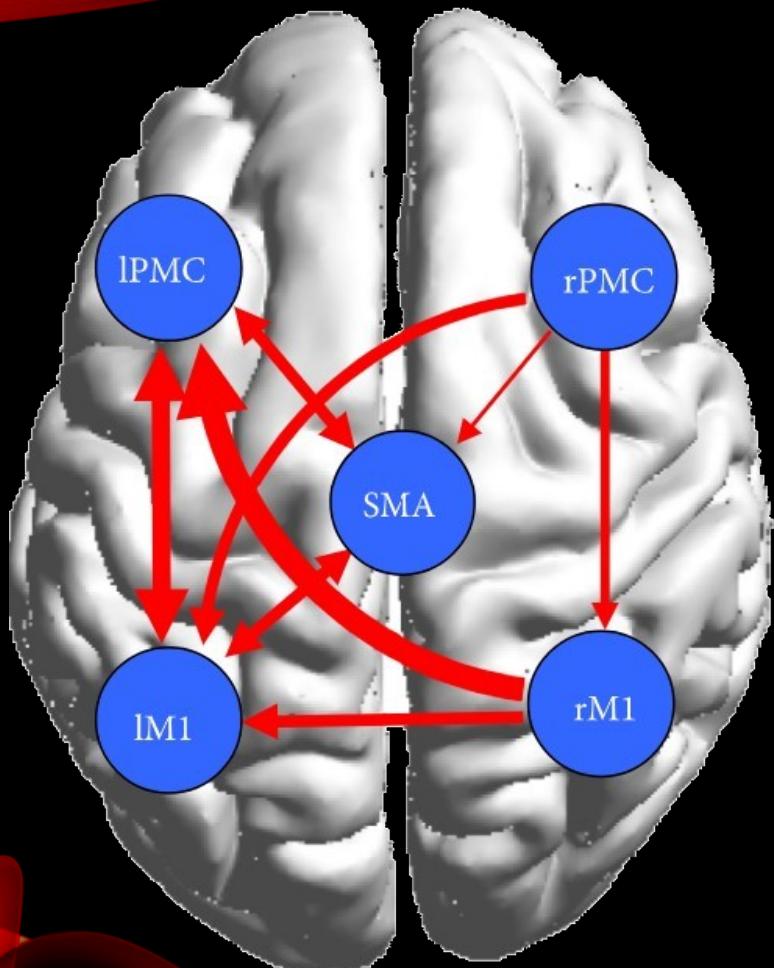


# STRUCTURALLY CONSTRAINED EFFECTIVE CONNECTIVITY



Lecture 4  
*Effective  
Connectivity*

Machine Learning  
for Neuroimaging  
and Neuroscience

Alessandro Crimi  
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<https://bam.sano.science/>

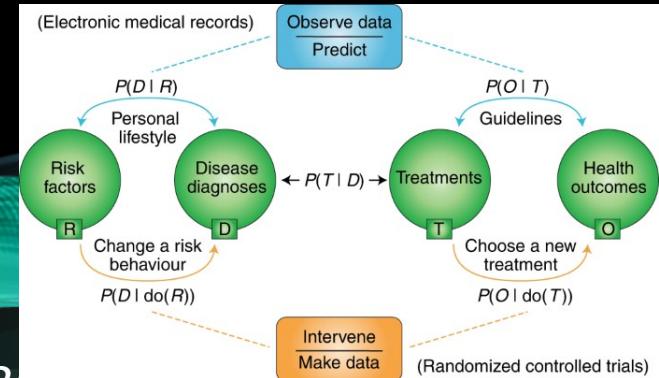
# AGENDA

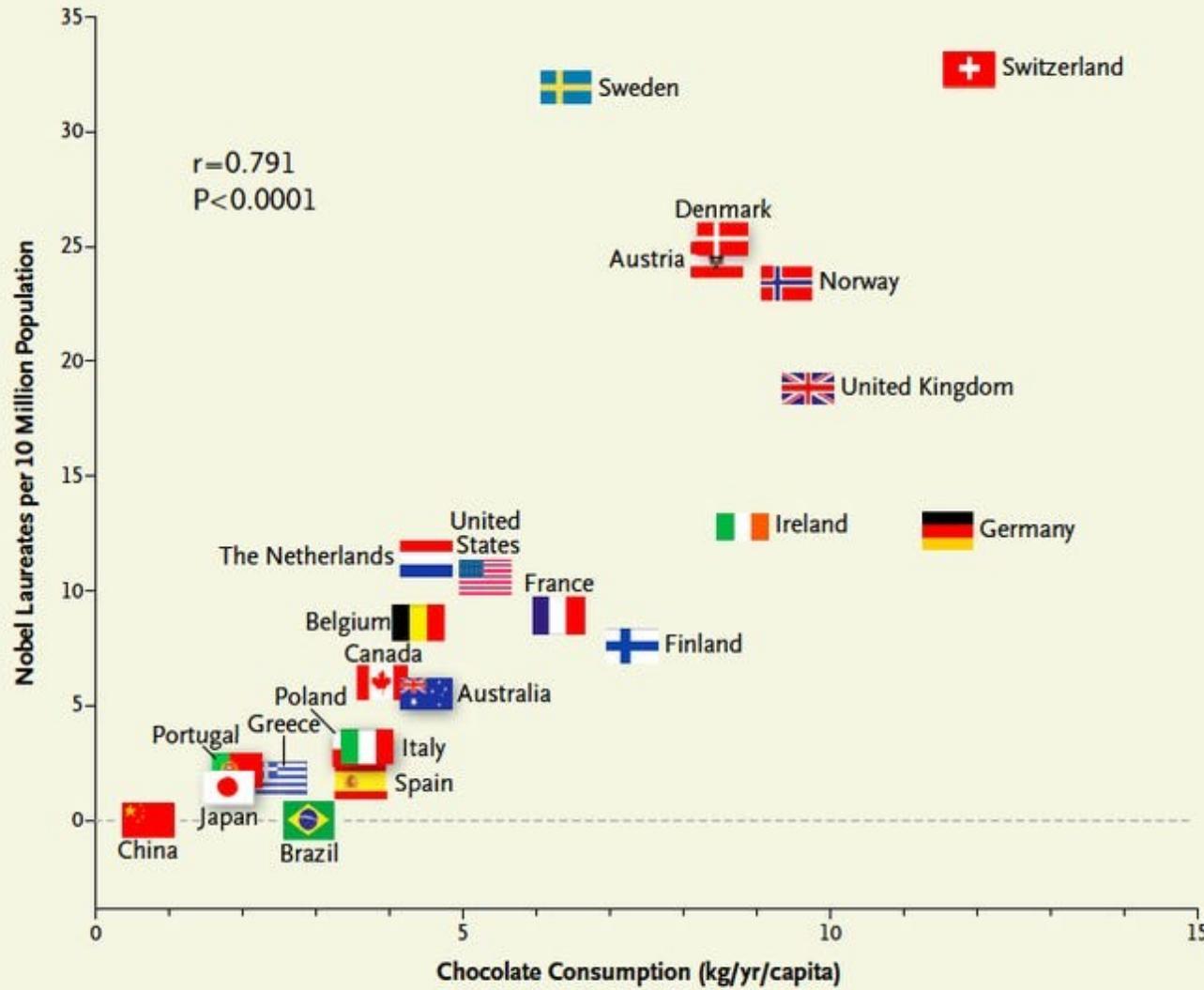
- Introduction
- Brush up on Friston's DCM, Pearl's, Granger's and Sugihara causality
- Structurally constrained effective connectivity (Granger version) (Crimi et al. Neuroimage 2021)
- Effective connectivity with Sugihara causality (Falco-Roget et al. PlosCompBio2023)

# DISCLAIMER

- Causal inference provides a rigorous framework for understanding and quantifying cause-and-effect relationships, which has important applications in domains such as healthcare, economics, social sciences, and policy-making.
- We do not focus here on causal inference for machine learning
- Künzel, Sören R., et al. “Metalearners for Estimating Heterogeneous Treatment Effects Using Machine Learning.” PNAS 2019

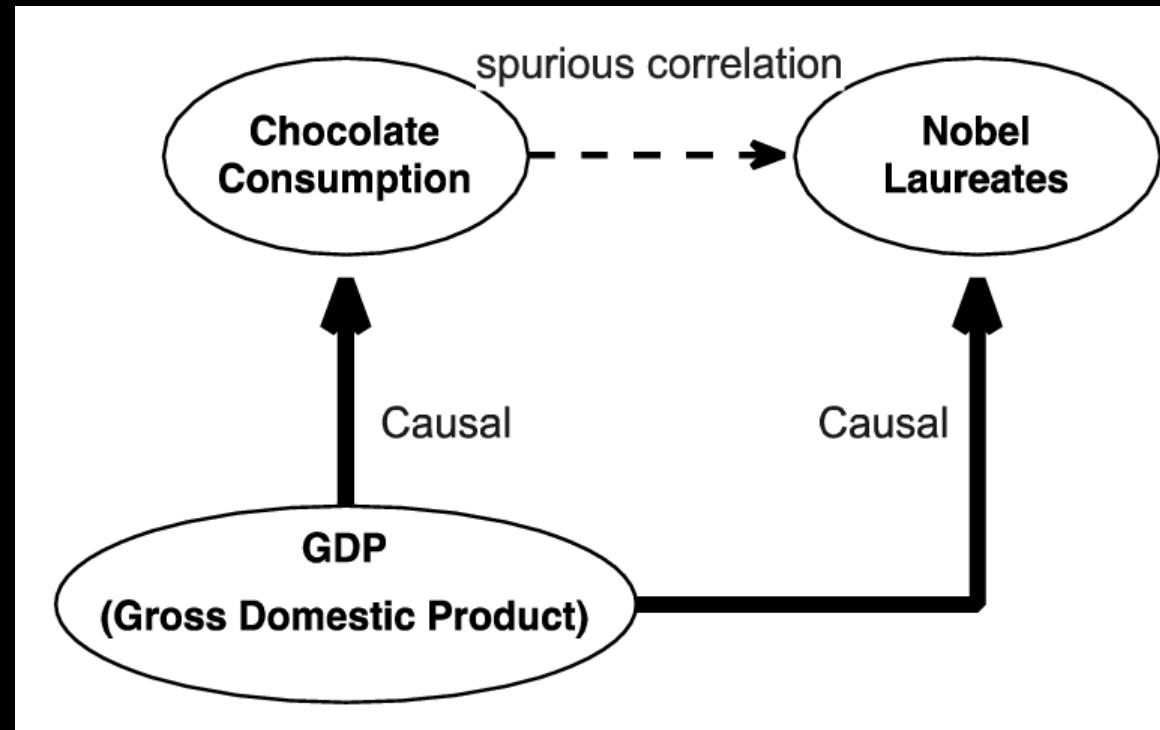
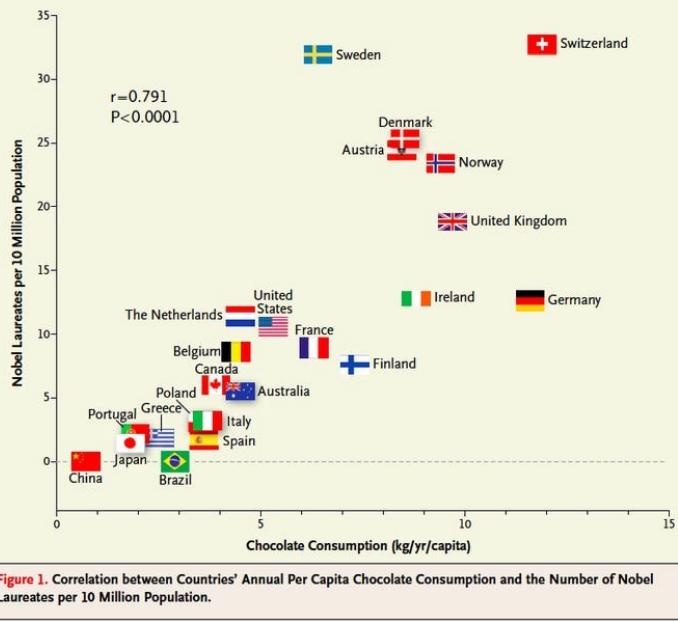
- “Causal inference” J. Pearl
- CausalML, CausalPy, DoWhy, GCASTLE





**Figure 1.** Correlation between Countries' Annual Per Capita Chocolate Consumption and the Number of Nobel Laureates per 10 Million Population.

*Milk, chocolate and Nobel prizes.* Linthwaite and Fuller, Practical Neurology 2013



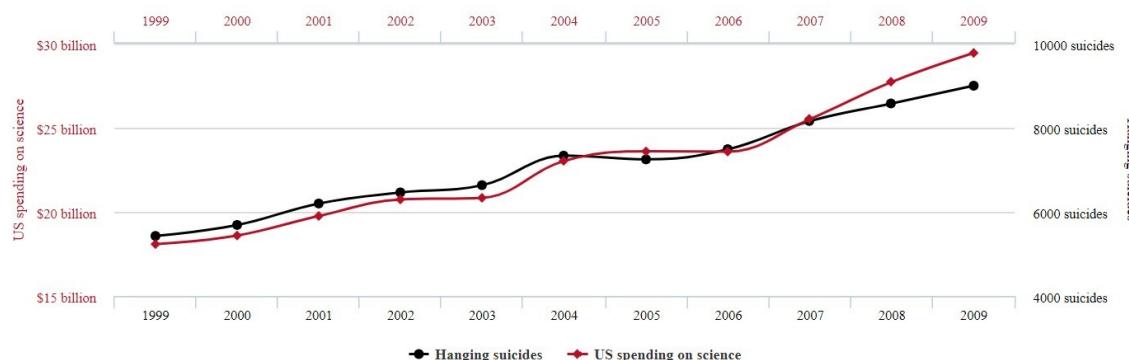
*Milk, chocolate and Nobel prizes.* Linthwaite and Fuller,  
Practical Neurology 2013

## US spending on science, space, and technology

correlates with

## Suicides by hanging, strangulation and suffocation

Correlation: 99.79% ( $r=0.99789126$ )



Data sources: U.S. Office of Management and Budget and Centers for Disease Control & Prevention

