

Whole-brain models, brain states, and phase transitions

Adrián Ponce-Alvarez

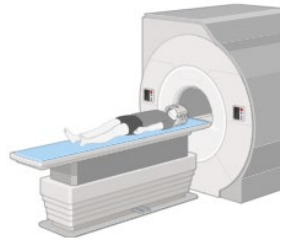
Department of Mathematics
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Centre de Recerca Matemàtica

Virtual Human Global Summit II 2025 – Barcelona



Linking brain structure to brain dynamics

Neuroimaging

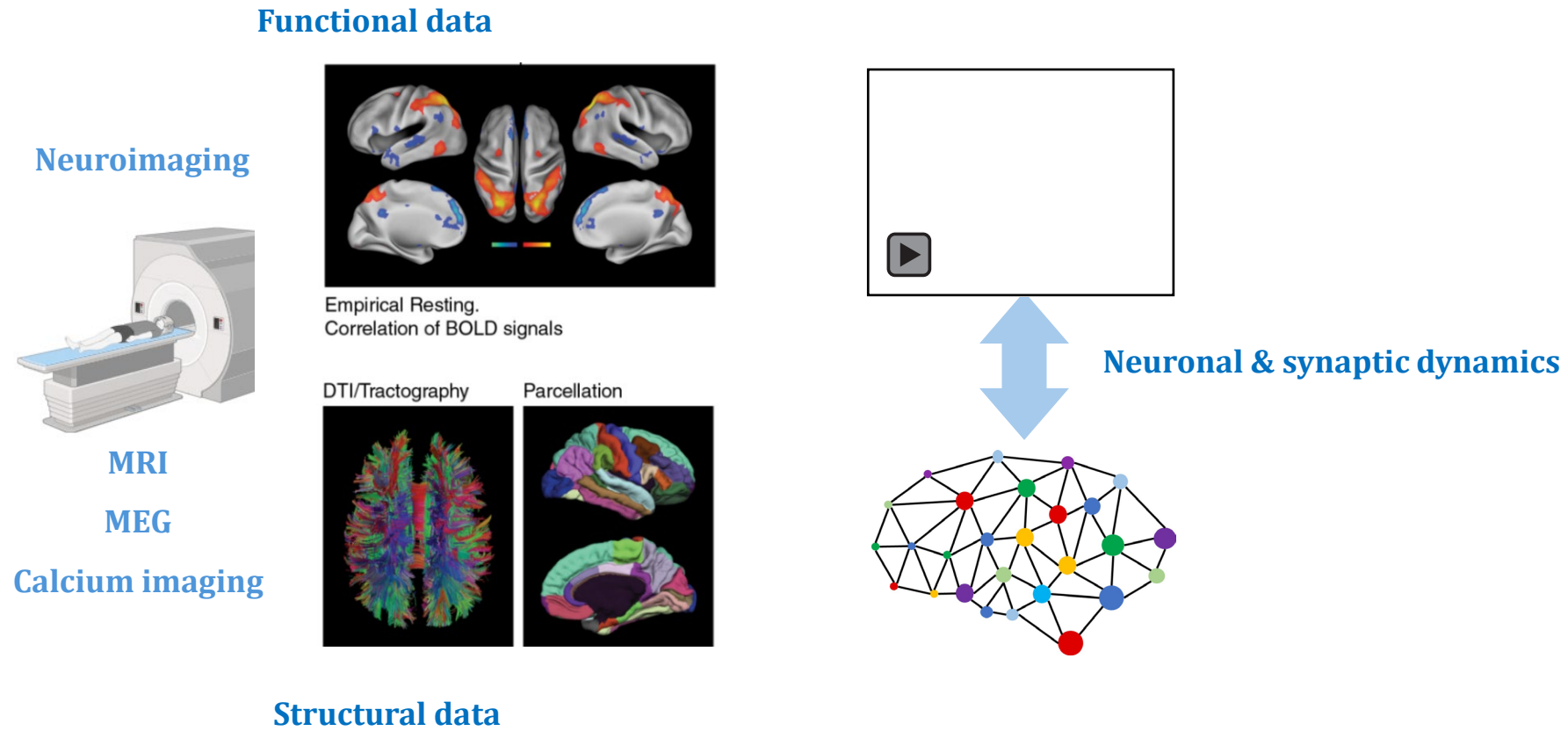


MRI

MEG

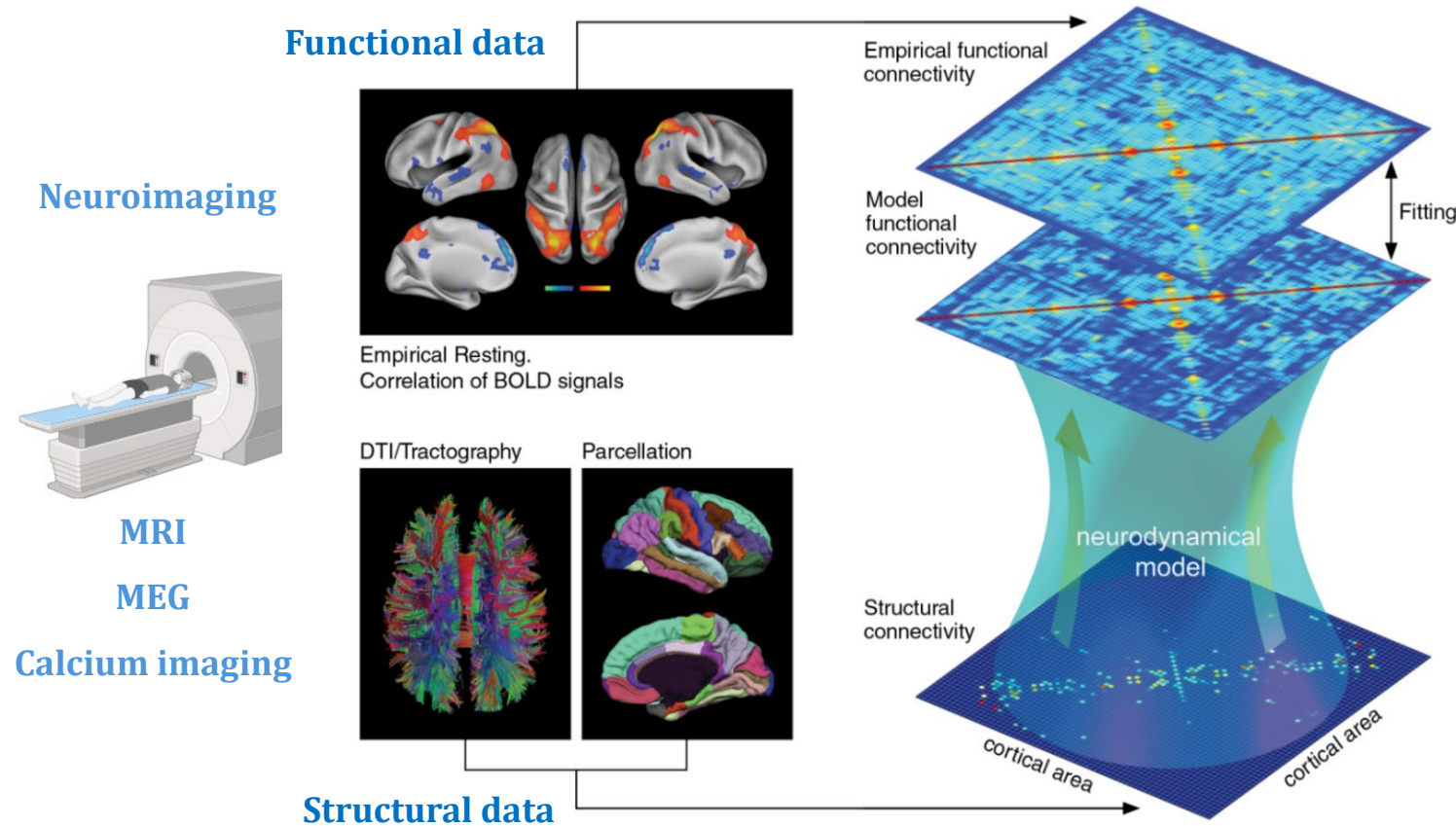
Calcium imaging

Linking brain structure to brain dynamics



The brain as a dynamical system

Theoretical framework to understand the emergence of spatiotemporal patterns in whole-brain models



$$\dot{\mathbf{r}} = f(\mathbf{W}\mathbf{r} + \mathbf{I})$$

Spiking networks and mean-field models

Deco, Ponce-Alvarez et al. 2013, *J neurosci*

Deco, Ponce-Alvarez et al. 2014, *J neurosci*

Ponce-Alvarez et al. 2015a, *PLoS Comput Biol*

Neural oscillations / neural communication

Ponce-Alvarez et al. 2015b, *PLoS Comput Biol*

Hahn et al. 2019 *Nat Rev Neurosci*

Task activity

Ponce-Alvarez et al. 2013 *PNAS*

Ponce-Alvarez et al. 2015a, *PLoS Comput Biol*

Behavioral states

sleep

Jobst et al. 2017 *Sci Rep*

Low-levels of consciousness (MCS and UWS)

