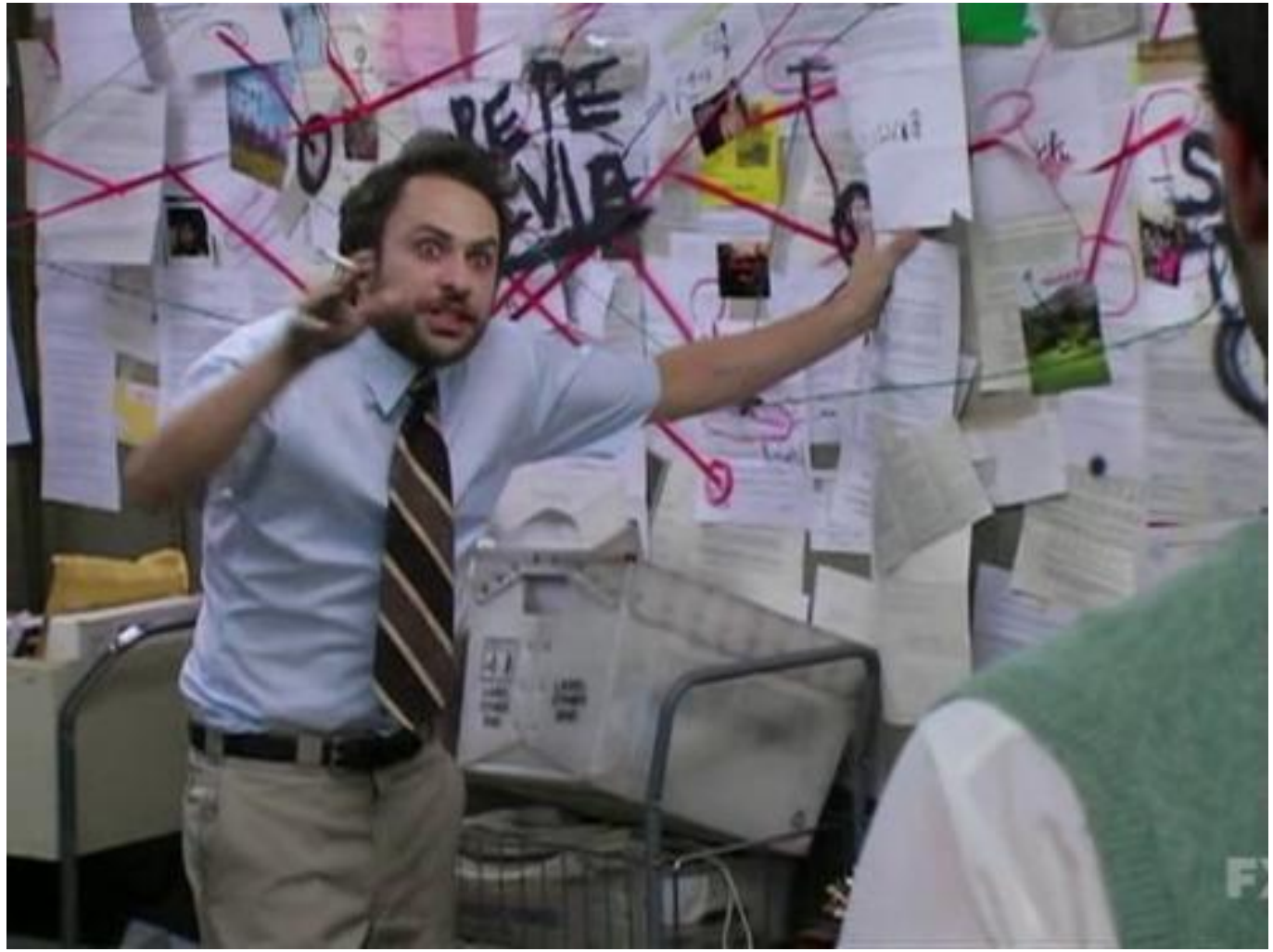
Criticality, integrated information, and… consciousness



Abuzar Mahmood
Katz Lab

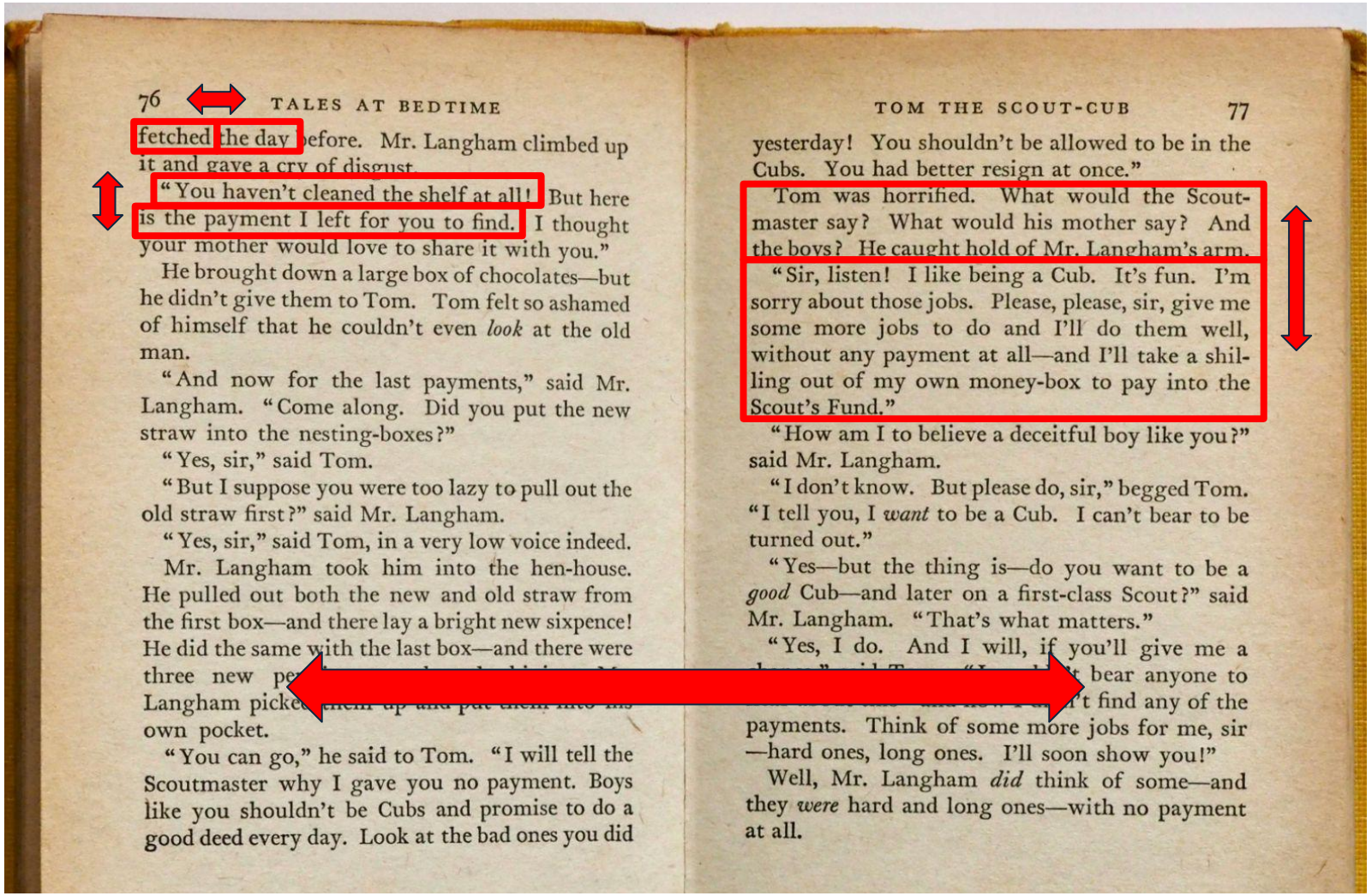
CSNJC 9/11/25

Sections

1. Criticality
   A. Properties of critical systems
   B. Criticality in neural activity and behavior
2. Criticality to Consciousness (via integrated information...kinda sorta)

Criticality, as you will see, is related to multi-scale properties / behavior.

(Hopefully) illustrative example of the importance of multi-scale processing



76 TALES AT BEDTIME

fetched the day before. Mr. Langham climbed up it and gave a cry of disgust.

"You haven't cleaned the shelf at all! But here is the payment I left for you to find. I thought your mother would love to share it with you."

He brought down a large box of chocolates—but he didn't give them to Tom. Tom felt so ashamed of himself that he couldn't even *look* at the old man.

"And now for the last payments," said Mr. Langham. "Come along. Did you put the new straw into the nesting-boxes?"

"Yes, sir," said Tom.

"But I suppose you were too lazy to pull out the old straw first?" said Mr. Langham.

"Yes, sir," said Tom, in a very low voice indeed.

Mr. Langham took him into the hen-house. He pulled out both the new and old straw from the first box—and there lay a bright new sixpence! He did the same with the last box—and there were three new pe[illegible] Langham picke[illegible] own pocket.

"You can go," he said to Tom. "I will tell the Scoutmaster why I gave you no payment. Boys like you shouldn't be Cubs and promise to do a good deed every day. Look at the bad ones you did

TOM THE SCOUT-CUB 77

yesterday! You shouldn't be allowed to be in the Cubs. You had better resign at once."

Tom was horrified. What would the Scoutmaster say? What would his mother say? And the boys? He caught hold of Mr. Langham's arm.

"Sir, listen! I like being a Cub. It's fun. I'm sorry about those jobs. Please, please, sir, give me some more jobs to do and I'll do them well, without any payment at all—and I'll take a shilling out of my own money-box to pay into the Scout's Fund."

"How am I to believe a deceitful boy like you?" said Mr. Langham.

"I don't know. But please do, sir," begged Tom. "I tell you, I *want* to be a Cub. I can't bear to be turned out."

"Yes—but the thing is—do you want to be a *good* Cub—and later on a first-class Scout?" said Mr. Langham. "That's what matters."

"Yes, I do. And I will, if you'll give me a [illegible] bear anyone to [illegible]'t find any of the payments. Think of some more jobs for me, sir —hard ones, long ones. I'll soon show you!"

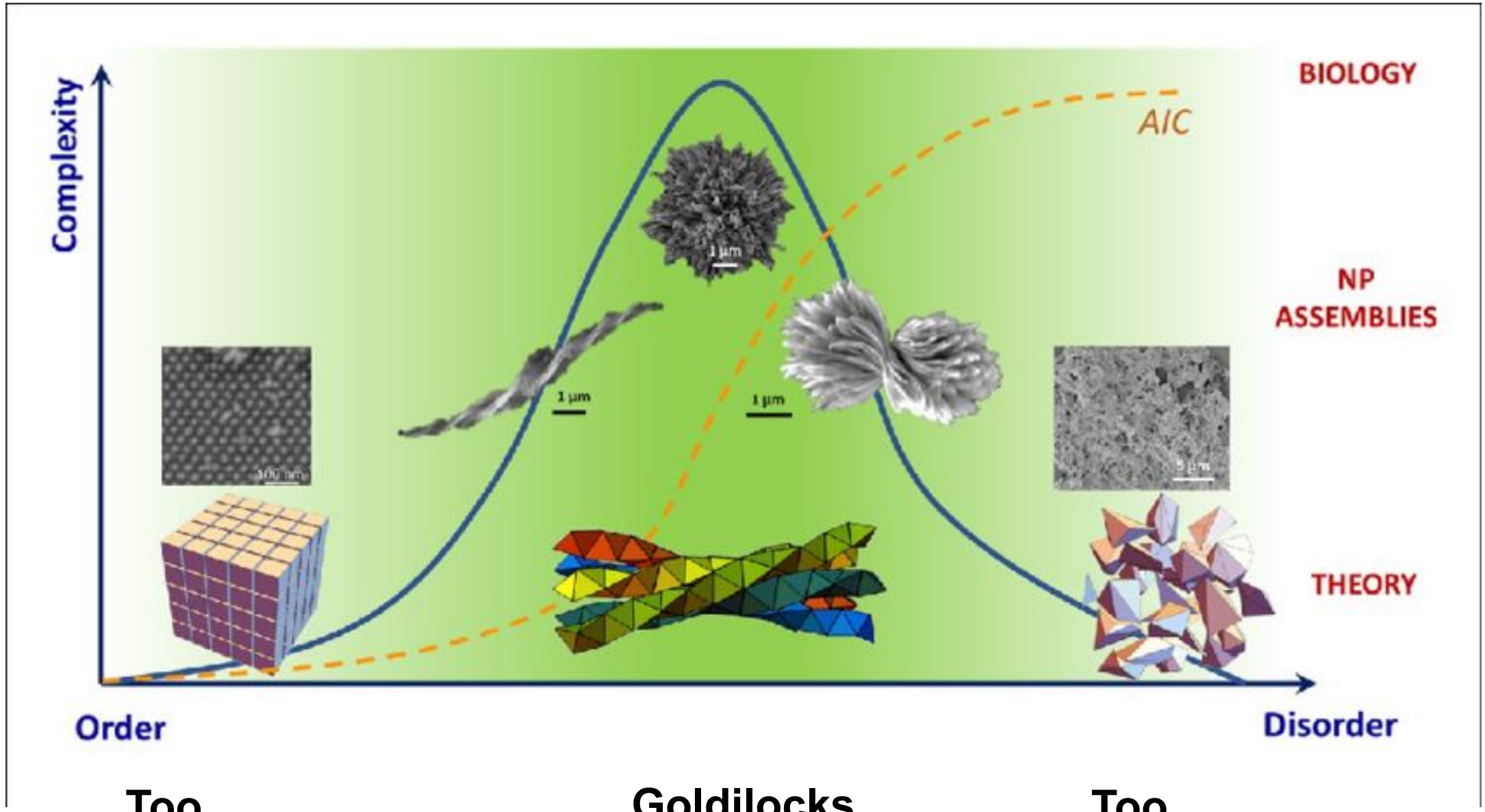
Well, Mr. Langham *did* think of some—and they *were* hard and long ones—with no payment at all.

