

# The Thermodynamics of Mind

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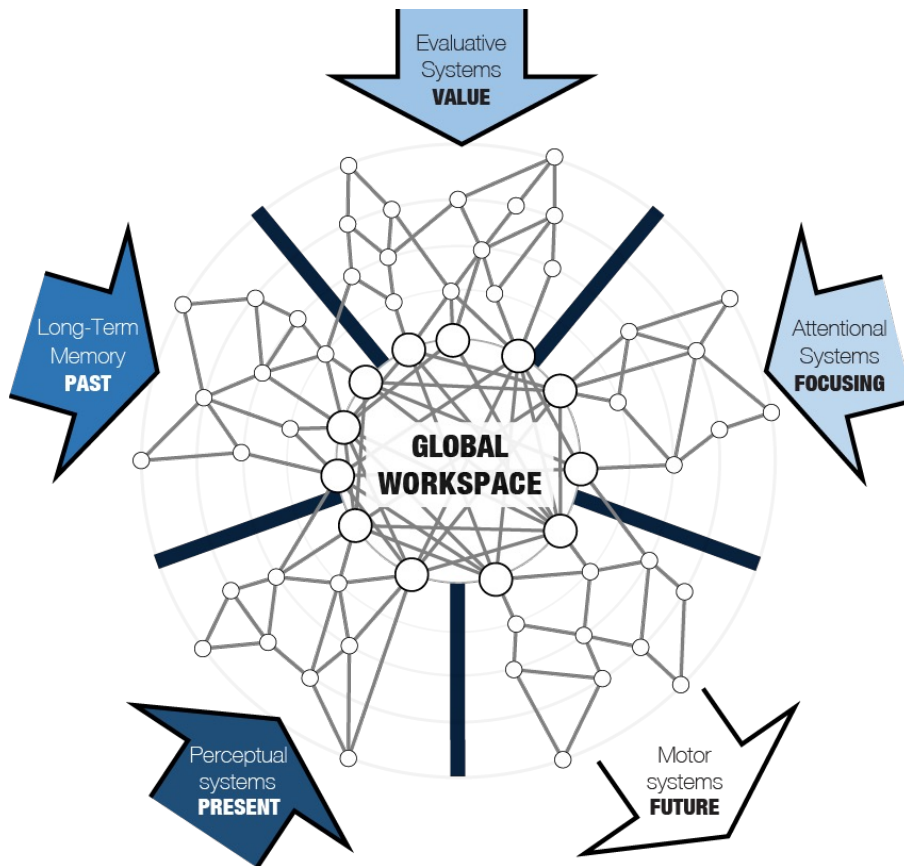
ICREA



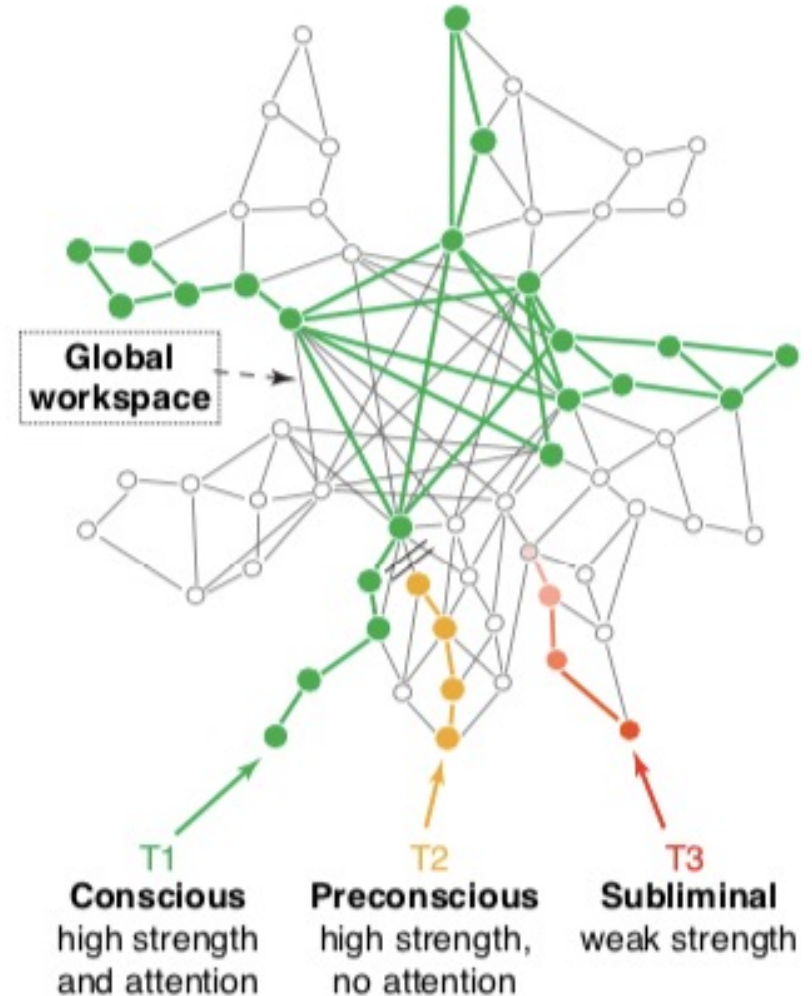
- Hierarchy in brain dynamics
- Hierarchy -> functional interaction
  - > breaking the detailed balance
- Capturing breaking detailed balance (hierarchy) by **Thermodynamics of Mind**: The arrow of time in brain signals  
(Non-reversibility – Non-equilibrium – Hierarchy)
- Non-equilibrium -> Turbulence -> Efficient information processing

# Overview

# Defining **Global Workspace**



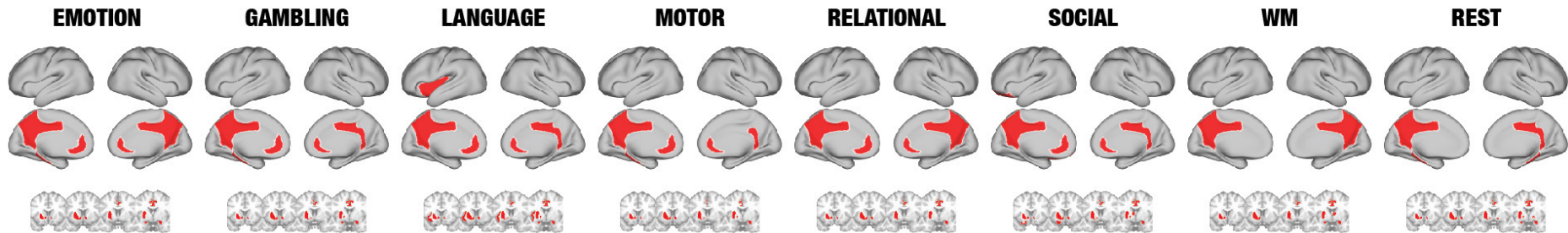
**Perceptual systems (PRESENT)**  
**Long-term memory (PAST)**  
**Evaluative systems (VALUE)**  
**Attentional systems (FOCUSING)**



# Discovering **Global Workspace** regions

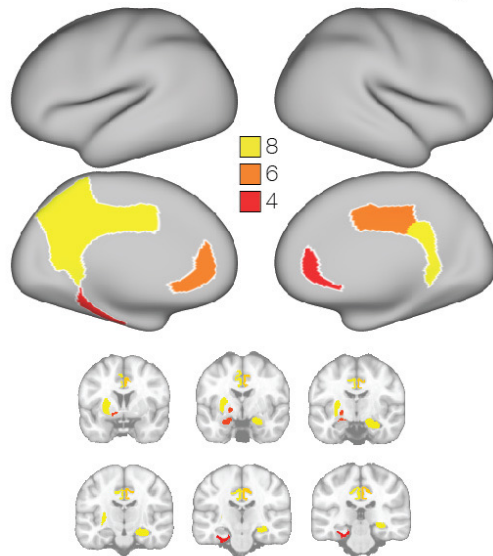
**A**

## FUNCTIONAL RICH CLUB (FRIC)



**B**

## GLOBAL WORKSPACE (intersection of FRICs)



### Intersection of all eight FRICs:

left precuneus  
left nucleus accumbens  
left posterior cingulate  
left putamen  
left, right isthmus cingulate  
right hippocampus  
right amygdala

### Further regions, threshold 6 FRICs:

right nucleus accumbens  
right posterior cingulate  
left, right rostral anterior cingulate

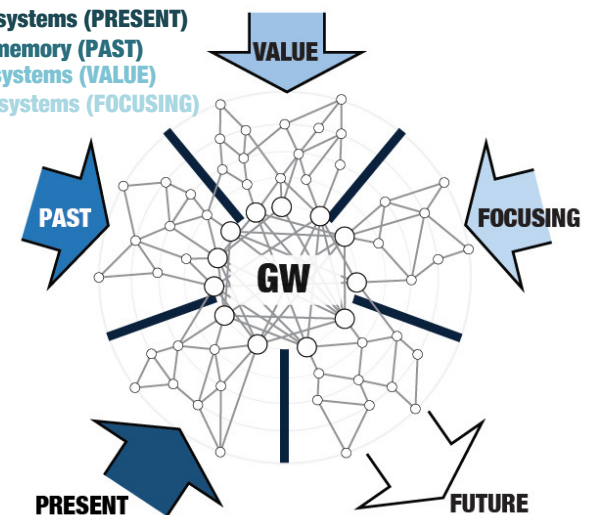
### Further regions, threshold 4 FRICs:

left globus pallidus internus  
left amygdala  
left parahippocampal

**C**

## INTEGRATION

Perceptual systems (PRESENT)  
Long-term memory (PAST)  
Evaluative systems (VALUE)  
Attentional systems (FOCUSING)