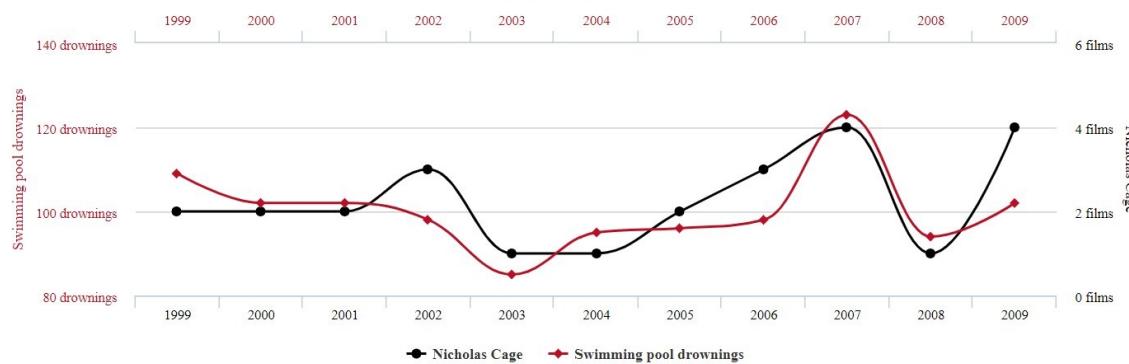
tylervigen.com

## Number of people who drowned by falling into a pool

correlates with

## Films Nicolas Cage appeared in

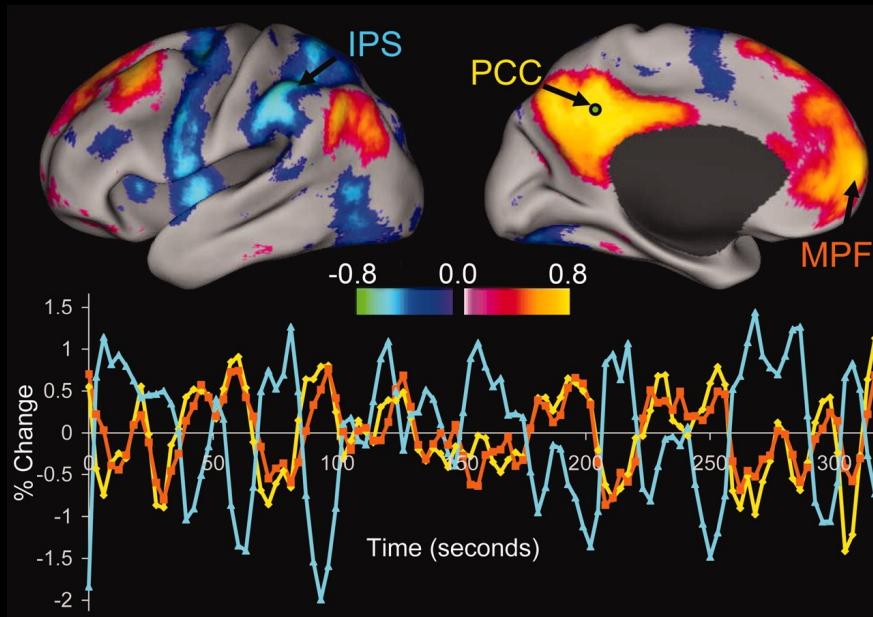
Correlation: 66.6% ( $r=0.666004$ )



tylervigen.com

# SPURIOUS CORRELATIONS ( WWW.TYLERVIGEN.COM)

# FUNCTIONAL CONNECTIVITY AND CAUSALITY

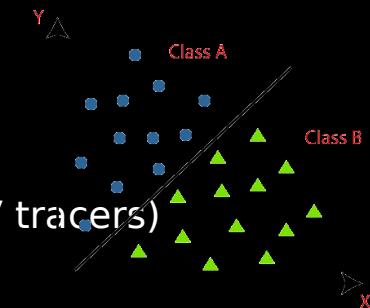
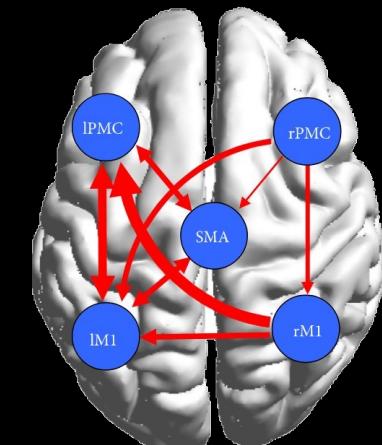
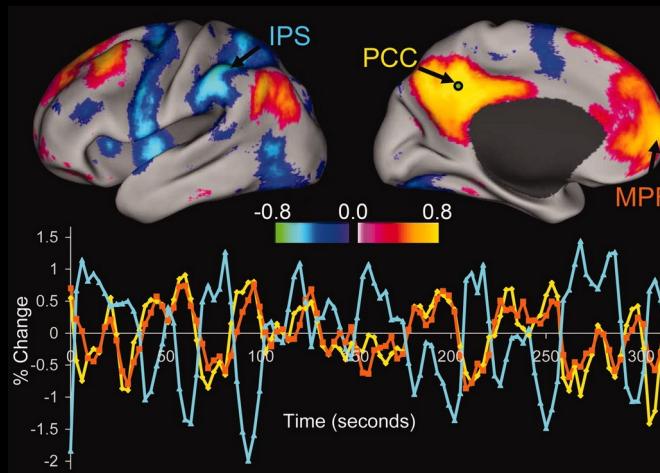
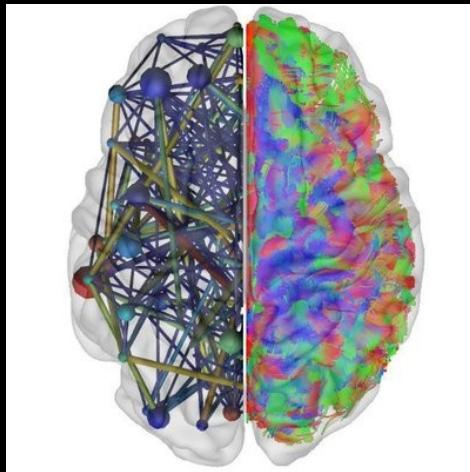


Fox et al. PNAS 2005

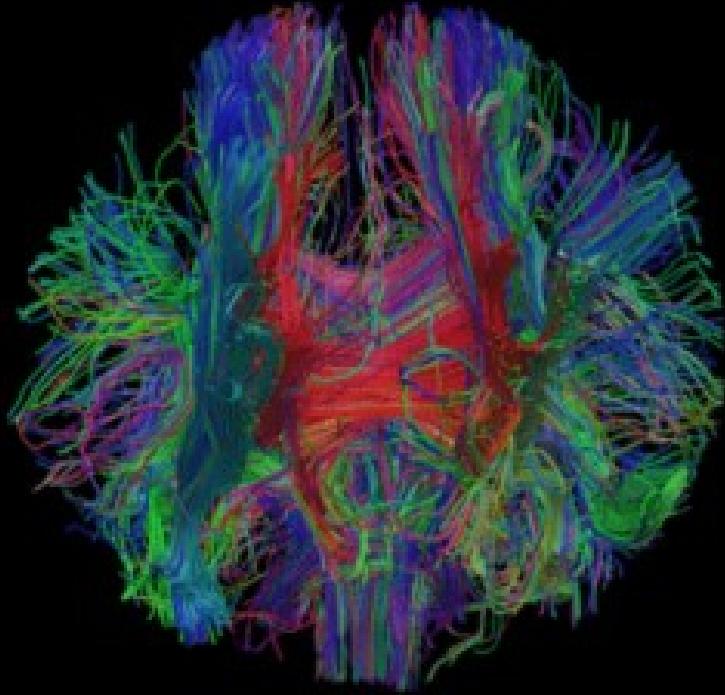
Research questions:

1. Can we assure causality (effective connectivity)?
2. What would be the state-of-art even with limitations?

# STRUCTURAL, FUNCTIONAL & EFFECTIVE CONNECTIVITY

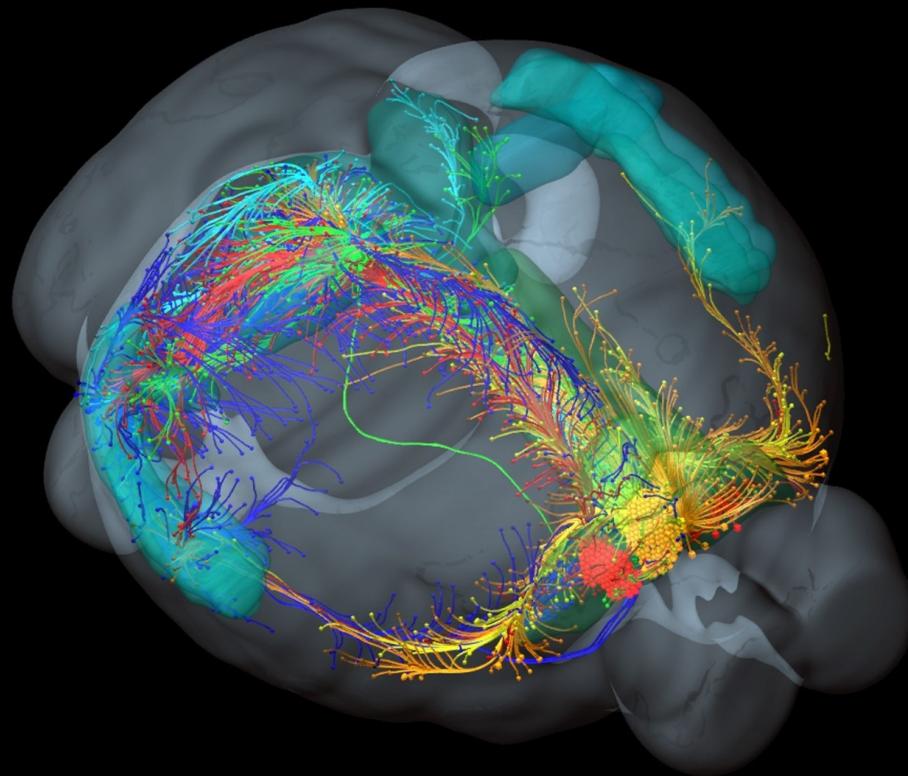


- **Structural/anatomical connectivity**  
= presence of axonal connections / white matter tracks (eg, DWI, AAV tracers)
- **Functional connectivity**  
= statistical dependencies between regional time series (eg, Pearson correlation, ICA,...)
- **Effective connectivity**  
= causal (directed) influences between neuronal populations (eg, DCM, Granger C., etc)
- Nobody cares about **Morphological connectivity...**

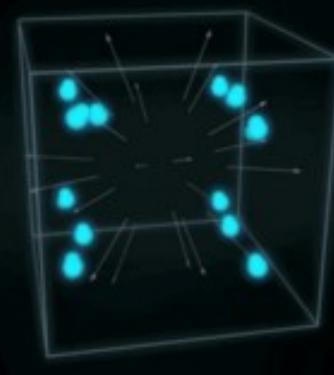


[www.dipy.org](http://www.dipy.org)

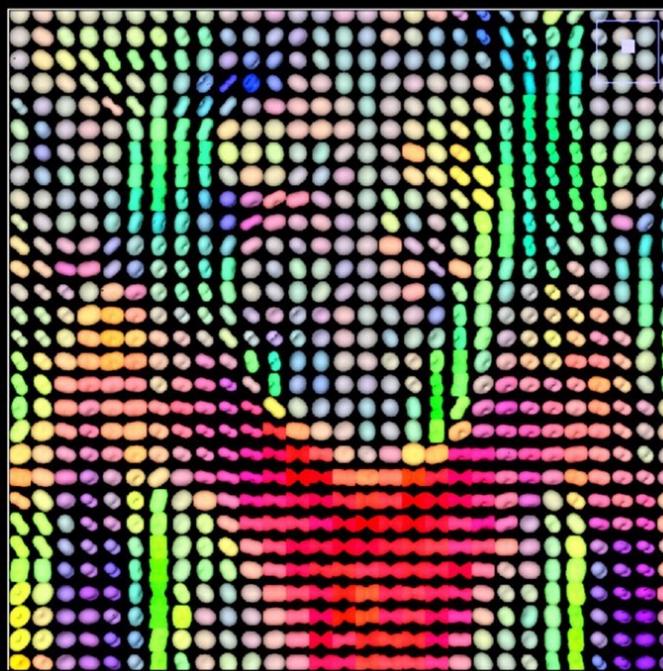
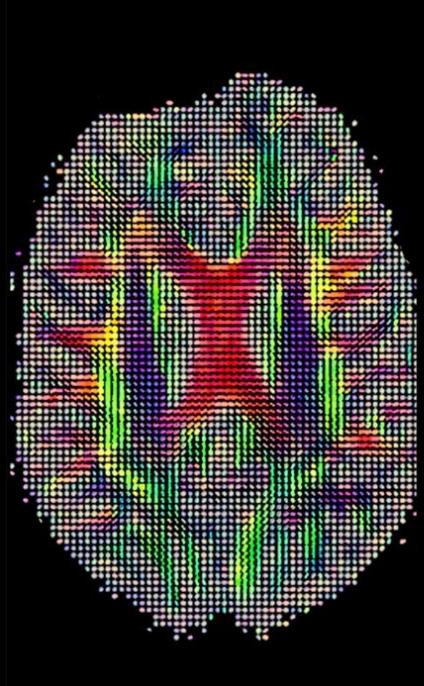




Oh. et al. 2014

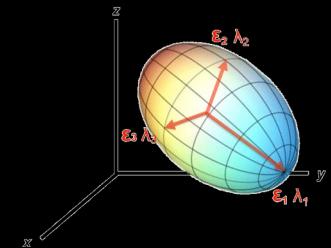


Credit: MaxPlanck Society

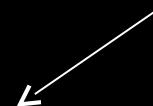
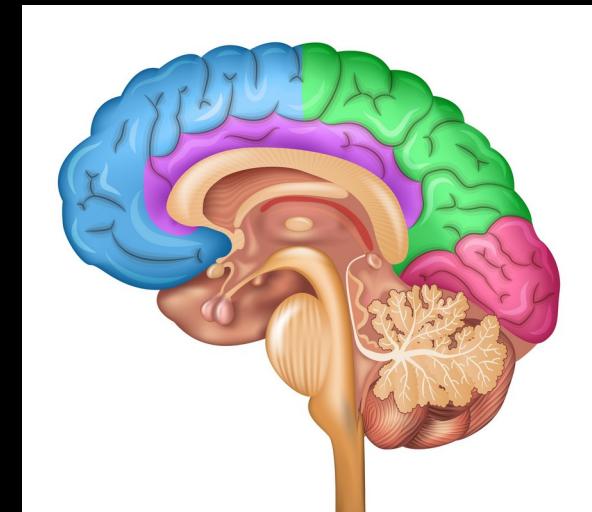
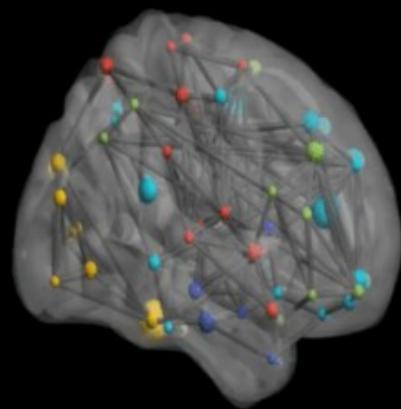
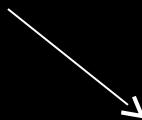
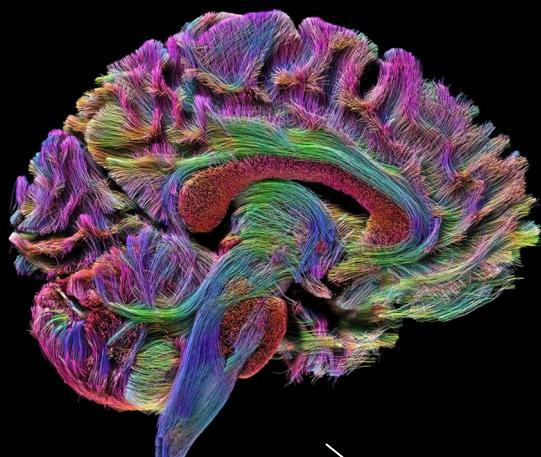


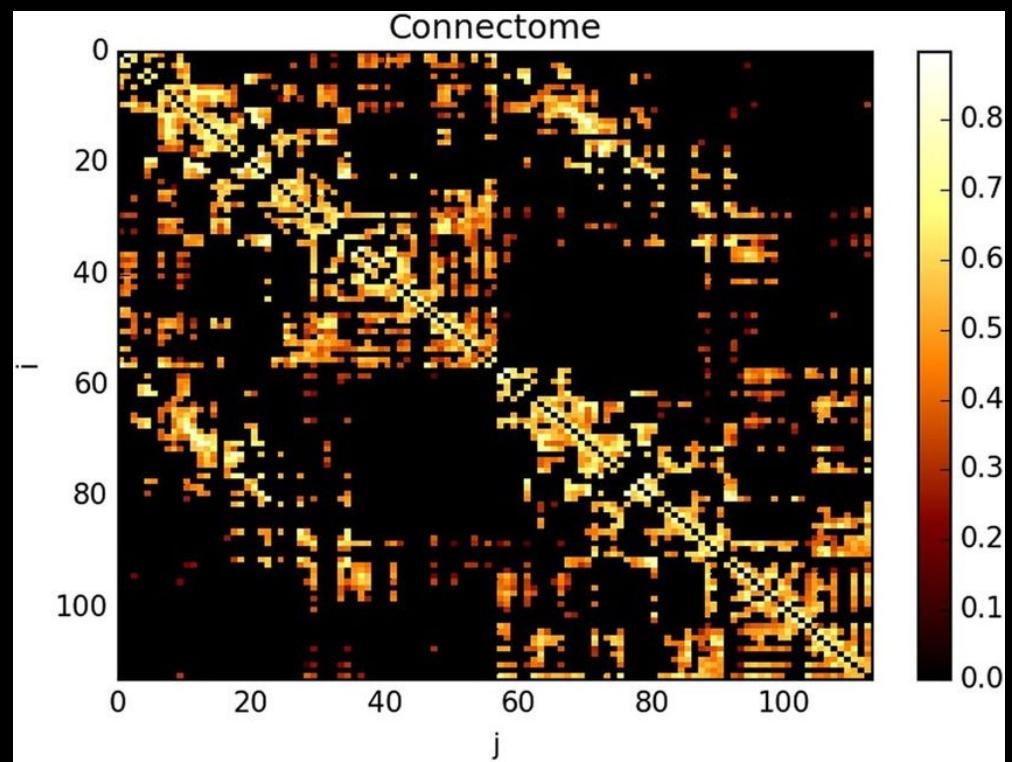
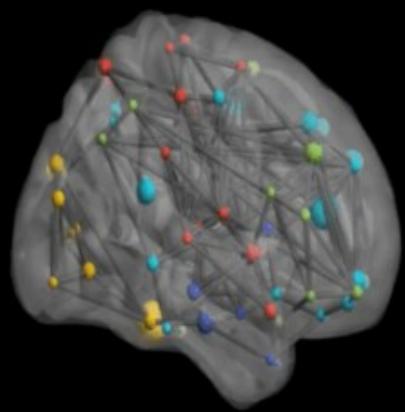
[\(Alger 2012 J.Neuroscience\)](#)

$$\bar{D} = \begin{vmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{vmatrix}$$

