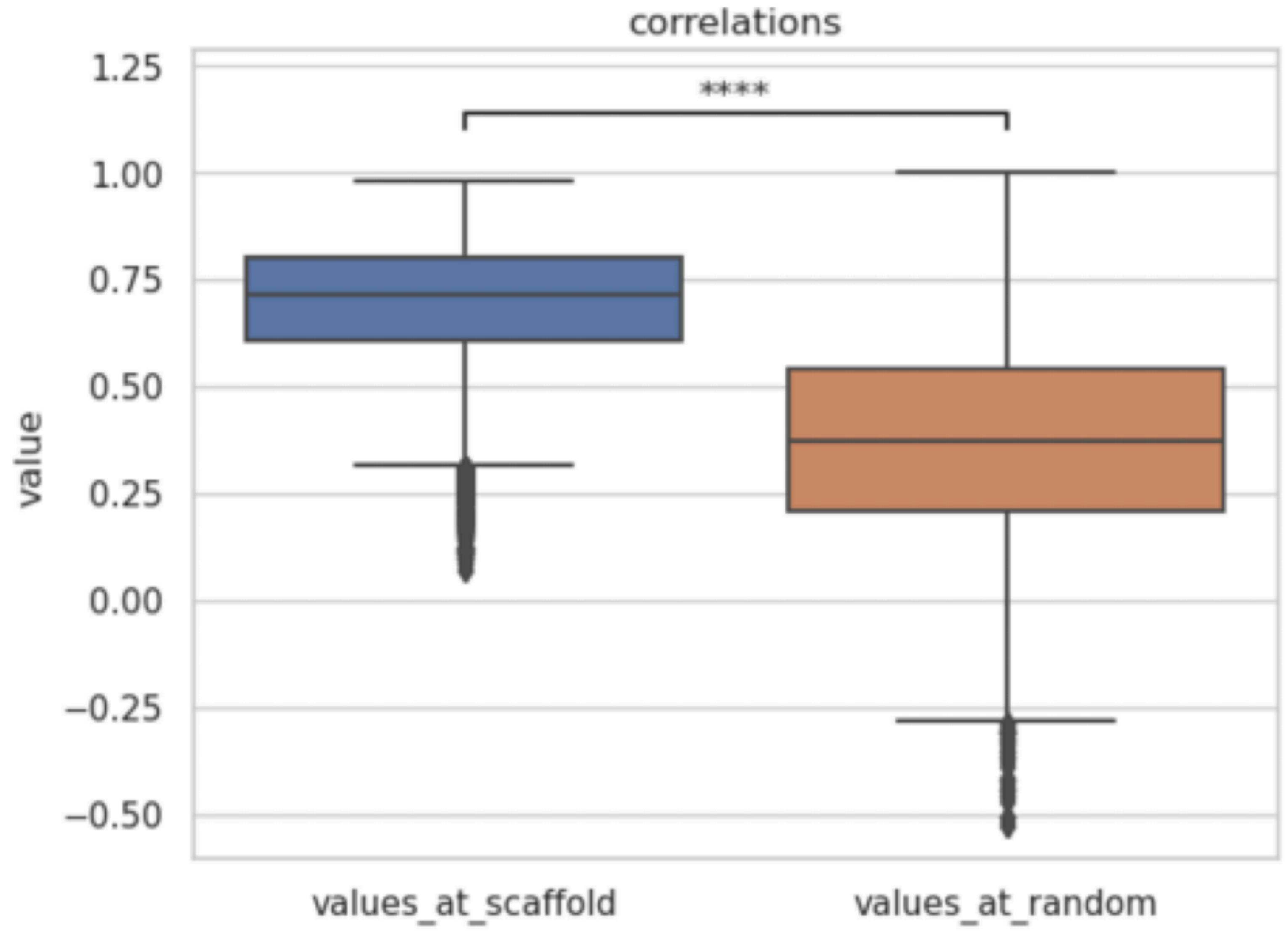

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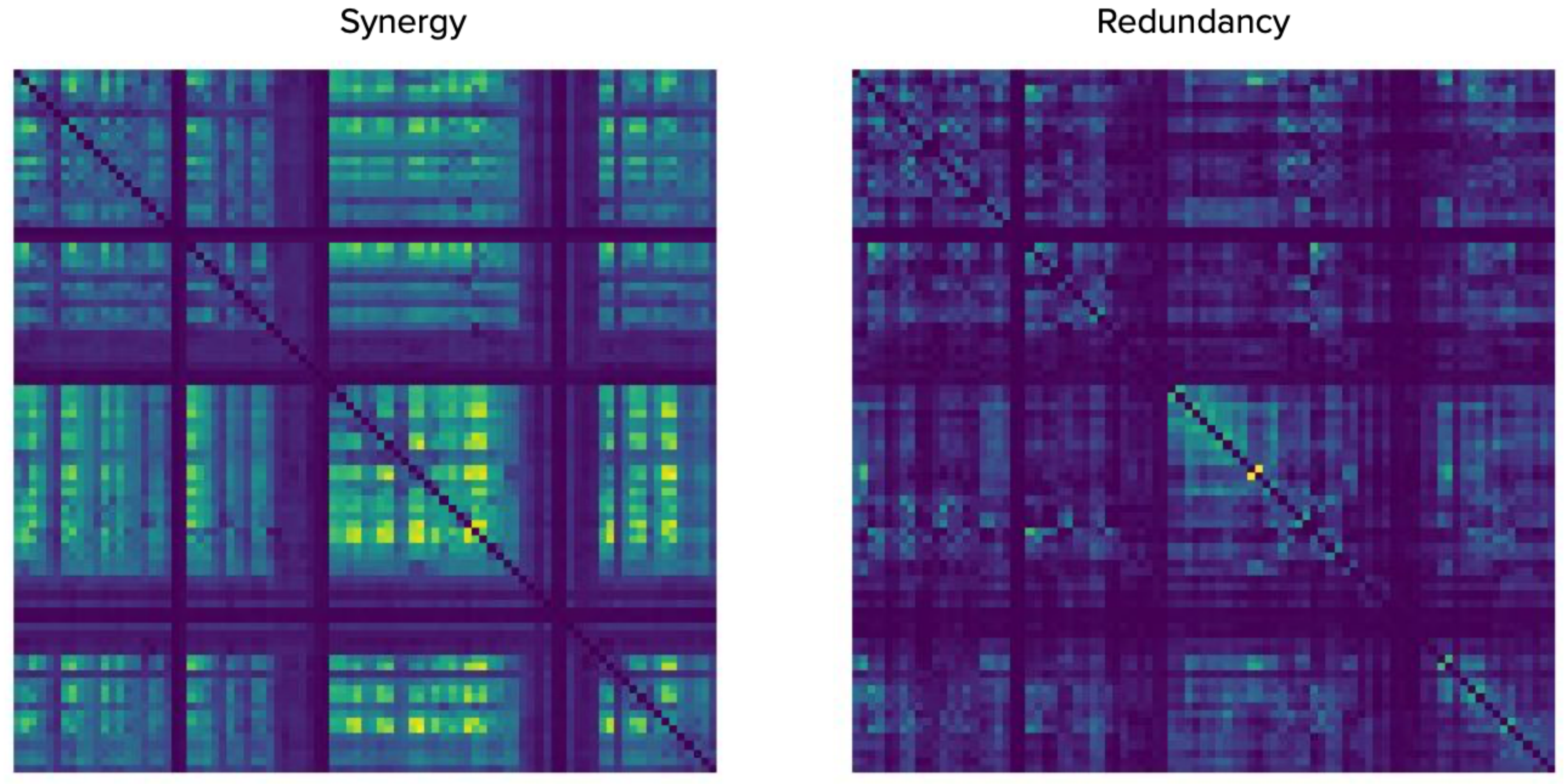

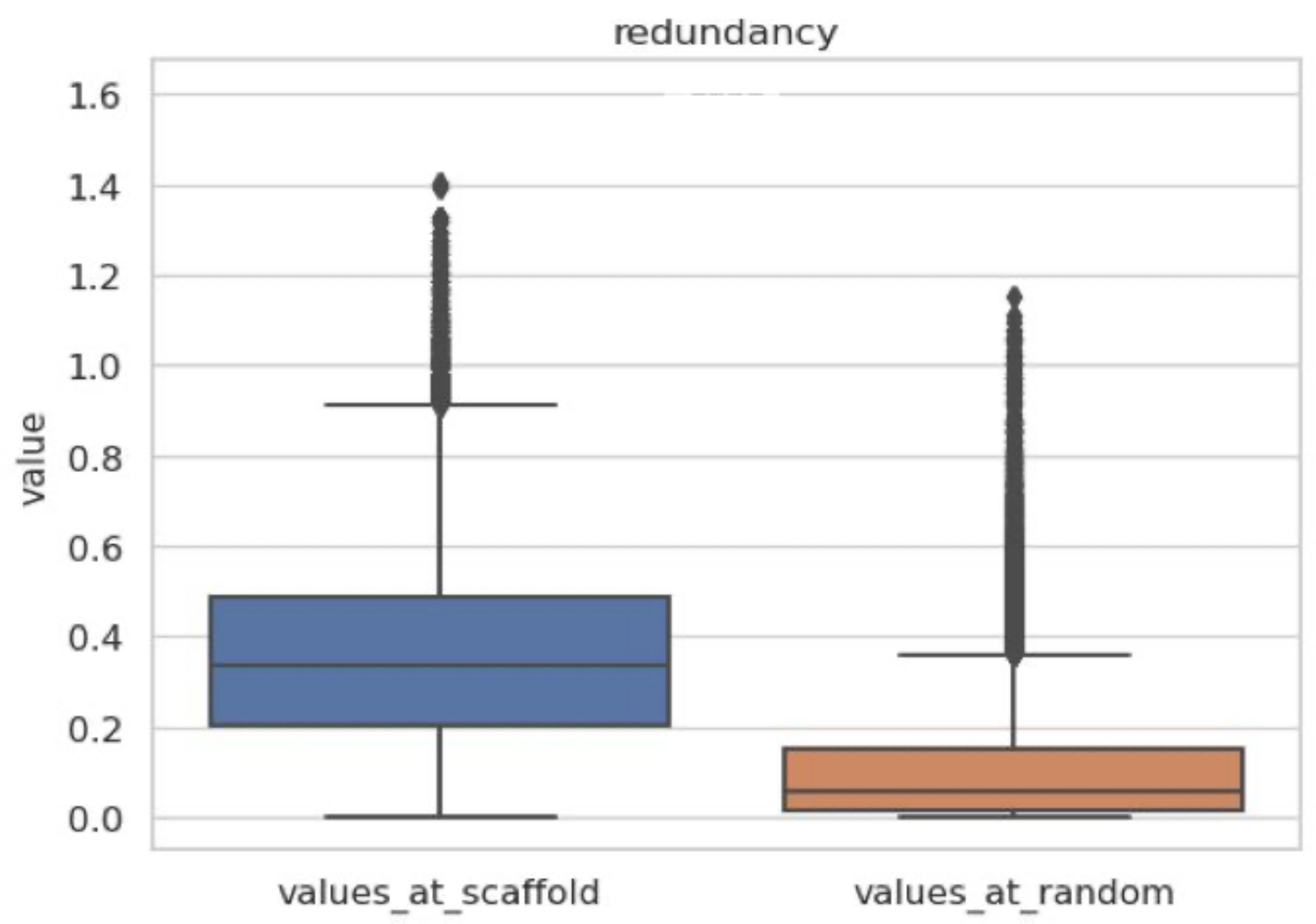

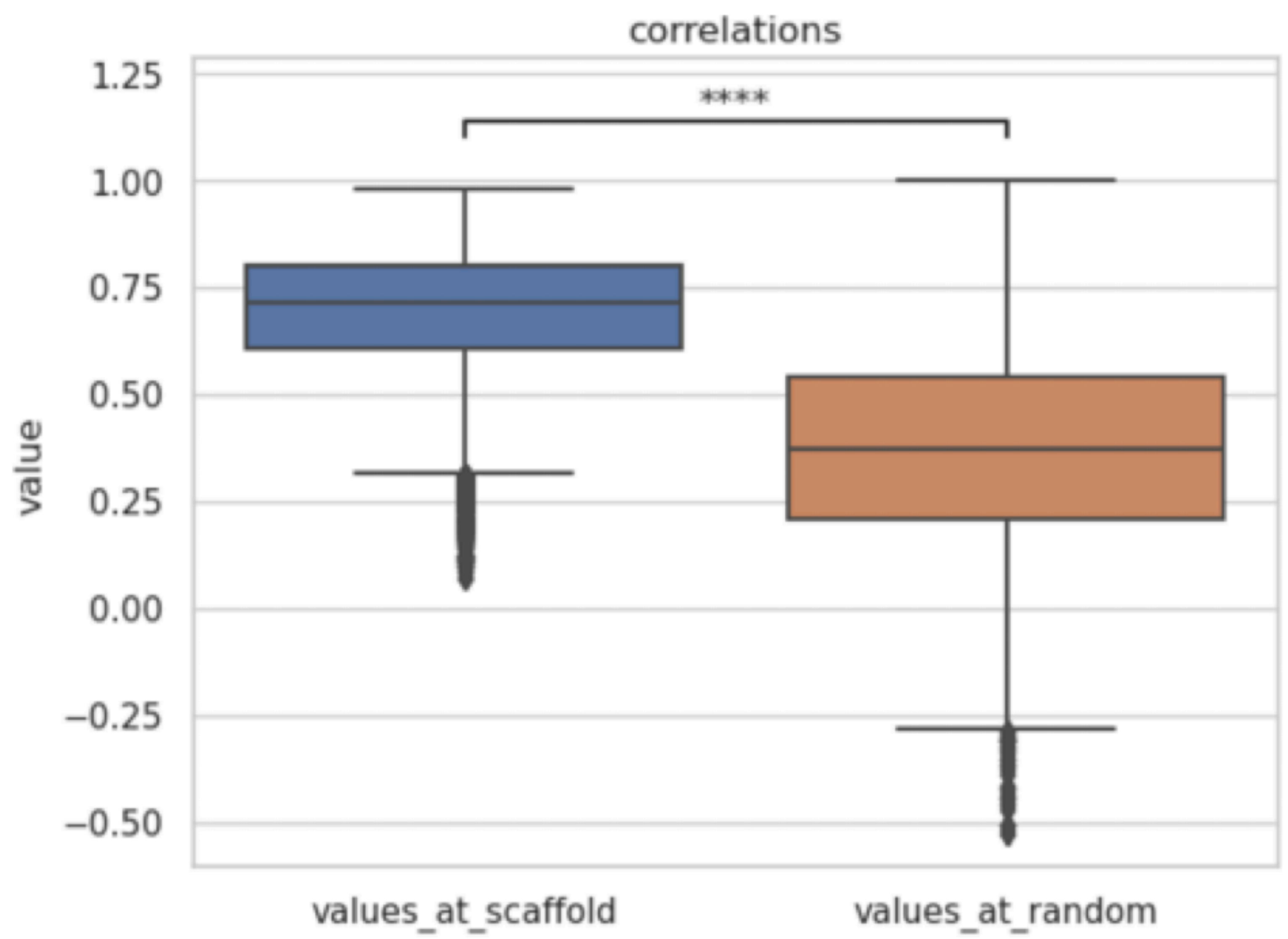

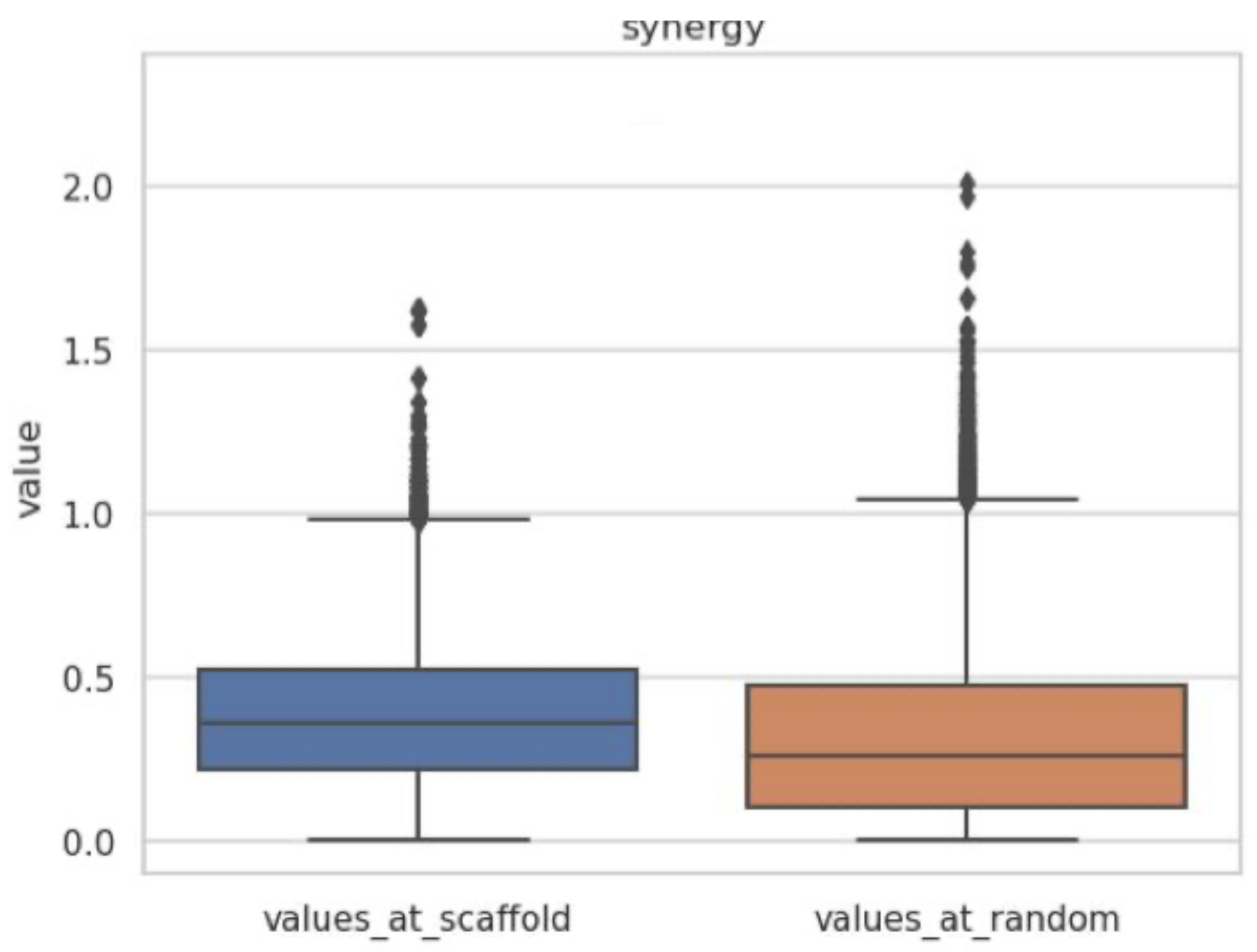

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Summing up

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- “Long” timescales (at least 100TRs fMRI)

What about time?

nature physics

Article https://doi.org/10.1038/s41567-022-01852-0

Higher-order organization of multivariate time series

Received: 18 March 2022

Accepted: 21 October 2022

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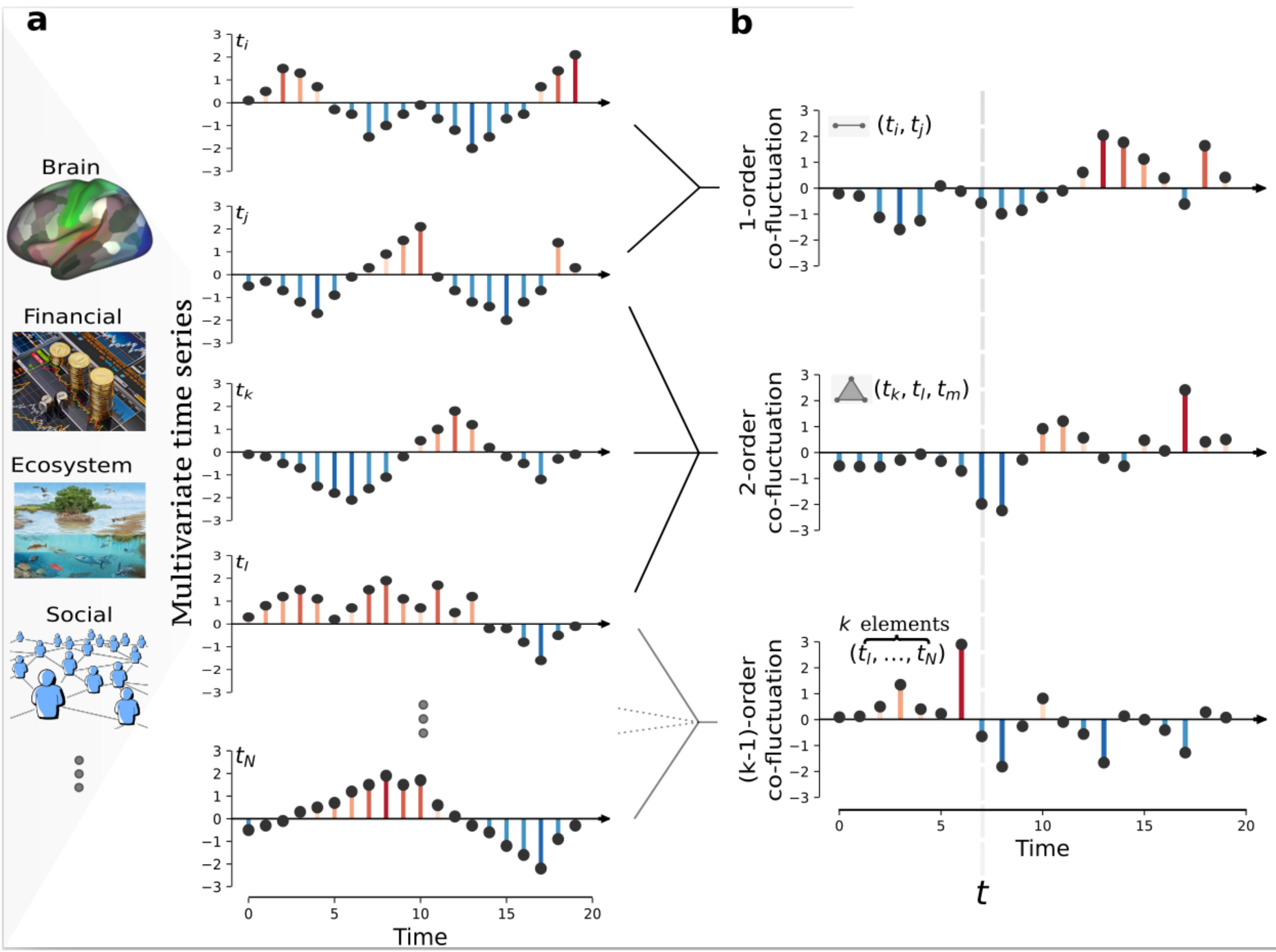
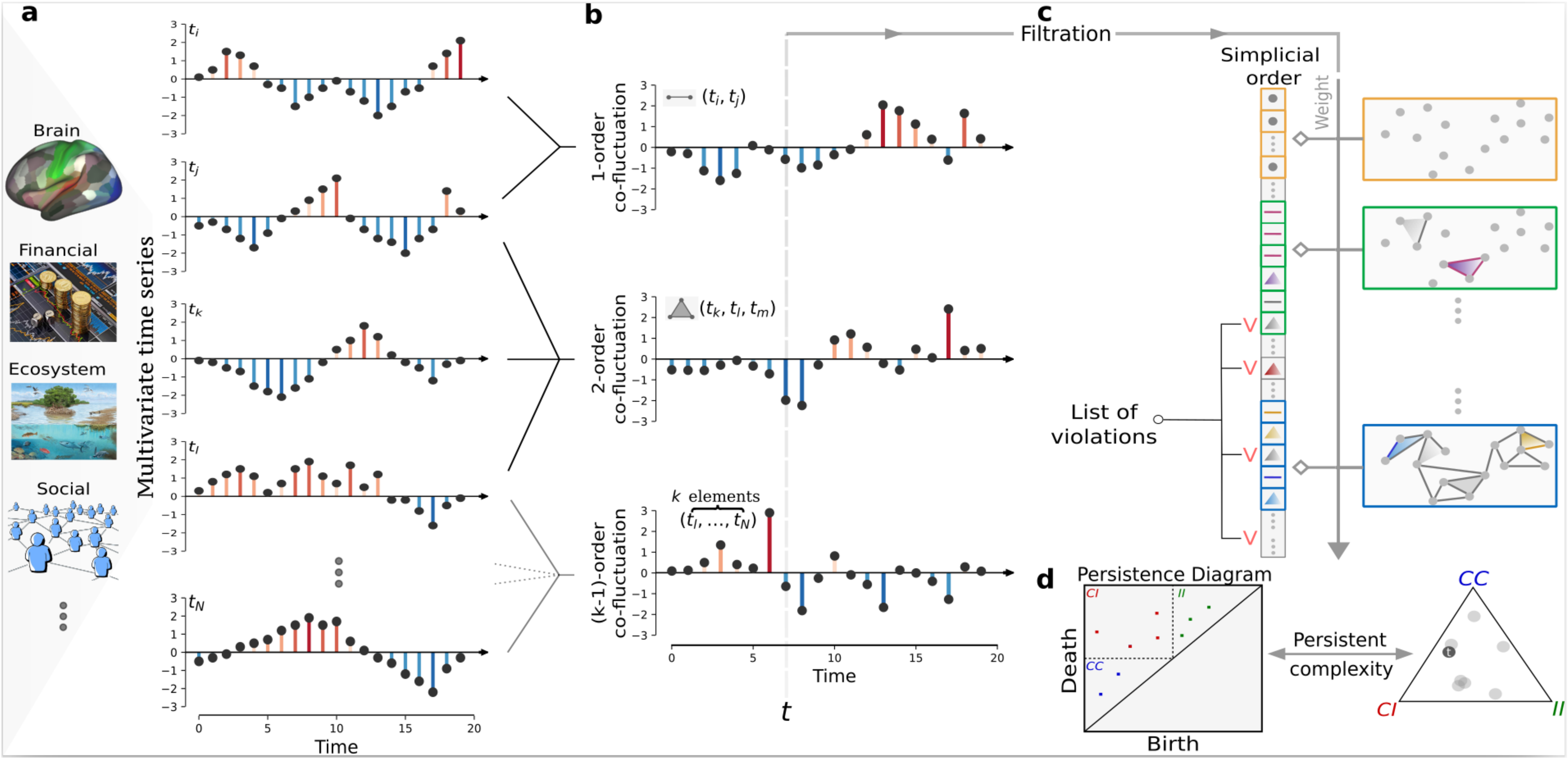
Andrea Santoro[1], Federico Battiston[2], Giovanni Petri[3] & Enrico Amico[1,4]

Time series analysis has proven to be a powerful method to characterize
several phenomena in biology, neuroscience and economics, and to

