



Two sides of the same coin Structural vs. Functional brain connectivity

LIF/LIB

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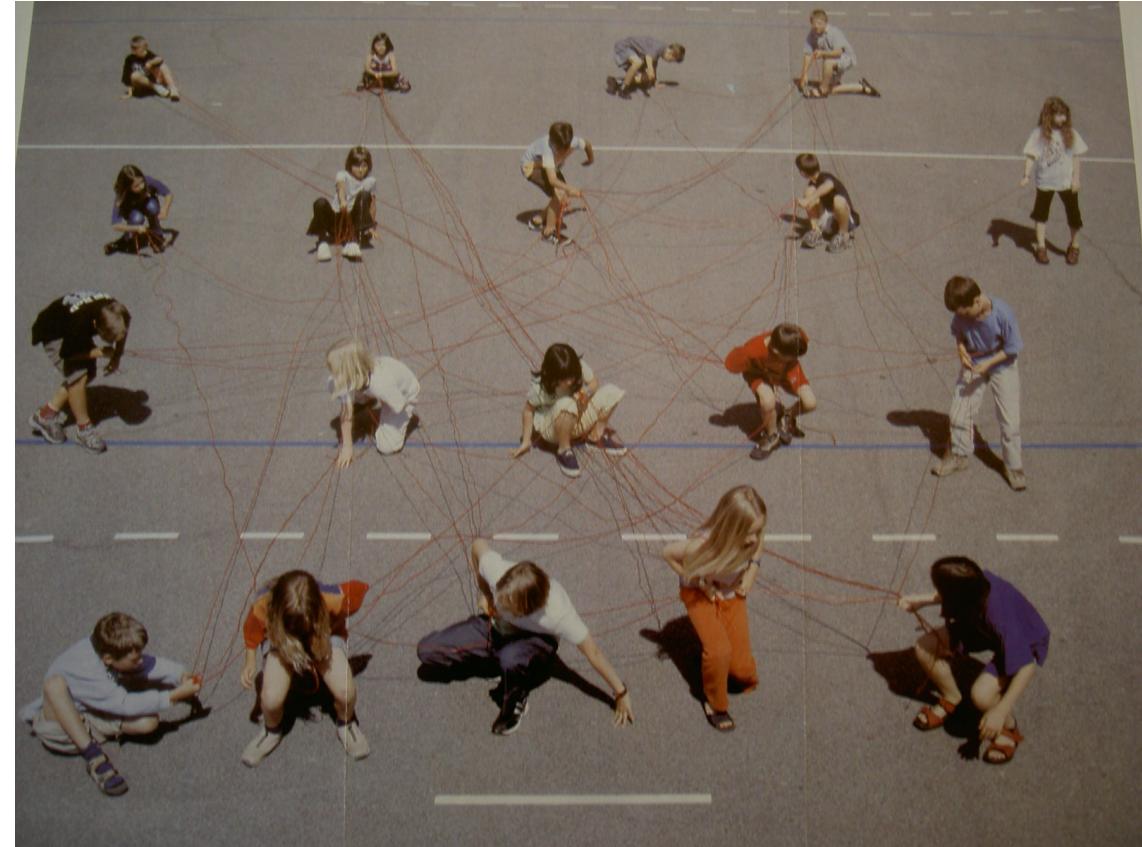
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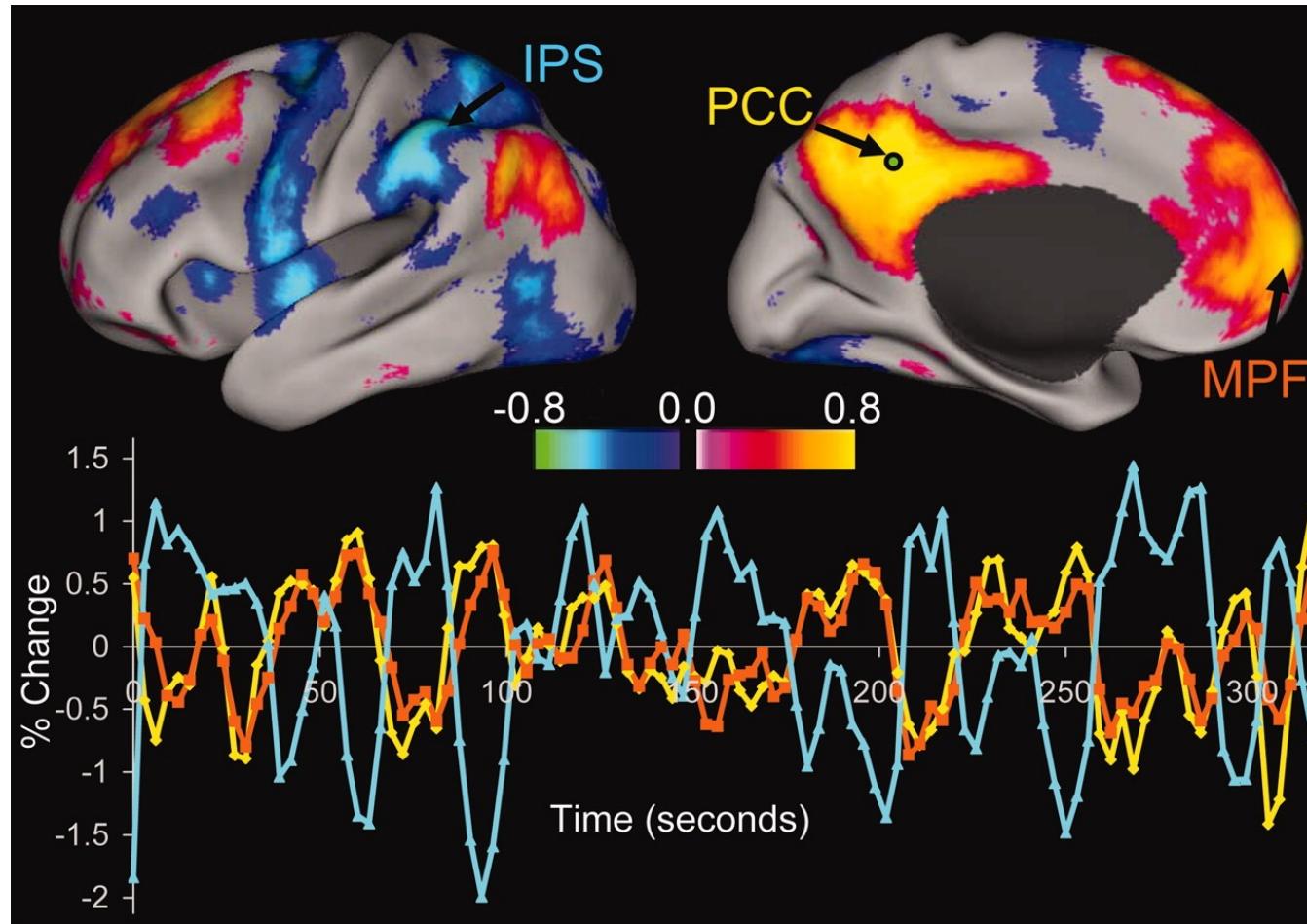
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Céline Delettre

Neurospin

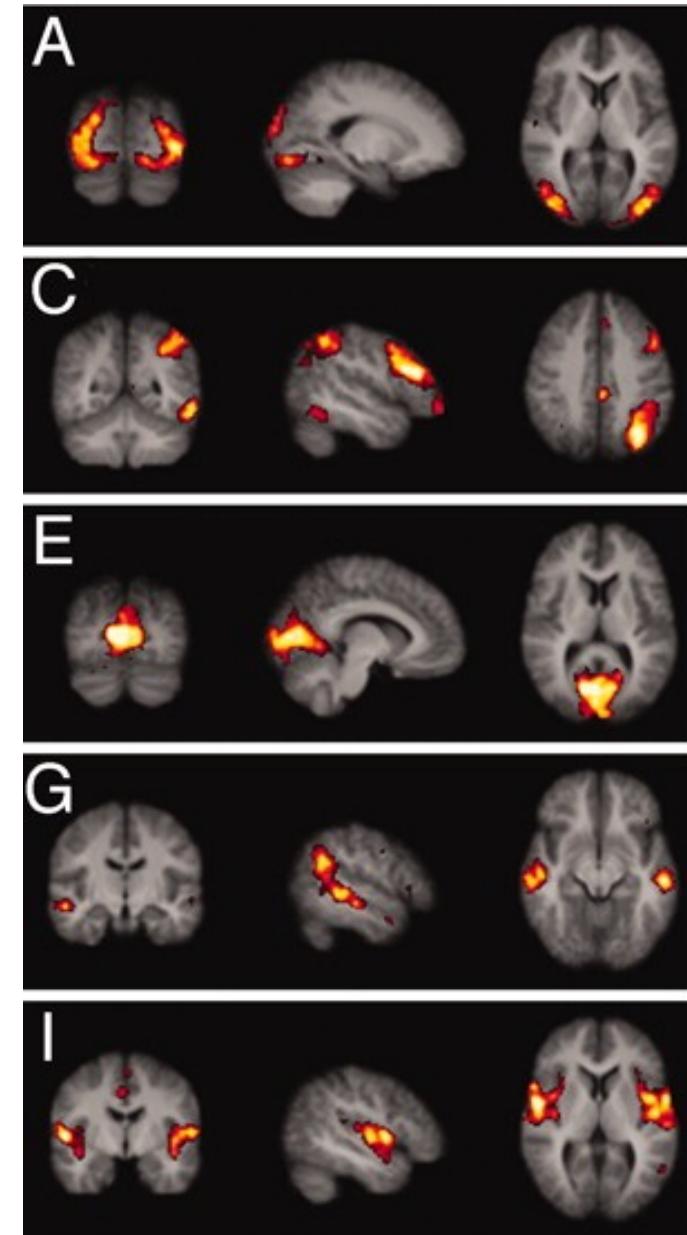
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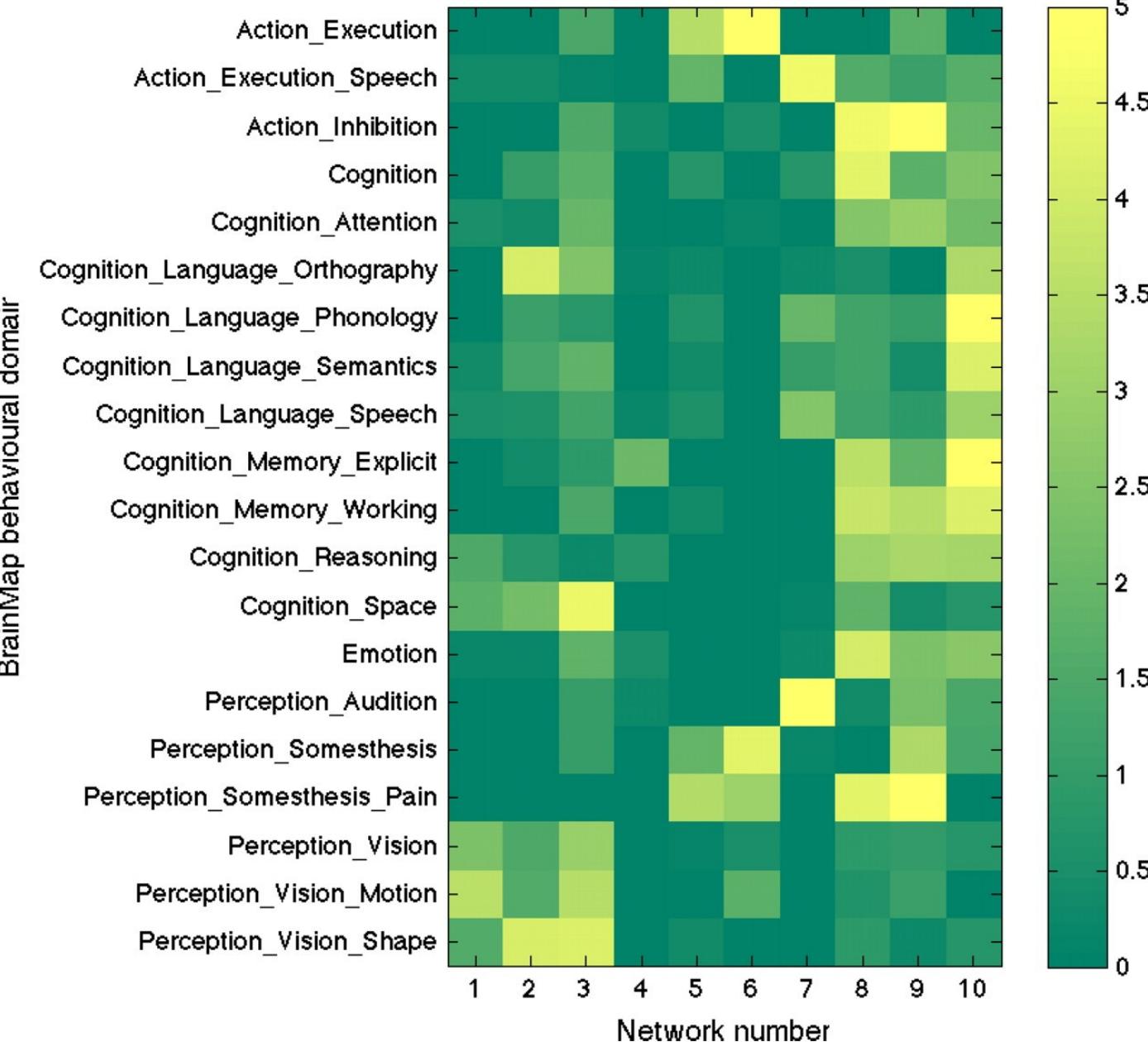
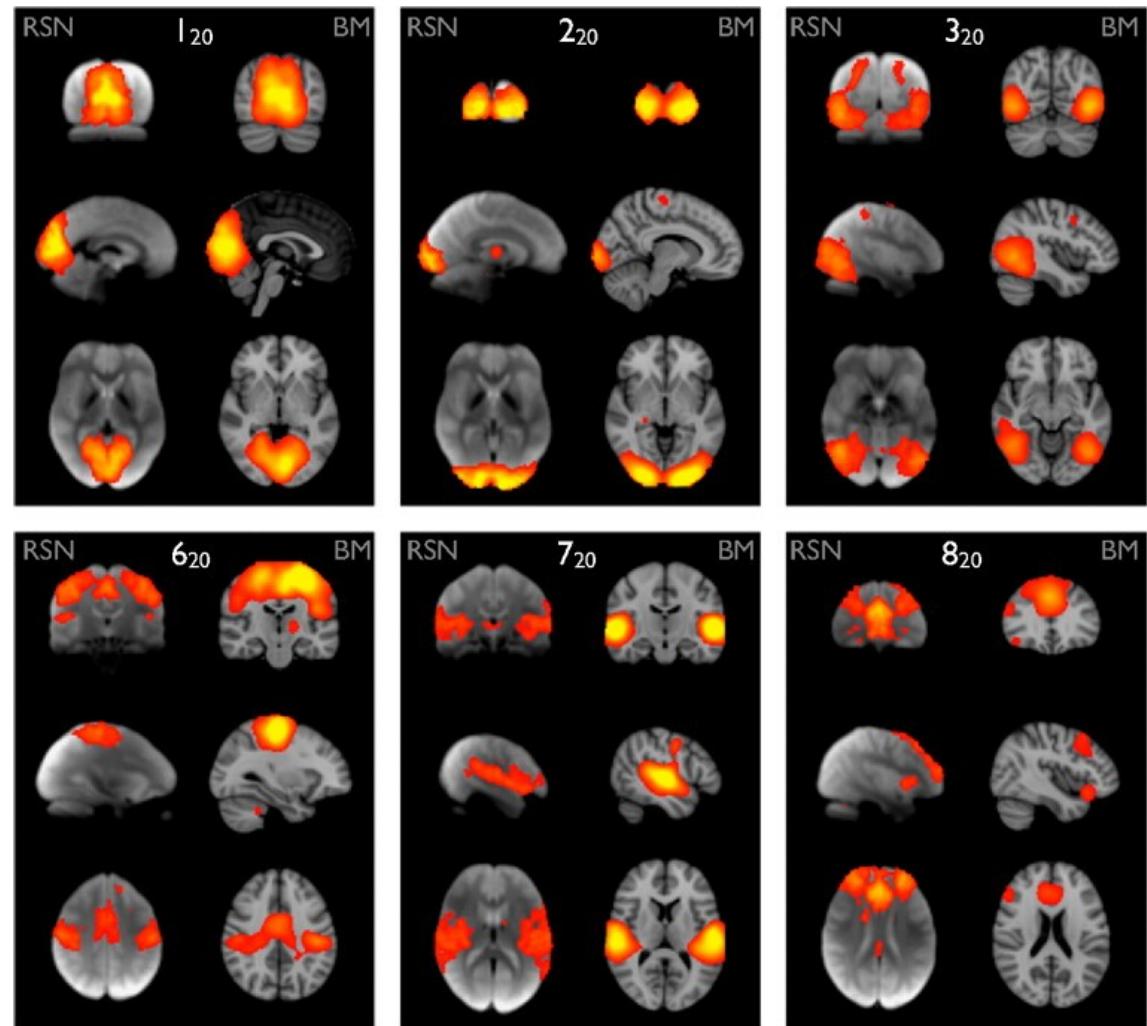
Fox et al. PNAS 2005

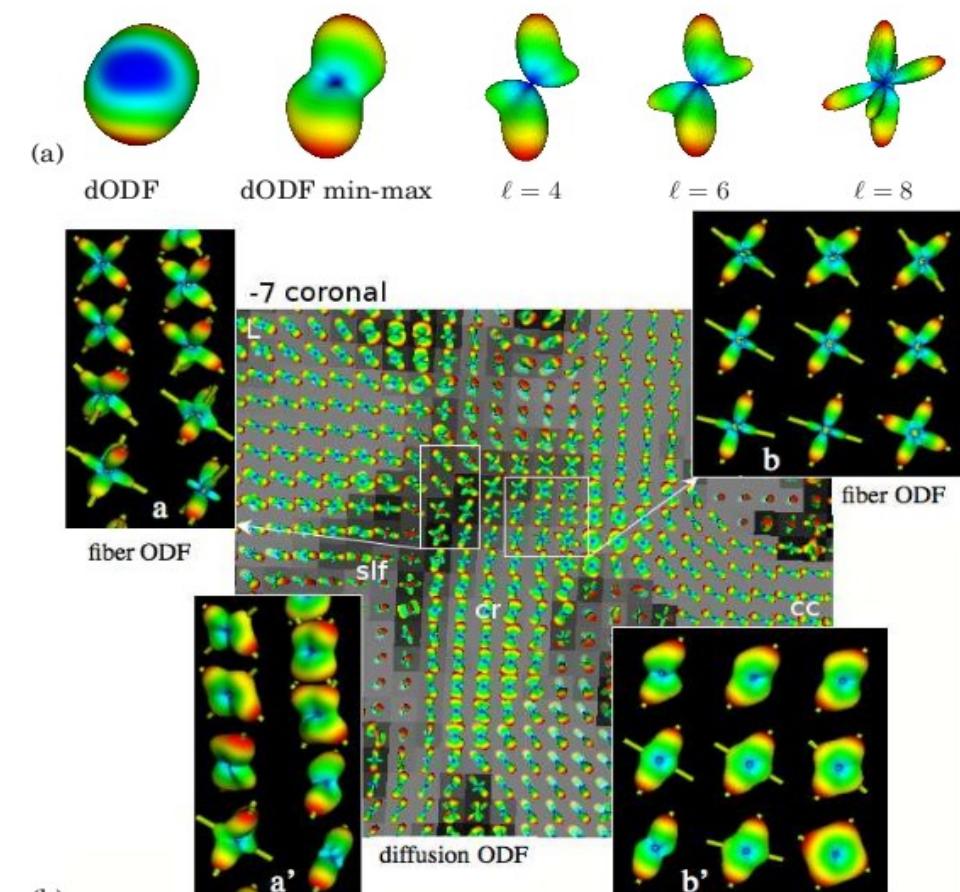


Damoiseaux et al. PNAS 2006

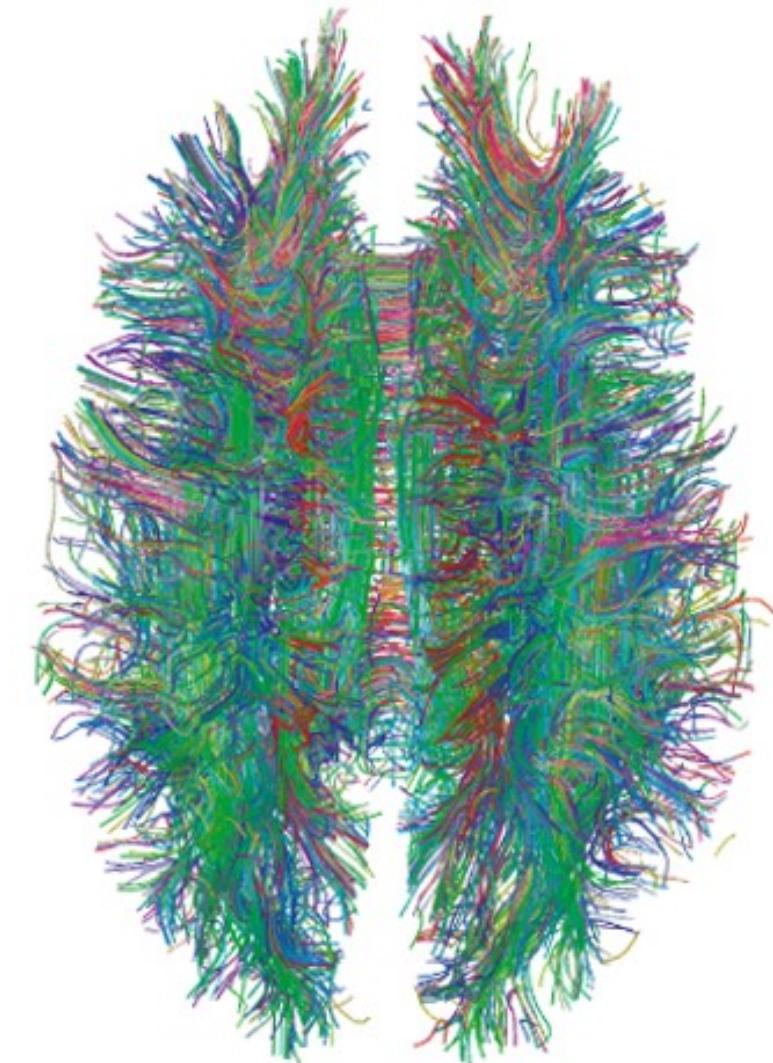
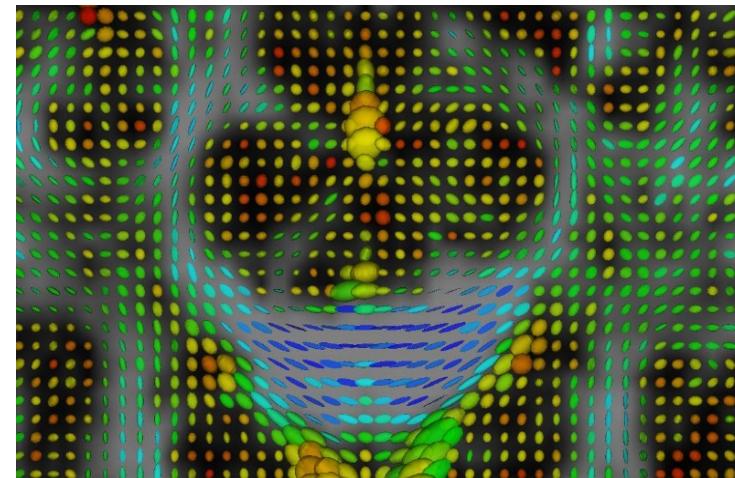


Smith et al. PNAS 2009

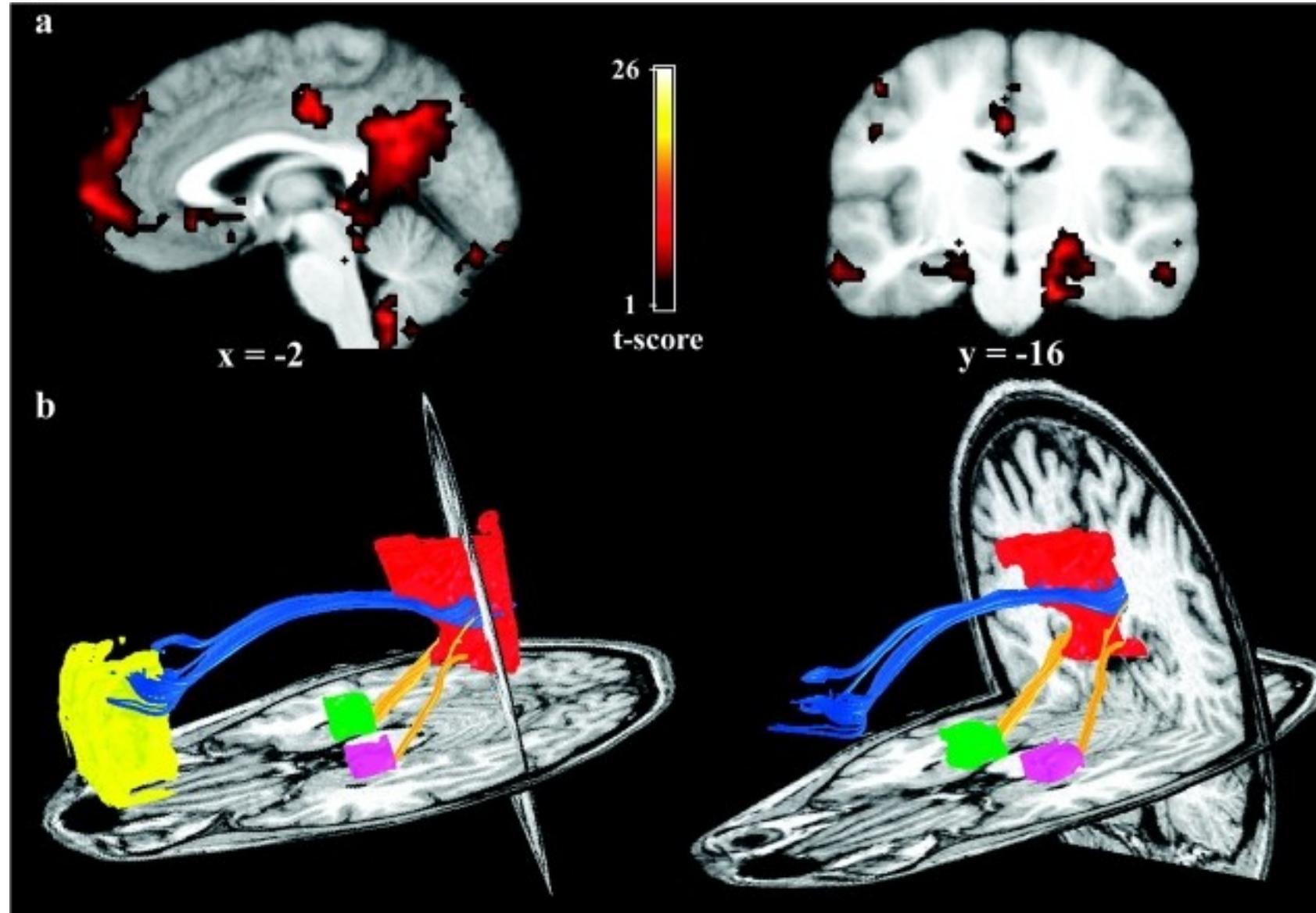


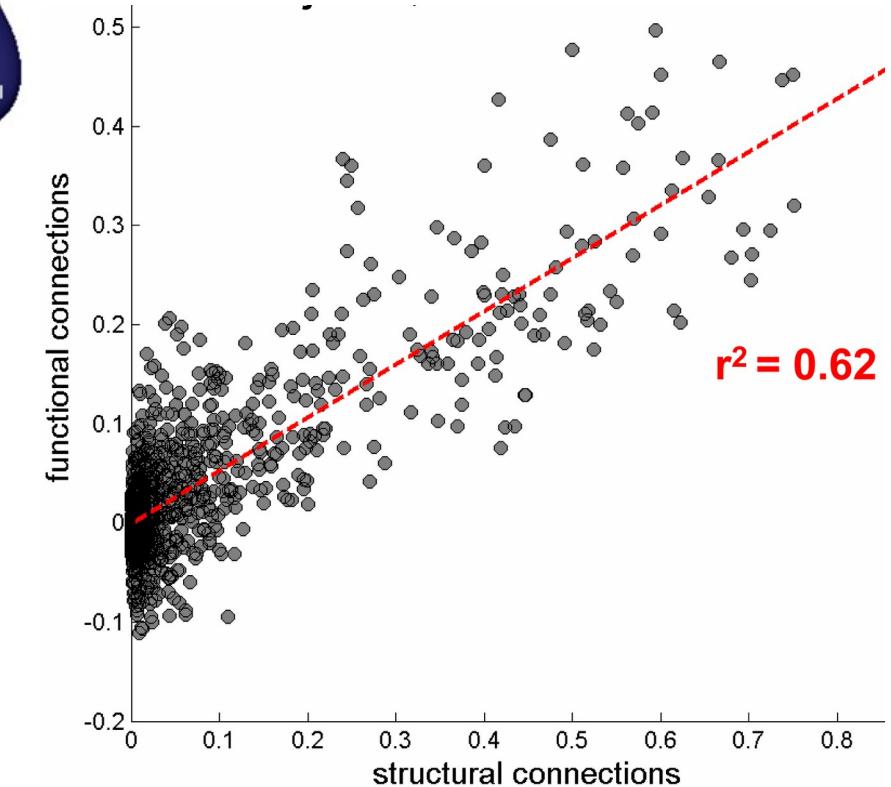
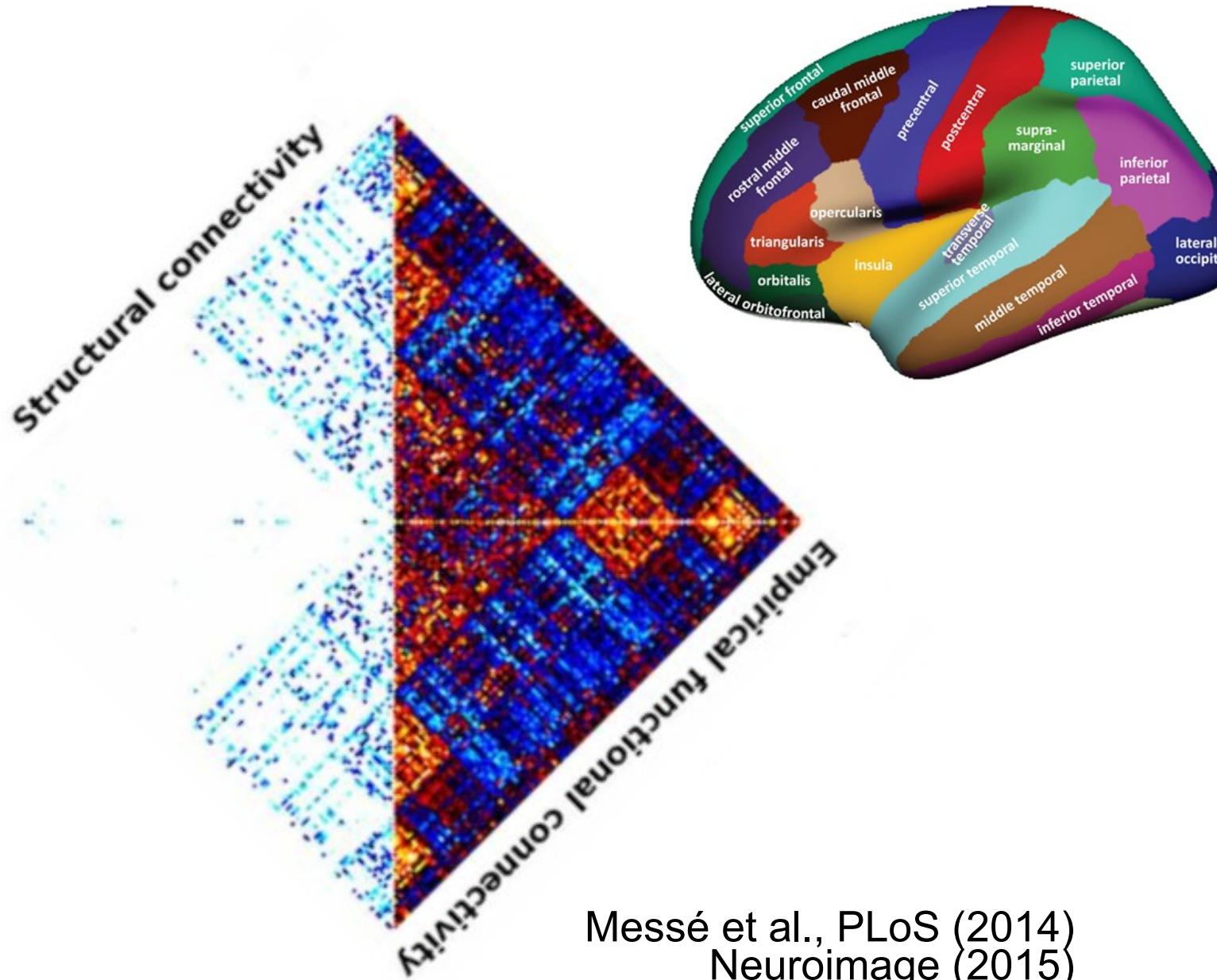


Descoteaux et al., MRM (2007)

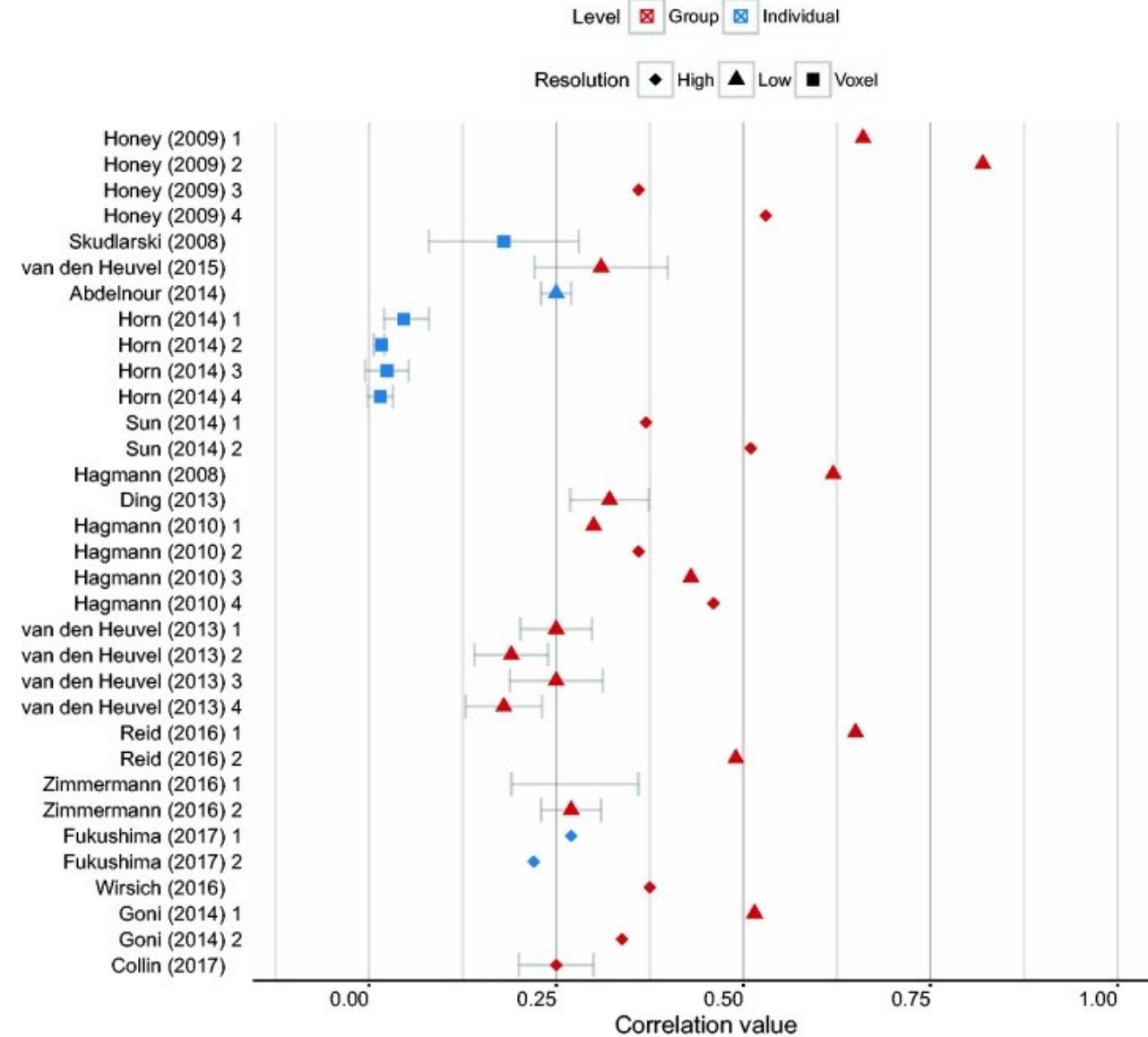
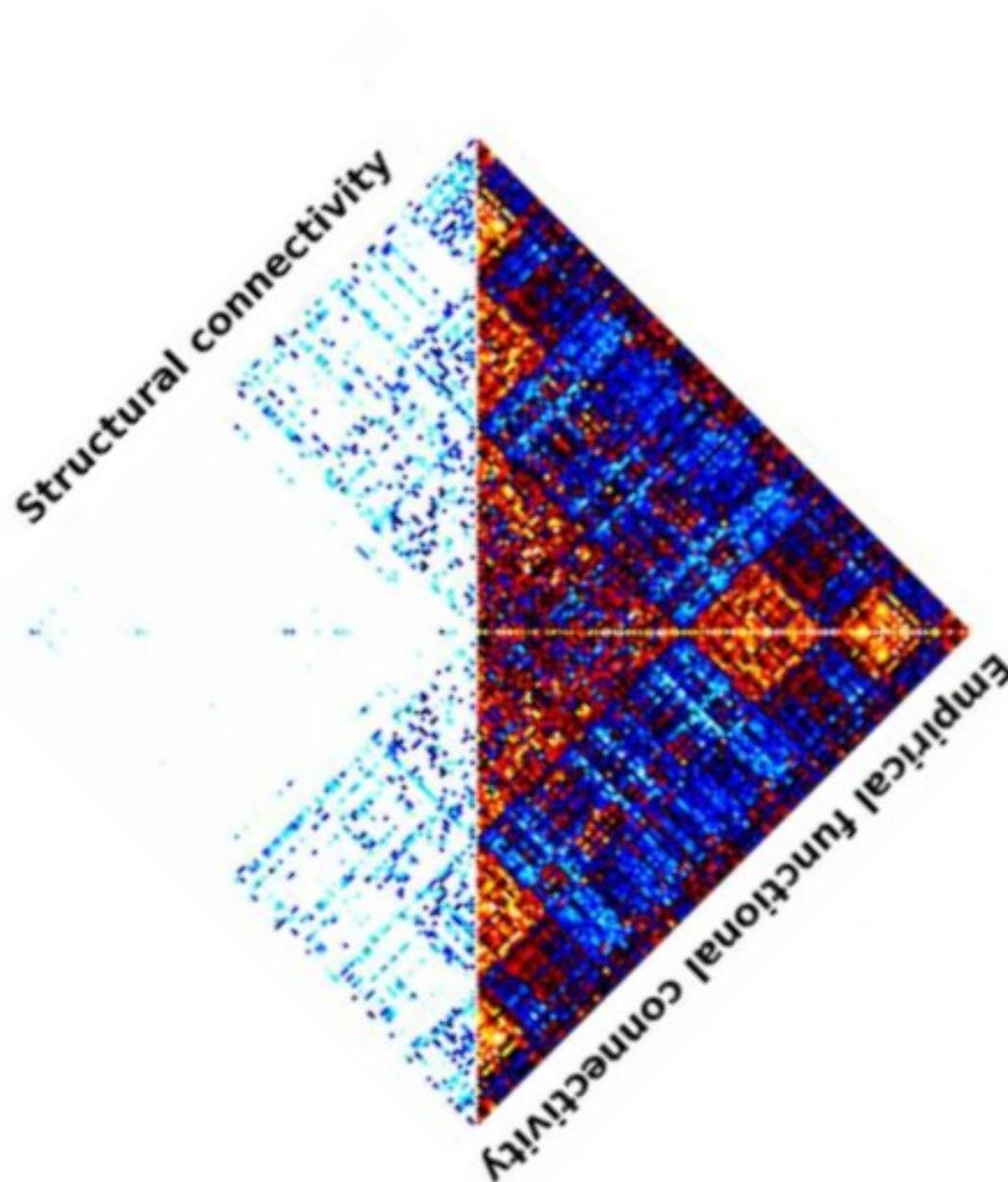


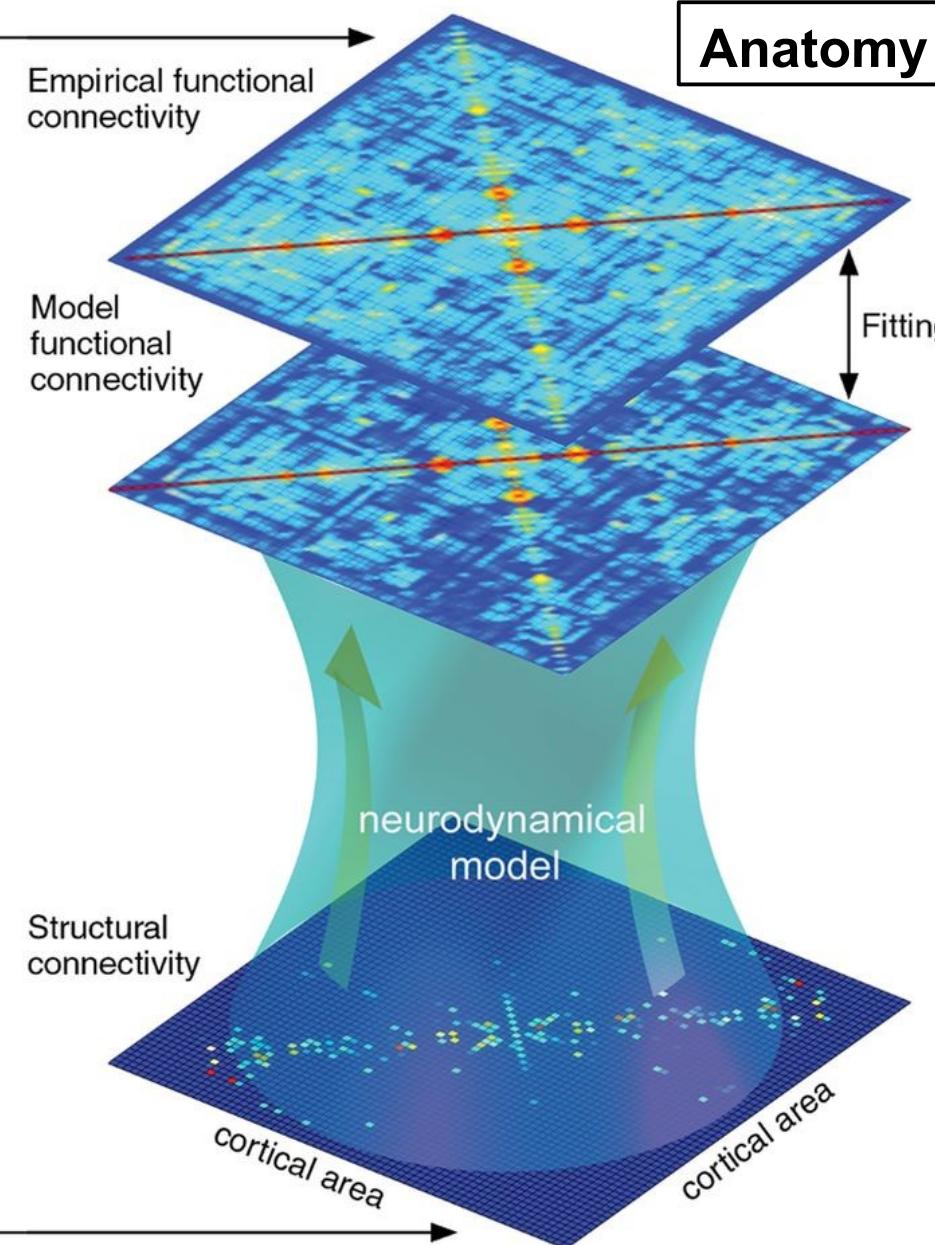
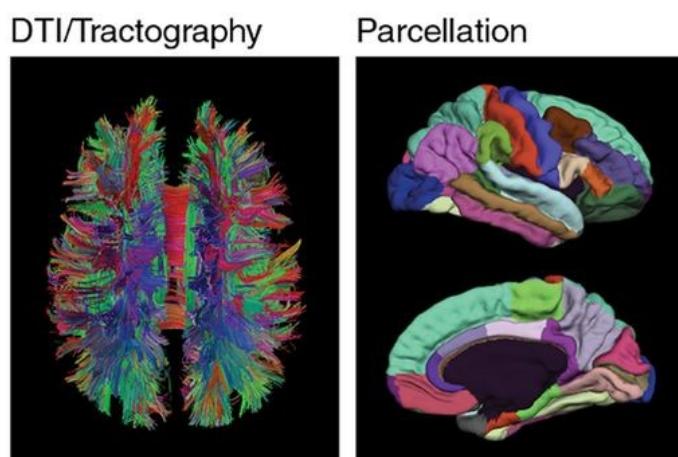
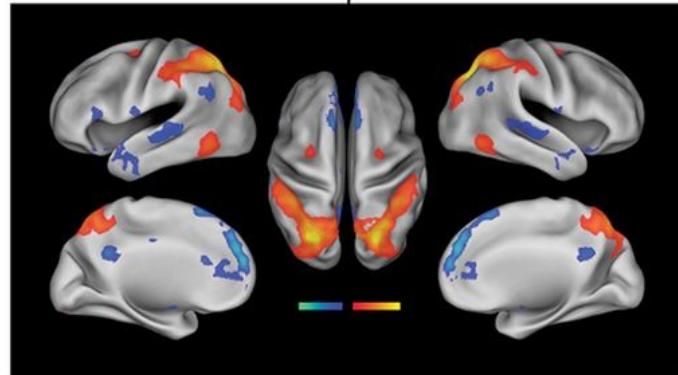
Greicius et al. Cerebral Cortex 2008



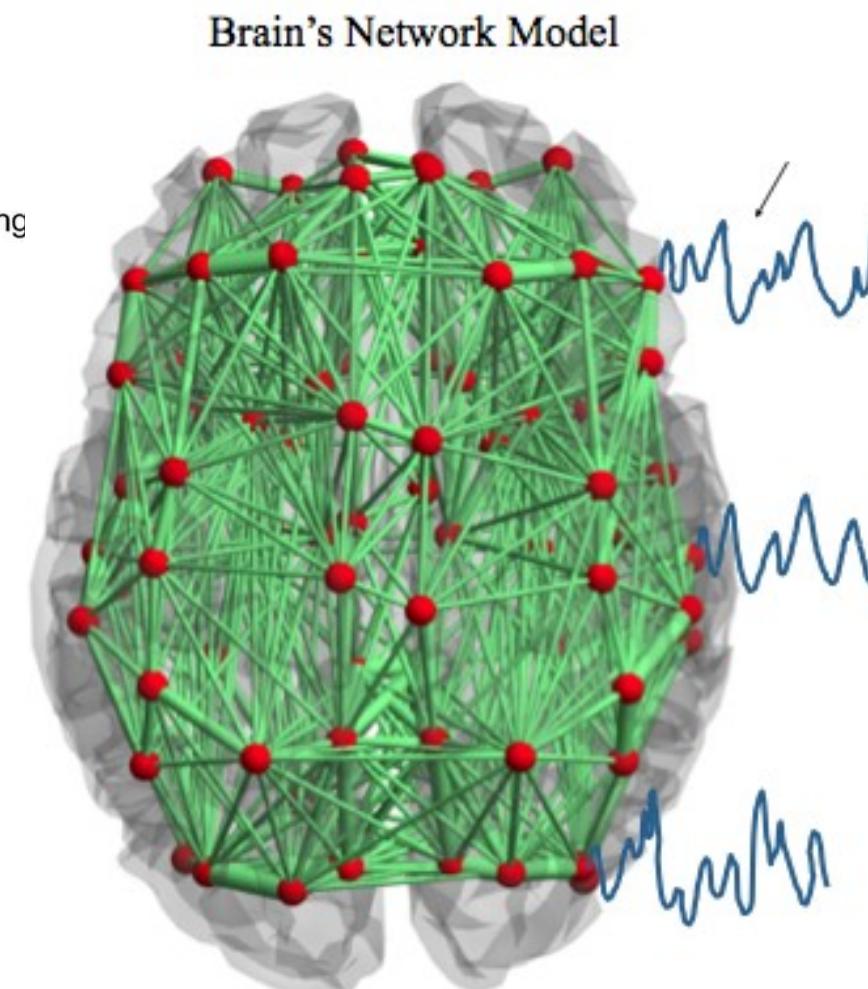


Hagmann et al., PLoS (2008)





Anatomy + Physiology = Ongoing activity



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

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

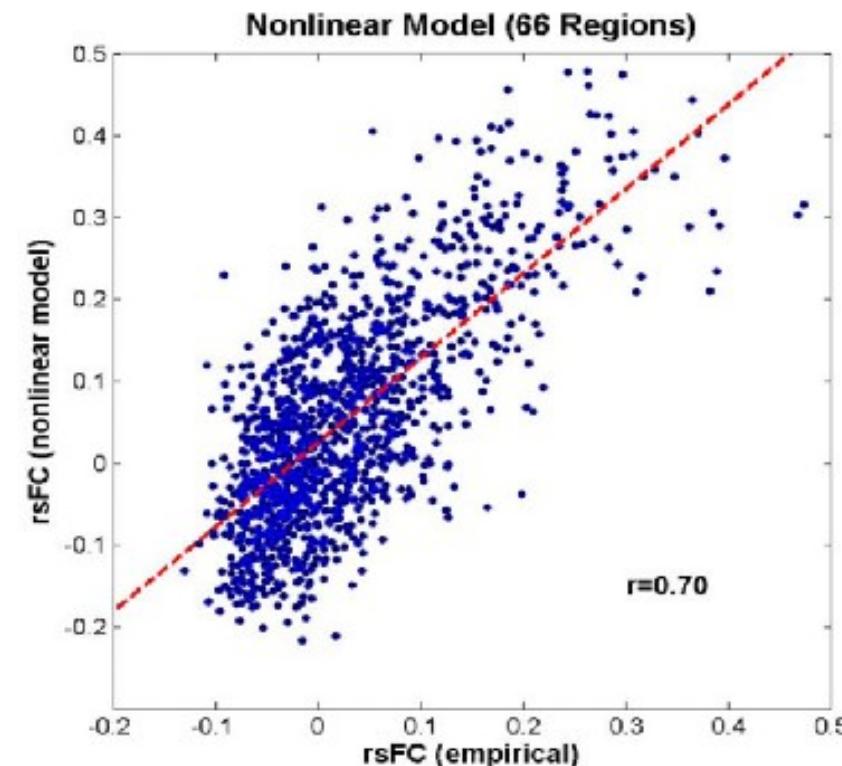
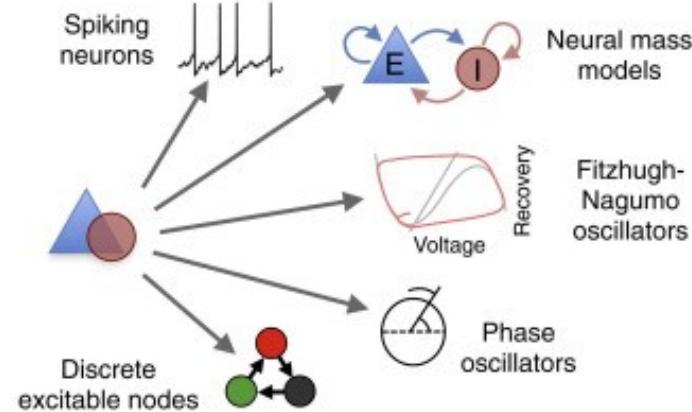
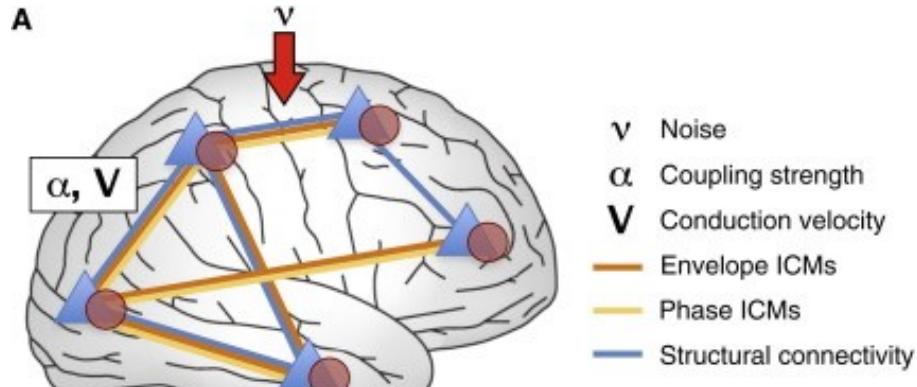
Ghosh et al. PLoS 2008

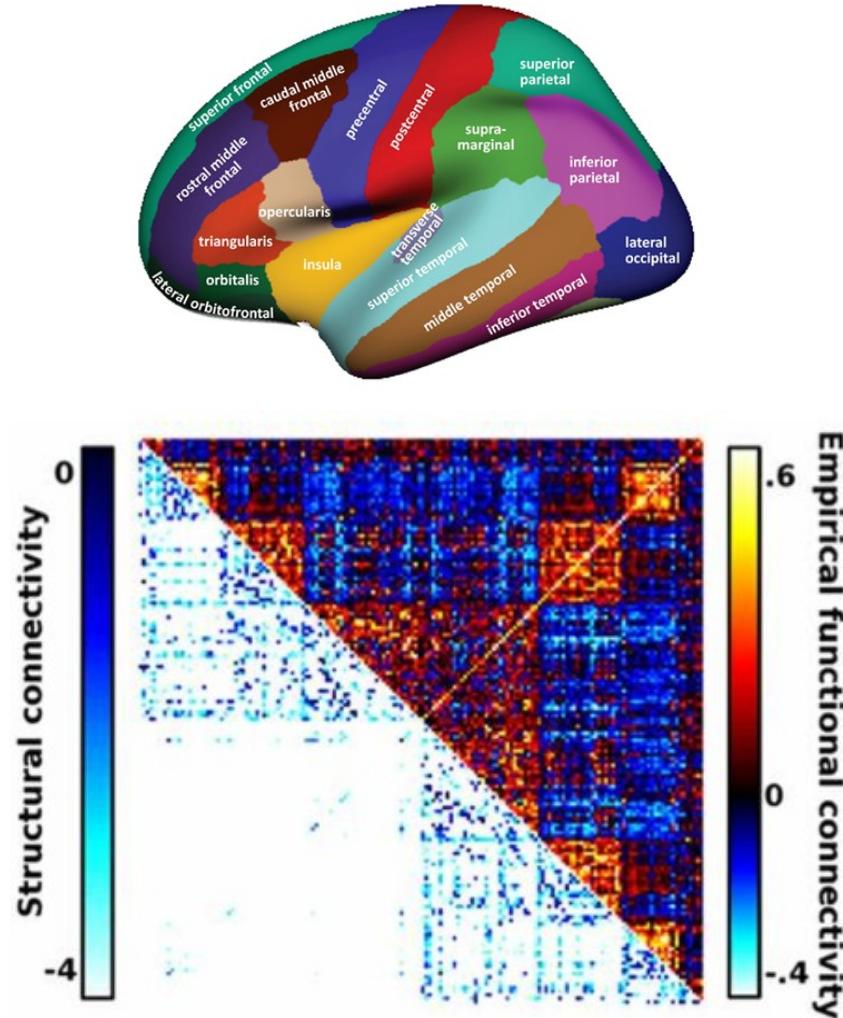
Deco et al. PNAS 2009

Honey et al. PNAS 2009

Cabral et al. Neuroimage 2011

Deco & Jirsa J Neuroscience 2012

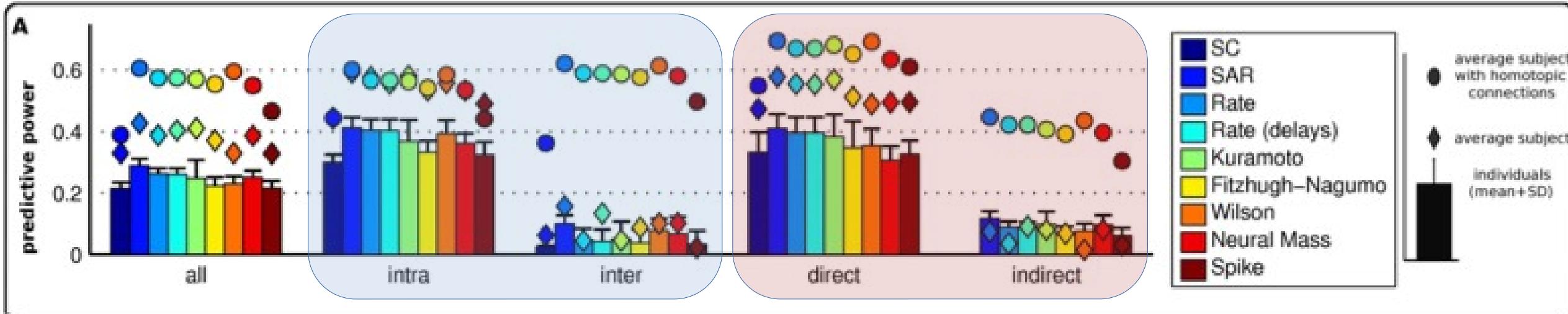


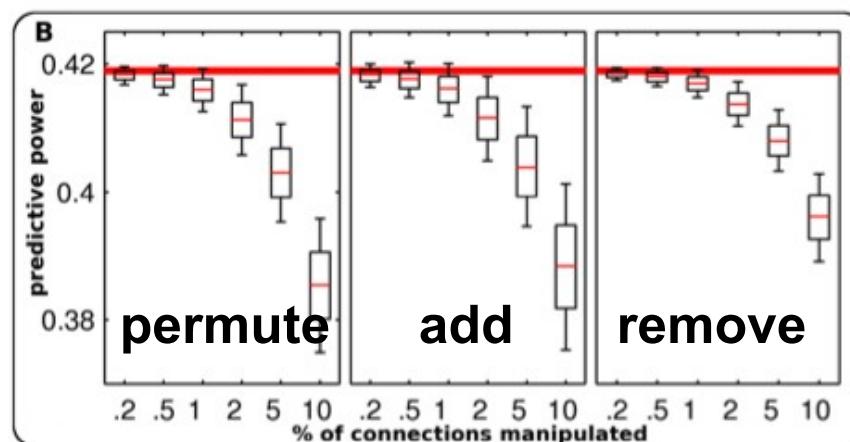
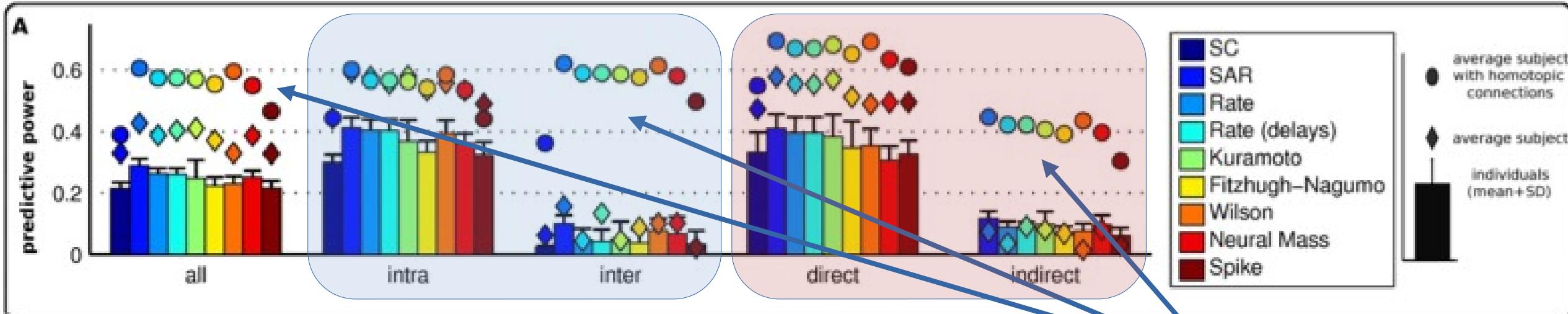


Messé et al., PLoS (2014)
Neuroimage (2015)

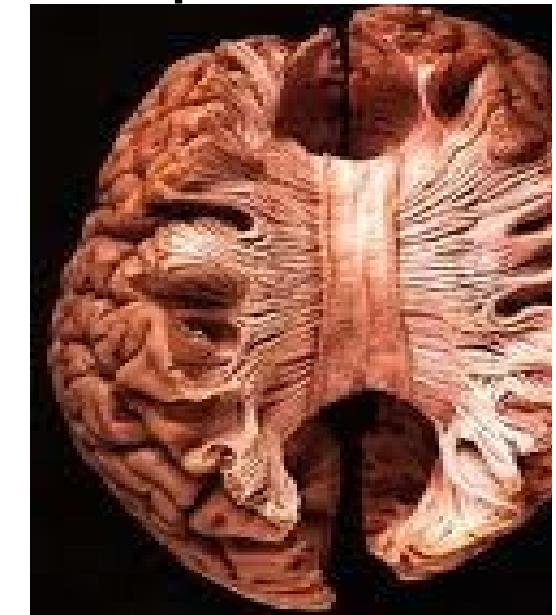
Table 1. Summary of computational models ordered in ascending complexity

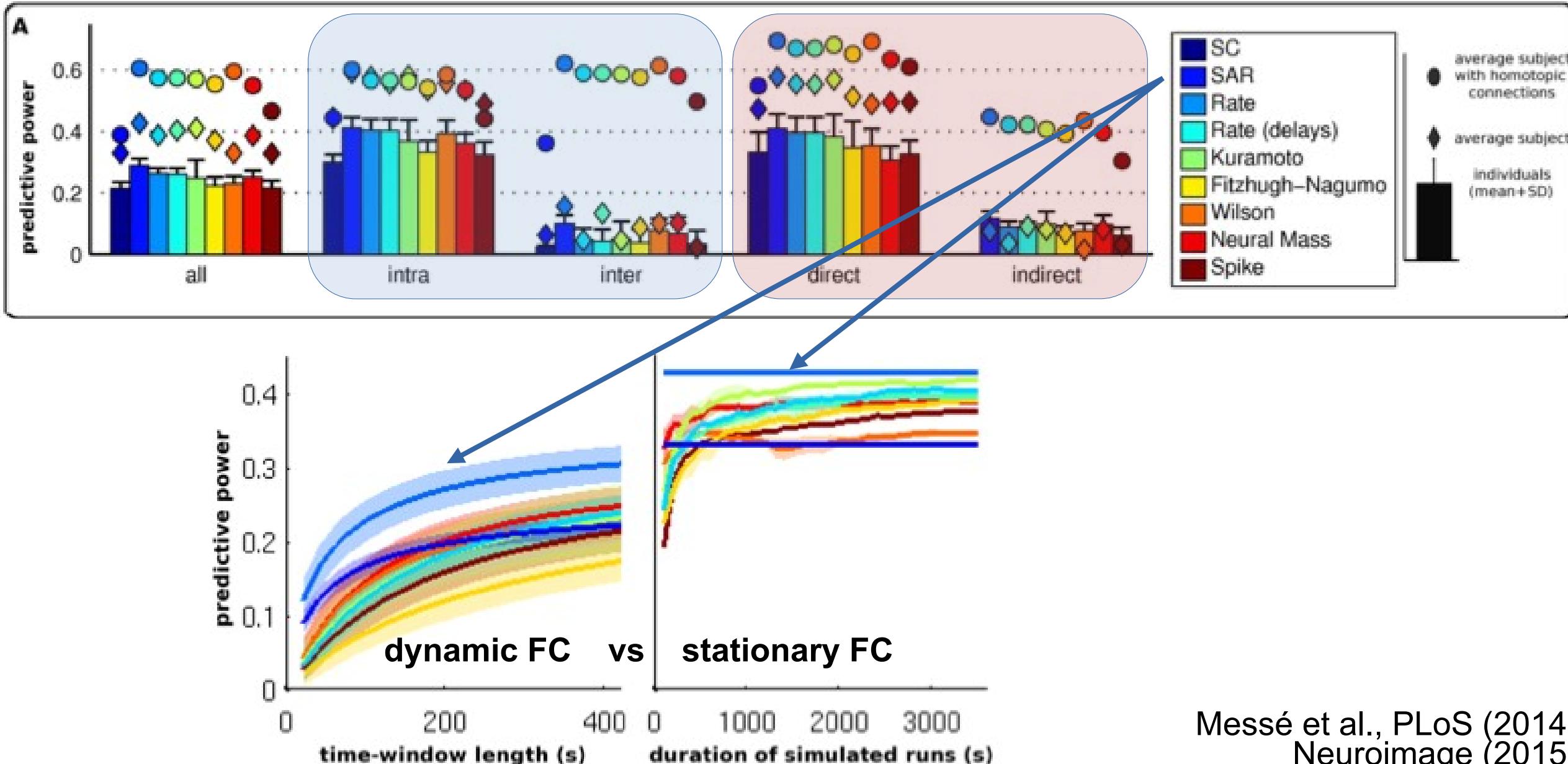
Model	Variables	Parameters	Complexity	
SAR	v , BOLD signal	σ	noise level	2
Rate	u , firing rate	v τ σ	velocity time scale noise level	4
Kuramoto	θ , oscillator phase	v ω σ	velocity intrinsic pulsation noise level	4
FitzHugh Nagumo	x , slow state y , fast state	v τ α, β, γ σ	velocity time scale ($\times 2$) parameters noise level	8
Wilson Cowan	E , excitatory neurons I , inhibitory neurons	v τ w_I, 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	g_{ion} T_{ion}, δ_{ion} ϕ, τ V, δ V_{ion} a_{ii}, a_{ee}, a_{ie} r_{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_I, 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 ($\times 2$) residual potentials refractory period synaptic strengths external synaptic conductances ($\times 2$) recurrent synaptic conductances ($\times 2$) rise and decay times decay time parameters	35

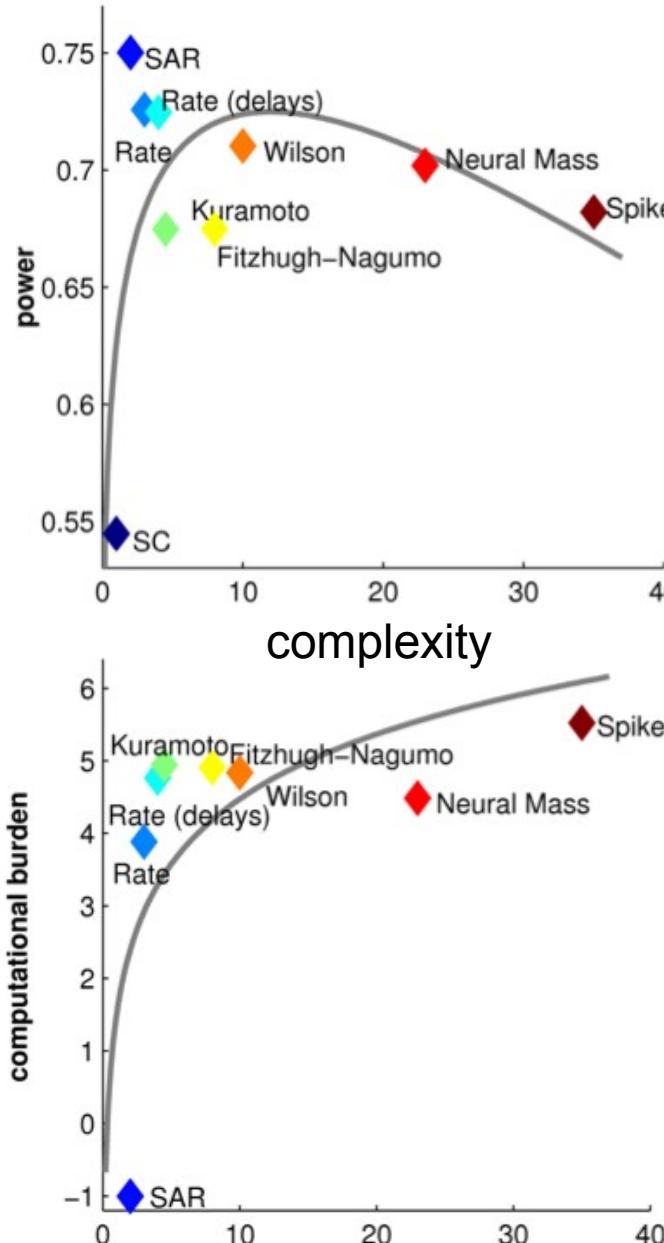




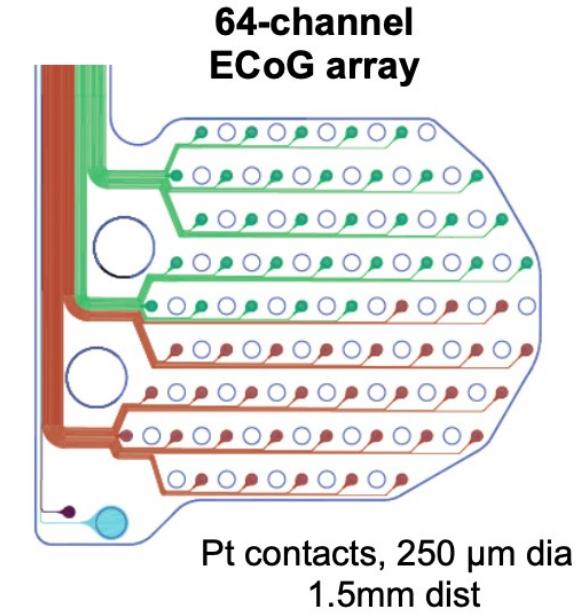
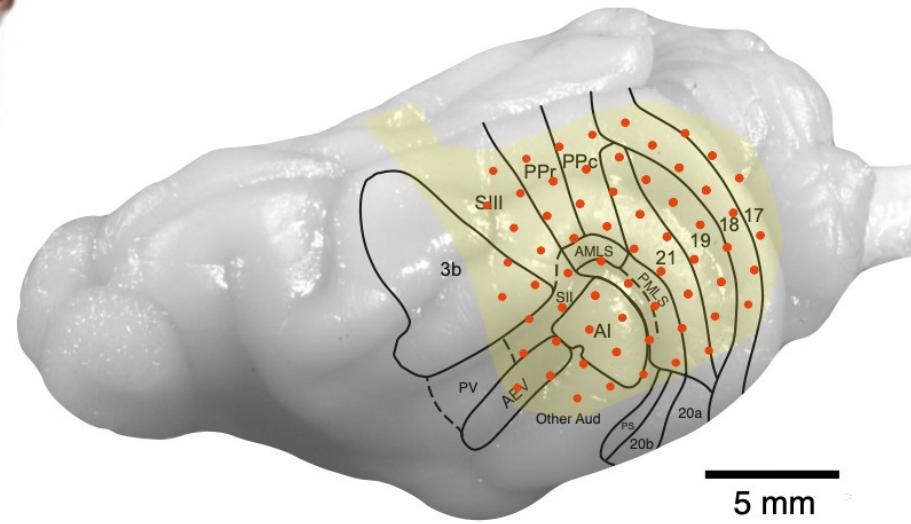
Homotopic connections!



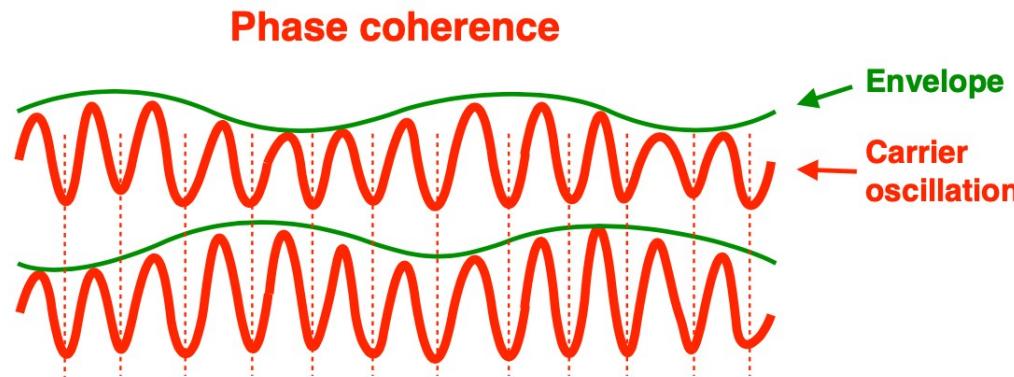
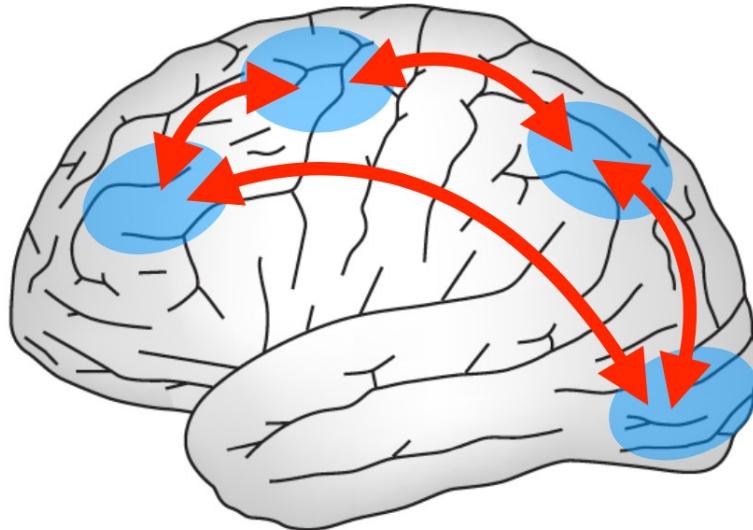




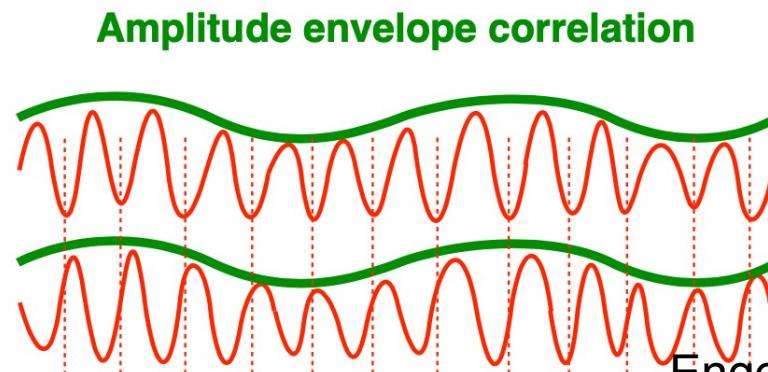
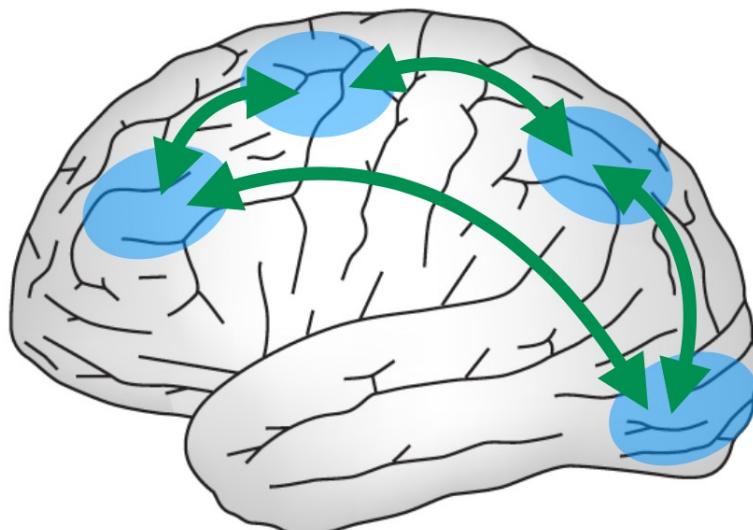
- **Consistent relationship SC and FC**
- **Model complexity ≠ model prediction**
- **FC appears substantially constrained by SC**
- **But fMRI...**



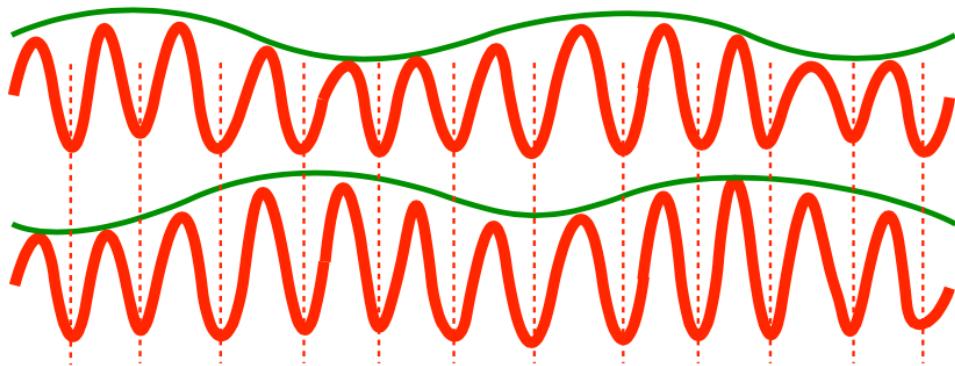
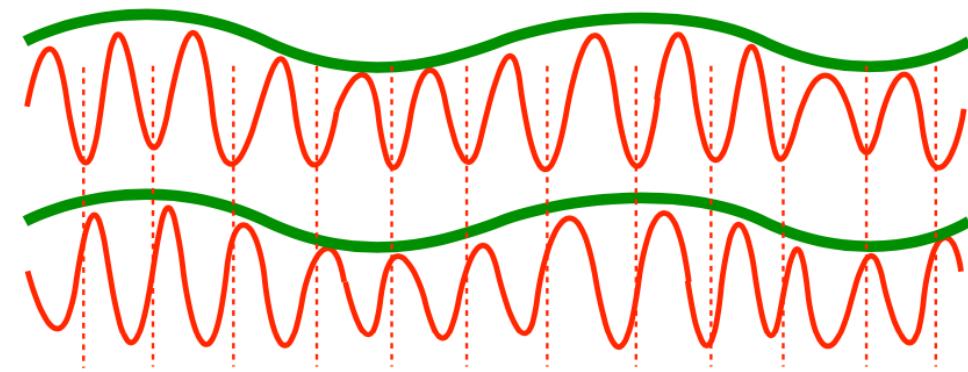
- Chronically implanted micro-ECoG 64 electrodes
- Superficial LFP signals over the posterior left hemisphere
- Ongoing activity / spontaneous behavior



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

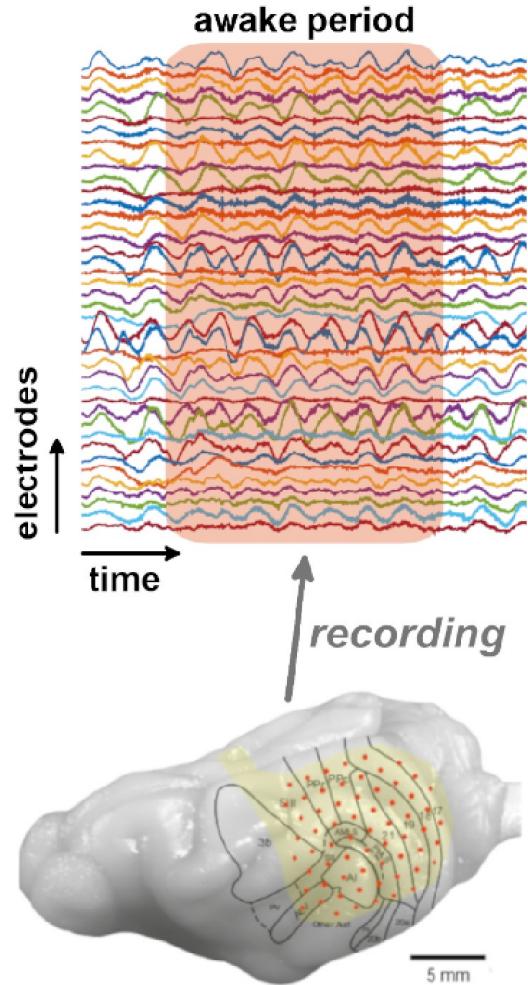


Engel, Fries & Singer, Nat Rev Neurosci 2001
Siegel, Donner & Engel, Nat Rev Neurosci 2012
Engel, Gerloff, Hilgetag & Nolte, Neuron 2013

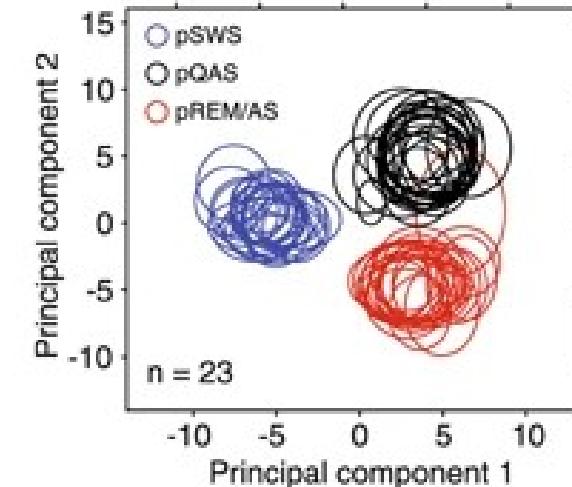
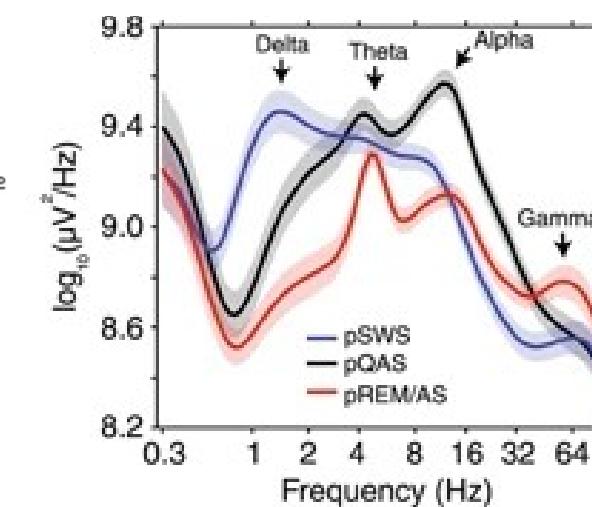
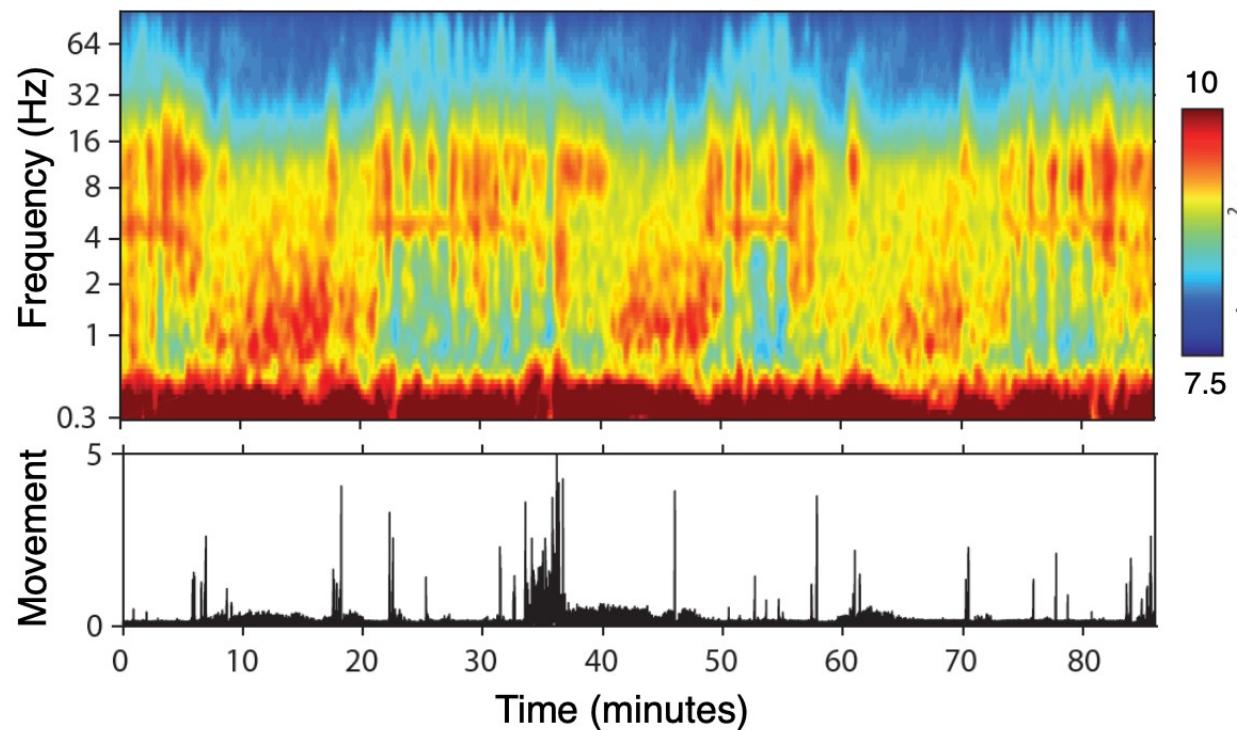
Phase ICMs**Phase coherence****Envelope ICMs****Amplitude envelope correlation**

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

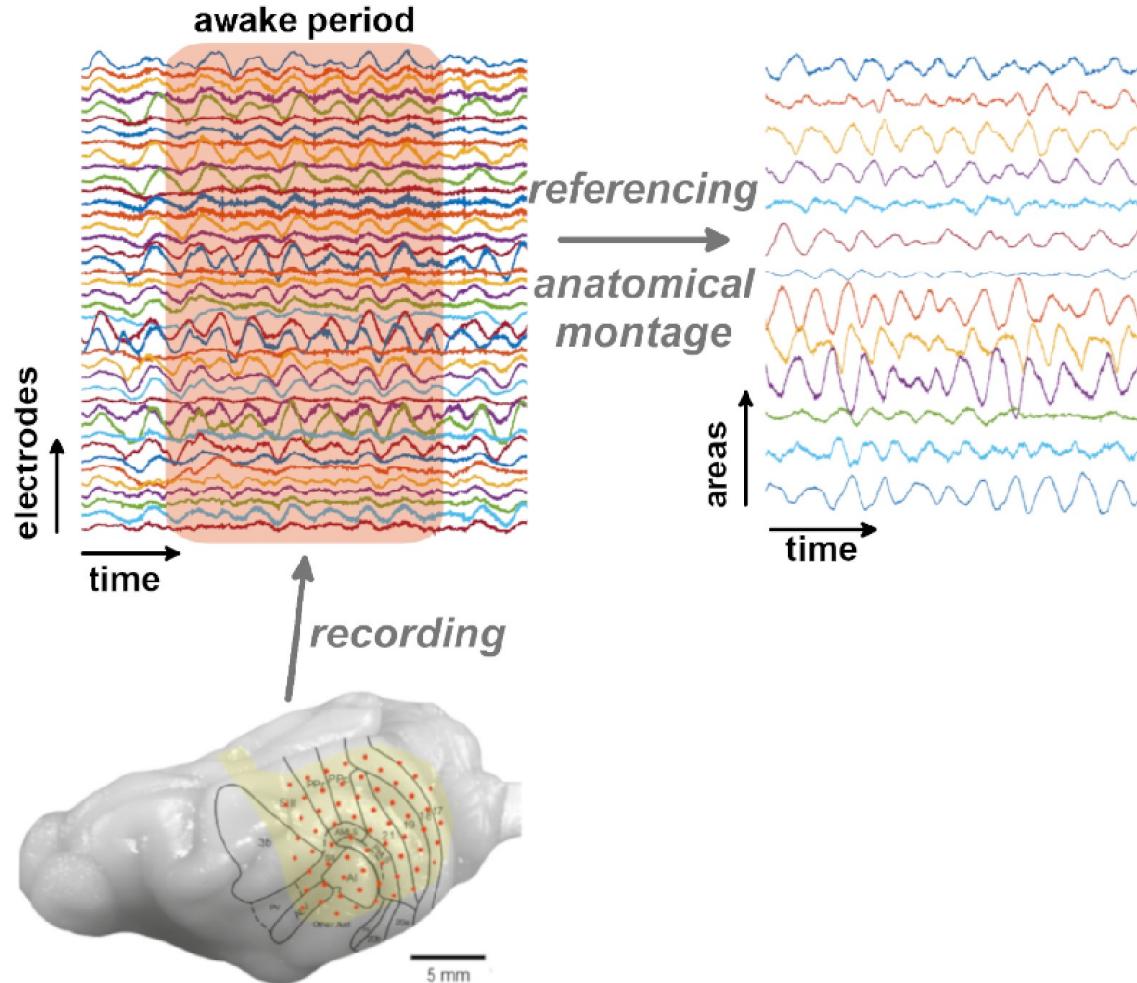
- FMRI, MEG, EEG, LFP, spikes
- Aperiodic scalefree (<0.1 Hz)
- AEC



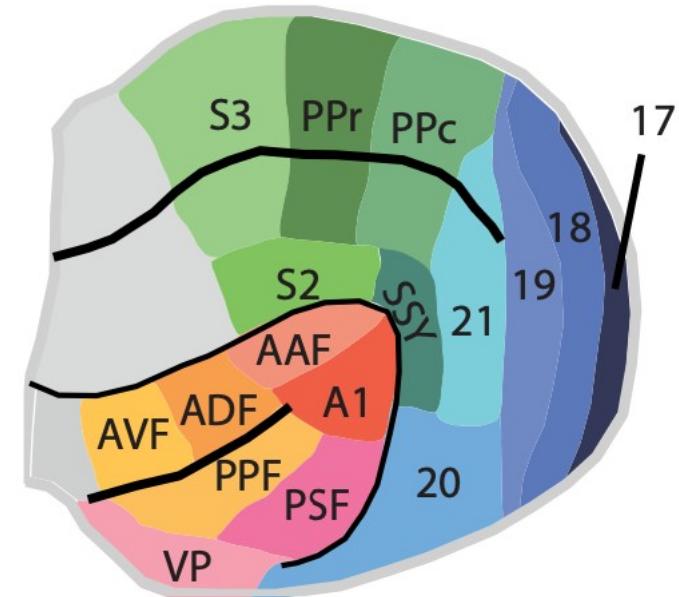
Stitt et al., Sci Rep (2017)



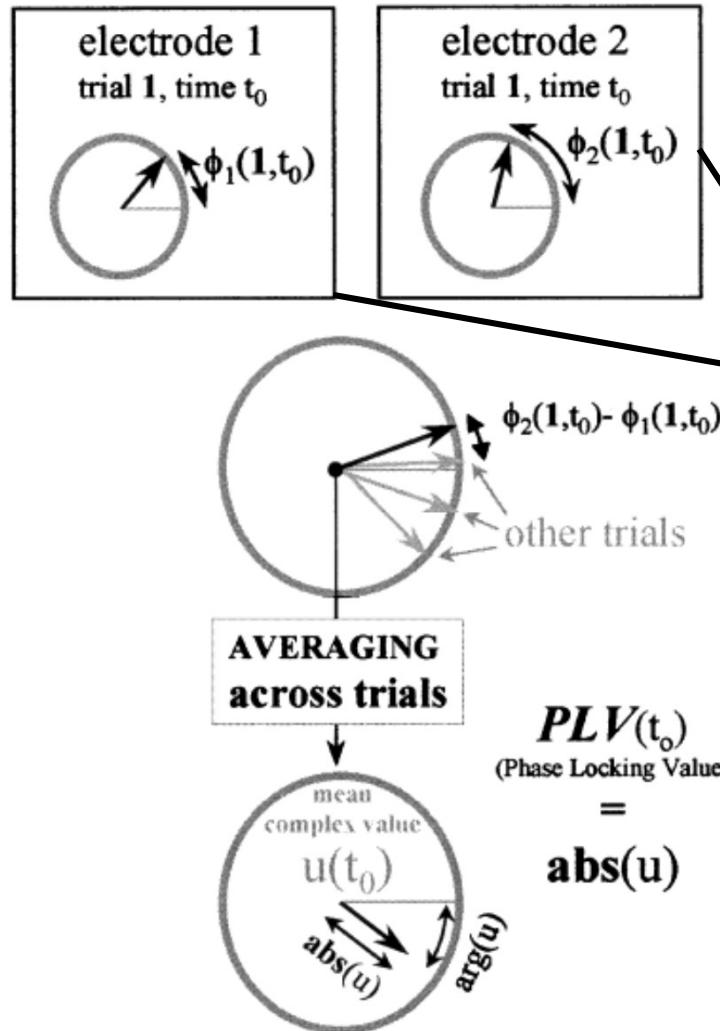
- Spectral changes in the slow oscillations (0.8-3Hz), theta-band (4-6 Hz) and alpha-band (8-16Hz)
- Classification of brain states: awake, REM sleep and slow wave sleep



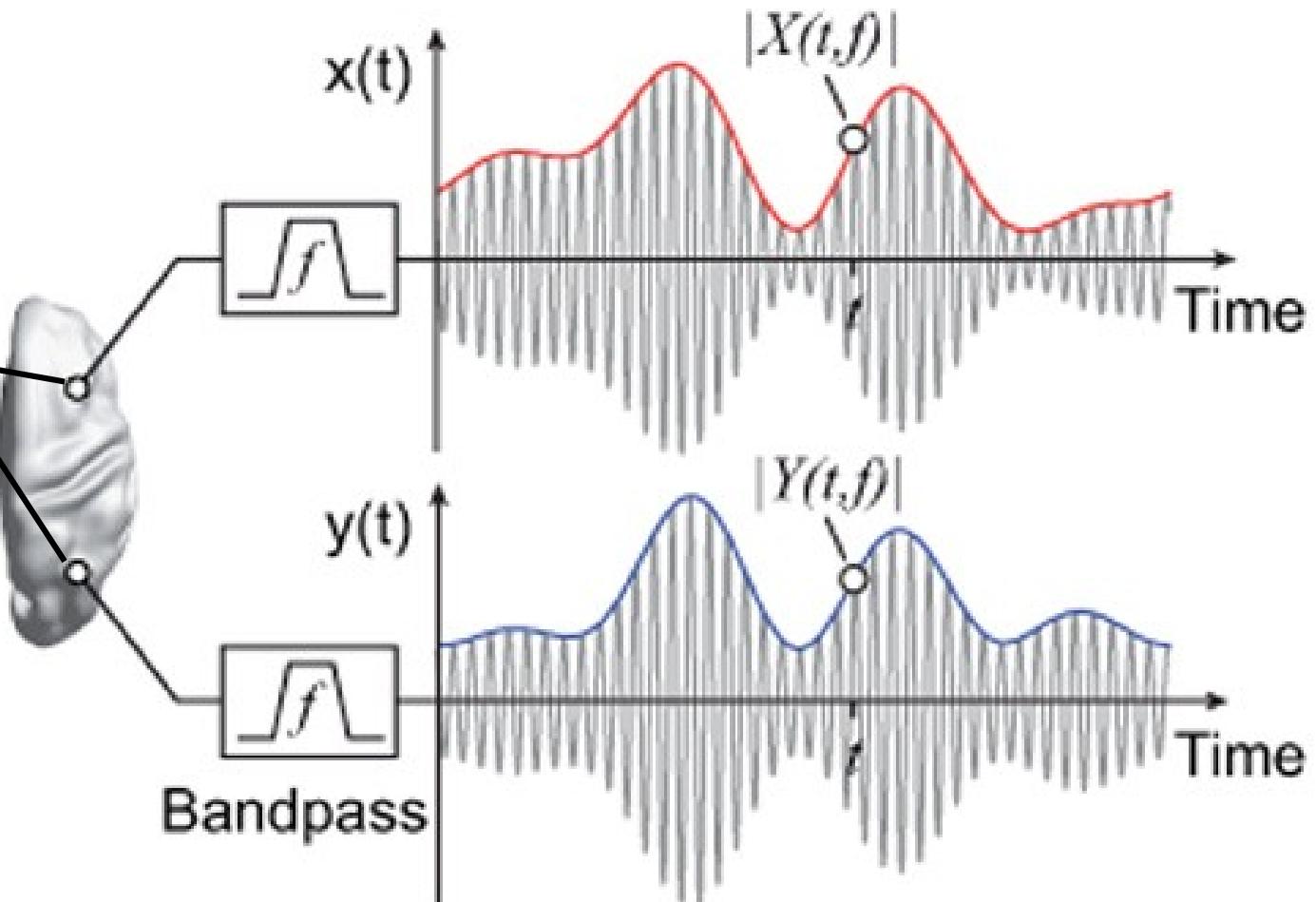
Bizley & King, Hear Res (2009)

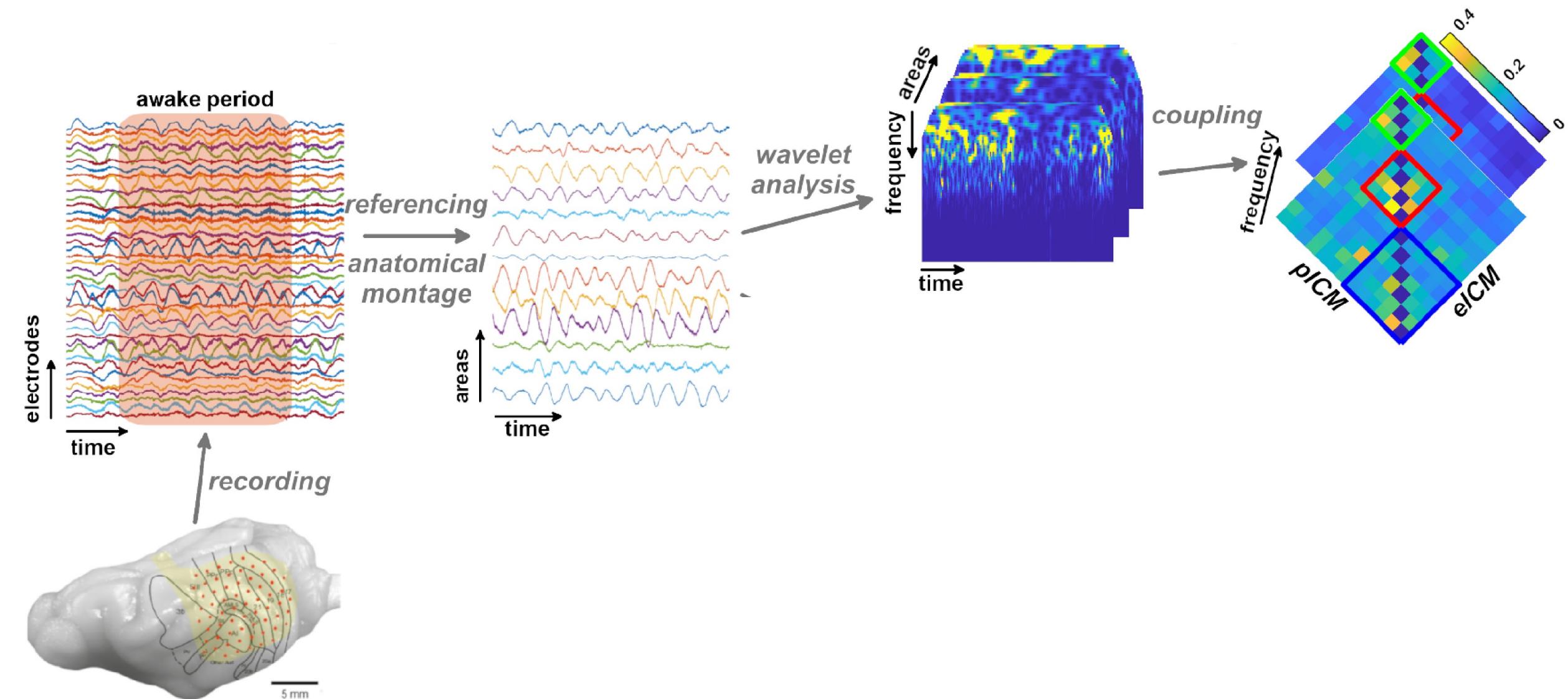


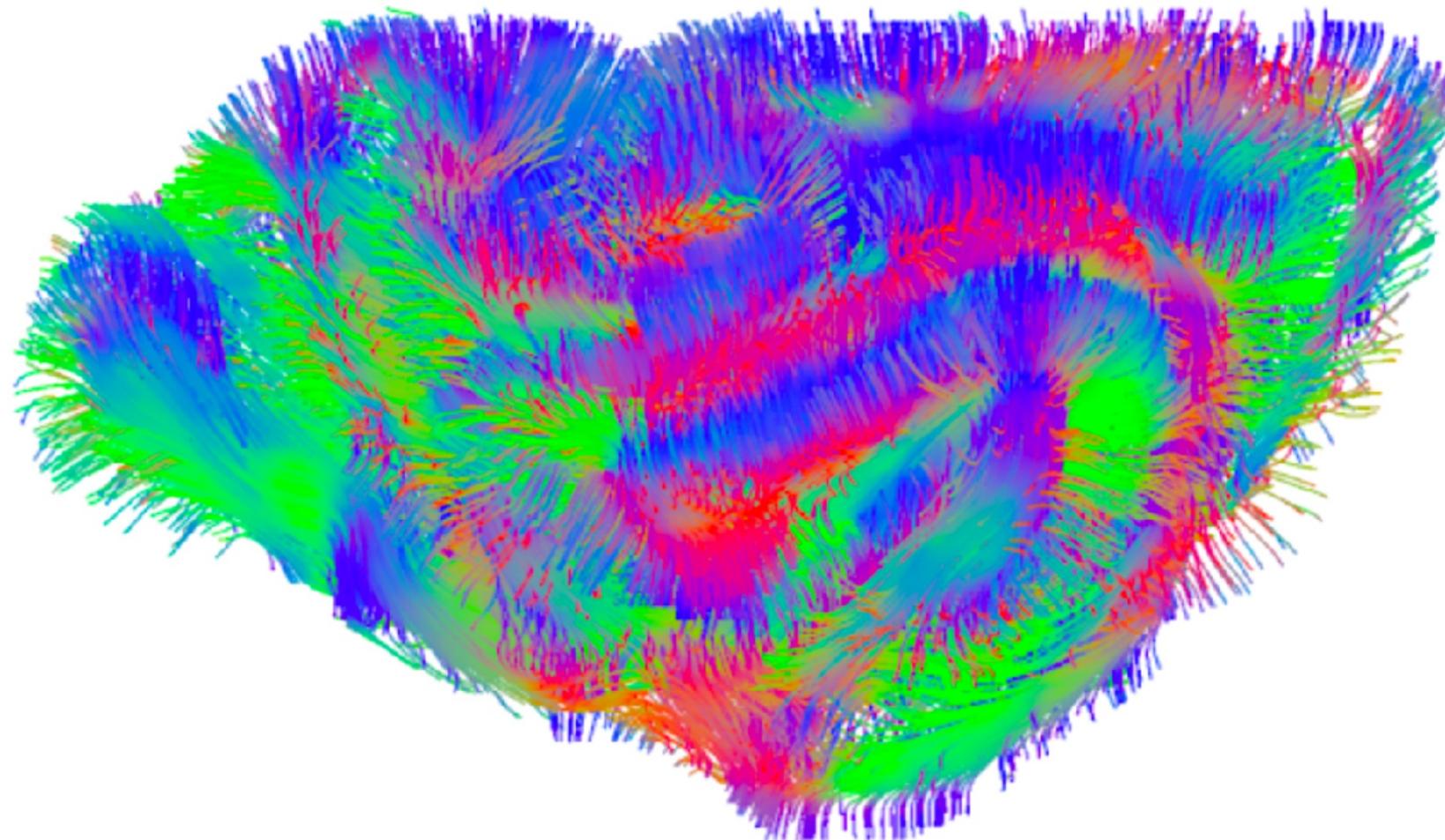
Phase locking value



Amplitude envelope correlation





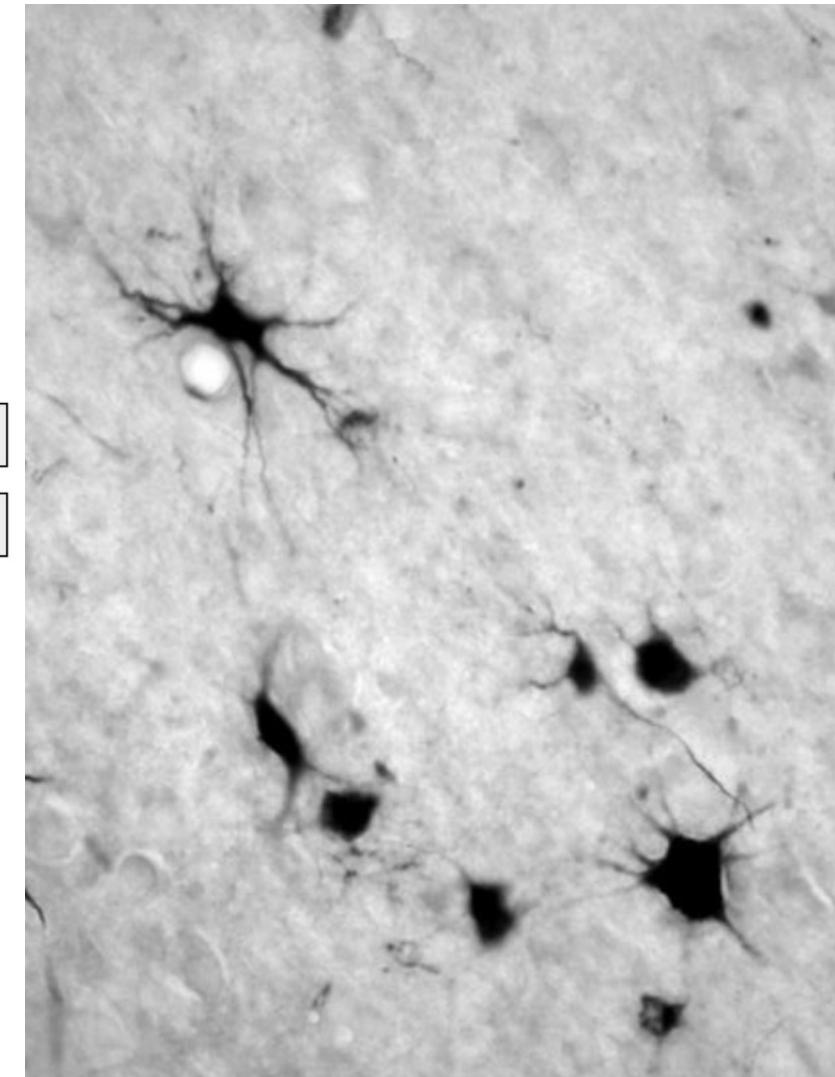
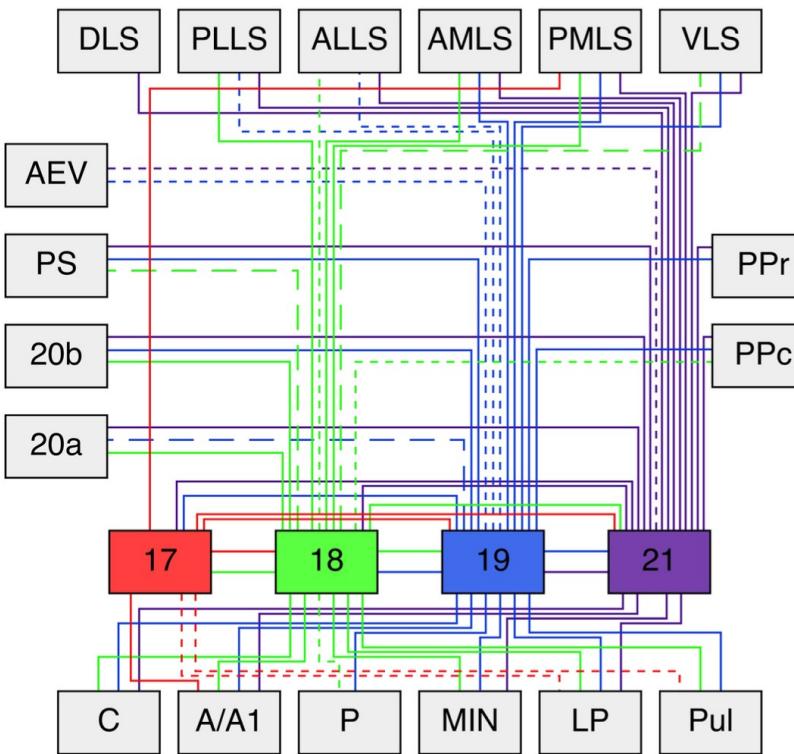
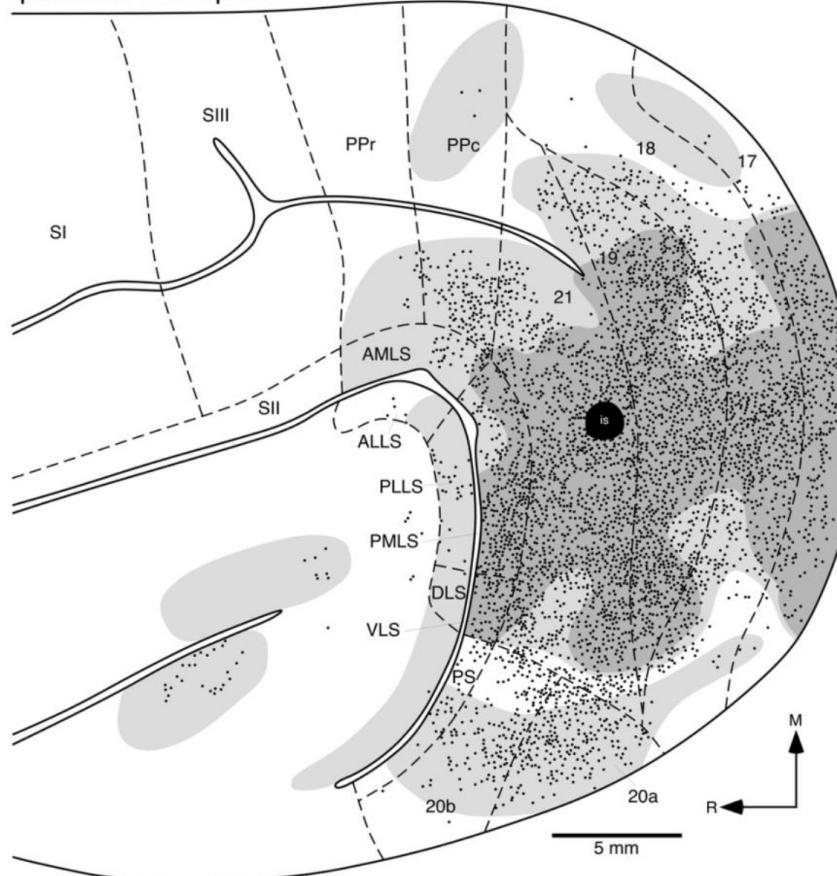


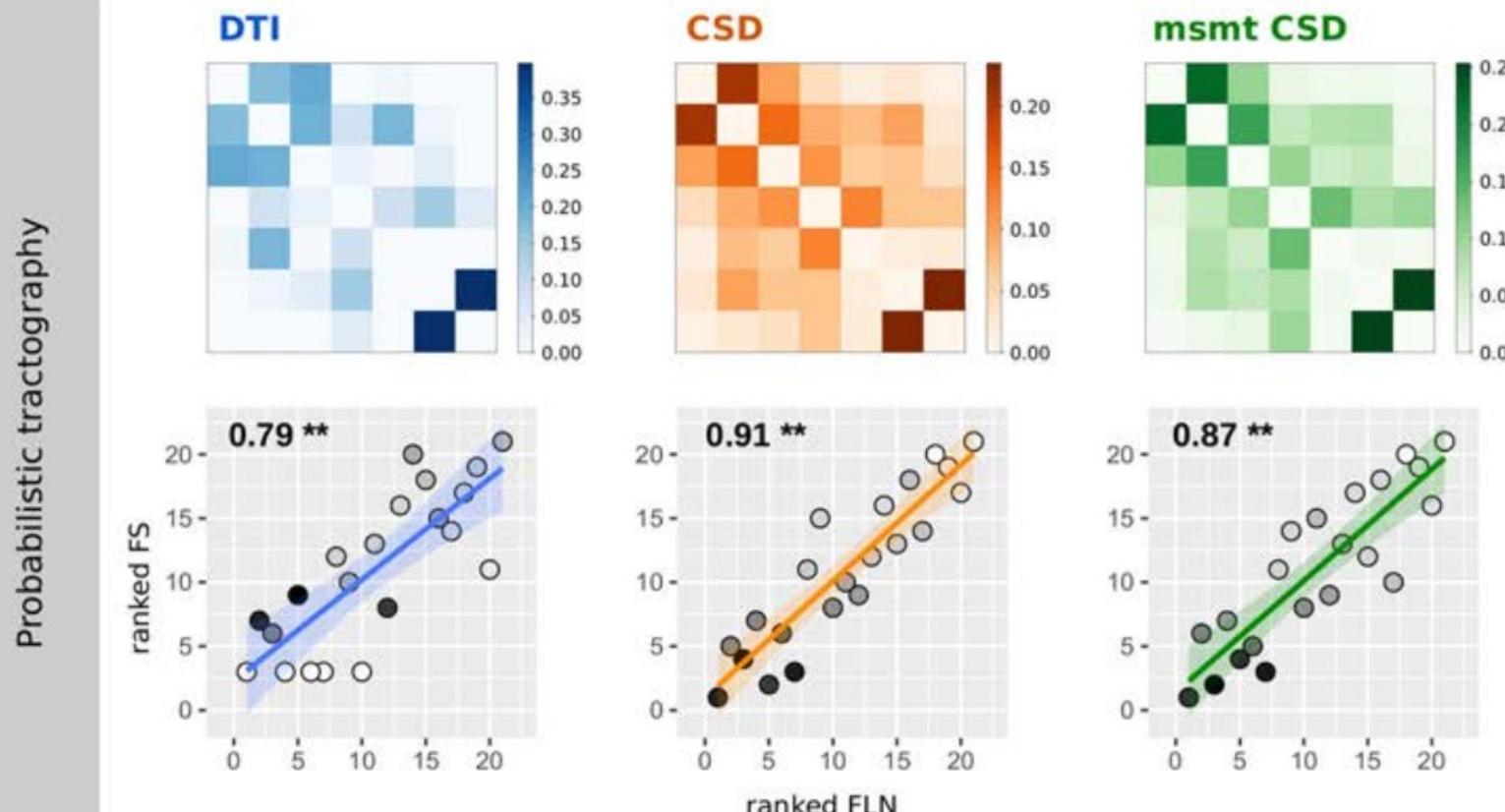
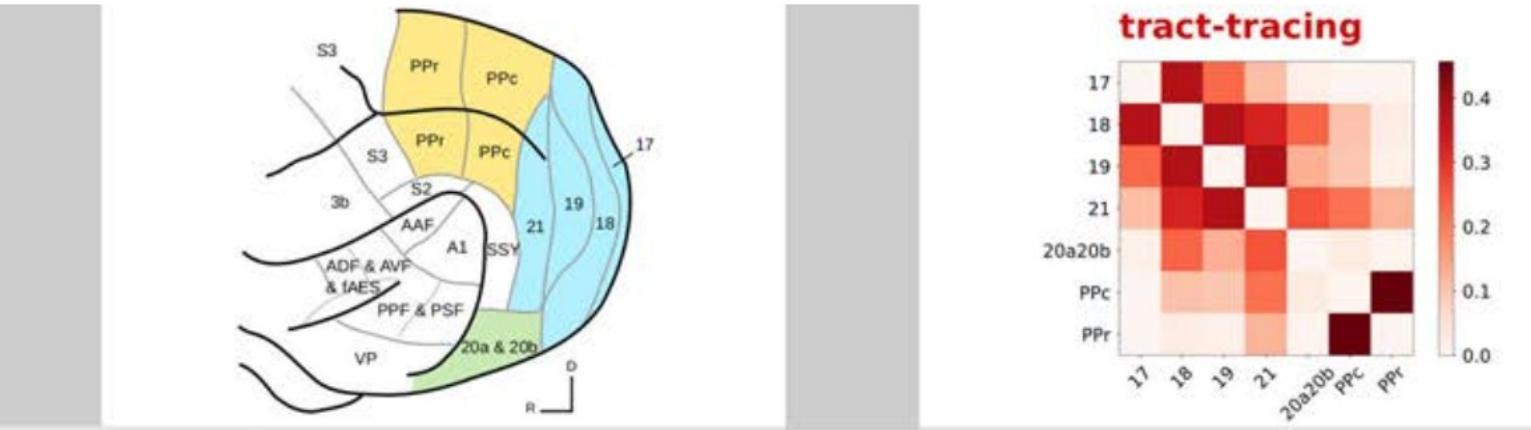
Diffusion MRI tractography based on **high-resolution *ex vivo* imaging** at 7T
Collaboration with Institut Pasteur and NeuroSpin, France

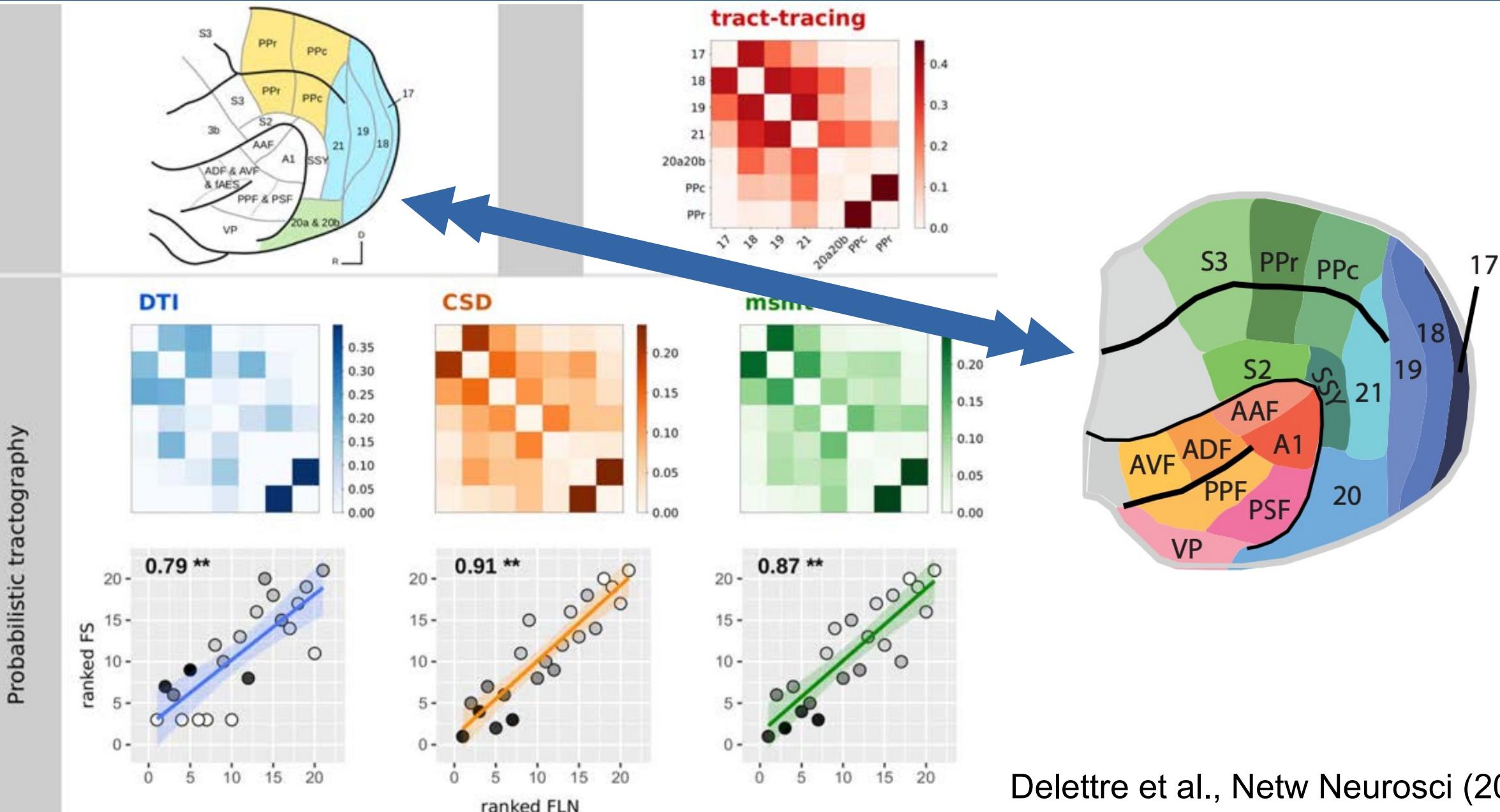
Delettre et al., Netw Neurosci (2019)

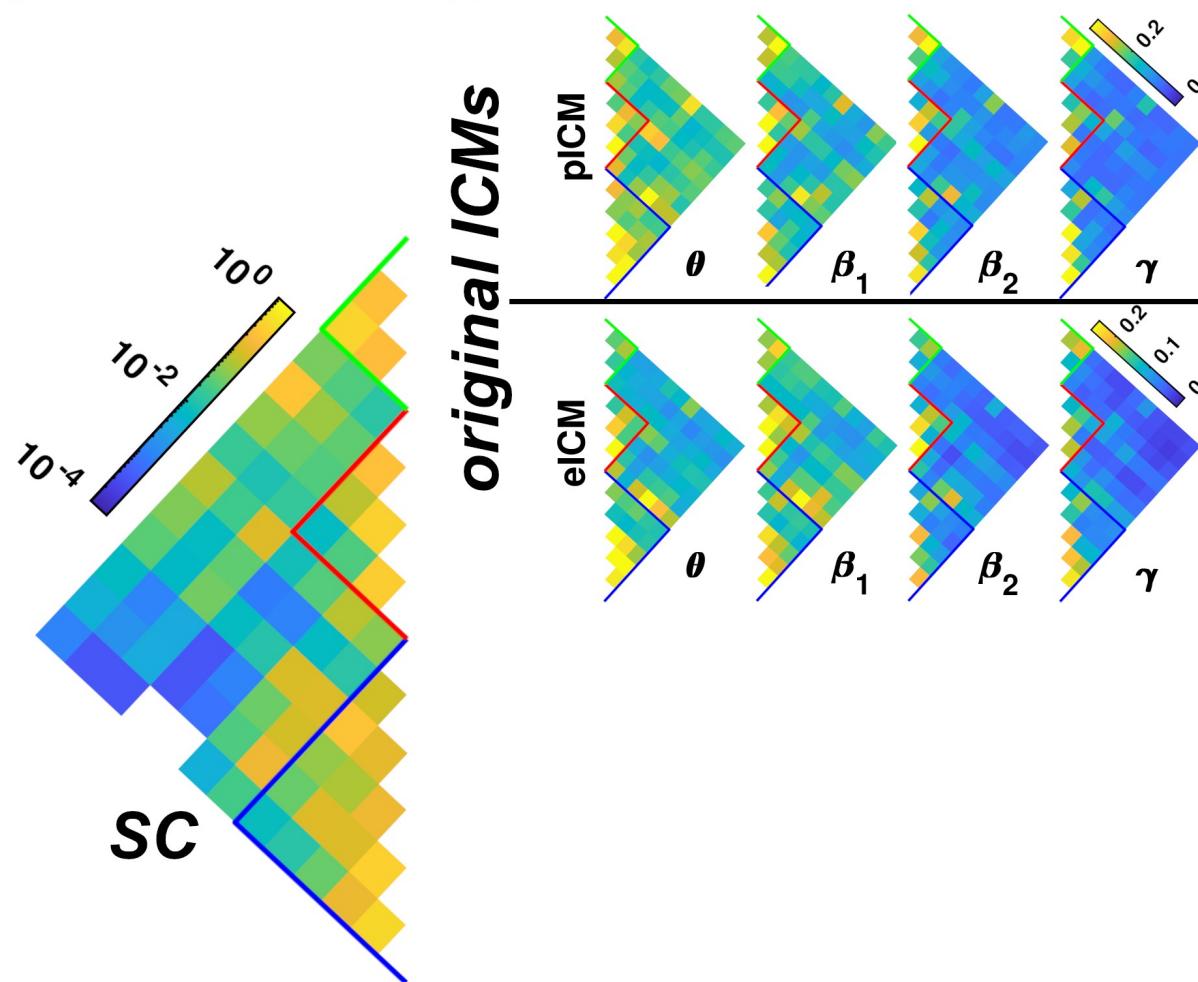
Tract-tracing

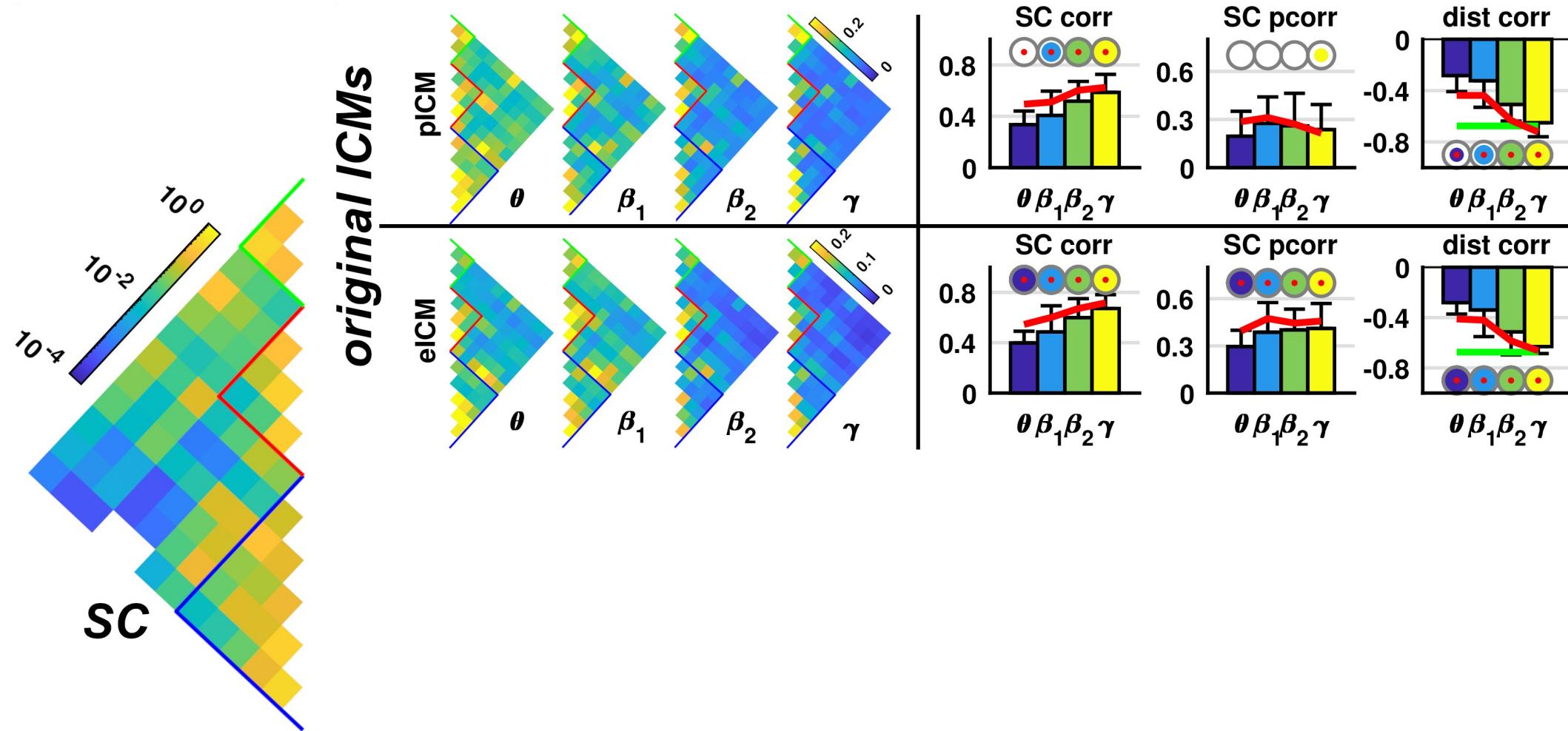
Ipsilateral hemisphere

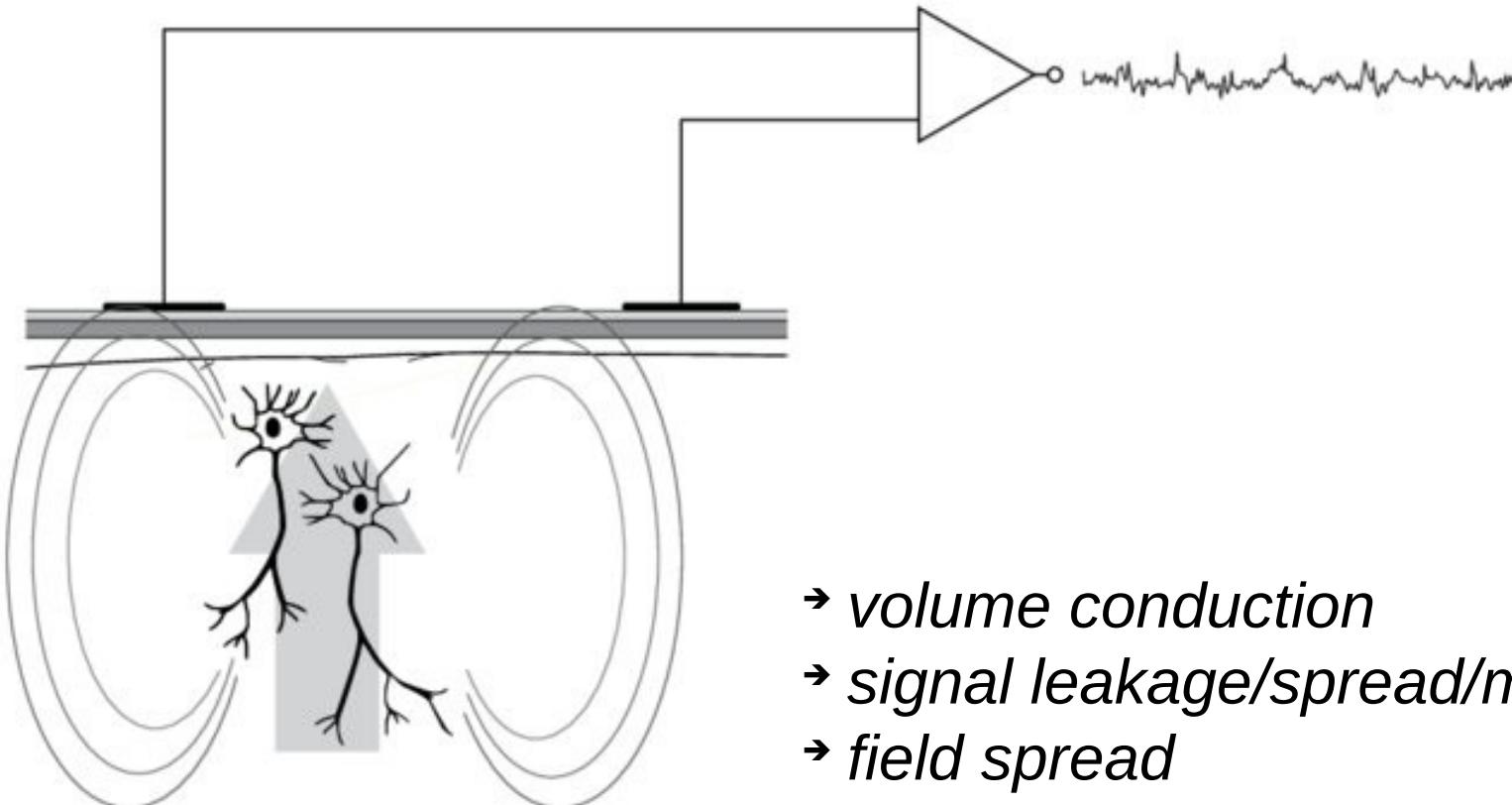






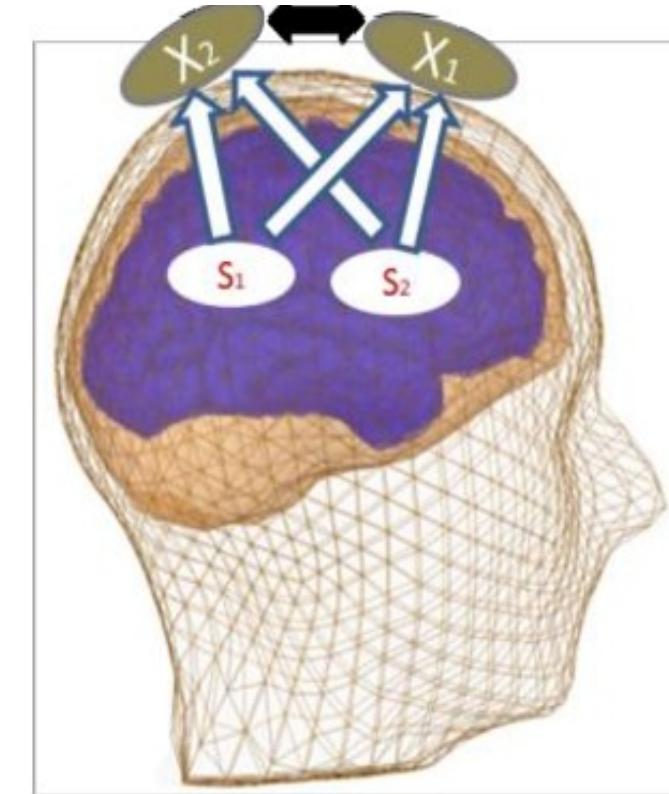


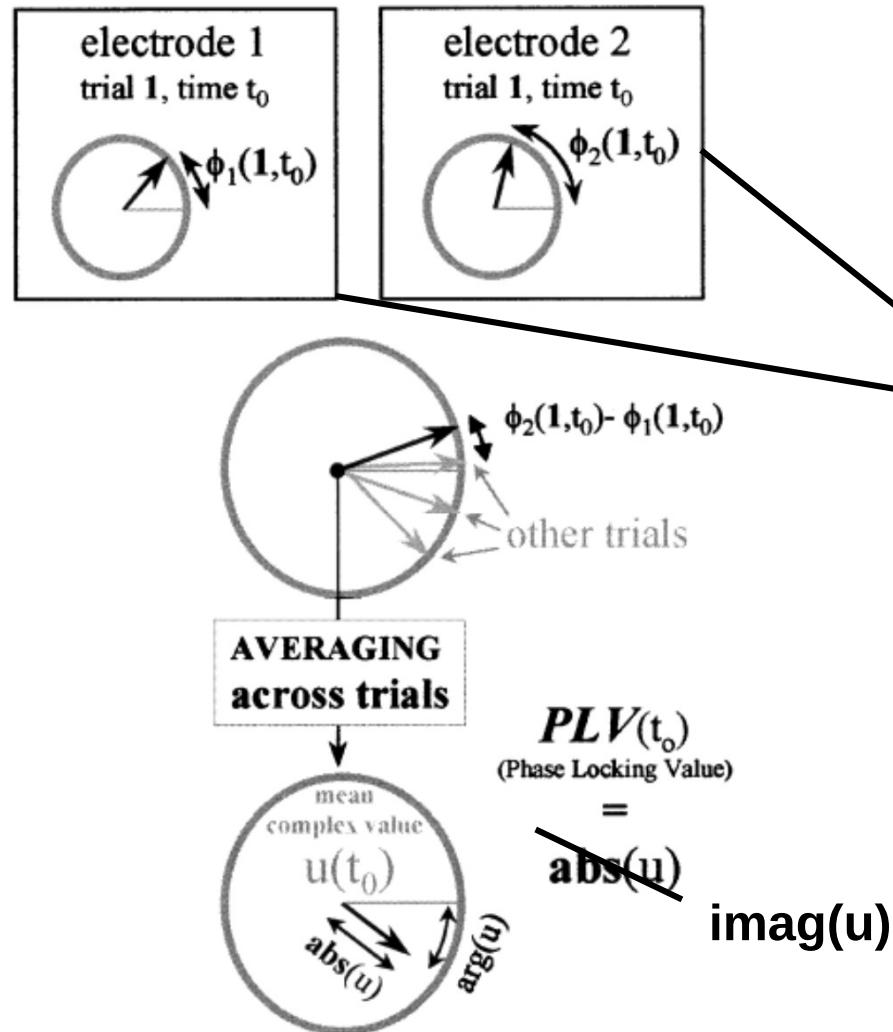
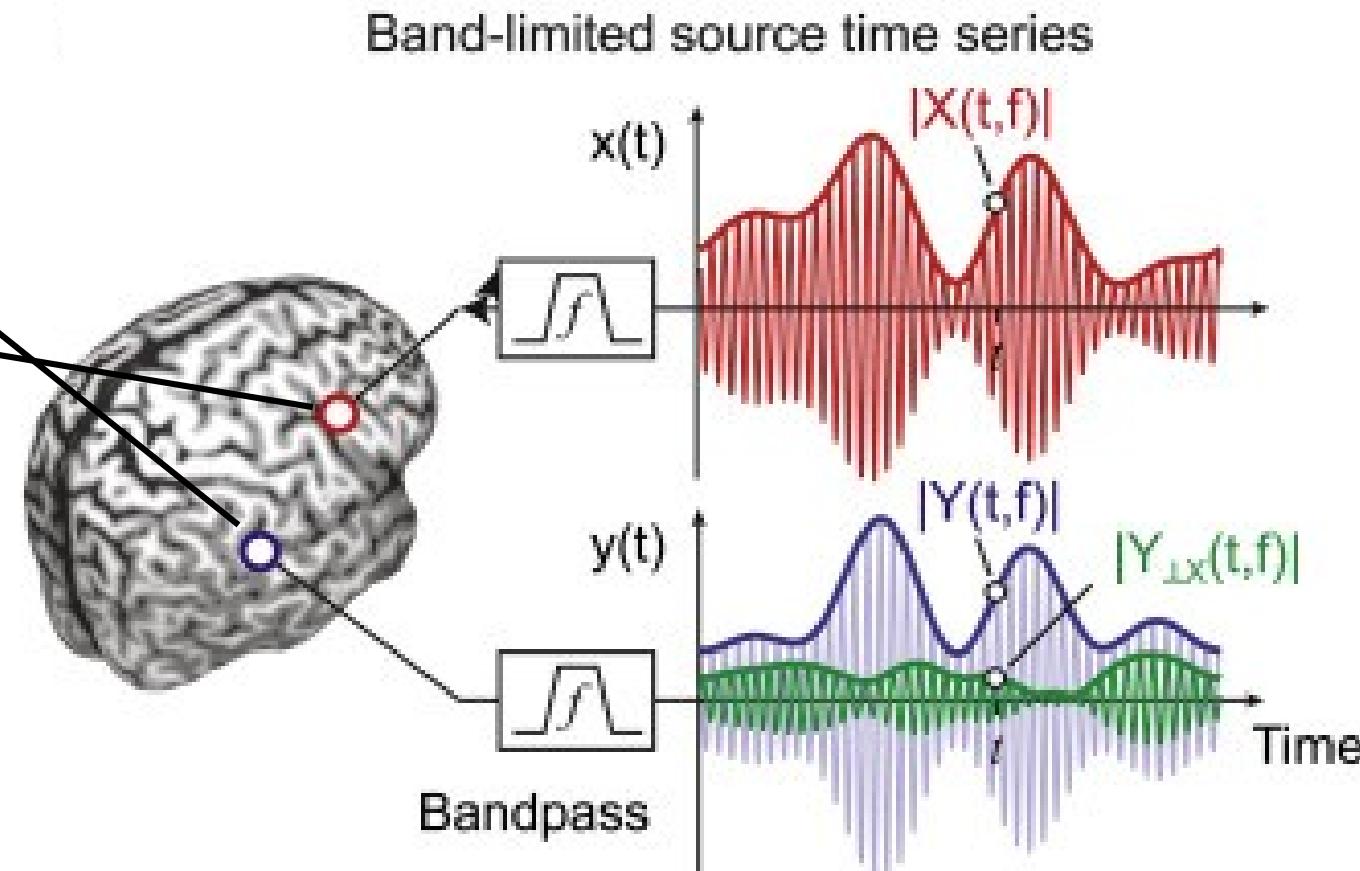


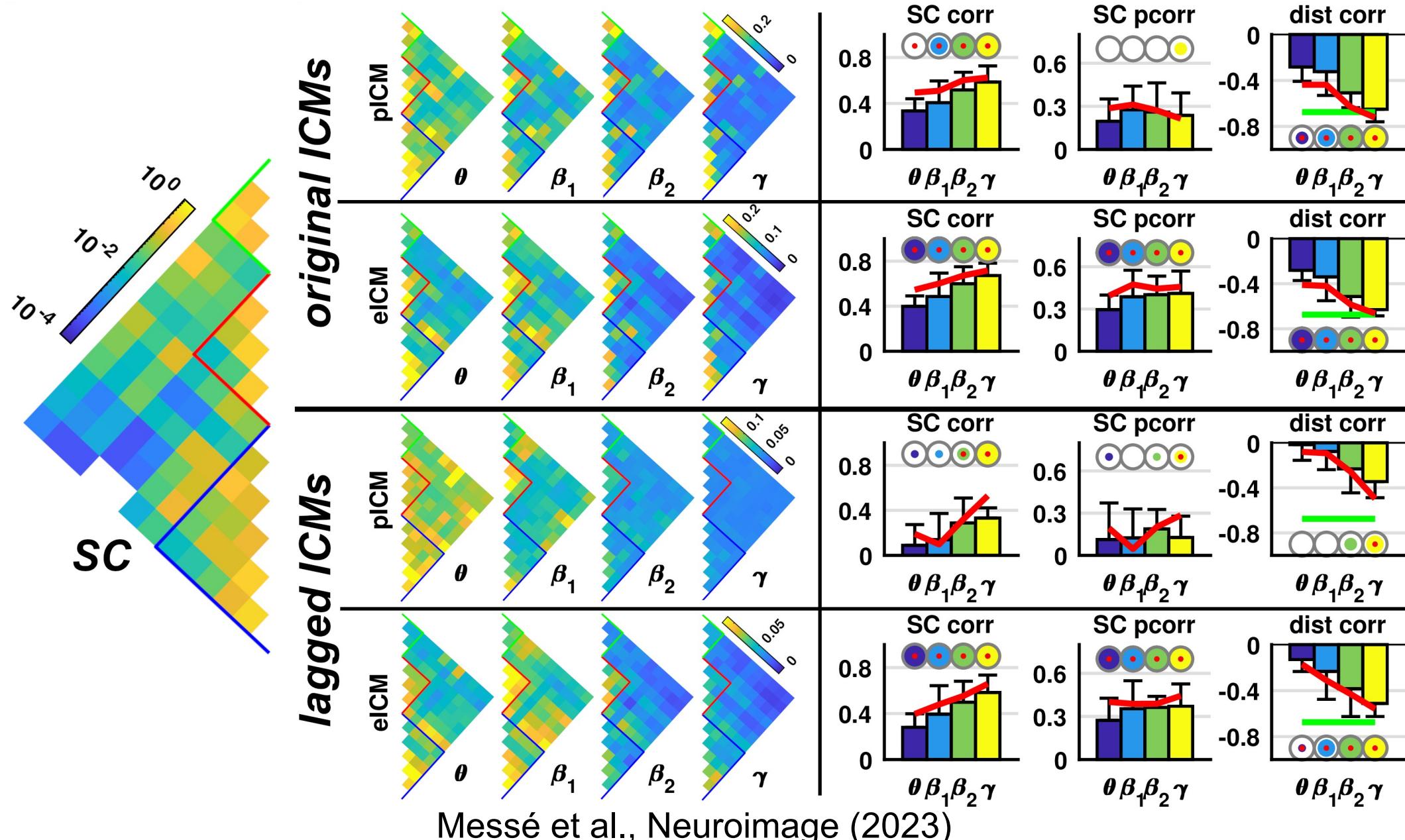


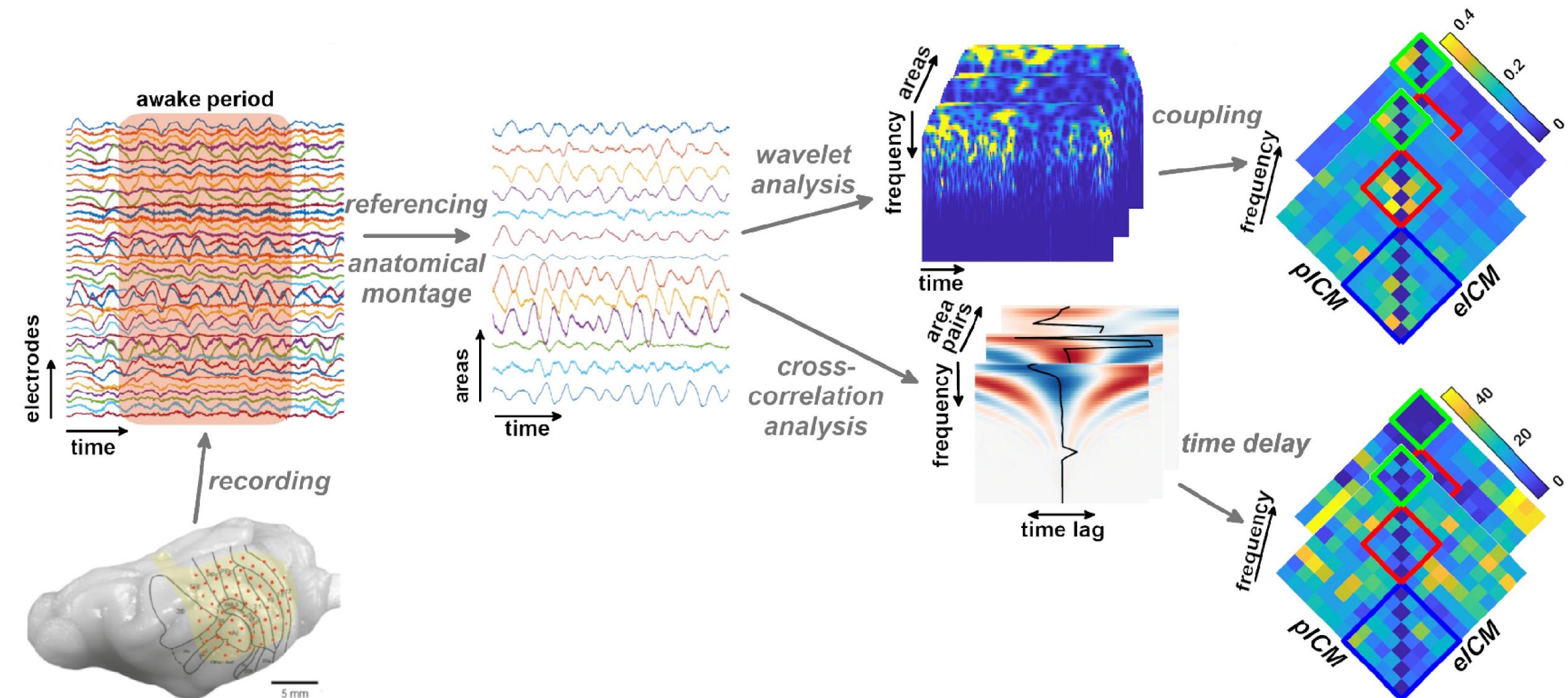
- volume conduction
- signal leakage/spread/mixing
- field spread

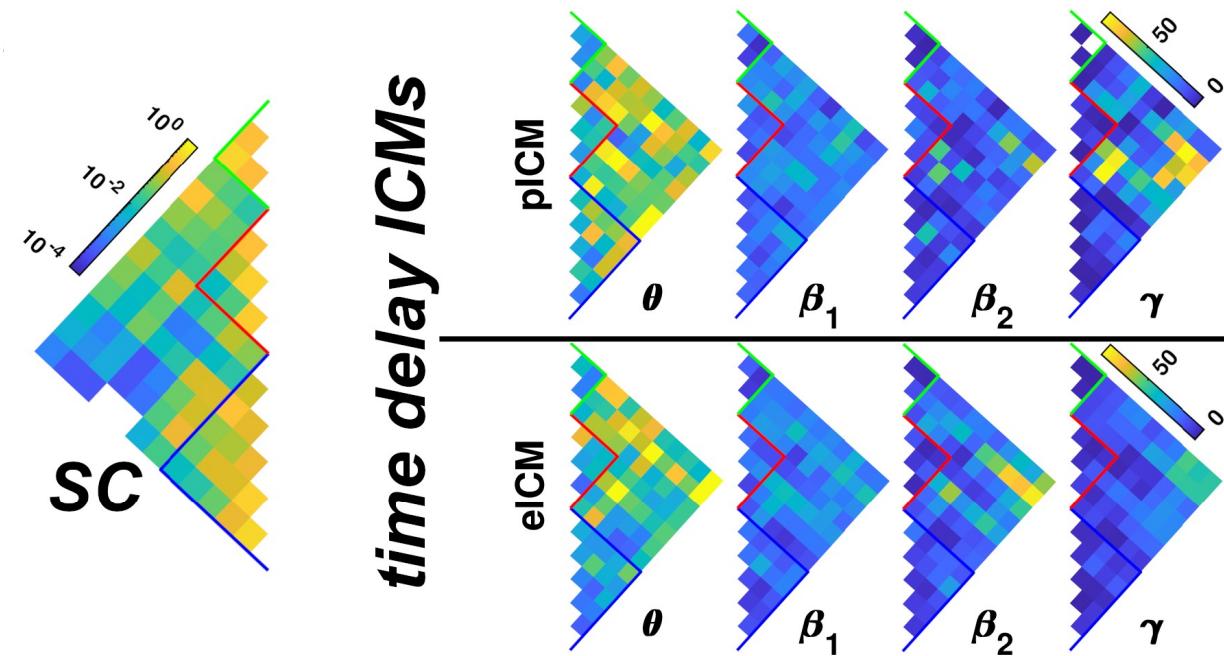
Instantaneous (zero-lag)

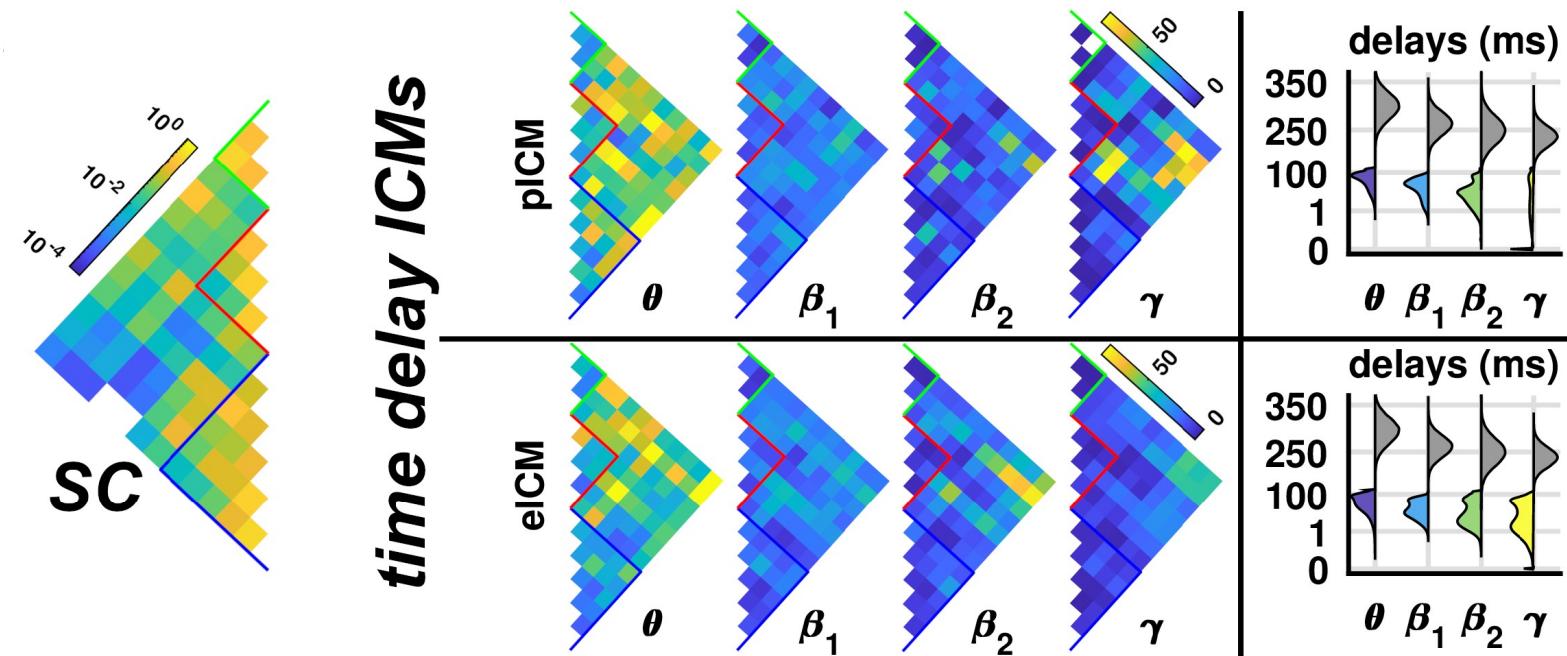


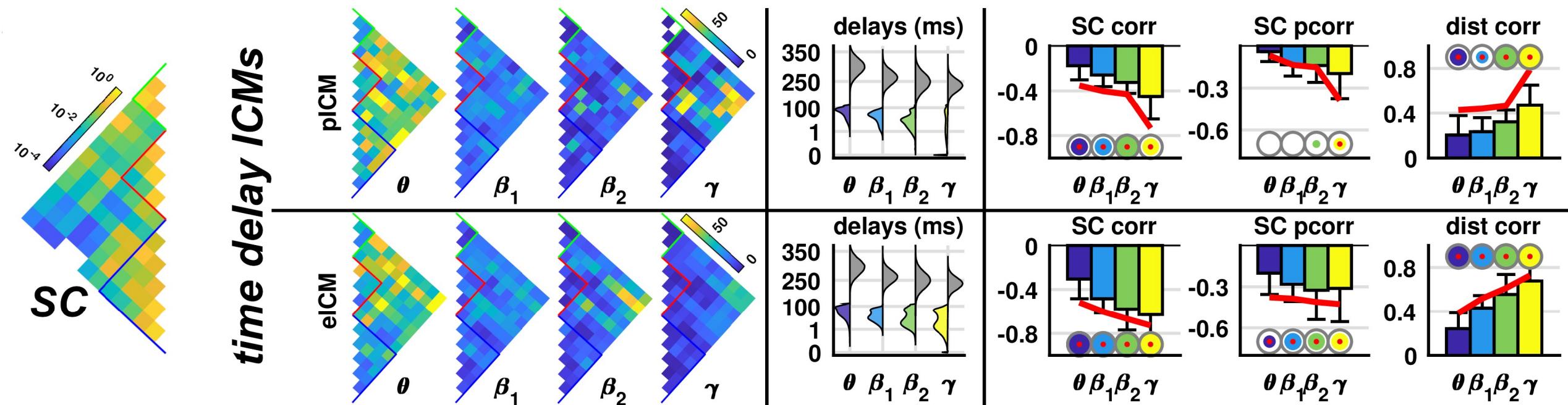
Imaginary phase locking value*Orthogonalized amplitude envelope correlation*

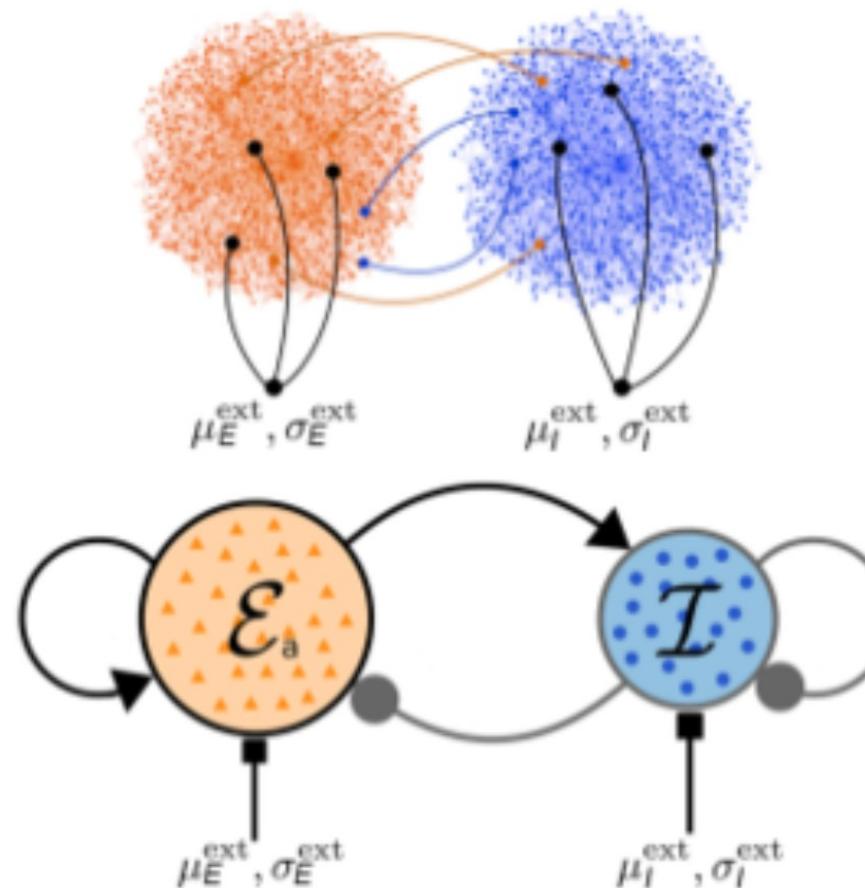
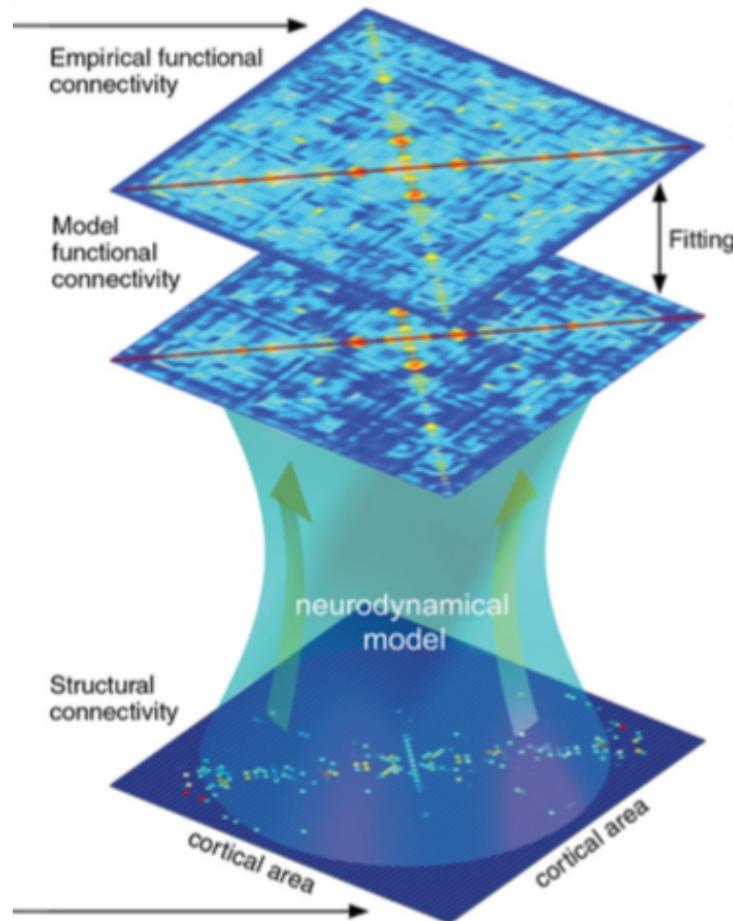












$$y = \omega D y + e$$

Messé et al., Neuroimage (2023)

Large-scale spiking attractor model

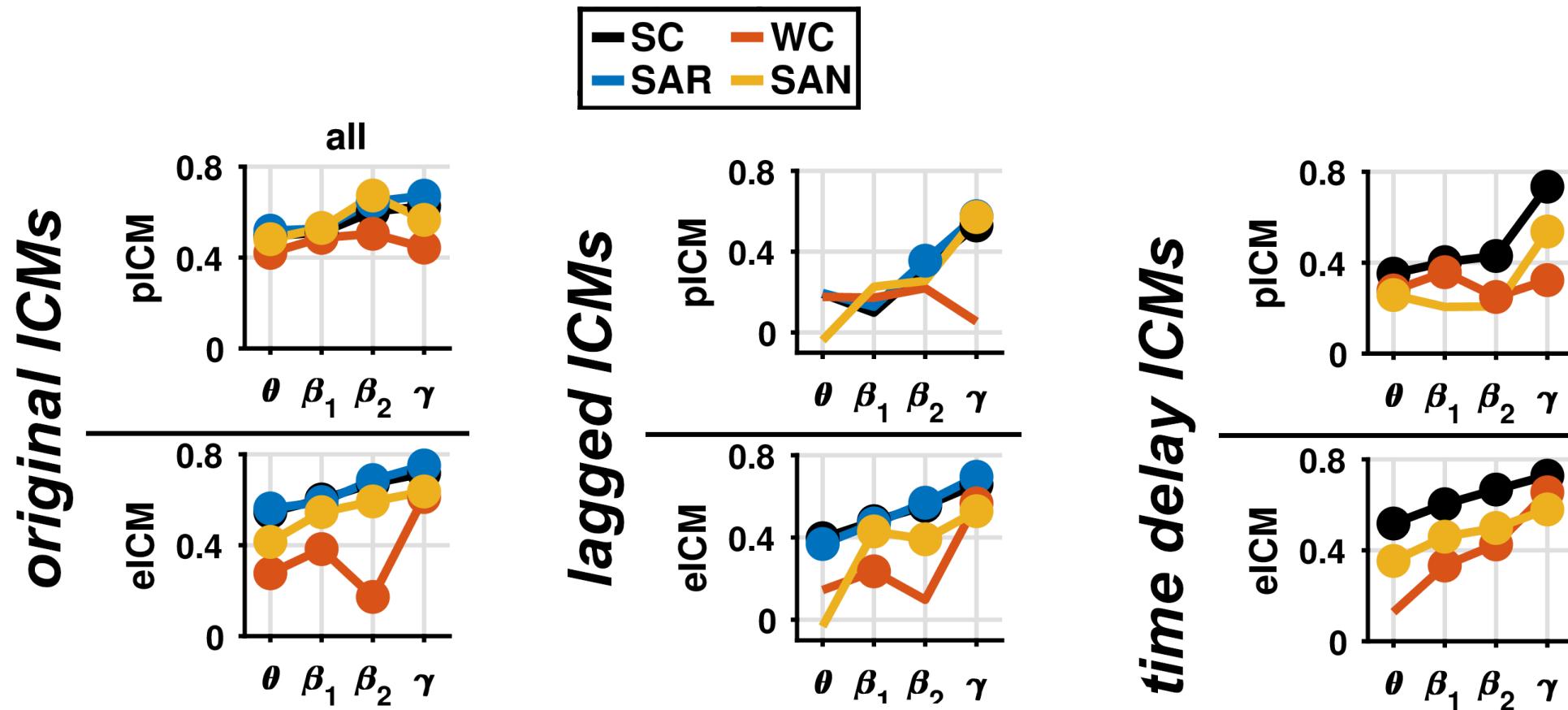
SAN

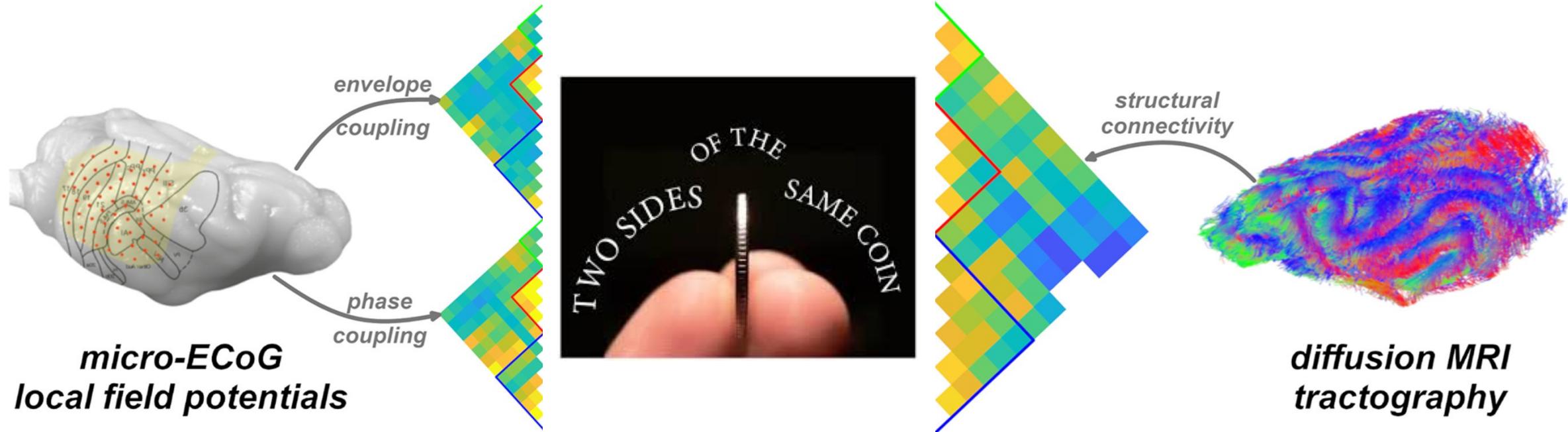
Wilson - Cowan neural-mass model

WC

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***