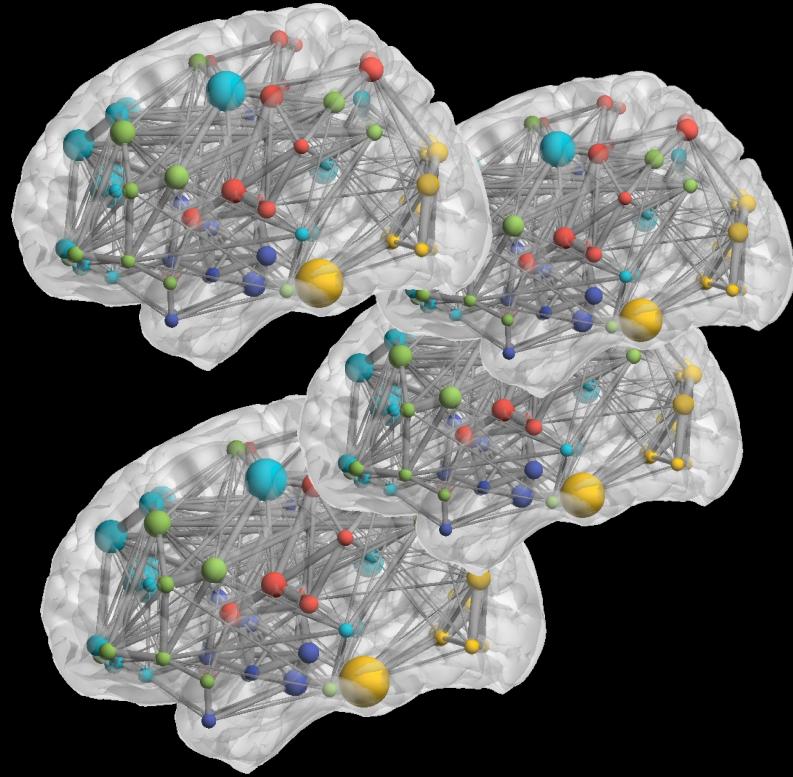


$$FA = \sqrt{\frac{(\lambda_1 - \lambda_2)^2 + (\lambda_2 - \lambda_3)^2 + (\lambda_1 - \lambda_3)^2}{2(\lambda_1^2 + \lambda_2^2 + \lambda_3^2)}}$$

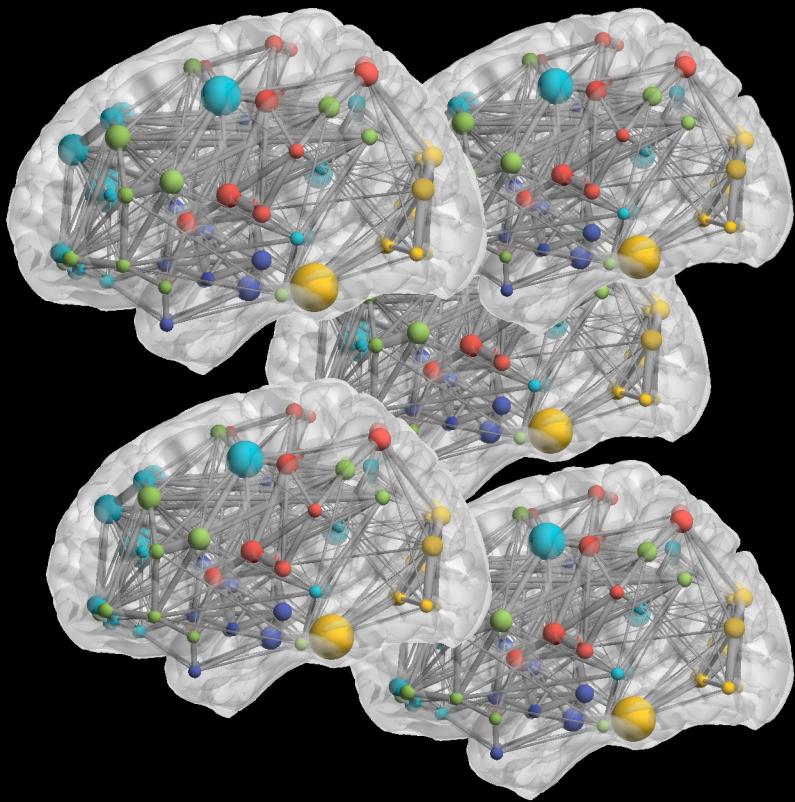


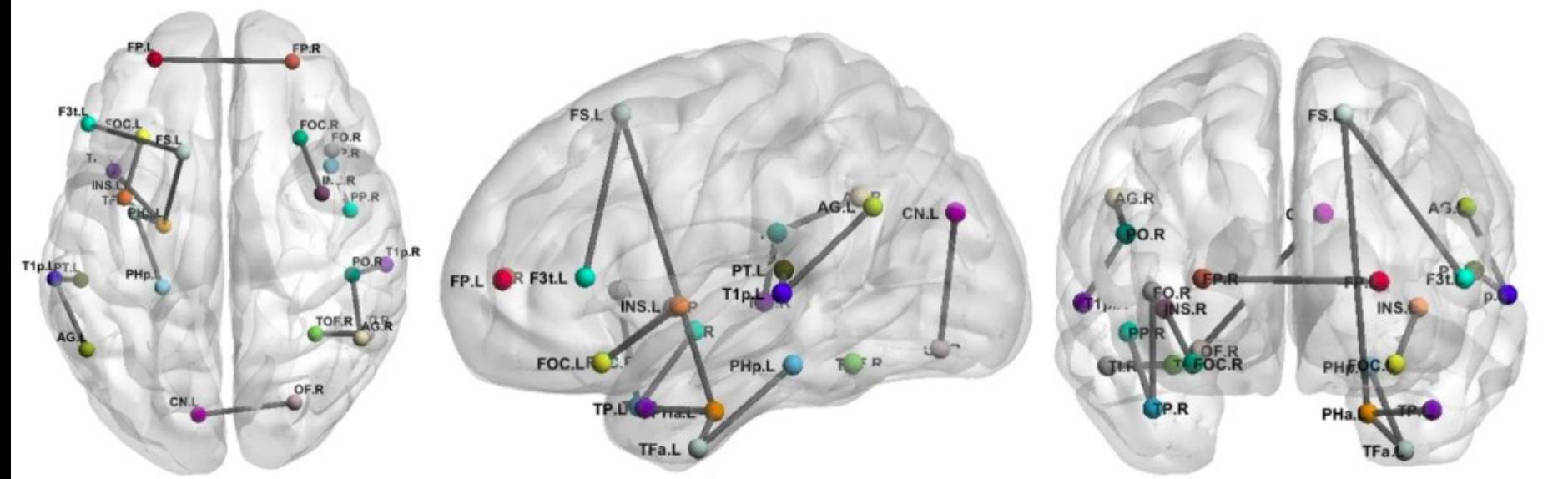


Alzheimer, Schizophrenia,...



Matched healthy control

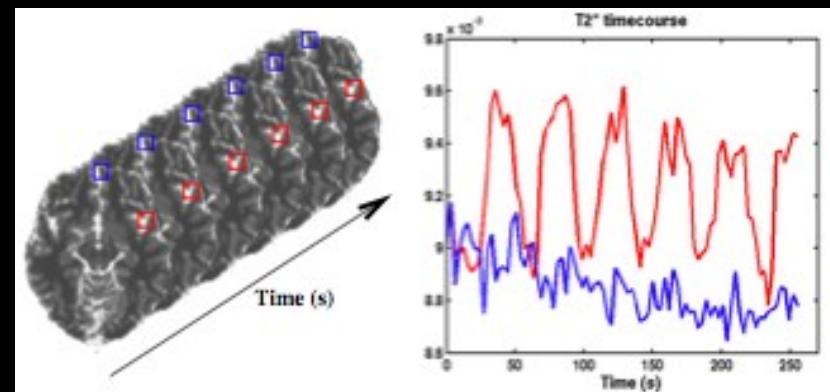




(Crimi et al., Nature Scientific Reports 2019)

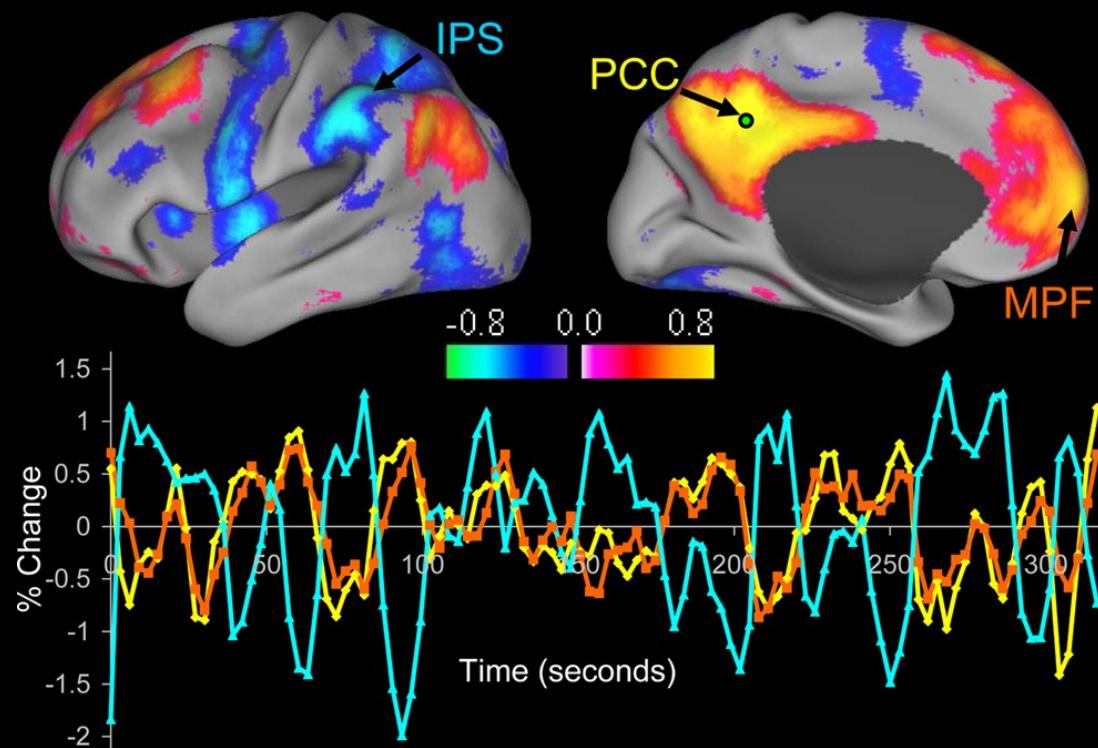
# FUNCTIONAL MRI

- Hemodynamic response: blood releases oxygen to firing neurons at a greater rate than to inactive neurons.
- This causes a change of the relative levels of oxyhemoglobin and deoxyhemoglobin (oxygenated or deoxygenated blood) that can be detected on the basis of their differential magnetic susceptibility.



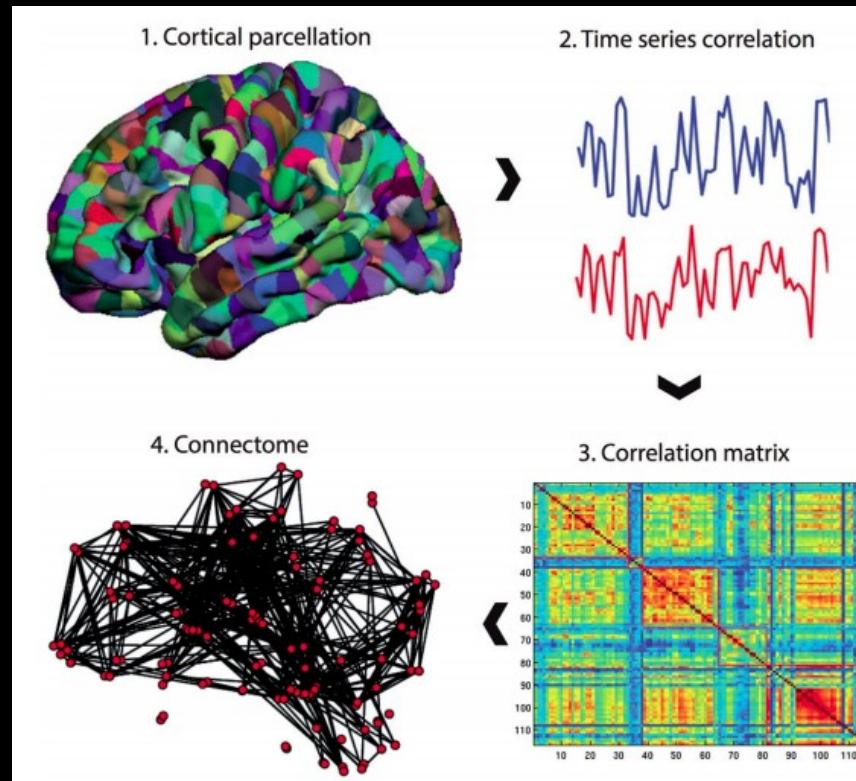
Gordon et al. (Cerebral Cortex 2014)

# BRUSH UP ON FUNCTIONAL CONNECTIVITY

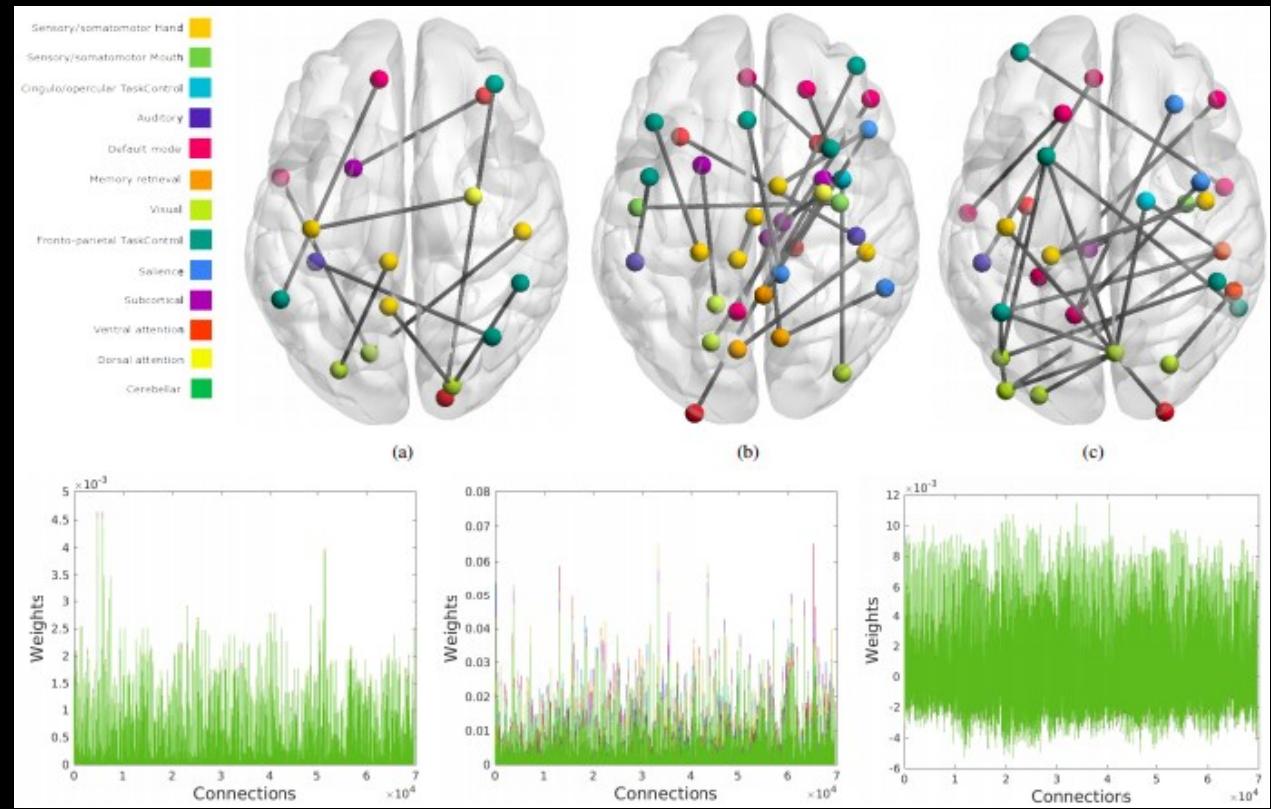
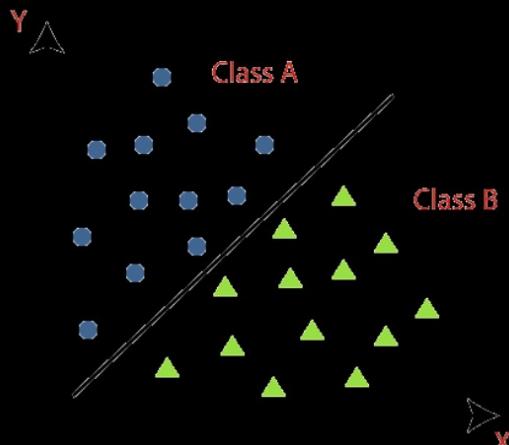