Temporal topology

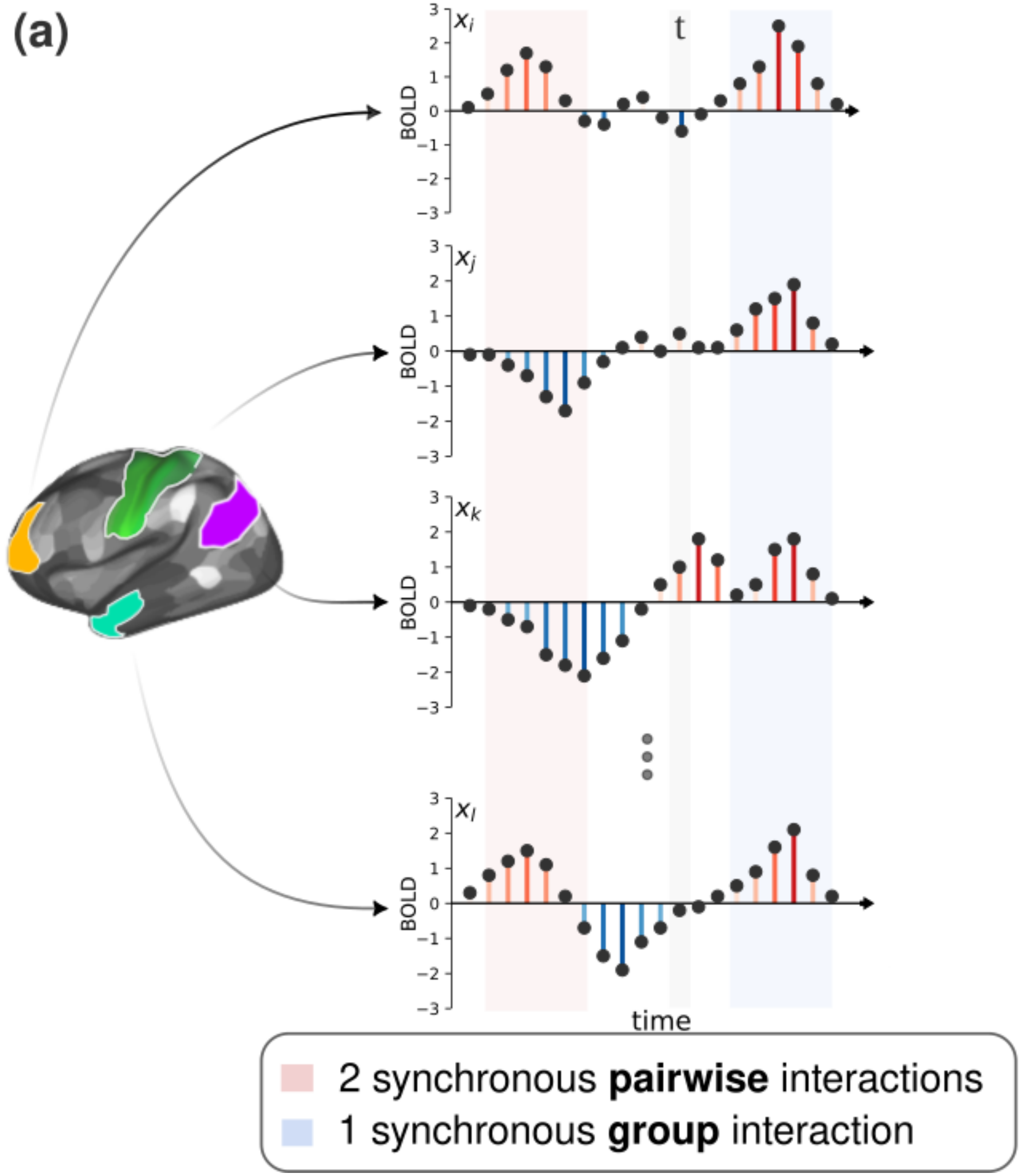


Temporal topology

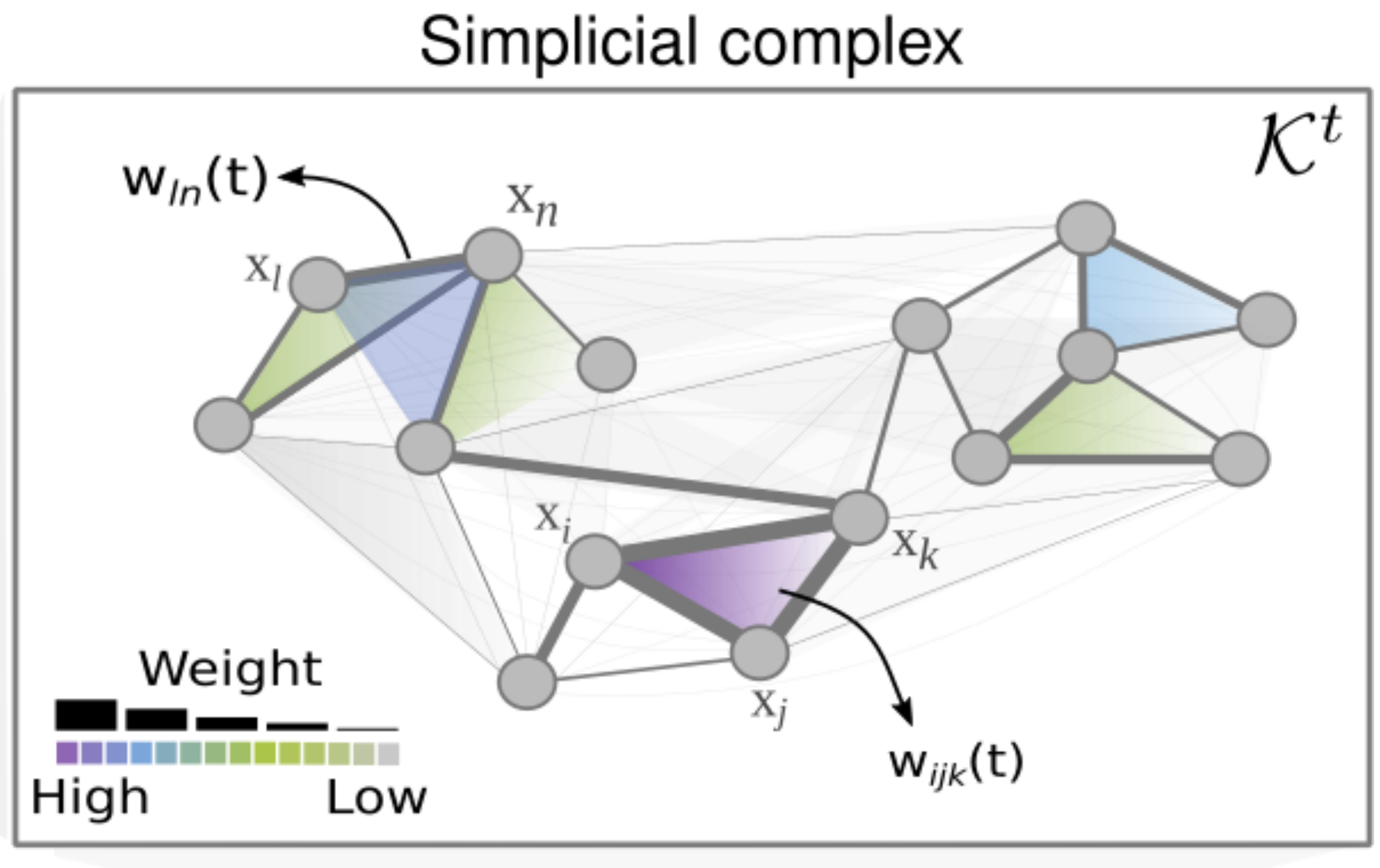


Temporal topology

(a)



(b)



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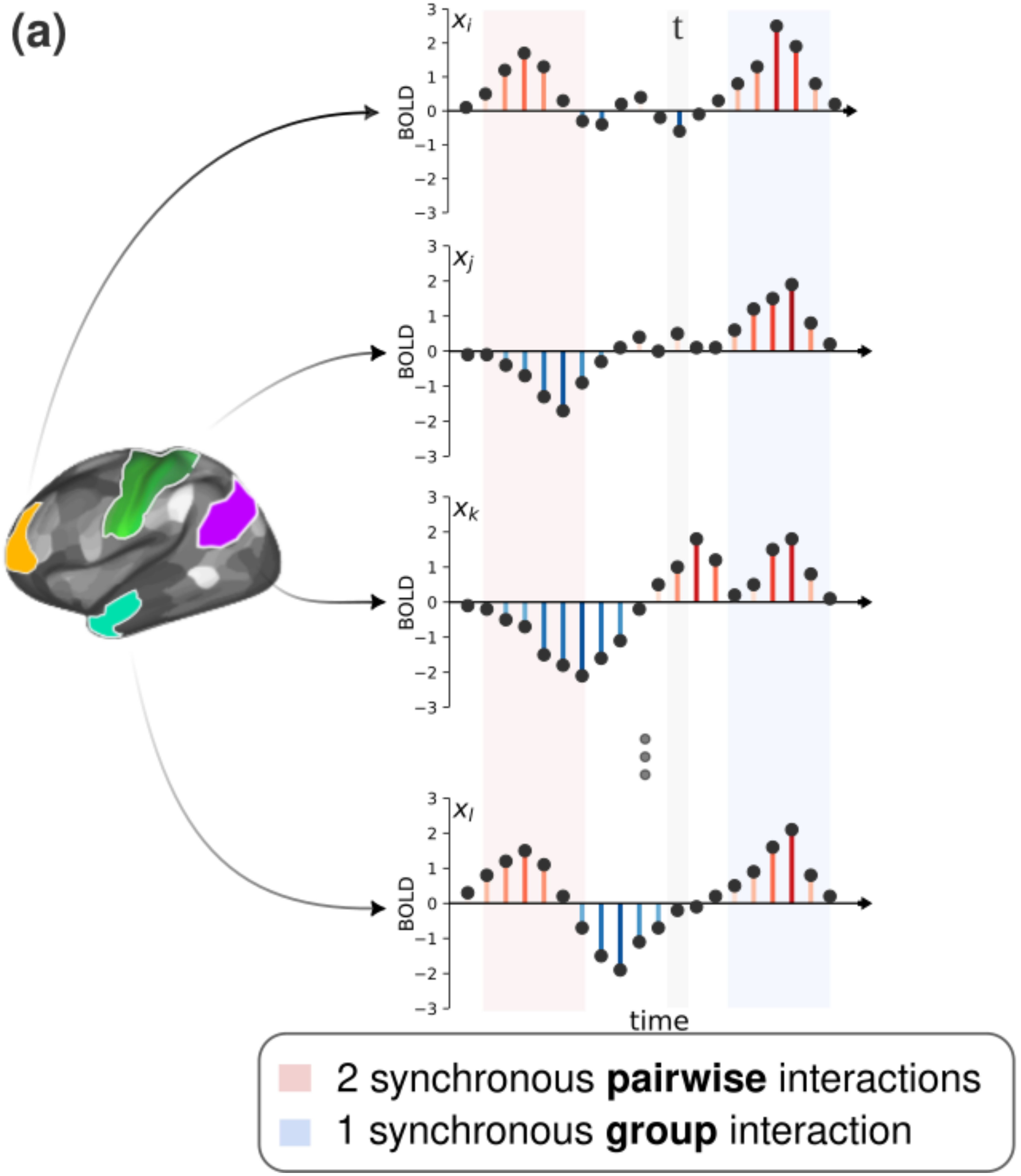

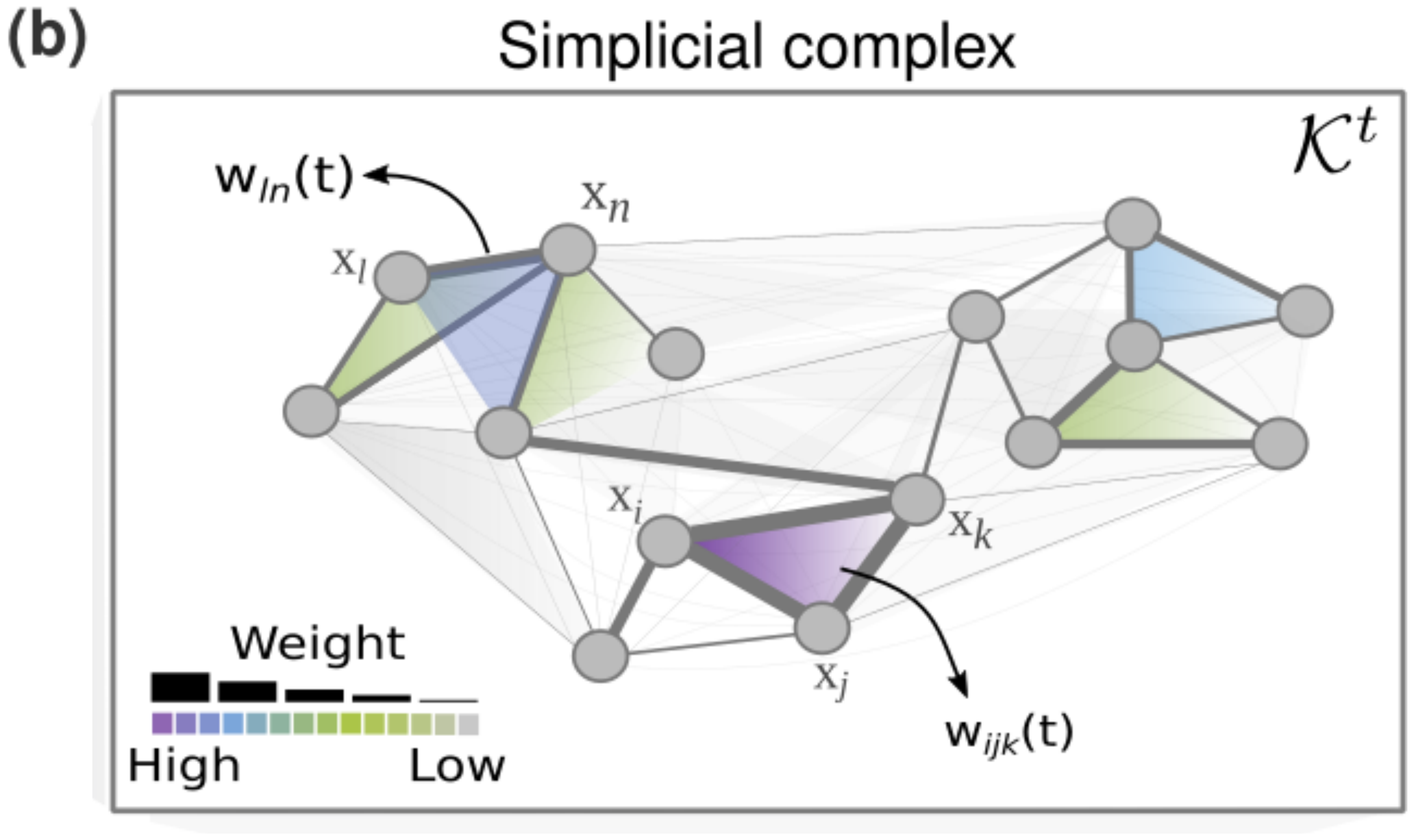

Hyper-Coherence

List of violating triangles

Temporal topology

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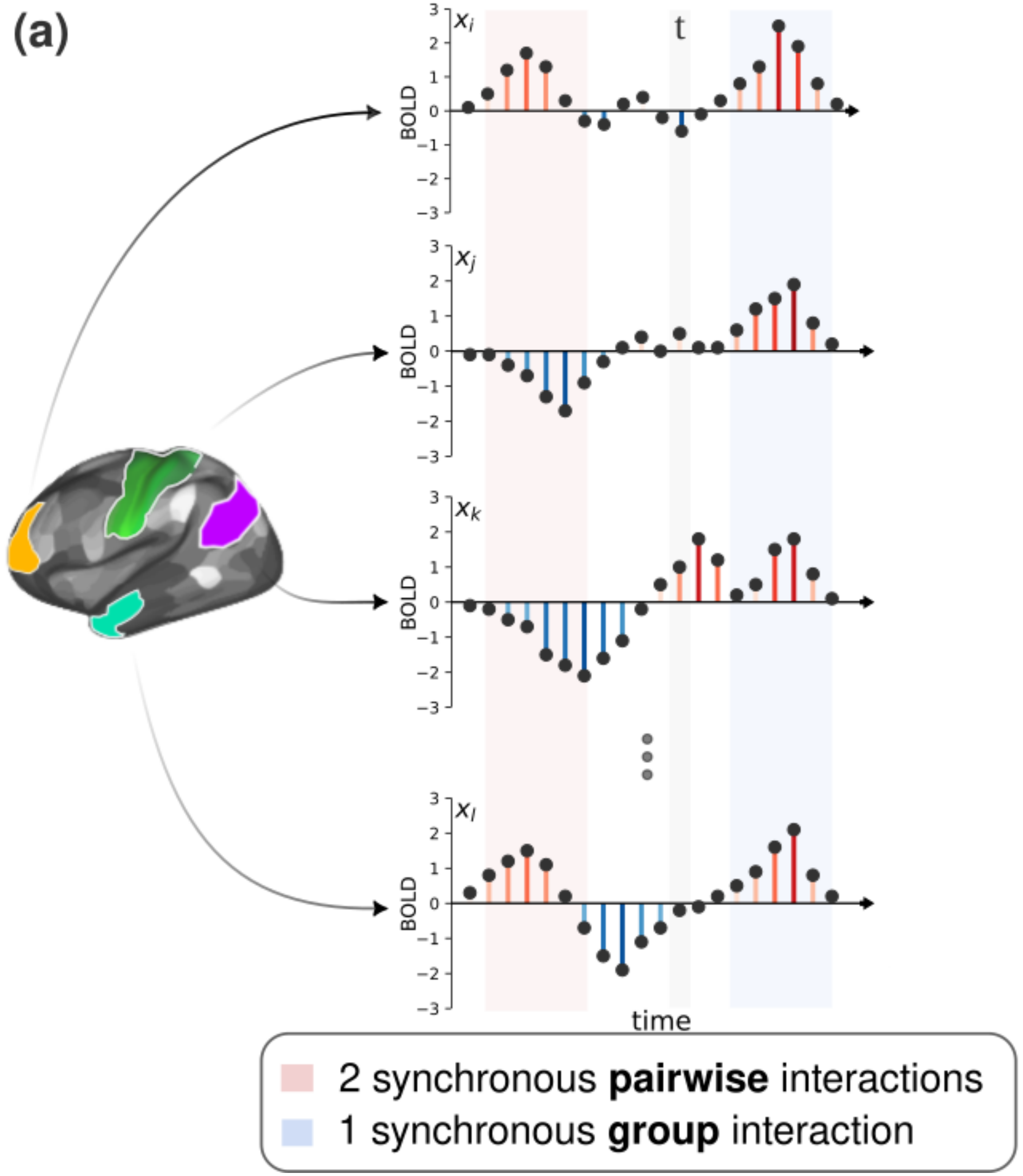

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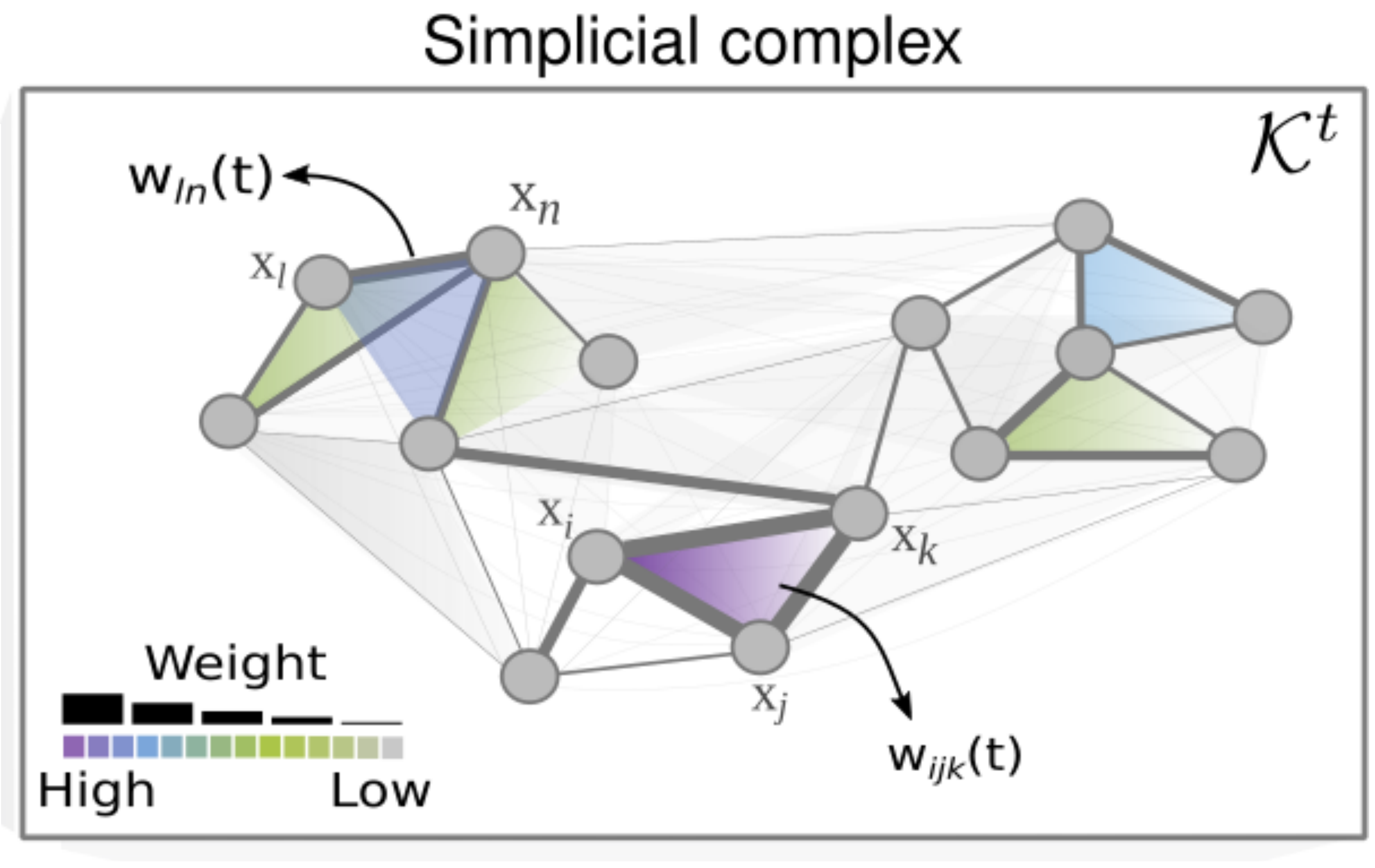

Hyper-Coherence

List of violating triangles

Hyper-Complexity

Homological scaffold

Temporal topology

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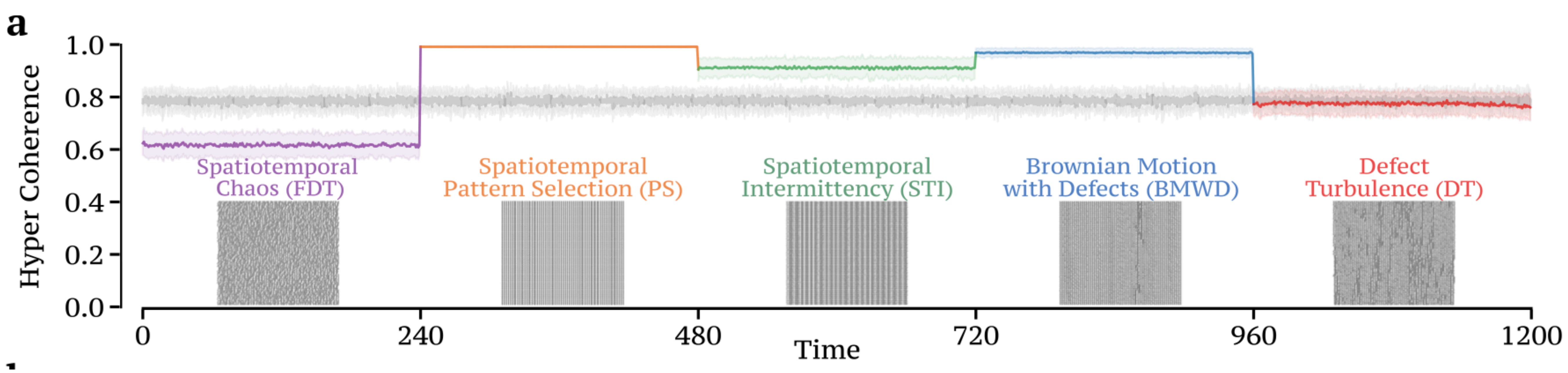
Hypercoherence:
Fraction of violating triangles



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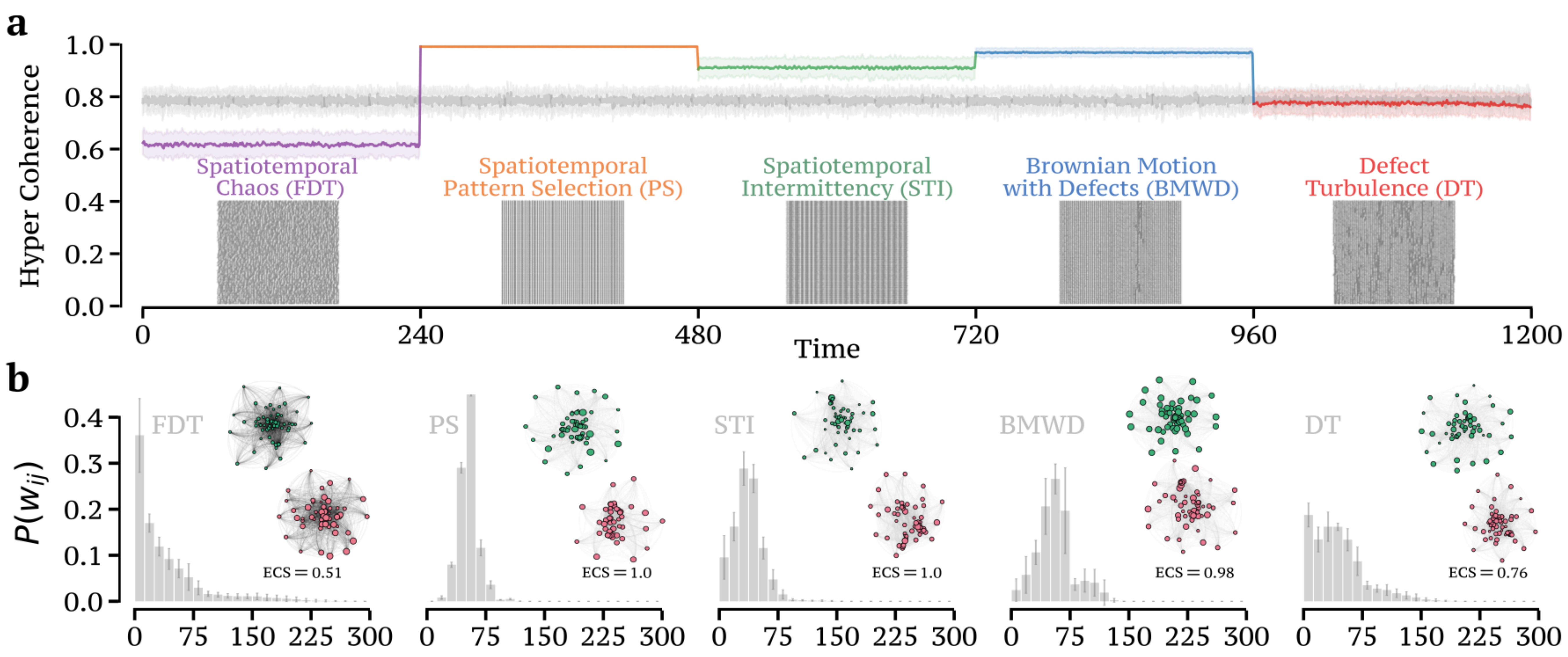
Hypercoherence:
Fraction of violating triangles

