



Two sides of the same coin

Structural vs. Functional brain connectivity

LIF/LIB

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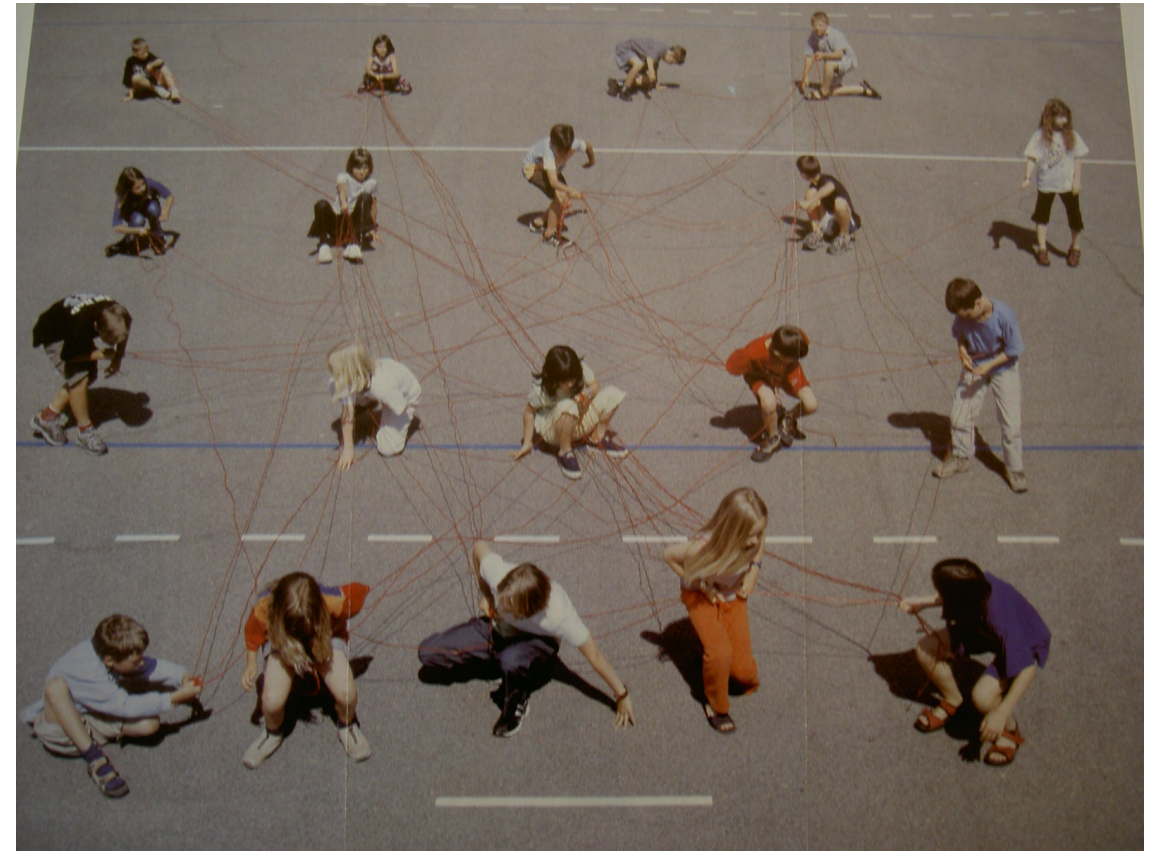
Claus Hilgetag
Andreas Engel
Karl Hollensteiner
Leigh-Anne Dell-Brown
Alexandros Goulas
Christian Gerloff
Florian Pieper
Edgar Galindo-Leon
Tobias Donner
Guido Nolte

Pasteur

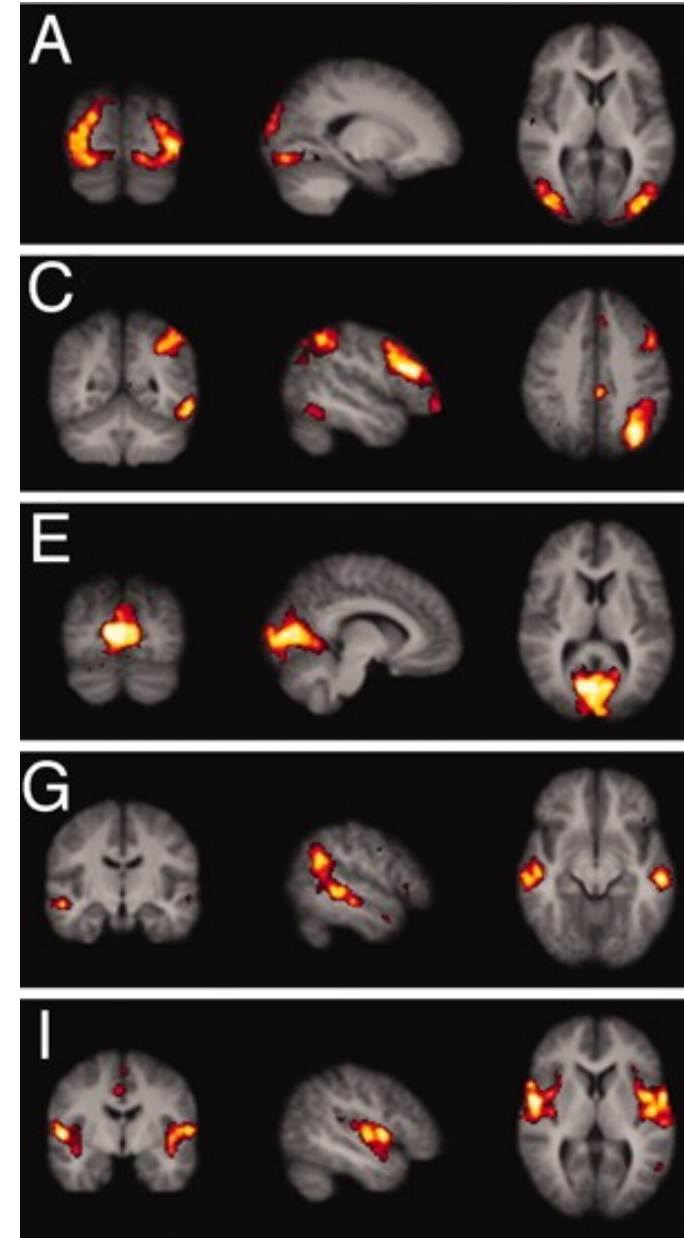
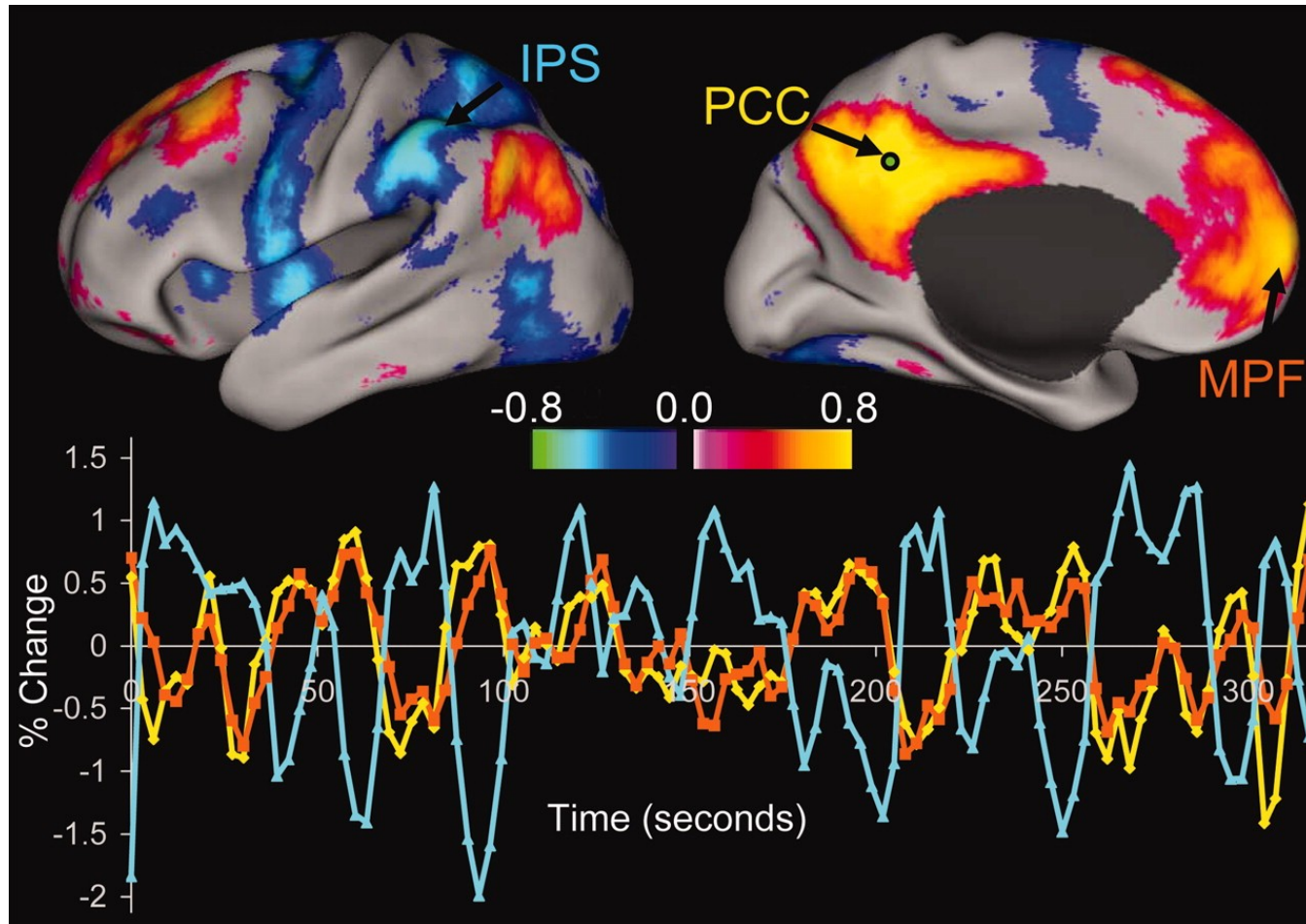
Roberto Toro
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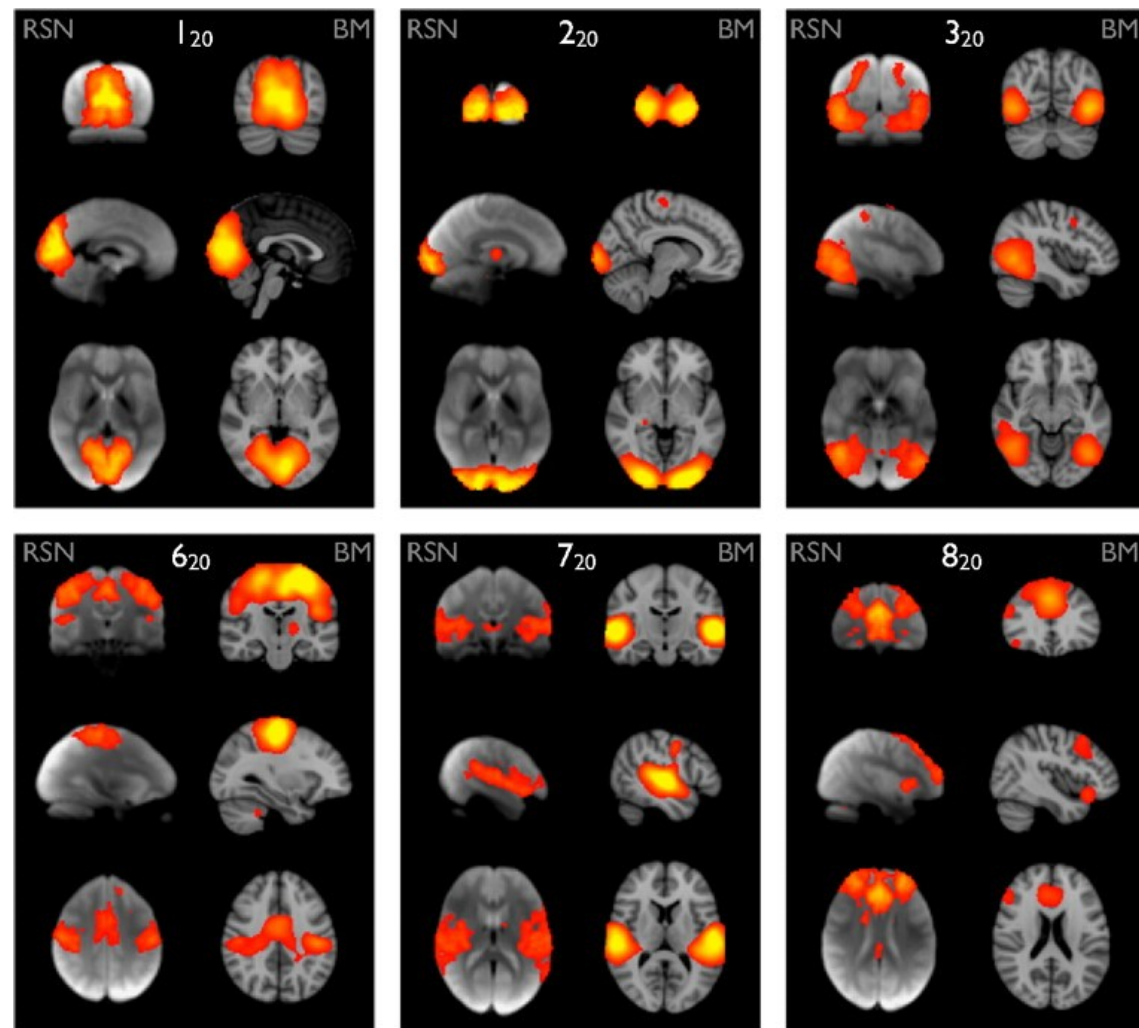


Fox et al. PNAS 2005

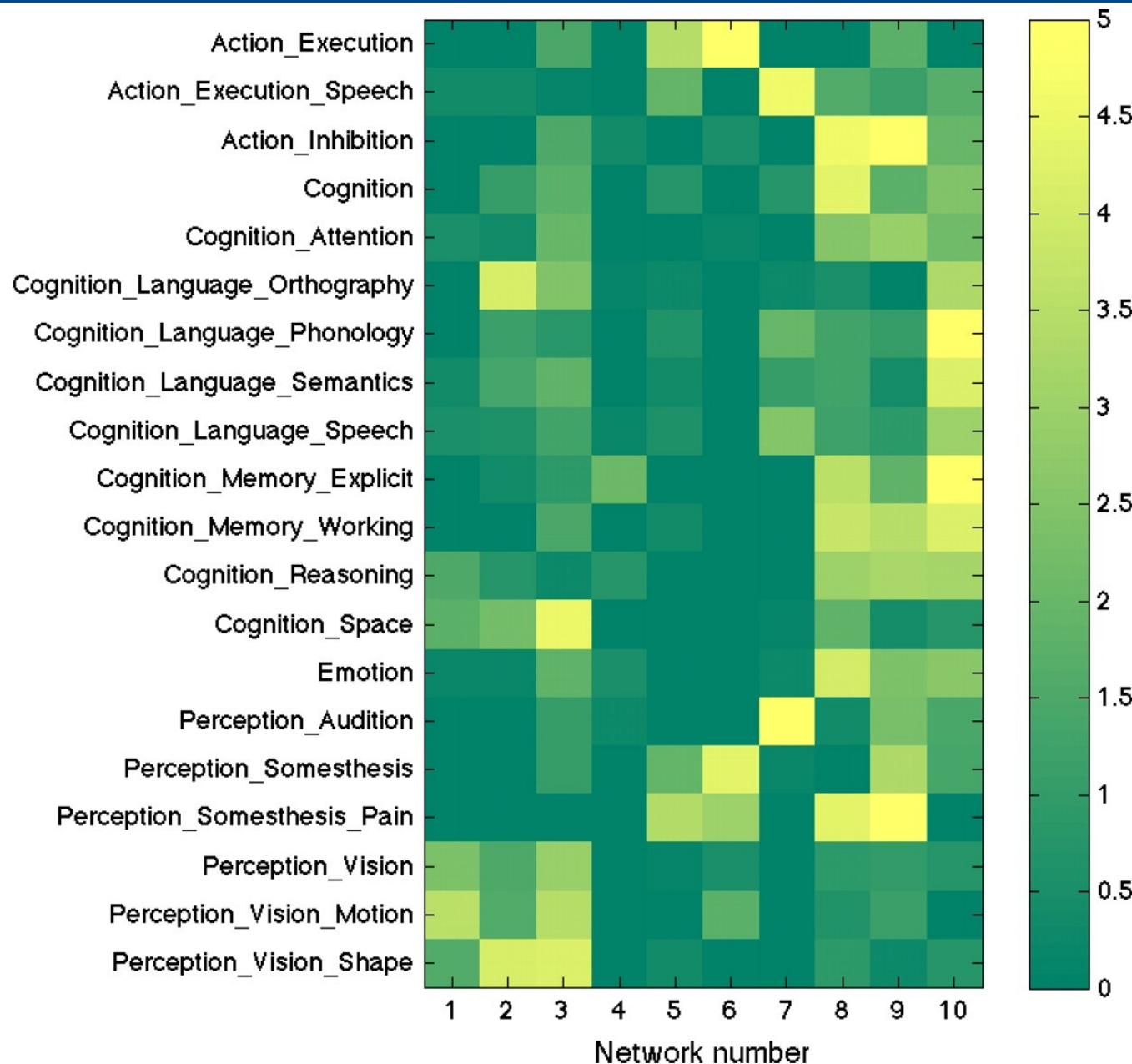


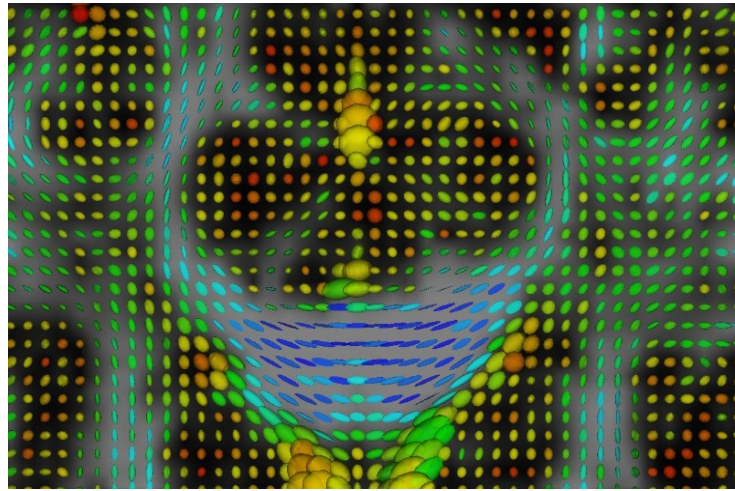
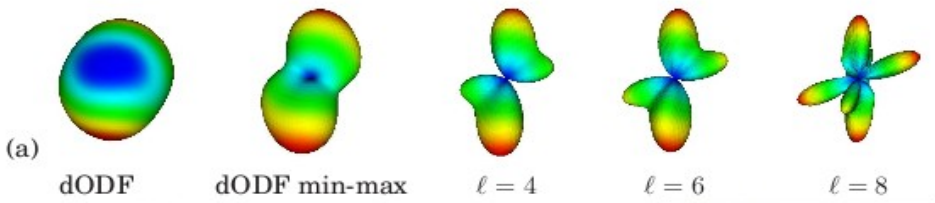
Damoiseaux et al. PNAS 2006