Section 1: Criticality

Criticality	an umbrella term that denotes the behaviour of a system perched between an ordered and a disordered phase

Cocchi, Luca, et al. “Criticality in the Brain: A Synthesis of Neurobiology, Models and Cognition.” *Progress in Neurobiology*, vol. 158, Nov. 2017, pp. 132–52. *ScienceDirect*, https://doi.org/10.1016/j.pneurobio.2017.07.002.

Much interesting biology happens in the “Goldilocks” zone



Too Rigid

Goldilocks Zone

Too Chaotic

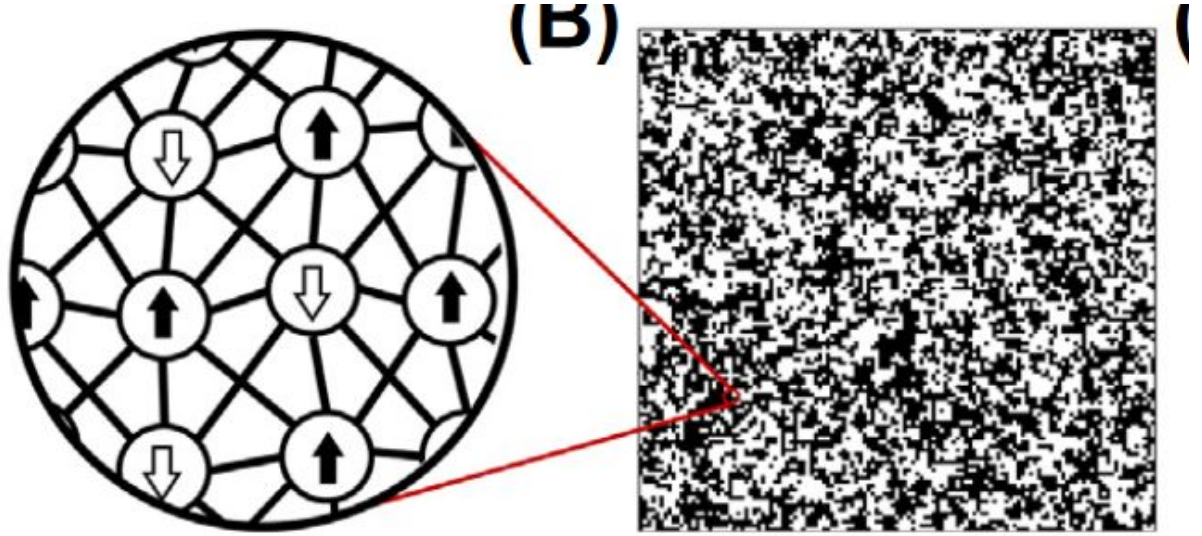
What does a critical system look like?

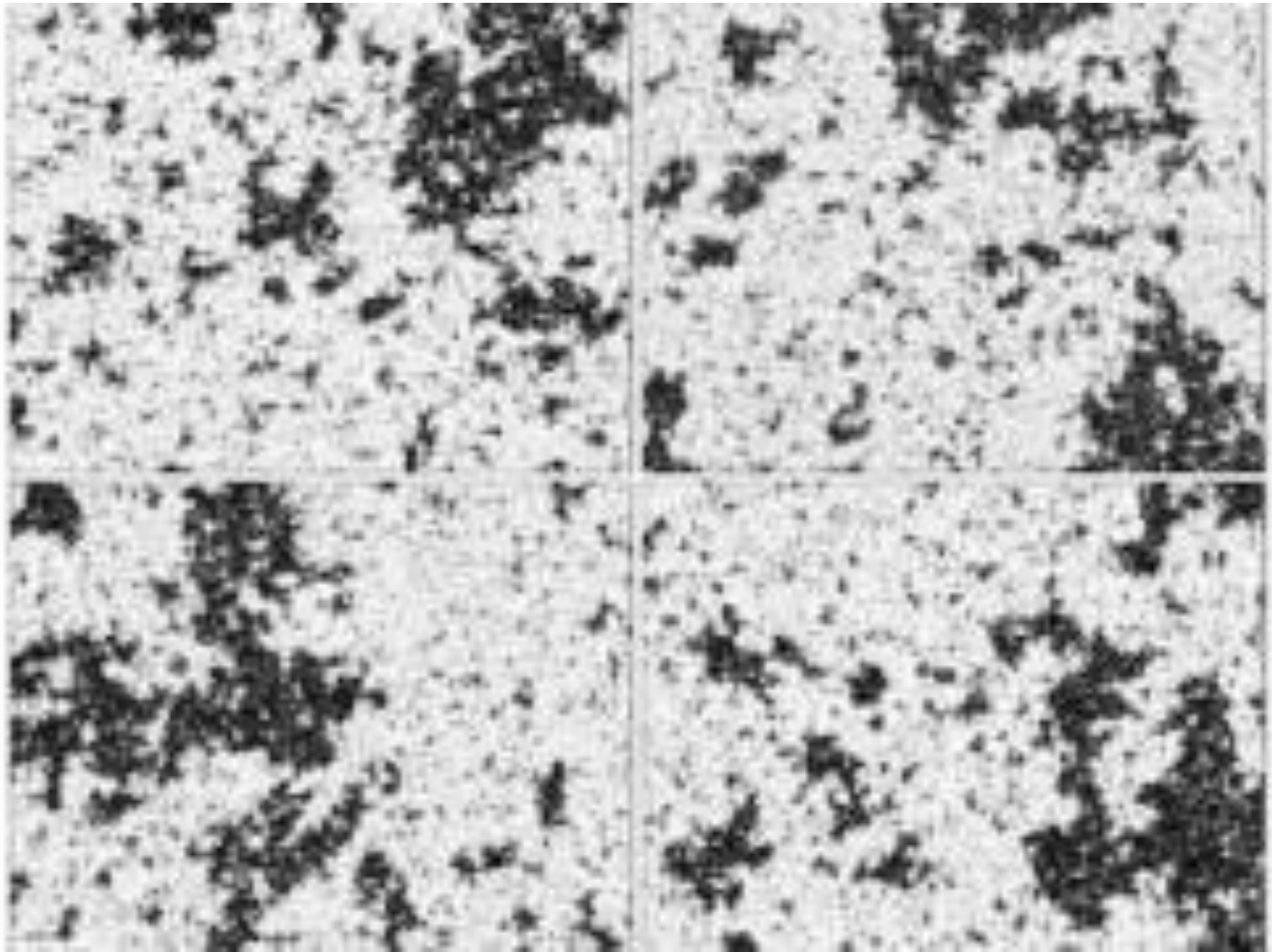
- Brief intro to **Ising model**:
  - Adjacent units interact and try to have same sign
  - Global “temperature” dictates probability of randomly flipping sign
  - Relative magnitude of local and global forces dictates large-scale patterns of activity.
  - Simultaneous coactivation of adjacent units is called an “avalanche”.

$$H = -\sum_{i,j} J_{ij}\sigma_i\sigma_j + h\sum_i \sigma_i$$

Inter-spin Interaction Field Interaction

$$m = \langle \sigma_i \rangle$$





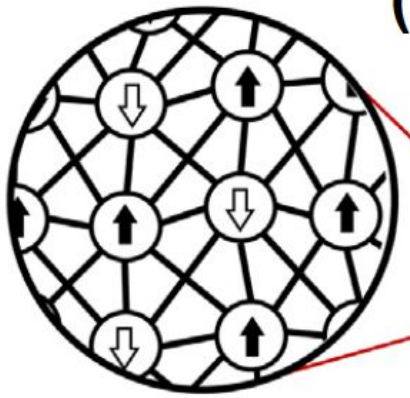
Properties of Different Phases

Ising Model

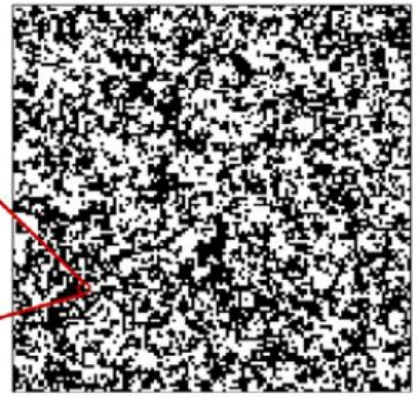
(A)

Disordered phase
(subcritical)

$m < 1$



(B)



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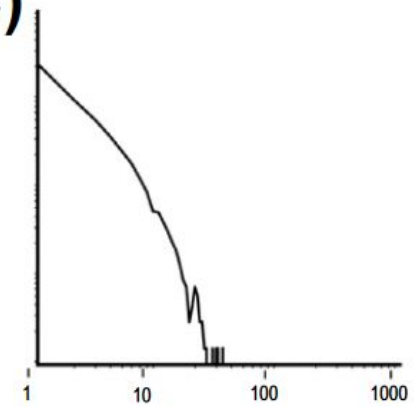
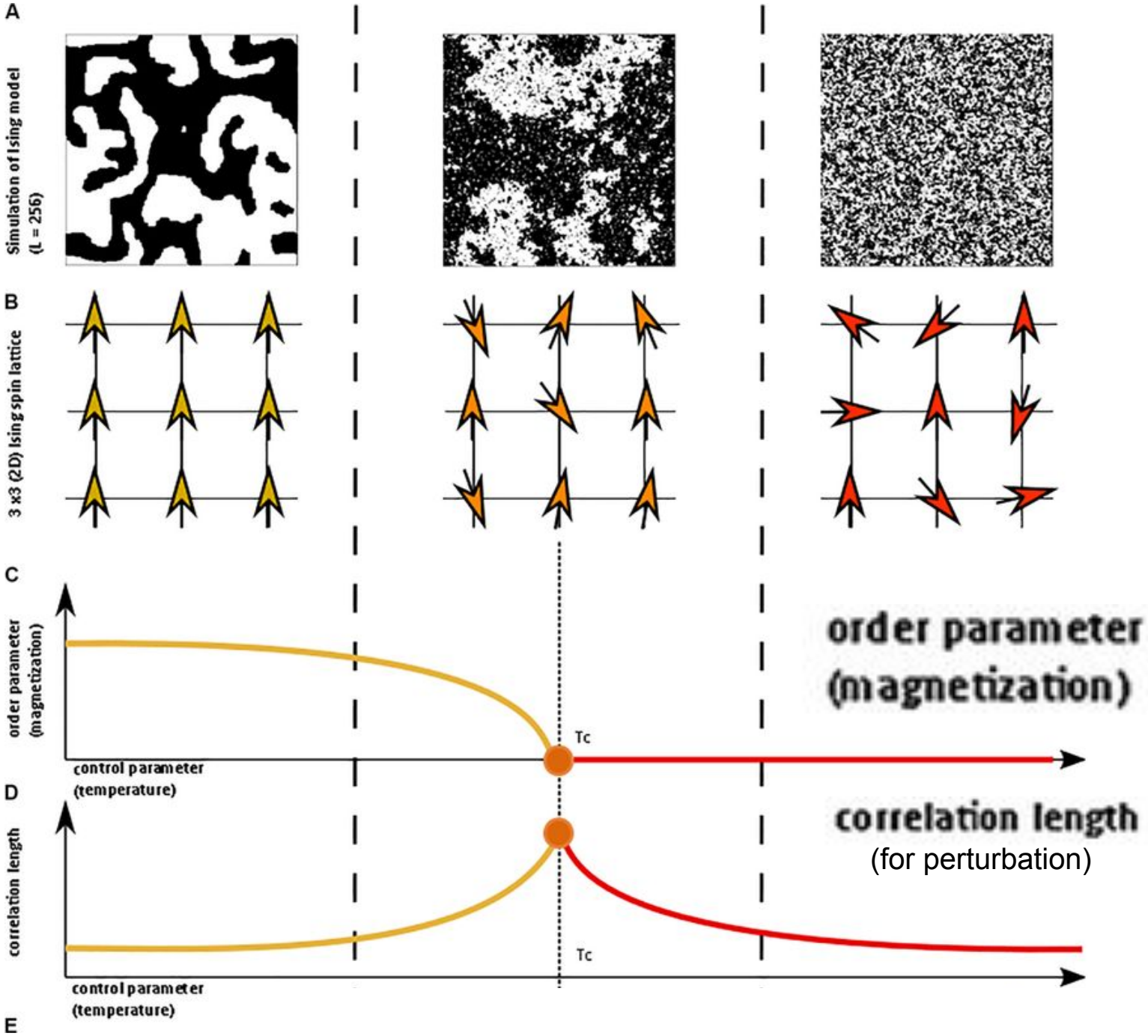


- Gaseous
- No long-range interactions
- Largest combinatorial complexity
- Low number of “system-wide” states

[O’Byrne 2021]

