

Introduction to EEG, MEG and analysis with the FieldTrip toolbox

Robert Oostenveld

*Donders Institute, Radboud University, Nijmegen, NL
NatMEG, Karolinska Institute, Stockholm, SE*

What is FieldTrip

a MATLAB toolbox for the analysis of MEG, EEG
and animal electrophysiology data

can import data from many different file formats

contains algorithms for spectral analysis, source
reconstruction, statistics, connectivity, ...

Talk outline

What kind of signals are generated in the brain

How do we record those signals

Analyzing those signals with FieldTrip

Background on the FieldTrip toolbox

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Background on the FieldTrip toolbox

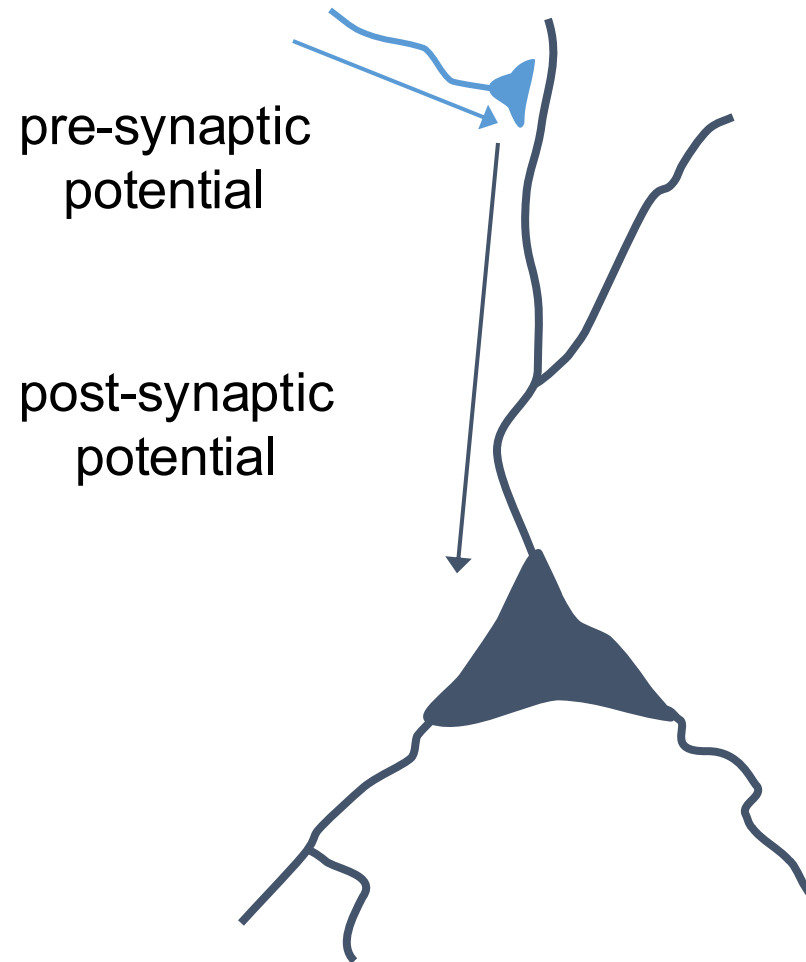
What kind of signals are generated in the brain

We measure the scalp potentials or field associated with post-synaptic potentials in pyramidal neurons

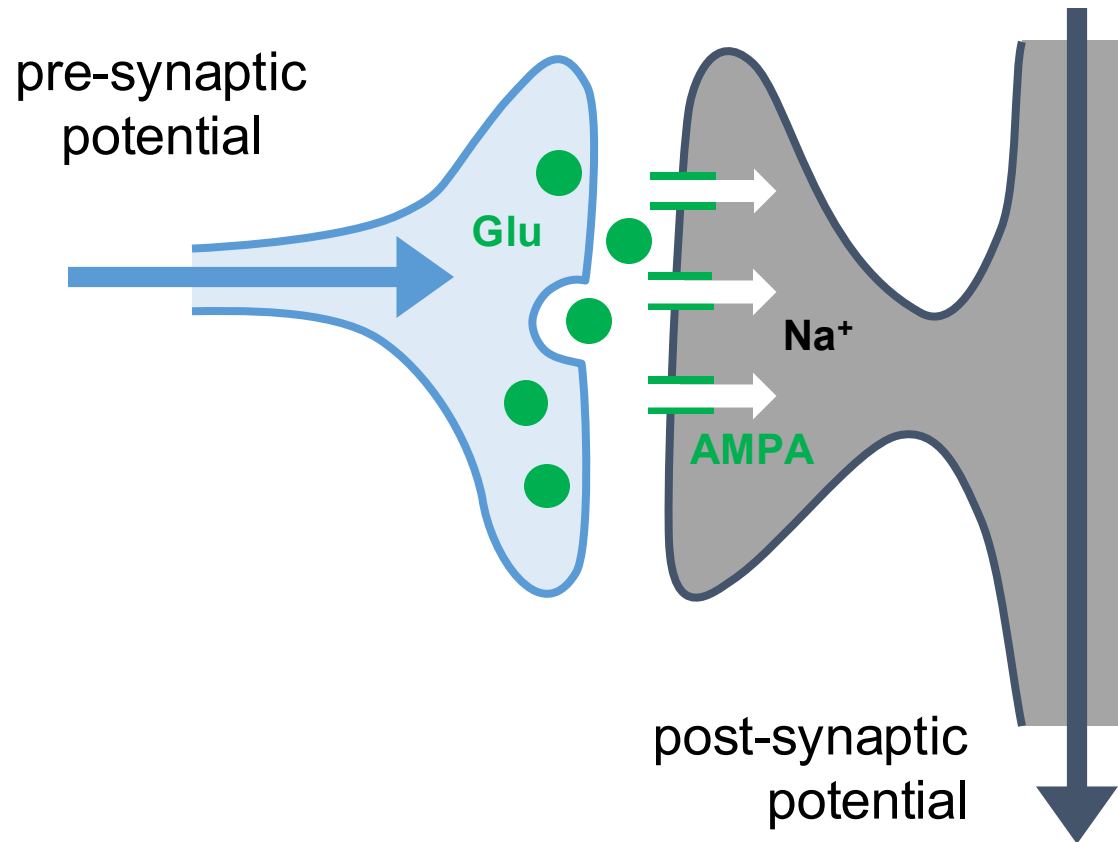
These PSPs represent the excitatory and inhibitory input that these neurons receive

Usually we study this neuronal input following the presentation of a stimulus or following a cognitive event