Triangle projection:
Project triangles on edges and count



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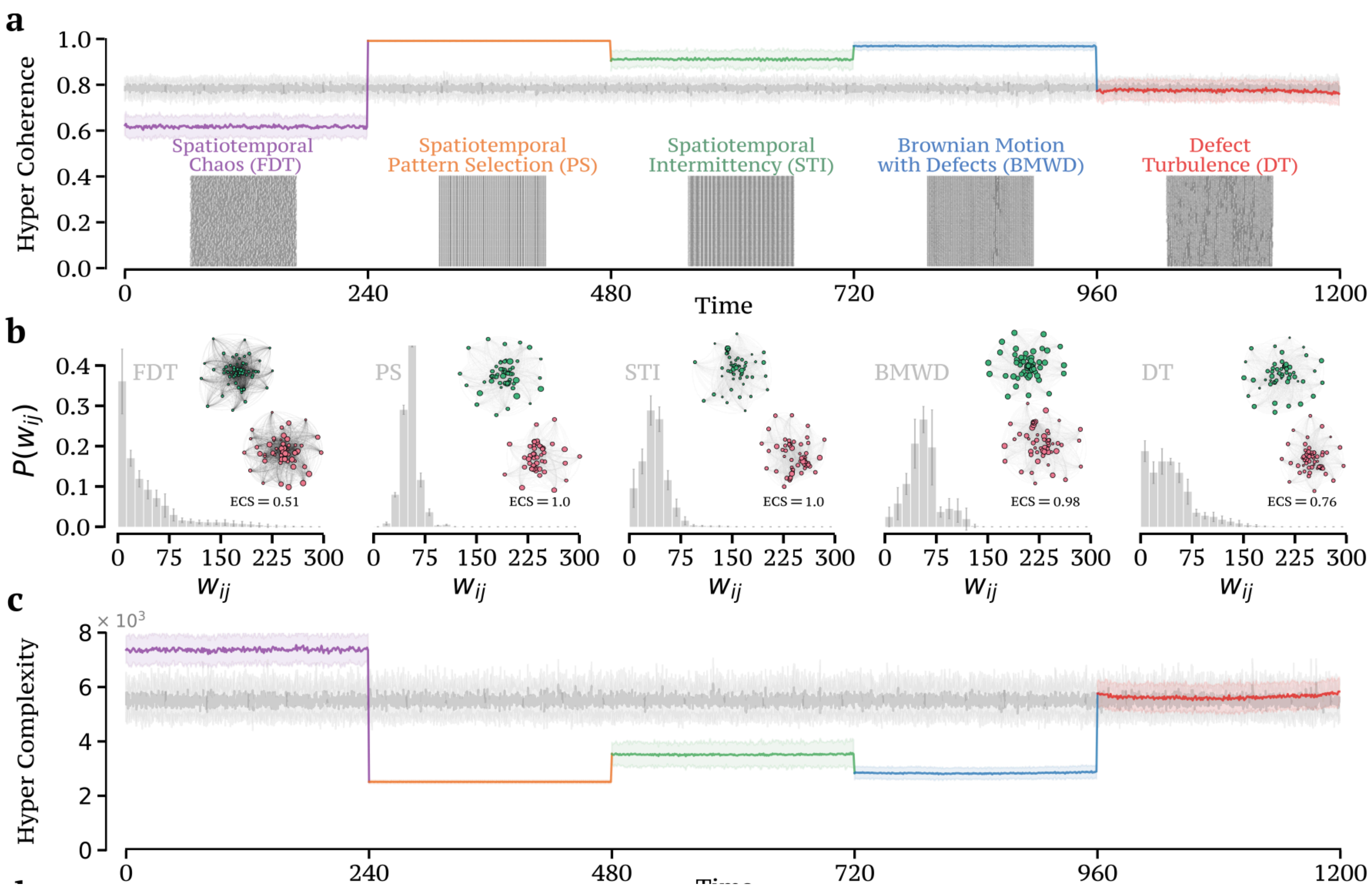
Total persistent complexity



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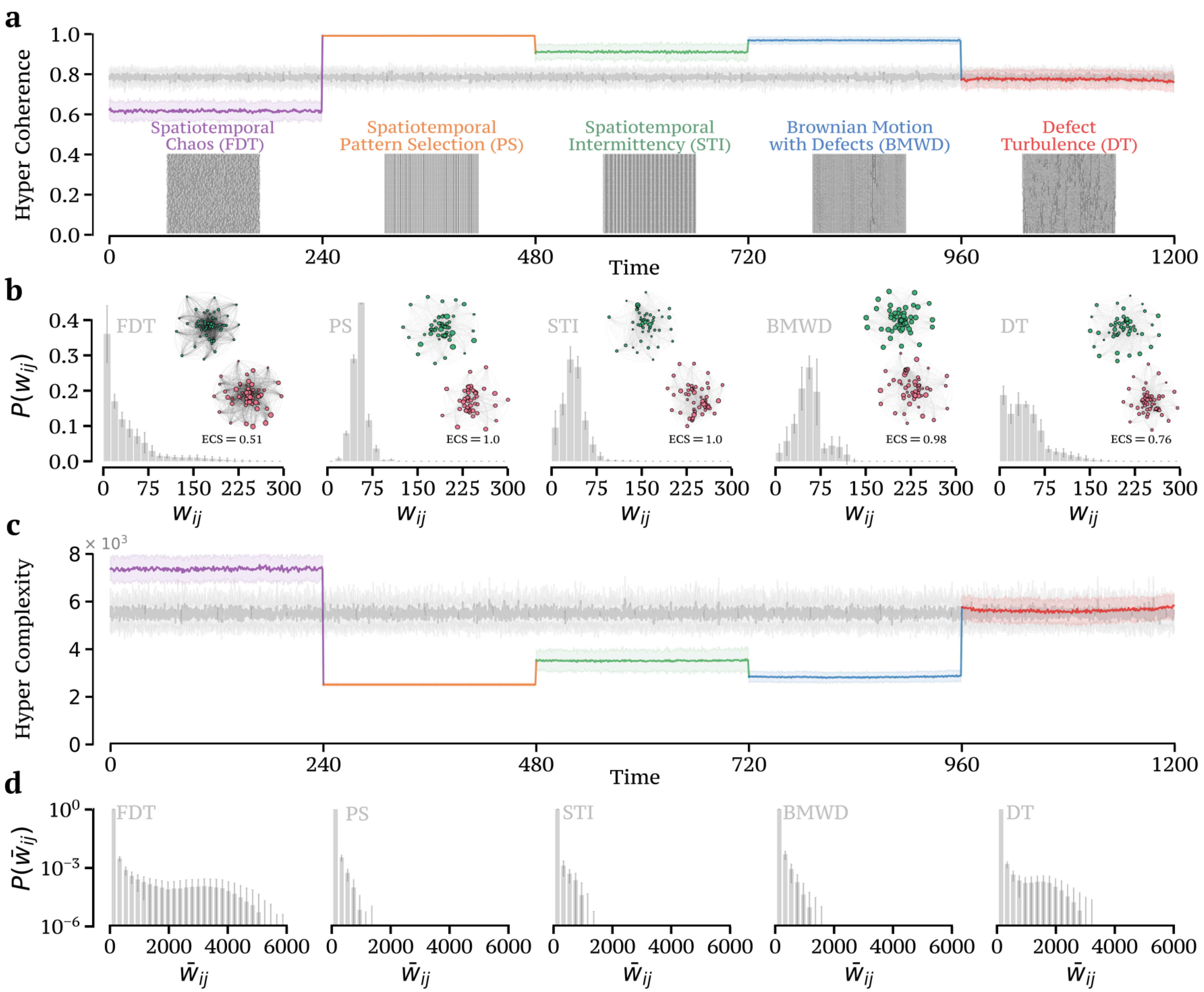
Scaffold weight distribution

$$x_i(t+1) = (1-\varepsilon)f[x_i(t)] + \frac{\varepsilon}{2}\left(f\left[x_{j-1}(t)\right] + f[x_{j+}\right.$$



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Temporal topology

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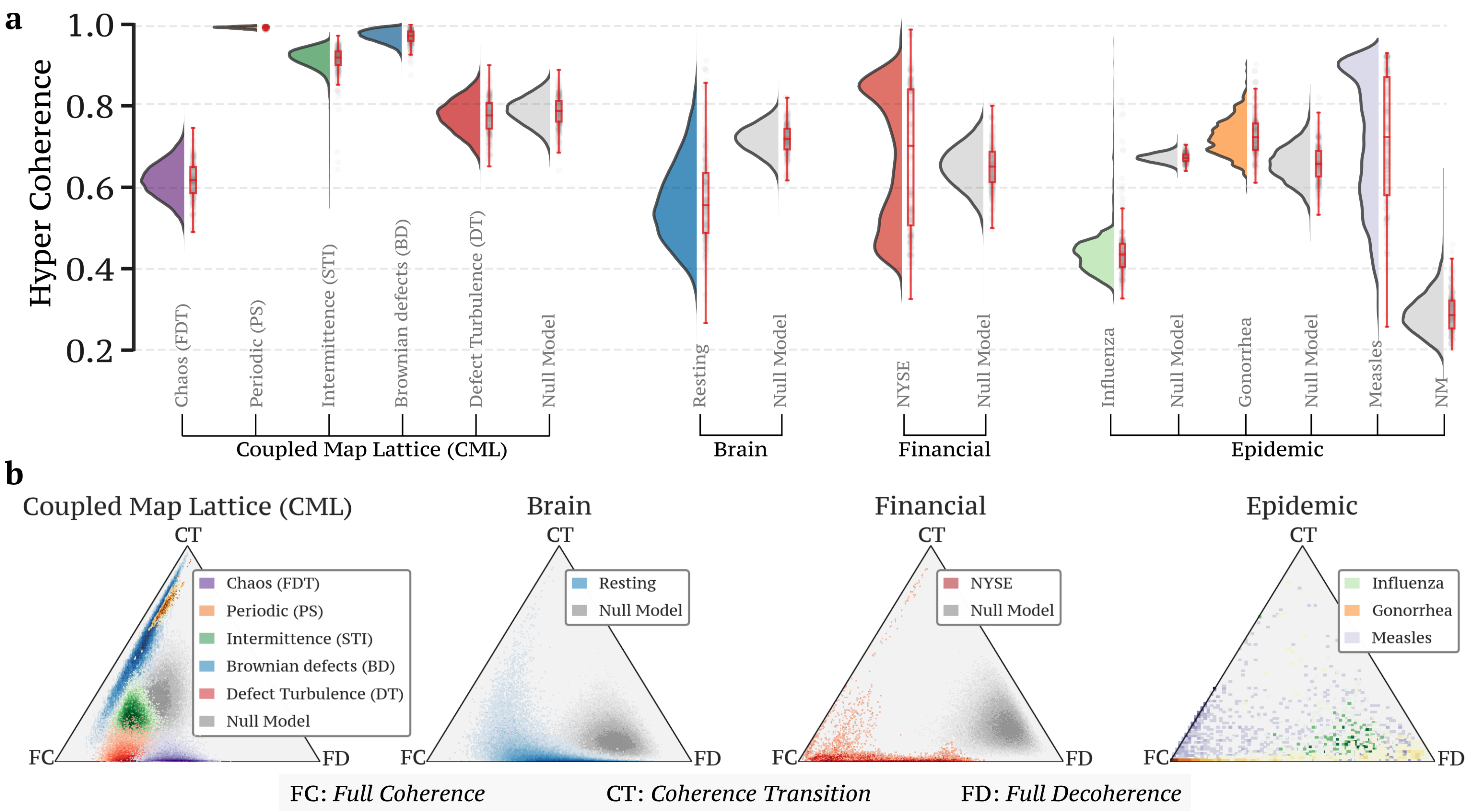

Aside: disease classification

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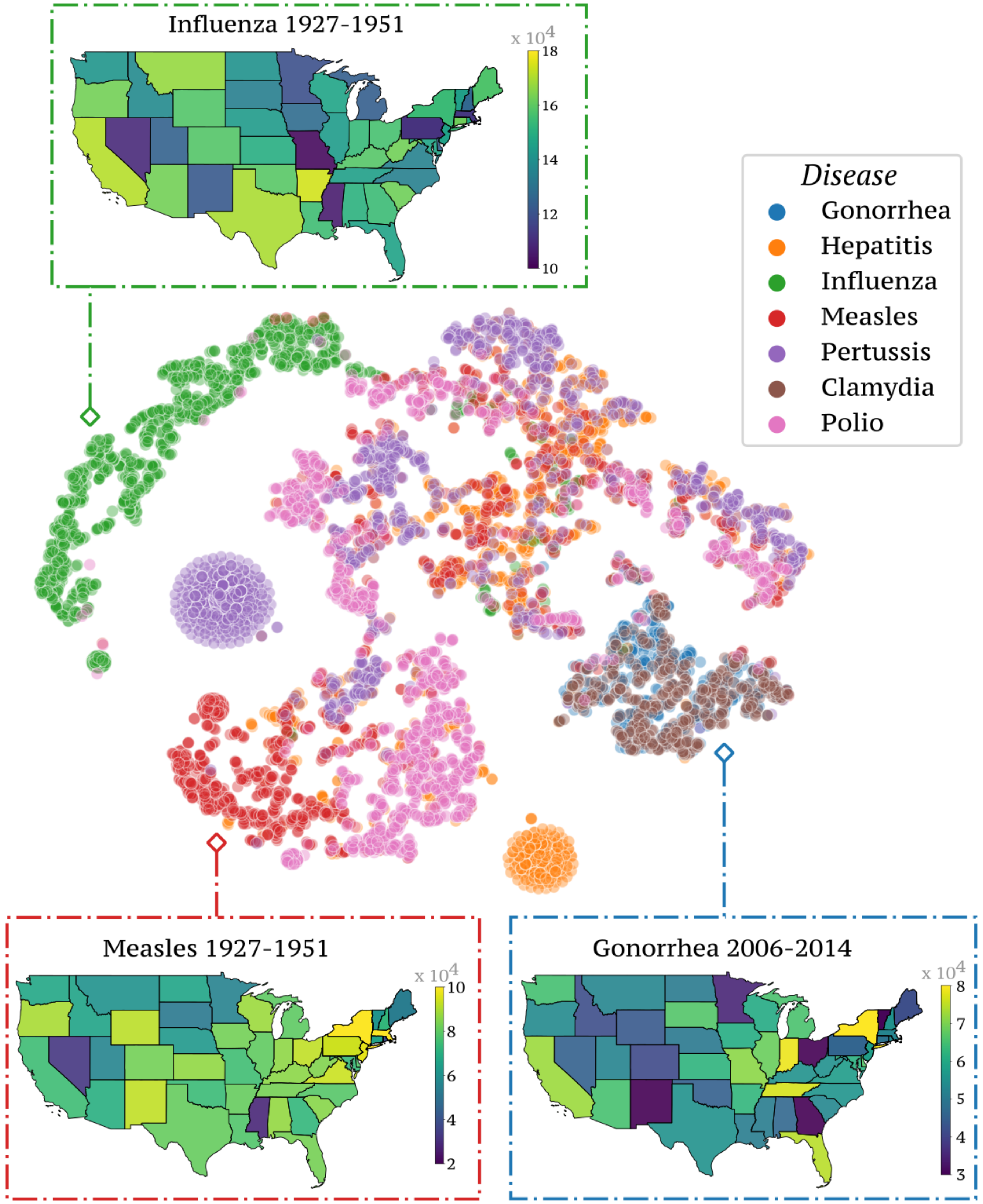

Embedding vectors for each time-point:

$\vec{t}$ = (Hyper-complexity, CC pers, CI pers, II pers, hypercoherence)

Classifier	Avg. accuracy	F1 weighted score
Gaussian NB	0.47	0.43
RBF SVM	**0.85**	0.85
Decision Tree	0.81	0.81
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k-NN	0.83	0.83

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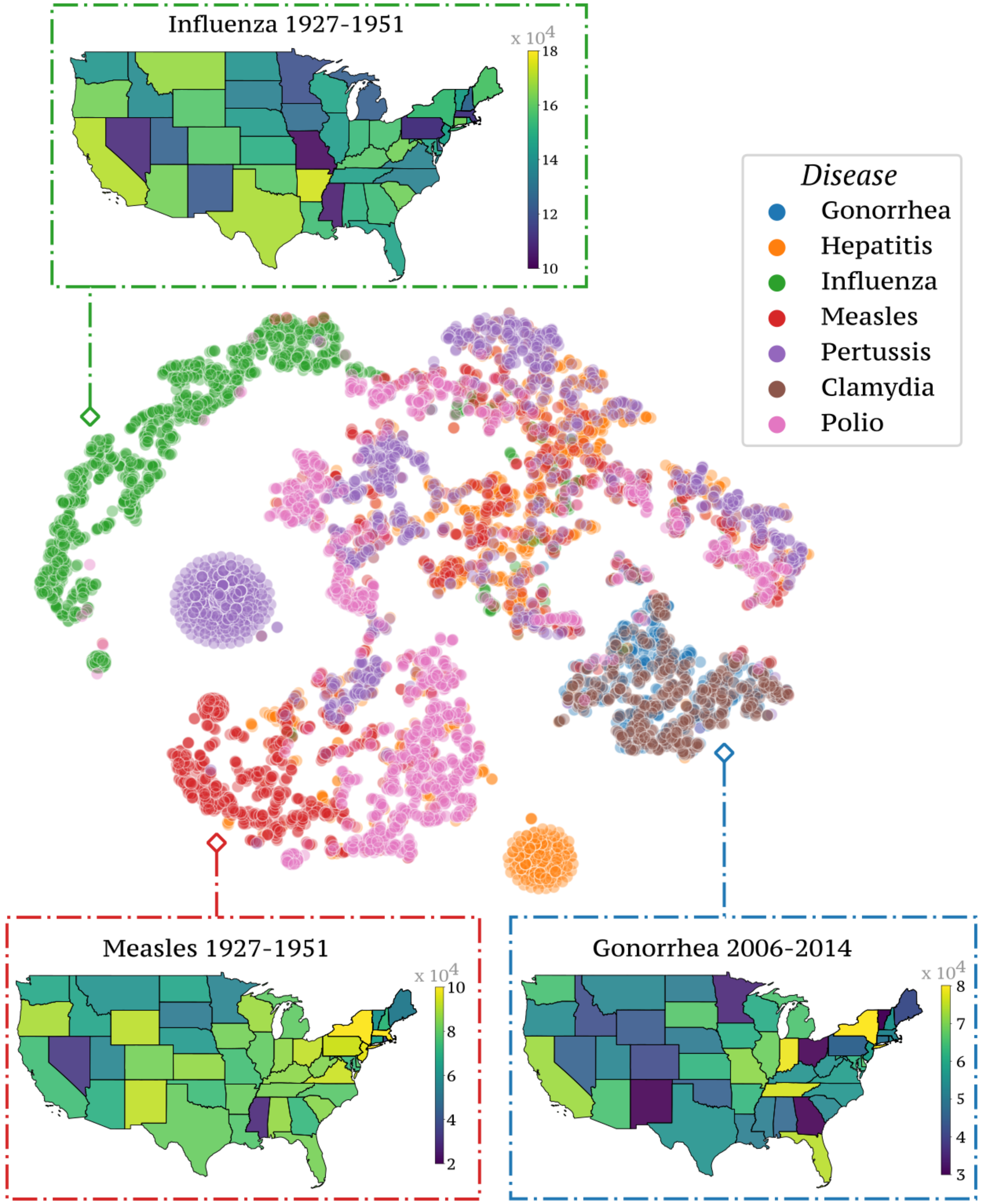

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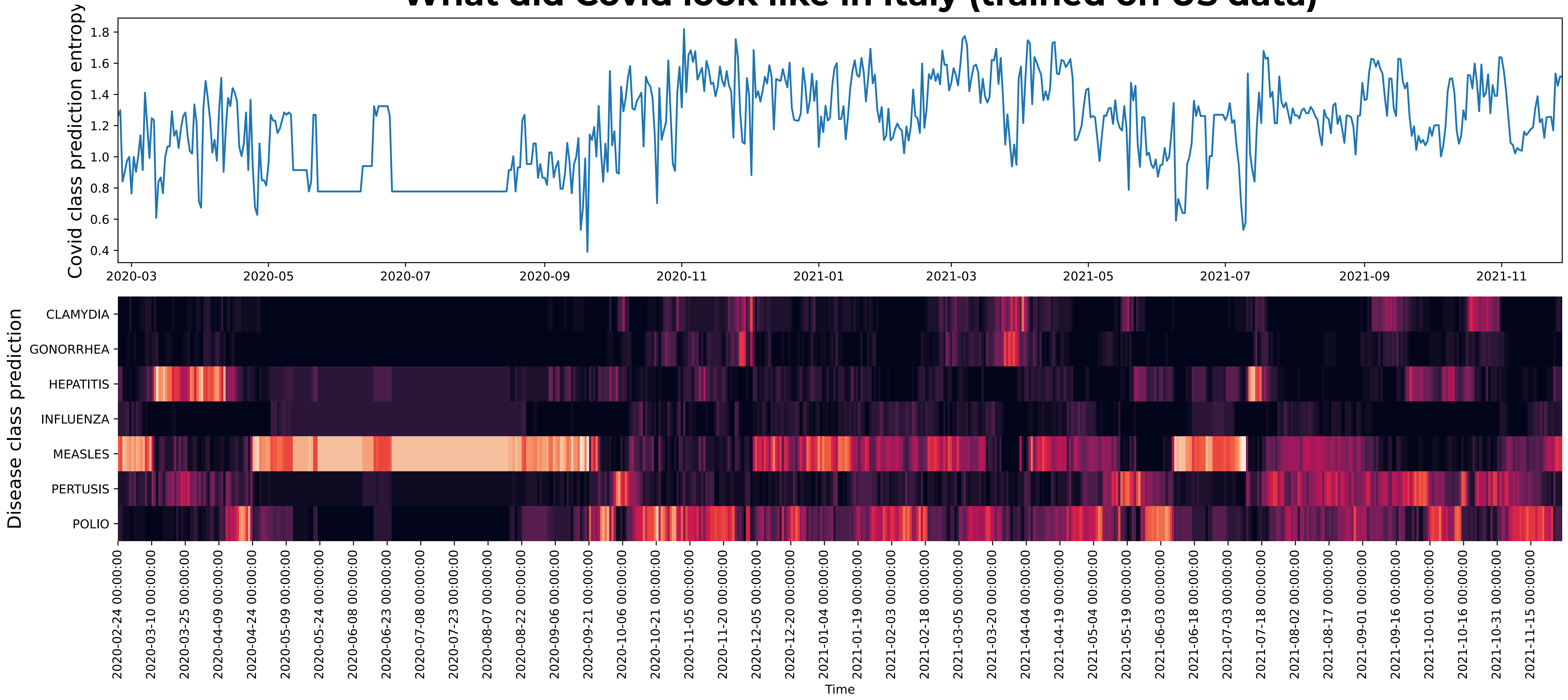
What did Covid look like in Italy (trained on US data)



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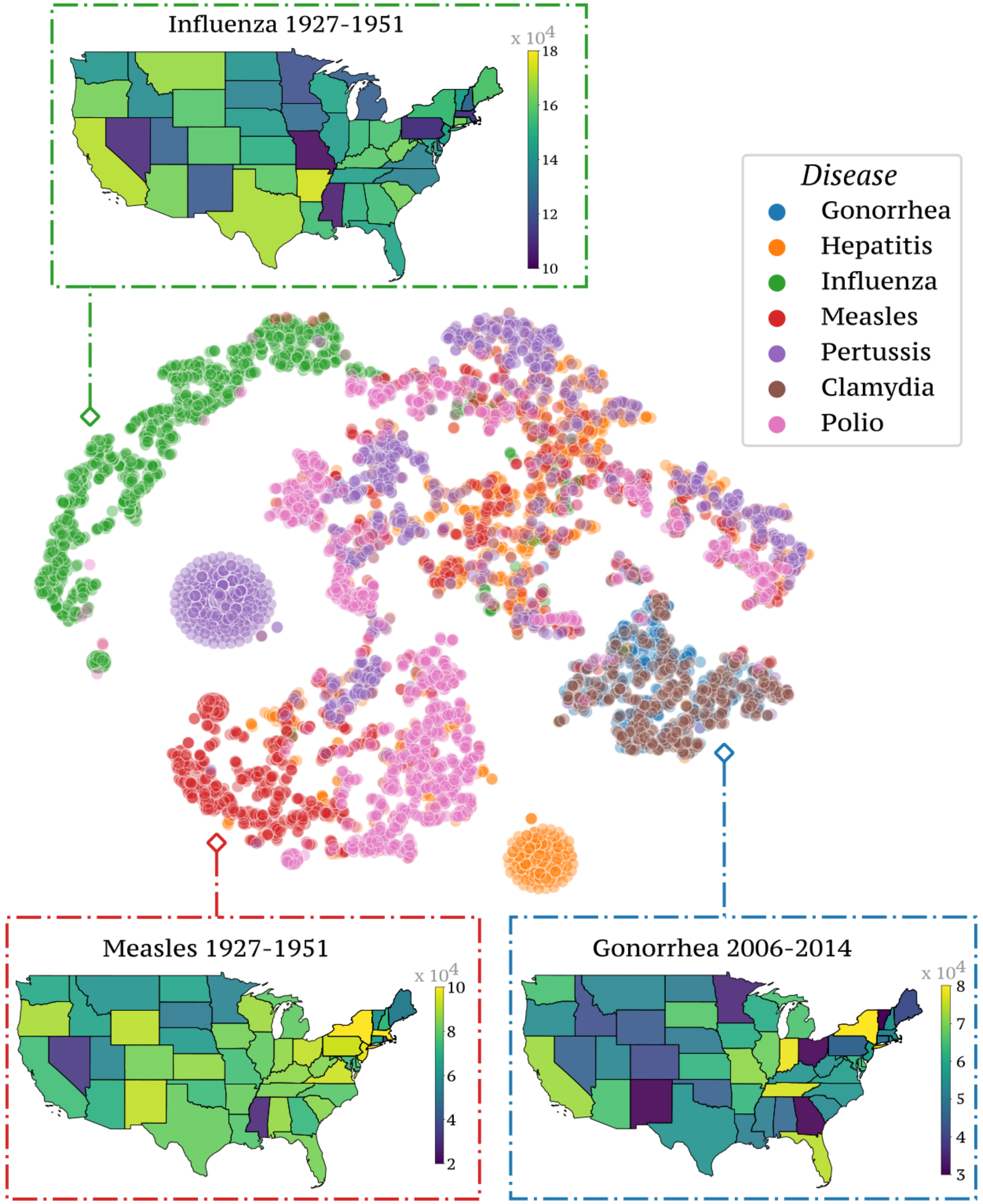

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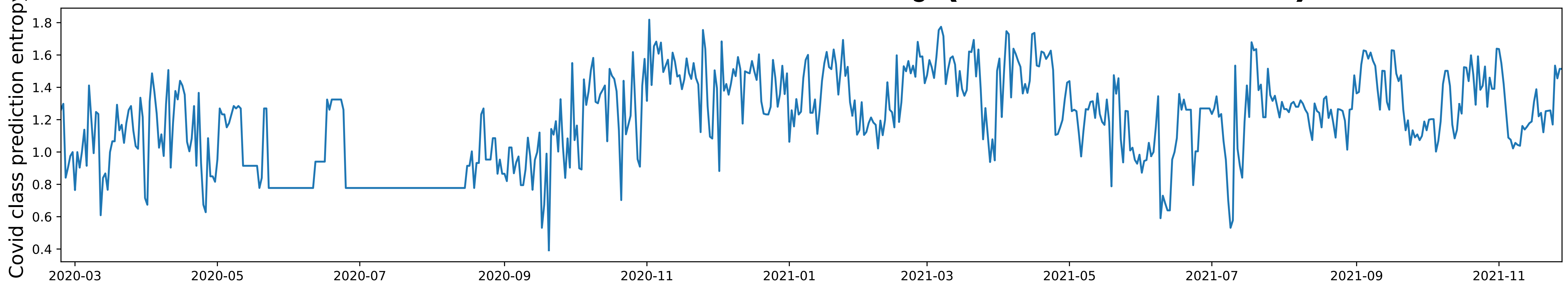

