

The Thermodynamics of Mind

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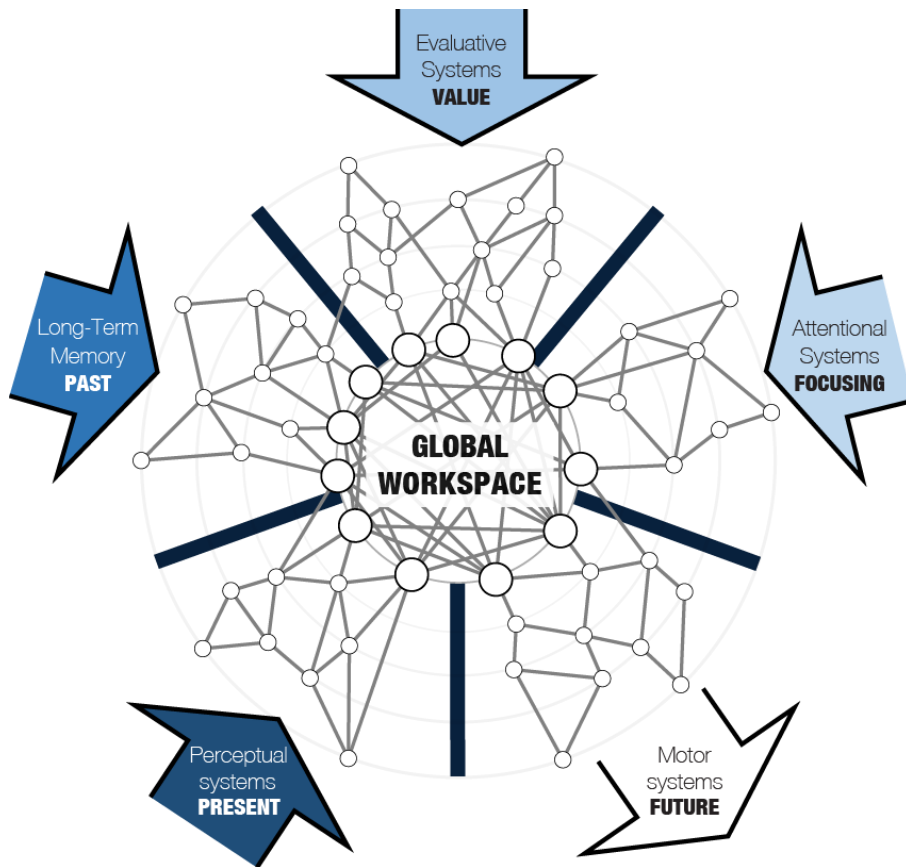
ICREA



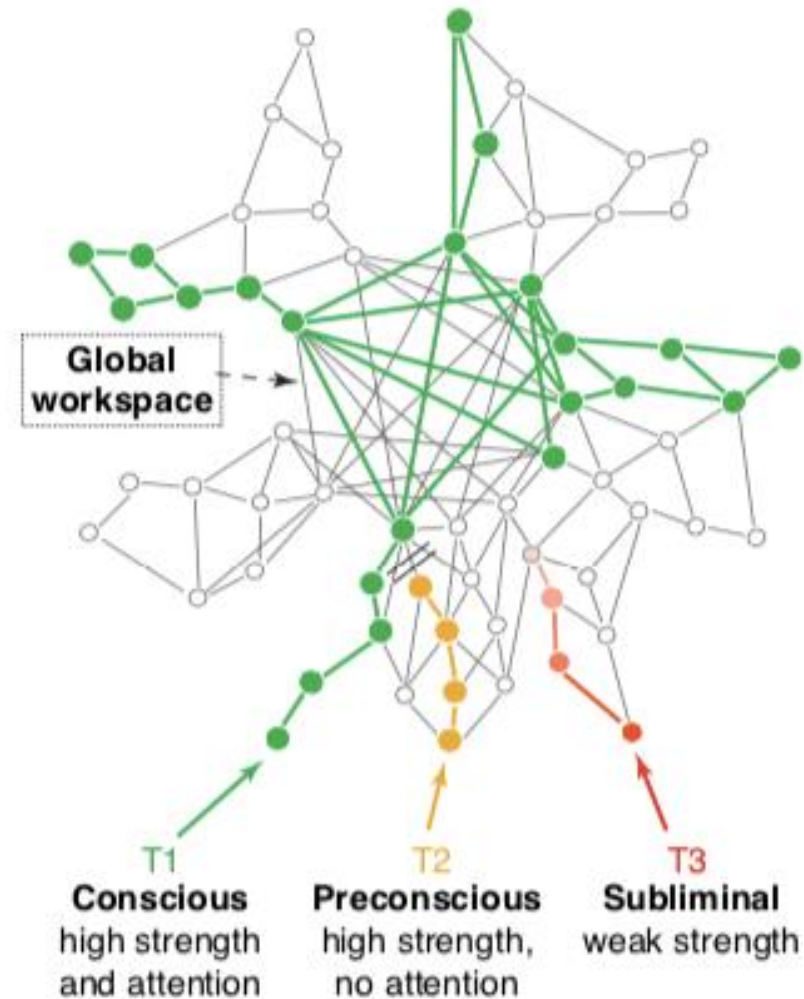
- **Hierarchy in brain dynamics**
- **Hierarchy -> functional interaction**
 - > **breaking the detailed balance**
- **Capturing breaking detailed balance (hierarchy) by Thermodynamics of Mind: The arrow of time in brain signals**
(Non-reversibility – Non-equilibrium – Hierarchy)
- **Modelling Non-reversibility (Generative Effective Connectivity)**

Overview

Defining Global Workspace



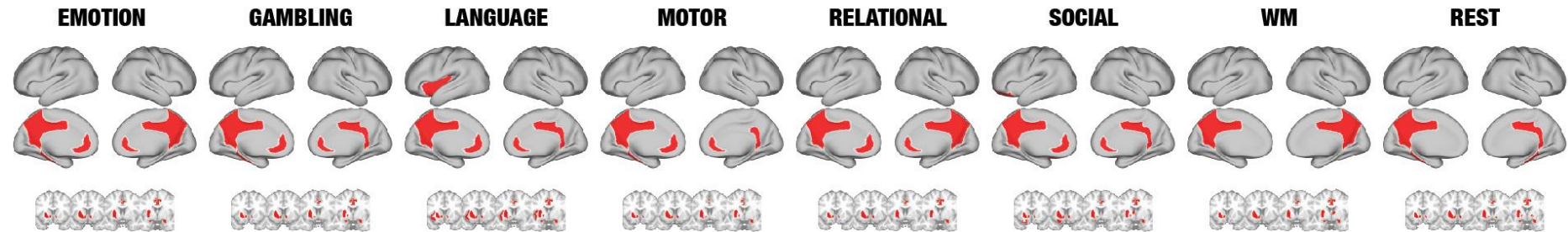
Perceptual systems (PRESENT)
Long-term memory (PAST)
Evaluative systems (VALUE)
Attentional systems (FOCUSING)



Discovering Global Workspace regions

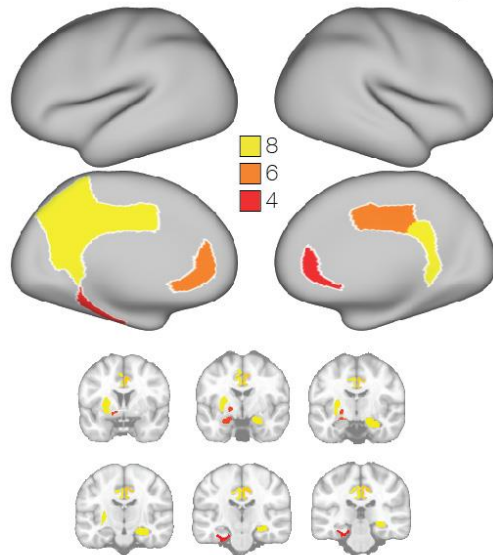
A

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

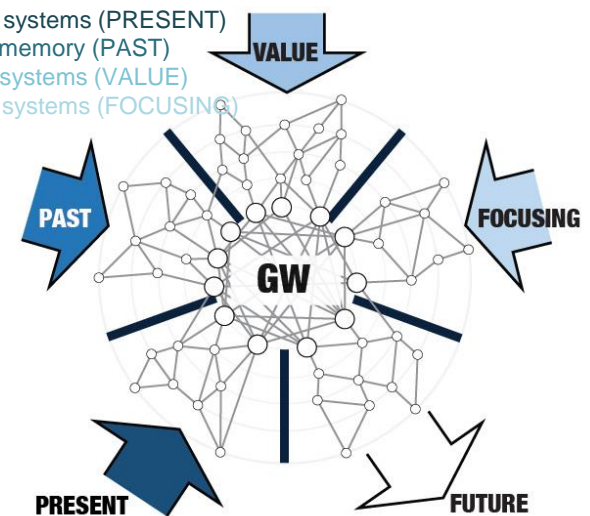
Further regions, threshold 4 FRICs:

left globus pallidus internus
left amygdala
left parahippocampal

C

INTEGRATION

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

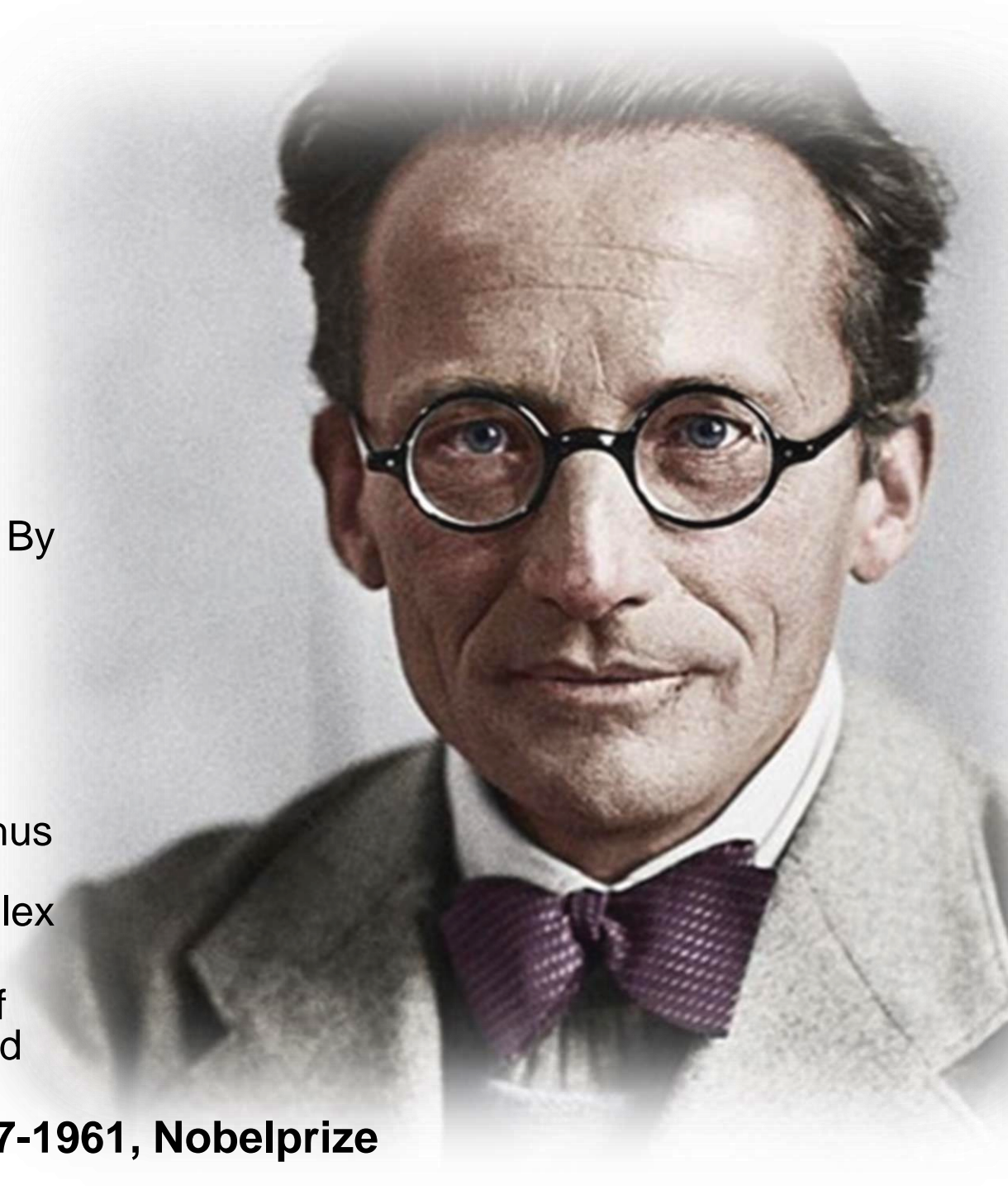


Thermodynamics of Mind (Model-free)

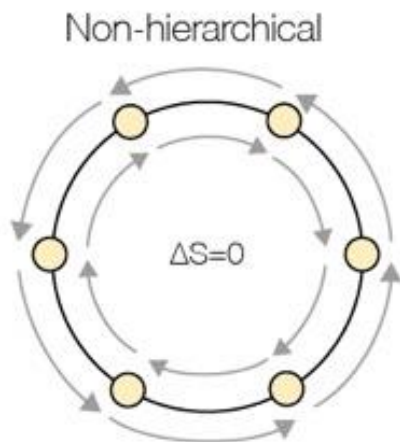
Arrow of time in Non- Equilibrium

- “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)