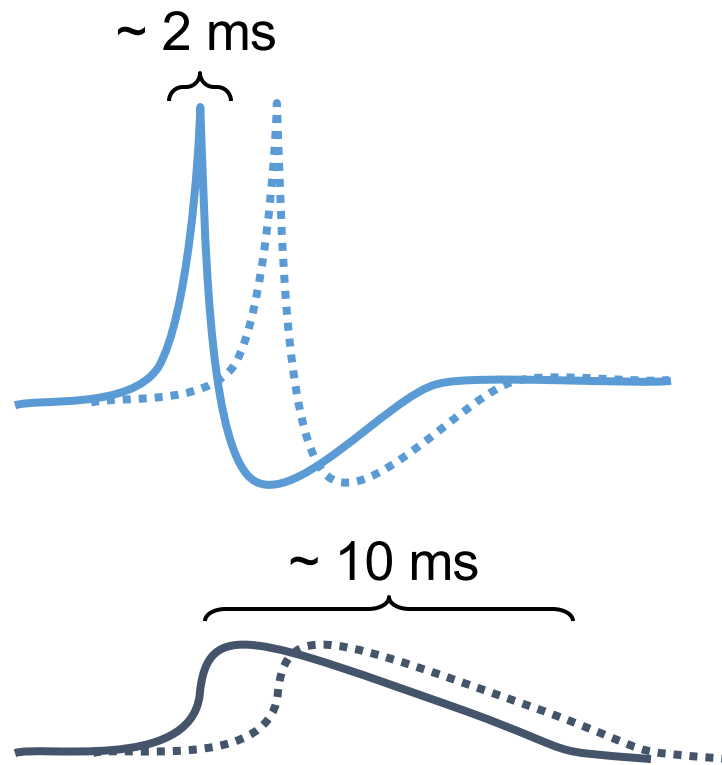
What generates the currents and fields



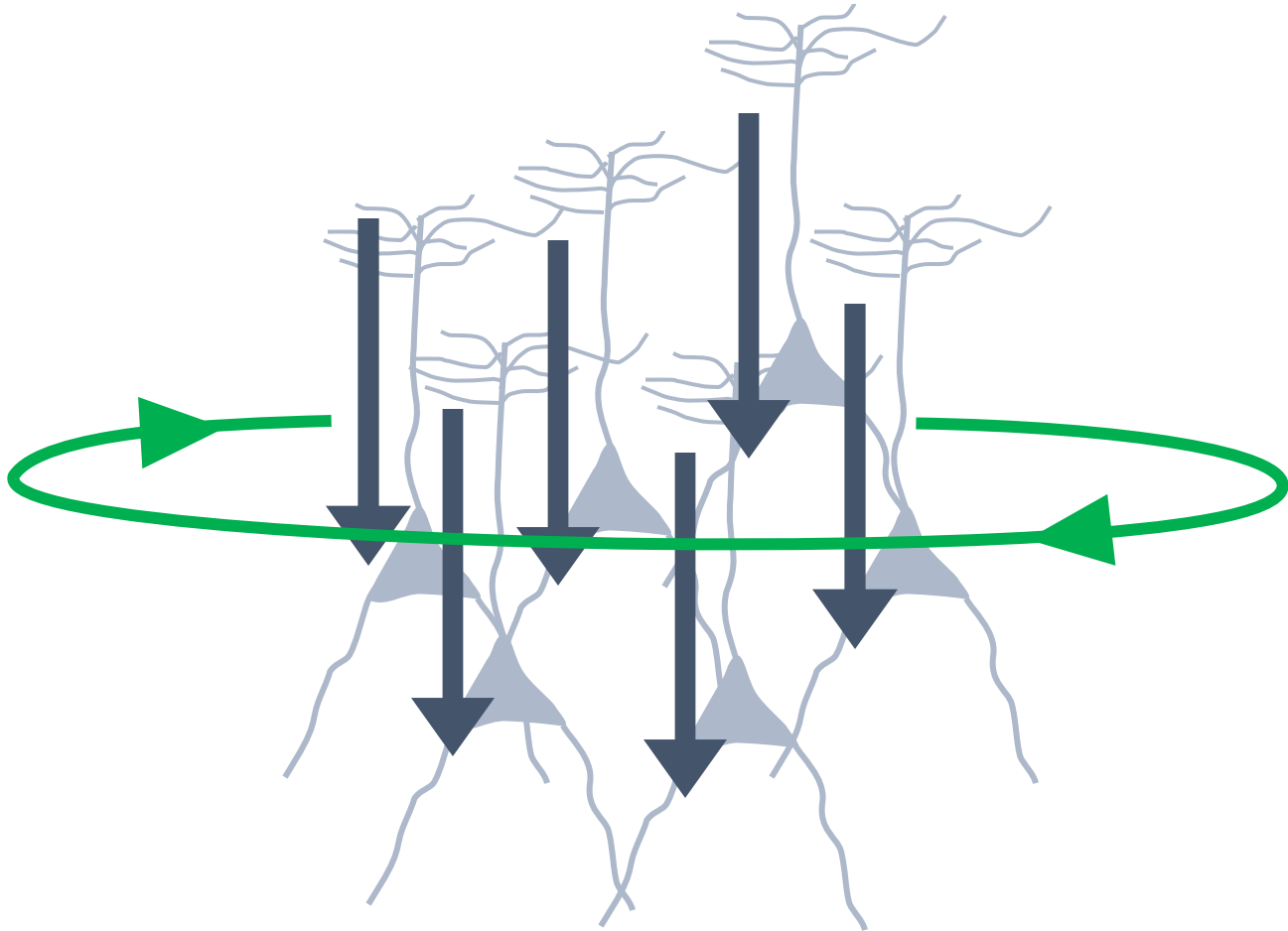
What generates the currents and fields



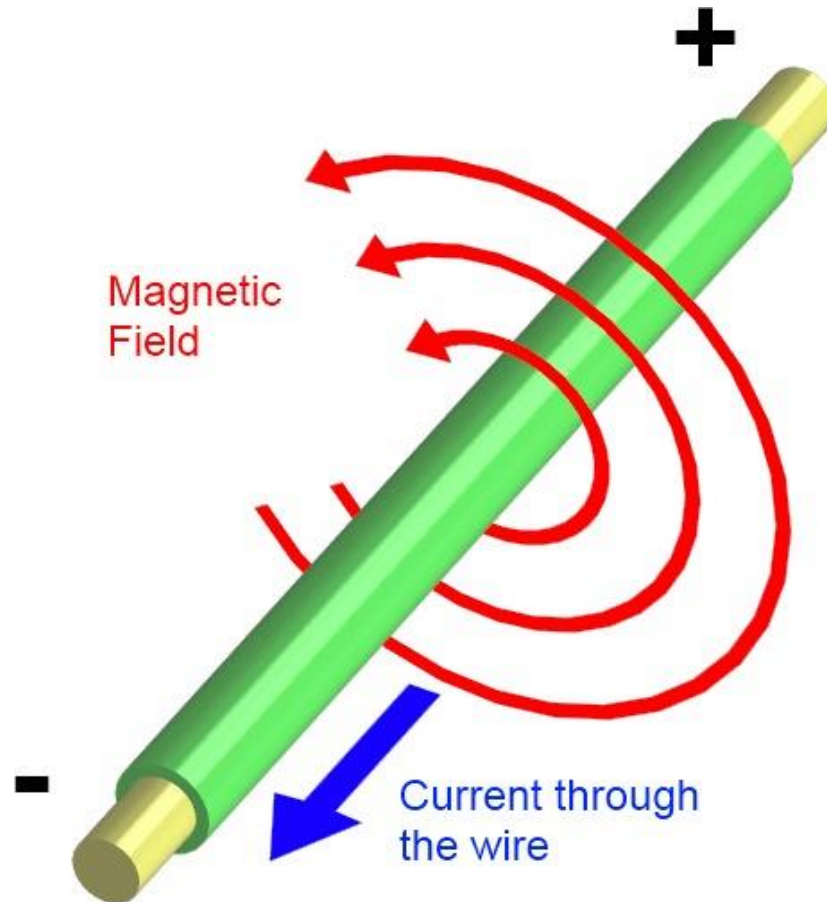
What generates the currents and fields



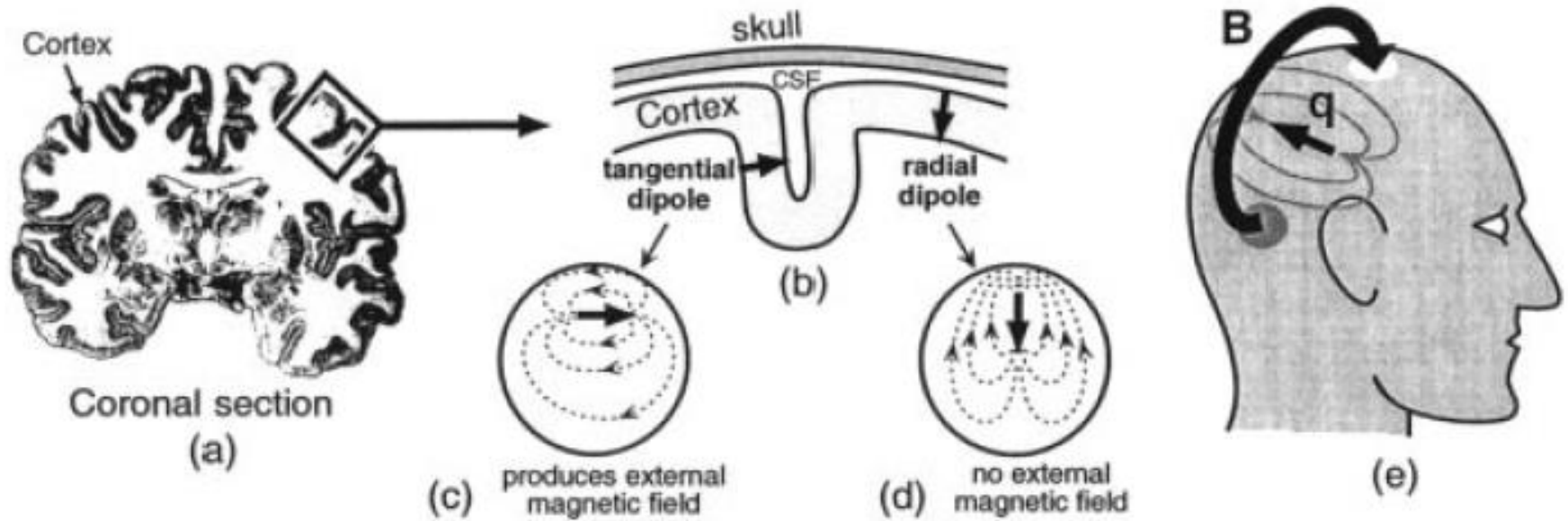
What generates the currents and fields



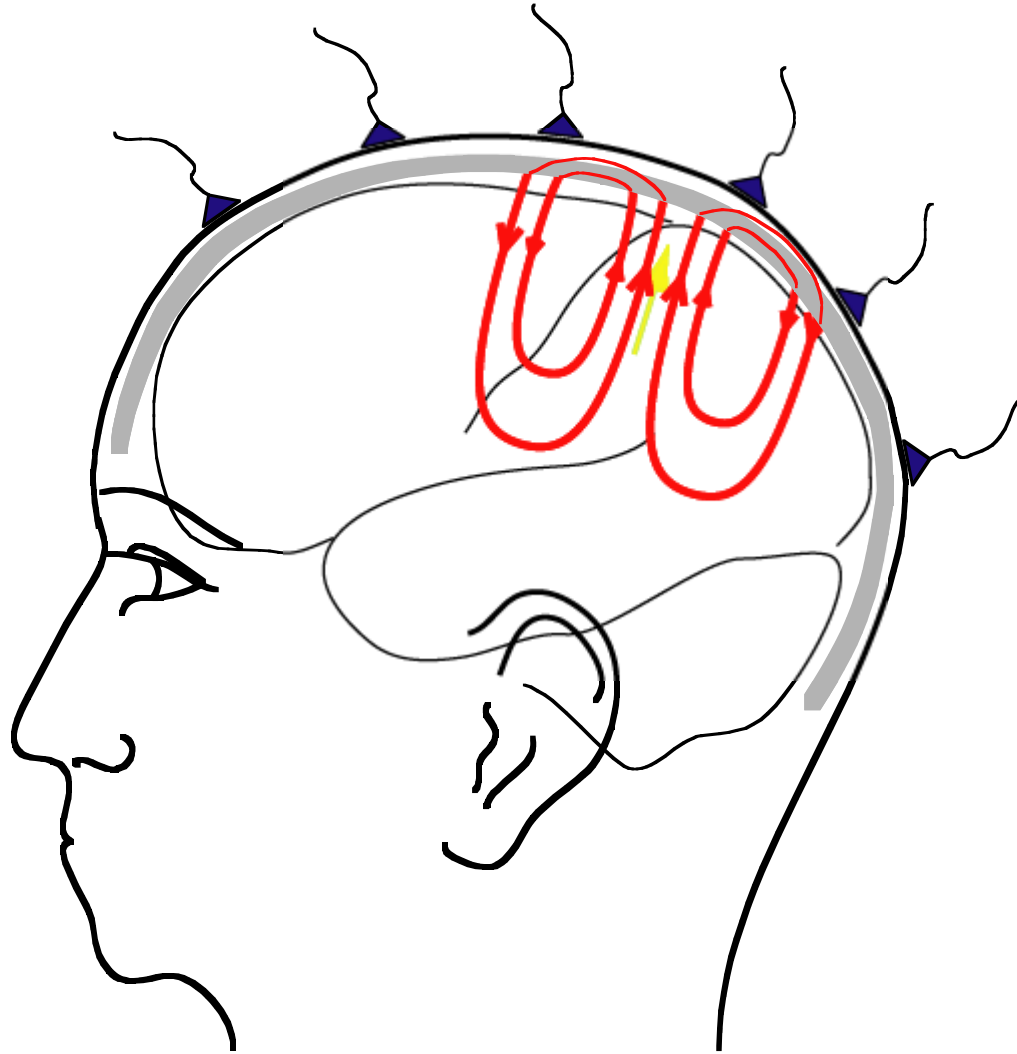
What generates the currents and fields



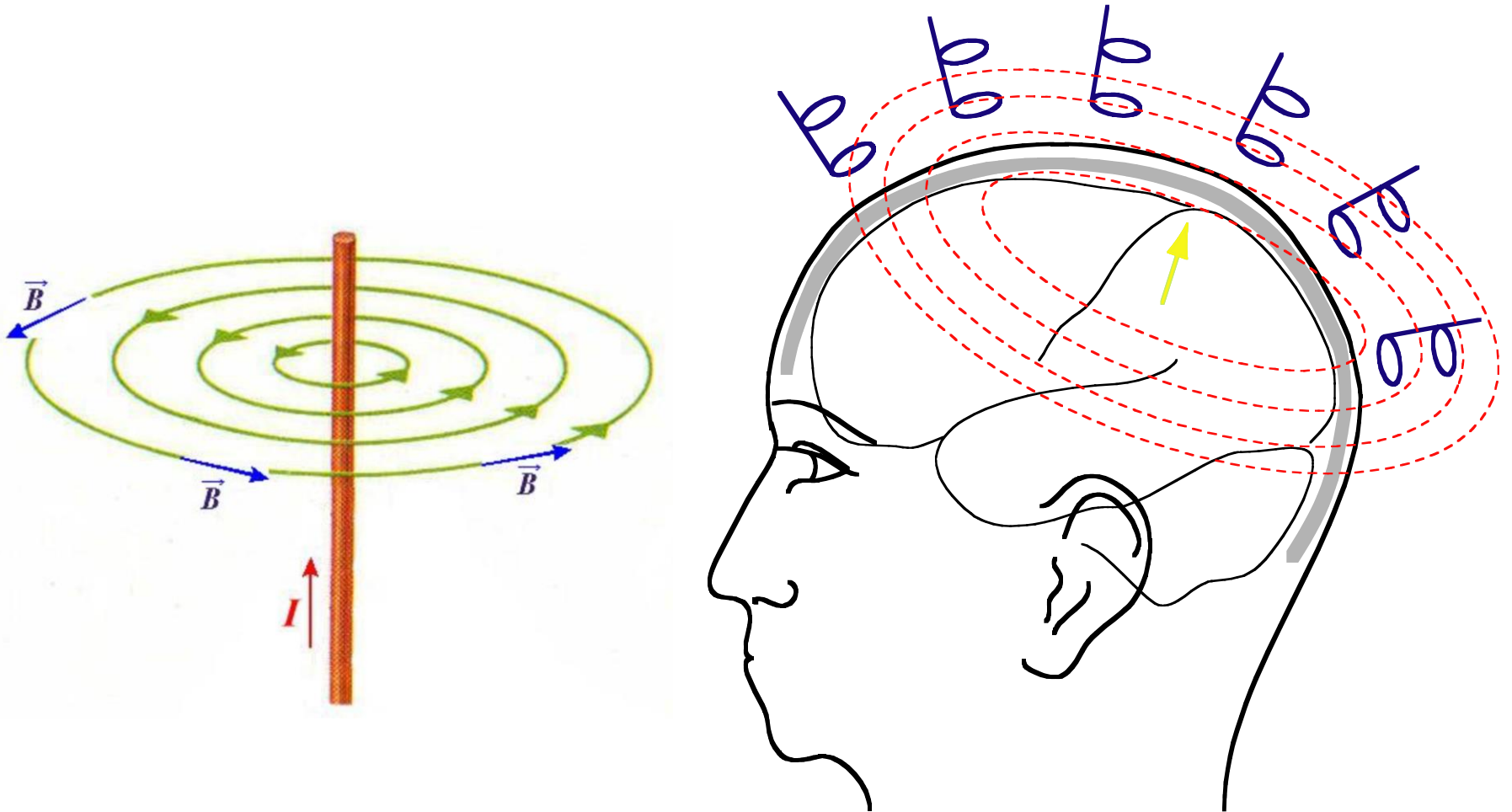
What generates the currents and fields



EEG volume conduction



Electric current \rightarrow magnetic field



Talk outline

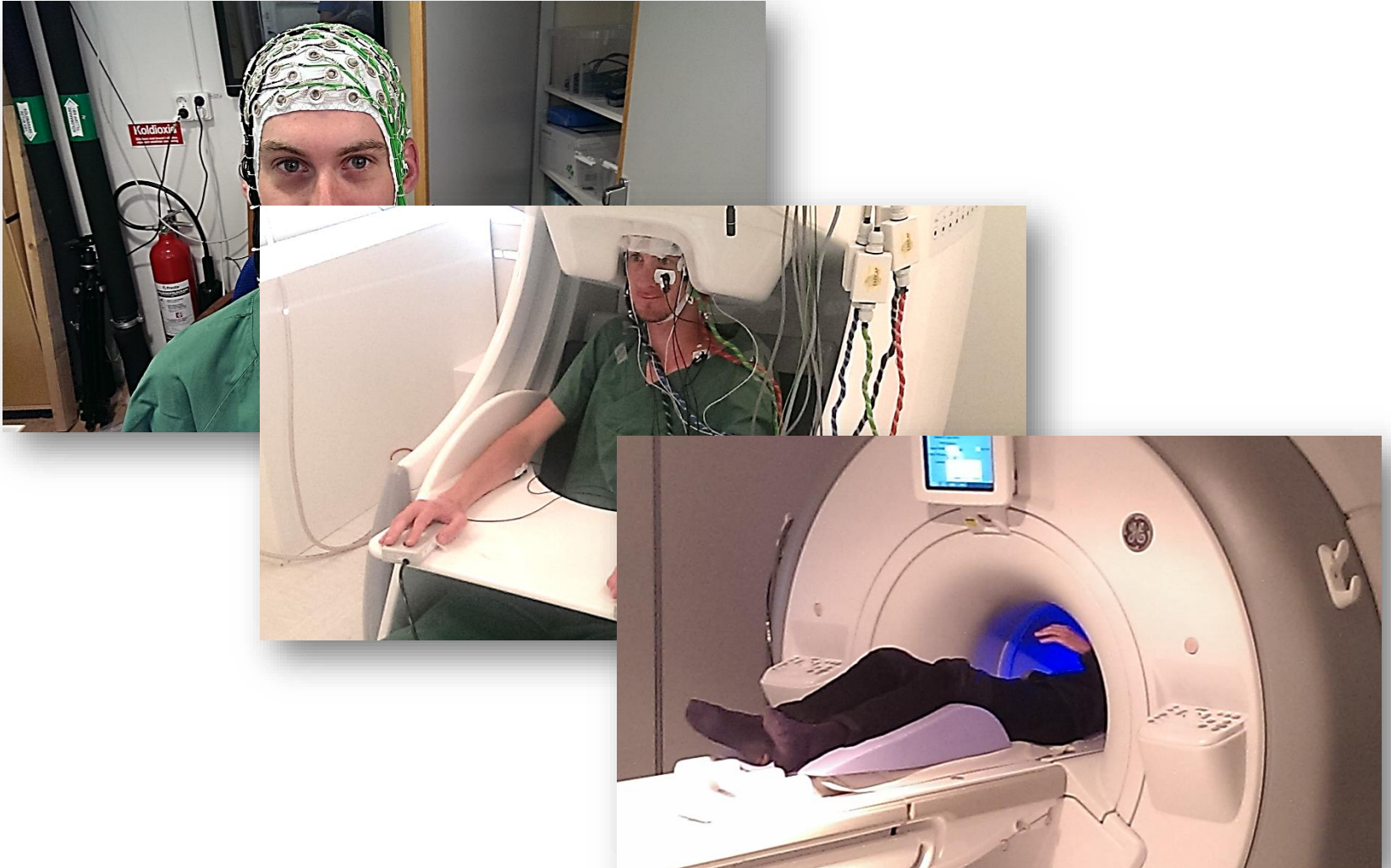
What kind of signals are generated in the brain

How do we record those signals

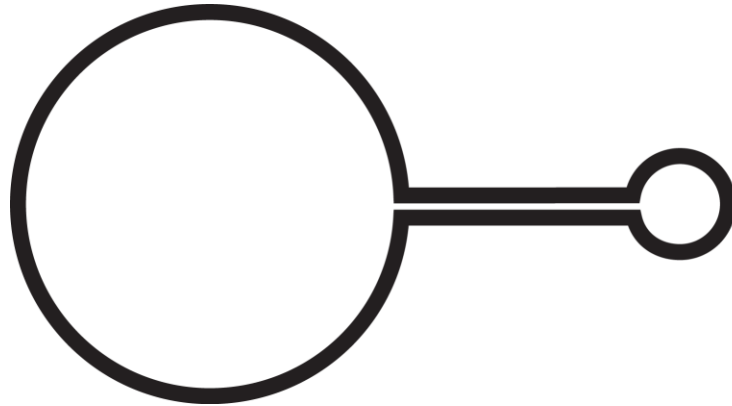
Analyzing those signals with FieldTrip

Background on the FieldTrip toolbox

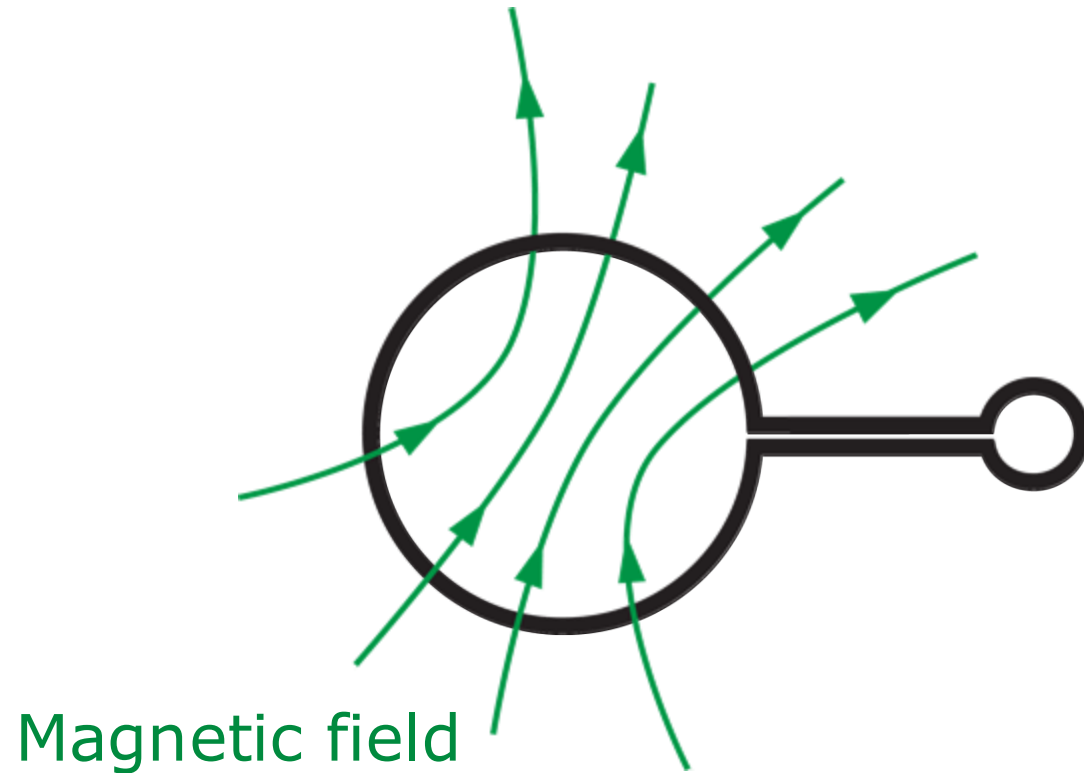
How do we record these signals from the brain



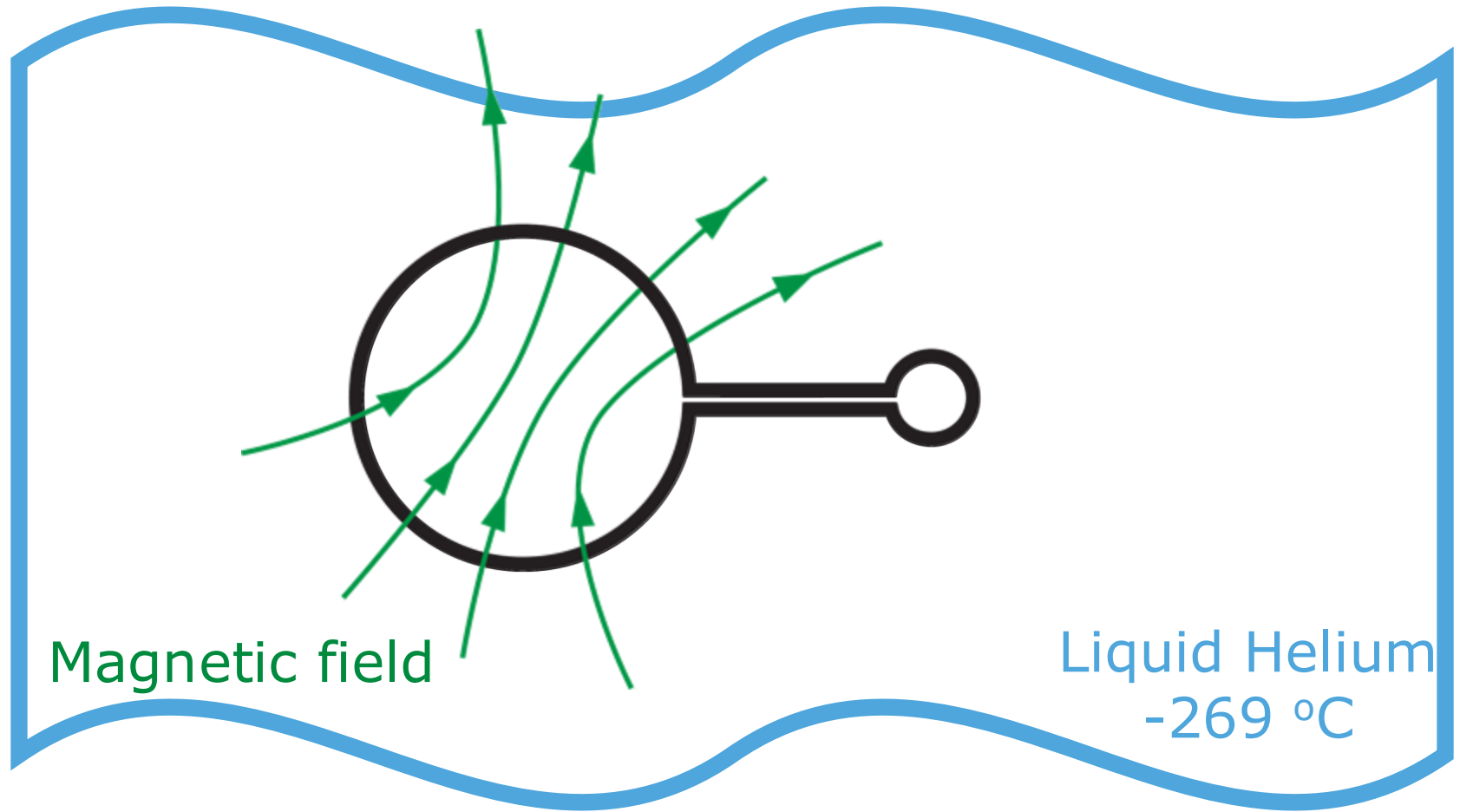
Recording small magnetic fields using SQUIDs



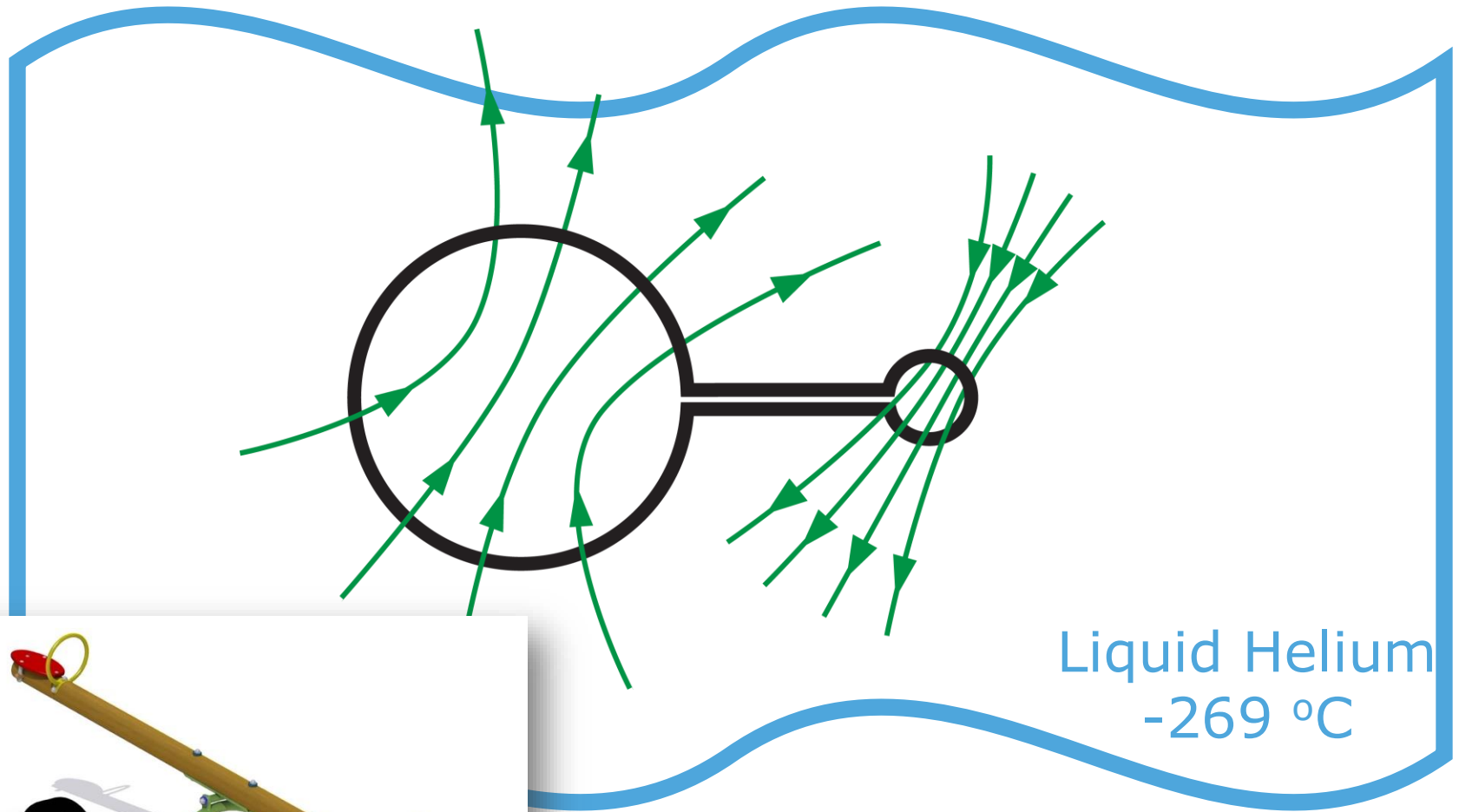
Recording small magnetic fields using SQUIDs



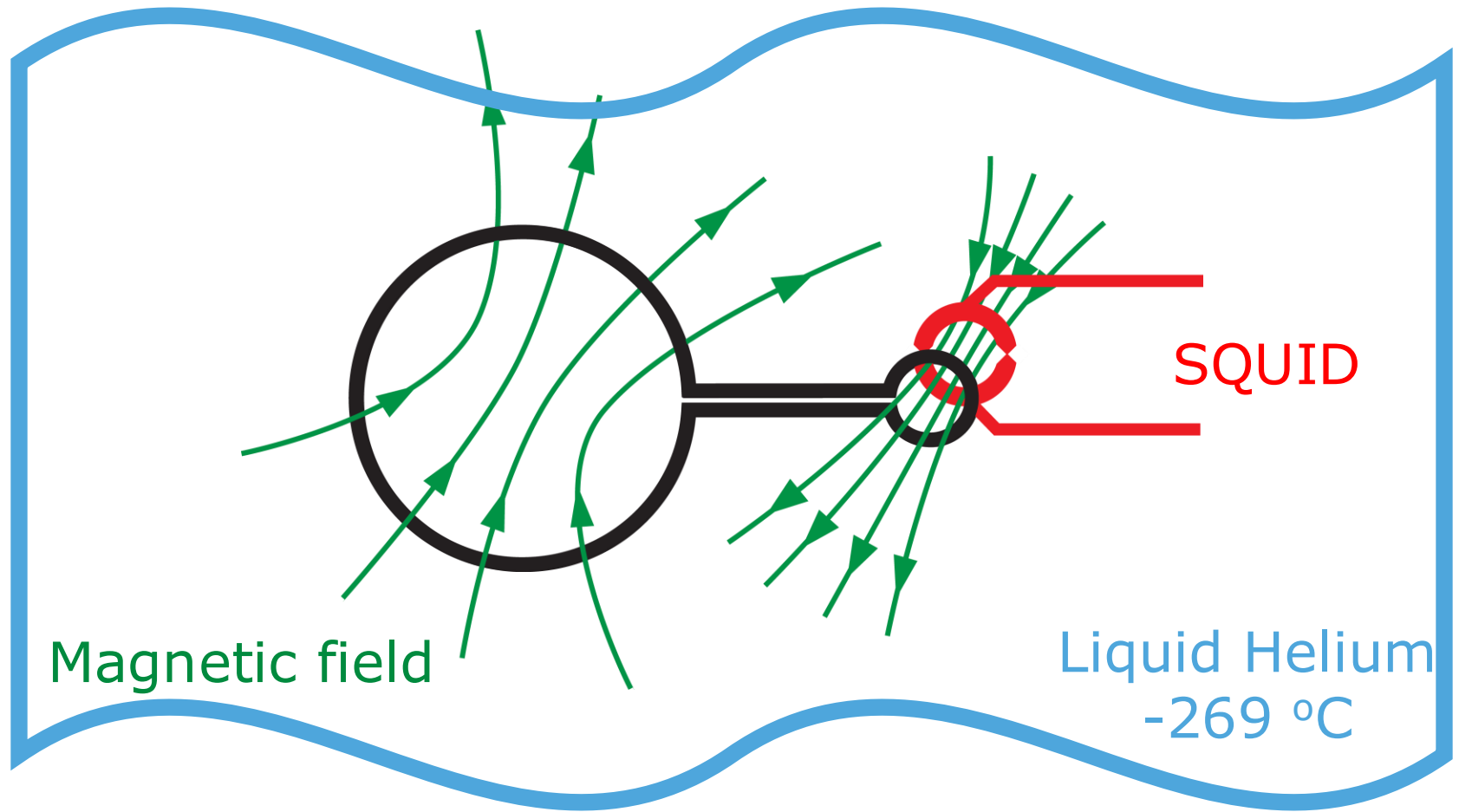
Recording small magnetic fields using SQUIDs