Fox & Greicius 2010

# FUNCTIONAL CONNECTIVITY

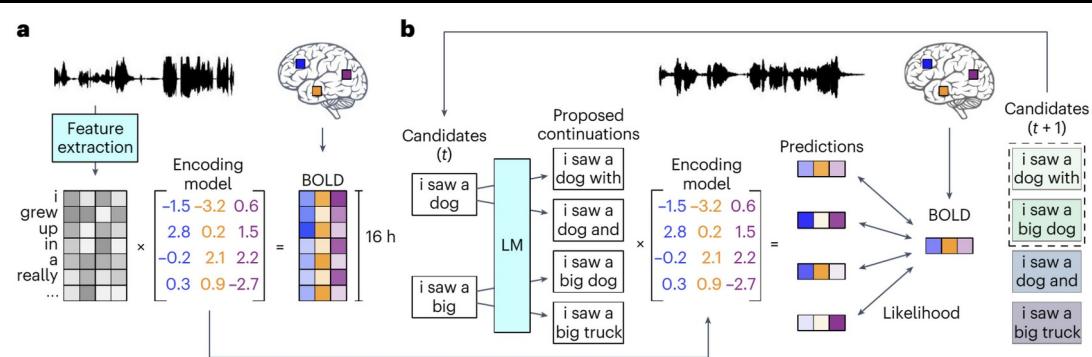


# USING SUPPORT VECTOR MACHINE



Crimi et al. Neuroimage  
2021 (work done in  
2014/2015)

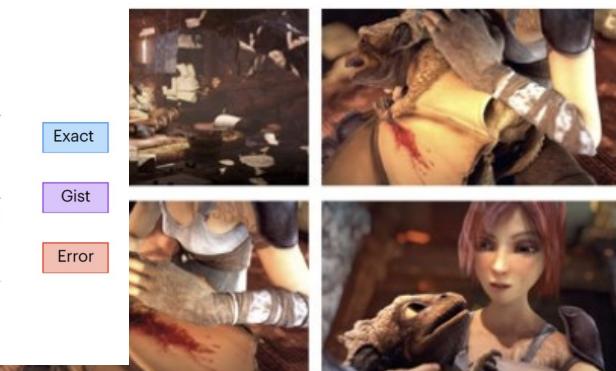
# "SEMANTIC RECONSTRUCTION OF CONTINUOUS LANGUAGE FROM NON-INVASIVE BRAIN RECORDINGS" TANG ET AL. NATURE NEUROSCIENCE 2023



**c**

Actual stimulus	Decoded stimulus
<i>i got up from the air mattress and pressed my face against the glass of the bedroom window expecting to see eyes staring back at me but instead finding only darkness</i>	<i>i just continued to walk up to the window and open the glass i stood on my toes and peered out i didn't see anything and looked up again i saw nothing</i>
<i>i didn't know whether to scream cry or run away instead i said leave me alone i don't need your help adam disappeared and i cleaned up alone crying</i>	<i>started to scream and cry and then she just said i told you to leave me alone you can't hurt me anymore i'm sorry and then he stormed off i thought he had left i started to cry</i>
<i>that night i went upstairs to what had been our bedroom and not knowing what else to do i turned out the lights and lay down on the floor</i>	<i>we got back to my dorm room i had no idea where my bed was i just assumed i would sleep on it but instead i lay down on the floor</i>
<i>i don't have my driver's license yet and i just jumped out right when i needed to and she says well why don't you come back to my house and i'll give you a ride i say ok</i>	<i>she is not ready she has not even started to learn to drive yet i had to push her out of the car i said we will take her home now and she agreed</i>

Actual stimulus



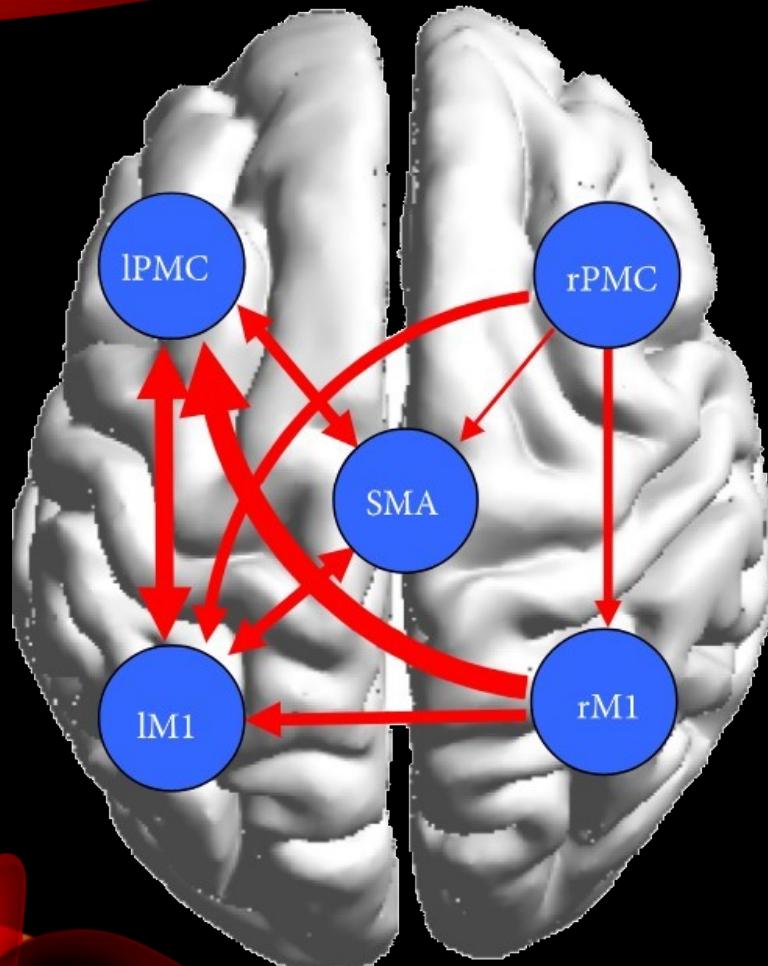
Decoded

*she was very weak i held her neck to get her breathing under control*



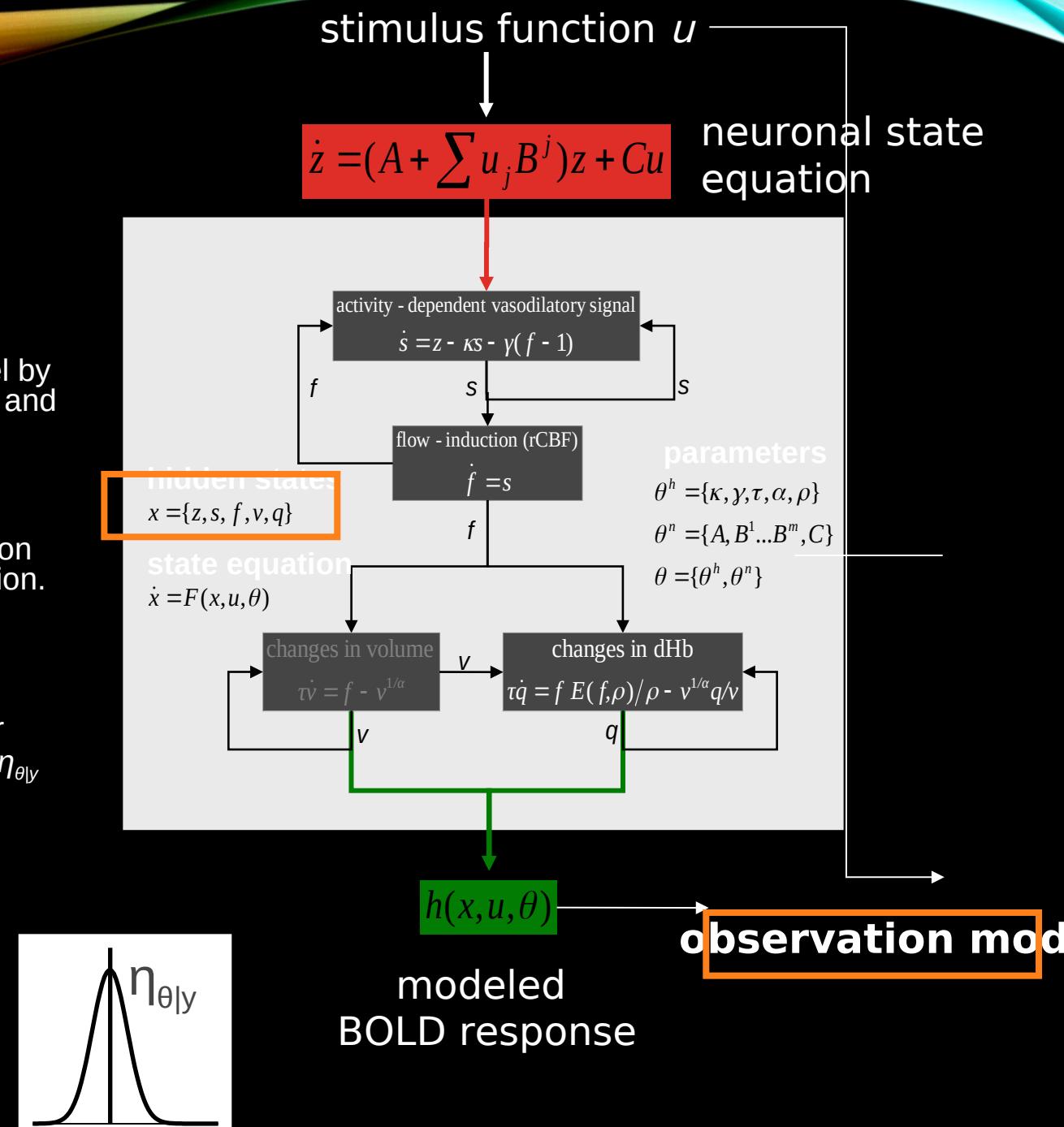
*i see a girl that looks just like me get hit on her back and then she is knocked off*

# STRUCTURALLY CONSTRAINED EFFECTIVE CONNECTIVITY



## DCM Overview: parameter estimation

- Specify model (neuronal and haemodynamic level)
- Make it an observation model by adding measurement error  $e$  and confounds  $X$  (e.g. drift).
- Bayesian parameter estimation using expectation-maximization.
- Result:  
(Normal) posterior parameter distributions, given by mean  $\eta_{\theta|y}$  and Covariance  $C_{\theta|y}$ .



# DCM Estimation: Bayesian framework

## Models of

- Haemodynamics in a single region
- Neuronal interactions

likelihood

$$p(y | \theta)$$

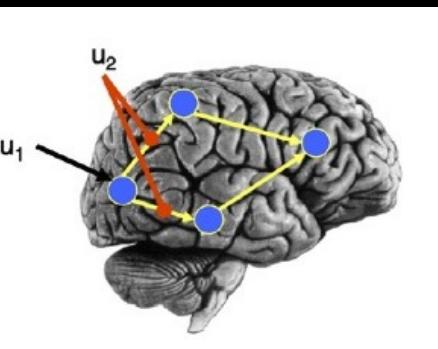
posterior

## Constraints on

- Haemodynamic parameters
- Connections

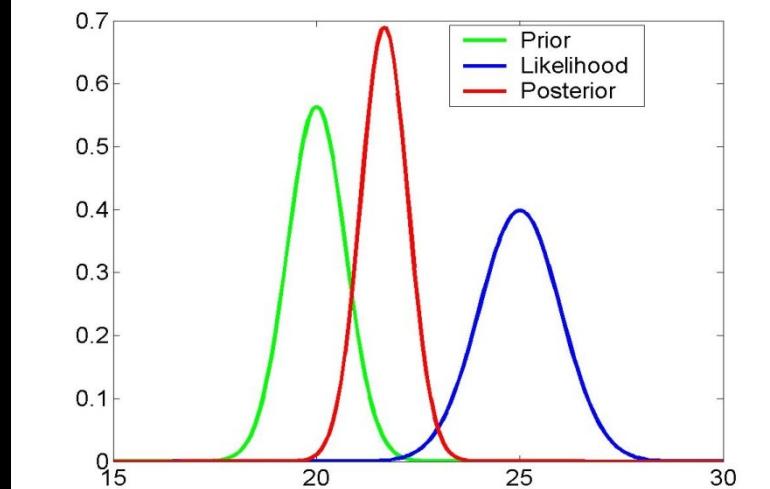
$$p(\theta)$$

priors



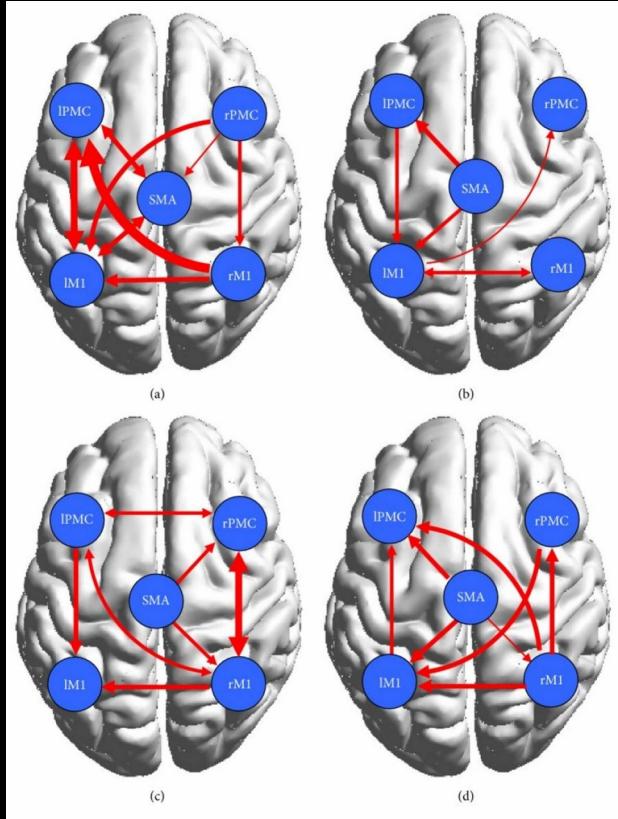
Friston et al.  
Neuroimage 2003

## Bayesian estimation



*Inferences on:*  
1. Parameters  
2. Models

# LEARN DCM AND PUT IT ASIDE



- DCM estimates neuronal interactions using a priori information about intrinsic physiology.
- High computational costs related to parameters and not scalable.
- Poor performance in resting-state (even using variations)
- Hypothesis driven to validate prior hypothesis (not really flexible and scalable).