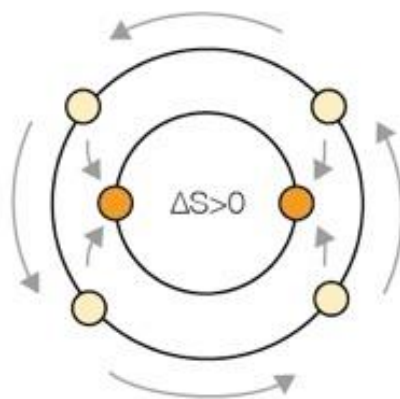
Hierarchy and breaking of detailed balance



Reversible



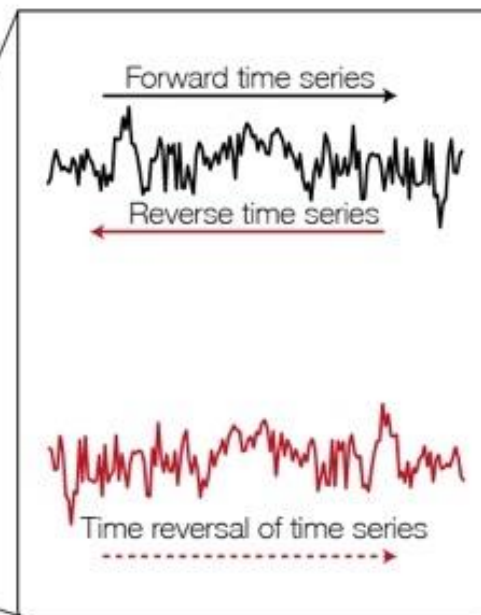
Hierarchical



Non-reversible



Arrow of time

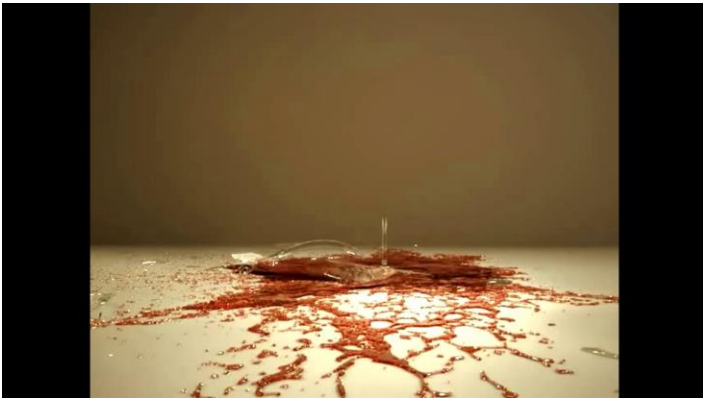


Non-reversible

Forward

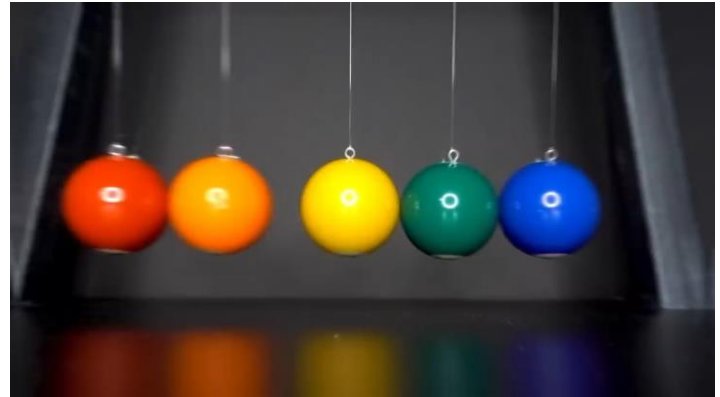


Time-reversal of backward trajectory



Reversible

Forward



Time-reversal of backward trajectory



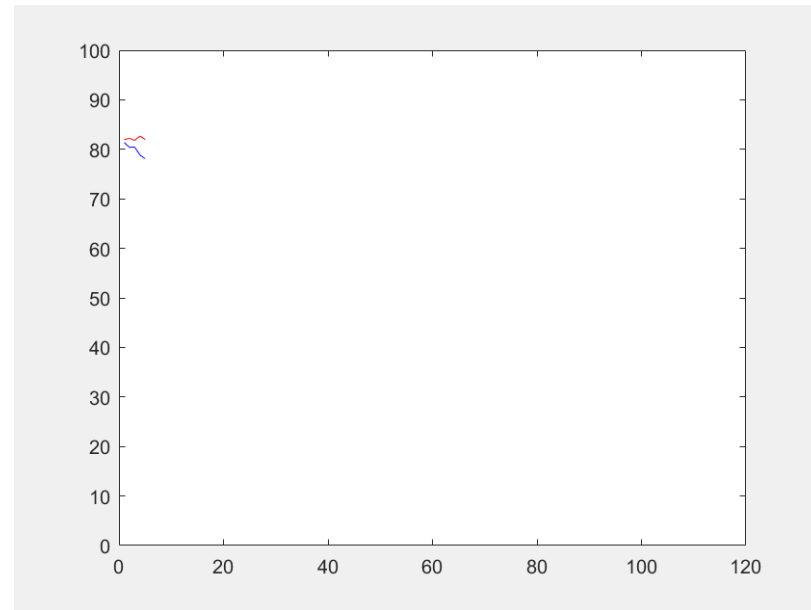
Arrow of time in physics

- 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



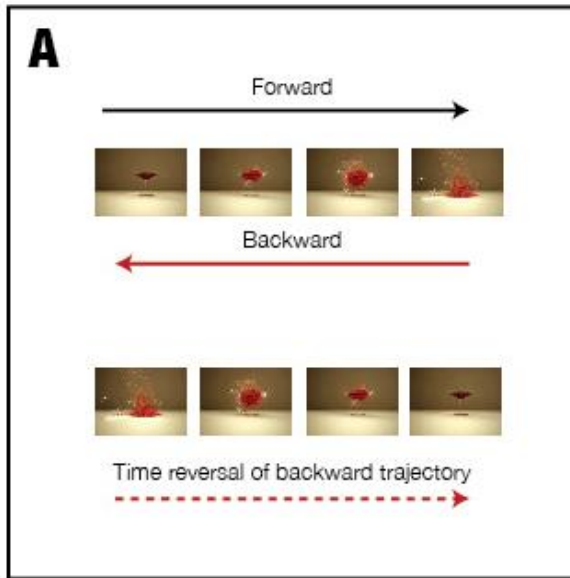
When we are shown a movie of a **microscopic** process, we **cannot** typically guess easily the direction

Seif ... & Jarzynski et al 2021 Nature Physics

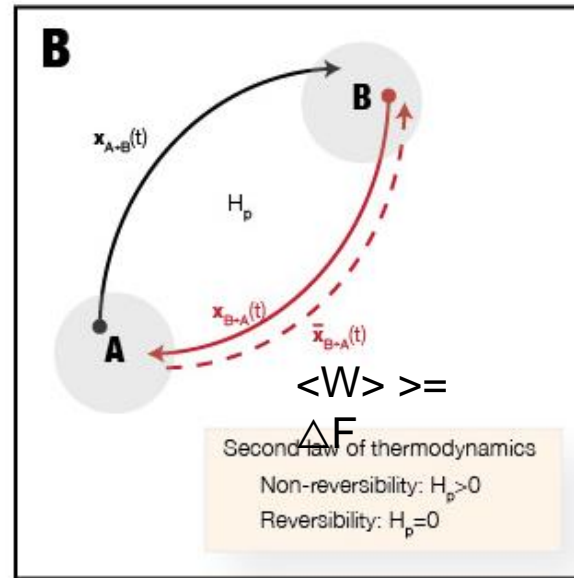
Thermodynamic arrow of time



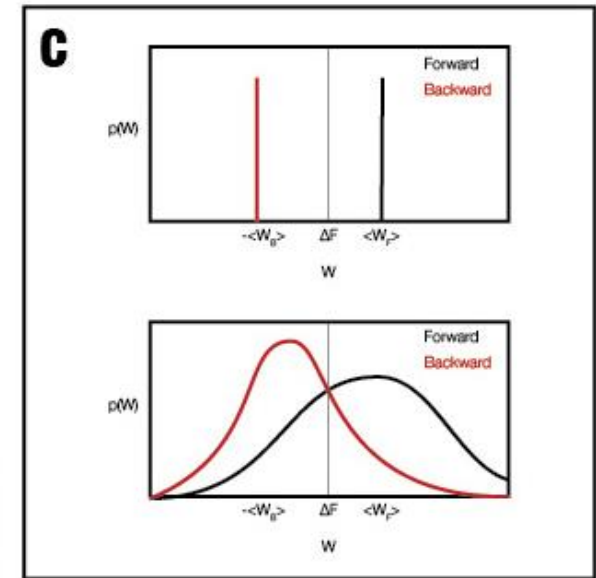
Rudolph **Clausius** Sadi **Carnot** Arthur **Eddington**



Arrow of time



Reversibility vs non-reversibility

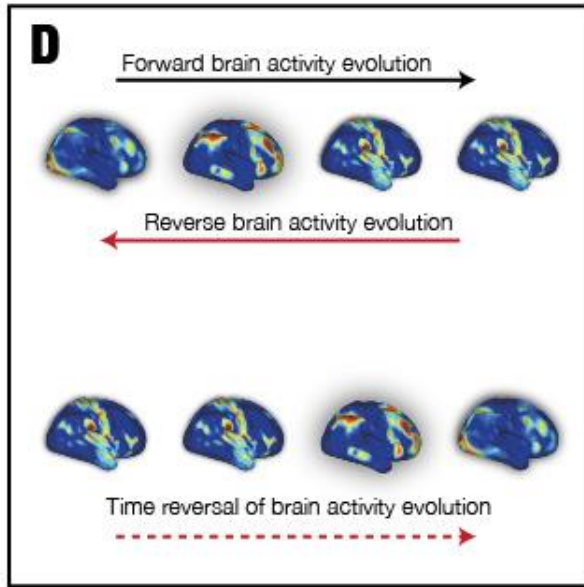


Fluctuations in work distribution

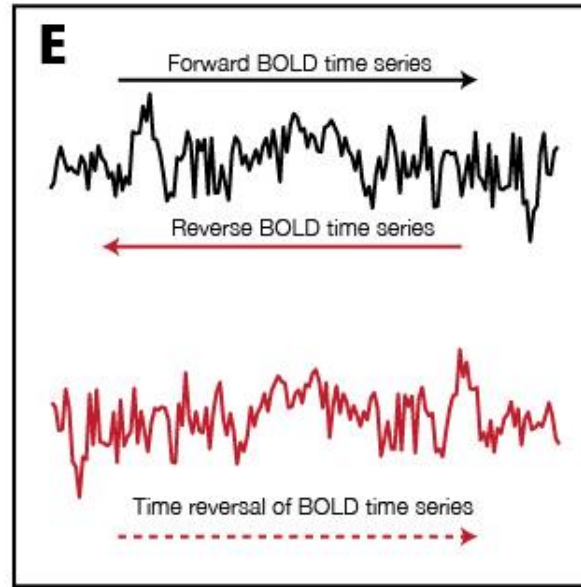
Arrow of time in physics

TENET

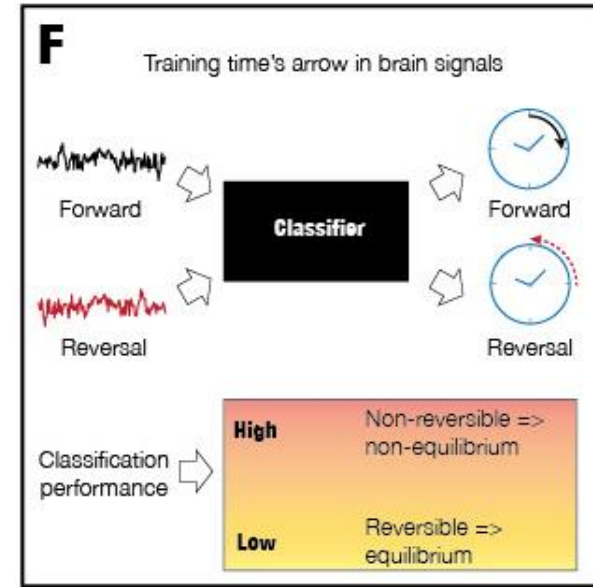
(Model-free machine learning
framework)