Recording small magnetic fields using SQUIDs

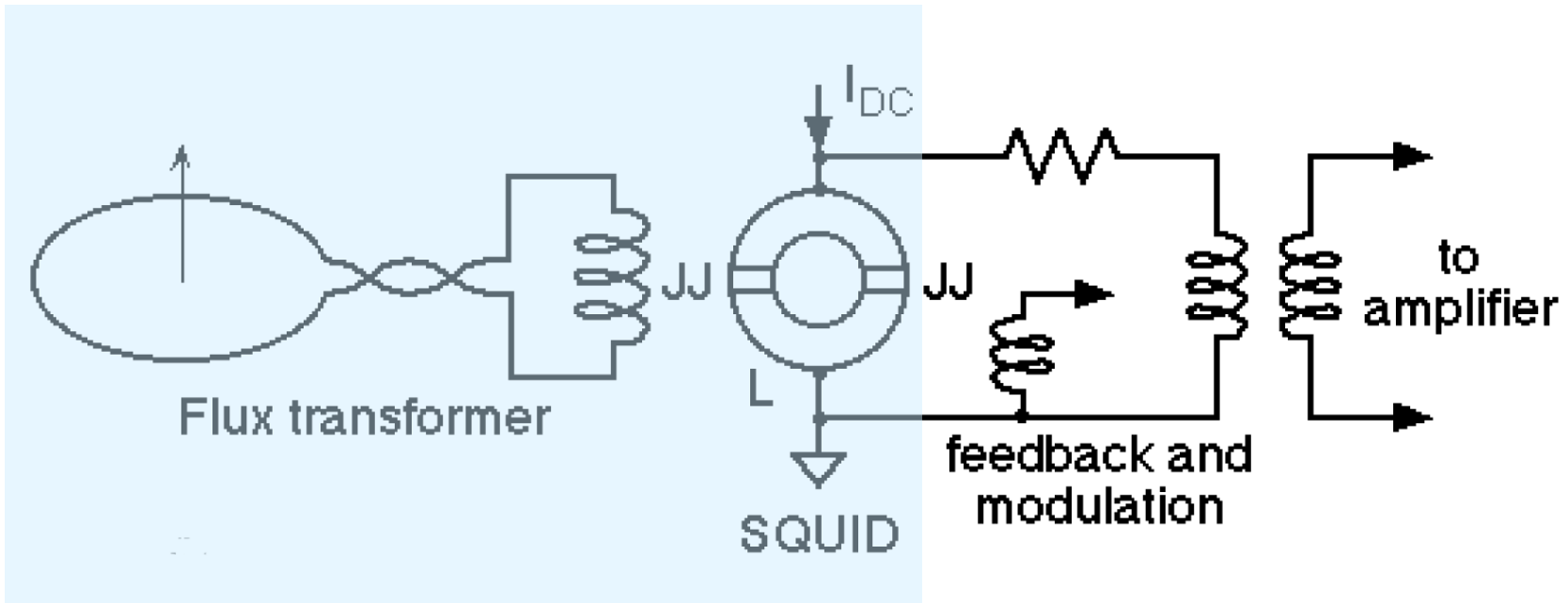
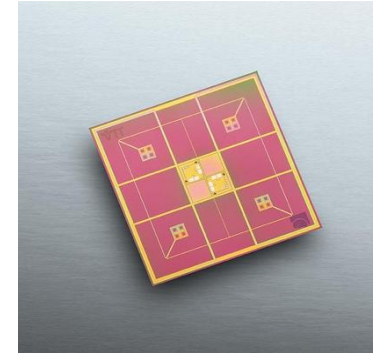


Recording small magnetic fields using SQUIDs



Magnetic field detectors

Superconducting **QU**antum **I**nterference **D**evice



Magnetic field strength - compared

10^0	1.5 - 3 T	MRI systems
10^{-3}	5 mT	typical refrigerator magnet
10^{-6}	30-60 μ T	earth's magnetic field
10^{-9}	0.1 -10 nT	heliosphere
10^{-12}	0.1 - 1.0 pT	spontaneous brain activity
10^{-15}	10-100 fT	ERF differences

Technical challenges of MEG

Requires sensitive magnetic detectors

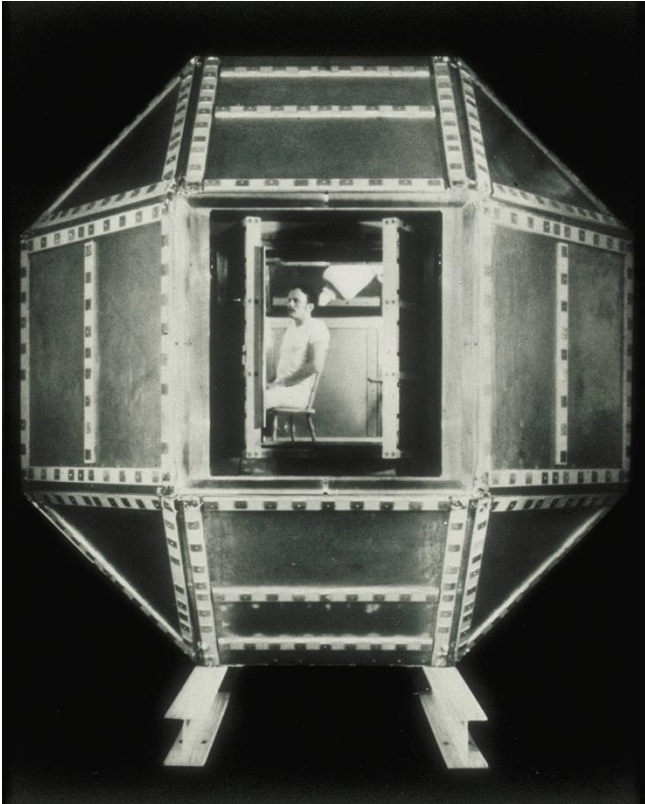
Deal with environmental noise

- shielding

- sensor design

- reference sensors for noise subtraction

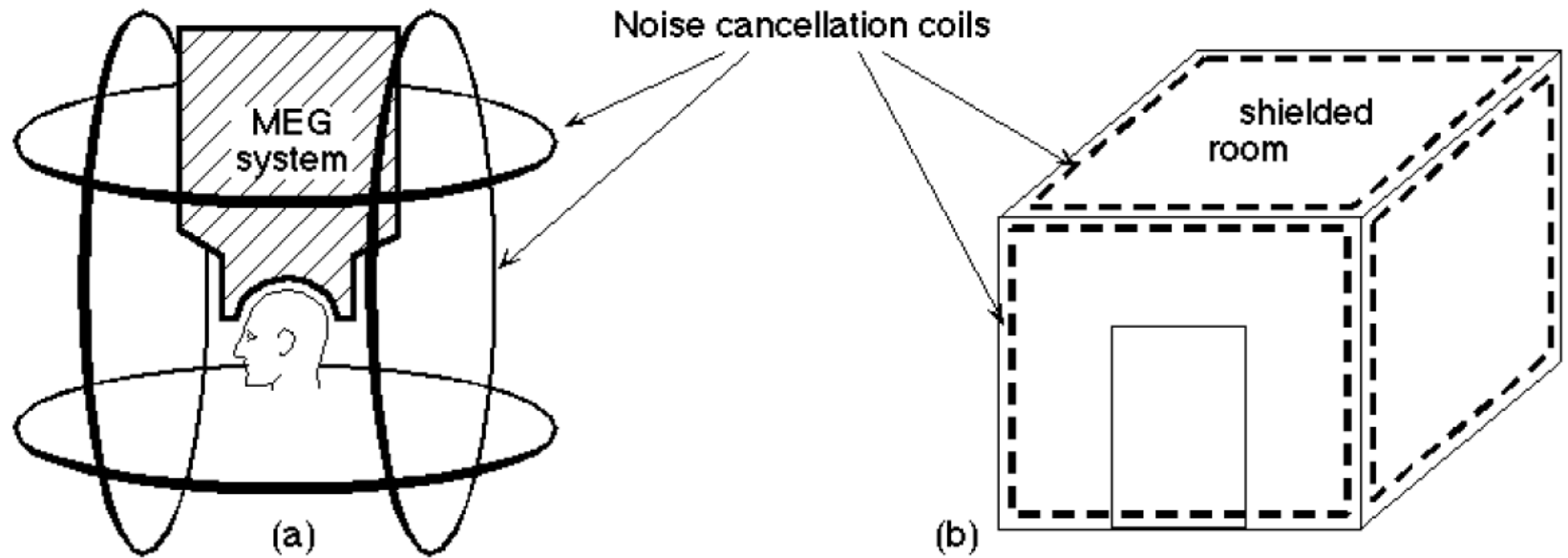
Shielding - passive



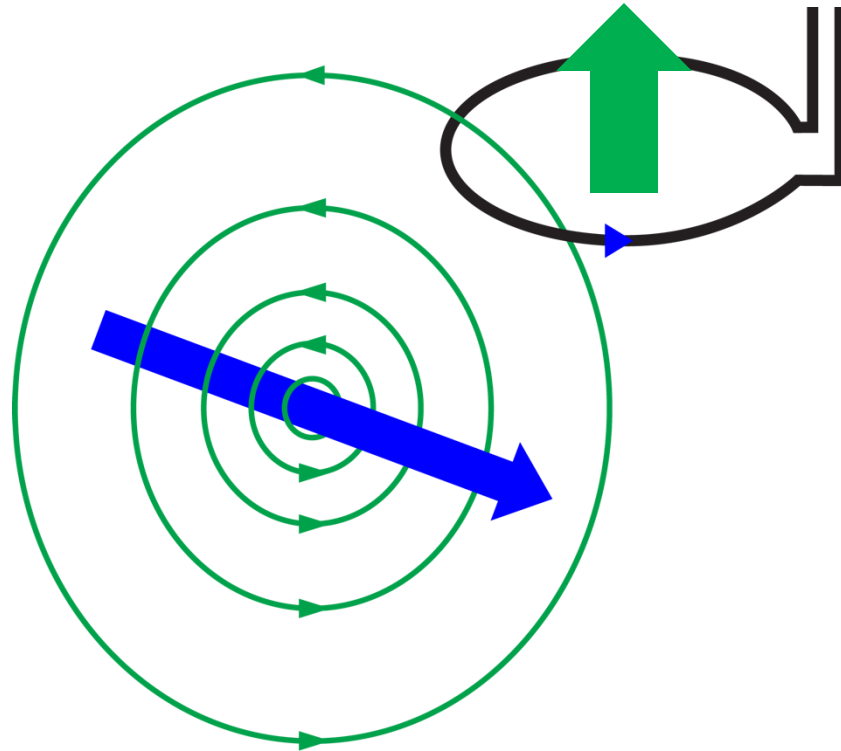
The magnetically shielded room built by David Cohen at MIT's Francis Bitter National Magnet Laboratory in 1969.



