Relaciones estructura-función en modelos biofísicos de cerebro completo

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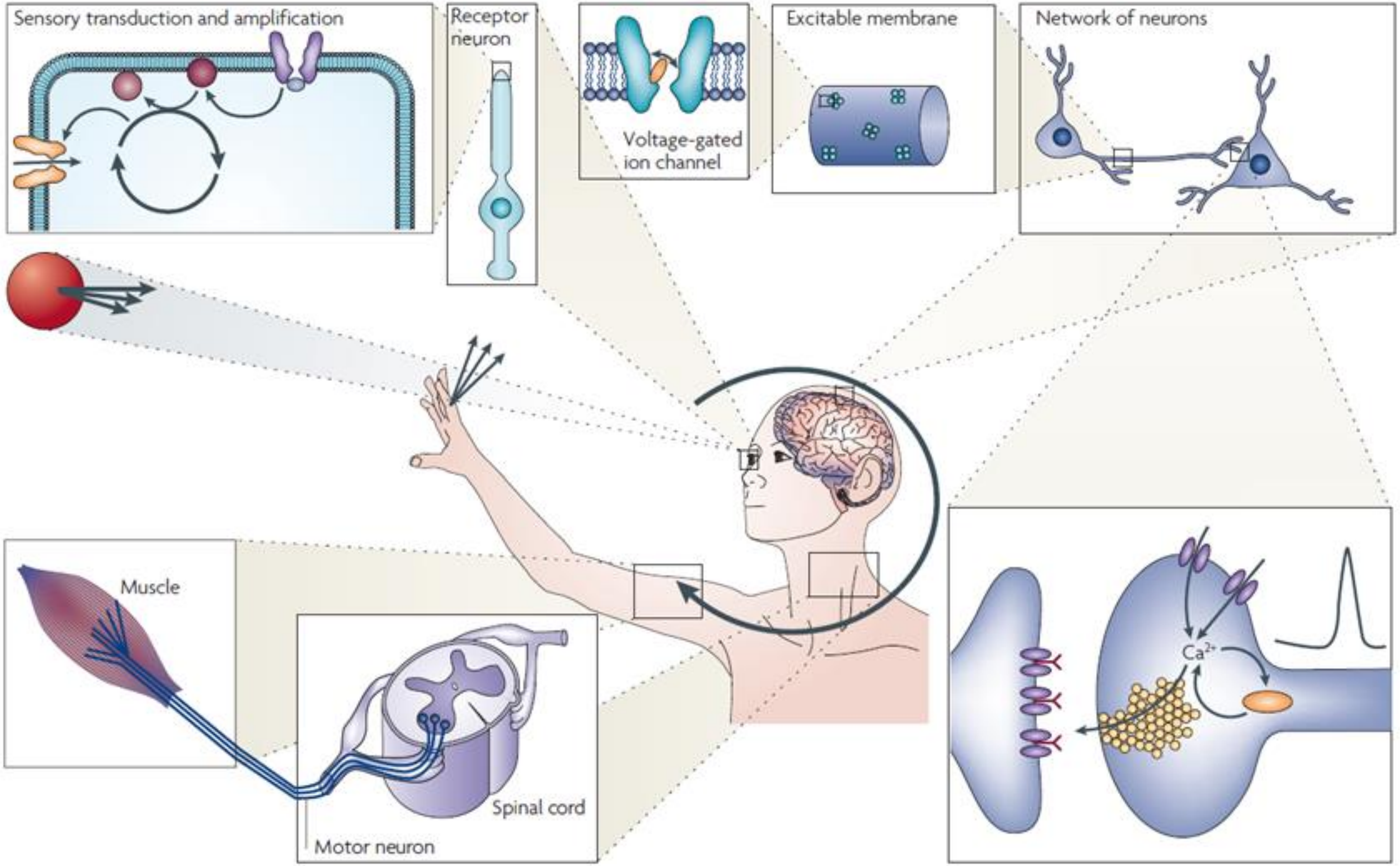
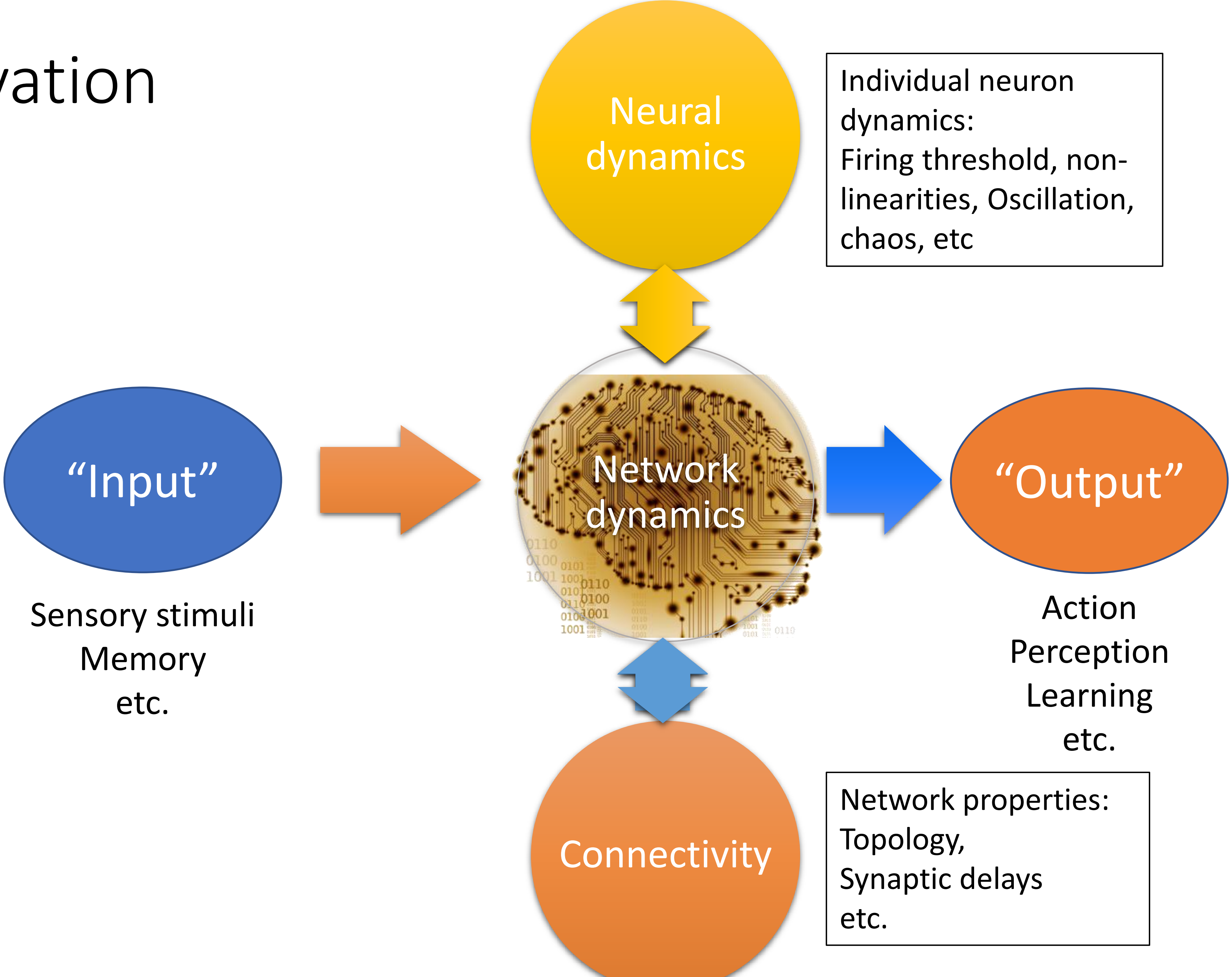
UV



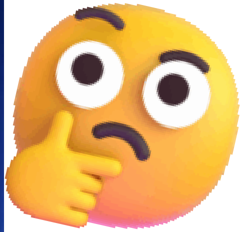
Adaptado de: Faisal A.A., Selen L. & Wolpert D.M.(2008).
Noise in the nervous system. *Nat Rev Neurosci* **9**:292-303

Motivation


Neural dynamics
Individual neuron dynamics:
Firing threshold, non-linearities, Oscillation, chaos, etc
“Input”
Sensory stimuli
Memory
etc.
Network dynamics
“Output”
Action
Perception
Learning
etc.
Connectivity
Network properties:
Topology,
Synaptic delays
etc.

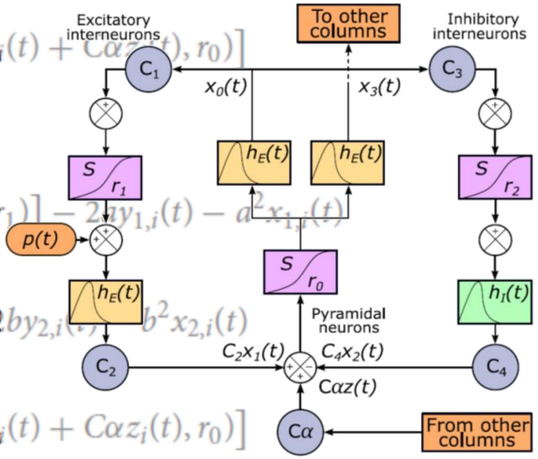
Brain dynamics ?