López-González et al. 2021 *Nat Comm Biol*

Stroke

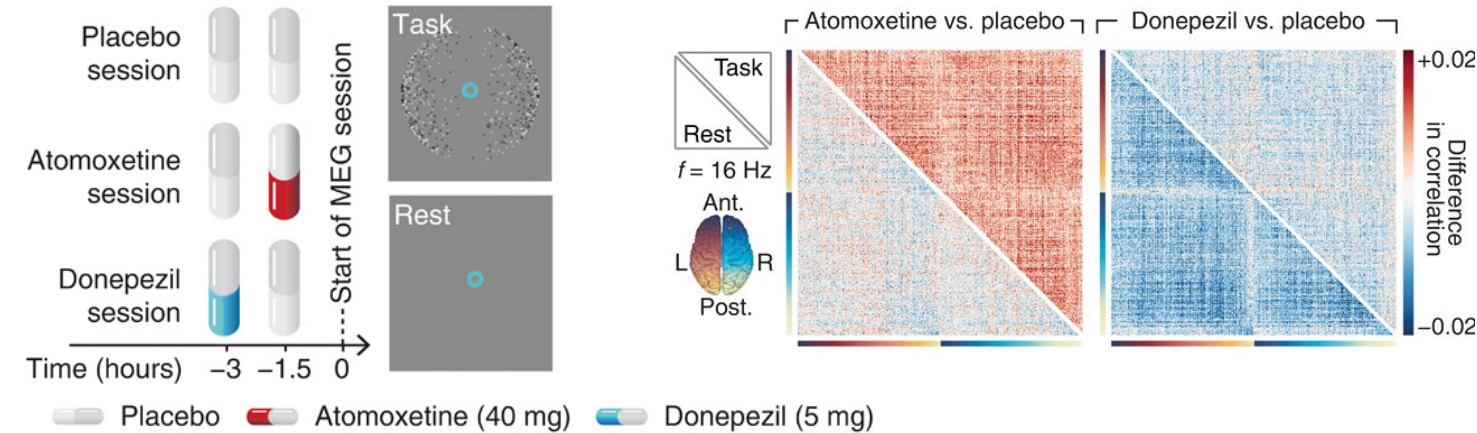
Saenger et al. 2018 *Cereb Cortex*

Neuromodulation

Pfeffer et al. 2021 *Science Advances*

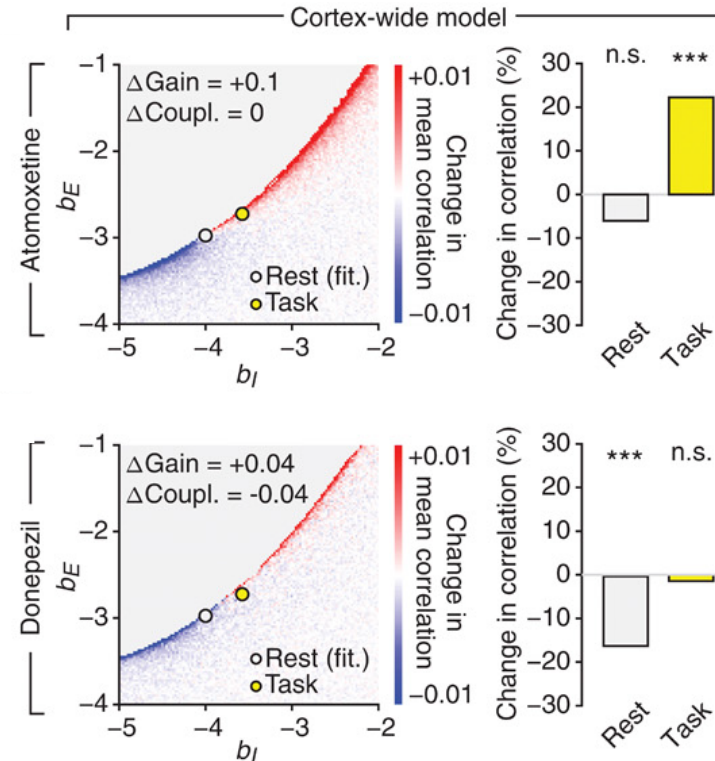
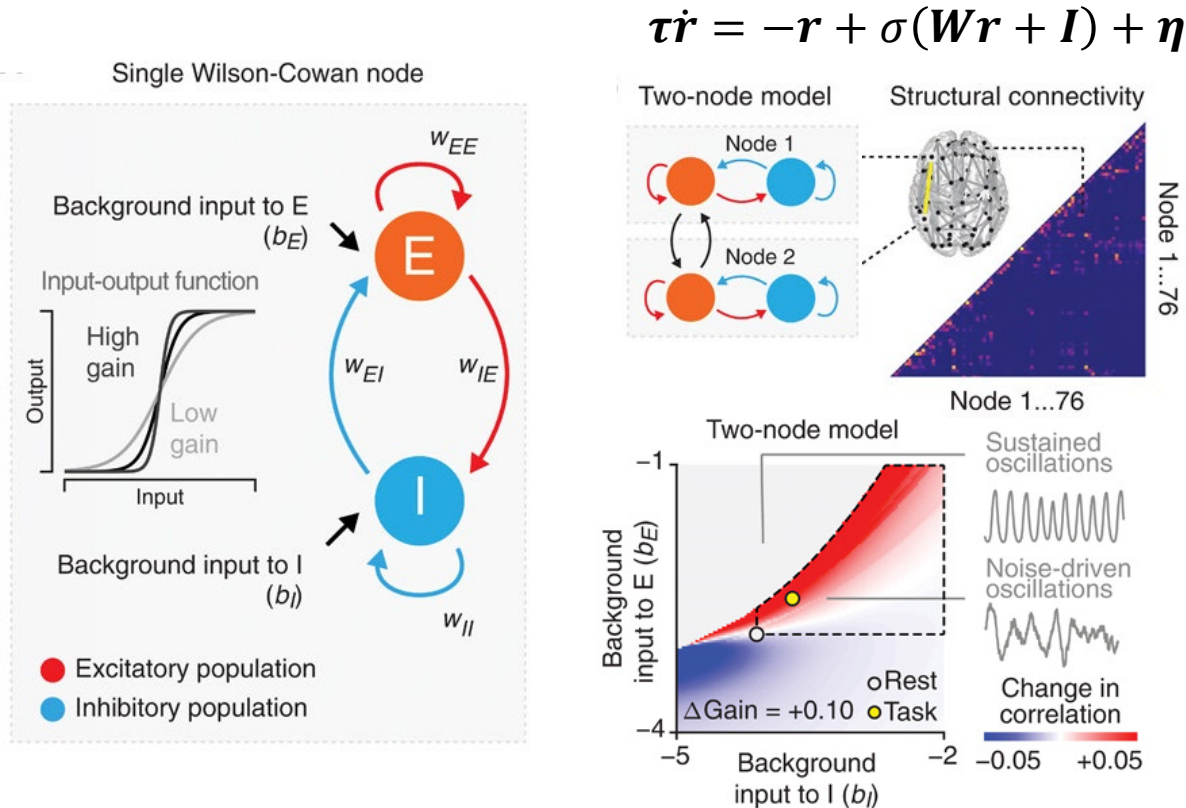
The brain as a dynamical system: **state-dependence**

Pfeffer et al. 2021 *Science Advances*



Functional connectivity:

- ↑ under ATX during task, but not during rest
- ↓ under DPZ during rest, but not during task

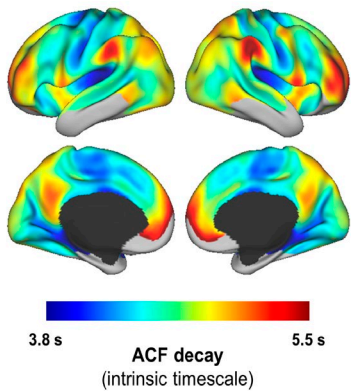
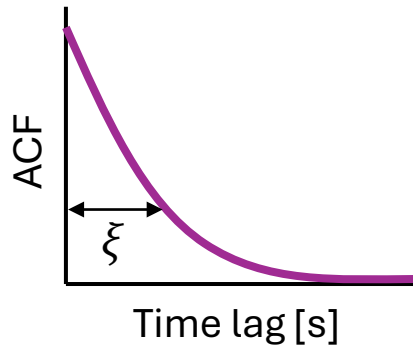




Hierarchy of timescales

Higher-order associative areas: slow fluctuations

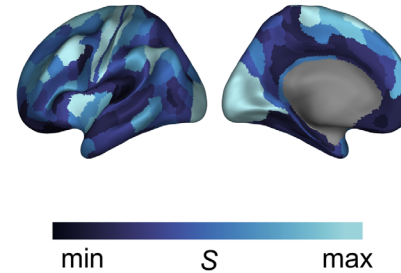
Lower-order sensory areas: fast fluctuations



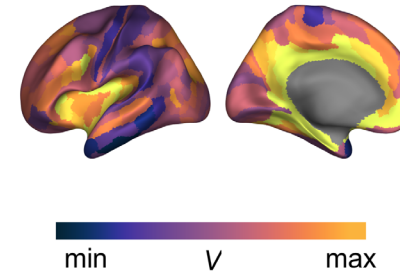
(Raut et al., 2020)