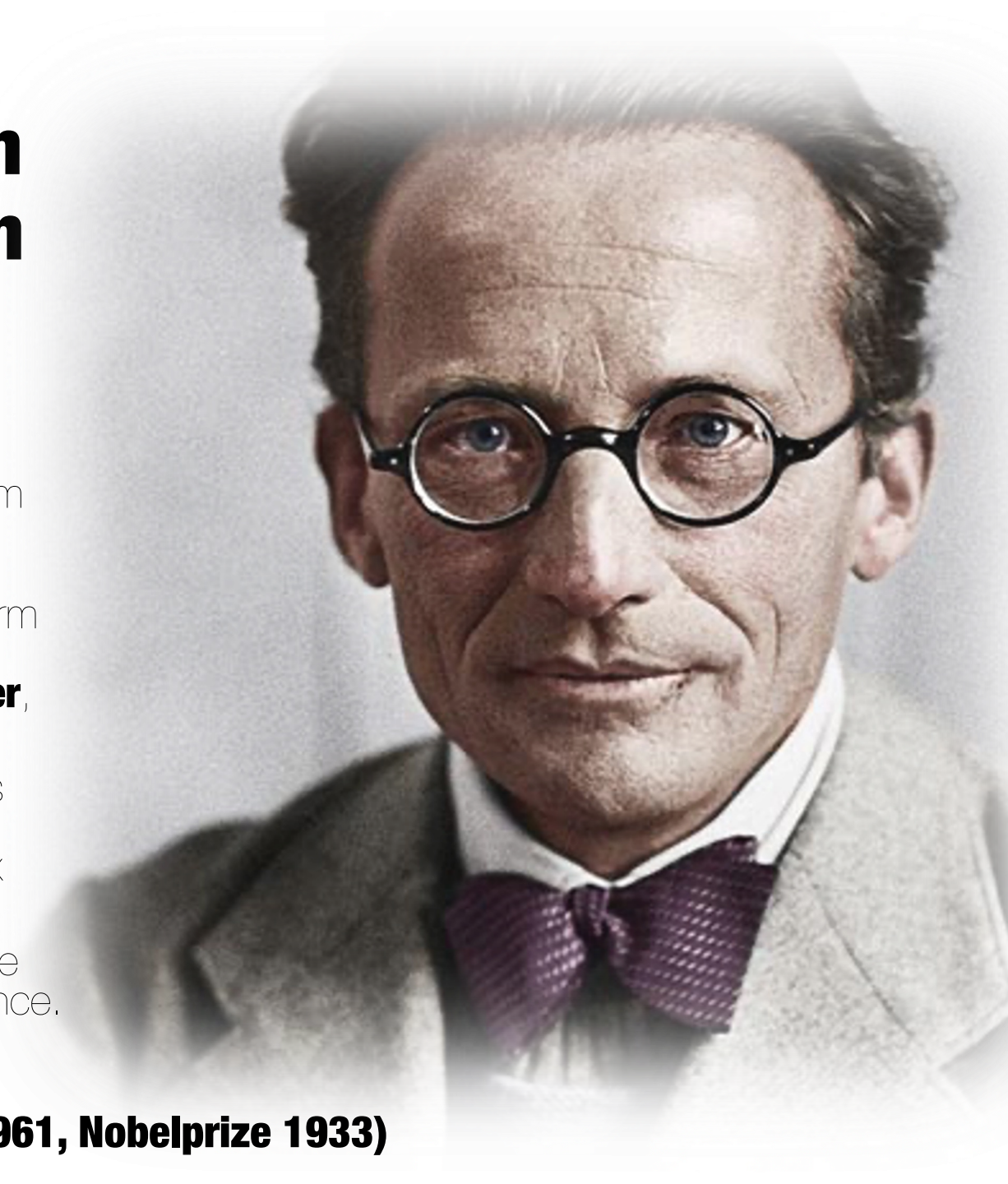




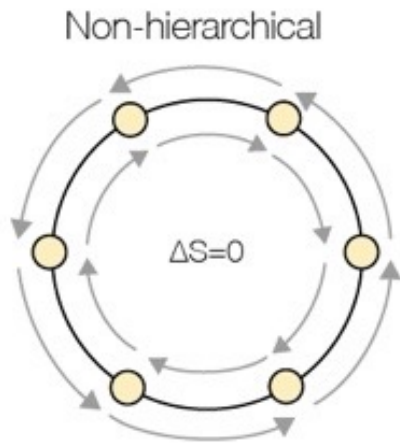
# Arrow of time in Non-Equilibrium

- “How does the living organism avoid decay? ... By eating, drinking, breathing and ... assimilating. The technical term is metabolism”  
 (“What is Life?”, **Schroedinger**, 1943)
- The avoidance of decay thus requires non-equilibrium interactions with the complex environment
- The brain is at the heart of the breaking of the detailed balance.

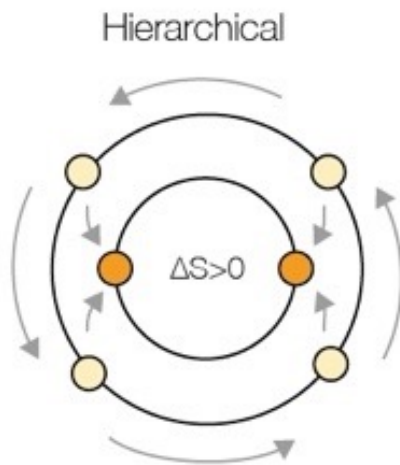
**Erwin Schroedinger (1887-1961, Nobelprize 1933)**



## Hierarchy and breaking of detailed balance



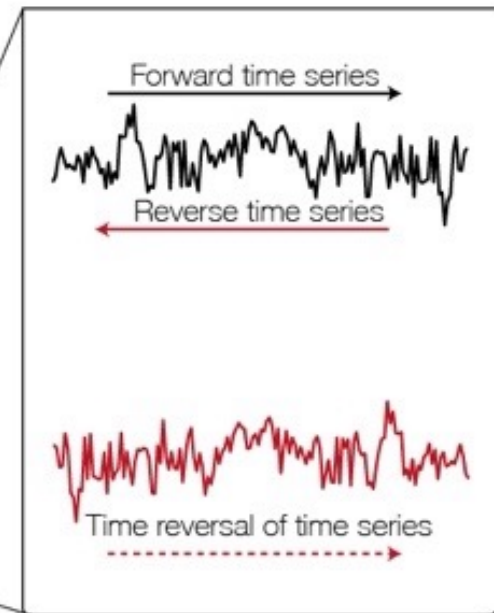
Reversible



Non-reversible



## Arrow of time

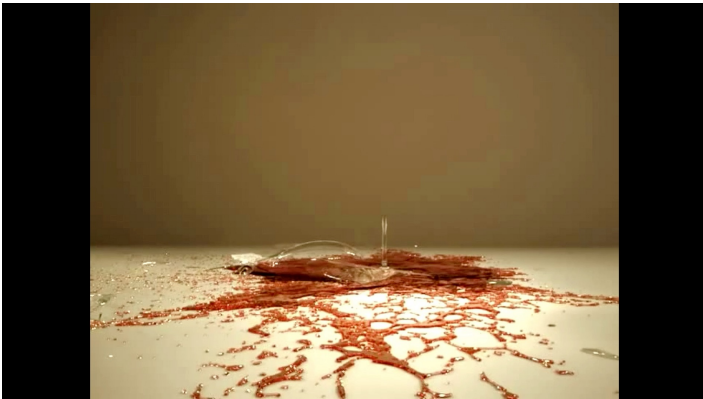


## Non-reversible

Forward

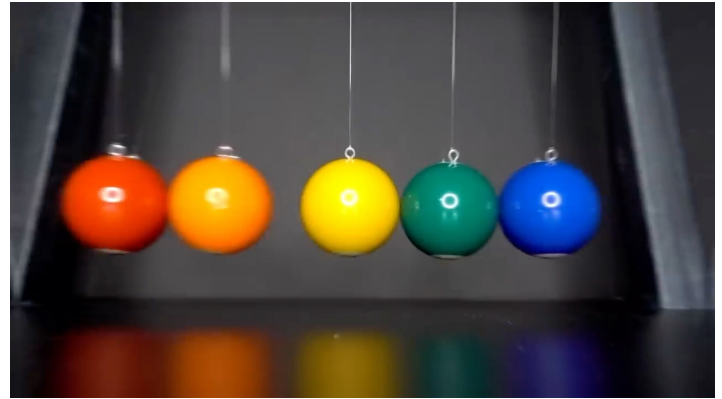


Time-reversal of backward trajectory



## Reversible

Forward



Time-reversal of backward trajectory



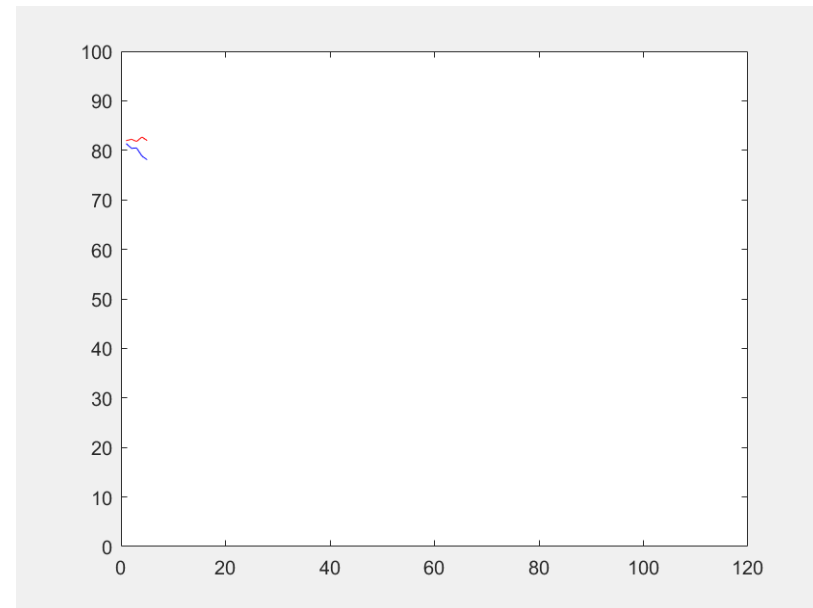
# Arrow of time in physics

- When is it difficult to determine the direction of the arrow of time?