VANDAL
Valparaíso
Neural Dynamics
Laboratory

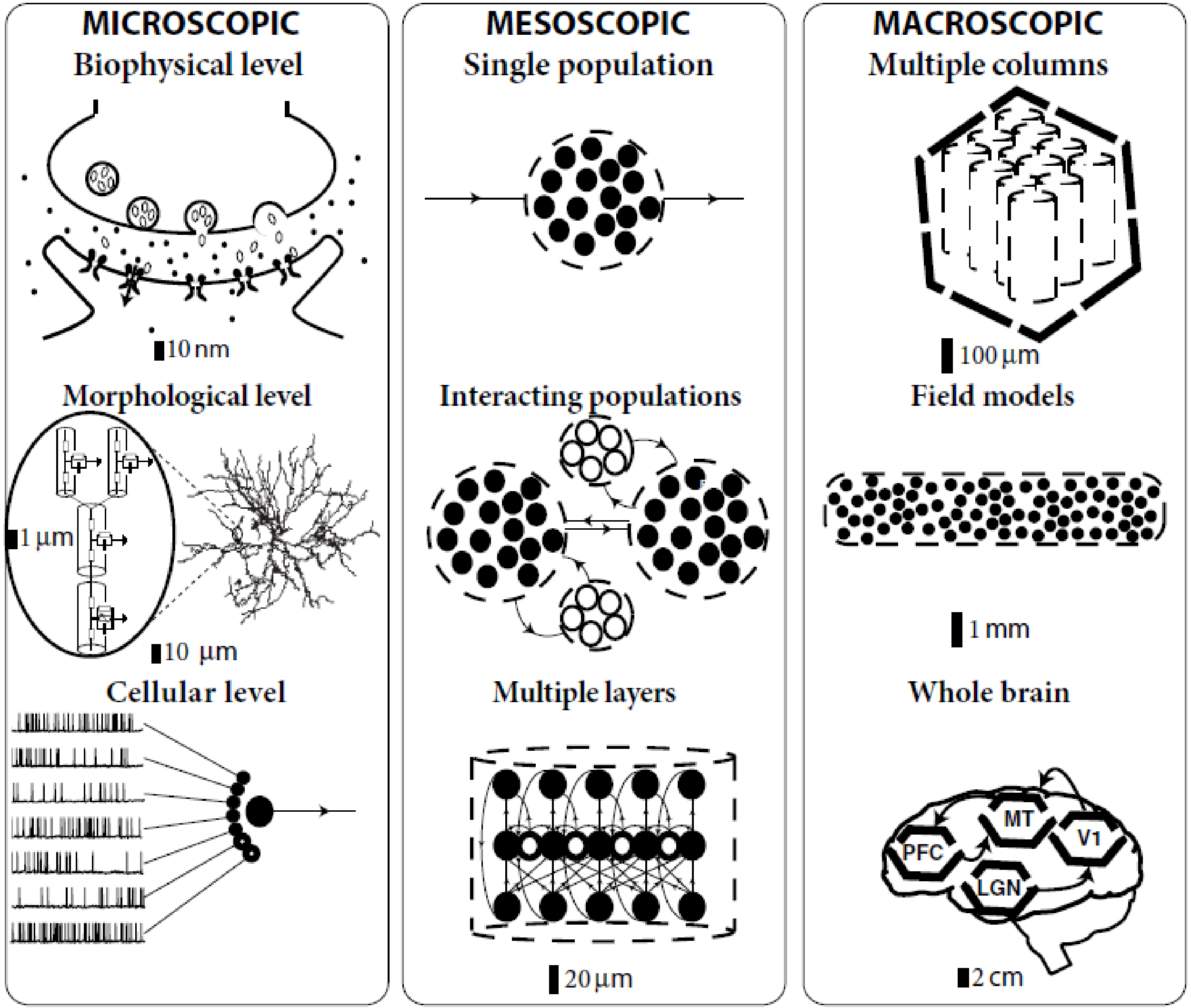





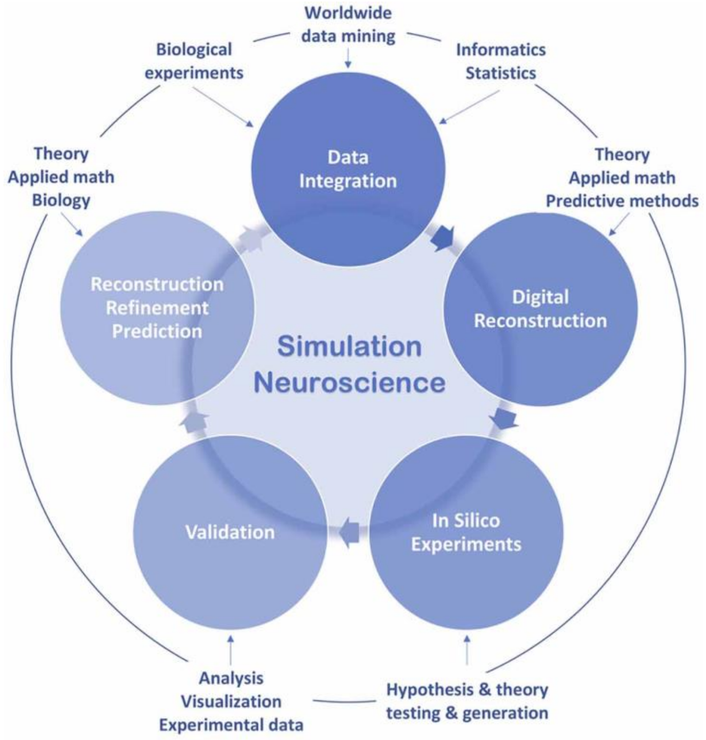

$$
\begin{aligned}
\dot{x}_{0,i}(t) &= y_{0,i}(t) \\
\dot{y}_{0,i}(t) &= Aa\left[S(C_2 x_{1,i}(t) - C_4 x_{2,i}(t) + C\alpha z_i(t), r_0)\right] \\
&\quad - 2a y_{0,i}(t) - a^2 x_{0,i}(t) \\
\dot{x}_{1,i}(t) &= y_{1,i}(t) \\
\dot{y}_{1,i}(t) &= Aa\left[p(t) + S(C_1 x_{0,i}(t), r_1)\right] - 2a y_{1,i}(t) - a^2 x_{1,i}(t) \\
\dot{x}_{2,i}(t) &= y_{2,i}(t) \\
\dot{y}_{2,i}(t) &= Bb\left[S(C_3 x_{0,i}(t), r_2)\right] - 2b y_{2,i}(t) - b^2 x_{2,i}(t) \\
\dot{x}_{3,i}(t) &= y_{3,i}(t) \\
\dot{y}_{3,i}(t) &= A\bar{a}\left[S(C_2 x_{1,i}(t) - C_4 x_{2,i}(t) + C\alpha z_i(t), r_0)\right] \\
&\quad - 2\bar{a} y_{3,i}(t) - \bar{a}^2 x_{3,i}(t)
\end{aligned}
$$



Models at different scales



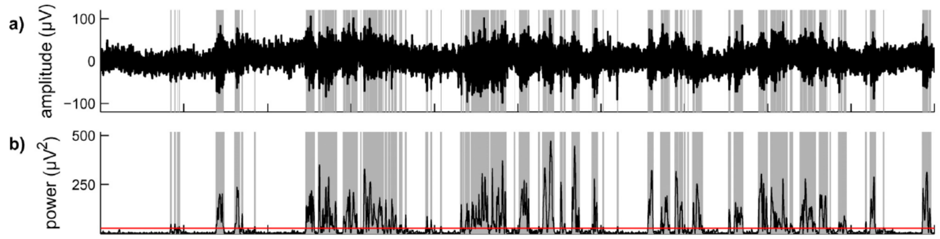
‘**Models**’ in the physics sense
- A set of rules that predict the time evolution (or the equilibrium statistics) of a system, *based on known or assumed physical laws.*

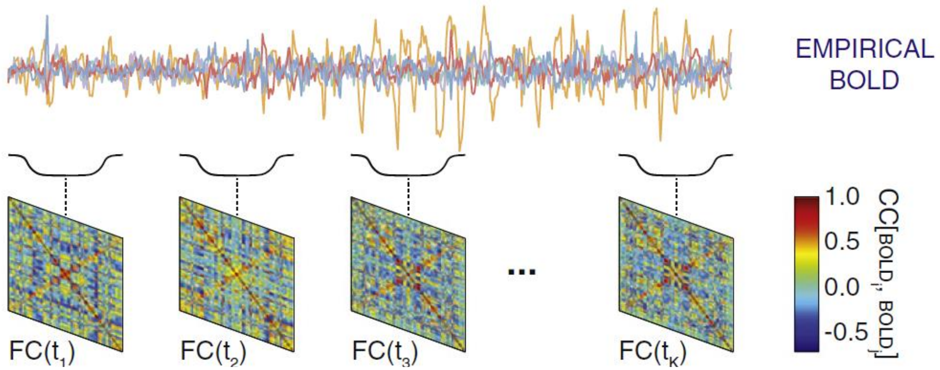


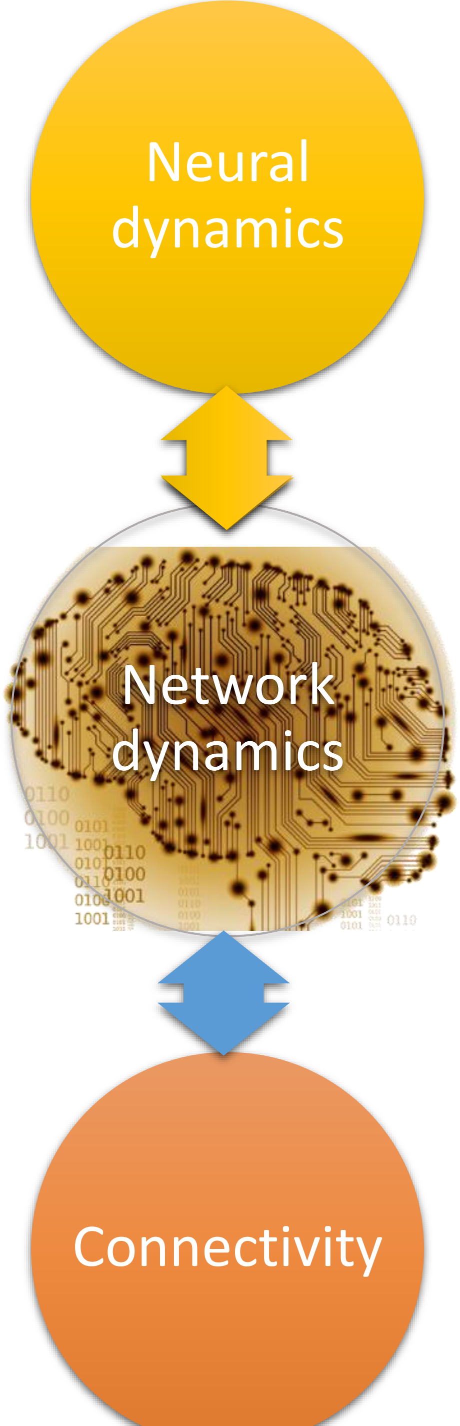
Ongoing Dynamics

- a.k.a. “Resting State”
  “Spontaneous activity”