Brain activity

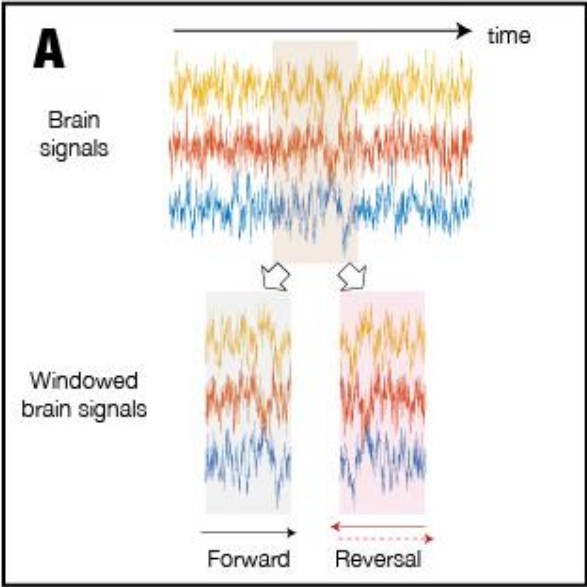


BOLD time series

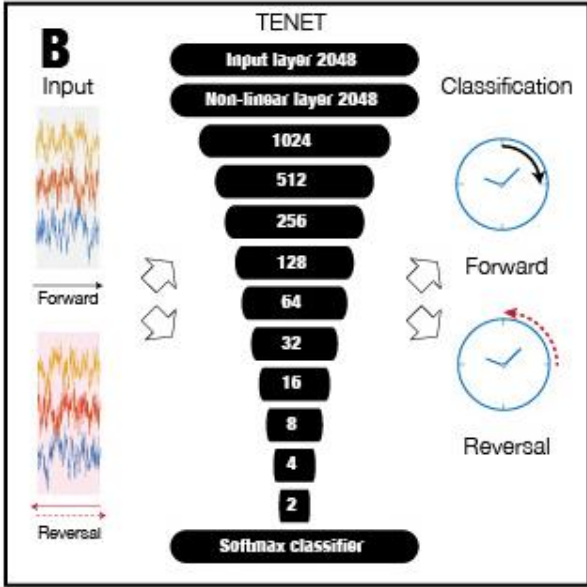


Classifying reversibility

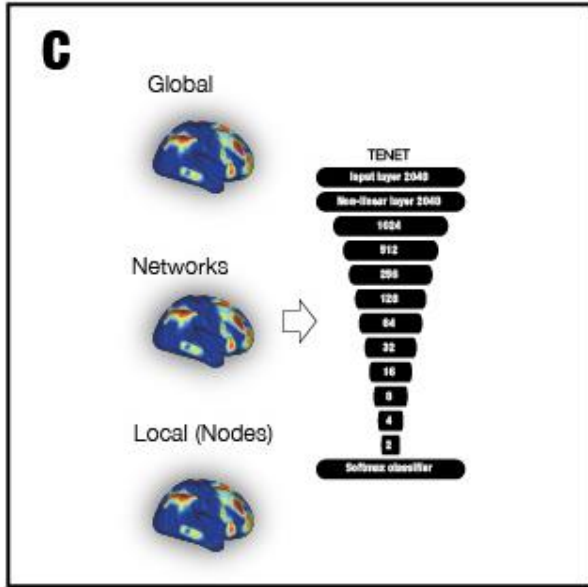
Arrow of time in the brain



Sliding Windows



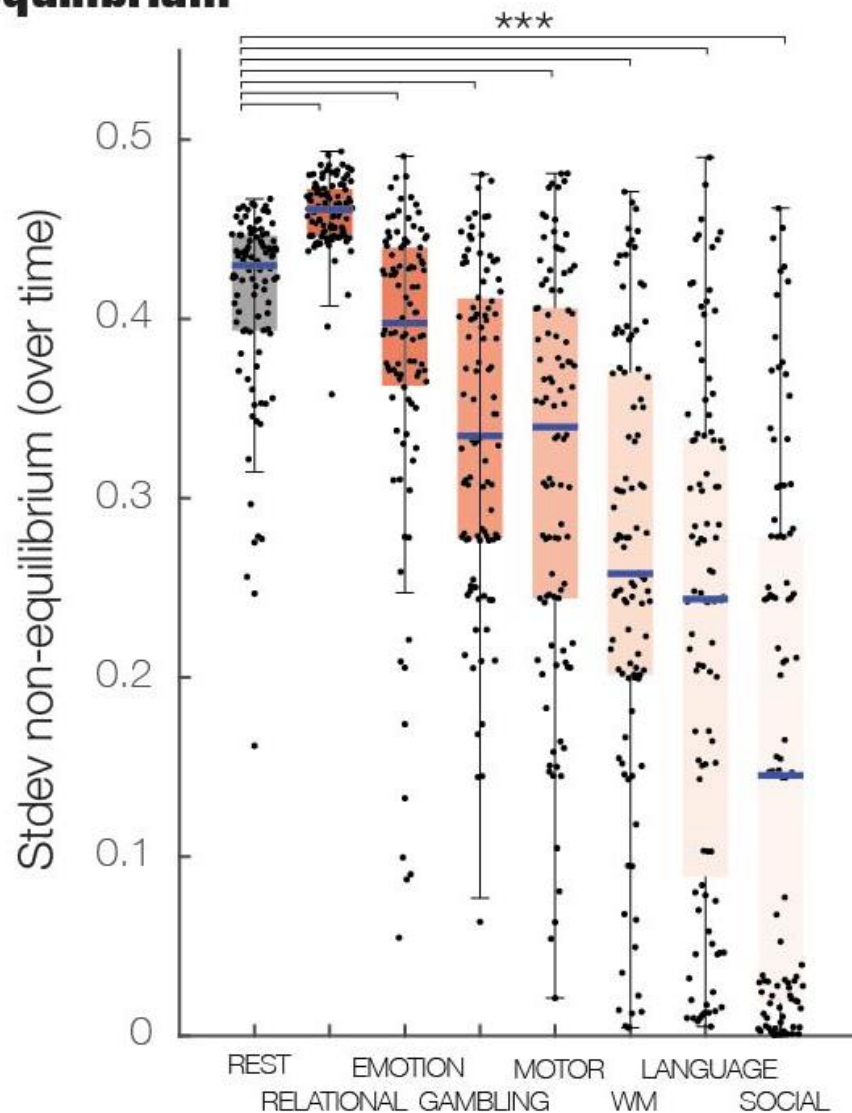
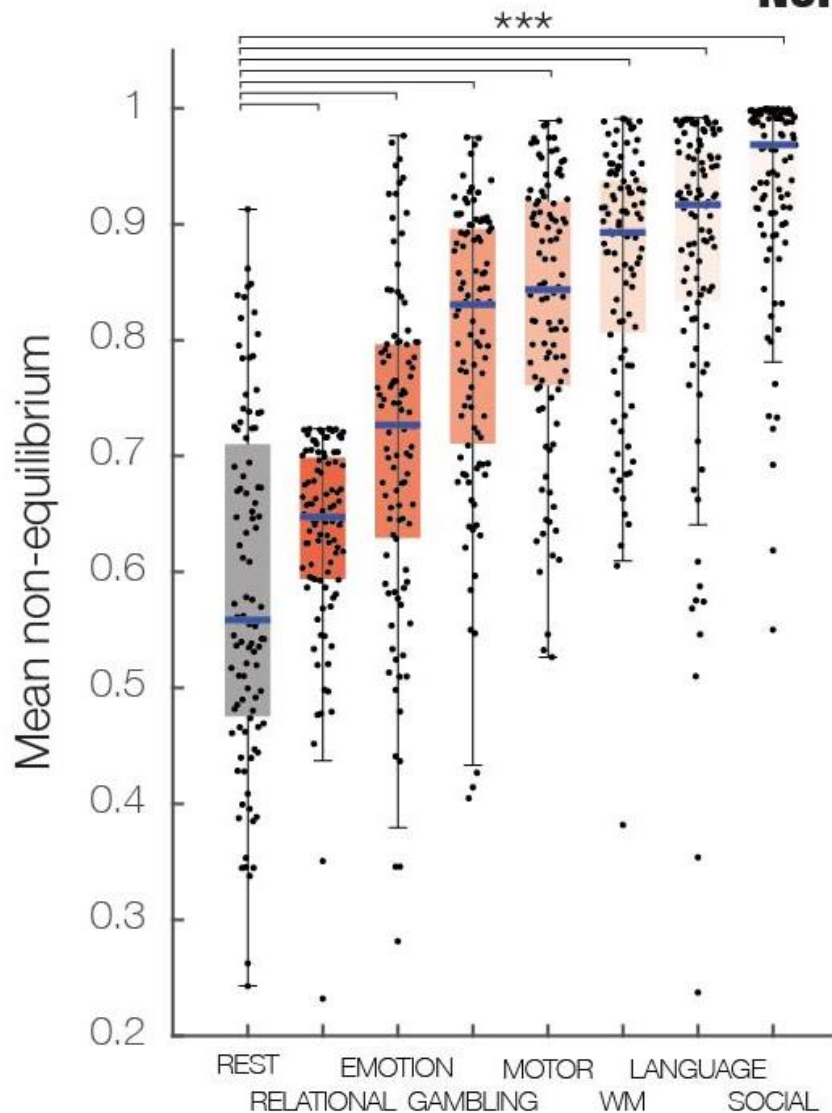
TENET: Deep learning



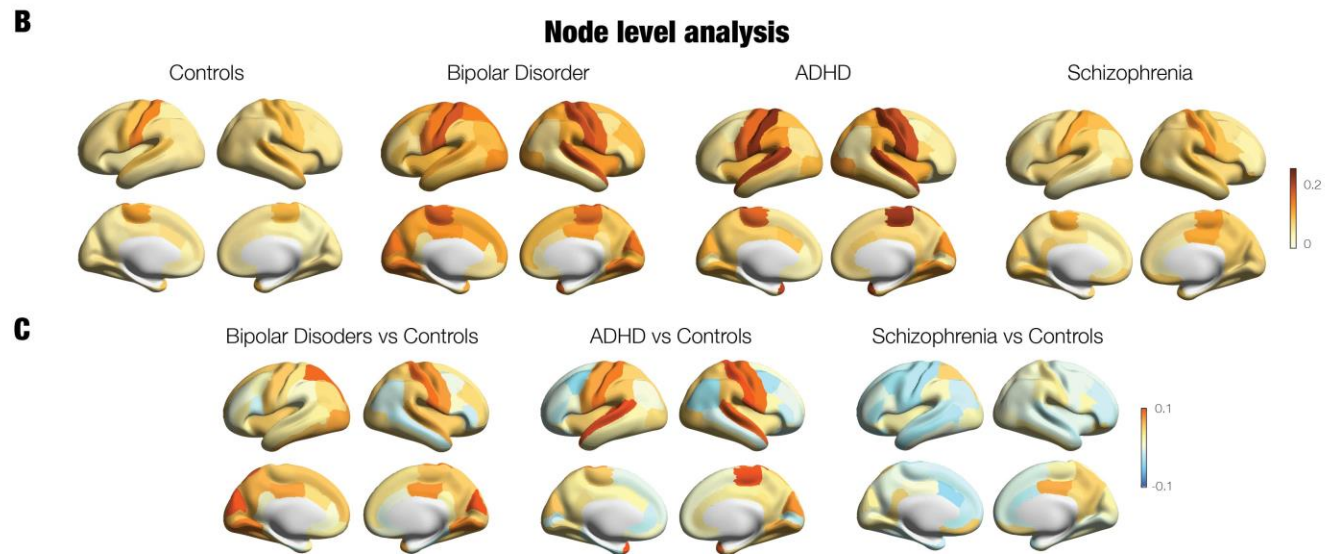
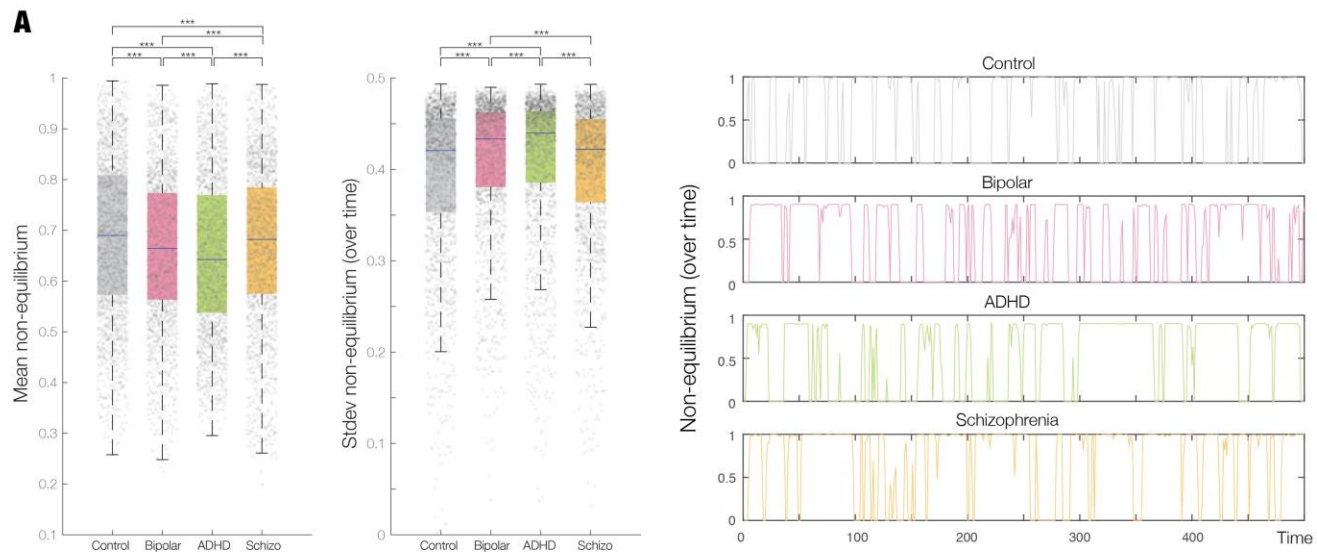
Global, nodes and networks

Temporal Evolution Net (TENET)

Non-equilibrium



Reversibility in HCP (Rest vs Task)