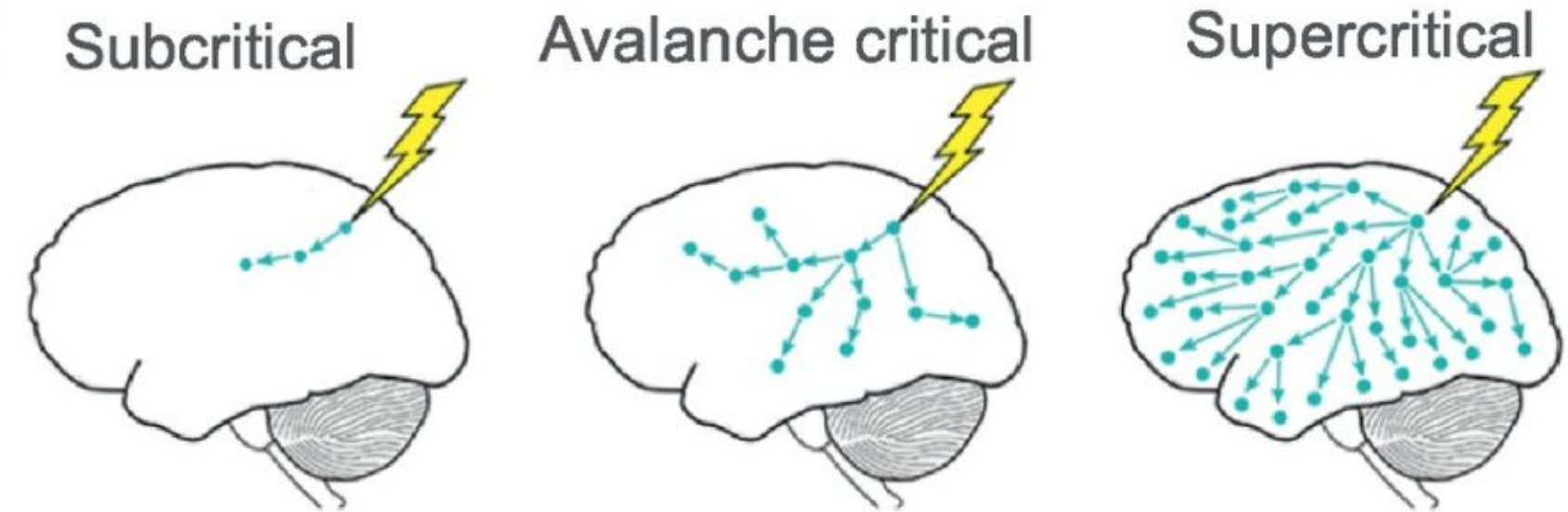
Avalanche size



Criticality and response to perturbations

Both sleep and seizure are states in which perturbations propagate poorly because of long-range order in the brain

[Zimmern 2020]

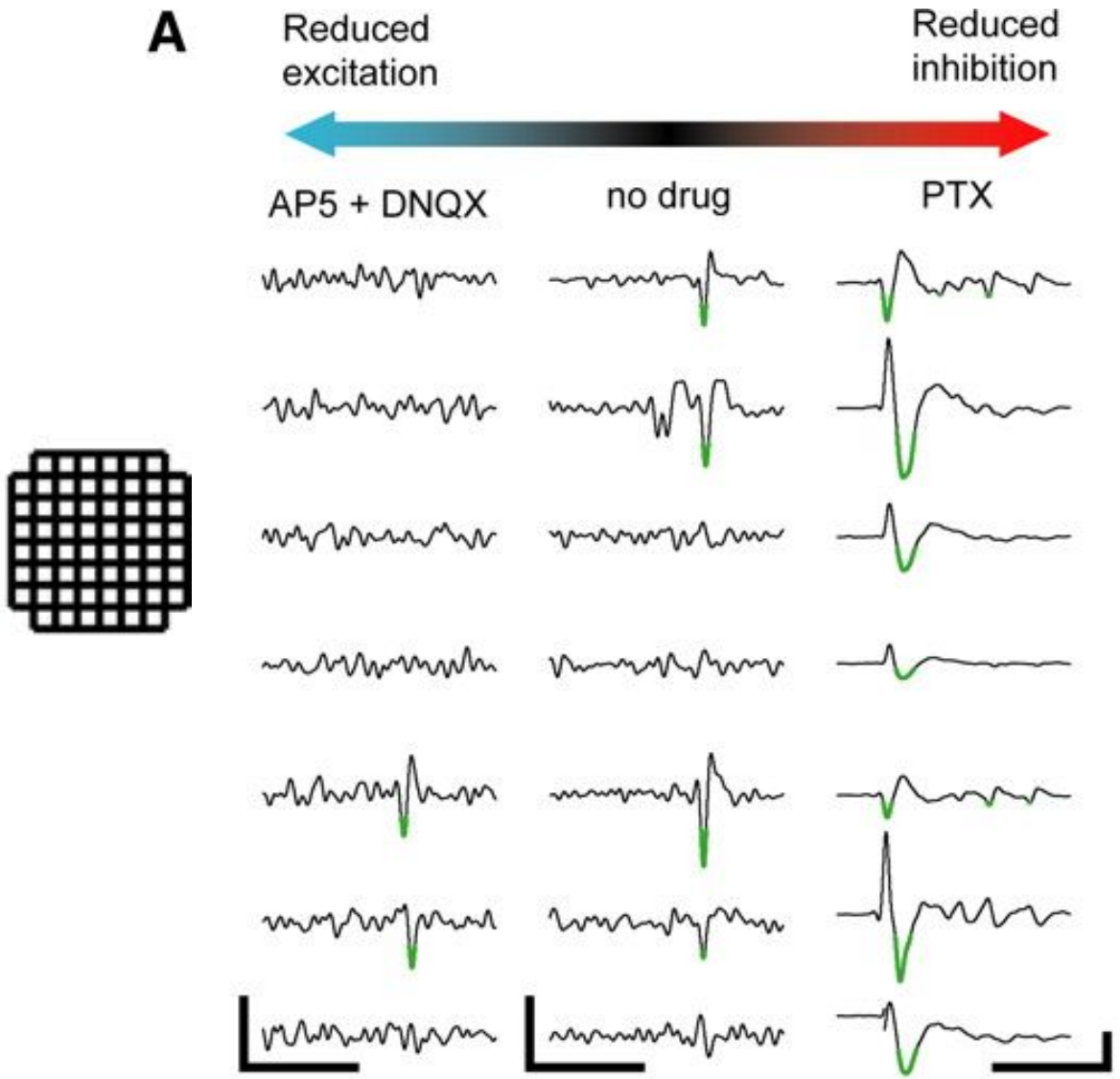


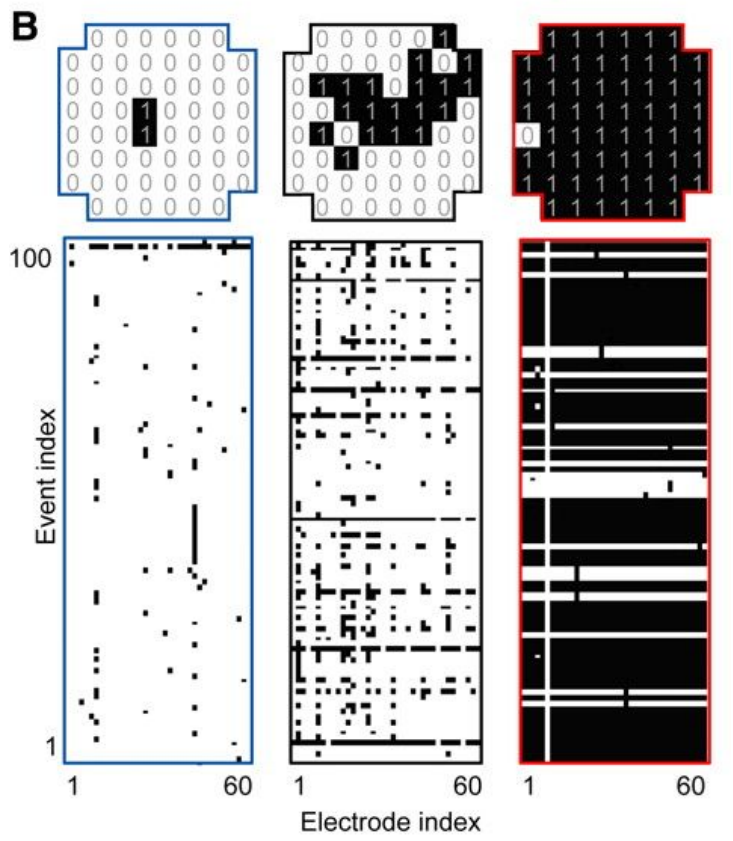
Propagation through space

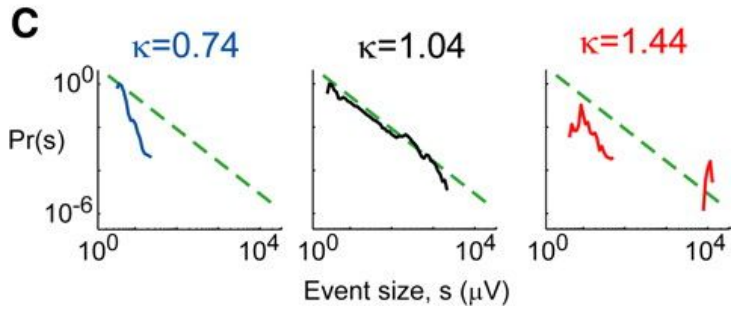
Why do we care about criticality in neuroscience?

- **YOU (and your brain) are critical**
- And you should WANT to be critical (Many useful properties of criticality)

Criticality maximizes Mutual information in cortex slice cultures cultures

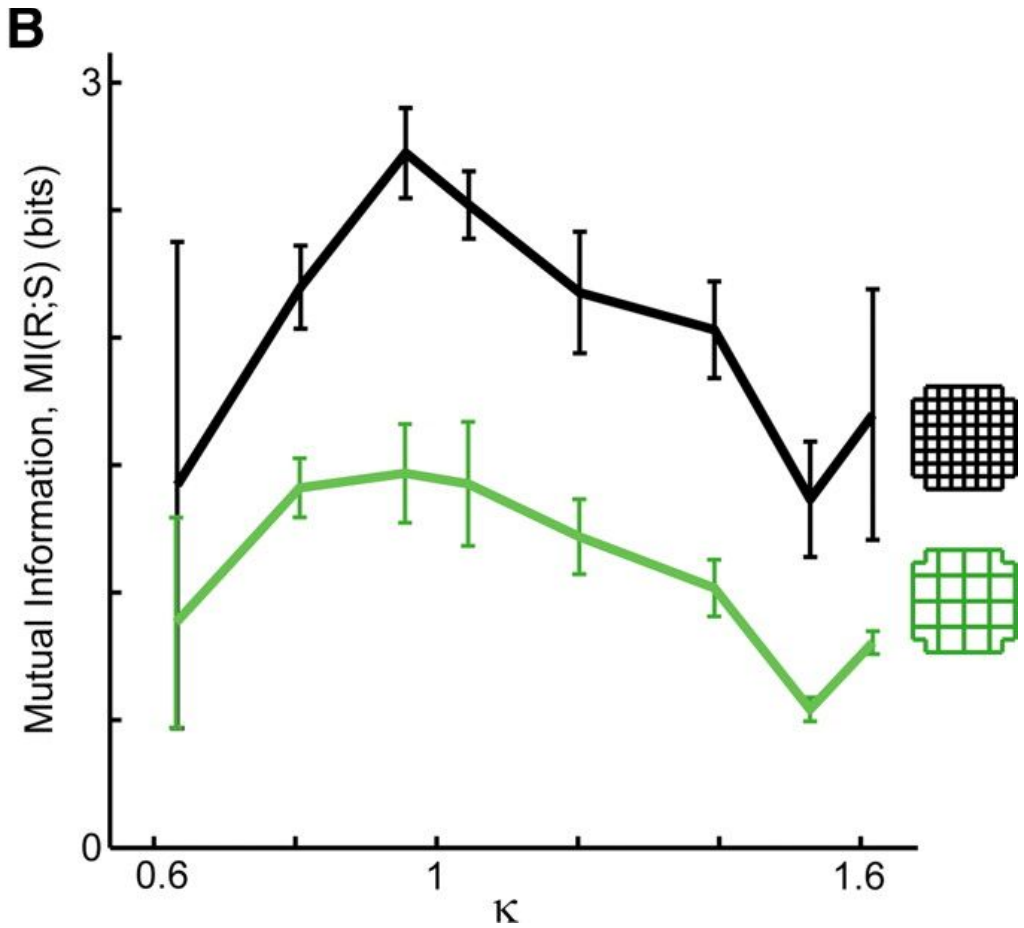






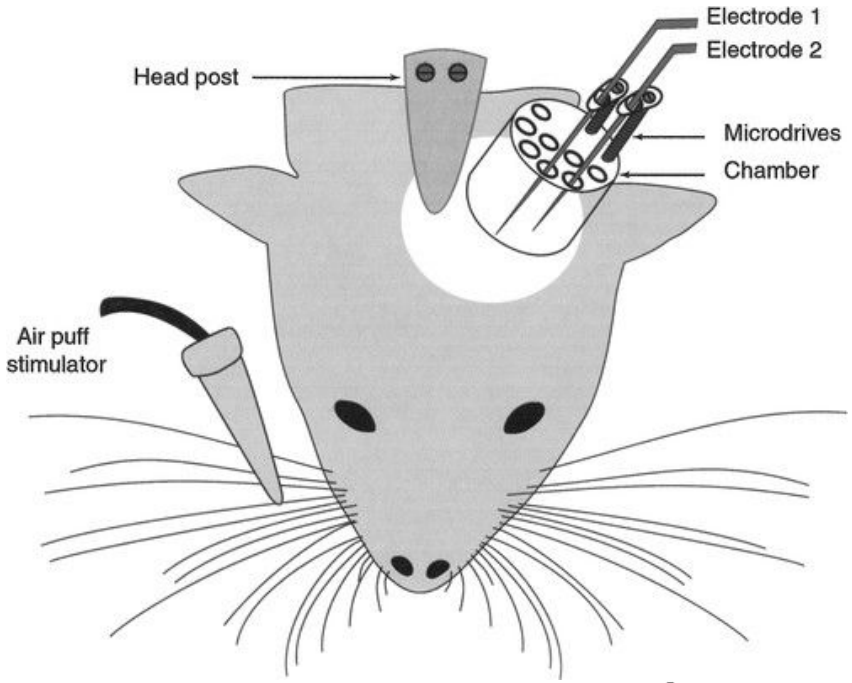
[Shew 2011]