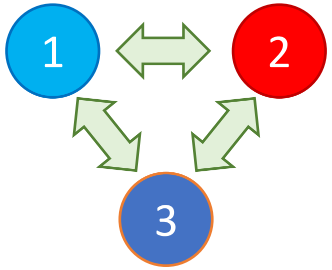
Multistability

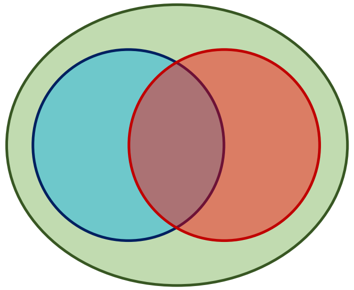




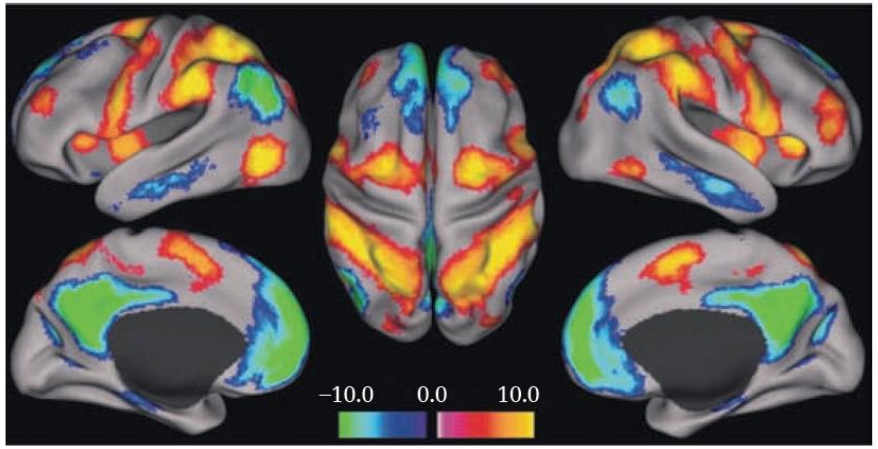


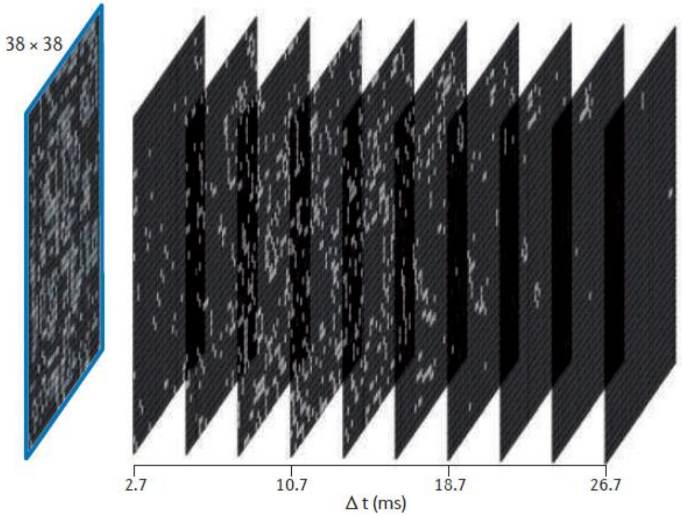
High-order interdependencies: Synergy, Redundancy

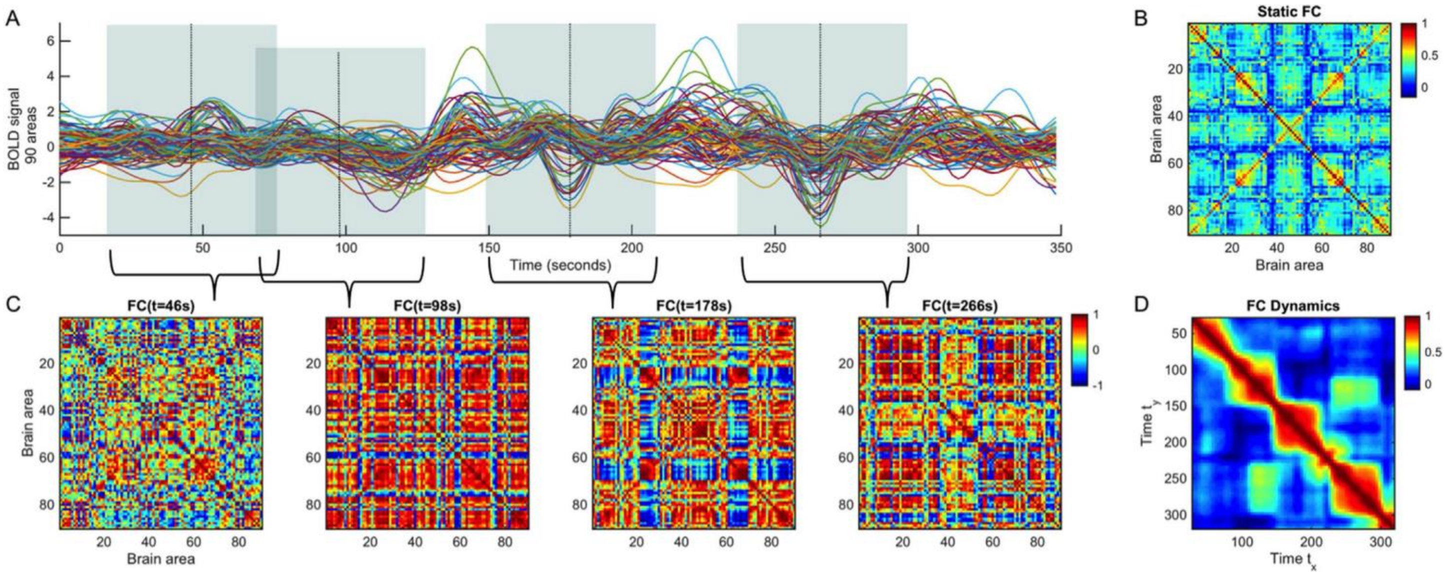




Multistability in Neural Networks



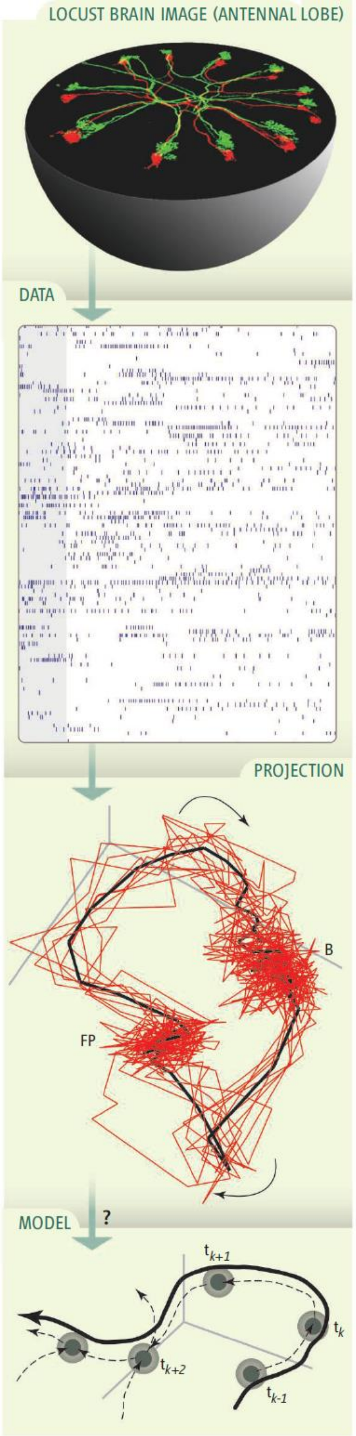




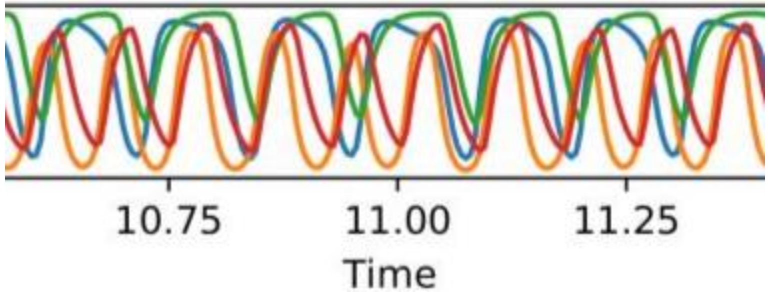
Observed in EEG/MEG and fMRI (diverse time scales)
“Resting” (no task) activity.

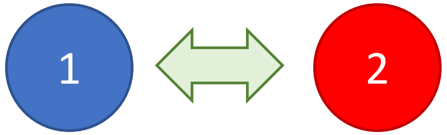
Multistability in Neural Networks

- Different subnetworks transiently engaging with phase synchrony or coherence.
- Allows the system to explore a large number of state configurations
  - efficient coding of the ever-changing surrounding environment
- Mechanism to deal with sensory novelty and allow for learning
- Associated to:
  - delays in synaptic communication.
  - Optimal range of the global coupling strength.
  - network topology: multi-stability is lost when the connections are randomized.
  - Chaotic and/or noisy dynamics

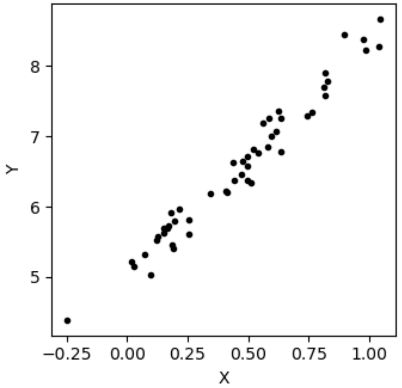


High-order interdependencies

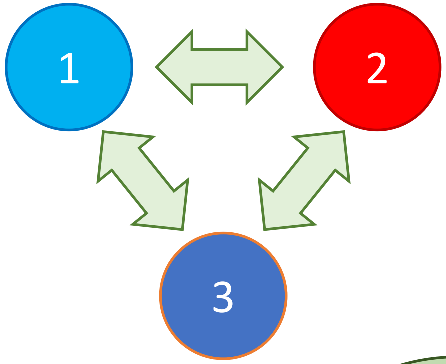


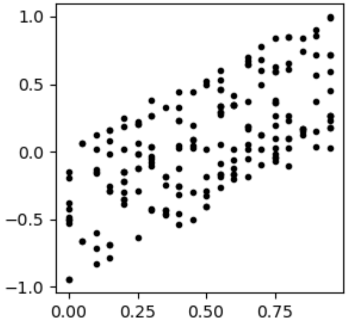


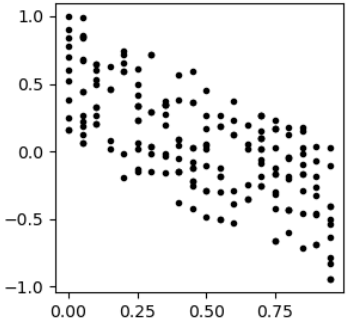
correlación



Información que 1 entrega acerca de 2



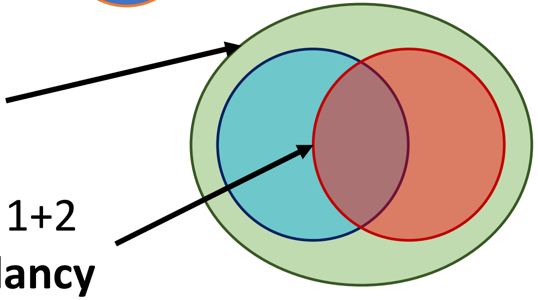


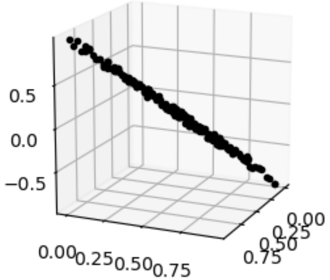


“The whole is more than the sum of its parts”