When we are shown a movie of a **macroscopic** process, we **can** typically guess easily whether the movie is played in the correct order or in time-reversed order

Christopher Nolan: TENET



When we are shown a movie of a **microscopic** process, we **cannot** typically guess easily the direction

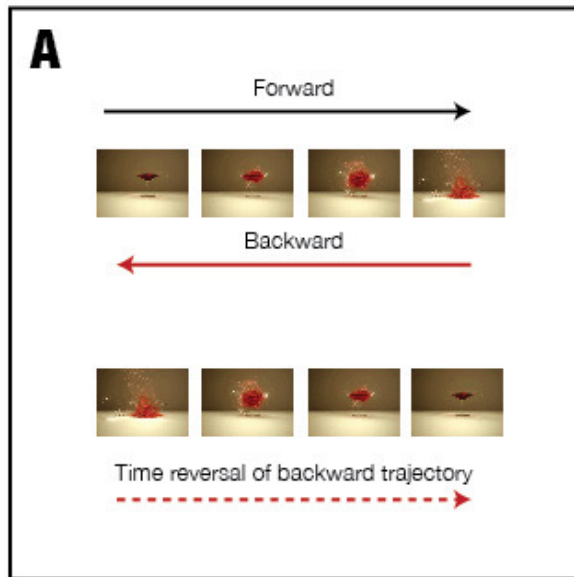
Seif ... & Jarzynski et al 2021 Nature Physics

# Thermodynamic arrow of time

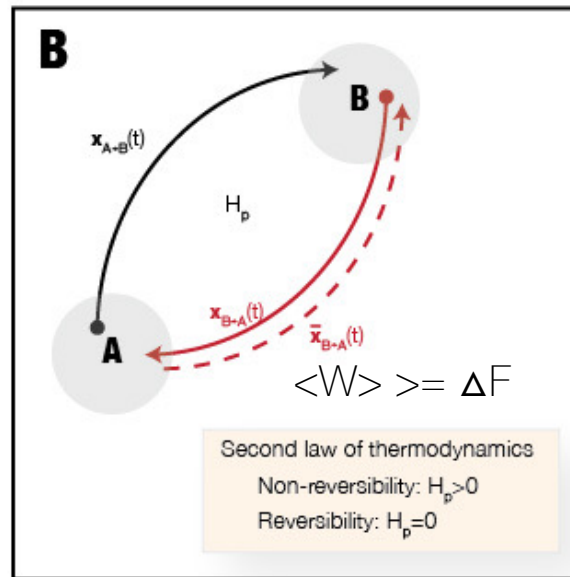




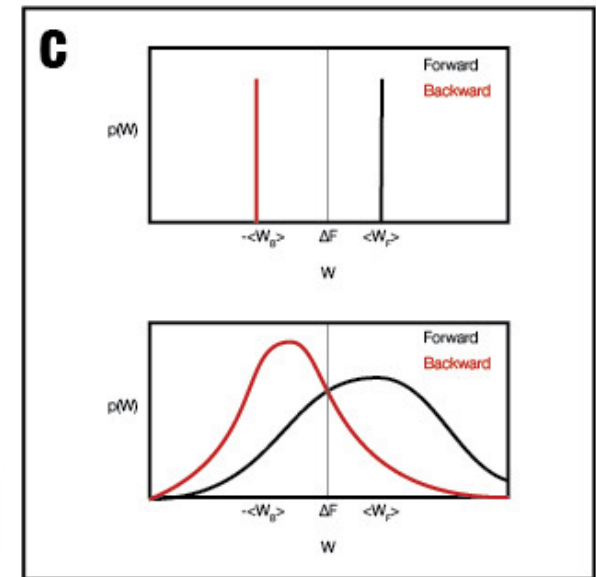
Rudolph **Clausius**   Sadi **Carnot**   Arthur **Eddington**