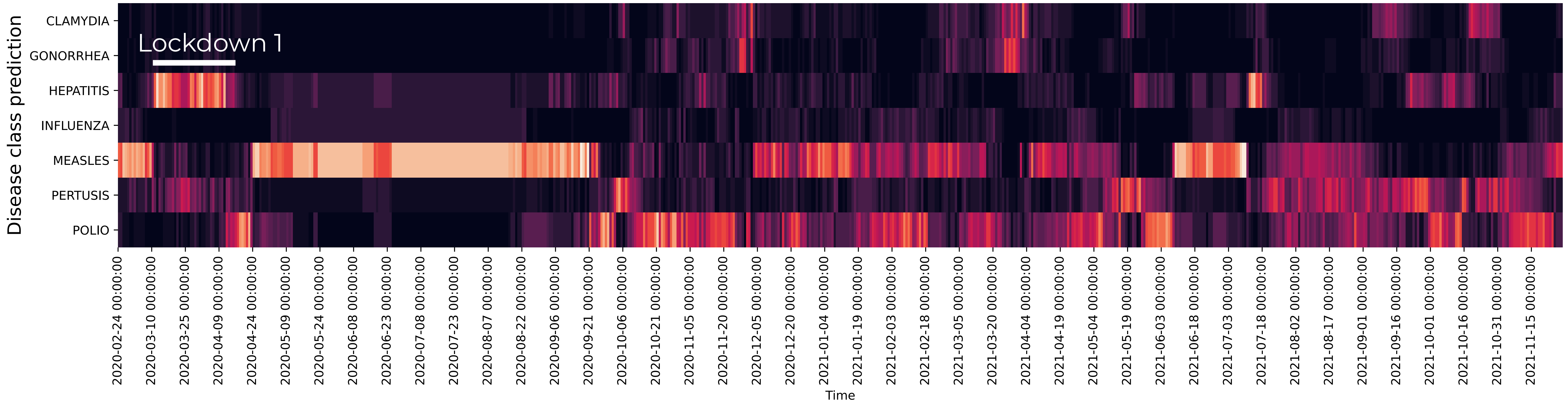

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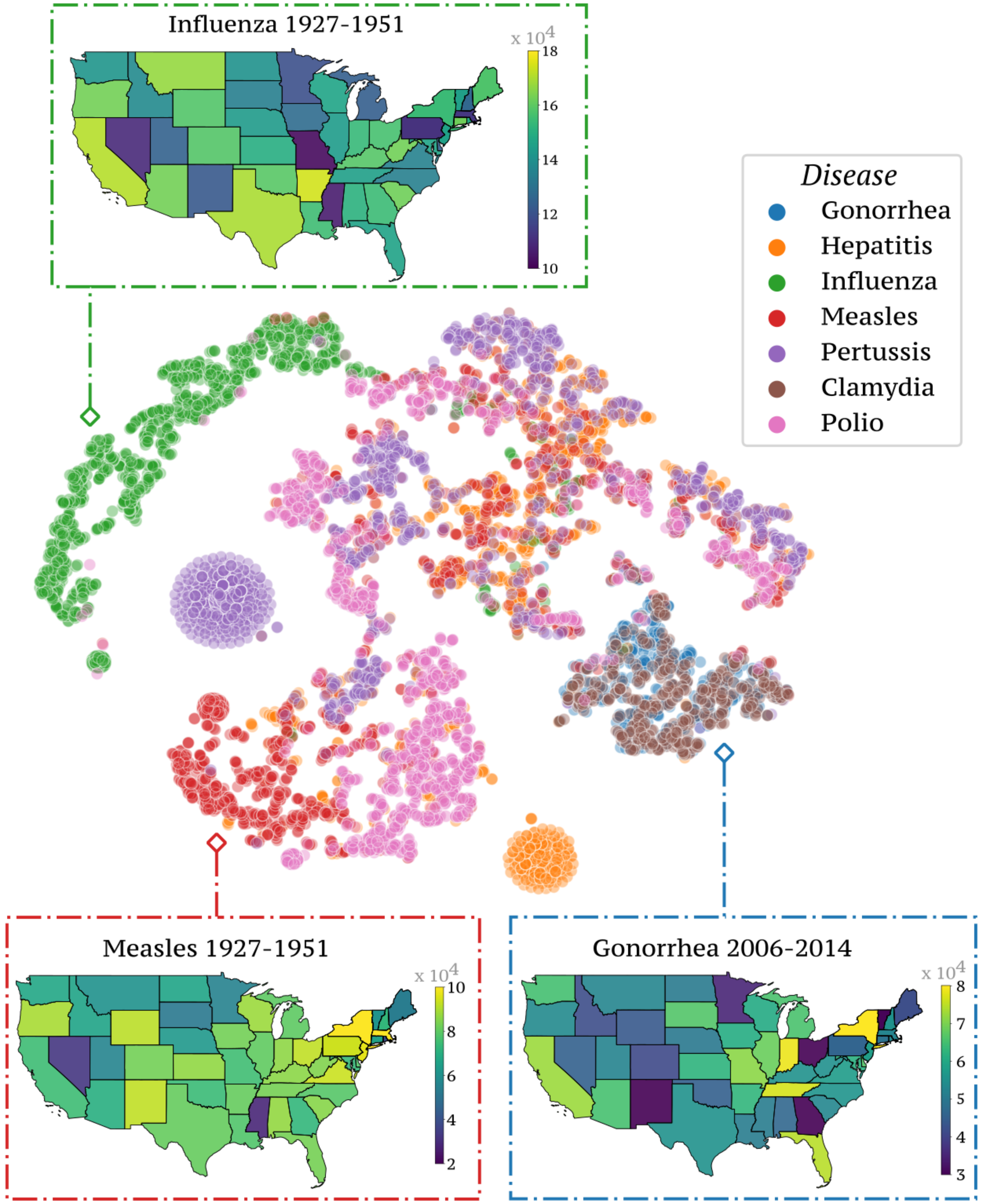

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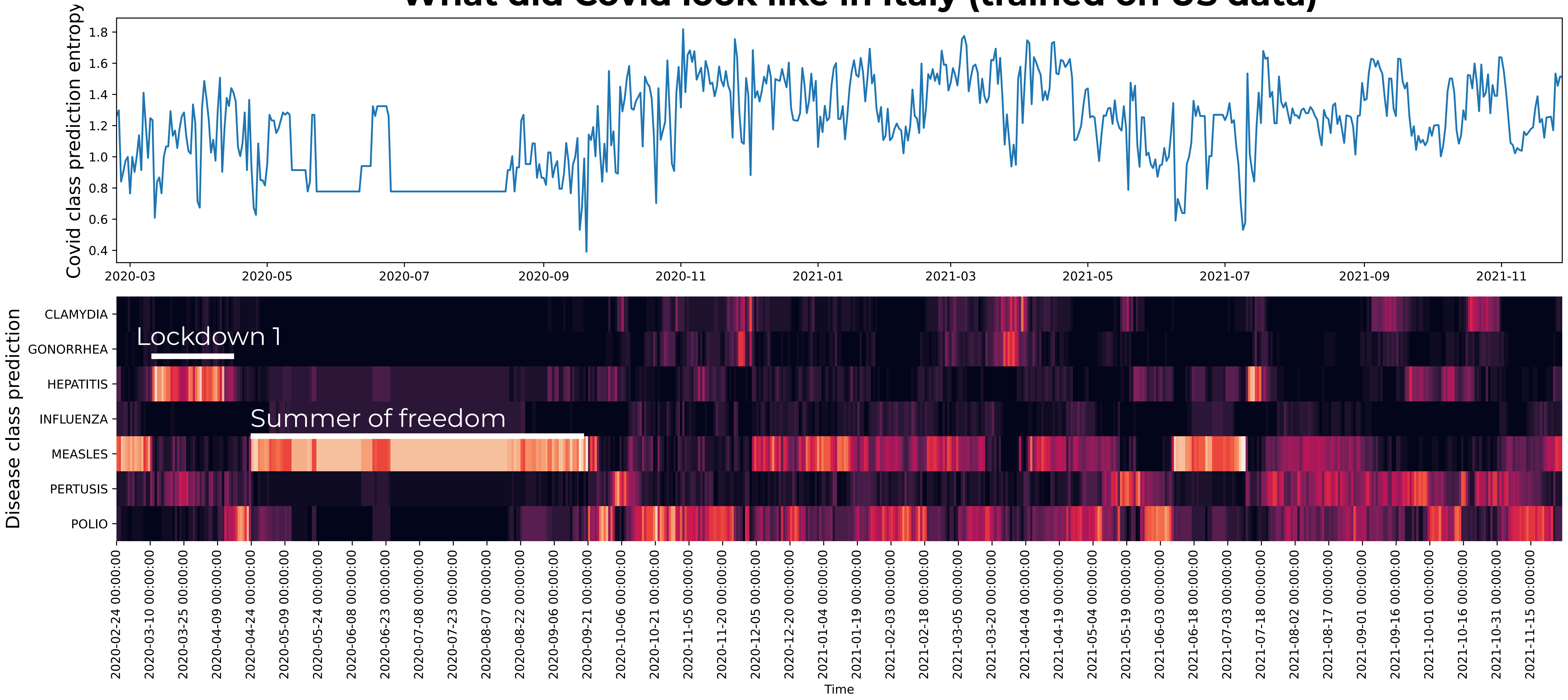

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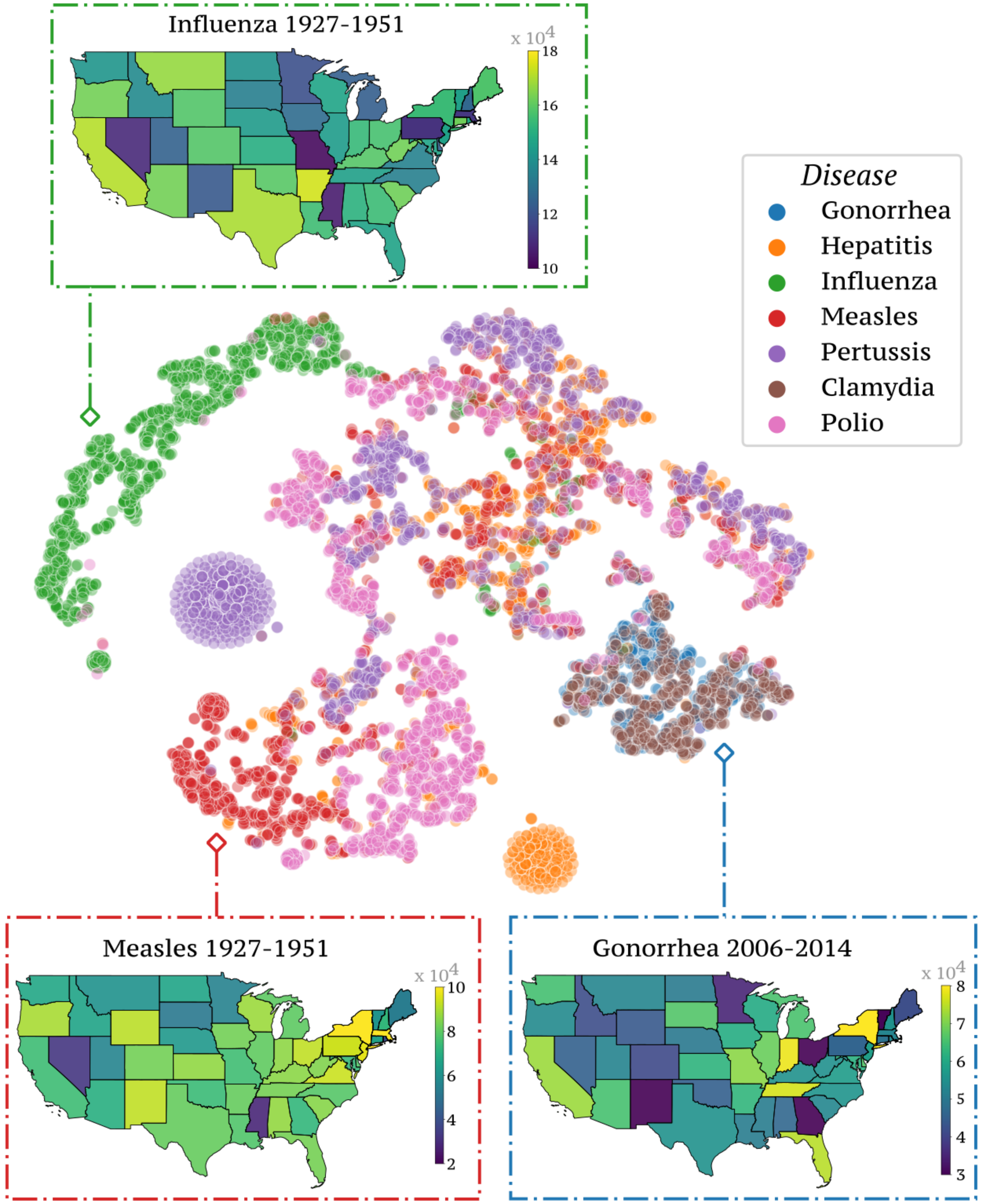

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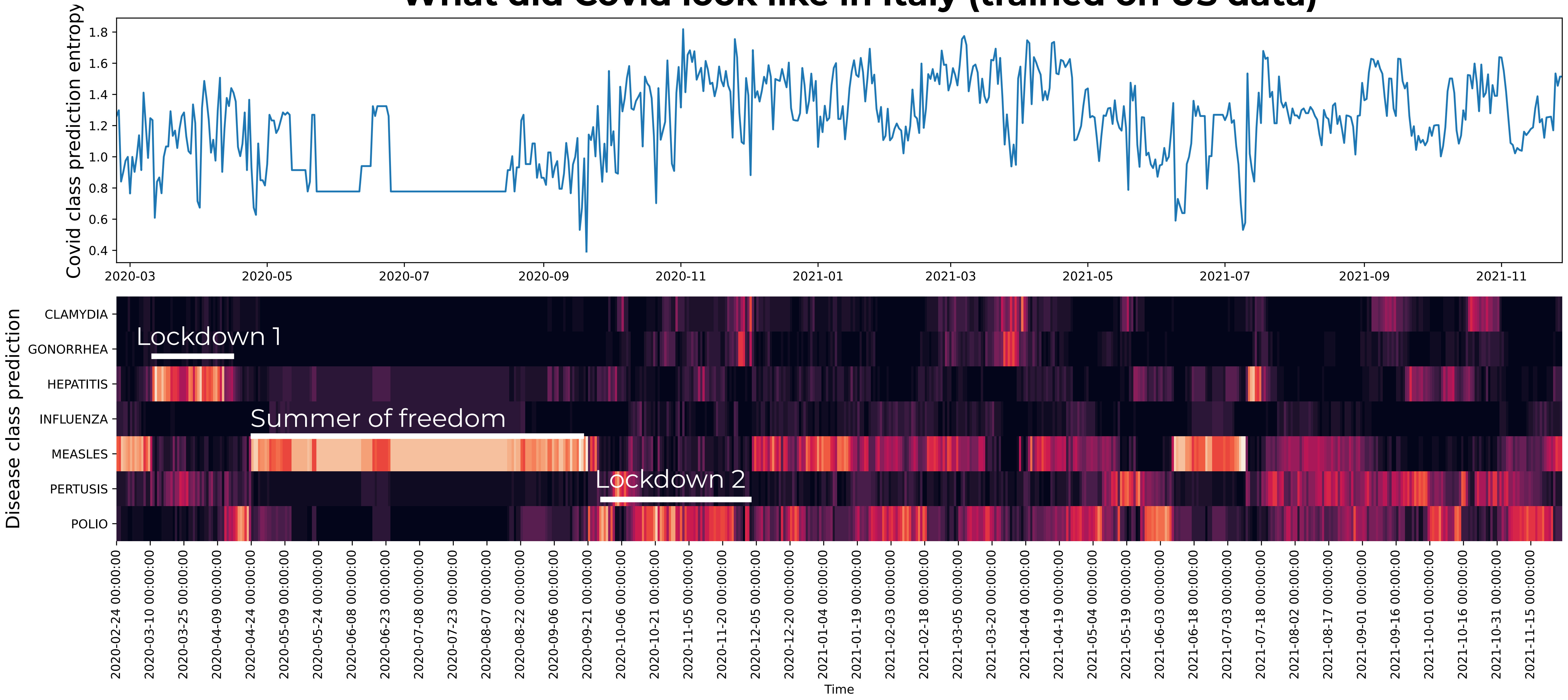

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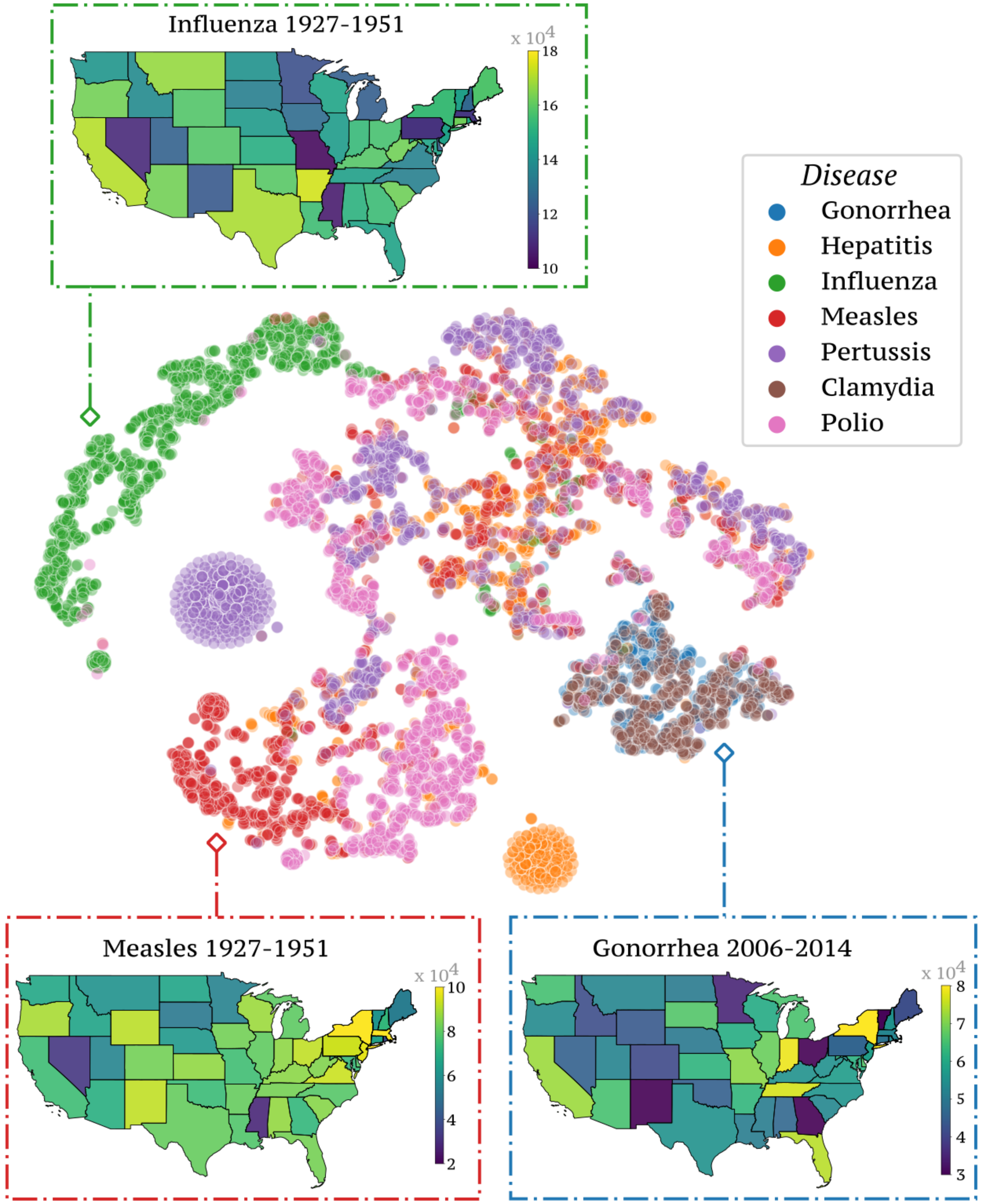

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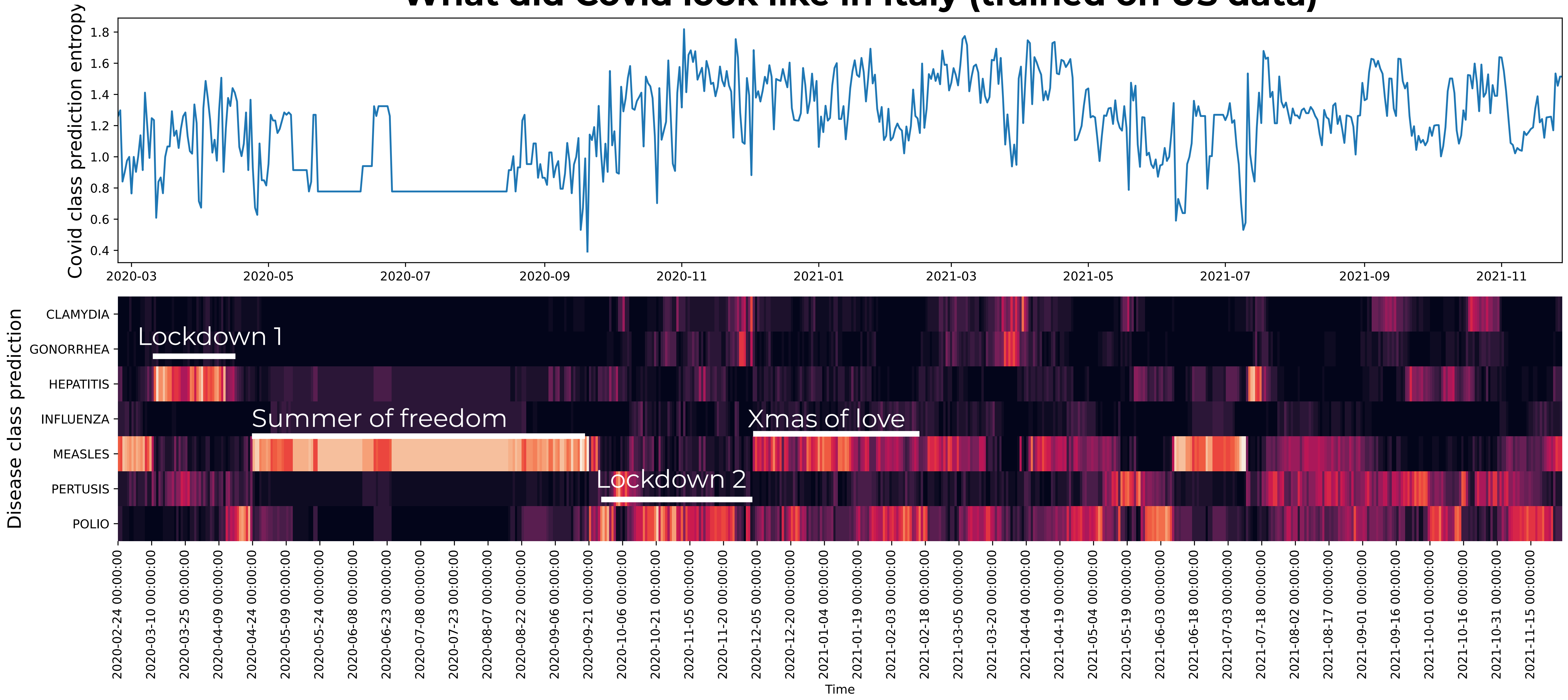

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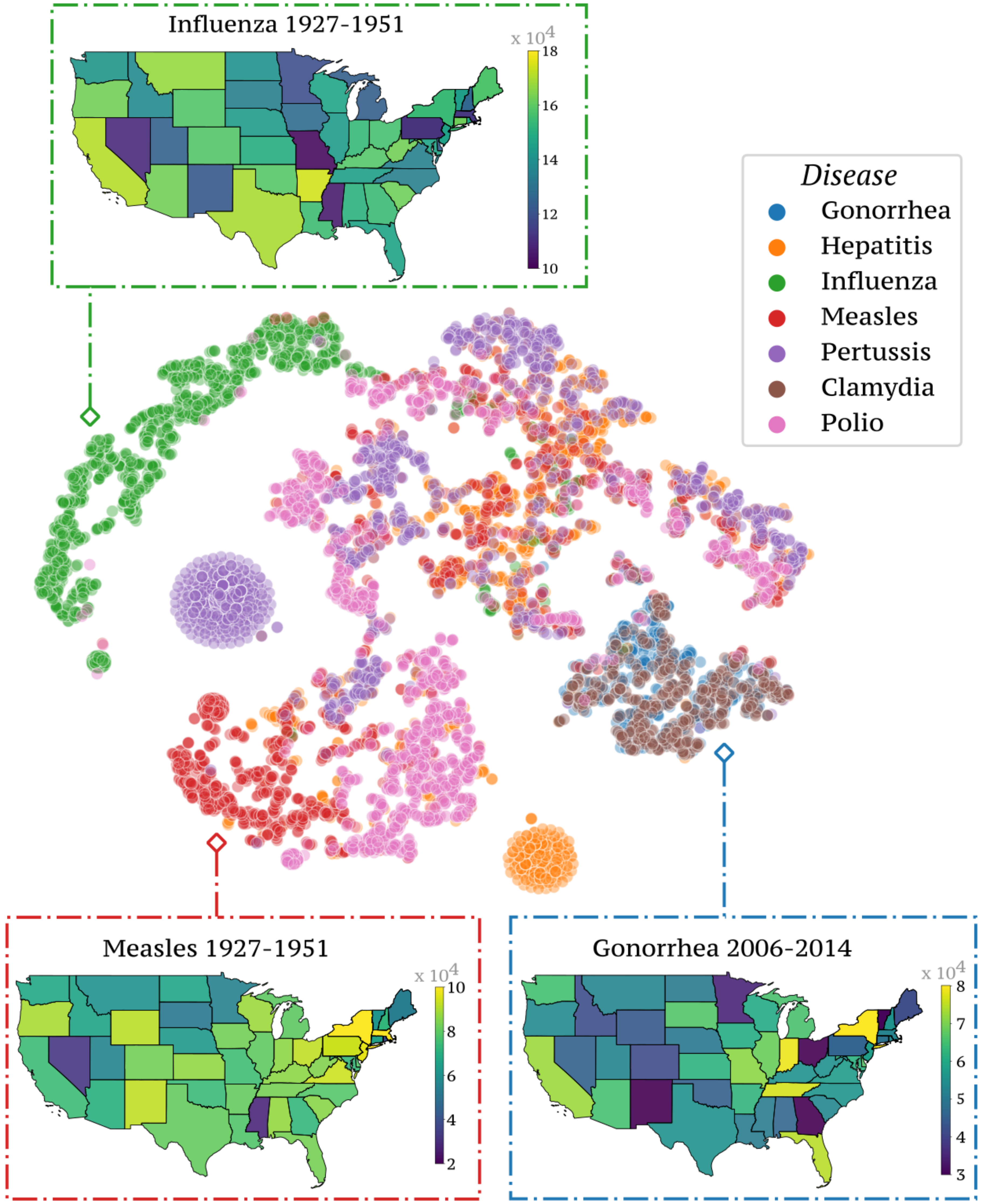
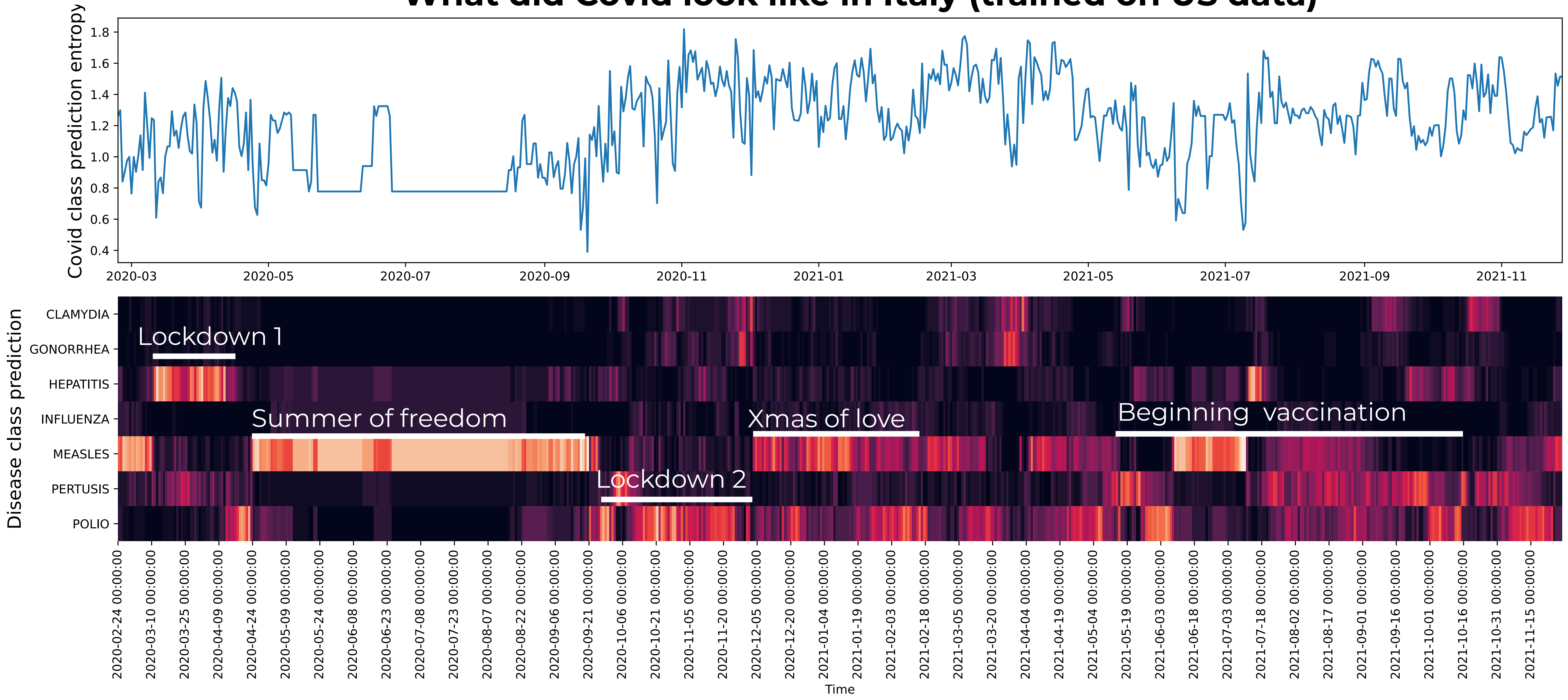


Embedding vectors for each time-point:

$\vec{t}$ = (Hyper-complexity, CC pers, CI pers, II pers, hypercoherence)

Classifier	Avg. accuracy	F1 weighted score
Gaussian NB	0.47	0.43
RBF SVM	**0.85**	0.85
Decision Tree	0.81	0.81
Random Forest	**0.85**	0.85
k-NN	0.83	0.83

What did Covid look like in Italy (trained on US data)



Back to brains!