1 y 2 > 1+2
Synergy

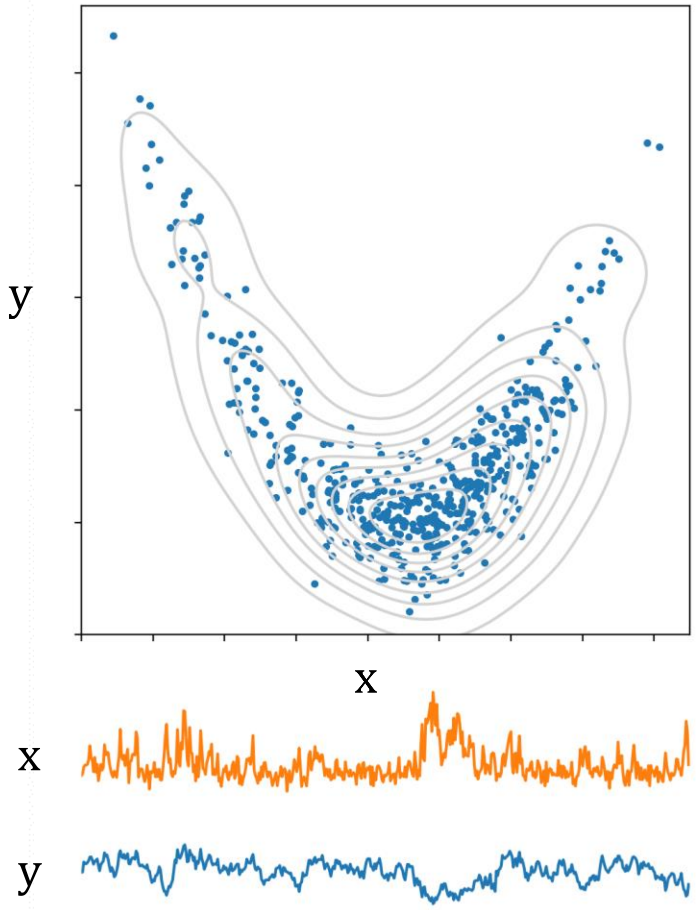
1 y 2 < 1+2
Redundancy

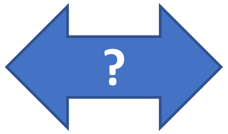


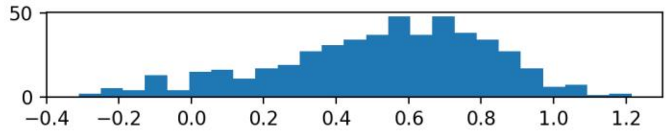


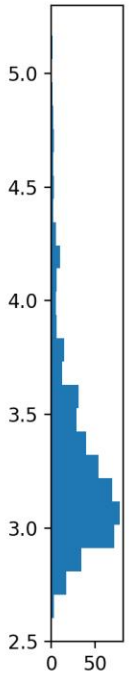
1 y 2

Mutual Information in 1 minute









Shannon Entropy

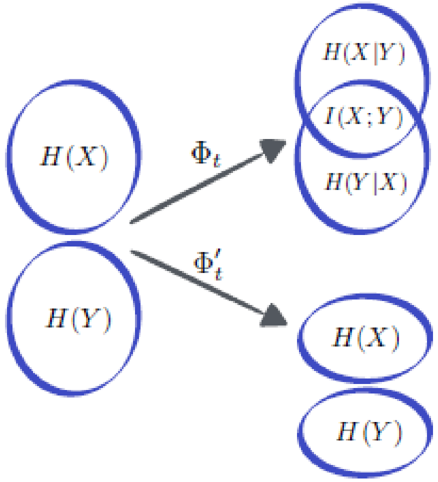
$$H(X) := -\sum_{x \in X} p(x) \log p(x)$$

$$H(X) = -\int_{\mathbb{X}} f(x) \log f(x)\, dx$$

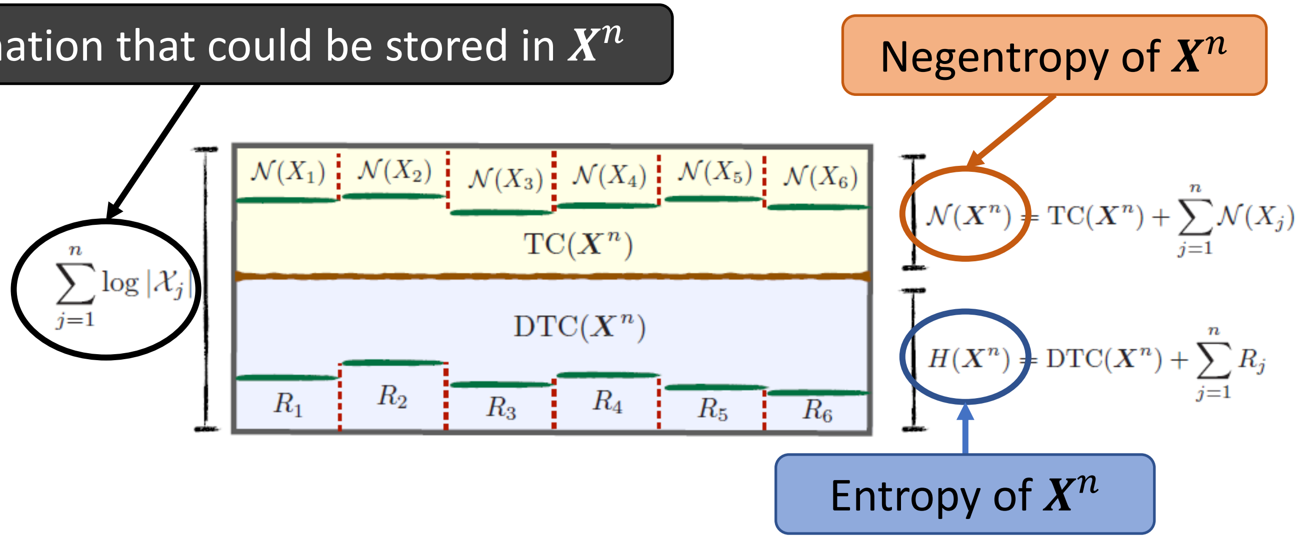
$$I(X;Y) = D_{\mathrm{KL}}\left(P_{(X,Y)} \parallel P_{(X)} \otimes P_{(Y)}\right)$$

Kullback–Leibler divergence.

$$I(X;Y) = \int_y \int_X P_{(X,Y)}(x,y) \log\left(\frac{P_{(X,Y)}(x,y)}{P_X(x)P_Y(y)}\right) dxdy$$



ϕ and ϕ’: Dynamical systems that decrease the entropy of the agents $\boldsymbol{X}$ and $\boldsymbol{Y}$



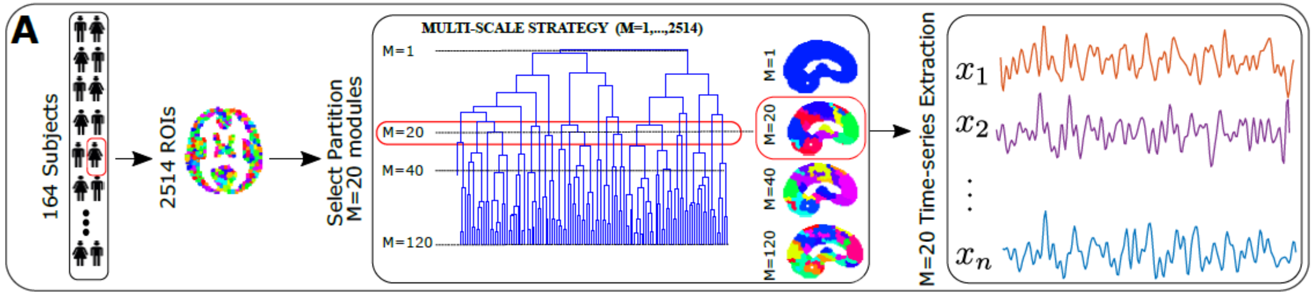
$H(\boldsymbol{X}^n) = DTC(\boldsymbol{X}^n) + \sum_{j=1}^{n} \boldsymbol{R}_j$	Entropy = shared randomness (DTC) + individual randomness ($\sum \boldsymbol{R}_j$)
$\mathcal{N}(\boldsymbol{X}^n) = TC(\boldsymbol{X}^n) + \sum_{j=1}^{n} \mathcal{N}(X_j)$	Negentropy = collective constraints (TC) + individual constraints
$\Omega(\boldsymbol{X}^n) = TC(\boldsymbol{X}^n) - DTC(\boldsymbol{X}^n)$	O-information $\Omega > 0$ → redundancy; $\Omega < 0$ → synergy
$\Sigma(\boldsymbol{X}^n) = TC(\boldsymbol{X}^n) + DTC(\boldsymbol{X}^n)$	S-information Total collective interactions

Mediano, P.A.M.; Rosas F; et al., 2018; 2019

High-order interdependencies in the aging brain

Marilyn Gatica[a,b], Rodrigo Cofré[c], Pedro A.M. Mediano[d], Fernando E. Rosas[e,f,g], Patricio Orio[a,h], Ibai Diez[i,j,k], S.P. Swinnen[l,m] and Jesus M. Cortes[n,o,p]

Brain Connectivity, 2021



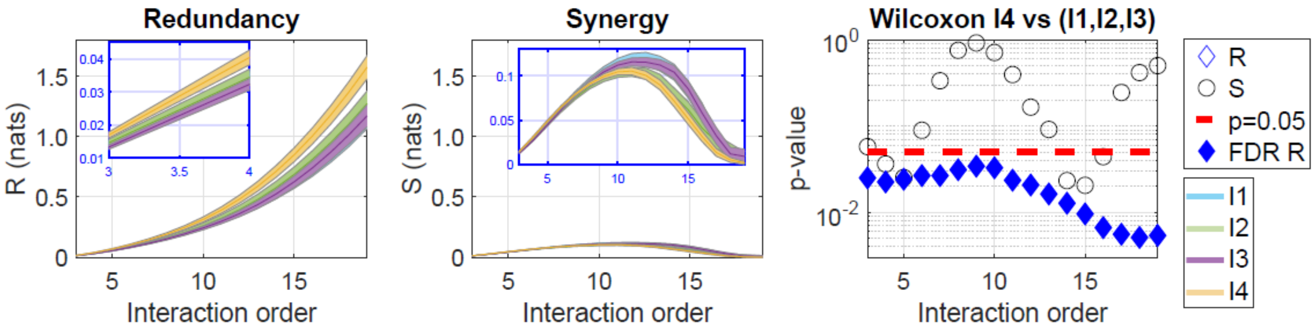


Figure 3: Significantly increased redundancy in older participants across all interaction orders. Average over all modules