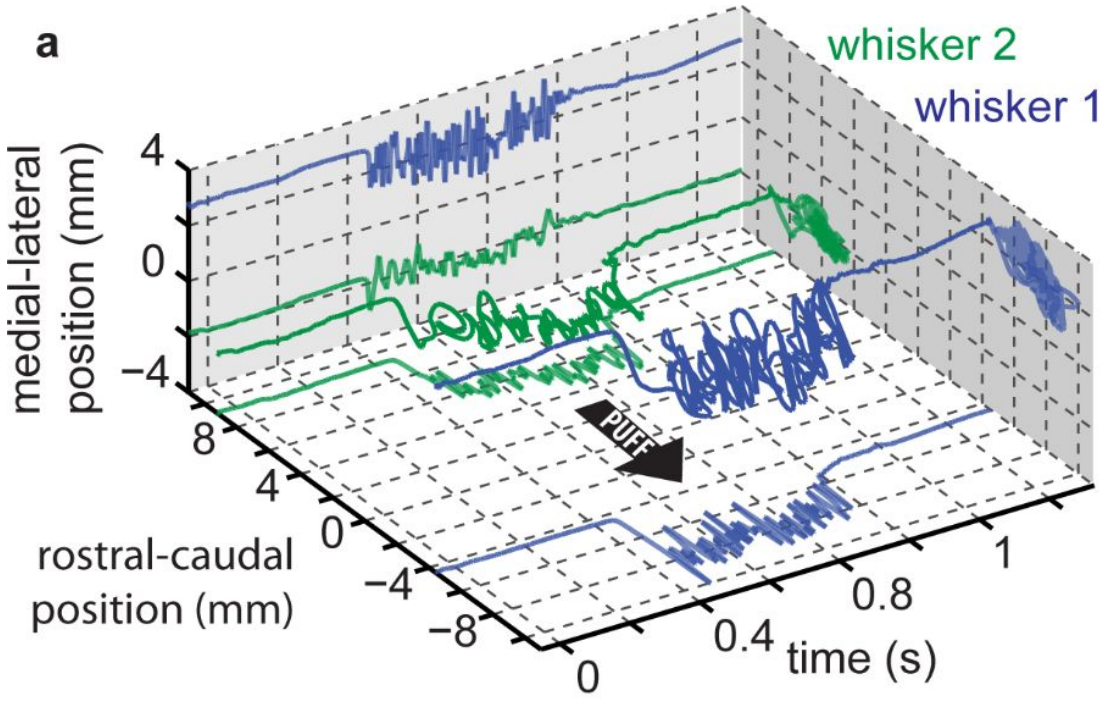
Criticality maximizes Mutual information in cortex slice cultures cultures

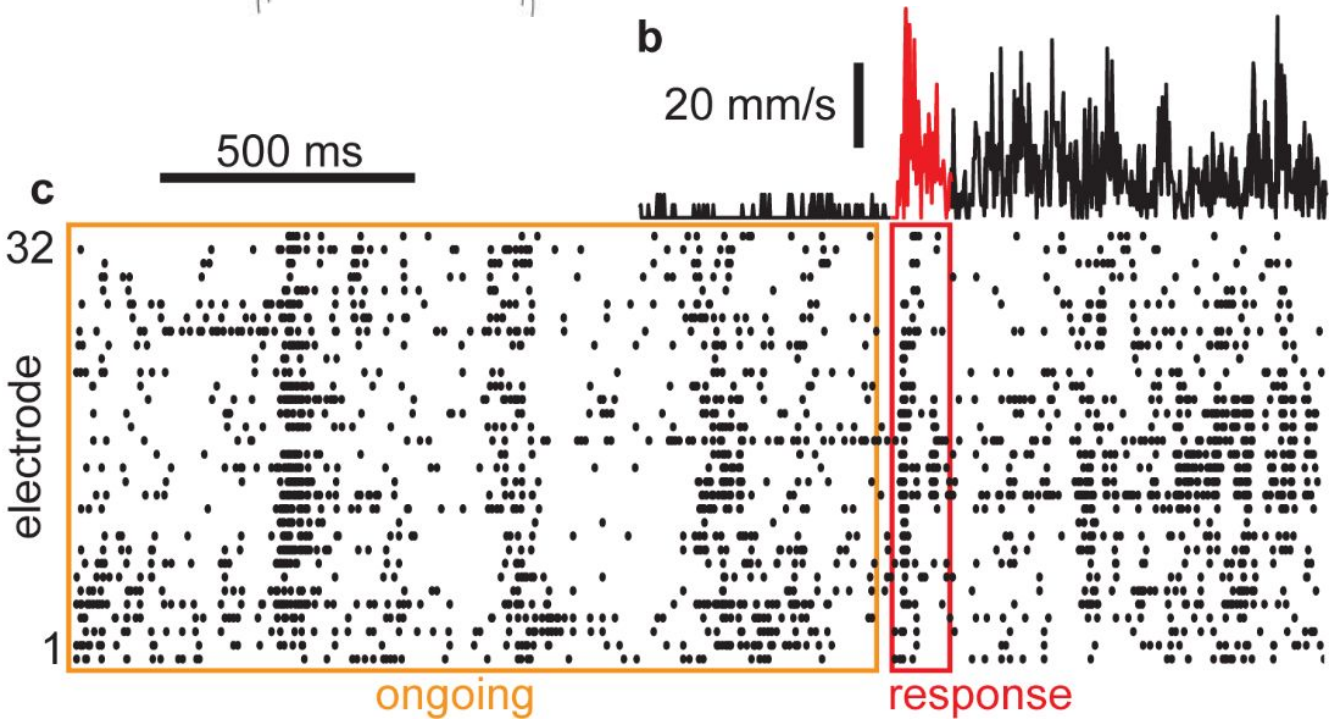


[Shew 2011]

Maximization of dynamic range close to criticality in barrel cortex

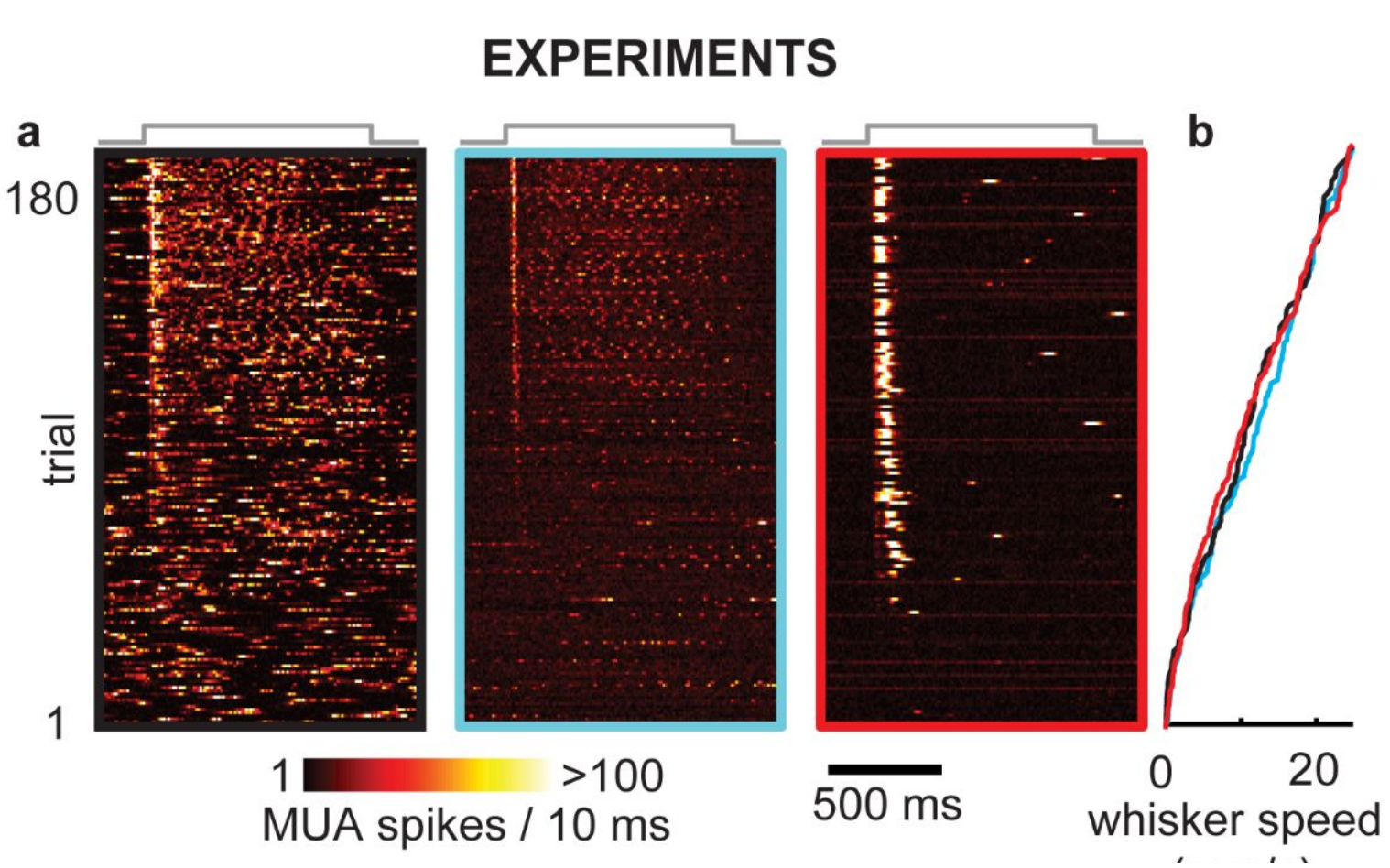


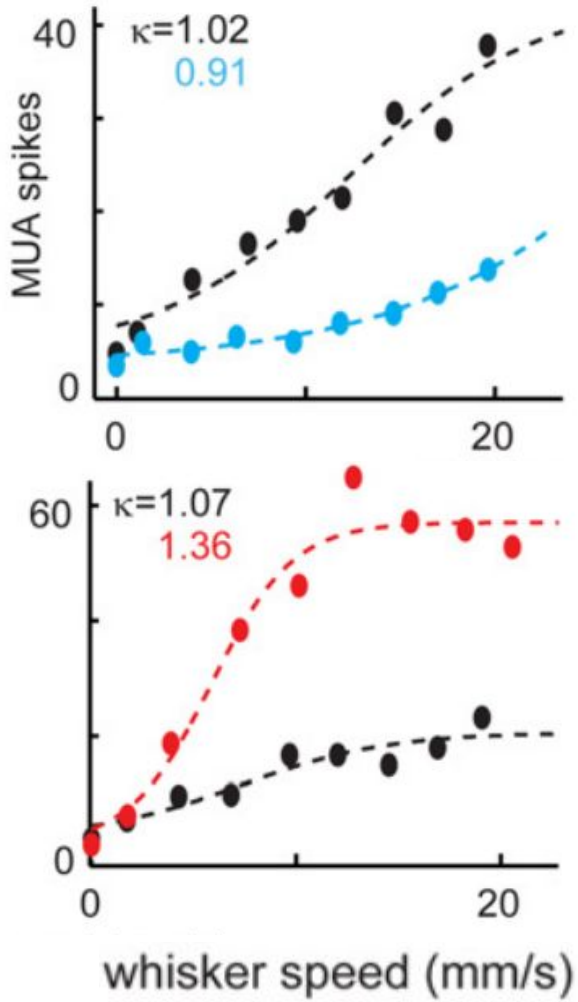


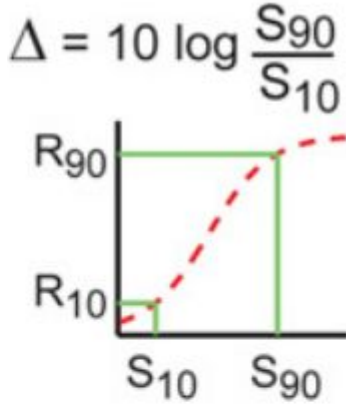


[Gautam 2015]

Maximization of dynamic range close to criticality in barrel cortex





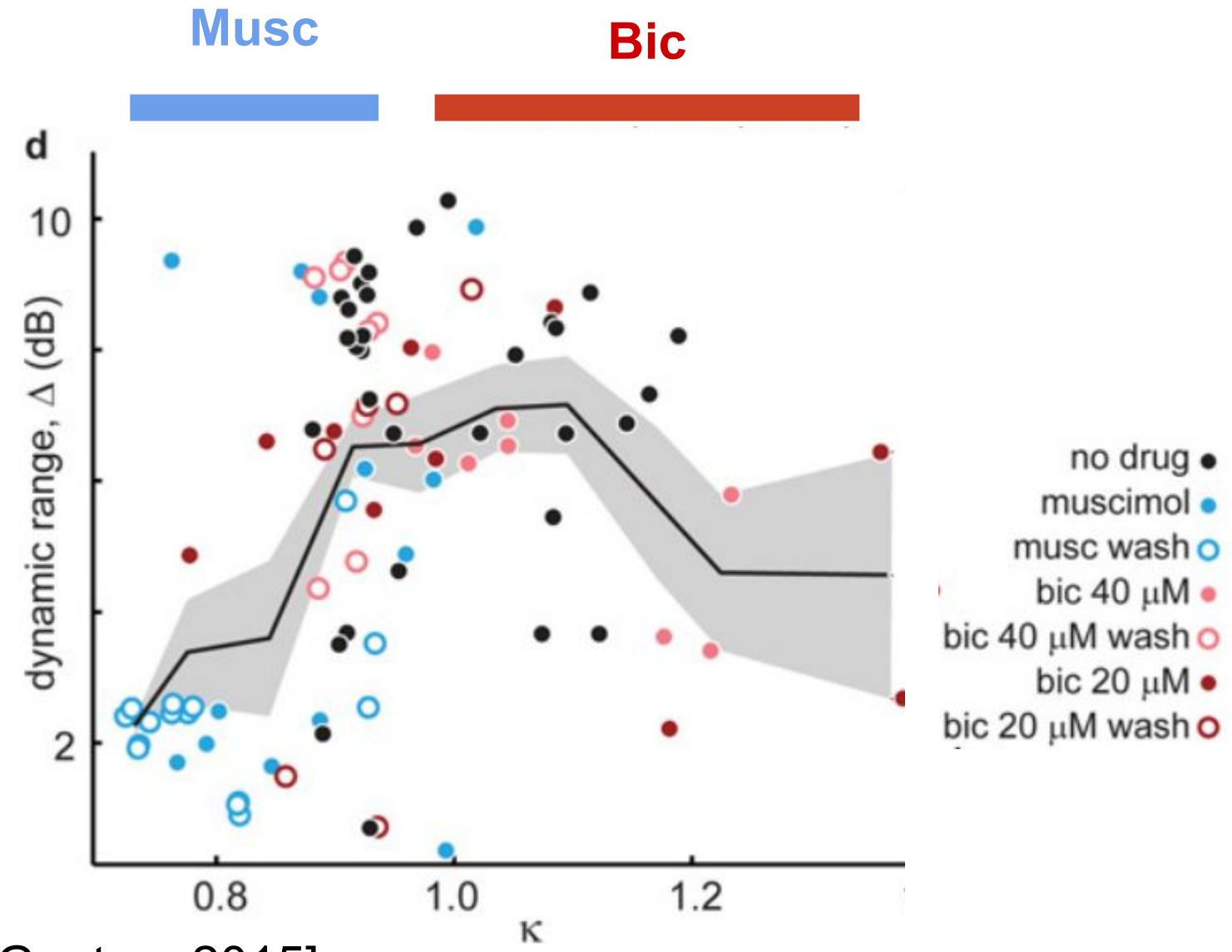


[Gautam 2015]