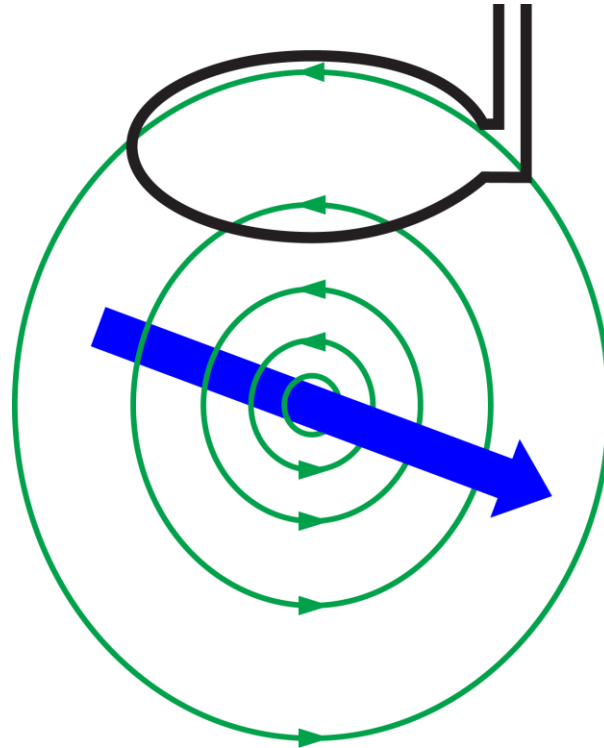
Shielding - active



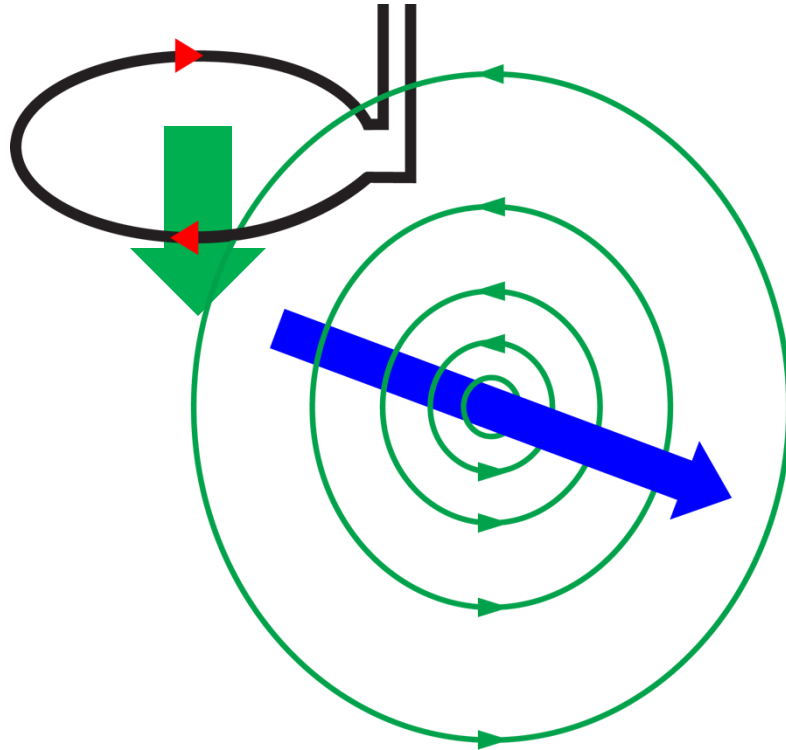
Magnetometer



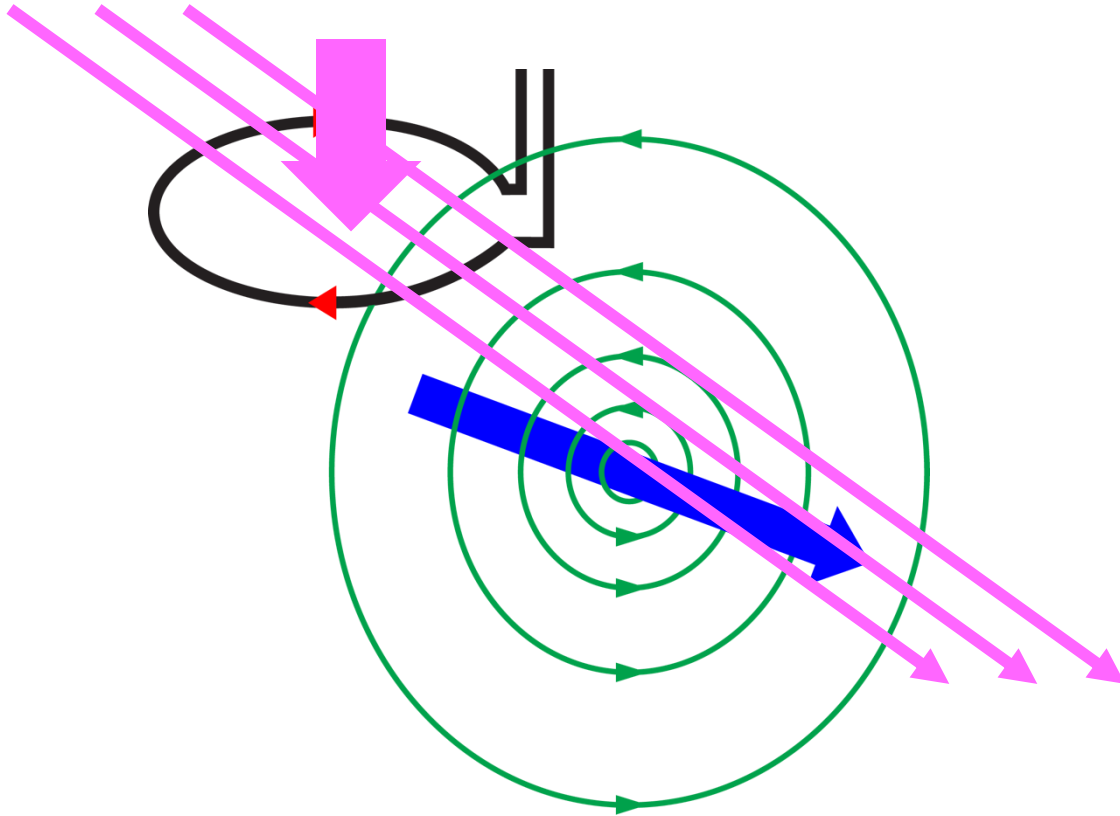
Magnetometer



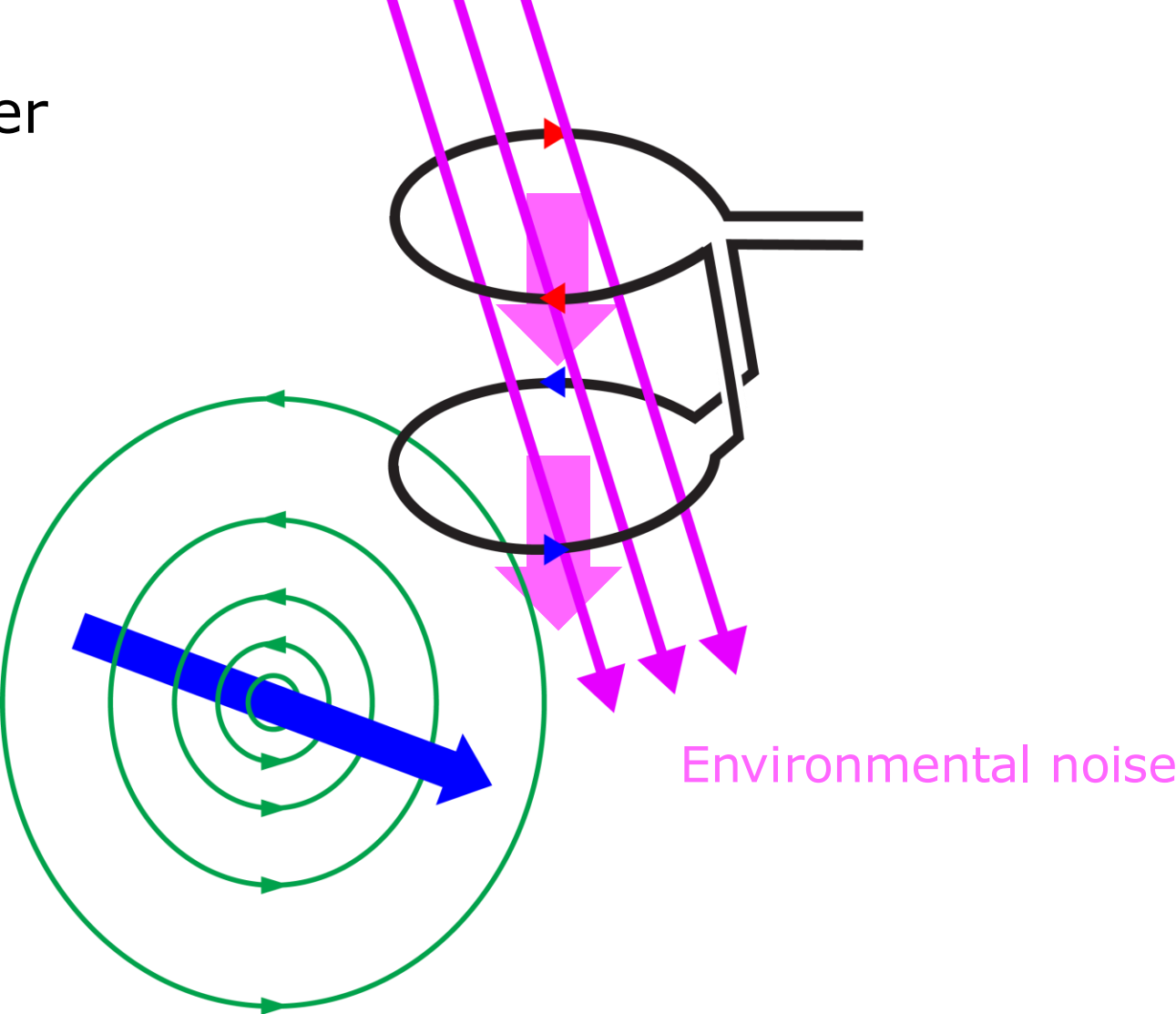
Magnetometer



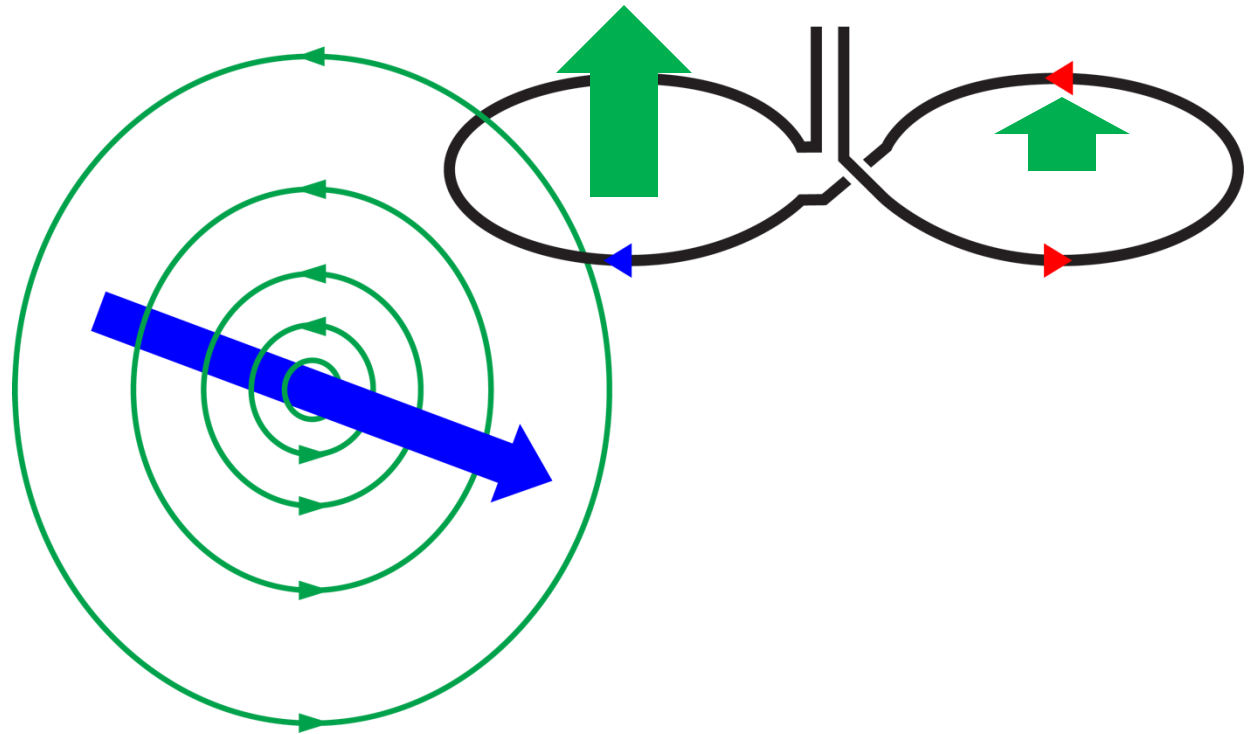
Magnetometer



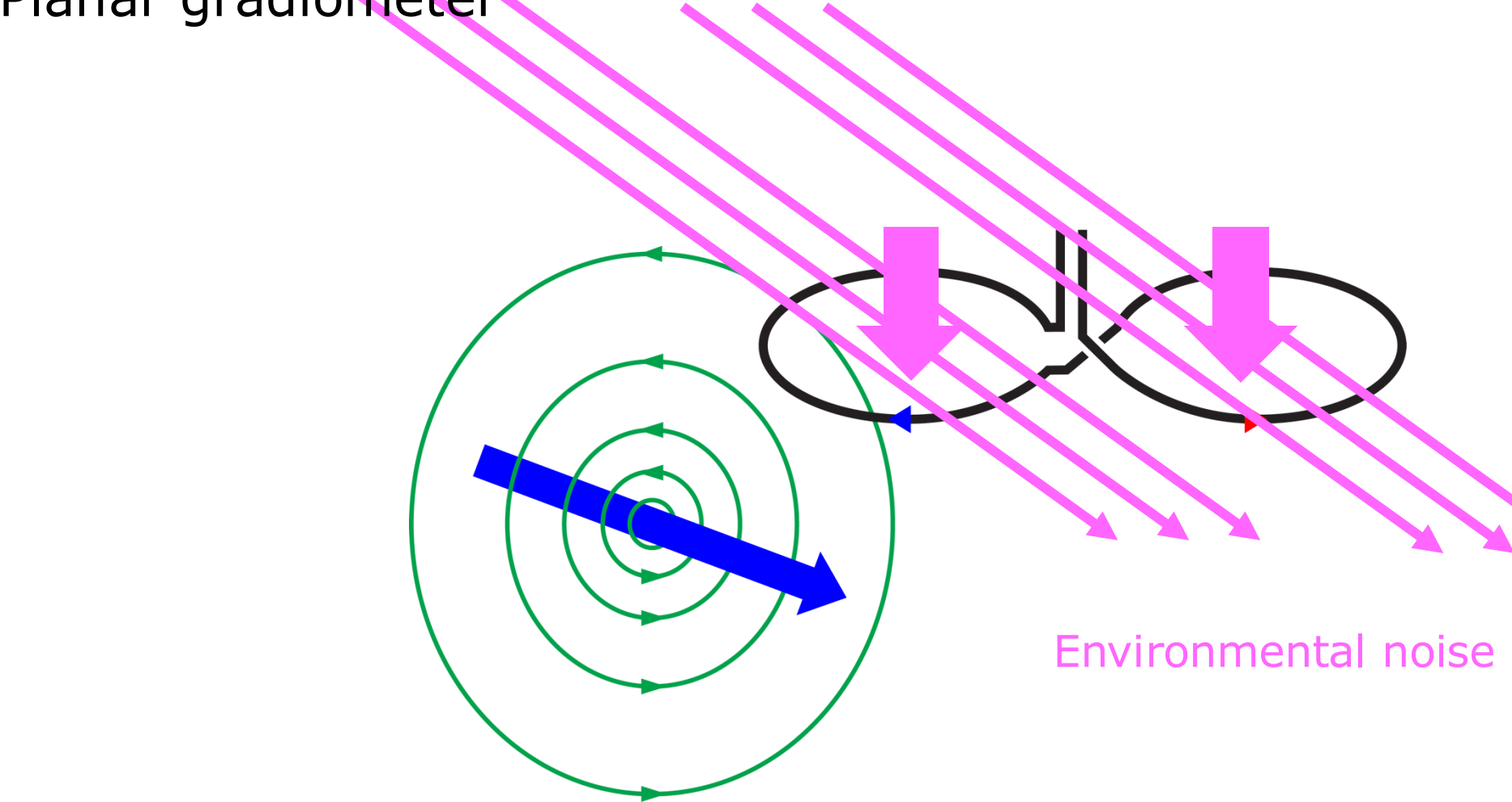
Axial gradometer



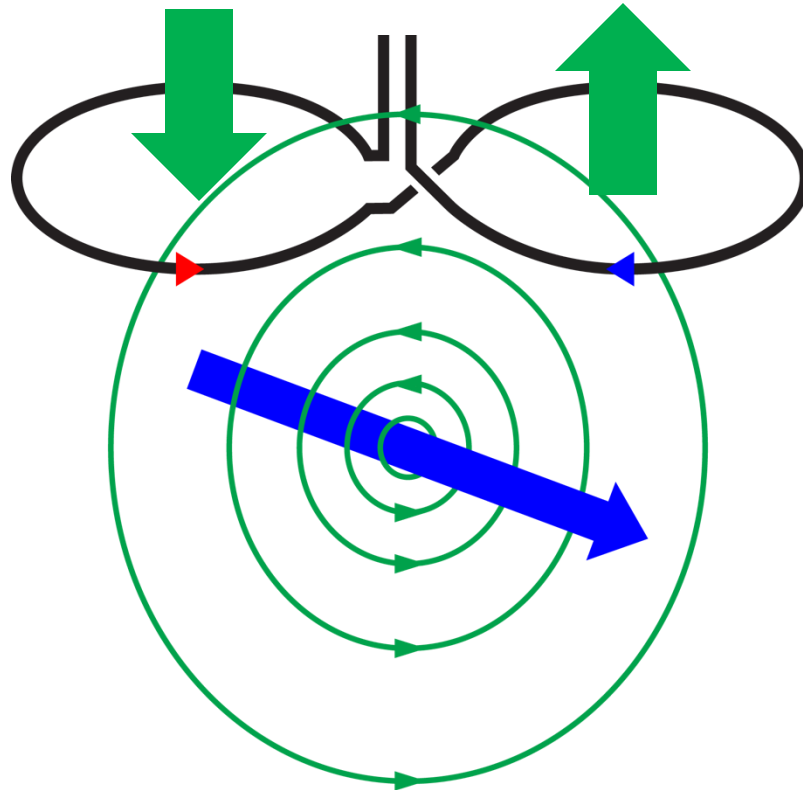
Planar gradiometer



Planar gradiometer

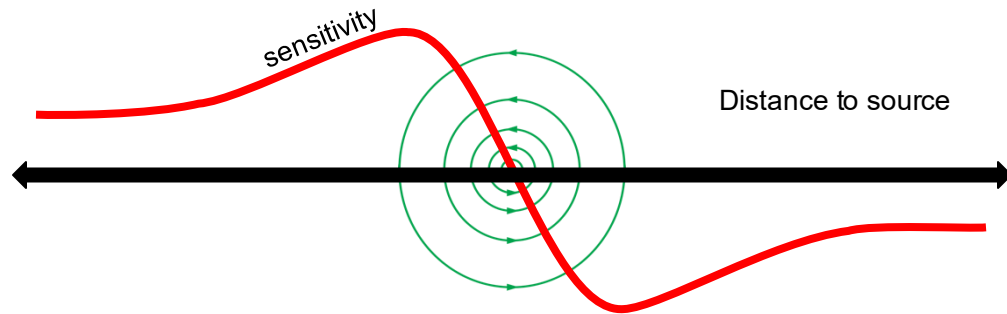
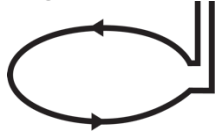


Planar gradiometer

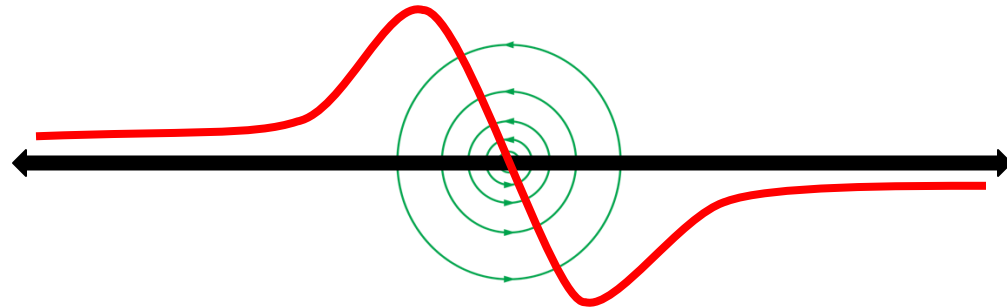
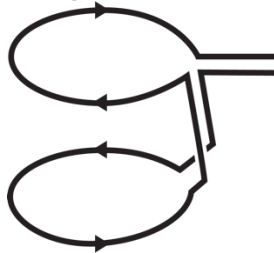


MEG sensor – sensitivity profile

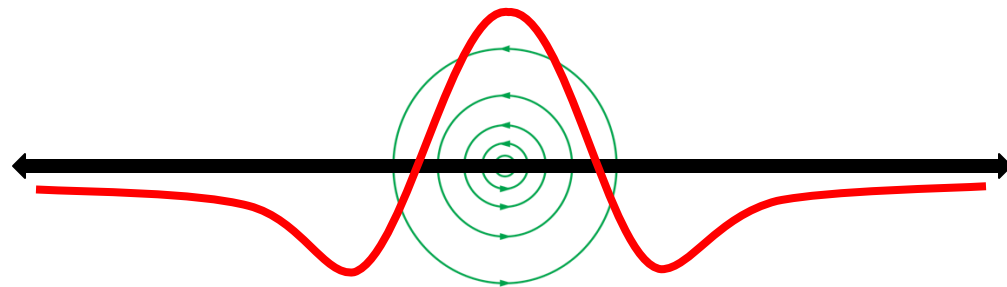
Magnetometer



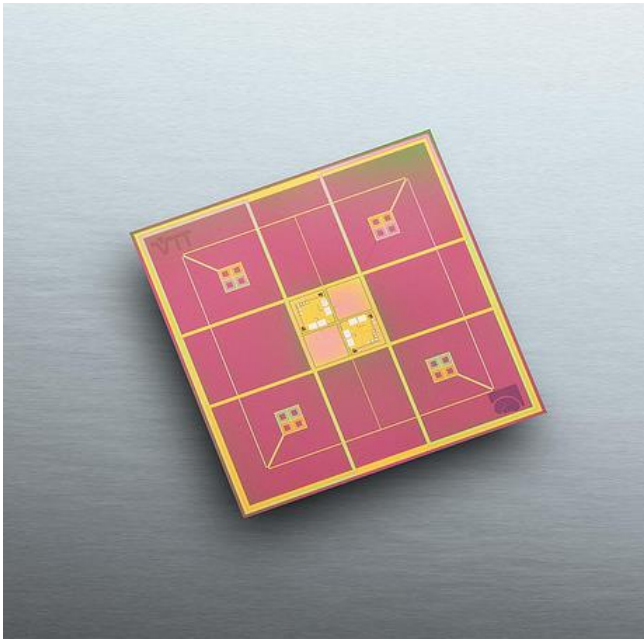
Axial gradiometer



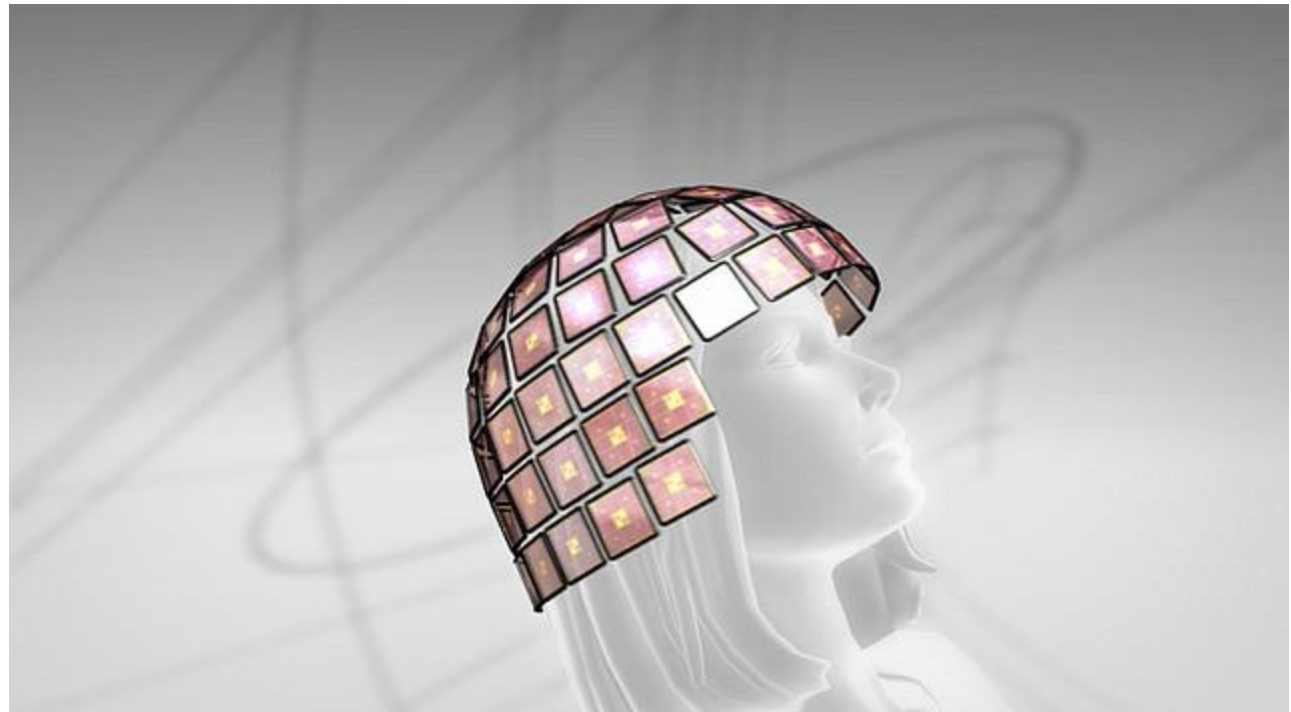
Planar gradiometer



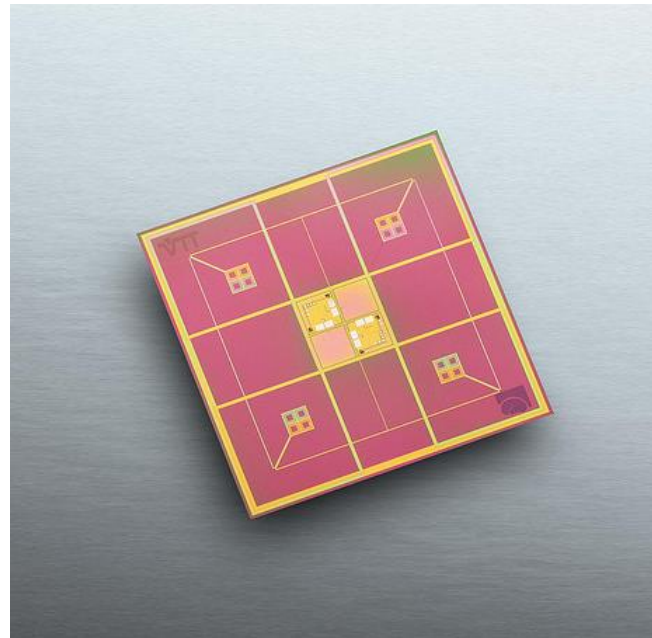
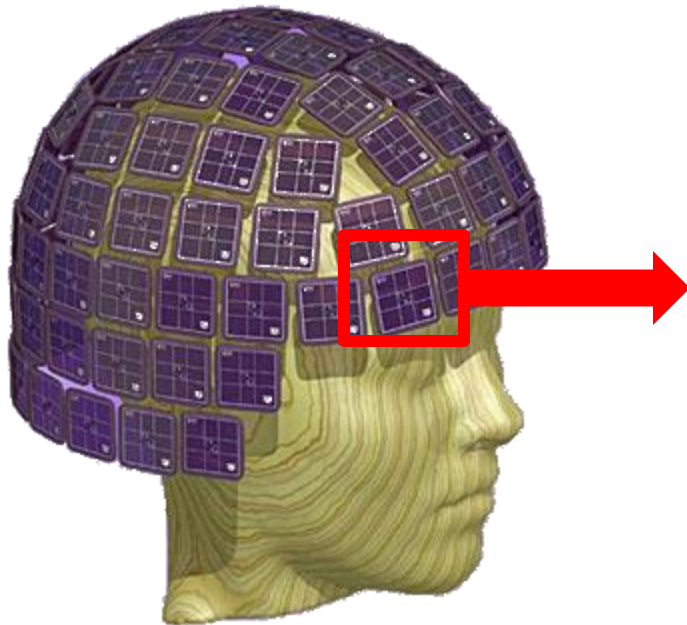
Neuromag/Elekta/Megin



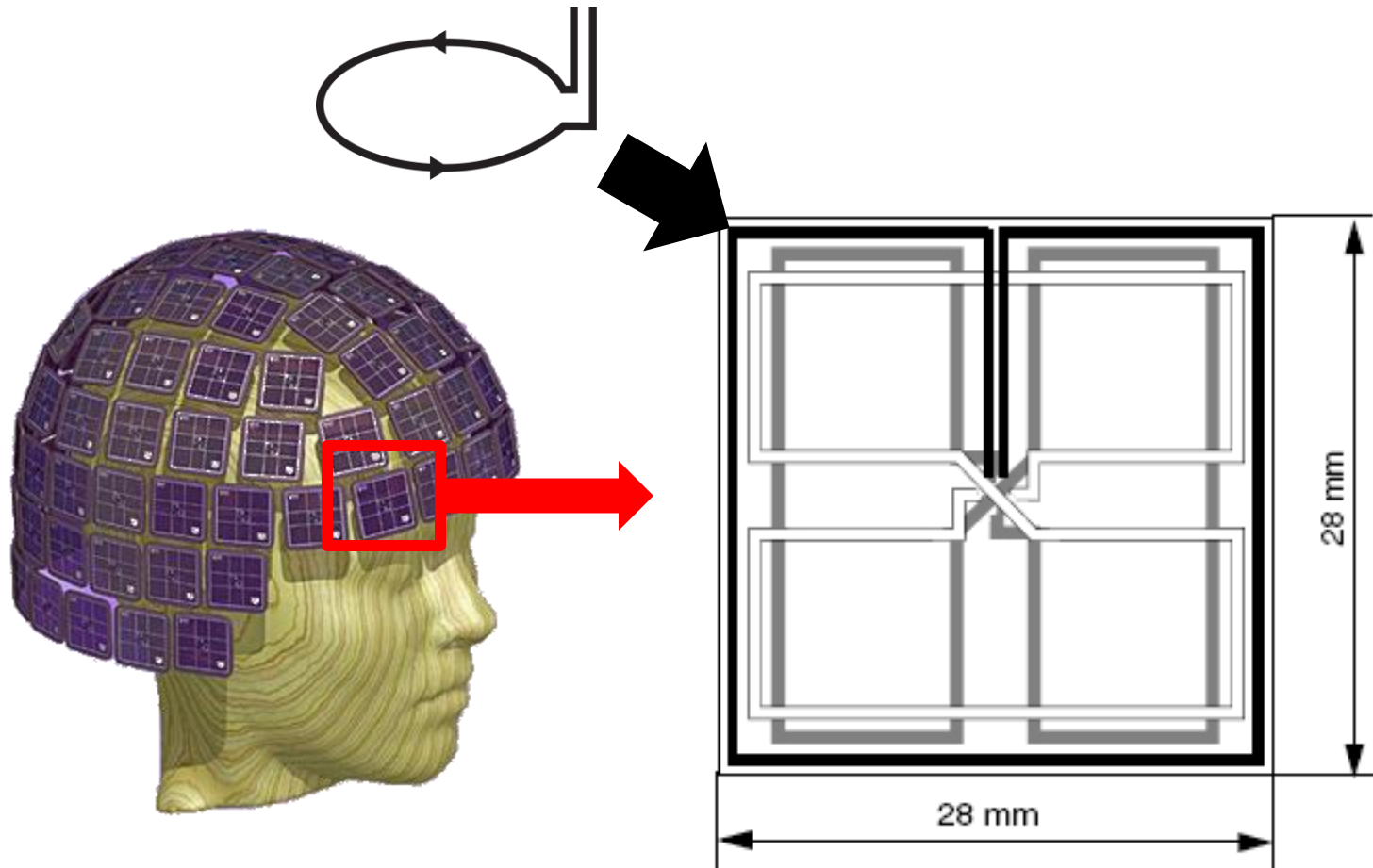
102 magnetometers
204 planar gradiometers
306 channels total