# What is causality?

- **Pearl causality or Perturbation causality**(no complaint):

“Variable X causes variable Y if some externally applied perturbation of X at a point in time results in a perturbation in Y at a future or current time”

It strictly holds only in epigenetics and TMS, unpractical

- **Granger causality:**

A time series X causes a time series Y if given the past information in X predicts future Y better than without the history of X. Here X values provide statistically significant information about future values of Y.

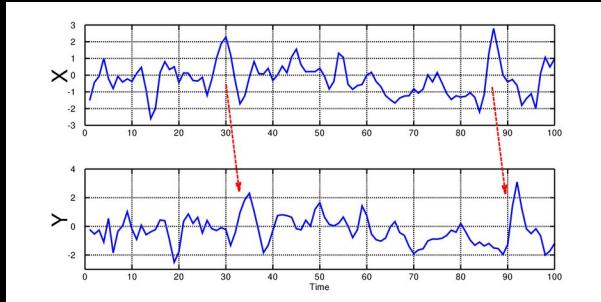
Criticized as working mostly in stationary signals, assuming separability.

- **Sugihara Causality and perturbation (later)**

# What is causality?

- **Granger causality:**

A time series X causes a time series Y if given the past information in X predicts future Y better than without the history of X. Here X values provide statistically significant information about future values of Y.



$$X(t) = \sum_{\tau=1}^L A_\tau X(t - \tau) + \varepsilon(t),$$

Then tested through a series of t-tests and F-tests.

Under the assumption of using Gaussian variables, GC is computed as transfer entropy: **X Granger causes Y if and only if the transfer entropy from X to Y is nonzero (Barret et al. 2009 Physics review)**

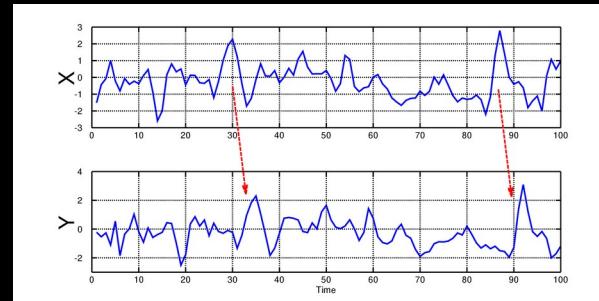
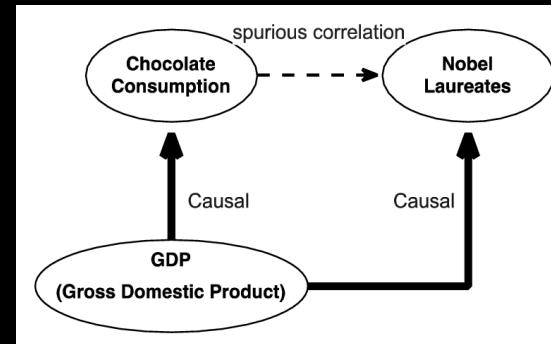
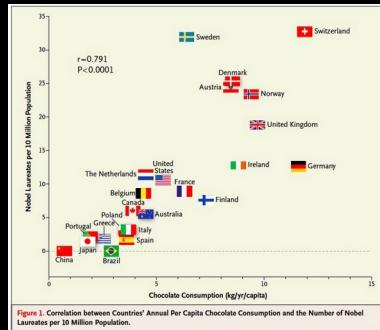
Criticized as working mostly in stationary signals, **assuming separability**.

For non-stationary signals = introduce windowing

For indirect connections = introduce propagators  
(Marinazzo, Roebroeck, Seth, etc)

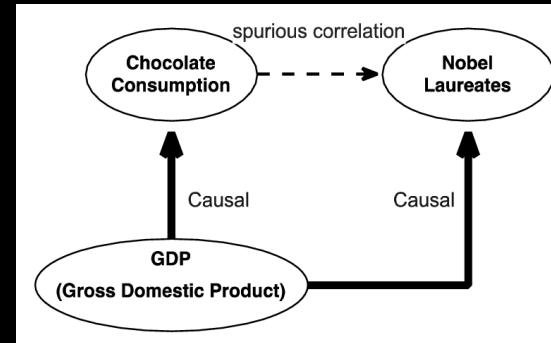
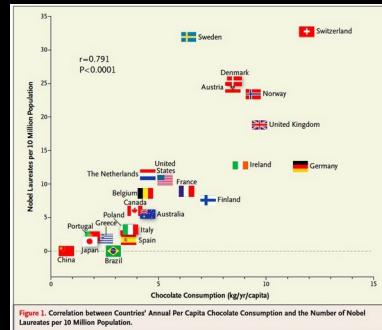
# Reichenbach Common Cause

“...If two events are correlated, then either there is a causal connection between the correlated events that is responsible for the correlation or there is a third event, a so called common cause, which brings about the correlation. In short we cannot assure that there is a real perturbation or just an unseen variable which is causing first one variable and then another one...”  
Reichenbach, 1956

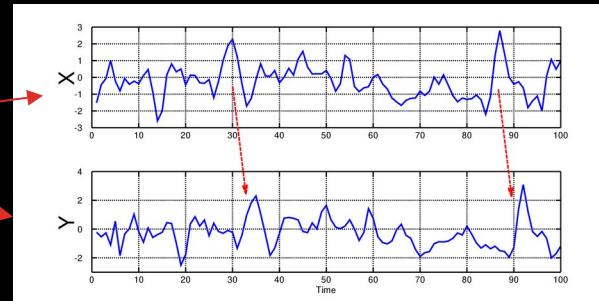


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Reichenbach, 1956



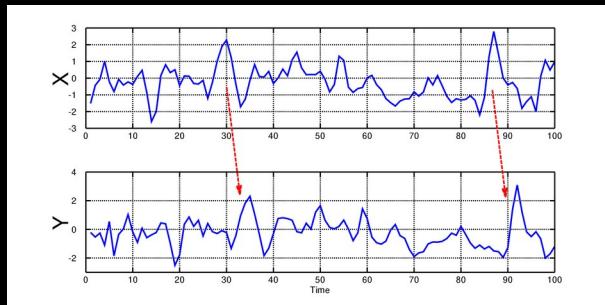
Z



# Structurally constrained Granger causality

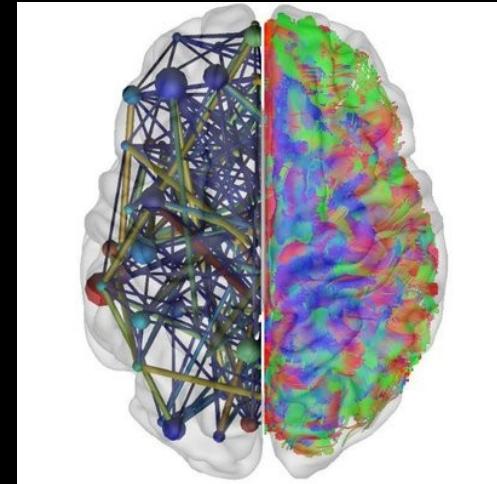
Crimi et al. Neuroimage 2021

$$X(t) = \sum_{\tau=1}^L A_\tau X(t - \tau) + \varepsilon(t),$$



Functional

B =



Structural

$$\widehat{\mathbf{A}}_i = \mathbf{A}_i \odot \mathbf{B} \quad (2)$$

where  $\odot$  denotes the Hadamard or element-wise product, and  $\mathbf{B}$  is an indicator matrix obtained by the structural connectivity  $\mathbf{A}_{\text{init}}$ , defined as

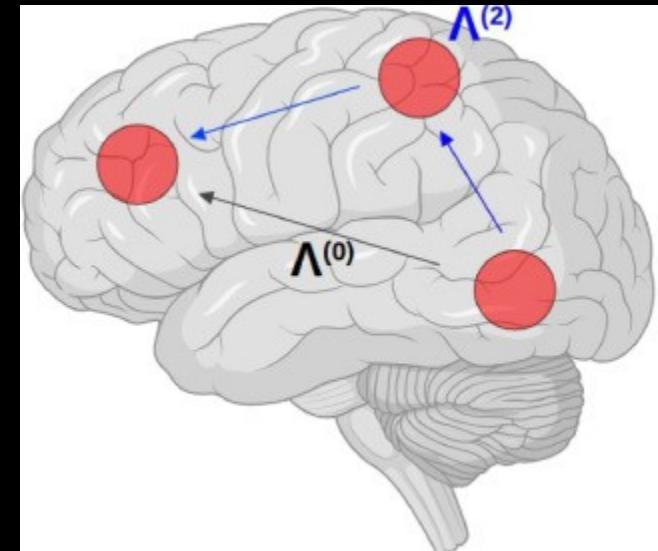
$$B_{uv} = \begin{cases} 0 & \text{if the element of } \mathbf{A}_{\text{init}} \text{ is 0} \\ 1 & \text{otherwise.} \end{cases}$$

# Structurally constrained Granger causality

Crimi et al. Neuroimage 2021

Model can be expanded as  
In the neural propagator of Robinson

$$X(t) = \sum_{\tau=1}^L A_\tau X(t - \tau) + \varepsilon(t),$$



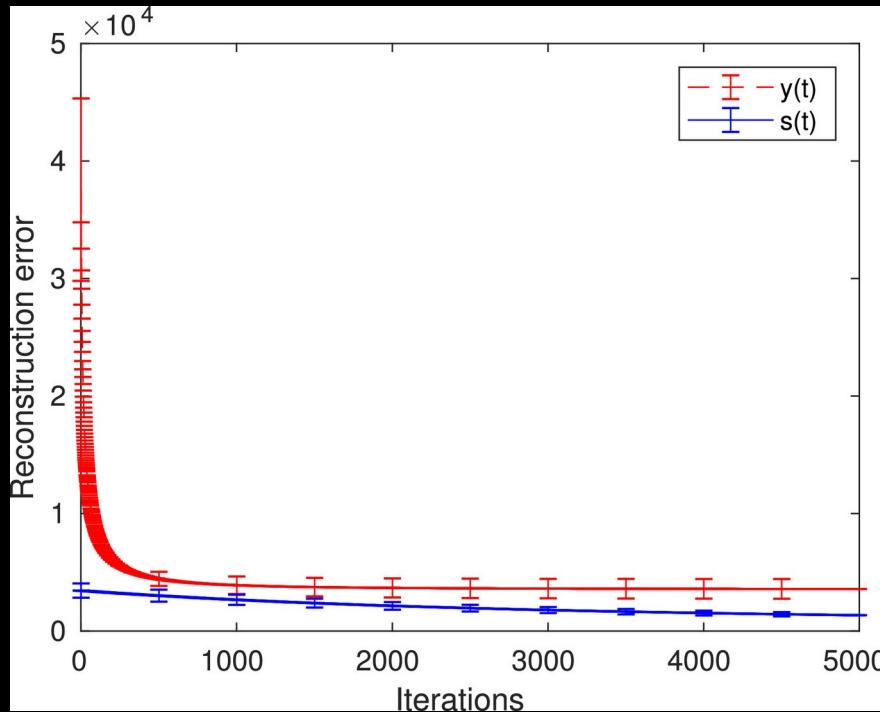
$$E = \frac{1}{2} \sum_{t=n}^T \left\| \mathbf{y}(t) - \sum_{i=1}^n \left( \mathbf{A}_i^{(0)} \odot \mathbf{B} + \mathbf{A}_i^{(2)} \odot \mathbf{B}^{(2)} \right) \mathbf{y}(t-i) \right\|_2^2.$$

# Practical considerations I

1. BOLD signal is hemodynamics not neuronal signal (but we can use deconvolution to get closer to the real signal)

Assuming a common HRF is shared across the various spontaneous point process events at a given voxel, the BOLD signal can be seen as the result of the convolution of neural states  $s(t)$  and HRF  $h(t)$ :

$$y(t) = s(t) \circledast h(t) + \epsilon(t)$$



Lesson learnt:  
If you can work  
with neural states  
not BOLD signal

# Practical considerations II

Functional ROIs are «far» from white-gray matter boundaries

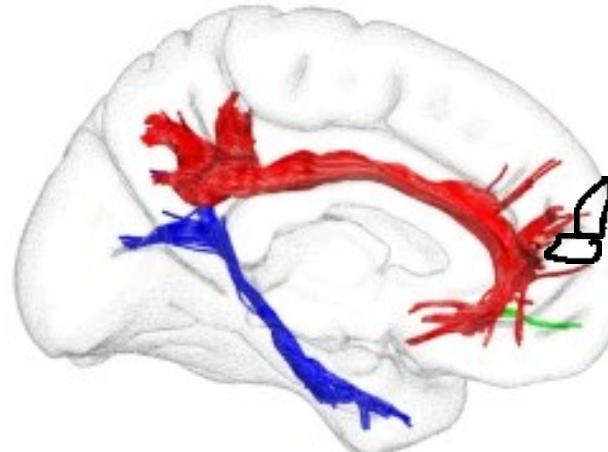
Lesson learnt: dilate ROI functional Atlas or use tricks in tractography

a

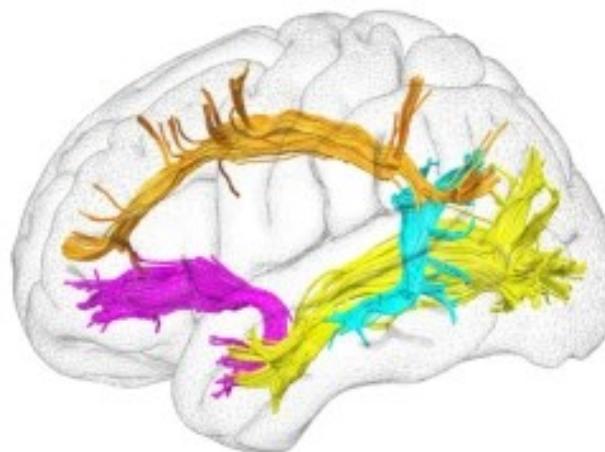
Association pathways

- █ Cingulum anterior
- █ Cingulum posterior
- █ Uncinate
- █ Superior longitudinal II
- █ Arcuate (posterior)
- █ Inferior longitudinal
- █ Frontal orbito-polar