Muscimol (GABA Agonist)

Bicuculline (GABA Antagonist)

Maximization of dynamic range close to criticality in barrel cortex



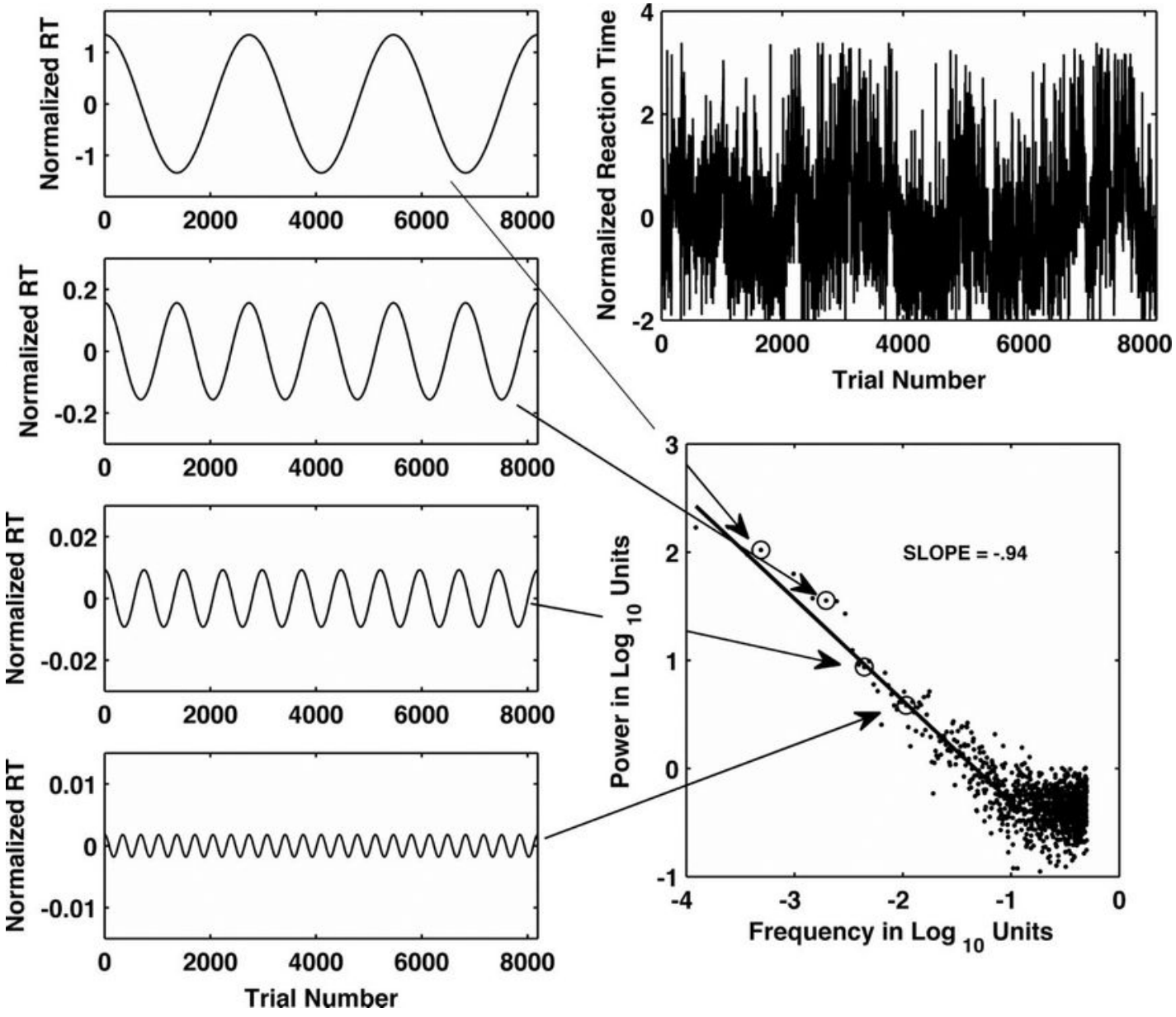
[Gautam 2015]

Why do we care about criticality in neuroscience?

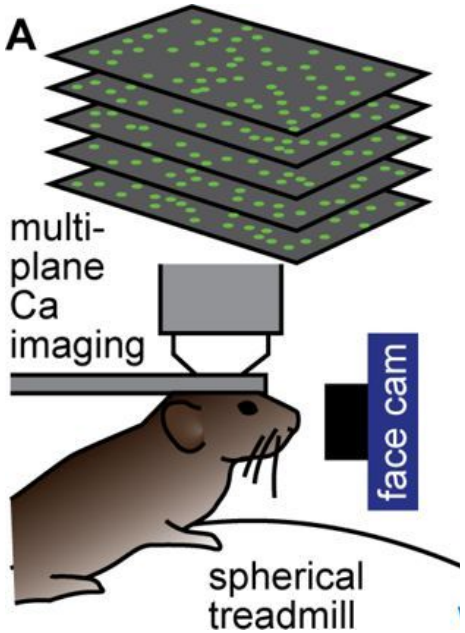
- Multi-scale-ness of interactions is required in a dynamic world where we need strength of interactions to change across both space and time.
  - i.e. only a “fluid” network can support both local and global interactions together
- You need to be somewhere in between the “disordered” and “ordered” phases to maximize potential complexity of system.

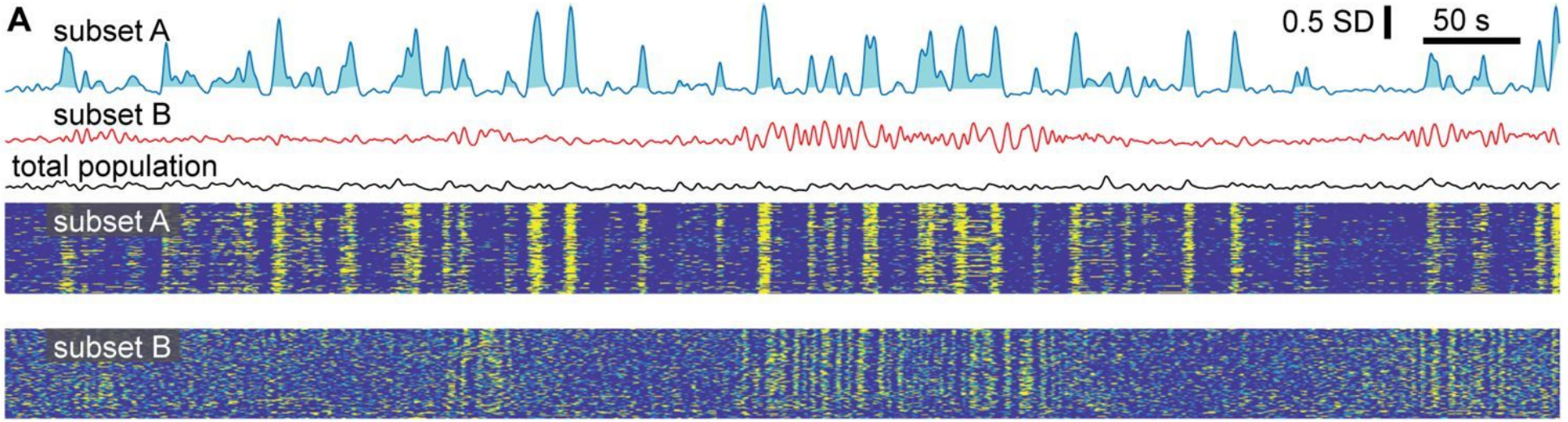
Scale-free behavior

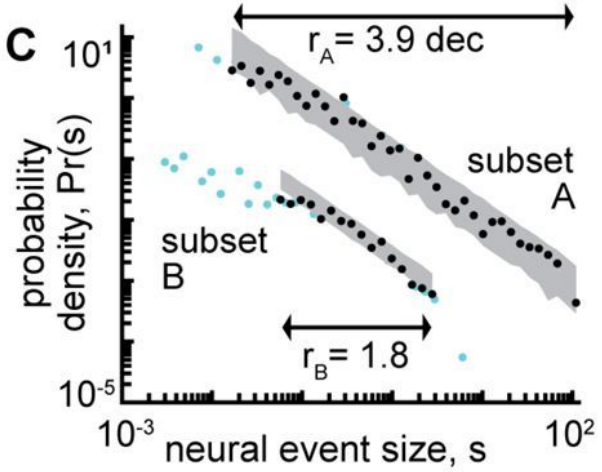
- **<u>Human reaction times:</u>**
- Holden, John & Choi, Inhyun & Amazeen, Polemnia & Orden, Guy. (2010). **Fractal 1/f Dynamics Suggest Entanglement of Measurement and Human Performance. Journal of experimental psychology.** Human perception and performance. 37. 935-48. 10.1037/a0020991.



Scale-free neural activity







[Jones 2023]

Is this relevant?

NOT CRITICAL

- Scale-free/multi-scale mechanisms will generate output that is scale-free/multi-scale.
- **Human fMRI:** Raut RV, Snyder AZ, Raichle ME (2020) **Hierarchical dynamics as a macroscopic organizing principle of the human brain.** Proceedings of the National Academy of Sciences 117:20890–20897.

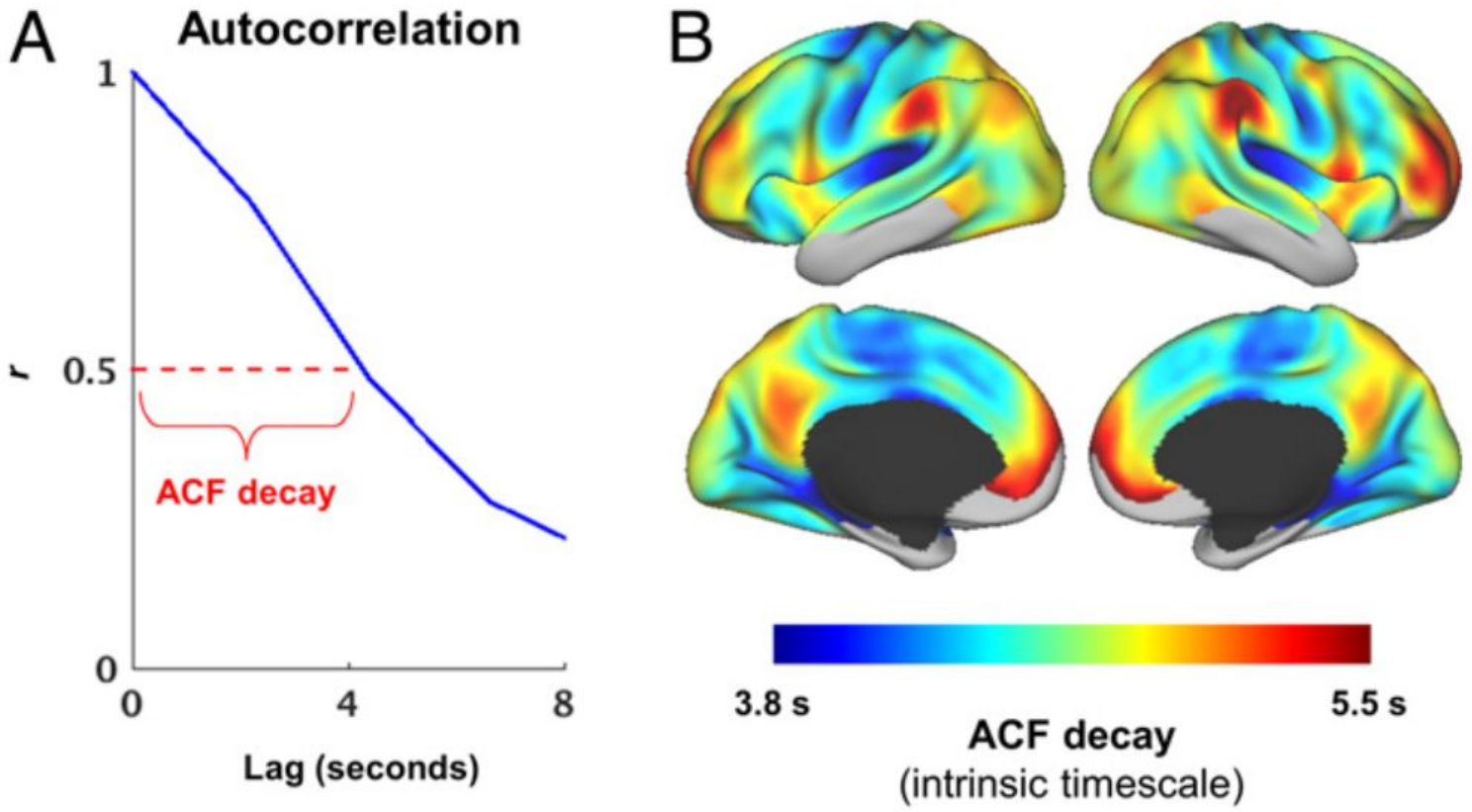
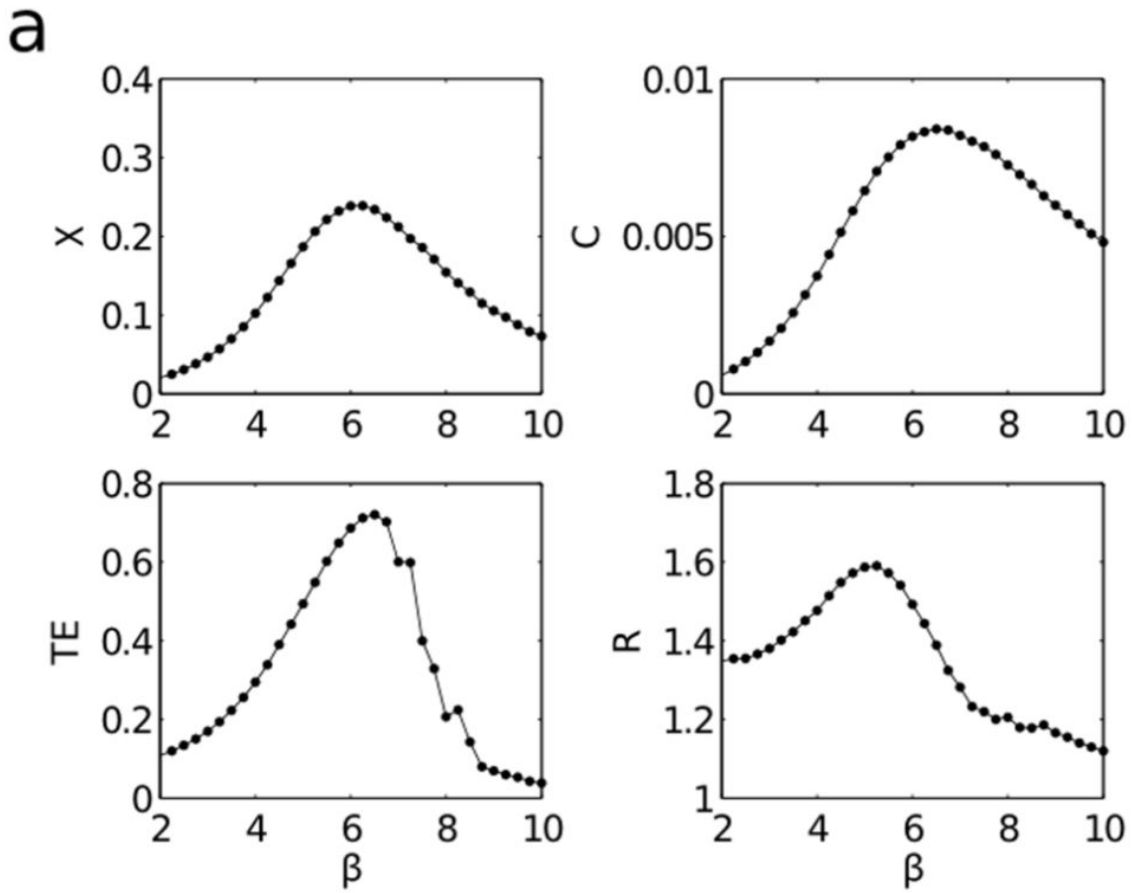