Smith et al. PNAS 2009



BrainMap behavioural domain

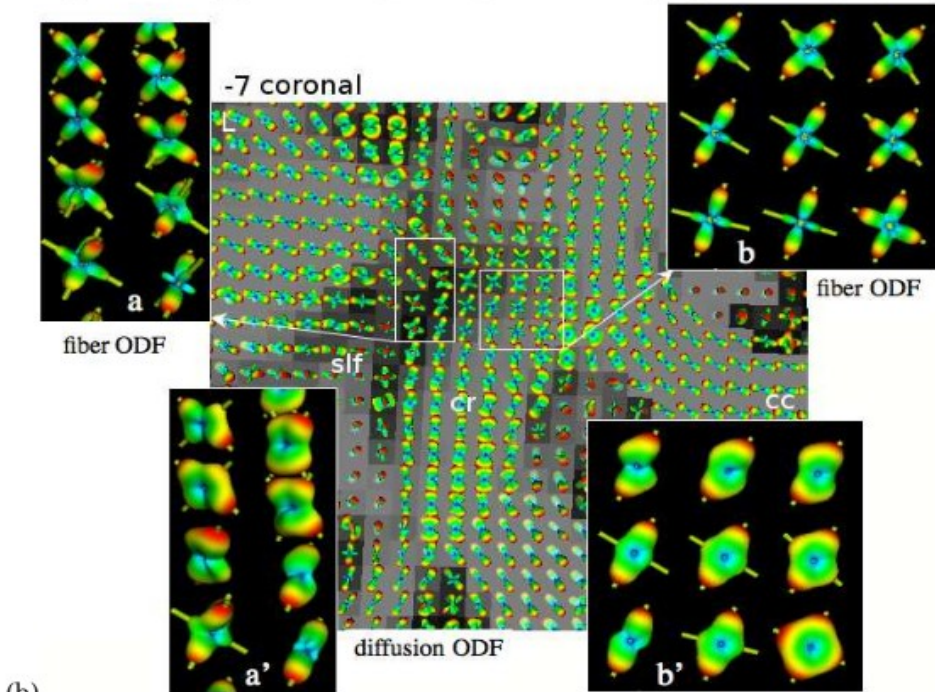




Basser et al., Biophys J (1994)

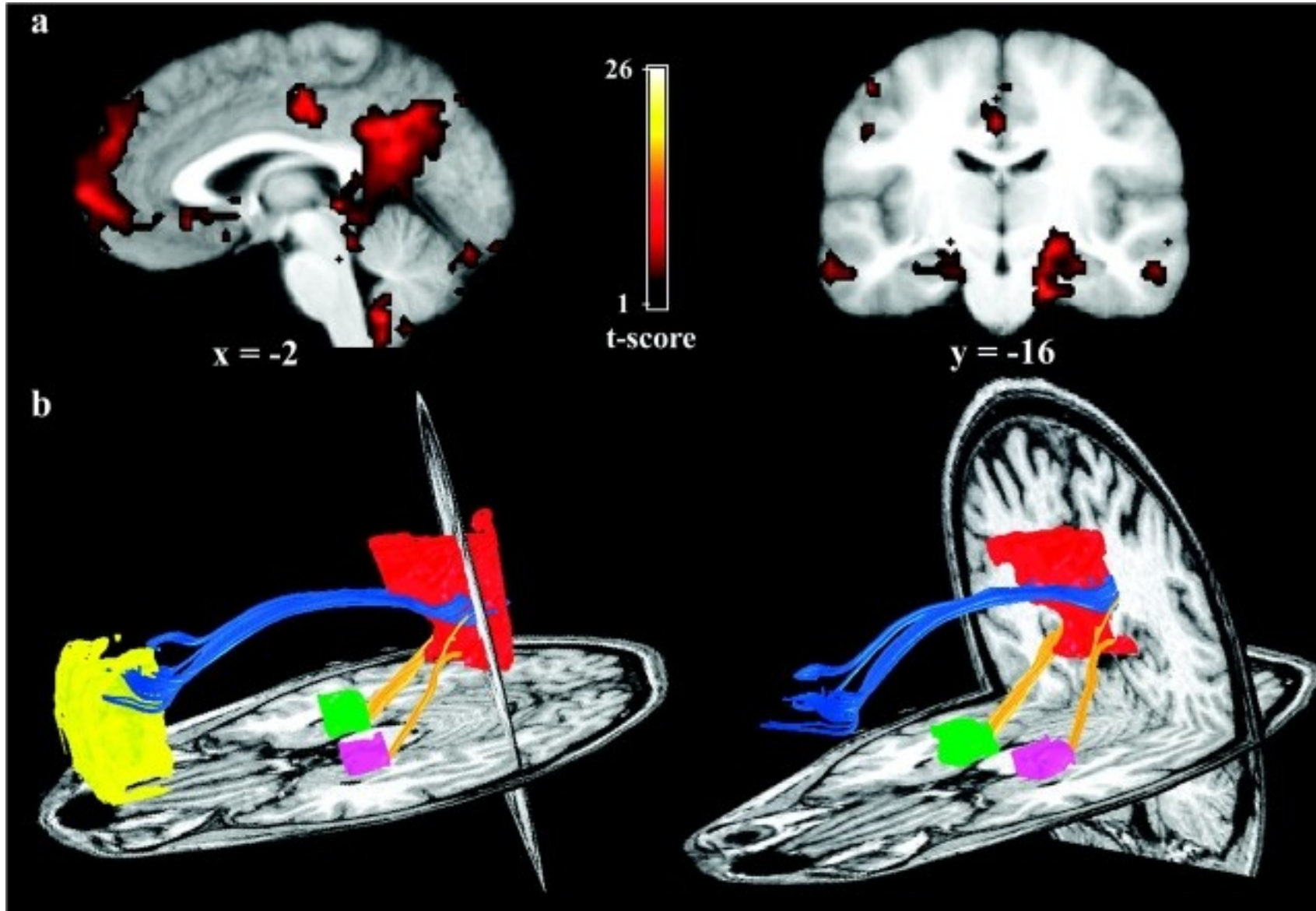


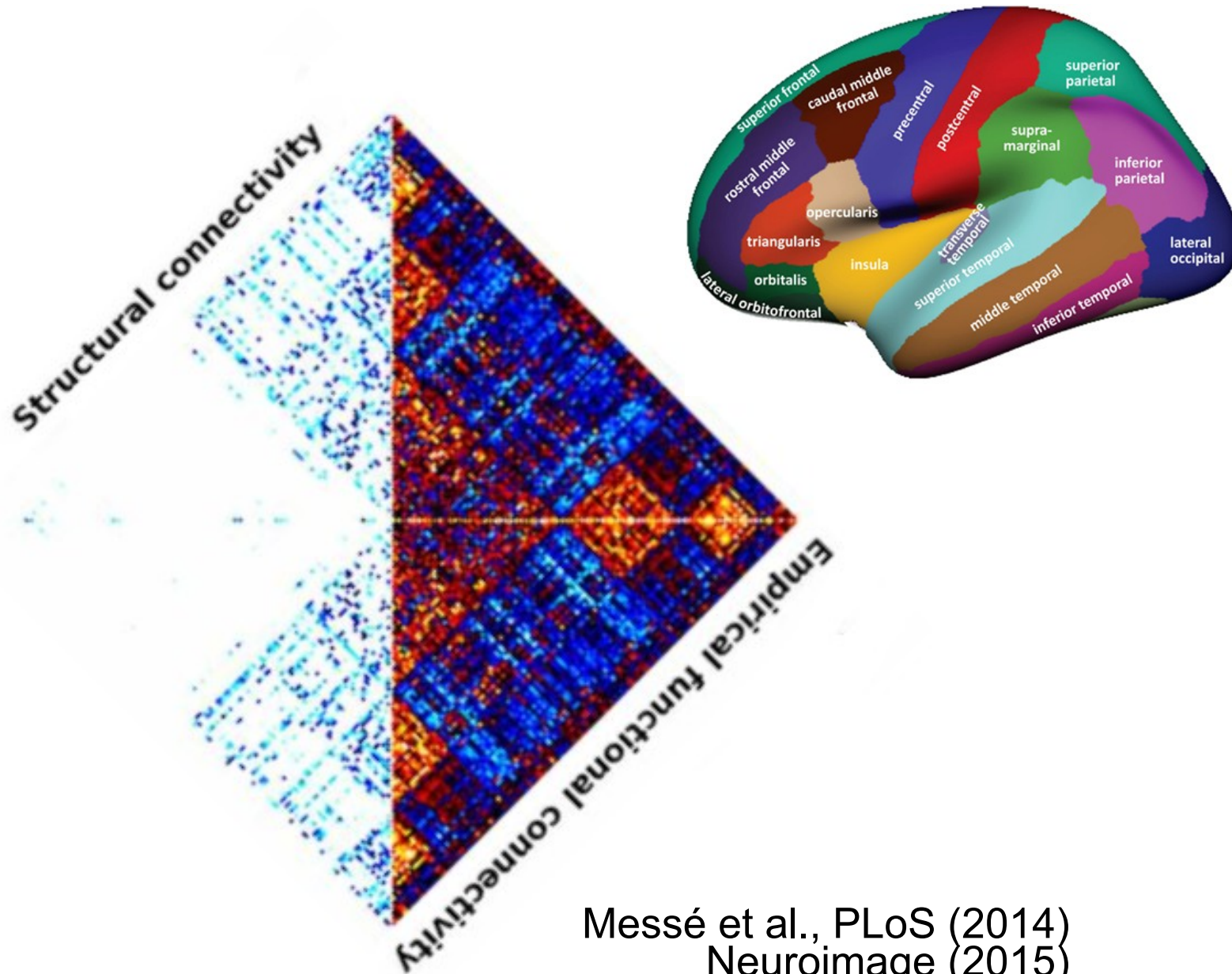
Hagmann et al., PLoS (2008)



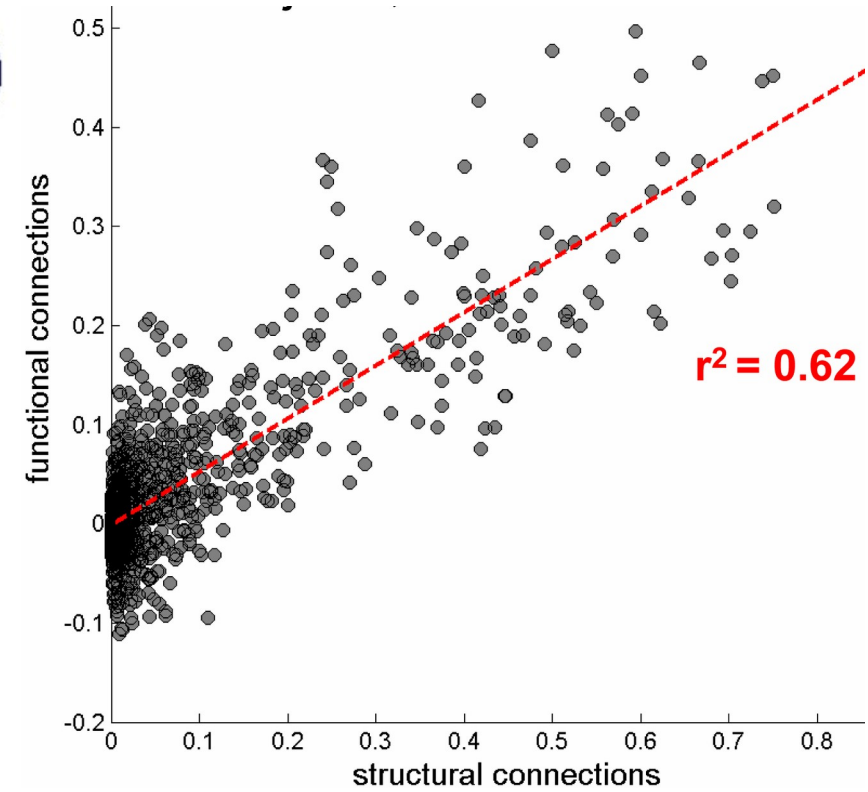
Descoteaux et al., MRM (2007)

Greicius et al. Cerebral Cortex 2008

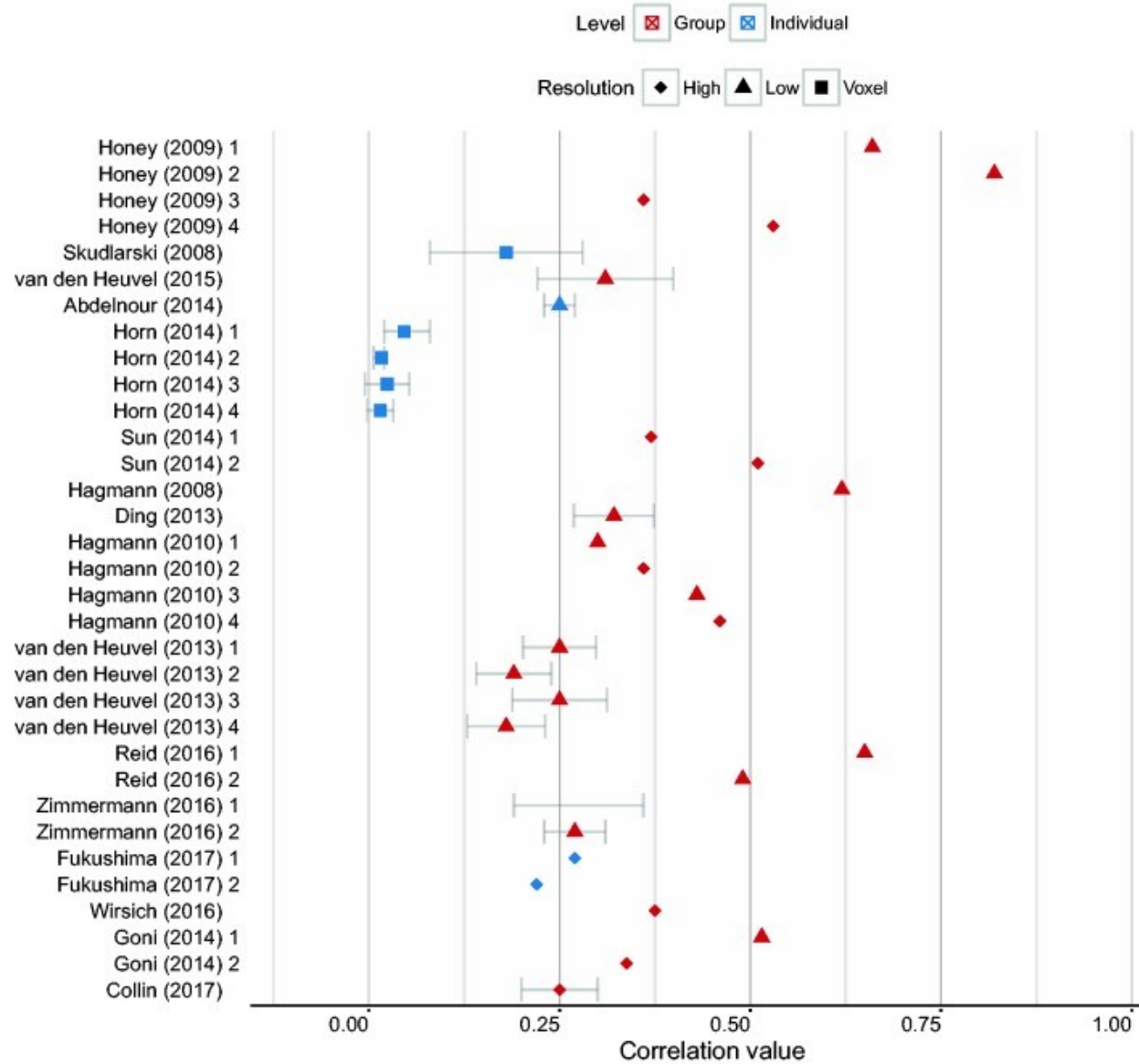
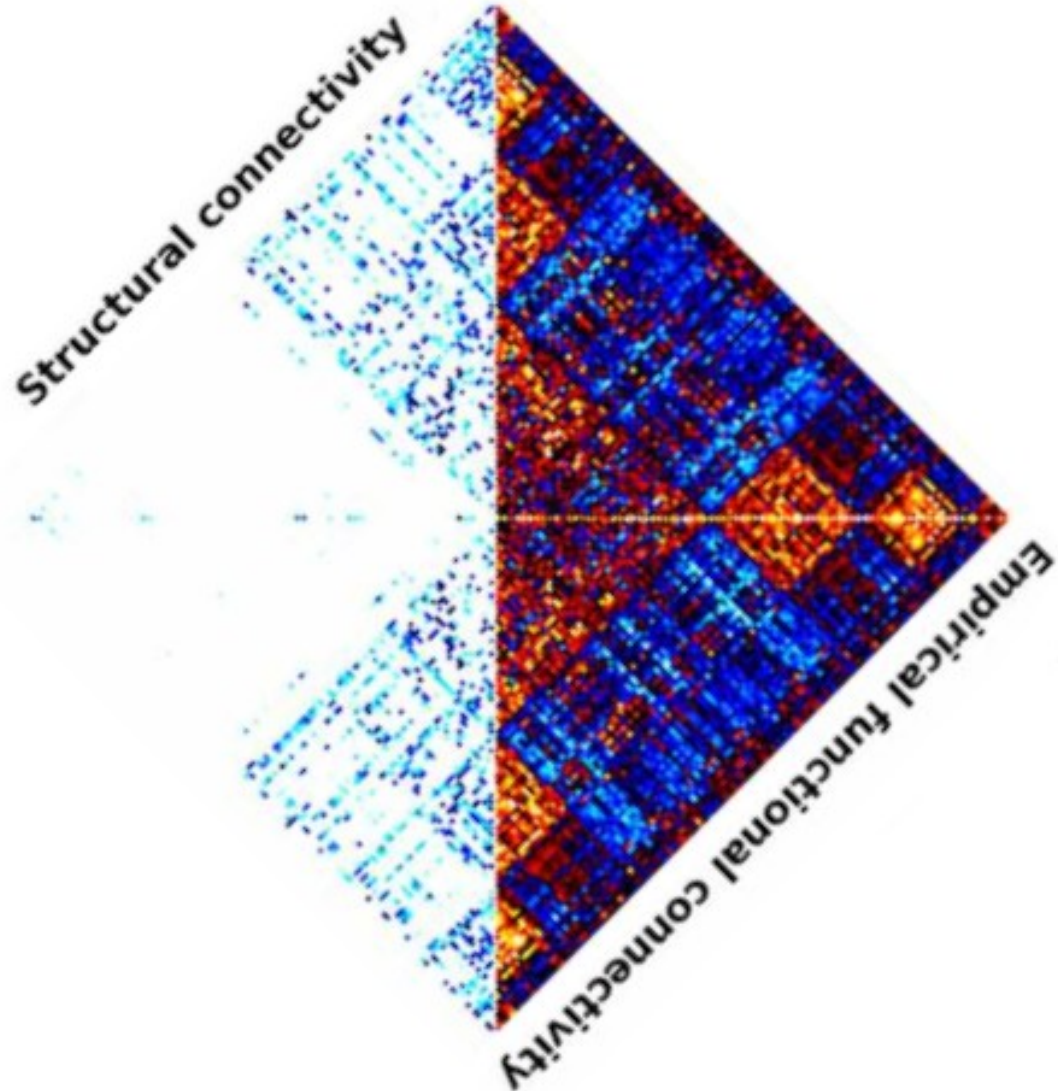




Messé et al., PLoS (2014)
Neuroimage (2015)

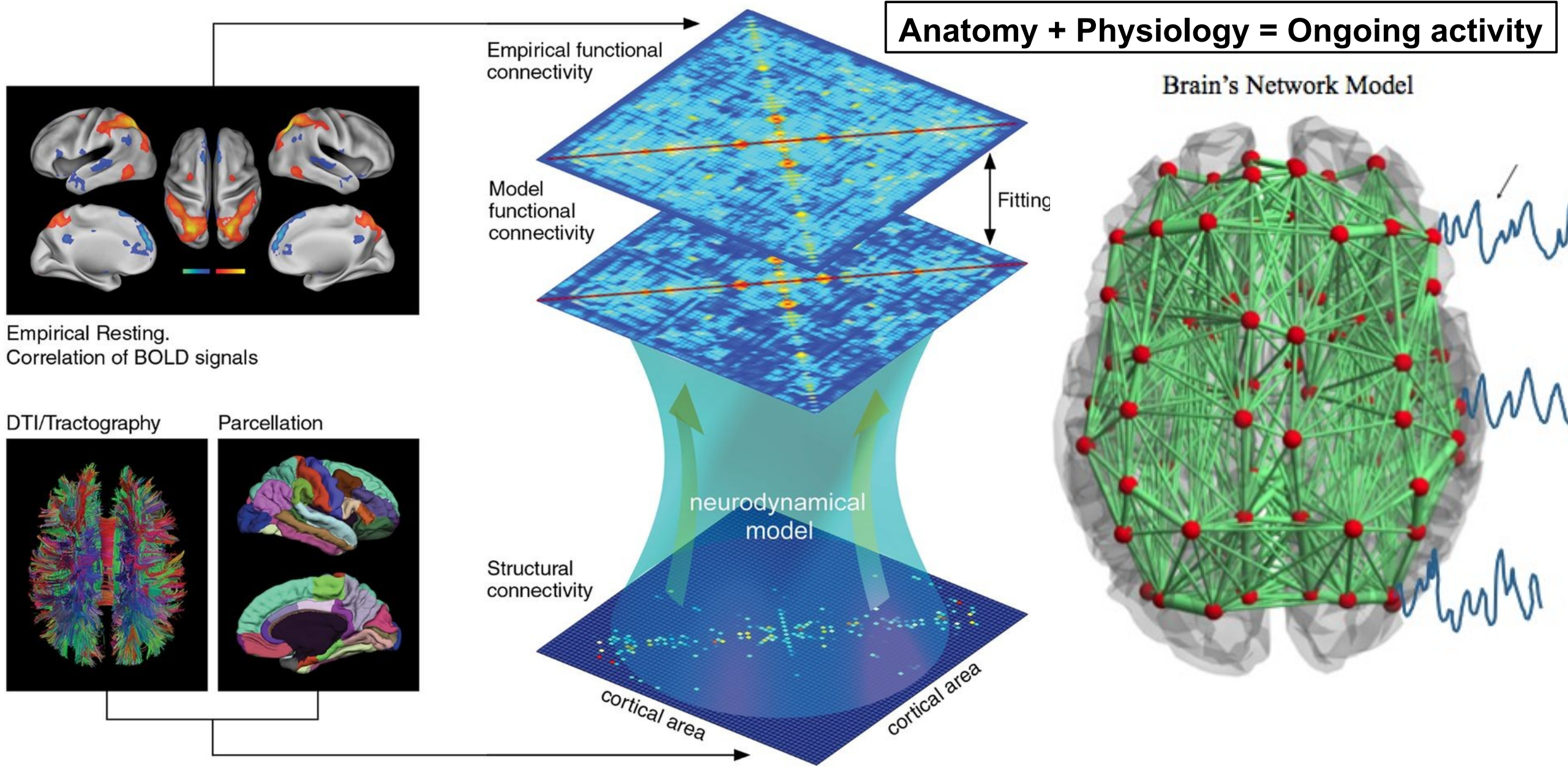


Hagmann et al., PLoS (2008)