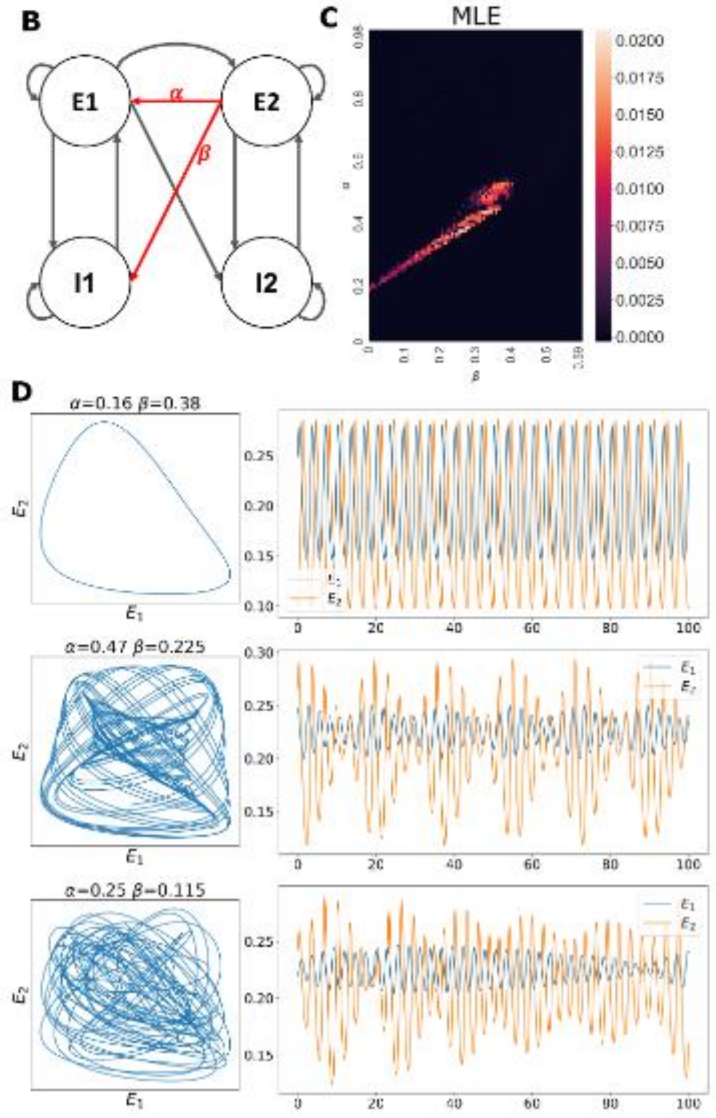
Preguntas de Investigación

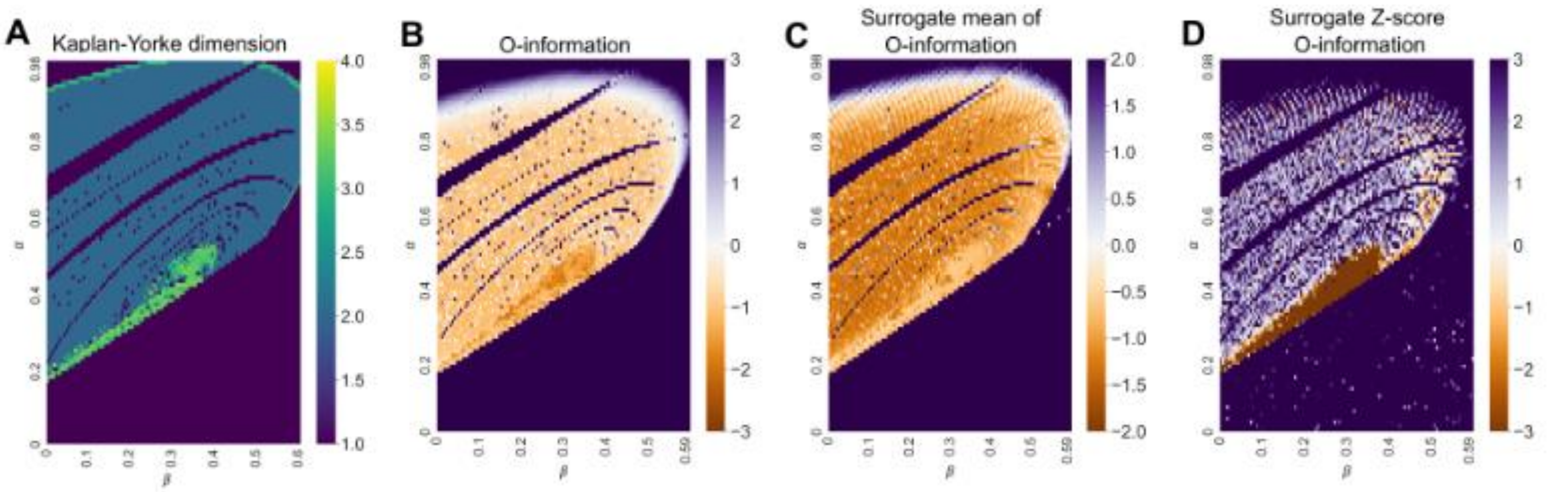
- ¿Cuáles son las condiciones para que emerja sinergia (redundancia) en sistemas dinámicos inspirados en la biofísica cerebral?

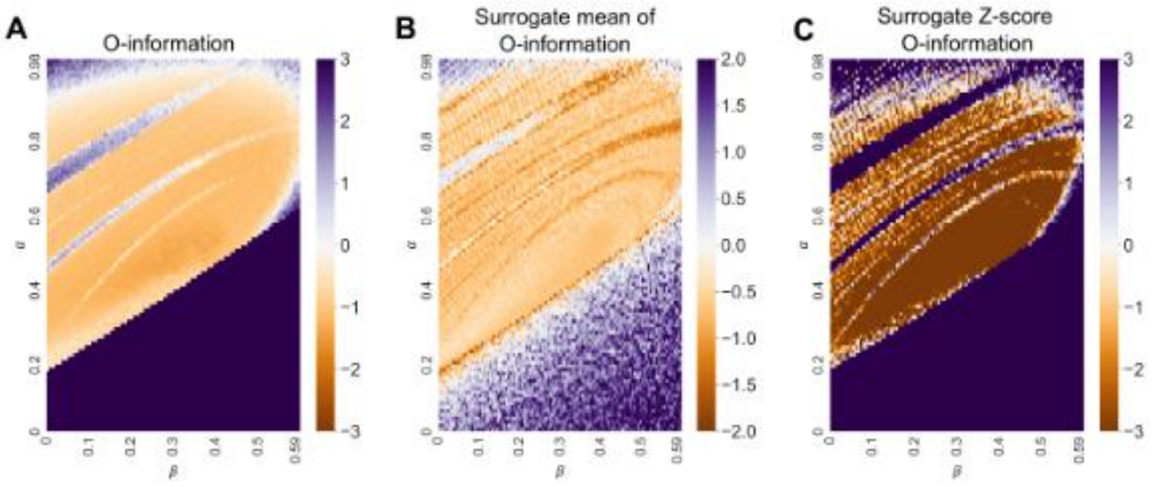
- ¿Cuáles son las condiciones para que riqueza dinámica en sistemas dinámicos inspirados en la biofísica cerebral?

- ¿Son las interacciones de alto orden y la multiestabilidad dinámica dos caras de la misma moneda?

Dinámica caótica y sinergia





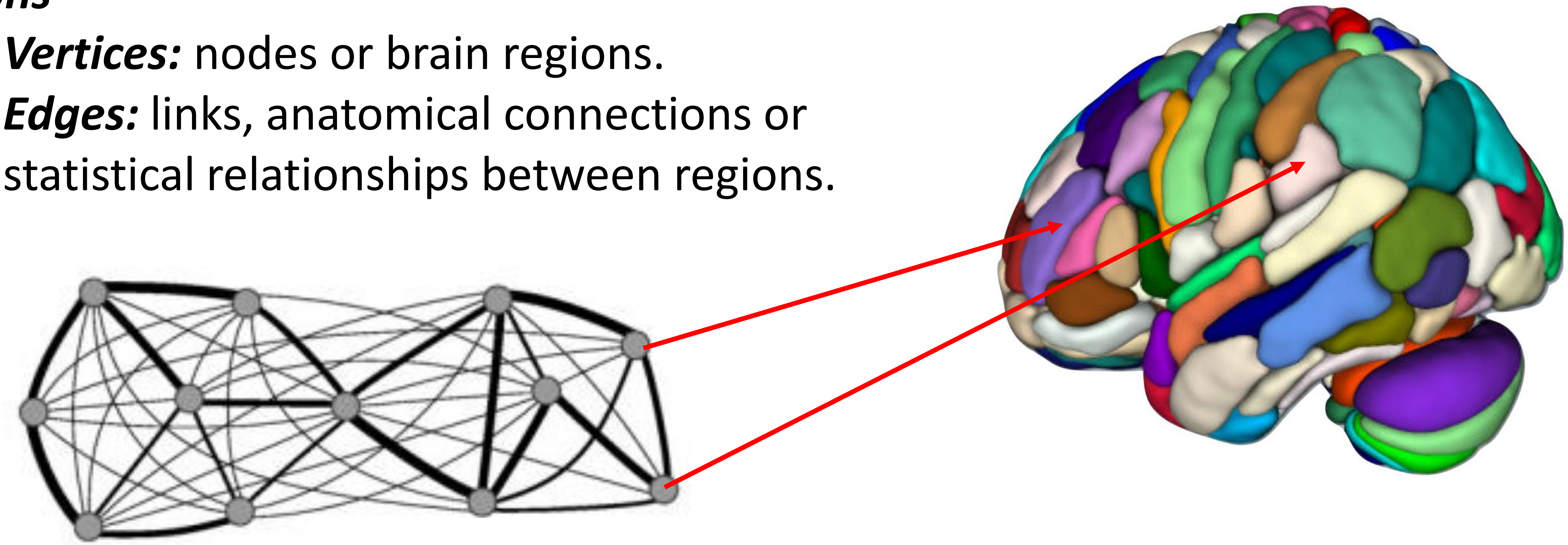


Papel de la topología de red

Networks and Graphs

Graphs

- ***Vertices:*** nodes or brain regions.
- ***Edges:*** links, anatomical connections or statistical relationships between regions.