Medial view



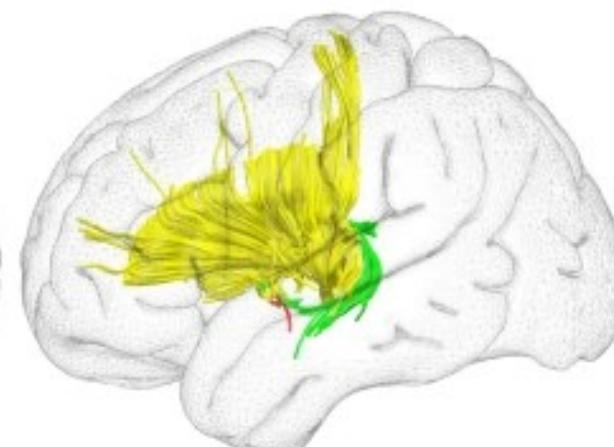
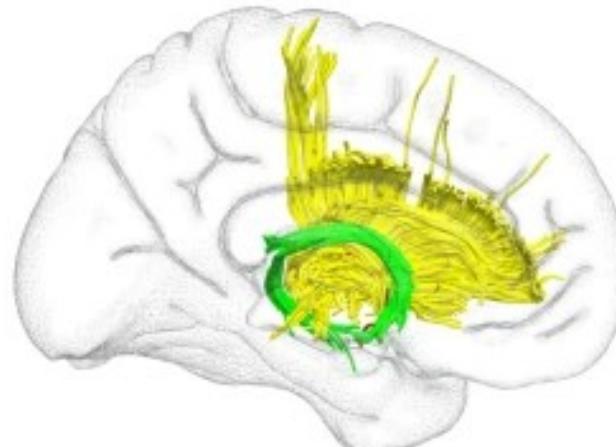
Lateral view



b

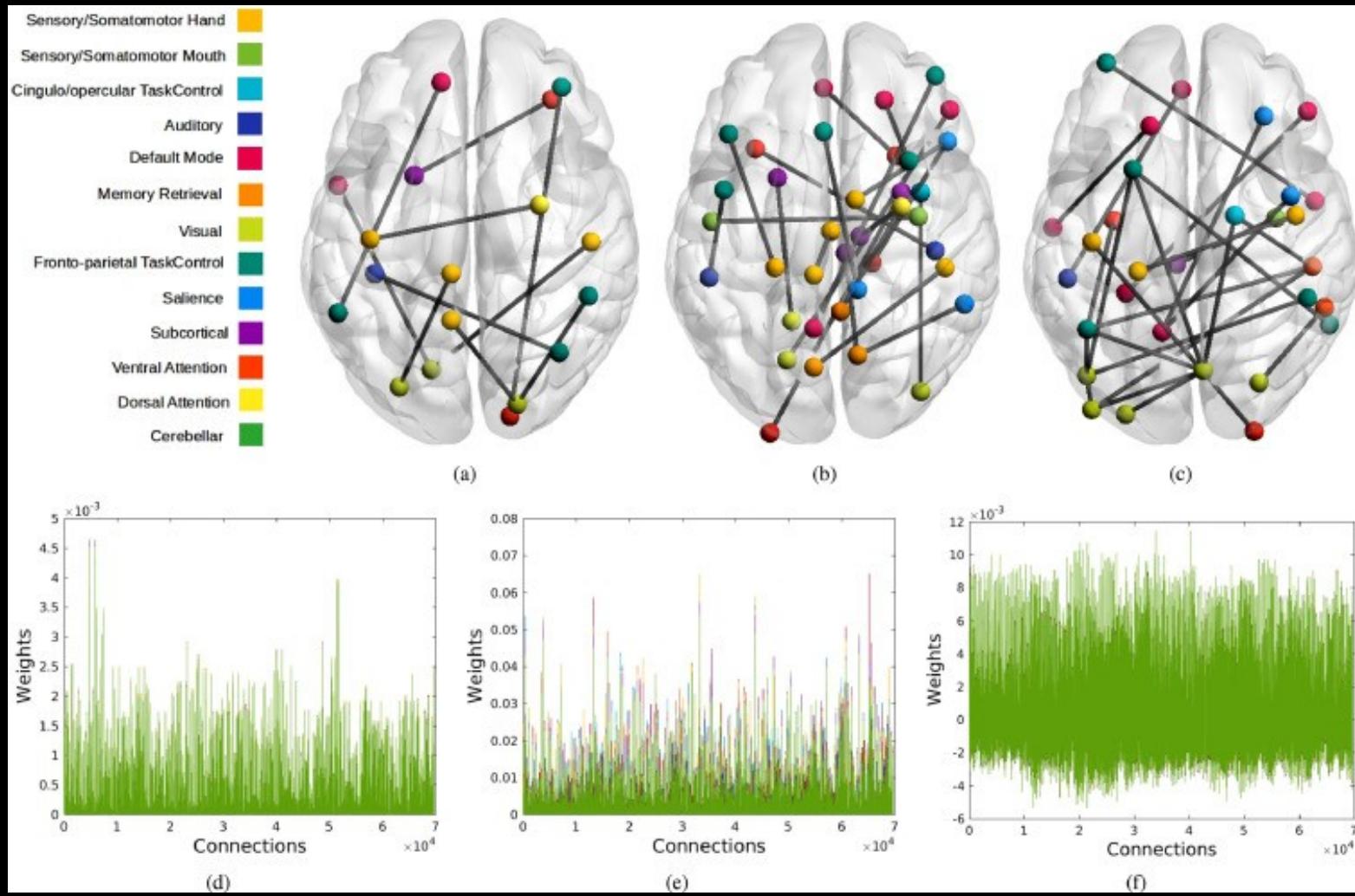
Projection pathways

- █ Basal forebrain - thalamus
- █ Anterior thalamic radiations
- █ Fornix



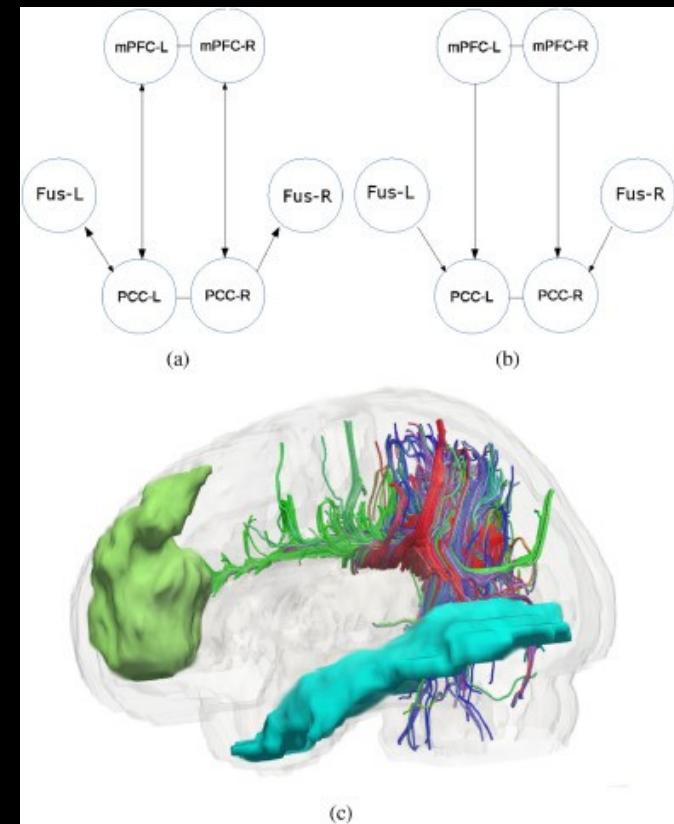
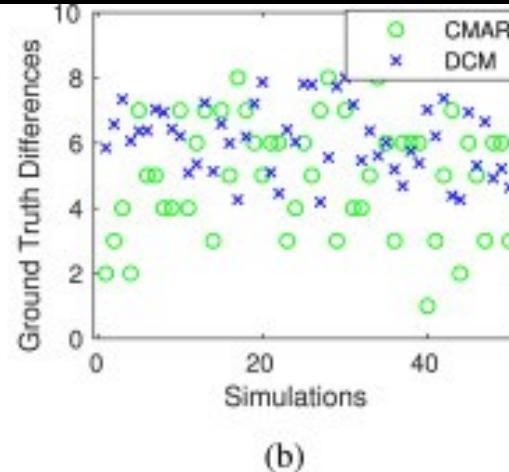
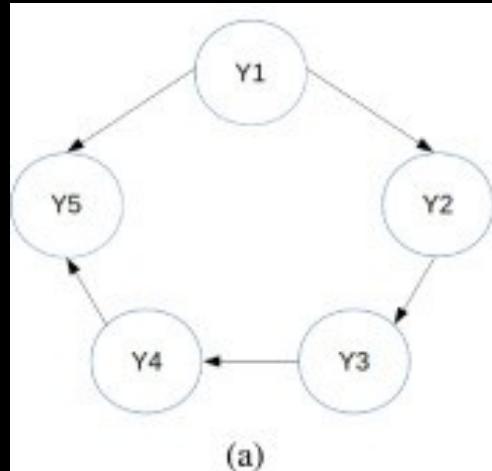
# Results I

In a classification task (SVM) from ASD dataset better performance were obtained with eff.conn., then func. Con. and lastly structural con.  
Discriminant func/eff connection were consistent with Yahata et al. Nat. Com 2016



# Results II

**More consistent than DCM (simulation and with DMN «ground-truth»)**

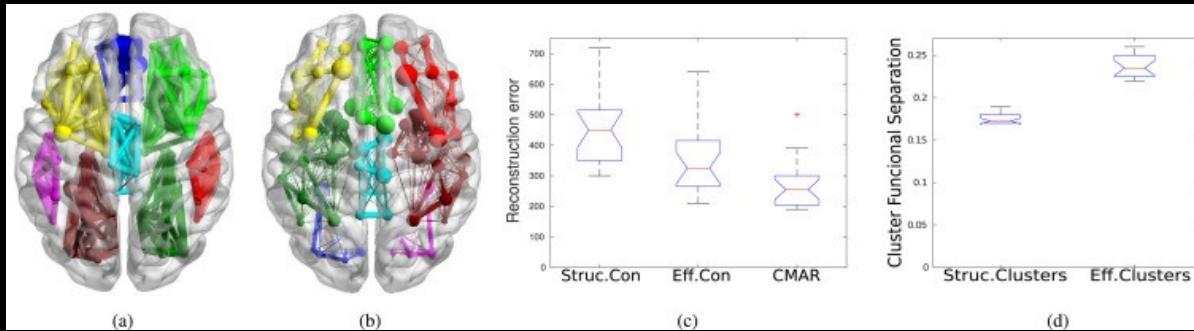


**Let's complain about DCM: it is not  
Good for resting-state, you need to use a  
Variation of it (stochastic-DCM)**

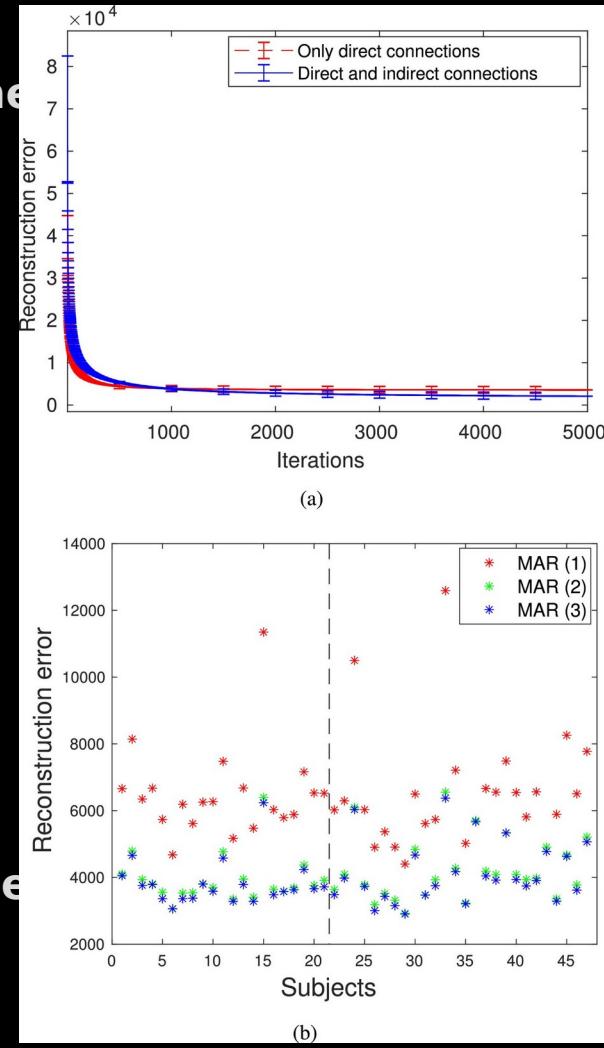
# Results III

**Lower reconstruction error using also indirect connections**

**For our signal up to 2 time point back was enough**



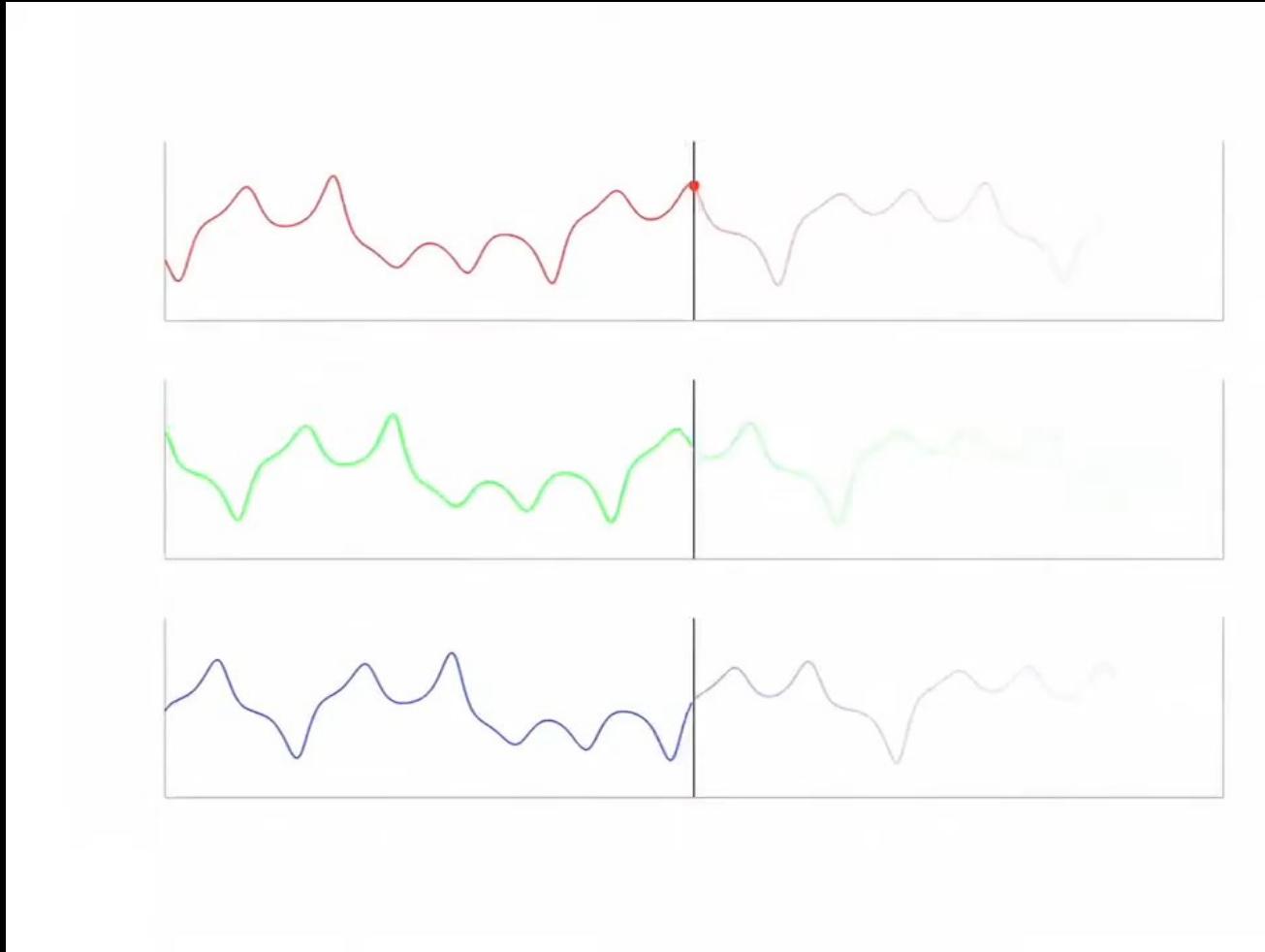
**If we do clustering, clusters are obviously with less nodes**



# Sugihara Causality

- Perturbation causality cannot be tested in all cases.
- **However, let's find something better than Granger causality (address the separability of X and Y)**
- if X drives Y, then a record of the X's influence will be present in the history of Y, and therefore a continuous delay map from Y to X exist
- primarily suited for weakly coupled components of non-linear dynamic systems
- justified by Takens theorems : when two different variables represent different parts of the same dynamical system their shadow manifolds are diffeomorphic to the true attractor and therefore to each other: If x has a causal influence on the dynamics of Y, then X will influence the dynamics of Y. (Sugihara et al. Science 2012).
- This is not an hypothesis testing approach as DCM as it can easily scaled to brain-wide scenarios.