Connectivity strength

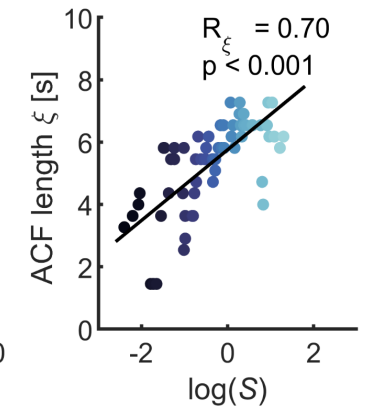
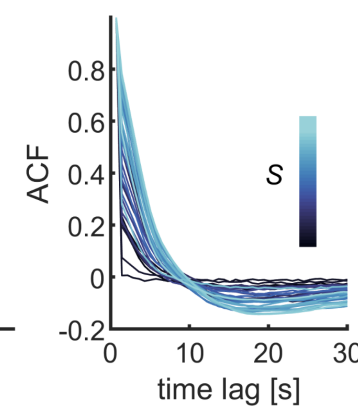
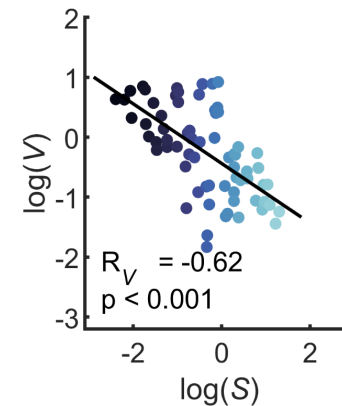
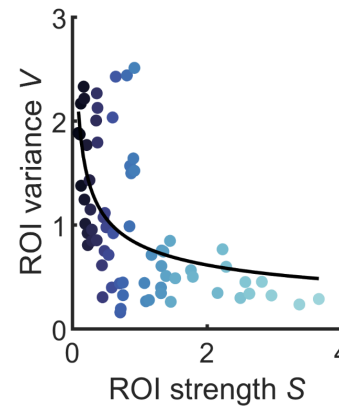
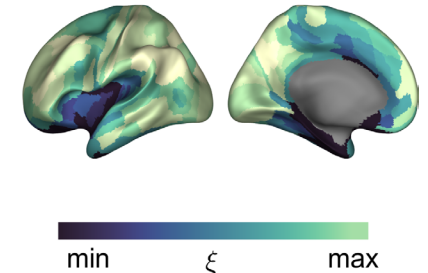
HCP

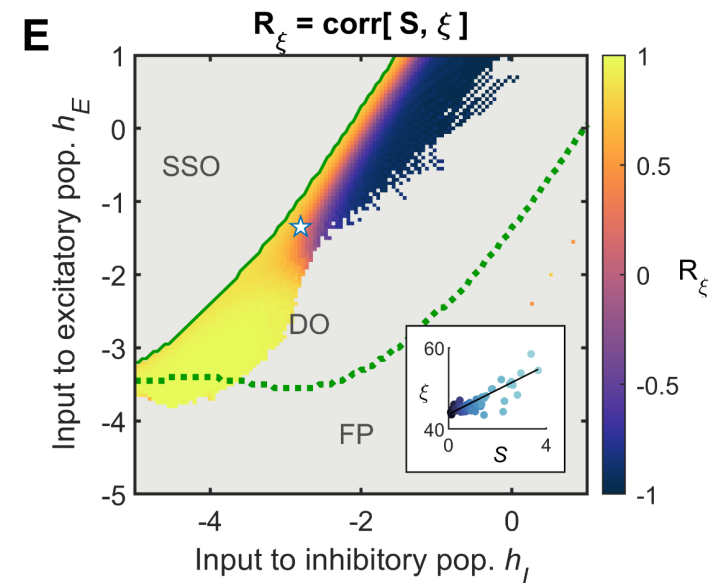
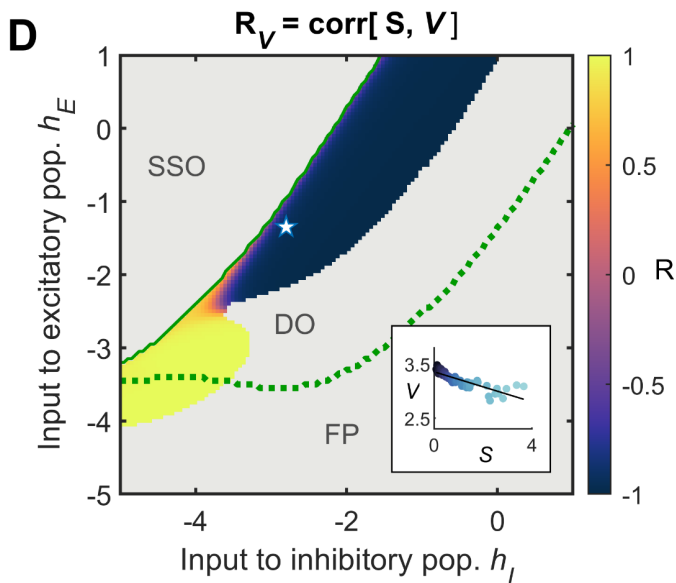
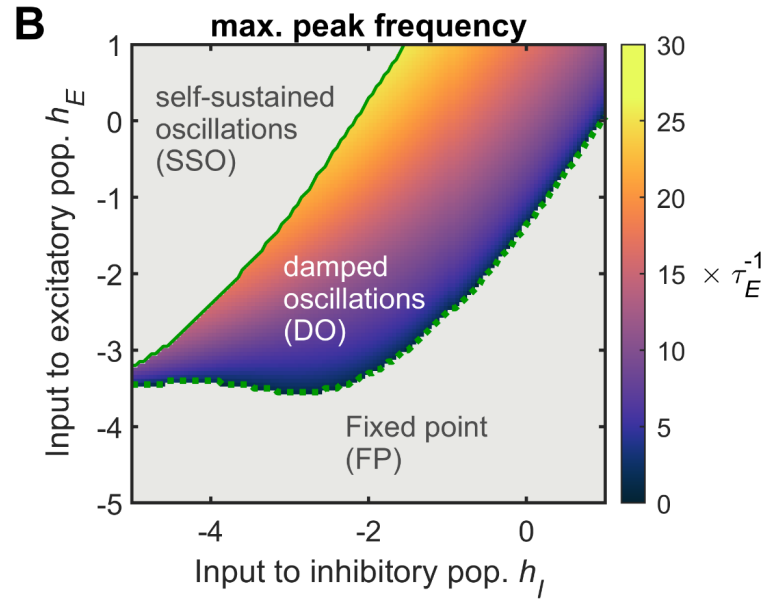
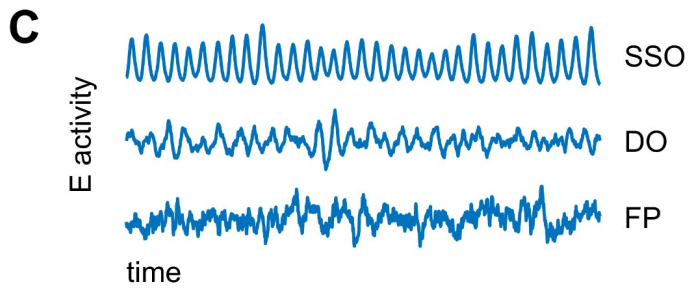
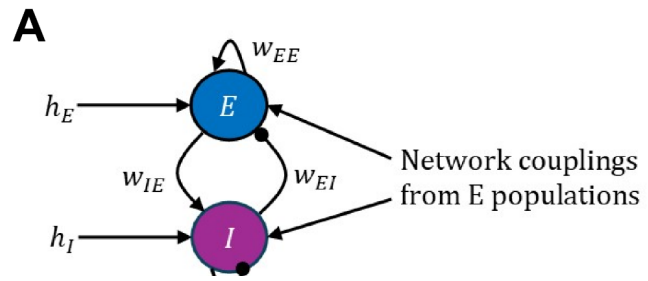