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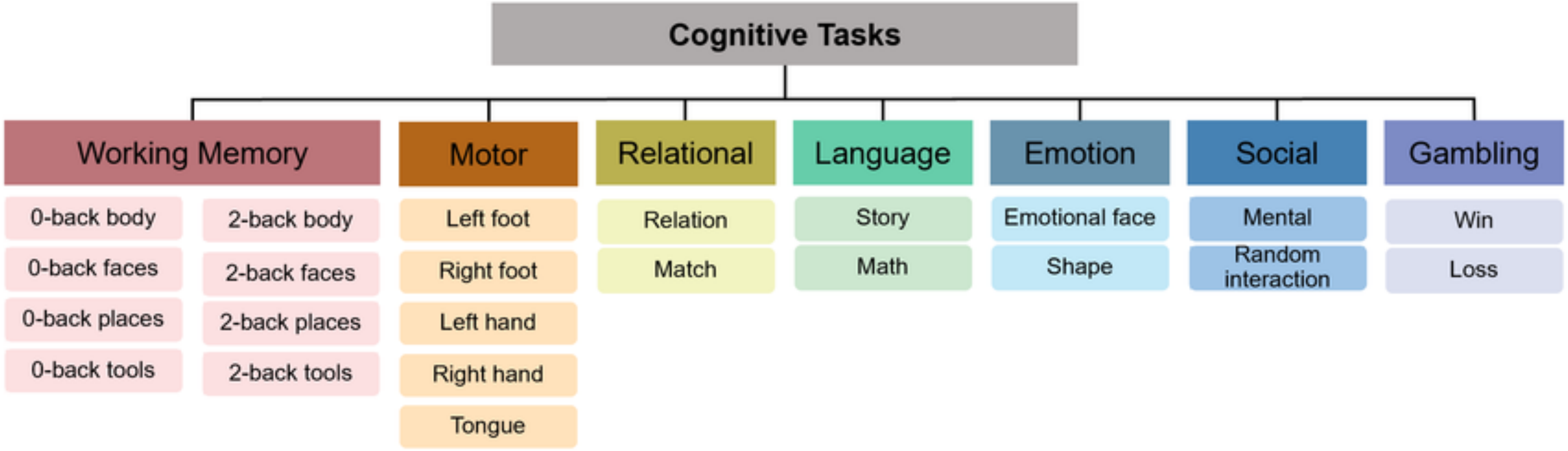
Dataset

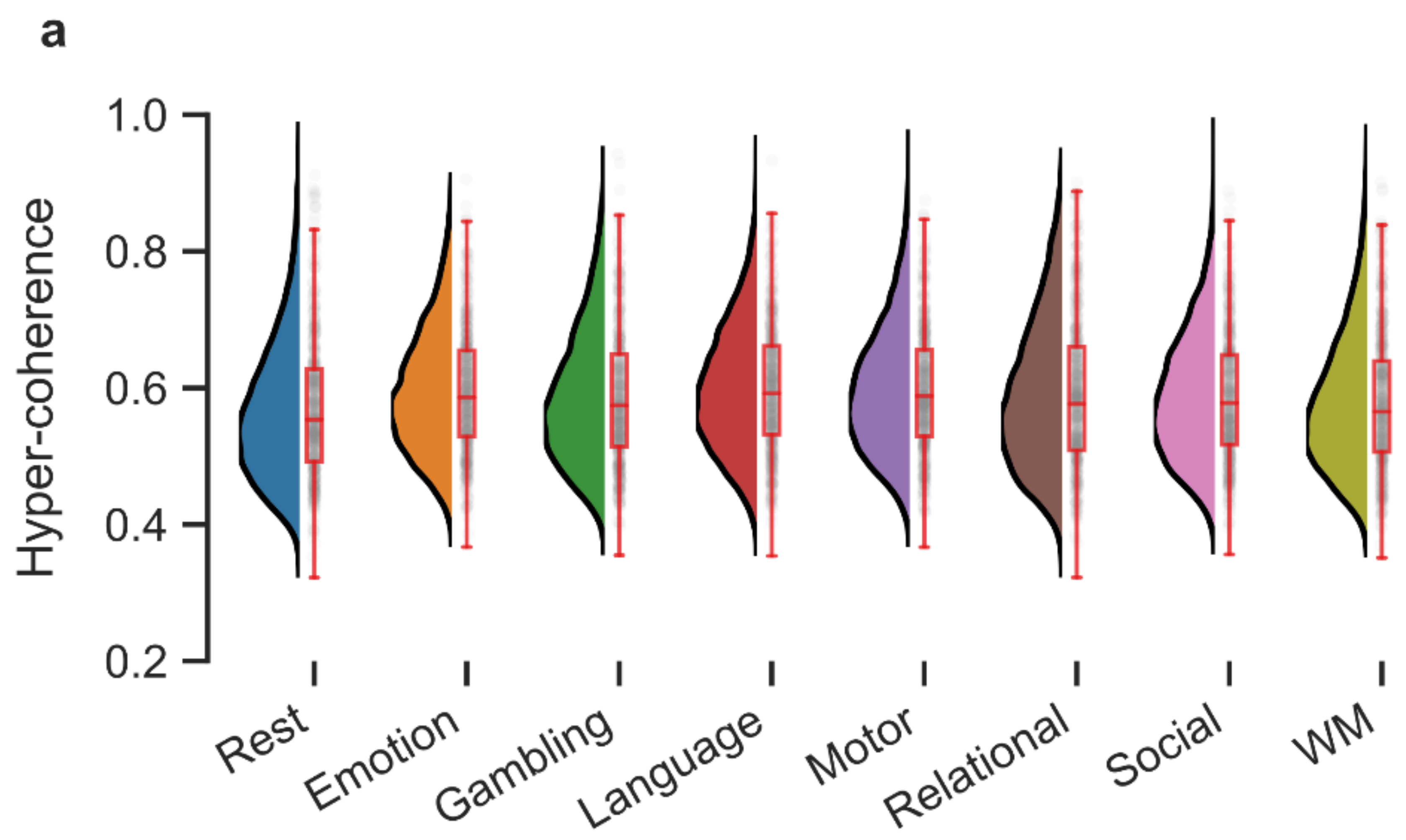
fMRI data

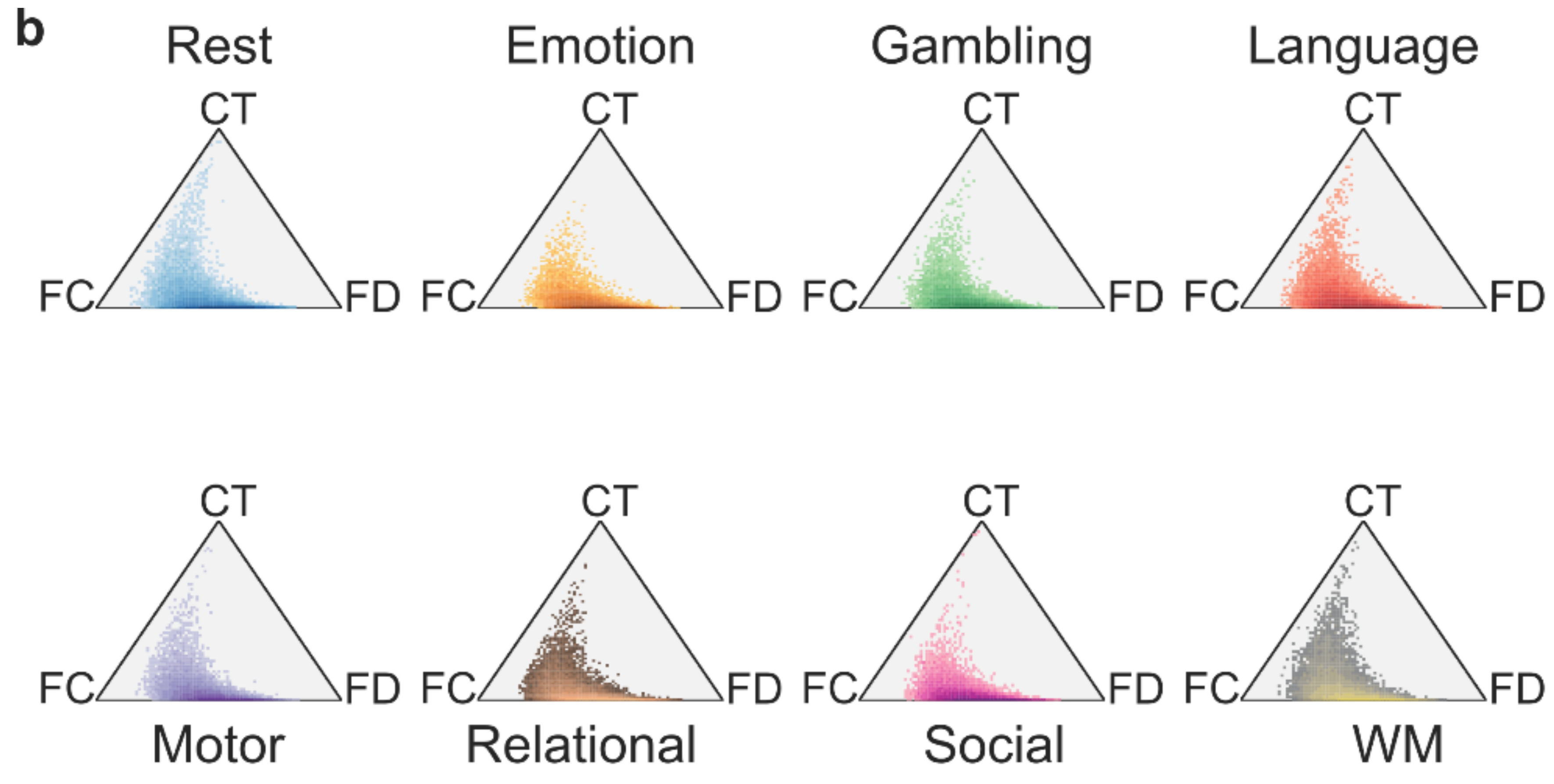
- 100 unrelated subjects of the Human Connectome Project (HCP)
- Resting-state & 7 different cognitive tasks
- 119 ROIs (100 Schaefer + 19 subcortical)

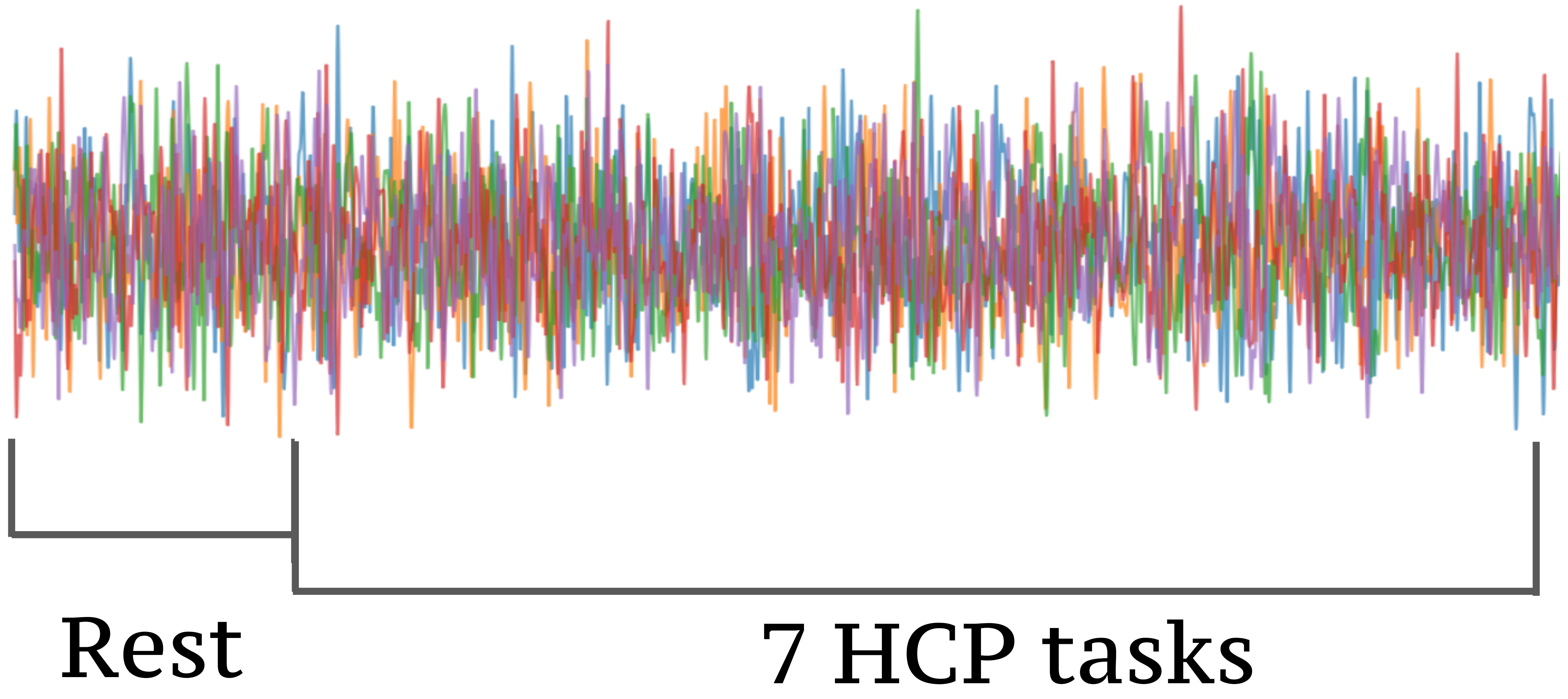


* Figure from Qu, Youzhi, et al. *International Workshop on Human Brain and Artificial Intelligence*. Singapore: Springer Nature Singapore, 2022.

Tasks


a
Hyper-coherence
1.0
0.8
0.6
0.4
0.2
Rest
Emotion
Gambling
Language
Motor
Relational
Social
WM


b
Rest
Emotion
Gambling
Language
CT
FC
FD
Motor
Relational
Social
WM


Rest
7 HCP tasks

Comparison with low-order

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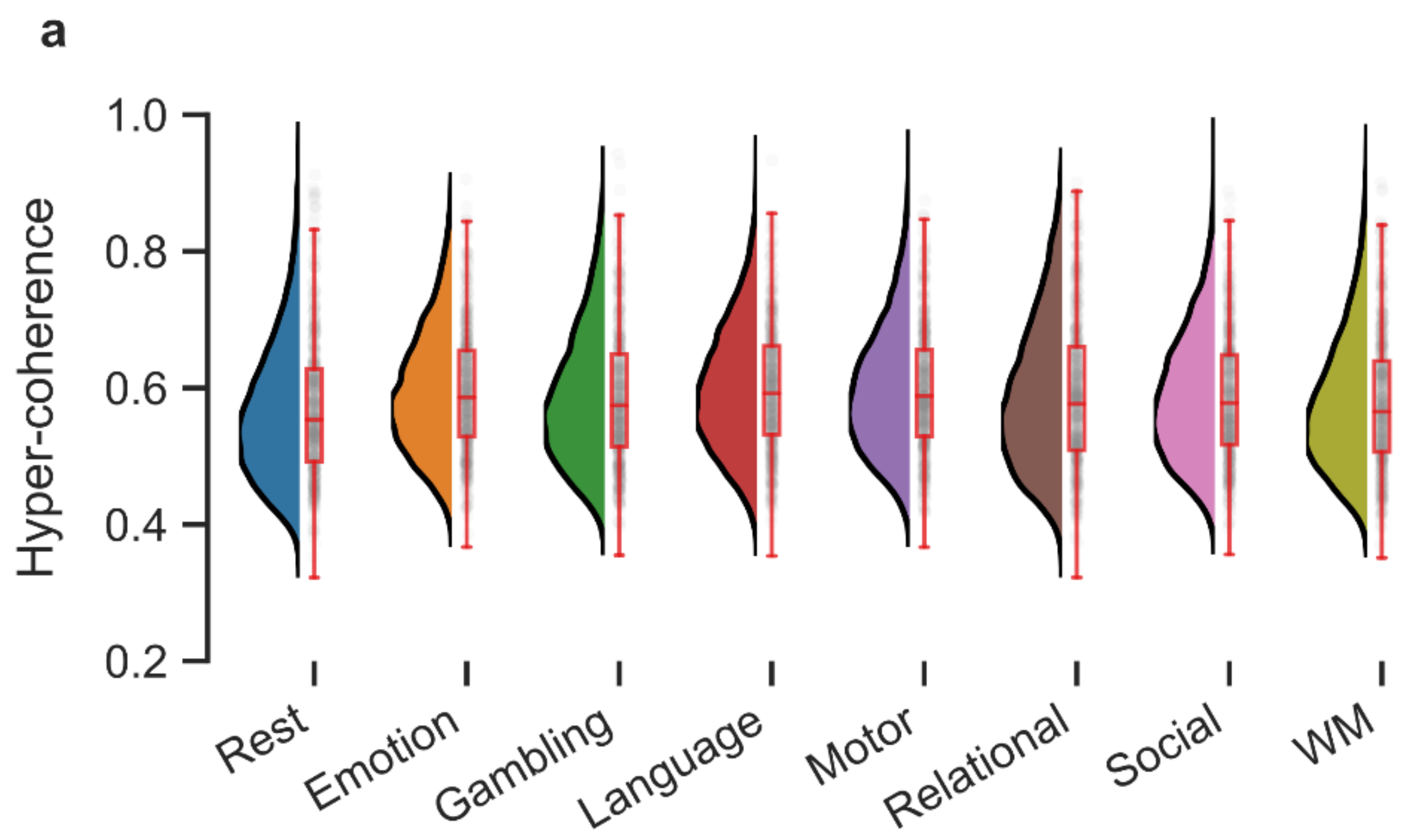
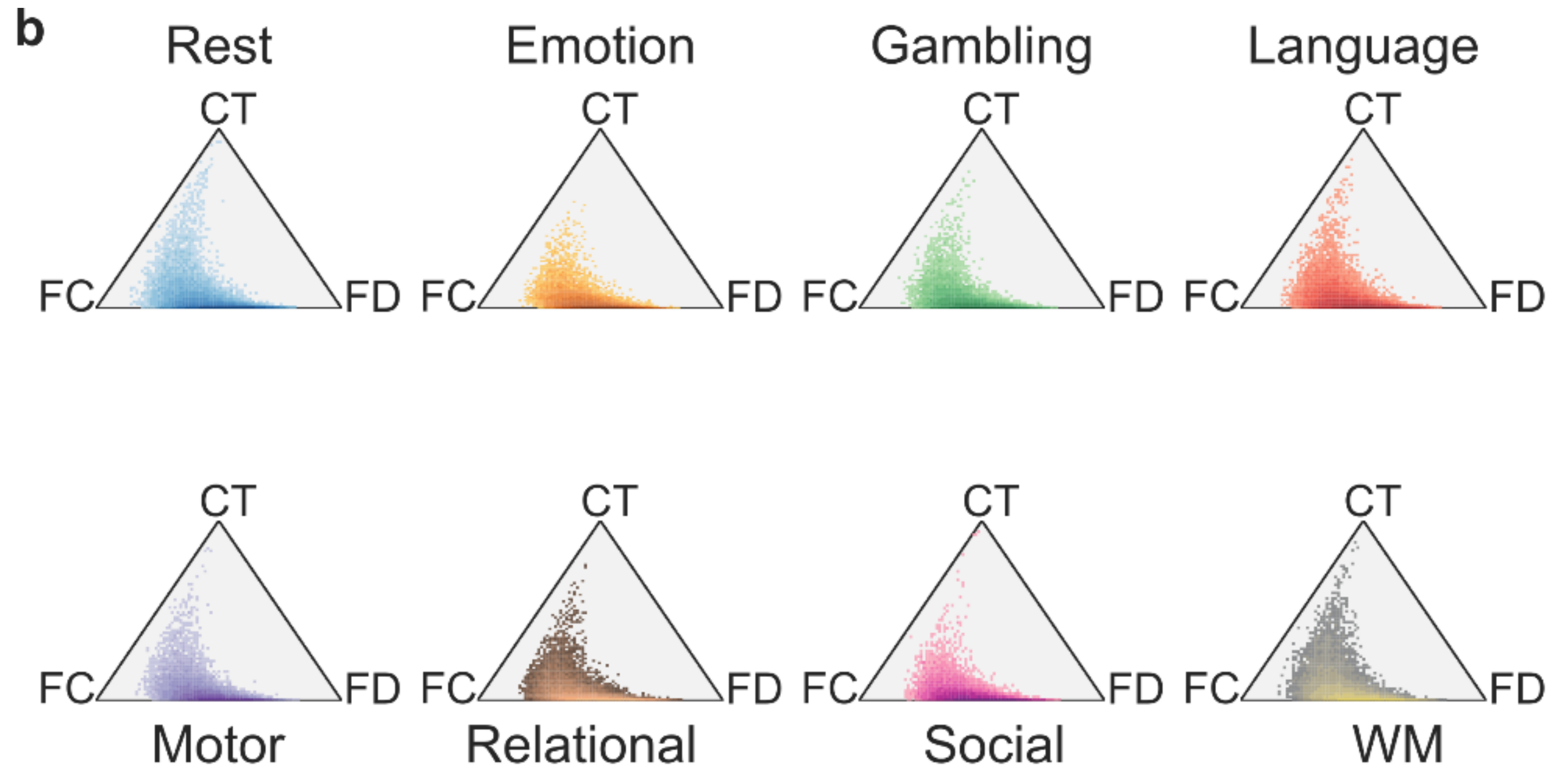
Different representations:

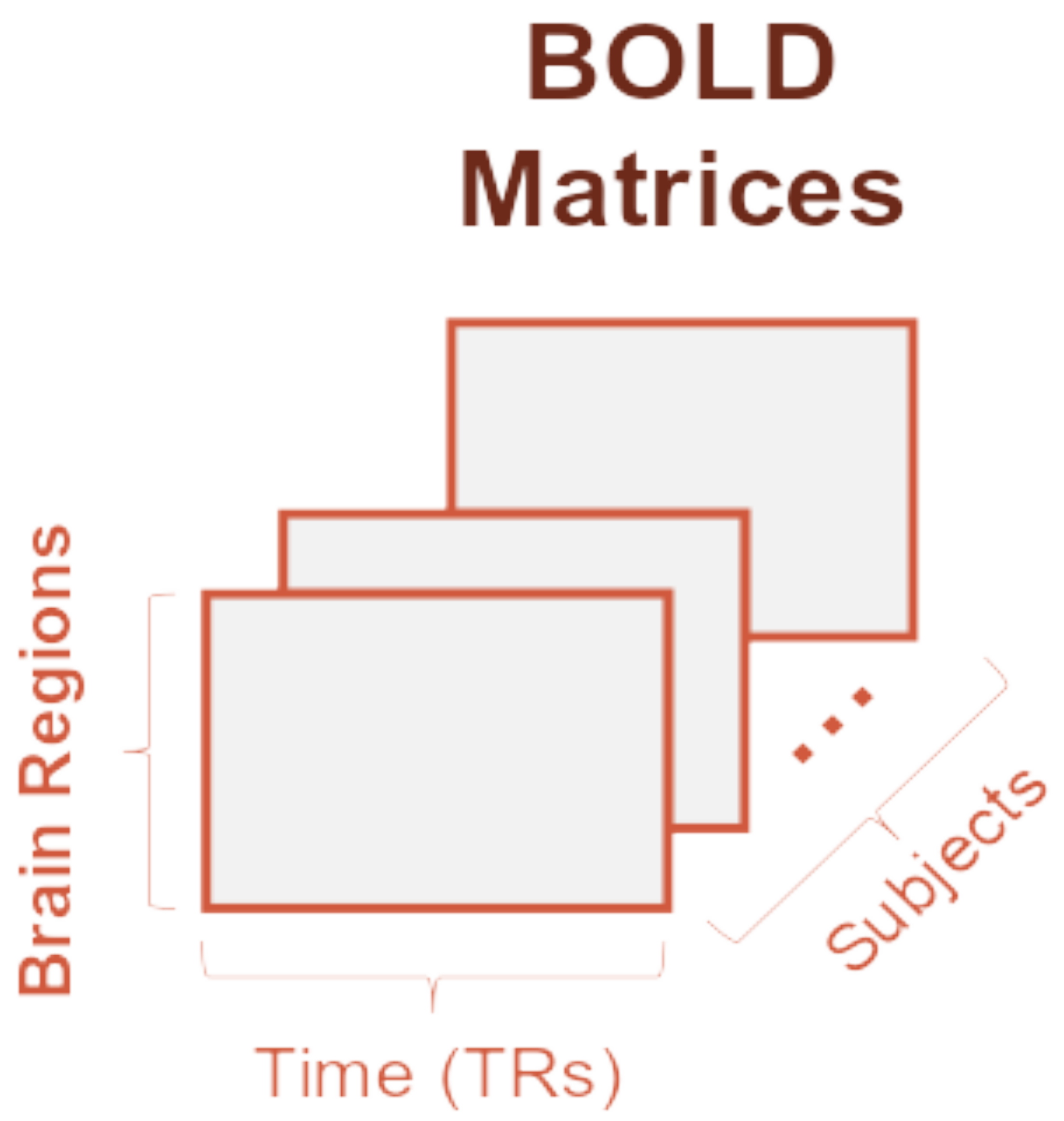
- Nodal level (BOLD signal & FC)
- Edge level (edge time series and eFC)
- Triangle level (Violating triangles)
- Topological level (Homological scaffold)