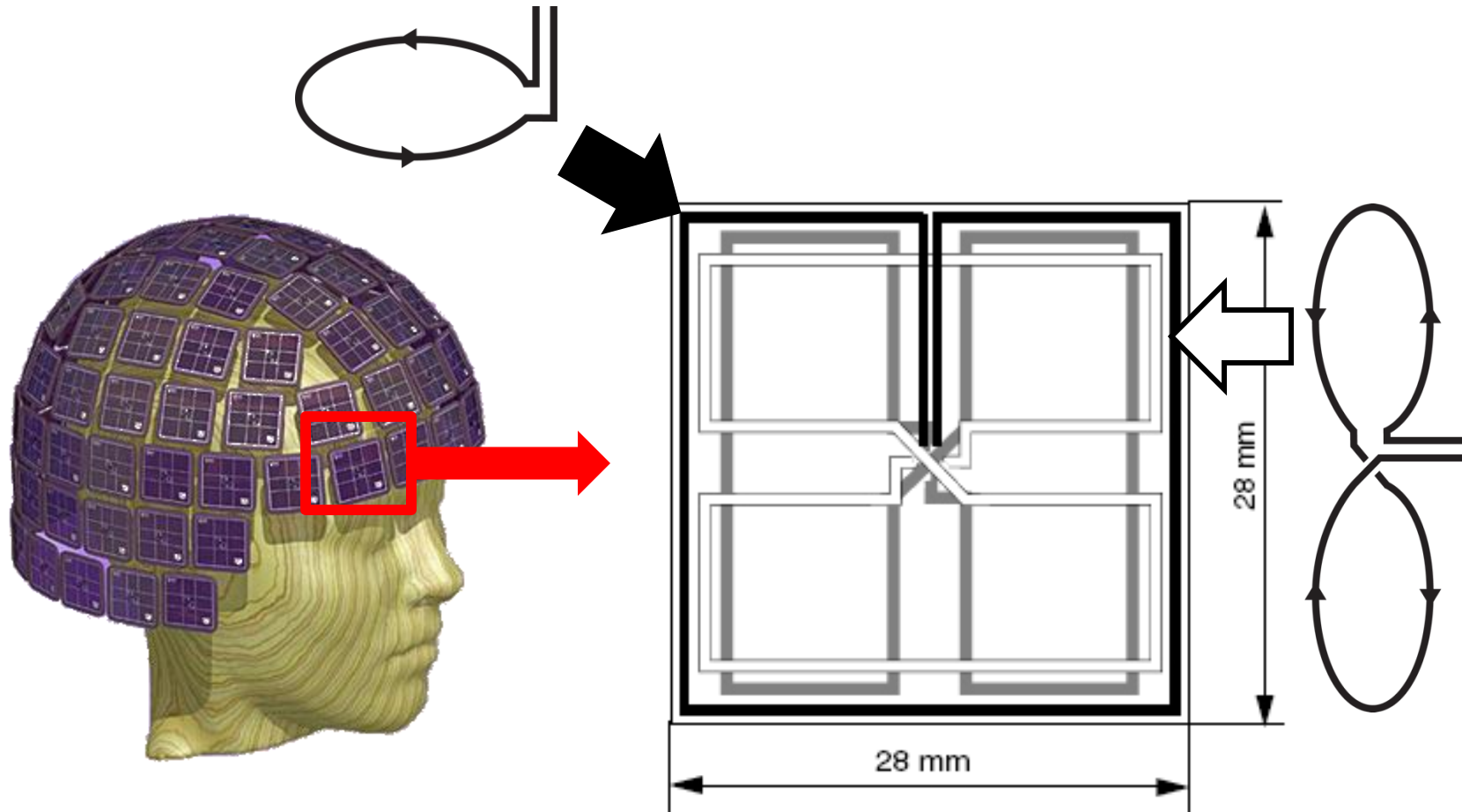
Neuromag/Elekta/Megin



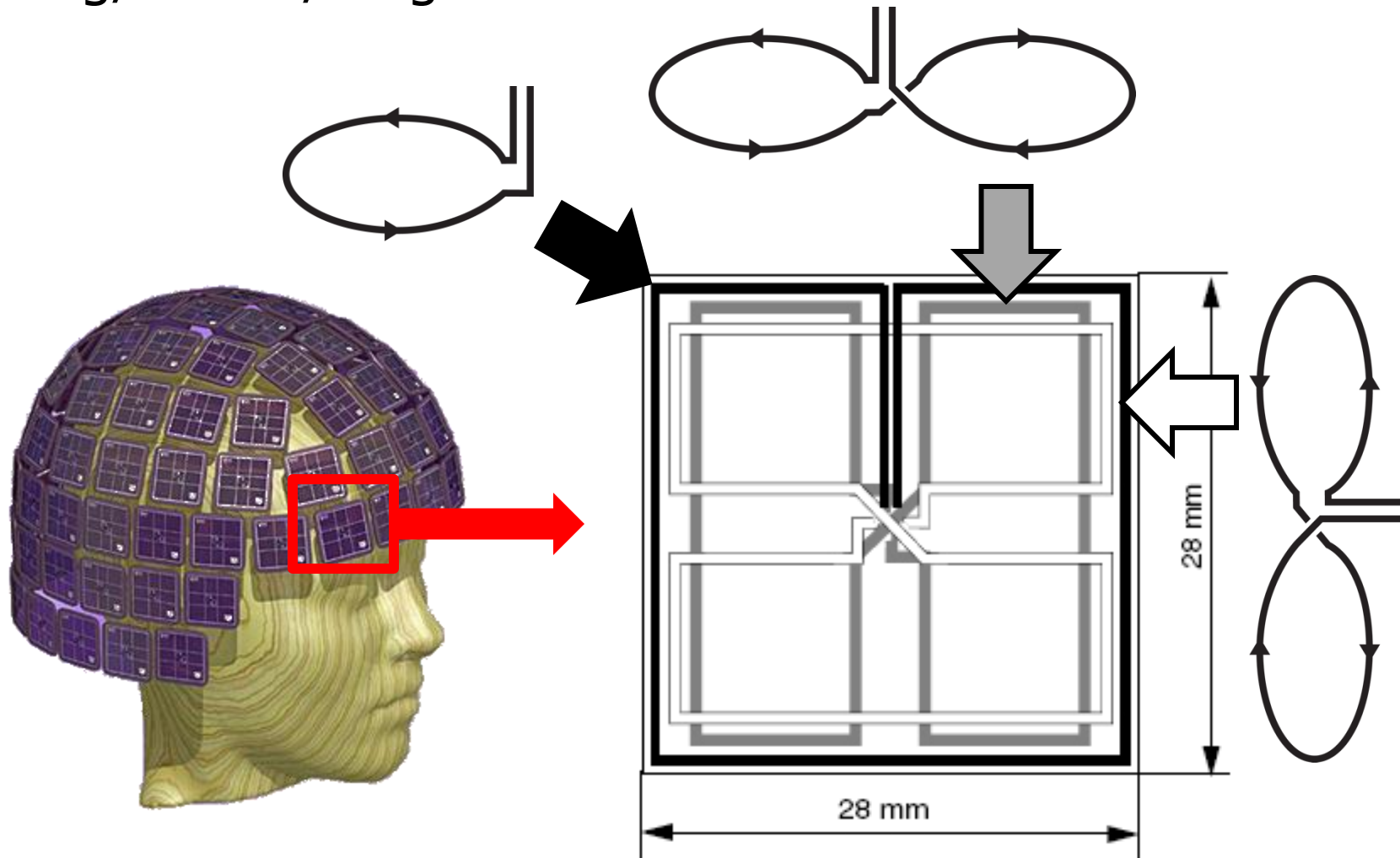
Neuromag/Elekta/Megin



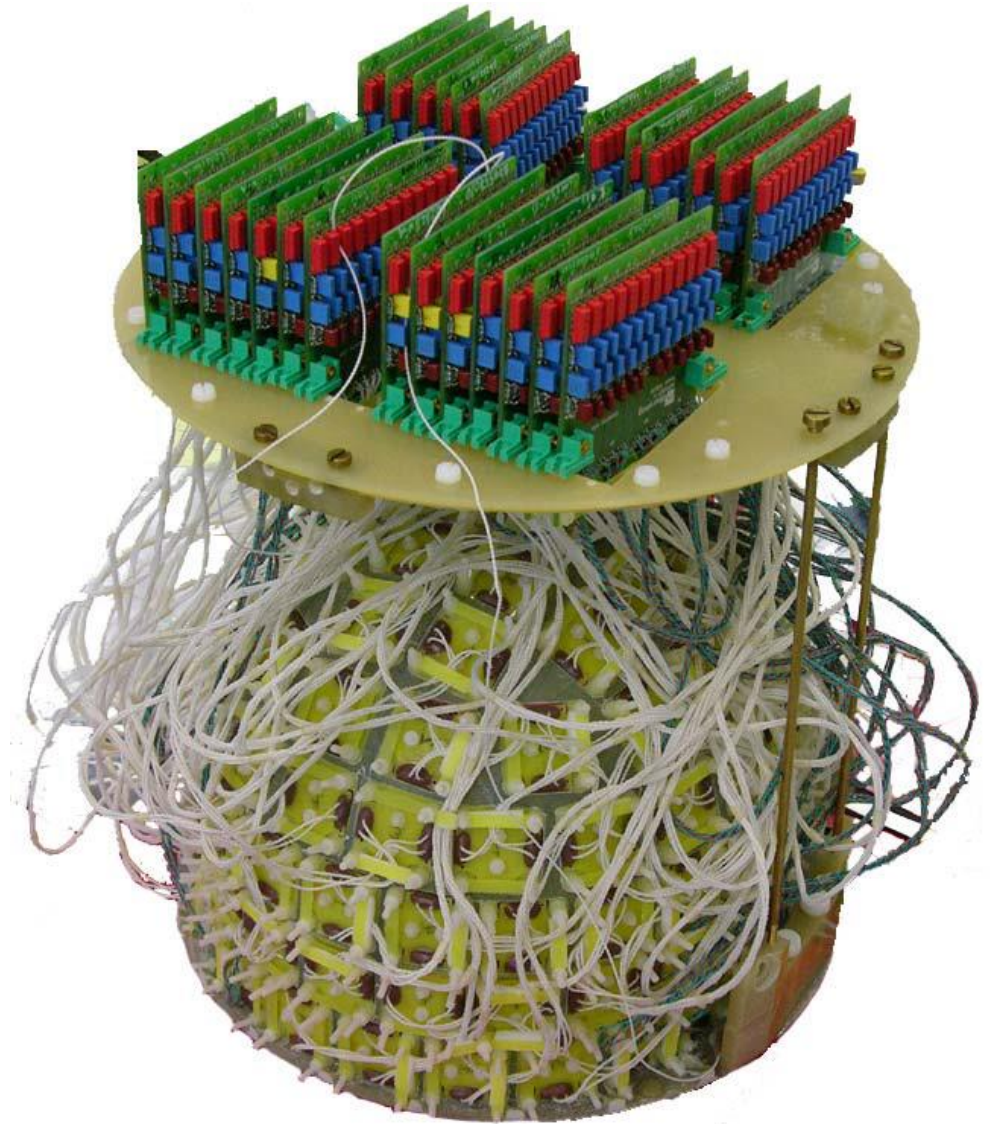
Neuromag/Elekta/Megin



Neuromag/Elekta/Megin

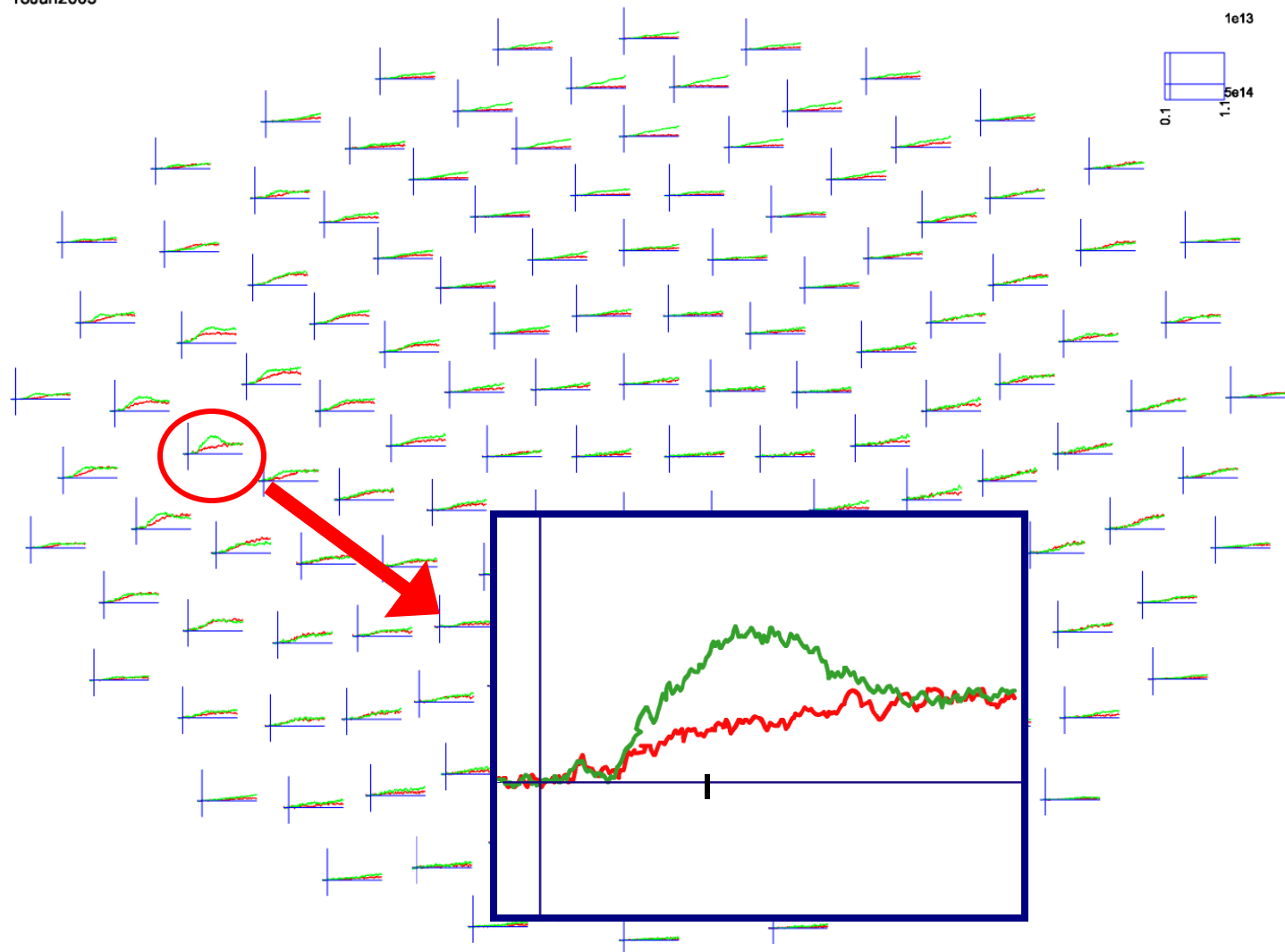


Neuromag/Elekta/Megin

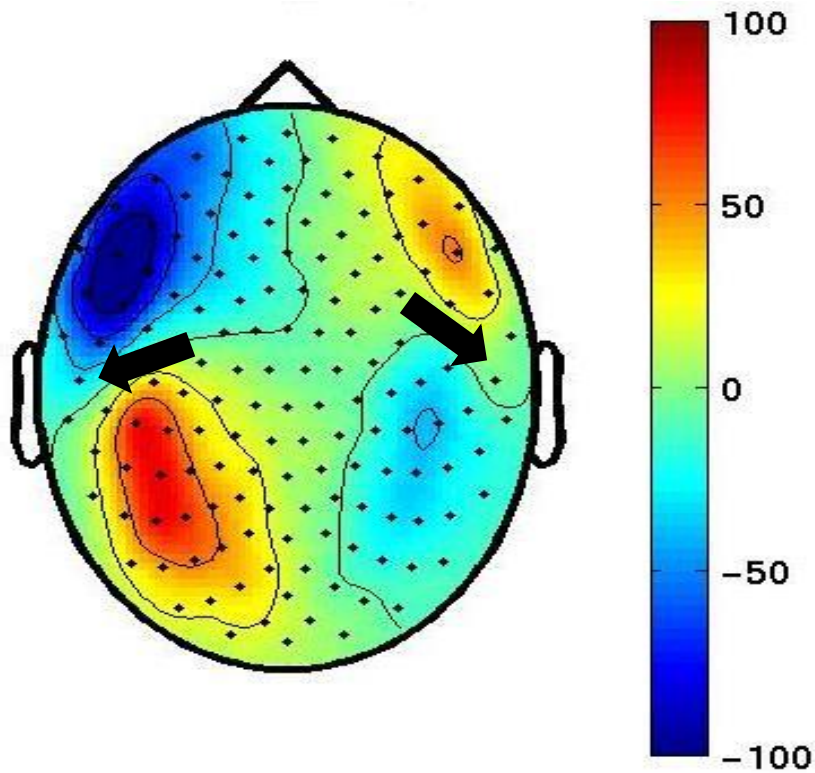


N400 response in MEG

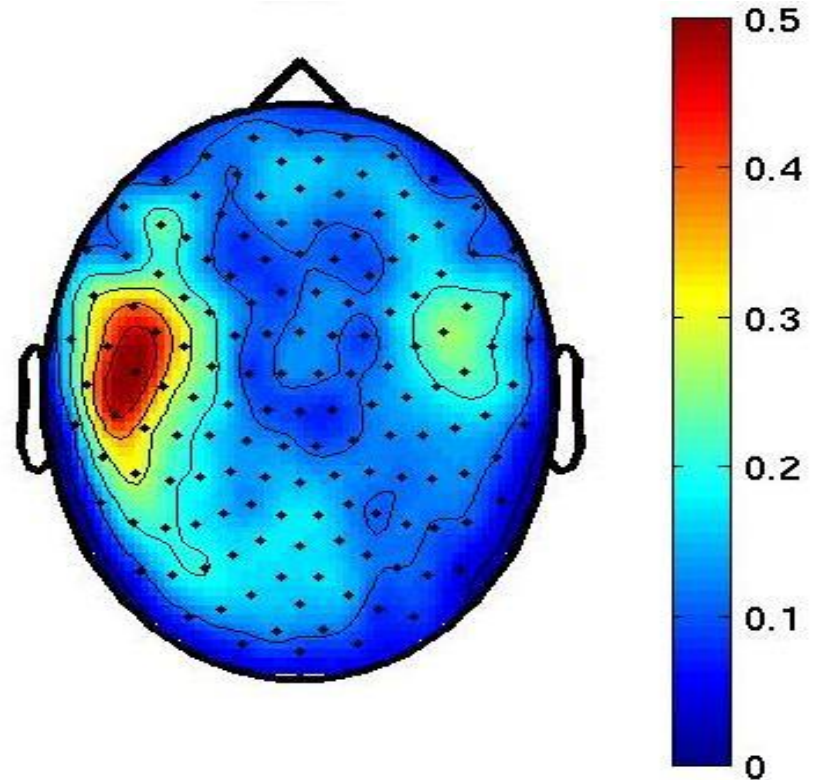
18Jun2003



N400 response - compared between MEG systems

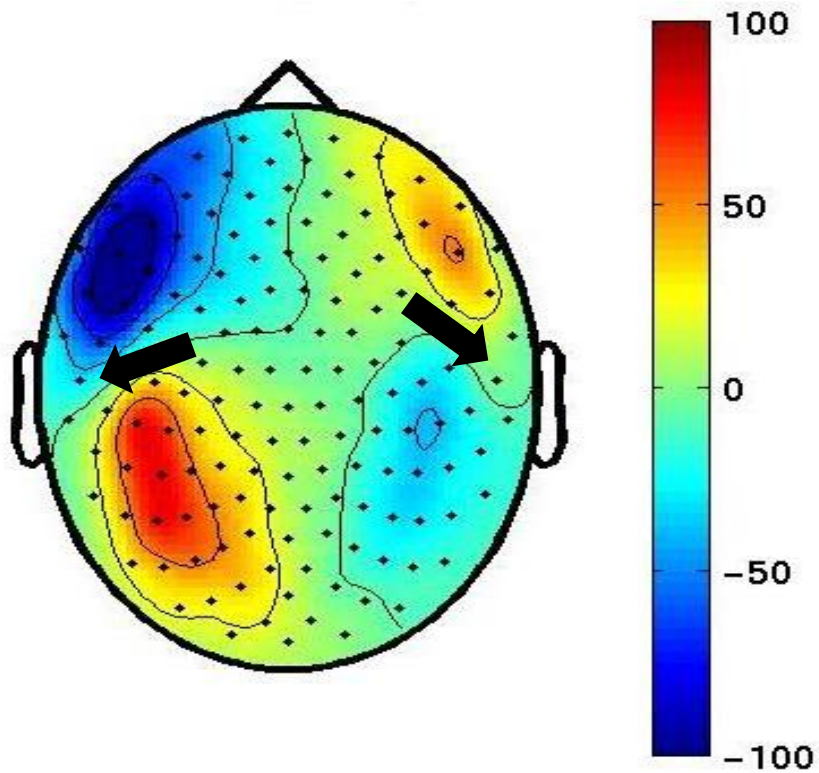


axial magnetic field

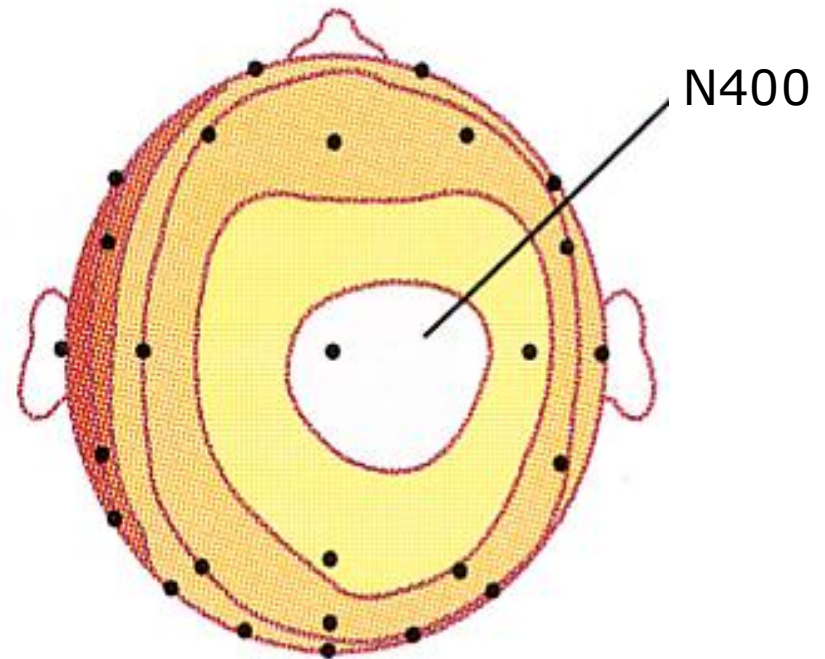


planar gradient

N400 response - compared between MEG and EEG



axial magnetic field



potential distribution

Moving magnetoencephalography towards real-world applications with a wearable system

Elena Boto^{1*}, Niall Holmes^{1*}, James Leggett^{1*}, Gillian Roberts^{1*}, Vishal Shah², Sofie S. Meyer^{3,4}, Leonardo Duque Muñoz³, Karen J. Mullinger^{1,5}, Tim M. Tierney³, Sven Bestmann^{4,6}, Gareth R. Barnes^{2,6}, Richard Bowtell^{1,6} & Matthew J. Brookes^{1,6}

Imaging human brain function with techniques such as magnetoencephalography¹ typically requires a subject to perform tasks while their head remains still within a restrictive scanner. This artificial environment makes the technique inaccessible to many people, and limits the experimental questions that can be addressed. For example, it has been difficult to apply neuroimaging to investigation of the neural substrates of cognitive development in babies and children, or to study processes in adults that require unconstrained head movement (such as spatial navigation). Here we describe a magnetoencephalography system that can be worn like a helmet, allowing free and natural movement during scanning. This is possible owing to the integration of quantum sensors^{2,3}, which do not rely on superconducting technology, with a system for nulling background magnetic fields. We demonstrate human electrophysiological measurement at millisecond resolution while subjects make natural movements, including head nodding,

stretching, drinking and playing a ball game. Our results compare well to those of the current state-of-the-art, even when subjects make large head movements. The system opens up new possibilities for scanning any subject or patient group, with myriad applications such as characterization of the neurodevelopmental connectome, imaging subjects moving naturally in a virtual environment and investigating the pathophysiology of movement disorders.