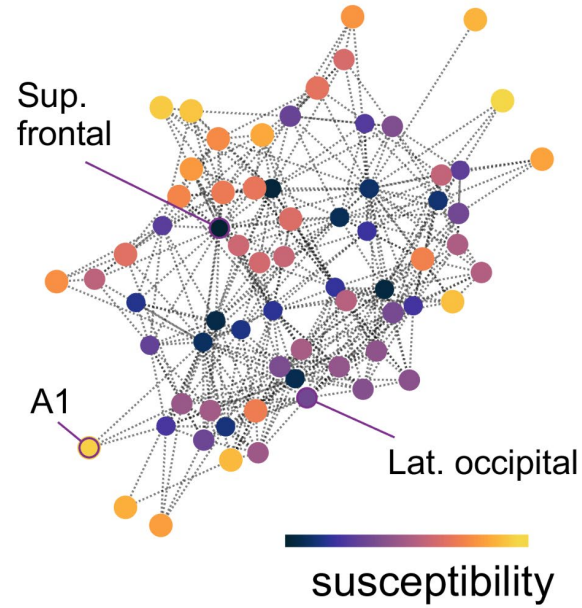
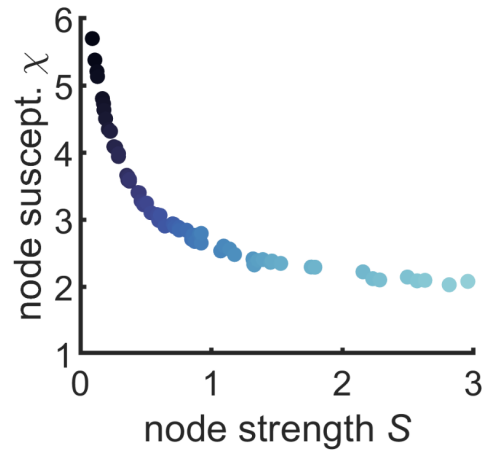
Variance



ACF decay

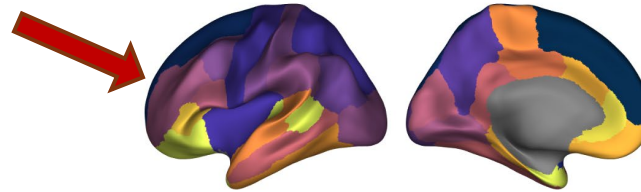




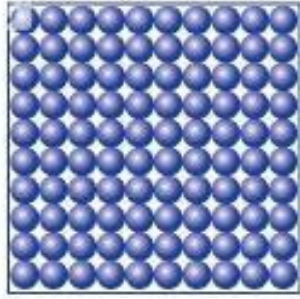


Trade-off between stability and responsiveness, with greater responsiveness at the network periphery, while the core ensures overall system stability.