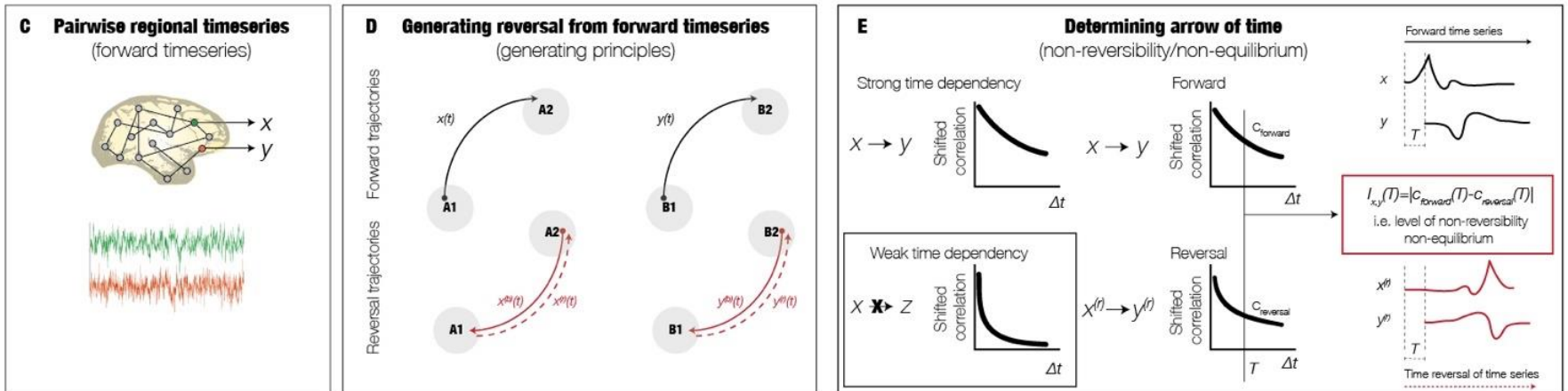


Neuropsychiatric disorders

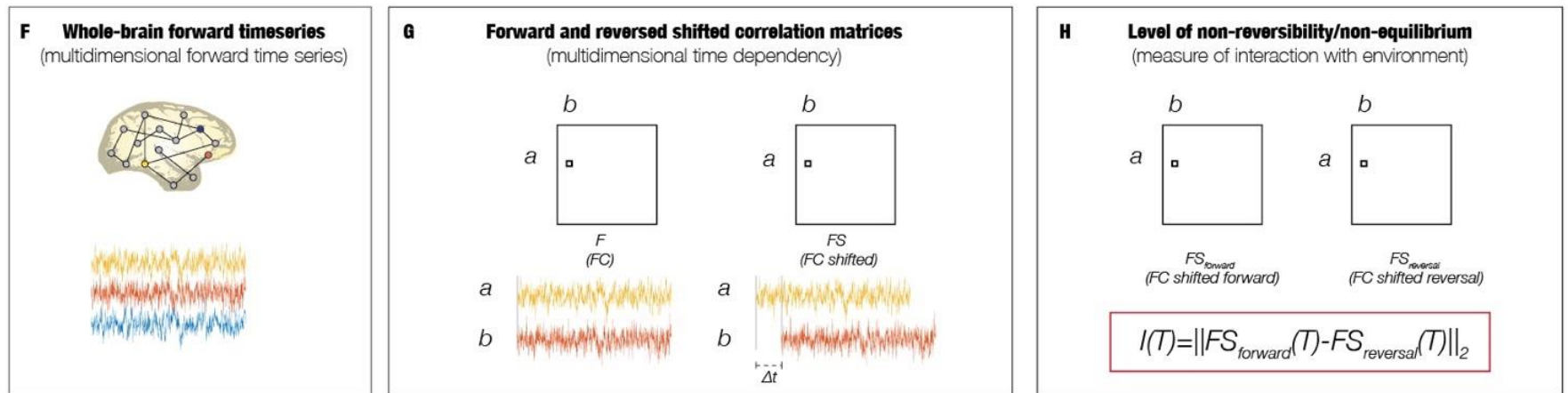
INSIDEOUT

(Model-free correlation framework)

Pairwise irreversibility of forward and reversal timeseries

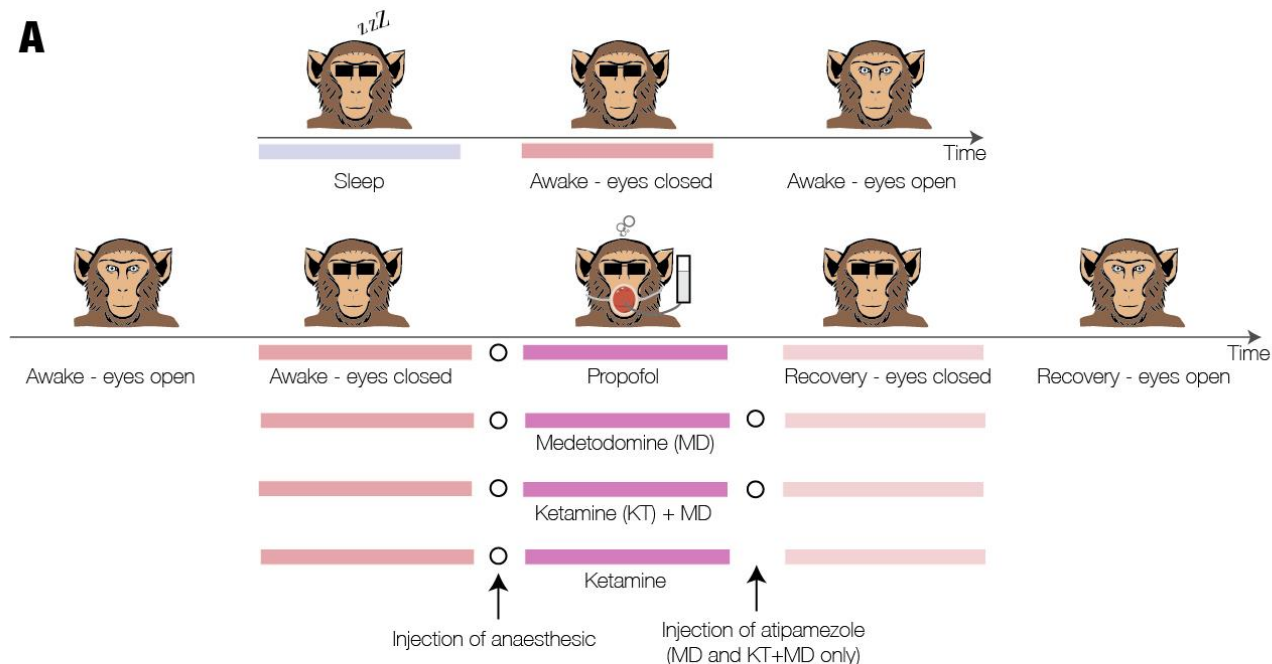
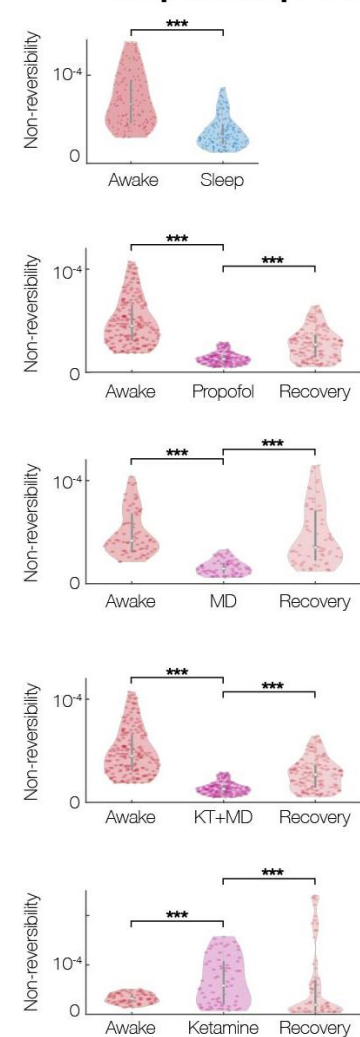
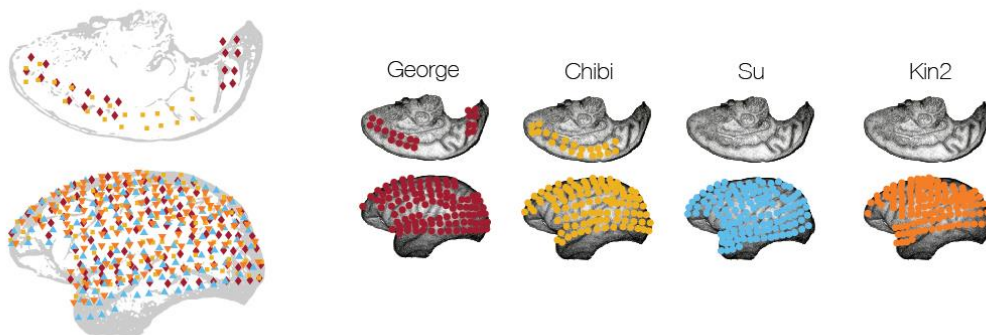


Whole-brain irreversibility of forward and reversal timeseries



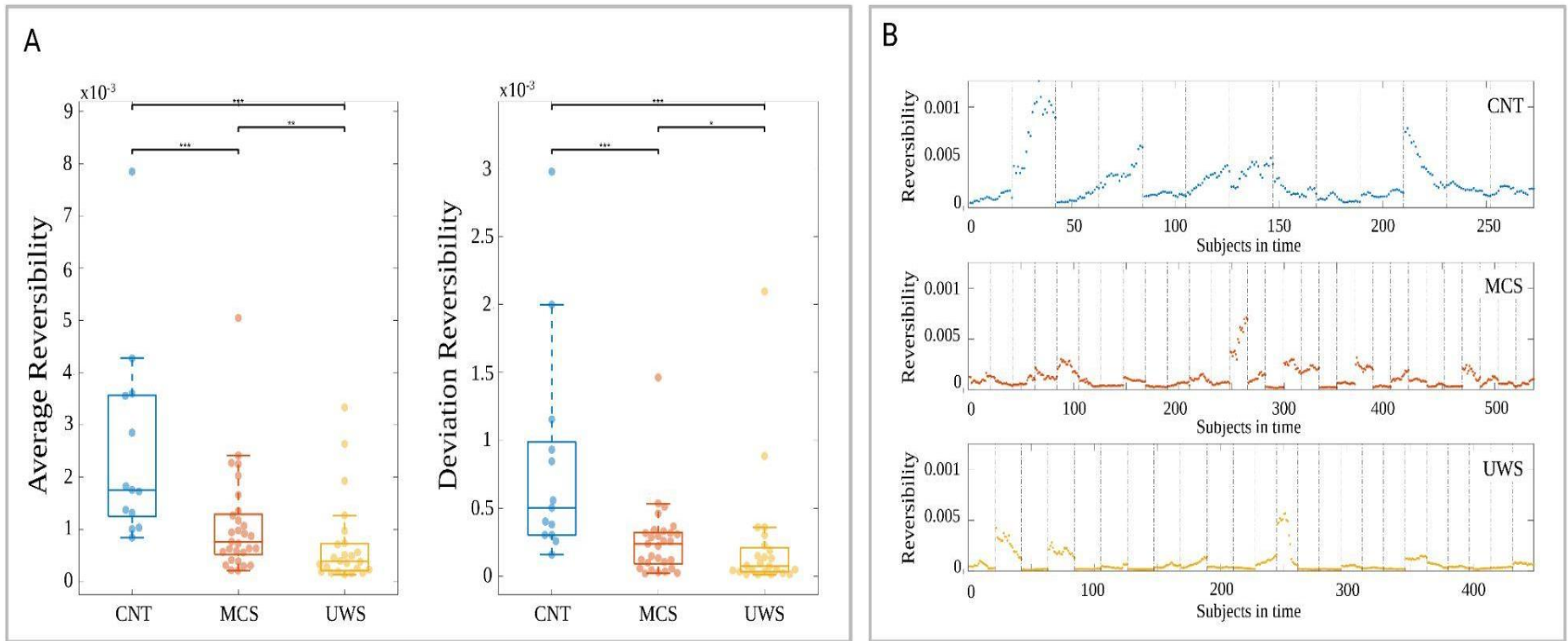
Deco, et al. (2022) *Nature Comm. Biology*

INSIDEOUT framework of reversibility

A**Group level comparison****B**Deco, et al. (2022) *Nature Comm. Biology*

ECOG data from brain states

Data: fMRI recordings; 13 CNT, 31 MCS and 24 UWS



García Guzman, et al. (2023) *Royal Society Interface Focus*

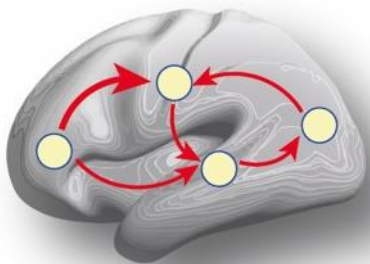
**INSIDEOUT framework of reversibility to fMRI
in DOC**

Thermodynamics of Mind

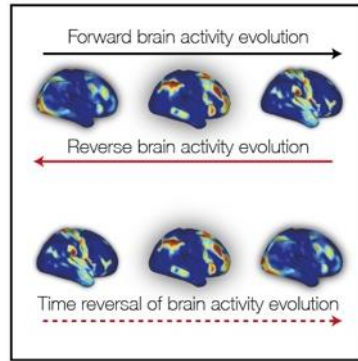
(Model-based: GEC framework)

B

Brain state information flow and hierarchy



Brain signals



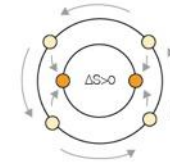
Detection of the arrow of time

Distinguishable

Non-distinguishable

Reversibility map of brain regions

Non-reversible

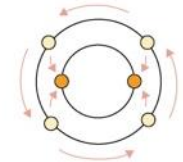


Fully reversible

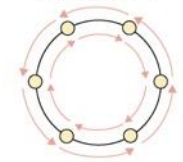


Inferring hierarchical interactions

Hierarchical

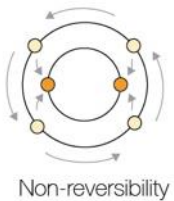


Non-hierarchical

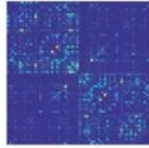
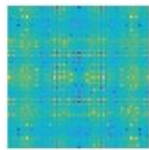