Straathof et al., J Cereb Blood Flow Metab (2019)

Anatomy + Physiology = Ongoing activity



$$C_m \frac{dV_i(t)}{dt} = -g_m(V_i(t) - V_L) - g_{AMPA,ext}(V_i(t) - V_E)s^{AMPA,ext}(t) - g_{AMPA,rec}(V_i(t) - V_E) \sum_{j=1}^{N_E} w_{ij}s_j^{AMPA,rec}(t) - \frac{g_{NMDA}(V_i(t) - V_E)}{1 + \lambda e^{-\beta V_i(t)}} \sum_{j=1}^{N_E} w_{ij}s_j^{NMDA}(t) - g_{GABA}(V_i(t) - V_I) \sum_{j=1}^{N_I} w_{ij}s_j^{GABA}(t),$$

$$\frac{\partial V(x_i)}{\partial t} = -m_{Ca}(g_{Ca} + r_{NMDA}a_{ee}((1-c)Q_V(x_i) + c\langle Q_V(x) \rangle))(V(x_i) - V_{Ca}) - (g_{Na}m_{Na} + a_{ee}((1-c)Q_V(x_i) + c\langle Q_V(x) \rangle))(V(x_i) - V_{Na}) - g_K m_K (V(x_i) - V_K) - g_L (V(x_i) - V_L) + a_{ie}ZQ_Z(x_i) + a_{ne}I_\delta$$

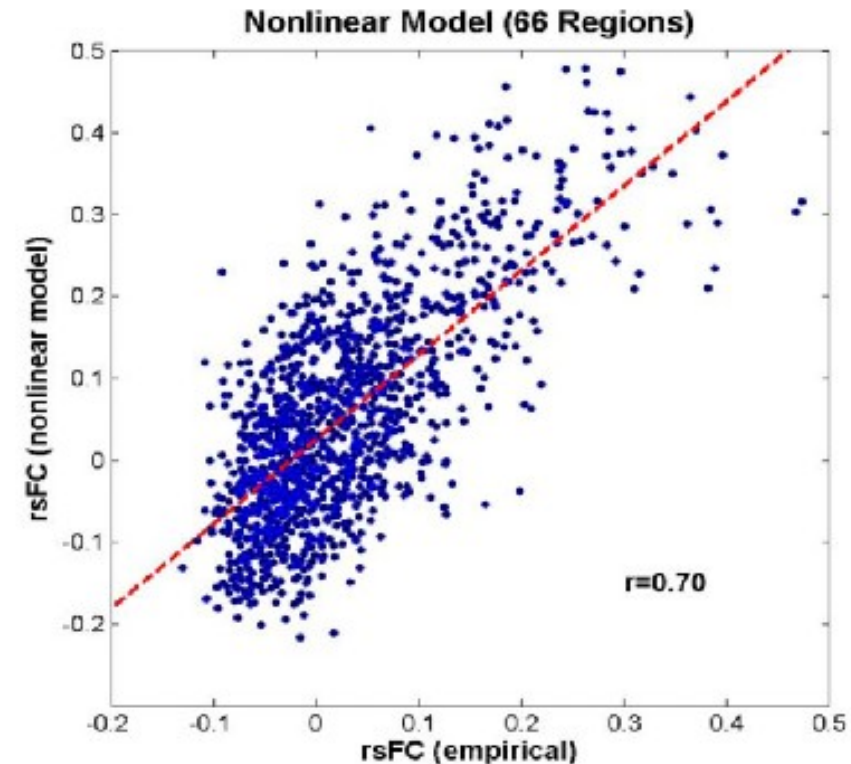
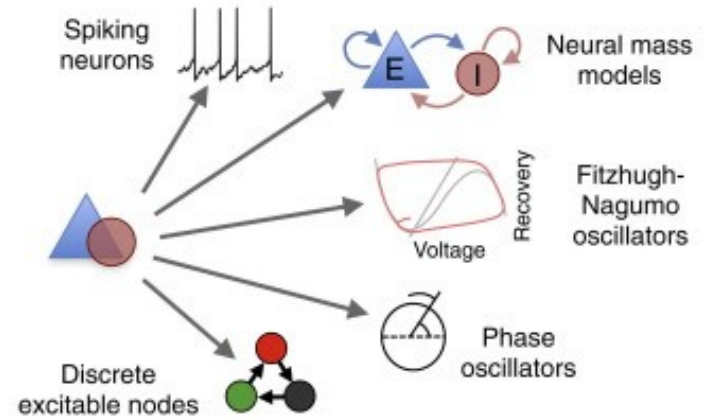
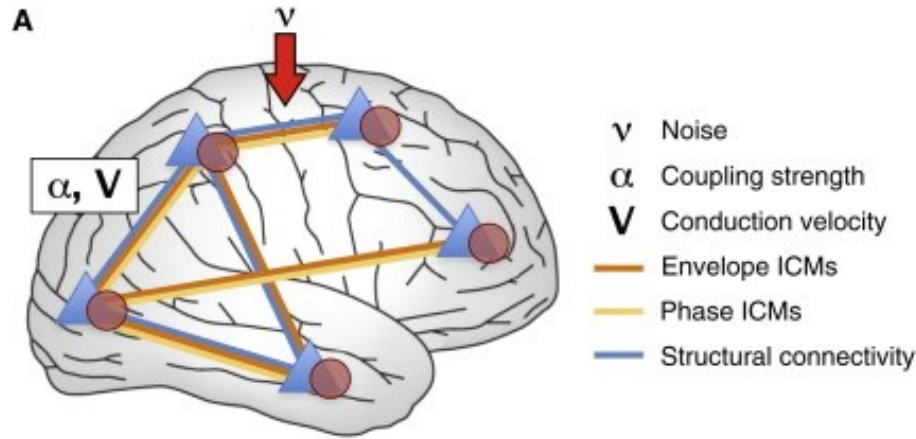
Ghosh et al. PLoS 2008

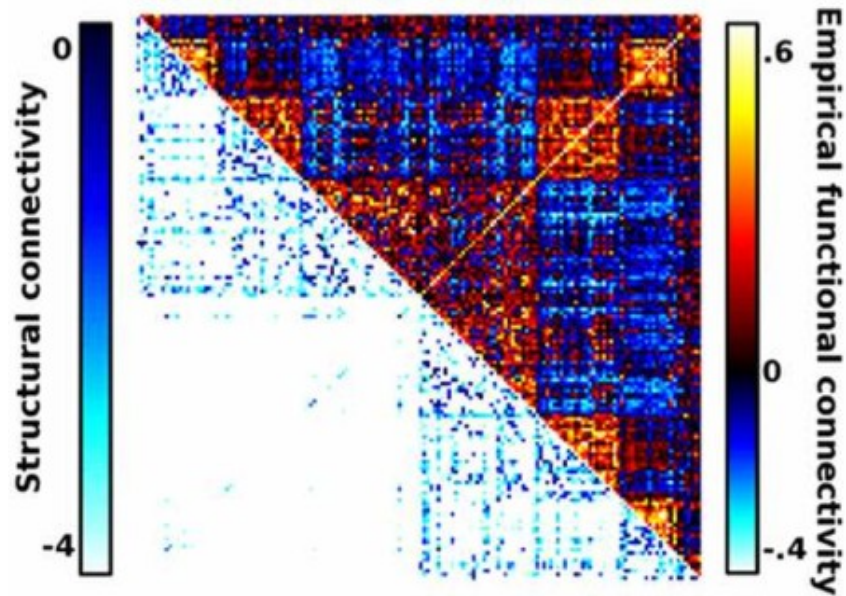
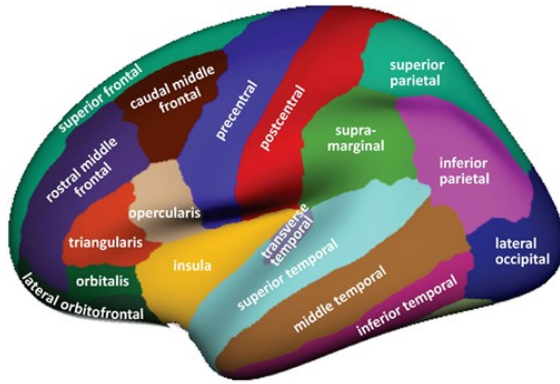
Deco et al. PNAS 2009

Honey et al. PNAS 2009

Cabral et al. Neuroimage 2011

Deco & Jirsa J Neuroscience 2012

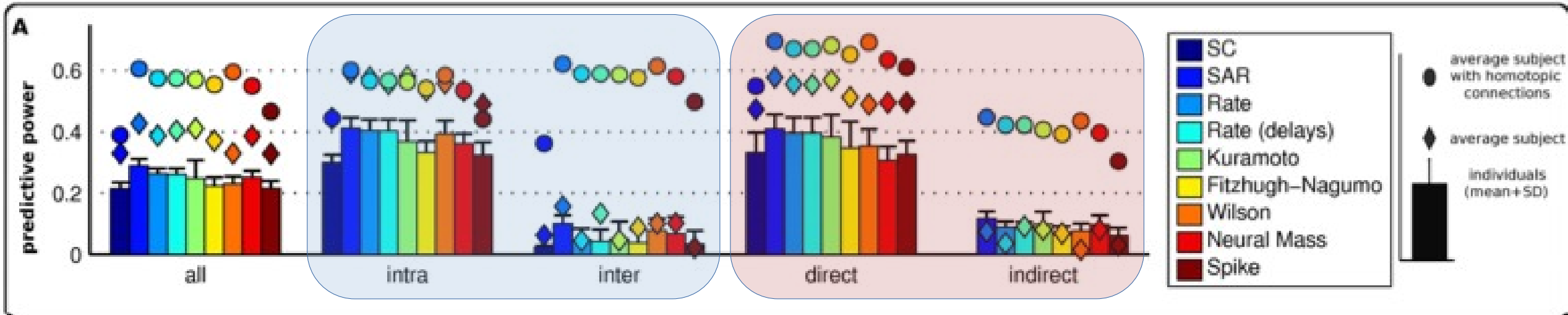


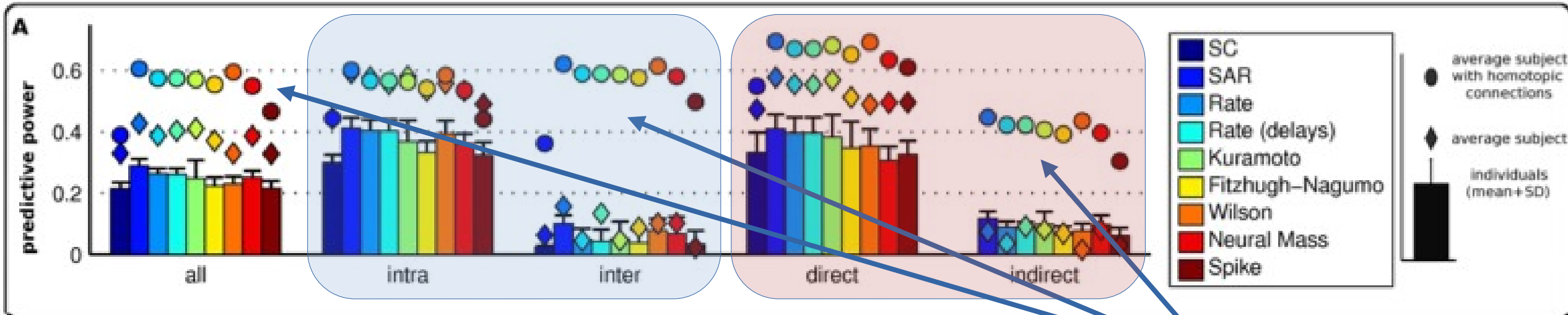


Messé et al., PLoS (2014)
Neuroimage (2015)

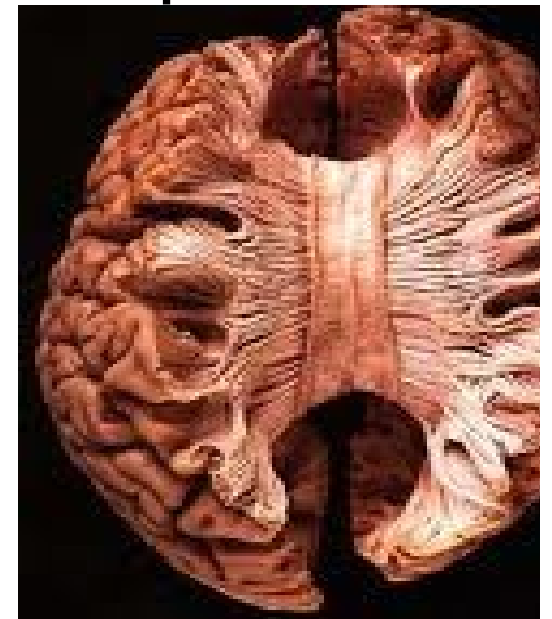
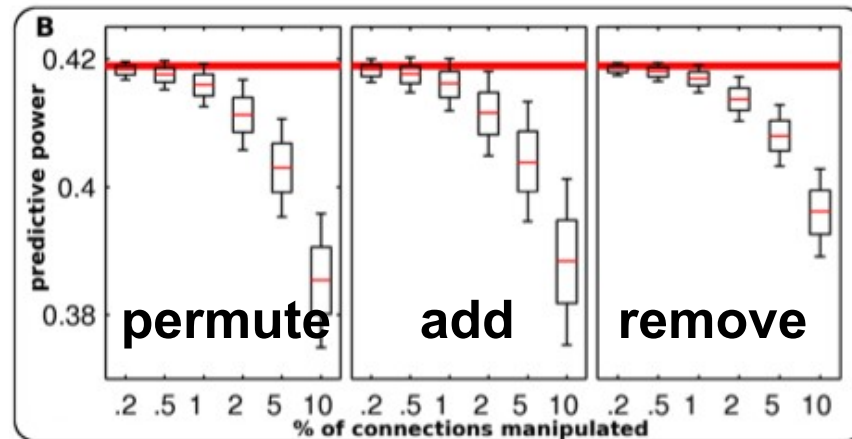
Table 1. Summary of computational models ordered in ascending complexity

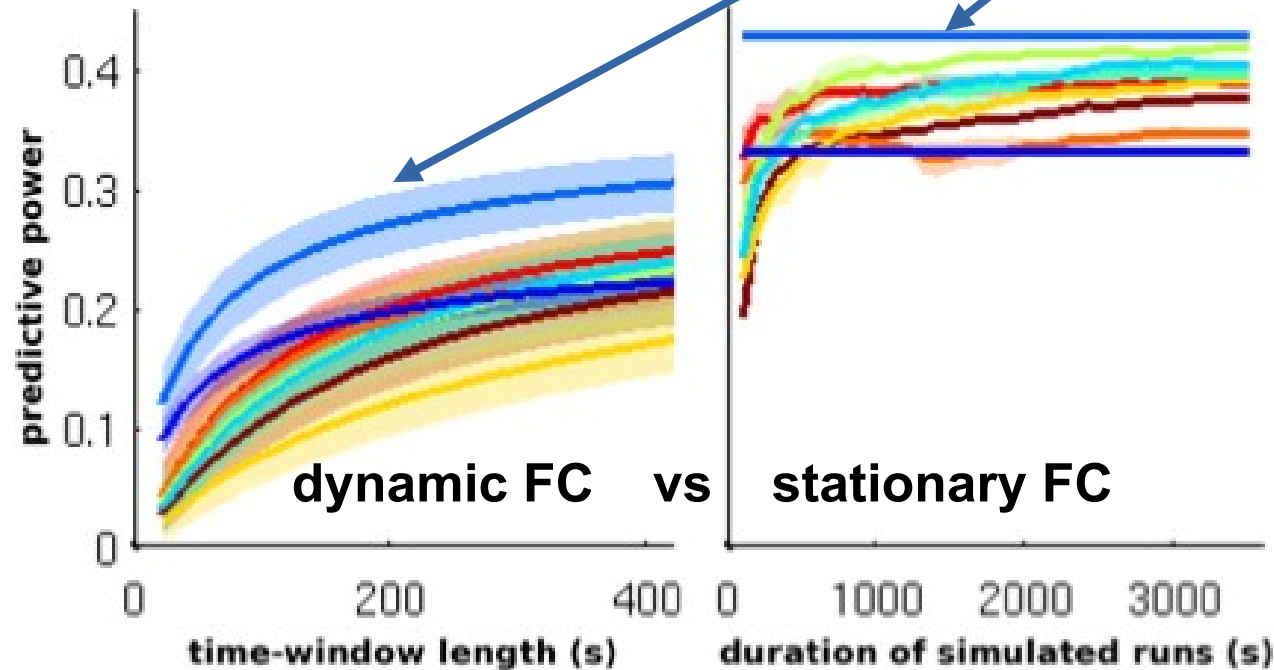
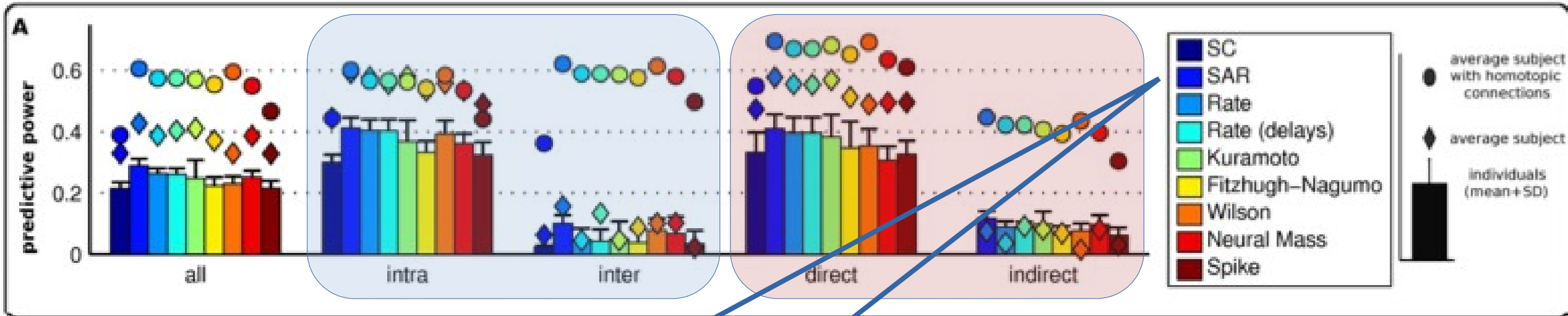
Model	Variables	Parameters	Complexity
SAR	v , BOLD signal	σ noise level	2
Rate	u , firing rate	v τ σ velocity time scale noise level	4
Kuramoto	θ , oscillator phase	v w σ velocity intrinsic pulsation noise level	4
Fitzhugh Nagumo	z , slow state v , fast state	v τ α, β, γ σ velocity time scale ($\times 2$) parameters noise level	8
Wilson Cowan	E , excitatory neurons I , inhibitory neurons	v τ w_j, w_+ a, b, c σ velocity time scale ($\times 2$) synaptic strengths transfer function parameters noise level	10
Neural-mass	V , excitatory neurons Z , inhibitory neurons	θ_{ion} T_{ion}, δ_{ion} ϕ, τ V, δ V_{ion} a_{ij}, a_{ee}, a_{ie} τ_{NMDA} conductance ($\times 3$) open ion channels parameters ($\times 3$) open potassium channels parameters neural-mass parameters ($\times 2$) Nernst potential ($\times 3$) synaptic strengths number of NMDA receptors	23
Spike attractor	E , excitatory neurons I , inhibitory neurons	N g_m C_m V_L V_{thr} V_{reset} τ_m V_f, V_E τ_{rf} w_j, w_+, w $g_{AMPA, ext}$ $g_{AMPA, rec}, g_{NMDA, rec}, g_{GABA}$ $\tau_{AMPA}, \tau_{NMDA, rise}, \tau_{GABA}$ $\tau_{NMDA, decay}$ α, β, γ number of neurons ($\times 2$) conductance ($\times 2$) capacitance ($\times 2$) resting potential ($\times 2$) subthreshold dynamics ($\times 2$) membrane potential ($\times 2$) time constant ($\times 2$) reserval potentials refractory period synaptic strengths external synaptic conductances ($\times 2$) recurrent synaptic conductances ($\times 2$) rise and decay times decay time parameters	35