Arrow of time

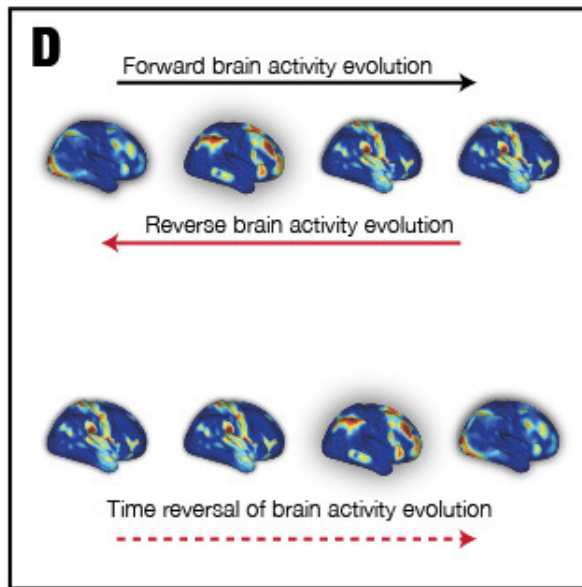


Reversibility vs non-reversibility

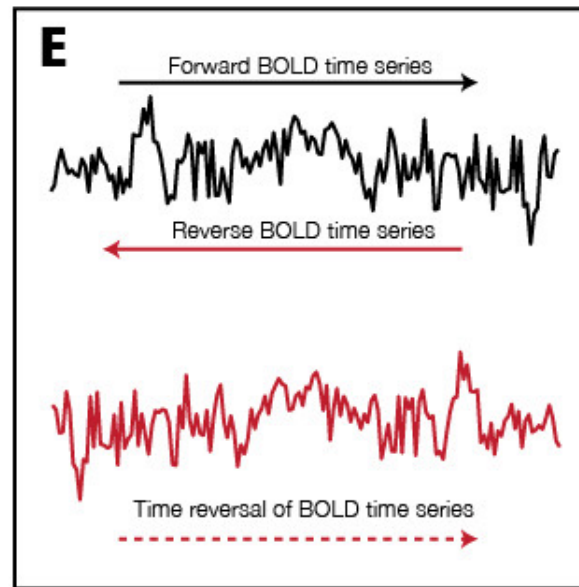


Fluctuations in work distribution

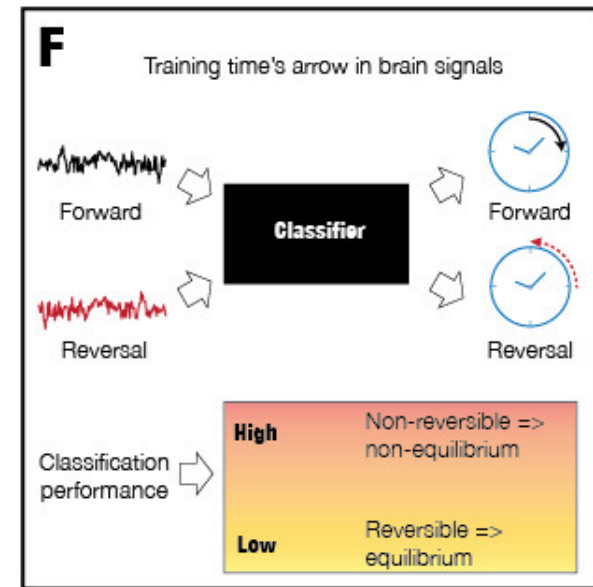
# Arrow of time in physics



Brain activity

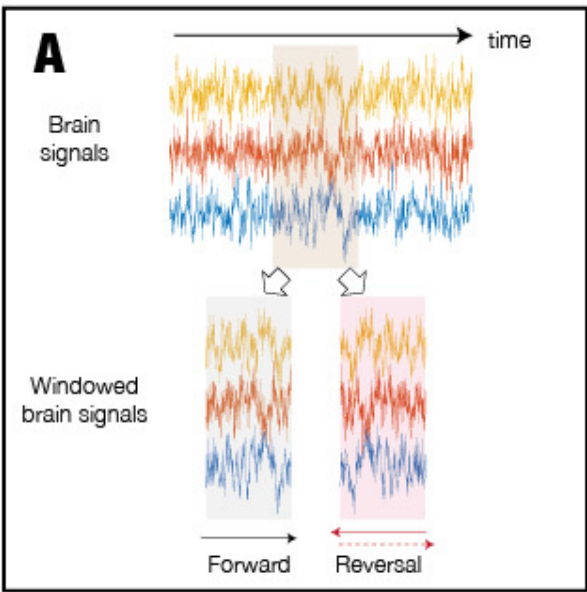


BOLD time series

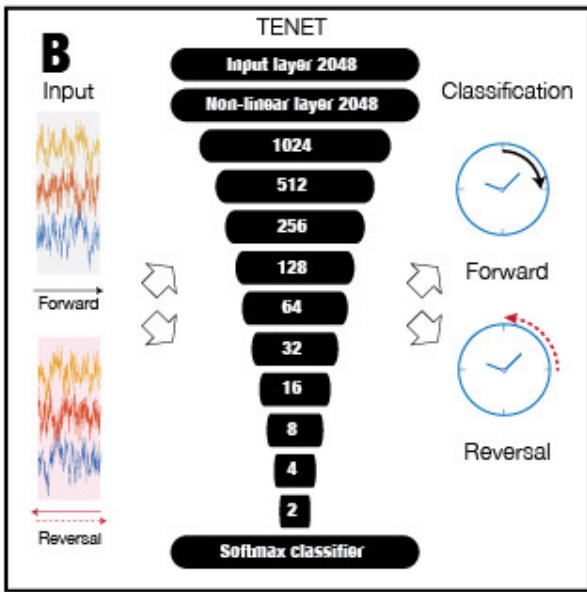


Classifying reversibility

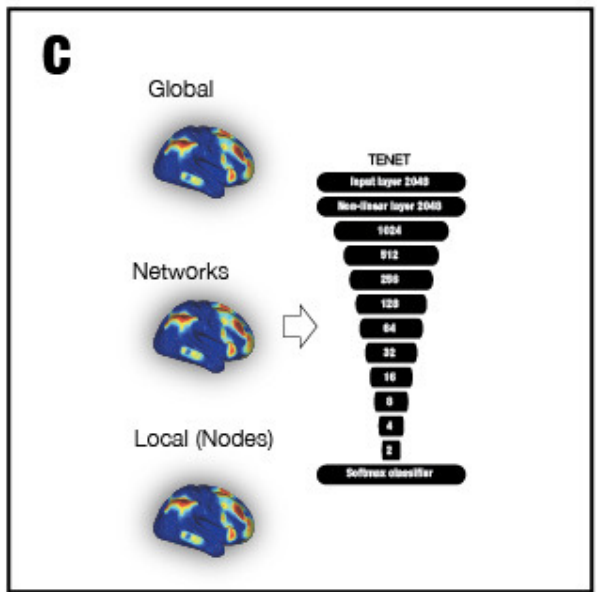
# Arrow of time in the brain



Sliding Windows



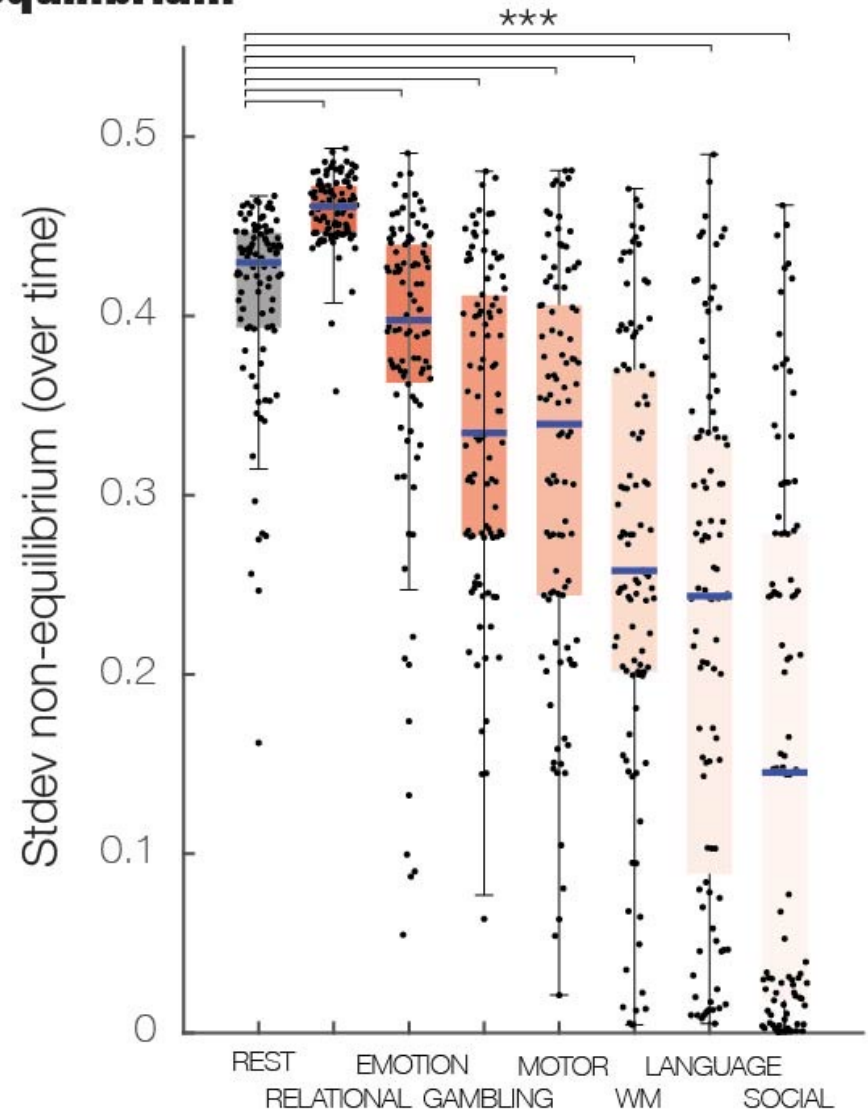
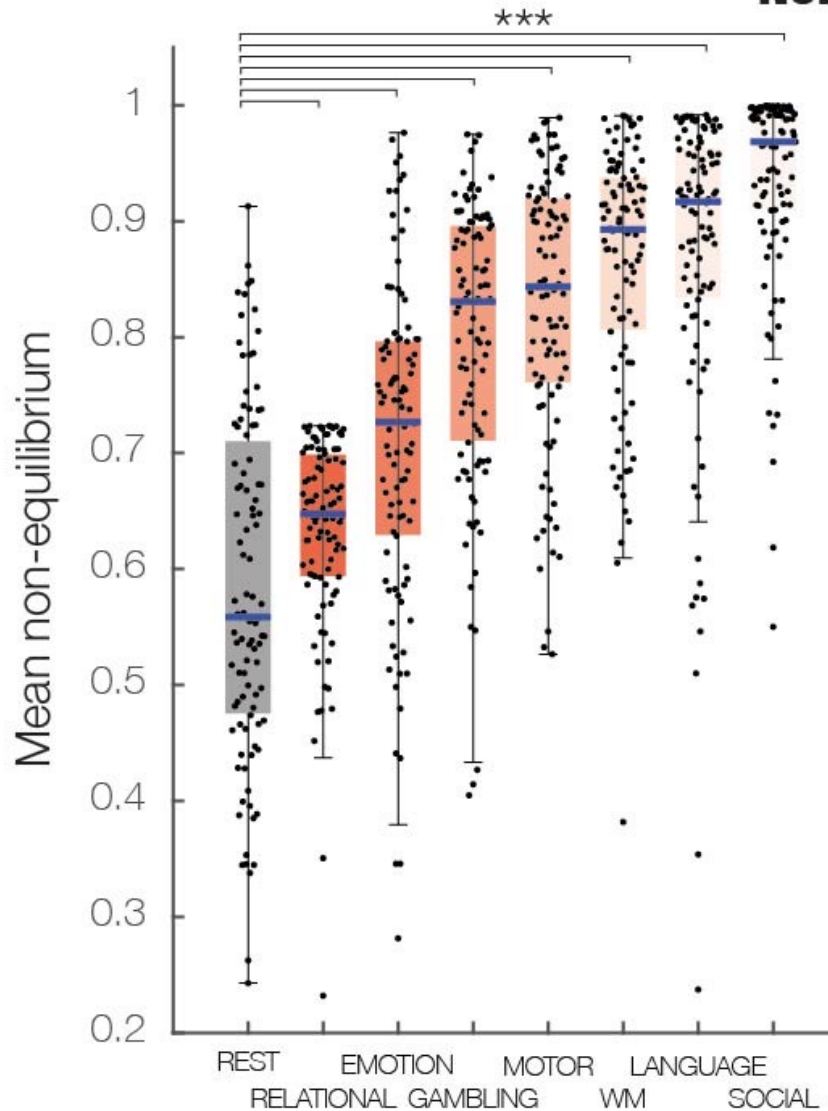
TENET: Deep learning