Santoro, A., Battiston, F., Lucas, M., Petri, G., & Amico, E. Higher-order connectomics for task classification and brain fingerprinting, bioRxiv, 2023.12. 04.569913

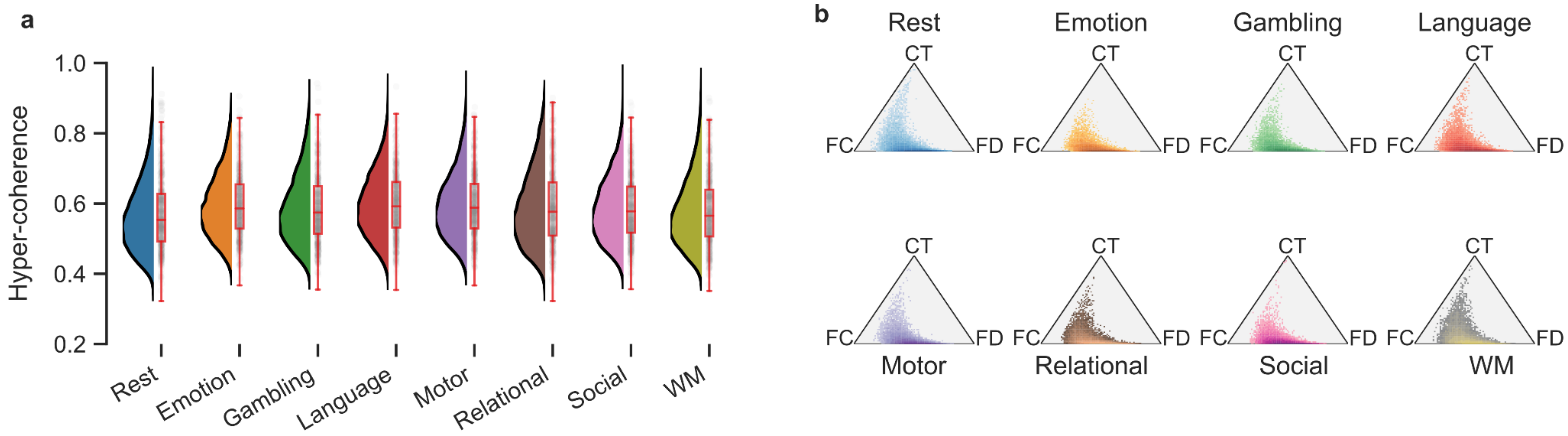
Time-resolved topology

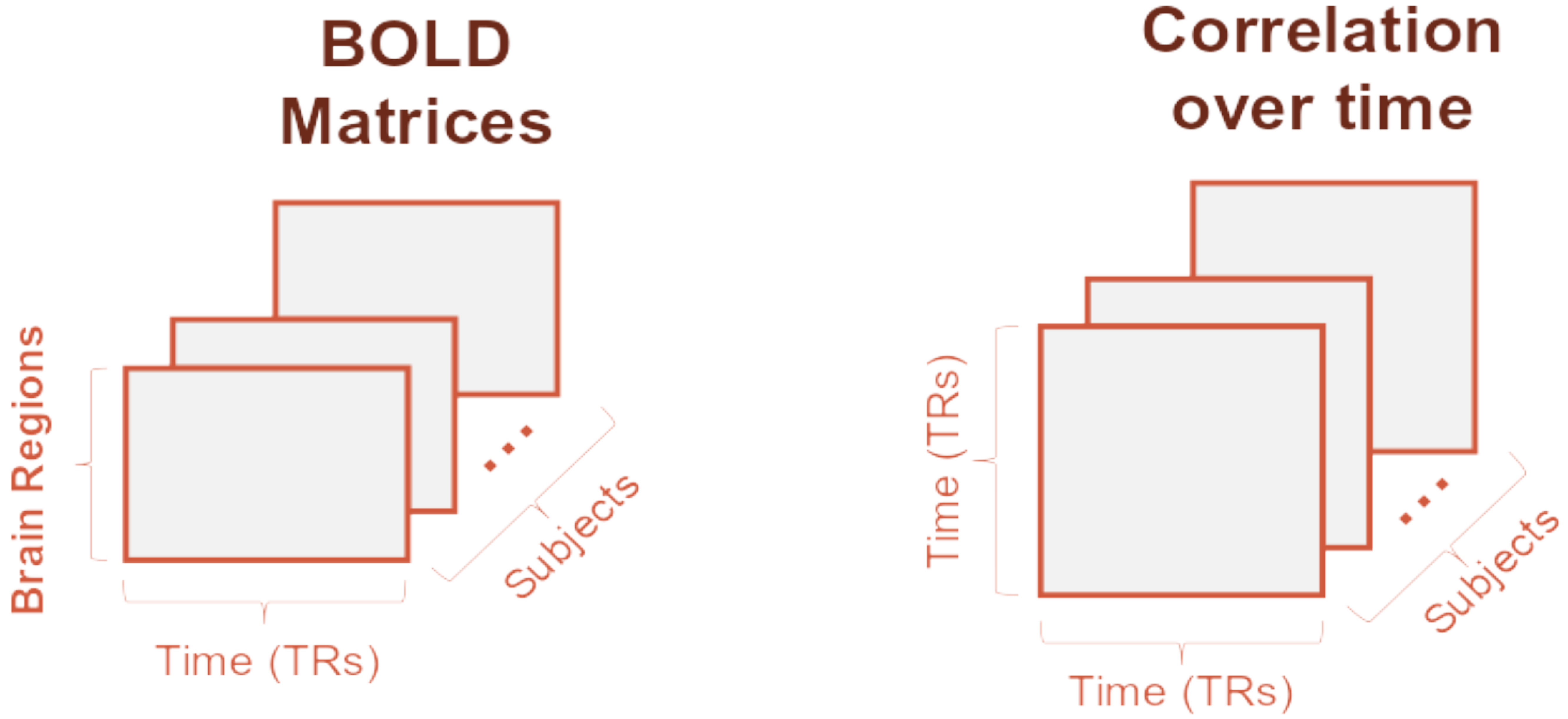




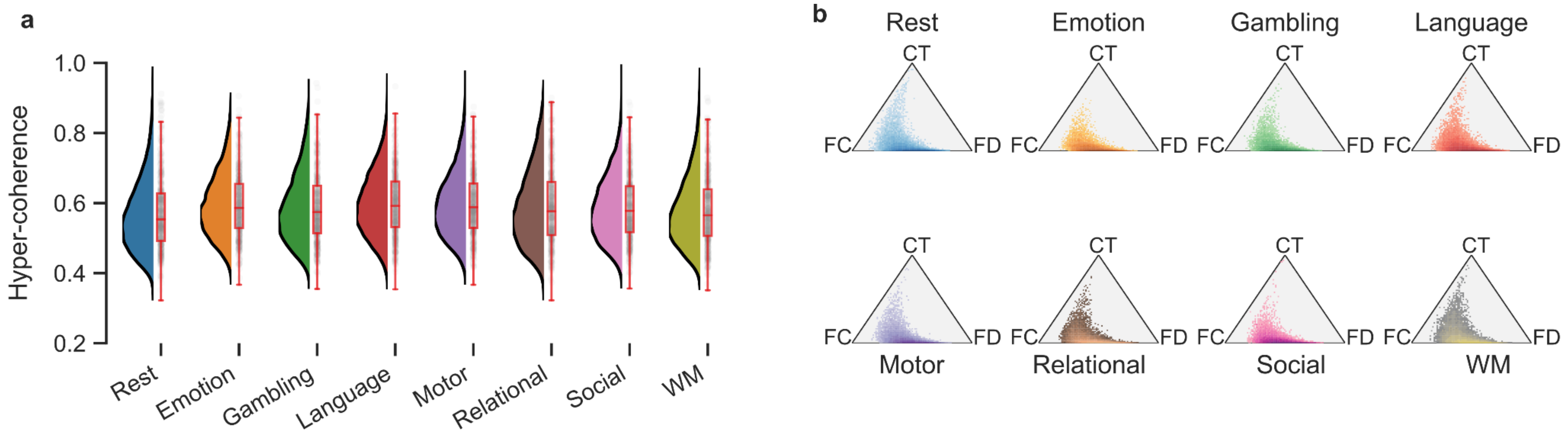


Time-resolved topology

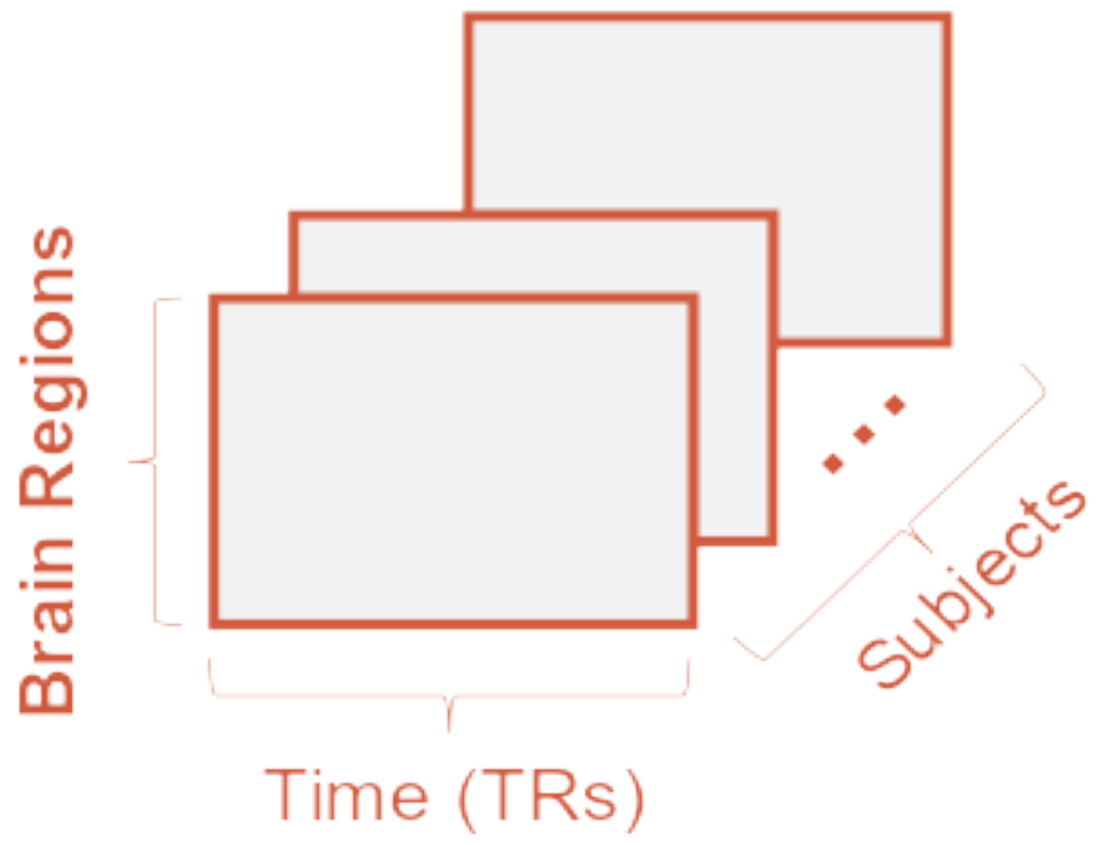




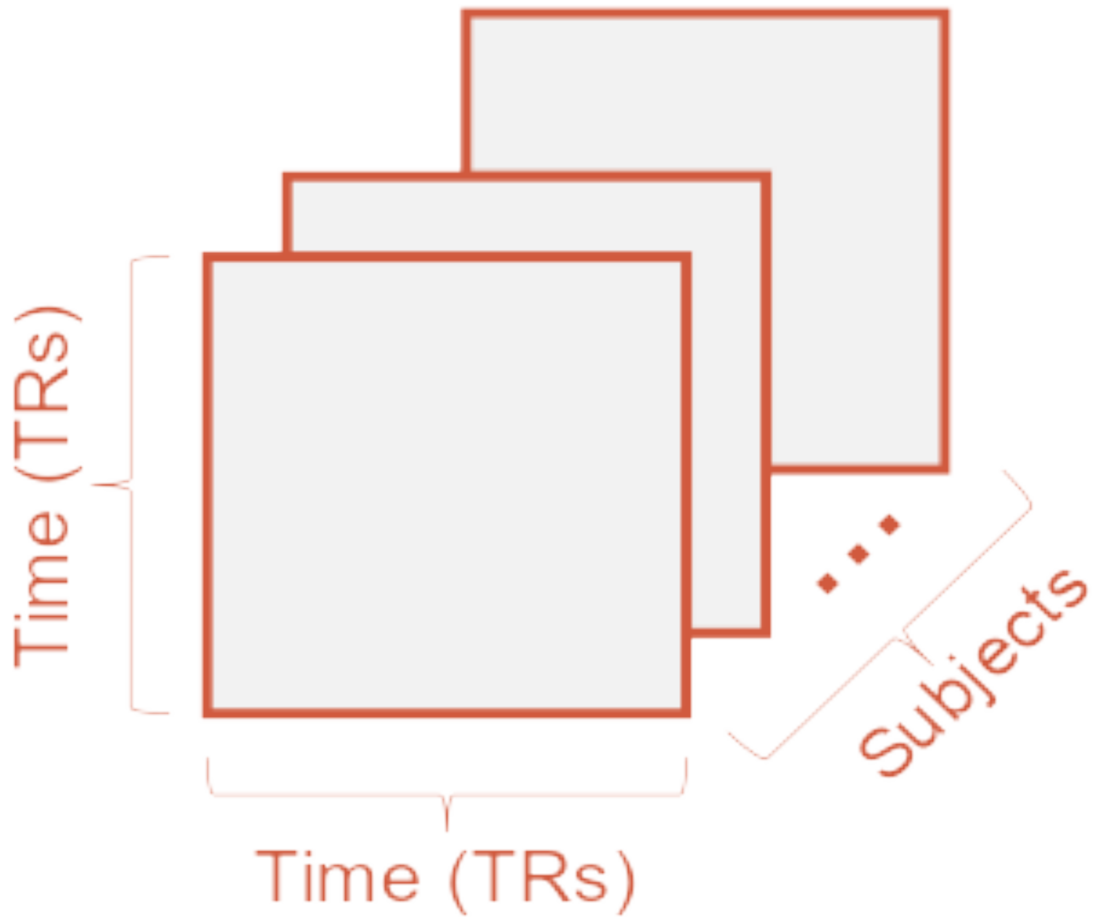
Time-resolved topology



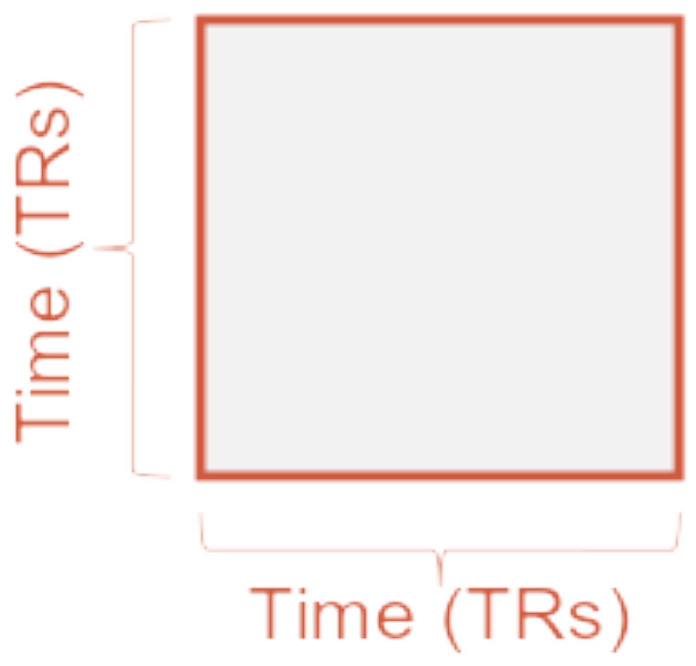
BOLD Matrices



Correlation over time



Average over subjects



Time-resolved topology

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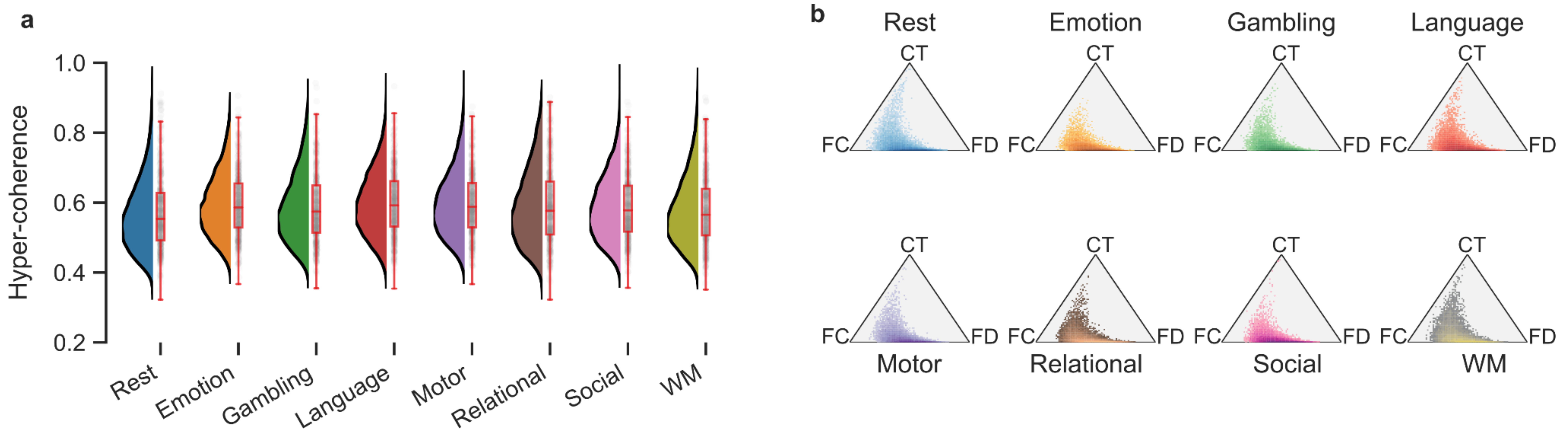

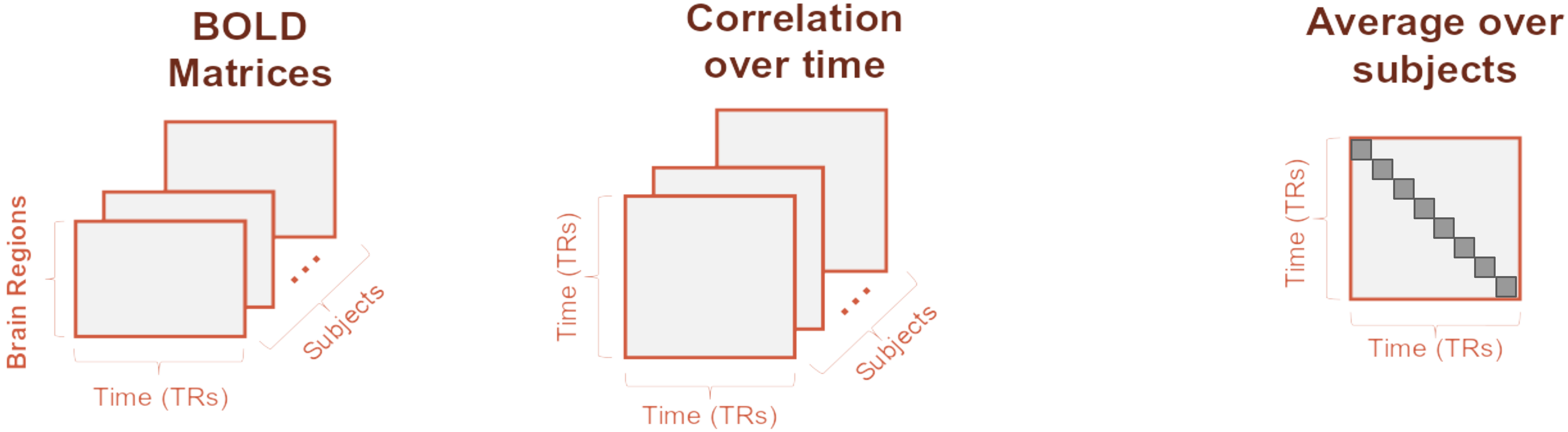

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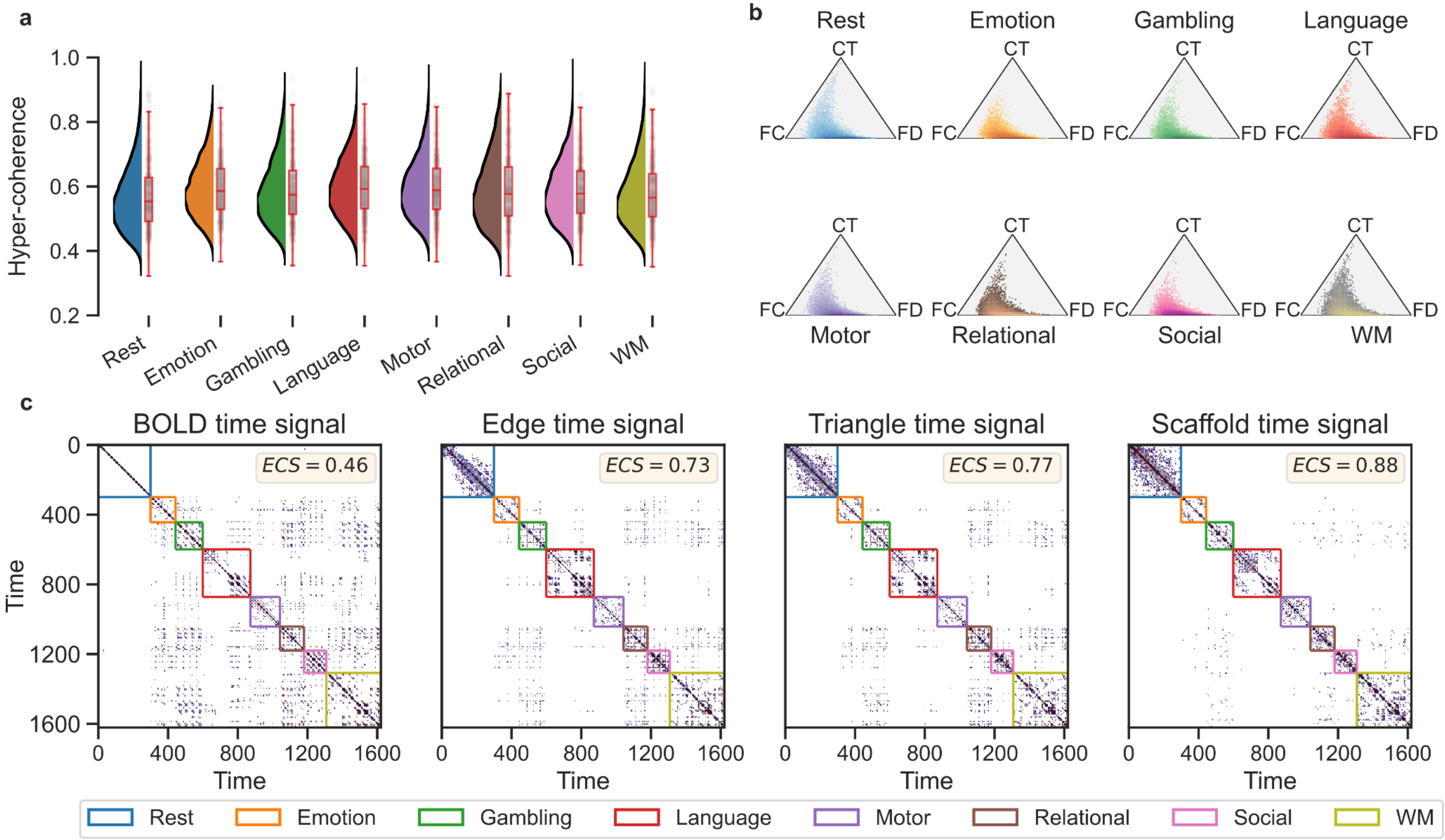
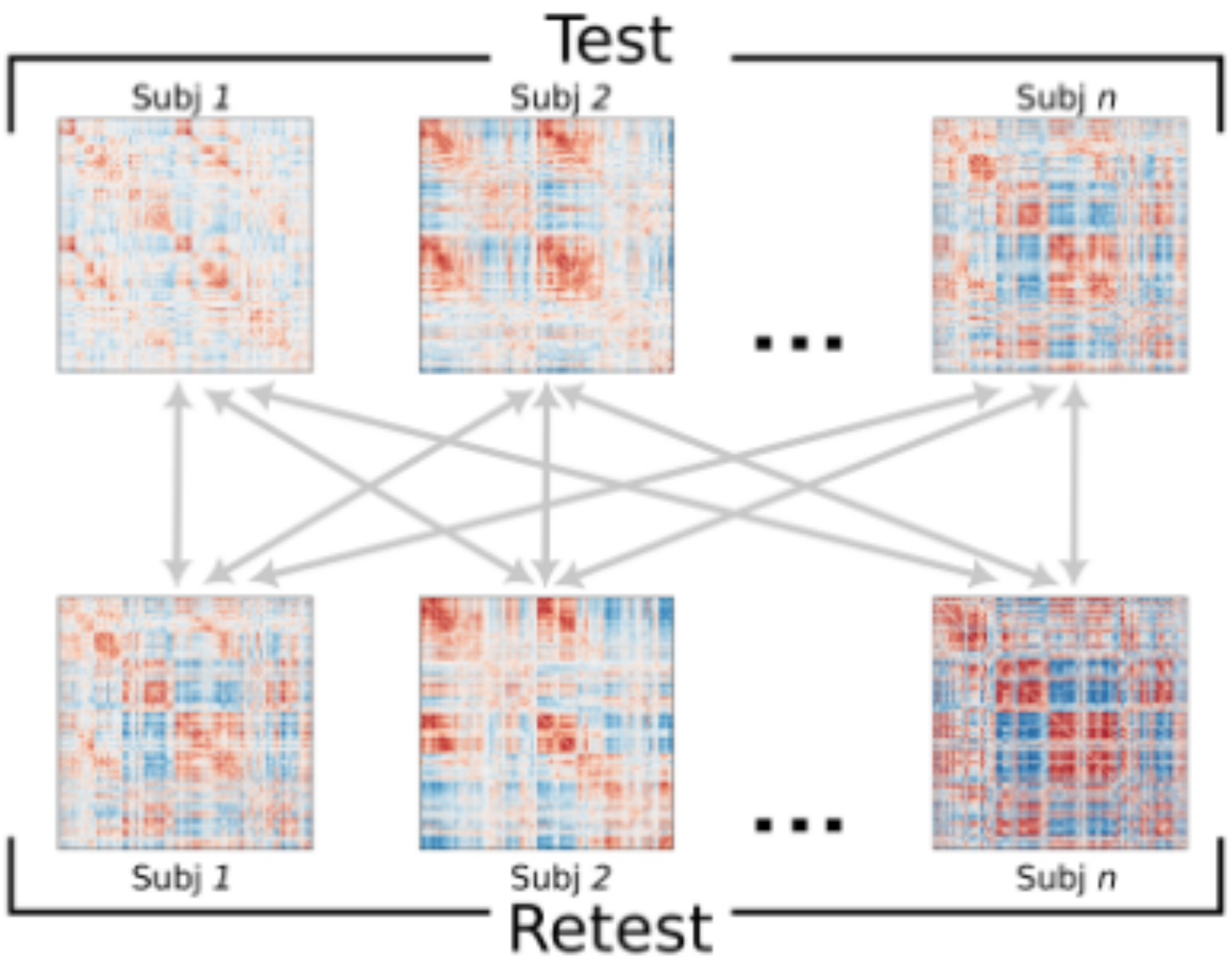


