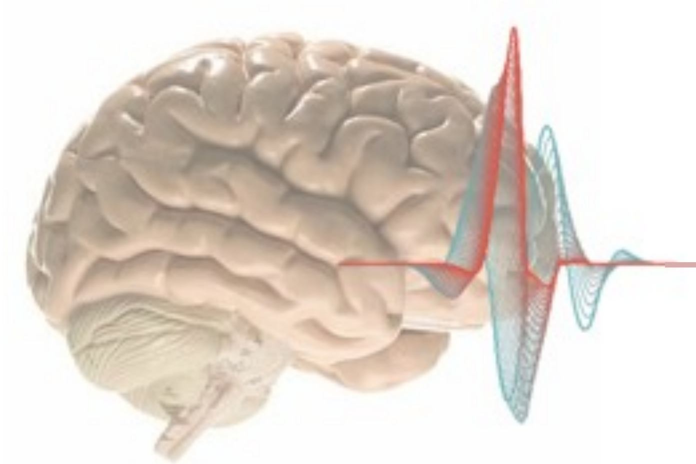

Brain dynamics and fractal behavior:

about (fast) EEG microstates and (slow) fMRI resting-state networks

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joint work with Juliane Britz and Christoph Michel

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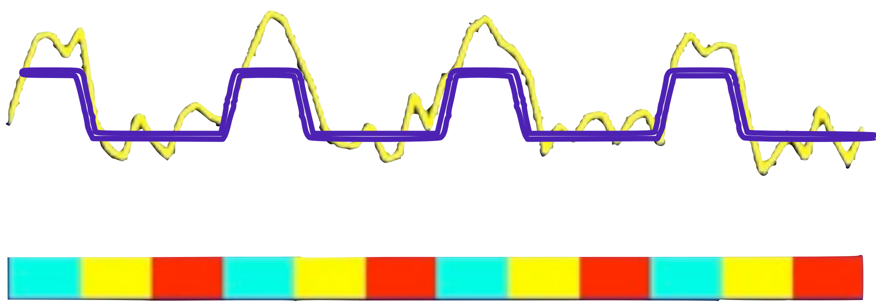
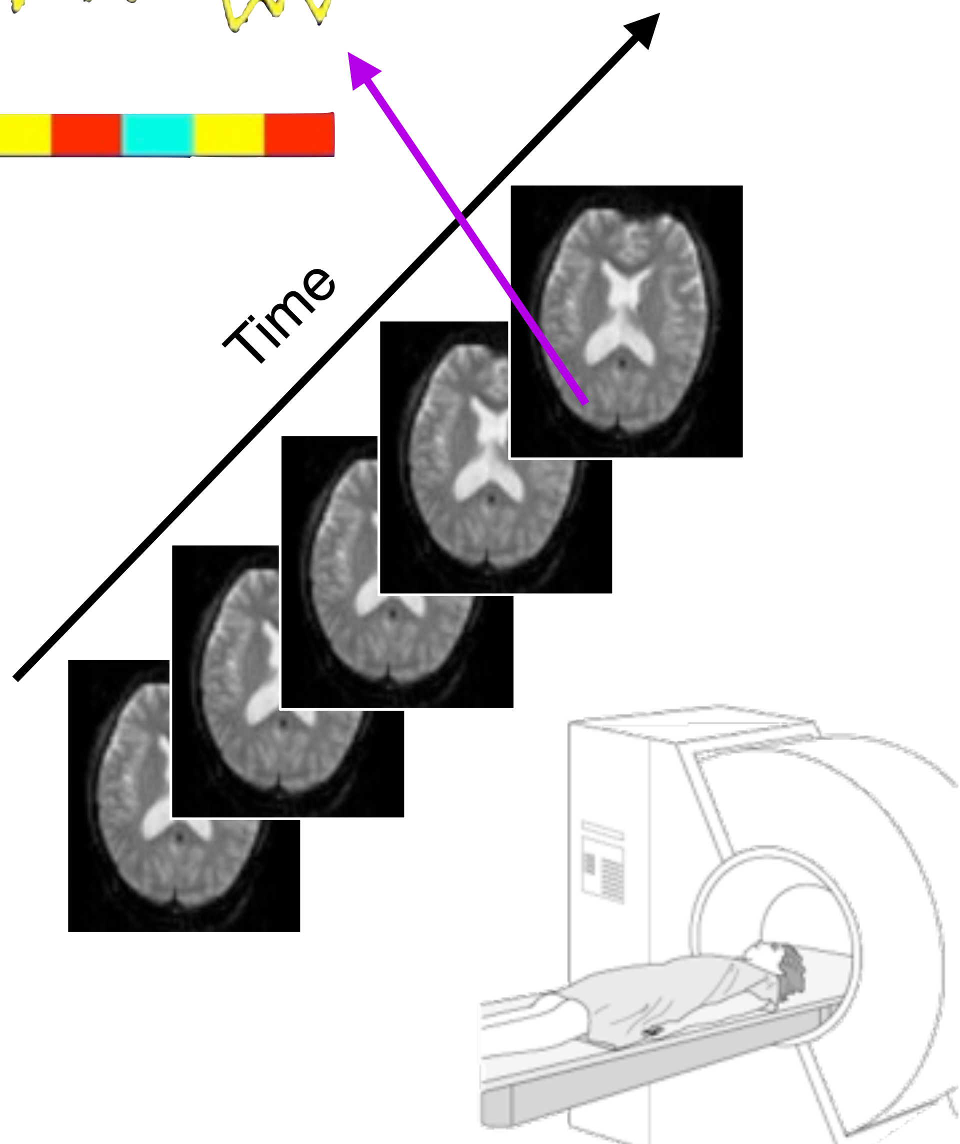
Villars, September 6, 2011

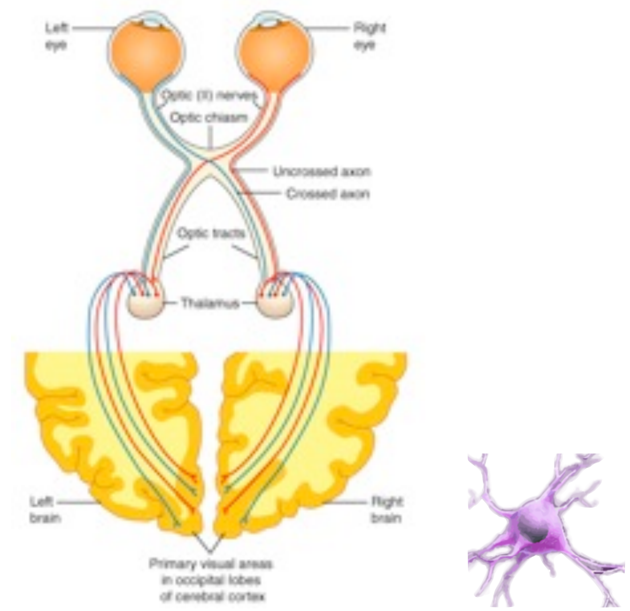
FMRI in a nutshell

Is there a face-selective brain region?

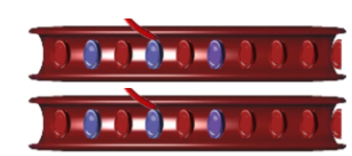




whole-brain scans
$2x2x2mm^3$
20-30 slices
every 2-4s



neurovascular coupling
hemodynamics



T2* effect
BOLD response

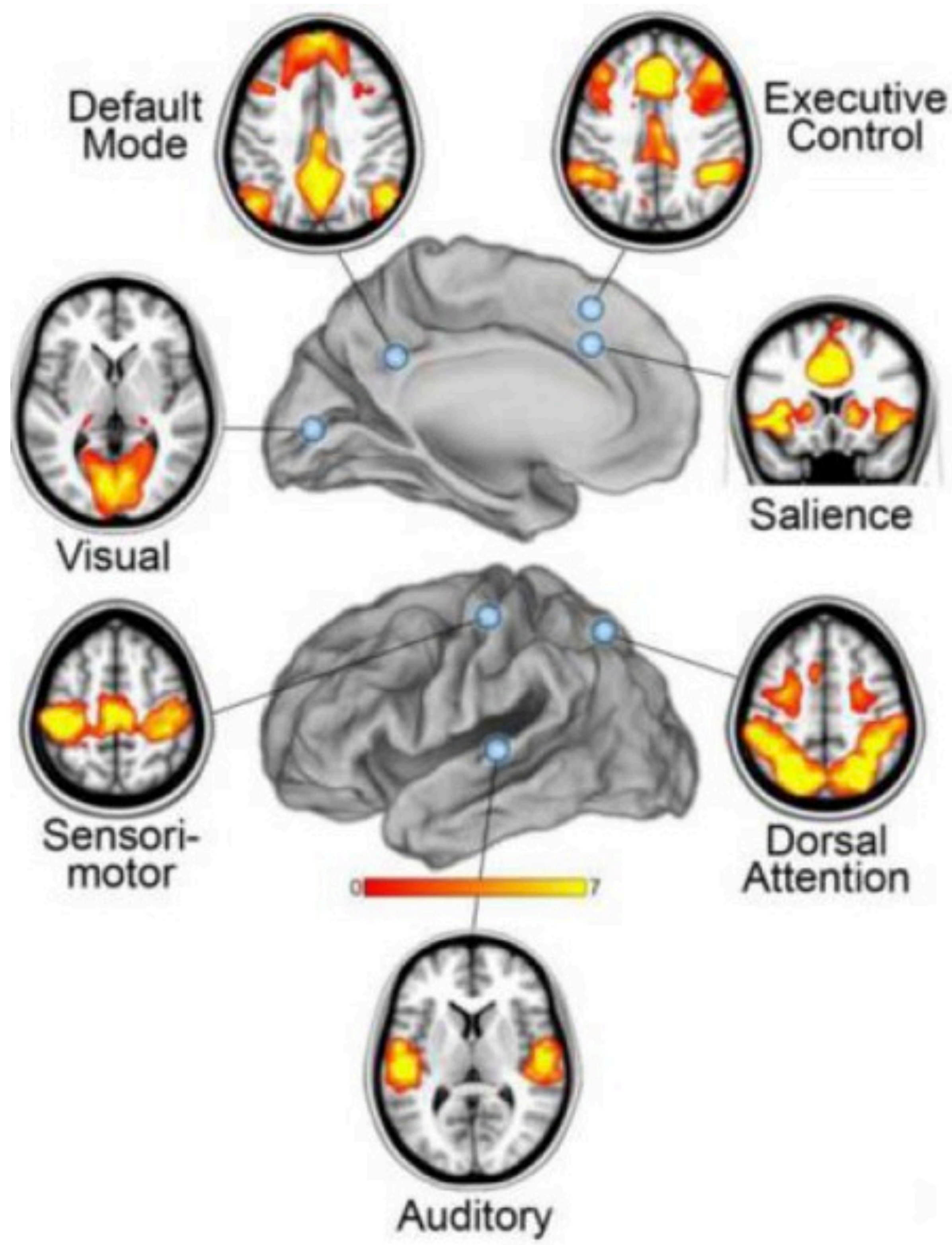
Resting-state fMRI

- Evoked activity
  - Brain consumes
    20% of energy budget
    - only 5% is needed for stimuli
    - 95% to maintain the machine
  - Consistent “deactivation” pattern in neuroimaging data such as PET and fMRI

[Raichle et al.]

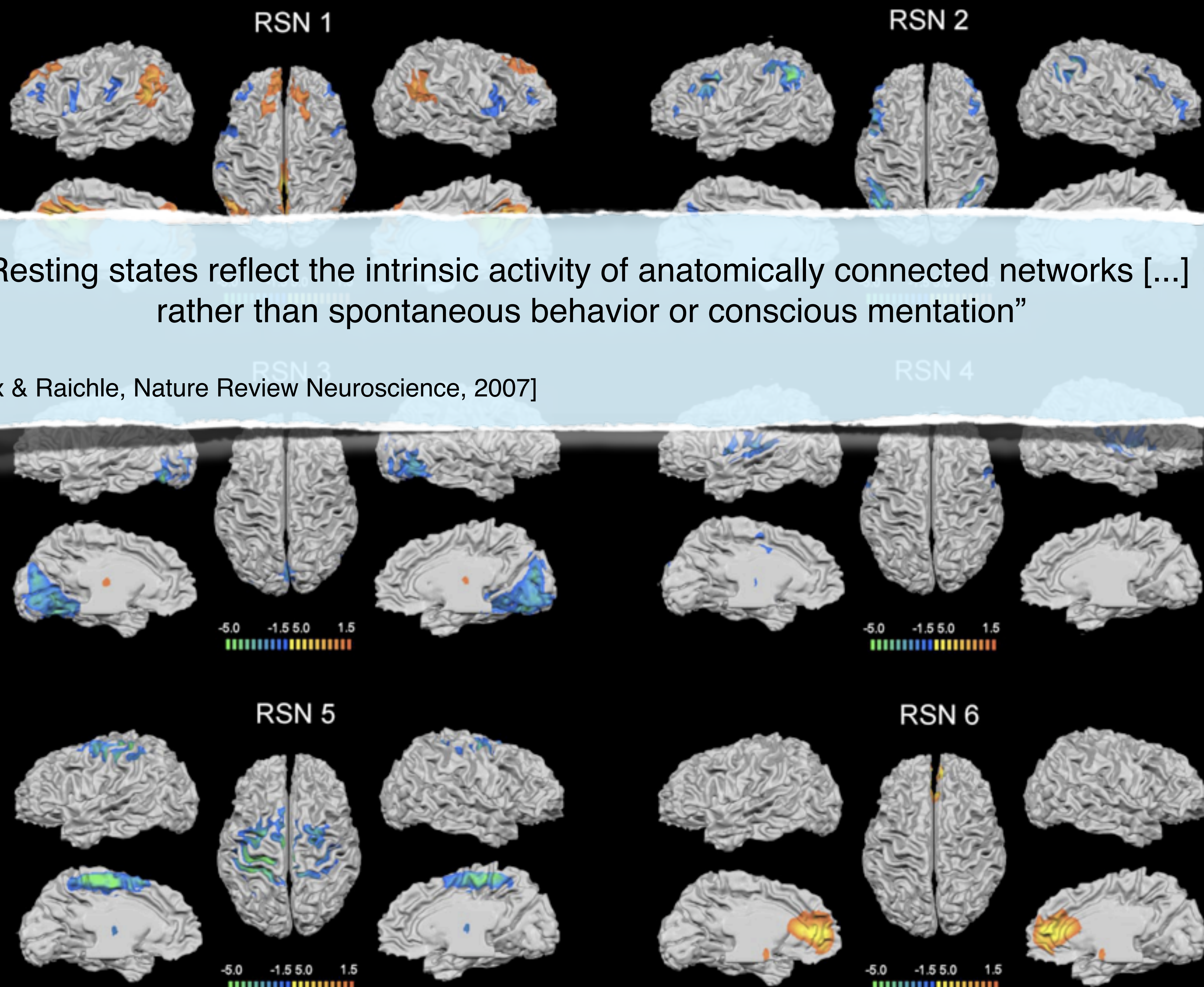
Resting-state fMRI

- Evoked activity
  - Brain consumes 20% of energy budget
    - only 5% is needed for stimuli
    - 95% to maintain the machine
  - "Deactivation" pattern in neuroimaging data such as PET and fMRI
- Intrinsic activity
  - *Seed voxel correlation*
  - Distinctive patterns of brain activity
  - Relevance for neurological disorder & disease



[Biswal, Raichle, Buckner, Greicius, Mason et al. 2007, ...]

Independent component analysis



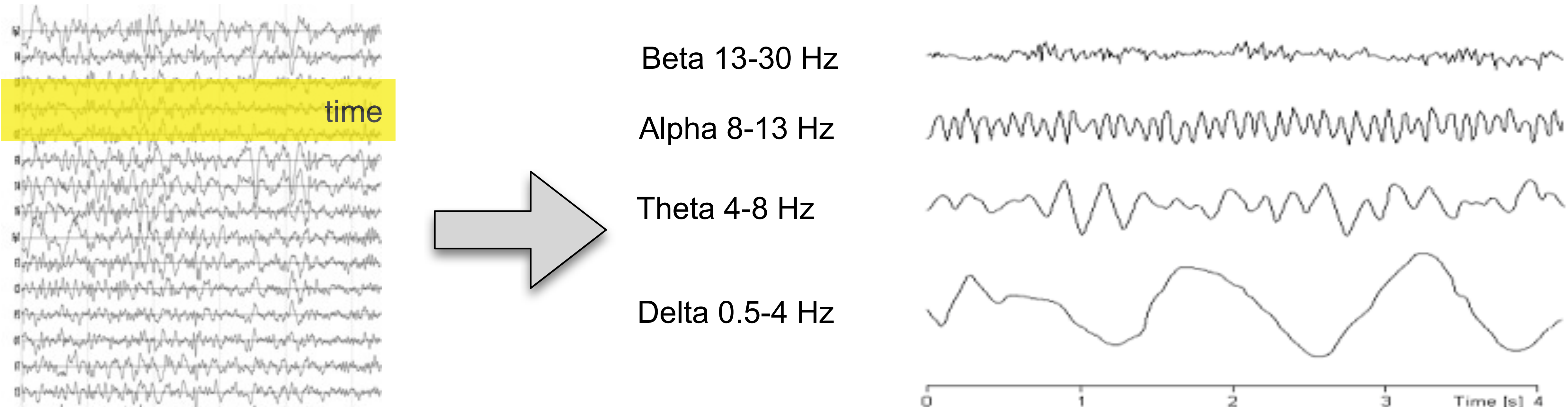
“Resting states reflect the intrinsic activity of anatomically connected networks [...] rather than spontaneous behavior or conscious mentation”

[Fox & Raichle, Nature Review Neuroscience, 2007]

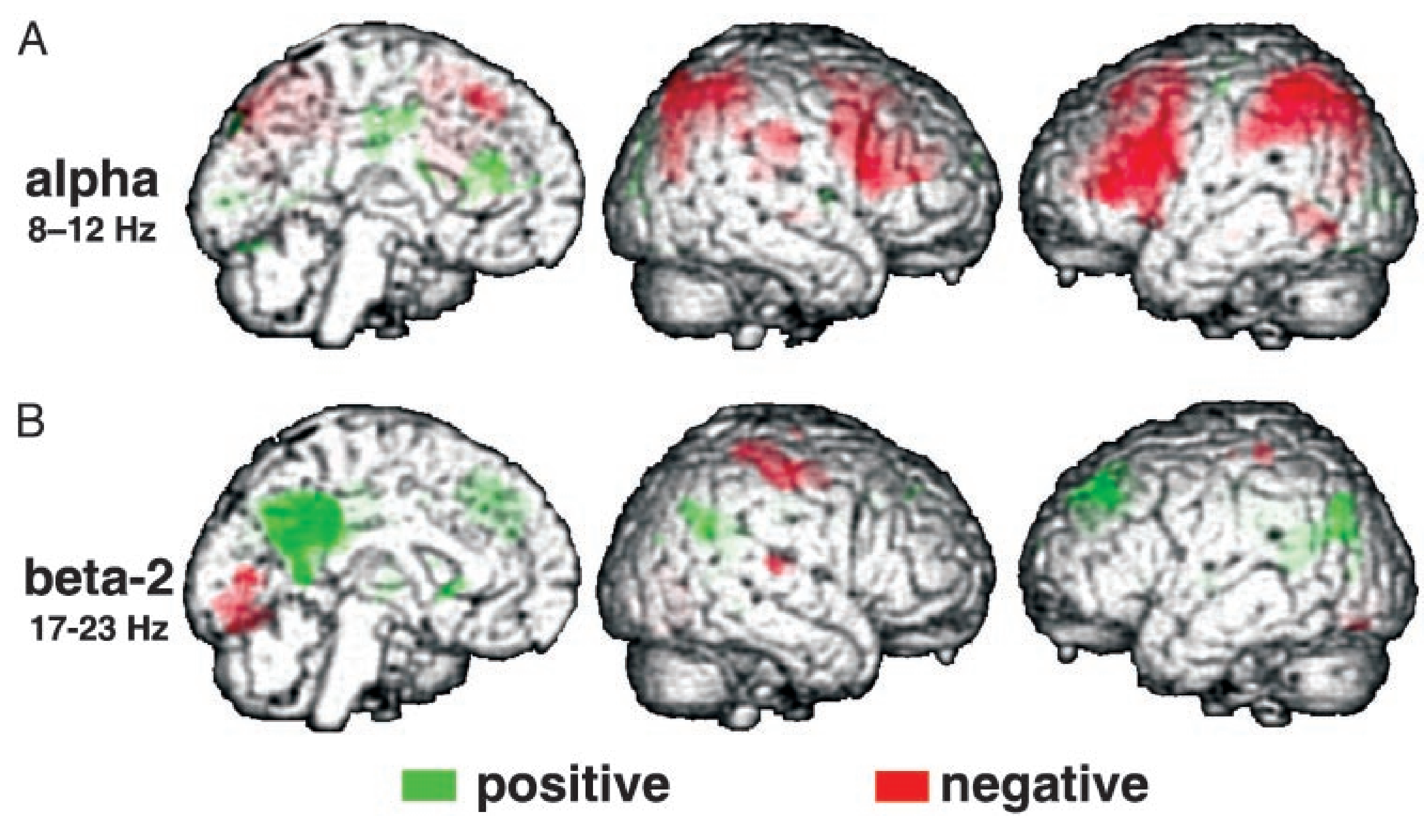
[Mantini et al., PNAS, 2007]

EEG rhythms

- Temporal frequency bands



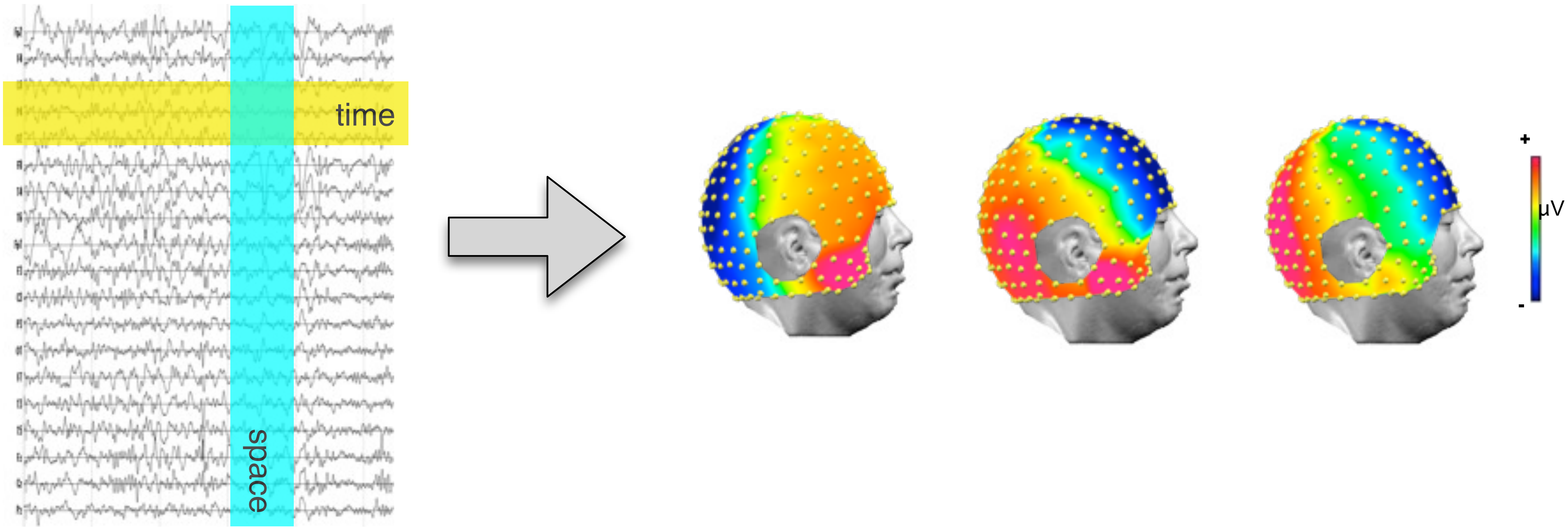
- Simultaneous EEG/fMRI can be acquired and cleaned
- Alpha-band energy correlates negatively with attention network

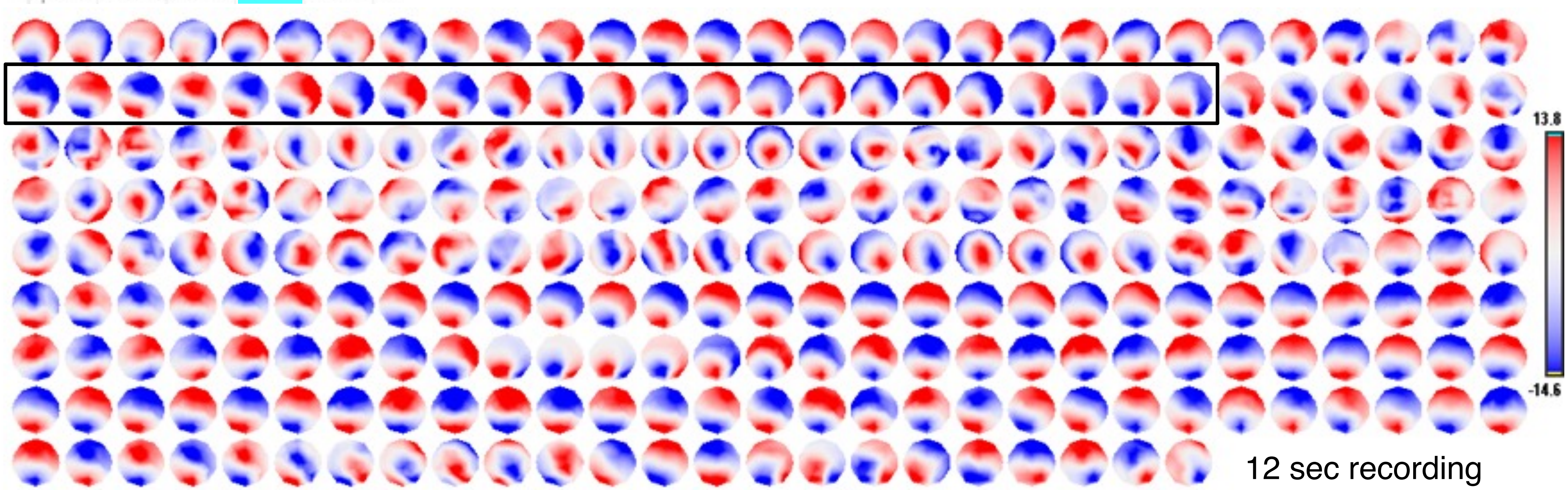


[Laufs et al., NeuroImage, 2005; Laufs et al, PNAS, 2003]

EEG mapping

- Spatial topography is important too

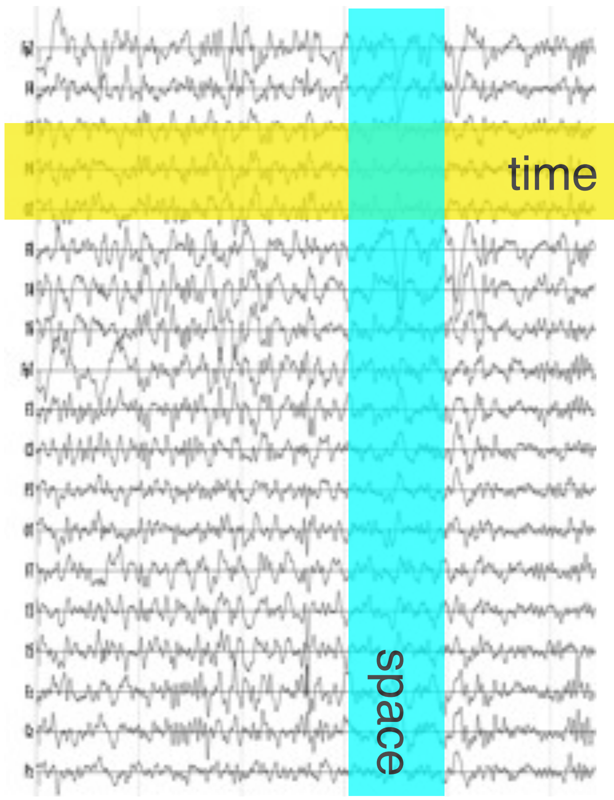


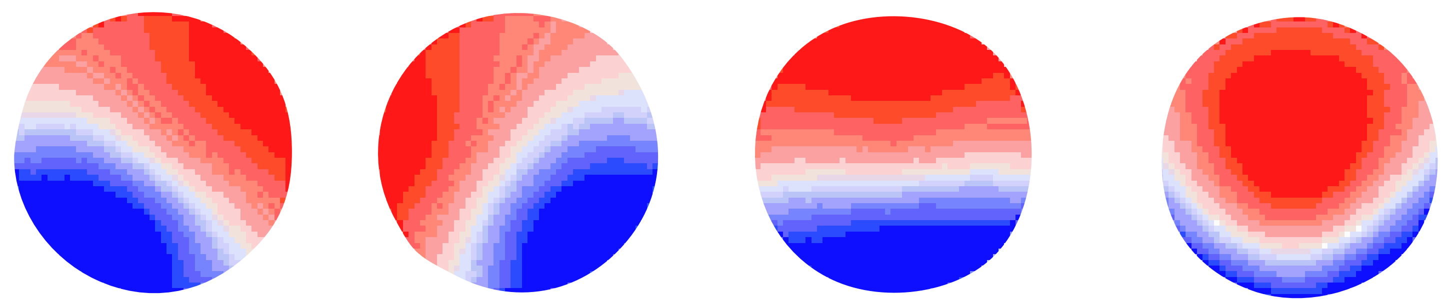


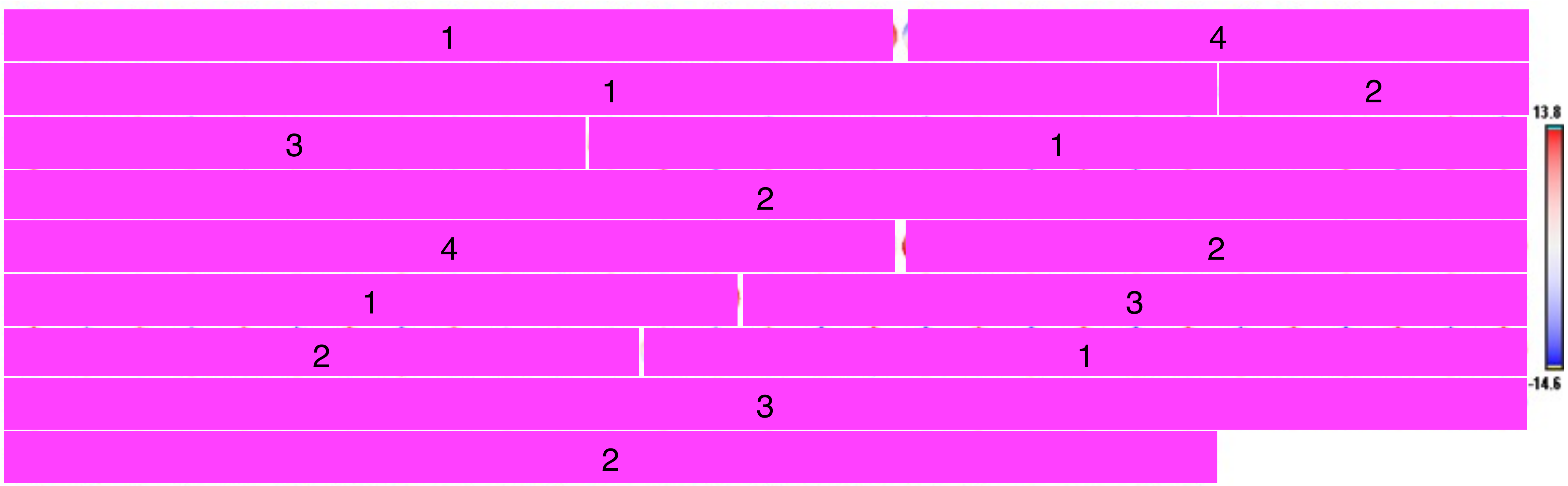
[Lehmann, 1971]

EEG microstates

- Spatial clustering of topography maps



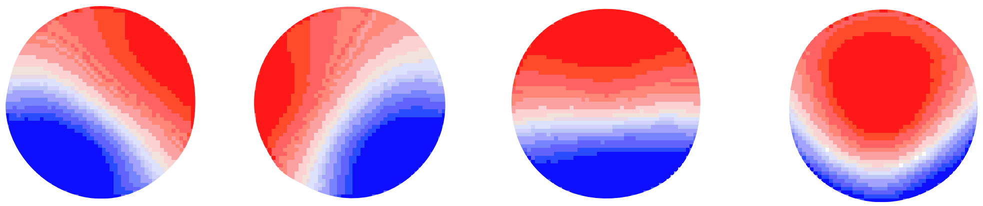




[Lehmann, 1971; Pascual-Marqui et al, 1995; Lehmann et al., 2009]

EEG microstates

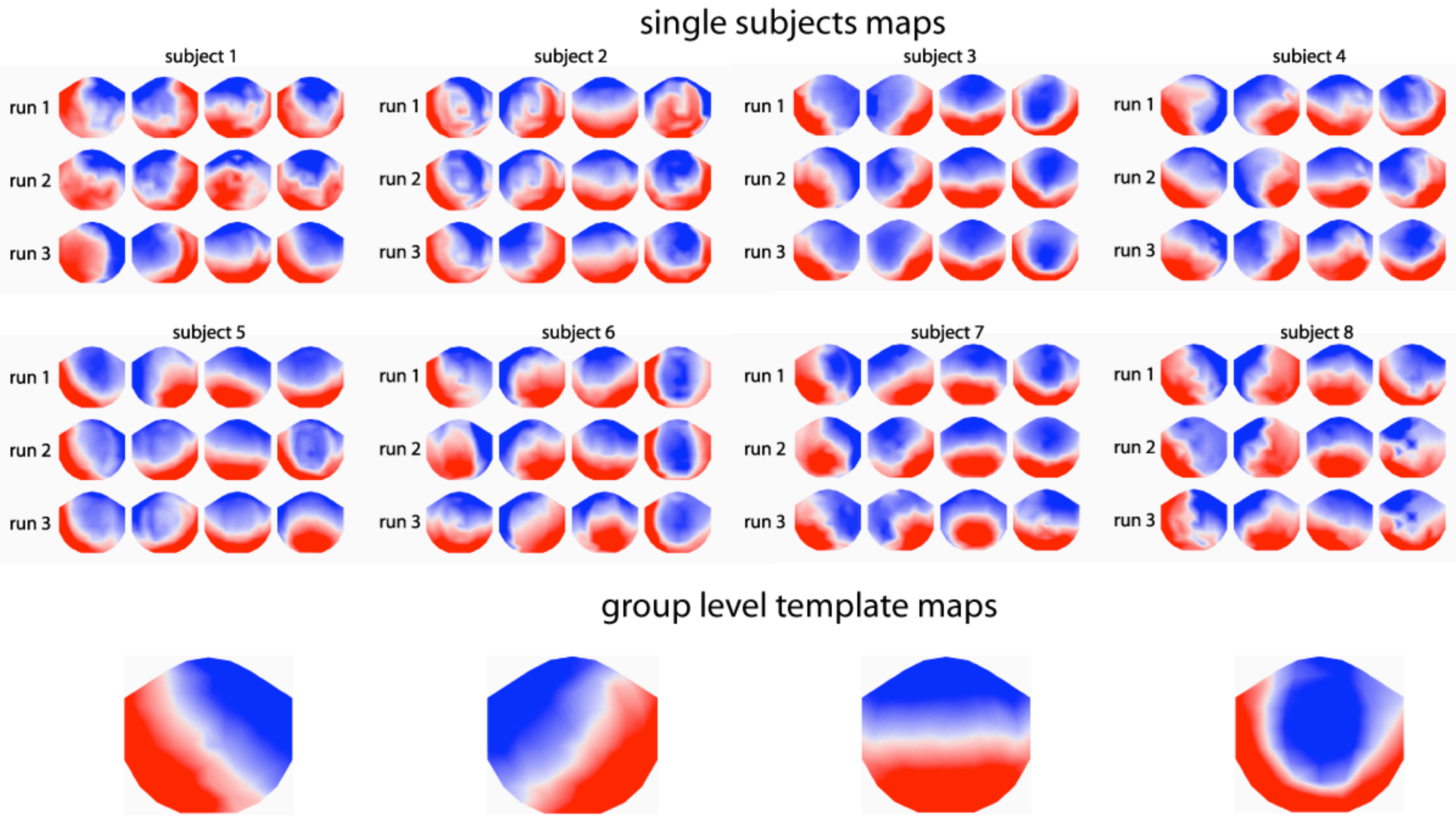
- Spatial clustering and cross-validation indicate
  - Four microstates explain spontaneous EEG (awake rest)
- Average duration of microstates is 100ms
  - Large cohorts (>500), age 6-67 [Koenig et al., 2002]
- Microstates are *functional*
  - Pre-stimulus microstate determines cognitive processing and perception [Mohr et al., 2009; Britz et al., 2009]
  - Modified in mental diseases
    - Duration is very sensitive parameter
    - Including schizophrenia, depression, Alzheimer



[Lehmann et al., 1998; Changeux, Michel, 2008; Lehmann et al., 2009]

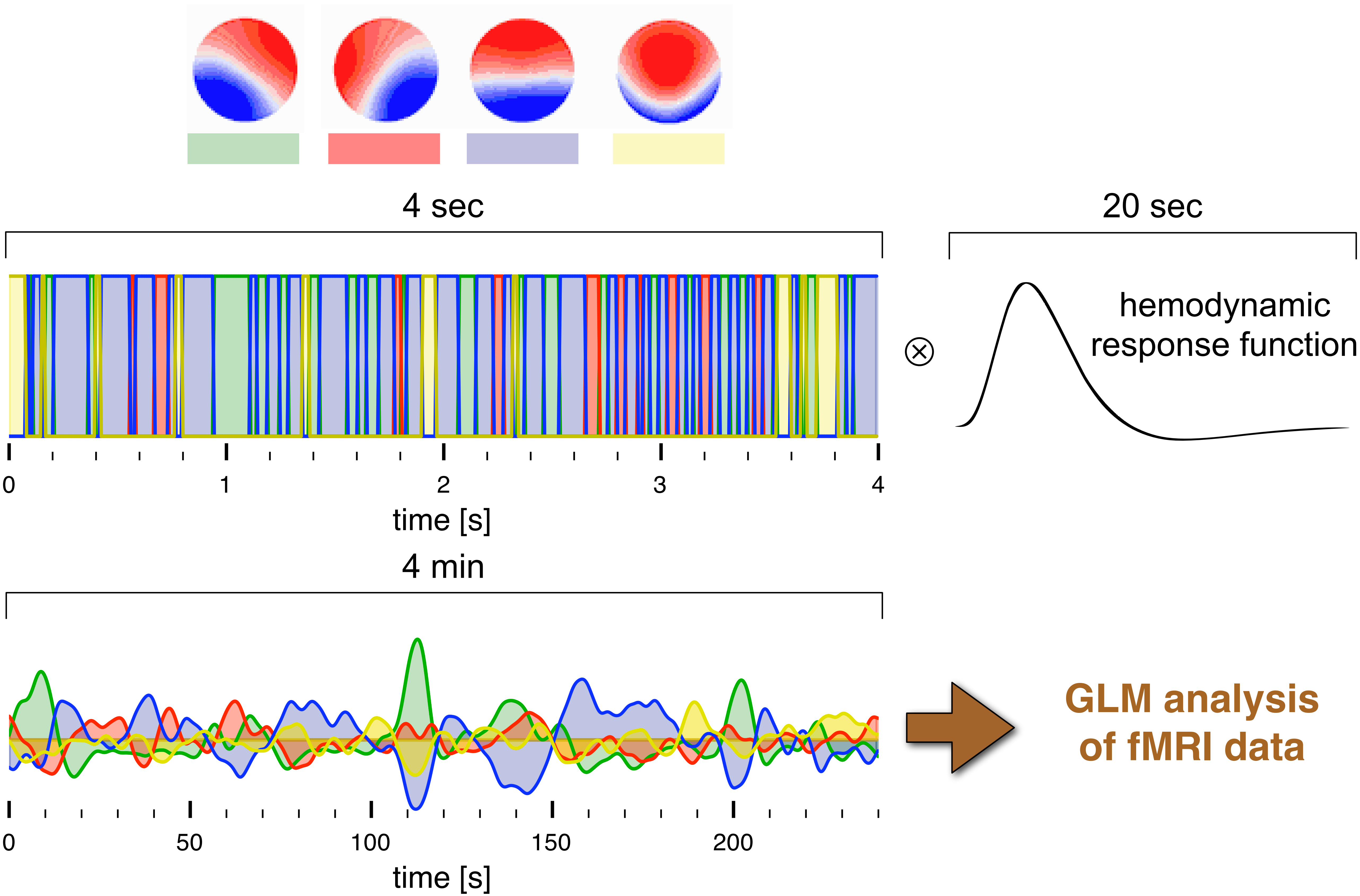
EEG microstates in the MR scanner

- Consistent topographies across subjects

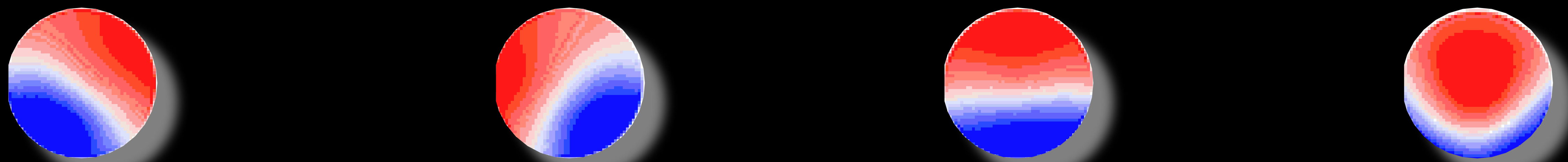


[Britz, VDV, Michel, NeuroImage, 2010]

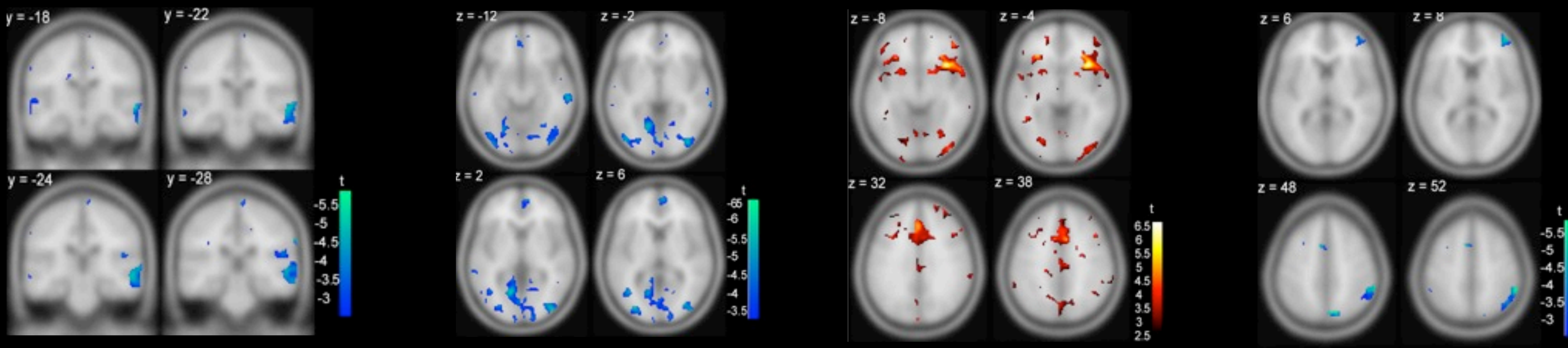
Making the bridge from EEG to fMRI



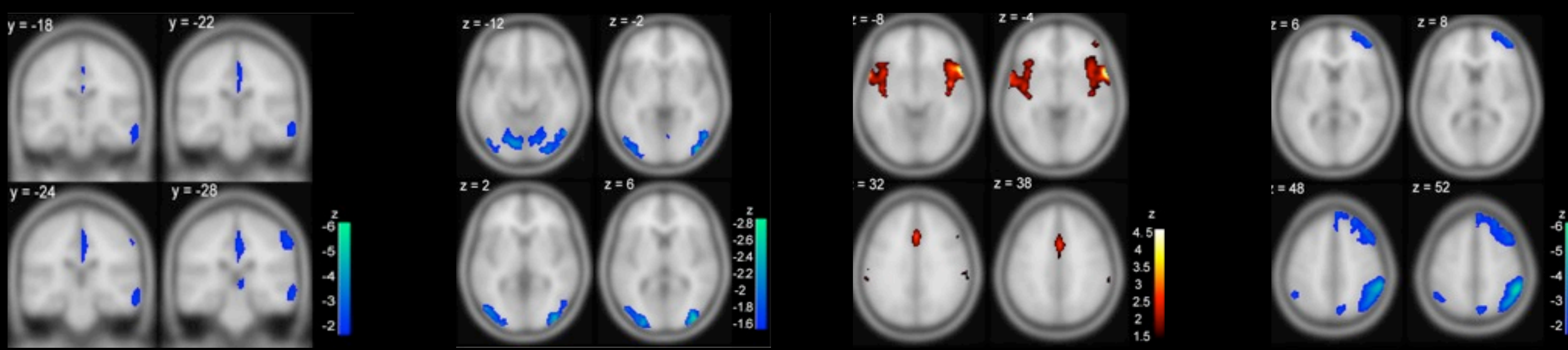
[Britz, VDV, Michel, NeuroImage, 2010]



Auditory-phonological | Visual | Self-referential | Dorsal attention

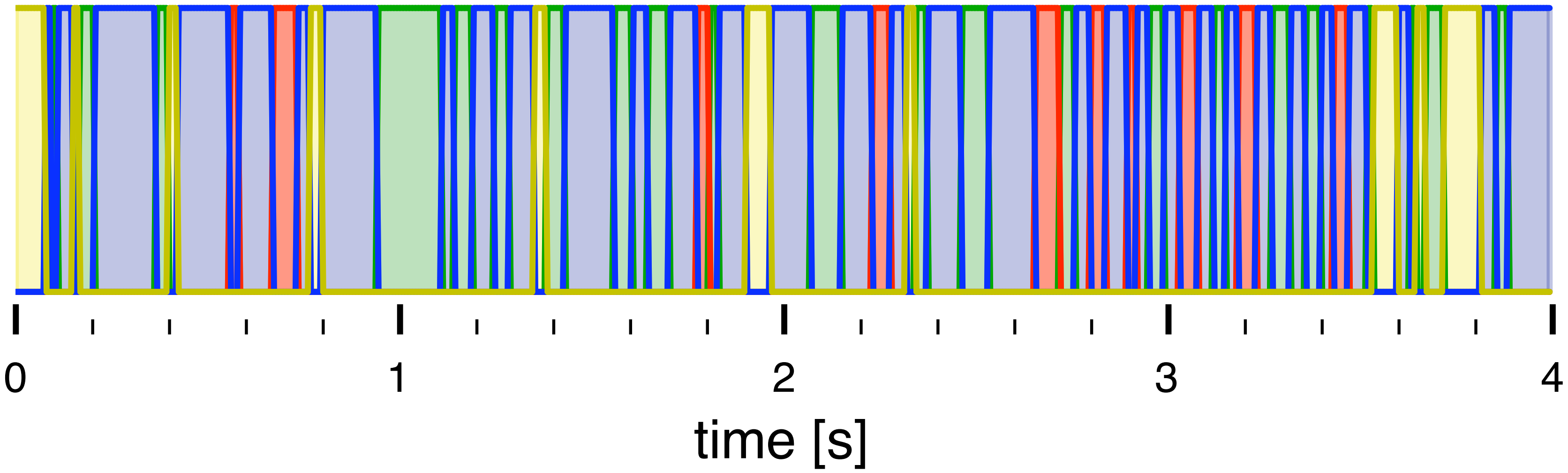


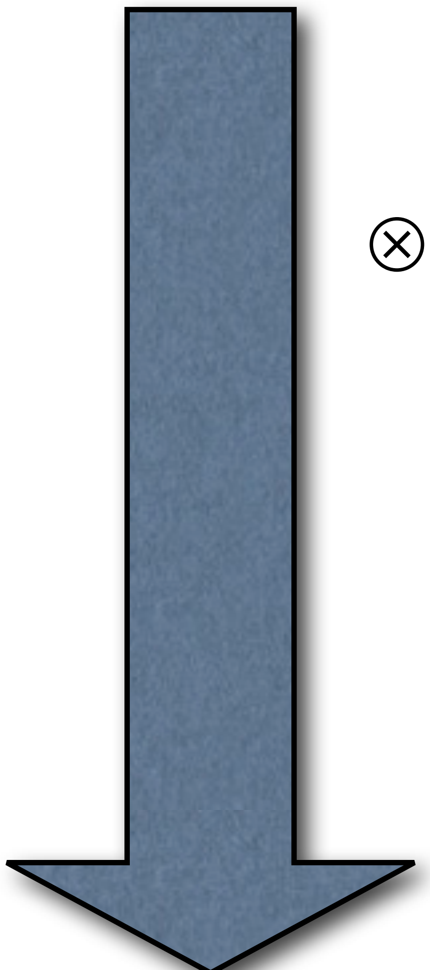
Same networks are confirmed by fMRI group ICA analysis (out of 20 components)



[Britz, VDV, Michel, NeuroImage, 2010]

EEG
100ms timescale





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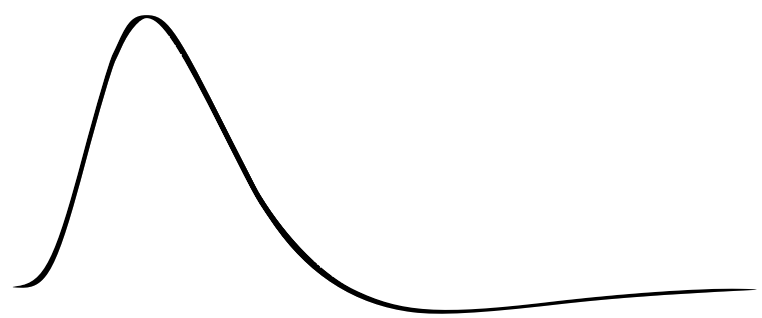
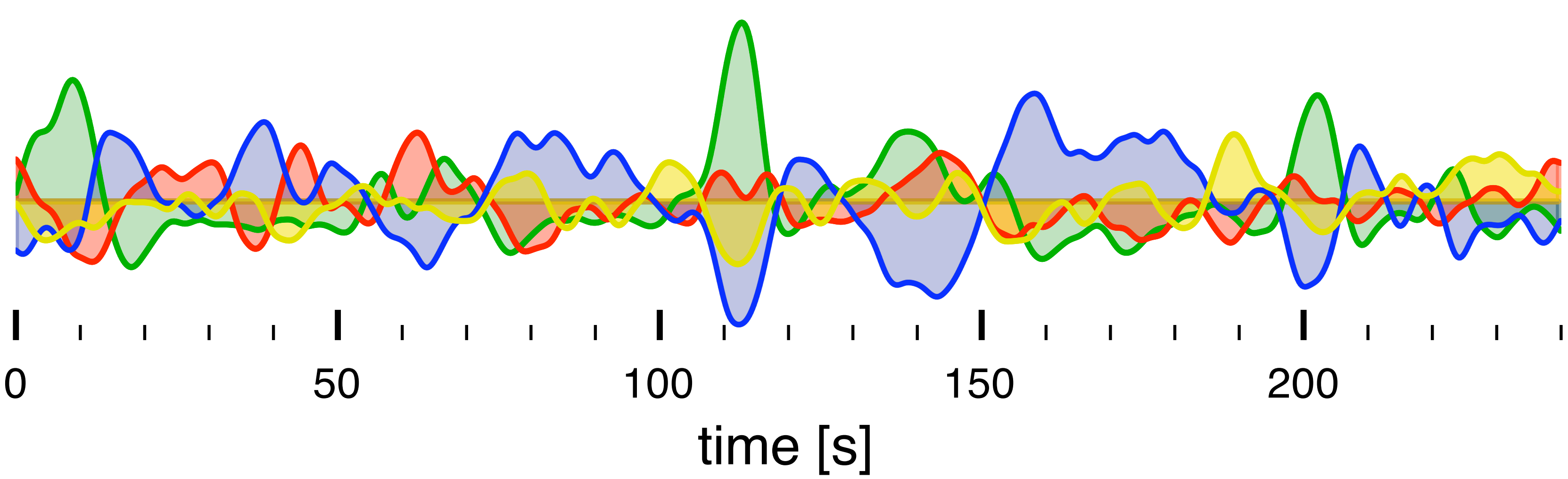


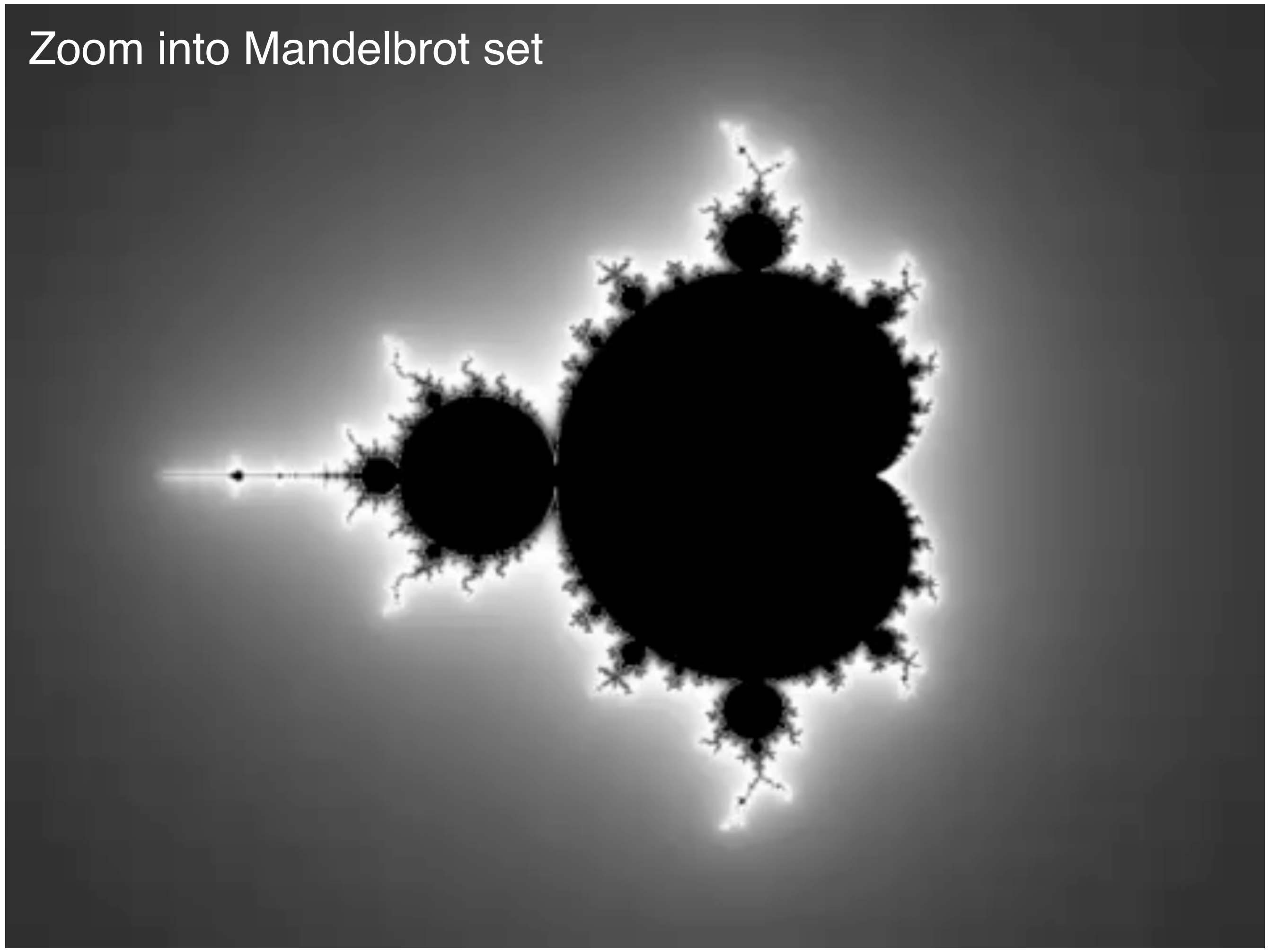
How to explain that EEG dynamics remain meaningful after huge temporal smoothing?

fMRI
10sec timescale



Fractals everywhere...?

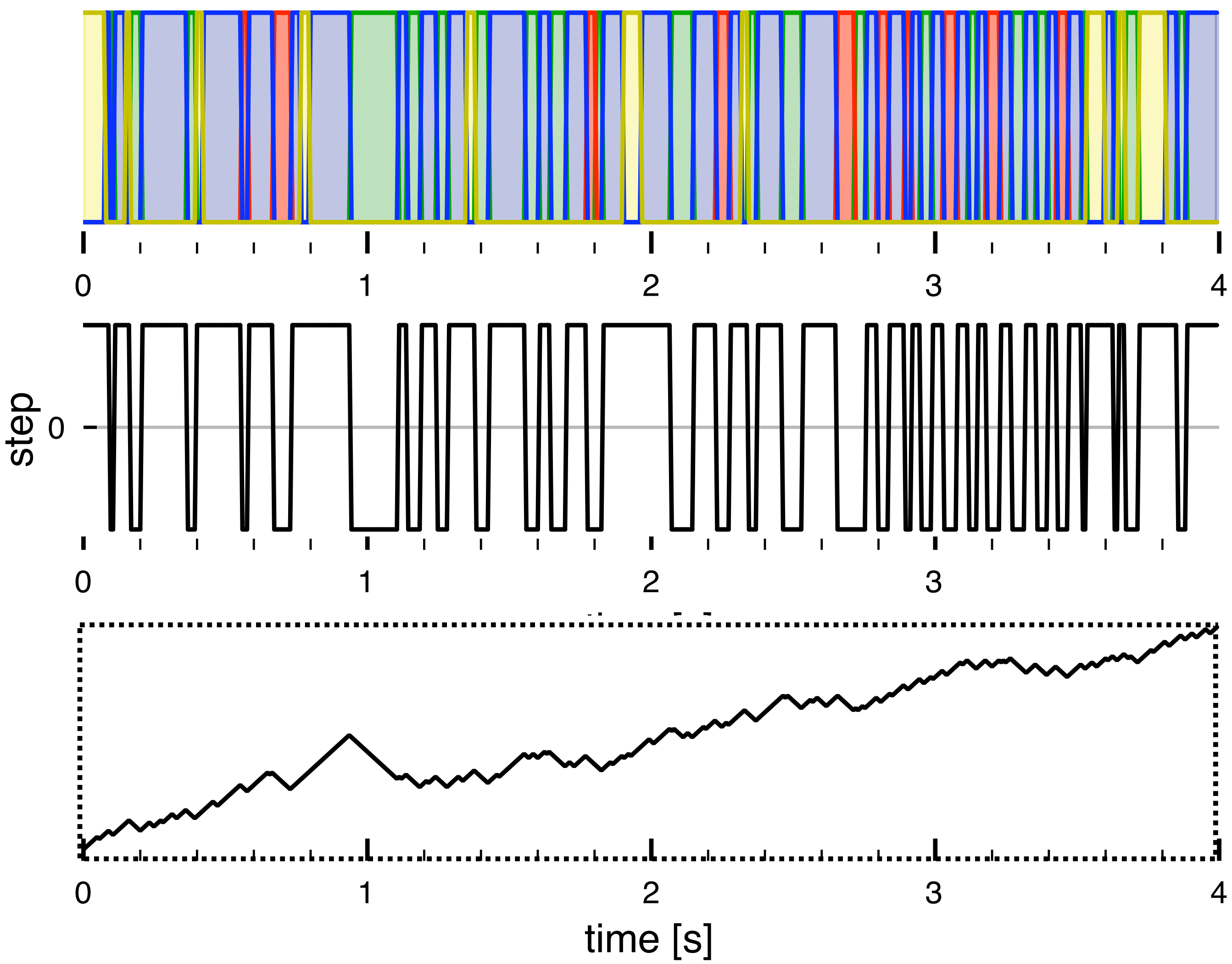
- Deterministic fractals
  - Completely predictable
  - Leads to exact or quasi self-similarity
  - E.g., Mandelbrot set
- Statistical fractals
  - Statistical measures are preserved across scales
  - E.g., stock market index, many physical and biological growth processes, hearth rhythm

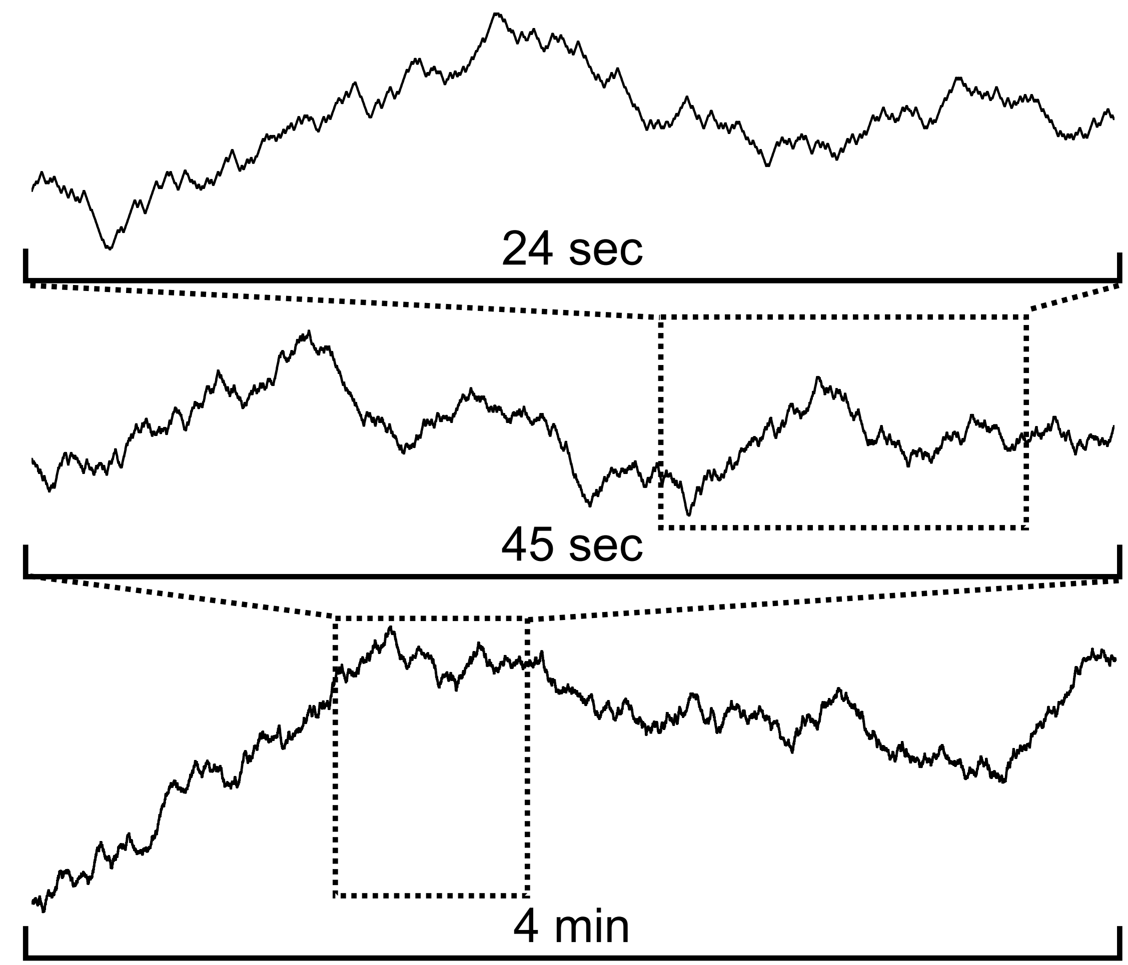


[Kolmogorov; Mandelbrot, 1982; Penland, 1984; Mumford, 2001]

Fractal analysis of microstates

- Bipartitioning and random-walk embedding
  - Four microstates (1, 2, 3, 4)...
    like the four bases of the DNA





$$\{X(t)\}_{t\in\mathbb{R}} = \{a^H X(t/a)\}_{t\in\mathbb{R}}, \quad a > 0$$

[Goldberger et al., PNAS, 2002; VDV, Britz, Michel, PNAS, 2010]

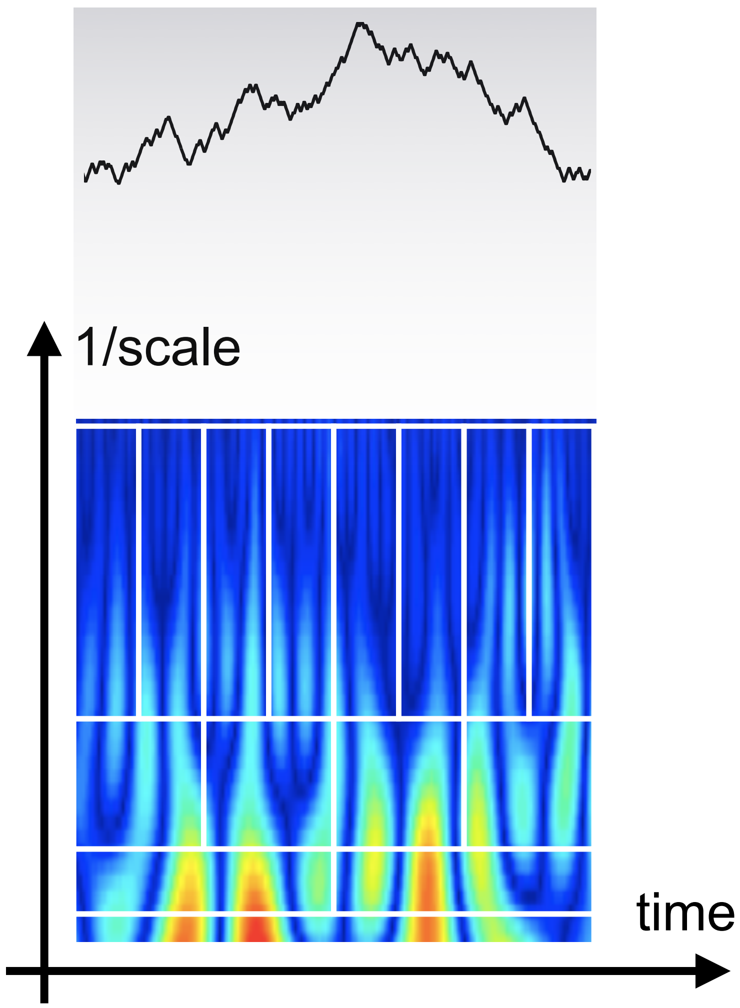
Statistical fractals and wavelets

Self-similar processes

- Statistically undistinguishable under dilation and change of scale

$$\{X(t)\}_{t\in\mathbb{R}} = \{a^H X(t/a)\}_{t\in\mathbb{R}}, \quad a > 0$$

- No characteristic scale of time, single Hurst exponent H
- Non-stationary and long-range dependency
- Variogram: $E[|X(t+a) - X(t)|^q] = C_q a^{qH}$

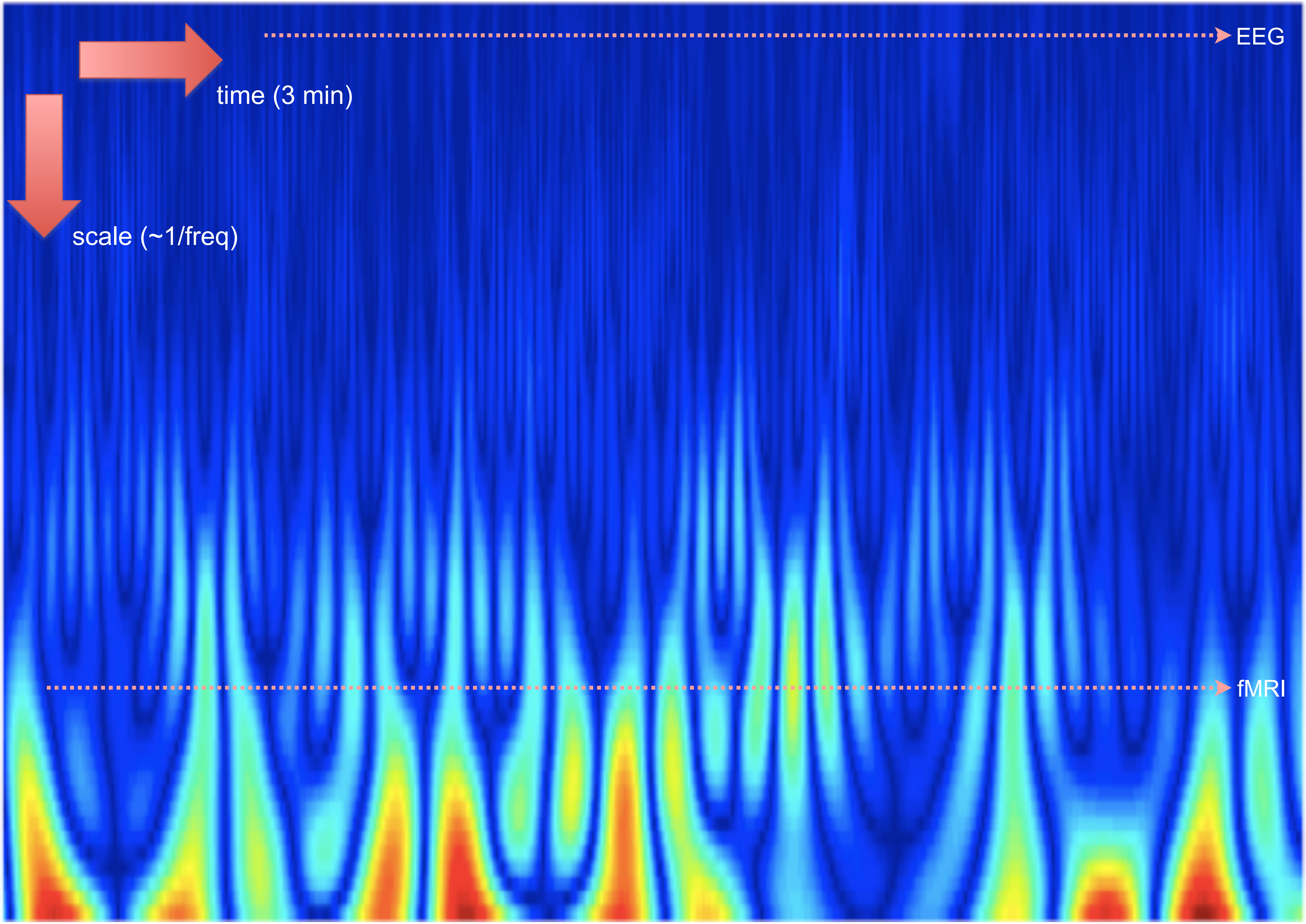


Wavelet fractal analysis

Coefficients $d_X(a,k) = \frac{1}{a}\int X(t)\psi(t/a - k)dt$

- Stationary at each scale
- Self-similarity, $\{d_X(0,k)\} = \{2^{-jH} d_X(2^j, k)\}$
- Short-range dependency

[Kolmogorov; Mandelbrot, 1982; Abry; Mumford, 2001; Jaffard, 2004]

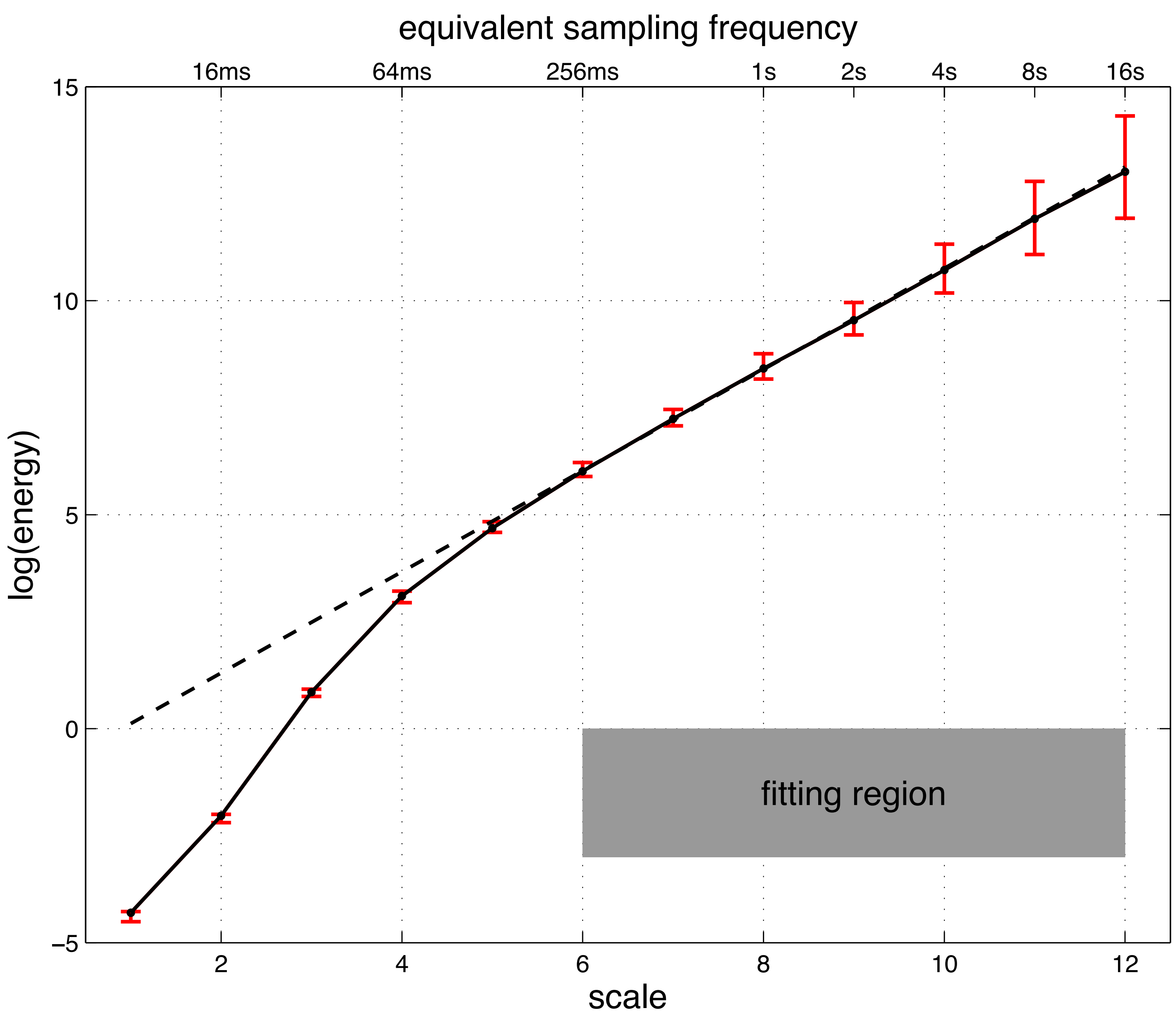


[VDV, Britz, Michel, PNAS, 2010]

Log-scaling diagram

- Estimating $E[|d_X(2^j,k)|^q]$ from the structure function

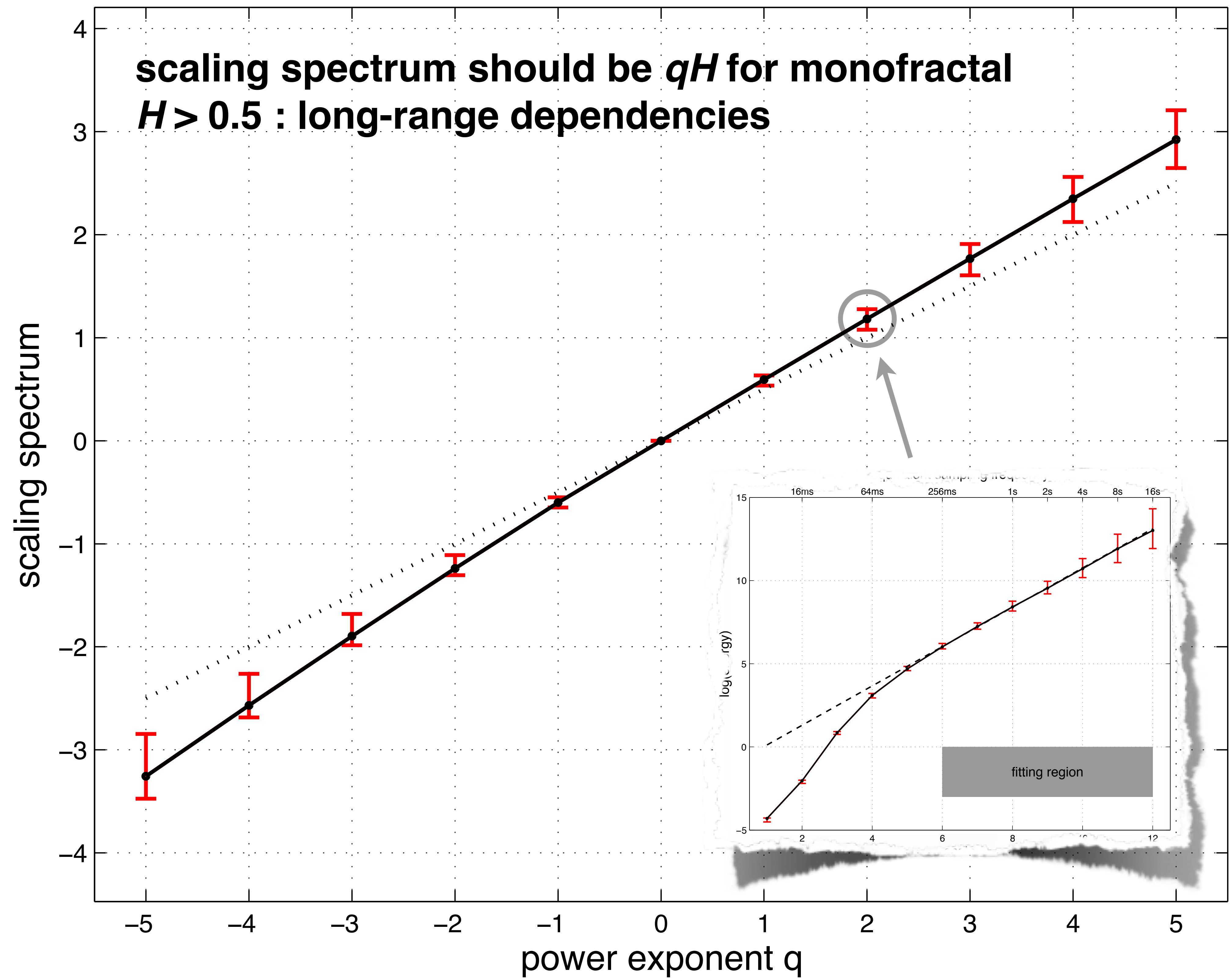
$$S(d_X,j,q) = \frac{1}{n_j}\sum_{k=1}^{n_j} \left|d_X(2^j,k)\right|^q$$



confirms weak self-similarity, similar to PSD (*q*=2)

[Van De Ville, Britz, Michel, PNAS, 2010]

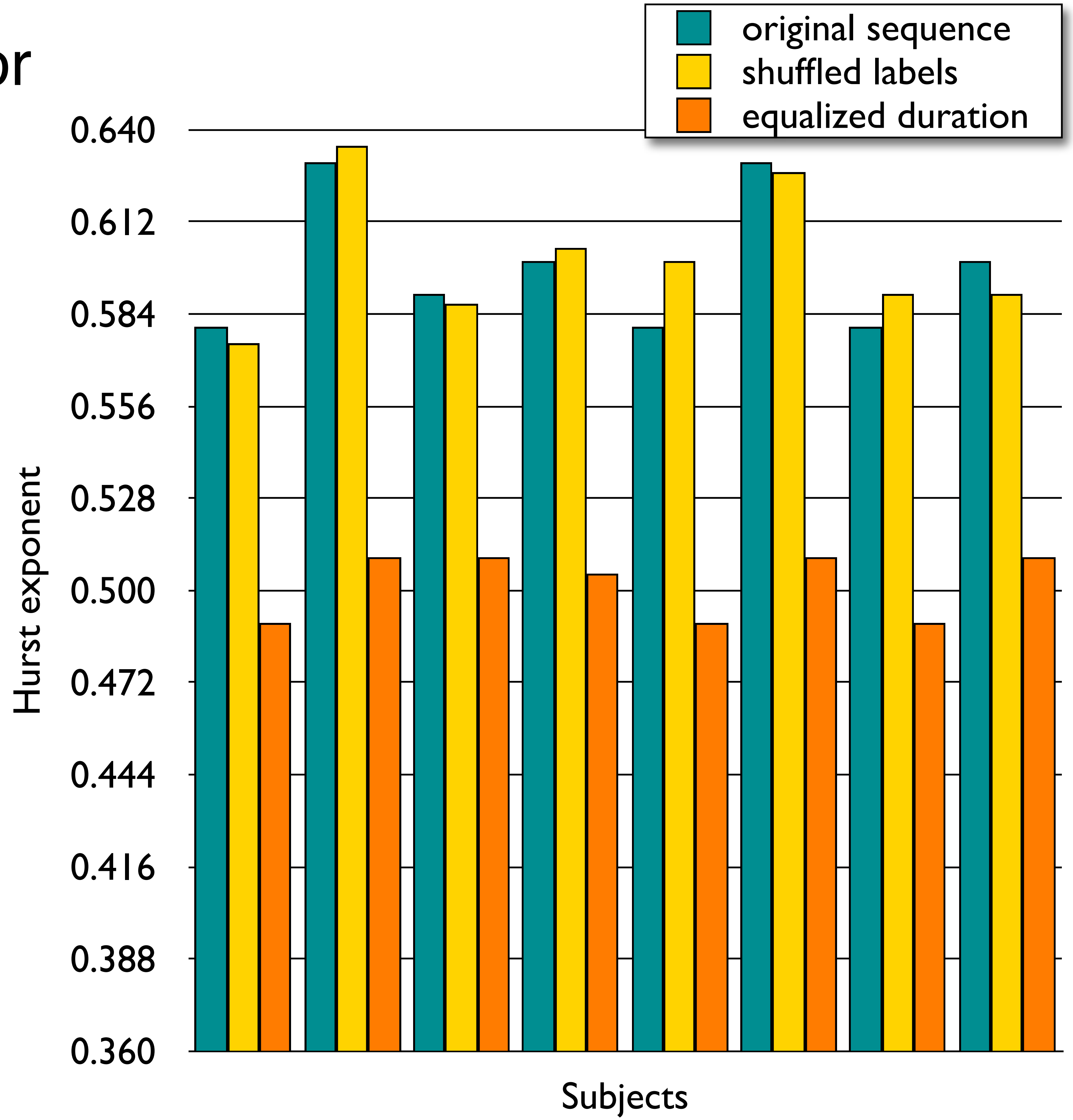
Scaling spectrum



[Van De Ville, Britz, Michel, PNAS, 2010]

Fractal organization of microstates

- Monofractal behavior over two orders of magnitude
  (256ms-16s)
- Shuffled labels give same fractal signature!
- Equalized durations result into white noise dynamics
  (H=0.50, p<0.05)



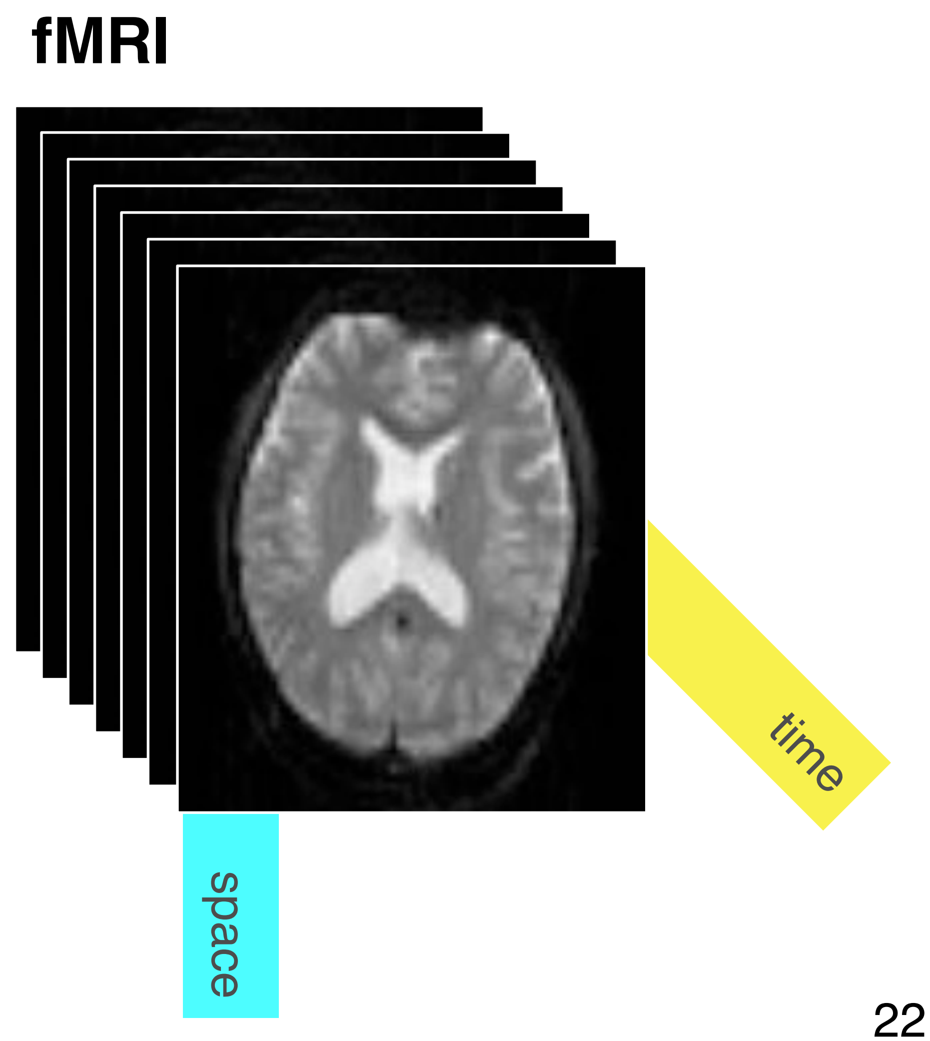
[Van De Ville, Britz, Michel, PNAS, 2010]

Criticality of the brain

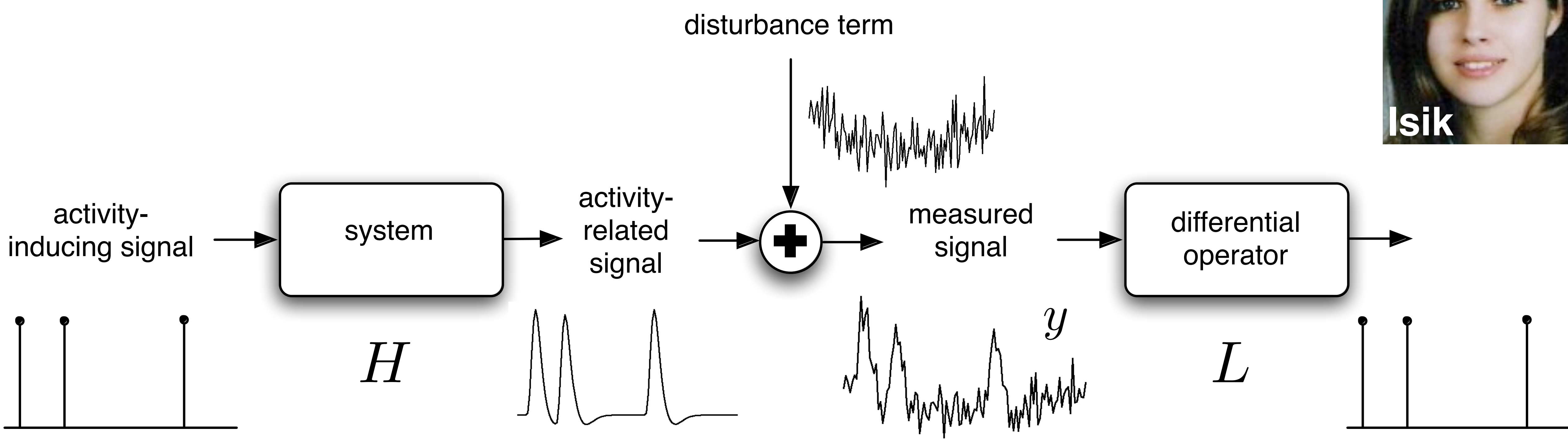
- Our findings
  - Microstates are a *global* functional brain measure
  - Dynamics are strongly monofractality
  - Implies non-stationarity and long-range correlations
- Scale-free organization is reminiscent of system at critical state near phase transition
- Further evidence to seminal work of Chialvo, Bullmore, Bak, ...
  - Power-law behavior of various brain measures
    - Space: scale-free small-world networks
    - Time: EEG, MEG-fMRI synchronization, ...
  - Universal organizing principle,
    in order to reorganize and adapt rapidly
    ~ self-organization of complex system

Implications for fMRI...

- Scale-free dynamics at the EEG timescale
- At the fMRI timescale
  - Despite hemodynamic blur (~10 sec), meaningful process (with same characteristics) is observed
  - Scale-free organization is key to maintain information through timescales
- A lot of redundant information is acquired
  - Time:
    - Hemodynamic response is slow
  - Spatial:
    - Vascular nature of signal, spatial extent

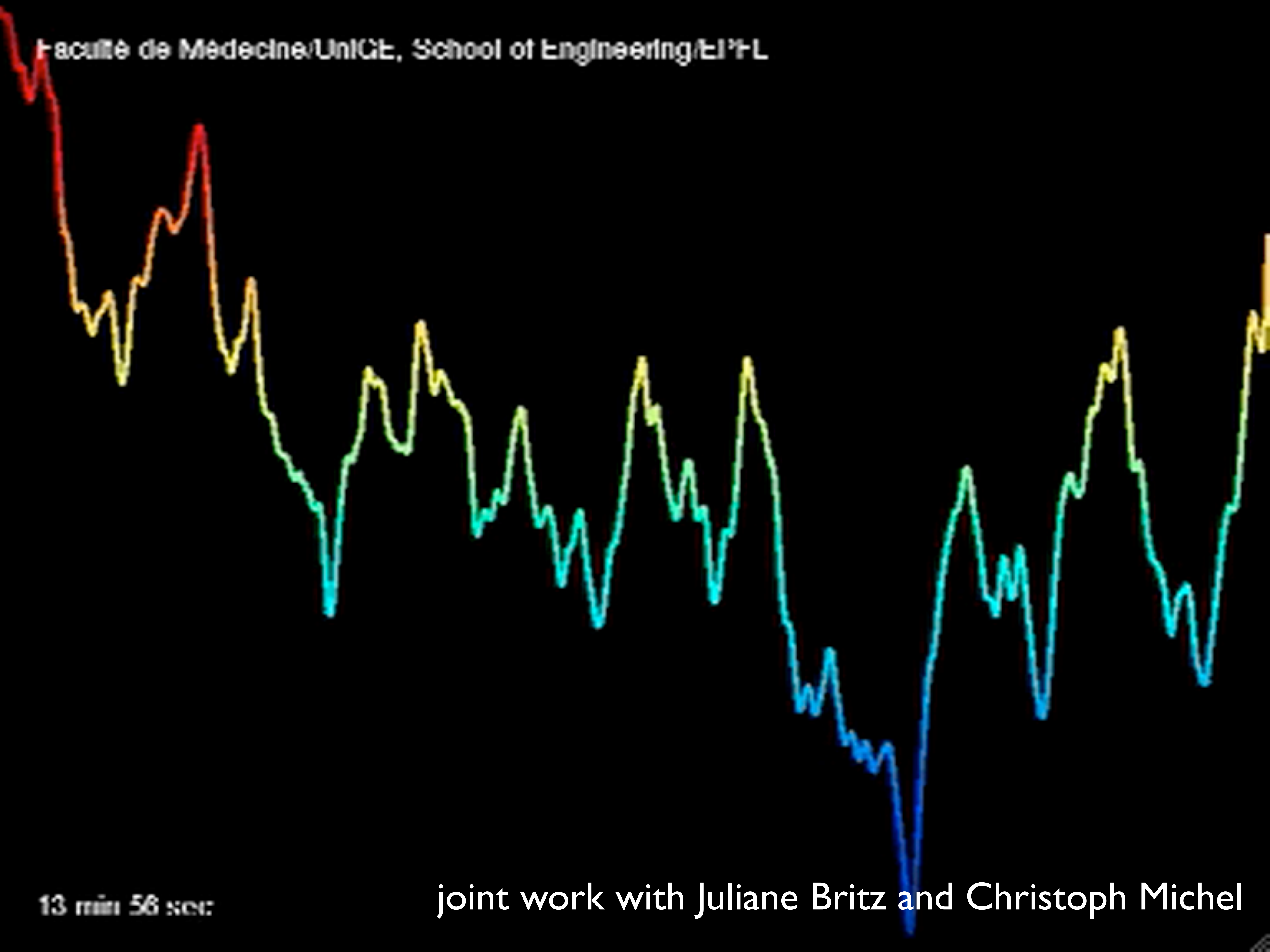


... and regularization for fMRI



- Identify differential operator *L* that “inverts” hemodynamic response
  - Linearization (first-order Volterra term)
- Analysis prior: $\hat{s} = \arg\min_{s} ||y - s||_2^2 + \lambda \, ||L\{s\}||_1$
  - Novel analysis method of fMRI data (“paradigm free”)
  - Deploy for image reconstruction

[Khalidov et al., SP; Gaudes-Caballero et al., HBM; Karahanoglu et al., IEEE TSP]



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