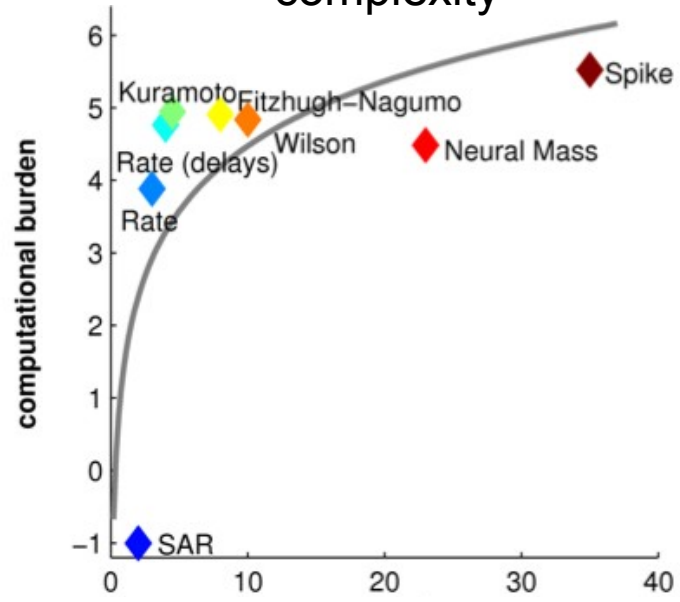
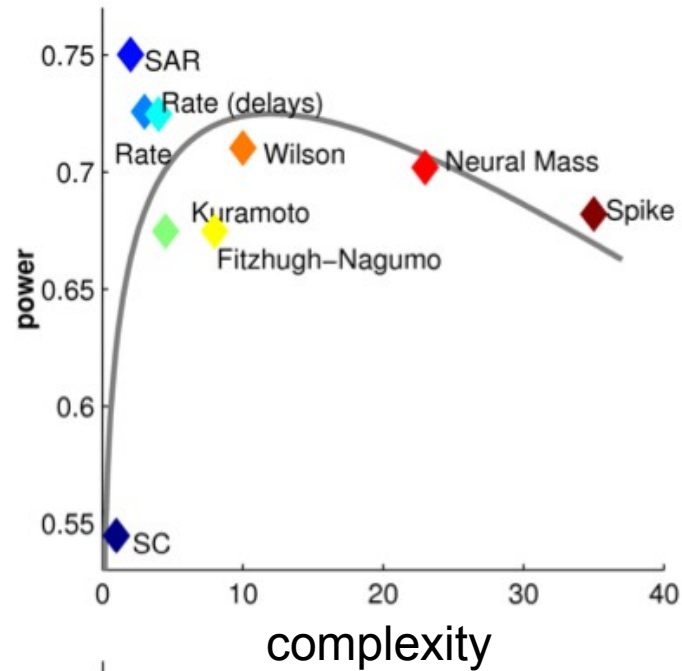




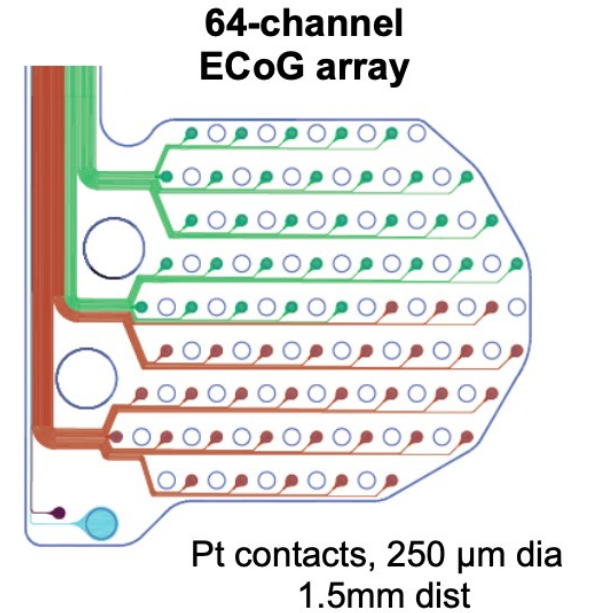
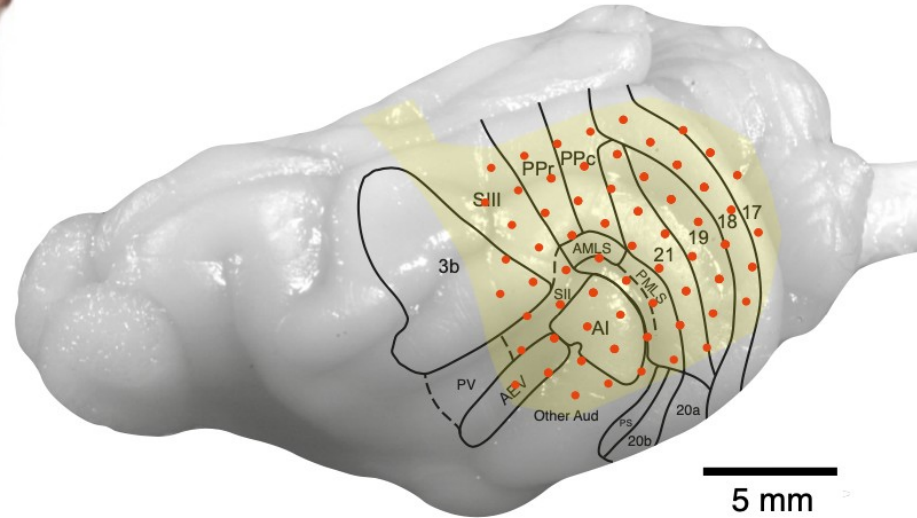
Homotopic connections!



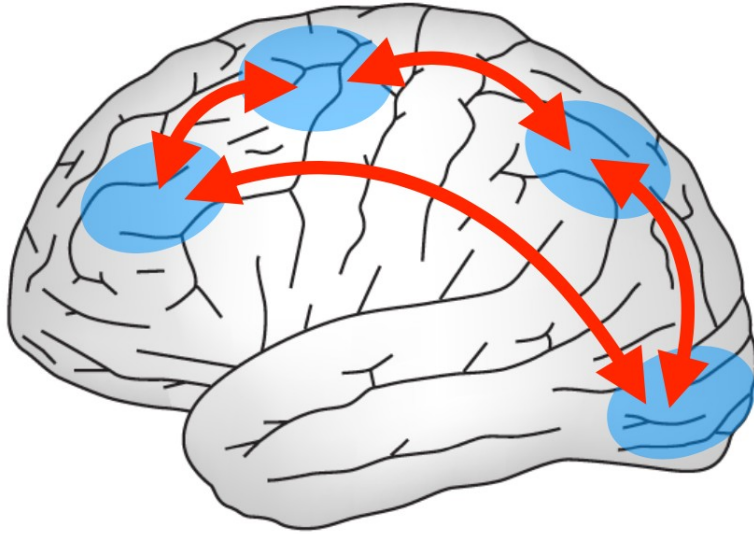




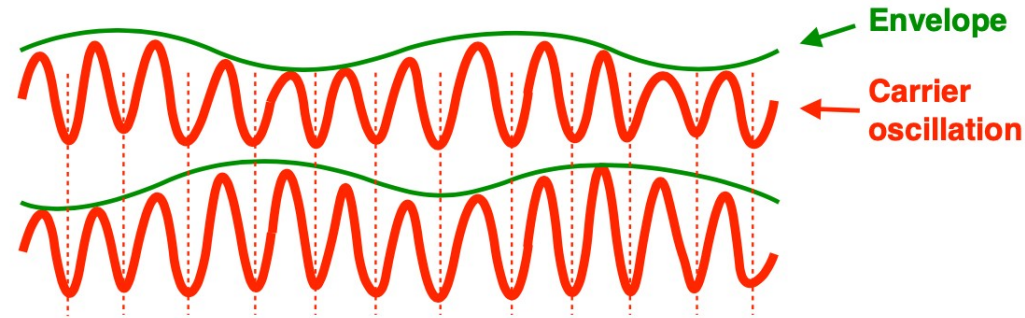
- **Consistent relationship SC and FC**
- **Model complexity \neq model prediction**
- **FC appears substantially constrained by SC**
- **But fMRI...**



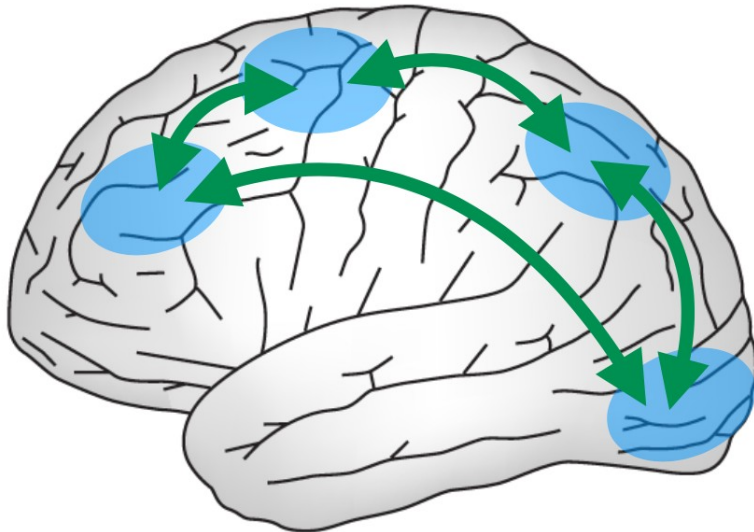
- *Chronically implanted micro-ECoG 64 electrodes*
- *Superficial LFP signals over the posterior left hemisphere*
- *Ongoing activity / spontaneous behavior*



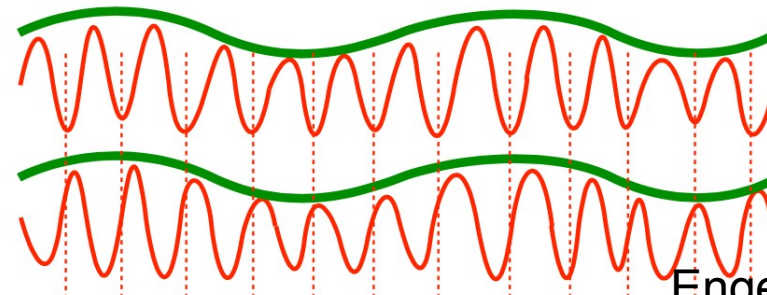
Phase coherence



- Couplings not imposed by stimuli/movements
- Occur during ongoing activity and tasks
- Route cognitive and sensorimotor processing
- Effective processing and communication

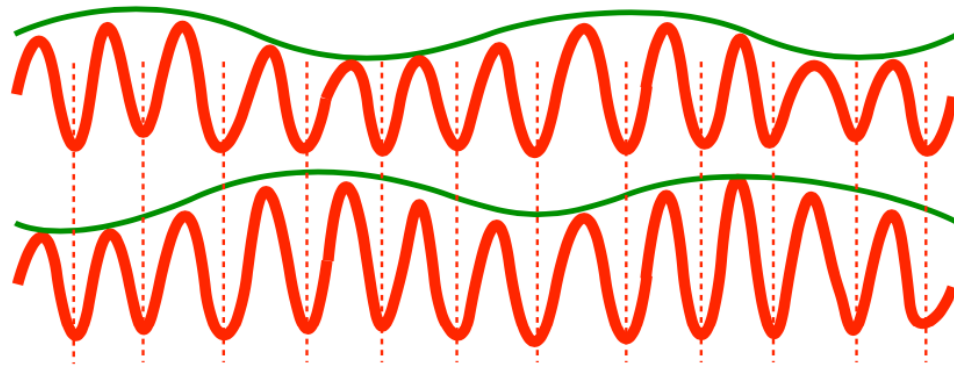


Amplitude envelope correlation



Engel, Fries & Singer, Nat Rev Neurosci 2001
 Siegel, Donner & Engel, Nat Rev Neurosci 2012
 Engel, Gerloff, Hilgetag & Nolte, Neuron 2013

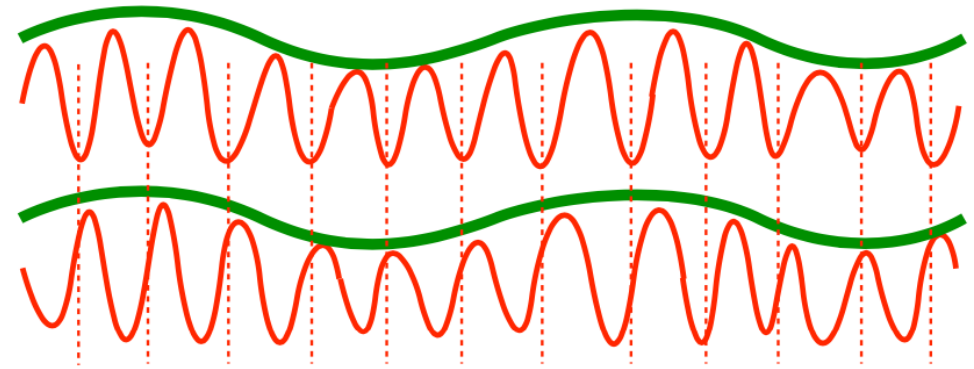
Phase ICMs



Phase coherence

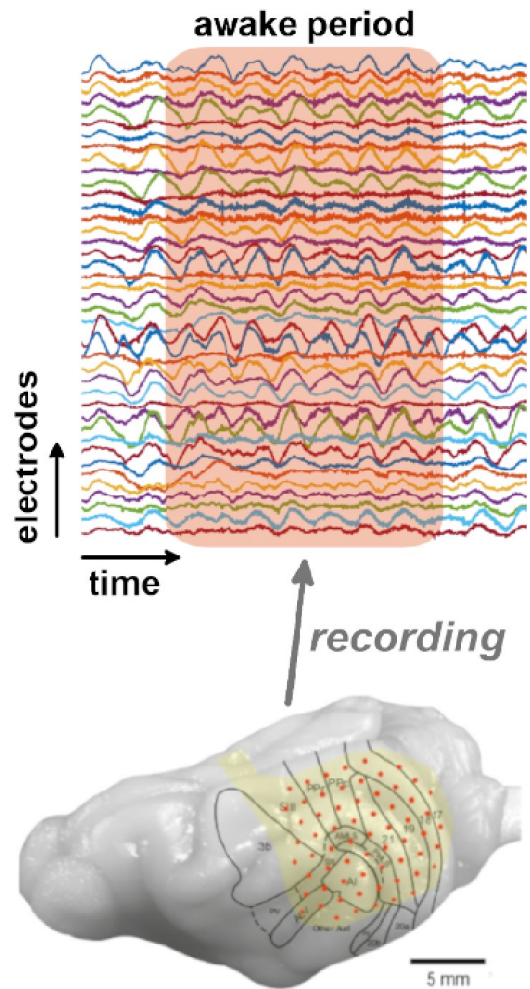
- MEG, EEG, LFP, spikes
- Band-limited oscillations (1-150 Hz)
- Coherence, PLV, PLI, PSI, etc

Envelope ICMs

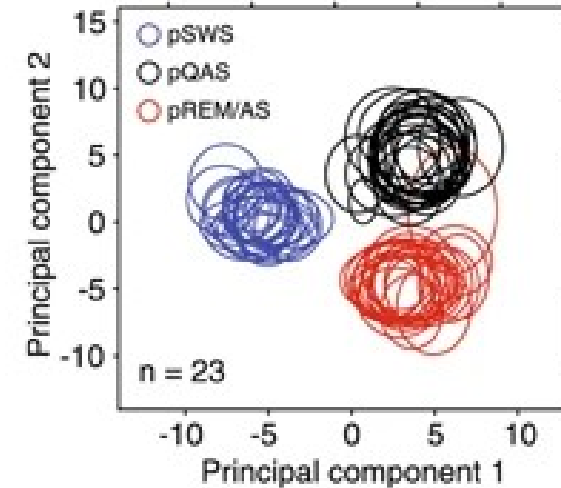
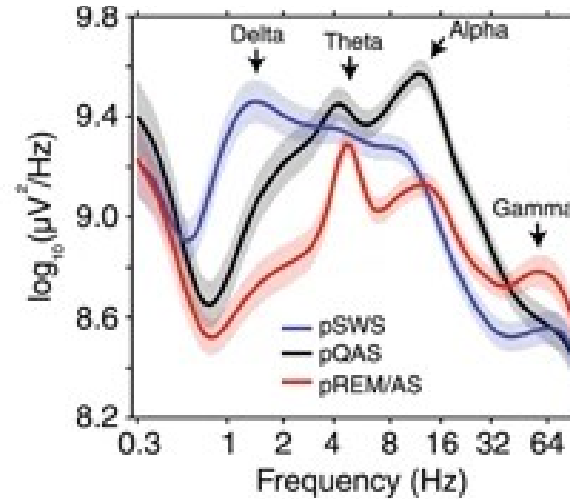
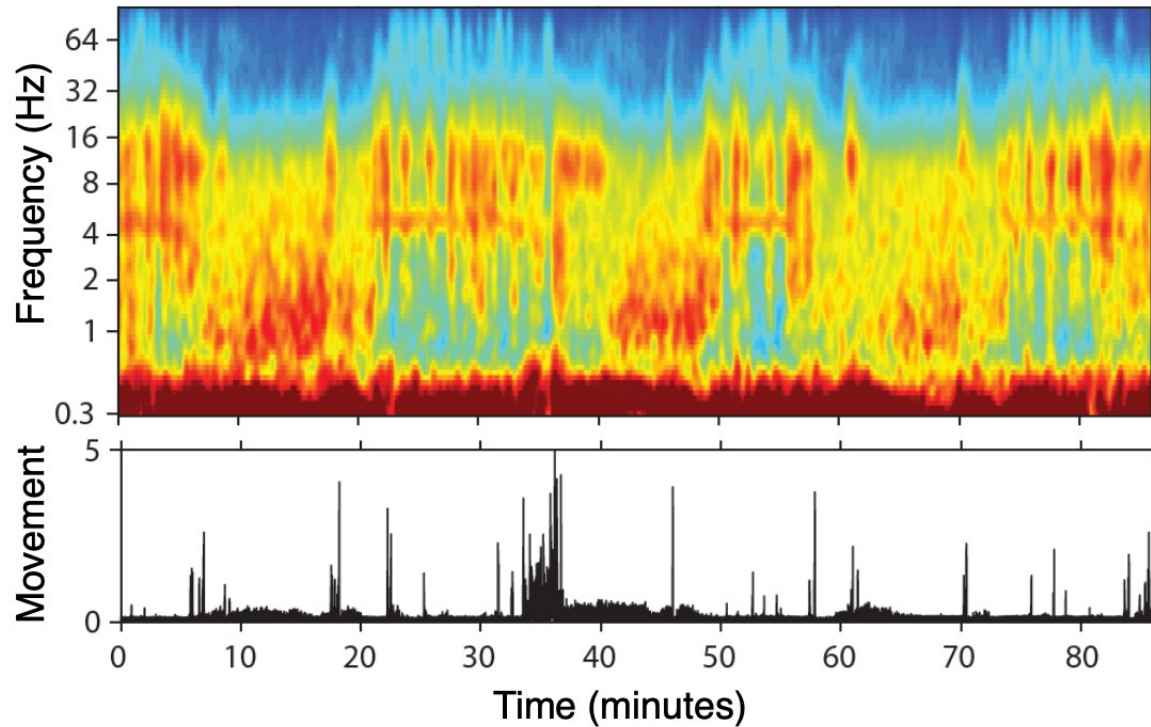