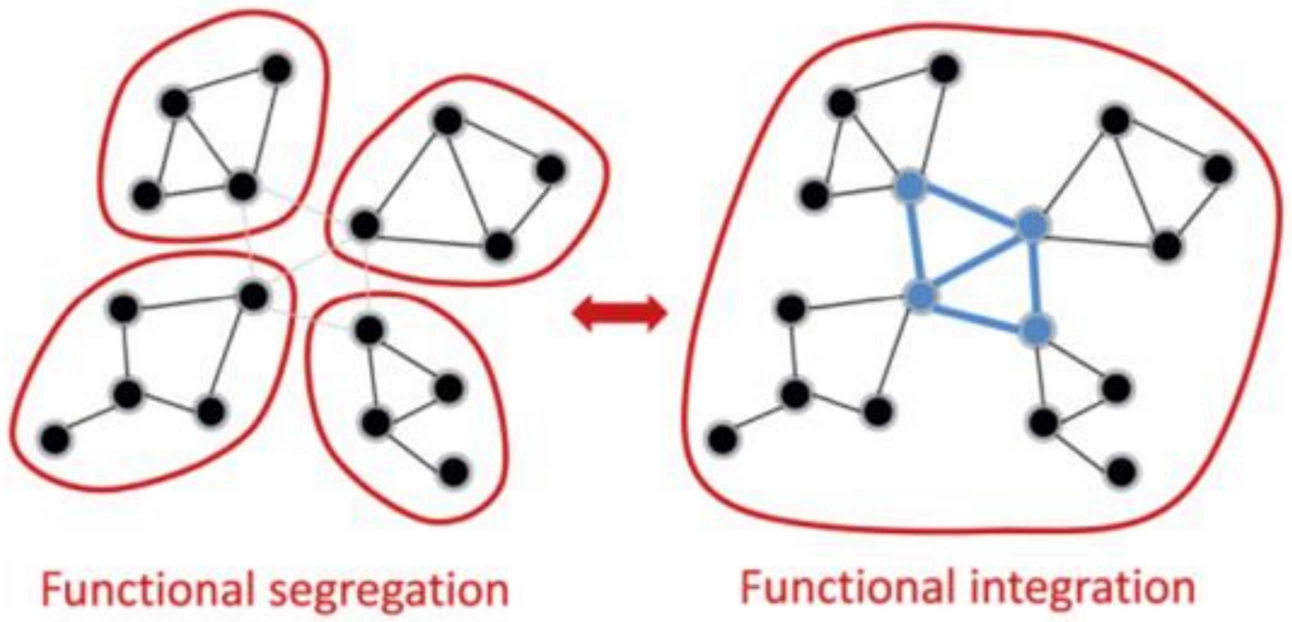
Rubinov & Sporns (2010)

Segregation (functional):

Specialized processing of information in locally and densely interconnected brain regions **(Rubinov & Sporns, 2010).**

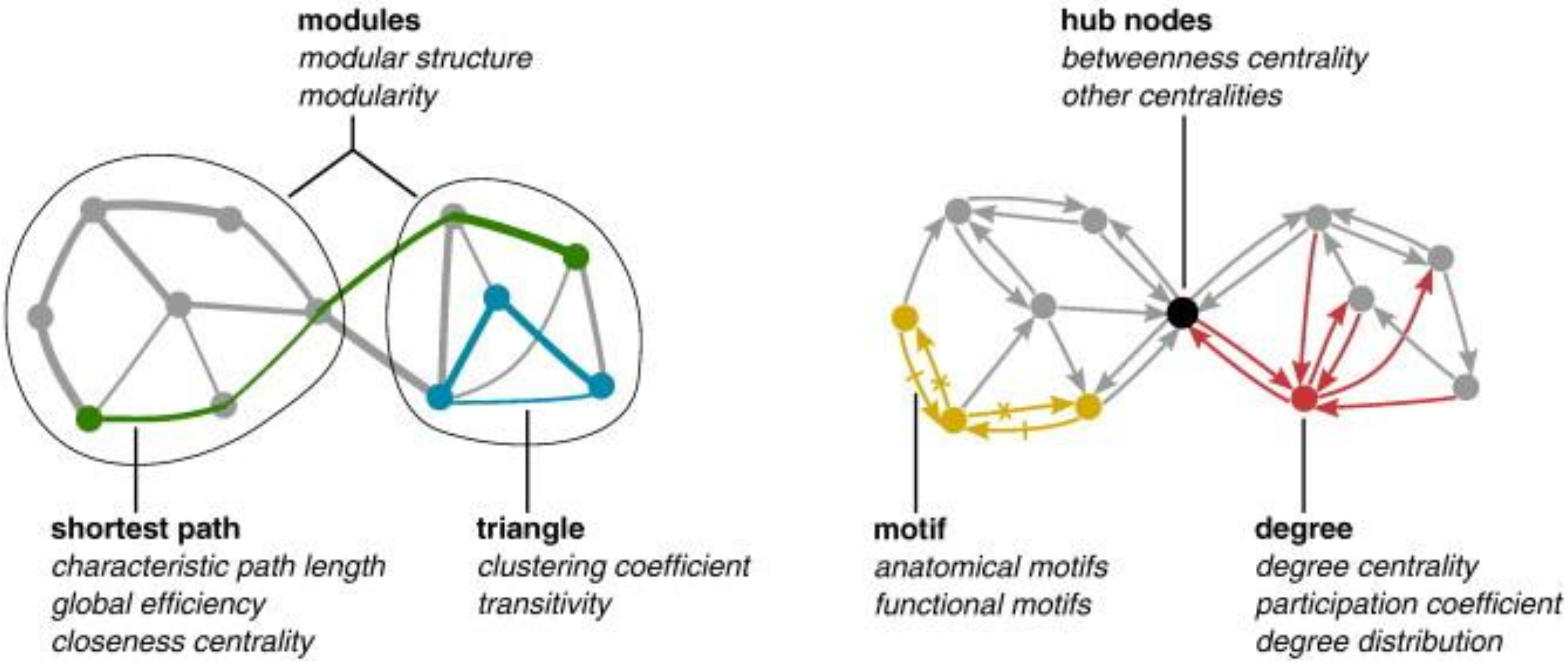
Integration (functional):

Ability of rapidly combine the specialized information of different and distant brain areas **(Rubinov & Sporns, 2010).**



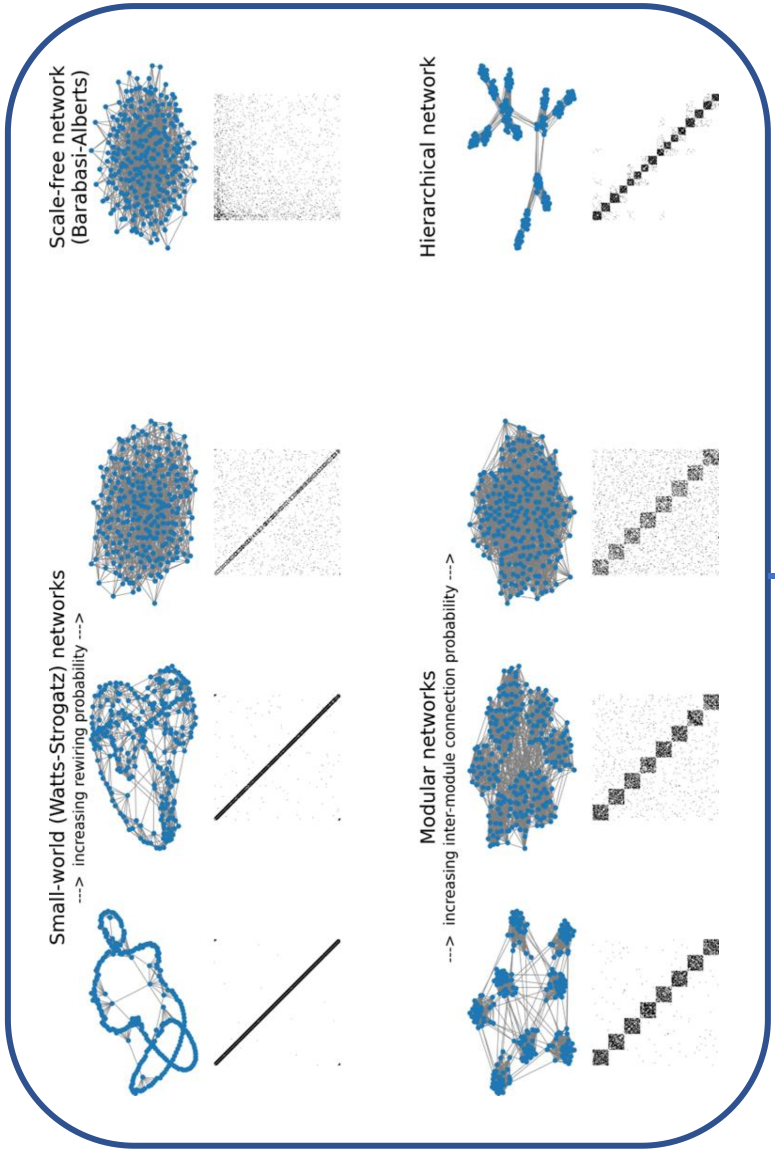
Cohen & D'Esposito (2016)