C

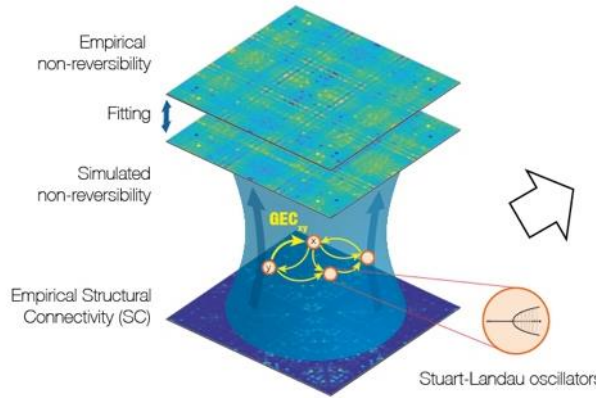
Model empirical inputs



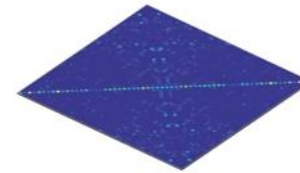
Structural connectivity



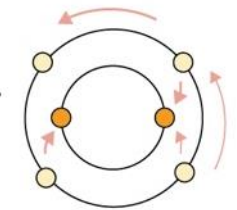
Generative whole-brain model



Generative Effective Connectivity (GEC)



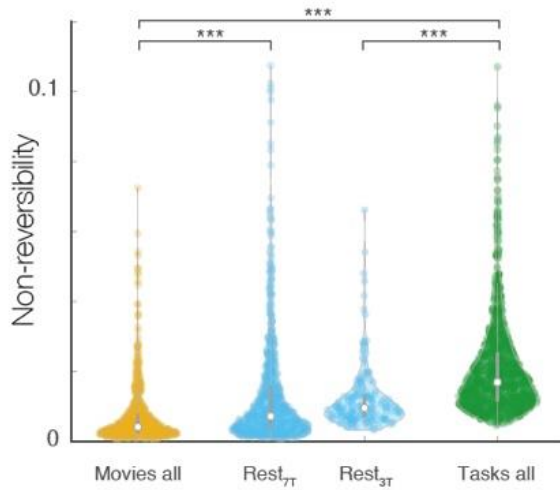
Generative hierarchy



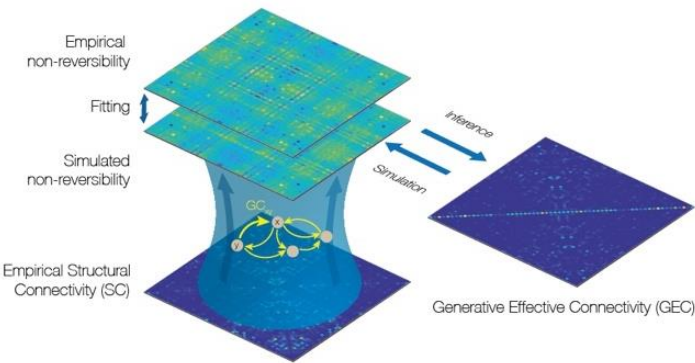
Kringelbach, Sanz, Tagliazuchi & Deco, Science Advances 2022

Thermodynamics of mind

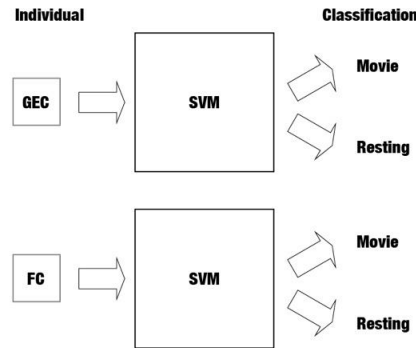
Movie, rest and tasks



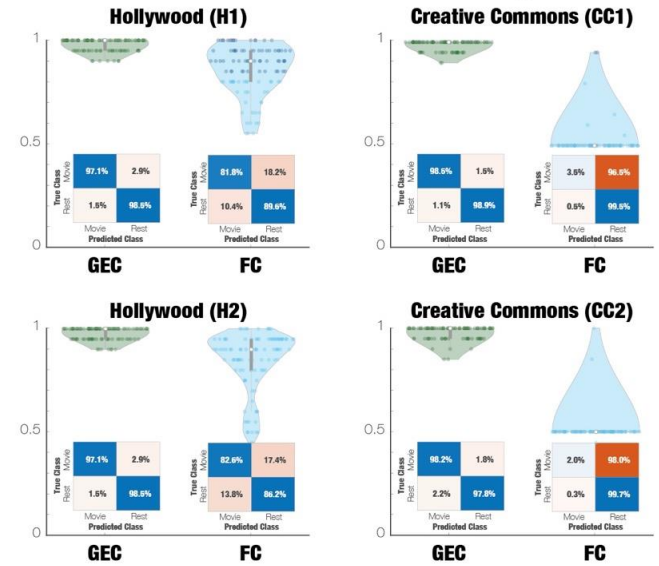
Generative whole-brain model



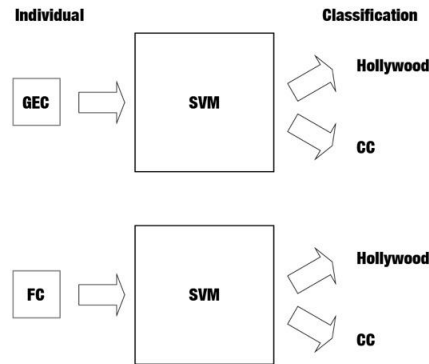
Classification procedure



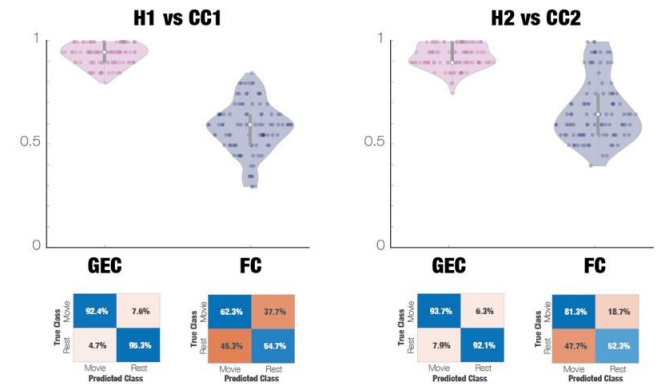
Classification Movies vs Resting



Classification procedure



Classification Hollywood vs CC

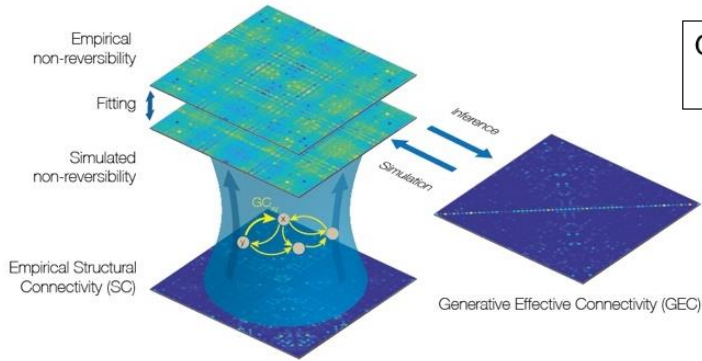


Kringelbach, Sanz, Tagliazuchi & Deco, Science Advances 2022

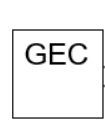
Effective Connectivity of Non-reversibility

E

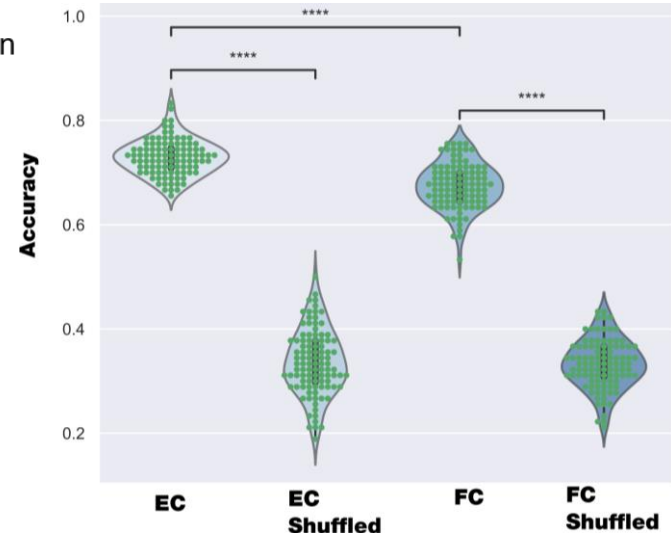
Generative whole-brain model



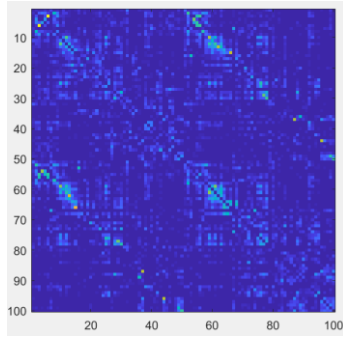
Individual



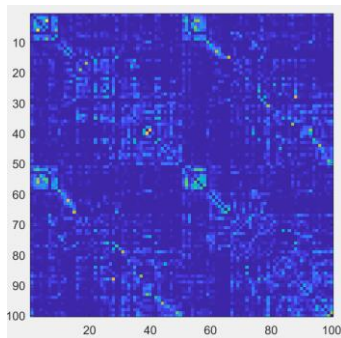
Classification



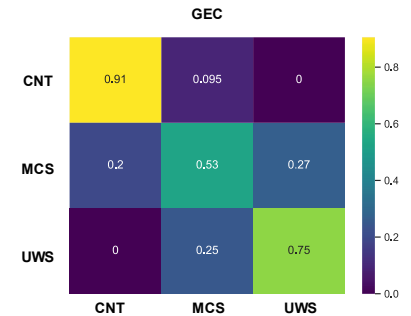
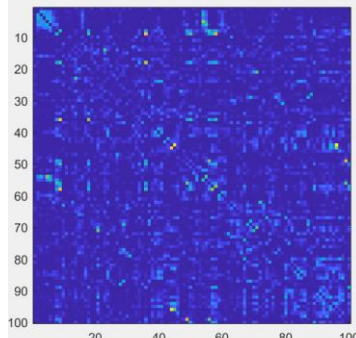
CNT



MCS



UWS

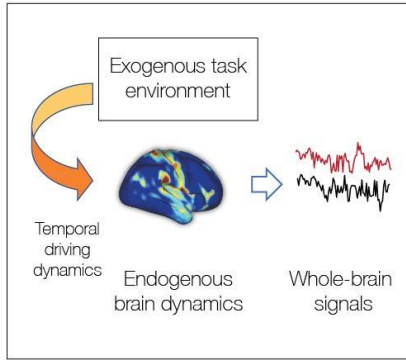


Effective Connectivity of Non-reversibility in DOC

Thermodynamics of Mind

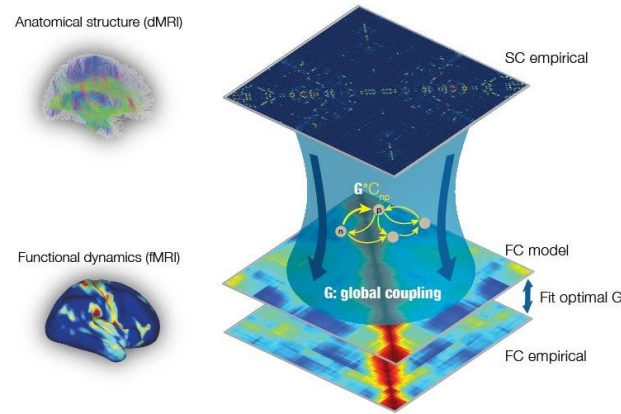
(Model-based: Production Entropy
framework)

A Extracting data in seven tasks and rest



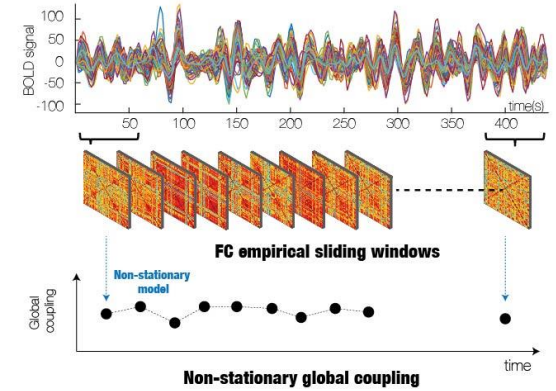
B

General whole-brain model of functional dynamics

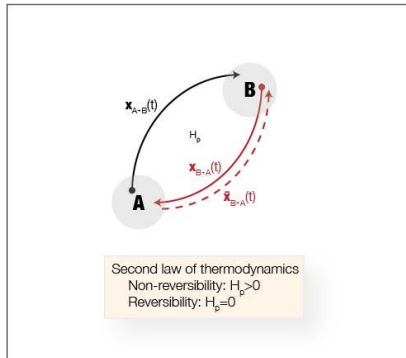


C

Fitting non-stationary whole-brain model

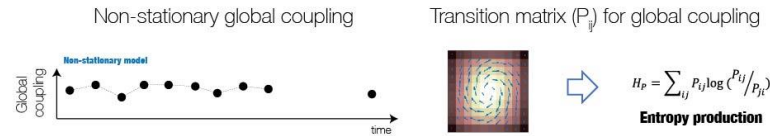


D Entropy production and reversibility



E

Estimation entropy production in generative space (each individual)