Amplitude envelope correlation

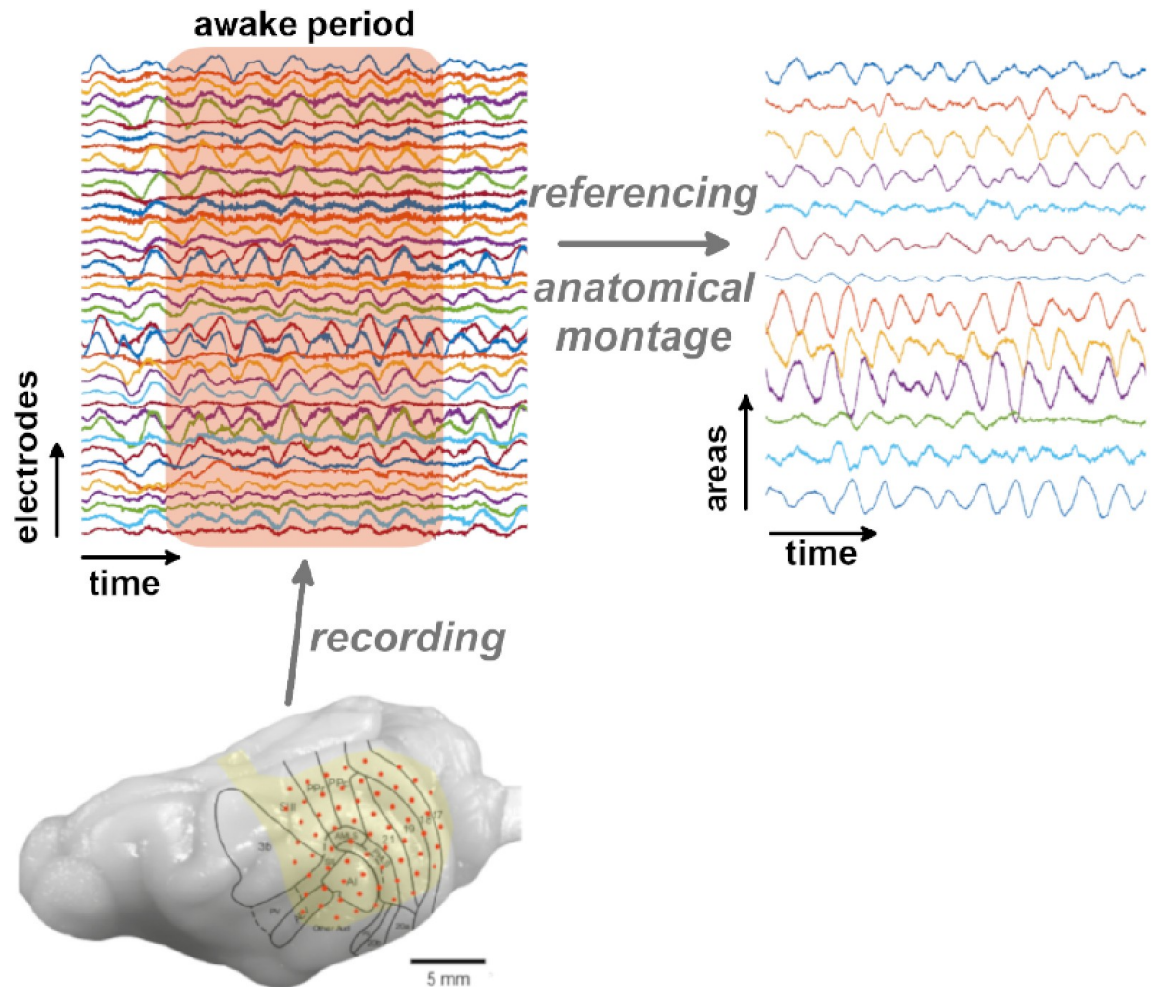
- FMRI, MEG, EEG, LFP, spikes
- Aperiodic scalefree (<0.1 Hz)
- AEC



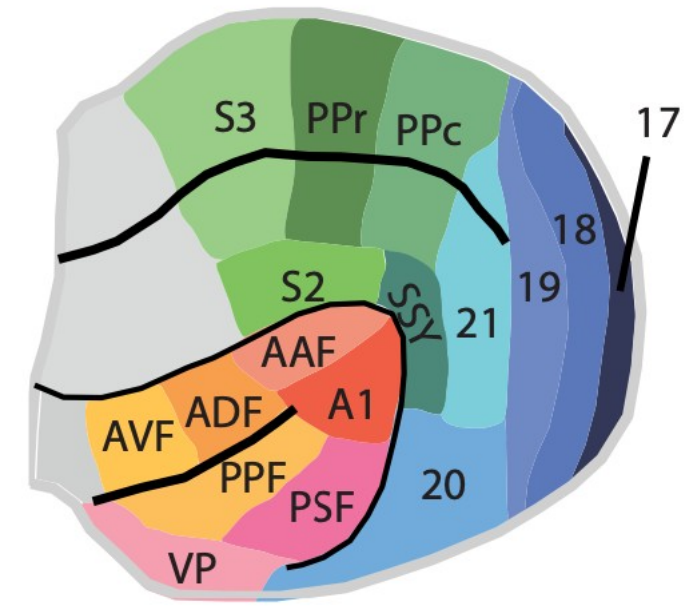
Stitt et al., Sci Rep (2017)



- *Spectral changes in the slow oscillations (0.8-3Hz), theta-band (4-6 Hz) and alpha-band (8-16Hz)*
- *Classification of brain states: awake, REM sleep and slow wave sleep*

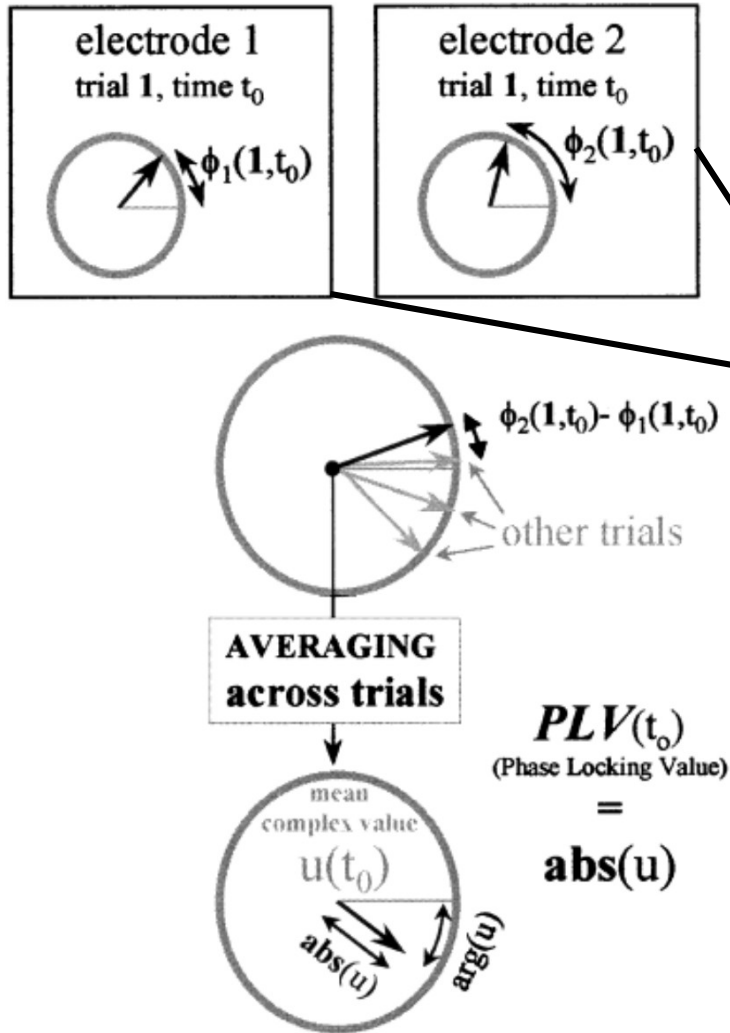


Bizley & King, Hear Res (2009)



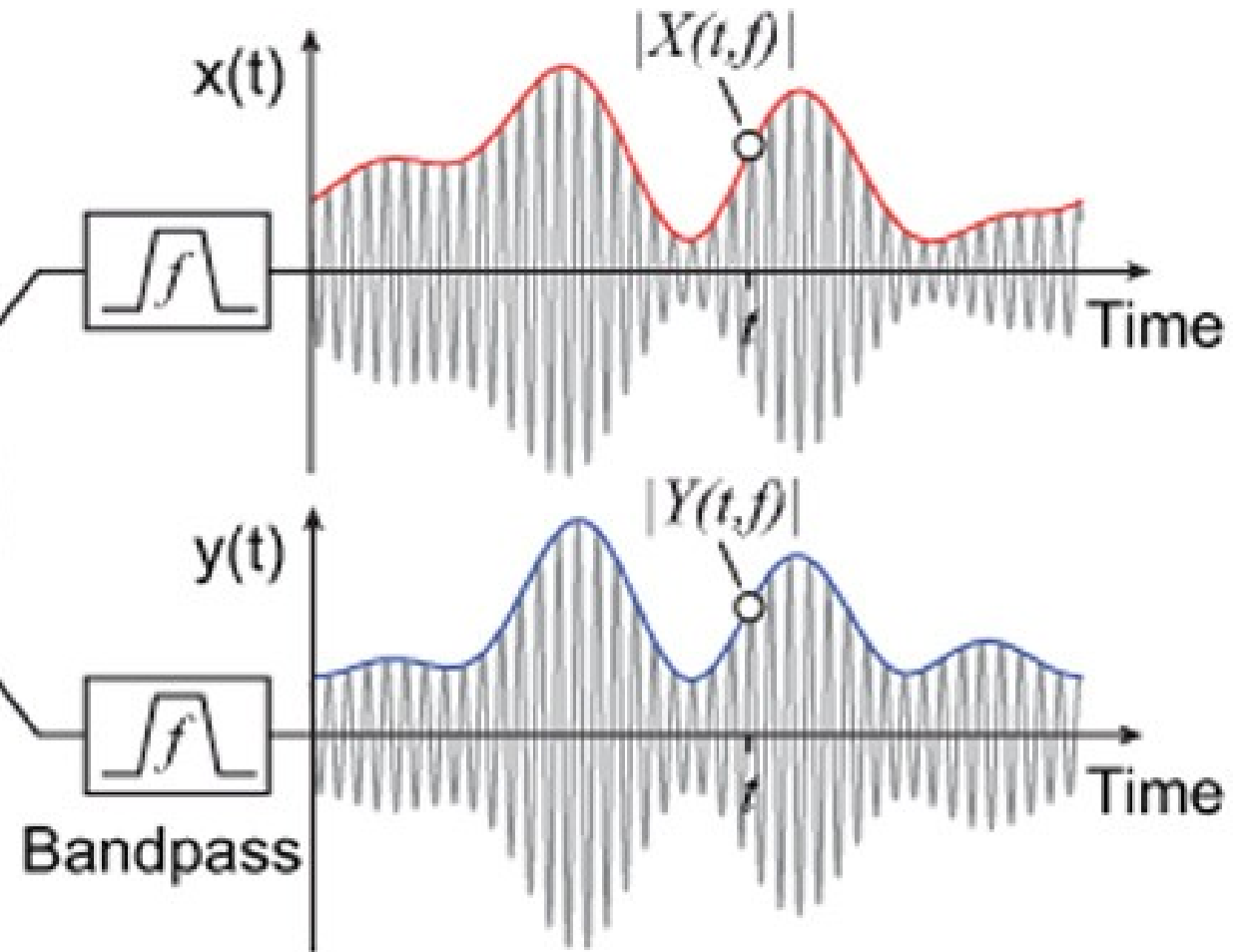
Messé et al., Neuroimage (2023)

Phase locking value

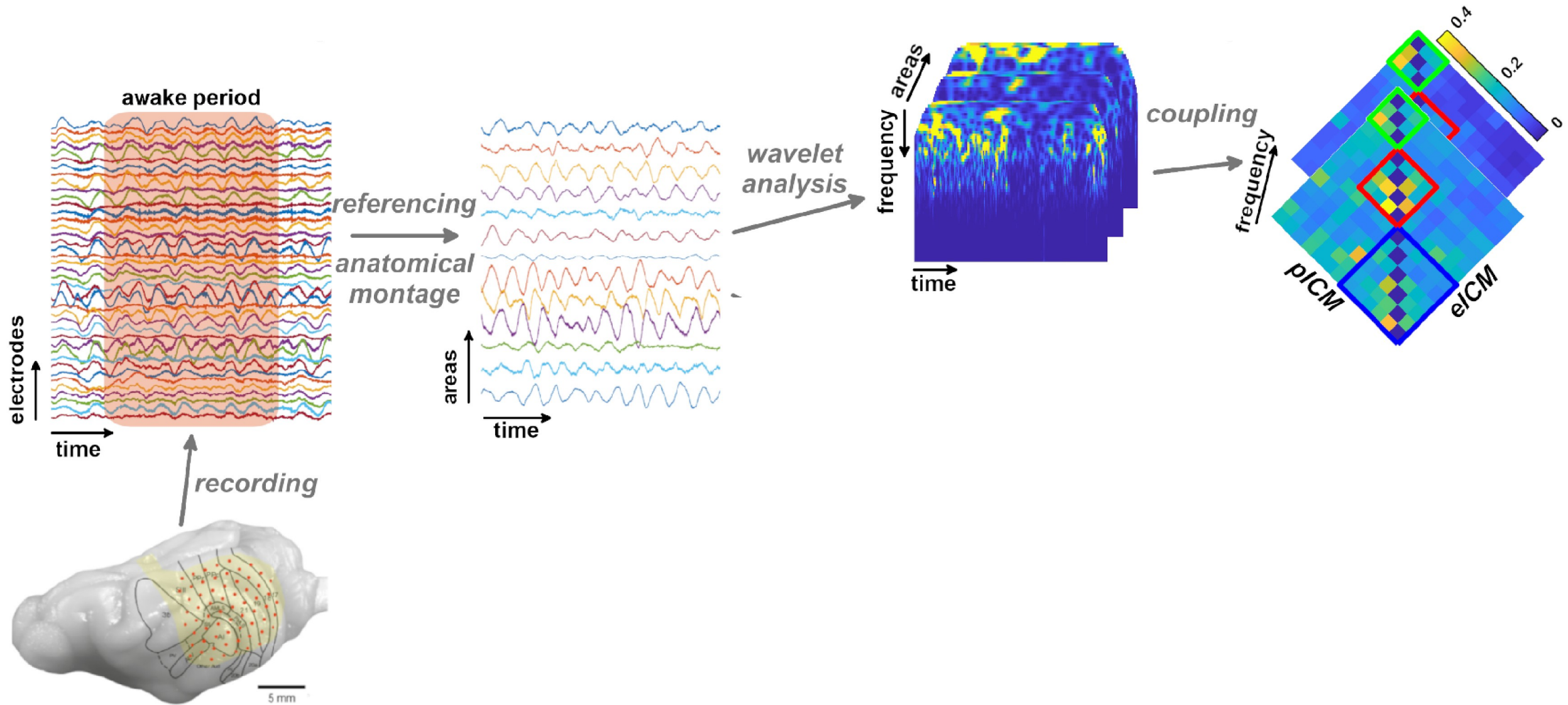


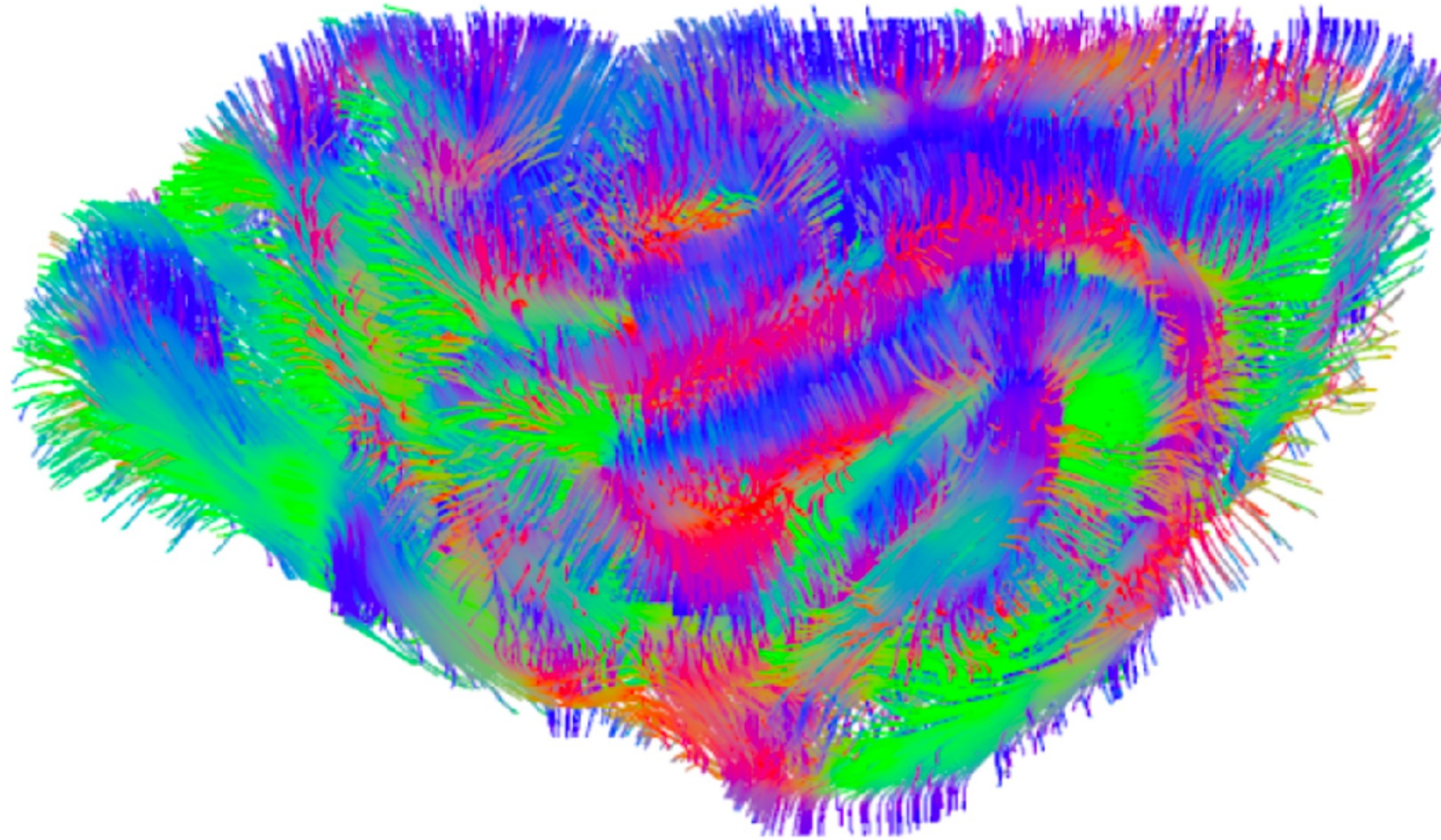
Lachaux et al., HBM (1999)

Amplitude envelope correlation



Hipp et al., Nat Neurosci (2012)

