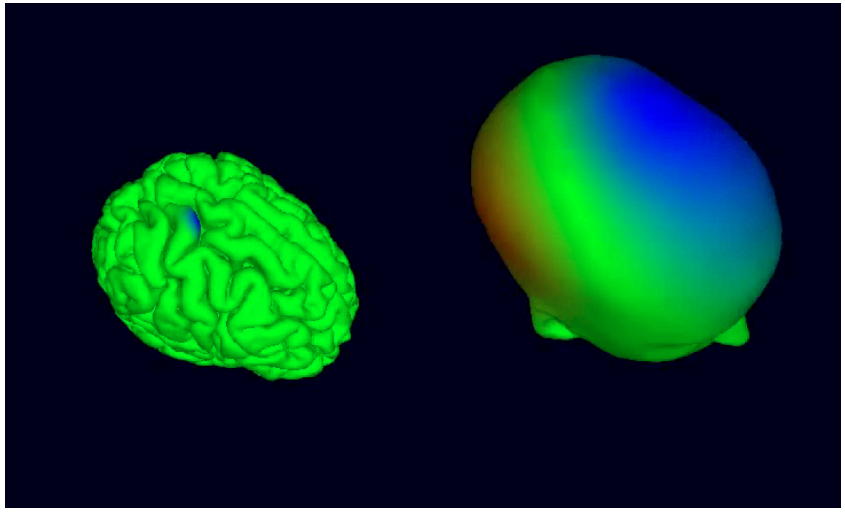


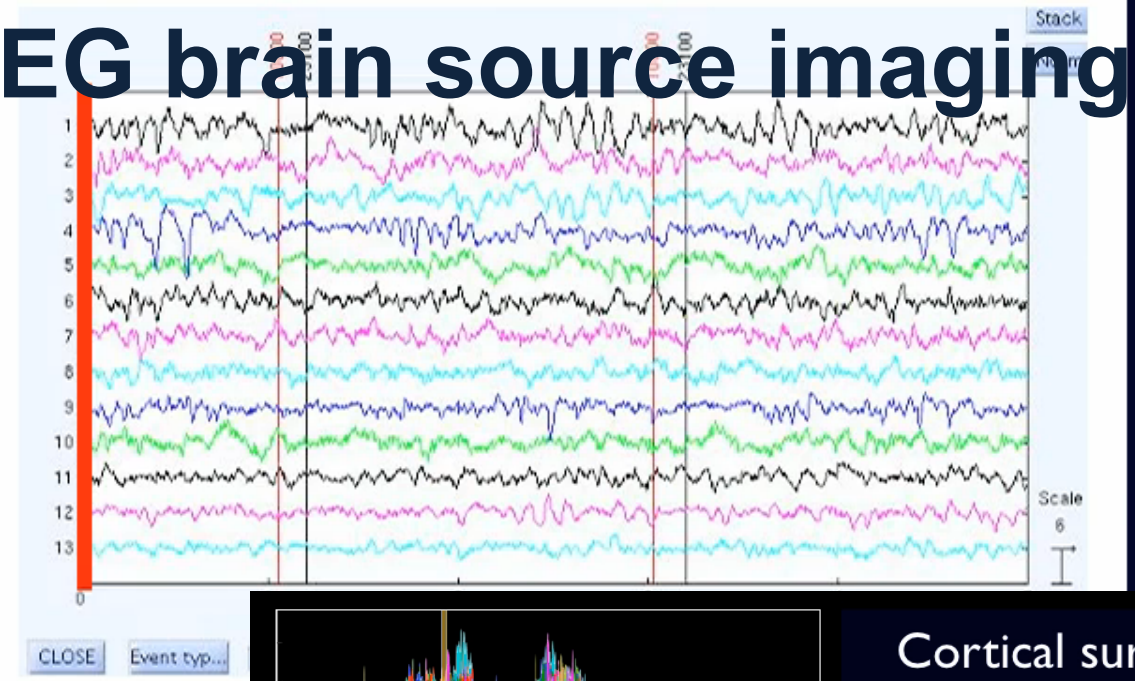
Source Localization: The EEG Forward and Inverse Problem

Zeynep AKALIN ACAR

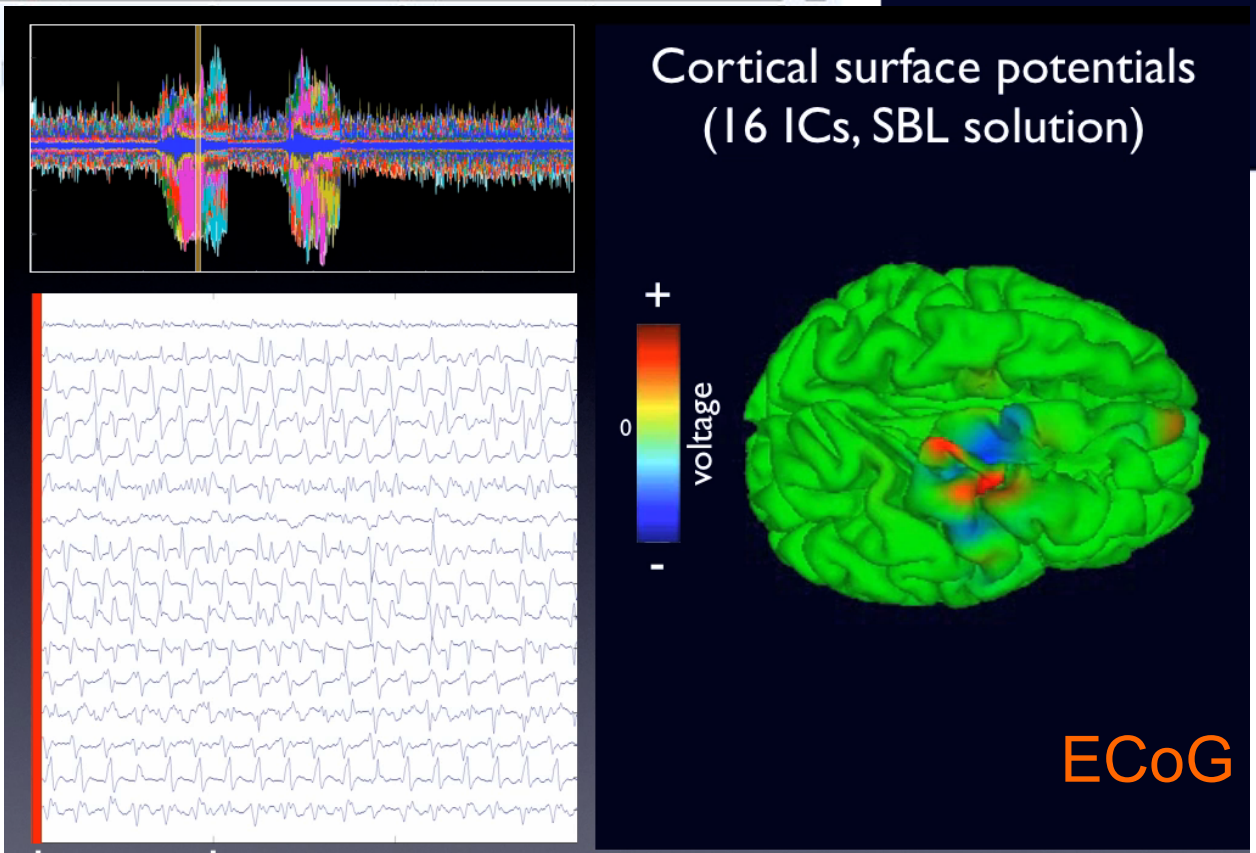
Swartz Center for Computational Neuroscience

November, 2016

EEG brain source imaging

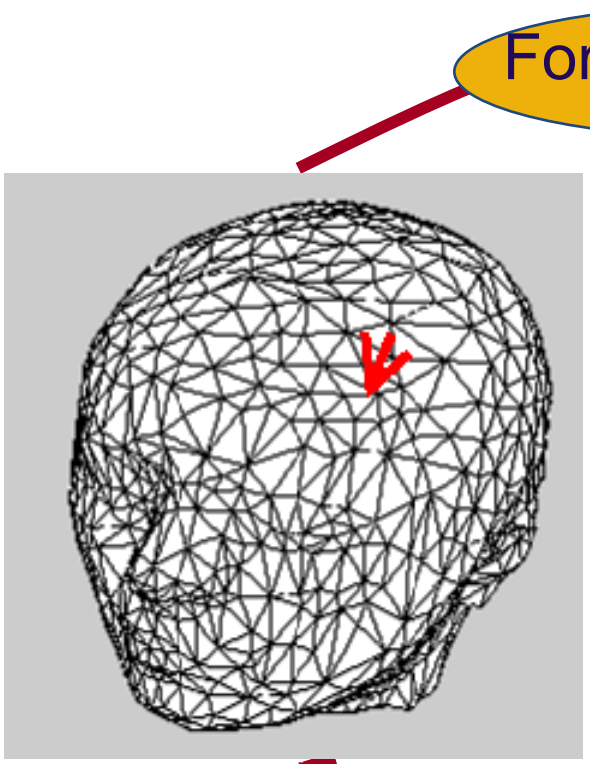


EEG



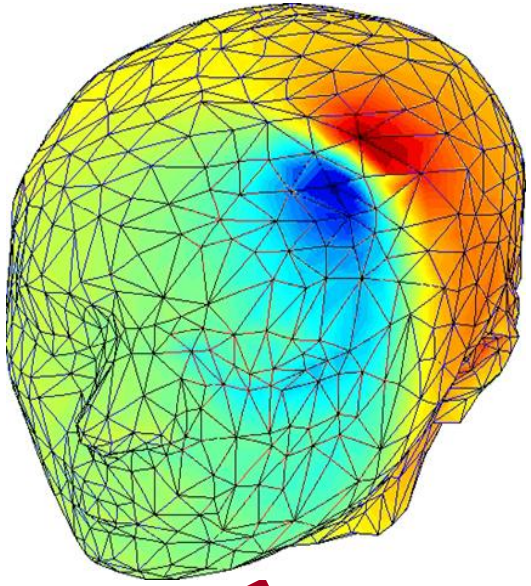
ECoG

Forward and inverse problem



Forward Problem

$$X = LS$$



EEG/ MEG

$$S = L^{-1}X$$

Inverse Problem

= 1000s of FP solution

Source localization is ill-posed

$$X = LS + n$$

X: scalp recorded potentials
S: current density vector
L: transfer matrix 'the head volume conductor model'

The inverse problem refers to finding S given known X.

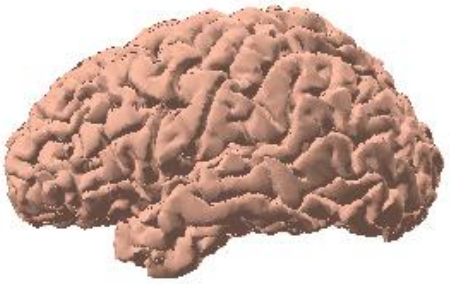
$$O(S) = \min \left\| X - LS \right\|^2$$ Infinite solutions!

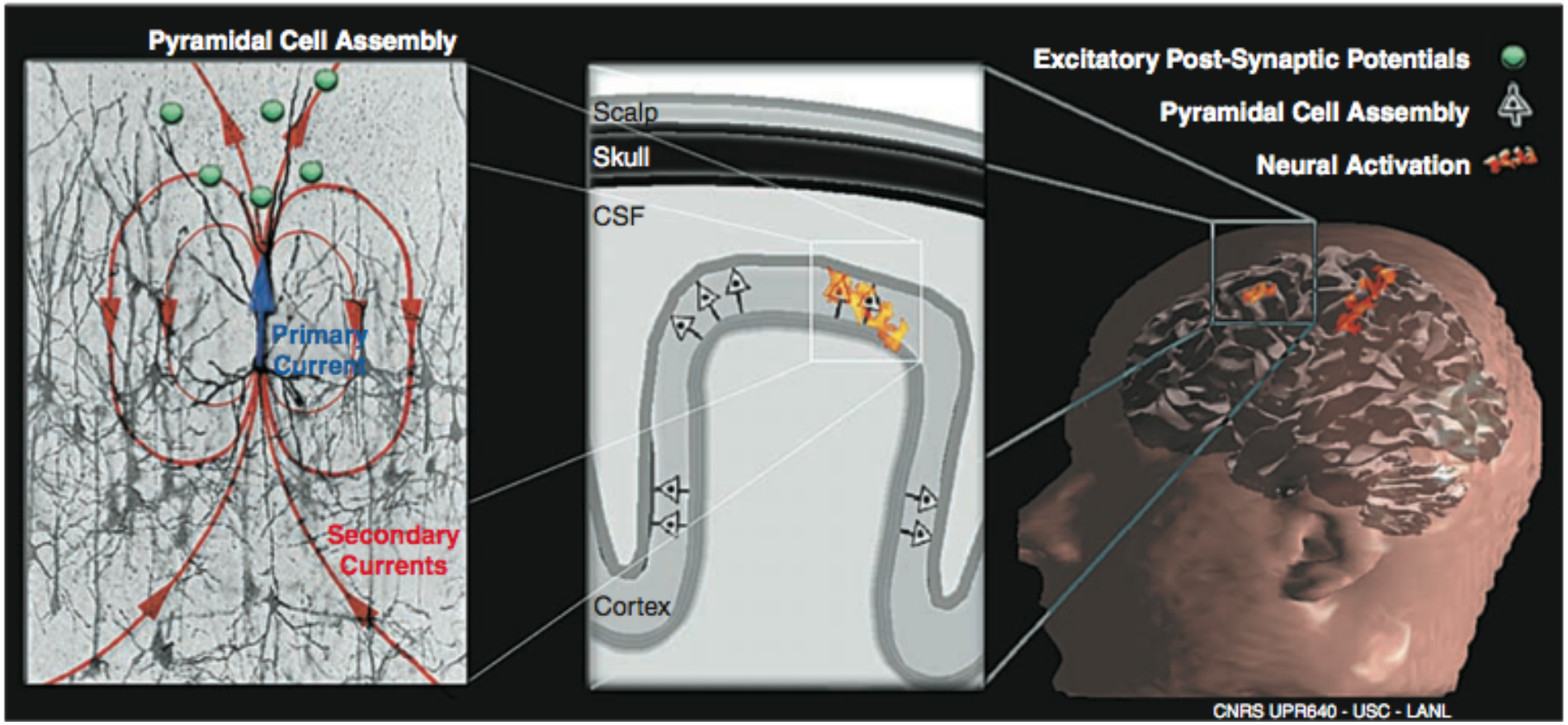
Apply electrophysiological neuroanatomical constraints

1. The electrical head model used,
2. The inverse solution itself

Generators of EEG

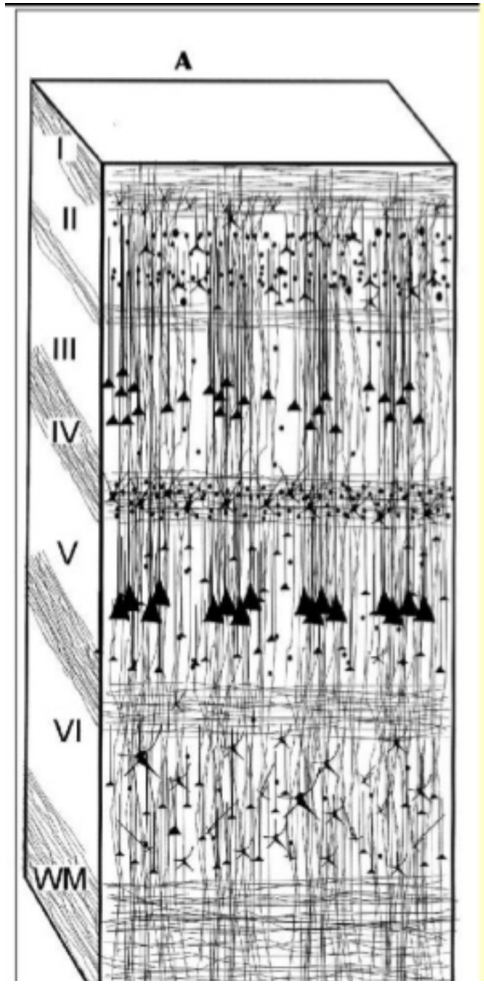
Cortical surface

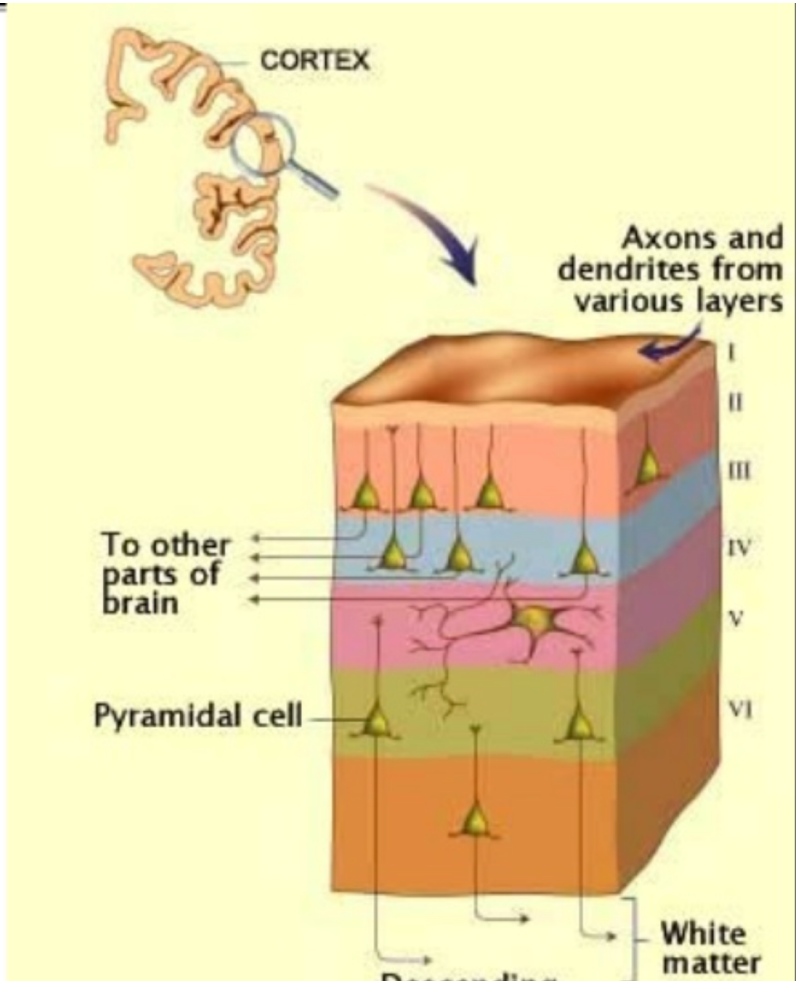




Baillet et al, 2001

Layers of cerebral cortex





The 2mm thick cortex can be divided into six layers.