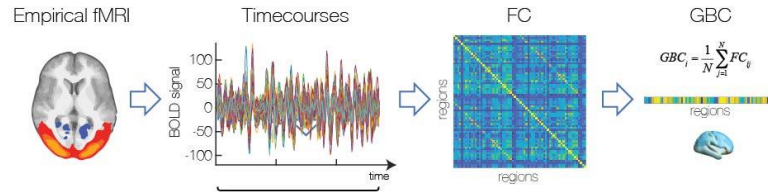
H

Identifying unifying drivers across all tasks



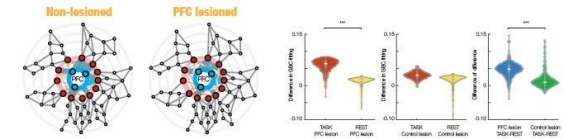
F

Estimation of GBC (each individual)



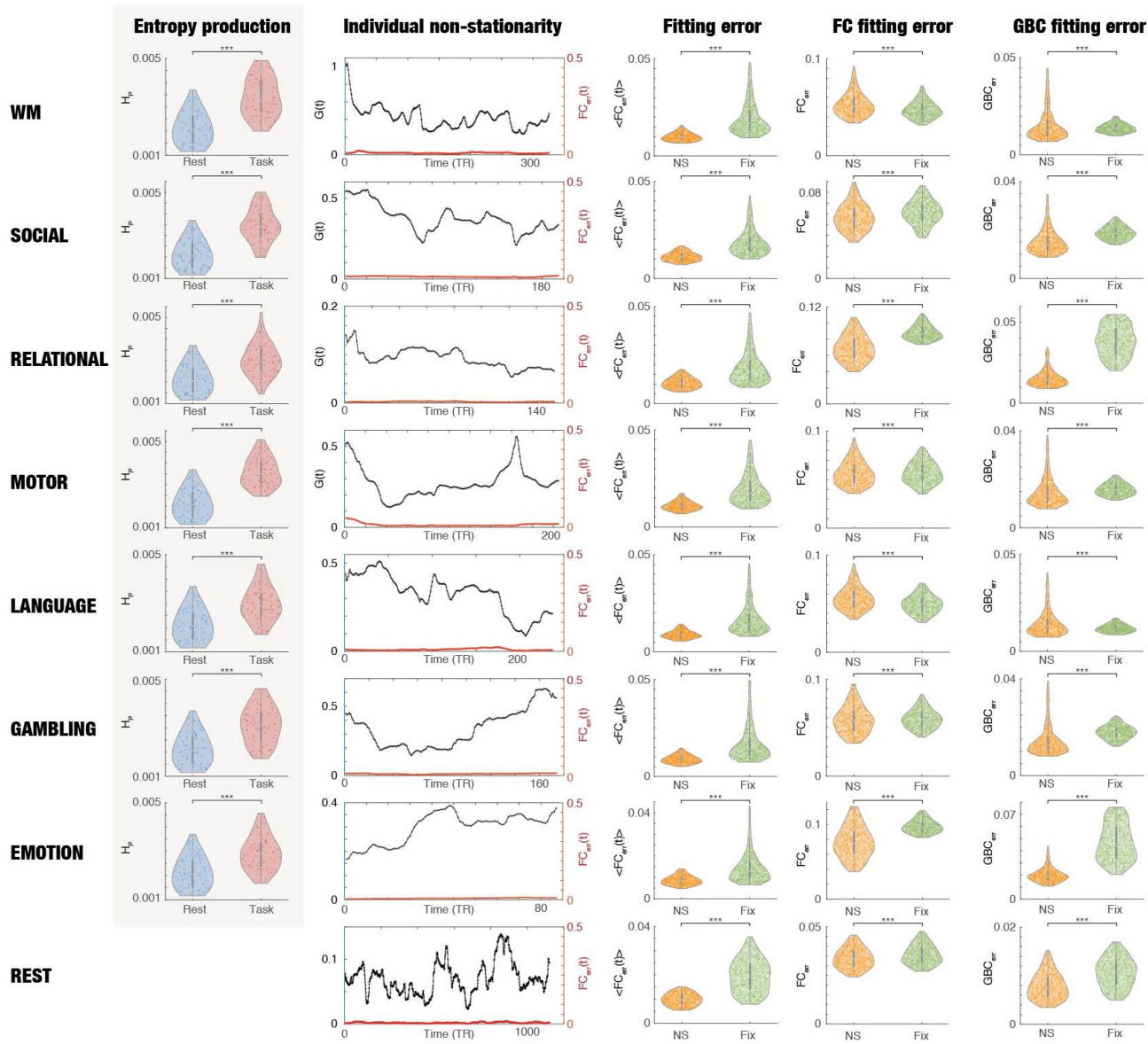
I

Causal mechanistic role of unifying drivers

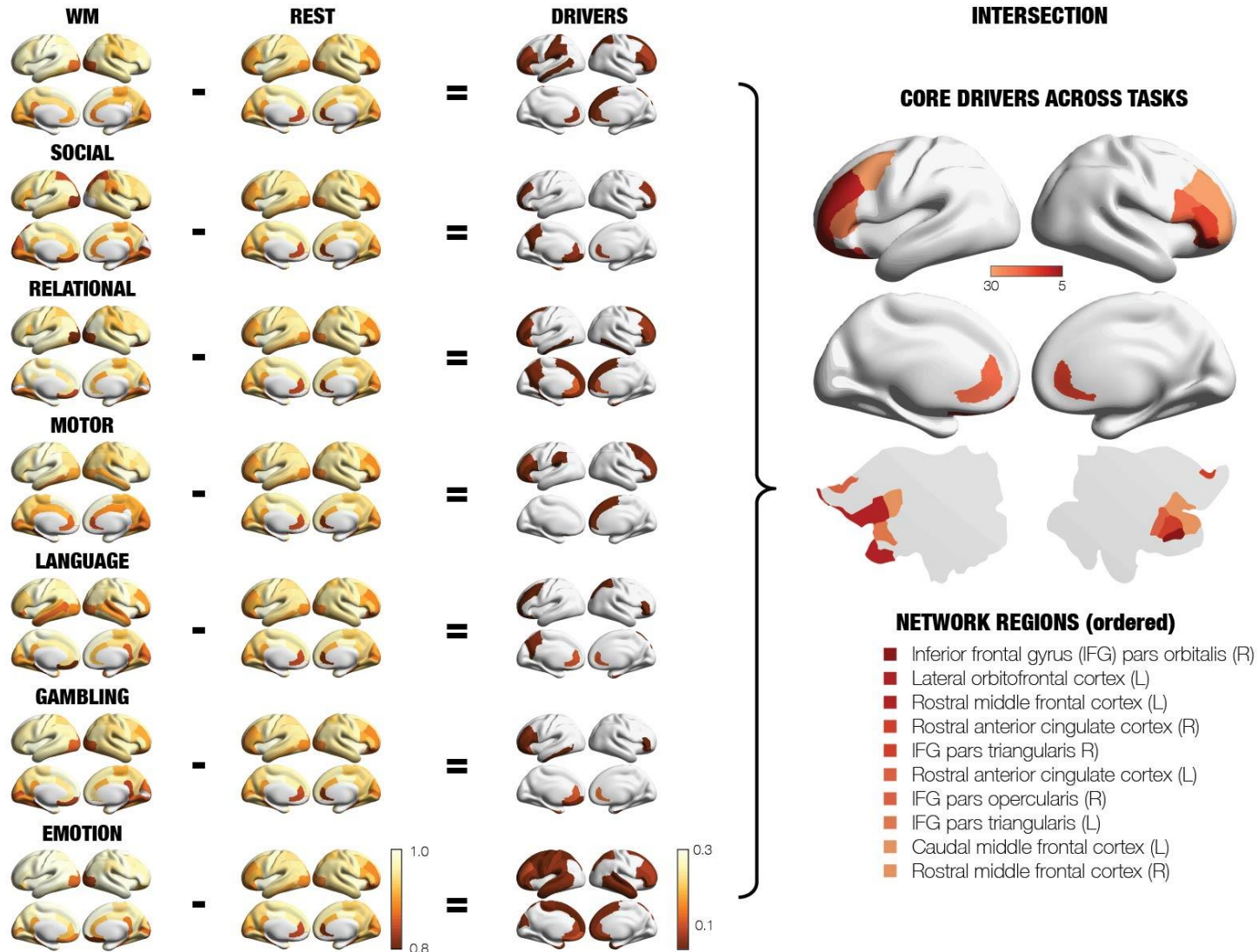


Deco ... & Kringelbach (2021) bioRxiv

Model-based entropy production



Model-based entropy production



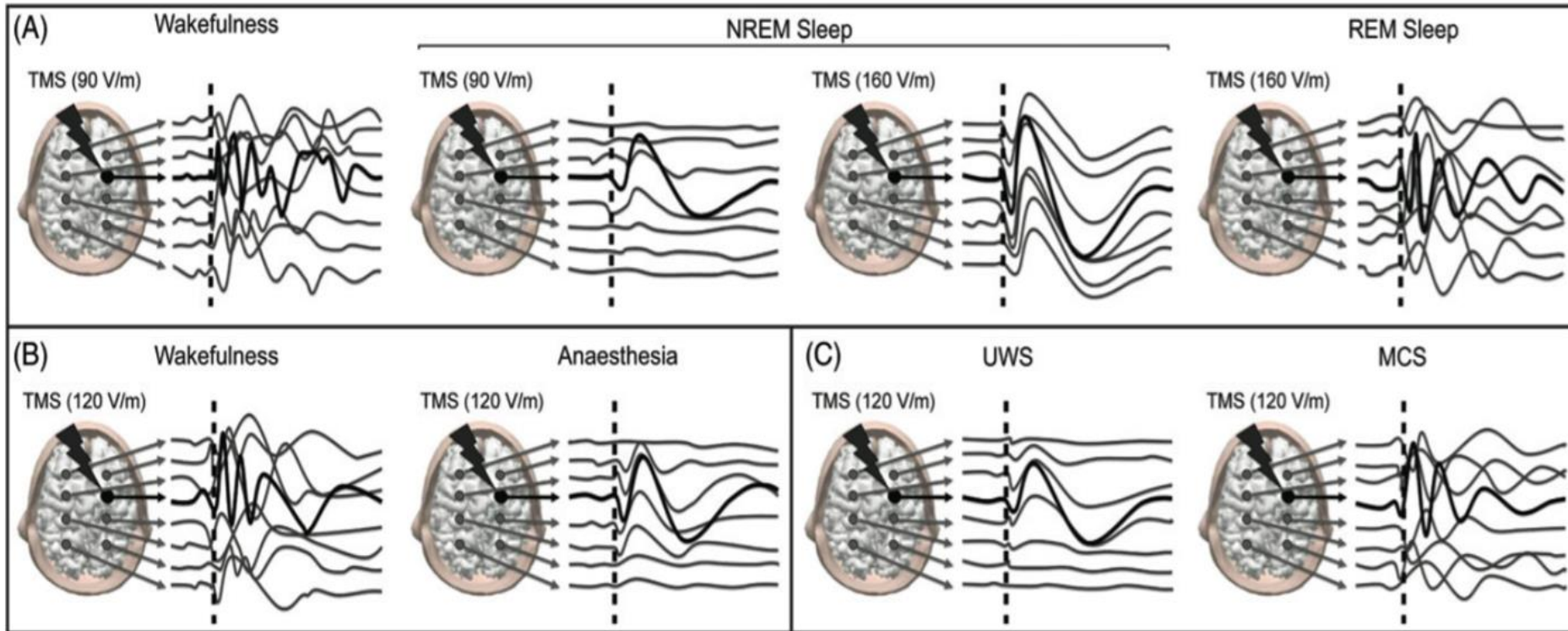
Deco ... & Kringelbach (2021) bioRxiv

One ring to rule them all

Future Perspectives

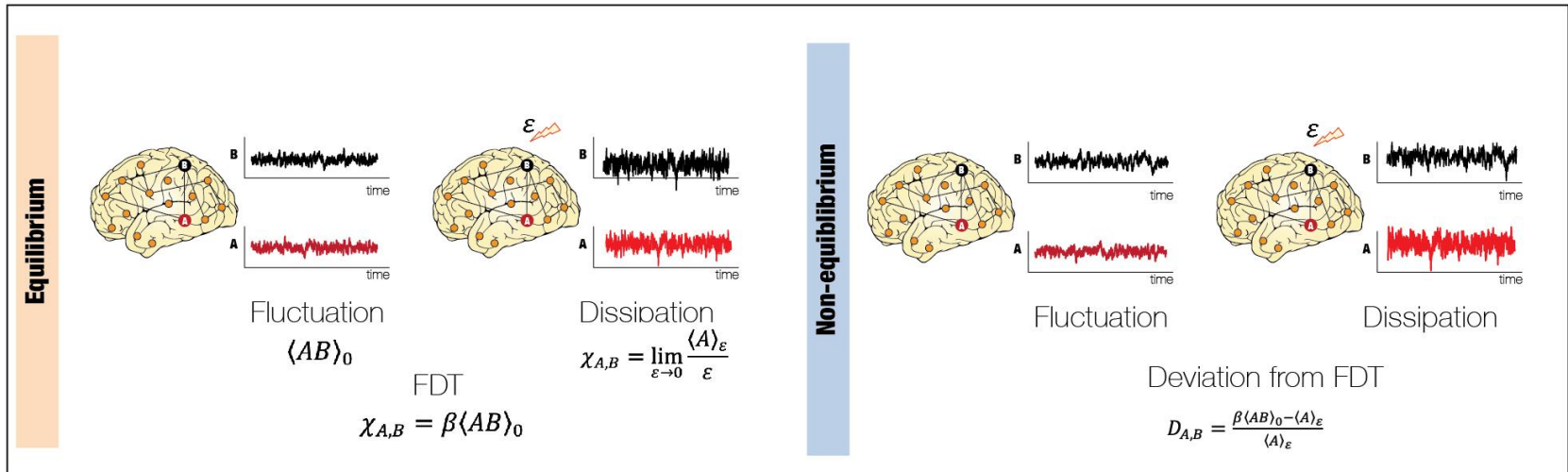
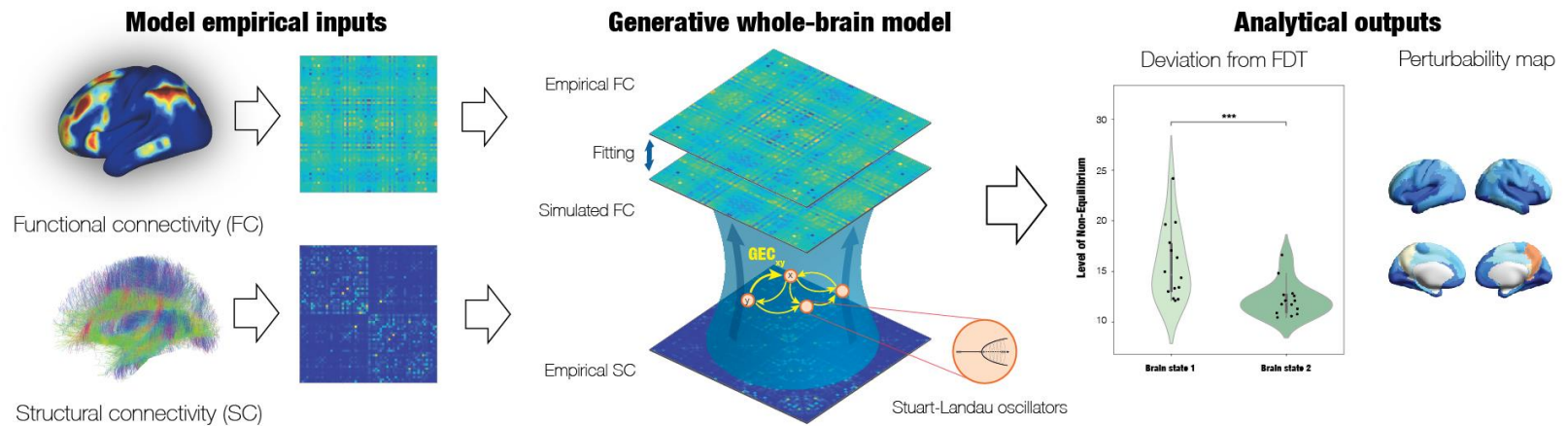
(Fluctuation-Dissipation Theorem)

Massimini's PCI

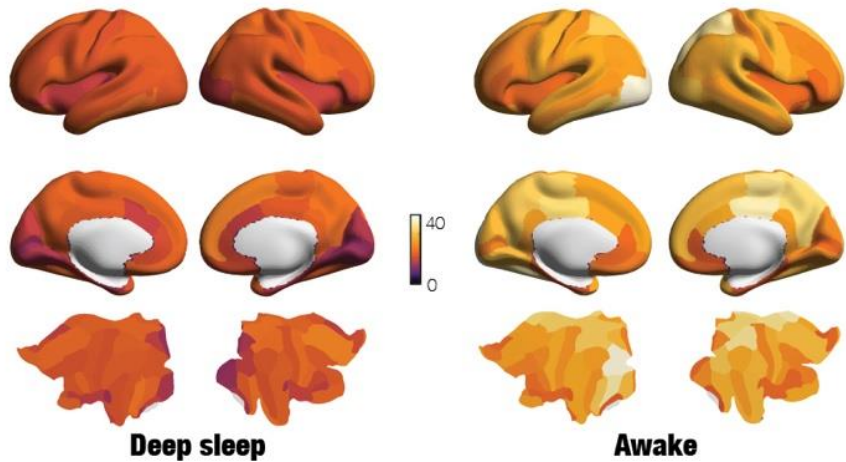
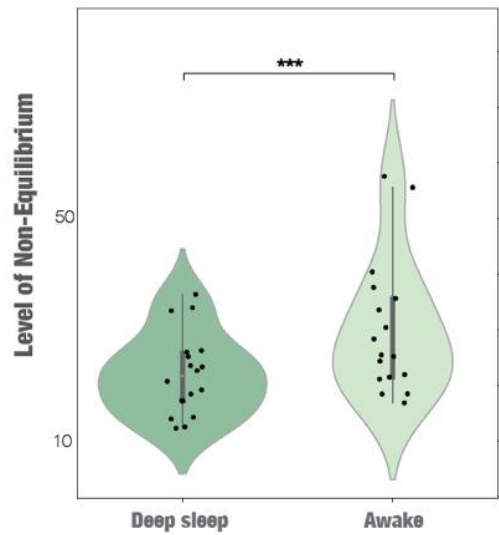


Napolitani et al. (2014)

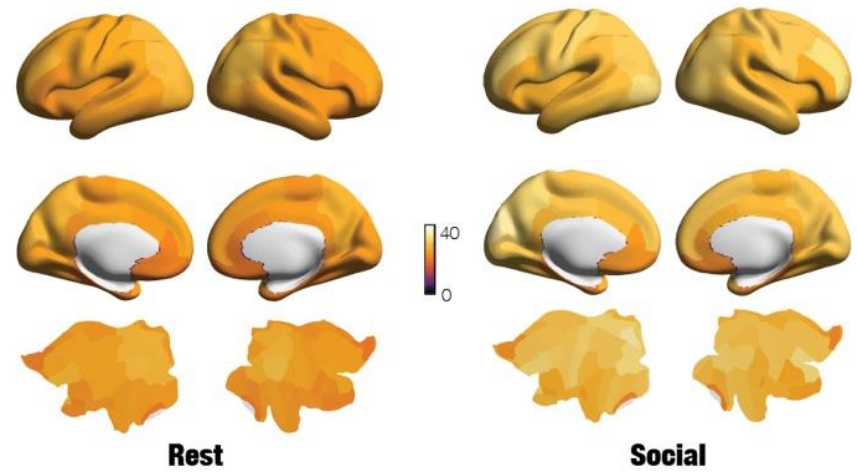
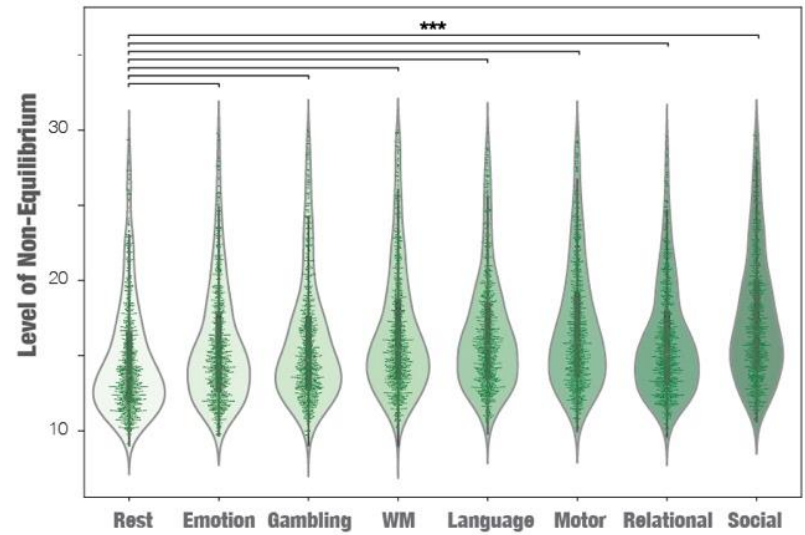