Magnetoencephalography¹ (MEG) allows direct imaging of human brain electrophysiology by measurement of magnetic fields generated at the scalp by neural currents. Mathematical analysis of those fields enables the generation of 3D images that show the formation and dissolution of brain networks in real time. MEG measurements of brain activity are currently made using an array of superconducting sensors placed around the head^{1,4}. These cryogenically cooled sensors have femtoTesla (fT) sensitivity, which is needed to detect the weak magnetic fields produced by the brain. Unfortunately, the requirement

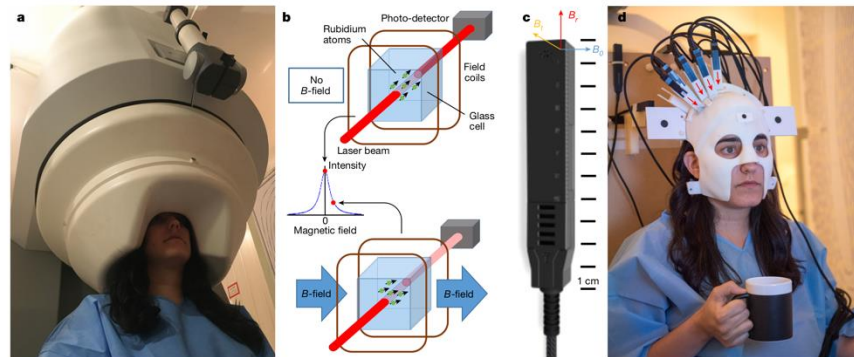


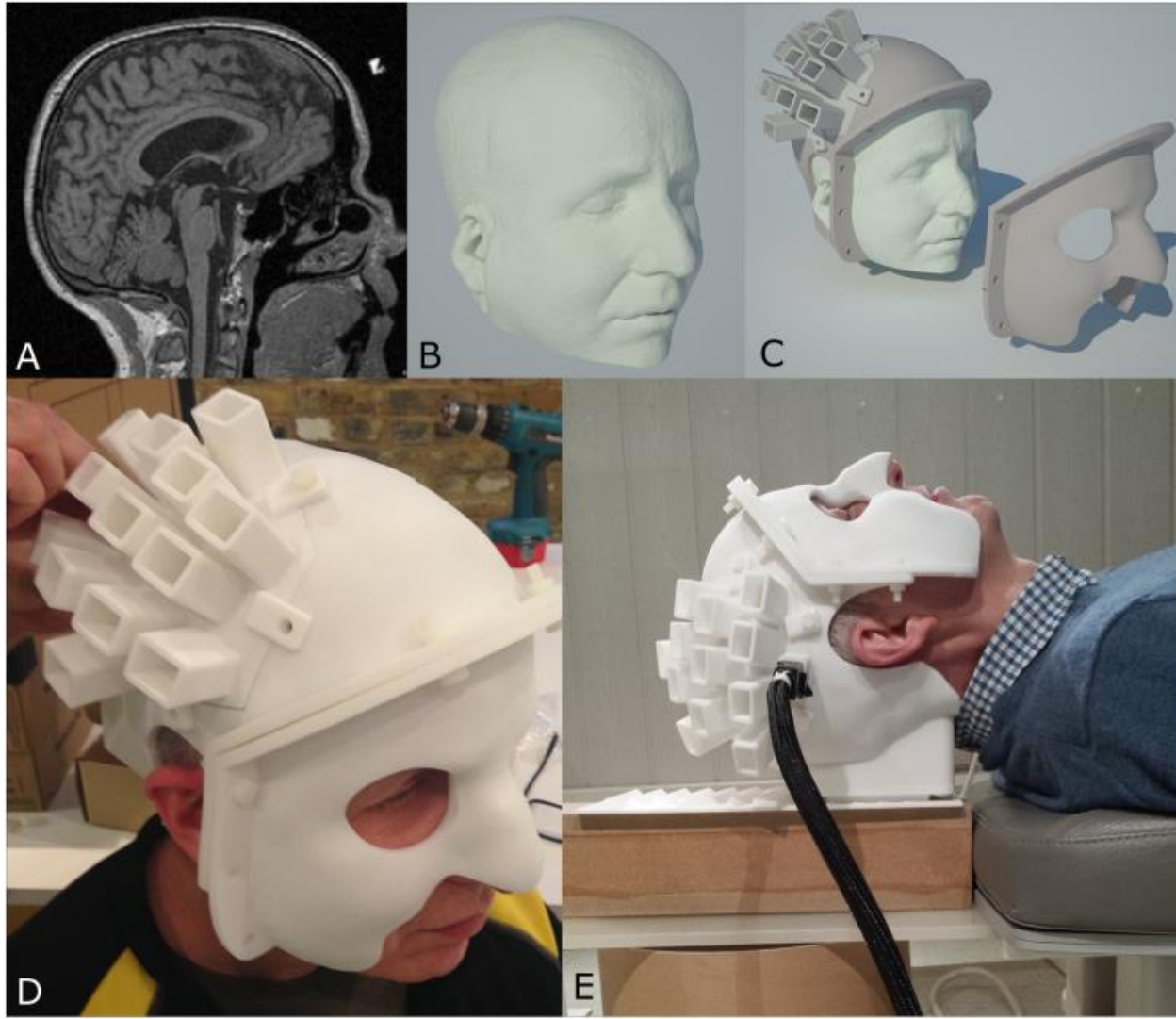
Figure 1 | A new generation of MEG system. **a**, A conventional 275-channel cryogenic MEG system. Weighing about 450 kg, the system is fixed and cumbersome and subjects must remain still relative to the fixed sensor array. **b**, Schematic illustration of zero-field resonance in an OPM sensor. Top, operation in zero-field; bottom, Larmor precession when an external field (B -field) impinges on the cell and the transmitted light intensity is reduced. **c**, A commercial OPM sensor made by QuSpin. The geometry used is illustrated by the coloured axes where B_r is the radial

field component, B_t the tangential field component and B_z the direction along which the laser beam is oriented. **d**, Our prototype OPM-MEG system helmet. The helmet weighs 905 g and is customized so that the sensors (which in this prototype cover only the right sensorimotor cortex) are directly adjacent to the scalp surface. The subject is free to move their head. The measured radial field direction for the sensors is illustrated by the red arrows.

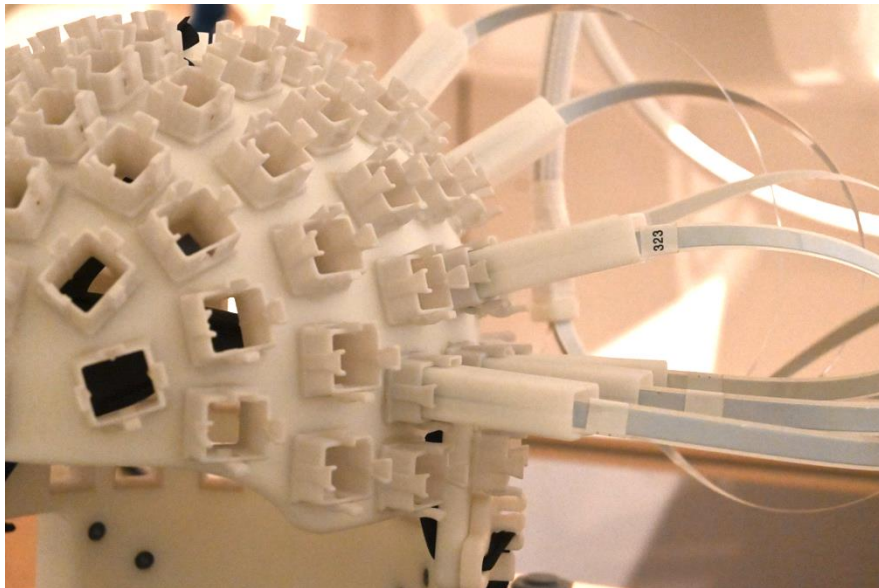
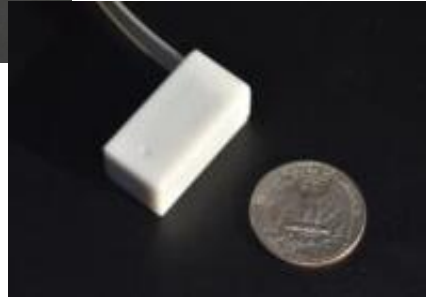
¹Sir Peter Mansfield Imaging Centre, School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, UK. ²QuSpin Inc., 331 South 104th Street, Suite 130, Louisville, Colorado 80027, USA. ³Wellcome Centre for Human Neuroimaging, UCL Institute of Neurology, University College London, 12 Queen Square, London WC1N 3BG, UK. ⁴Institute of Cognitive Neuroscience, University College London, 17–19 Queen Square, London WC1N 3AZ, UK. ⁵Centre for Human Brain Health, School of Psychology, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK. ⁶Sobell Department for Motor Neuroscience and Movement Disorders, UCL Institute of Neurology, University College London, Queen Square House, Queen Square, London WC1N 3BG, UK.

*These authors contributed equally to this work.

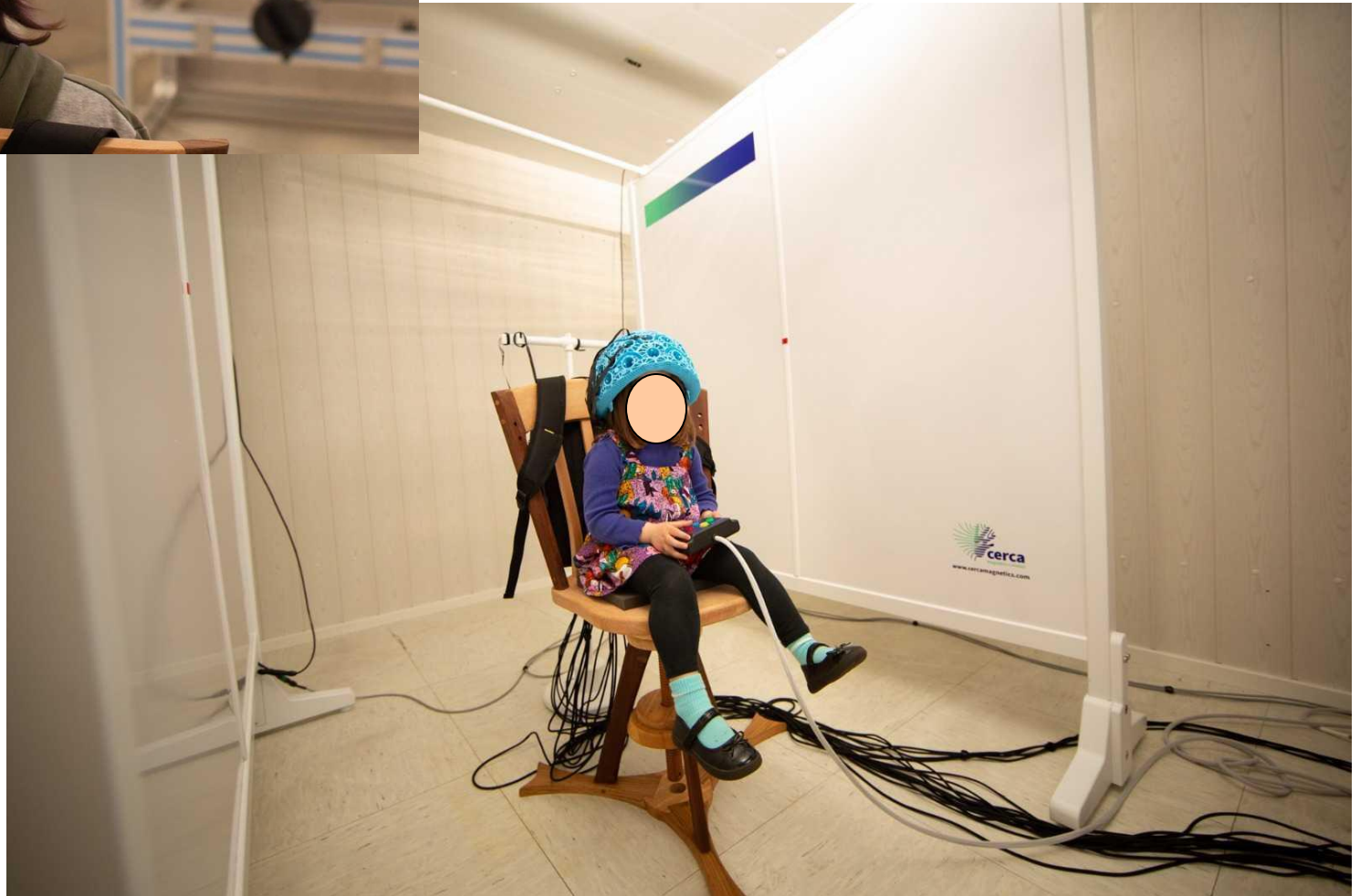
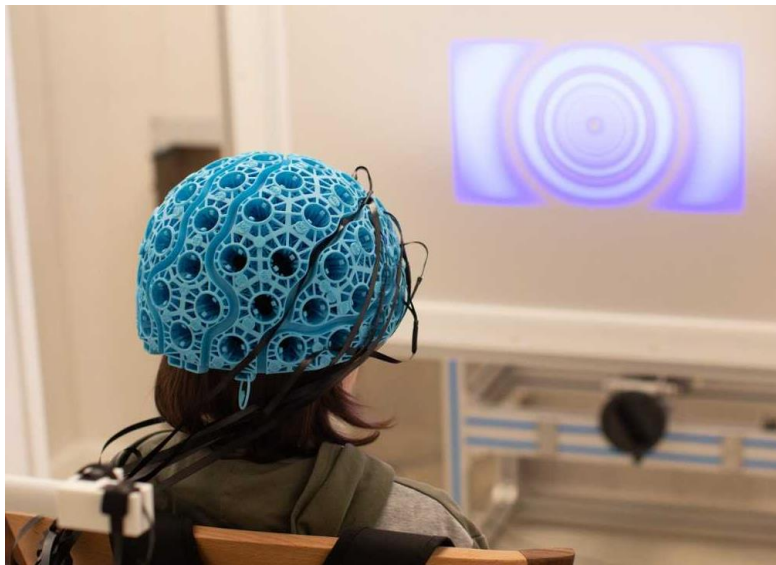
§These authors jointly supervised this work.



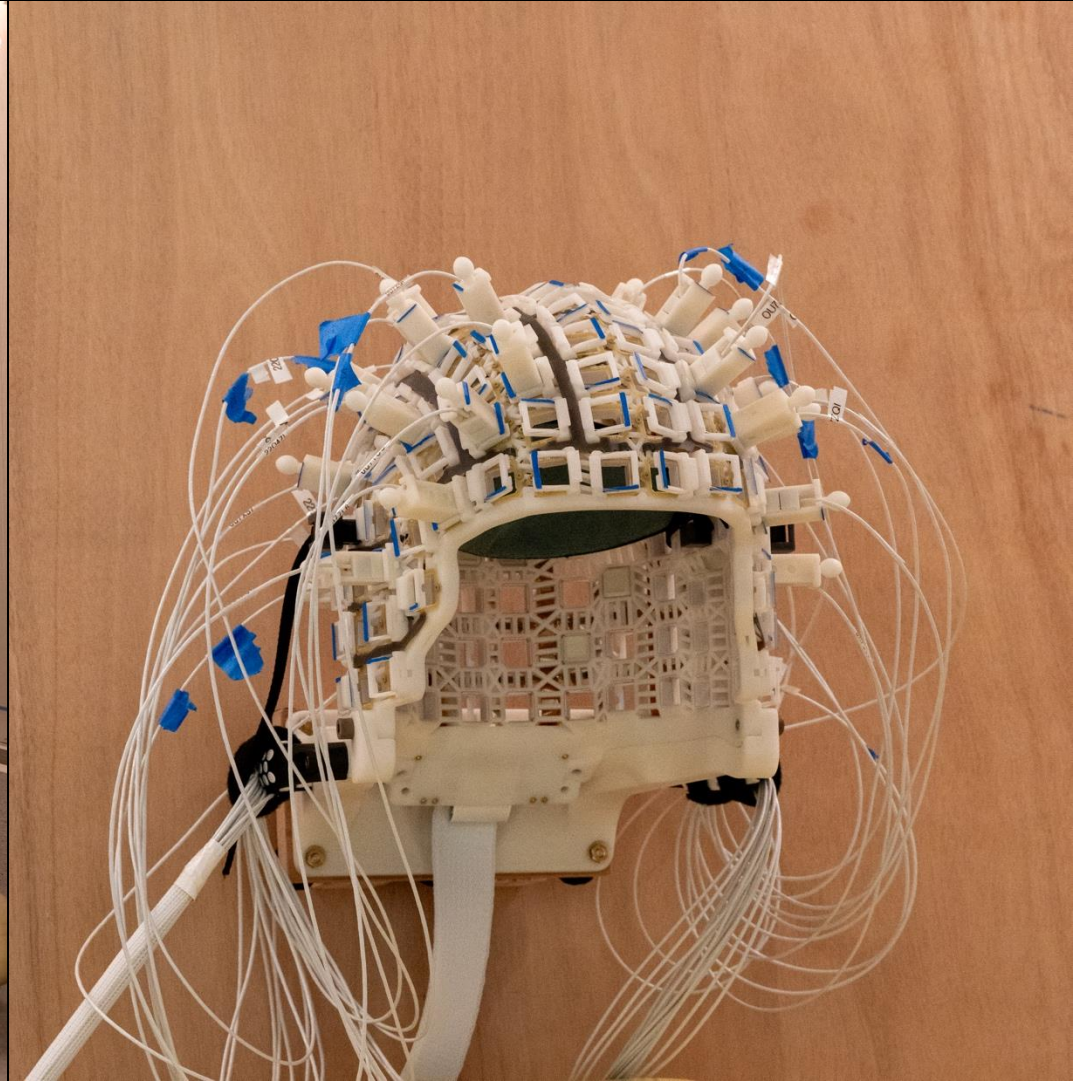
FieldLine OPM system in Stockholm

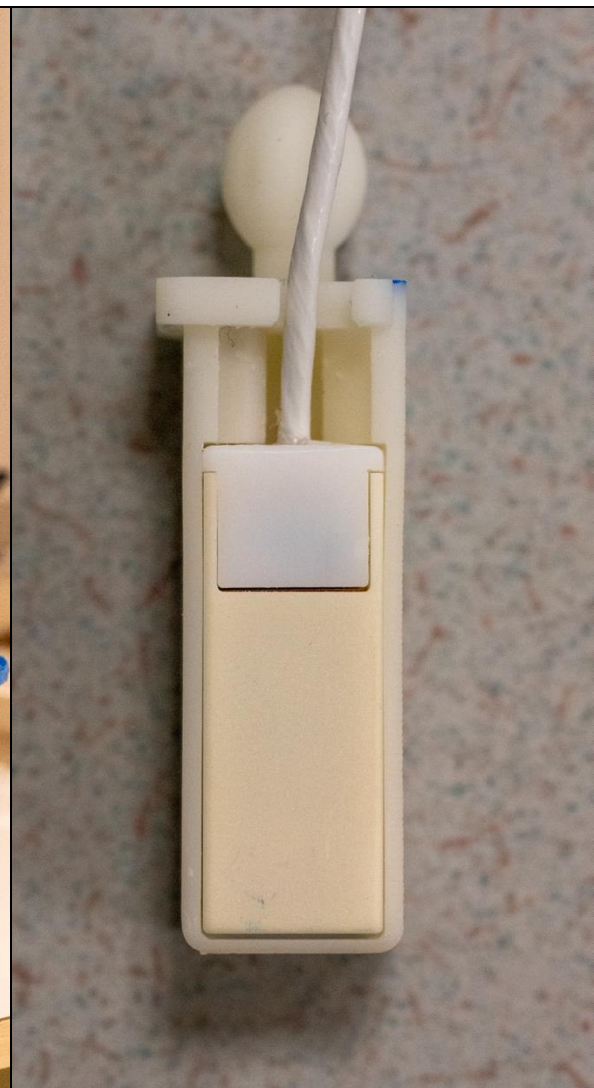
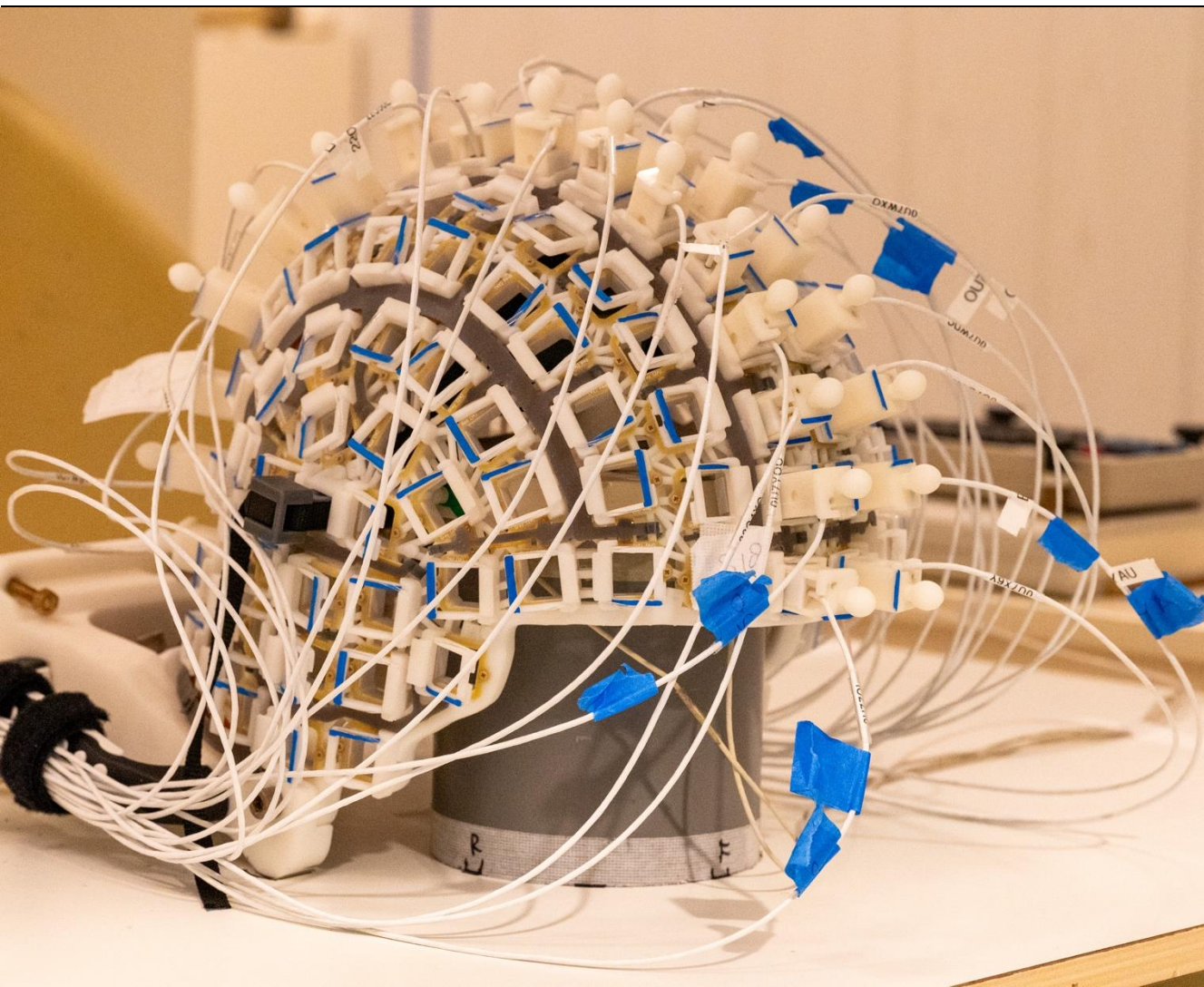