Santoro, A., Battiston, F., Lucas, M., Petri, G., & Amico, E. Higher-order connectomics for task classification and brain fingerprinting, bioRxiv, 2023.12. 04.569913

Instantaneous fingerprinting



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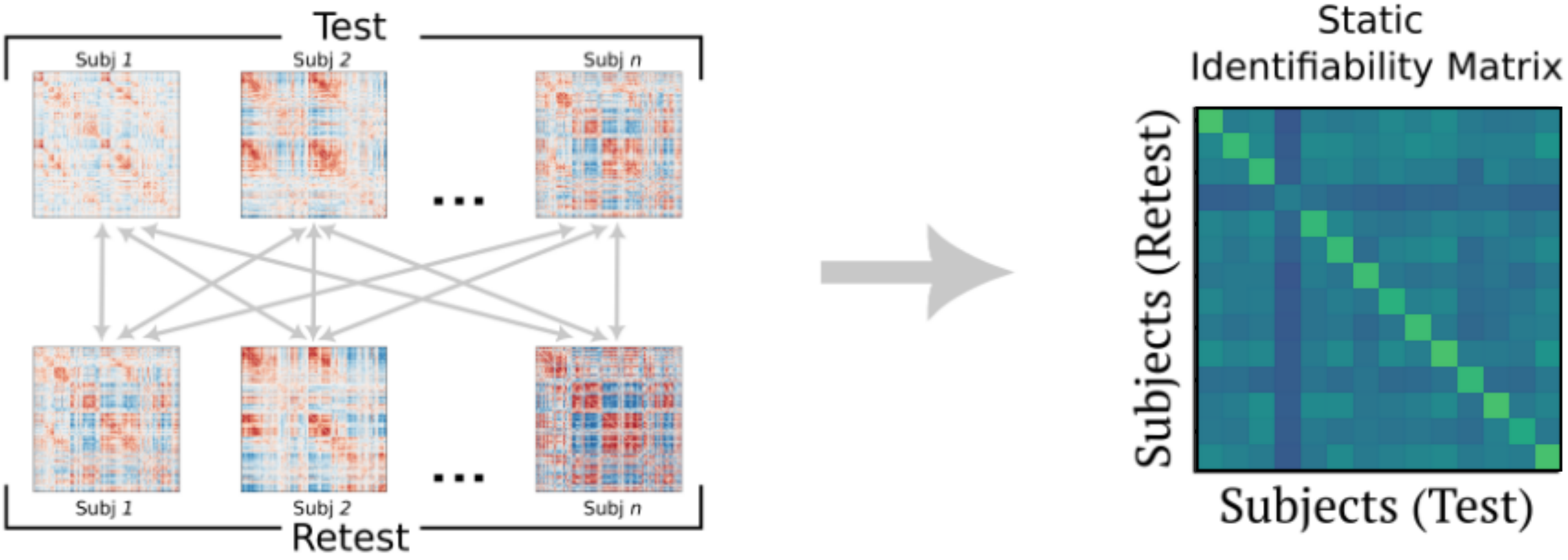

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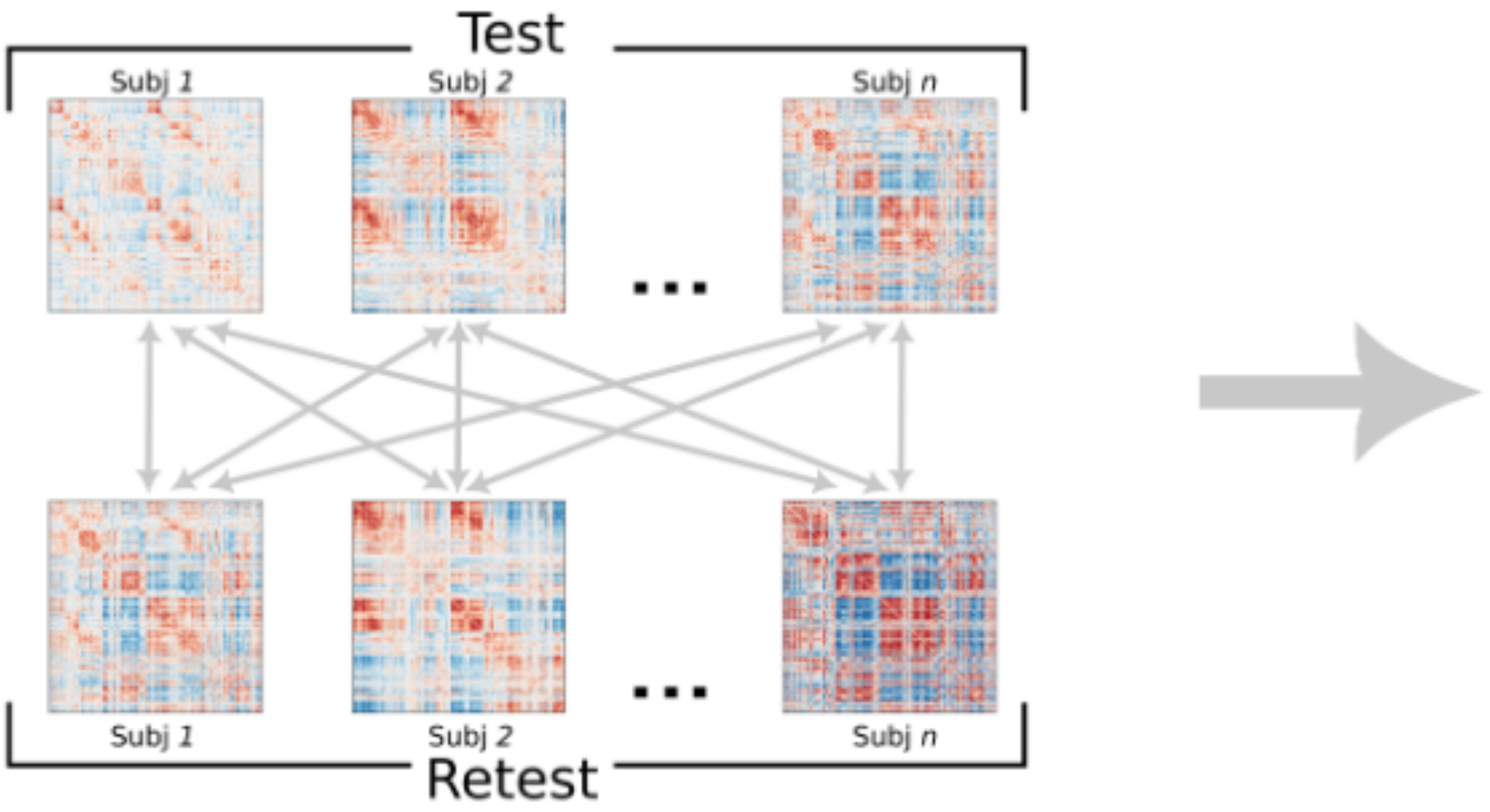

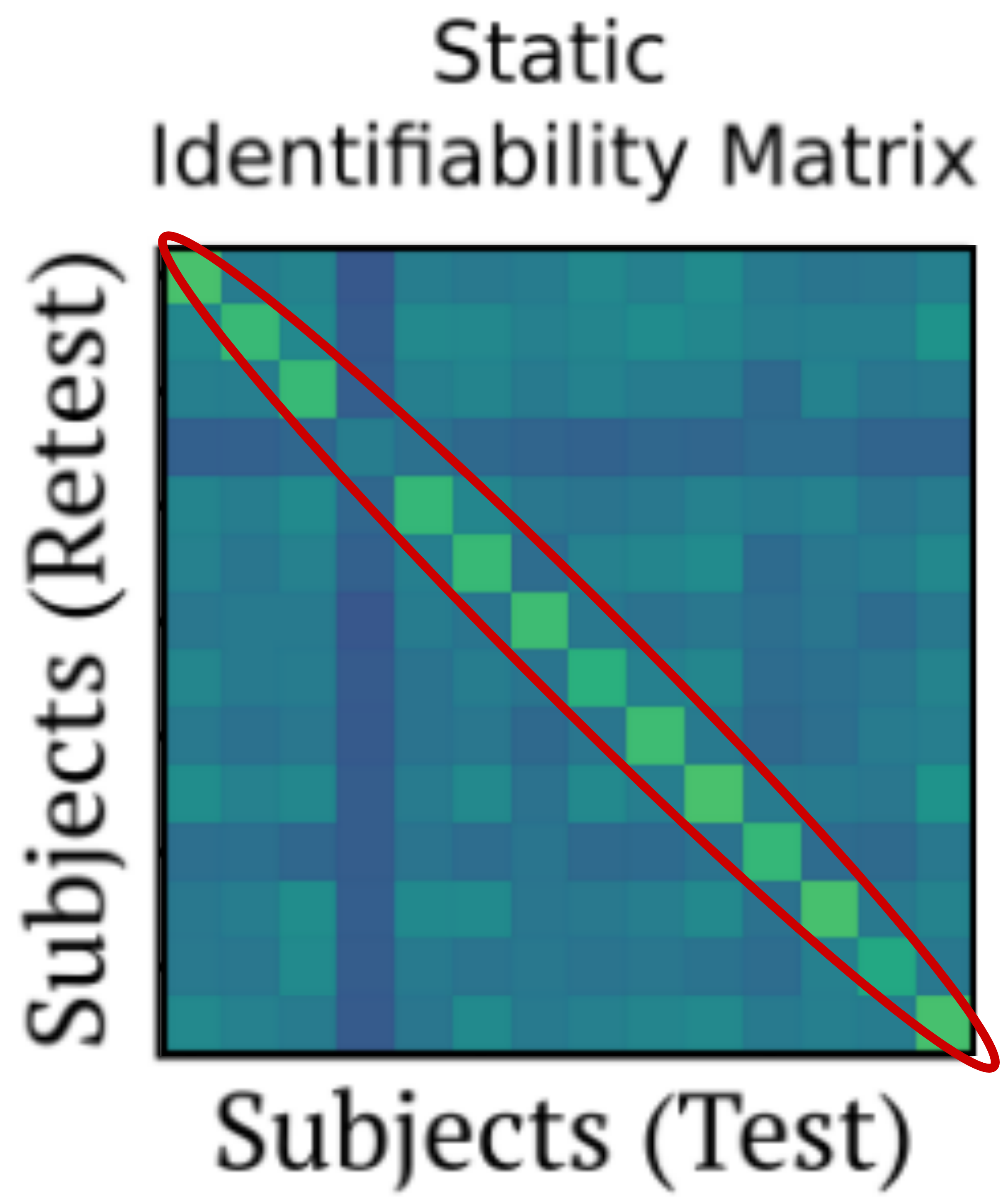

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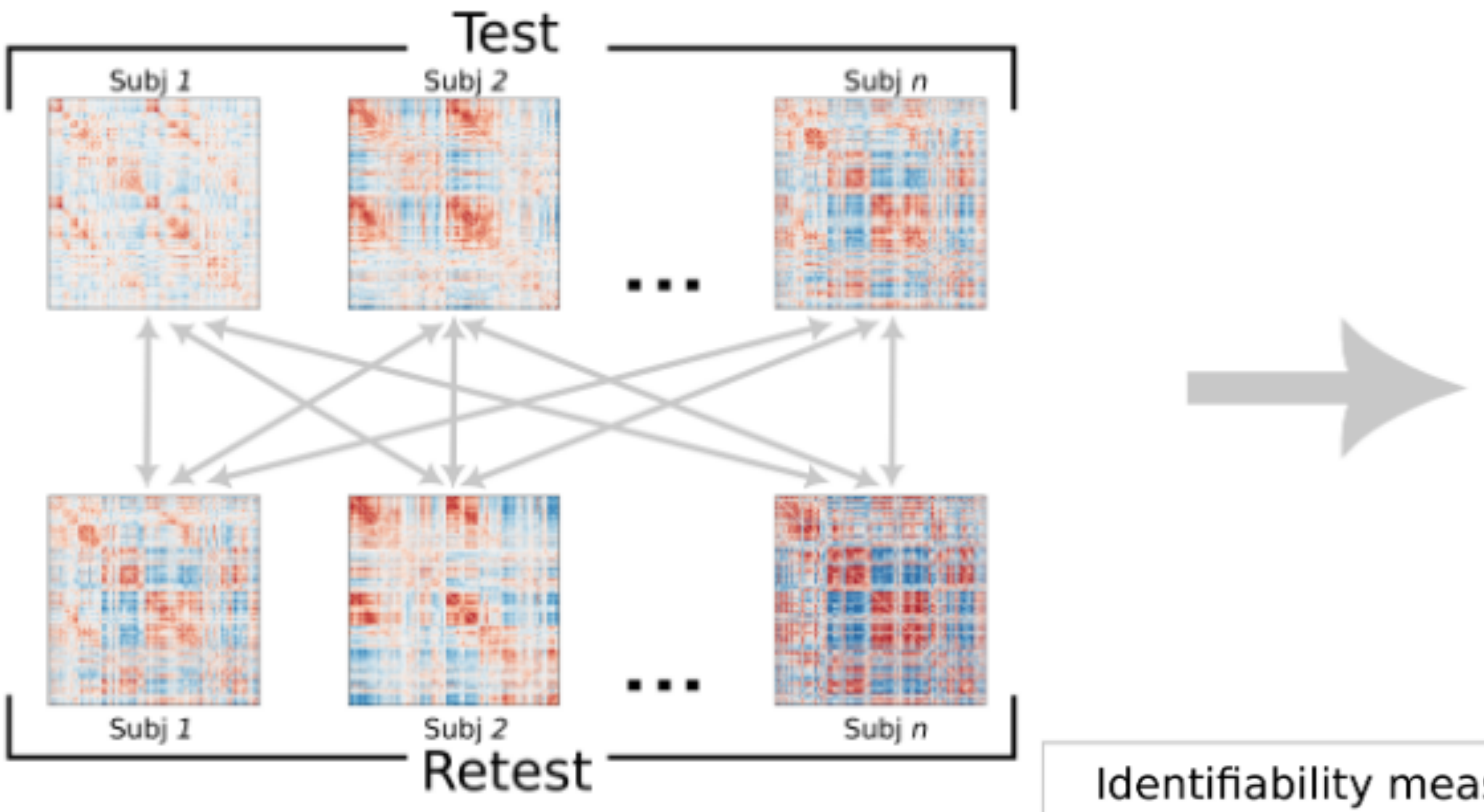

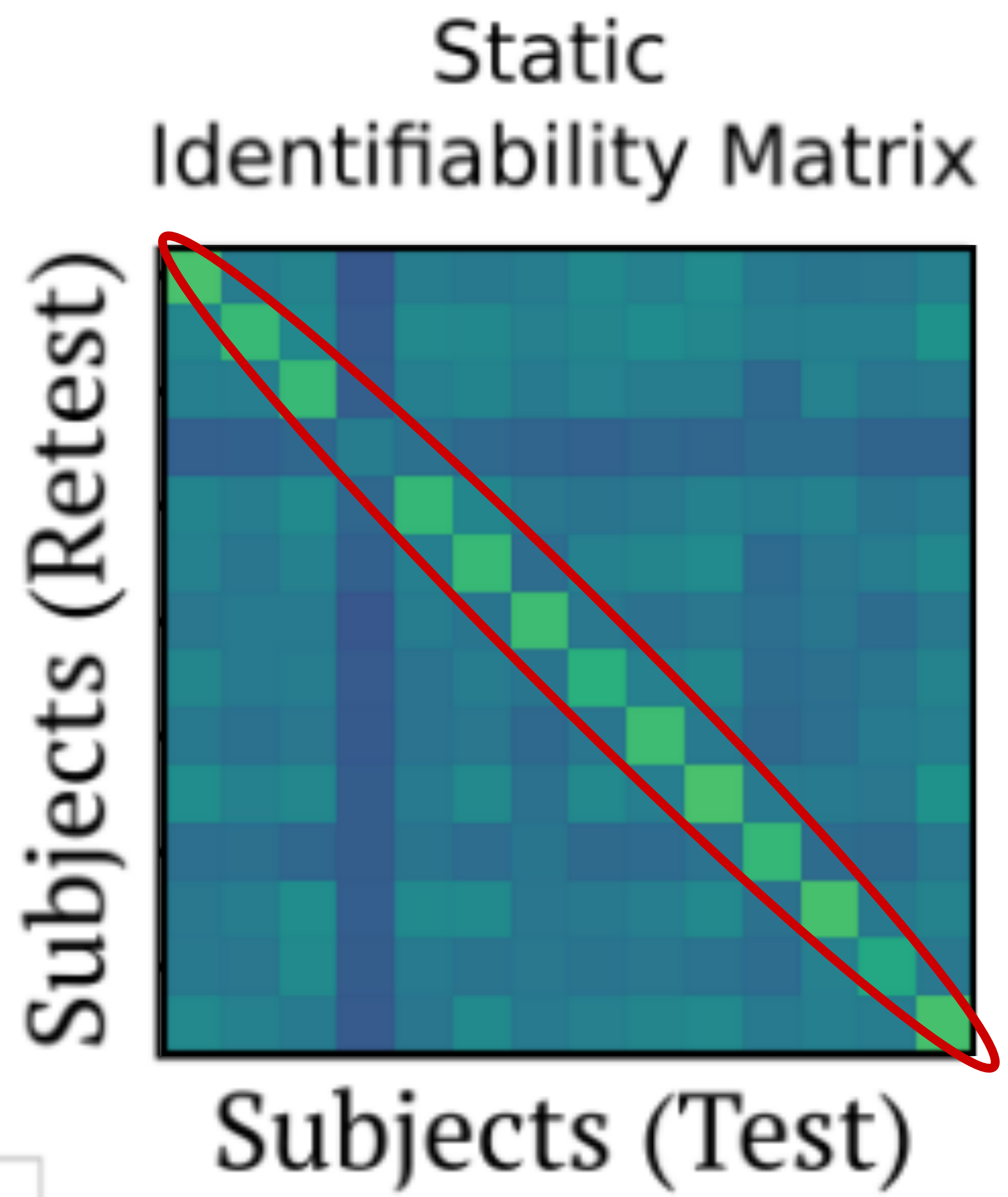

Identifiability measures

$I_{self} = <a_{ii}>$ $I_{others} = <a_{ij}>$

$I_{diff} = (I_{self} - I_{others})*100$

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Instantaneous fingerprinting

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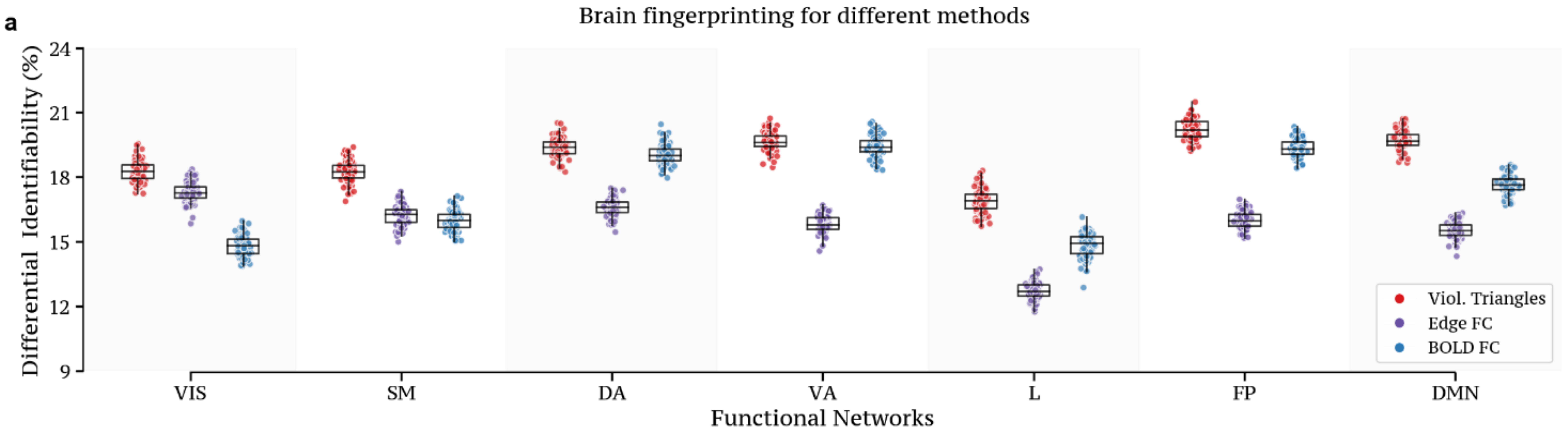

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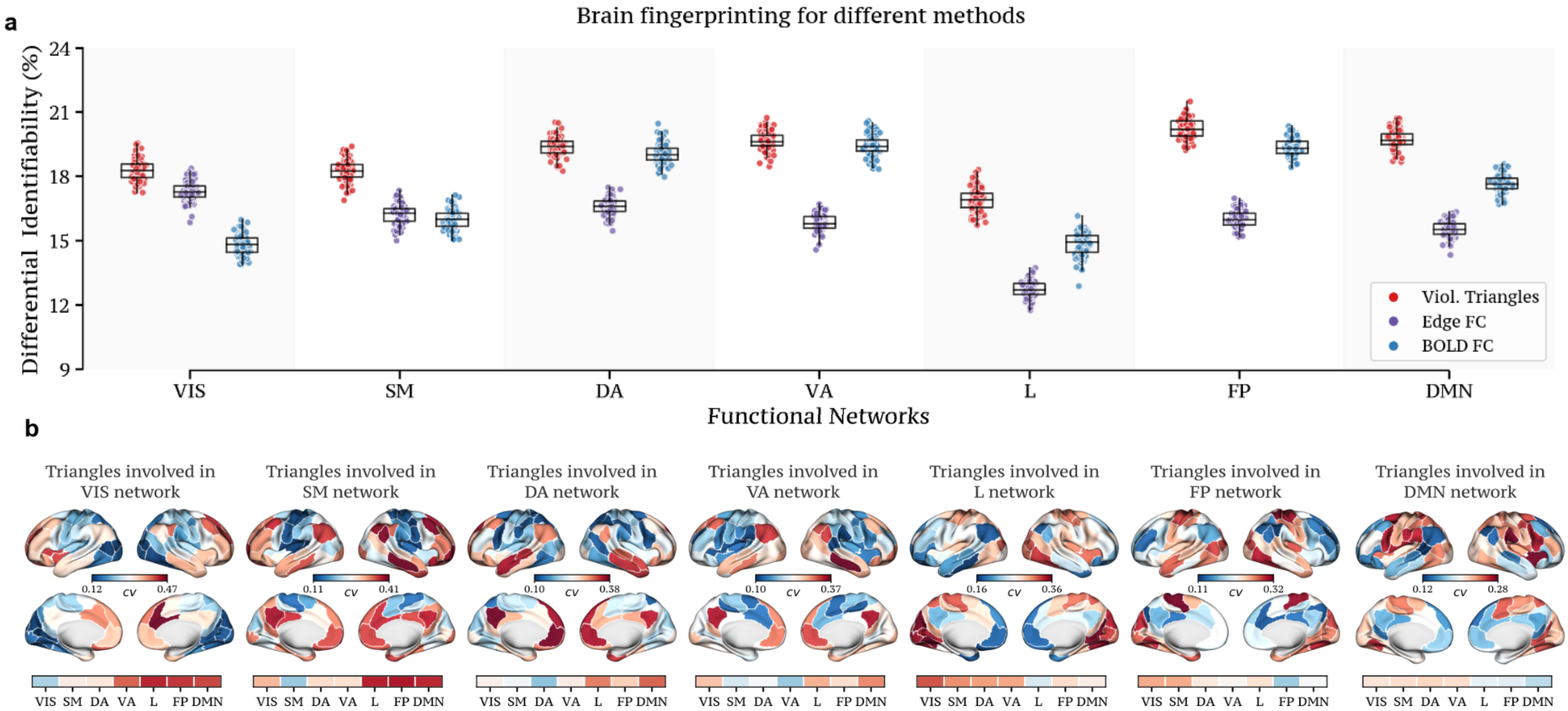

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Time-resolved topology

Summing up

Conundrum:

Time-resolved topology

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Summing up

- Global higher-order indicators are not able to distinguish between rest and tasksLocal markers (scaffold) incredibly powerful.
- Local higher-order information can be used to discriminate tasks“
- Hyper-coherent triangles outperform other methods for individual identification

Conundrum:

Time-resolved topology

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Conundrum:

- Global information (scaffolds) very discriminative at long timescales

Summing up

- Global higher-order indicators are not able to distinguish between rest and tasksLocal markers (scaffold) incredibly powerful.
- Local higher-order information can be used to discriminate tasks“
- Hyper-coherent triangles outperform other methods for individual identification

Conundrum:

- Global information (scaffolds) very discriminative at long timescales
- Local information (triangles) at short timescale

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Main collaborators:

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Maxime Lucas

Manish Saggar

Matteo Diano

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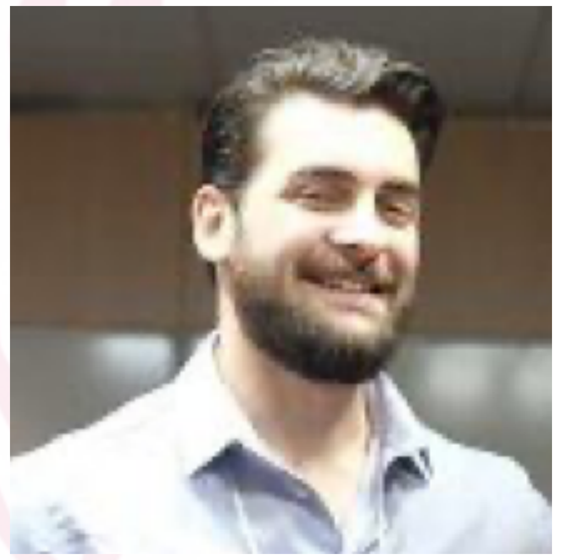