Global, nodes and networks

# Temporal Evolution Net (TENET)

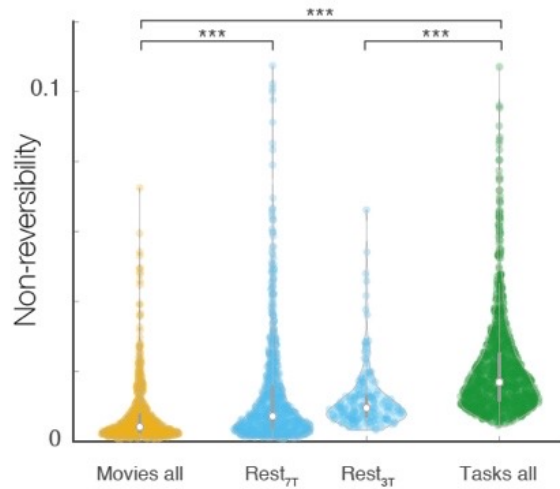
## Non-equilibrium



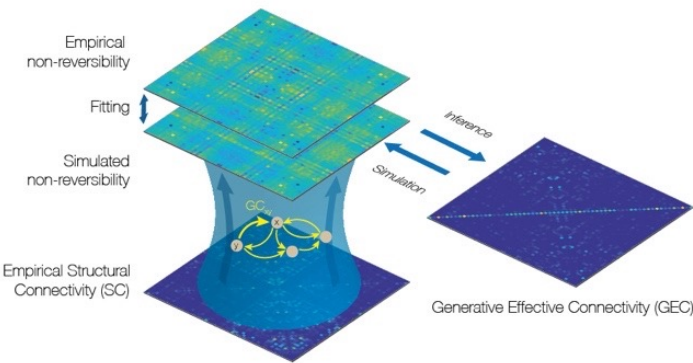
# Reversibility in HCP (Rest vs Task)



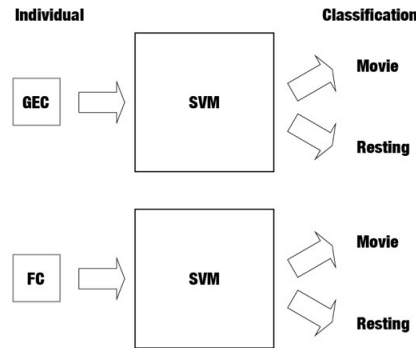
## Movie, rest and tasks



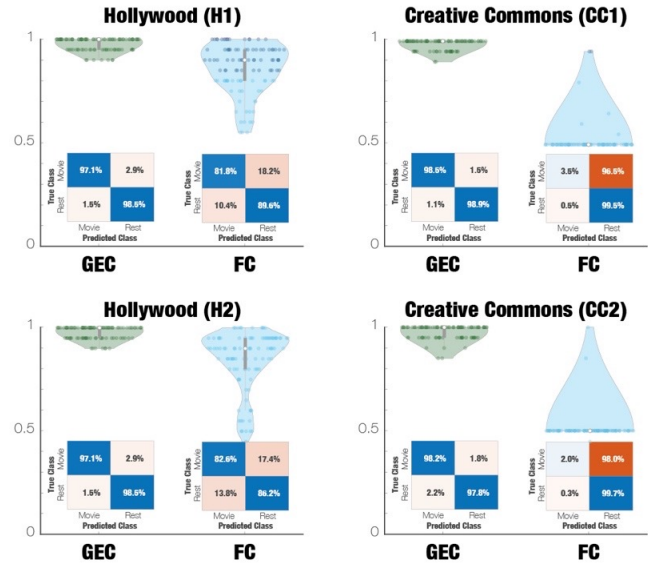
## Generative whole-brain model



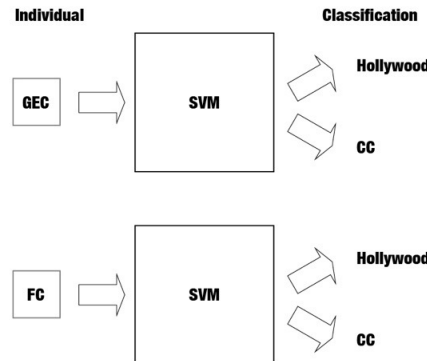
## Classification procedure



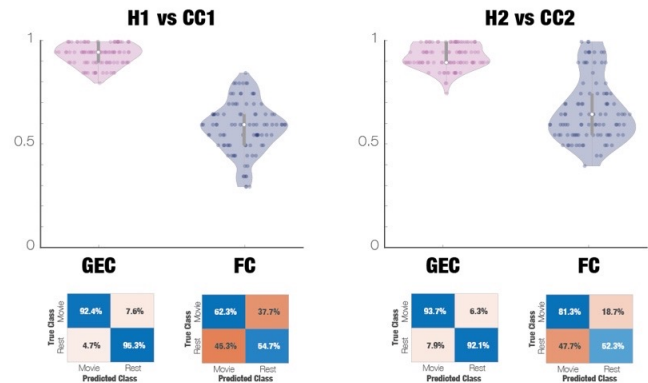
## Classification Movies vs Resting



## Classification procedure



## Classification Hollywood vs CC



# Whole-Brain Modeling of Non-reversibility





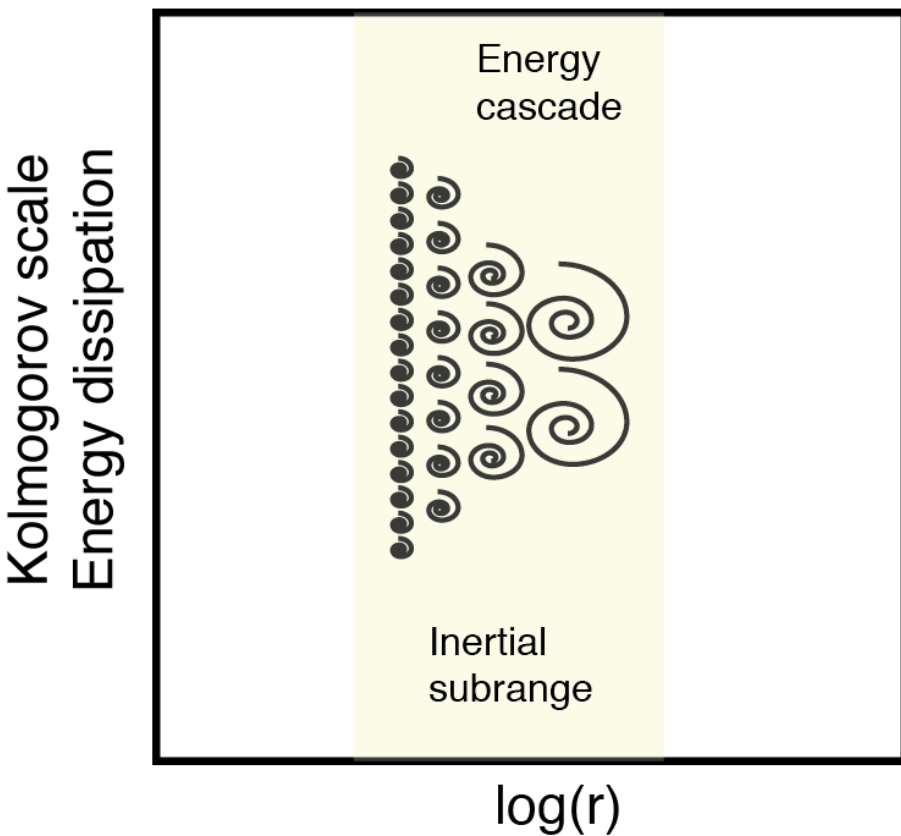
*Leonardo da Vinci*

*“turbolenza”*









“

*Big whirls have little whirls  
that feed on their velocity,  
And little whirls have lesser whirls  
and so on to viscosity*

”

*Lewis F. Richardson 1922  
(paraphrasing Jonathan Swift)*

*Siphonaptera:*

*Great fleas have little fleas upon their backs to bite ‘em  
And little fleas have lesser fleas, and so ad infinitum*

# Energy **cascade**



Kolmogorov's concept of *structure functions* of a variable  $u$  is defined by

$$S(\mathbf{r}) = \langle (u(\bar{\mathbf{x}} + \mathbf{r}) - u(\bar{\mathbf{x}}))^2 \rangle = 2[B(0) - B(\mathbf{r})]$$

where the basic spatial correlations of two points separated by an Euclidean distance  $r$ , are given by

$$B(r) = \langle u(\bar{\mathbf{x}} + \mathbf{r})u(\bar{\mathbf{x}}) \rangle$$

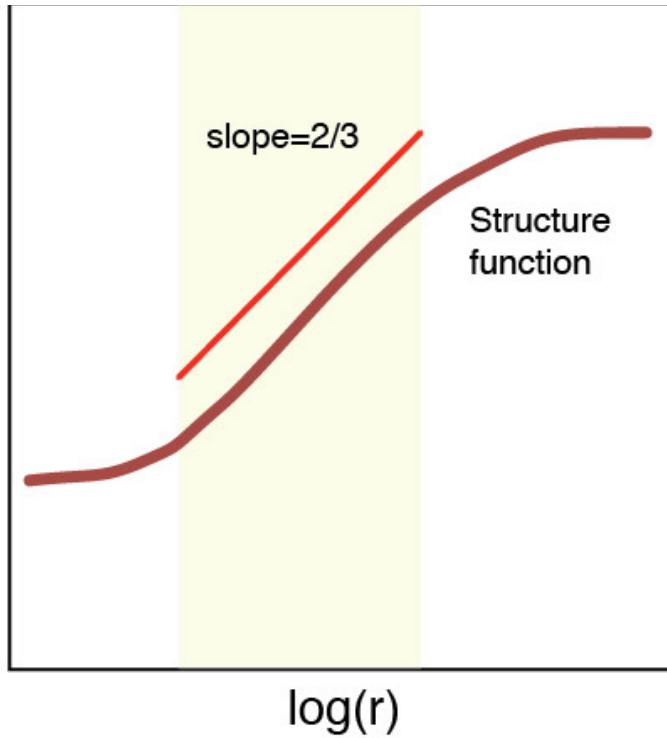
where  $u$  contains the spatiotemporal dynamics