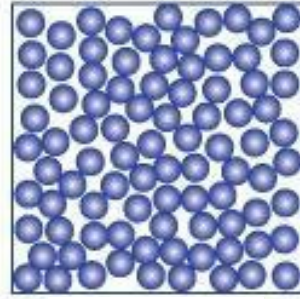
Stimulus



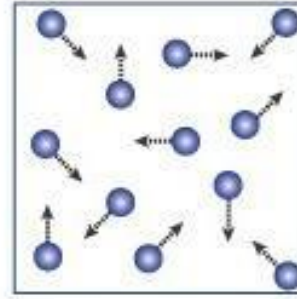
The brain as a condensed matter



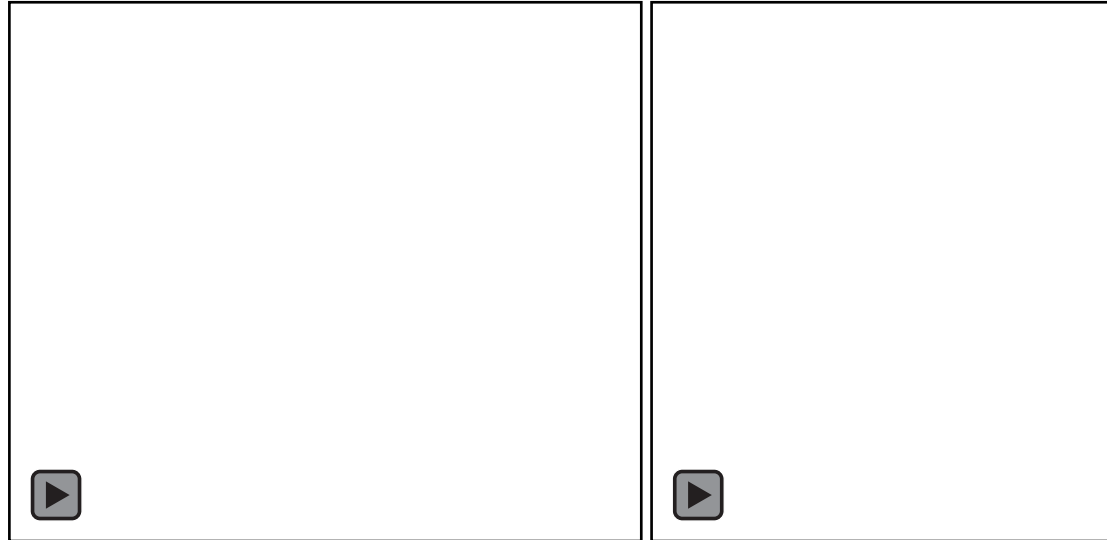
Solid



Liquid



Gas



At critical points:

❑ Optimal communication (susceptibility and transmission)
[Beggs and Plenz, 2003; Tanaka et al., 2009; Shew et al., 2011](#)

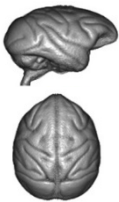
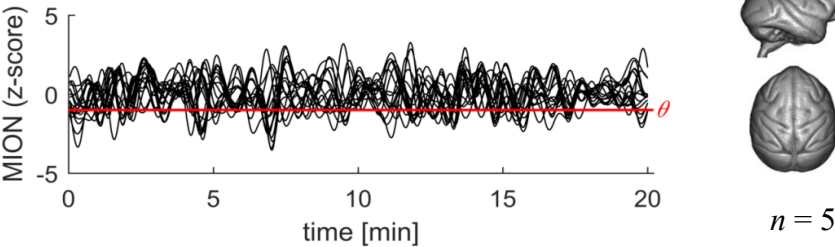
❑ Optimal information storage
[Kauffman et al., 2004; Haldeman and Beggs, 2005](#)

❑ Optimal computational power
[Bertschinger and Natschlager, 2004](#)

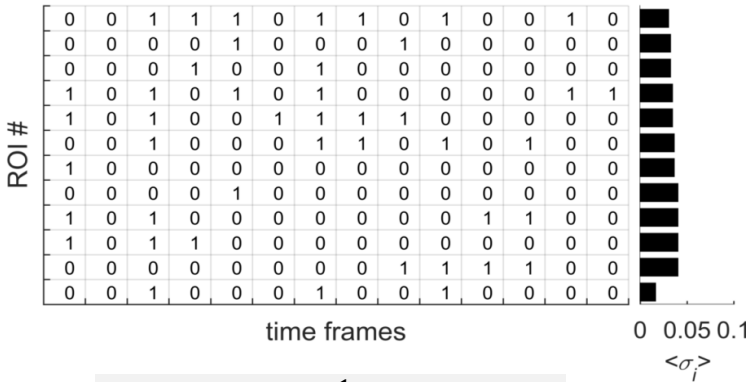
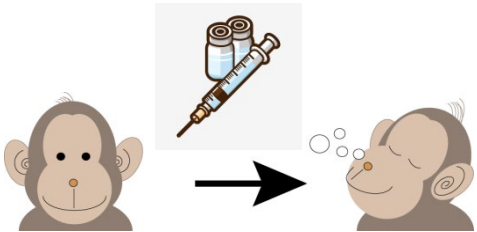
❑ Optimal dynamic range
[Kinouchi and Copelli, 2006; Shew et al., 2009](#)



