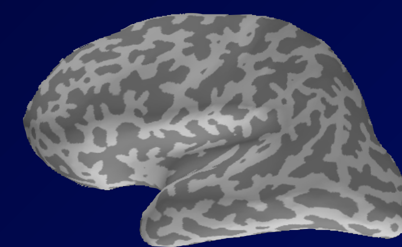
From Neural Currents to Data: MEG Instrumentation and the Forward Problem

Matti Hämäläinen



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Jyväskylä Summer School 2013

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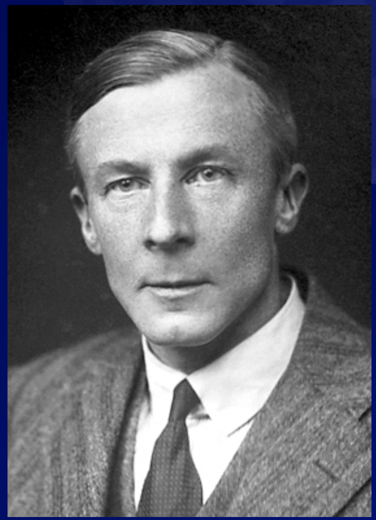
"That is a very long way from saying that the EEG can tell us how the subject will think and act. In fact, the information which it gives relates to a very limited field.

But the limitation arises mainly from the fact that we can only record the gross effects and not the detailed patterns in the brain. With present methods the skull and the scalp are too much in the way, and we need some new physical method to read through them."

"In these days we may look with some confidence to the physicists to produce such an instrument, for it is just the sort of thing they can do."

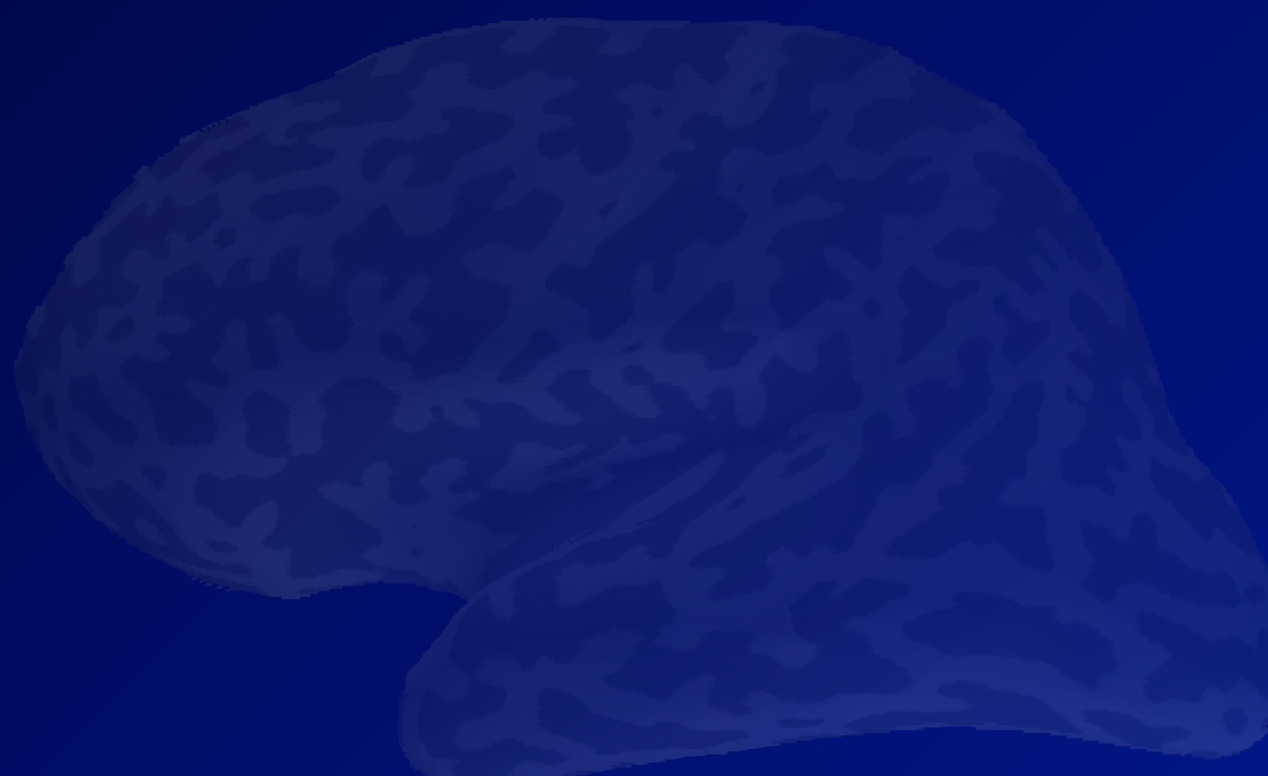


Edgar D. Adrian: Brain Rhythms
Nature 1944, **153**: 360-362

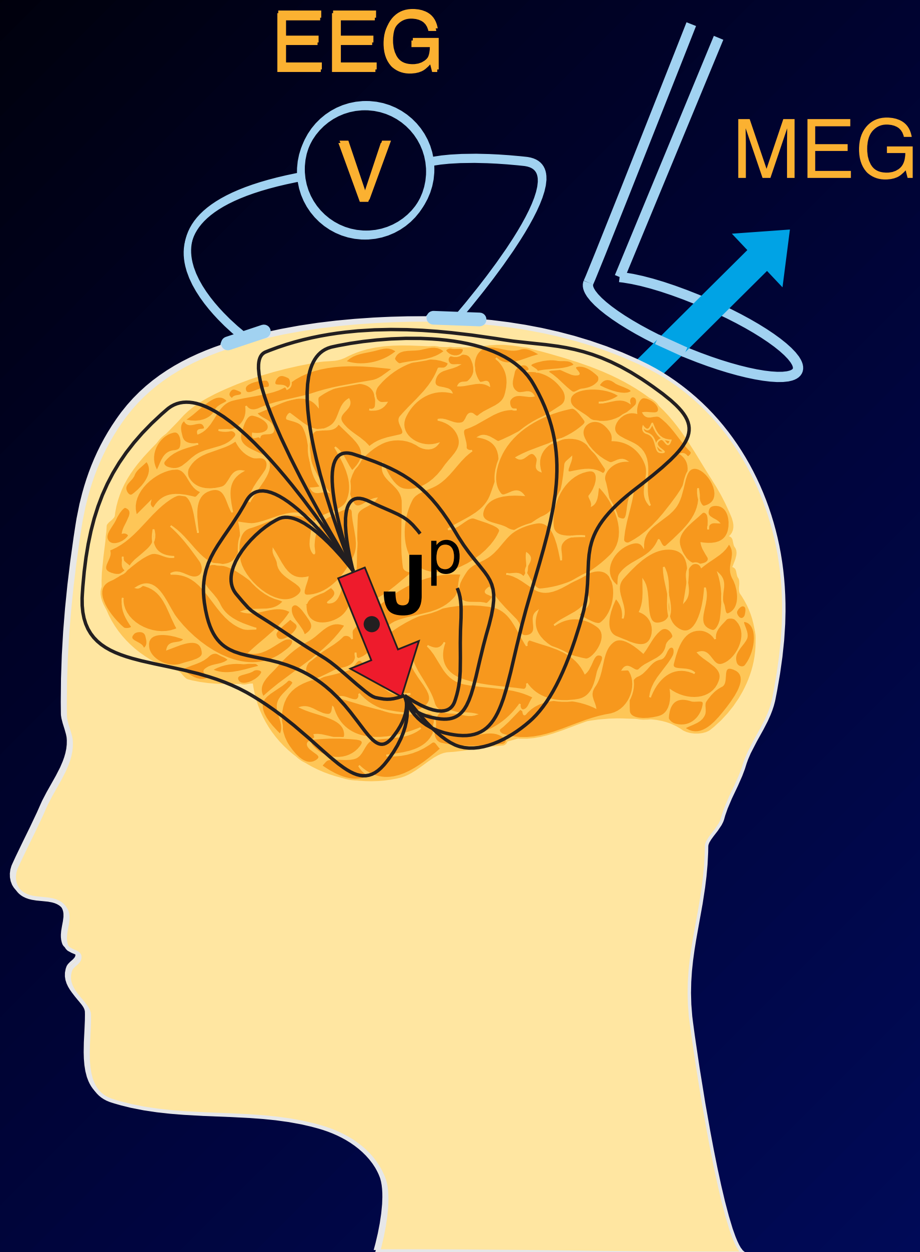
Contents

- General about MEG/EEG forward models
- Properties of the sphere model
- From sources to measurements
- The equivalent current dipole
- Multiple and extended sources
- MEG Instrumentation
- Summary

MEG and EEG forward models



MEG and EEG



- The primary current is related to the postsynaptic activity
- The primary current generates a potential distribution (EEG) and the associated volume currents
- The primary and volume currents together also create a magnetic field (MEG)
- However, the net effect of volume currents is rather straightforward to take into account in MEG whereas the it is difficult to compute the EEG potential distribution accurately

Forward models: overview

- MEG and EEG signals are slow: time dependencies can be ignored from the Maxwell's equations (quasistatic approximation)
- MEG is an "integral" effect of currents
- EEG is a local measure of the electric field: conductivity matters
- MEG and EEG have common neural sources

Forward models for MEG and EEG

Sphere model

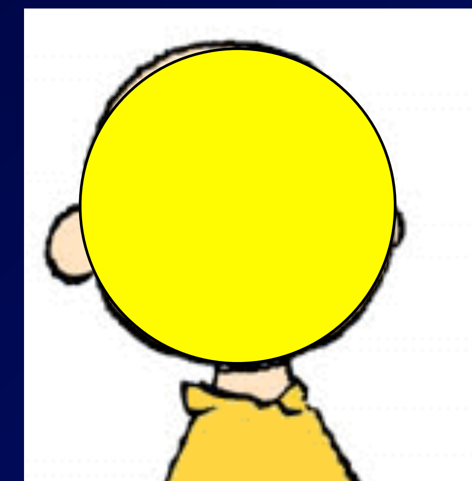
$\sigma = \sigma(r)$

MEG

=

EEG

≠



Boundary-element models (BEMs)

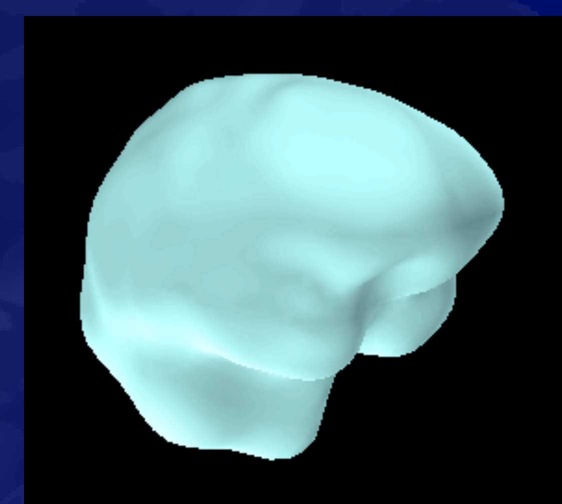
Skull and scalp taken into account

MEG

≈

EEG

≠



Homogeneous model:
skull taken as an insulator

Theoretical analysis: Hämäläinen and Sarvas, 1989
Experimental validation: Okada *et al.*, 1999