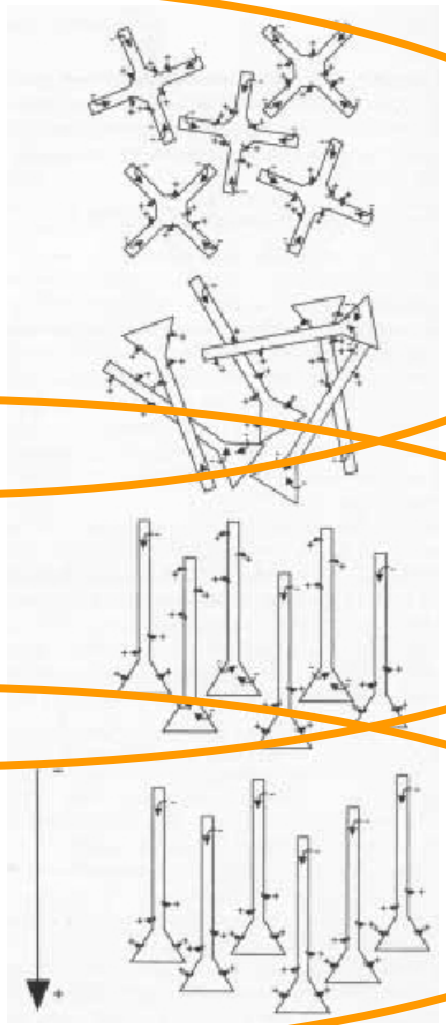
It is believed that the activation of the large pyramidal cells of layer V is what is reflected in most EEGs.

Symmetry, orientation and activation

radially symmetric, i.e.
randomly-oriented

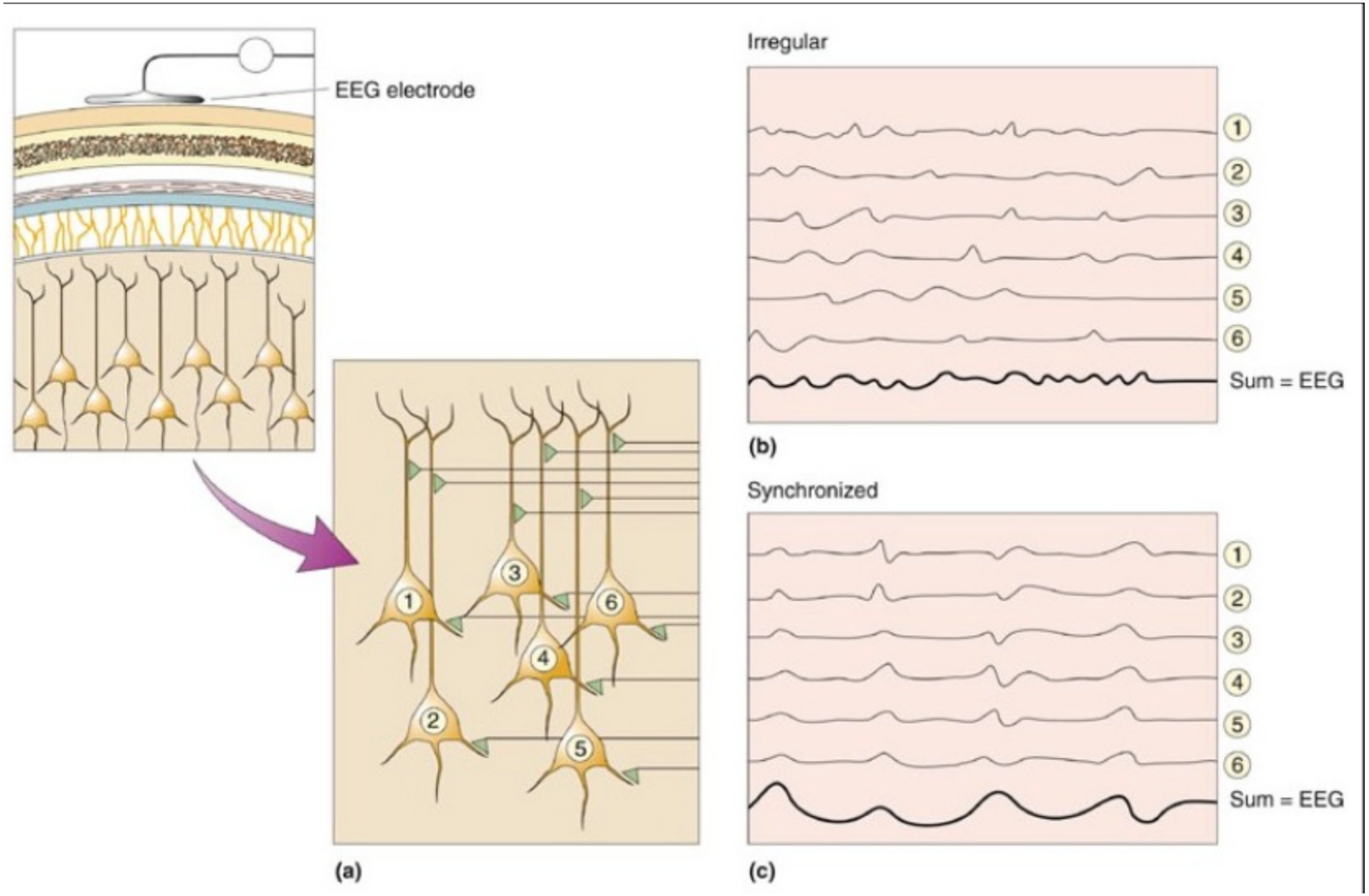
asynchronously activated

synchronously activated
parallel-oriented



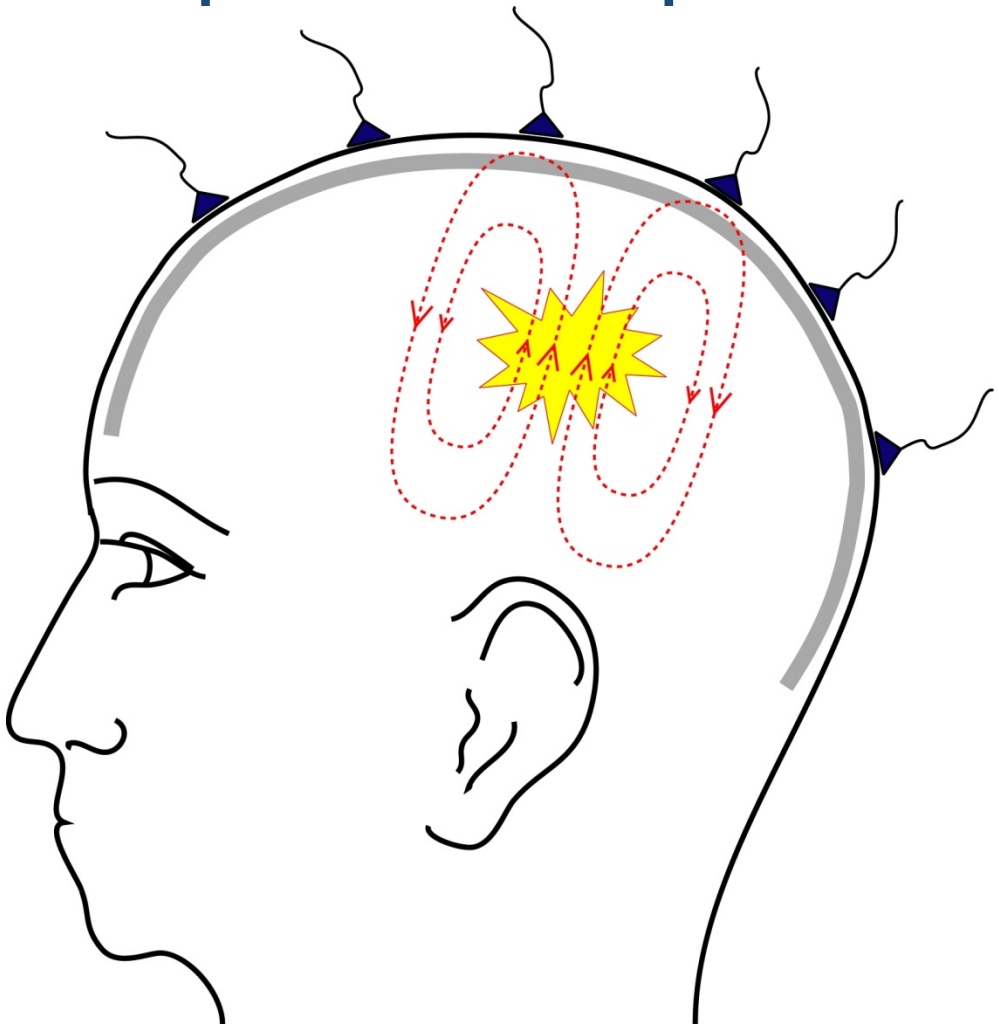
R. Oostenveld, S. Makeig, 2016

EEG



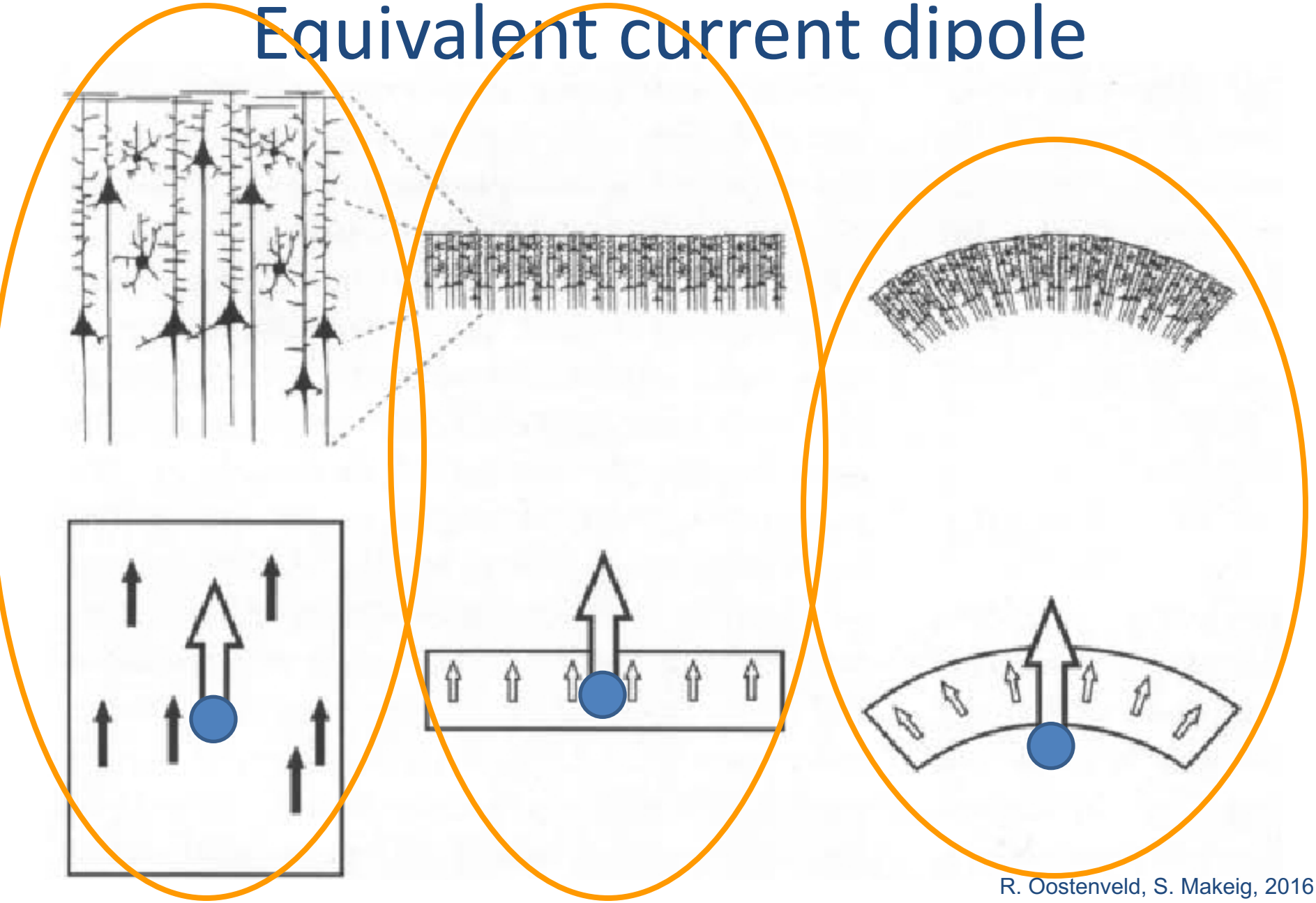
Many neurons need to sum their activity in order to be detected by EEG electrodes. Synchronized neural activity produces larger signals.