# Sugihara Causality



# Sugihara Causality

## State Space Reconstruction: Convergent Cross Mapping

A supplemental simulation and animation for  
“Detecting Causality in Complex Ecosystems”

George Sugihara, Robert May, Hao Ye, Chih-hao Hsieh,  
Ethan Deyle, Mike Fogarty, and Stephan Munch

animation by: Hao Ye and George Sugihara

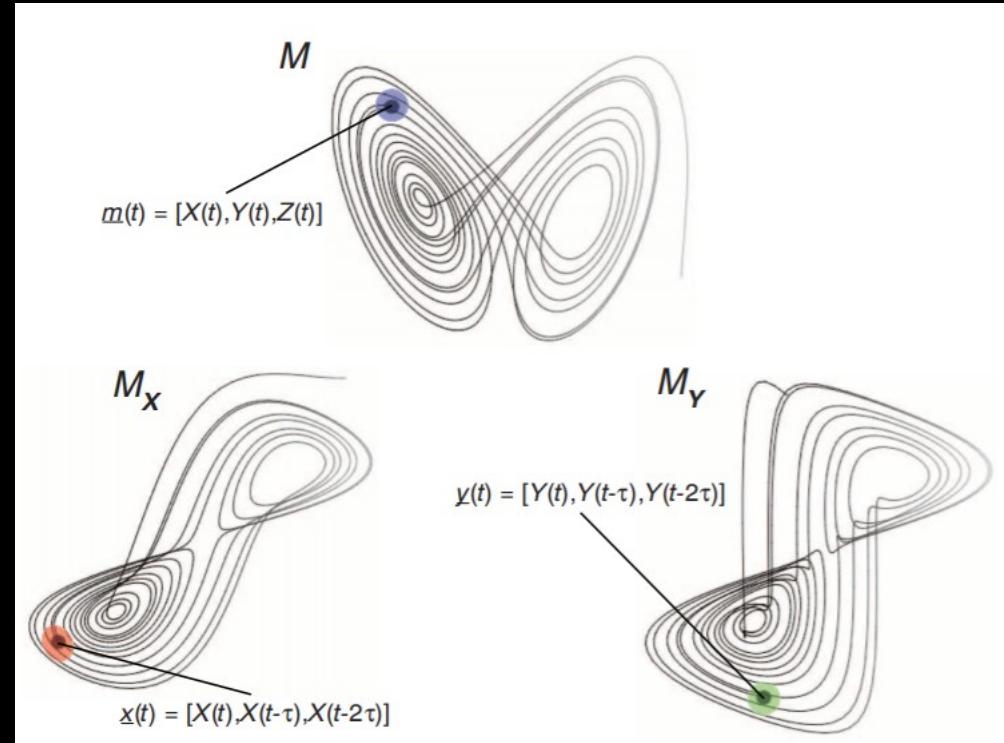
© August 2012

# Sugihara Causality

$$\mathbf{x}_t = [x(t-(d-1)), \dots, x(t-1), x(t)],$$

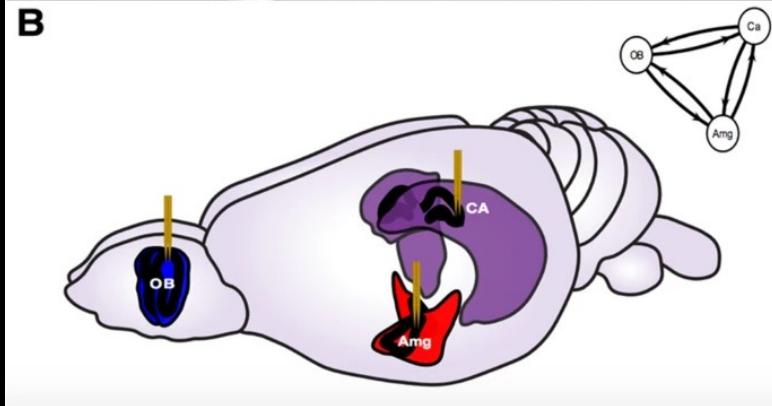
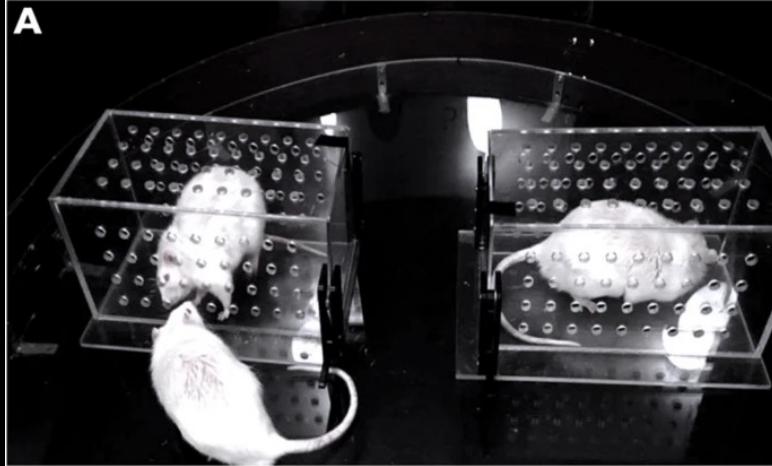
$$\hat{y}(t) | \mathbf{M_x} = \sum_{i=1}^{d+1} w_i y(t_i)$$

$$w_i = \frac{e^{-\|\mathbf{x}_t - \mathbf{x}_{t_i}\|^2 / \|\mathbf{x}_t - \mathbf{x}_{t_1}\|^2}}{\sum_{j=1}^{d+1} e^{-\|\mathbf{x}_t - \mathbf{x}_{t_j}\|^2 / \|\mathbf{x}_t - \mathbf{x}_{t_1}\|^2}}$$

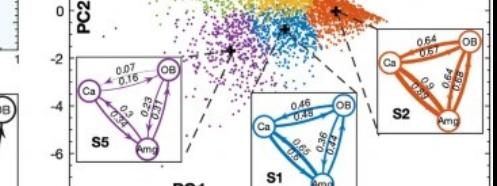
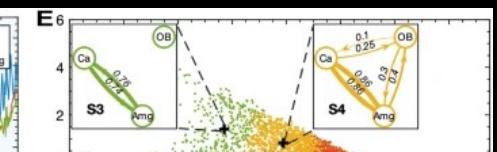
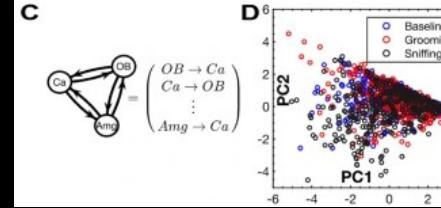
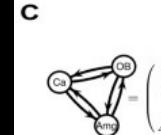
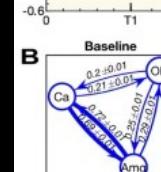
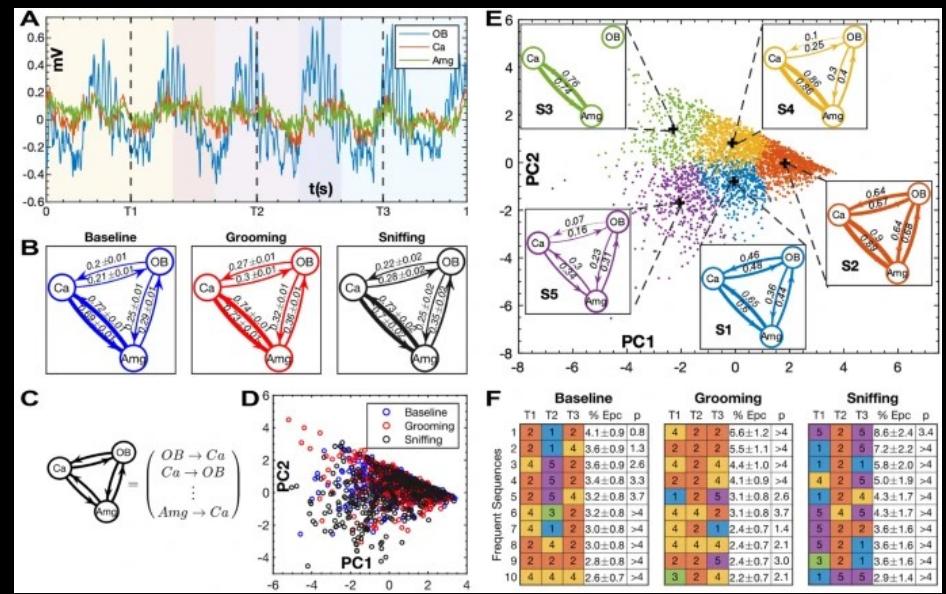


Sugihara et al. Science 2012

# Sugihara Causality in Neuroimaging



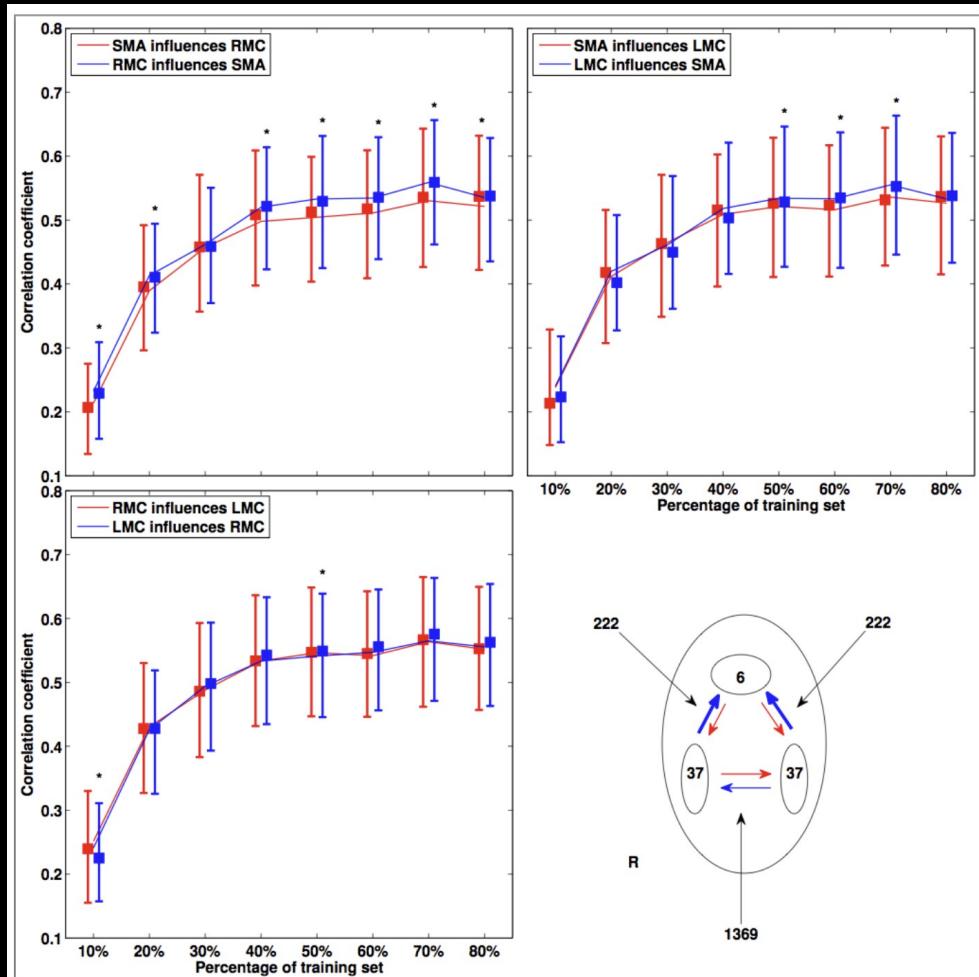
Rats were surgically implanted with electrodes for electrophysiological recordings in the main olfactory bulb (OB), hippocampus (CA) and medial amygdala (Amg).  
Breston et al. Nature SciRep 2021



# Sugihara Causality in Neuroimaging

Tapping experiment

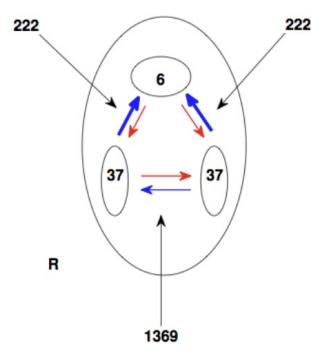
Wisemueller et al. 2019 Biorxiv



supplementary motor area (SMA)

Left somatomotor cortex (LMC)

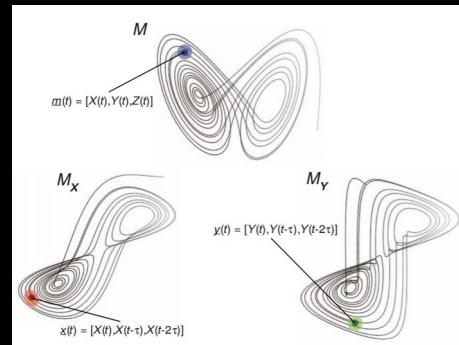
Right somatomotor cortex (RMC)



# Structurally constrained Sugihara Causality

$$\mathbf{x}_t = [x(t-(d-1)), \dots, x(t-1), x(t)],$$

$$\hat{y}(t) | \mathbf{M}_{\mathbf{x}} = \sum_{i=1}^{d+1} w_i y(t_i)$$



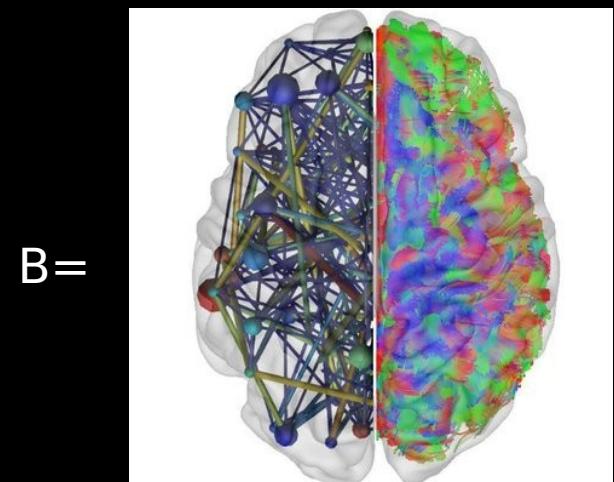
$$w_i = \frac{e^{-\|\mathbf{x}_t - \mathbf{x}_{t_i}\|^2 / \|\mathbf{x}_t - \mathbf{x}_{t_1}\|^2}}{\sum_{j=1}^{d+1} e^{-\|\mathbf{x}_t - \mathbf{x}_{t_j}\|^2 / \|\mathbf{x}_t - \mathbf{x}_{t_1}\|^2}}$$

$$\widehat{\mathbf{A}}_i = \mathbf{A}_i \odot \mathbf{B} \quad (2)$$

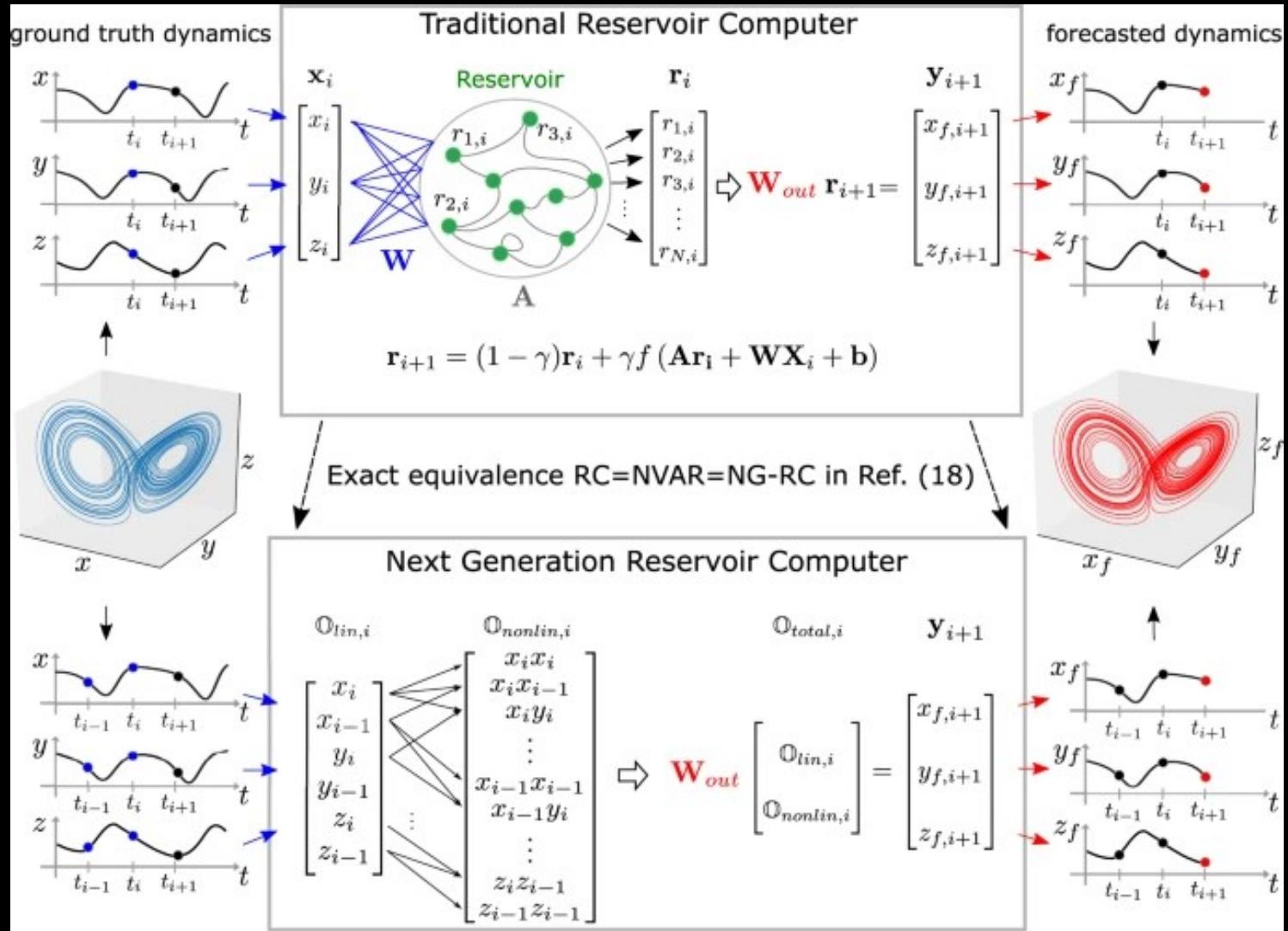
where  $\odot$  denotes the Hadamard or element-wise product, and  $\mathbf{B}$  is an indicator matrix obtained by the structural connectivity  $\mathbf{A}_{\text{init}}$ , defined as

$$B_{uv} = \begin{cases} 0 & \text{if the } u \text{th element of } \mathbf{A}_{\text{init}} \text{ is } 0 \\ 1 & \text{otherwise.} \end{cases}$$