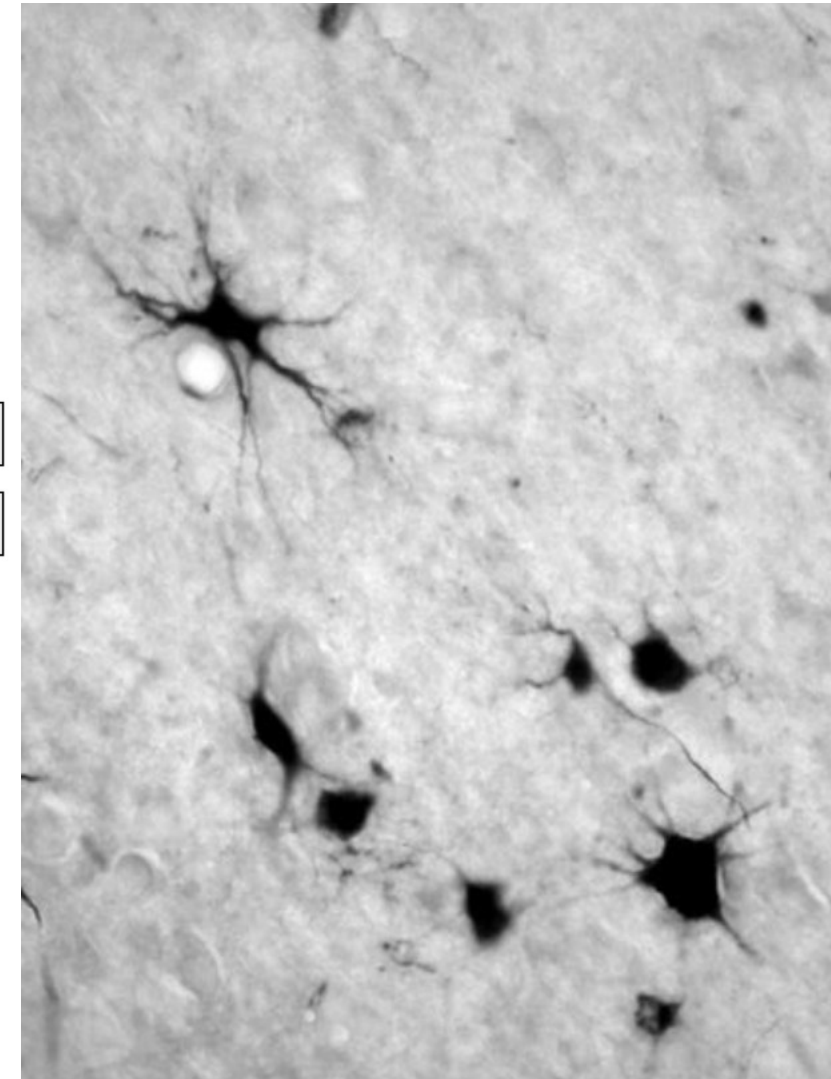
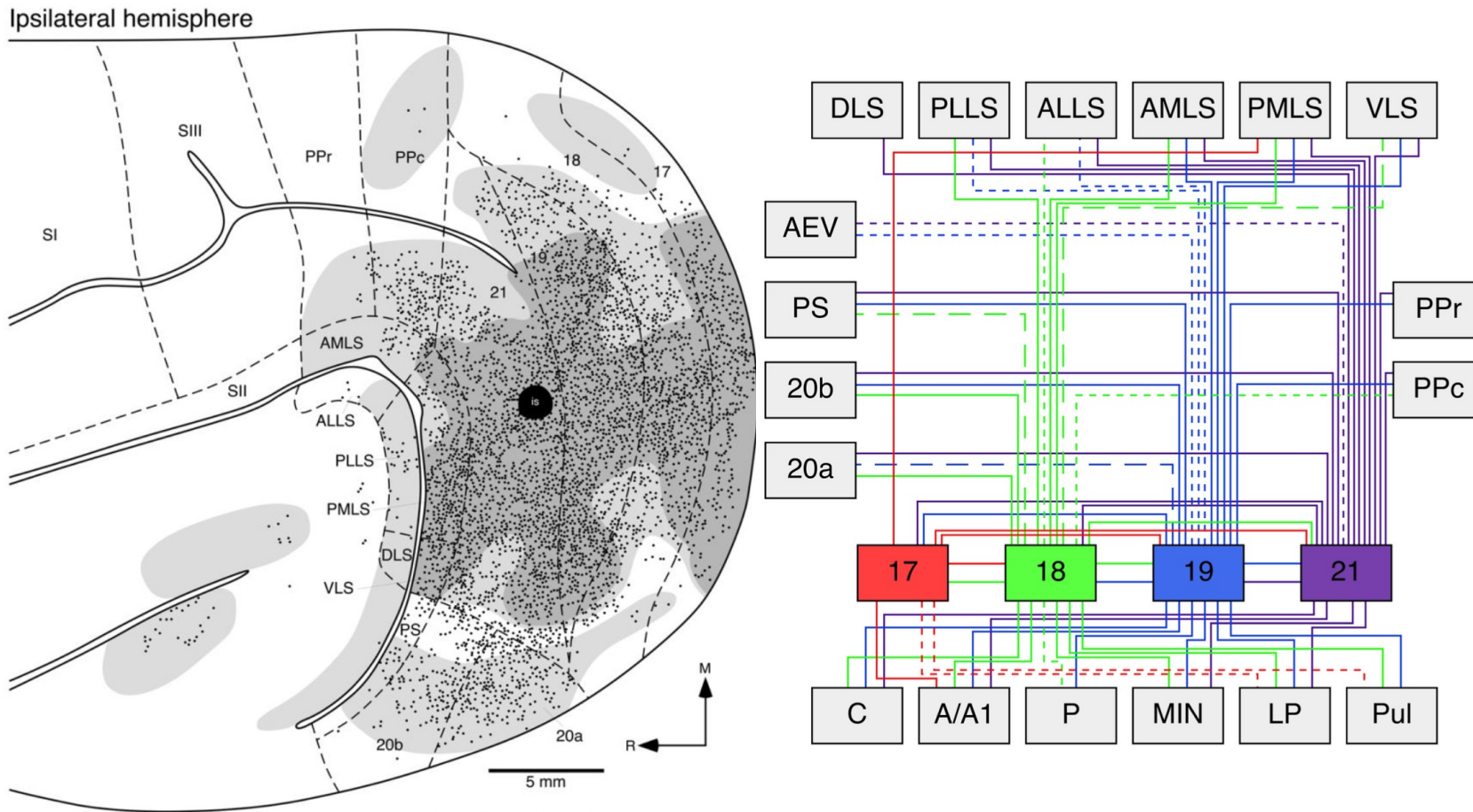


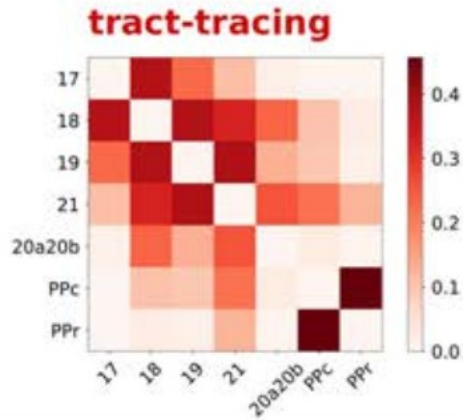
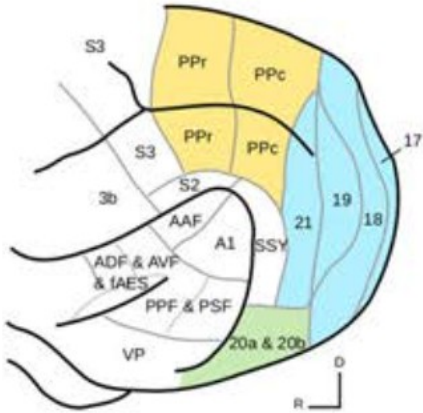


Diffusion MRI tractography based on **high-resolution *ex vivo* imaging** at 7T
Collaboration with Institut Pasteur and NeuroSpin, France

Delettre et al., Netw Neurosci (2019)

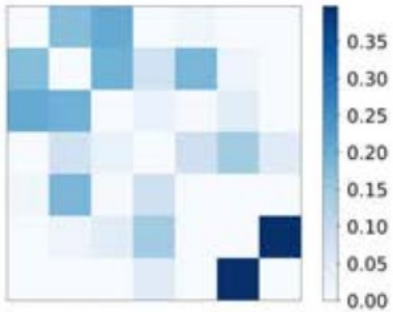
Tract-tracing



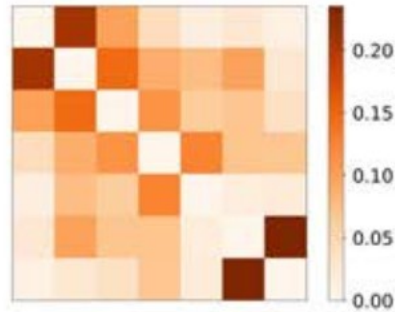


Probabilistic tractography

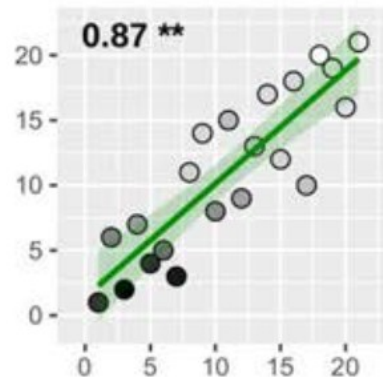
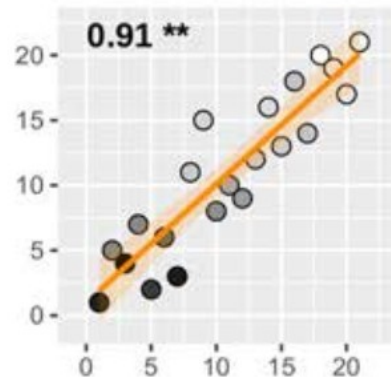
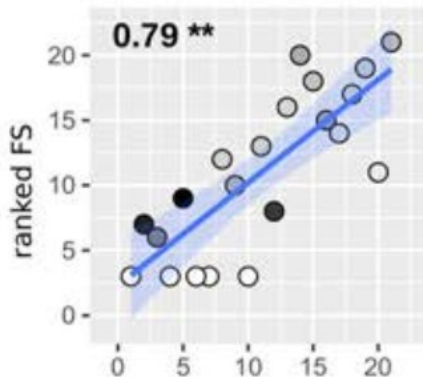
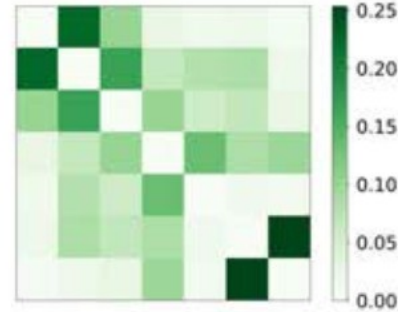
DTI

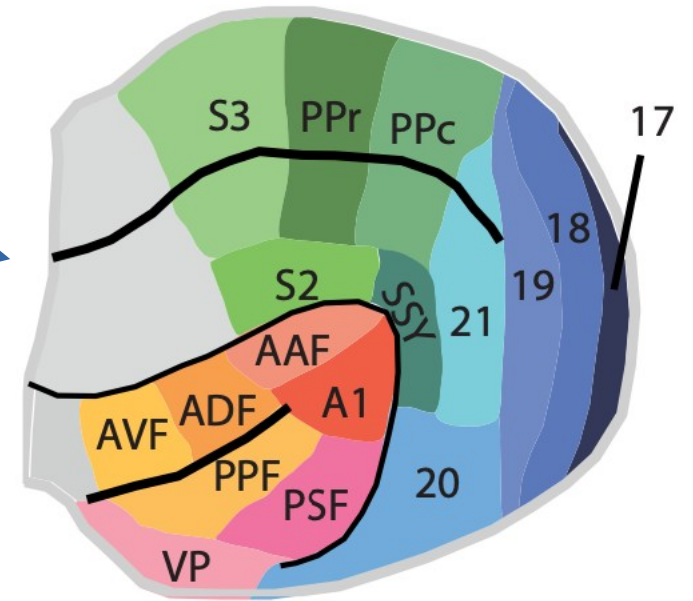
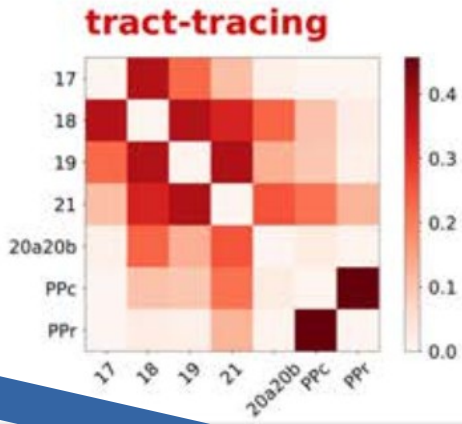
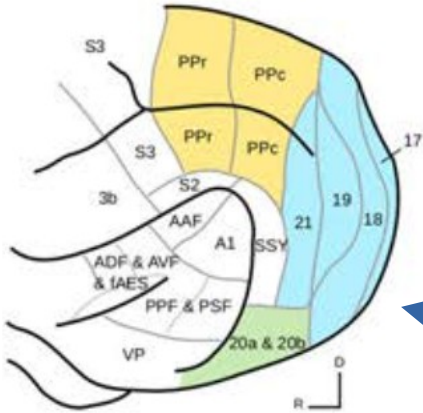


CSD

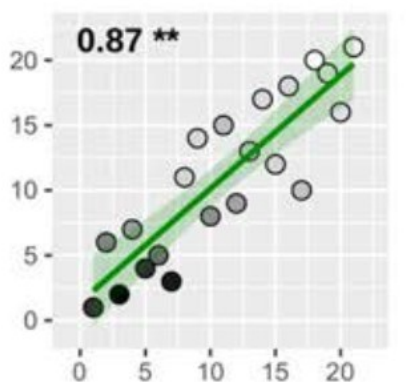
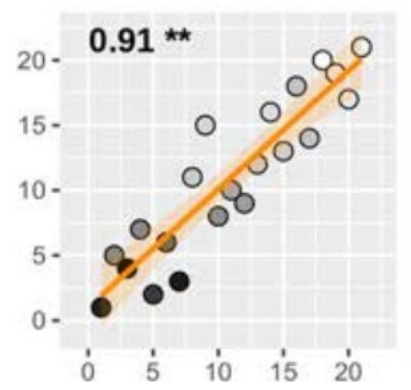
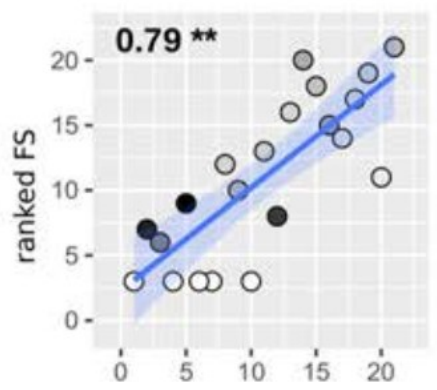
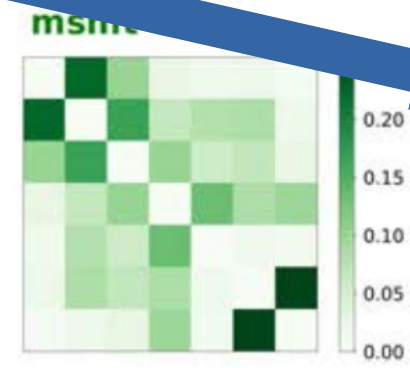
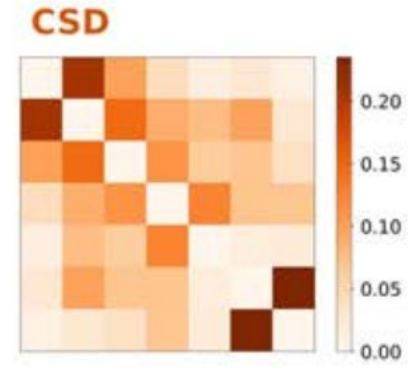
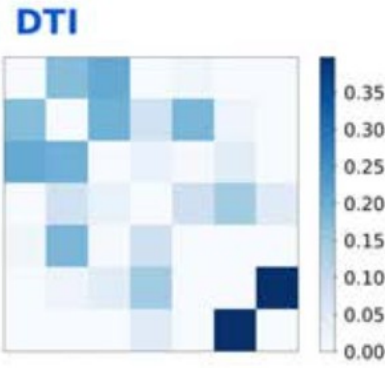