EEG volume conduction
→ dipolar field patterns

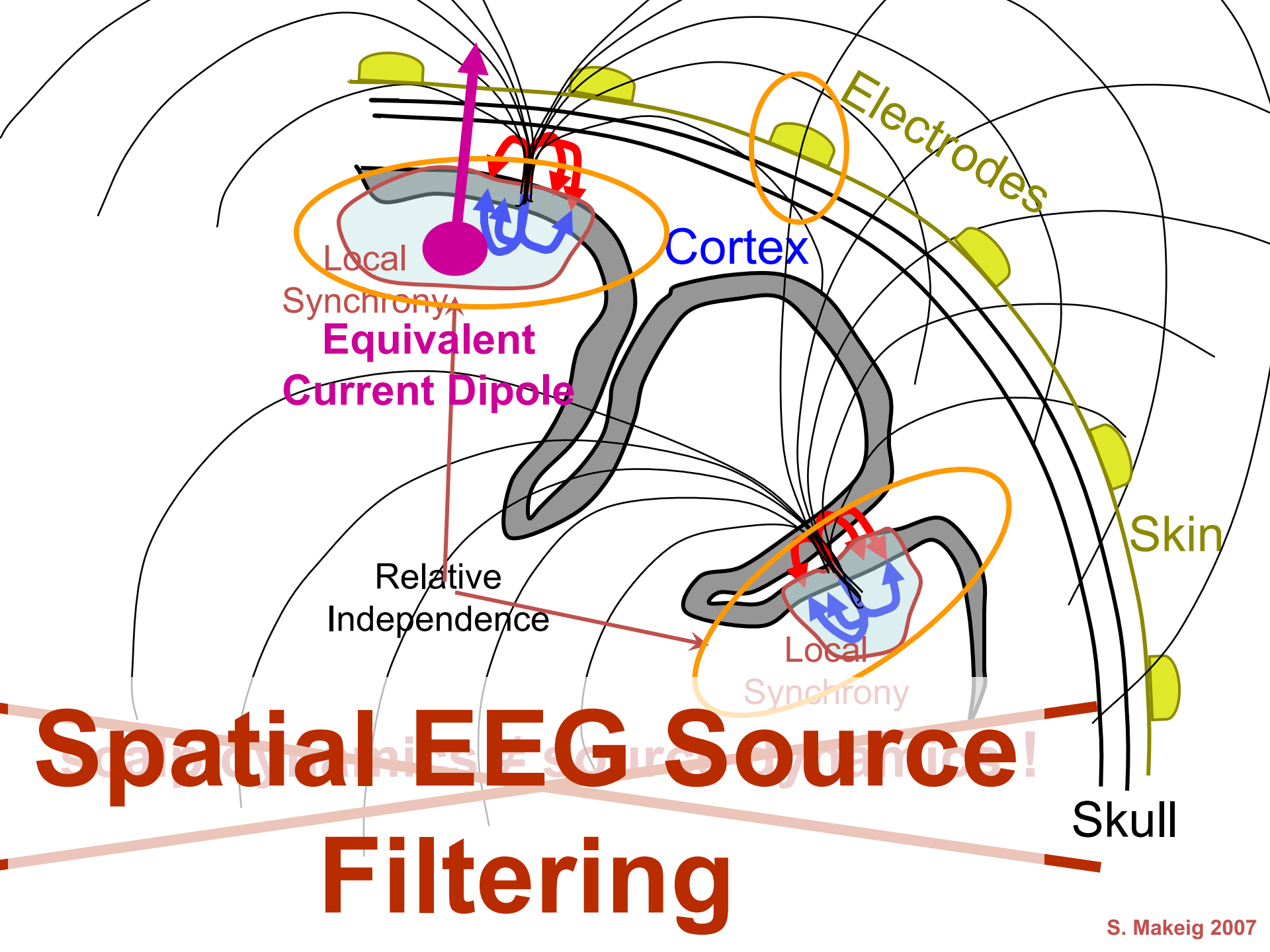


R. Oostenveld, S. Makeig, 2016

Equivalent current dipole



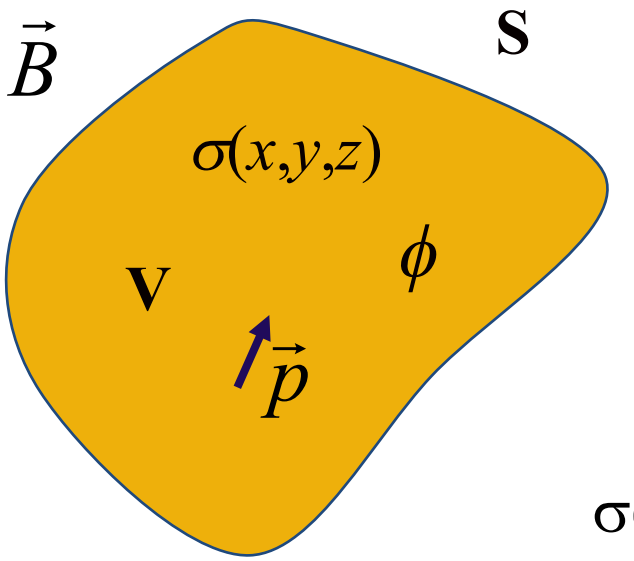
R. Oostenveld, S. Makeig, 2016



Spatial EEG Source Filtering

S. Makeig 2007

Formulation of the FP



$$\nabla \cdot (\sigma \nabla \Phi) = -\nabla \cdot J^P \quad \text{inside } V$$

$$\sigma \frac{\partial \Phi}{\partial n} = 0 \quad \text{on } S$$

$\sigma(x,y,z)$: conductivity distribution

$\vec{p}$: current source

Reference: Gulrajani, R., Bioelectricity and biomagnetism

EEG volume conduction

- **Potential differences between electrodes** measures summed current flowing through scalp
  - Only a tiny fraction of *brain source currents* pass through the skull
  - Therefore a forward head model should describe *brain, skull, and scalp tissues* as accurately as possible.
- **Problems with skull**
  - Poorly visible in anatomical MRI (T1/T2) images
  - Thickness varies regionally
  - Conductivity is not homogeneous
  - Complex geometry at front and base of skull

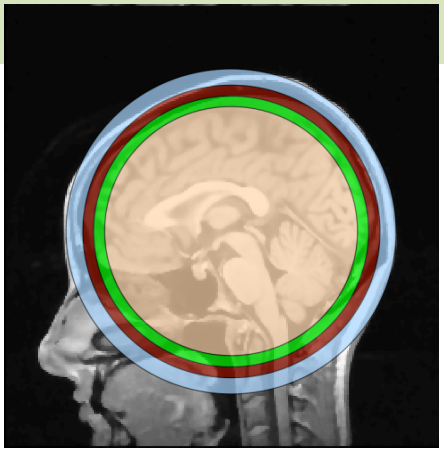
  → **Individual skull conductivity** variable & unknown

Head volume conductor model

Simple Head Models

- Single layer sphere, spheroid
- 3-4 layer sphere

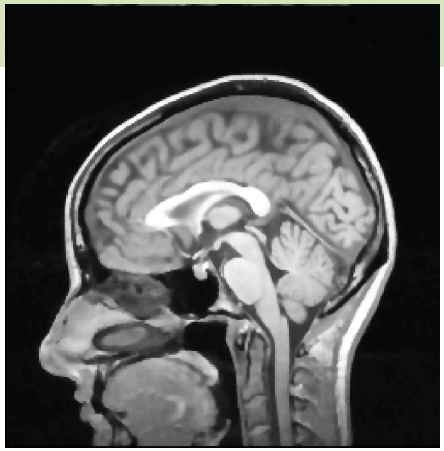
ANALYTICAL SOLVER
Simple, fast, but not accurate

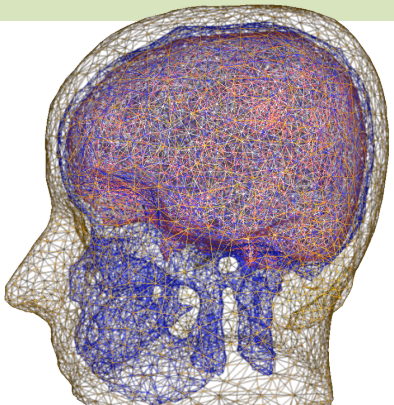


Realistic Head Models

- Boundary Element (BEM)
- Finite Element (FEM)
- Finite Difference (FDM)

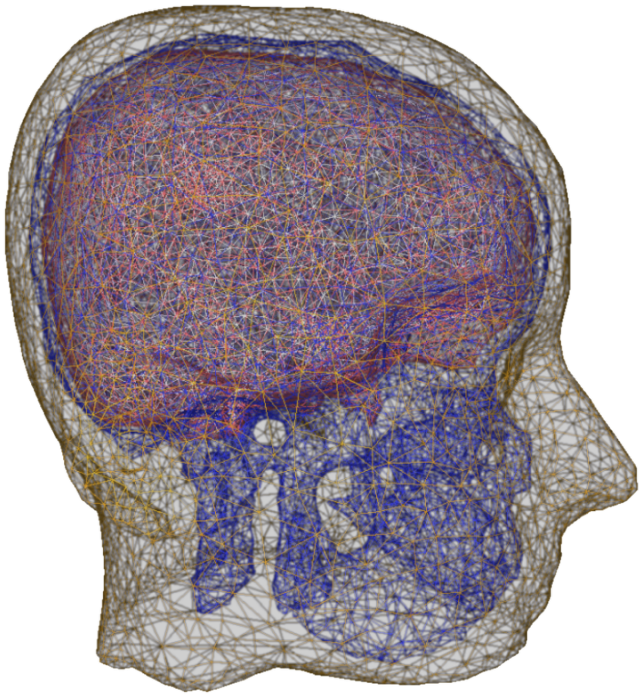
NUMERICAL SOLVER
Represents head shape better, but computationally complex





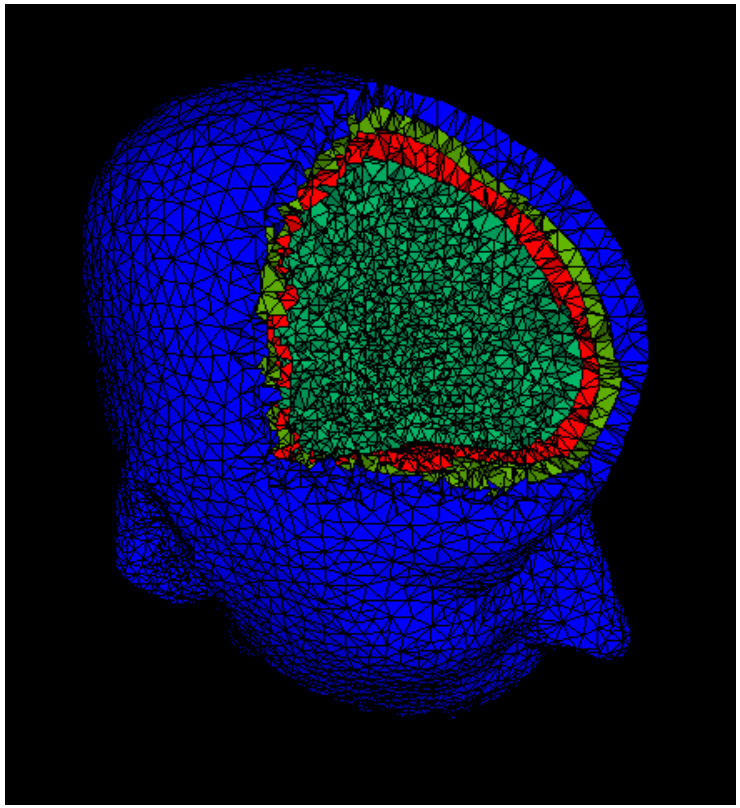
Numerical Head Models

BEM



NFT BEM mesh

FEM



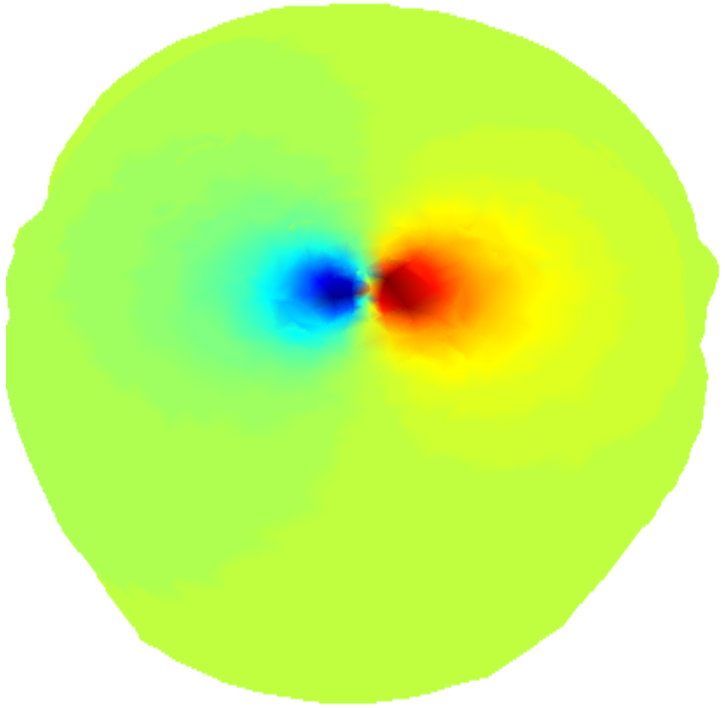
Generated using Tetgen
from NFT BEM mesh

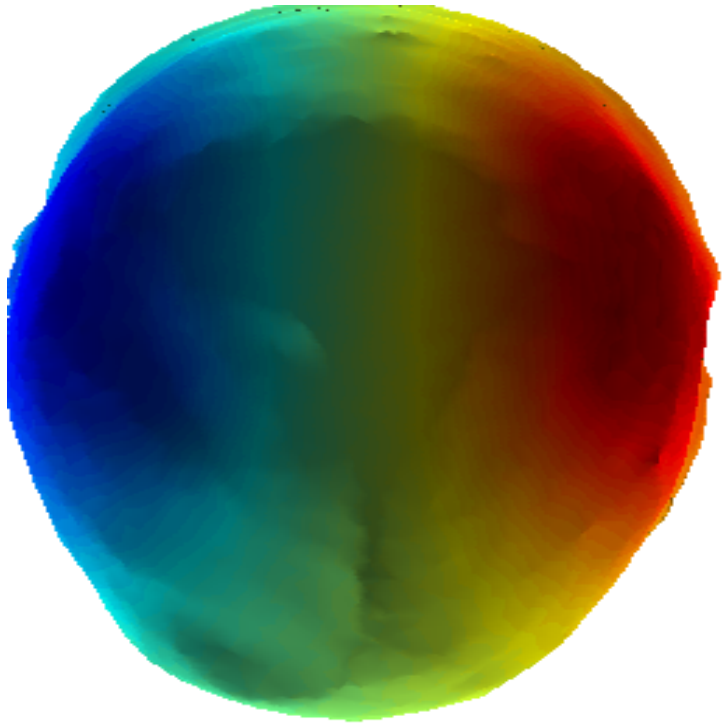
Tangential dipoles

Shallow tangential source

Deep tangential source

right





left

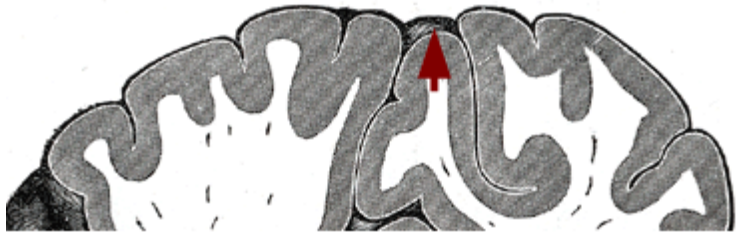
front

top view of head

front

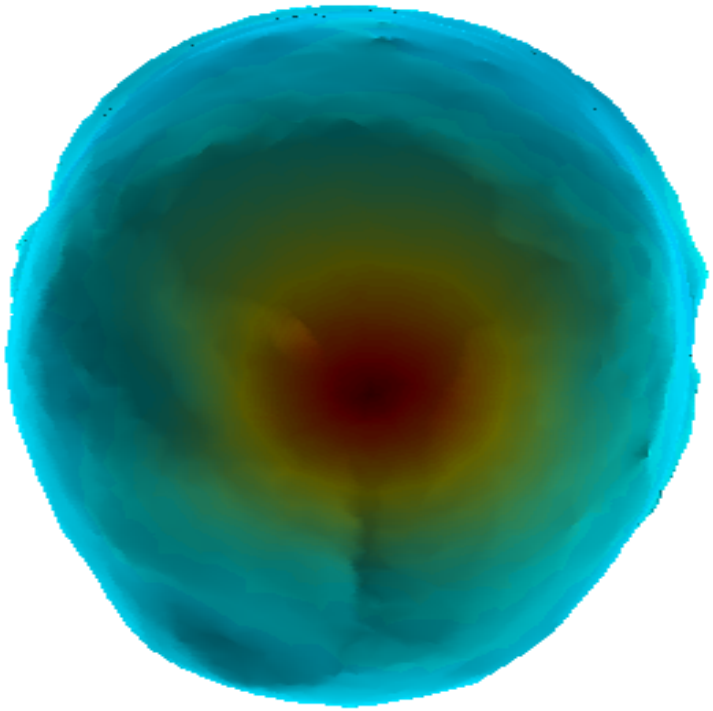
Radial dipoles

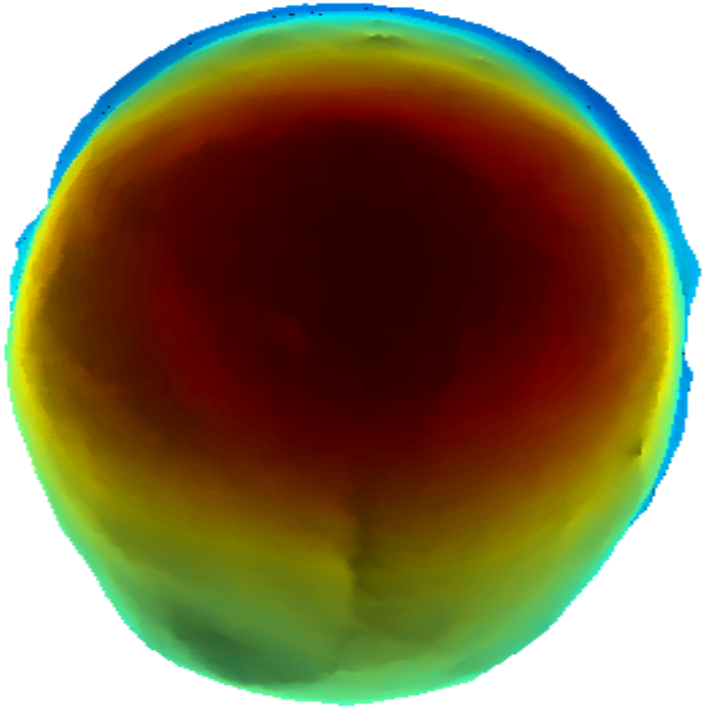
Shallow radial source



Deep radial source

right



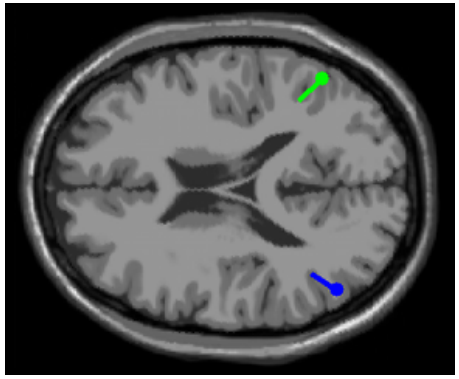


left

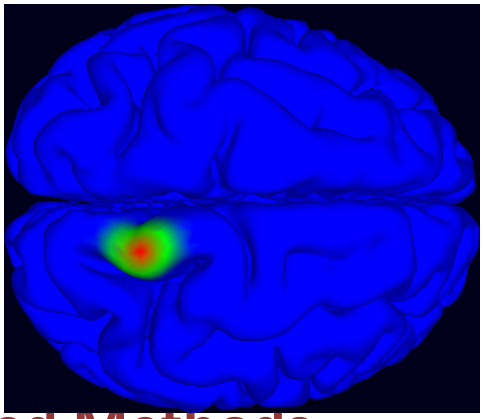
front

top view of head

front



Inverse Problem



Equivalent dipole Methods

- Overdetermined
- Searches for parameters of a number of dipoles
- Nonlinear optimization techniques
- May converge to local minima
- Non-linear least squares, beamforming, MUSIC, simulated annealing, genetic algorithms, etc.