Pairwise but Brainwide

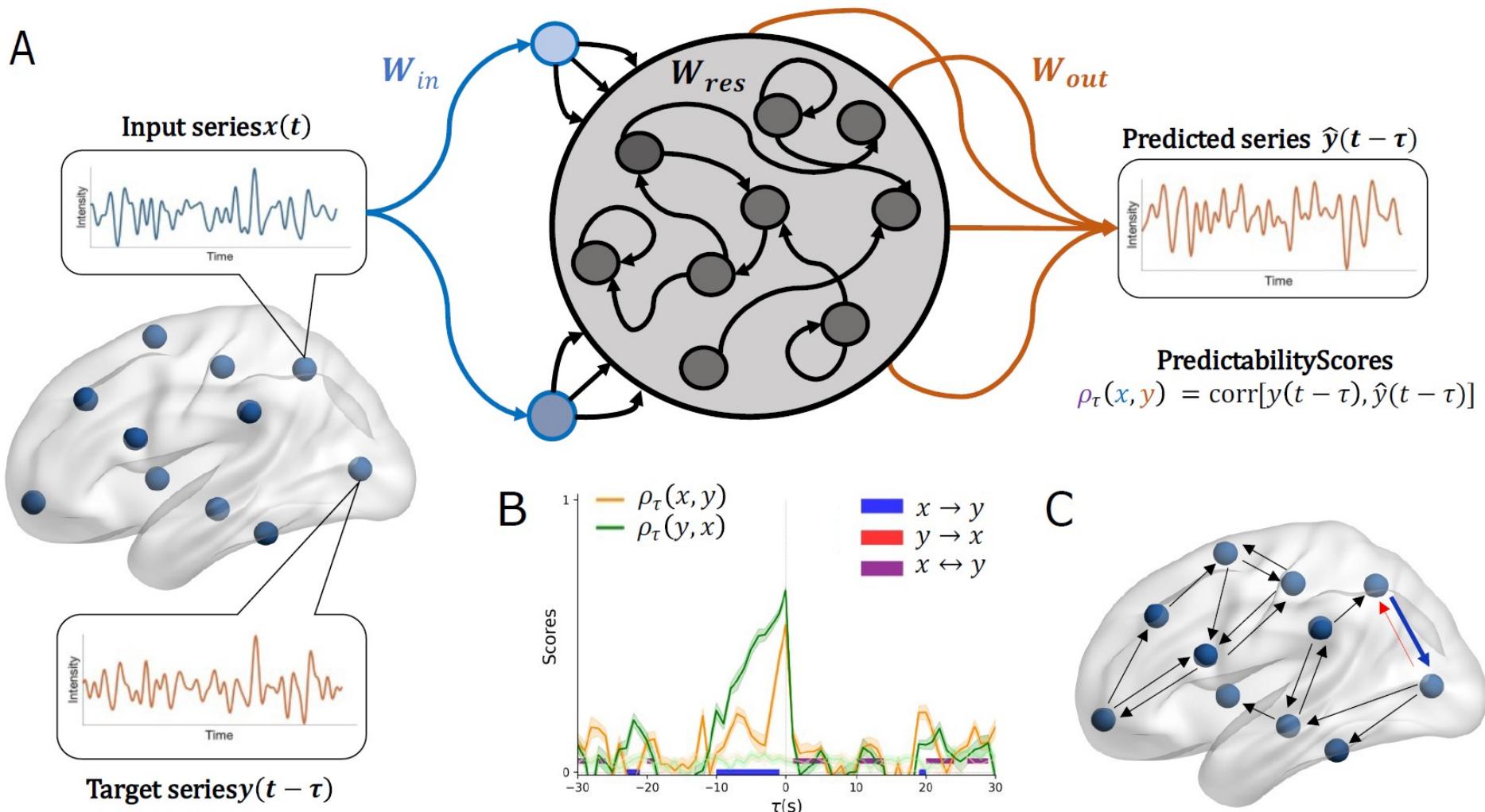


# Recurrent neural networks

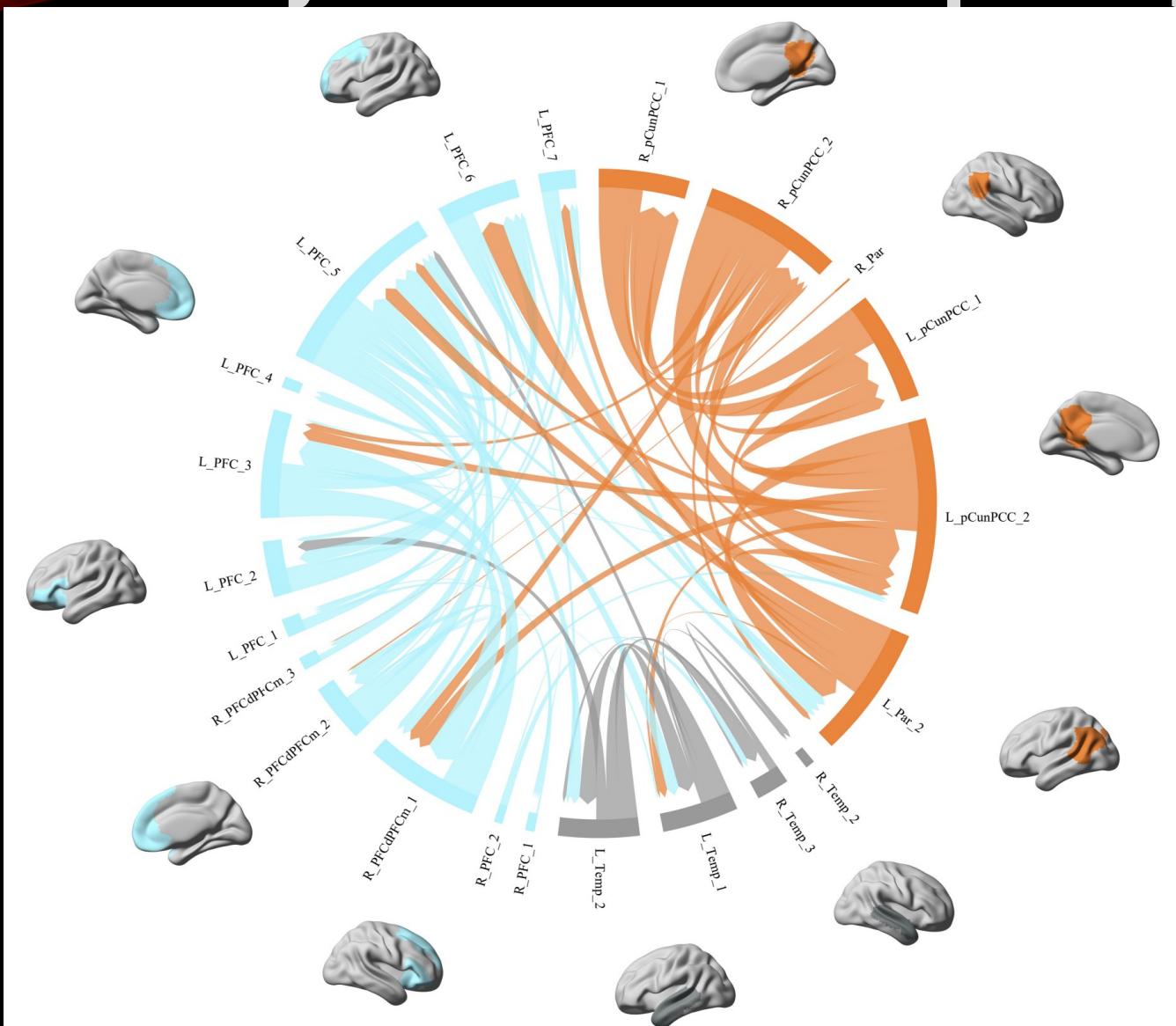


# Causality reservoir computing

A

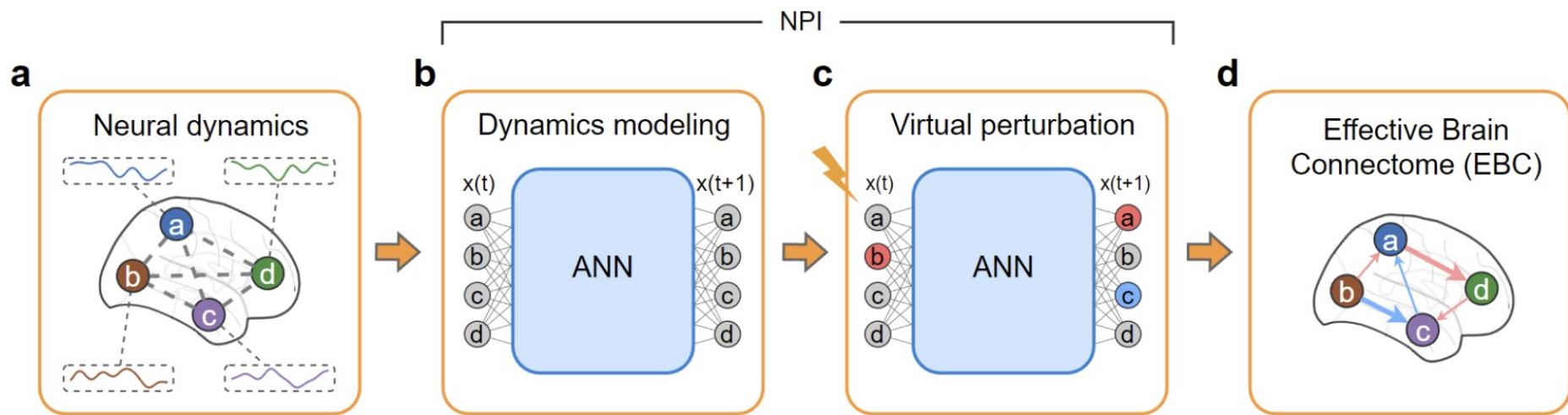


# Causality reservoir computing

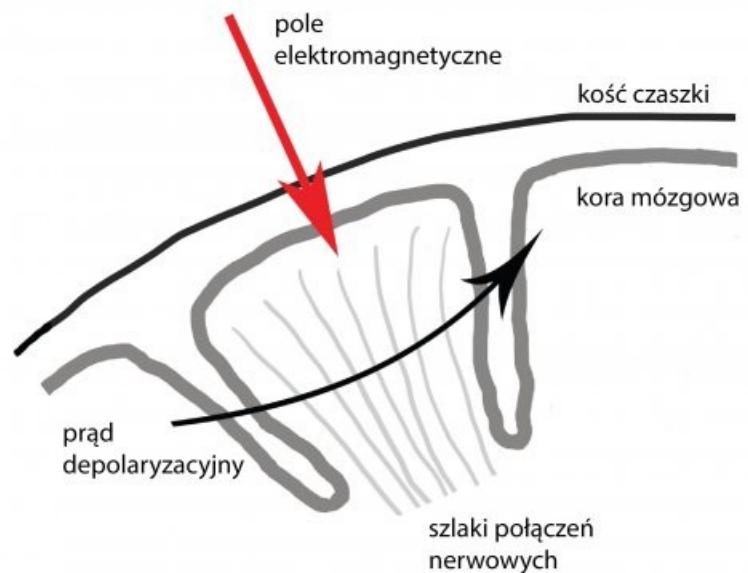
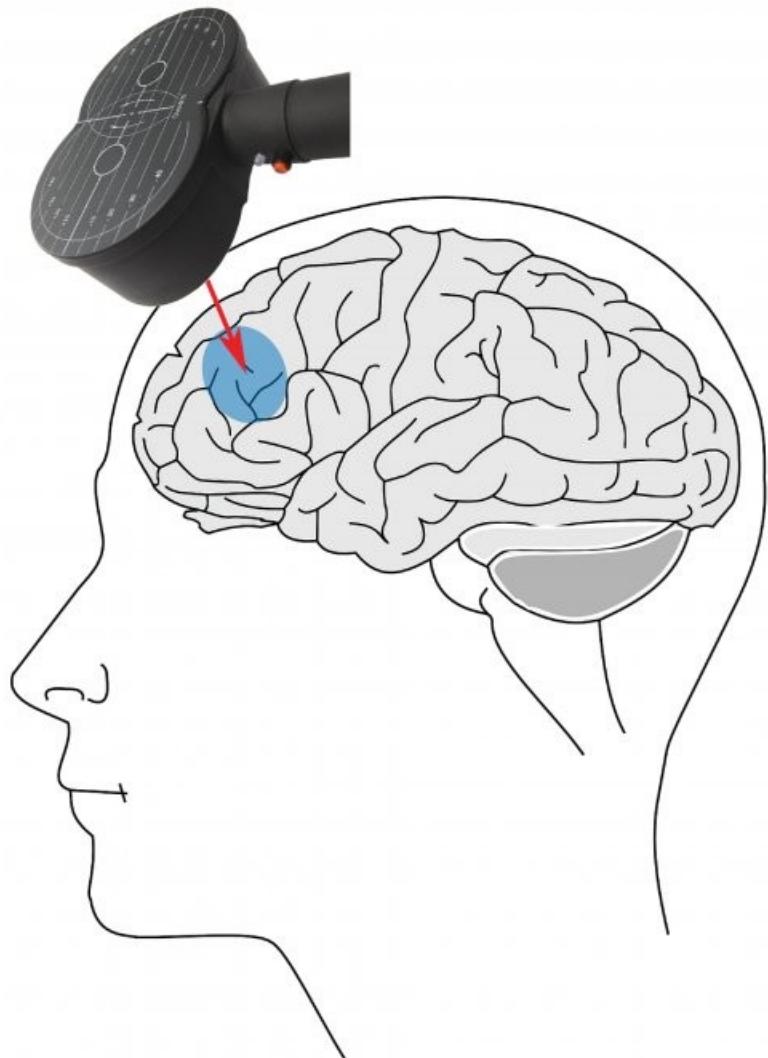


Falco-Roget, Onicas, Crimi Biorxiv  
2023

# Neural perturbation inference



# Real perturbation



# Conclusions

- Eating chocolate won't give you the business prize but living in a country with high GDP will raise the chances.
- Sugihara solves the separability issue of Granger causality, it is worth exploring, as there are many other study related to brain state as attractors.
- Reservoir computing address many things (though not resolving the unseen variables issue)
- Pearl Causality is still holding the best position:  
Construct experiments using TMS or similar.
- Maybe we should give up our obsessions for effective connectivity and simply use functional connectivity biomarkers