Macaque (binarized) fMRI activity

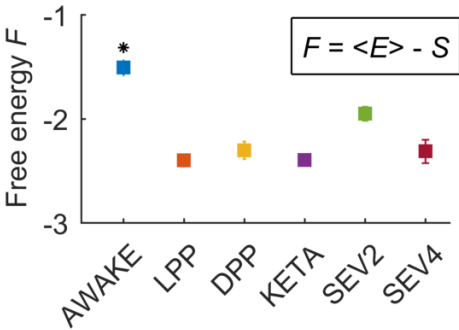


$n = 5$

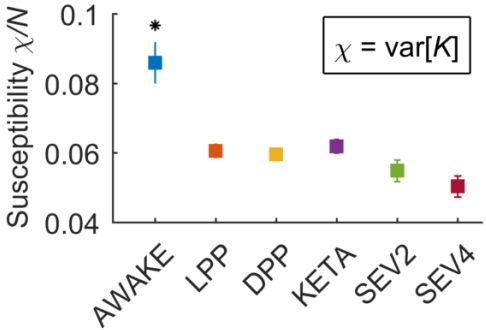


$$P(\sigma; T) = \frac{1}{Z} e^{-E(\sigma)/T}$$

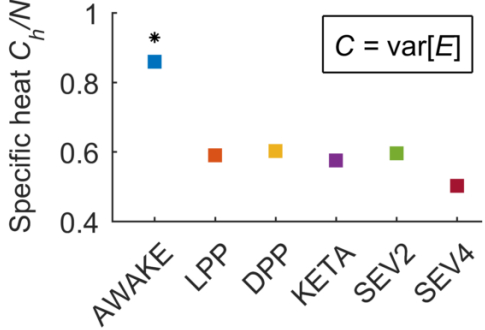
Useful energy



Susceptibility

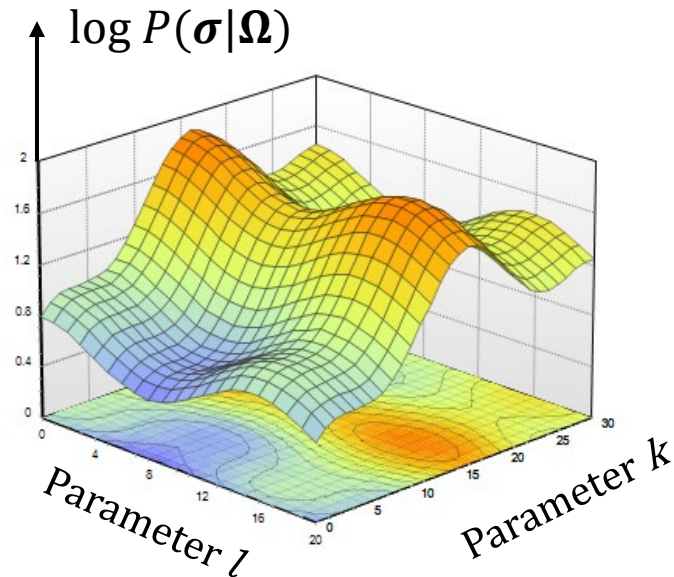


Repertoire of states

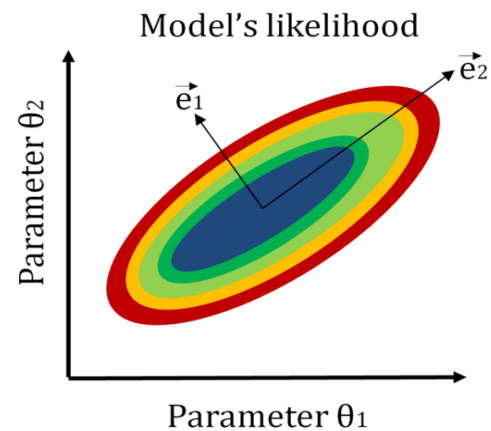


Phase transition

from **critical** dynamics in the **awake** state
to **supercritical** dynamics in the **anesthetized** state.

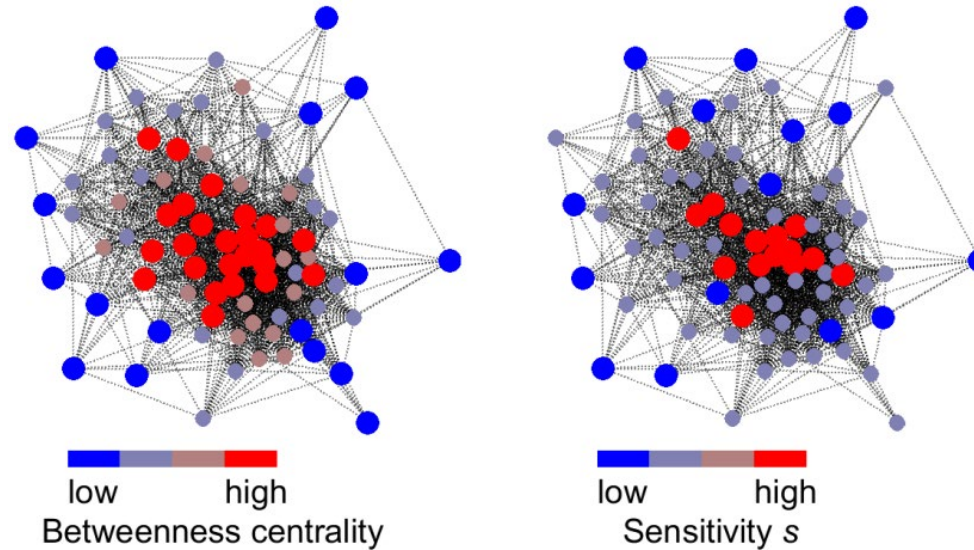


Stiff and **sloppy** parameters



Fisher Information matrix (FIM):

- Curvature of the log-likelihood of the model
- Importance of each parameter (stiff vs. sloppy)



- Brain/cortical state transitions along stiff dimensions (network core).
- Stimulus-driven activity evolves along sloppy dimensions (periphery).



Renormalization Group Theory

Critical systems display fluctuations that are **statistically self-similar**

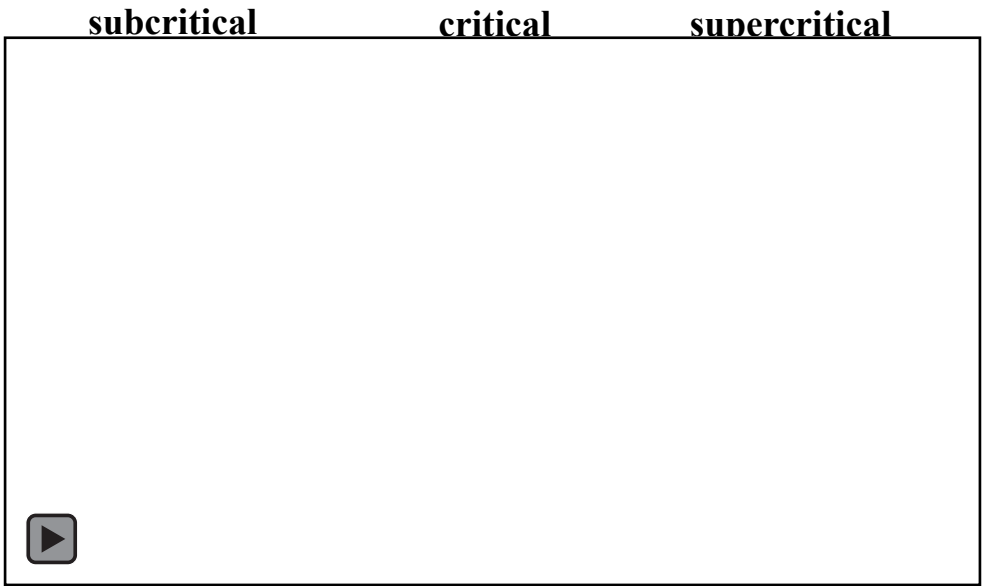
- ❑ Their statistics are re-scaled after gradual elimination of the correlated degrees of freedom: Renormalization Group (RG) procedure.
- ❑ For critical systems at equilibrium, $P(\vec{\sigma})$ is scale-invariant under iterated coarse-graining (fixed point of the RG).