**Analysing** large-scale data  
(Kolmogorov's Phenomenology Theory)

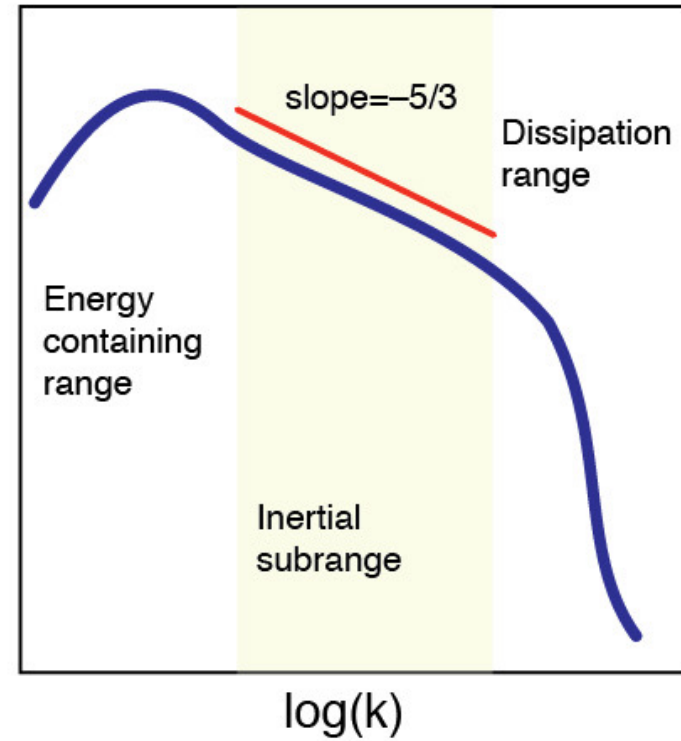


*Andrey Kolmogorov*  
(1903-1987)

$S(r)$

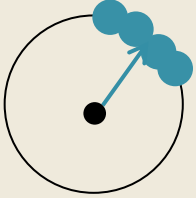


$\log(E)$

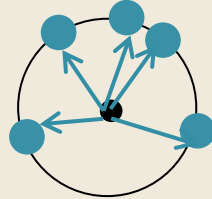


# Kolmogorov's turbulence laws

### Level of Synchronisation



$R \approx 1$

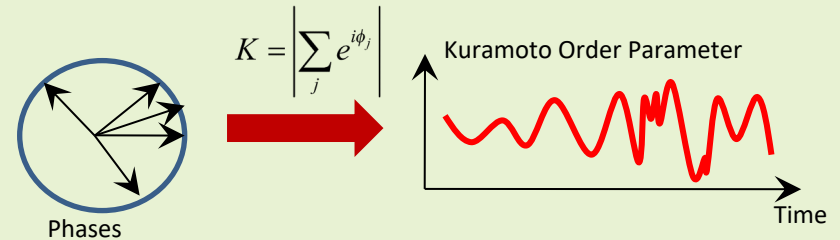


$R \approx 0$

$$R(t)e^{i\phi(t)} = \frac{1}{N} \sum_{n=1}^N e^{i\theta_n(t)}$$

Global Kuramoto Order Parameter

### Richness of the Dynamical Repertoire



Metastability

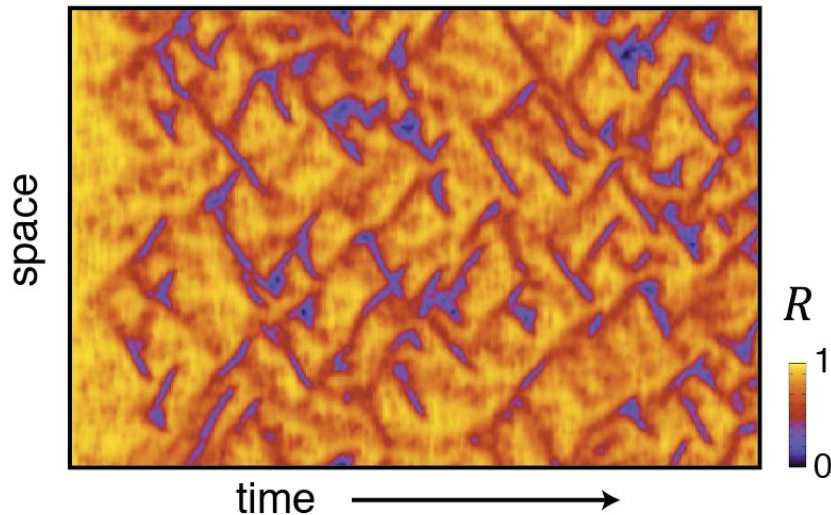
# Synchronisation, Kuramoto Order Parameter and Metastability

$$\partial_t X(x,t) = F[X(x,t)] + \hat{K} \int_{-\infty}^{\infty} dx' G(x-x') X(x',t) + \sqrt{\sigma} \boldsymbol{\eta}(x,t).$$

System of non-locally coupled Oscillators

$$R(x,t) \exp[i\Theta(x,t)] = \int_{-\infty}^{\infty} dx' G(x-x') \exp[i\phi(x',t)].$$

**Local Kuramoto Order Parameter**



$$G(x) = \frac{1}{2} \exp(-|x|),$$

Non-local Coupling

$$\langle R^2 \rangle - \langle R \rangle^2$$

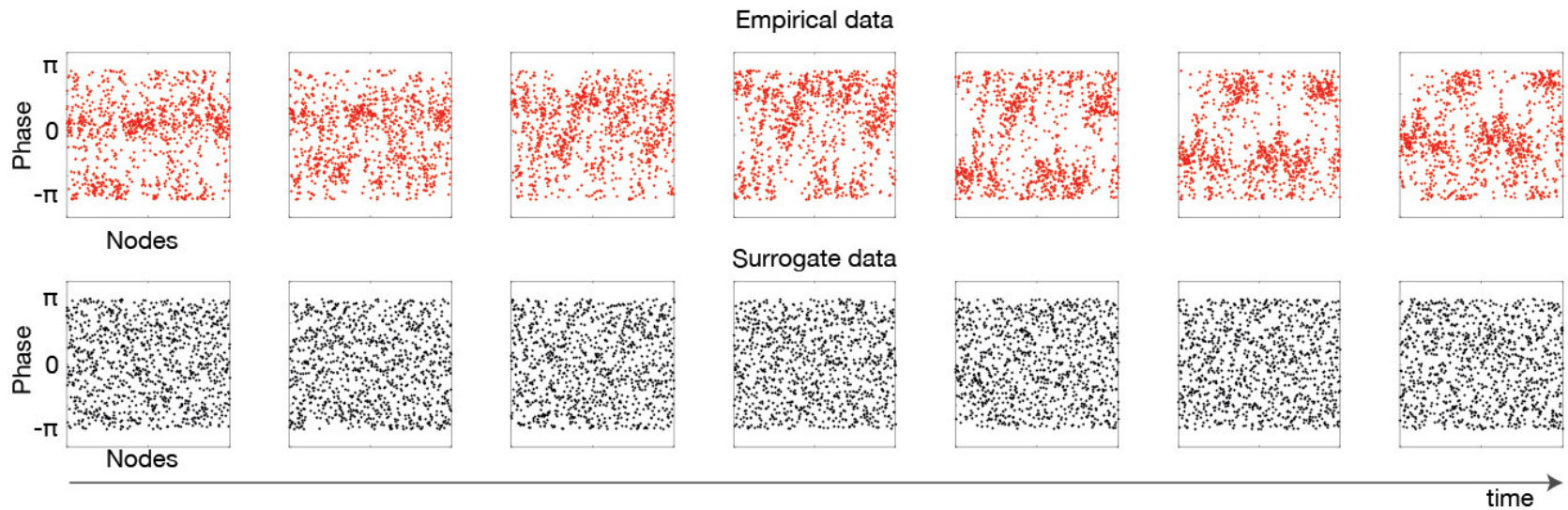
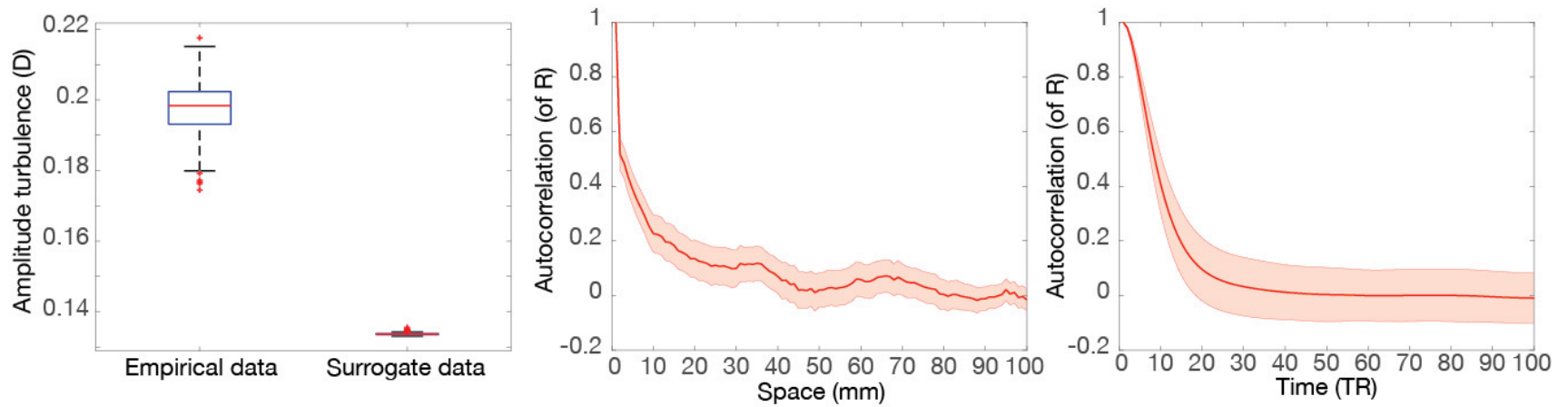
Local Metastability  
Order Parameter  
(Amplitude Turbulence)