The sphere model

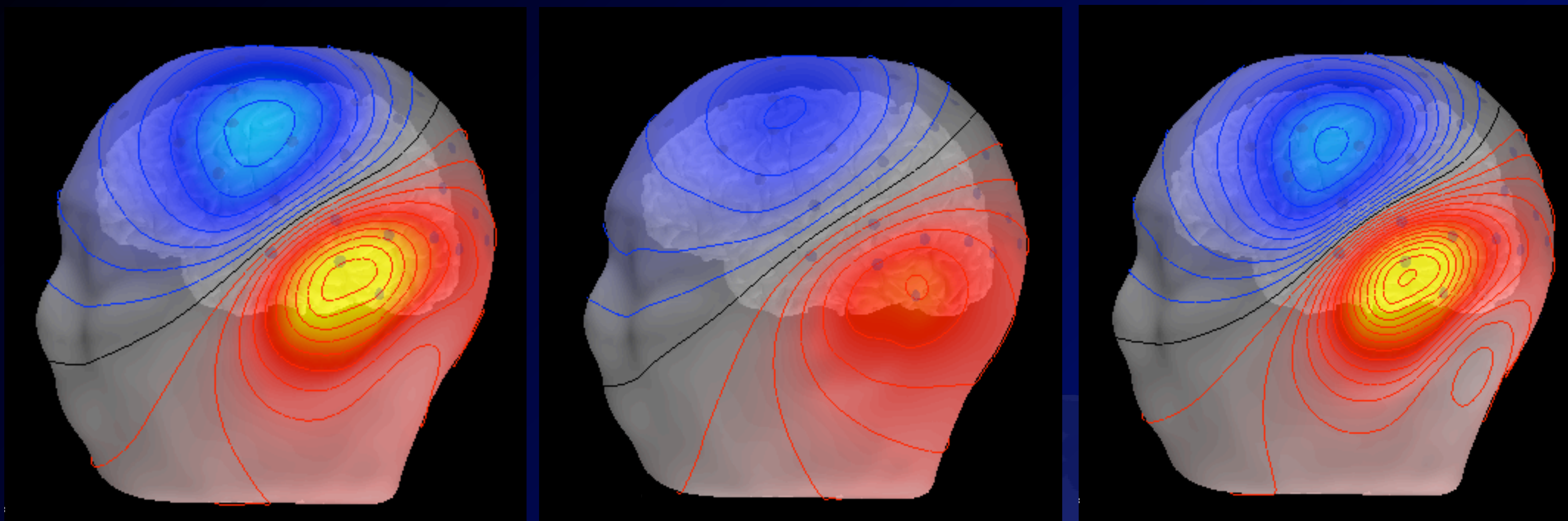
MEG and EEG in the sphere model

MEG: Conductivity profile is irrelevant

EEG: Conductivity information needed

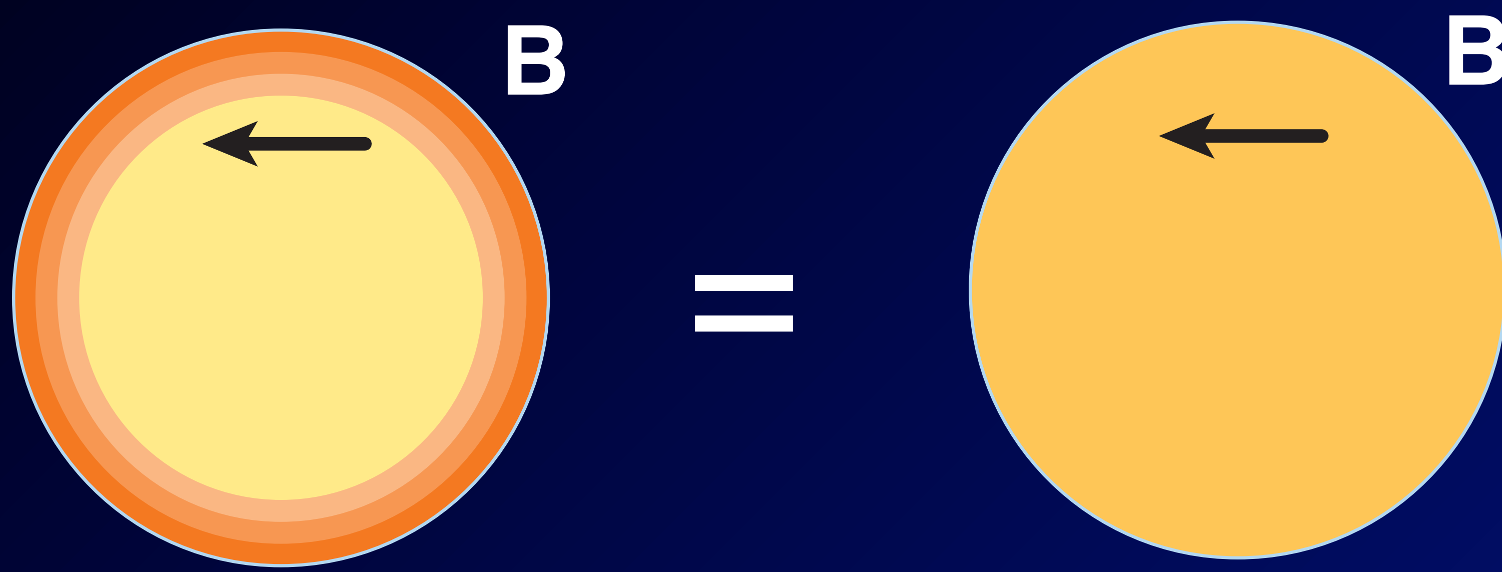
Effect of Conductivities on EEG

Homogeneous | With skull | Poorly conducting skin

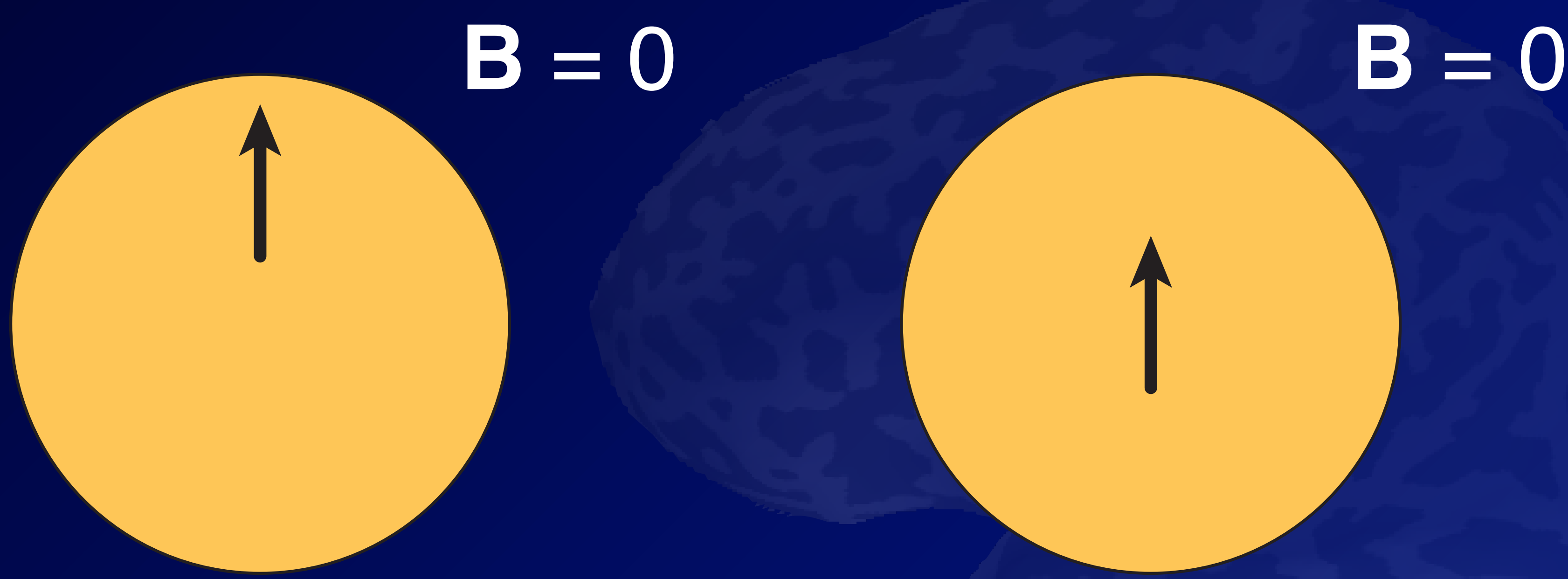


Note: MEG remains unchanged

Sphere model properties

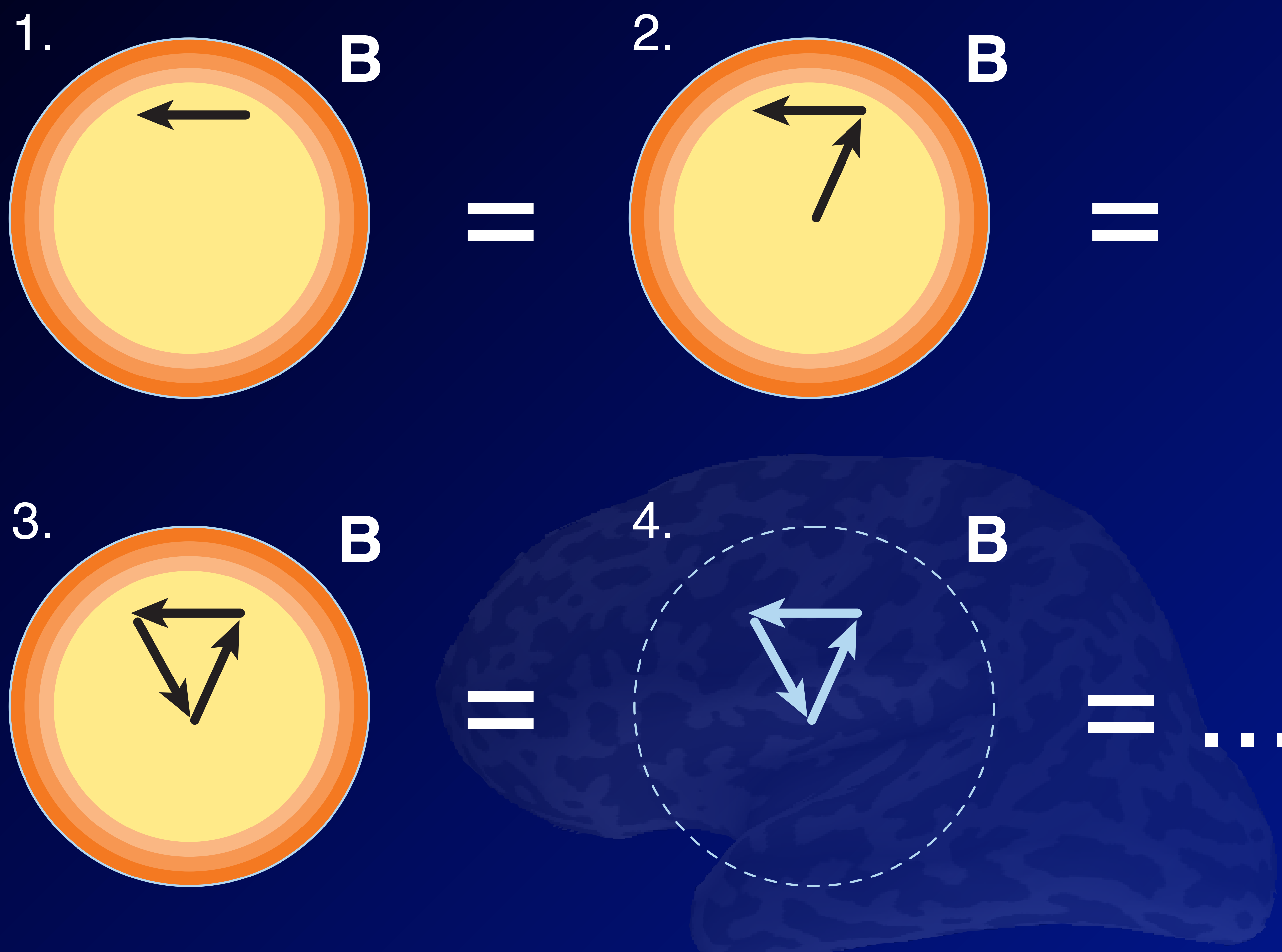


Conductivity profile is irrelevant



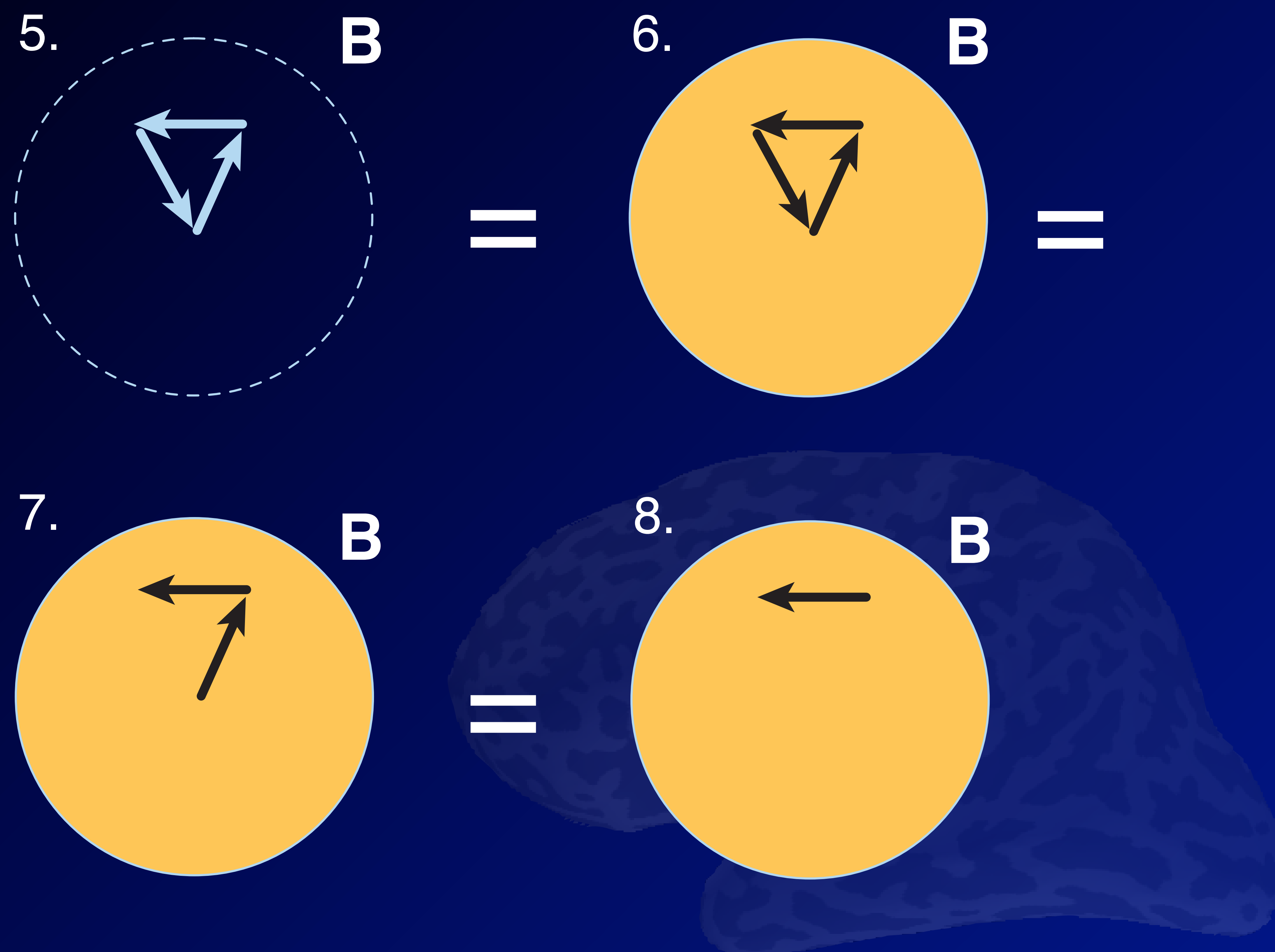
No magnetic field from radial currents

Dipole in a sphere: Add radial sources

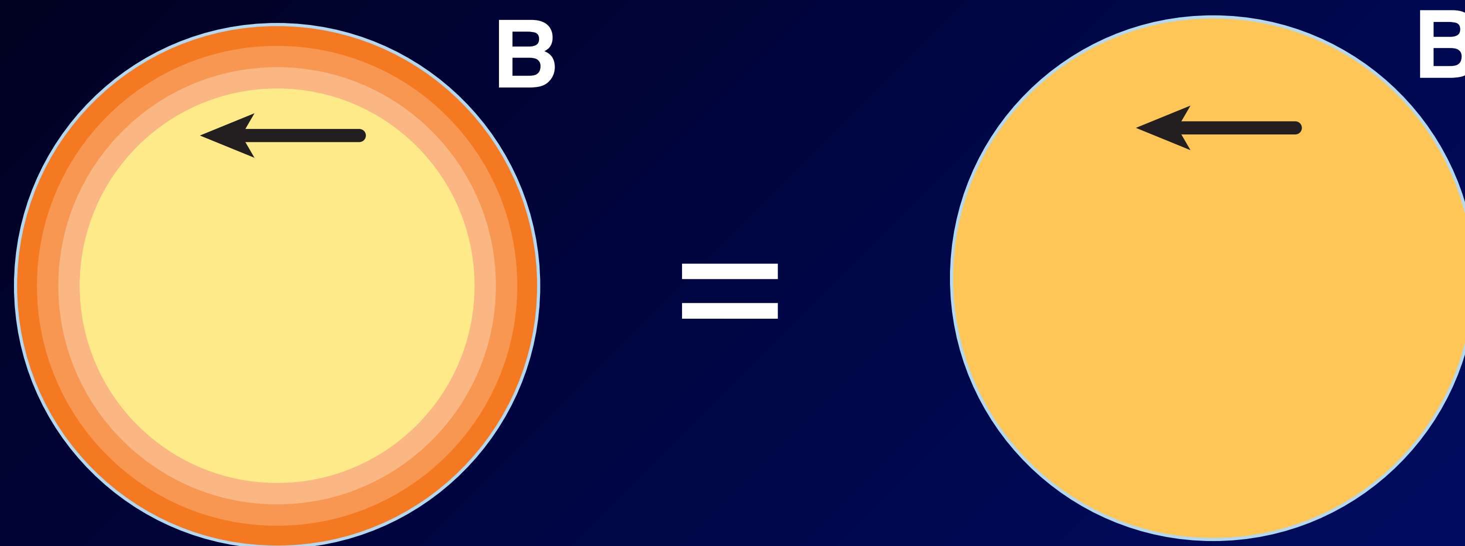


Ilmoniemi, Hämäläinen and Knuutila, 1984

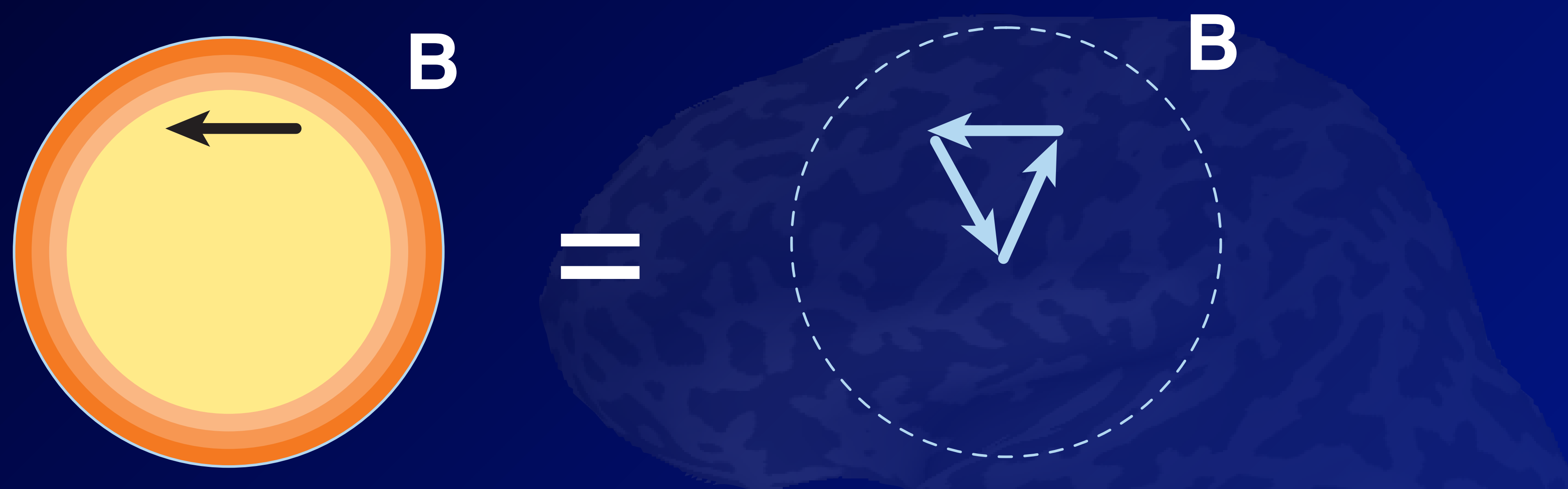
Change to a homogeneous sphere



Summary of the sphere model graph theory



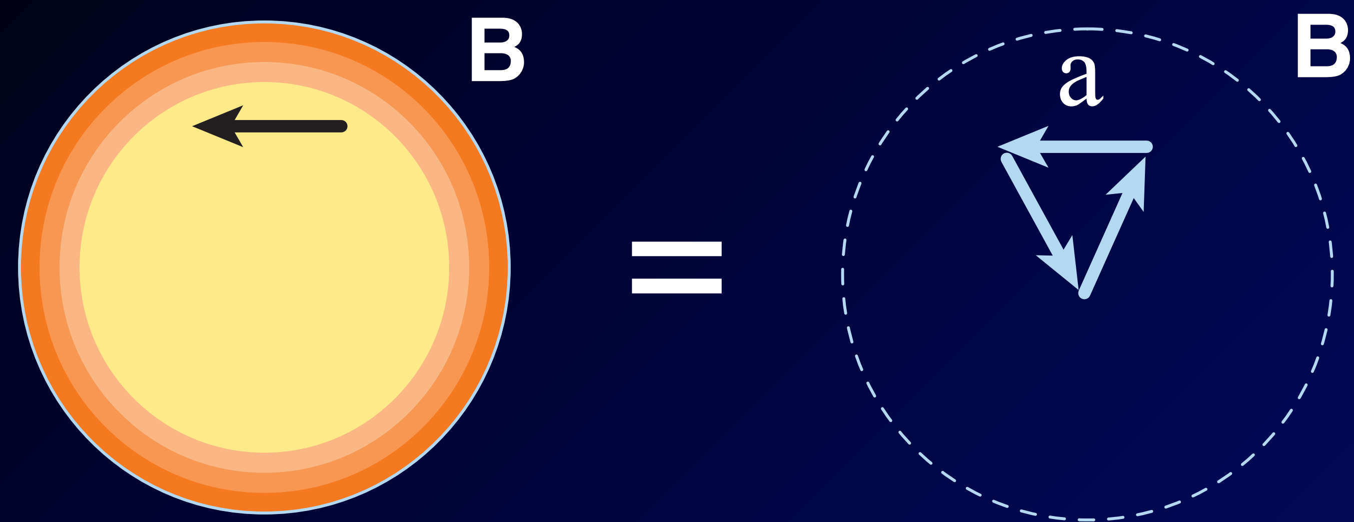
Conductivity profile is irrelevant



Simplified forward calculation

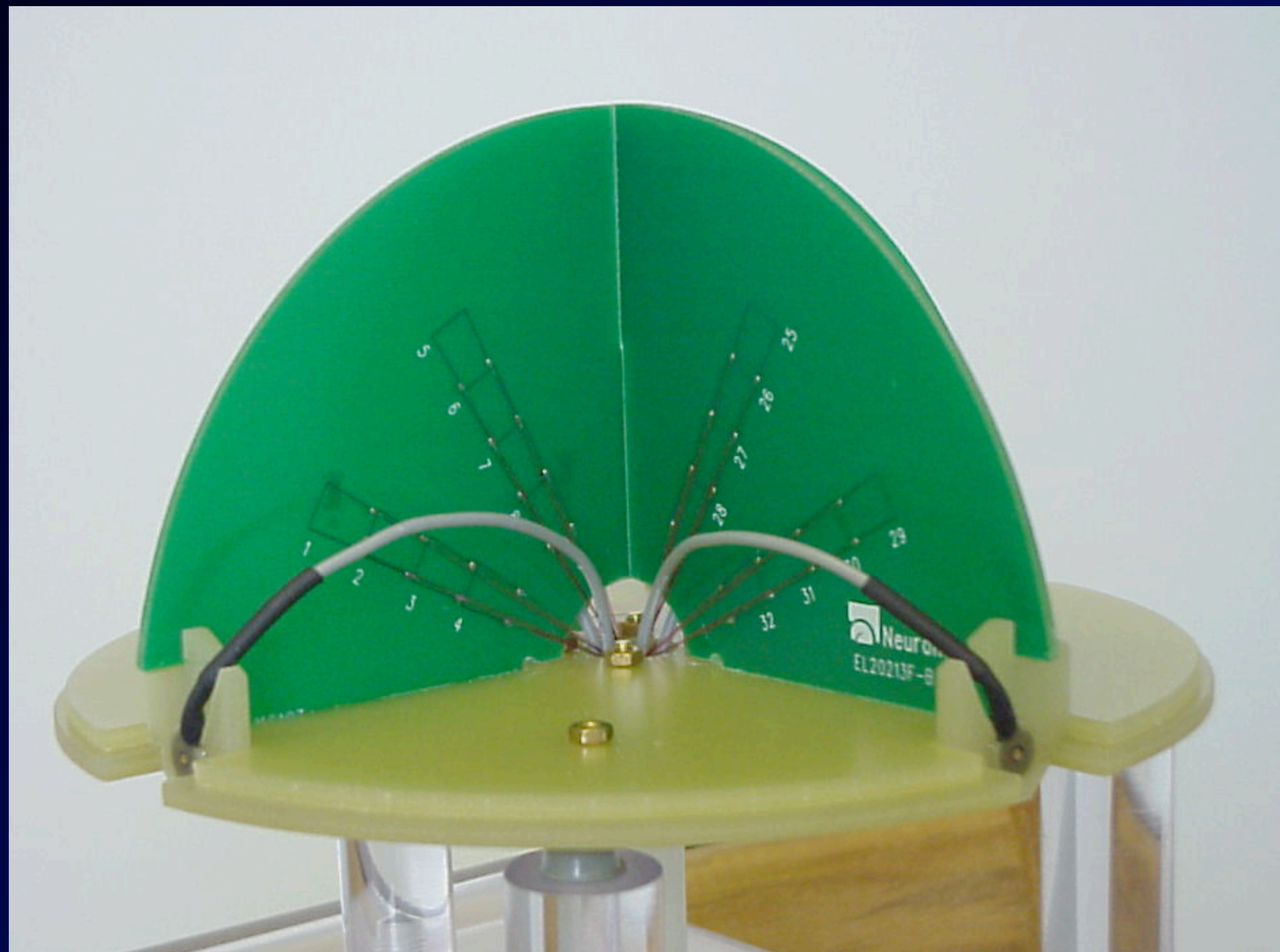
A dry phantom can be constructed

Application: New way to compute the forward solution in the sphere model

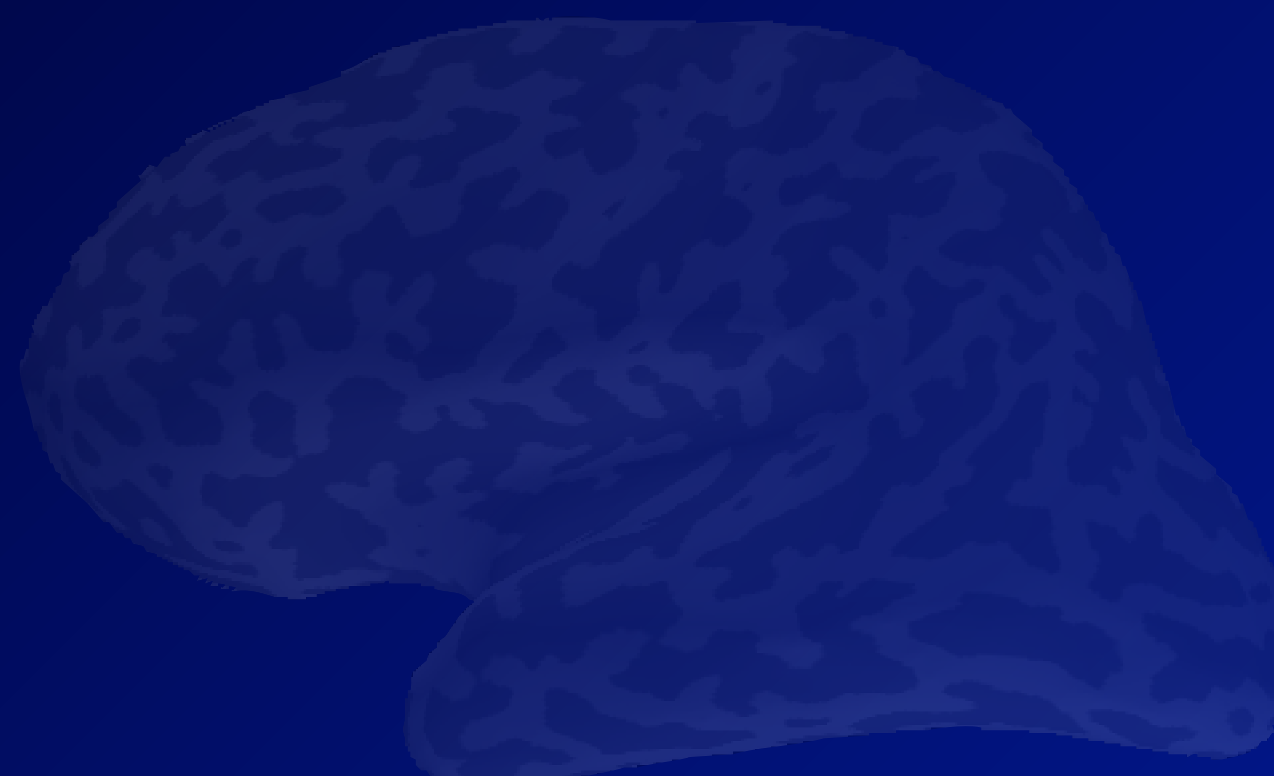


- Do a line integral over the loop to get the magnetic scalar potential Φ_m outside the conductor
- Take the limit $a \to 0$ keeping $aI = Q$ constant
- Calculate the gradient of Φ_m to obtain $\vec{B}$

Application: a dry dipole phantom

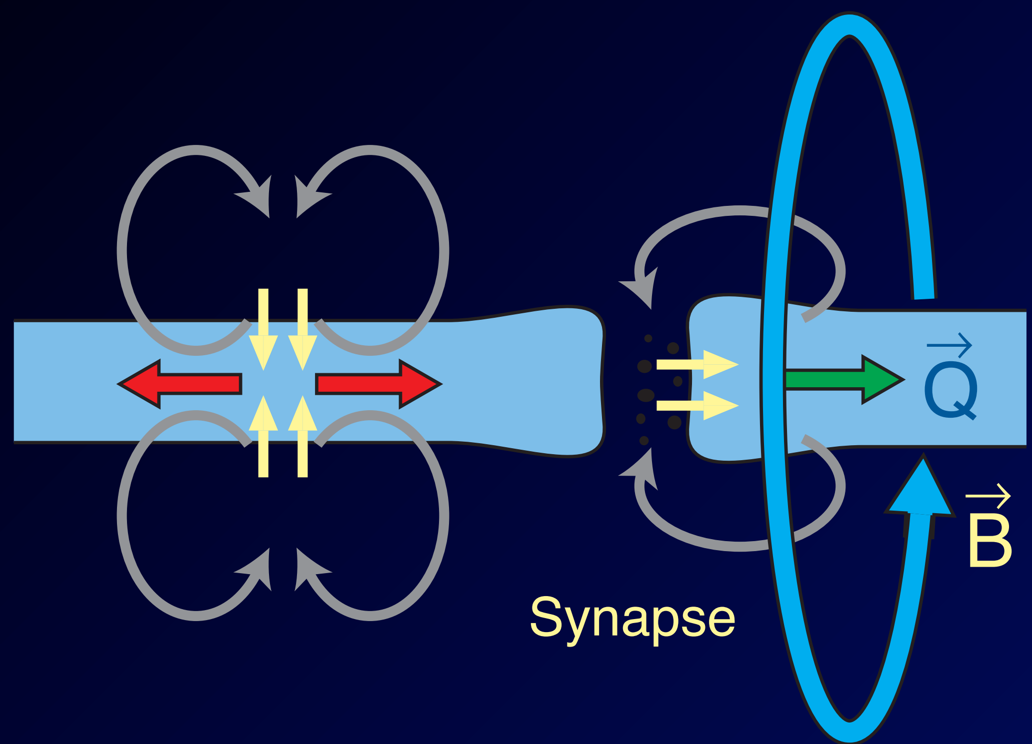


MEG/EEG Sensitivity to Neural Sources



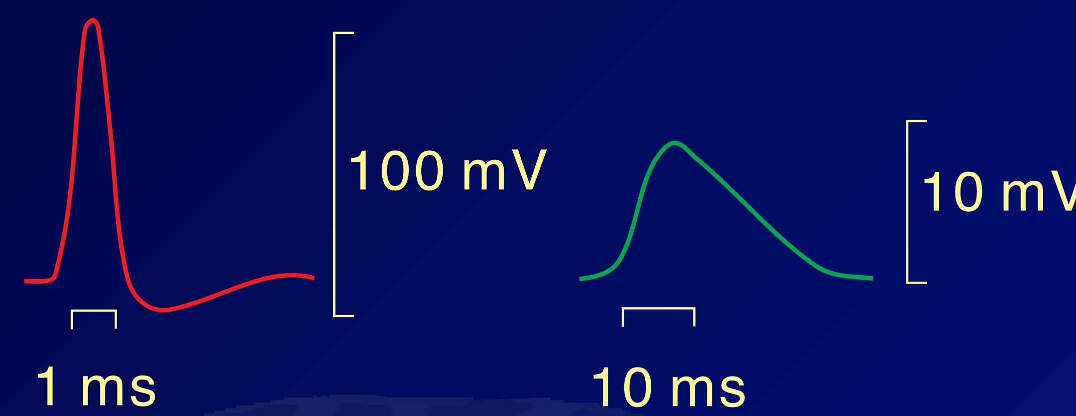
Neural sources of MEG and EEG

Current configurations



Action currents Postsynaptic currents

Time behavior

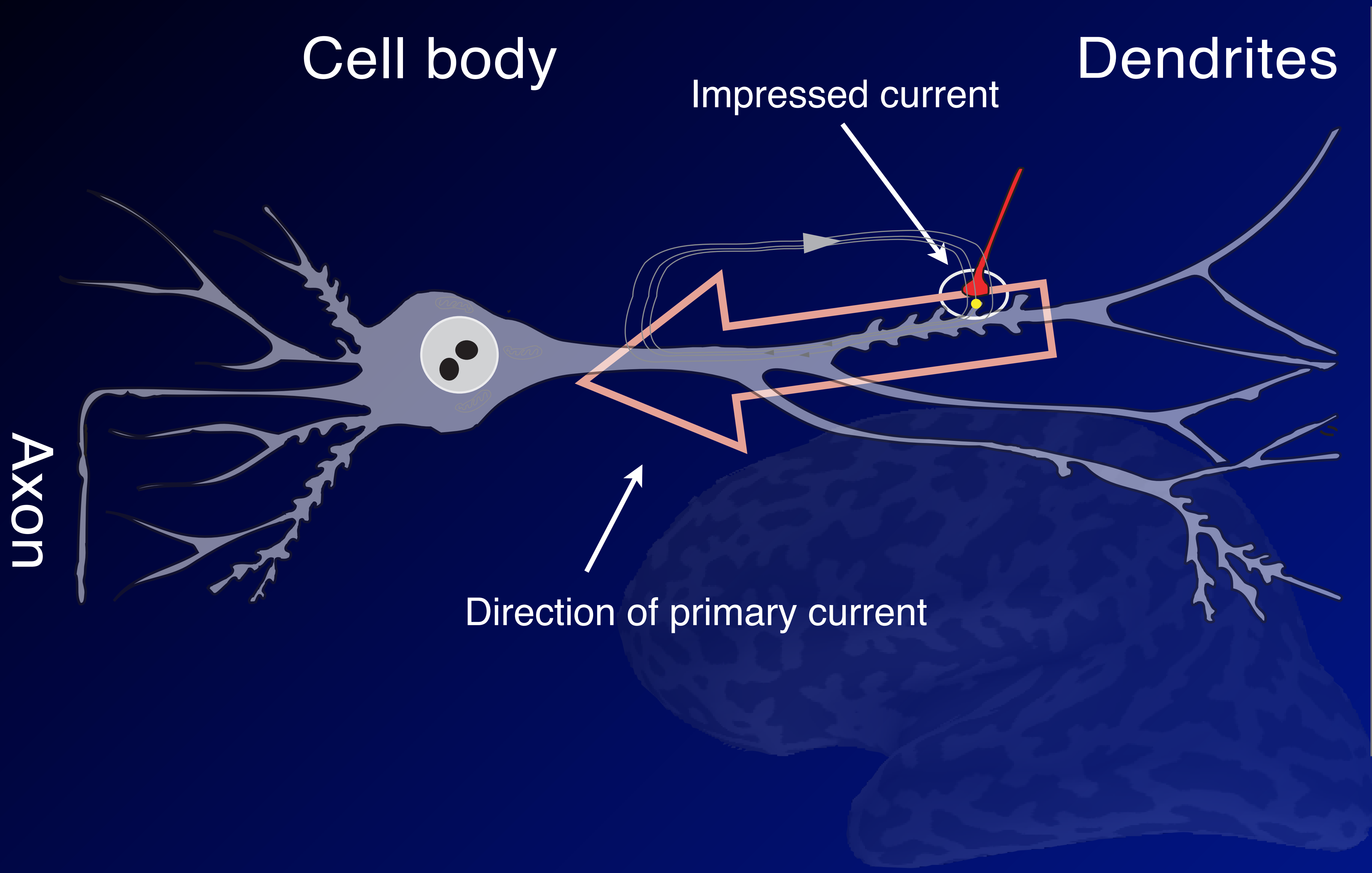


Action potential Postsynaptic potential

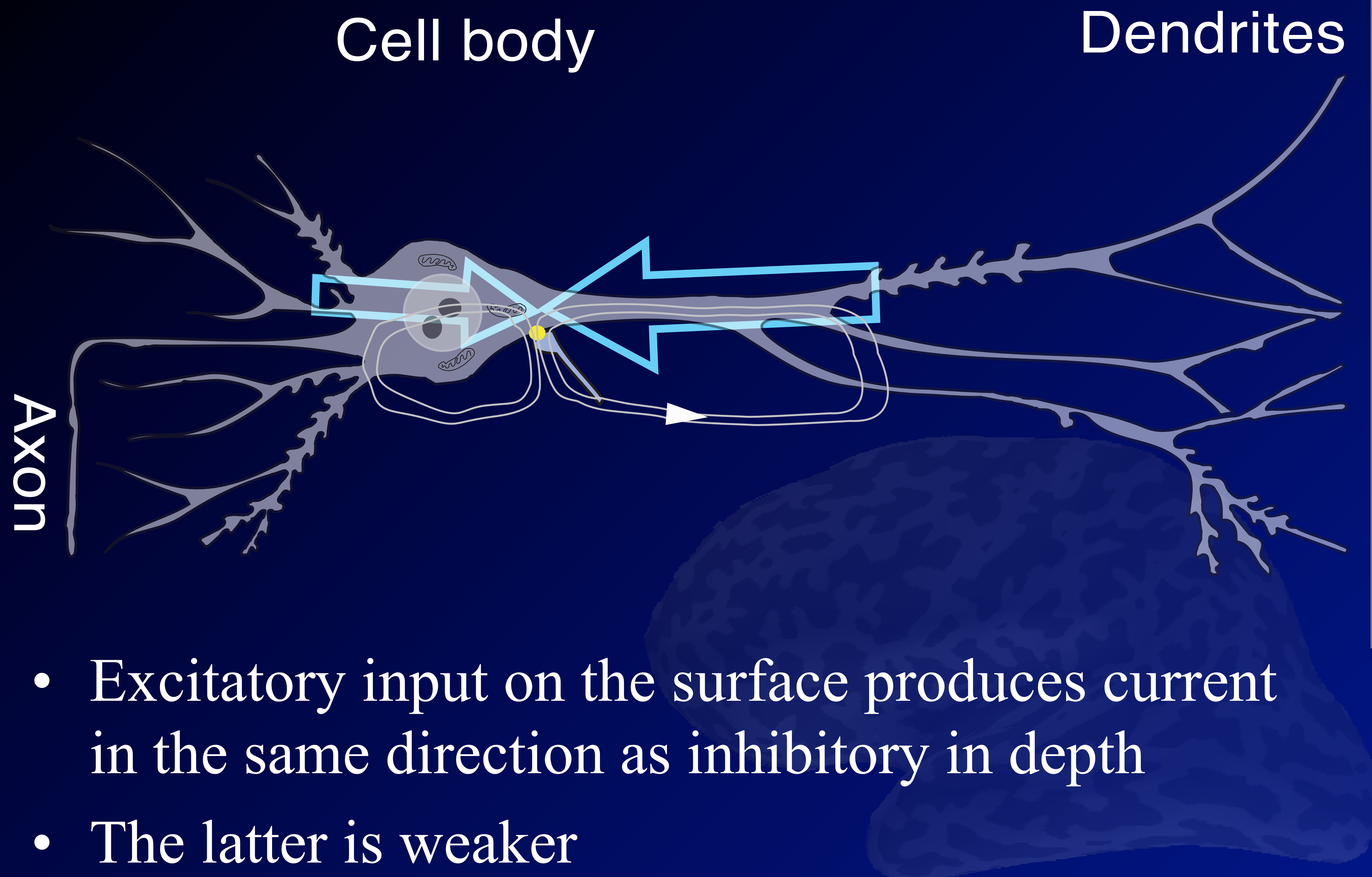
Postsynaptic currents dominate:

- Unidirectional (dipolar) currents
- Longer time course

Excitatory synaptic current

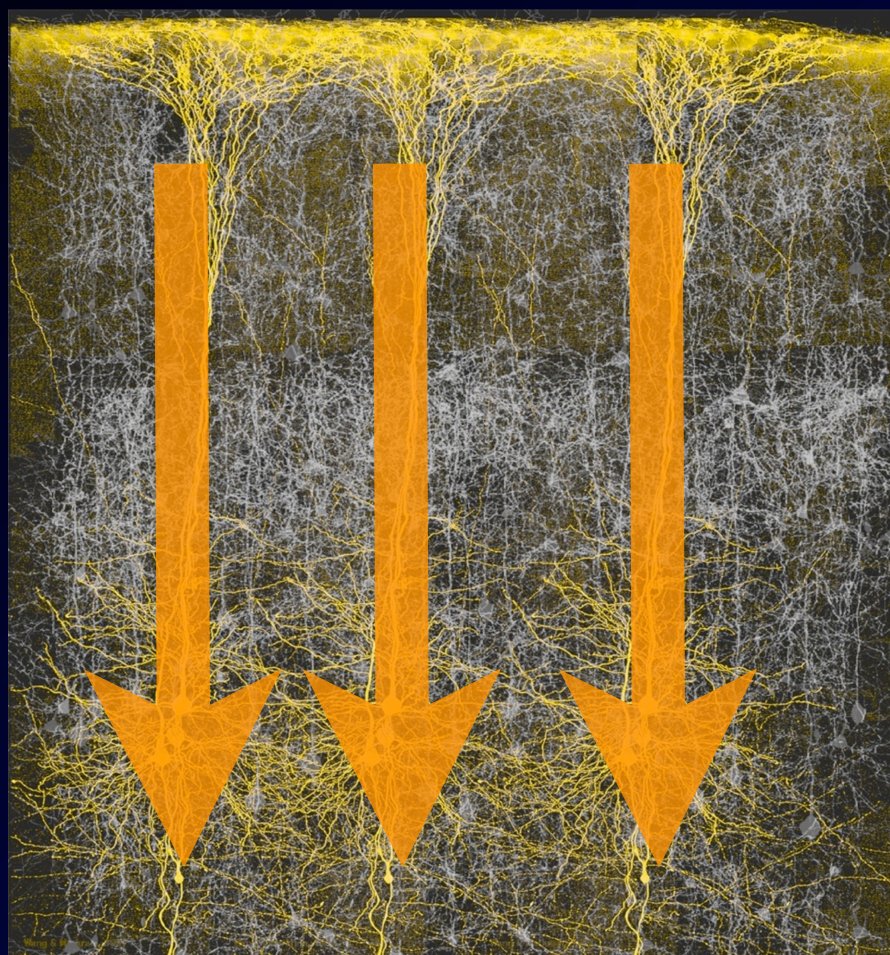


Inhibitory synaptic current

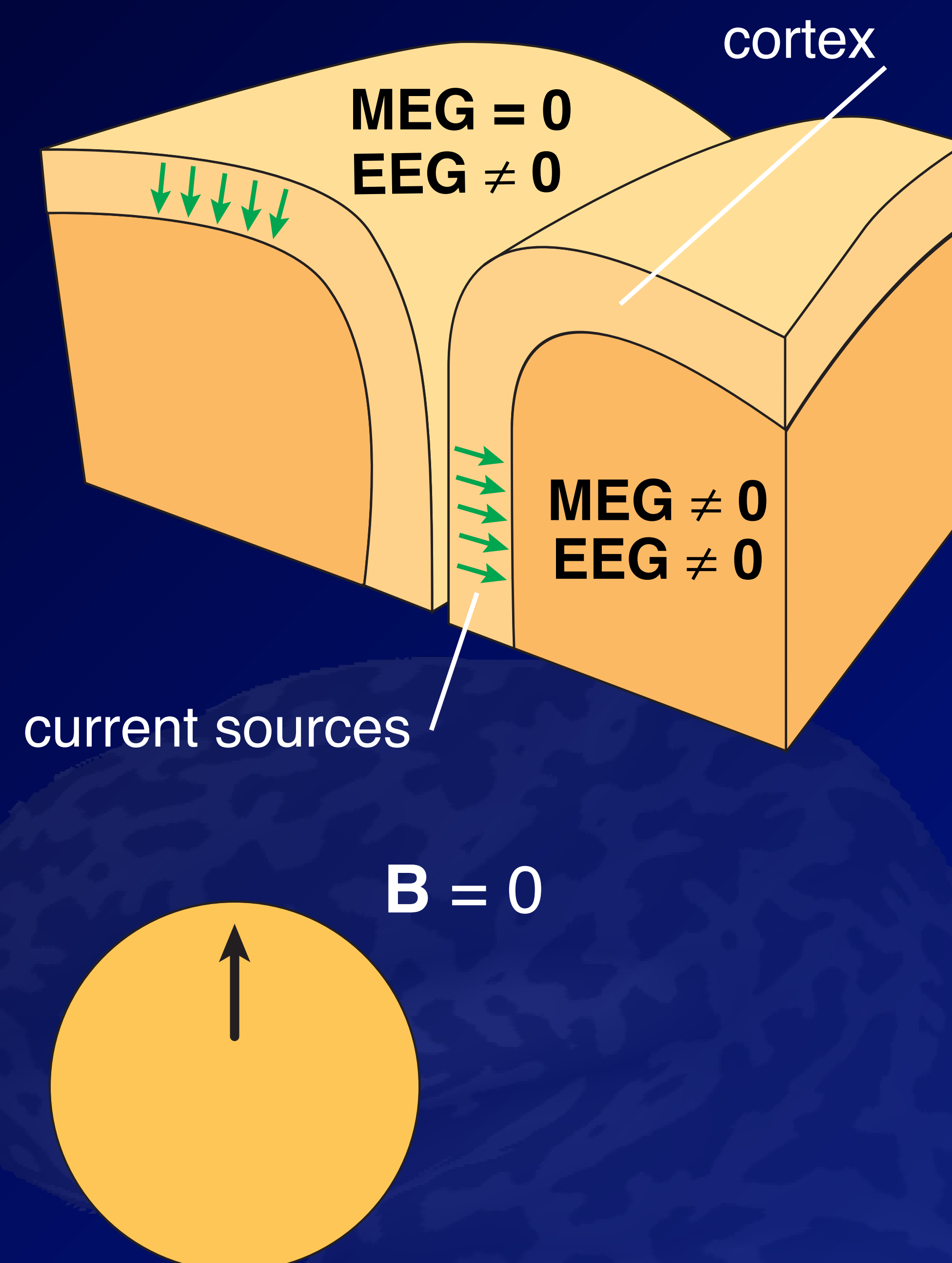


- Excitatory input on the surface produces current in the same direction as inhibitory in depth
- The latter is weaker

Primary currents in the cortex



Primary currents



No magnetic field from radial currents in the sphere model

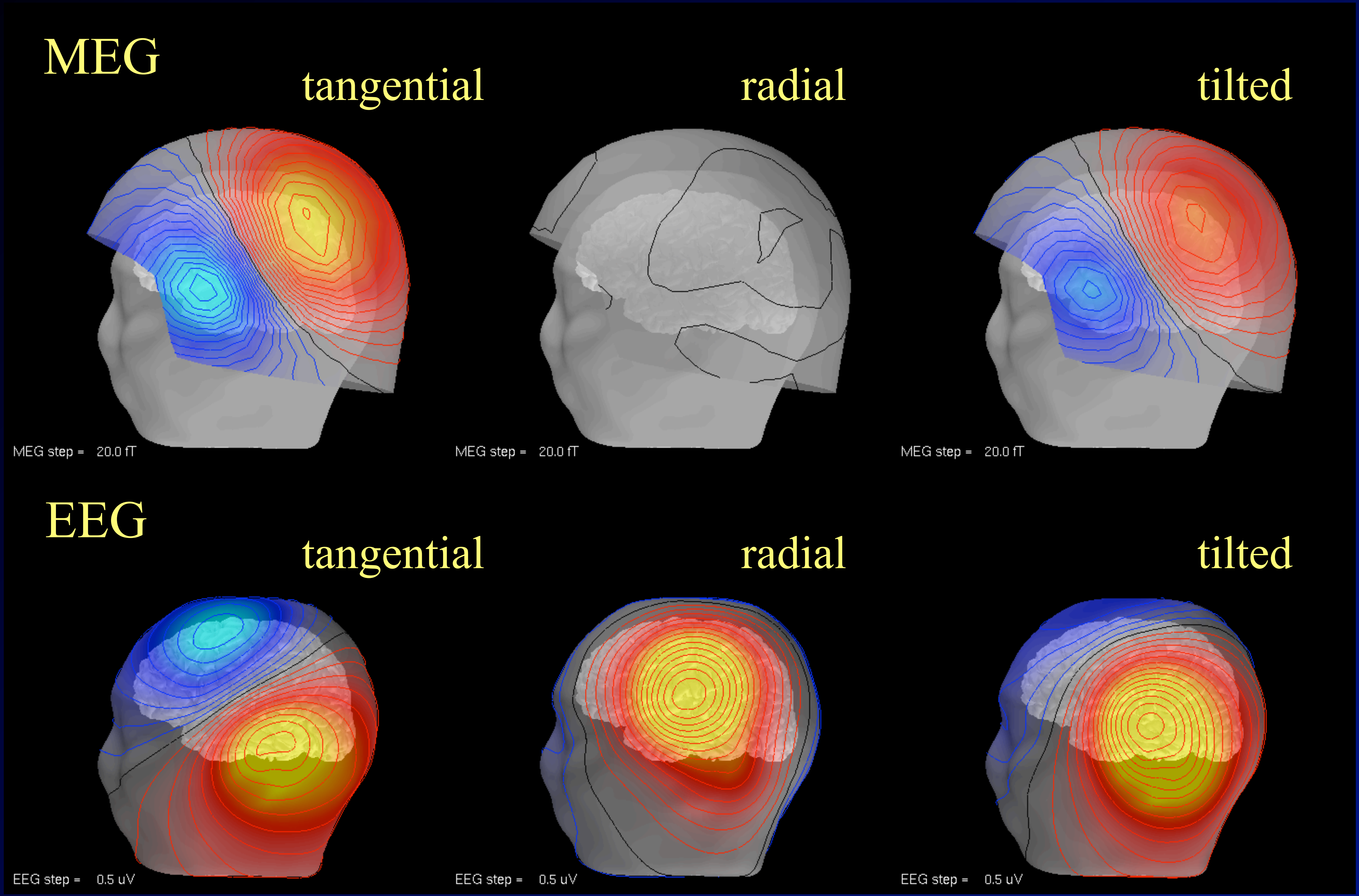
Silent sources

No MEG

No EEG

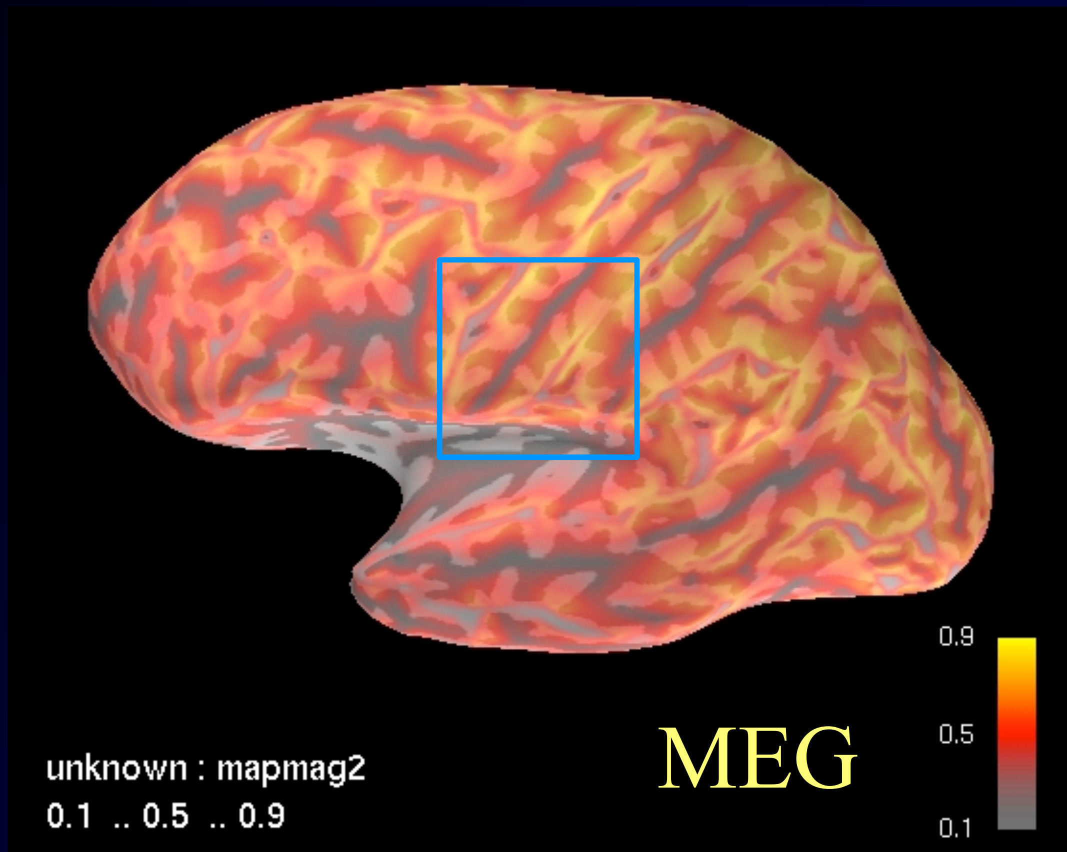
Neither MEG nor EEG

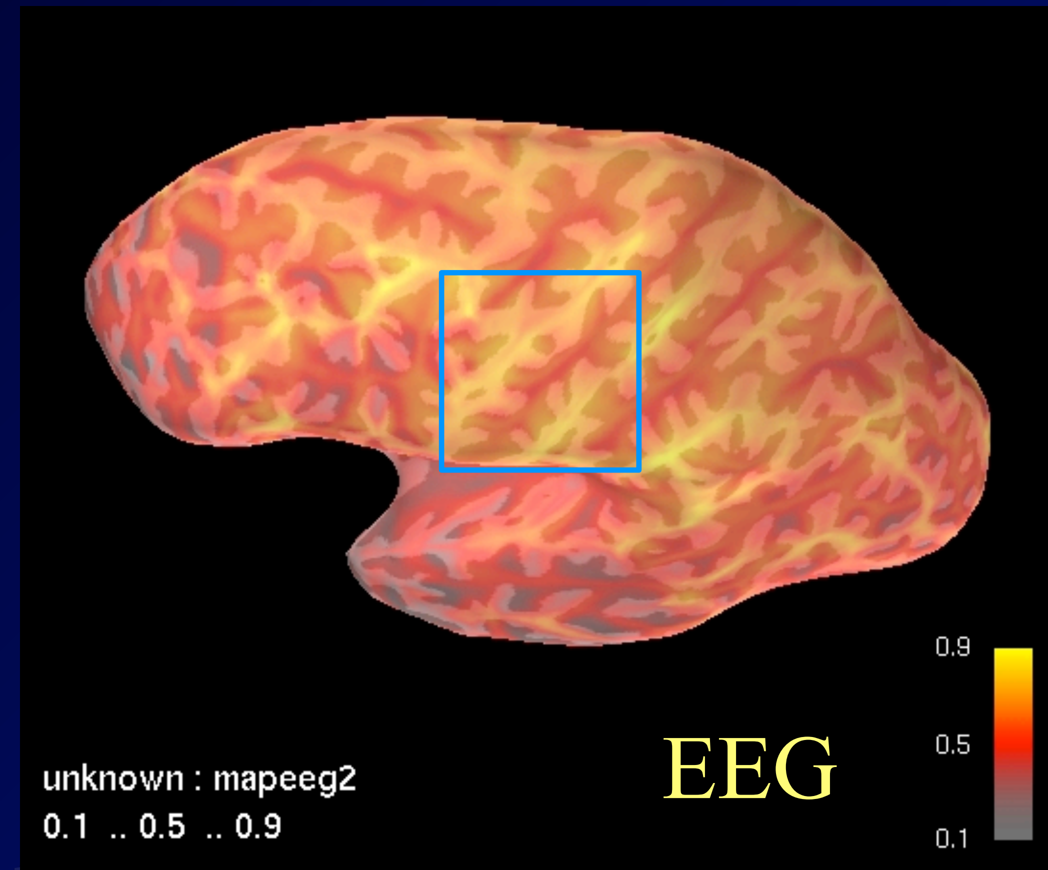
Tangential, radial, and tilted sources

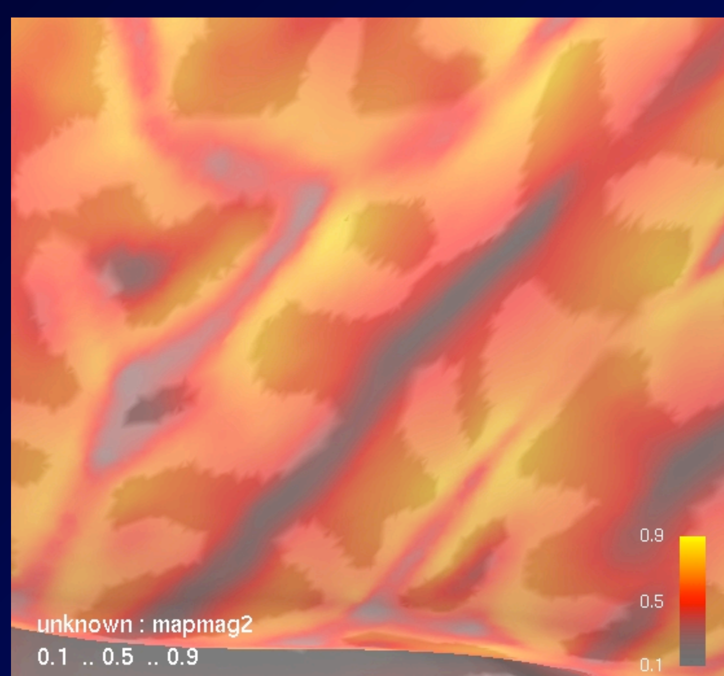


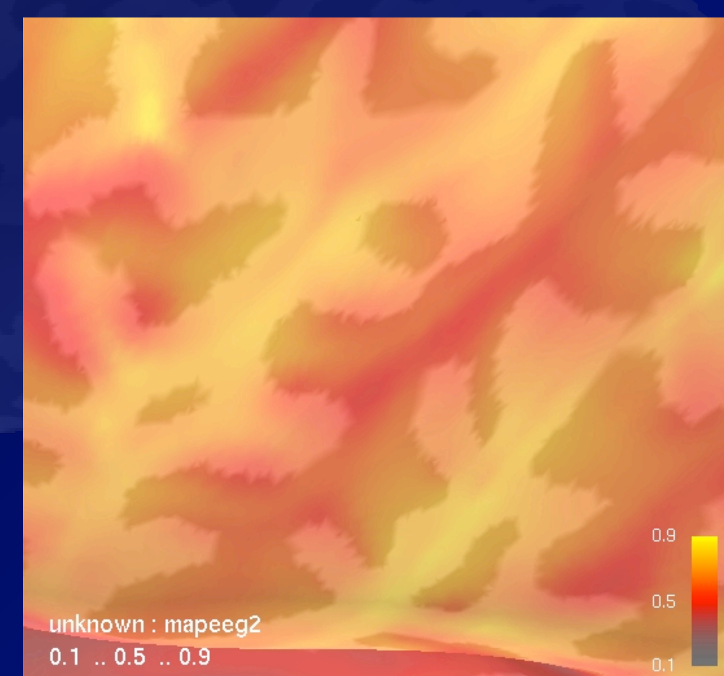
MEG has only one prototypical field pattern

MEG and EEG sensitivity to cortical sources

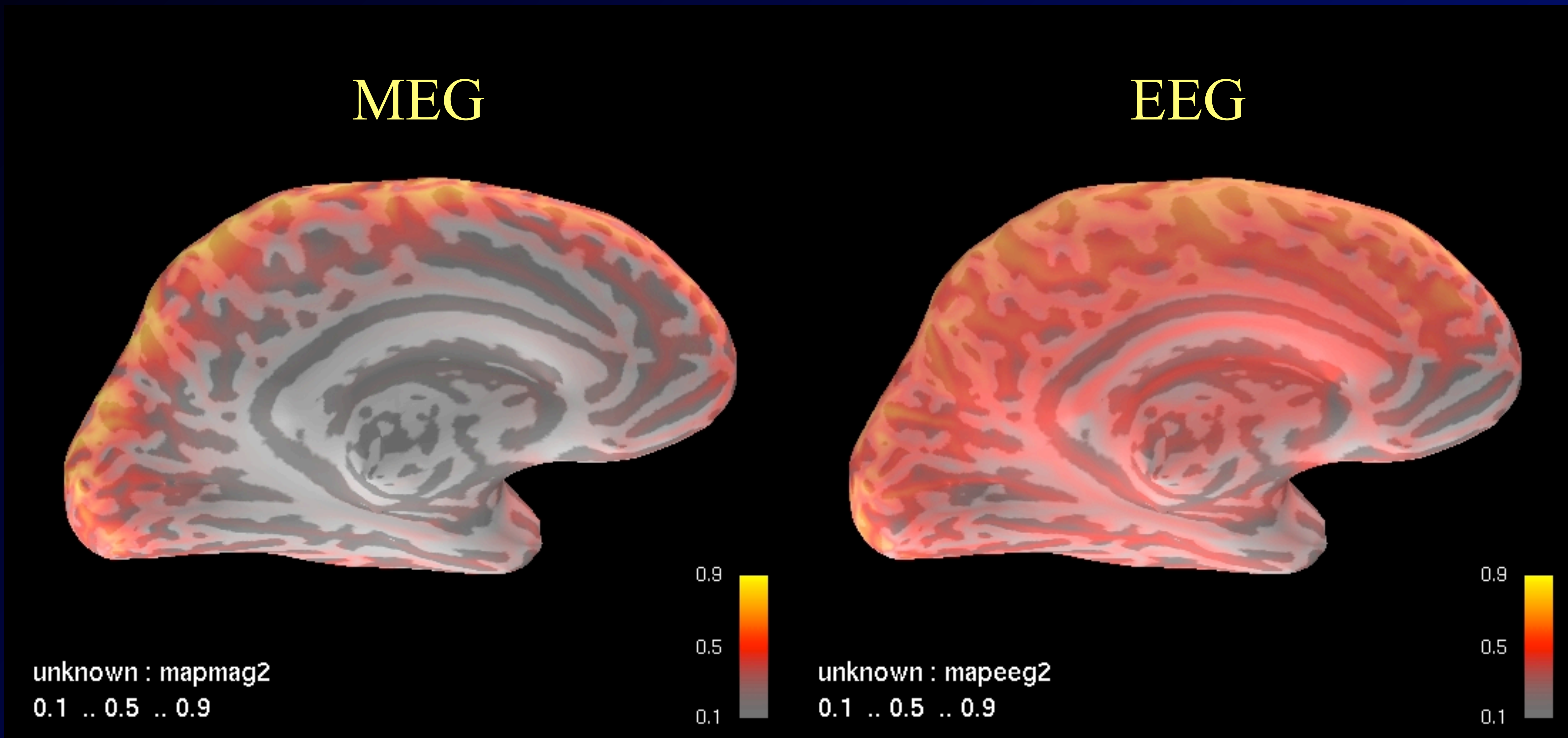




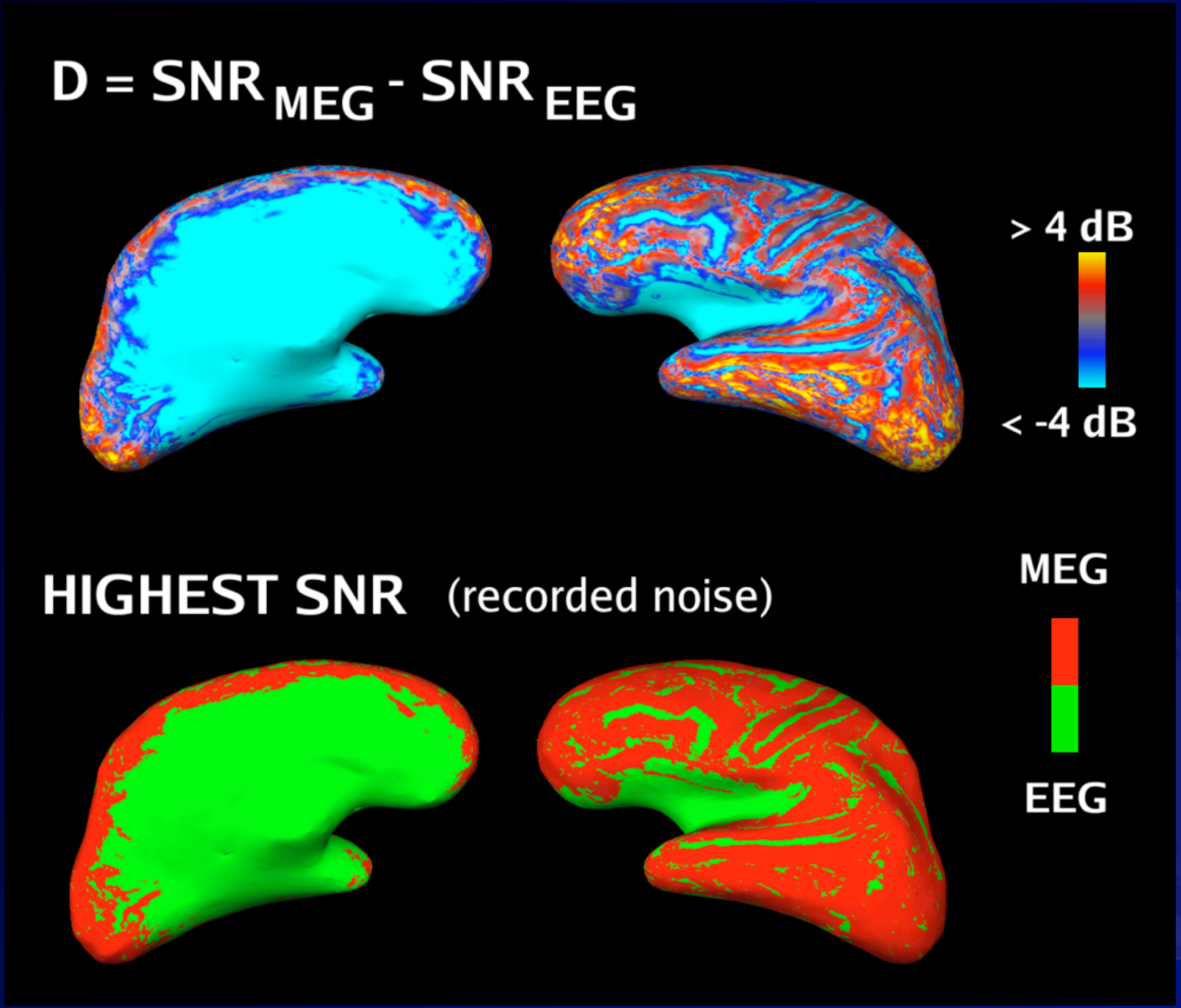




MEG and EEG sensitivity: Medial view

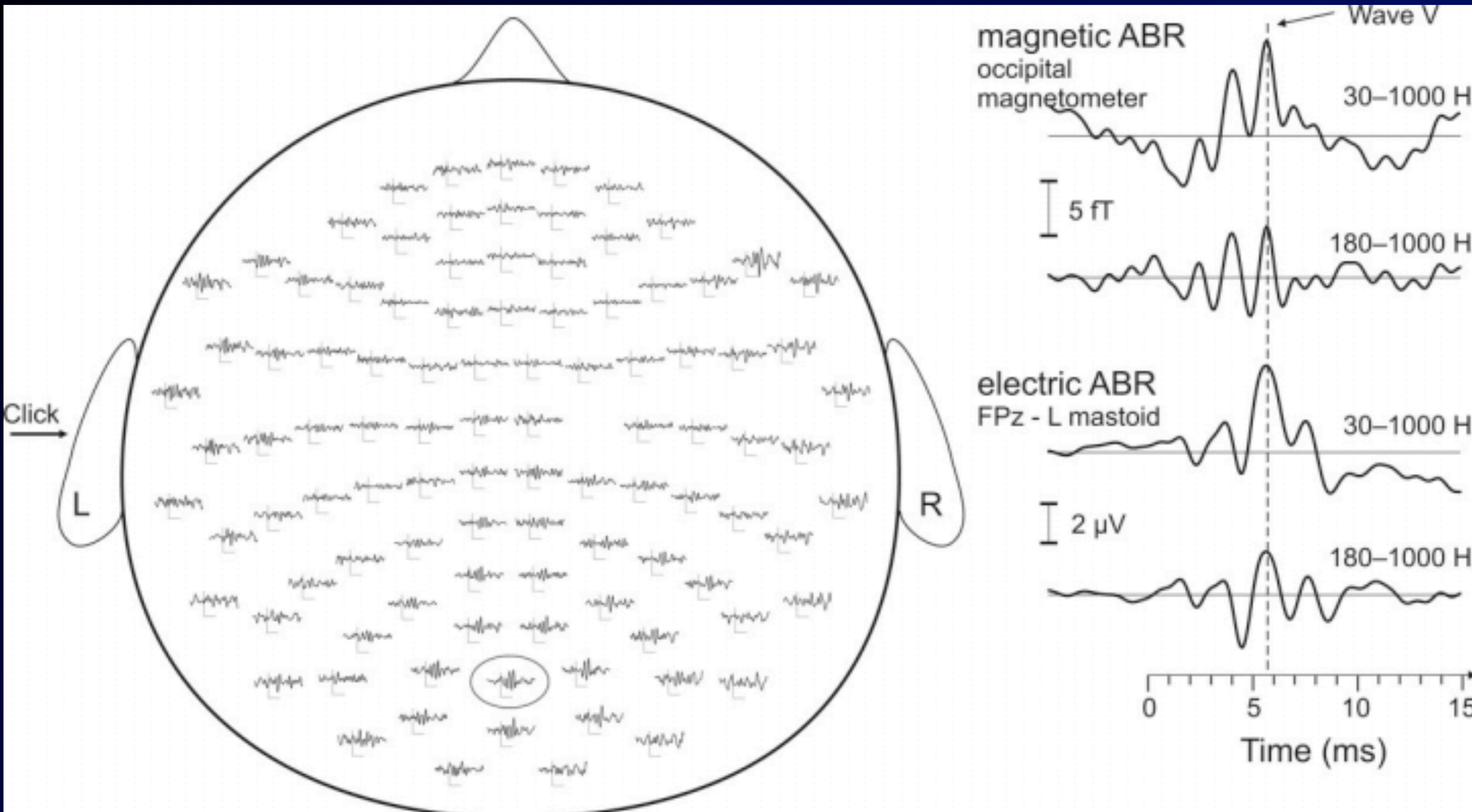


MEG and EEG SNR



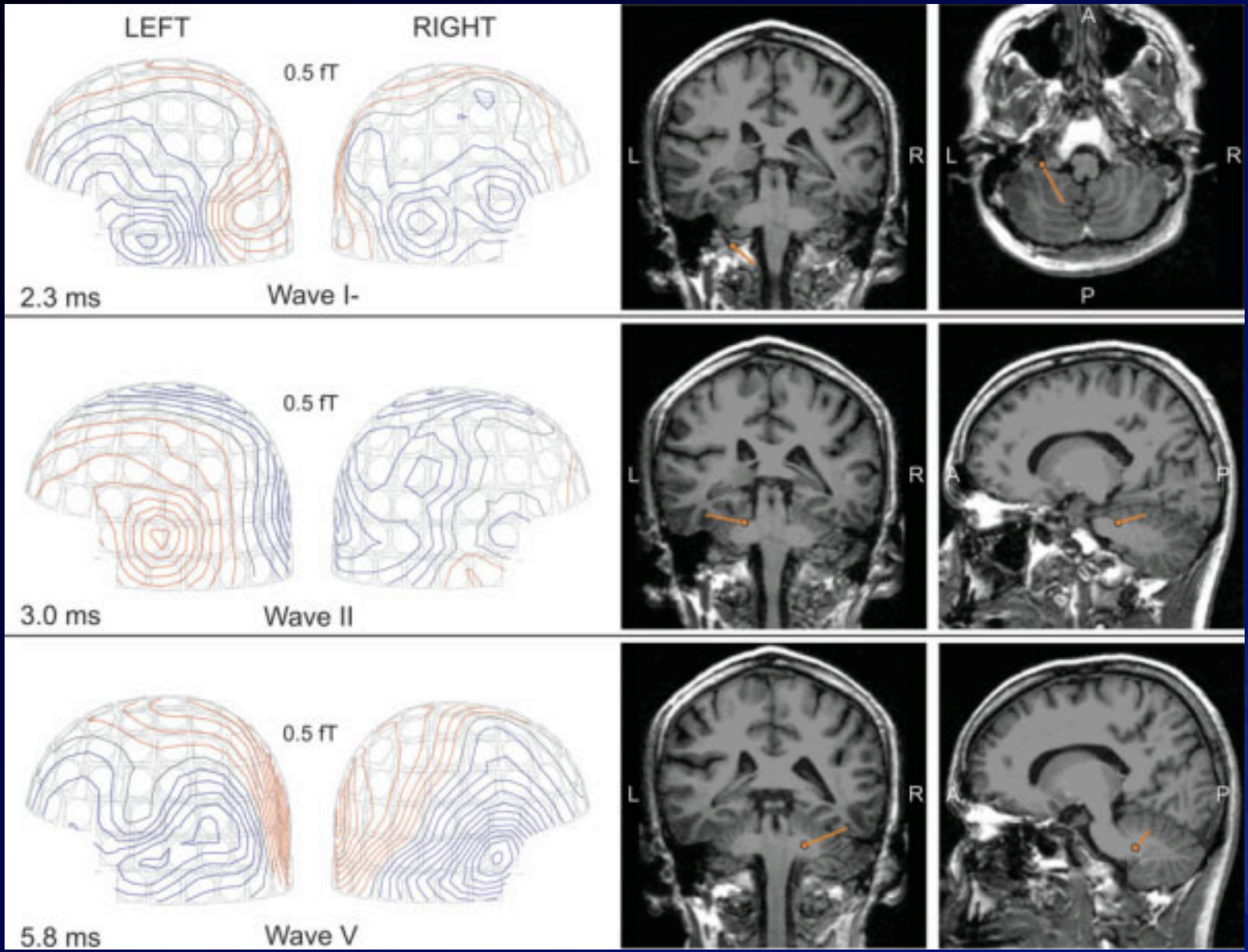
Goldenholz et al., 2009

Auditory Brainstem Responses



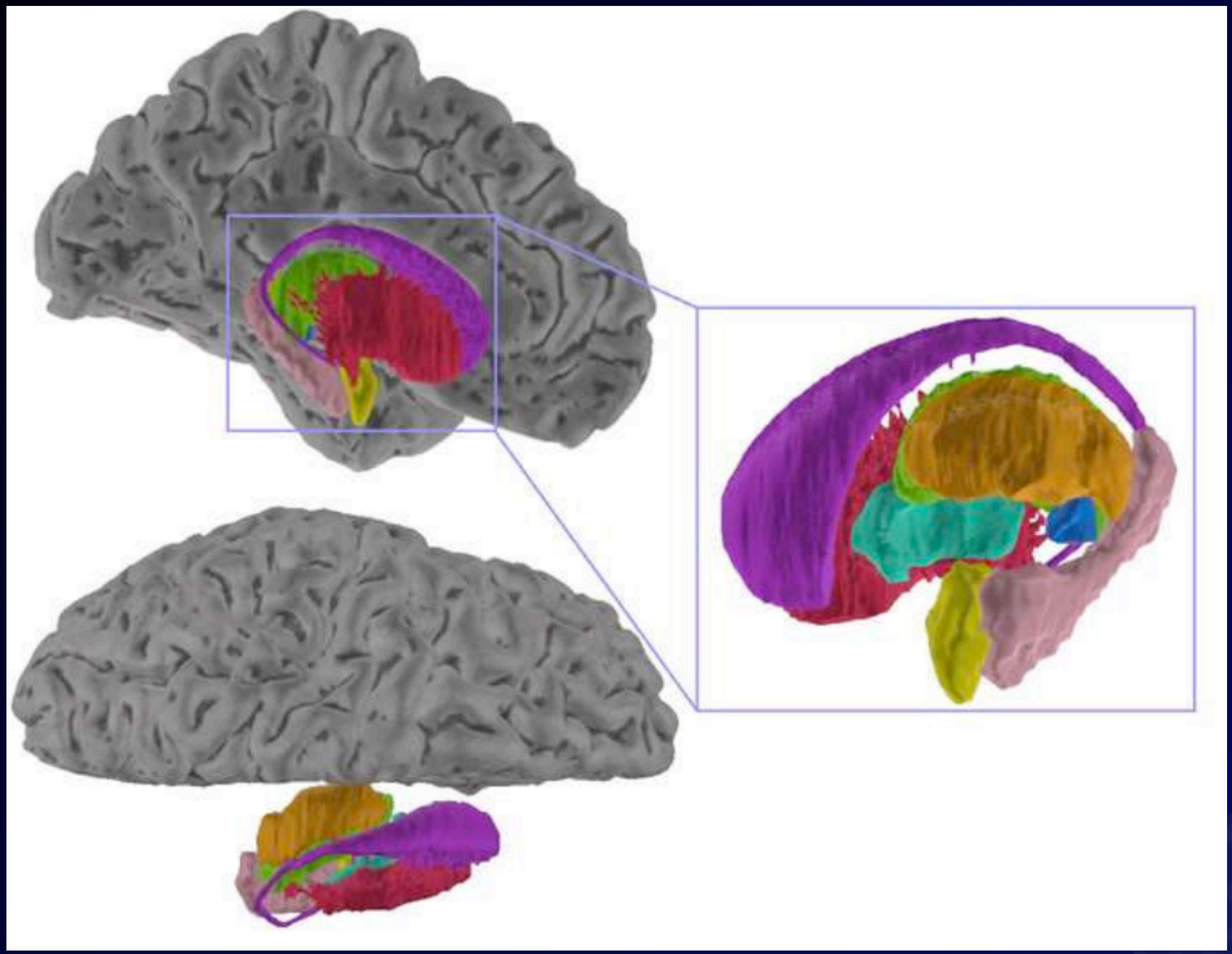
Parkkonen *et al.*, 2009

Auditory Brainstem Sources (MEG)



Parkkonen *et al.*, 2009

Simulations to explore the feasibility of detecting deep sources



- Anatomical model of the cortex and subcortical structures
- Volumetric and surface sources
- Realistic current densities
- Ongoing cortical activity

Attal et al., 2007

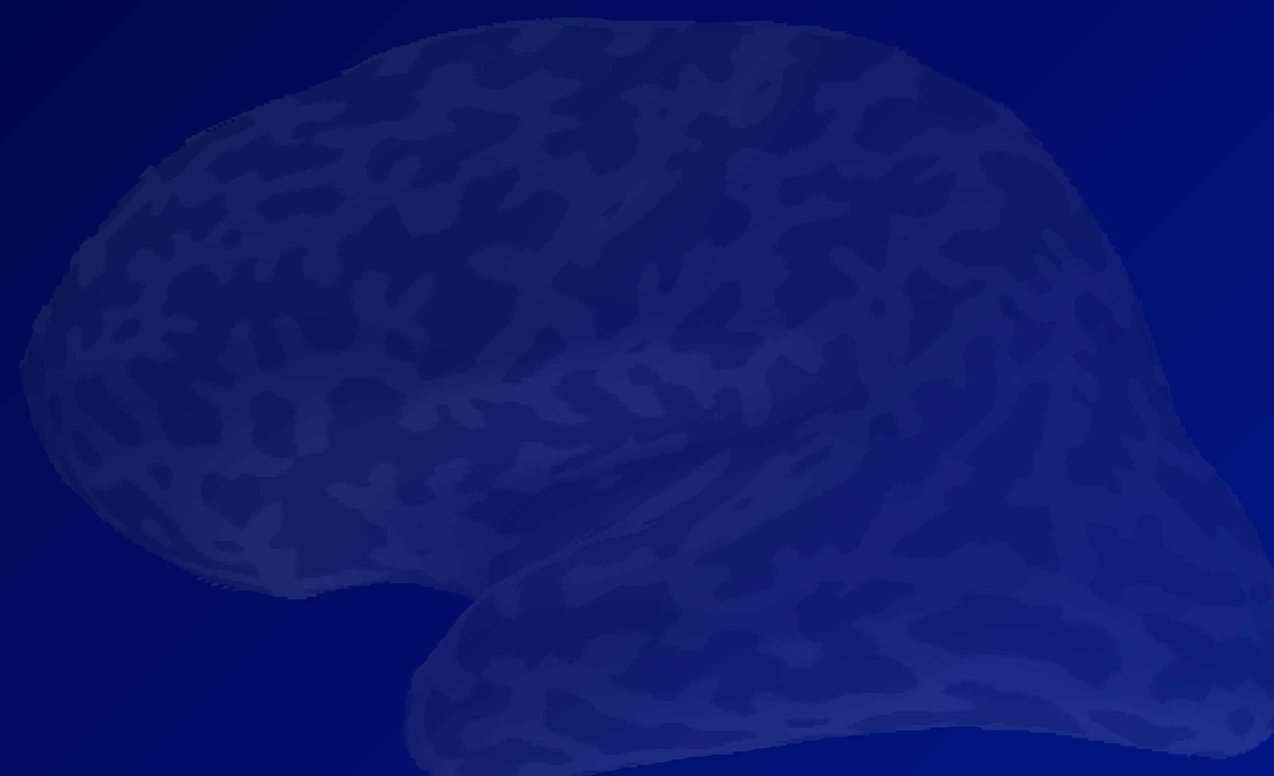
Selected simulation results

Quantity	Cortex	Hippocampus	LGN	Thalamus	EGP
MEG [fT]	120	90	25	2.9	0.61
EEG [μV]	8	6.5	2.2	0.48	0.24
MEG/EEG [fT/μV]	15.0	13.8	11.4	6.0	2.5
Min # trials					
MEG		21	400	3500	> 10 000
EEG		45	490	3700	> 10 000

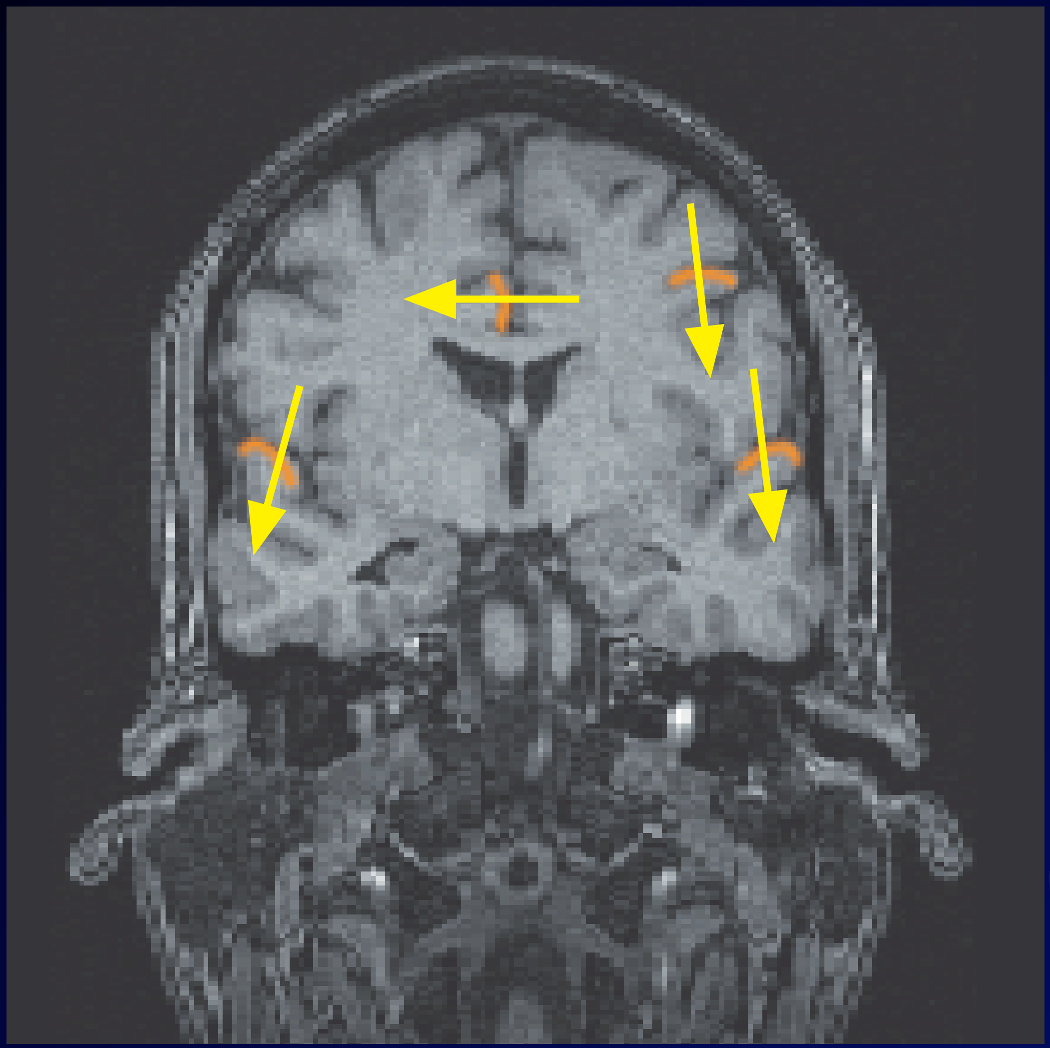
MEG and EEG may have very similar SNRs

Attal et al., 2007

The equivalent current dipole



The Current Dipole as an Elementary Source



- The neural currents on a few-cm^2 patch of cortex are approximated with a current dipole
- This surrogate source is called an equivalent current dipole or a “regional source”

Scherg *et al.*, 1984

Sam Williamson † and Lloyd Kaufman (NYU):

- First VEF and mapping of somatosensory fields
- Interdisciplinary approach
- Magnetic Source Imaging (MSI)

Dipolar field patterns: focal sources

Somatically Evoked Magnetic Fields of the Human Brain

Abstract. *The human brain is found to produce a magnetic field near the scalp which varies in synchrony with periodic electrical stimulation applied to a finger. Use of a highly sensitive superconducting quantum interference device as a magnetic field detector reveals that the brain's field is sharply localized over the primary projection area of the sensory cortex contralateral to the digit being stimulated. The phase of the response at the stimulus frequency varies monotonically with the repetition rate and at intermediate frequencies yields a latency of approximately 70 milliseconds for cortical response.*

We report here the detection of magnetic fields associated with the flow of electric current in the brain in response to electrical stimulation of the fingers. Weak magnetic fields resulting from visual stimulation have previously been detected outside the scalp (*1–4*). In contrast to the diffuse nature of the visually evoked potential (VEP), which is conventionally measured with scalp electrodes, the visually evoked field (VEF) is located over the visual cortex (*2*). This is to be expected as the electric currents giving rise to the VEF flow within the visual projection areas of the brain, while accompanying weaker currents in the skin remain undetected. The VEF has proved to be a significant indicator of brain function since its latency is directly correlated with the reaction time of a subject when the spatial frequency of a stimulus is varied (*5, 6*). The confined location of the VEF and its correlation with a measure of human performance prompted us to search for neuromagnetic responses evoked by other stimuli. The neuromagnetic response evoked by electrical stimulation of individual fingers of the hand—the somatically evoked field (SEF)—is similarly found to be well localized over the primary projection area, in this case on the contralateral hemisphere in the region SI for the stimulated digit. The observed features of the SEF indicate that the neuromagnetic techniques can provide unique advantages for medical research.

A split-ring electrode, fashioned from a rubber grommet and two stainless steel

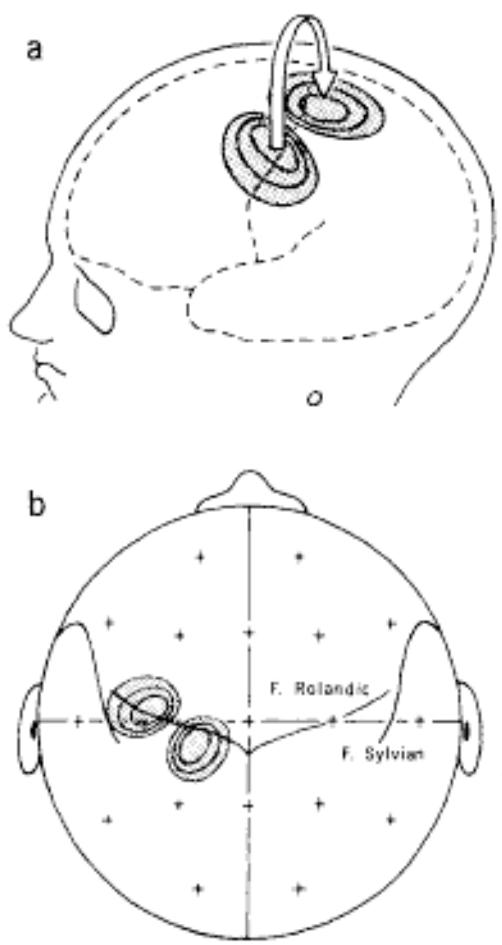
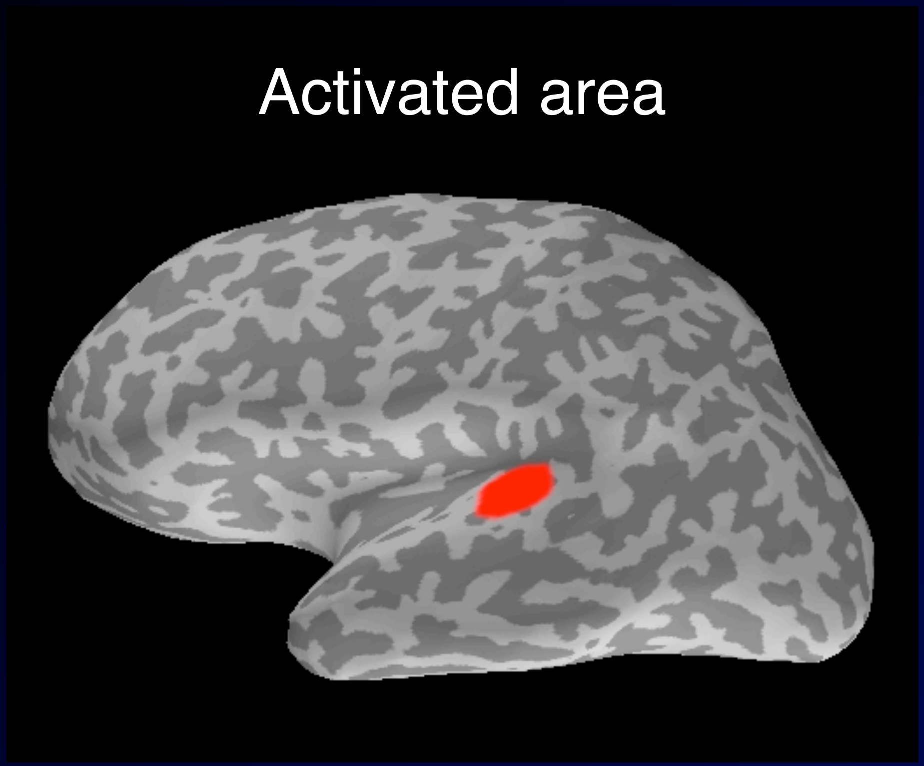


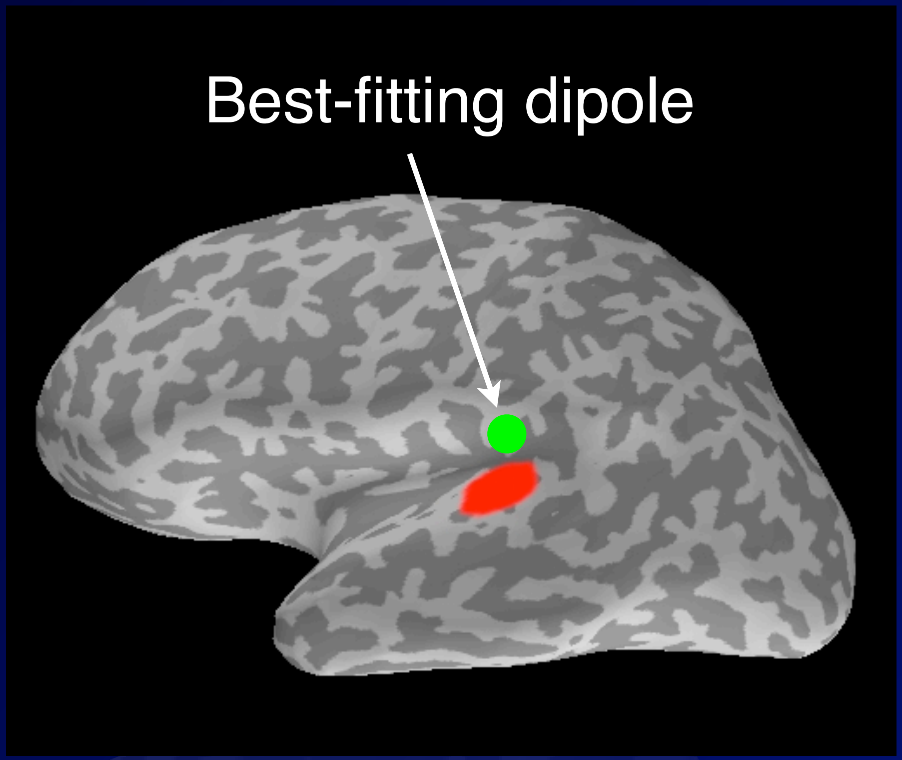
Fig. 1. (a) Neuromagnetic field patterns on the left hemisphere for an electrical stimulus at 13 hertz applied to the little finger of the right hand. Contours of equal magnetic flux indicate the relative amplitude of response for 0.9, 0.7, and 0.5 of the maximum response at the stimulus frequency. (b) The same pattern drawn on the conventional 10–20 electrode map. Abbreviation: *F.*, fissure.

Dipolar field patterns observed in several primary MEG responses: a current dipole seemed to be a reasonable model

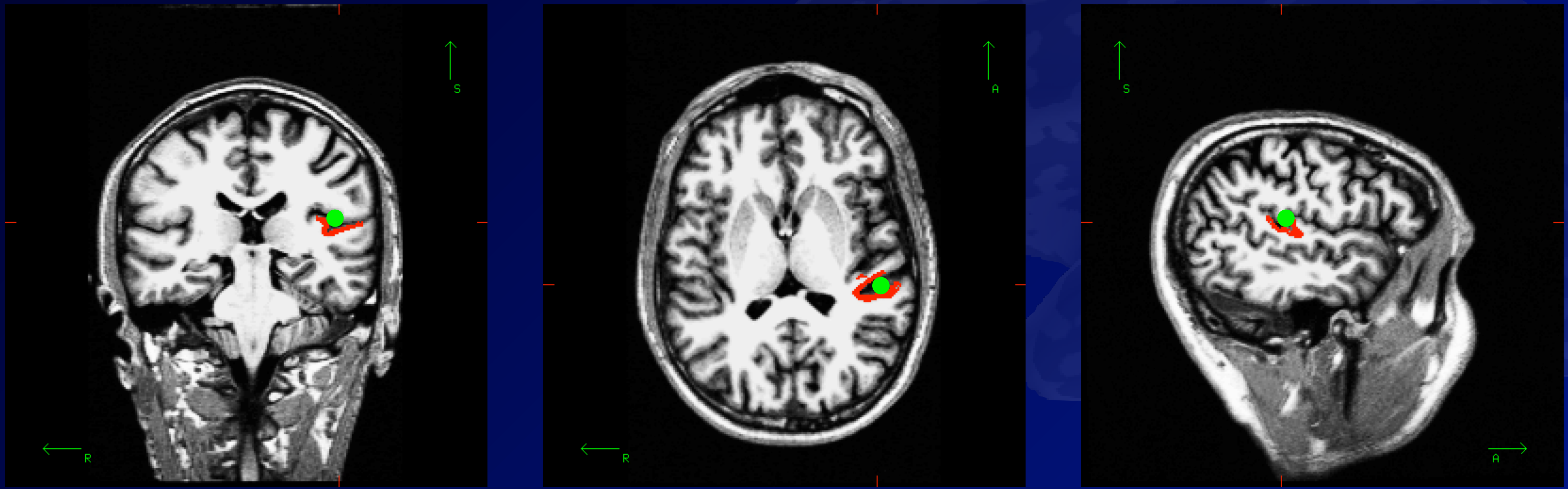
D. Brenner, J. Lipton, L. Kaufman, *S.J. Williamson,* Science, 1977

Are dipoles good for extended sources?





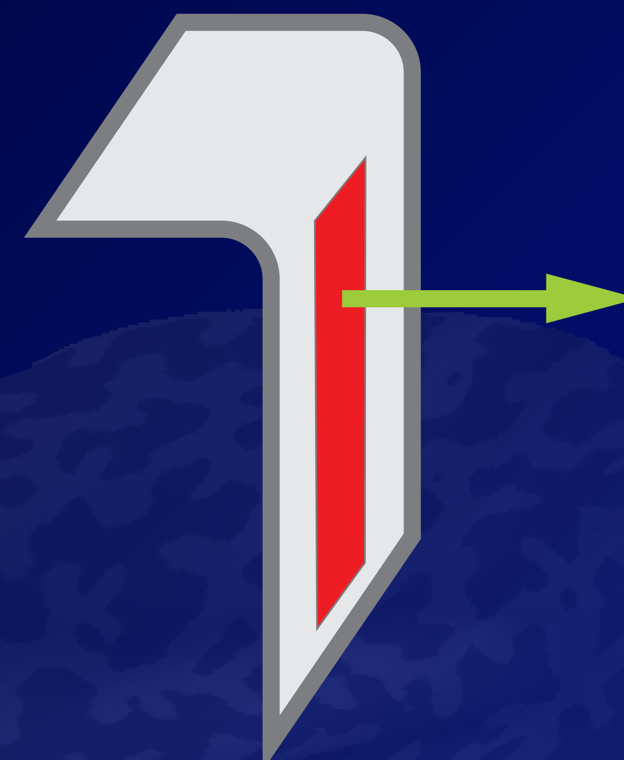
gof = 99.9%



Effect of source extent on dipole estimates

Tangential extension

Radial extension

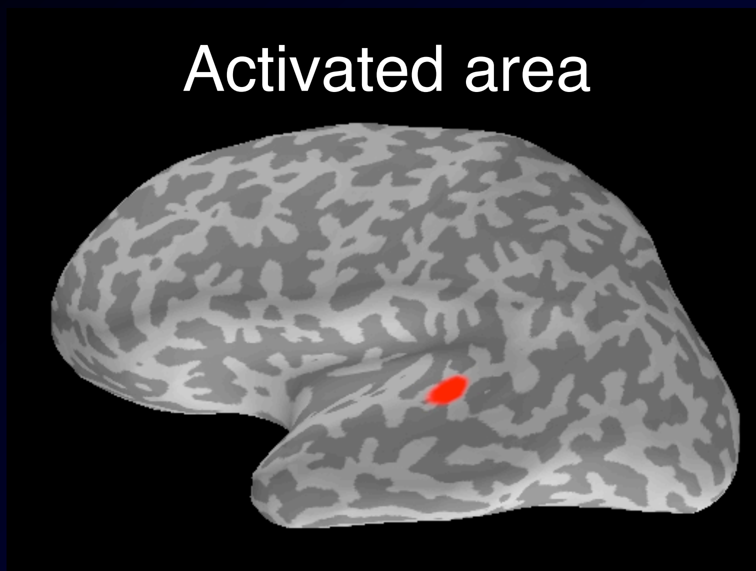


Depth overestimated

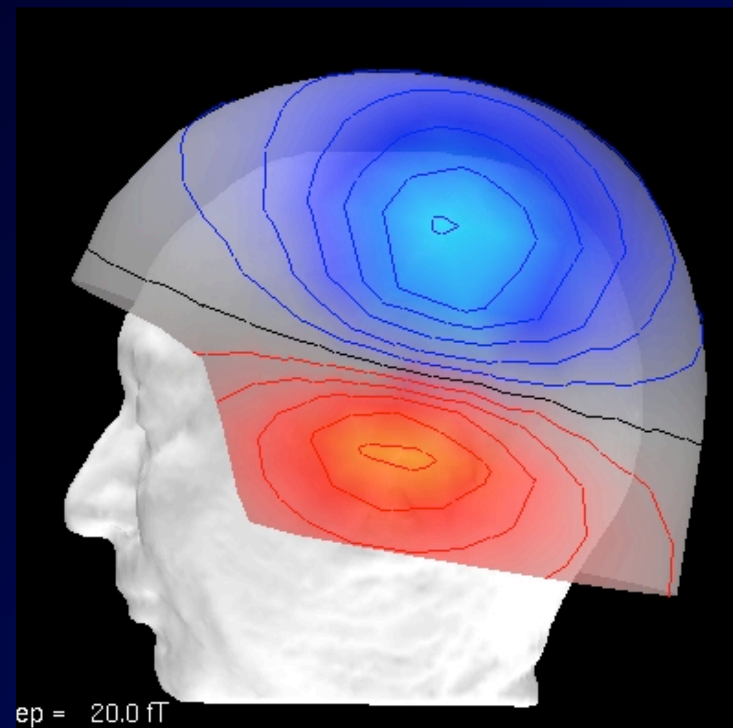
Depth underestimated

Tuesday, August 13, 2013

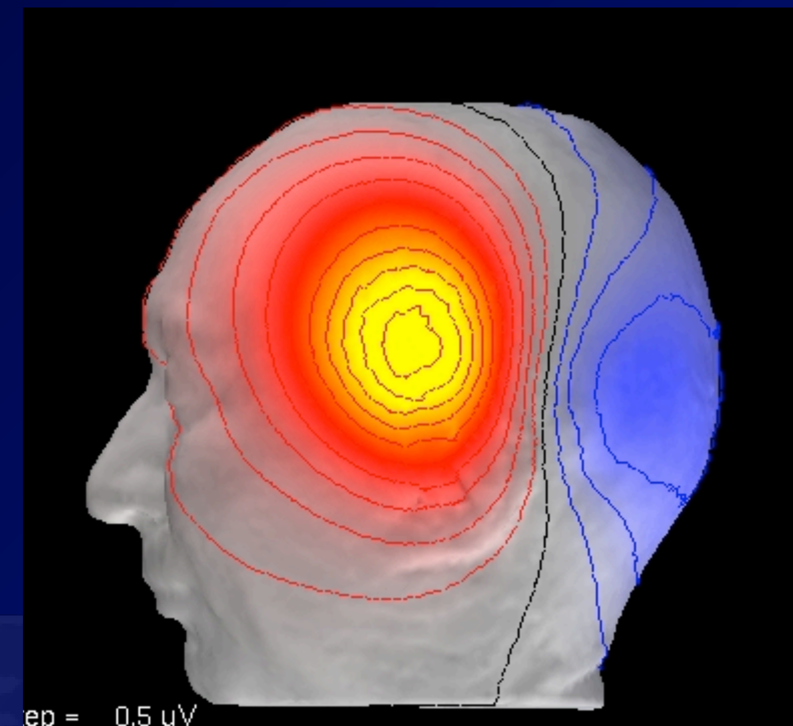
Active patch at the crest of a gyrus



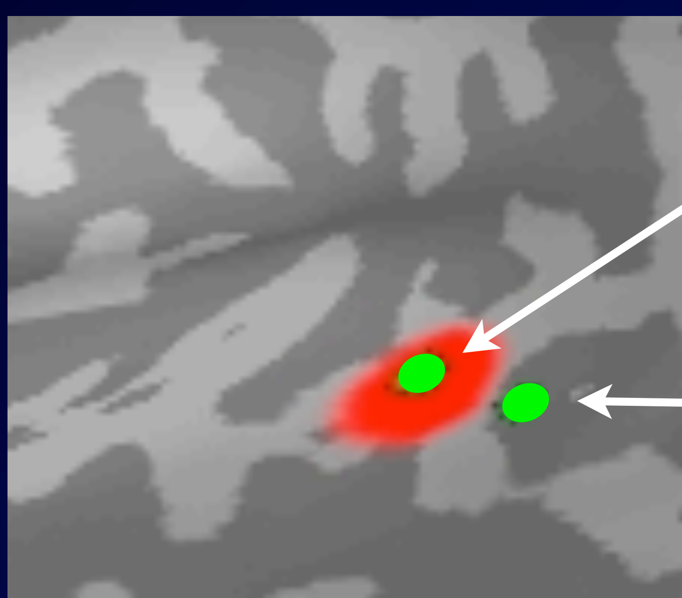
MEG



EEG



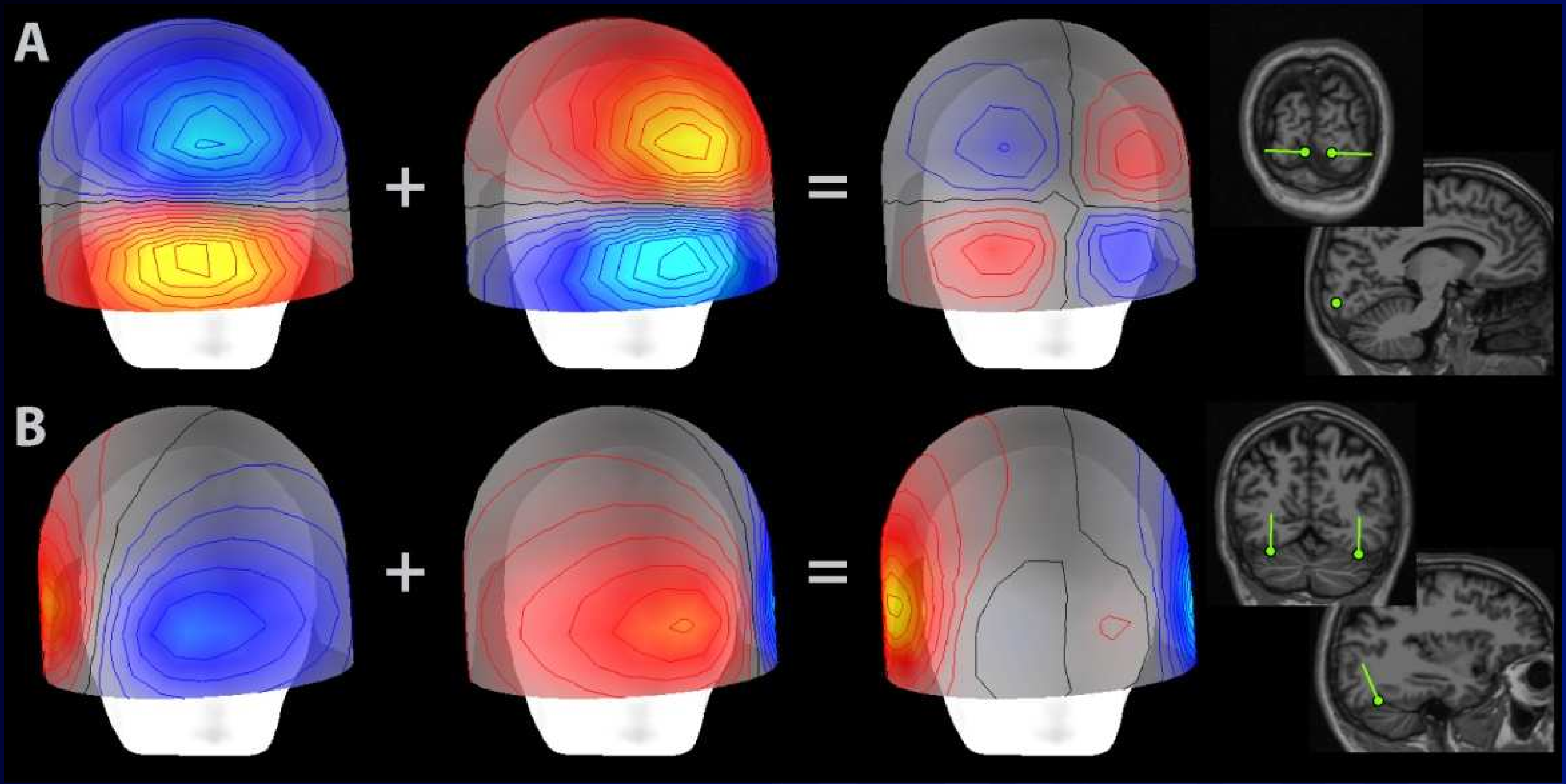
Dipole fitting results



EEG: more correct because sees both radial and tangential parts

MEG: offset because does not see the “radial” part of the current

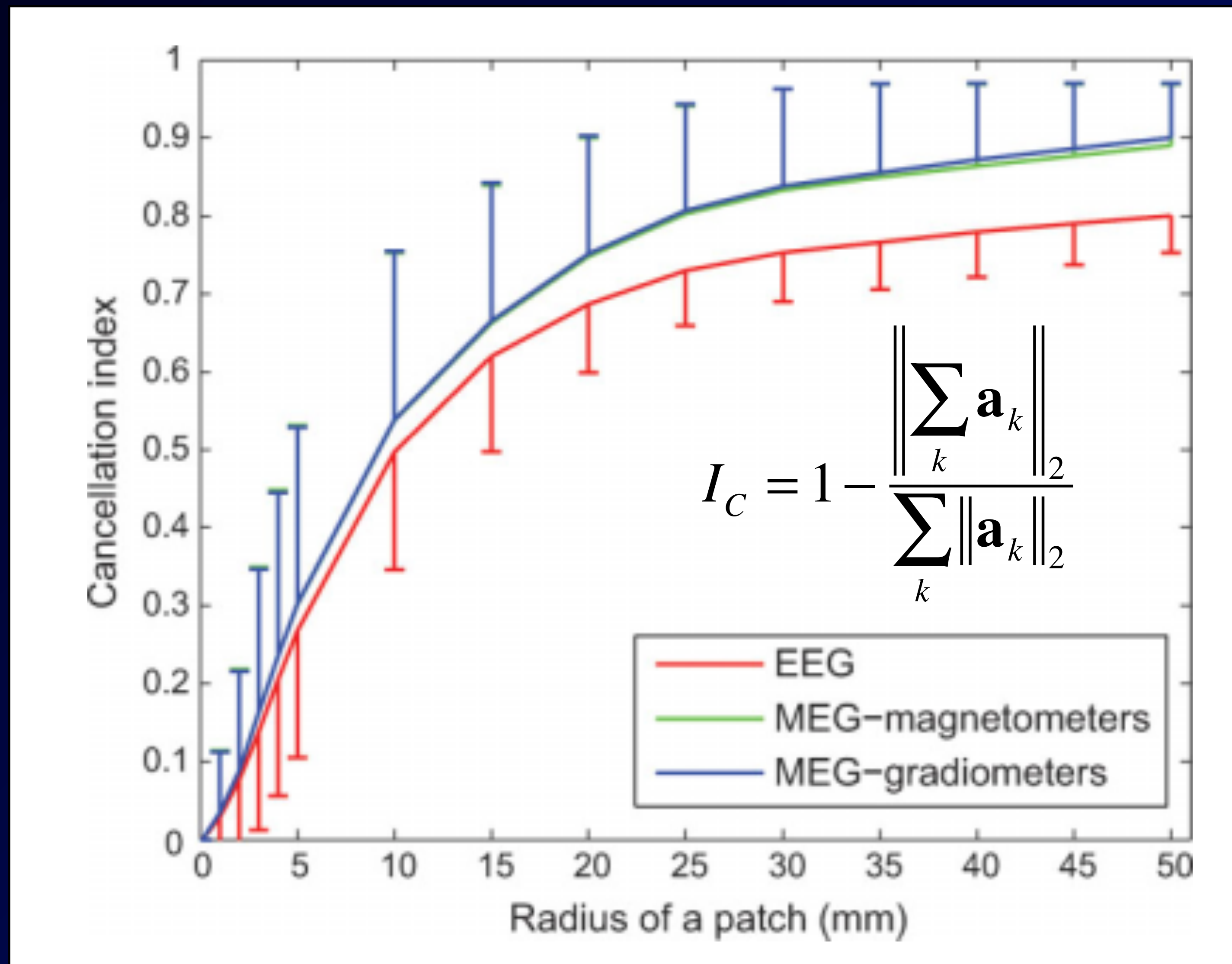
Cancellation due to multiple sources



Straightforward sensor-space analysis
may be very misleading

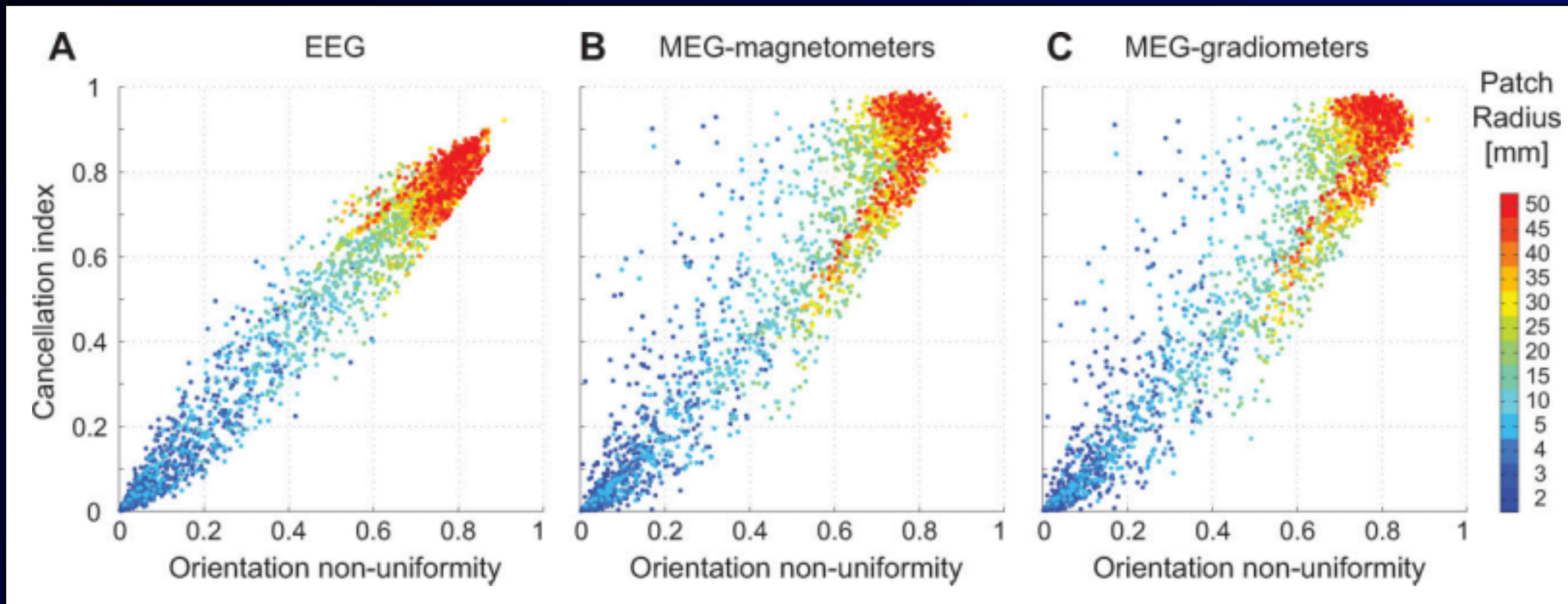
Ahlfors *et al.*, 2009

Cancellation of MEG/EEG due to extended sources



- Signals from a coherently active cortical patch are likely to be attenuated

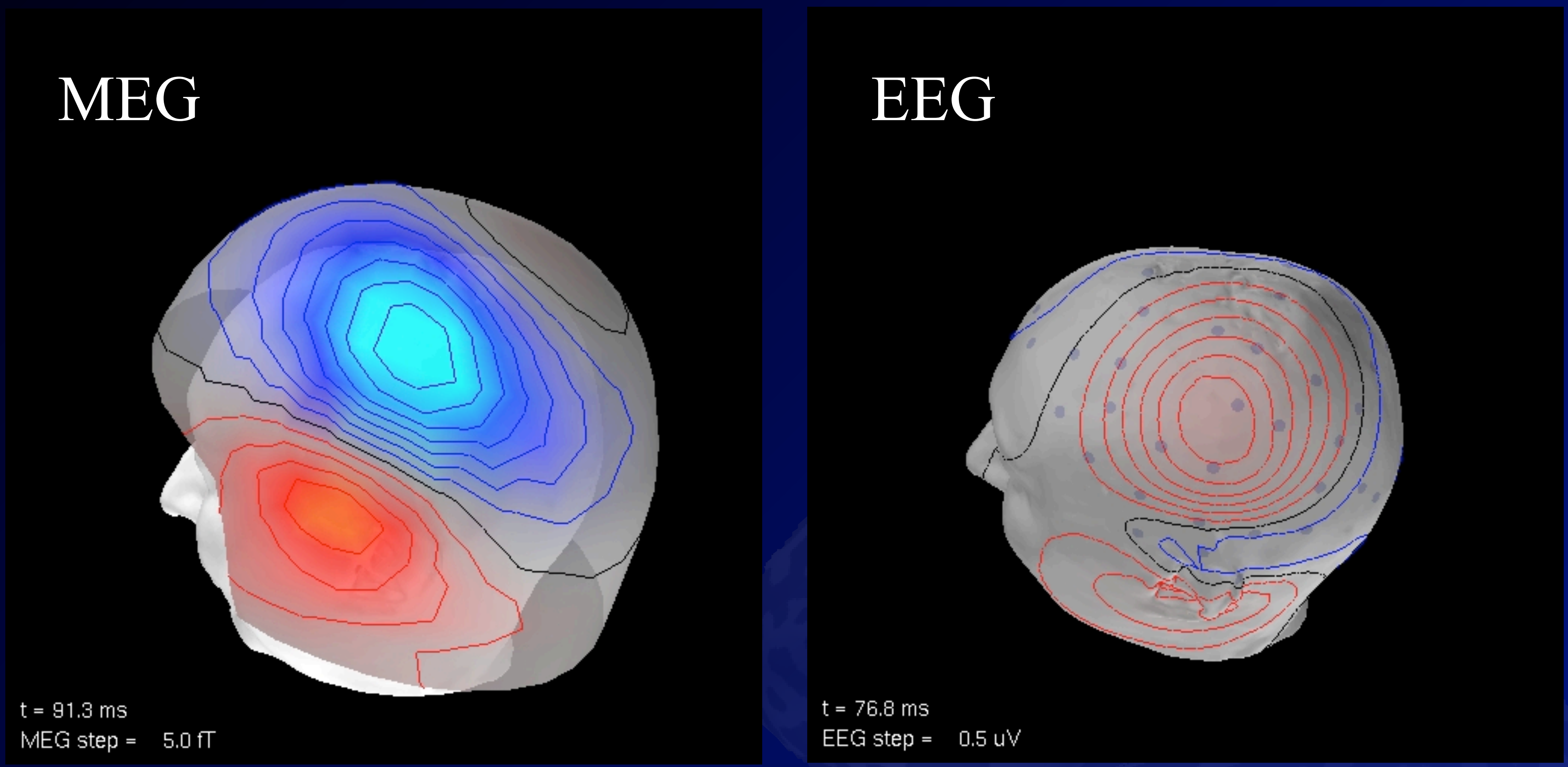
Patch cancellation effect and source orientations



- Cancellation is due to different source orientations within a cortical patch

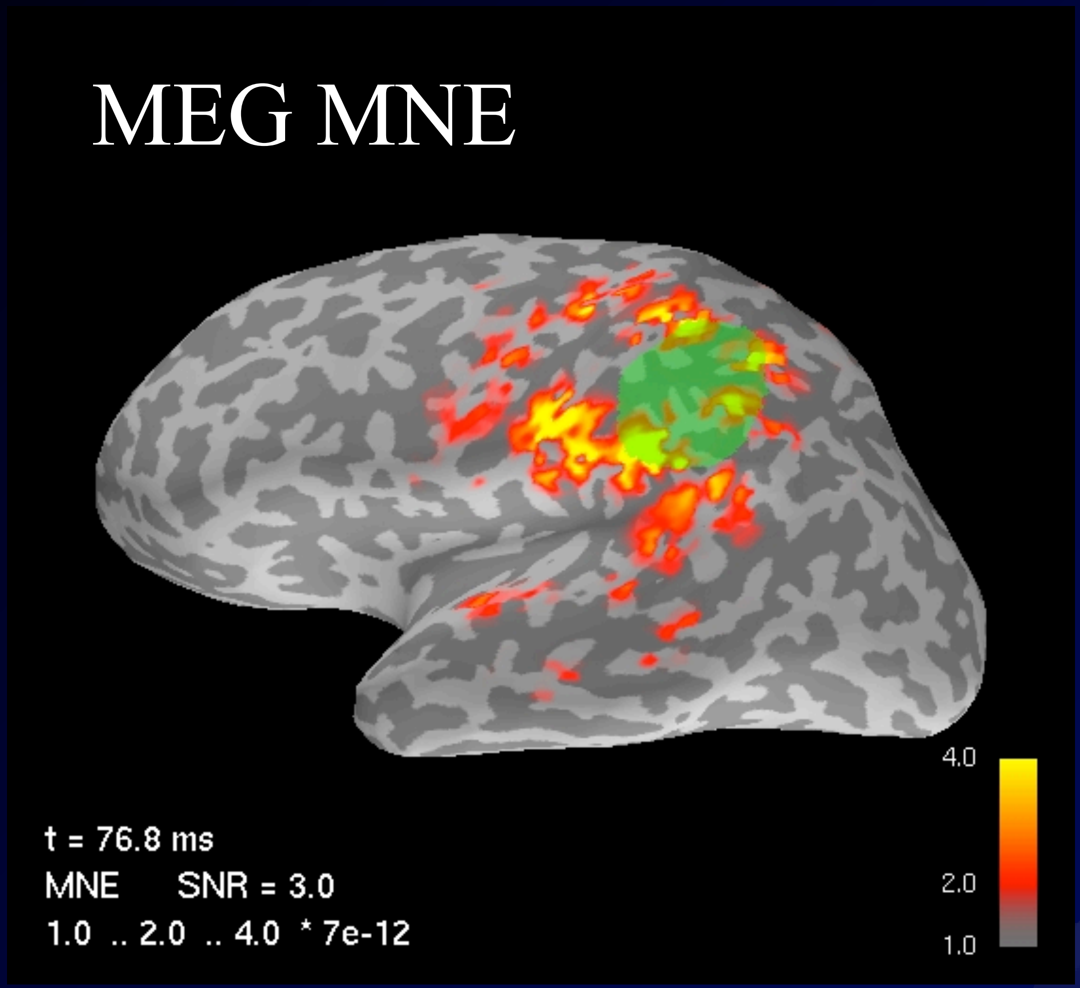
Ahlfors *et al.*, 2009

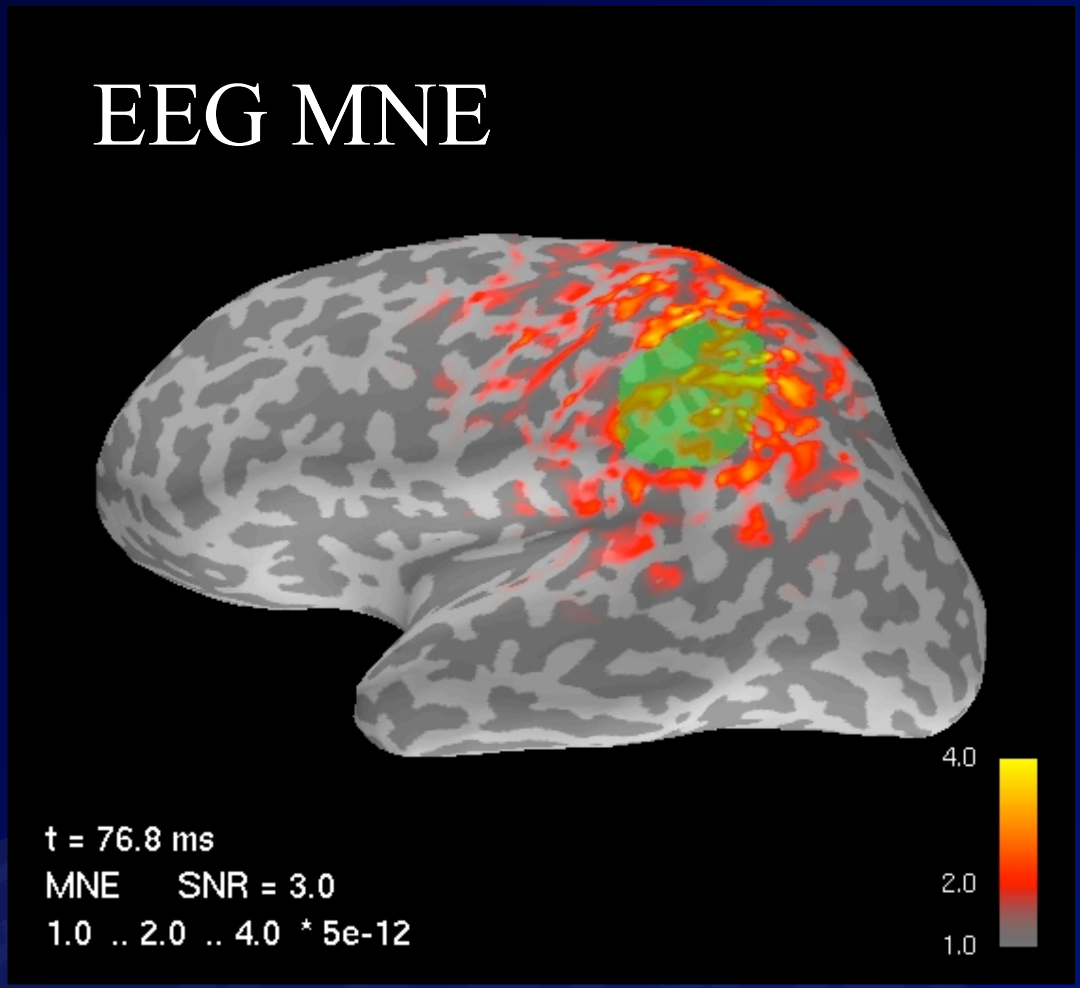
Extended cortical activation: Simulated signals



- MEG gives an indication of (two) tangential sources
- EEG is compatible with a single radial source in between

Extended cortical activation: MEG and EEG source estimates

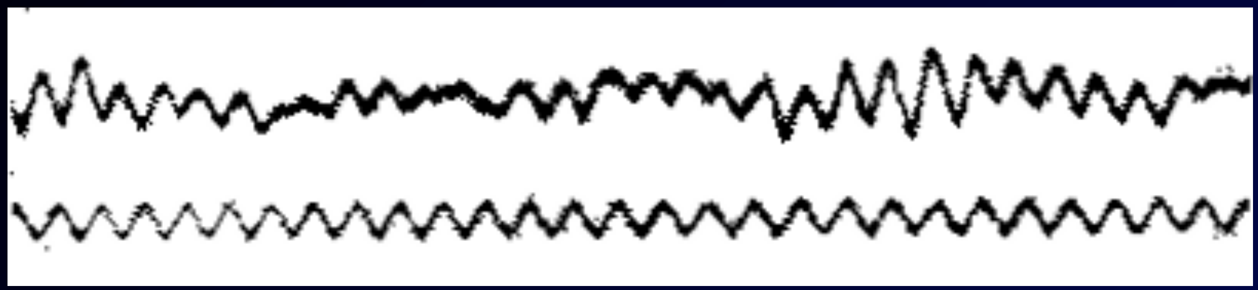




- MEG does not see the radially-oriented sources: “ripples” remain
- EEG sees the activity in the gyri and at the bottom of the sulci
- EEG and MEG may thus reveal different aspects of cortical activity if large patches of cortex are synchronously active

MEG and EEG measurements

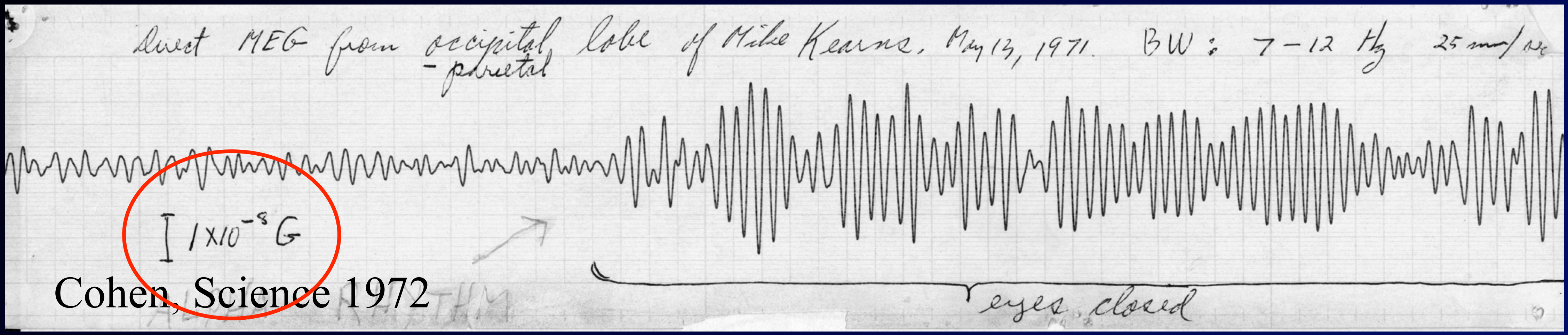
EEG Measurements



Hans Berger's alpha rhythm traces (~ 1929)

A modern EEG array:
- Fast setup
- 256 Electrodes

First real-time magnetoencephalogram



Cohen, Science 1972

Measuring the MEG signal is like trying to hear a needle drop on a pillow in a loud disco.

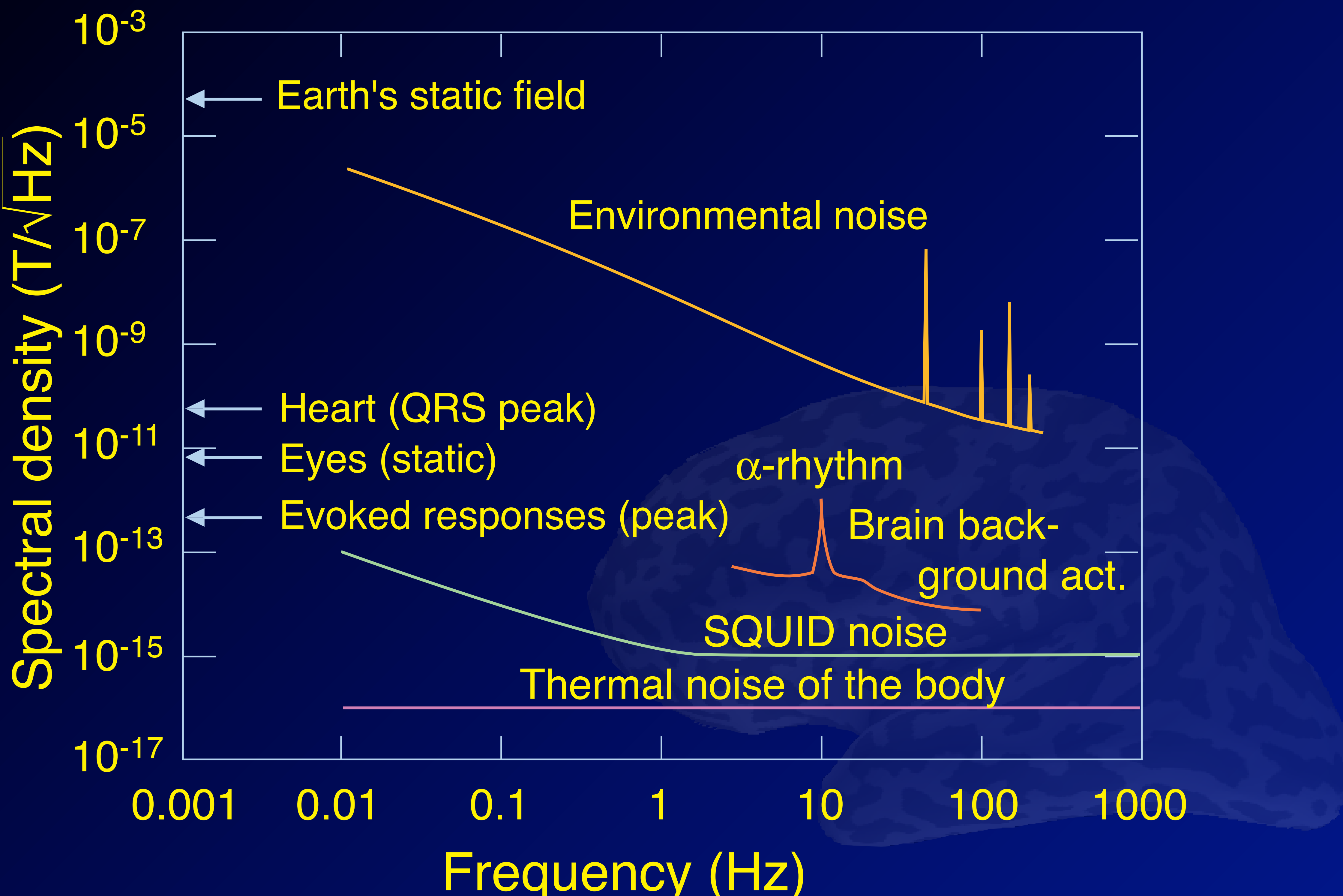
Therefore, we need:

1. sensitive detectors (SQUID)
2. a magnetically-shielded room

David Cohen (MIT, now also MGH):

- First MEG measurements
- Pioneering experiments and modeling studies

Noise Sources

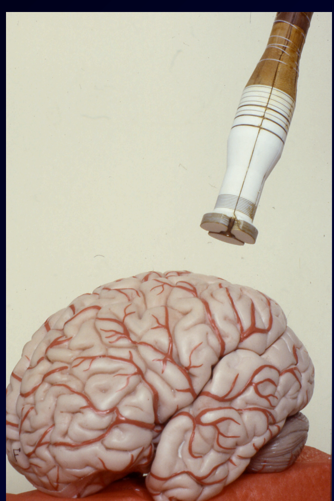


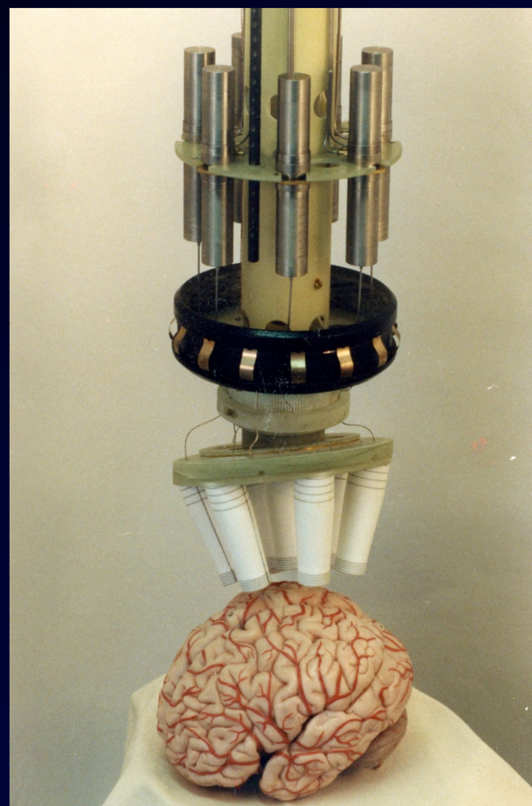
Jim Zimmerman:

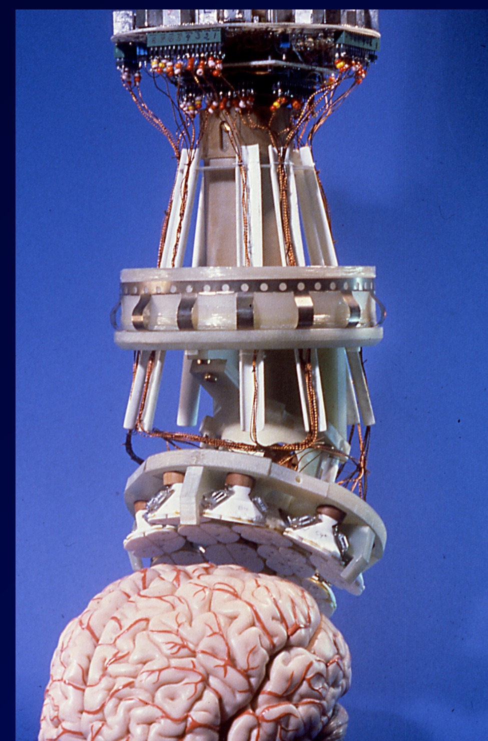
- Introduced the SQUID magnetometer

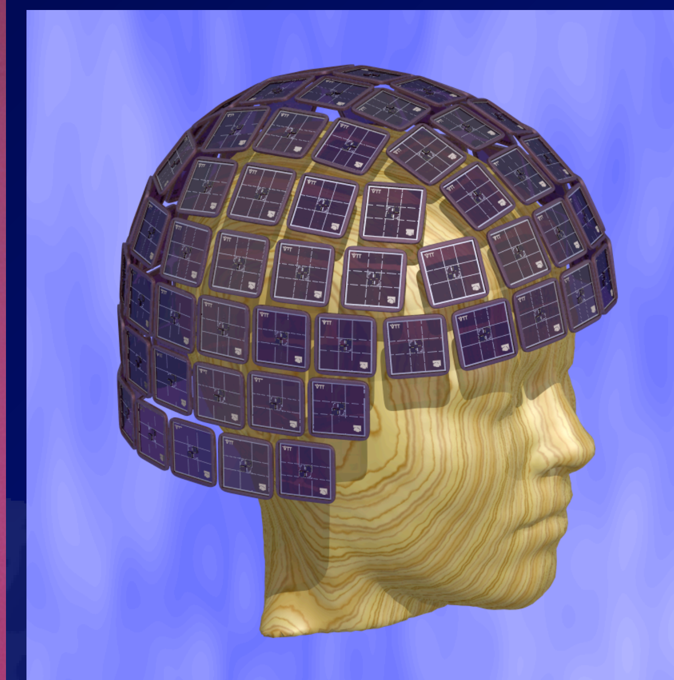
MEG development in Helsinki

1984 1986 1989 1992 1998









4 7 24 122 306 kanavaa

HUT

SITRA

Neuromag

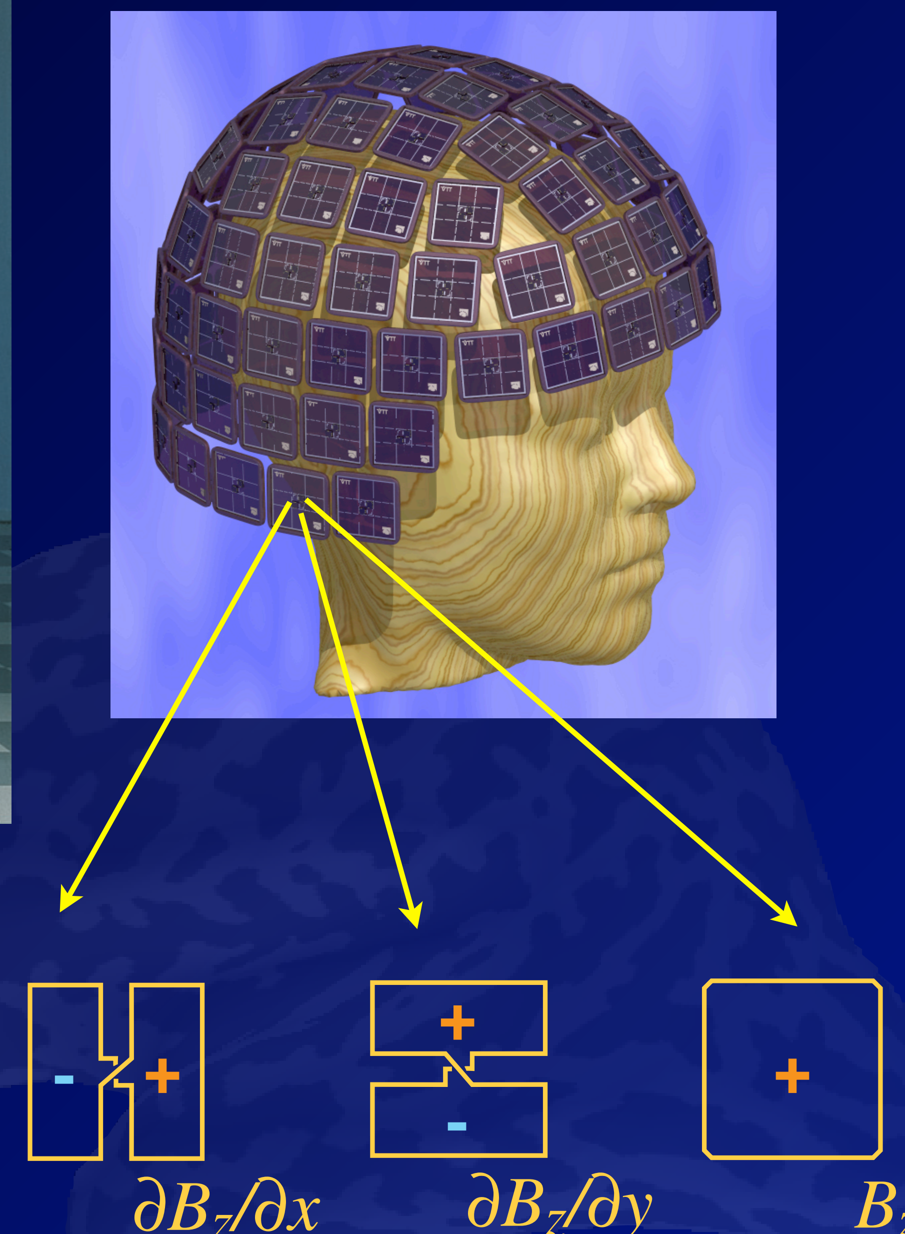
Matti Hämäläinen 4/2013

Olli Lounasmaa (Low Temperature Lab, HUT):

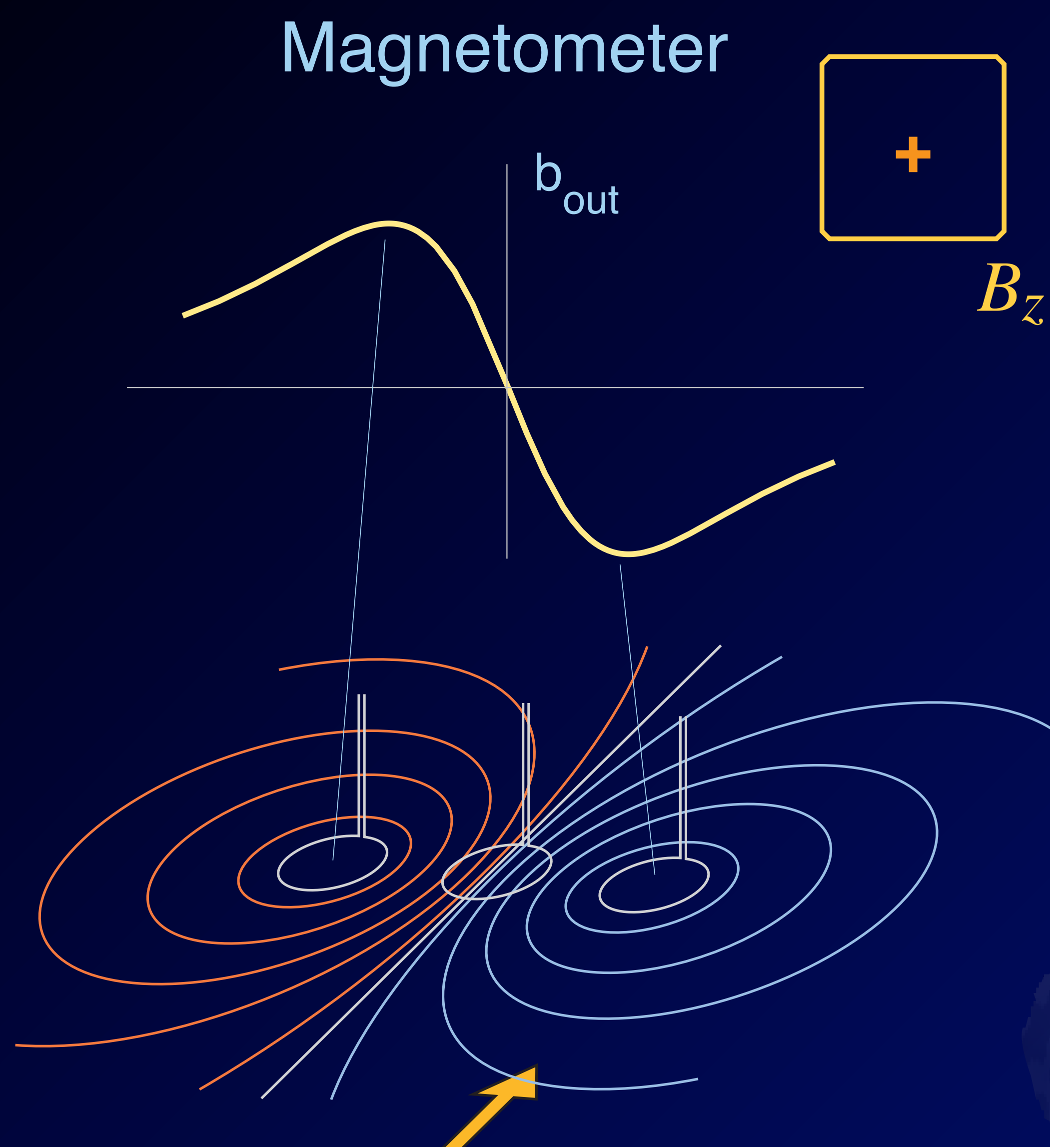
1. We need to and can build a whole-head MEG system
2. Researchers from different disciplines need to work together full time in the same laboratory.

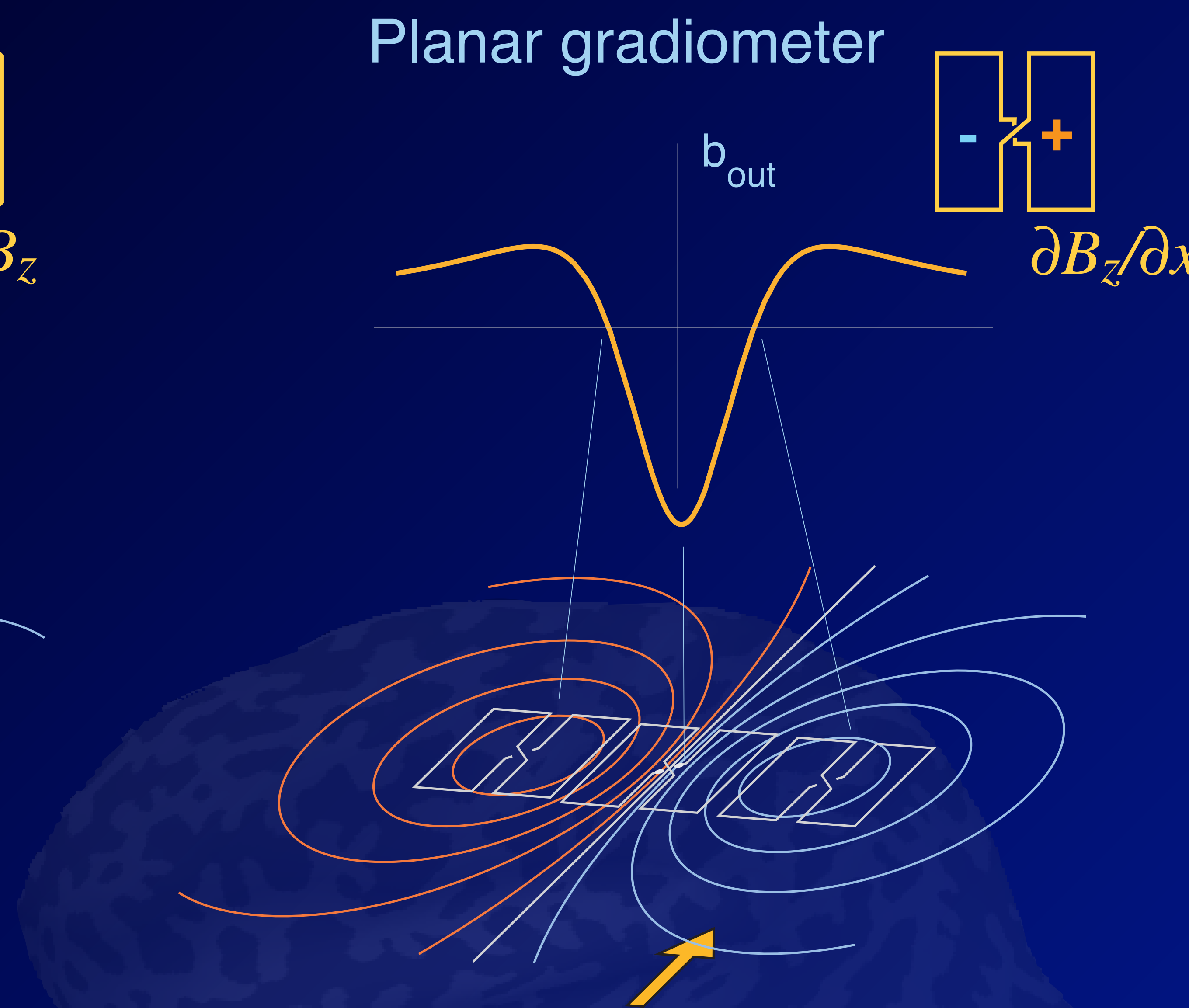
A typical MEG system

306-channel
SQUID sensor array



Magnetometers and planar gradiometers





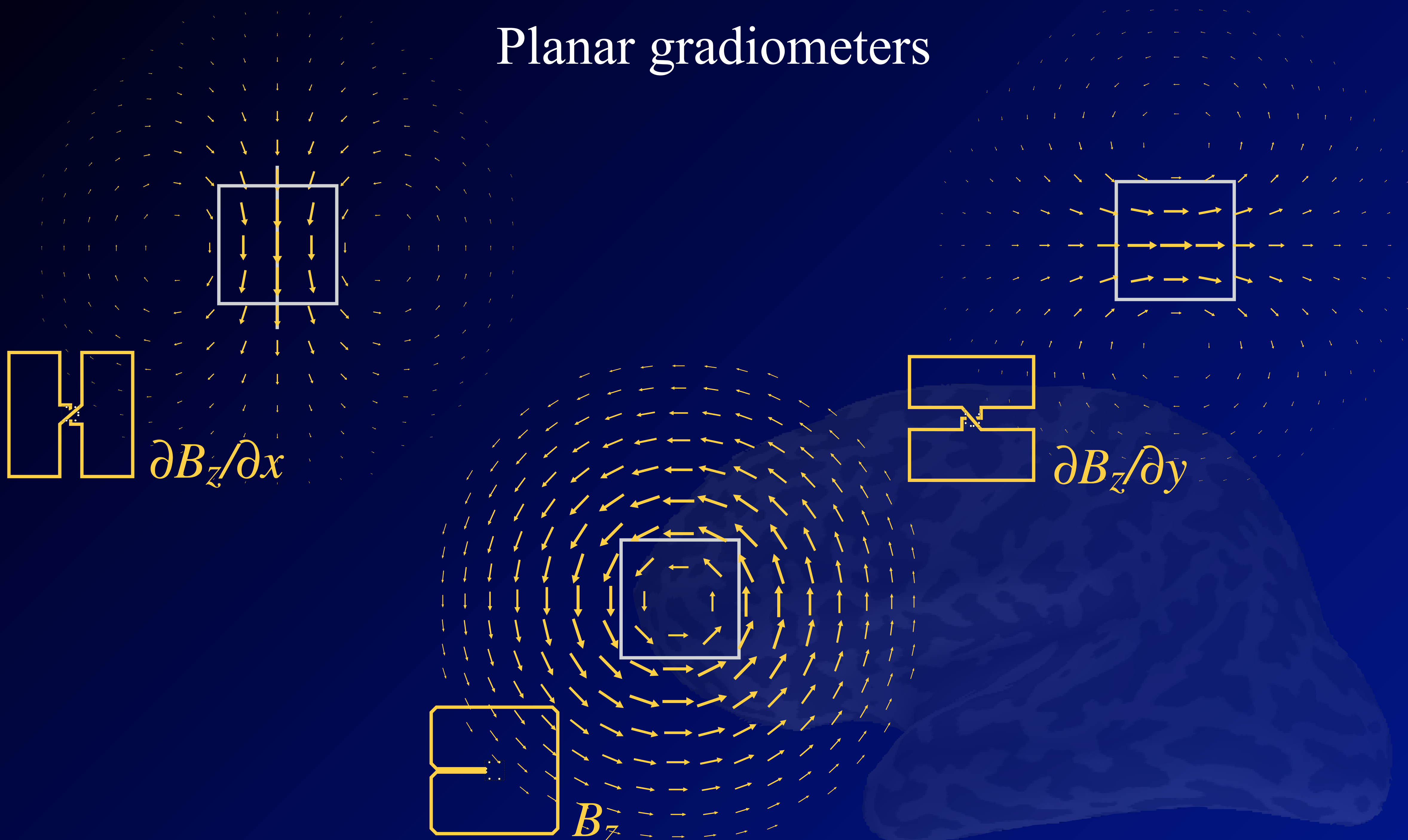
Peaks indicate where the sources are not located!

Peaks indicate approximate source locations.

Cohen, 197x

Lead fields

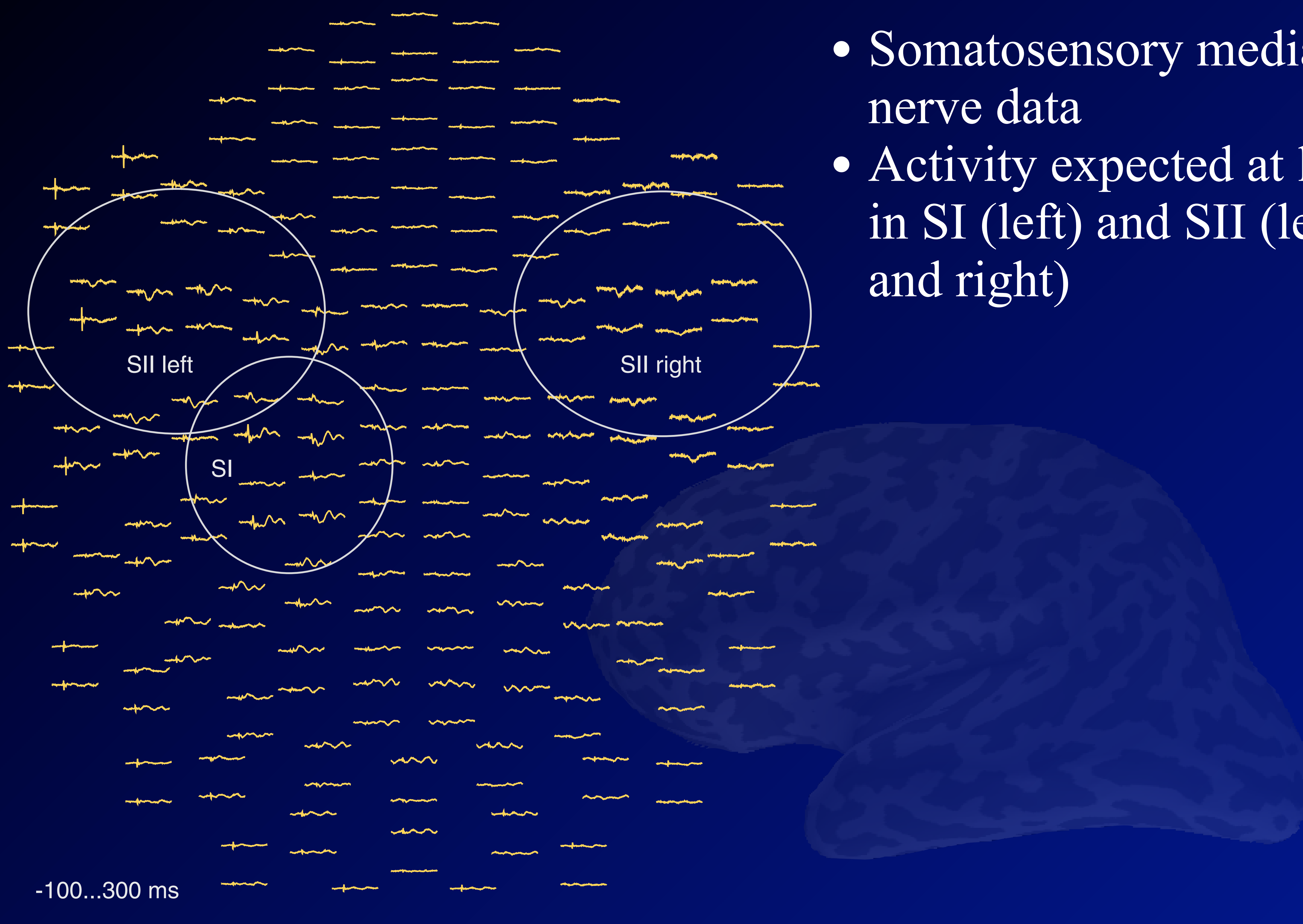
Planar gradiometers



Magnetometer

Cohen, 1979

An example of averaged MEG data

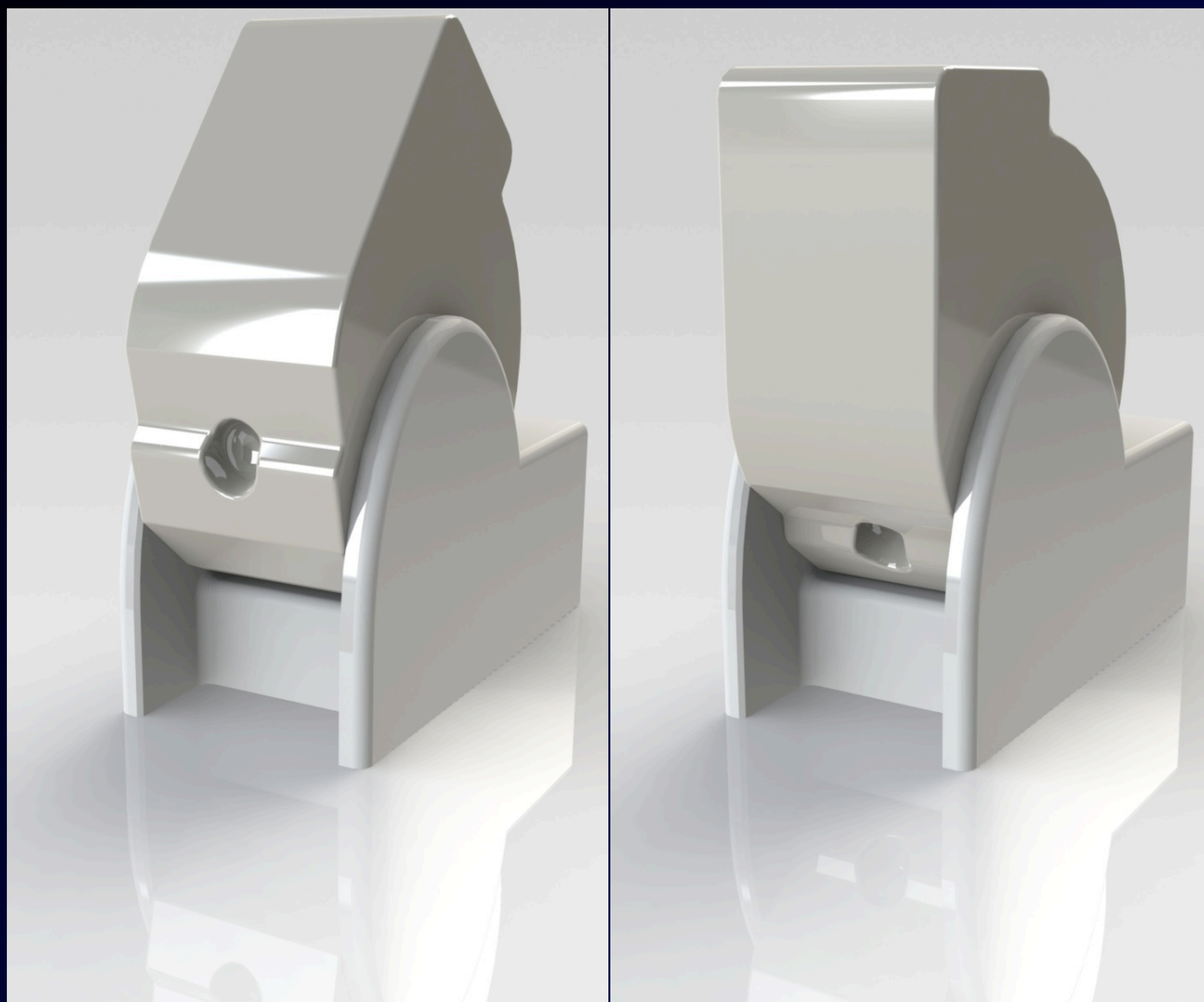


- Somatosensory median nerve data
- Activity expected at least in SI (left) and SII (left and right)

Present systems

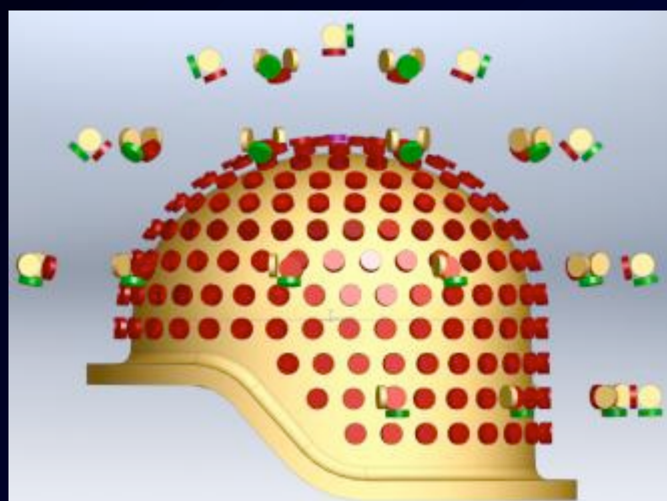
- SQUID sensors operated in a liquid helium
- Noise-level: 2 – 3 $fT/Hz^{1/2}$
- ~ 300 sensors in a helmet-shaped array
- Sensors are at least 20 mm away from the head
- “One size fits all”
- Software and hardware noise-cancellation techniques

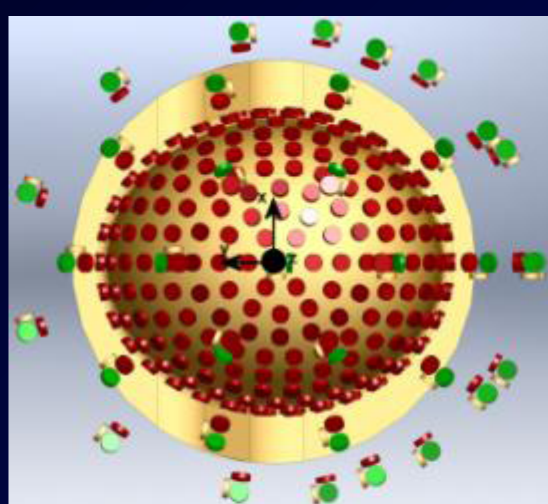
BabyMEG System



- Will be installed in Boston Children's Hospital Fall 2013
- Joint project between MGH and BCH, supported by NSF

Some BabyMEG characteristics

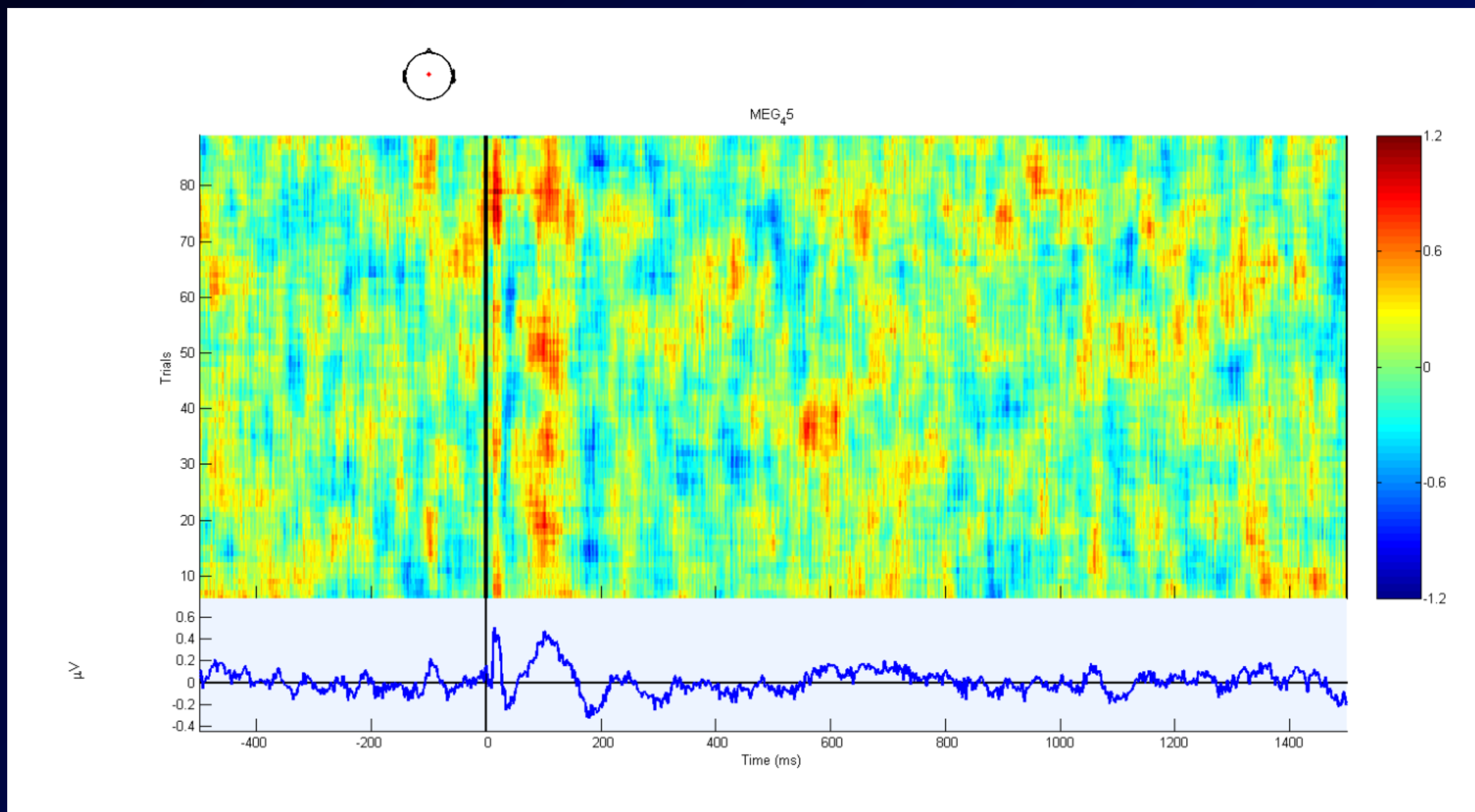




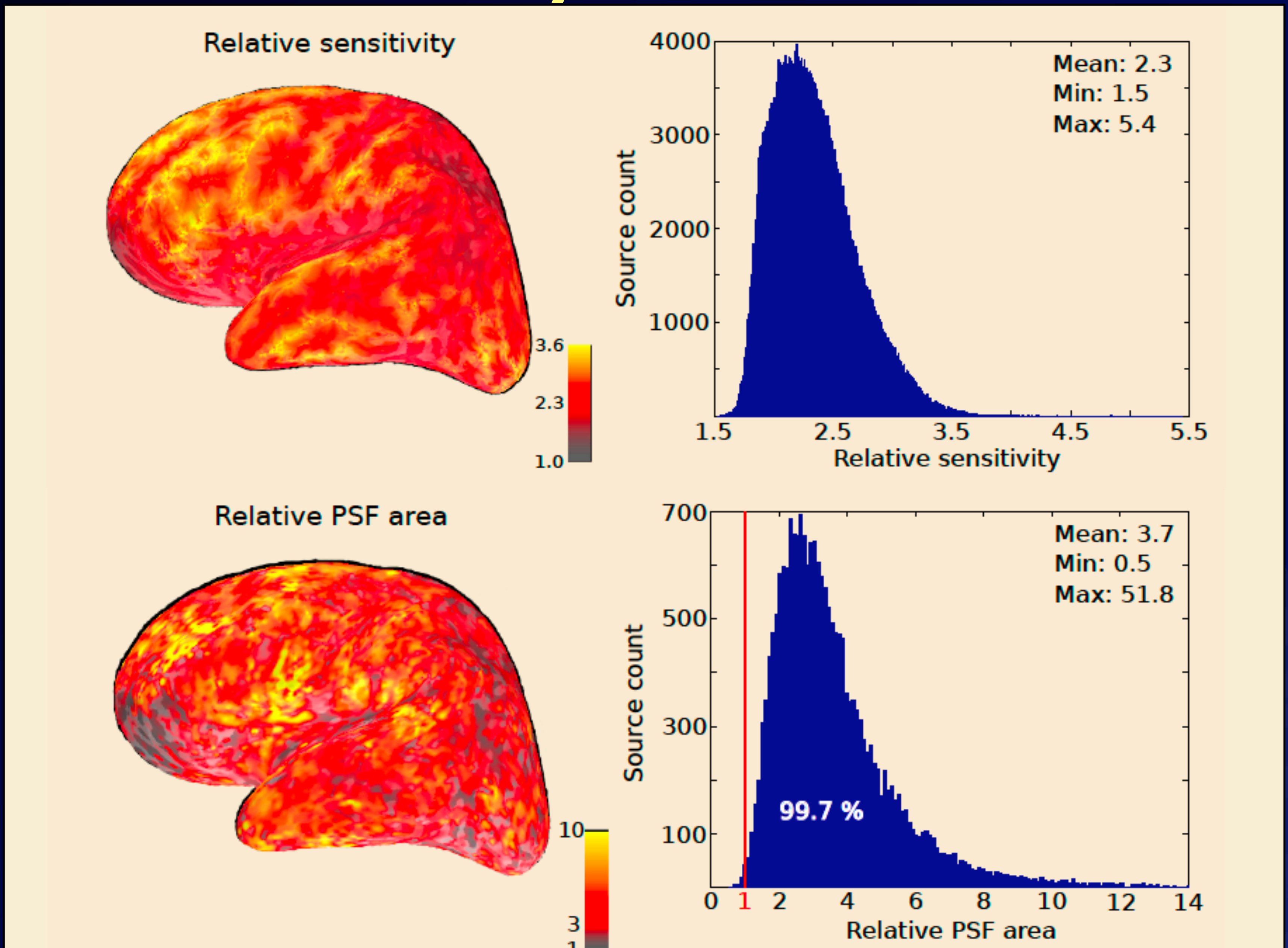
- Low-Tc SQUID system
- 271 primary magnetometers
- 108 three-axis compensation magnetometers
- Distance from sensors to room temperature (~ 7 mm)

Single-trial analysis with an infant MEG system

- Tactile stimulation, trial-to-trial variability



Benefits from bringing the sensors next to the head (SQUID vs. atomic magnetometer systems)

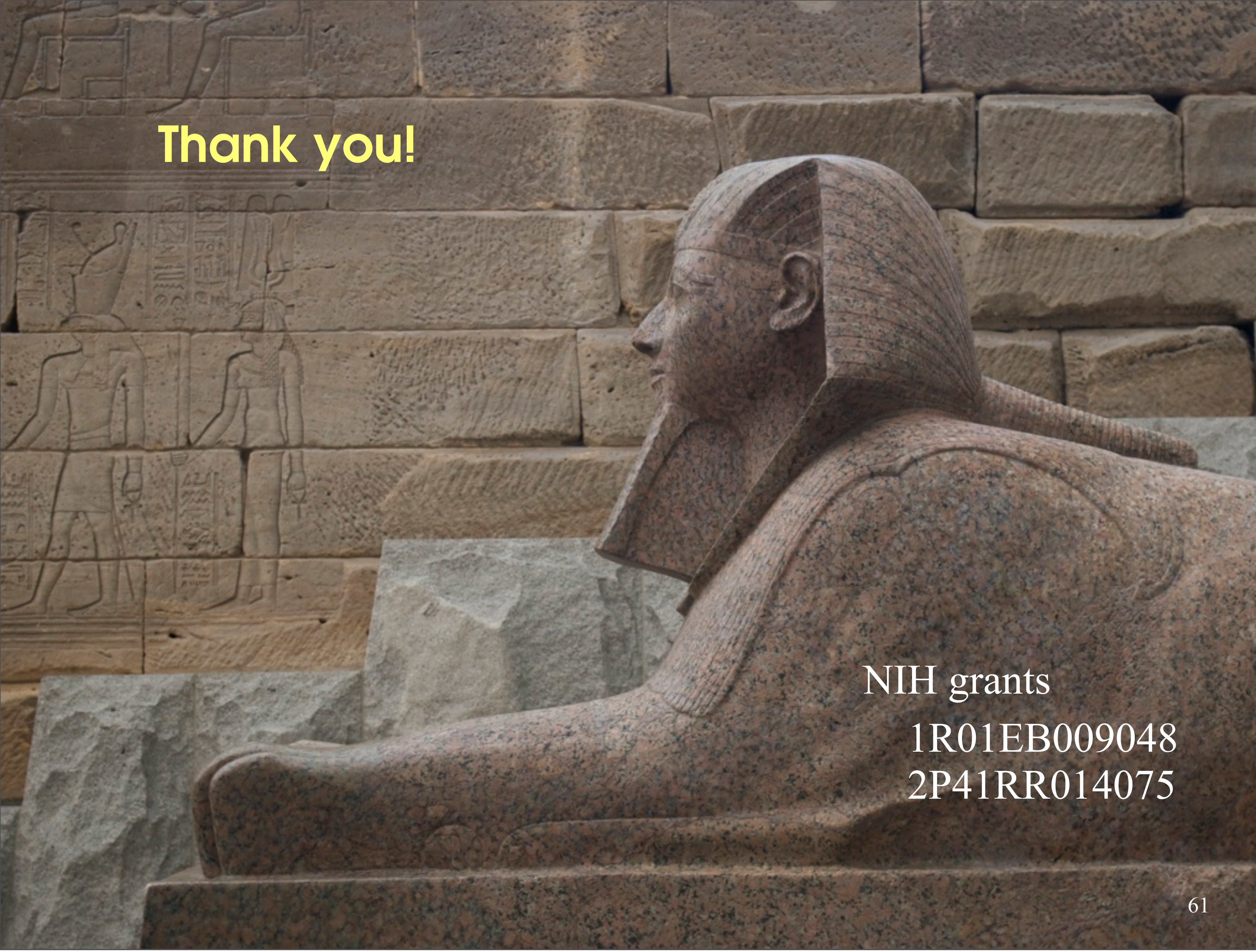


Iivanainen et al., OHBM 2013

- Significant gains in both sensitivity and point-spread function (PSF)
- Note: identical noise characteristics assumed

Summary

- MEG and EEG measure the same neural sources
- MEG is easier to analyze than EEG because it is largely independent of conductivities
- MEG is preferentially sensitive to tangential sources, currents in the sulci
- The current dipole is the appropriate elementary source model
- The equivalent current dipole can be used to model cortical source patches
- Due to the vectorial nature of the currents there are cancellation effects when multiple sources are active or when the sources are extended



Thank you!

NIH grants

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