Cercamagnetics OPM system installed in Cardiff

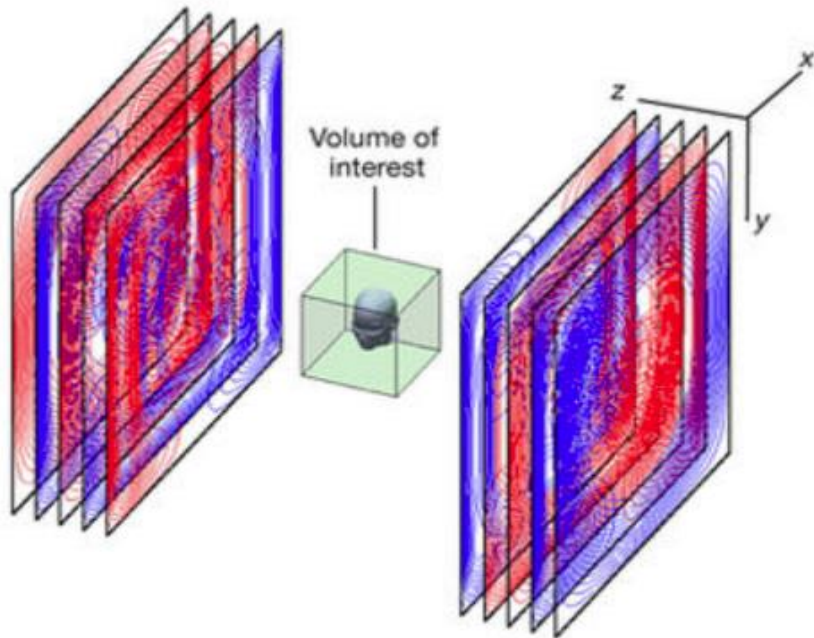


32 sensor FieldLine system installed at DCCN

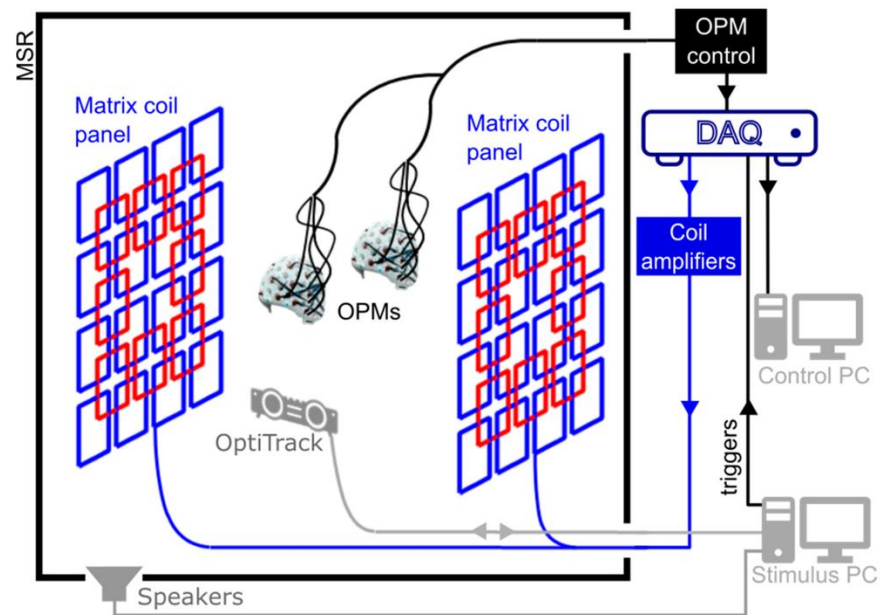




Ambient field nulling coils



Bi-planar coils

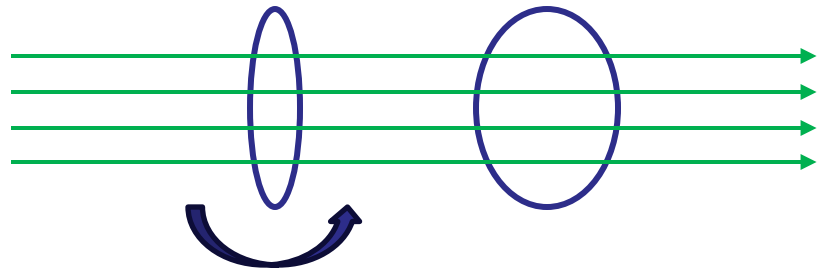
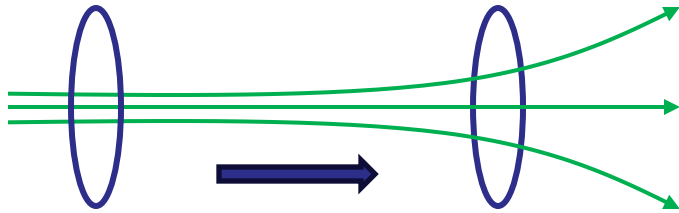


Matrix coils

Simple Helmholtz-style coils in our MSR



OPM magnetometer movements pick up residual magnetic fields and gradients



Mapping out the residual field in our MSR

Outside

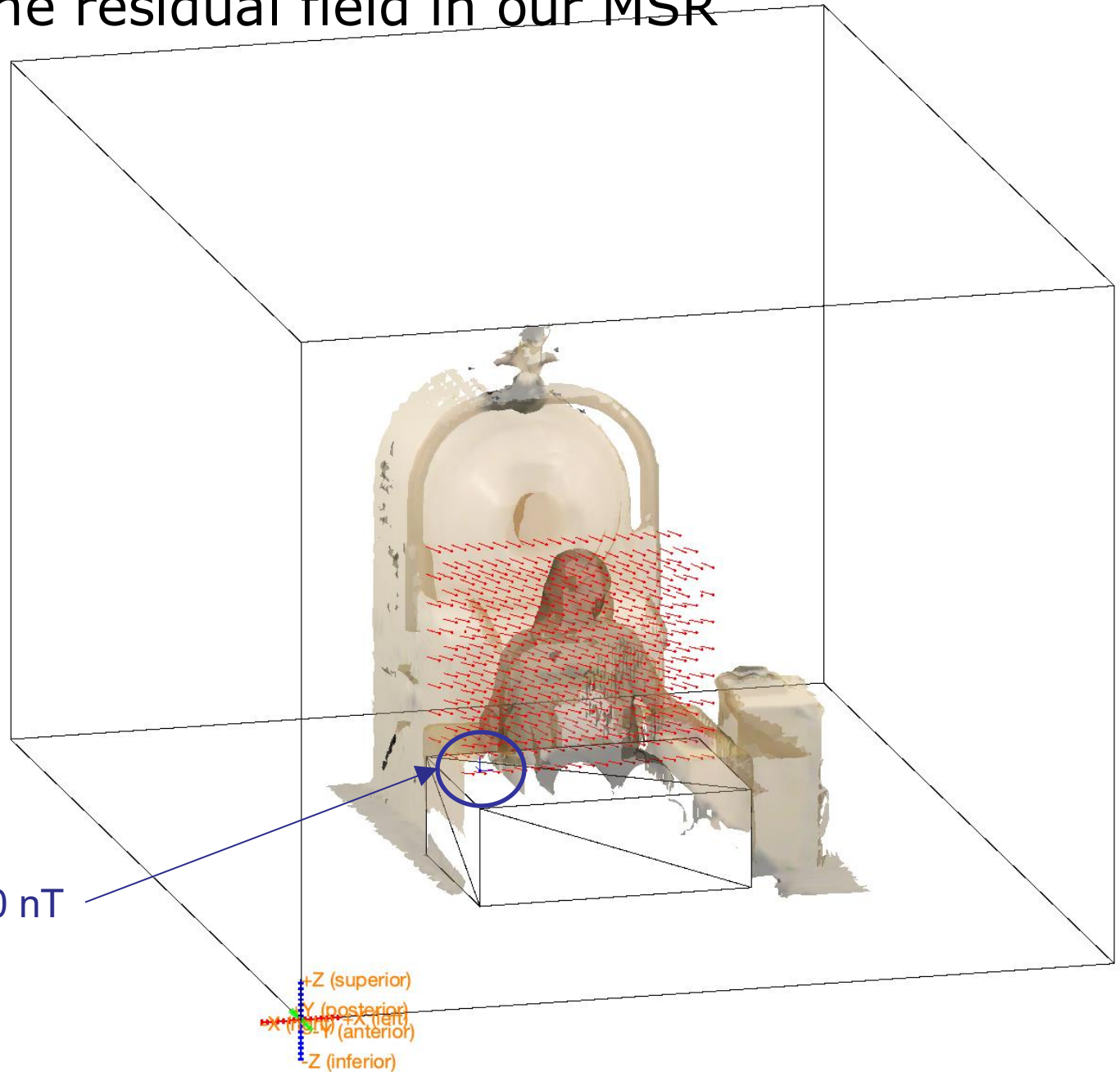
50 μT

50.000 nT

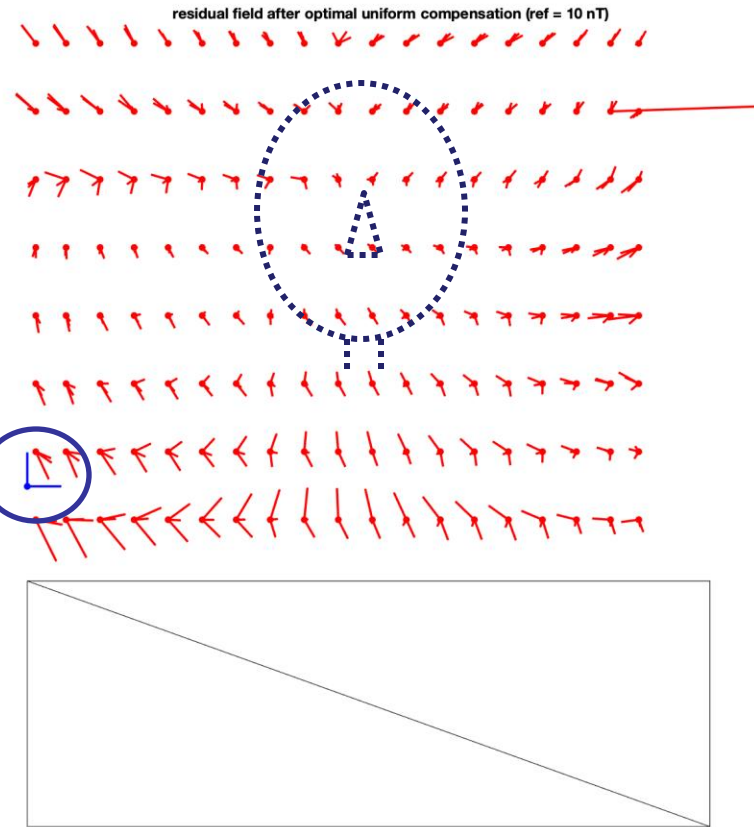
Inside

50-60 nT

Blue arrows are 50 nT

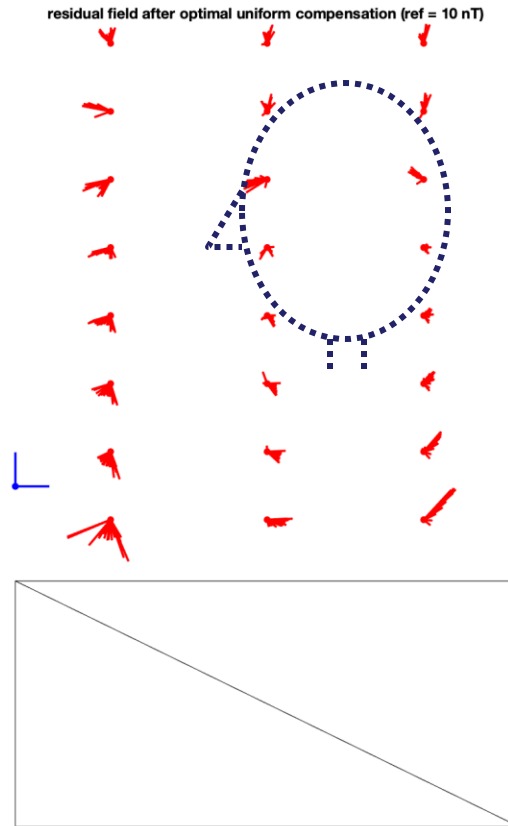


Residual gradient – seen from front



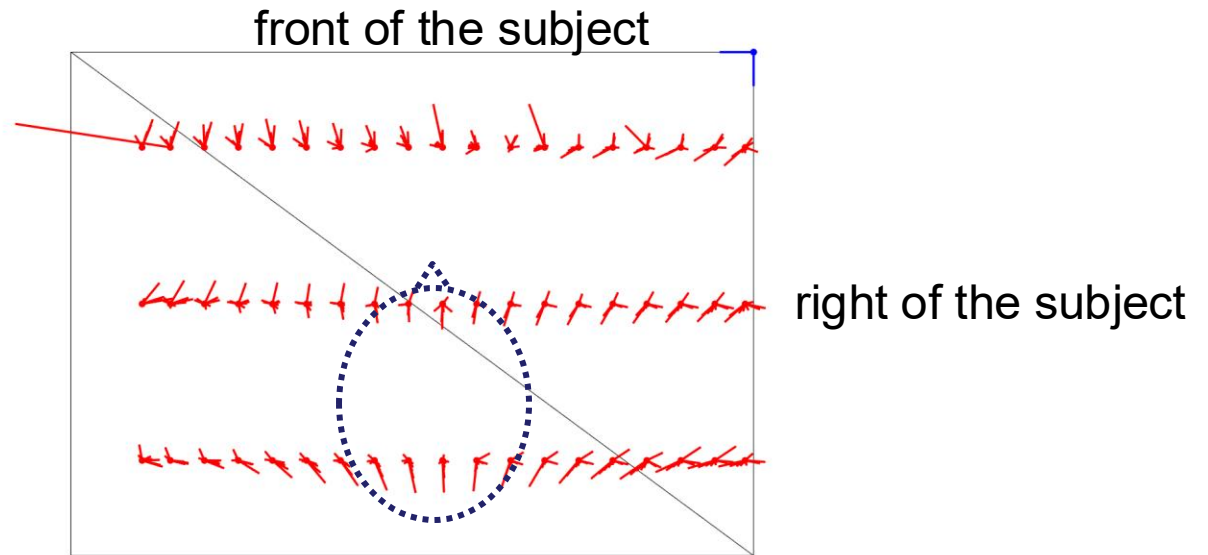
Blue arrows are 10 nT

Residual gradient – seen from left



Residual gradient – seen from top

residual field after optimal uniform compensation (ref = 10 nT)



Talk outline

What kind of signals are generated in the brain

How do we record those signals

Analyzing those signals with FieldTrip

Background on the FieldTrip toolbox

M/EEG signal characteristics considered during analysis

timecourse of activity

-> ERP

spectral characteristics

-> power spectrum

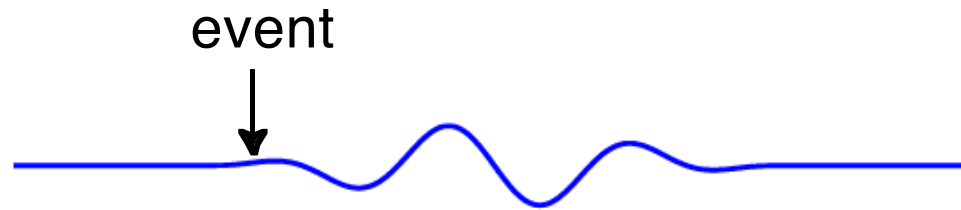
temporal changes in power

-> time-frequency response (TFR)

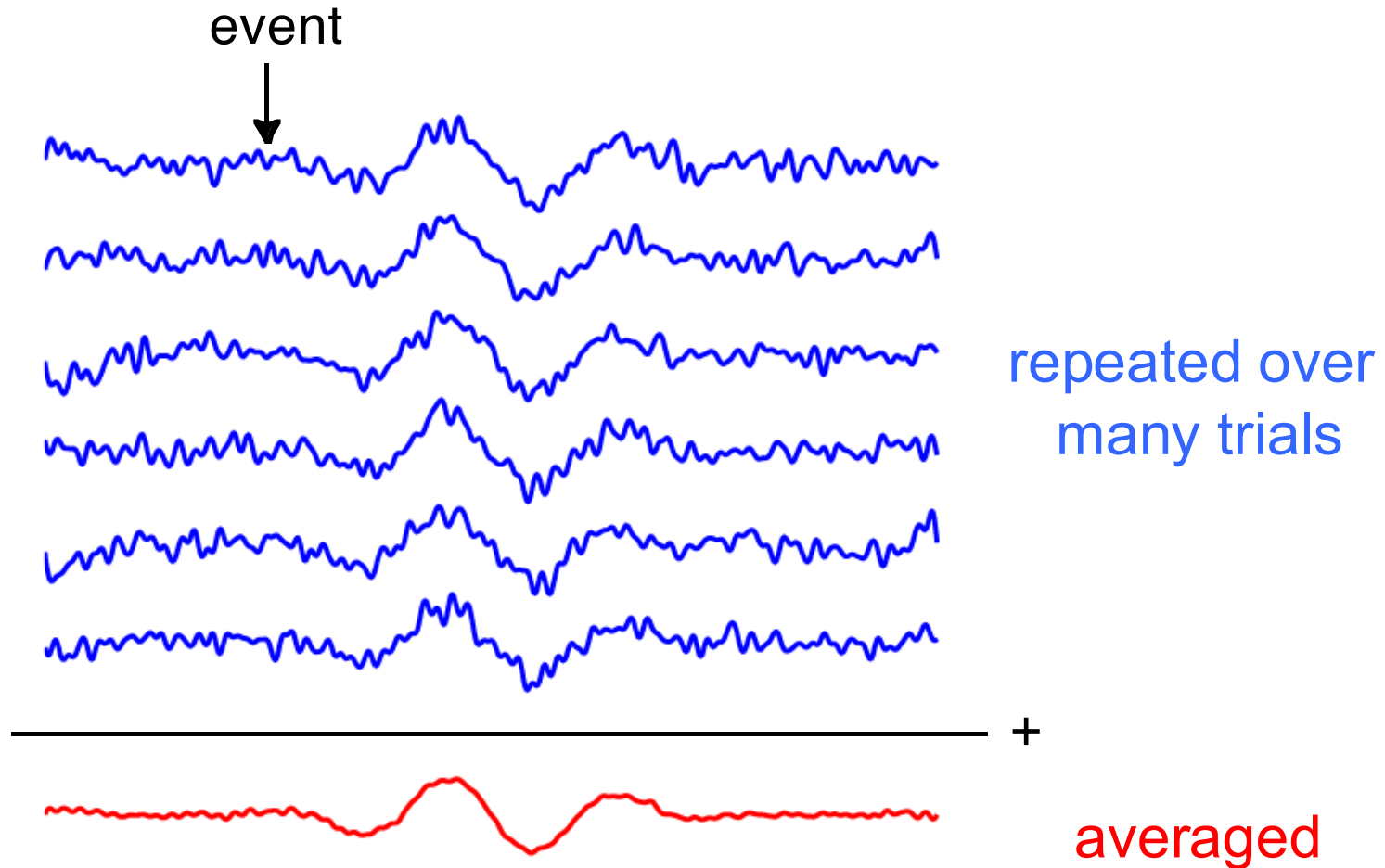
spatial distribution of activity over the head