$$v(x,t) = 2\partial_x \Theta(x,t)$$

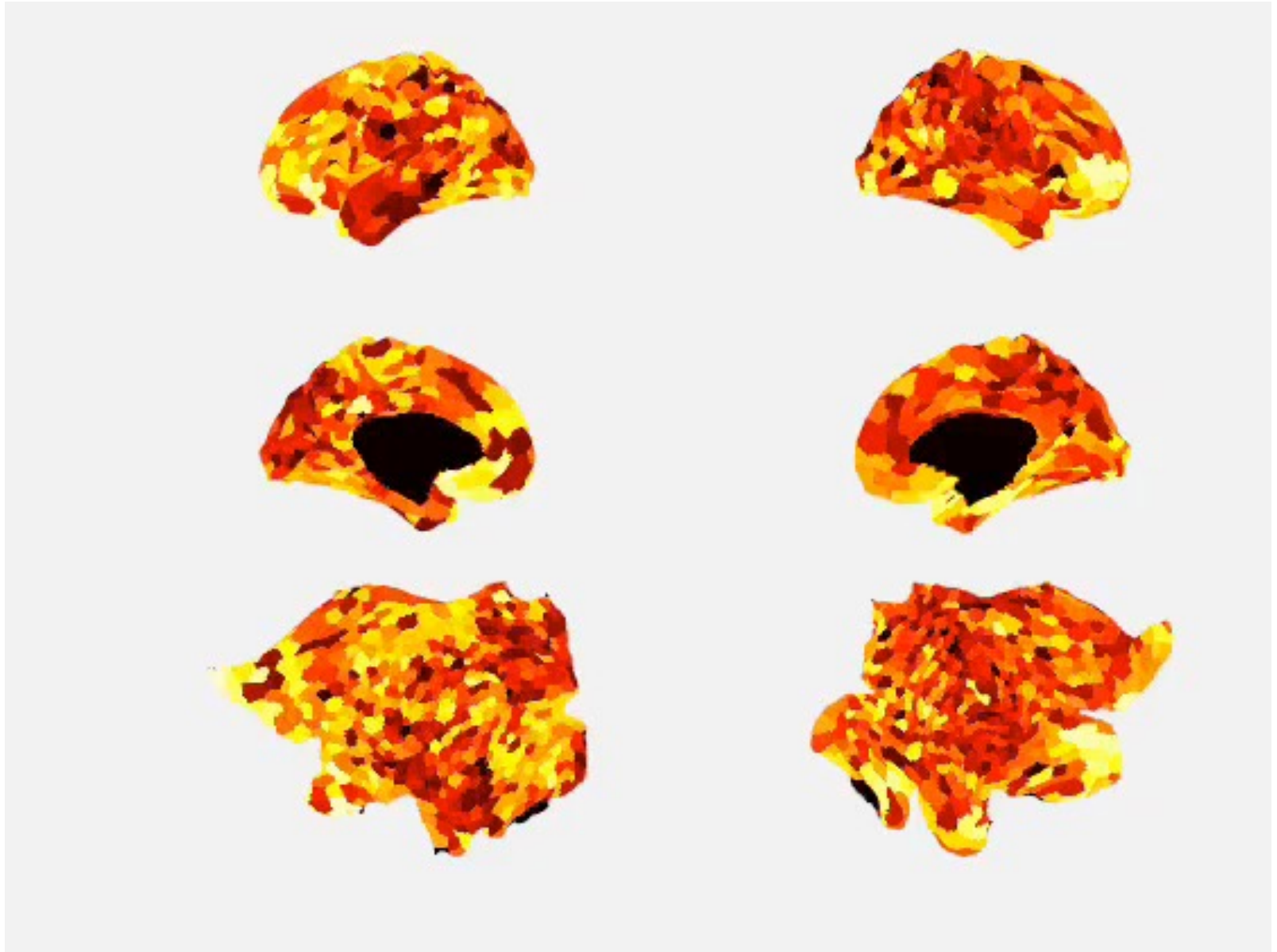
Phase Order Parameter  
(Phase Turbulence)

Amplitude Phase **Turbulence**





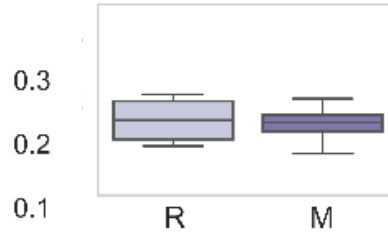
**Turbulence** in empirical data



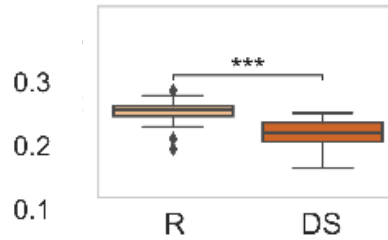
Turbulence **movies**

# Turbulence

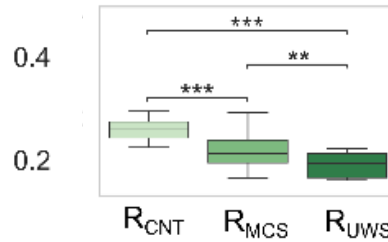
Meditation



Sleep

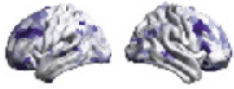


DoC

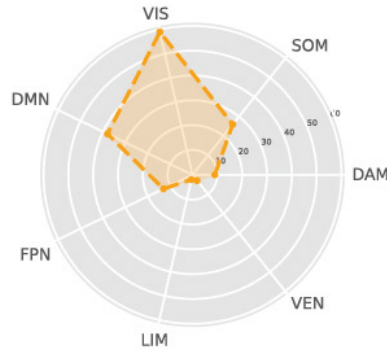


# Brain States

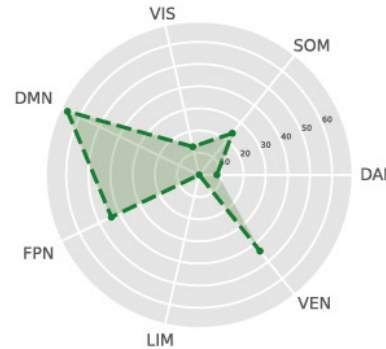
## Meditation



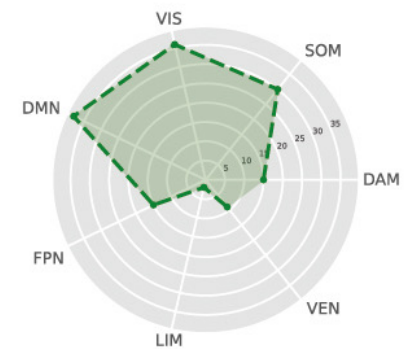
## Sleep



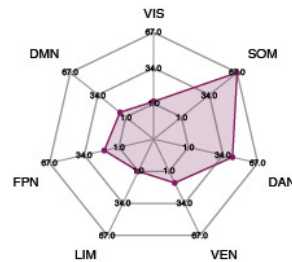
## DOC



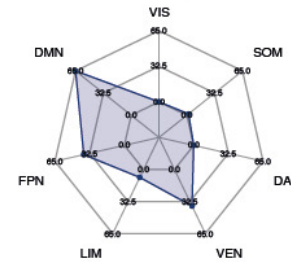
## MCS



## LSD



## Psilocybin



# Comparing fingerprints brain states



- **Hierarchy**: Brain causal interactions could be indirectly extracted through the arrow of time
- **Arrow of time** significantly different in different brain states
- **Arrow of time => Non-equilibrium => Turbulence**
- **Turbulence** is the backbone of efficient information processing
- **Turbulence** as a signature of **brain states**