Future perspectives

A**Fluctuation-dissipation theorem (FDT) for characterising brain states****B****Discovering differences in non-equilibrium in empirical brain states****Future perspectives**

A Sleep data (18 participants)



B HCP data (970 participants)



Fluctuation-Dissipation theorem (FDT)

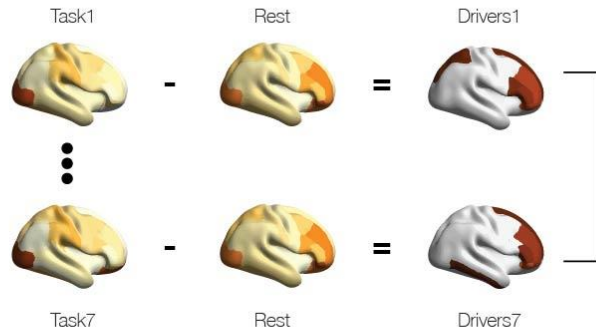
- **Hierarchy:** Brain causal interactions could be indirectly extracted through the arrow of time
- **Arrow of time** significantly different in different brain states
- **Arrow of time => Non-equilibrium => Turbulence**
- **Generative Effective Connectivity** based on Non-reversibility is more informative (underlying mechanisms)
- **Central role of PFC** in orchestrating cognition

Conclusion

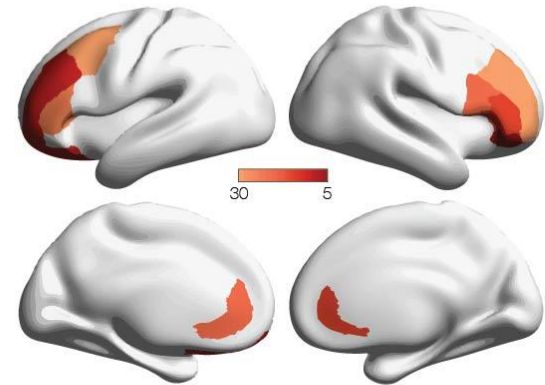


Thank You

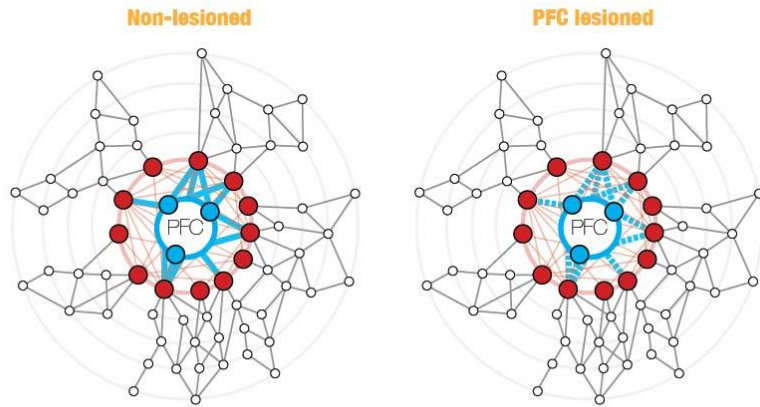
A Identifying unifying drivers across all tasks