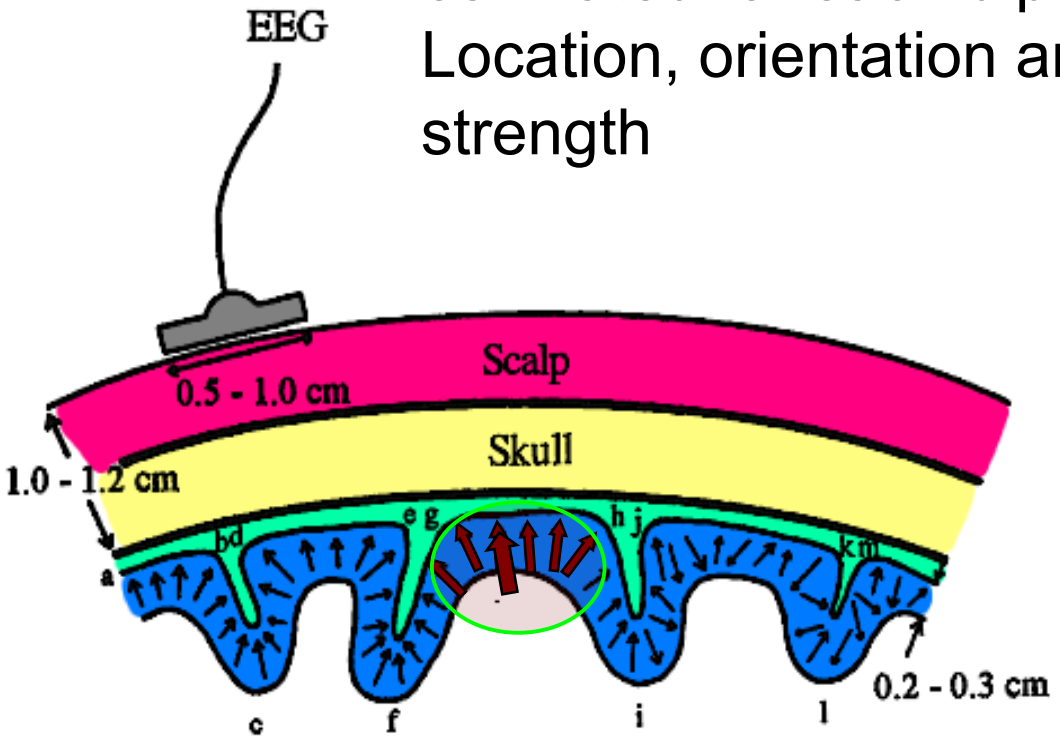
Linear distributed Methods

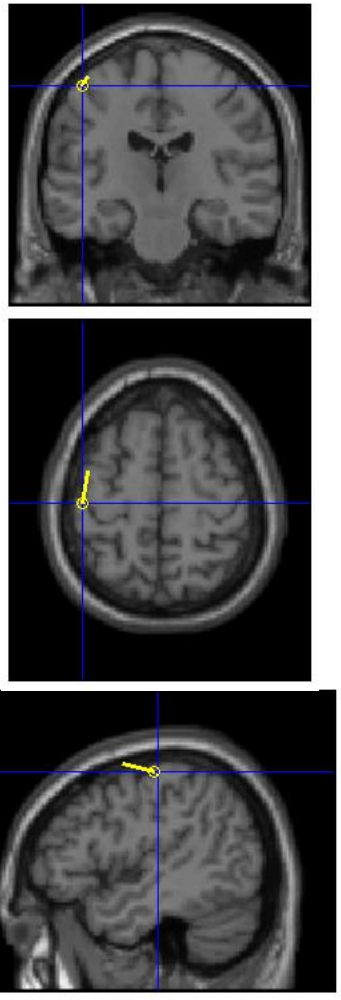
- Underdetermined
- Searches for activation in given locations.
- Linear optimization techniques
- Needs additional constraints
- Bayesian methods, MNE, LORETA, LAURA, etc.

Equivalent current dipole (ECD)

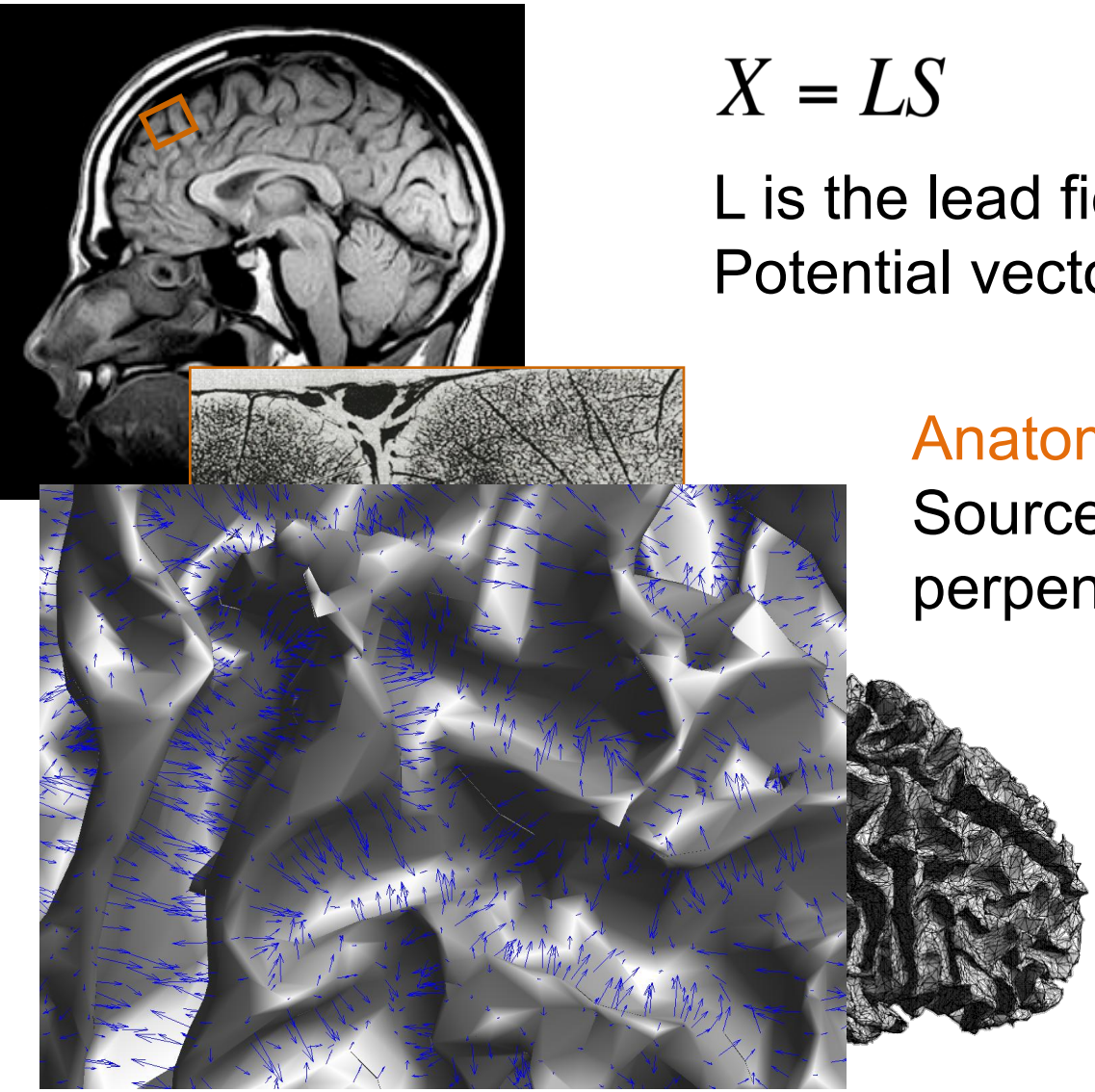
$$O(S) = \min \left\| X - LS \right\|^2$$

6 parameters are estimated for each dipole: Location, orientation and strength





Linear distributed methods



$$X = LS$$

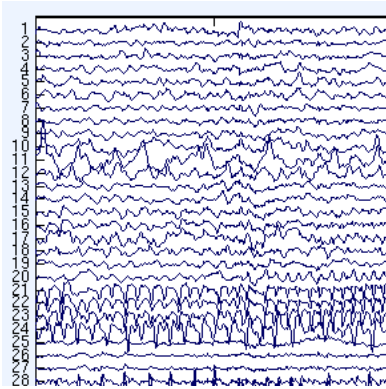
L is the lead field matrix:
Potential vectors of all possible solutions

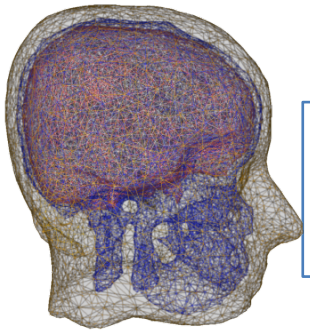
Anatomical constraint:
Sources are on the cortex
perpendicular to the cortex

Summary

MRI / Electrode locations

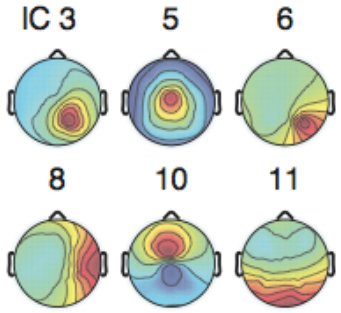
EEG/ECoG/MEG



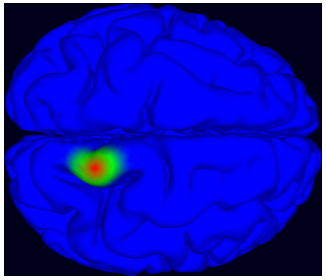


Volume conductor model

ICA



Source localization on single effective brain activity



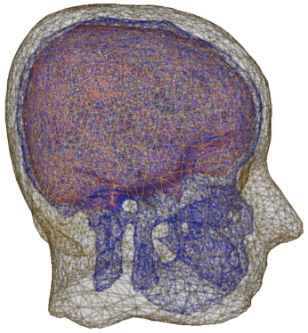
Components of EEG source imaging

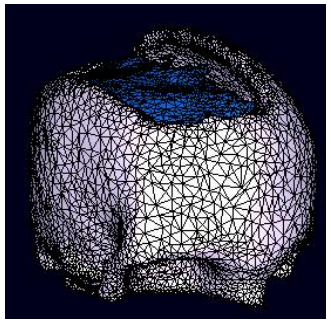
NFT

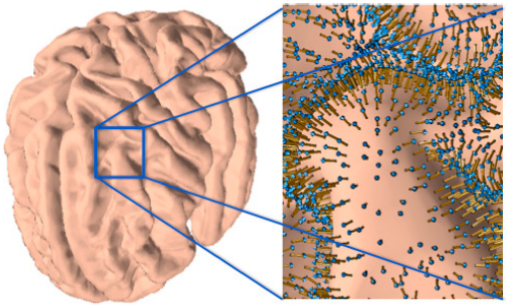
- Forward model (geometry and conductivity distribution)
- Forward solver (FEM, BEM)
- Electrode co-registration
- EEG source separation

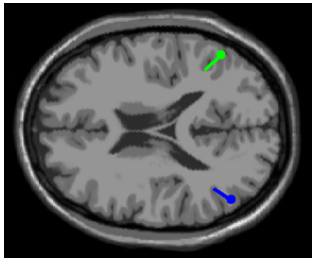
NIST

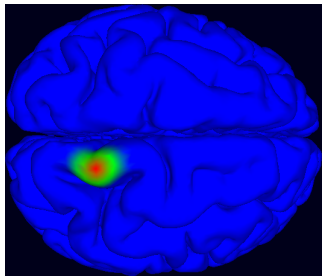
- Brain source space
- Source localization



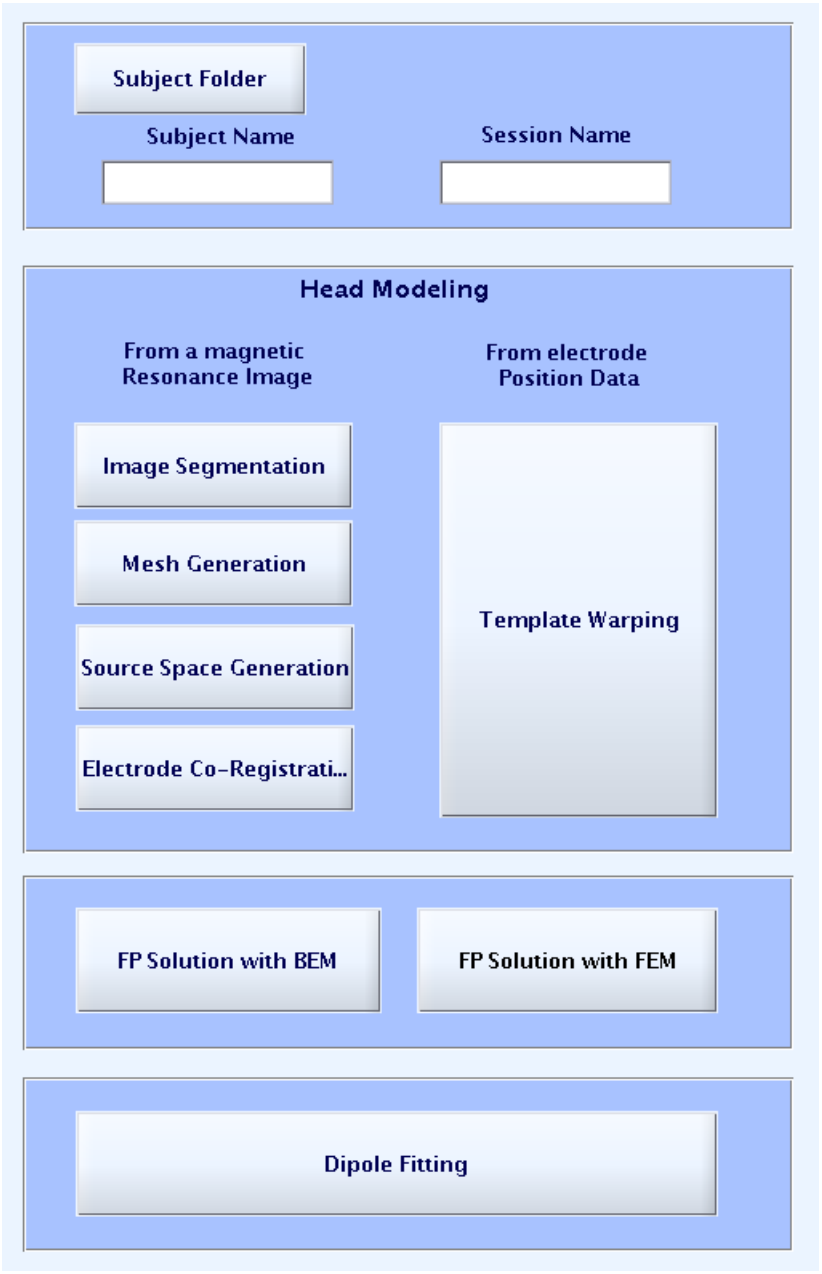


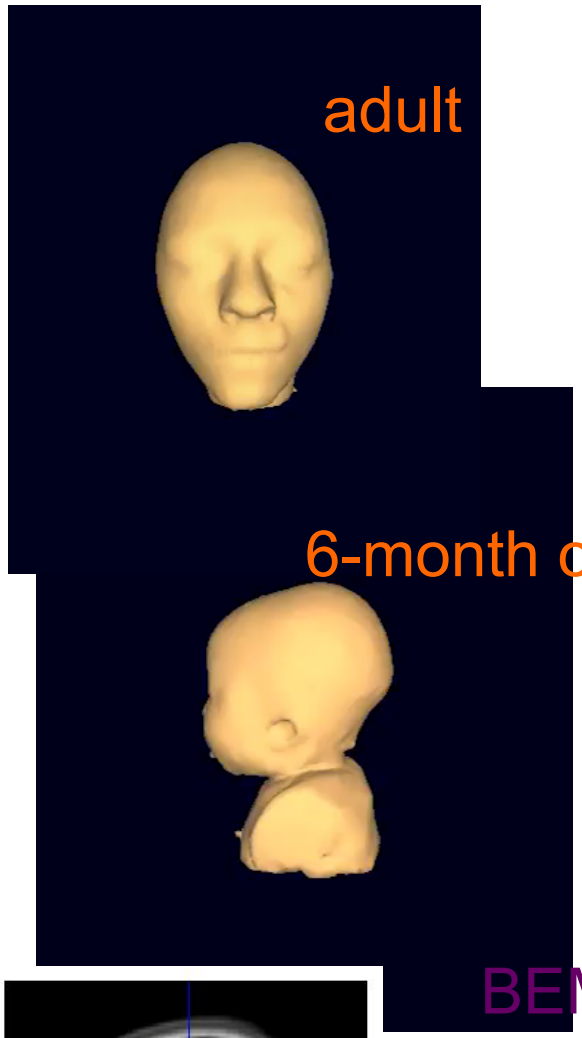


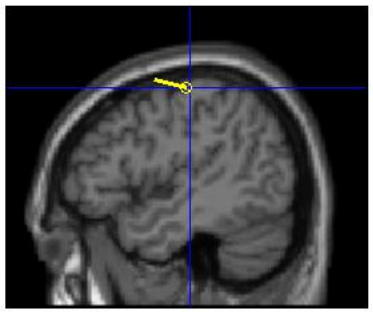




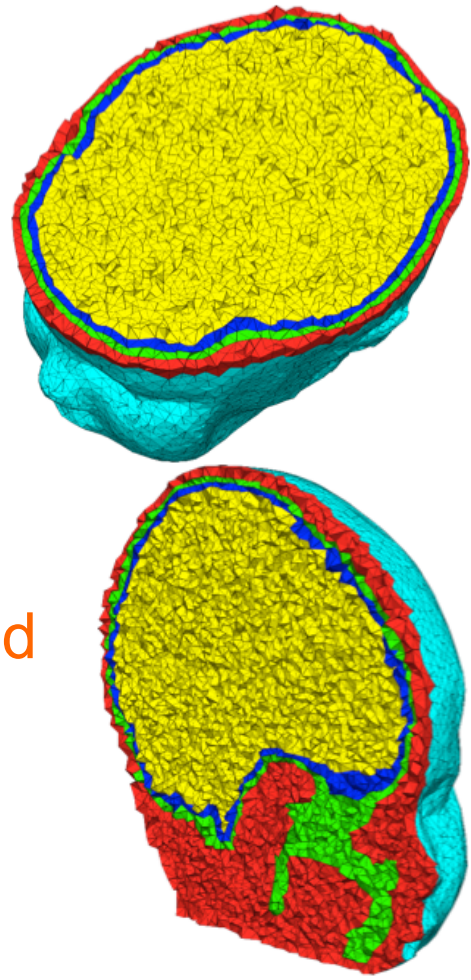
NFT







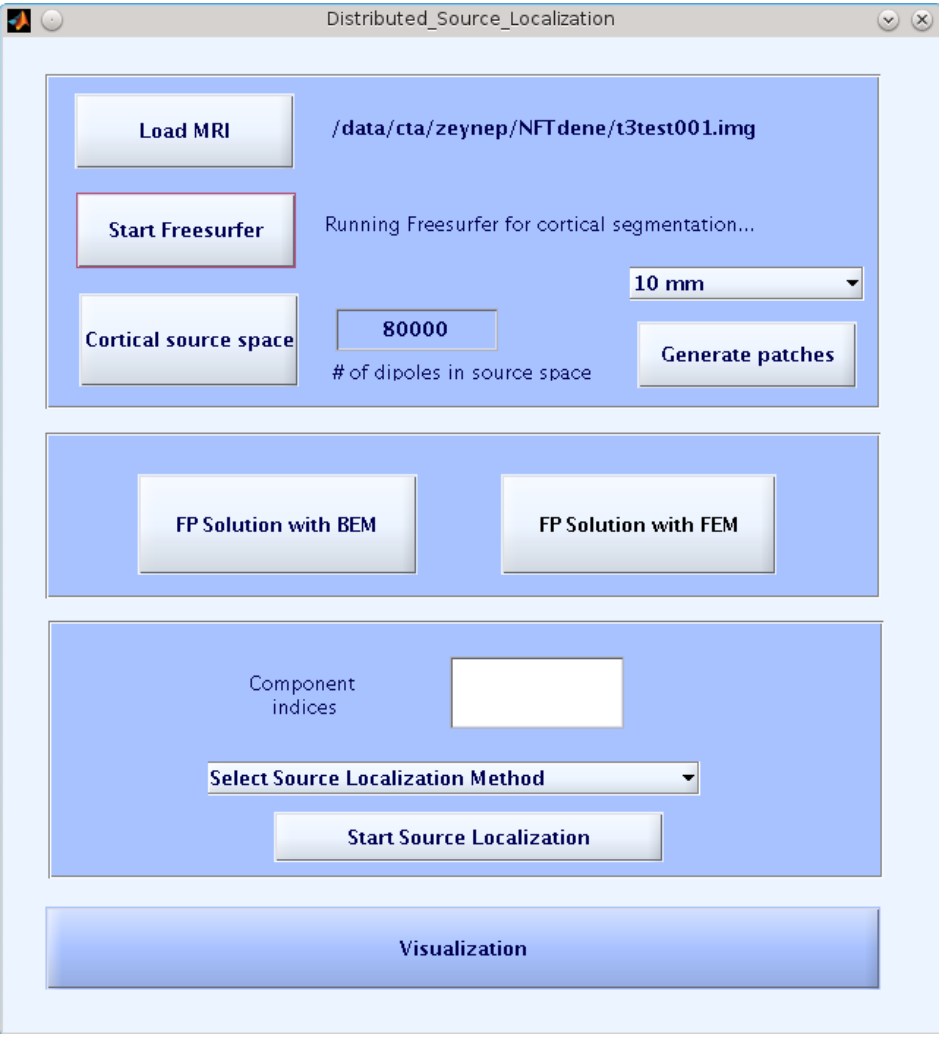
BEM models

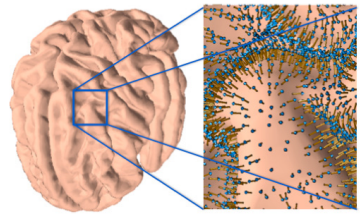


FEM models

Akalin Acar & Makeig, 2010

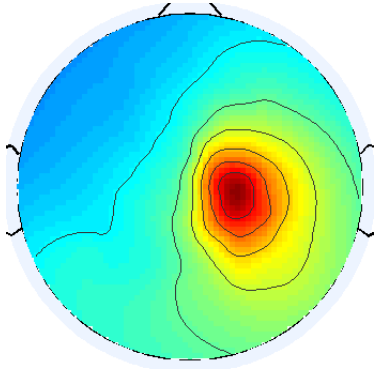
NIST



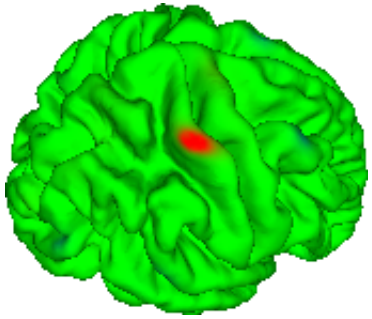


Source space

Scalp map

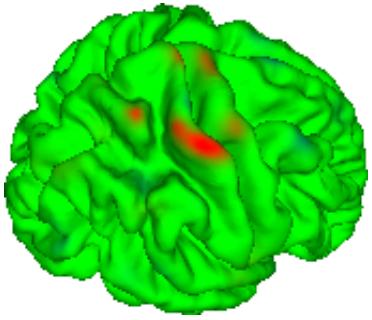


SCS

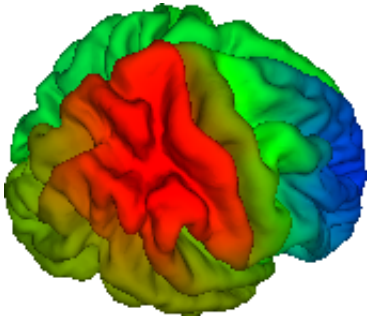


Cheng Cao, 2012

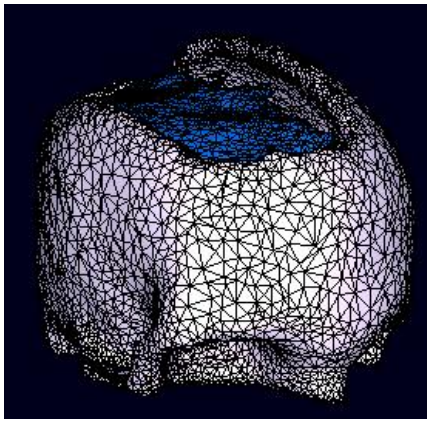
Patch-based SBL

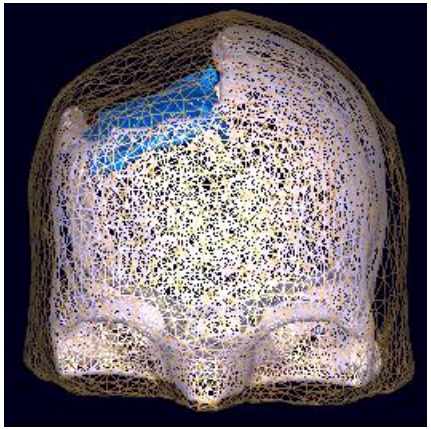


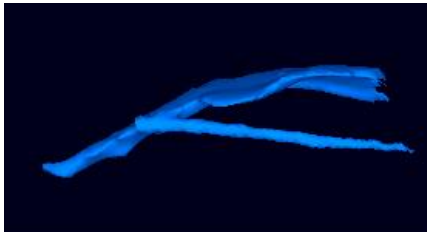
sLORETA

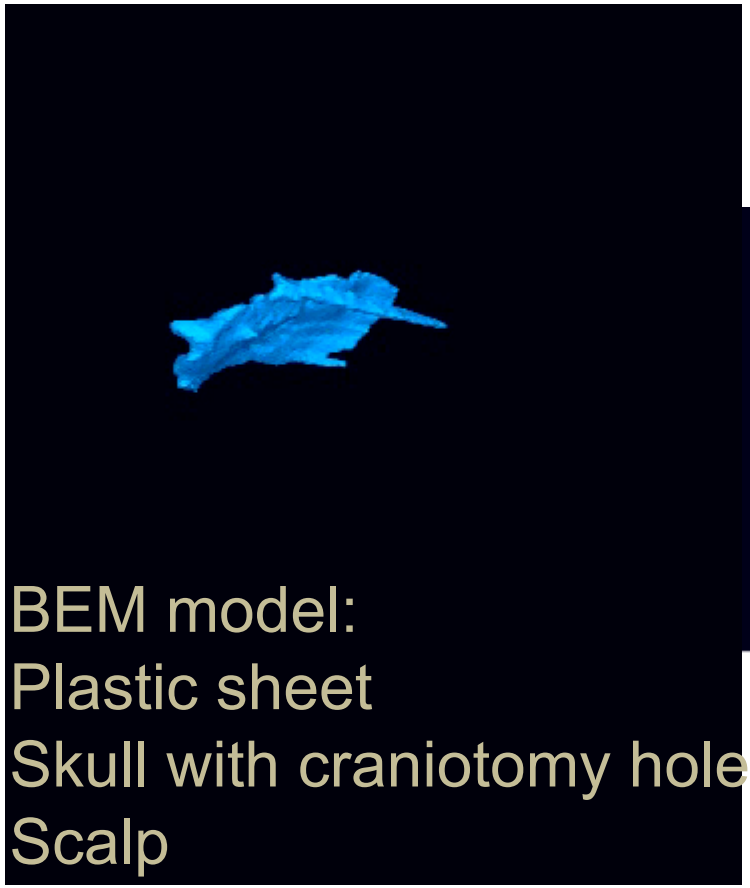


EEG/ECoG source localization - Forward modeling



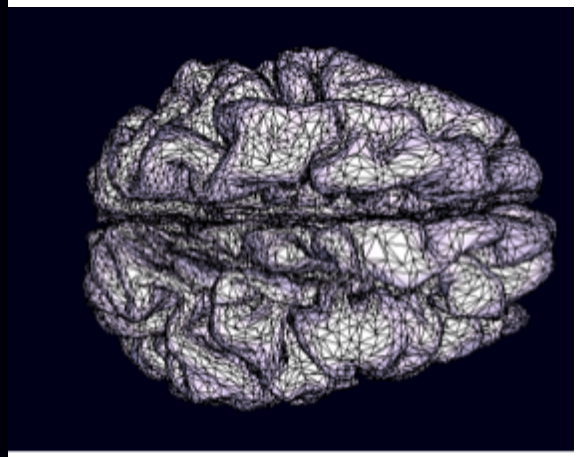






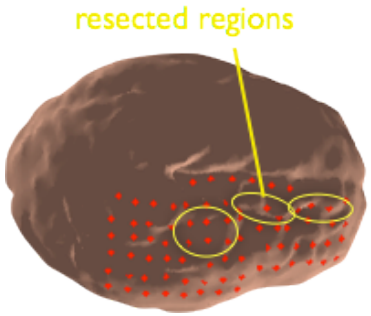
BEM model:
Plastic sheet
Skull with craniotomy hole
Scalp

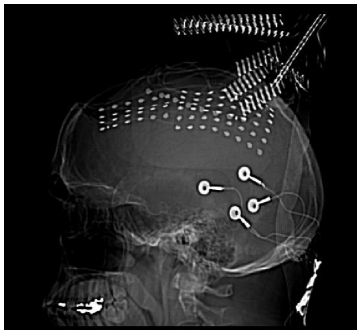
Cortex (Freesurfer)



80 000 source vertices

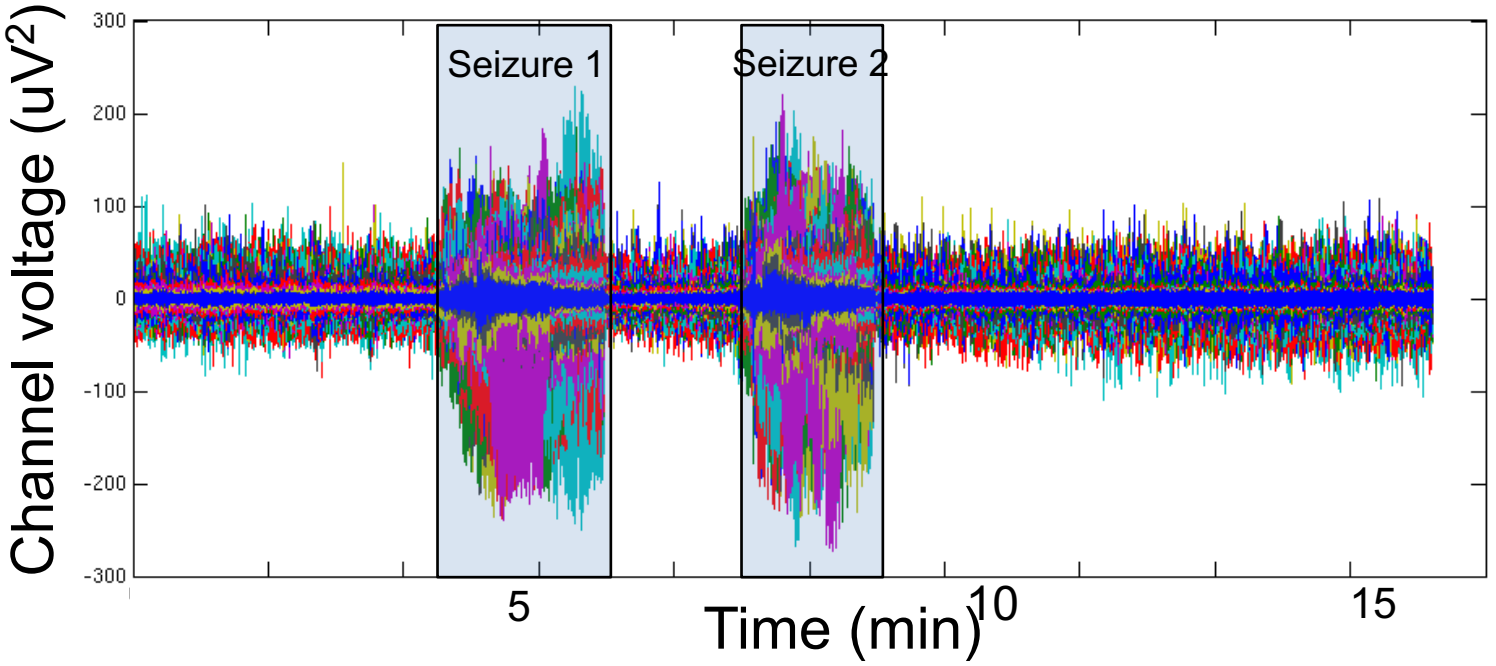
Analyzing Epilepsy Recordings



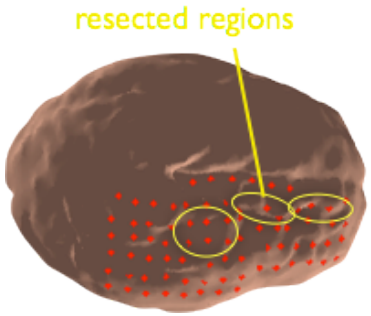


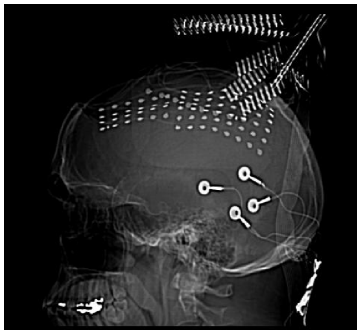
- Pre-Surgical Evaluation
- Rest Data
- 78 ECoG (subdural EEG) electrodes
- 29 scalp electrodes
- Surgical Outcome: Positive (seizure free)
- Provided by Dr. Greg Worrell, Mayo Clinic

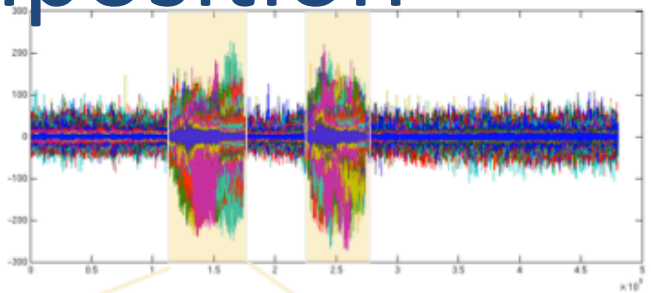
16 min of data, 2 seizures



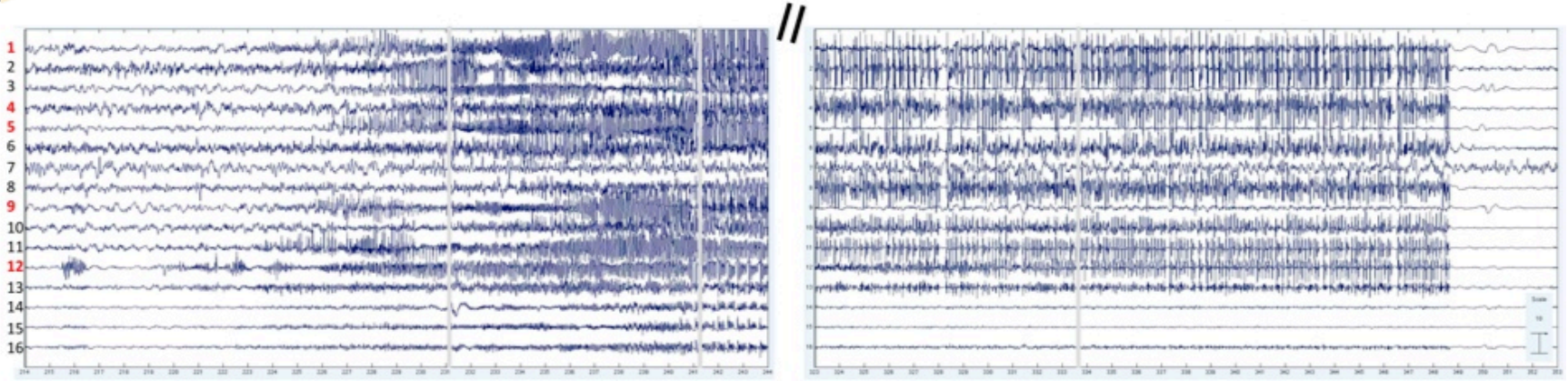
ICA decomposition





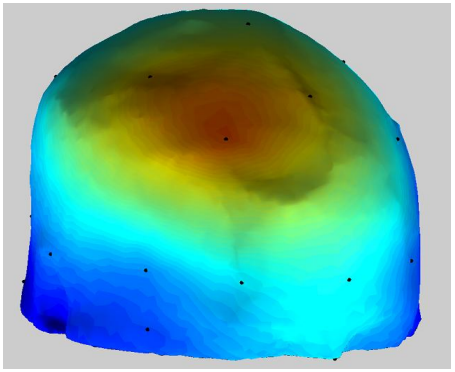


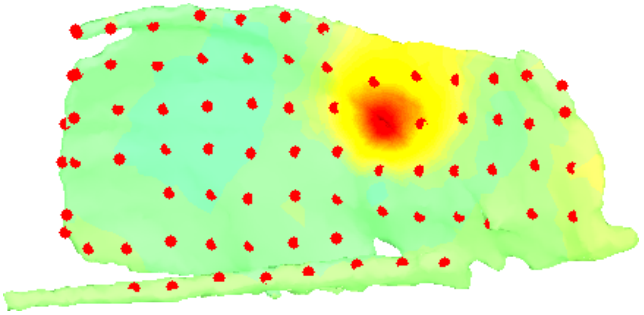
Extended Infomax ICA Decomposition
16 seizure components (ICs) selected

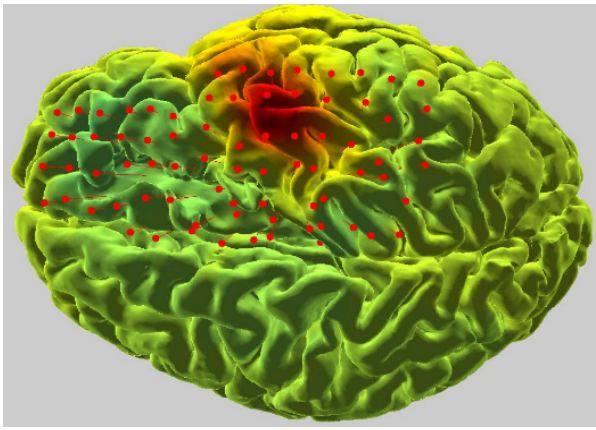


Independent Components

IC 1





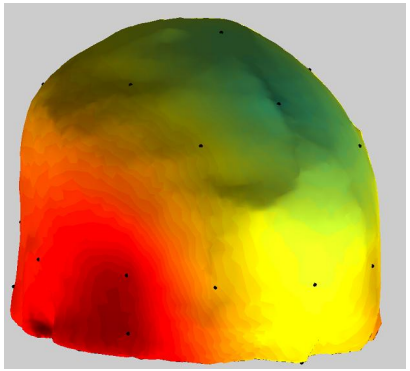


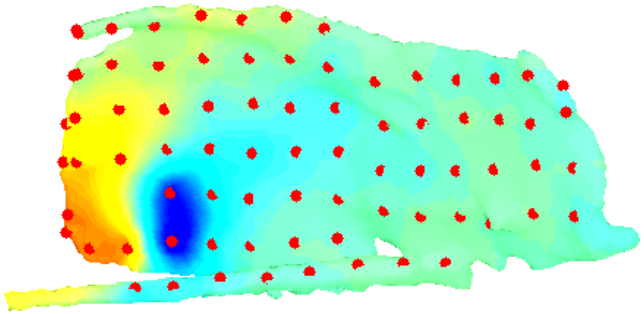
Potentials on scalp

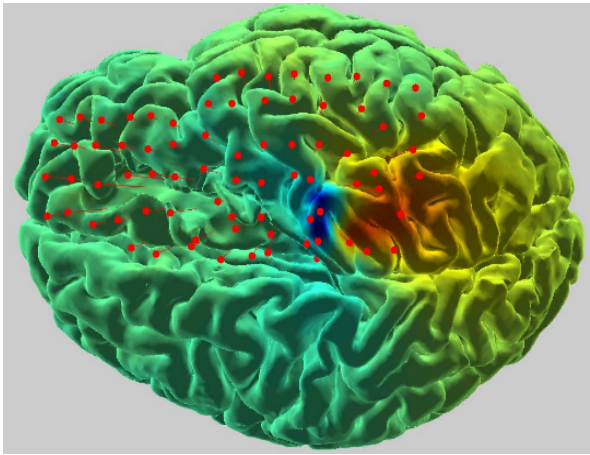
Potentials on plastic sheet

On the brain surface

IC 2



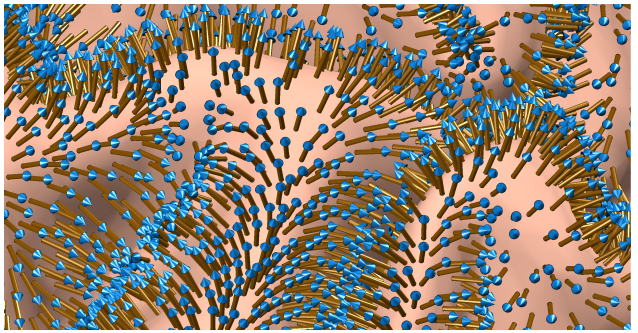


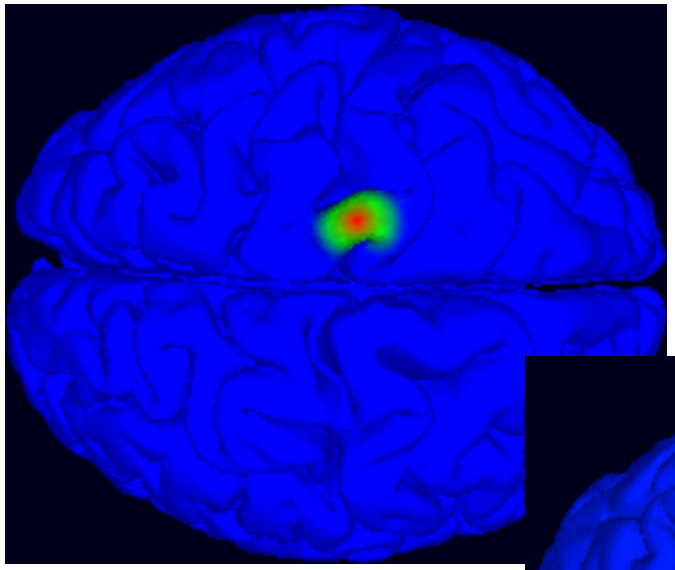


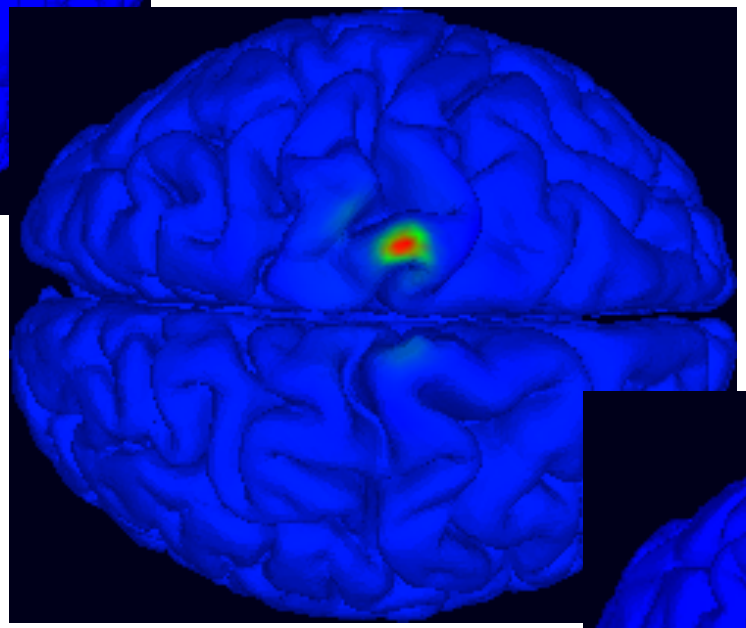
Distributed source localization

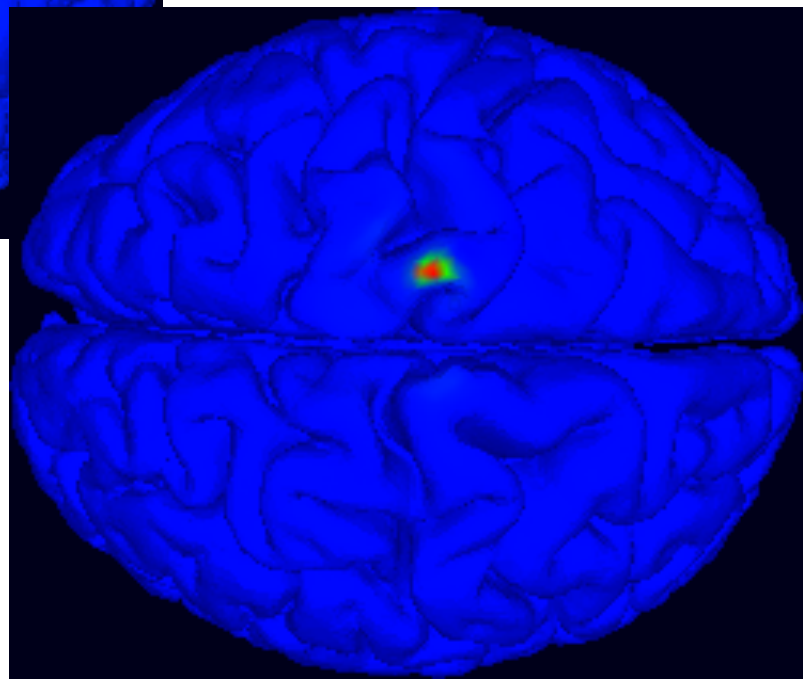
using a multiscale patch basis

0. Build a high-res. cortical surface mesh; give each voxel an oriented dipole









1. Compute a ‘dictionary’ of Gaussian patches conforming to the cortical surface centered at each cortical mesh voxel.
2. Use a ‘sparsifying’ approach to find the sum of the *fewest* of these patches that together produce the given source scalp or grid map.

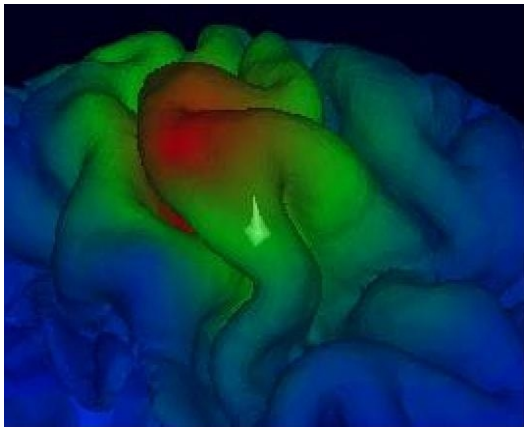
Zeynep Akalin Acar,, S. Makeig, G. Worrell, ’09-’16

Source Localization Results

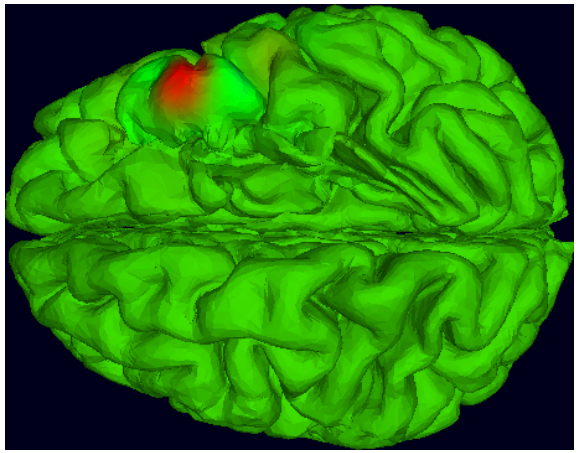
Dipole source localization

Distributed source localization - SBL

IC 1

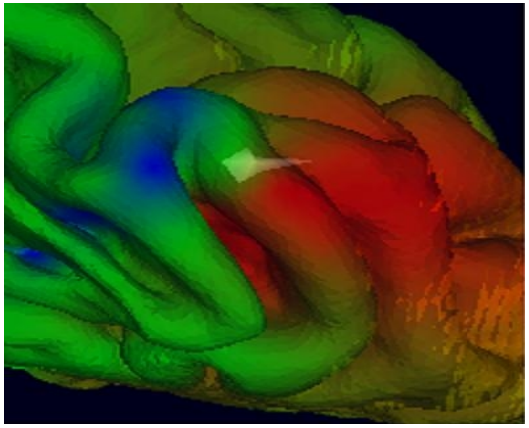


Radial source

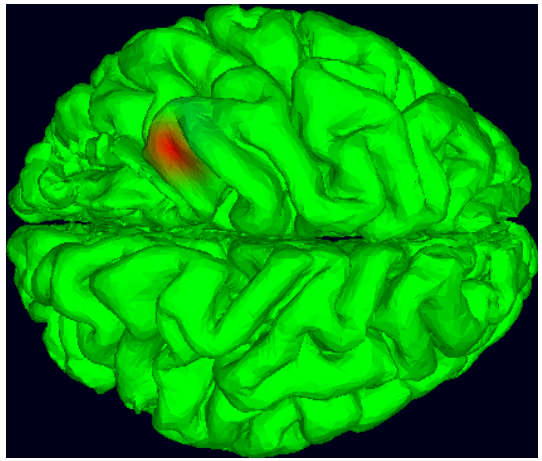


Gyral source

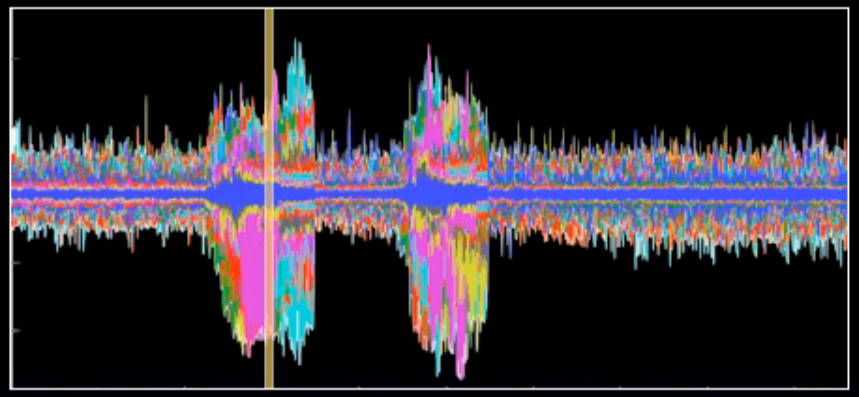
IC 2



Tangential source

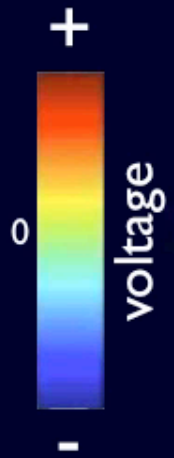


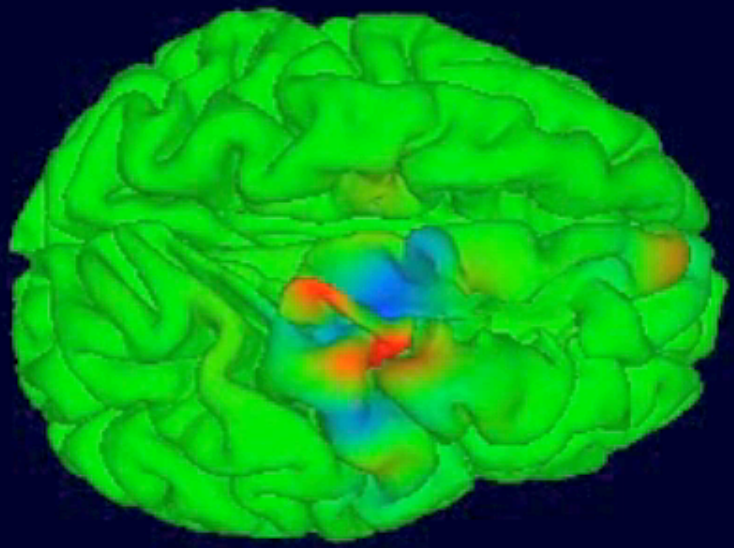
Sulcal source



1 sec

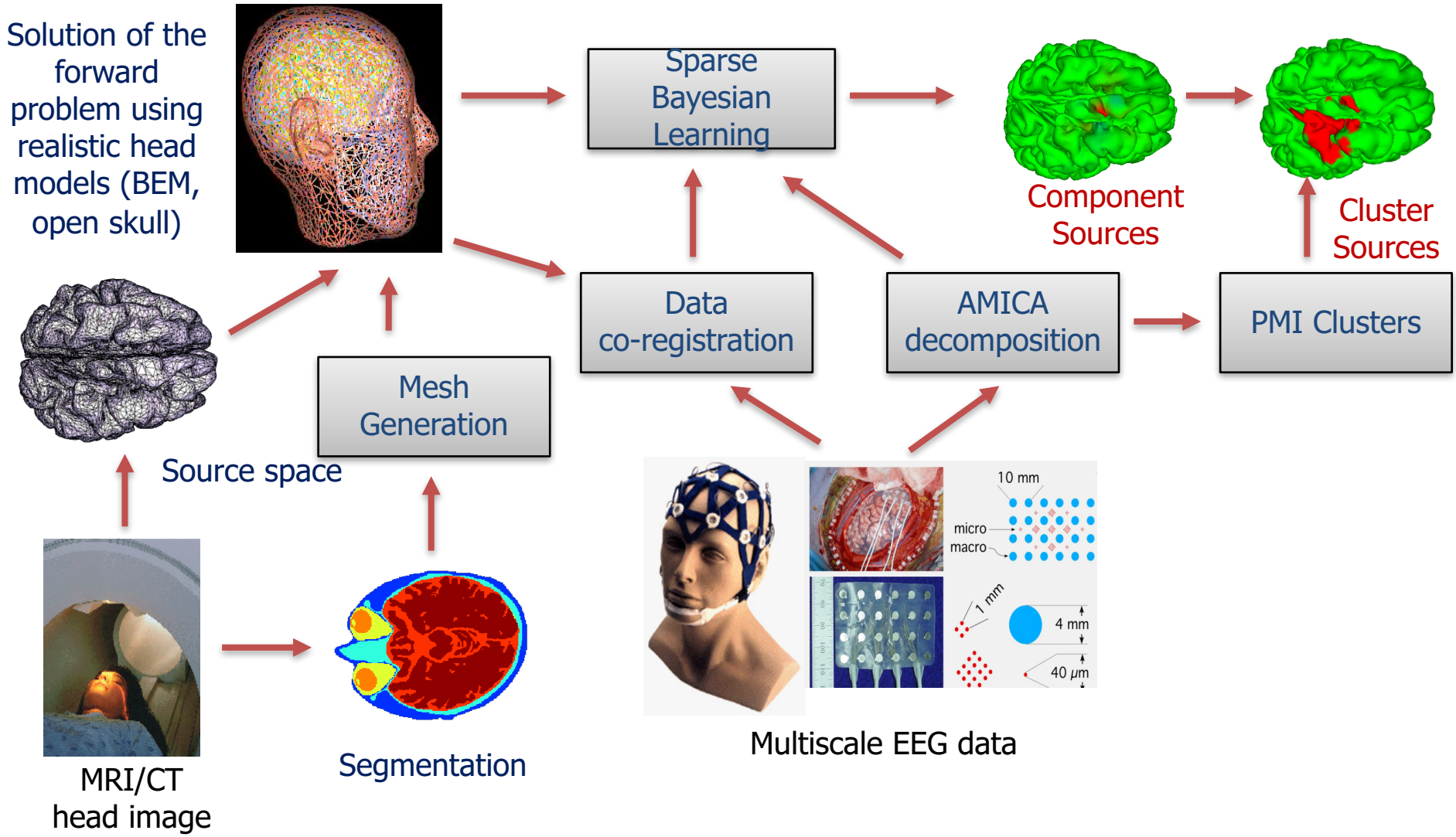
Cortical surface potentials (16 ICs, SBL solution)

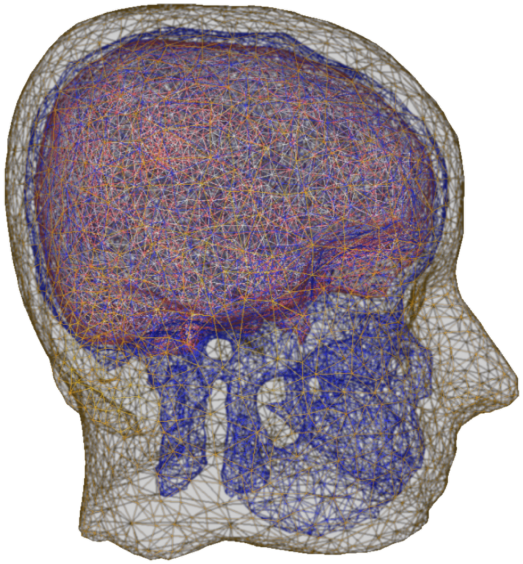


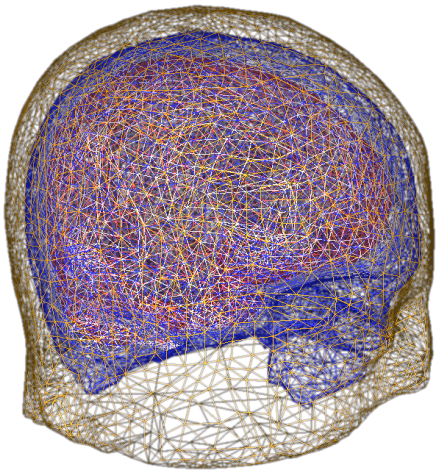


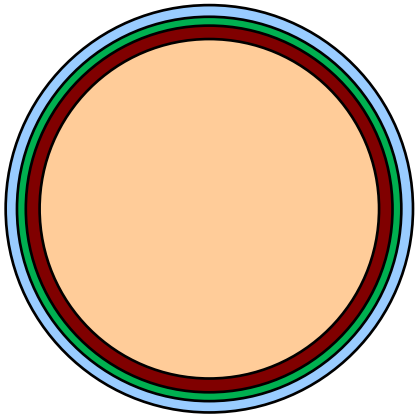
playback at 1/5 actual speed

Project Summary









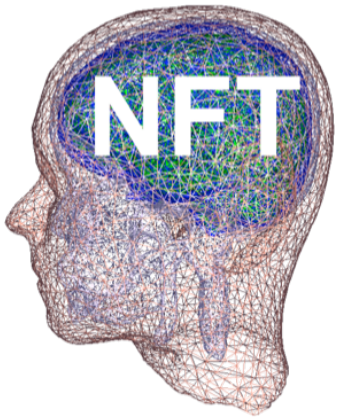
Effects of Forward Model Errors on EEG Source Localization

MODELING ERRORS

- HEAD MODELING ERRORS
- CO-REGISTRATION ERRORS
- INCLUSION OF WHITE MATTER
- # OF ELECTRODES AND DISTRIBUTION OF ELECTRODES
- MIS-ESTIMATION OF SKULL CONDUCTIVITY

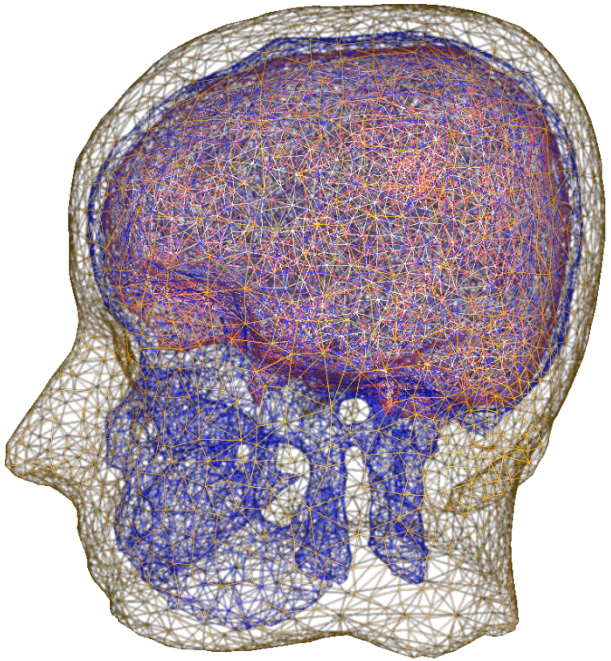
Head Model Generation

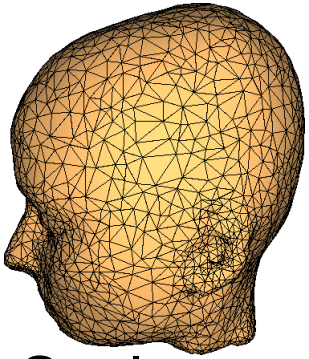
- Reference Head Model
  - From whole head T1 weighted MR of subject
  - 4-layer realistic BEM model
- MNI Head model
  - From the MNI head
  - 3-layer and 4-layer template BEM model
- Warped MNI Head Model
  - Warp MNI template to EEG sensors
- Spherical Head model
  - 3-layer concentric spheres
  - Fitted to EEG sensor locations

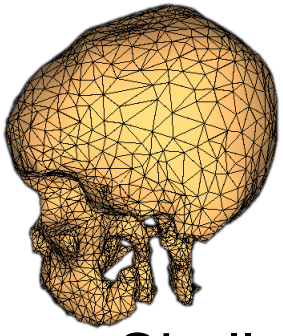


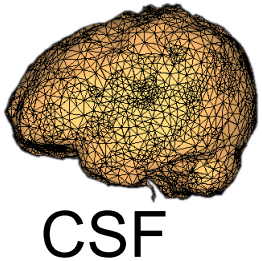
The Reference Head Model

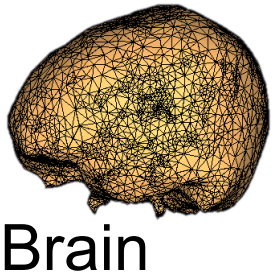
- 18541 nodes
- 37090 elements
  - 6928 Scalp
  - 6914 Skull
  - 11764 CSF
  - 11484 Brain



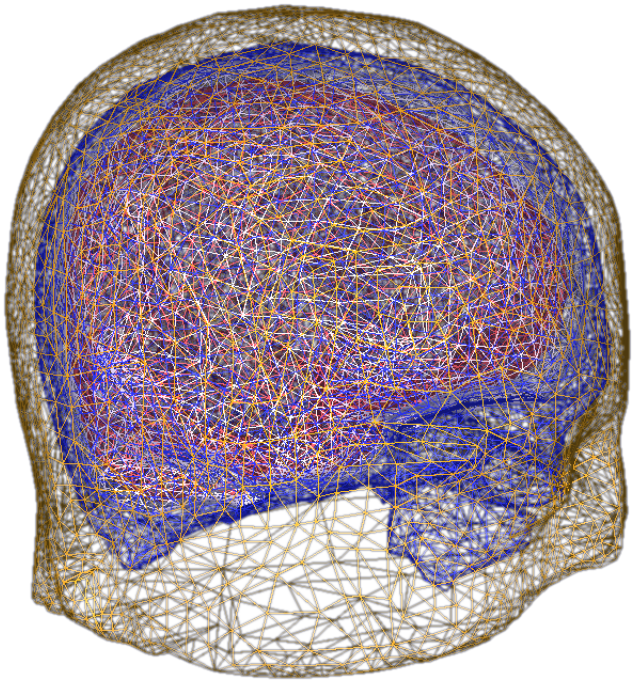




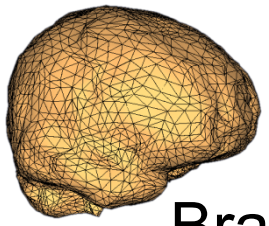


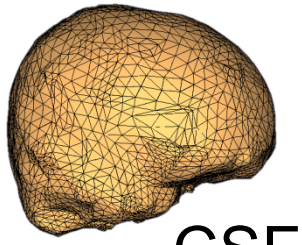


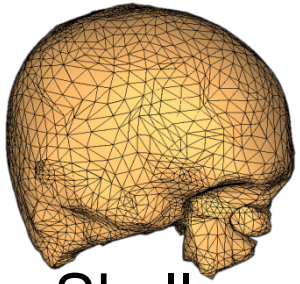
The MNI Head Model

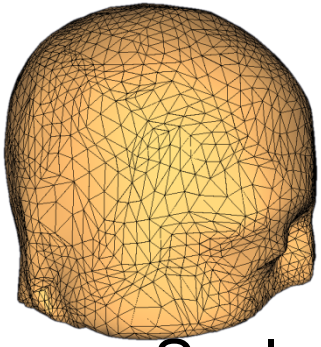


- 4-layer
  - 16856 nodes
  - 33696 elements
- 3-layer
  - 12730 nodes
  - 25448 elements

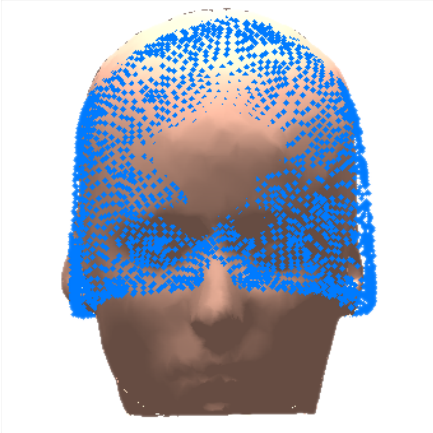

Brain

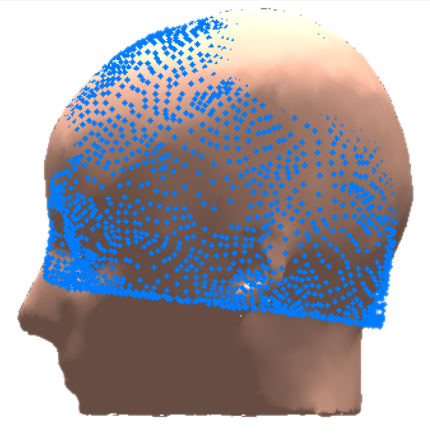

CSF


Skull

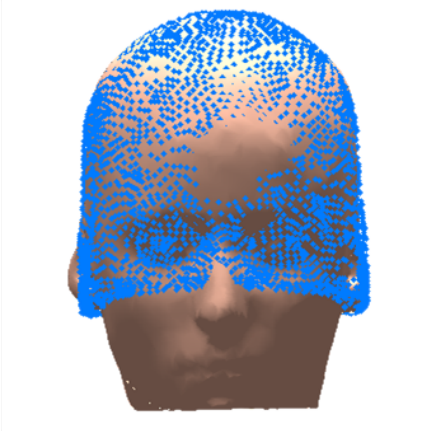

Scalp

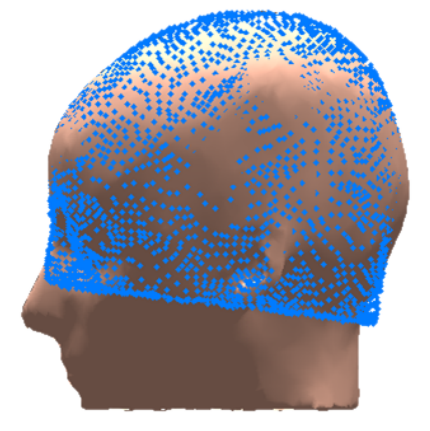
The Warped MNI Head Model





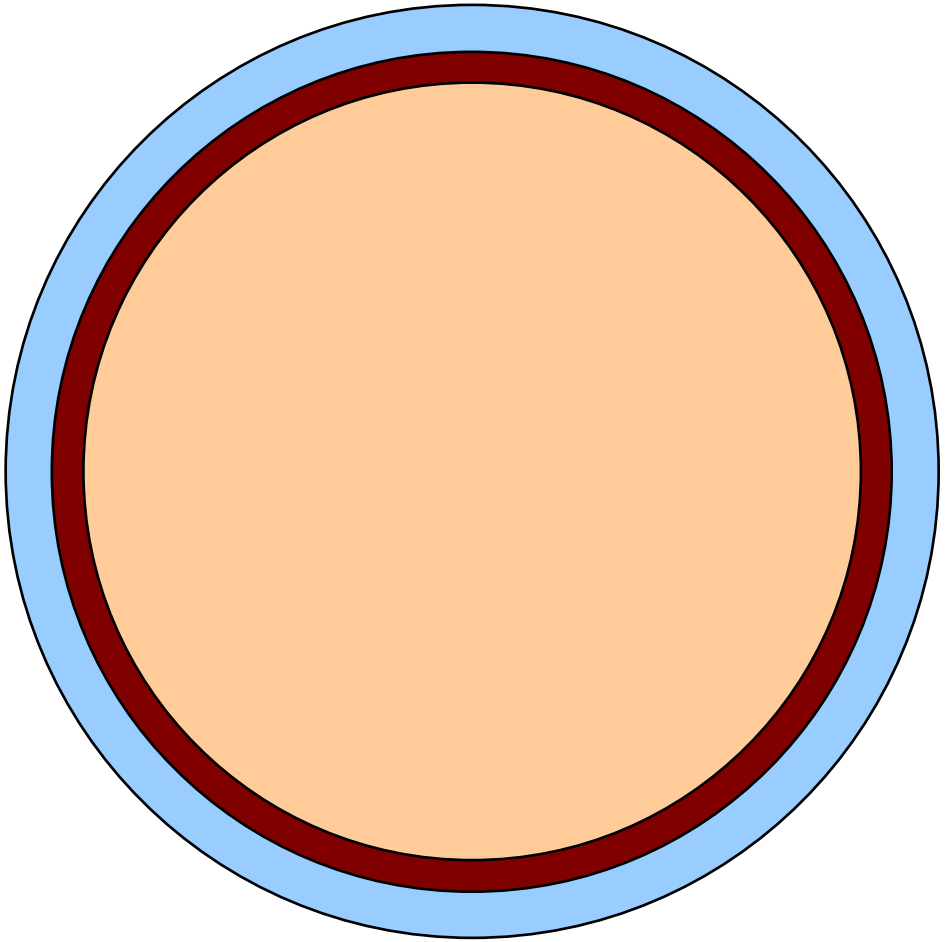
Registered MNI template





Warped MNI mesh

The Spherical Head Model

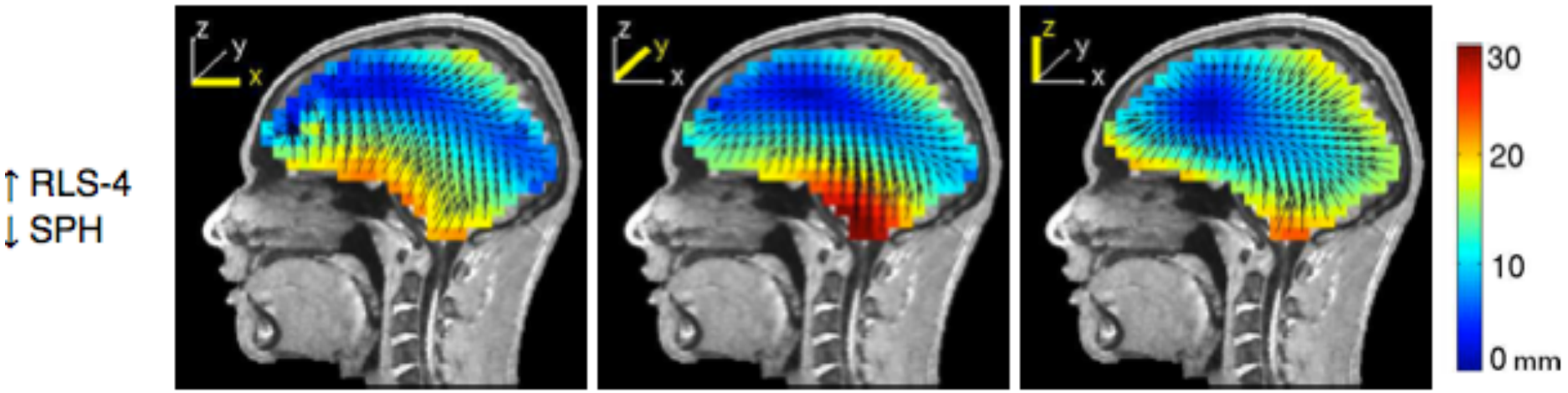


3-Layer model
Outer layer is fitted to electrode positions

Head Modeling Errors

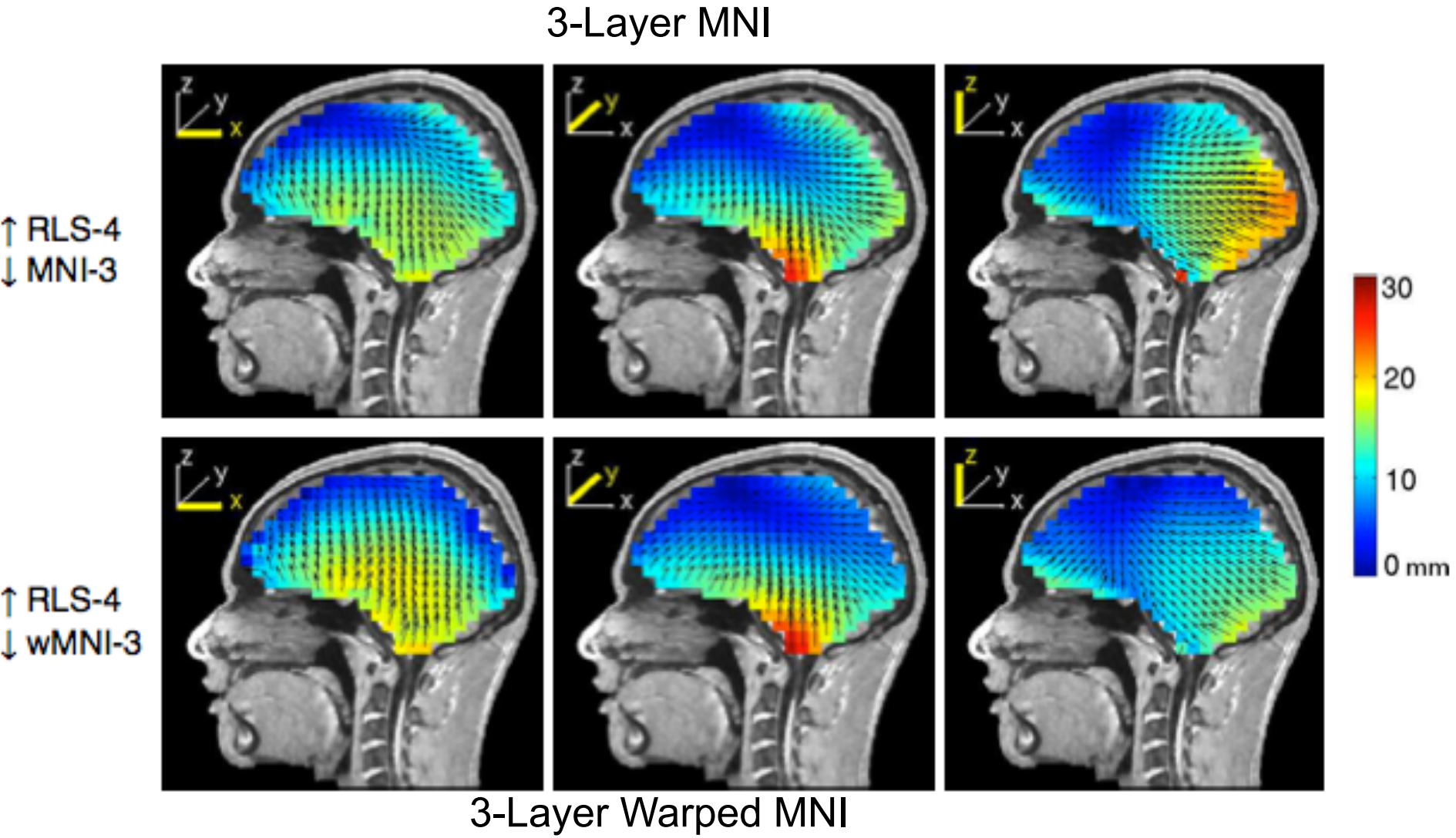
- Solve FP with reference model
  - 3D grid inside the brain.
  - 3 Orthogonal dipoles at each point
  - ~7000 dipoles total
  - 4 subjects
- Localize using other head models
  - Single dipole search.
- Plot location and orientation errors

Spherical Model Location Errors

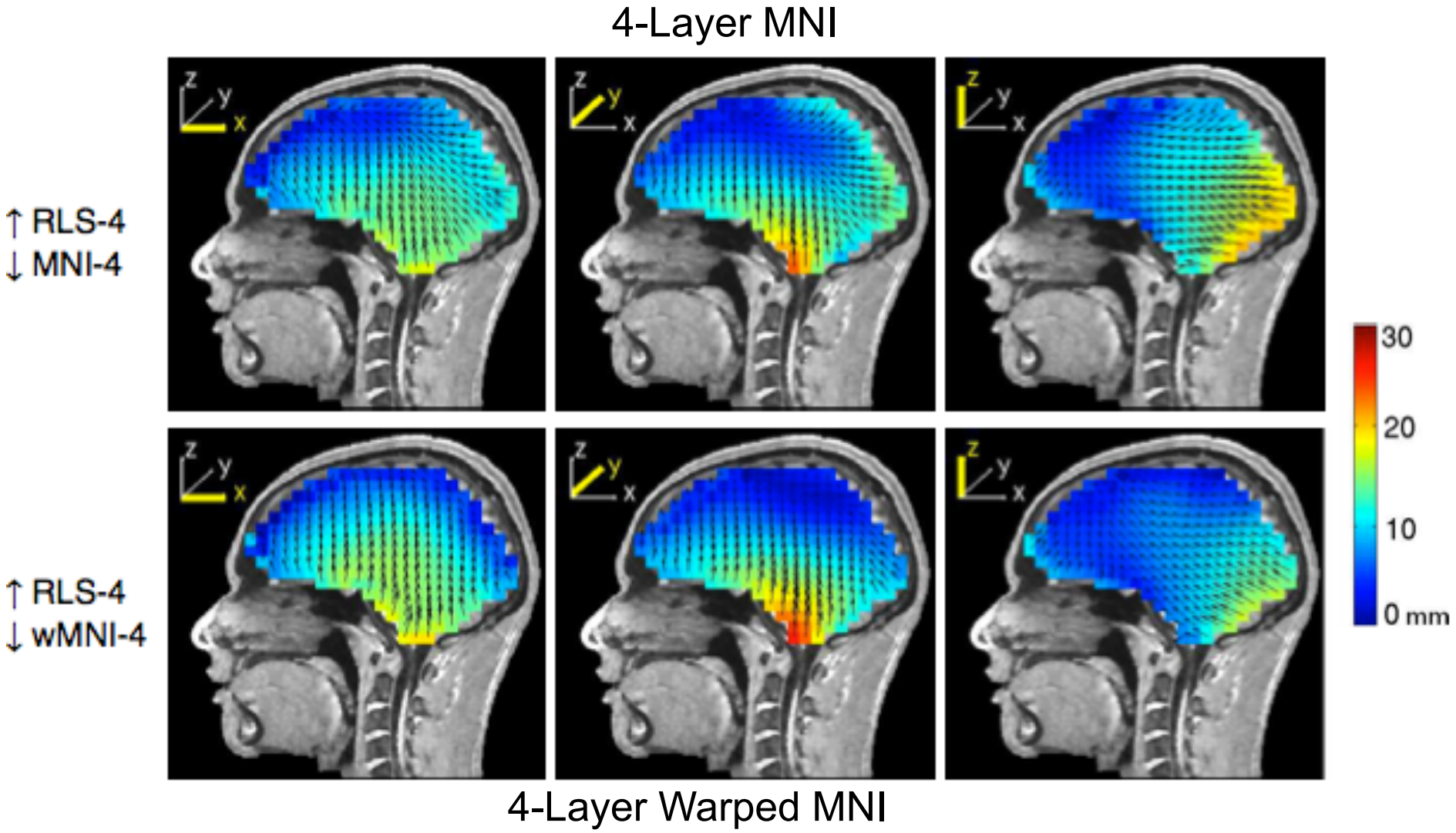


Localization errors may go up to 4 cm when spherical head models are used for source localization.
The errors are largest in the inferior regions where the spherical models diverged most from the 4-layer realistic model.

3-Layer MNI Location Errors



4-Layer MNI Location Errors

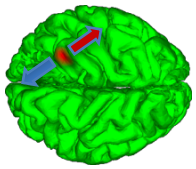


Observations

- Spherical Model
  - Location errors up to 3.5 cm. Cortical areas up to 1.5 cm.
- 3-Layer MNI
  - Large errors where models do not agree.
  - Higher around chin and the neck regions.
- 4-Layer MNI
  - Similar to 3-Layer MNI.
  - Smaller in magnitude.

Summary

- If we have MRI of the subject:
  - Subject specific head model
  - Distributed source localization
- If we don't have MRIs
  - Warped 4-layer MNI model
  - Dipole source localization
- Skull conductivity estimation is as important as the head model used.
- WM modeling does not have much effect on source localization.



Summary

- An electromagnetic **forward head model** is required to interpret the sources of scalp maps
- Interpretation of scalp maps in terms of brain source distributions is "**inverse** source estimation"

→ Mathematical techniques are available to aid in interpreting scalp maps as arising from particular brain sources

→ These require an **inverse source model**, i.e. assumptions about the possible locations and nature of the sources (i.e., what attributes make them ***physiologically plausible***).

→ Then search for the ***most plausible*** source model.

R. Oostenveld, & S. Makeig, 2016

Thank you…

Swartz Center for Computational Neuroscience