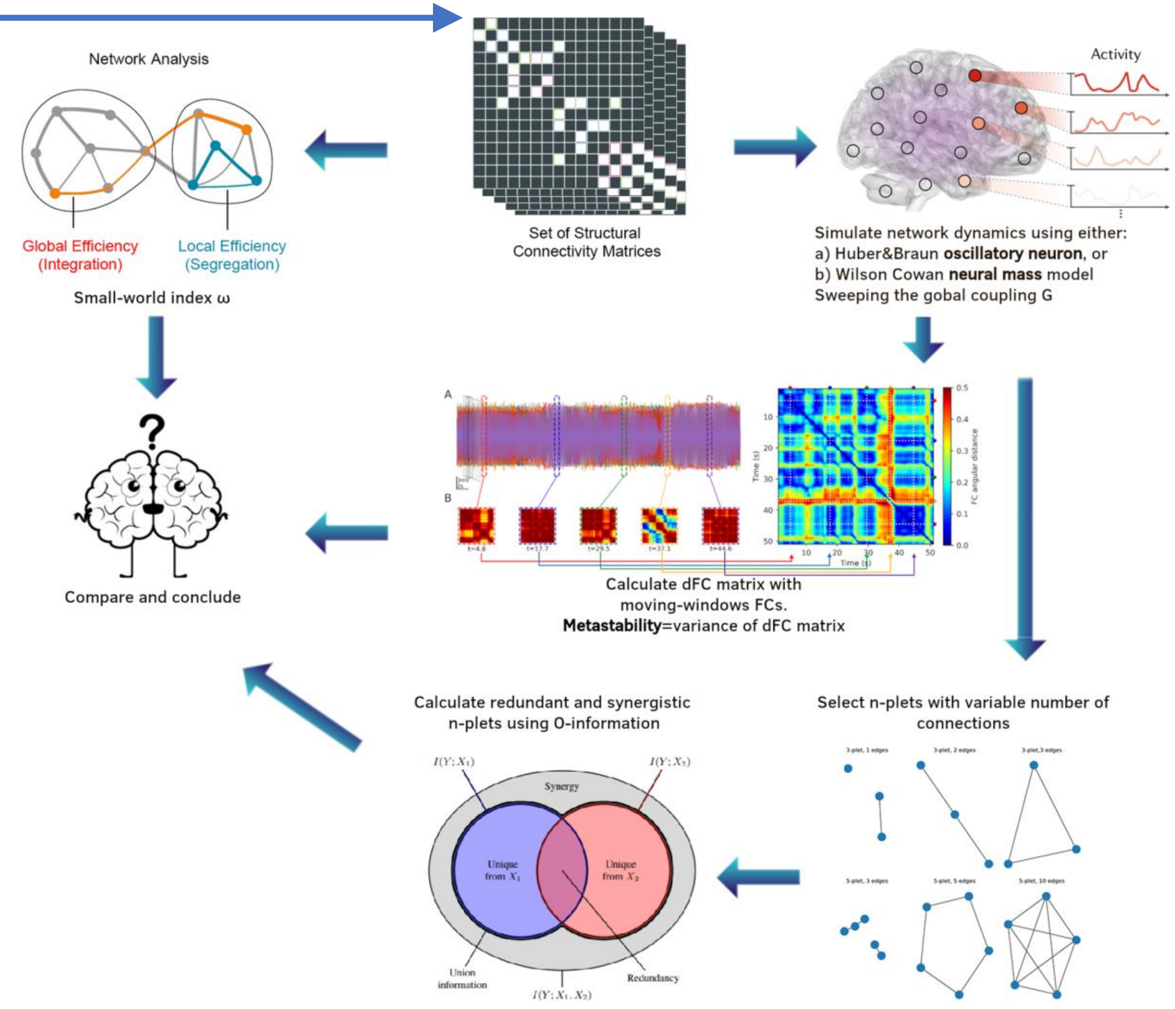
Network topological measures



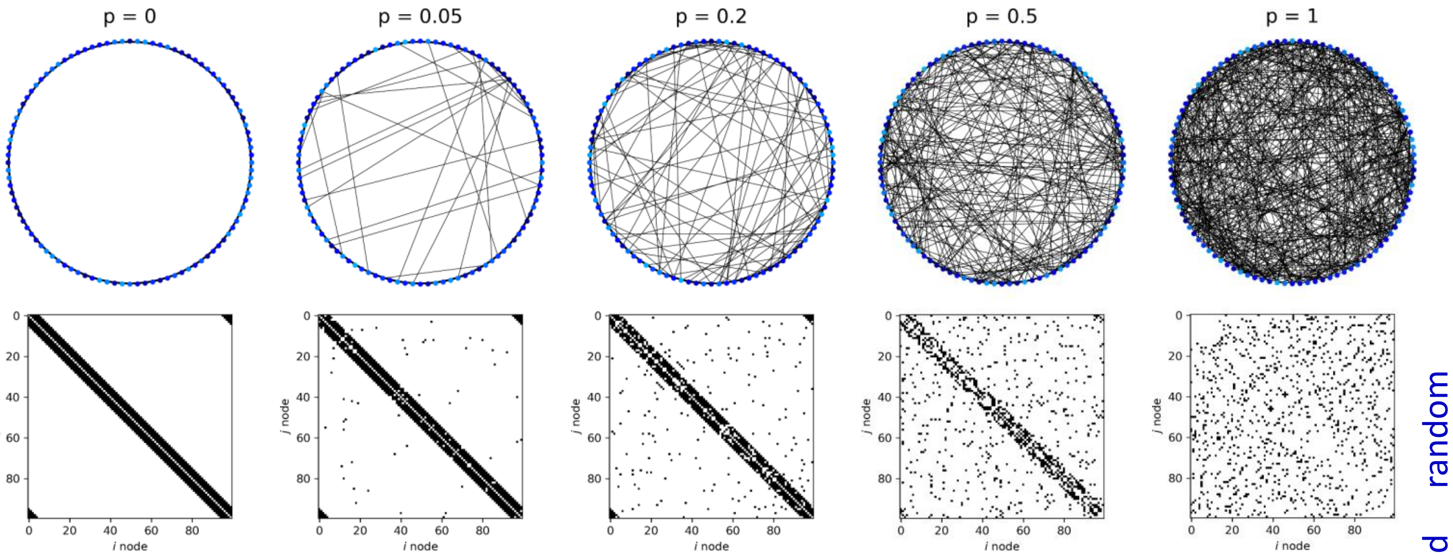
Rubinov & Sporns, 2010

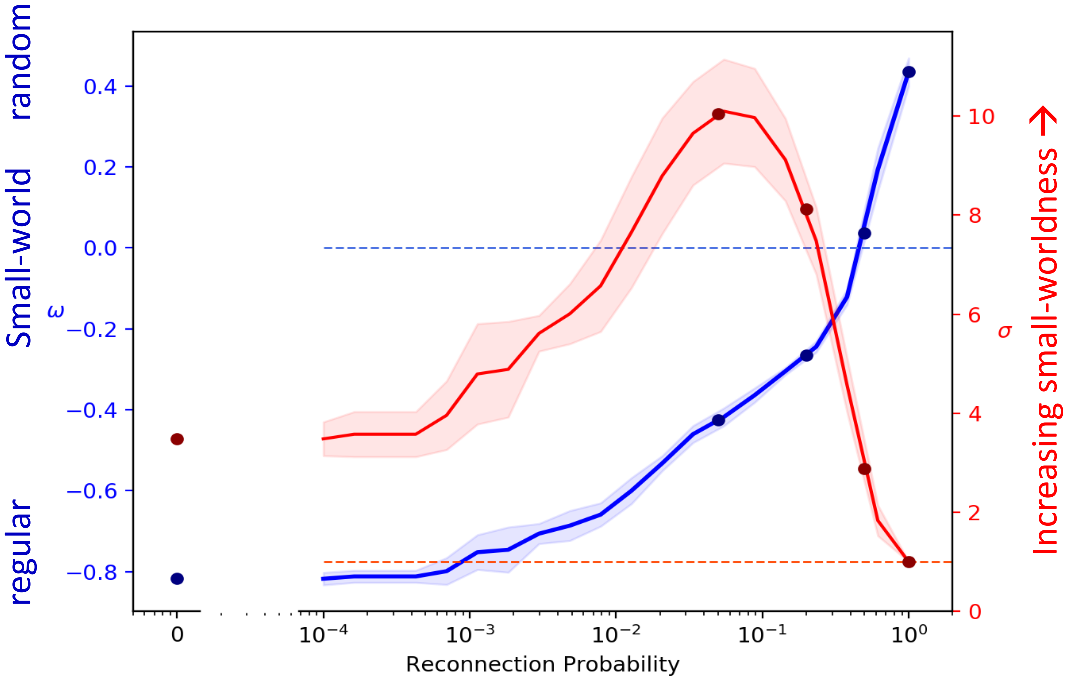
Rol de la topología de red





From regular to random

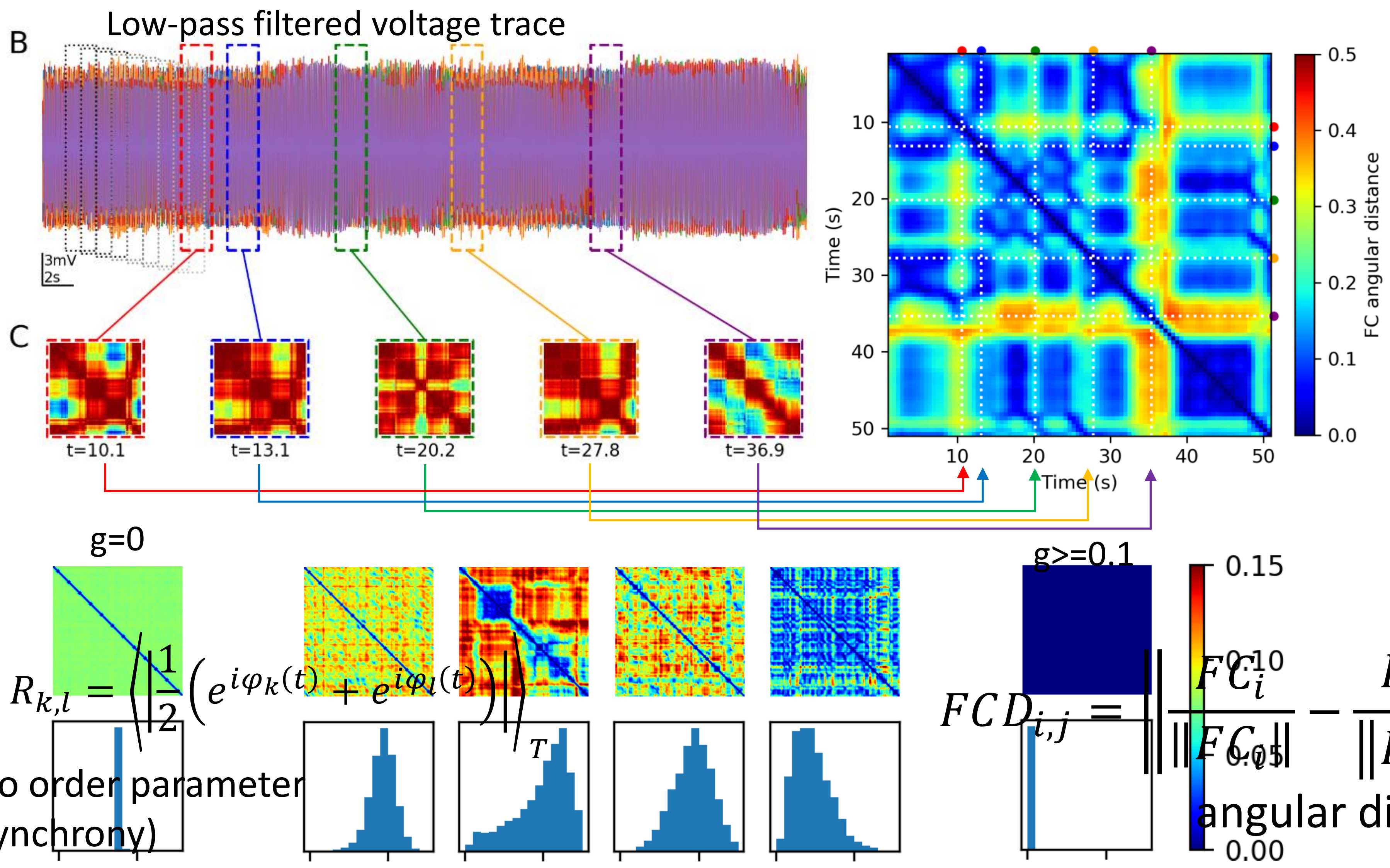




Small world indices:
σ (Humphries) and ω (Telesford):