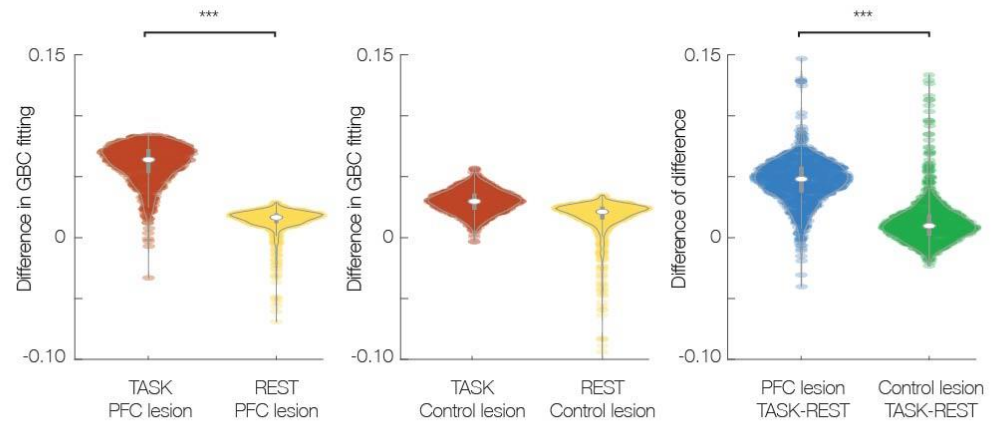
B Unifying PFC drivers of cognition



C Confirming causal mechanistic role of unifying drivers

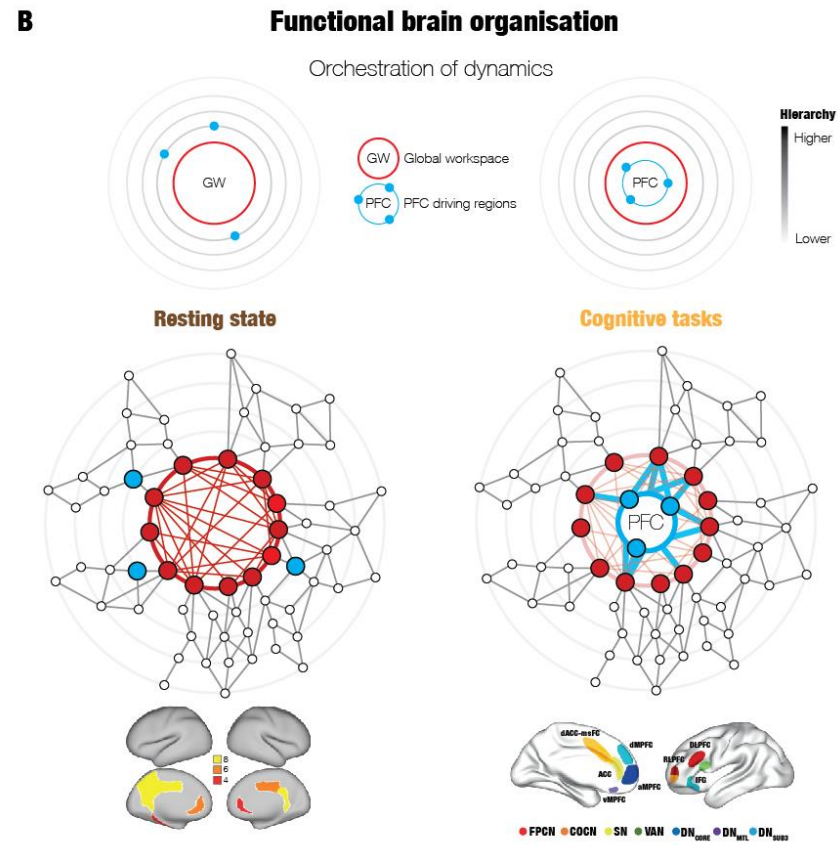
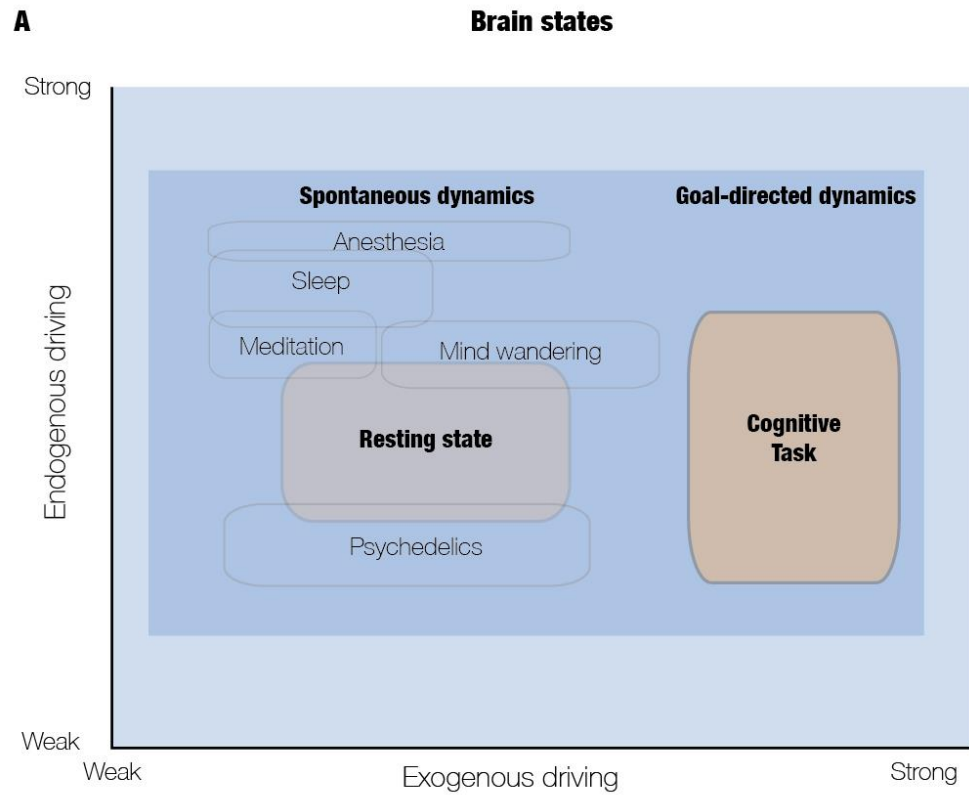


D Causal mechanistic role of unifying drivers



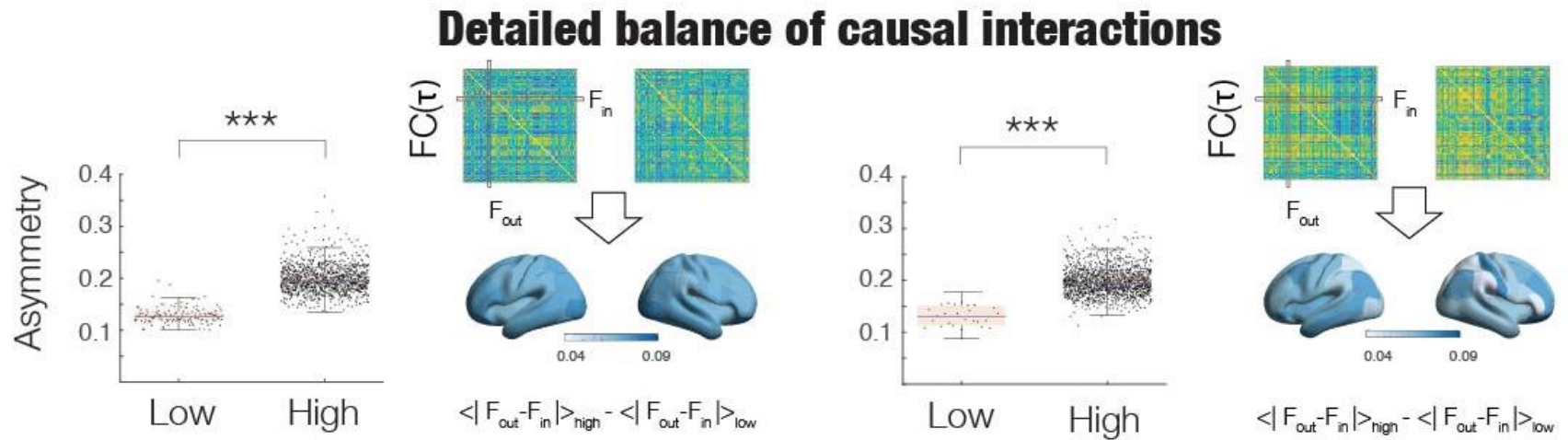
Deco ... & Kringelbach (2021) bioRxiv

Causal evidence of PFC



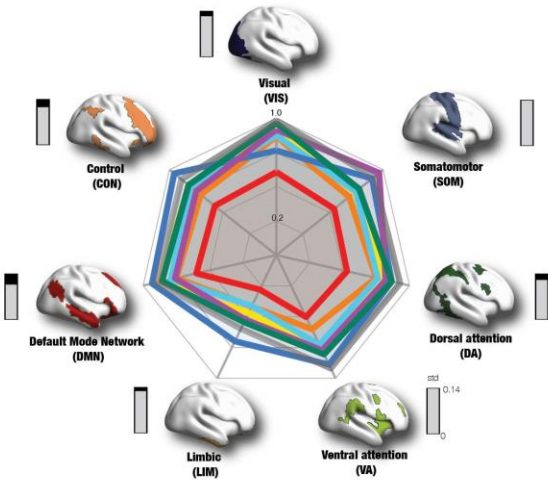
Deco ... & Kringelbach (2021) bioRxiv

Orchestration of dynamics

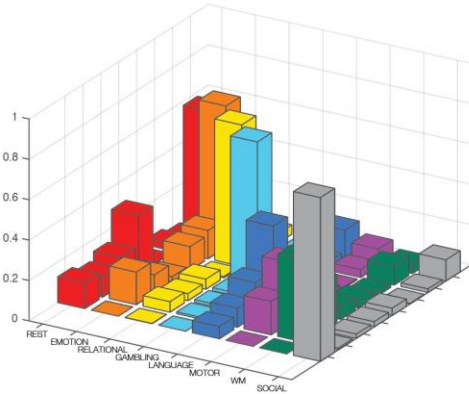
C

Breaking detailed balance

A Level of non-equilibrium of networks in rest and tasks



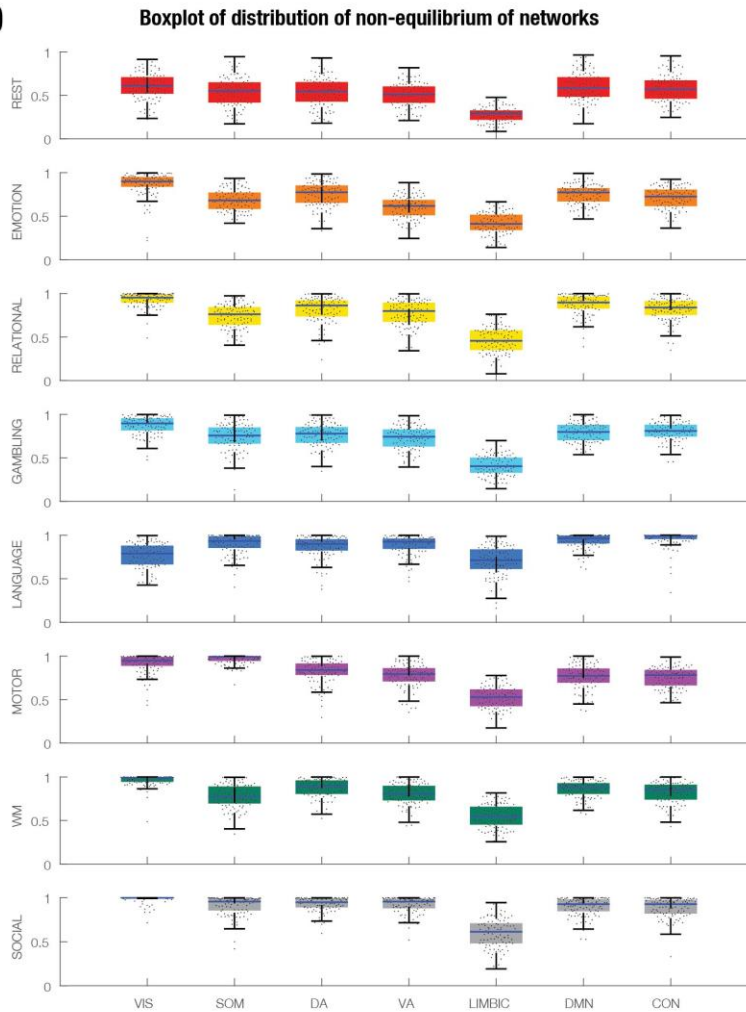
B Performance of classification of rest and tasks



C



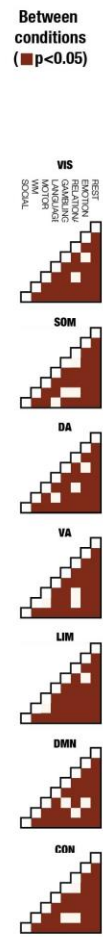
D



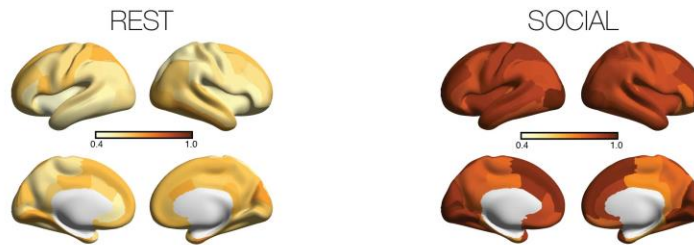
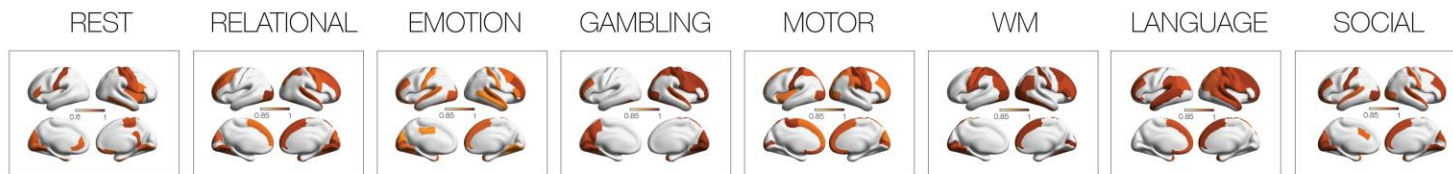
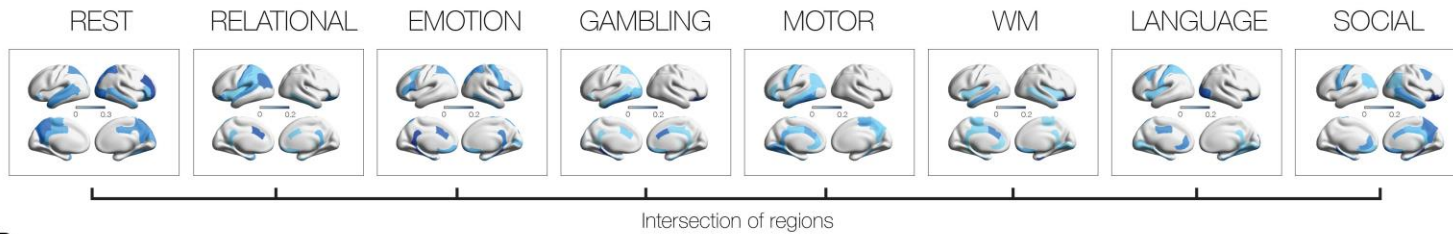
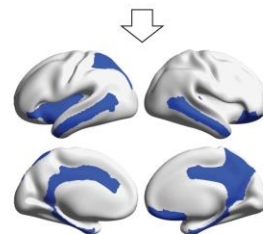
E



F



Network-level reversibility

A**Nodal non-equilibrium/non-reversibility****B****Regions highly driven by the environment****C****Regions weakly driven by the environment****D****DMN-like network is endogenously orchestrating cognition**

DMN-like network rules cognition