## Conclusion

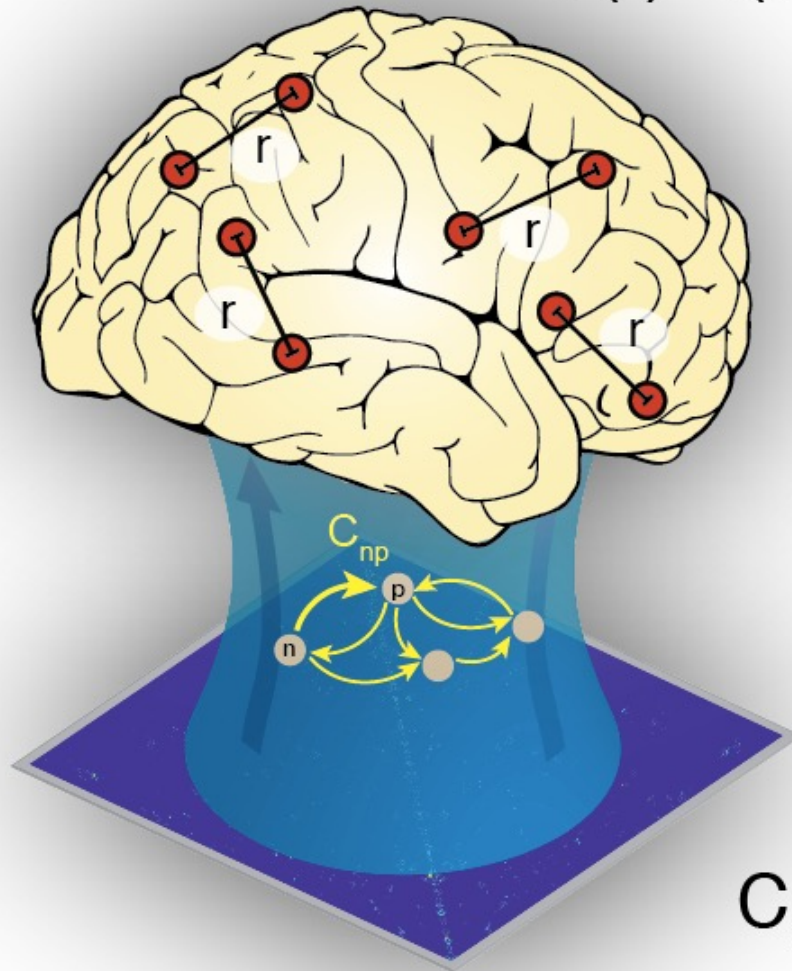


**Thank You**

$$S(r) = \langle (u(\bar{x}+r) - u(\bar{x}))^2 \rangle$$



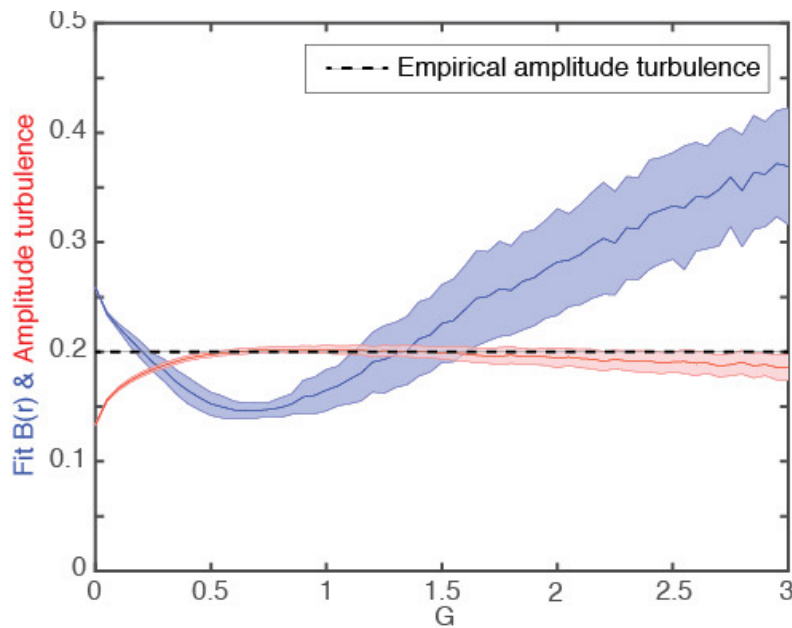
Structure  
function



Whole-brain  
model

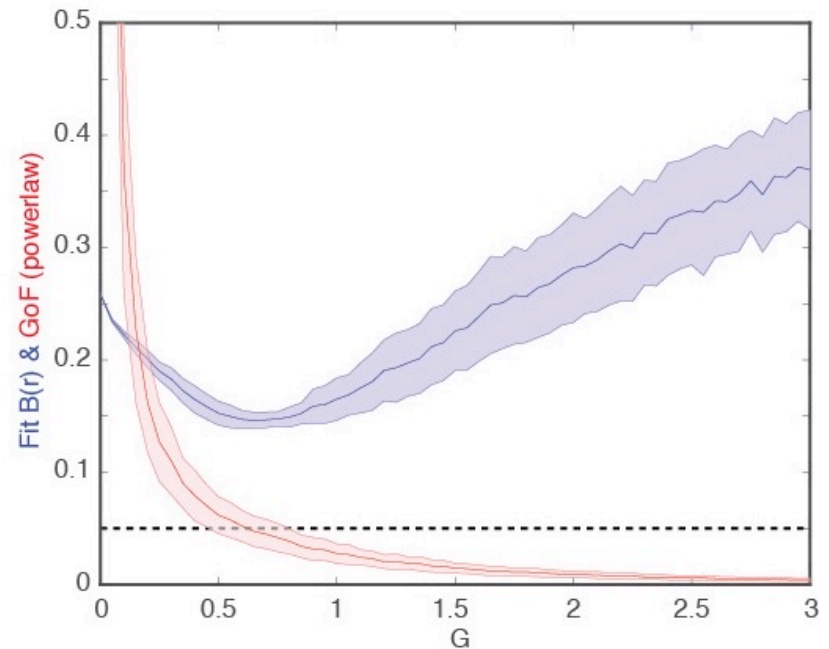
$$C_{np} = Ge^{-\lambda(r(n,p))}$$

Whole-brain **modelling**

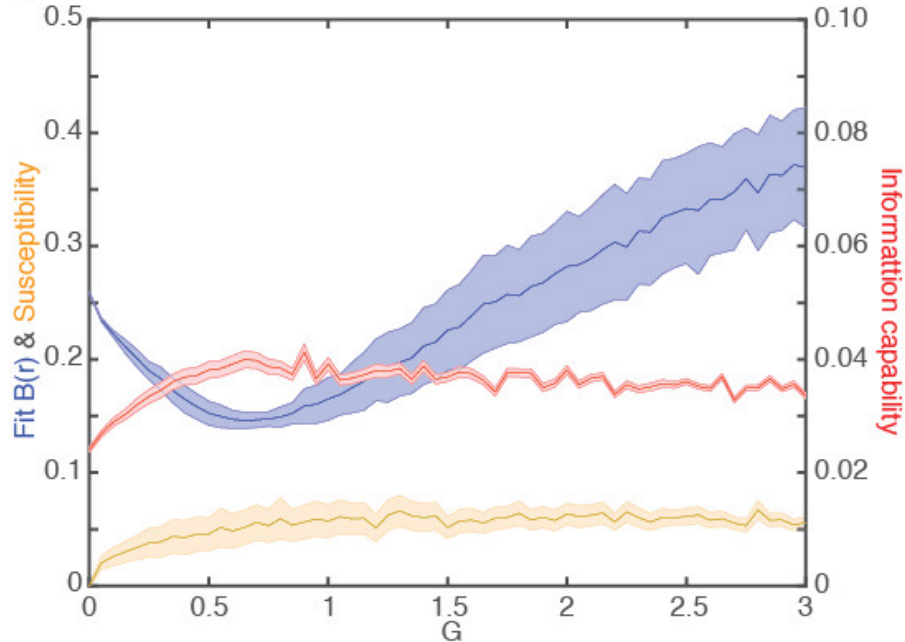


GoF of **Power Law**  
(Kolmogorov Correlation)  
Information Cascade

**Amplitude Turbulence**  
(STD of Locally Weighted  
Kuramoto Order  
Parameter)

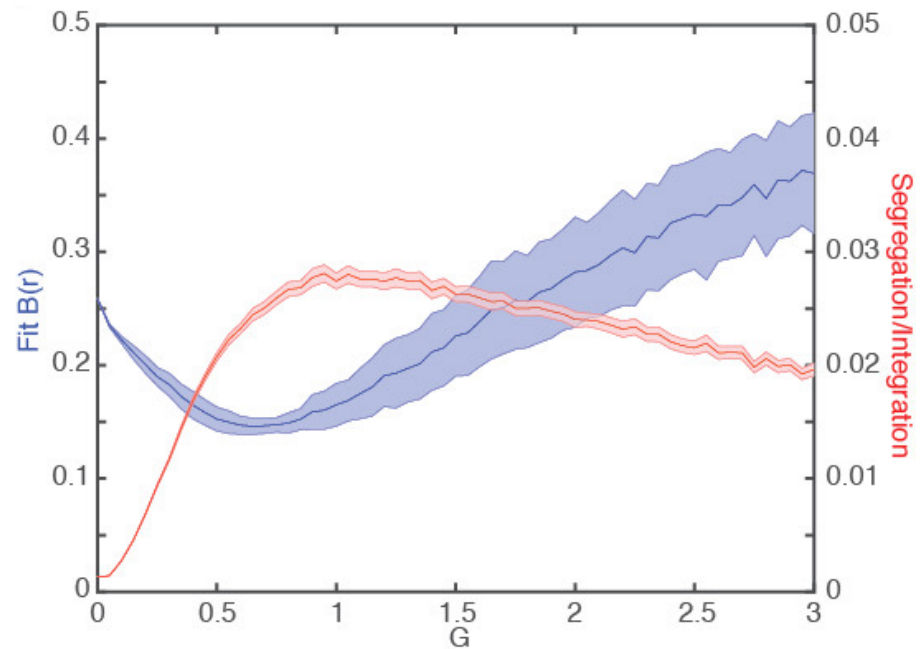


**Turbulence** in whole-brain



## Information Capability & Susceptibility

## Segregation/Integration



Information **processing** capabilities