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By Doug Ashton

Self-similarity



Power-laws (scaling laws)

Variance:

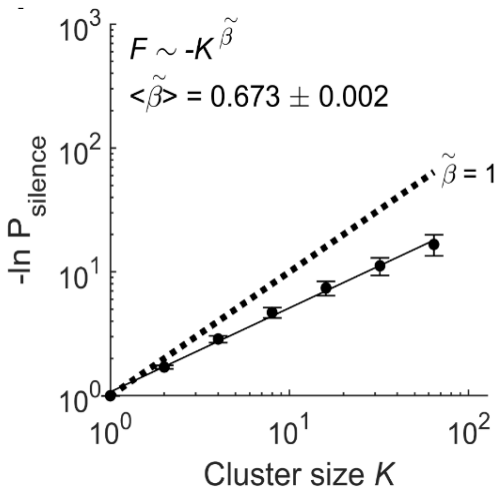
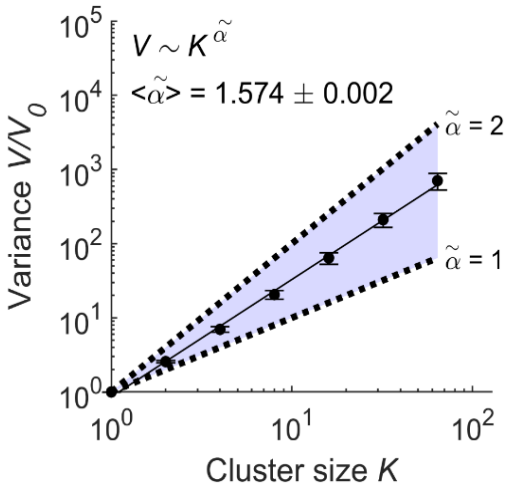
$$V \sim K^{\tilde{\alpha}}$$

$$\langle \tilde{\alpha} \rangle = 1.574 \pm 0.002$$

Free energy:

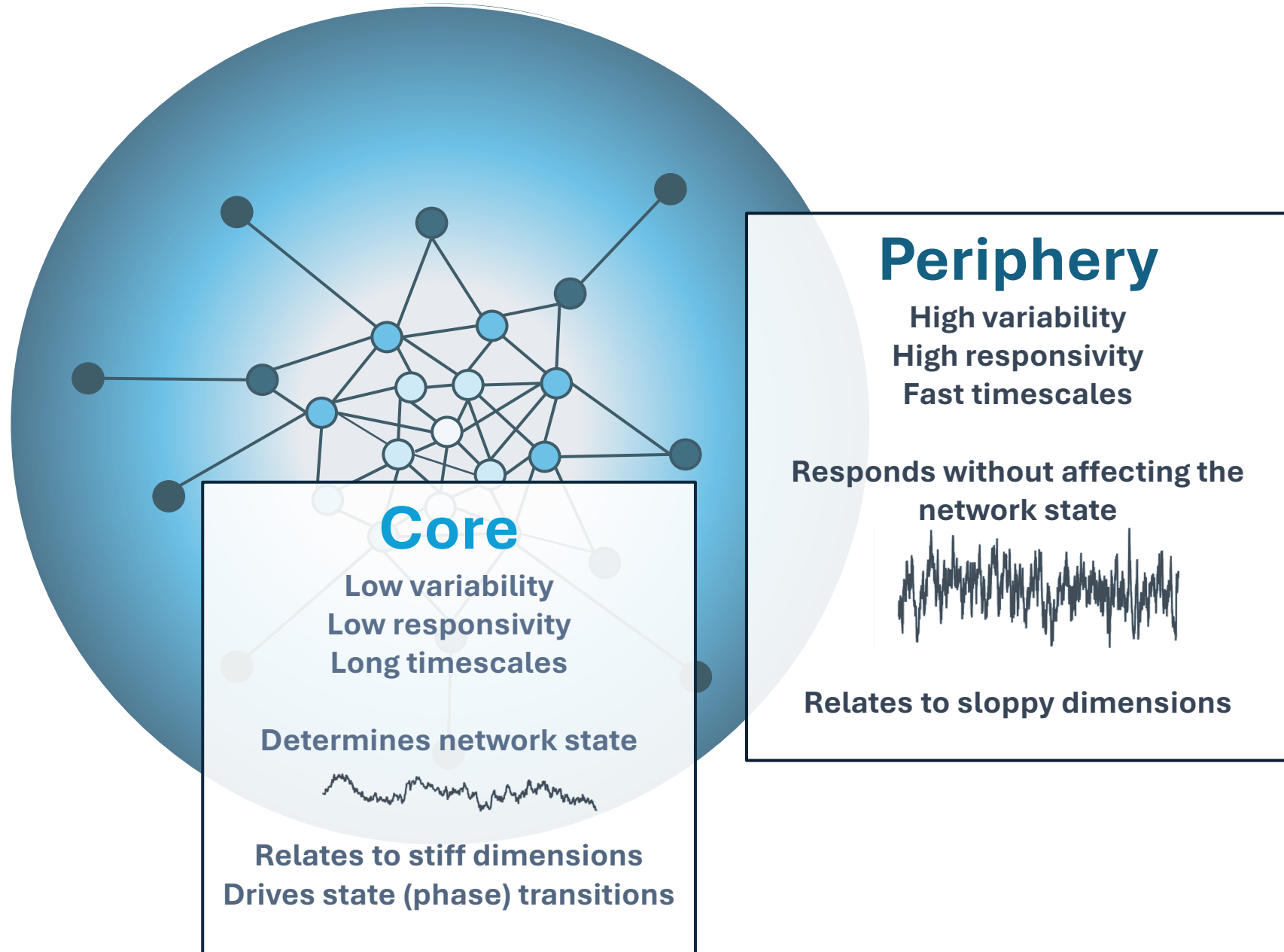
$$F = -\ln P_{\text{silence}} \sim -K^{\tilde{\beta}}$$

$$\langle \tilde{\beta} \rangle = 0.673 \pm 0.002$$



fMRI binarized signals
(parcellation of $N = 1,000$ ROIs, $n = 1,003$ human subjects).

CONCLUSIONS



Thank you

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[Ponce-Alvarez et al. 2025 *J Neurosci*](#)



[Ponce-Alvarez et al. 2020 *eLife*](#)



[Ponce-Alvarez et al. 2022 *Cereb Cortex*](#)



[Ponce-Alvarez et al. 2023 *Nat Comm Biol*](#)