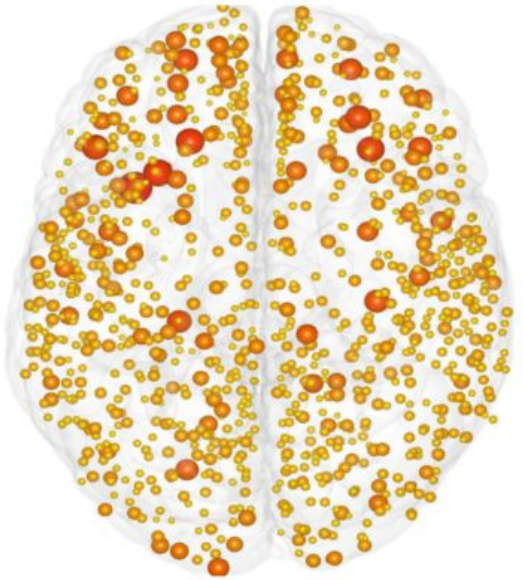
Fig. 1. Hierarchy of intrinsic timescales revealed from fMRI autocorrelation. (*A*) Intrinsic timescale was estimated for each cortical vertex as the temporal autocorrelation decay during the resting state, quantified as half of the full width at half maximum of the ACF (*Methods*). (*B*) Vertex-wise map of mean intrinsic timescale (n = 1,139 subjects).

Is this relevant?

And many more -> [Ribeiro 2021]

Information Transfer and Criticality in the Ising Model on the Human Connectome





β = Inverse Temperature

χ = Susceptibility

C = Heat Capacity

TE = Transfer Entropy

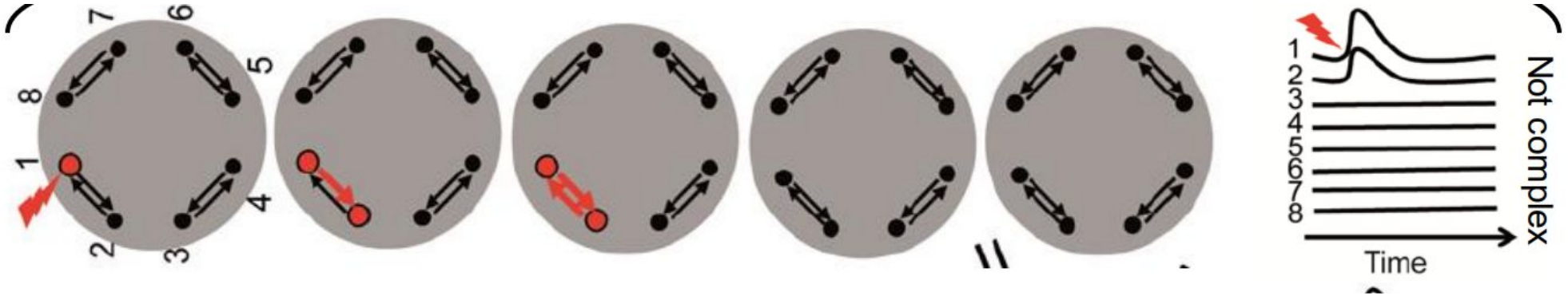
R = ratio of outgoing and incoming information flows

Section 2: Criticality to Consciousness (via integrated information…kinda sorta)

- Got here talking about scale-free properties
- Relax constraint to “multi-scale”

Visual explanation of integrated information

[Sarasso 2014]



Time

Note on diversity of responses

- Sparsity of evoked responses is the most “efficient” representation but is akin to the disconnected state
- Labelled lines suggest a homogeneity of responses, which are similar to the fully connected state
- Diversity of responses (distribution of response entropies…what we observe), is expected from a critical system

Choudhary, Anshul, et al. “Neuronal Diversity Can Improve Machine Learning for Physics and Beyond.” *Scientific Reports*, vol. 13, no. 1, Aug. 2023, p. 13962. *www.nature.com*, https://doi.org/10.1038/s41598-023-40766-6.

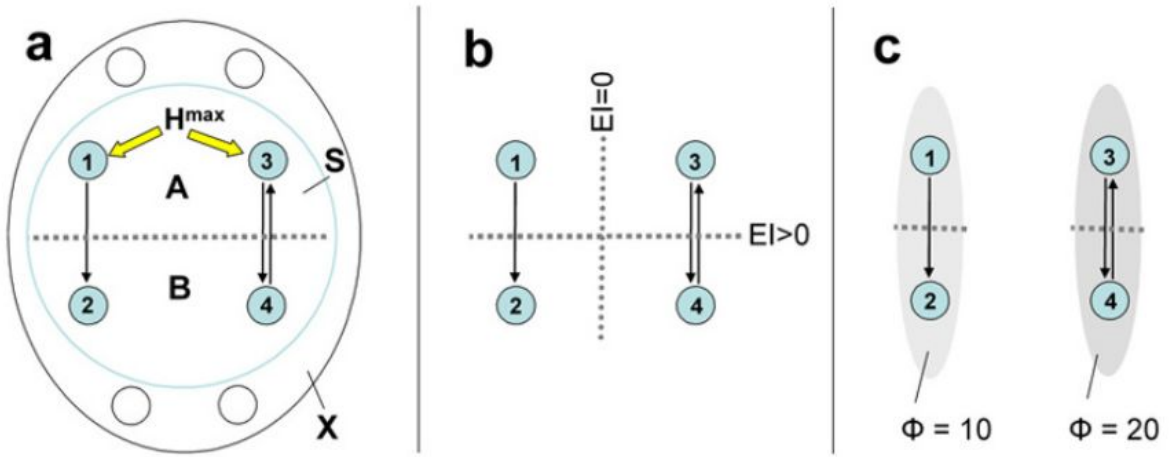
Mathematical Formulation of Integrated Information

- Effective Information
  - MI(A;B) = H(A) + H(B) - H(AB)
  - EI(A→B) = MI(A_Hmax;B)
  - EI(A<->B) = EI(A→B) + EI(B→A)

Measuring information transfer

Mathematical Formulation of Integrated Information

- Φ is the amount of effective information that can be exchanged across the minimum information bipartition of a complex.
- Qualitatively, ↑Φ = ↑response complexity

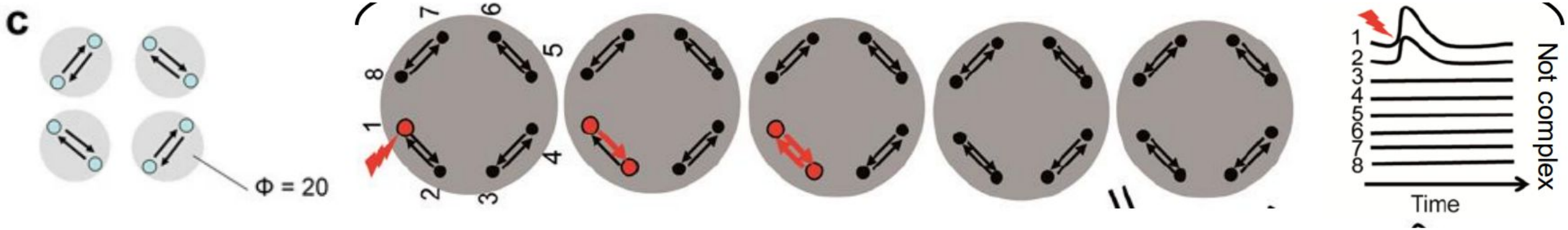


Visual explanation of integrated information

[Sarasso 2014]

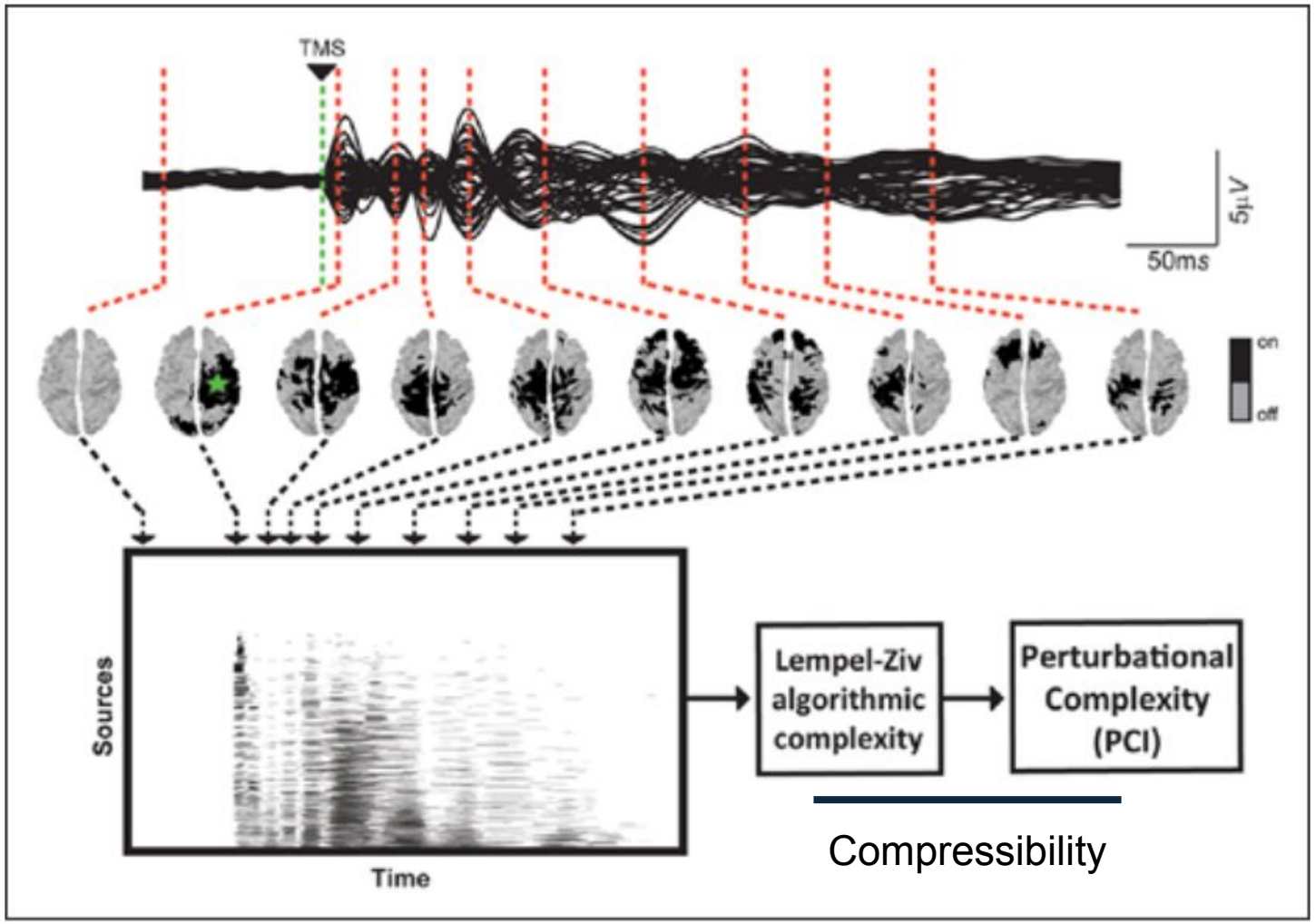
<u>One interpretation:</u>

Integrated information quantifies a systems ability to "collectively"/"connectedly" utilize combinatorial complexity.