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Federico Battiston

Andrea Santoro

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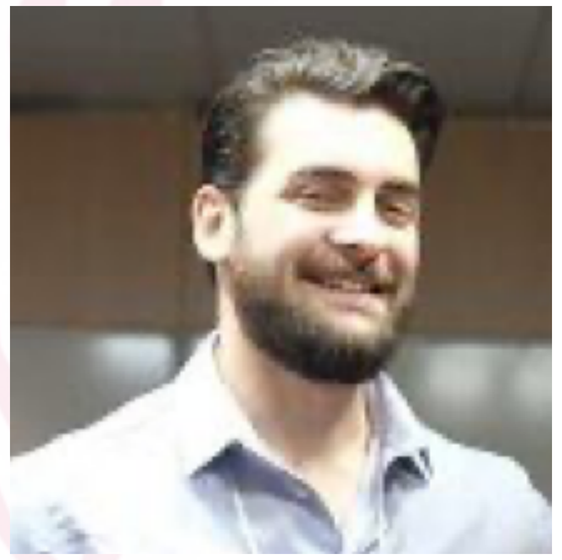


Enrico Amico

Federico Battiston

Andrea Santoro

nature physics

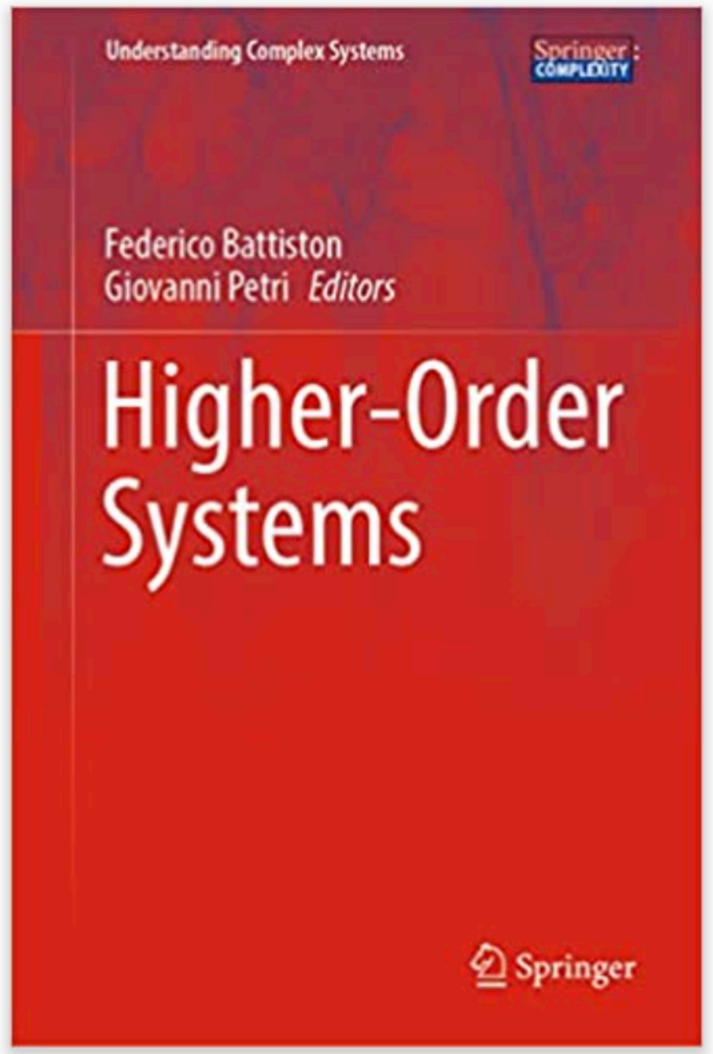
PERSPECTIVE

https://doi.org/10.1038/s41567-021-01371-4

Check for updates

The physics of higher-order interactions in complex systems

Federico Battiston[1]✉, Enrico Amico[2,3], Alain Barrat[4,5], Ginestra Bianconi[6,7], Guilherme Ferraz de Arruda[8], Benedetta Franceschiello[9,10], Iacopo Iacopini[1], Sonia Kéfi[11,12], Vito Latora[6,13,14,15], Yamir Moreno[8,15,16,17], Micah M. Murray[9,10,18], Tiago P. Peixoto[1,19], Francesco Vaccarino[20] and Giovanni Petri[8,21]✉



Understanding Complex Systems

Book Series

There are 141 volumes in this series

Published 2004 - 2021

Contributors: Bianconi, Krioukov, Moreno, Barrat, Scarpino, Jost, Vaccarino, Bobrowski, Arenas, Skardal, Bick, Porter, Pikowski, Lambiotte, Schaub, ….

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CETI THEORY

Network Science Institute

at Northeastern University

We are hiring PhDs (in London!)

nature physics

PERSPECTIVE

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Check for updates

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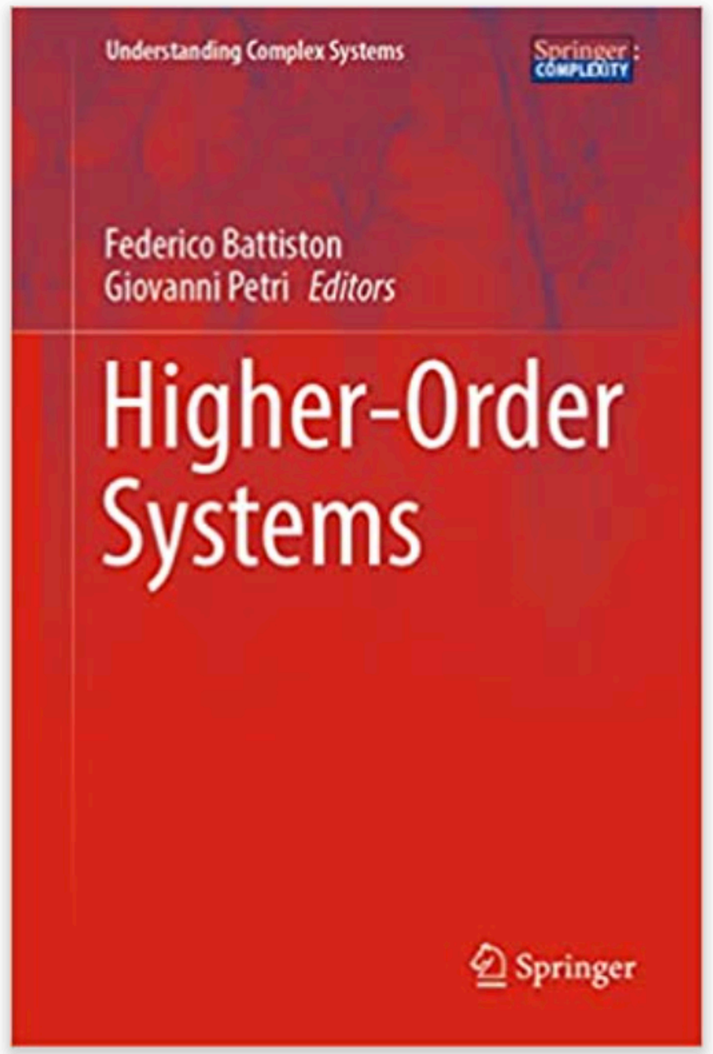

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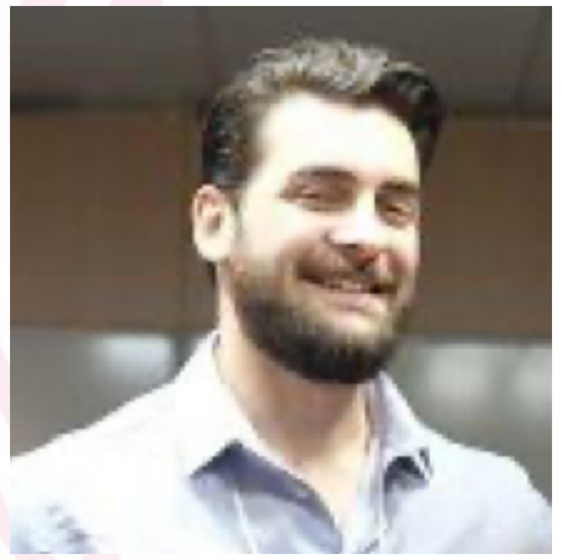


Enrico Amico

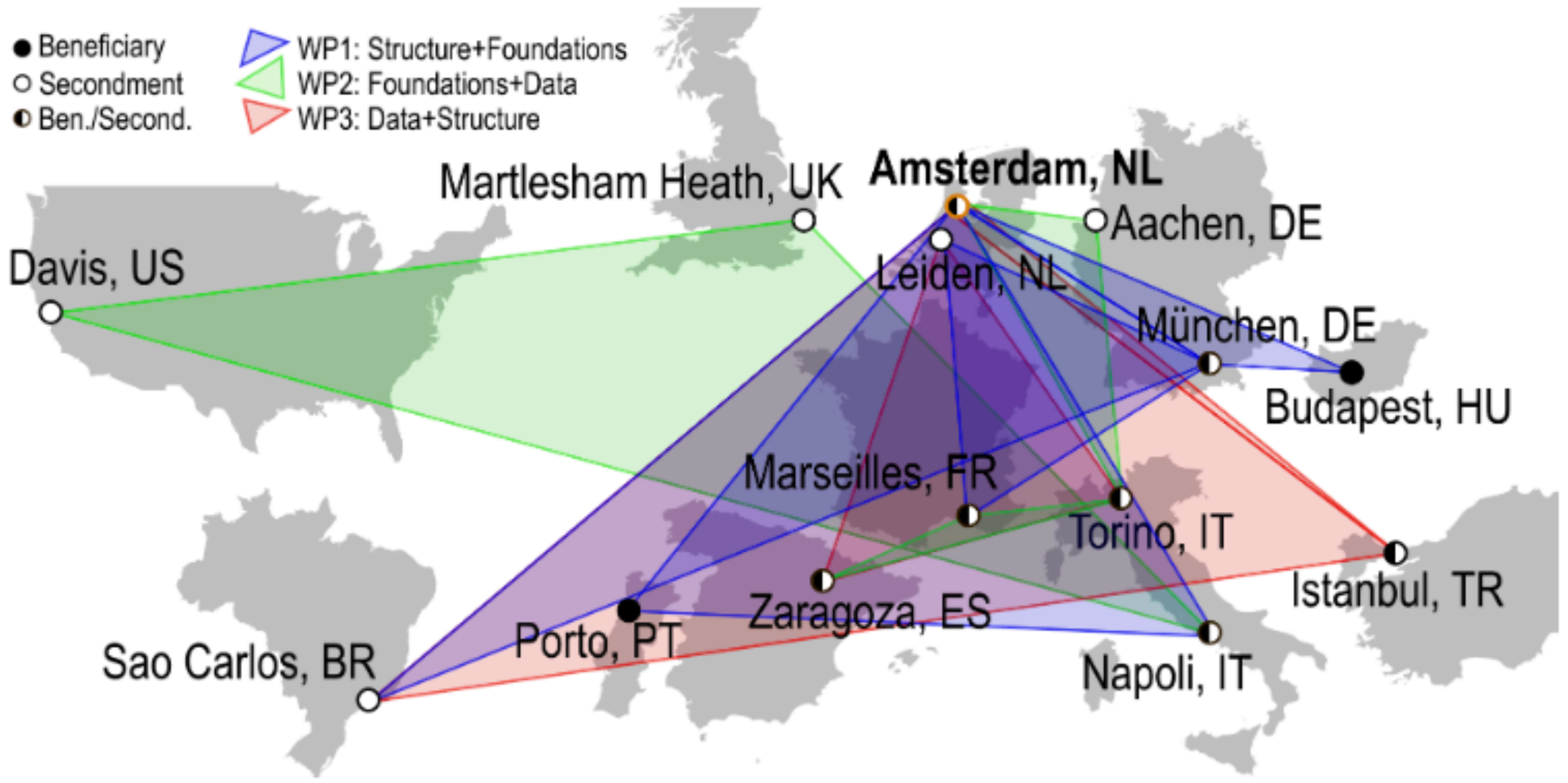
Federico Battiston

Andrea Santoro

BEYOND THE EDGE.NETWORK

MSCA Doctoral Network

Consortium



Coordinator

Vrije Universiteit Amsterdam	Netherlands (NL)

Beneficiaries

Alfréd Rényi Institute of Mathematics	Hungary (HU)
Universidade do Porto	Portugal (PT)
Technische Universität München	Germany (DE)
Universita degli Studi di Napoli Federico II	Italy (IT)
Aix Marseille Université	France (FR)
CENTAI Institute SPA	Italy (IT)
Universidad de Zaragoza	Spain (ES)
Kadir Has Universitesi	Turkey (TR)

Associated Partners

Amsterdam UMC - VUmc	Netherlands (NL)
Universiteit van Amsterdam	Netherlands (NL)
Universidade de Sao Paulo	Brazil (BR)
Rheinisch–Westfälische Technische Hochschule Aachen	Germany (DE)
University of California, Davis	United States of America
CWTS B.V.	Netherlands (NL)
BT Wireless	United Kingdom (UK)
Politecnico di Torino	Italy (IT)
Eötvös Loránd University	Hungary (HU)

We are recruiting!

BeyondTheEdge is recruiting 10 PhD students across the consortium members; these positions are subject to eligibility requirements.

BeyondTheEdge PhD Position at Alfréd Rényi Institute of Mathematics (Budapest, HU)
The theory of graph limits turned out to be a powerful tool for solving problems in extremal combinatorics and random graphs. The limit object is usually not a graph anymore (e.g., it can be a probability measure or an operator). The goal of the project is to discover extensions of this theory to hypergraphs, describe limit objects of random hypergraphs and higher-order networks, and find applications for mean-field limit theories for dynamics on heterogeneous networks. *[Prospective research secondments at TU Munich and VU Amsterdam]*
Contact: Ágnes Backhausz
Prospective starting date: September 2, 2024
Apply at: renyi.hu (from February 9, 2024)

BeyondTheEdge PhD Position at the University of Porto (Porto, PT)
We will develop a coupled cell hypernetwork formalism, which captures higher-order interactions in networks given by differential equations, to determine the existence and stability of network synchronization patterns. Applying this framework to research concrete model equations (e.g., ecological models) will allow to understand and control synchrony, synchrony breaking, as well as the emergence of periodic (e.g., cyclic competition between species) and heteroclinic behavior. *[Prospective research secondments at VU Amsterdam and Universita degli Studi di Napoli Federico II]*
Contact: Ana Dias
Prospective starting date: October 1, 2024
Apply at: cmup.fc.up.pt (will be posted in February 2024)

BeyondTheEdge PhD Position at the Technical University of Munich (Munich, DE)
We are going to study mean-field limit dynamics on hypergraphs using a combination of tools from dynamical systems and graph limit theory. A focus will be the case of adaptive (or co-evolutionary) hypergraph dynamics for several concrete models arising in applications and their analysis using bifurcation theory. *[Prospective research secondments at Aix-Marseille University (AMU) and CWTS]*
Contact: Christian Kuehn
Prospective starting date: On or before October 1, 2024
Apply at: multiscale.systems (will be posted in February 2024)

BeyondTheEdge PhD position at Vrije Universiteit (Amsterdam, NL)
Coupled oscillator networks give rise to higher-order phase interactions. This project will consider the structure and properties of such derived higher-order interaction networks and how these relate to collective phenomena —synchronization and beyond—of the oscillator network. *[Prospective research secondments at Technical University of Munich (TUM) and University of Sao Paulo (USP)]*
Contact: Christian Bick
Prospective starting date: On or before October 1, 2024
Apply at: workingat.vu.nl (will be posted in February 2024)

BeyondTheEdge PhD position at University of Naples Federico II (Napoli, IT)
Analysis, Control and Application of Network with Higher-Order Interactions: Control of complex networks typically involves devising strategies for networks characterized by pairwise interactions. The project will extend these approaches to many-body interactions in real world applications offering new opportunities for manipulating the collective dynamics arising in complex systems. *[Prospective research secondments at University of California, Davis and BT Wireless]*
Contact: Mario di Bernardo
Prospective starting date: November 1, 2024
Apply at: To be announced in March/April 2024

BeyondTheEdge PhD position at Aix-Marseille University (Marseille, FR)
The PhD will consist in a data-driven development of new approaches and tools to deal with higher order networks (HONs). We will define tools to characterize relevant and central structures in HONs, develop comparison methods between HONs, tools to extract timescales and states in temporal HONs. We will also consider models of dynamical processes involving higher-order structures and study the role of the various structures we have defined in these processes. *[Prospective research secondments at CENTAI and Universidad de Zaragoza]*
Contact: Alain Barrat
Prospective starting date: October 1, 2024
Apply at: cpt.univ-mrs.fr (will be posted in February 2024)

BeyondTheEdge PhD position at CENTAI Institute (Torino, IT)
The PhD project aims to develop methods for inferring higher-order dynamical mechanisms in systems from biology and neuroscience, where data is often incomplete or aggregated. It focuses on distinguishing between network (pairwise) and higher-order interactions using limited data. The project will create new analysis and modeling techniques, using both empirical and synthetic models, to study the impact of data aggregation on identifying different process types. *[Prospective research secondments at Rheinisch-Westfaelische Technische Hochschule (RWTH) Aachen and Amsterdam UMC - VUmc]*
Contact: Giovanni Petri
Prospective starting date: October 31, 2024
Apply at: To be announced in March/April 2024

BeyondTheEdge PhD position at Vrije Universiteit (Amsterdam, NL)
Development, evaluation, and (clinical) application of statistical methods for assessing higher-order interactions in functional magnetic resonance (fMRI) data. The project focuses on the formulation, statistical inference, and goodness-of-fit analysis of parametric models for multivariate non-Gaussian observations. In these models, higher-order interactions are quantified by higher-order multivariate cumulants. In a second stage, the models are complemented by hemodynamic observation models. *[Prospective research secondments at Amsterdam UMC - VUmc and Kadir Has Universitesi]*
Contact: Rikkert Hindriks
Prospective starting date: On or before October 1, 2024
Apply at: workingat.vu.nl (will be posted in February 2024)

BeyondTheEdge PhD position at University of Zaragoza (Zaragoza, ES)
The PhD student will work on the general topic of developing a mathematical and computational framework to characterize the structure and dynamics of higher-order networked systems. More specifically, we aim at elucidating when graph metrics are suited to characterize higher-order interactions (HOIs), both in terms of the structure and the dynamics, and when and which new metrics need to be introduced. Critical questions include what metrics reveal relevant hypergraph structural and dynamical features and how to properly capture their interdependency. *[Prospective research secondments at CENTAI and CWTS]*
Contact: Yamir Moreno
Prospective starting date: Between September 1 and October 15, 2024
Apply at: cosnet.bifi.es (will be posted in February 2024)

BeyondTheEdge PhD position at Kadir Has University (Istanbul, TR)
The PhD student will address the problem of reconstructing complex systems' network structure from data to understand and predict sudden changes in network dynamics. Using the framework of complex systems, we will pioneer methods for characterizing the network dynamics from data that can feature in diverse fields such as geology, climate science, chemistry, and neuroscience by blending tools from the fields of Dynamical Systems and Machine Learning. This project will investigate mathematical brain hypernetworks. *[Prospective research secondments at Universidade de Sao Paulo (USP) and Universiteit van Amsterdam]*
Contact: Deniz Eroglu
Prospective starting date: October 1, 2024
Apply at: nodds.khas.edu.tr (will be posted in February 2024)

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NPL RESEARCH

CETI THEORY

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nature physics

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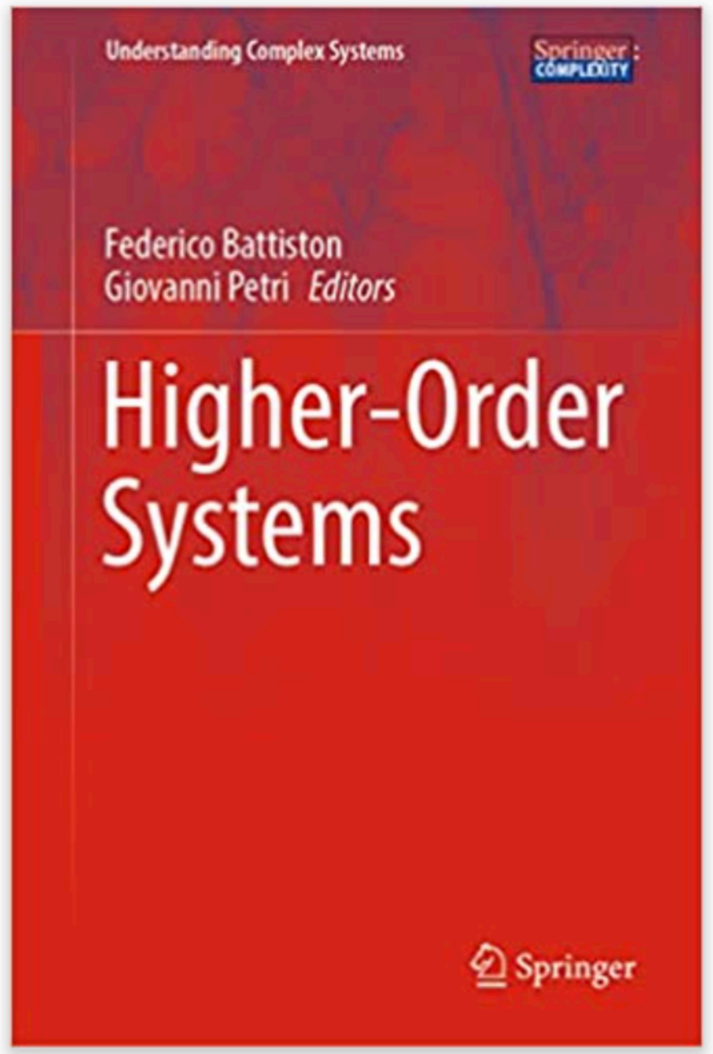

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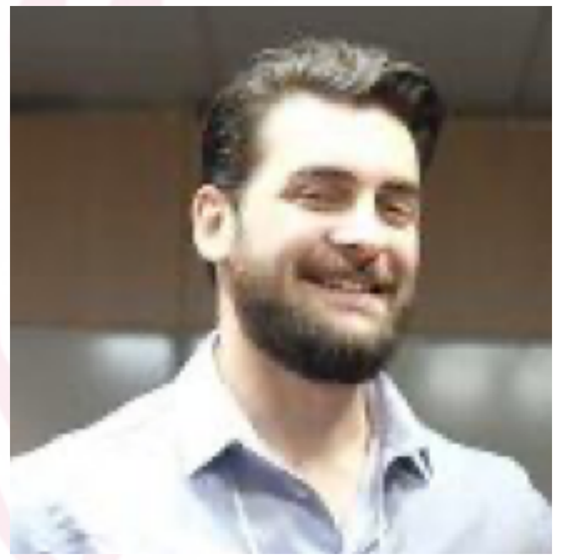

Enrico Amico

Federico Battiston

Andrea Santoro

Talk to me @lordgrilo Check stuff out @ lordgrilo.github.io

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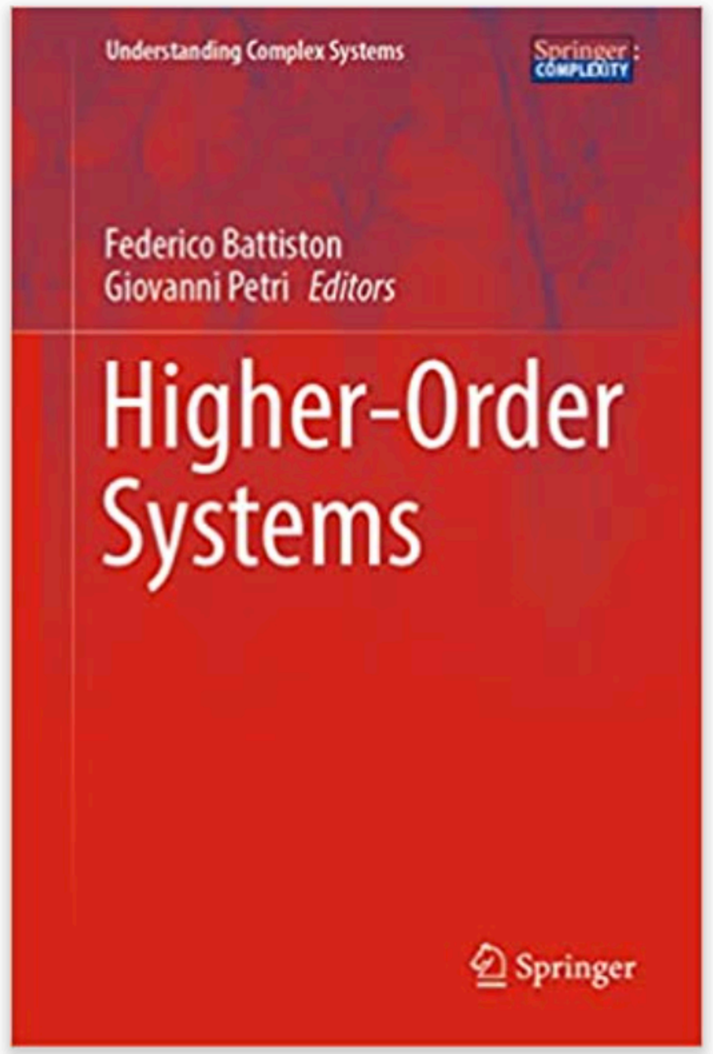
The physics of higher-order interactions in complex systems

Federico Battiston[1]✉, Enrico Amico[2,3], Alain Barrat[4,5], Ginestra Bianconi[6,7], Guilherme Ferraz de Arruda[8], Benedetta Franceschiello[9,10], Iacopo Iacopini[1], Sonia Kéfi[11,12], Vito Latora[6,13,14,15], Yamir Moreno[8,15,16,17], Micah M. Murray[9,10,18], Tiago P. Peixoto[1,19], Francesco Vaccarino[20] and Giovanni Petri[8,21]✉



Understanding Complex Systems

Book Series
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Published 2004 - 2021

Contributors: Bianconi, Krioukov, Moreno, Barrat, Scarpino, Jost, Vaccarino, Bobrowski, Arenas, Skardal, Bick, Porter, Pikowski, Lambiotte, Schaub, ….

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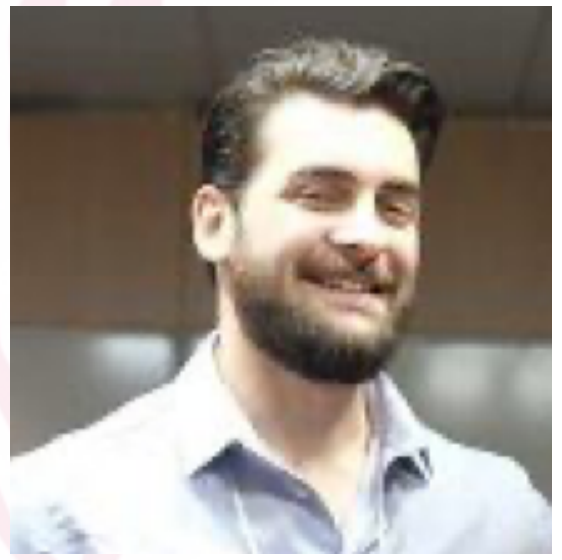

Enrico Amico

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Slides here: