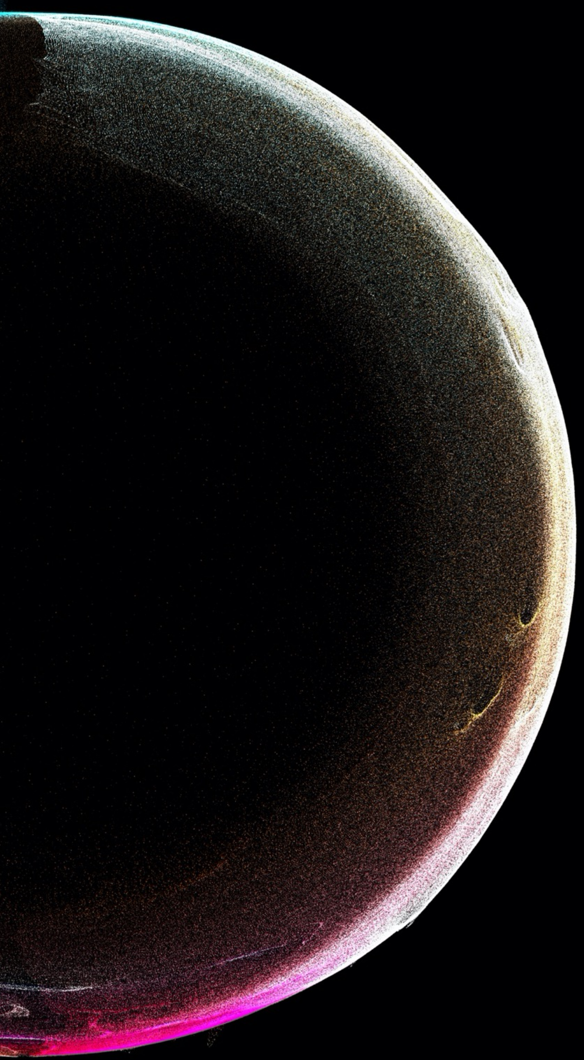


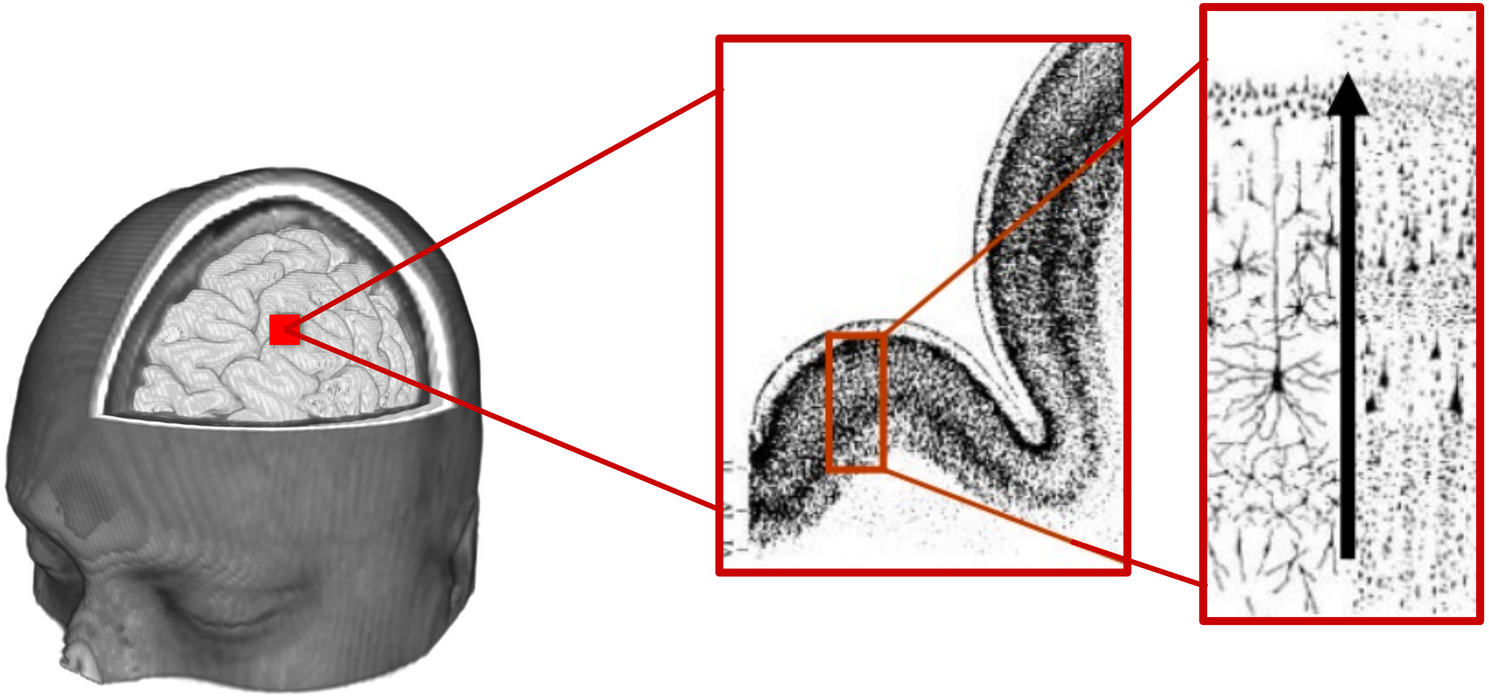
EEG Source Imaging

Prof. Pieter van Mierlo

GHENT UNIVERSITY

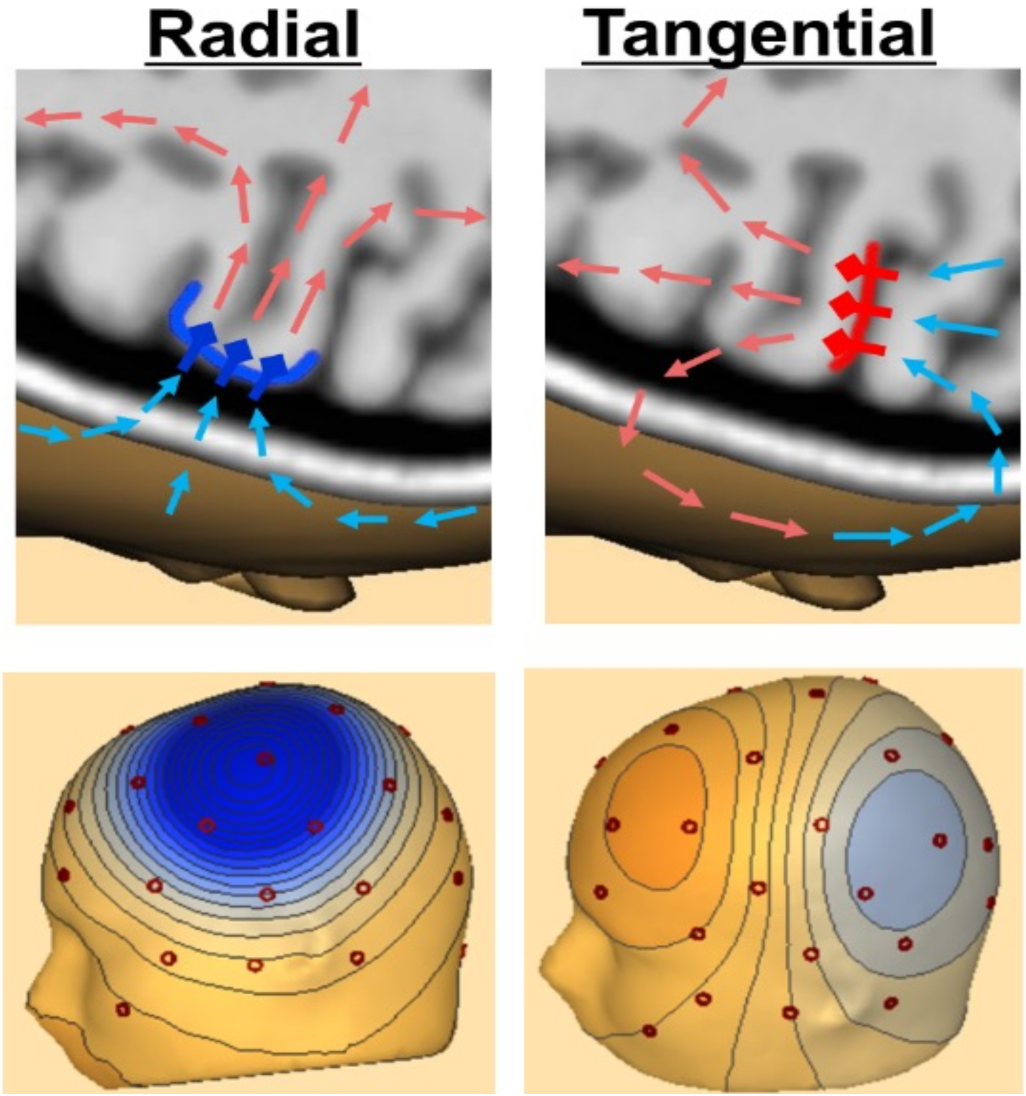
EPILOG
BRAIN FUNCTION QUANTIFICATION

What are we measuring with EEG?

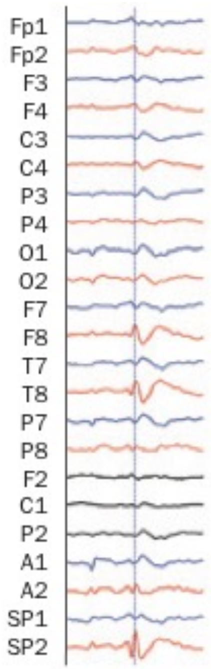


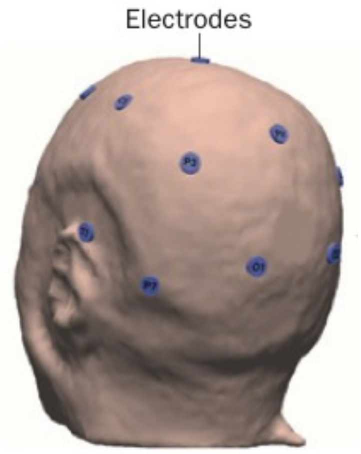
- ~100,000 simultaneously active neurons are needed to generate a measurable EEG signal
- Pyramidal cells are the main direct neuronal sources of EEG signals
- EPSP/IPSP but not action potentials generate EEG signals

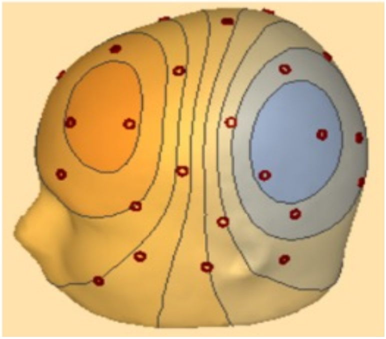
Radial vs. Tangential sources



EEG Source Imaging

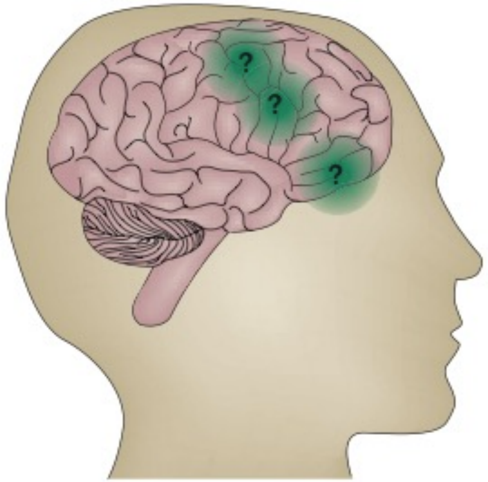




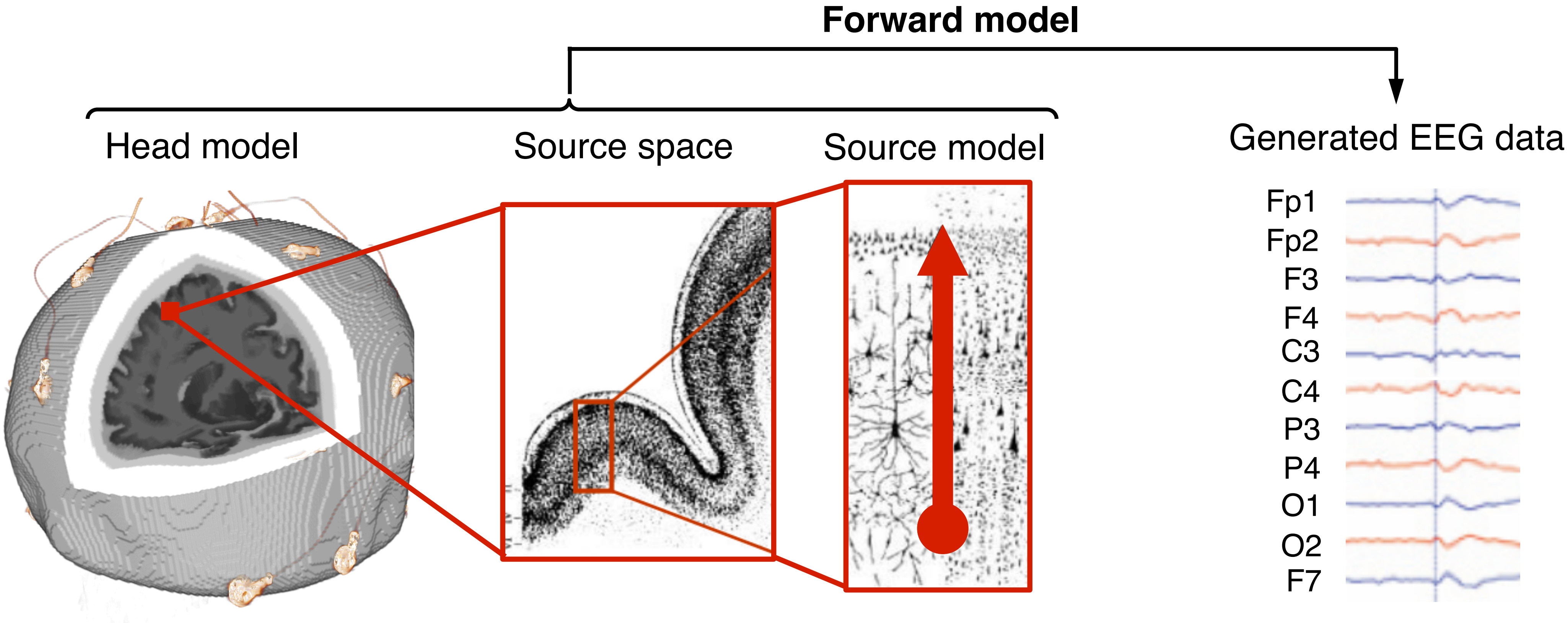


Inverse problem?

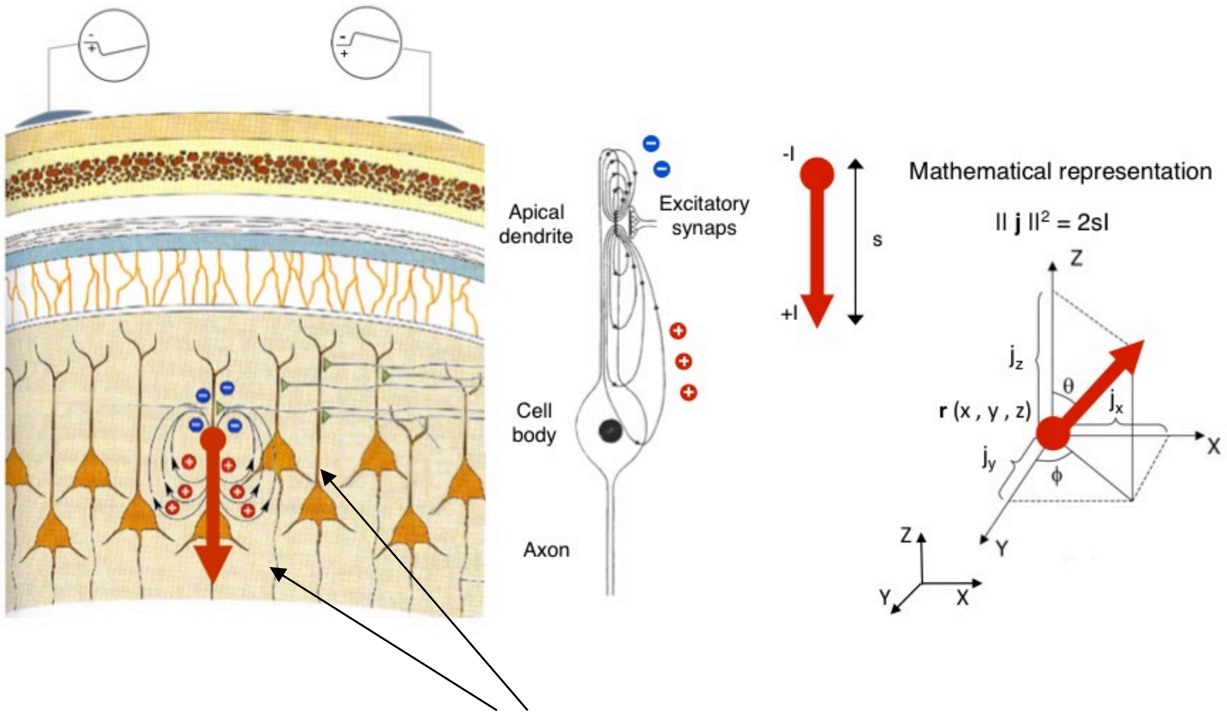
→



Forward model



The current dipole



Pyramidal neurons

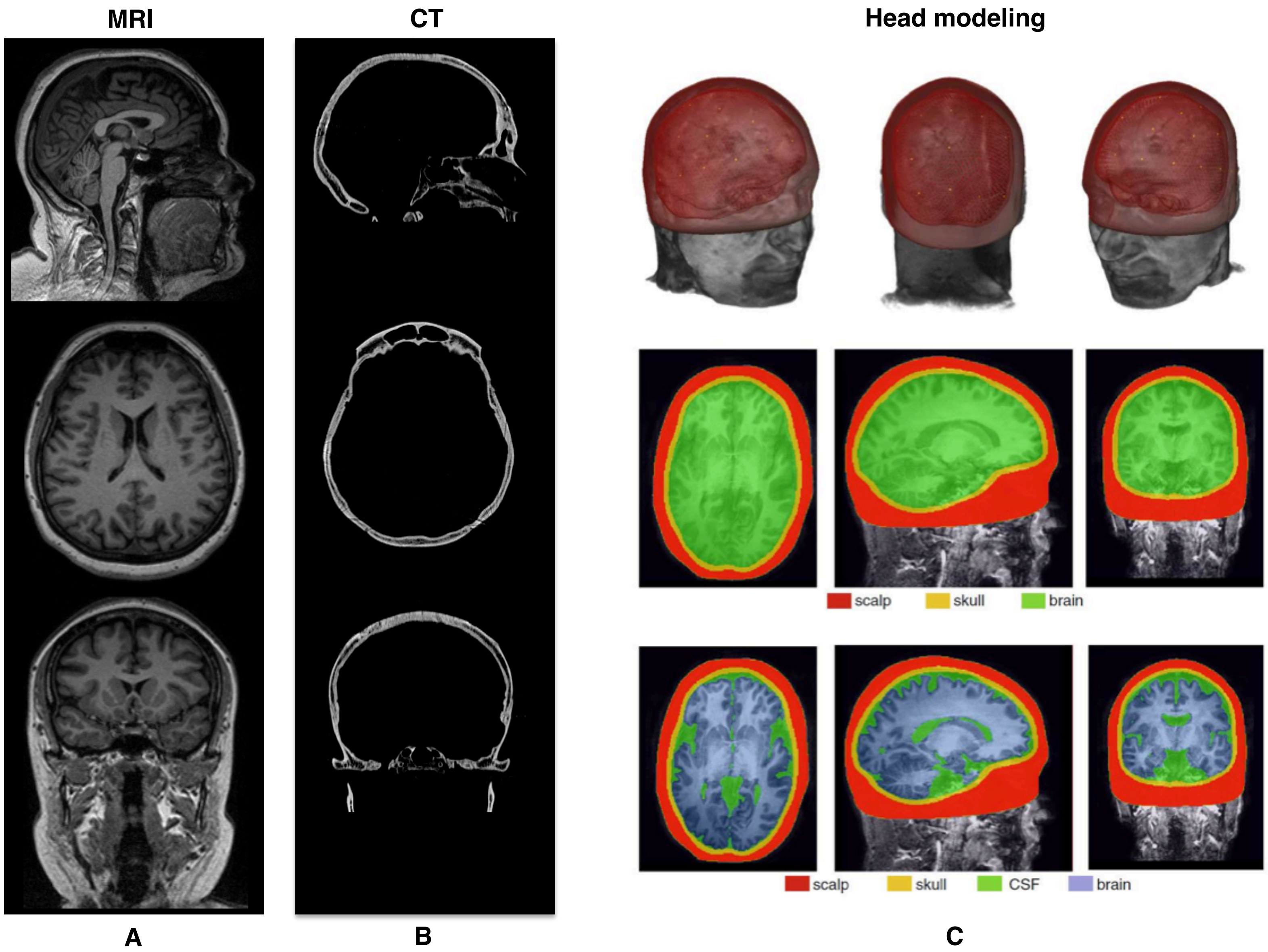
- Long apical dendrites oriented in parallel, perpendicular to the cortex
- Are believed to be the main EEG generators

One dipole represents the electrical activity of a small area of the cortex (focal source)

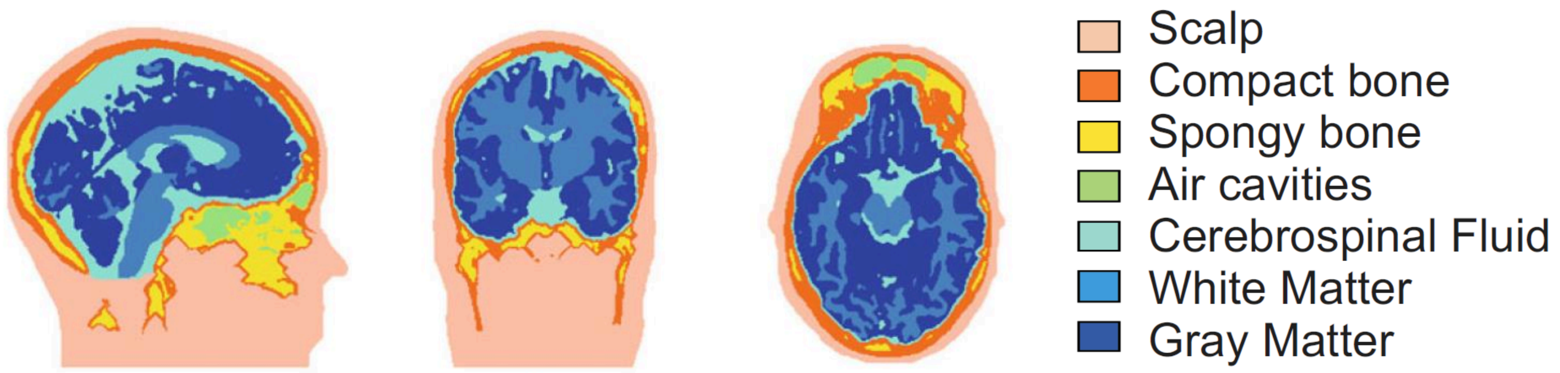
6 parameters:

- Location: r_d
- Orientation: e_d
- Strength or intensity: I

Forward model - Geometry

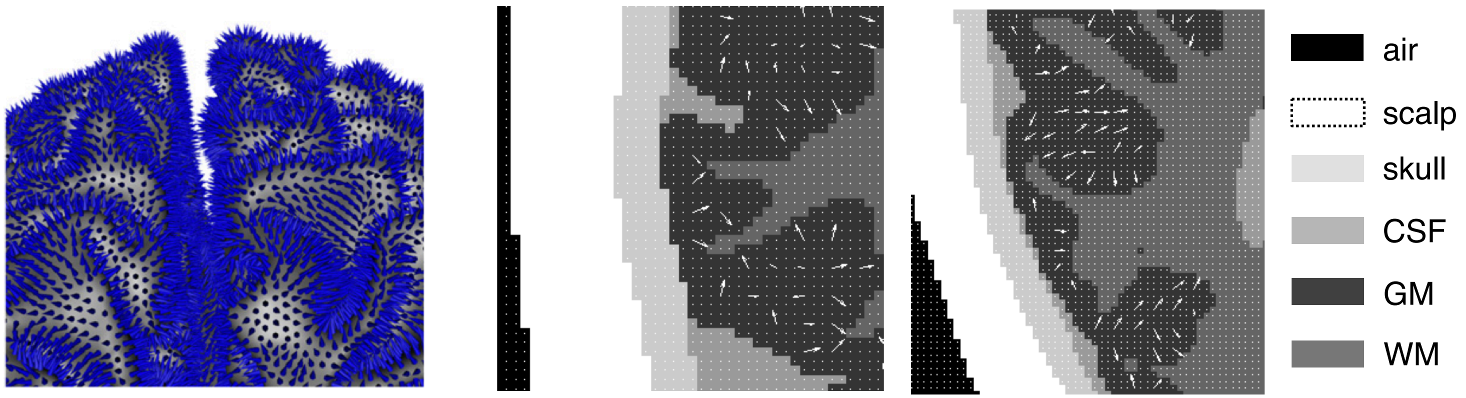


Forward model – Tissue Conductivity



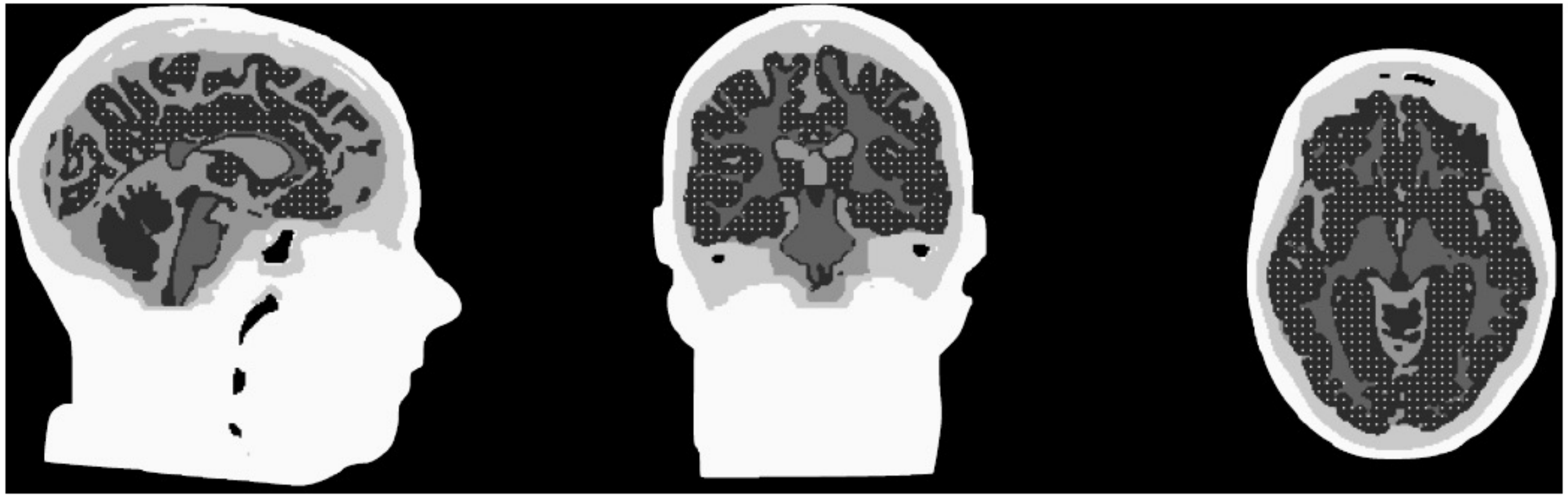
	Conductivity (S/m)			
	[34]	[35]	[36]	[37]
Scalp	0.33	0.22	0.3279	0.43
Compact bone	-	-	0.0064	0.008
Spongy bone	-	-	0.02865	0.025
Skull	0.0041	0.015	0.0041	0.01
Gray Matter	0.33	0.22	0.3333	0.33
White Matter	0.33	0.22	0.1428	0.14
CSF	-	-	1.79	1.79
Air	-	-	0	0

Forward model – Solution space

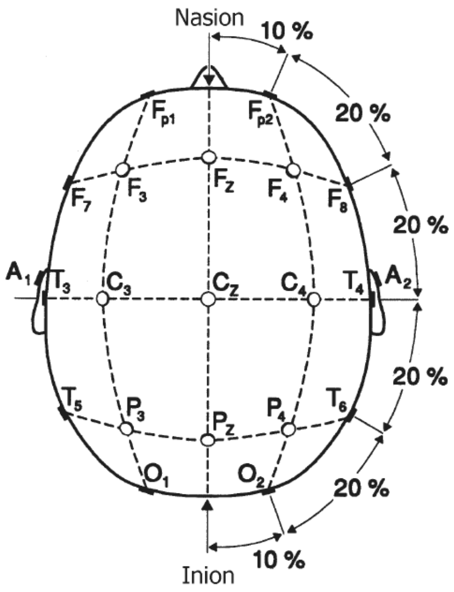


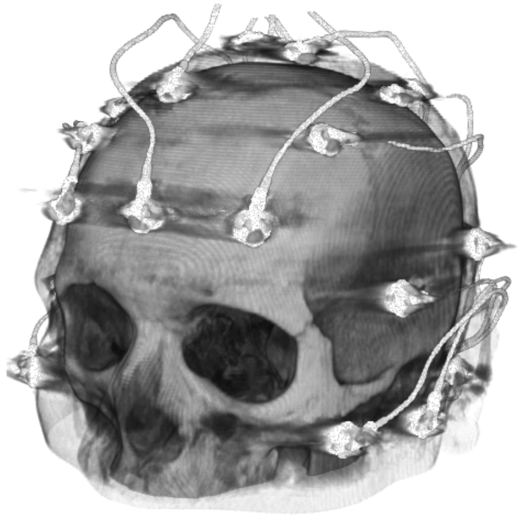
A
cortical surface

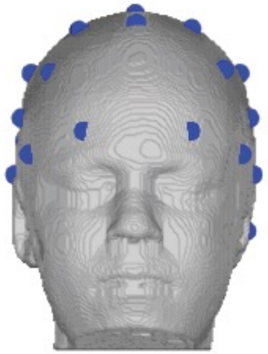
B
inside the gray matter

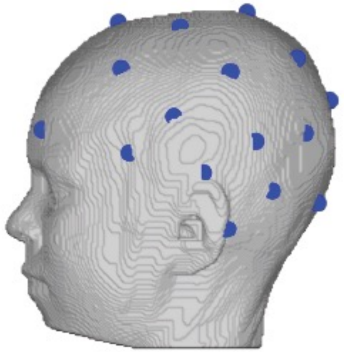


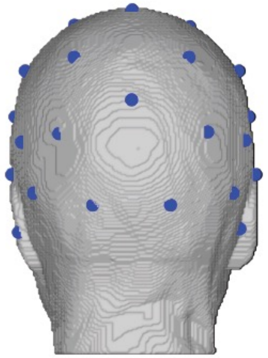
Forward model – Electrode positions







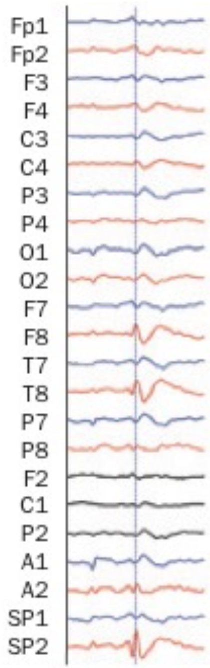




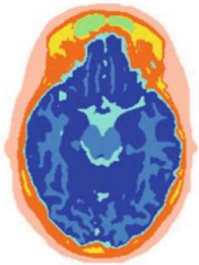
Algebraic representation of the forward model

$$\mathbf{V} = \mathbf{L}(\mathbf{r})\mathbf{j}(\mathbf{r})$$

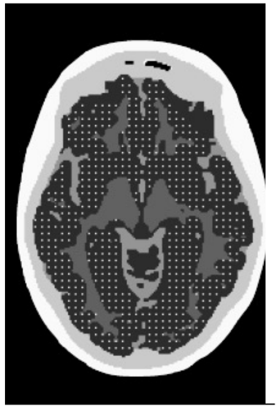
EEG

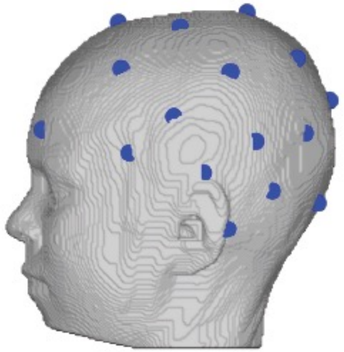


leadfield matrix

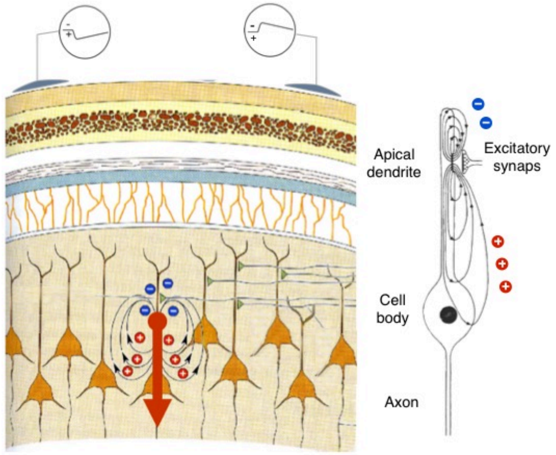


- Scalp
- Compact bone
- Spongy bone
- Air cavities
- Cerebrospinal Fluid
- White Matter
- Gray Matter





Dipole source



Algebraic representation of the forward model

Multiple sources

$$\mathbf{V} = \mathbf{L}(\mathbf{r}_1)\mathbf{j}(\mathbf{r}_1) + \mathbf{L}(\mathbf{r}_2)\mathbf{j}(\mathbf{r}_2) + \cdots + \mathbf{L}(\mathbf{r}_P)\mathbf{j}(\mathbf{r}_P)$$

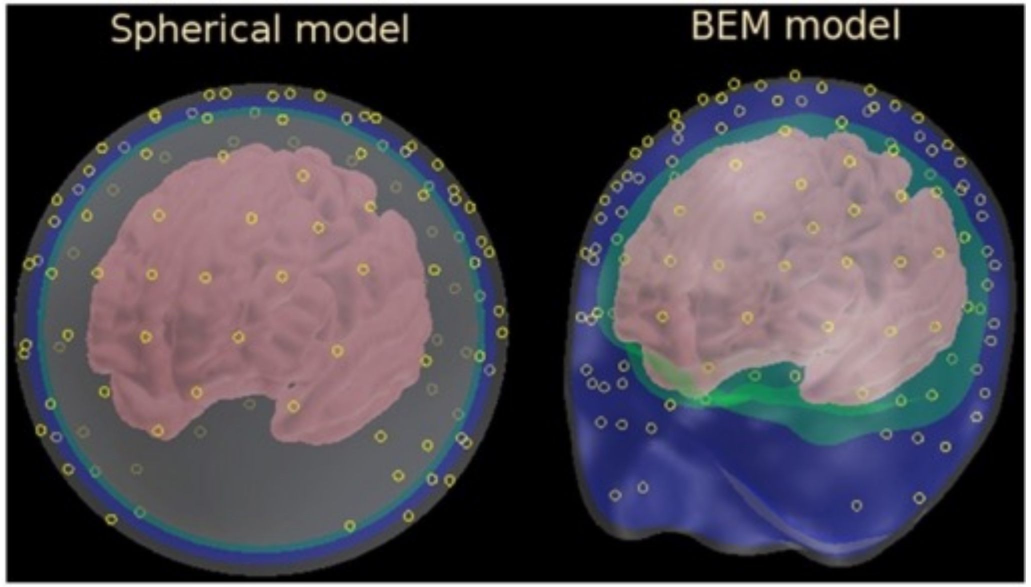
$$\mathbf{V} = \mathbf{L}\mathbf{J}$$

How do we calculate this leadfield matrix **L**?

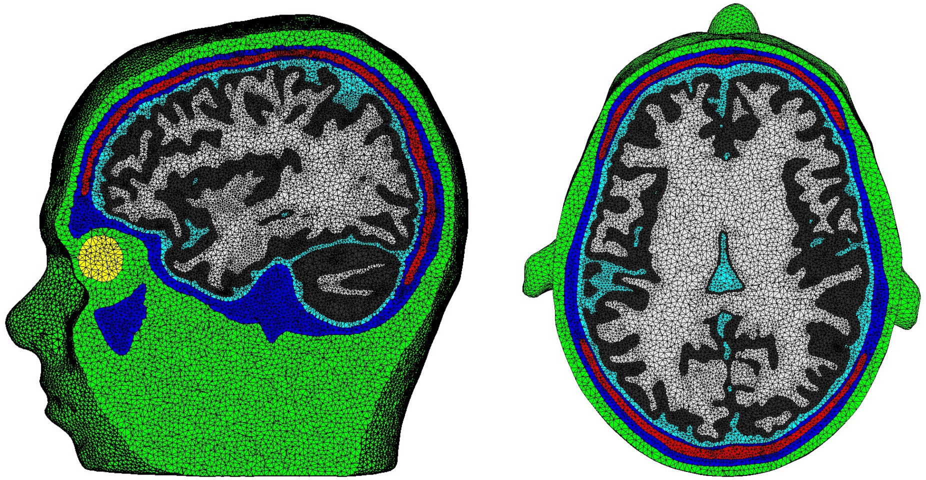
Leadfield calculation

Solution methods

- Dipole in spherical headmodel: analytical expression
- Dipole in realistic headmodel: numerical methods required
  - BEM: boundary element method
  - FEM: finite element method

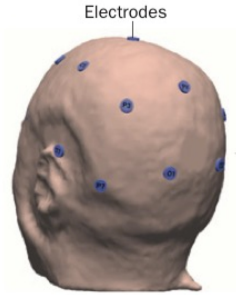


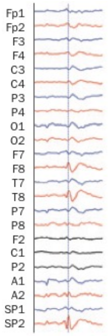
FEM model



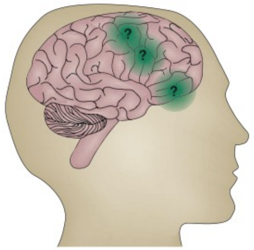
Solving the inverse problem

$$\mathbf{V} = \mathbf{L}\mathbf{J}$$

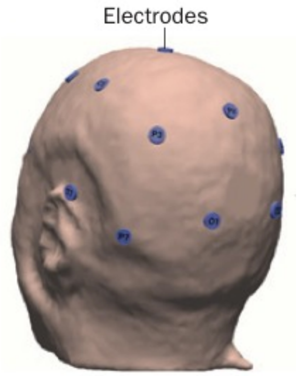


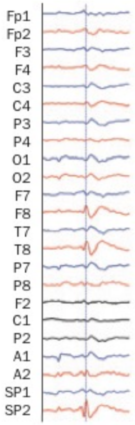


Inverse problem

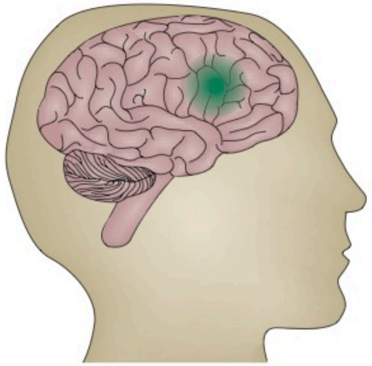


Example: minimize $||\mathbf{V} - \mathbf{L}\,\mathbf{J}||^2$
in function of the parameters of the sources in the forward model

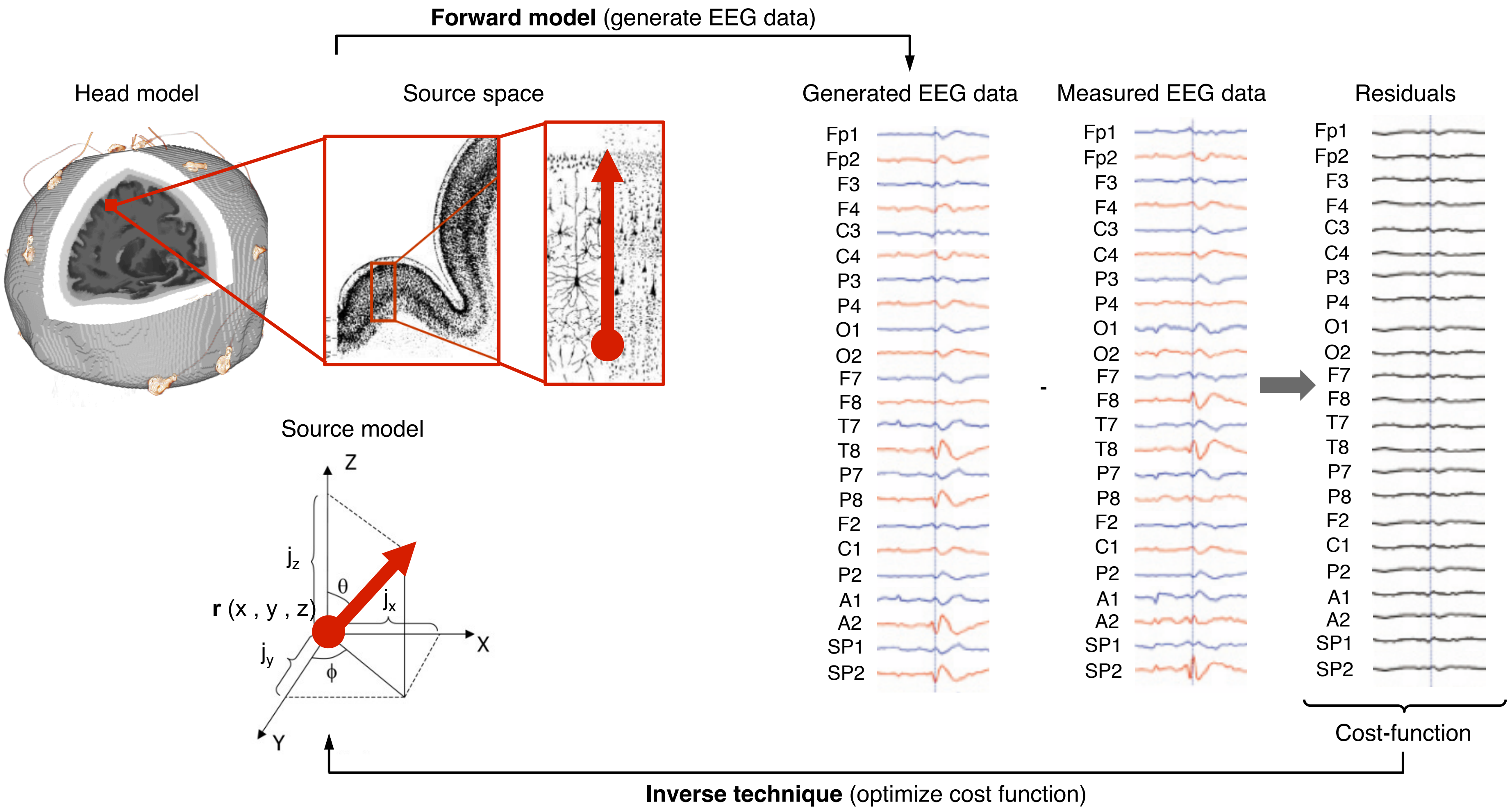




Forward problem



Optimizing cost function to solve inverse problem

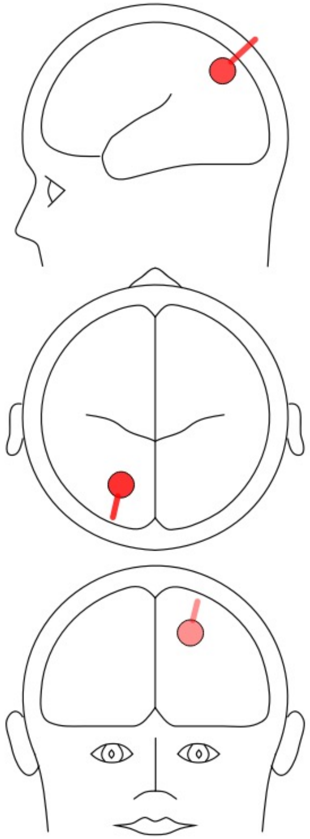


Inverse solution techniques

- The equivalent current dipole (ECD) approaches, where the EEG signals are assumed to be generated by a relatively small number (< 10) of focal sources (Scherg *et al.*, 1999; Aine *et al.*, 2000).

- Distributed dipoles approaches, where all possible source locations (typically around 10.000) are considered simultaneously (Hämäläinen & Ilmoniemi, 1994; Pascual-Marqui *et al.*, 1999; Uutela *et al.*, 1999).

Equivalent current dipole



Single dipole model at one time point

$$RRE = \frac{\|\mathbf{V_m} - \mathbf{L}(\mathbf{r})\mathbf{j}(\mathbf{r})\|}{\|\mathbf{V_m}\|}$$

Minimize RRE with respect of [x, y, z, θ, φ, I]

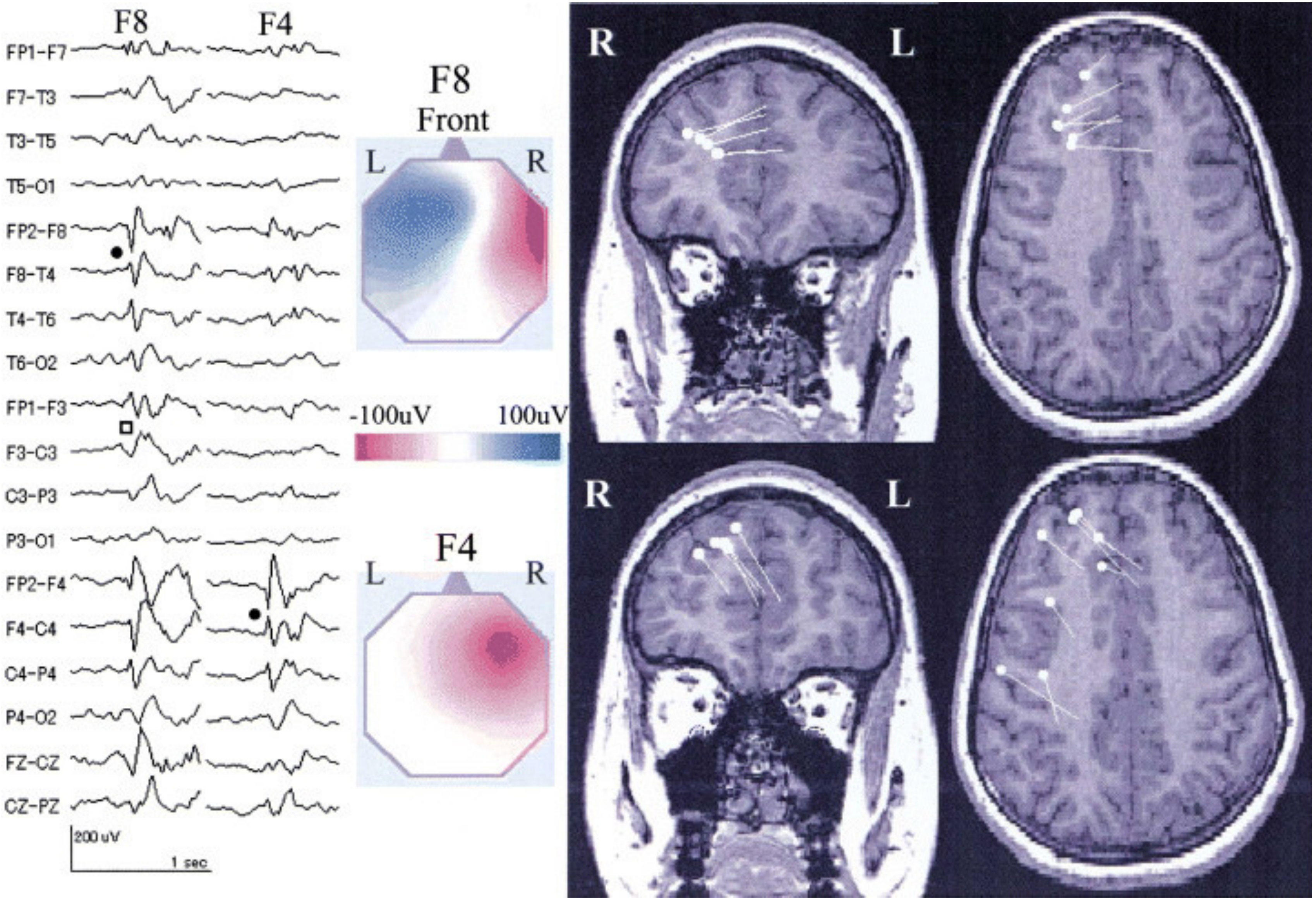
6D problem

Position r =[x, y, z]

Orientation = θ and φ

Intensity = I

Equivalent current dipole localization of epileptic spikes



Distributed EEG source imaging

$$\hat{\mathbf{J}} = \underset{\mathbf{J}}{\operatorname{argmin}} \left(\underbrace{||\mathbf{V}_{meas} - \mathbf{L}\mathbf{J}||^2_{\mathbf{R}}}_{\text{Data fit}} + \underbrace{\alpha f(\mathbf{J})}_{\text{regularization}} \right)$$

Minimum norm solution

$$\hat{\mathbf{J}}_{\mathrm{MNE},\alpha} = \mathbf{L}^T \left(\mathbf{L}\mathbf{L}^T + \alpha \mathbf{I}_{N_e} \right)^{-1} \mathbf{V}_{meas}$$

Constraint: the current distribution over all solution points has minimum energy (minimizing the least-square error, i.e., the L2-norm) and that the forward solution of this distribution optimally explains the measured data.

Disadvantage: MN solutions are biased toward superficial sources because of their spatial vicinity to the sensors.

Distributed EEG source imaging

$$\hat{\mathbf{J}} = \underset{\mathbf{J}}{\operatorname{argmin}} \left(||\mathbf{V}_{meas} - \mathbf{L}\mathbf{J}||^2_{\mathbf{R}} + \alpha f(\mathbf{J}) \right)$$

Data fit regularization

Weighted Minimum norm solution

$$\hat{\mathbf{J}}_{\mathrm{WMNE},\alpha} = \left(\mathbf{W}^T\mathbf{W}\right)^{-1}\mathbf{L}^T\left(\mathbf{L}\left(\mathbf{W}^T\mathbf{W}\right)^{-1}\mathbf{L}^T + \alpha\mathbf{I}_{N_e}\right)^{-1}\mathbf{V}_{meas}$$

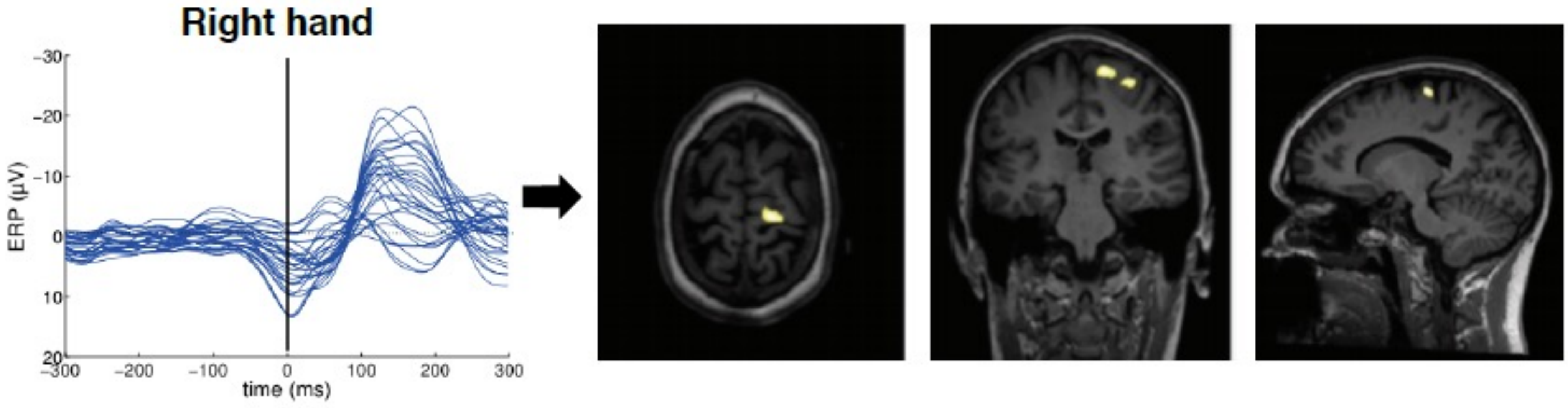
Weighting parameters have been introduced to mitigate the bias towards superficial sources, leading to the so-called weighted minimum norm (WMN) solutions

LORETA

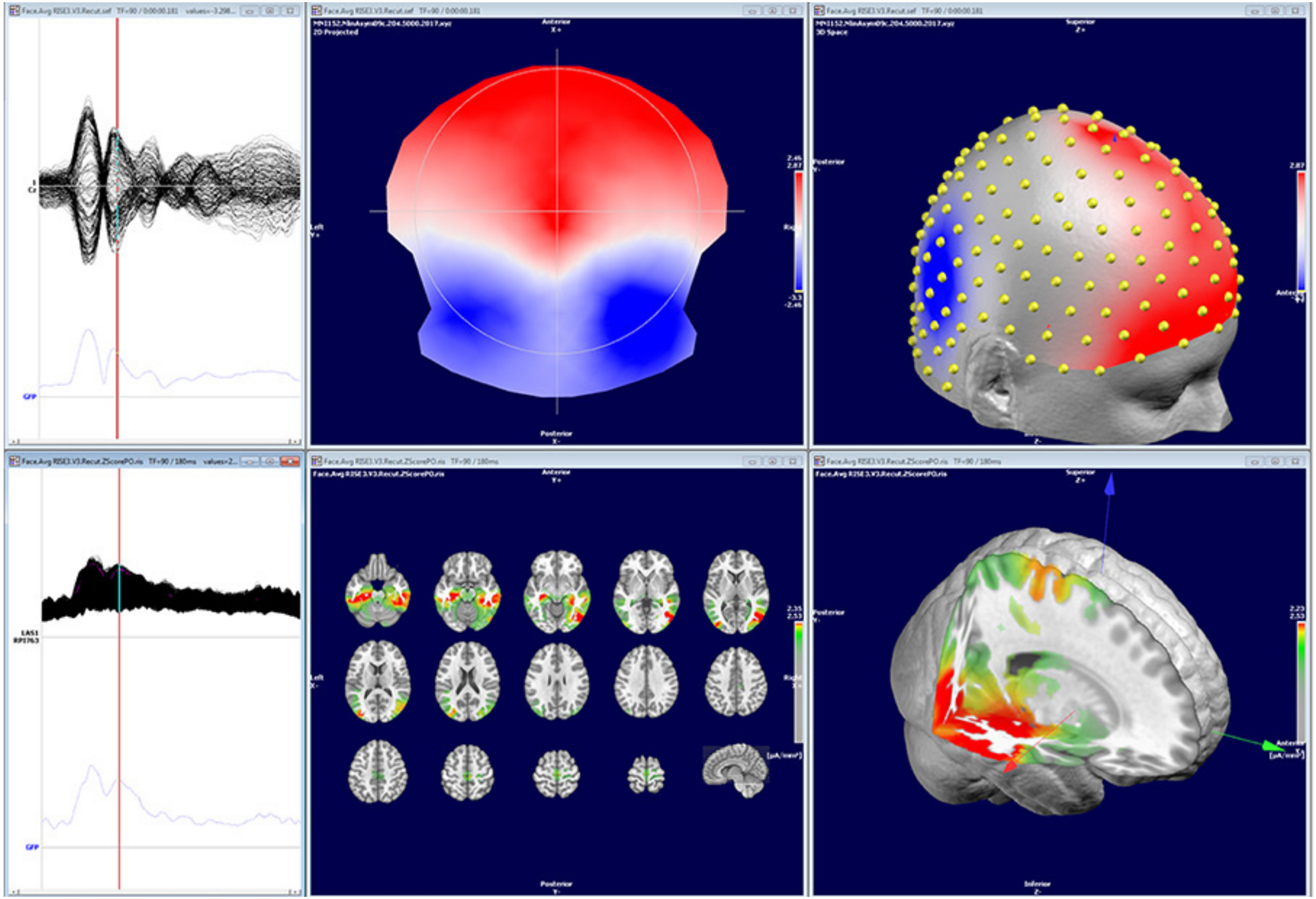
$$\hat{\mathbf{J}}_{\mathrm{LOR},\alpha} = \left(\mathbf{W}\Delta^T\Delta\mathbf{W}\right)^{-1}\mathbf{L}^T\left(\mathbf{L}\left(\mathbf{W}\Delta^T\Delta\mathbf{W}\right)^{-1}\mathbf{L}^T + \alpha\mathbf{I}_{N_e}\right)^{-1}\mathbf{V}_{meas}$$

A variation of WMN is the low resolution electromagnetic tomography (LORETA) in which the norm of the second-order spatial derivative of the current source distribution is minimized to **ensure spatial coherence and smoothness**

Localization of right hand movement using LORETA

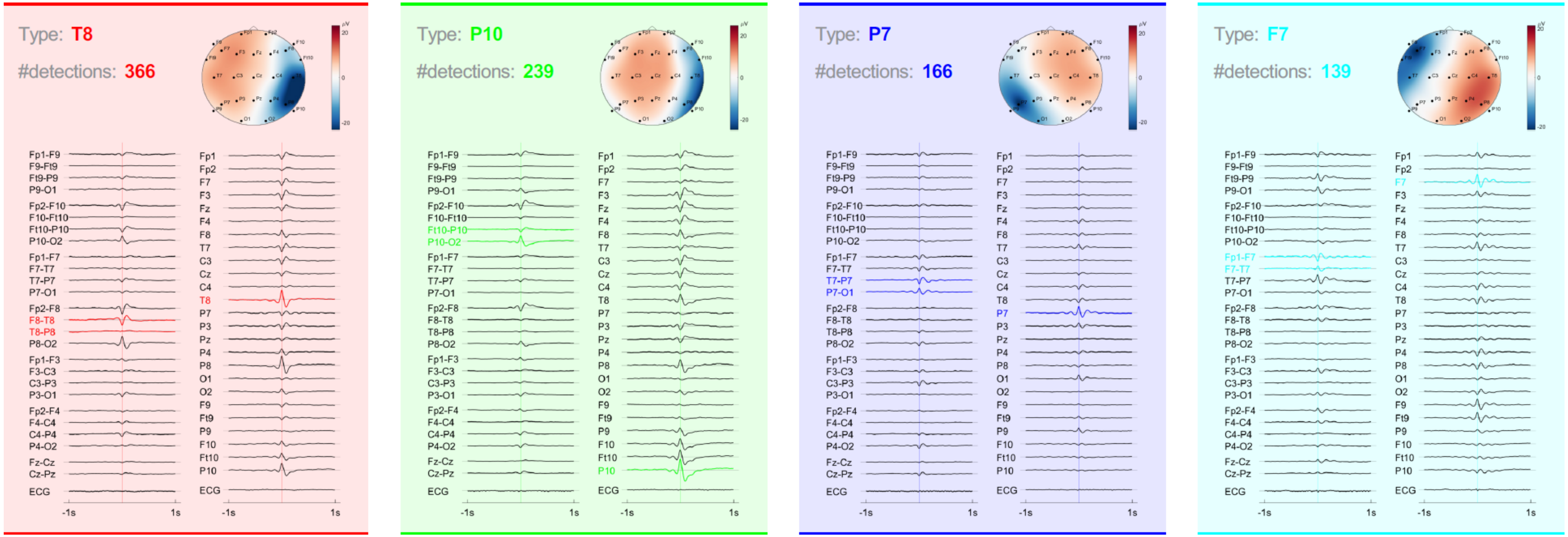


Localization of visual evoked potential (face presentation)

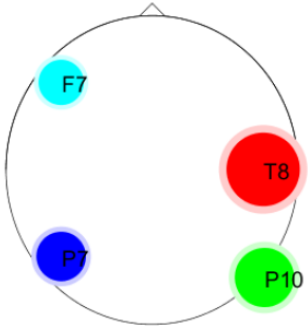


Automated localization of epileptic spikes

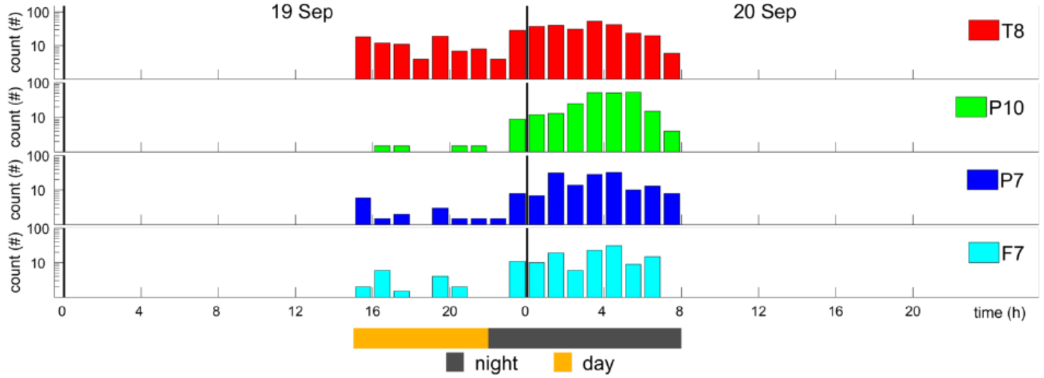
Detected Clusters



Lateralization

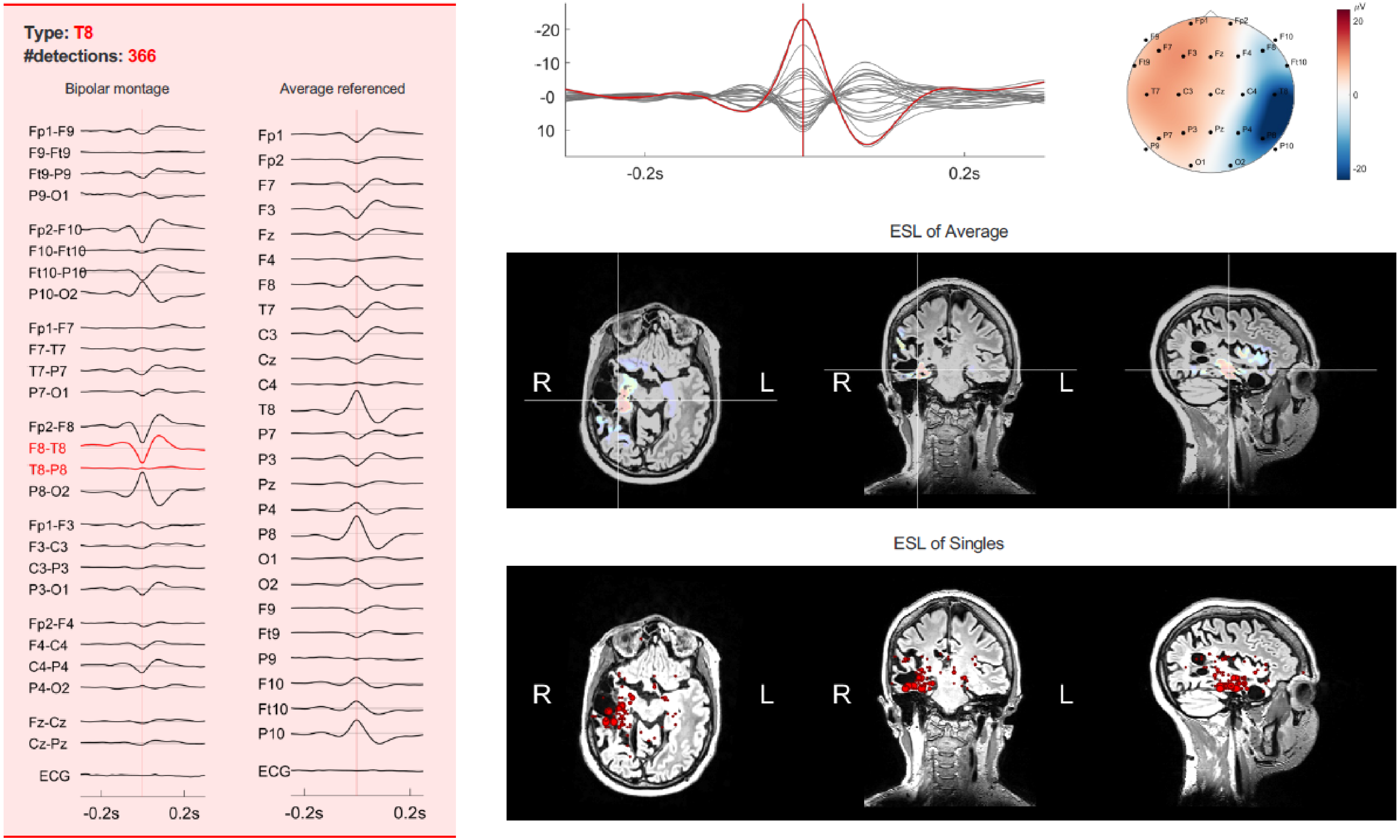


Timing

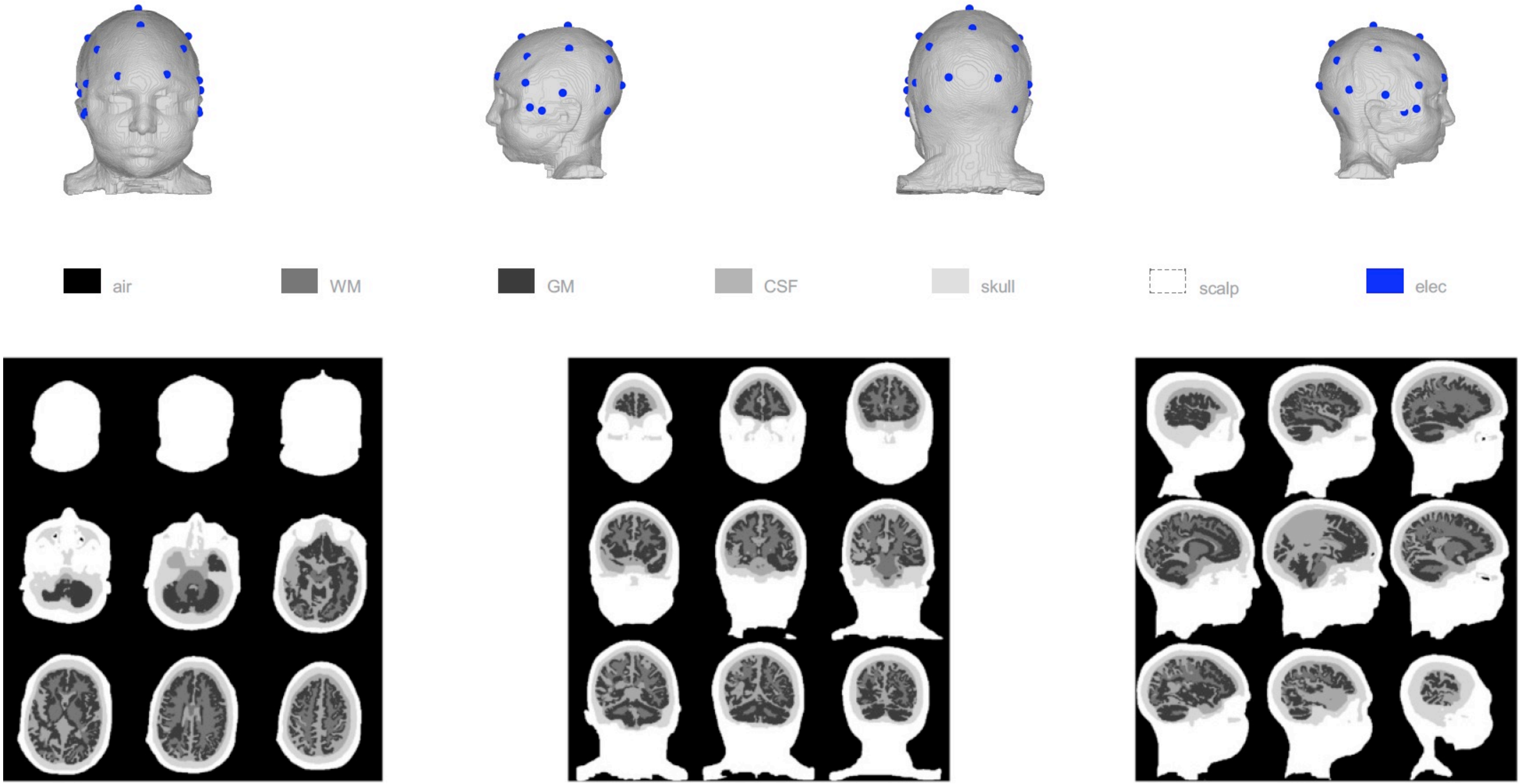


Automated localization of epileptic spikes

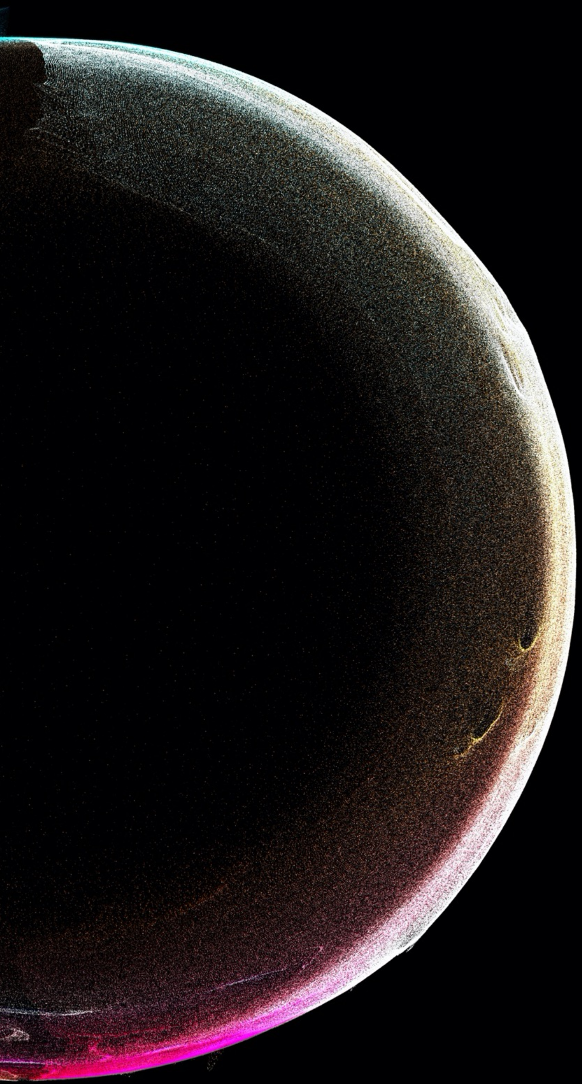
EEG Source Localization / PEAK



Automated localization of epileptic spikes



Name	Website	Inverse models
ACADEMIC SOFTWARE PACKAGES		
Brainstorm	https://neuroimage.usc.edu/brainstorm	Dipole modeling, Beamformer, sLORETA, dSPM
Cartool	https://sites.google.com/site/cartoolcommunity/	Minimum Norm, LORETA, LAURA, Epifocus
EEGLab	https://sccn.ucsd.edu/eeglab/index.php	Dipole modeling
Fieldtrip	http://www.fieldtriptoolbox.org/	Dipole modeling, Beamformer, Minimum Norm
LORETA	http://www.uzh.ch/keyinst/loreta.htm	LORETA, sLORETA, eLORETA
MNE	https://martinos.org/mne/stable/index.html	MNE, dSPM, sLORETA, eLORETA
NUTMEG	https://www.nitrc.org/projects/nutmeg	Beamformer
SPM	https://www.fil.ion.ucl.ac.uk/spm/	dSMP
COMMERCIAL SOFTWARE PACKAGES		
BESA	http://www.besa.de/products/besa-research/besa-research-overview/	Dipole modeling, RAP-MUSIC, LORETA, sLORETA, LAURA, SSLOFO
brainvision analyzer	https://www.brainproducts.com/	LORETA
BrainVoyager	https://www.brainvoyager.com/	Beamformer, Minimum Norm, LORETA, LAURA
GeoSource	https://www.usa.philips.com/healthcare/solutions/neuro/neuro-research-applications	Minimum Norm, LORETA, sLORETA, LAURA
CURRY	https://compumedicsneuroscan.com/curry-source-reconstruction/	Dipole modeling, MUSIC, Beamformer, Minimum norm, sLORETA, eLORETA, SWARM



Summary

EEG source imaging needs a forward model and an inverse solution technique.

The forward model contains the head geometry, tissues conductivity, electrode positions and the solution space.

The inverse technique optimizes the source space solution by imposing some constraints.

EEG source localization can be used to localize ERPs or epileptic spikes.