Time

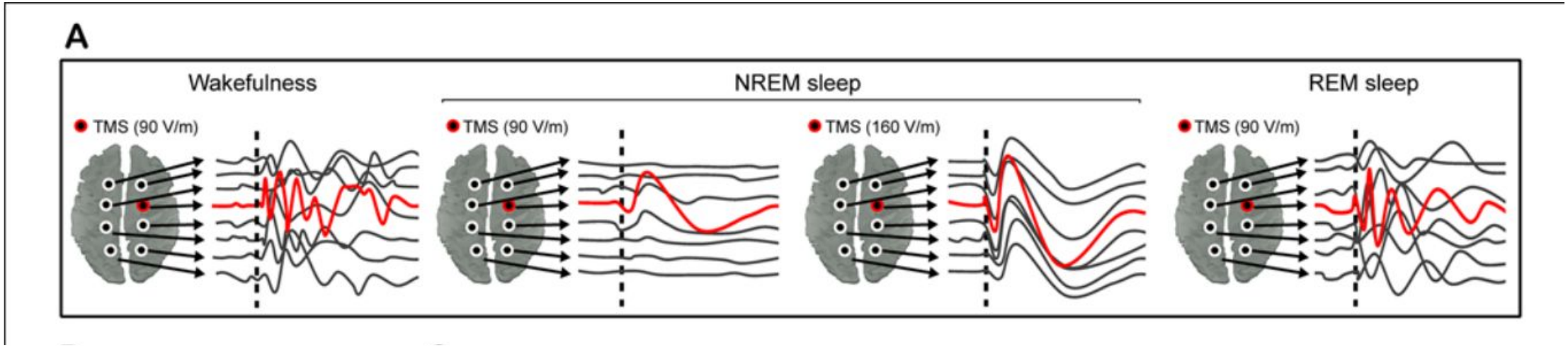
Can’t actually calculate Φ for real systems

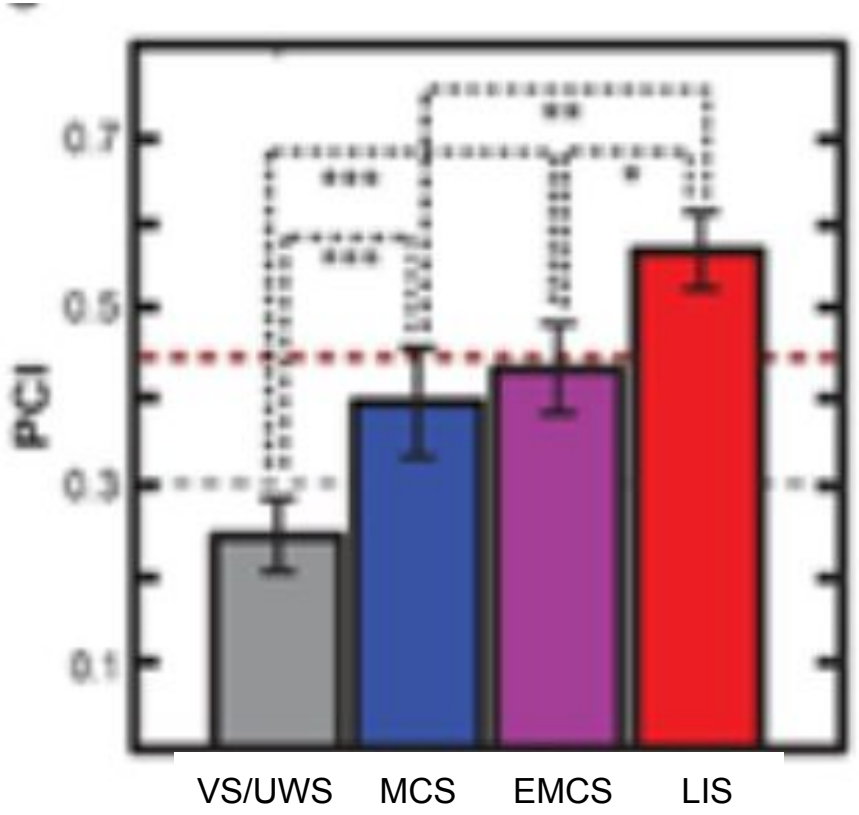


[Sarasso 2014]

CLAIM:

Scale-free neural dynamics/interactions are related to a “conscious” state





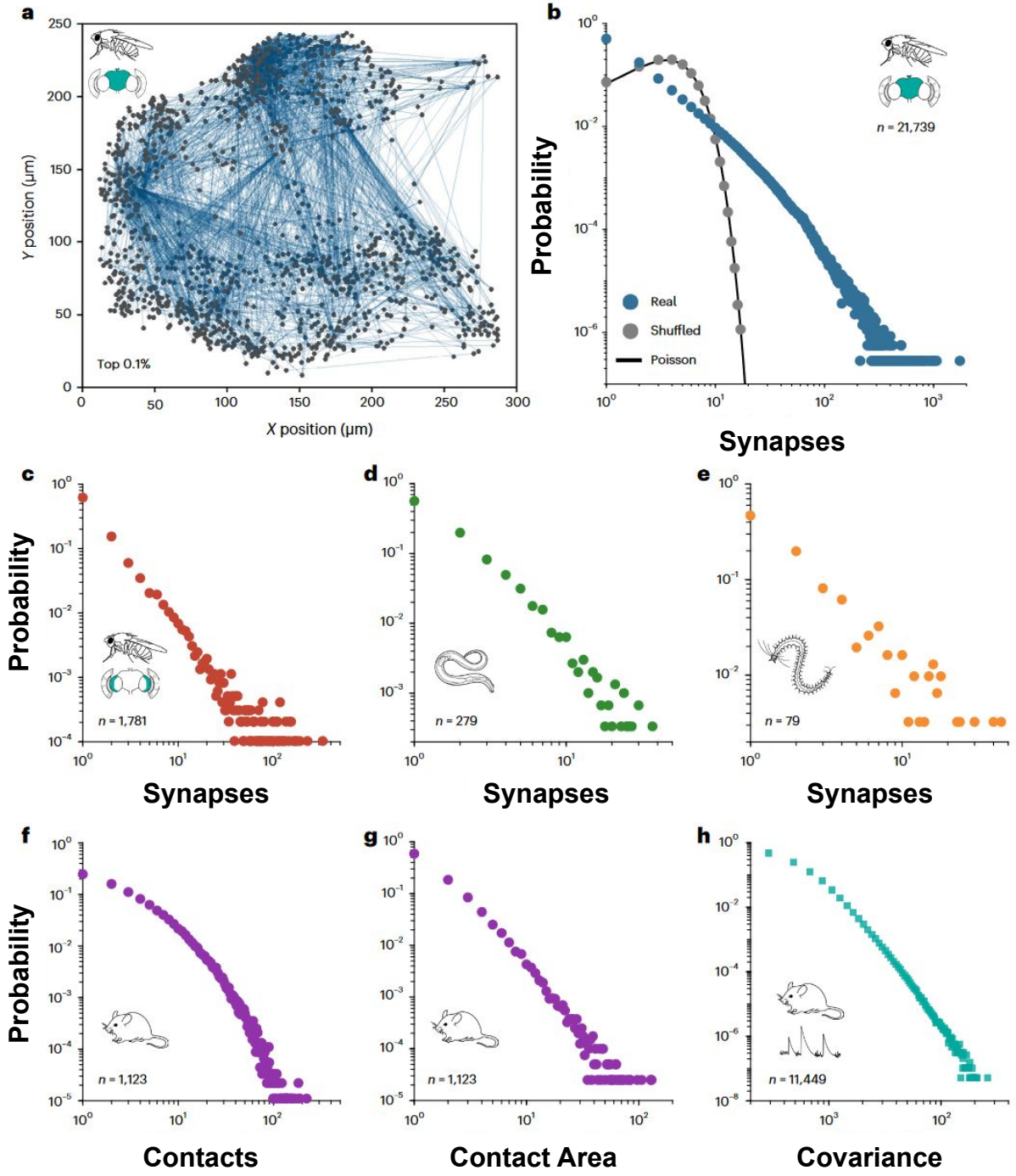
vegetative state (VS) unresponsive wakefulness syndrome (UWS)	awake, but entirely unaware
minimally conscious state (MCS)	shows some evidence of awareness but is unable to communicate their thoughts or feelings.
eMCS	Recovery of functional communication
locked-in syndrome (LIS)	fully conscious and awake, but paralyzed

STRONGER CLAIM:

Conscious perception **requires** multi-scale interactions.

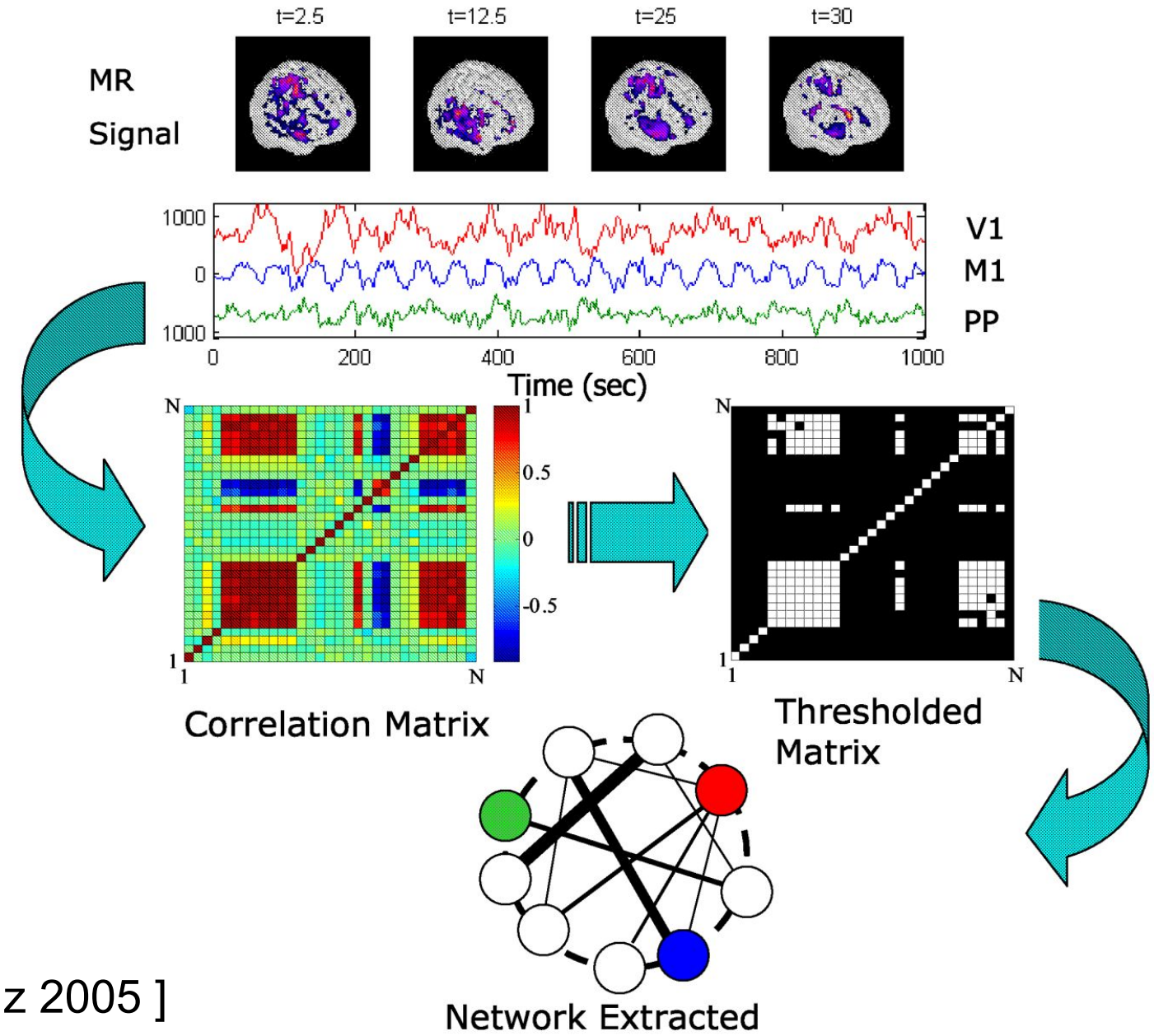
- The brain has been shown to operate in an "interaction-dominant" regime, marked by scale-free features.
- Hence, it may not be surprising if these multi-scale interactions are a **requirement** for conscious perception.