$$\sigma = \frac{C/C_r}{L/L_r} \qquad \omega = \frac{L_r}{L} - \frac{C}{C_0}$$

Functional connectivity dynamics



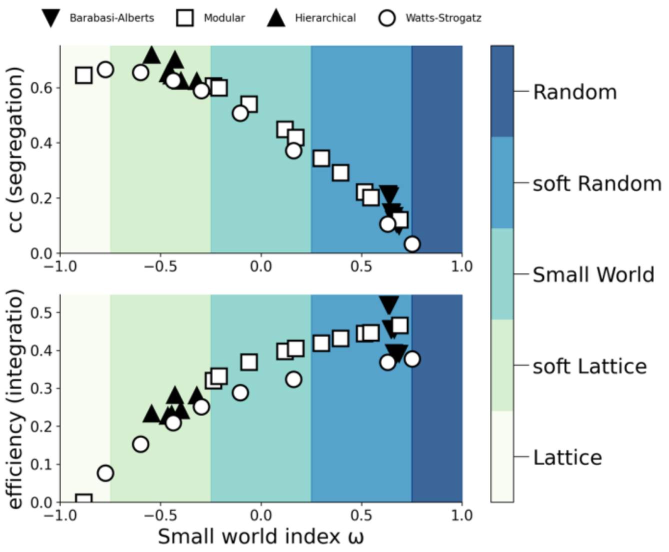
$$FC_{k,l} = R_{k,l} = \left\langle \left\| \frac{1}{2} \left(e^{i\varphi_k(t)} + e^{i\varphi_l(t)} \right) \right\| \right\rangle_T$$

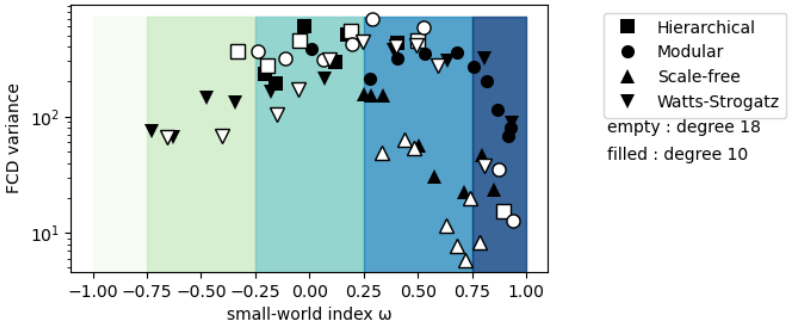
Kuramoto order parameter
(Phase synchrony)

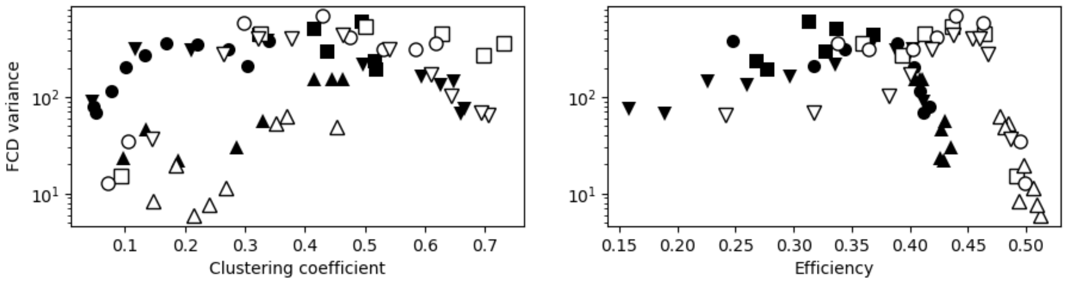
$$FCD_{i,j} = \left\| \frac{FC_i}{\|FC_i\|} - \frac{FC_j}{\|FC_j\|} \right\|$$

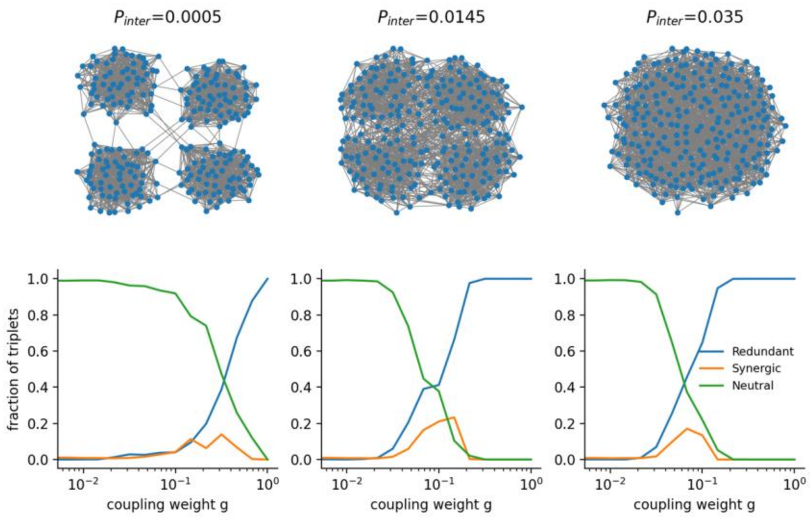
angular distance

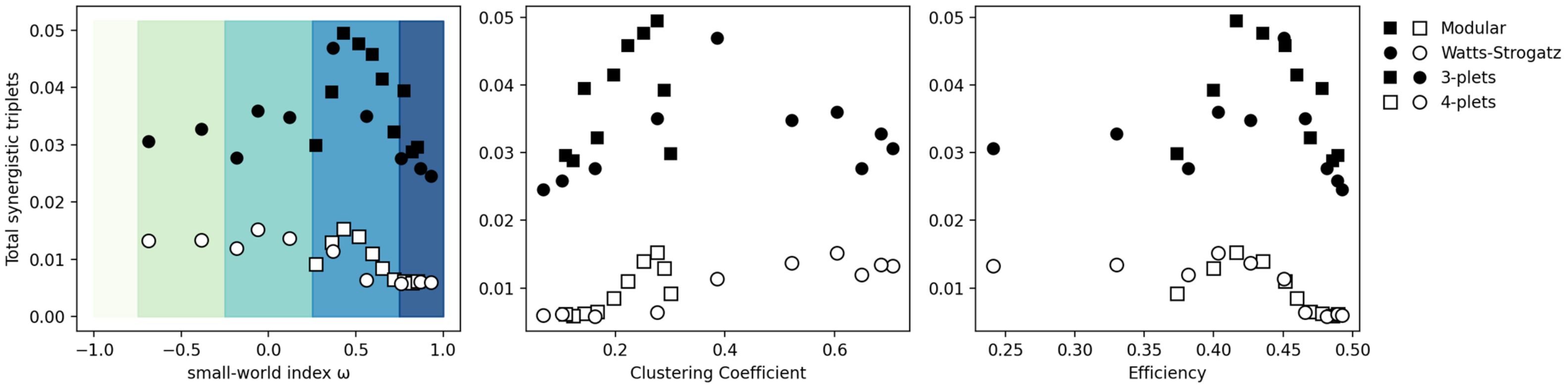
Redes tipo *small-world* maximizan la conectividad functional dinámica *y* la existencia de *n*-pletas sinérgicas









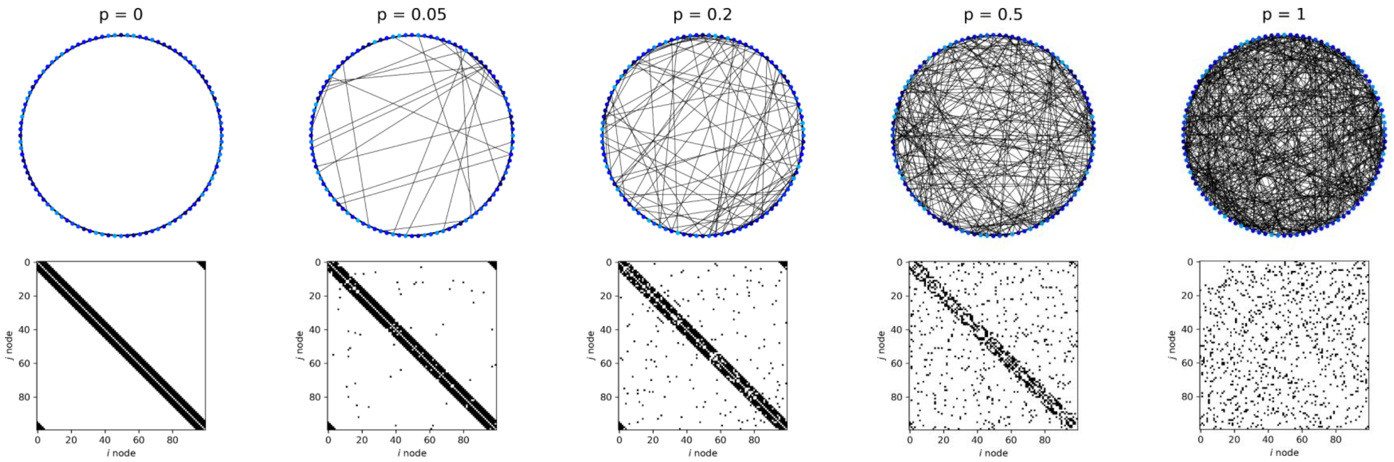


Work in progress

- Simulaciones usando como red estructural conectomas humanos obtenidos con diferentes algoritmos de parcelación.

- ***Pero*** estos conectomas son muy similares en propiedades de red

- ***TAREA:*** *aleatorizar y 'laticizar' un conectoma humano, caracterizándolo en propiedades de red.*



Envejeciendo el conectoma