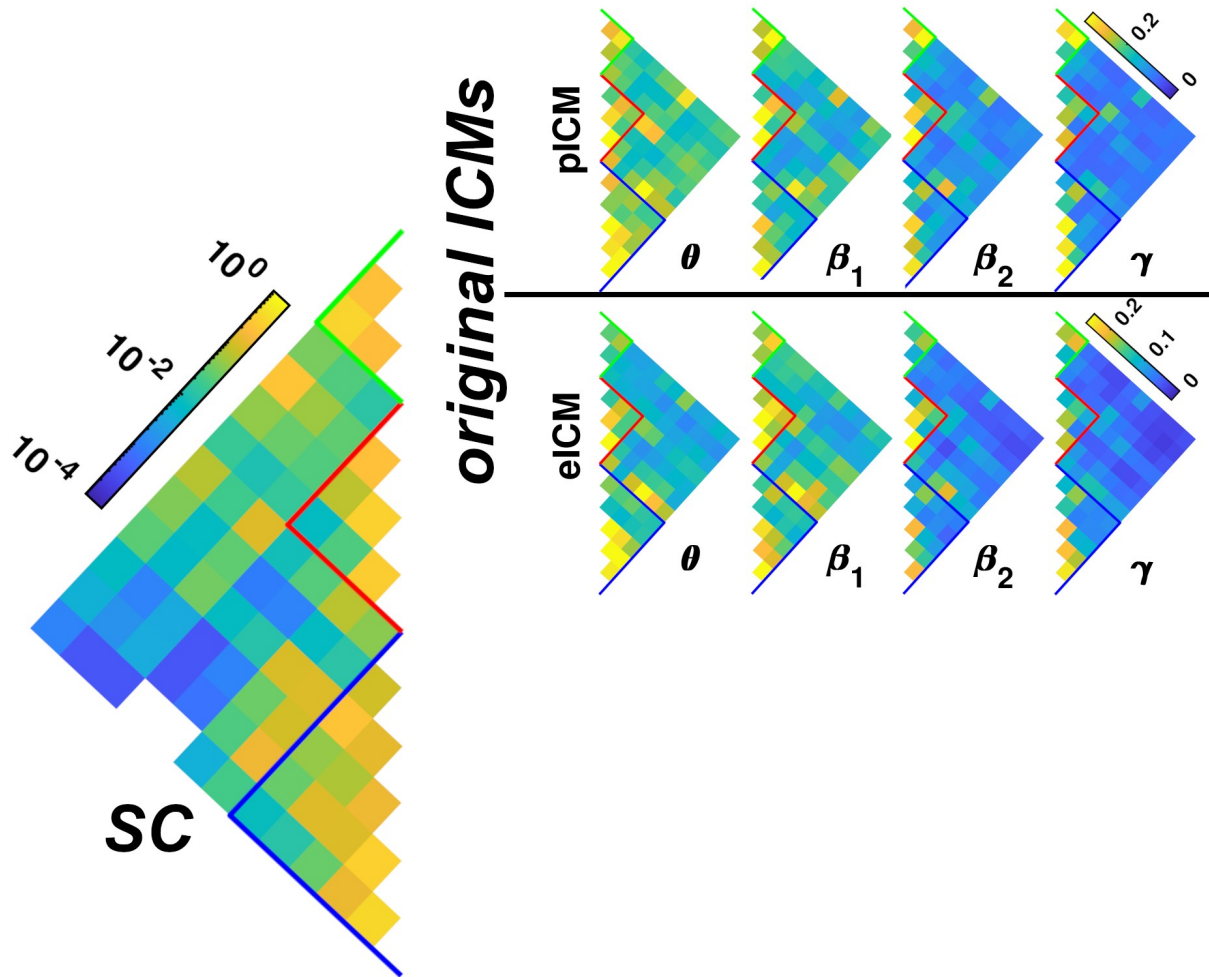
msmt CSD

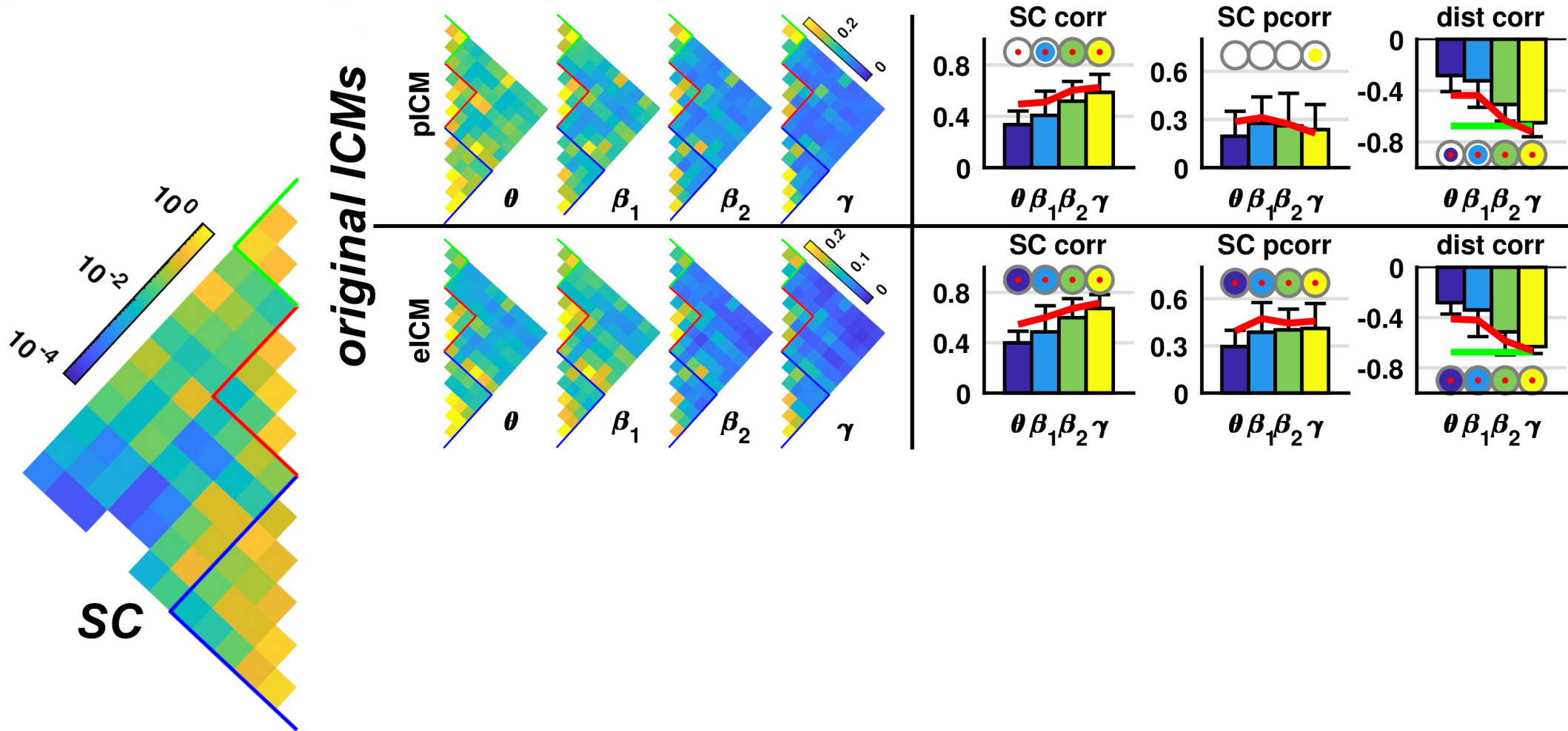


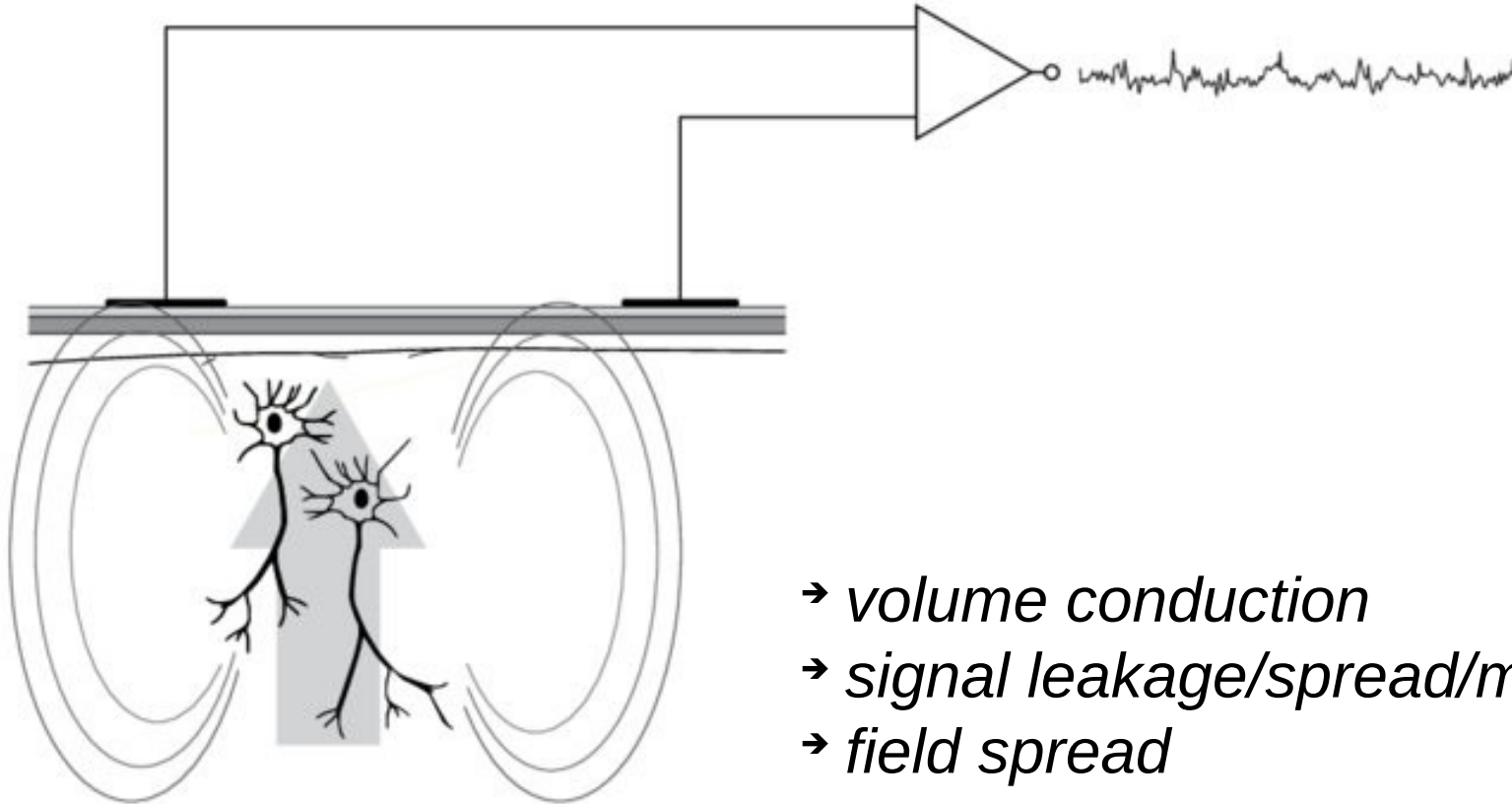


Probabilistic tractography



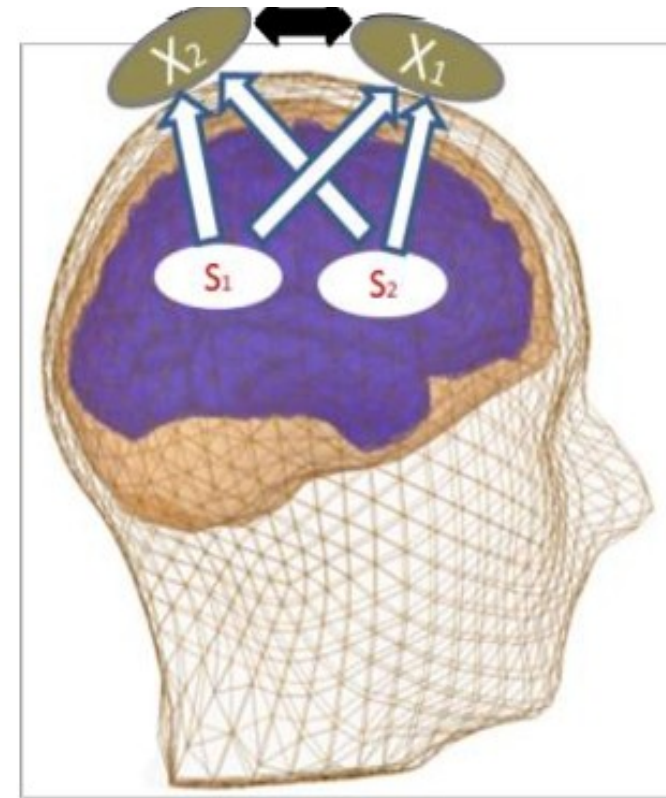




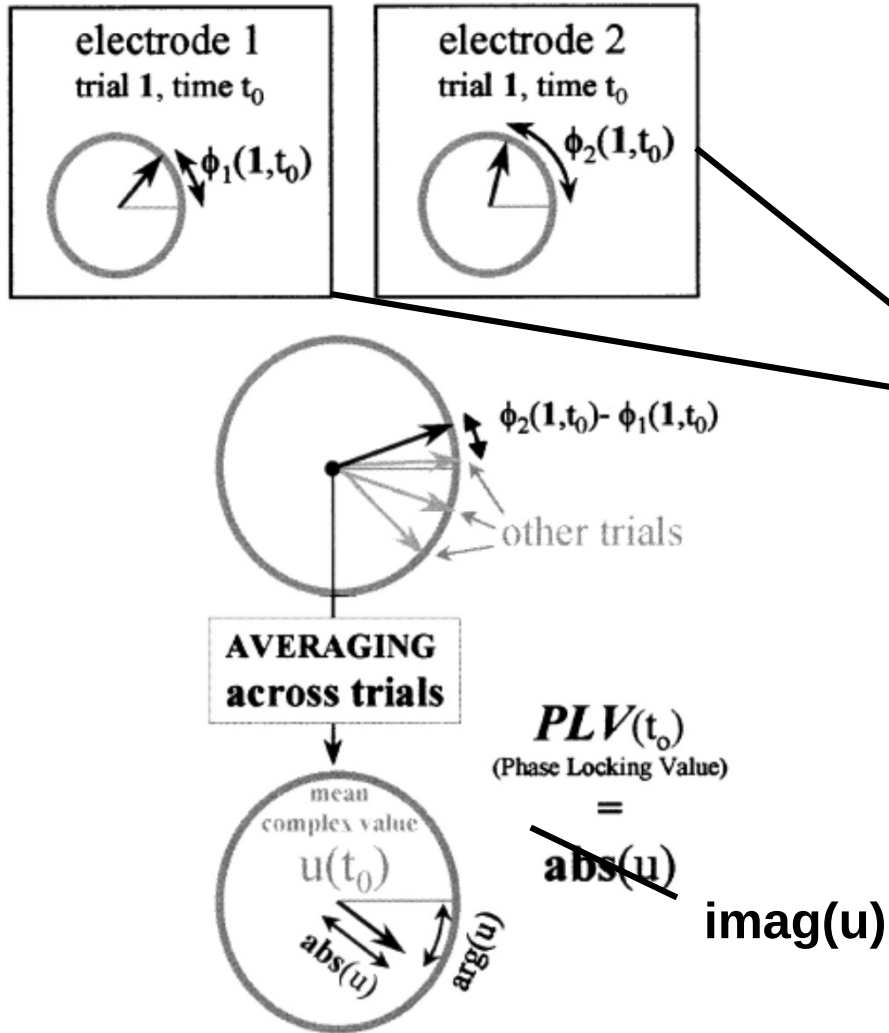


- *volume conduction*
- *signal leakage/spread/mixing*
- *field spread*

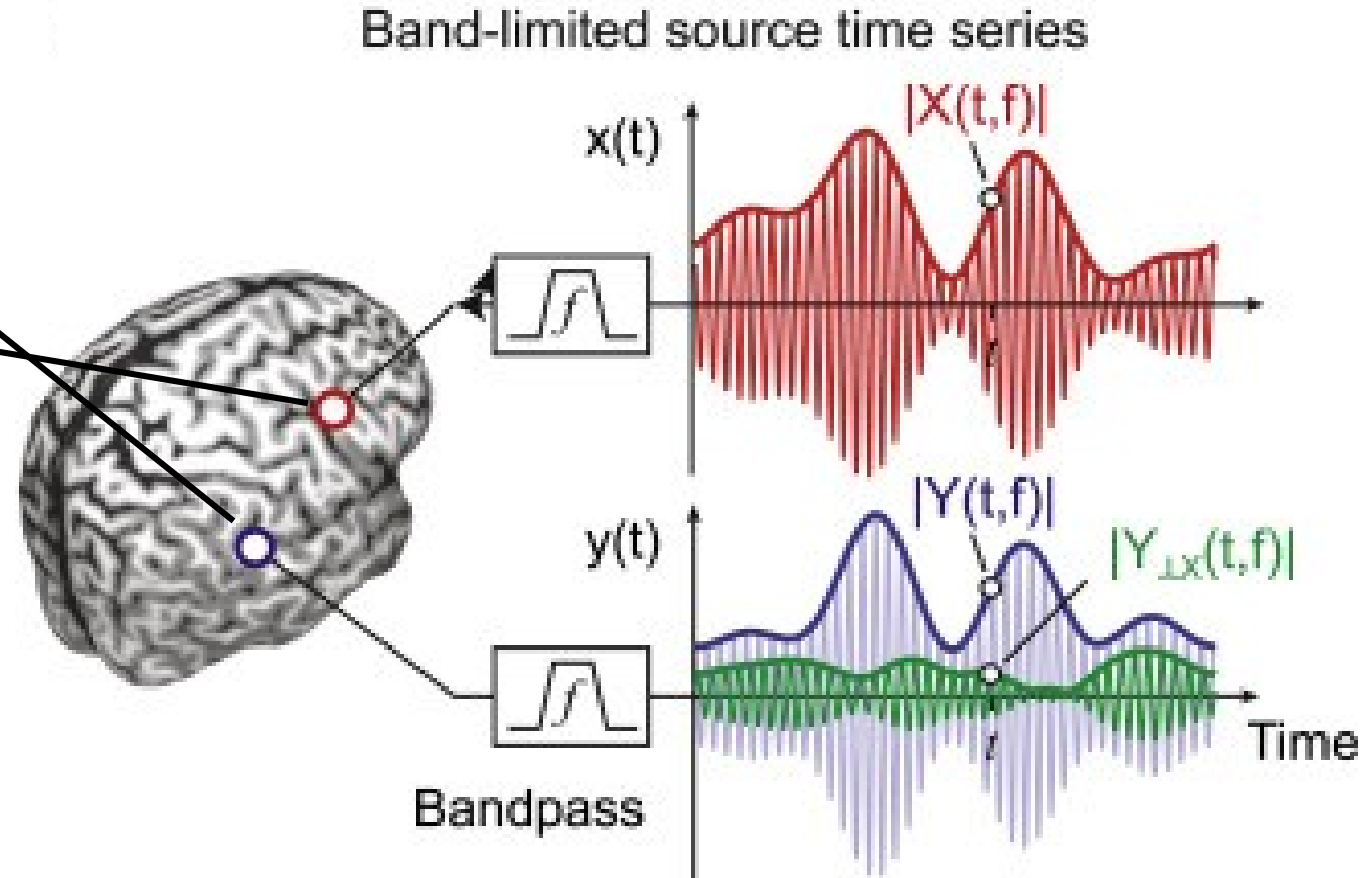
Instantaneous (zero-lag)