Scale-free connections in real nervous systems



[Lynn 2024]

Scale-free “functional connectivity” during task performance



[Eguíluz 2005]

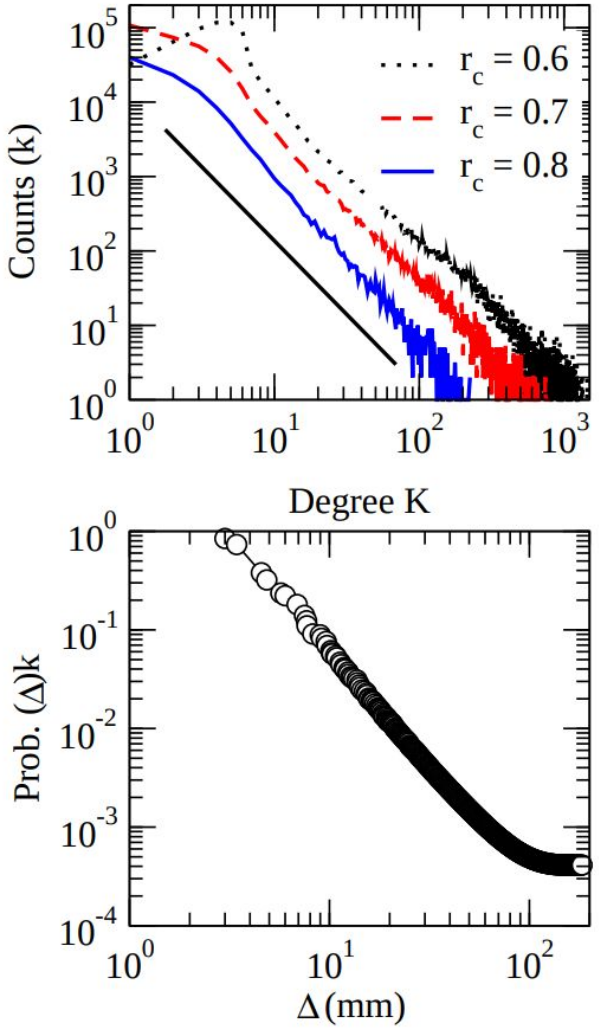
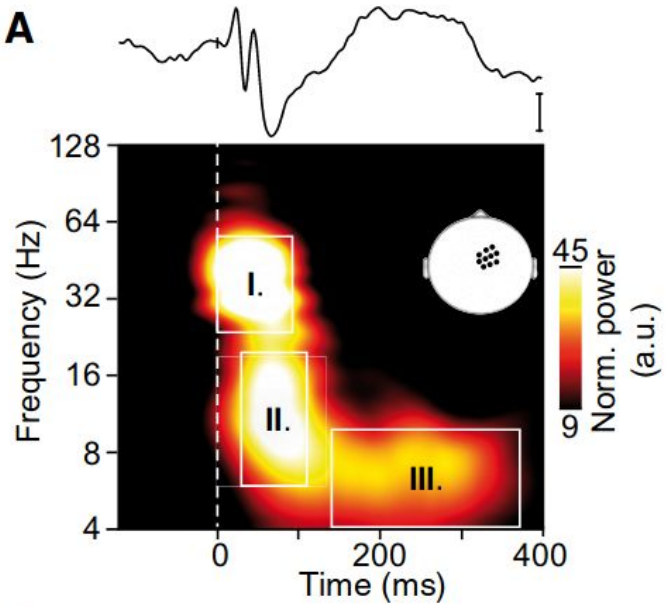


FIG. 3: (Color online) Average scaling taken from 22 networks extracted from seven subjects. Top Panel: Average degree distribution. The straight line illustrates a decay of k^{-2}. Bottom panel: Average probability of finding a link between two nodes separated by a distance larger than Δ (using $r_c = 0.6$).

The rest is reading between the lines

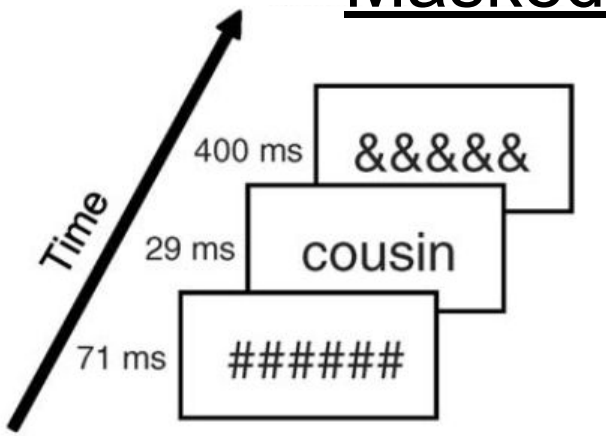
Long-range connections in conscious processing, Part 1



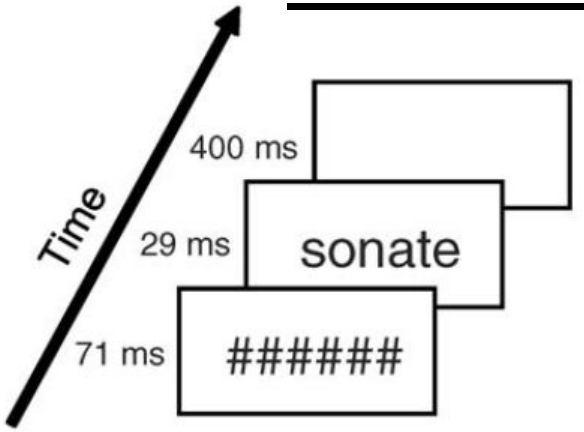
[Supp 2011]

Long-range connections in conscious processing, Part 2

Masked



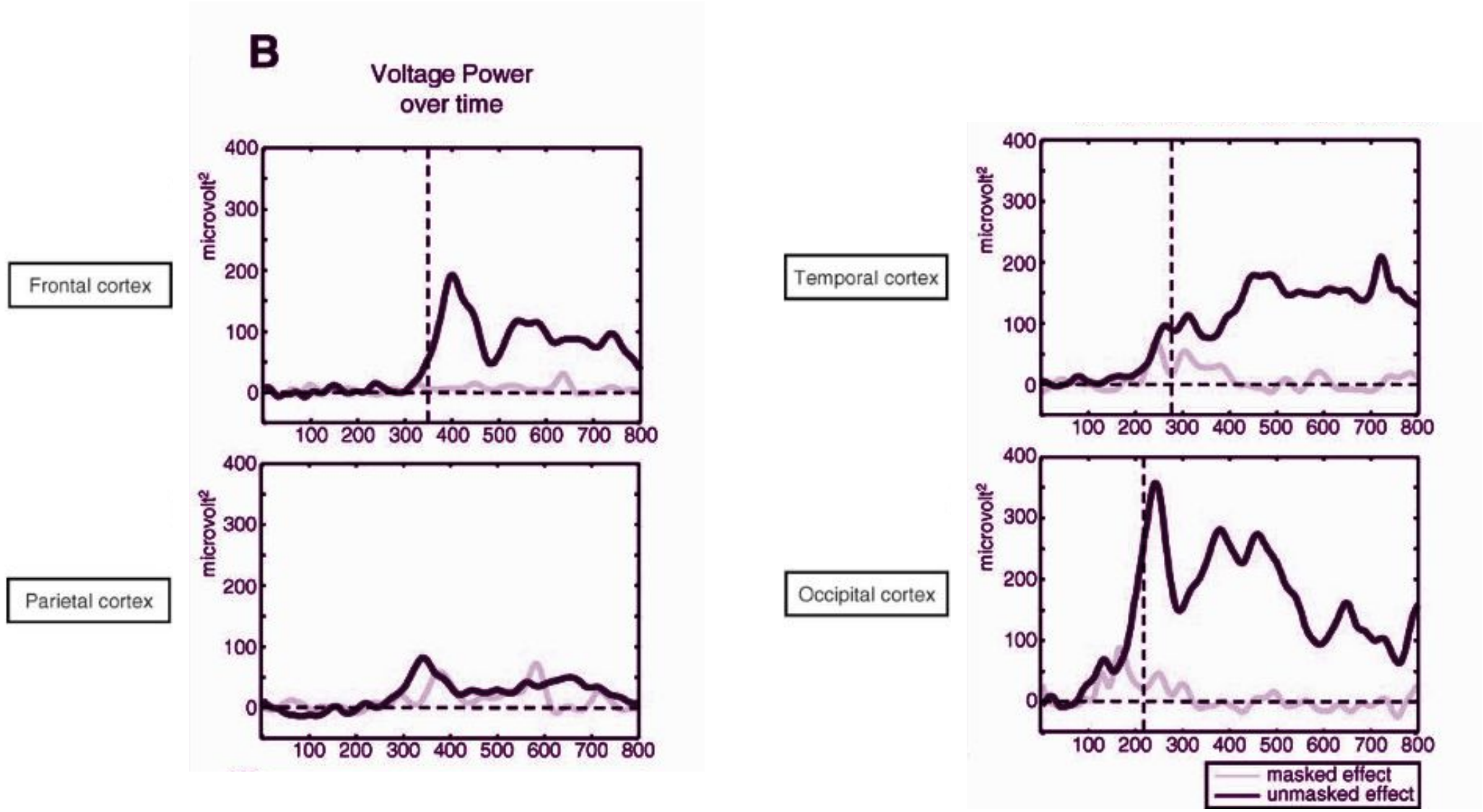
Unmasked



- Asked to give “emotional valence of words”
- p<0.0001 for positive vs negative worlds in *Un*masked
- p=0.38 for positive vs negative worlds in Masked

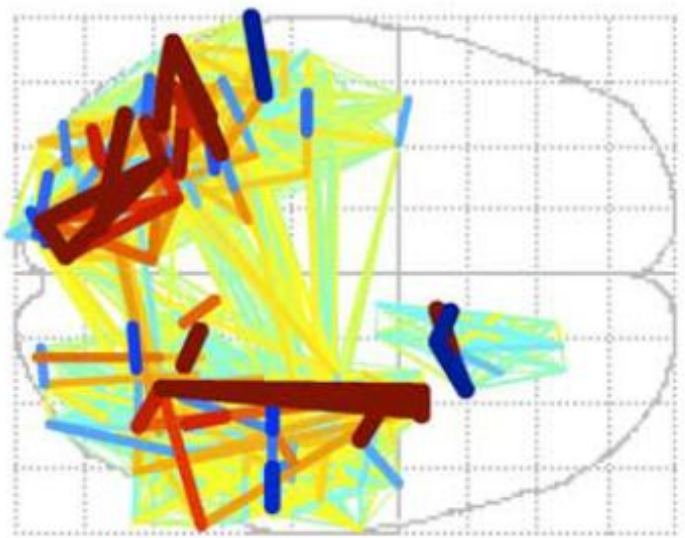
[Gaillard 2009]

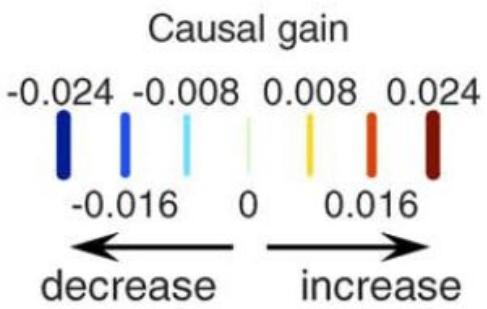
Long-range connections in conscious processing, Part 2



Long-range connections in conscious processing, Part 2

Unmasked





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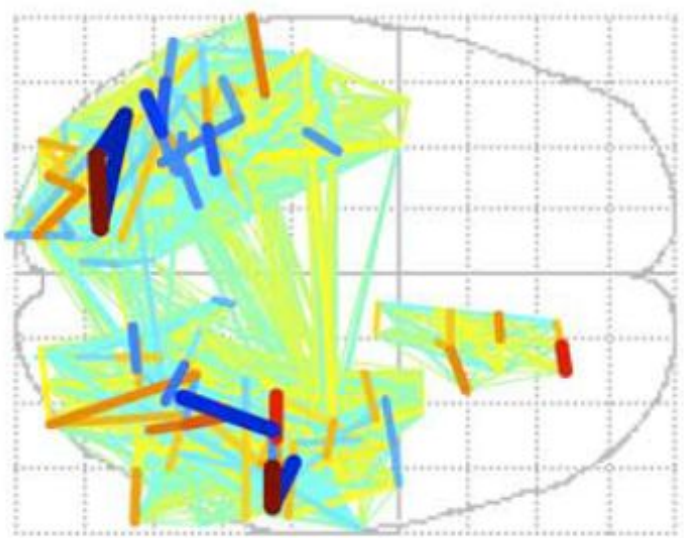

[Gaillard 2009]

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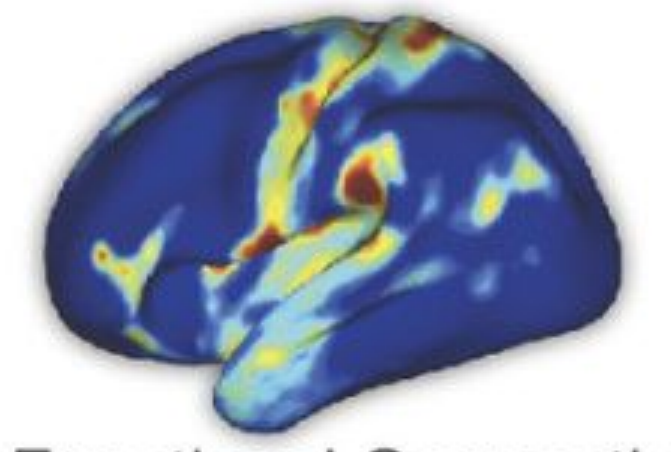

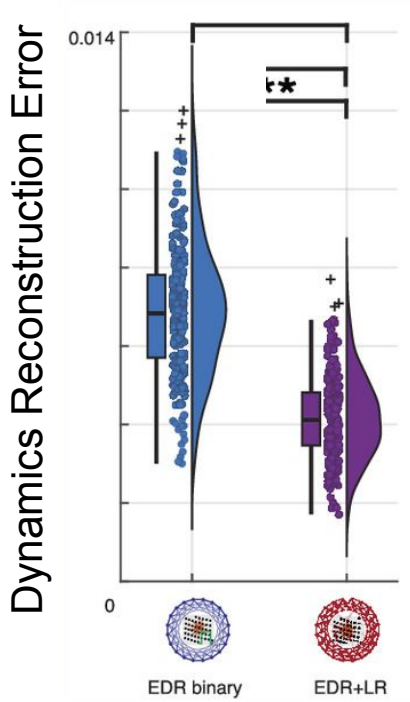

EDR = Exponential Distance Rule
LR = Long Range

Conclusion

- Criticality is a “requirement” for conscious processing in biological networks.
- If dynamics of a system are not close to critical, it will likely not be “functioning” too well.

You (likely) function best as a critical system, remember to zoom out

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