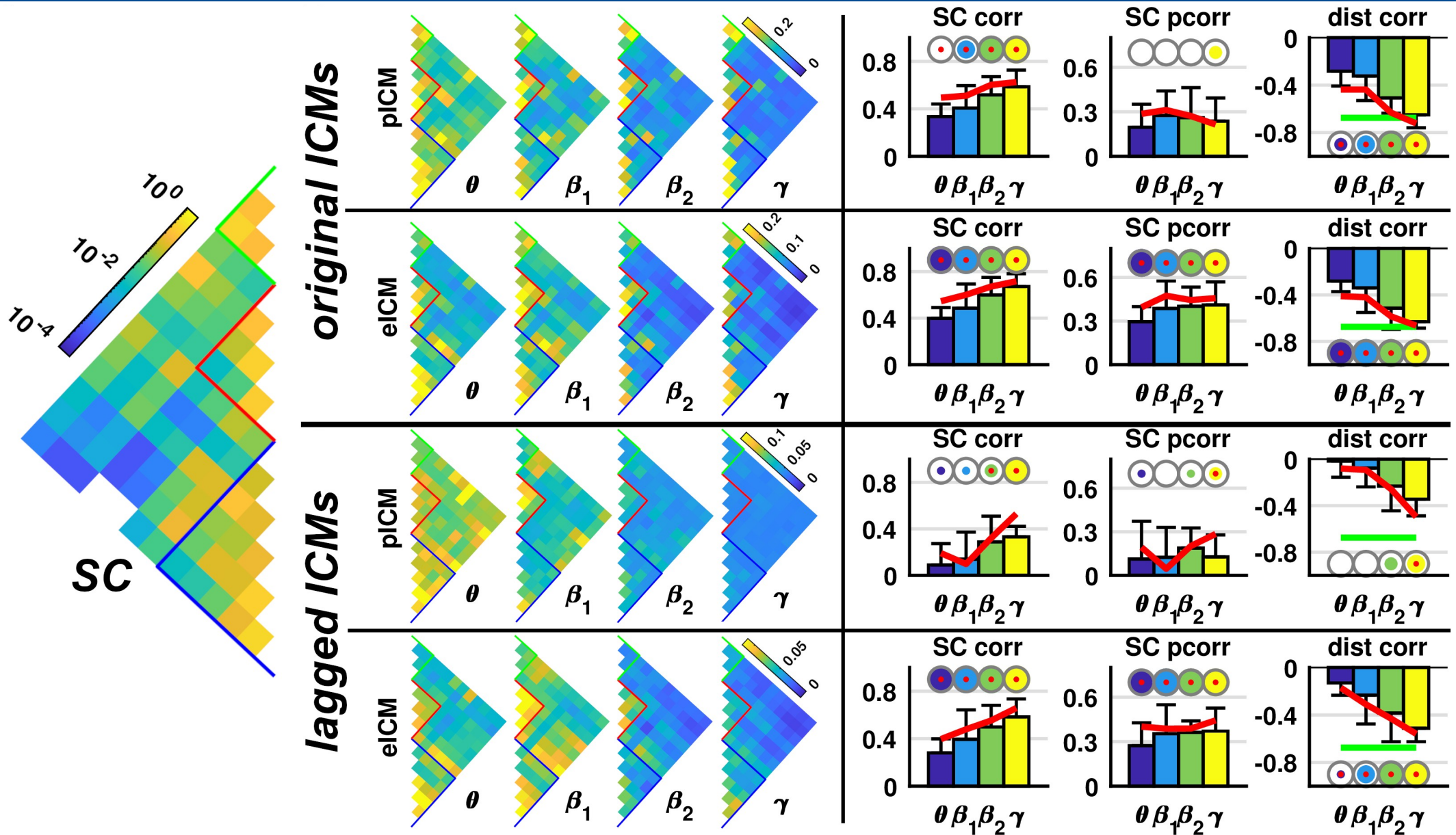


Imaginary phase locking value

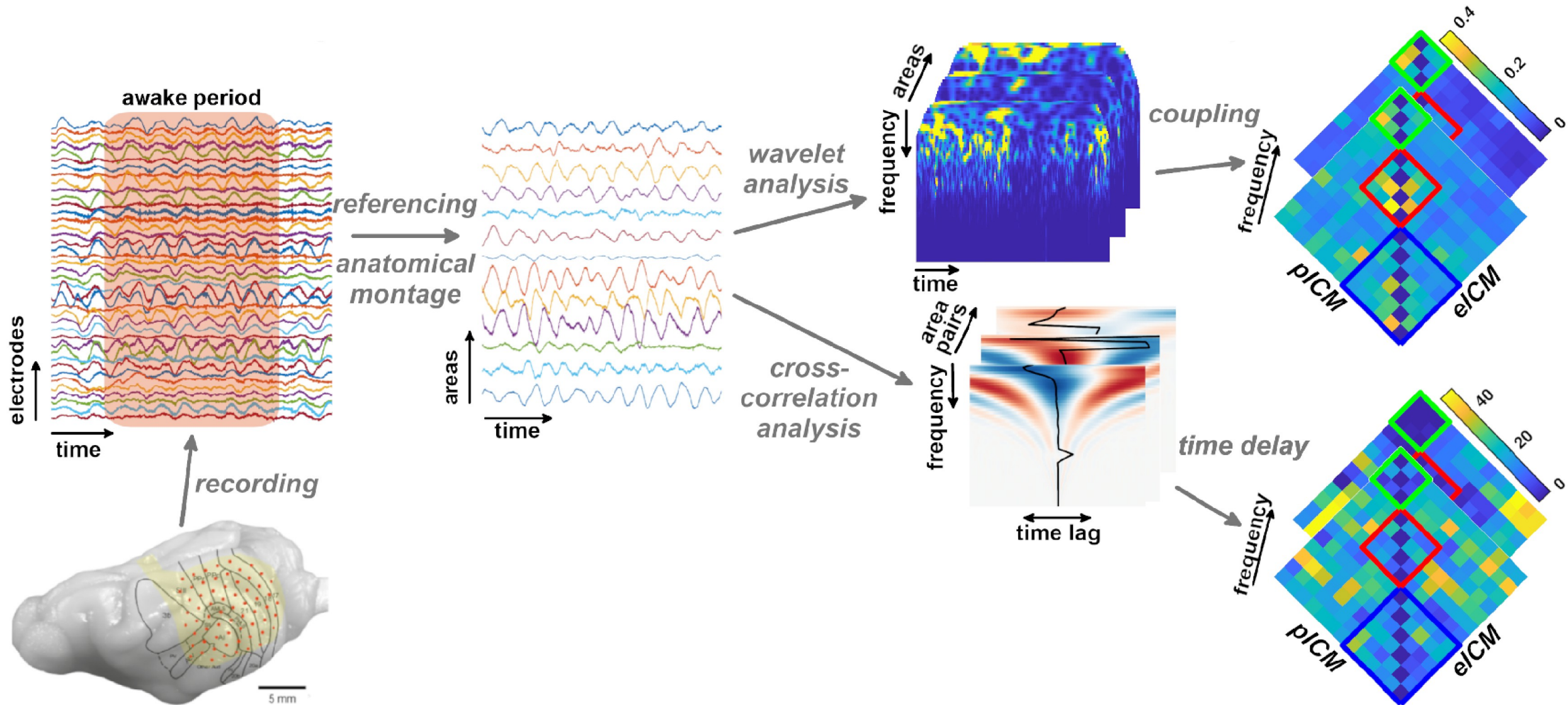


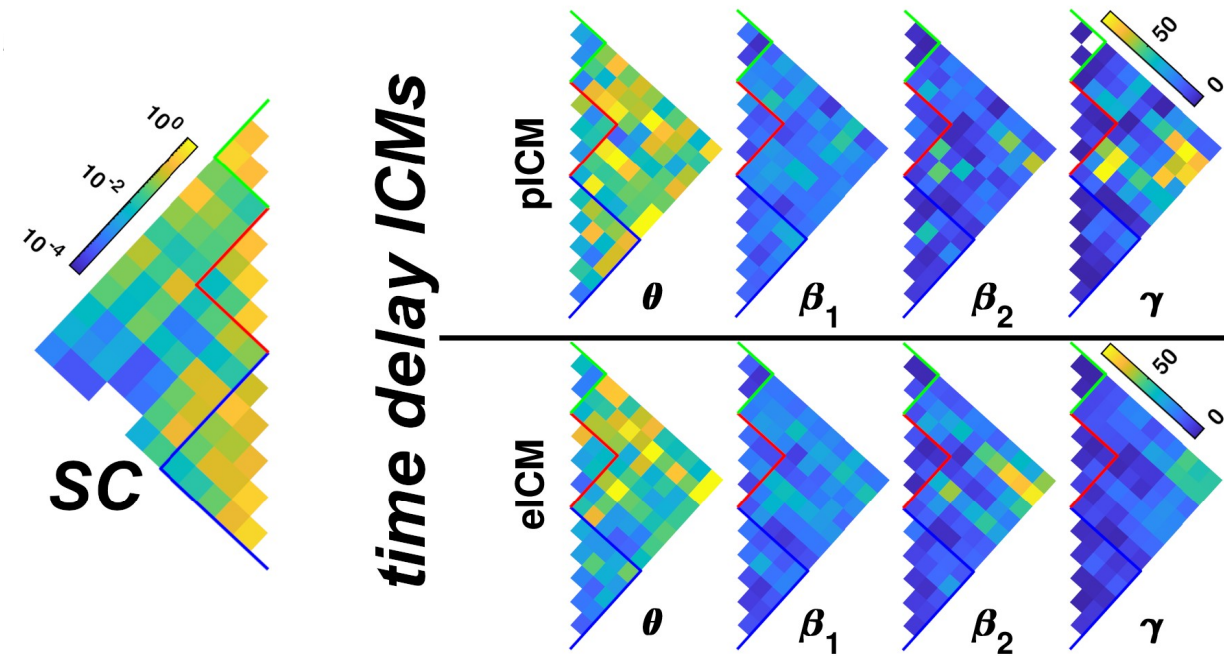
Orthogonalized amplitude envelope correlation

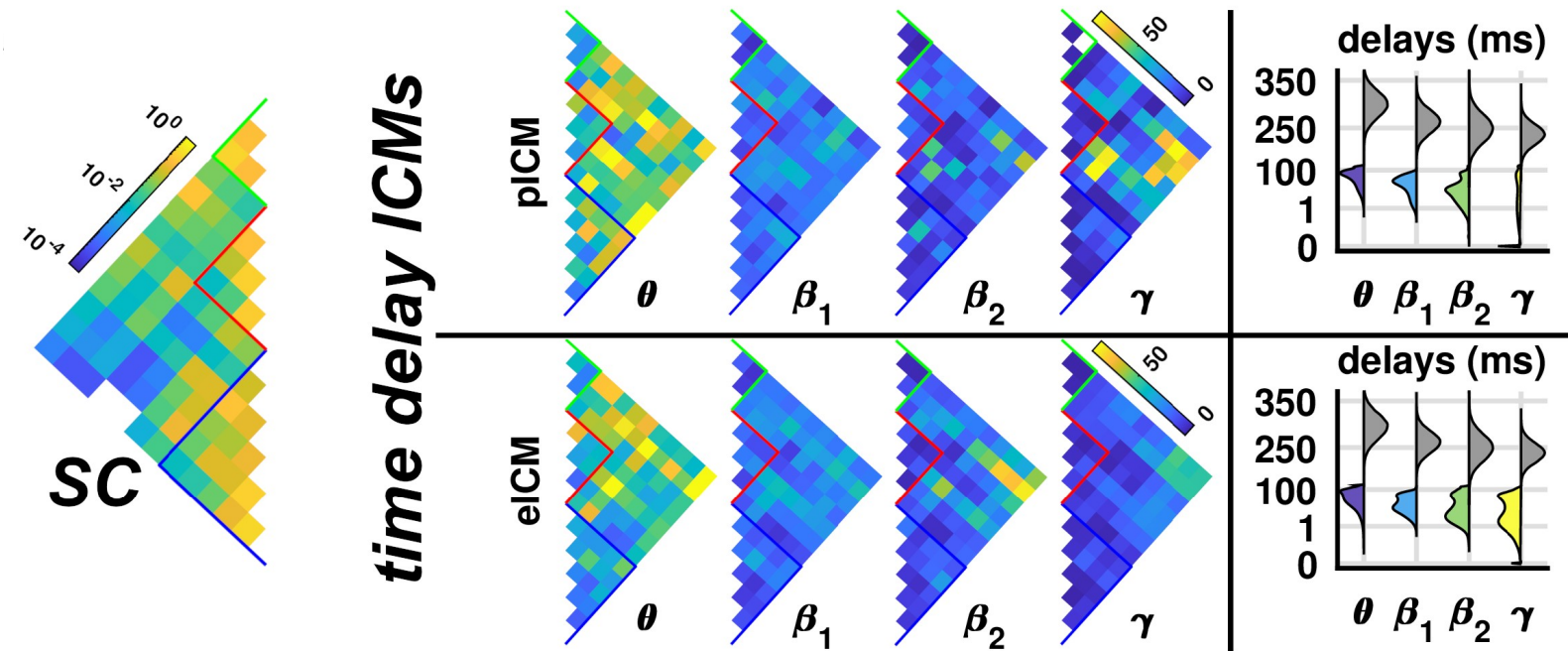


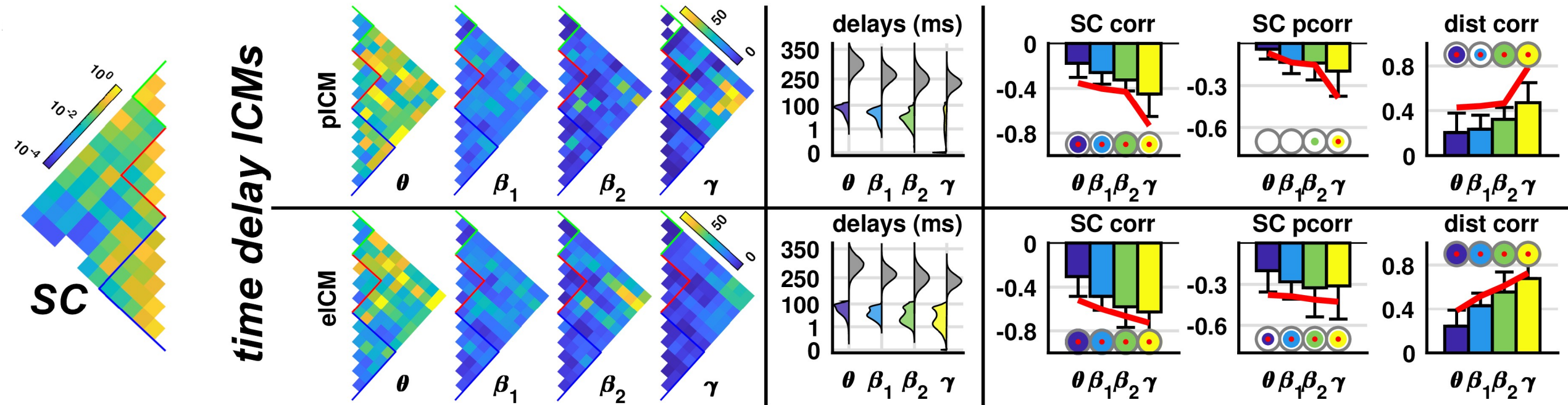


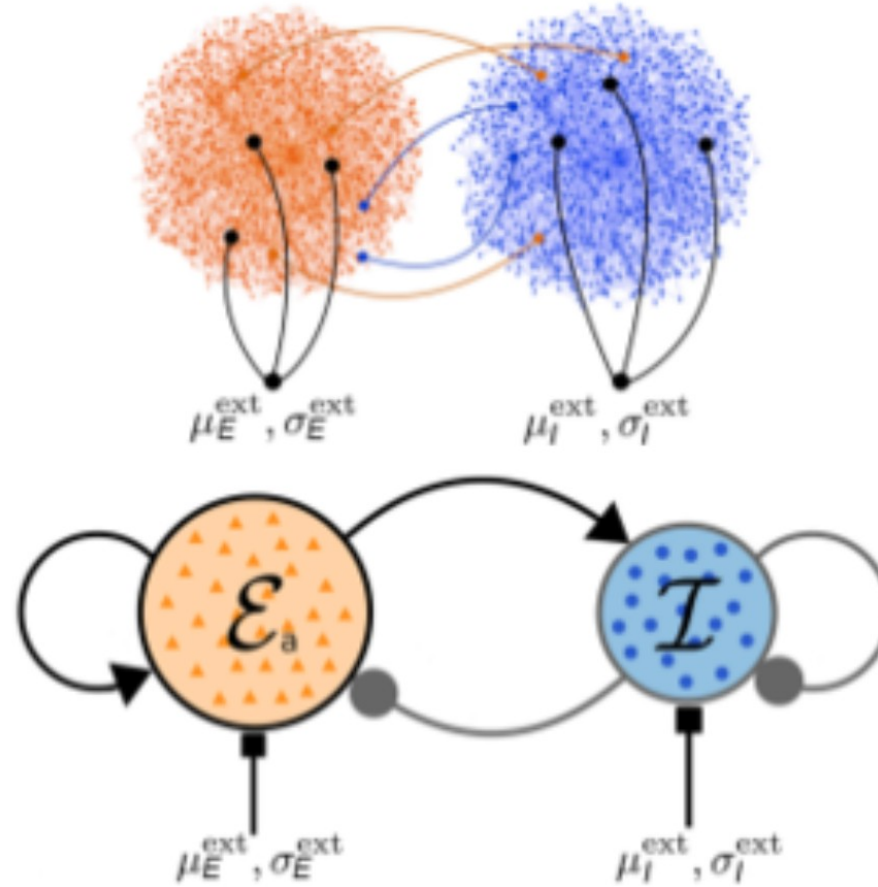
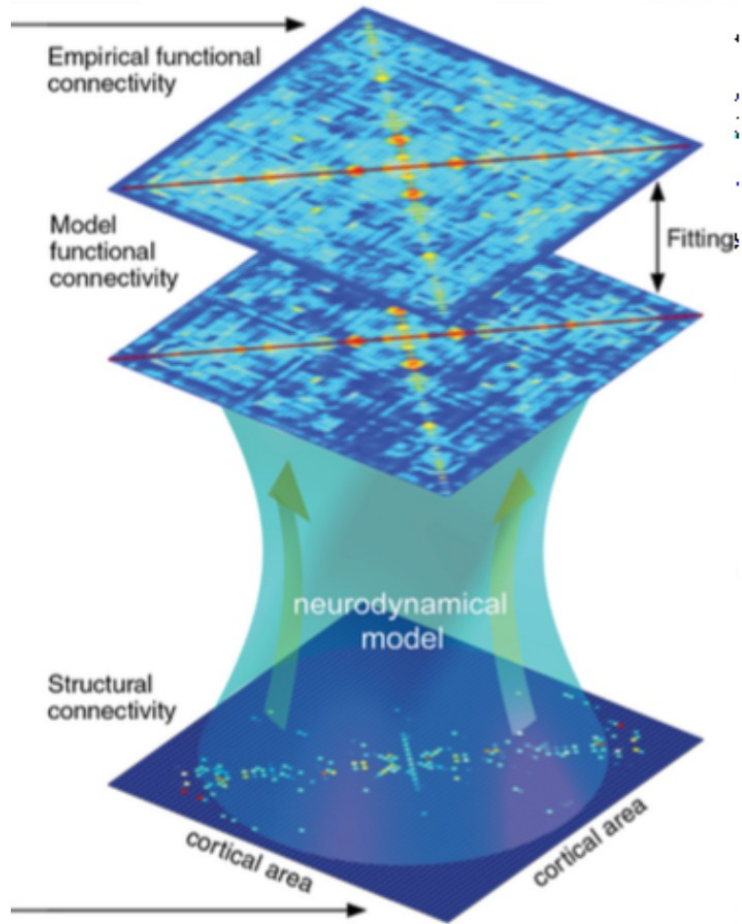
Messé et al., Neuroimage (2023)











Large-scale spiking attractor model

SAN

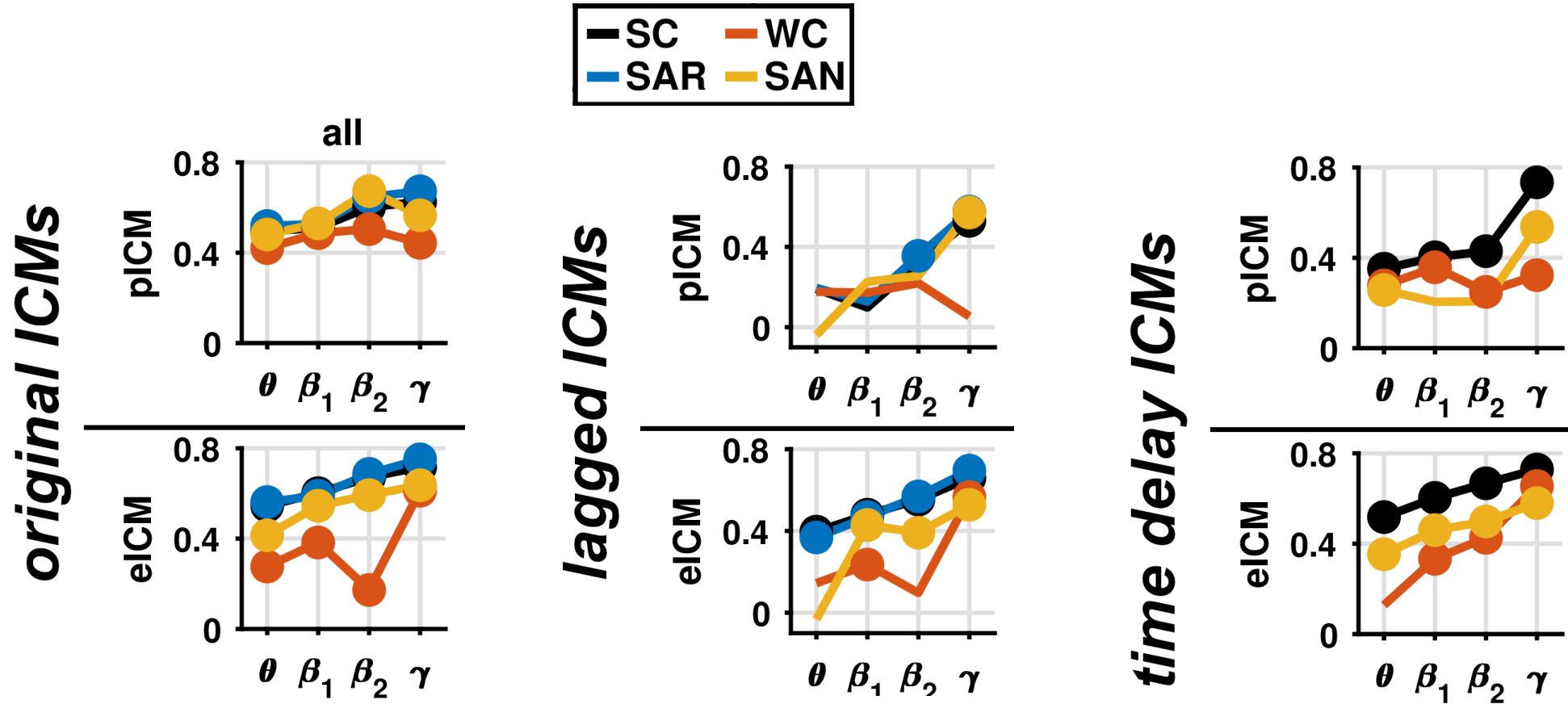
Wilson-Cowan neural-mass model

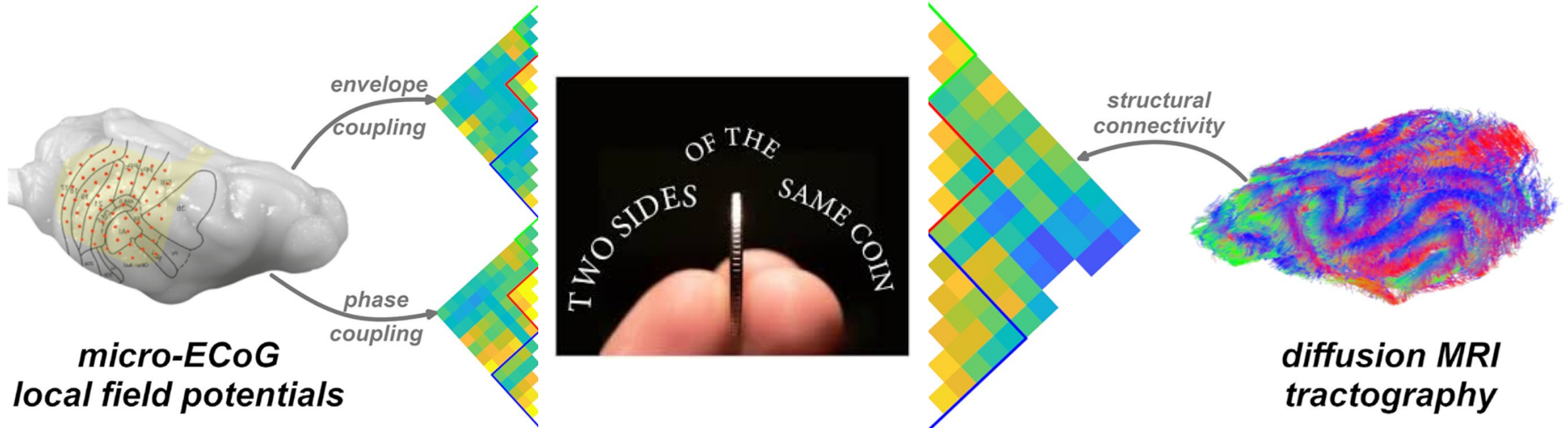
WC

$$y = \omega Dy + e$$

Statistical autoregressive model

SAR





- **Consistent relationship between phase and envelope ICMs with SC**
- **The relation between structural and functional coupling is not artifact**
- **Computational models are challenged to predict ICMs**
- **ICMs appear substantially constrained by the underlying structural scaffold**
- **Dominant role of direct, short-distance, near zero-lag interactions**