-> source reconstruction

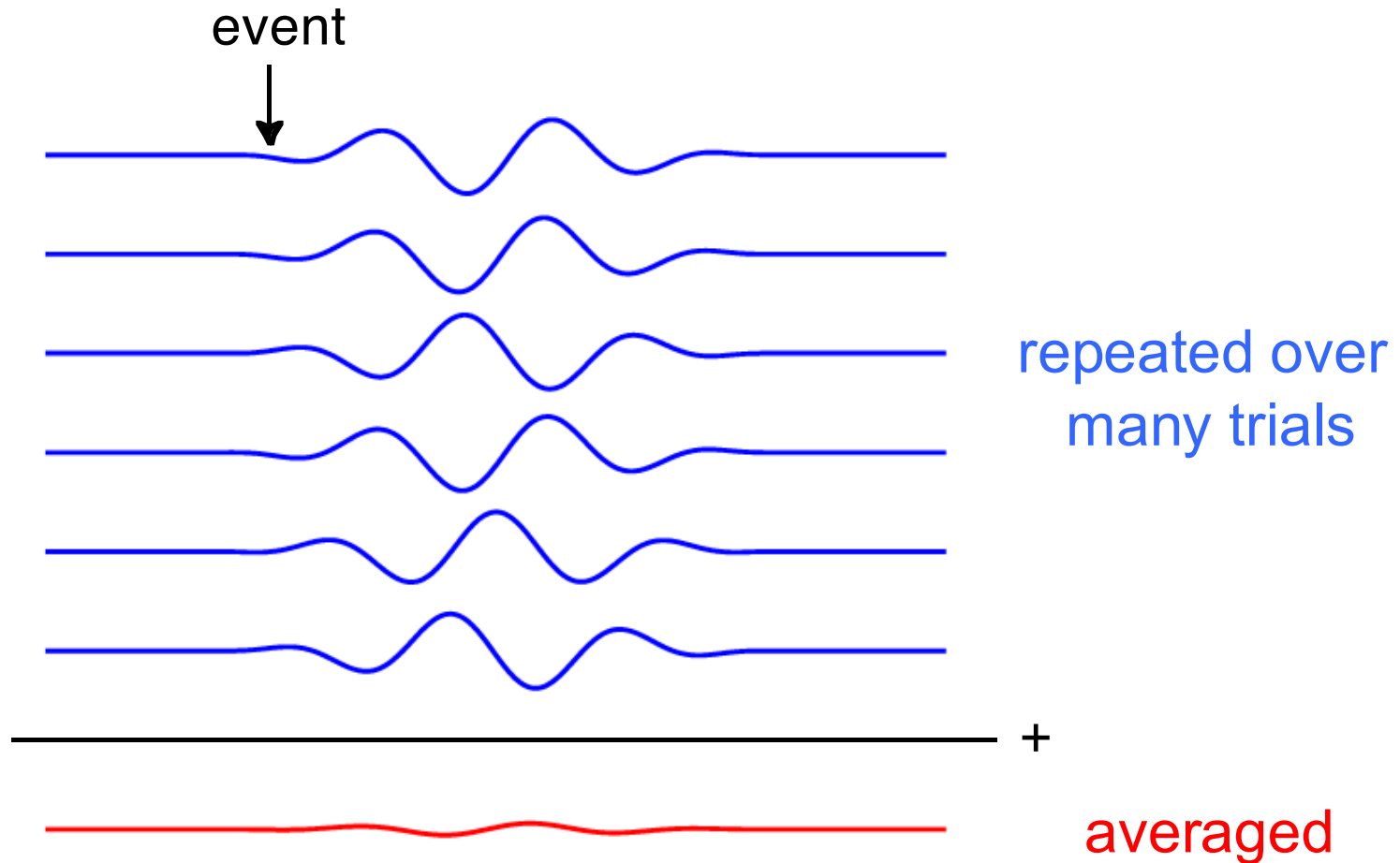
Evoked activity



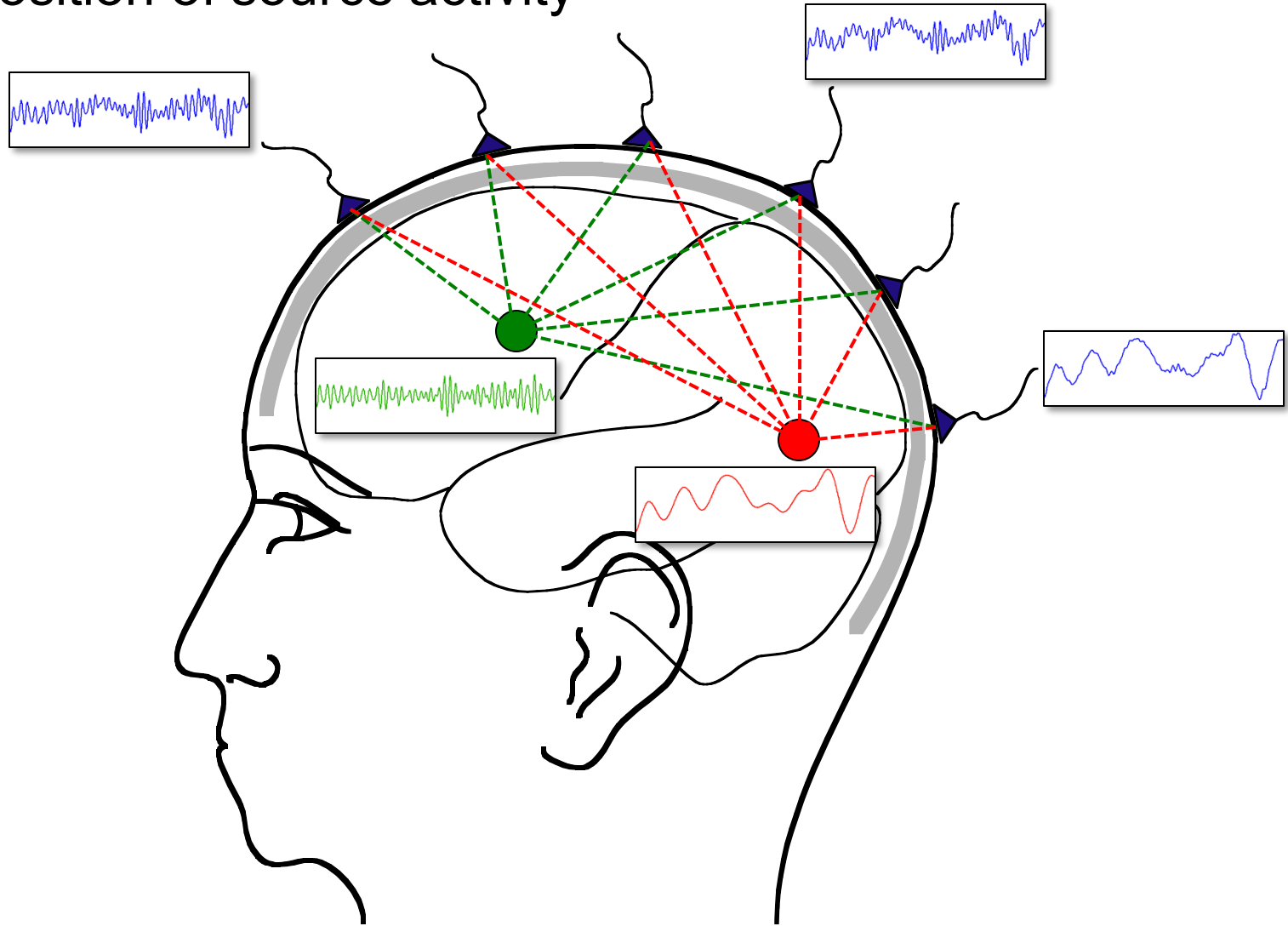
Evoked activity



Induced activity



Superposition of source activity



Separating activity of sources

Use the temporal aspects of the data
at the channel level

- ERF latencies

- ERF difference waves

- Filtering the time-series

- Spectral decomposition

Use the spatial aspects of the data

- Volume conduction model of head

- Estimate source model parameters

Talk outline

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Background on the FieldTrip toolbox

Some FieldTrip basics

```
dataout = functionname(cfg, datain, ...)
```

```
functionname(
```

```
dataout = func
```



the “cfg” argument is a configuration structure, e.g.

```
cfg.channel = {'C3', 'C4', 'F3', 'F4'}
```

```
cfg.foylim = [1 70]
```

FieldTrip v.s. default Matlab

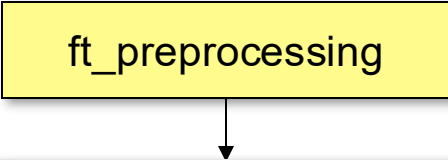
```
dataout = functionname(cfg, datain, ...)
```

```
cfg.key1 = value1  
cfg.key2 = value2
```

```
dataout = functionname(datain, key1, value1, ...)
```

Using functions in an analysis protocol

ft_preprocessing



FT_PREPROCESSING reads MEG and/or EEG data according to user-specified trials and applies several user-specified preprocessing steps to the signals.

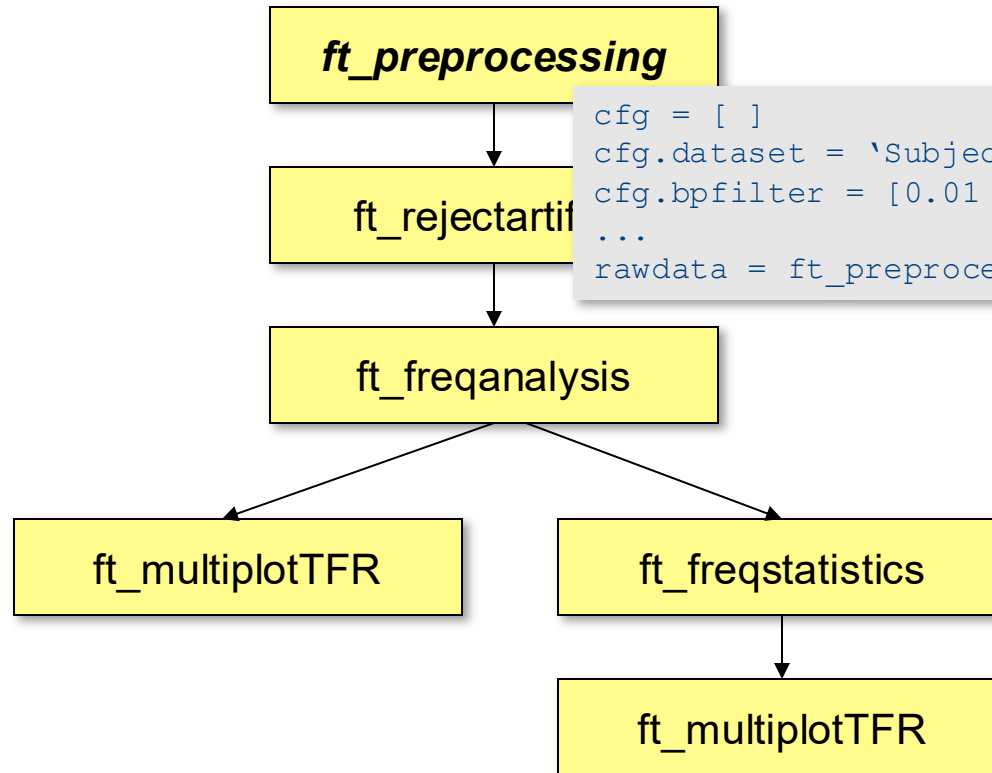
Use as

```
[data] = ft_preprocessing(cfg)
or
[data] = ft_preprocessing(cfg, data)
```

The first input argument "cfg" is the configuration structure, which contains all details for the dataset filenames, trials and the preprocessing options. You can only do preprocessing after defining the segments of data to be read from the file (i.e. the trials), which is for example done based on the occurrence of a trigger in the data.

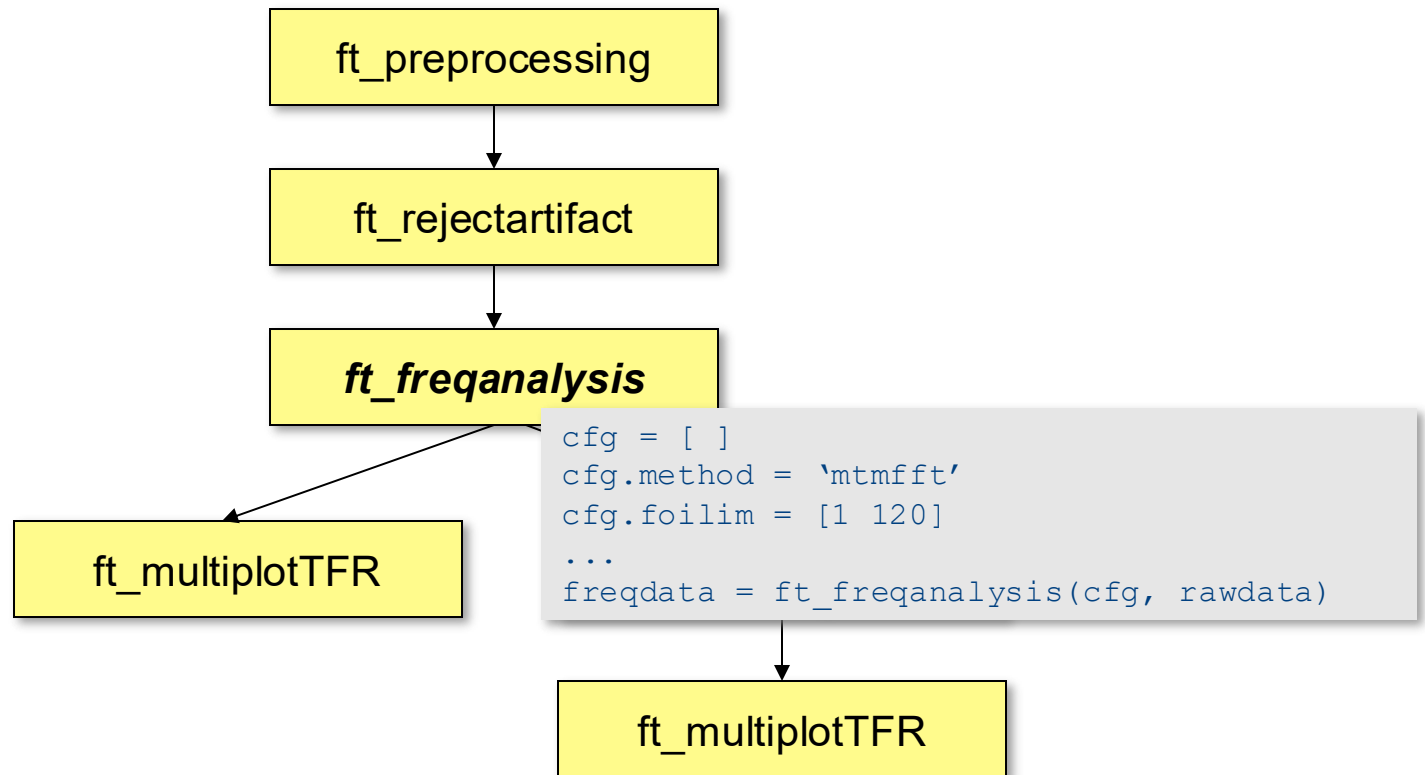
...

Using functions in an analysis protocol



```
cfg = [ ]  
cfg.dataset = 'Subject01.ds'  
cfg.bpfiler = [0.01 150]  
...  
rawdata = ft_preprocessing(cfg)
```

Using functions in an analysis protocol



Raw data structure

```
rawData =  
    label: {151x1 cell}  
    trial: {1x80 cell}  
    time: {1x80 cell}  
    fsample: 300  
    hdr: [1x1 struct]  
    cfg: [1x1 struct]
```

Event related response

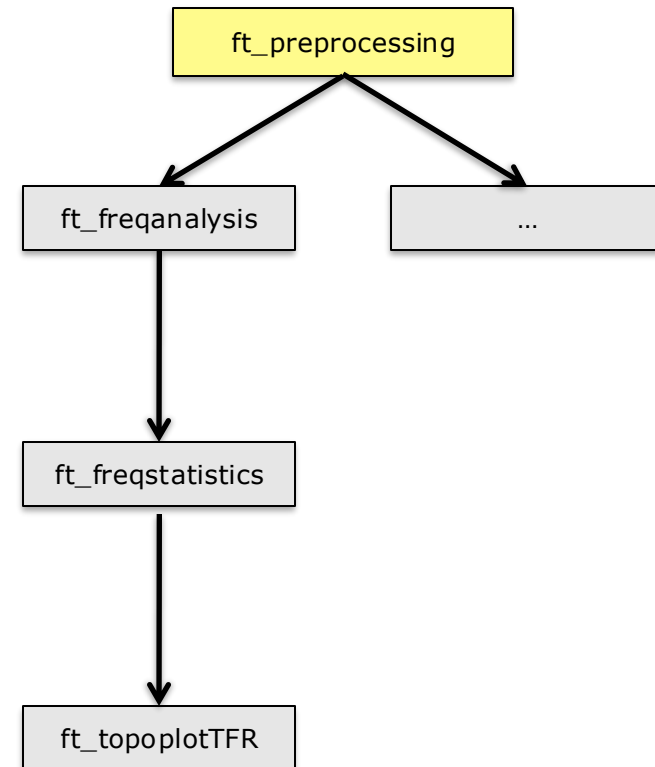
```
timelockData =  
    label: {151x1 cell}  
    avg: [151x900 double]  
    var: [151x900 double]  
    time: [1x900 double]  
    dimord: 'chan_time'  
    cfg: [1x1 struct]
```


Example use in scripts

```
cfg = []  
cfg.dataset = 'Subject01.ds'  
cfg.bpfiler = [0.01 150]  
...  
rawdata = ft_preprocessing(cfg)
```

```
cfg = []  
cfg.method = 'mtmfft'  
cfg.foilim = [1 120]  
...  
freqdata = ft_freqanalysis(cfg, rawdata)
```

```
cfg = []  
cfg.method = 'montecarlo'  
cfg.statistic = 'indepsamplesT'  
cfg.design = [1 2 1 2 2 1 2 1 1 2 ... ]  
...  
freqstat = ft_freqstatistics(cfg, freqdata)
```

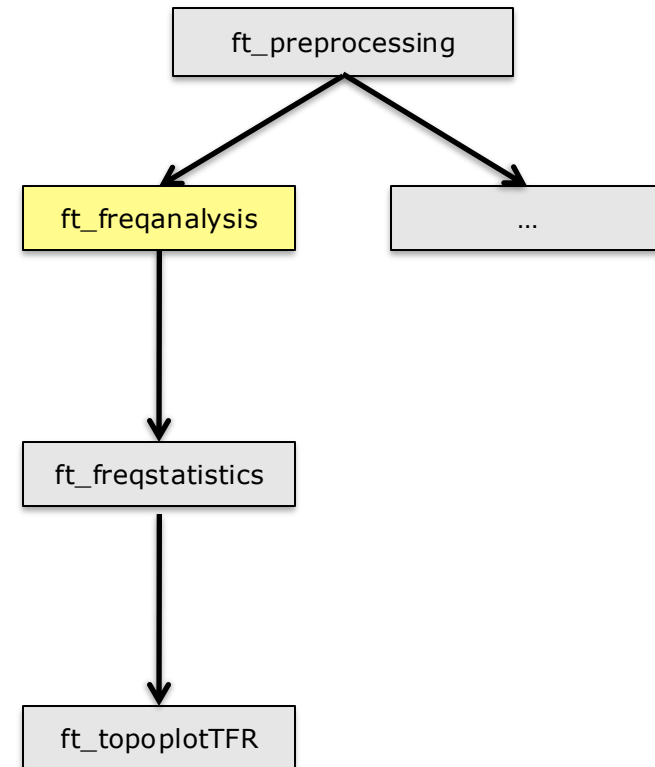


Example use in scripts

```
cfg = []  
cfg.dataset = 'Subject01.ds'  
cfg.bpfiler = [0.01 150]  
...  
rawdata = ft_preprocessing(cfg)
```

```
cfg = []  
cfg.method = 'mtmfft'  
cfg.foylim = [1 120]  
...  
freqdata = ft_freqanalysis(cfg, rawdata)
```

```
cfg = []  
cfg.method = 'montecarlo'  
cfg.statistic = 'indepsamplesT'  
cfg.design = [1 2 1 2 2 1 2 1 1 2 ... ]  
...  
freqstat = ft_freqstatistics(cfg, freqdata)
```

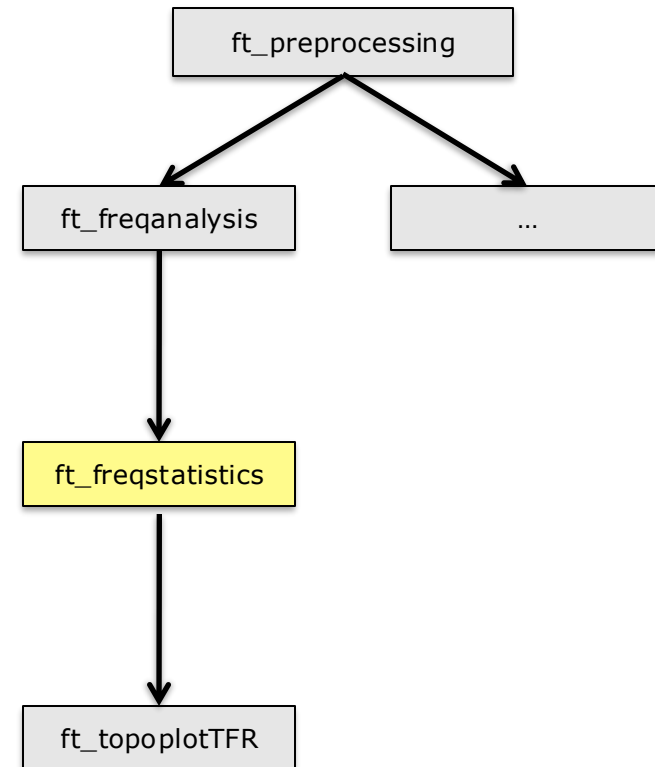


Example use in scripts

```
cfg = []
cfg.dataset = 'Subject01.ds'
cfg.bpfiler = [0.01 150]
...
rawdata = ft_preprocessing(cfg)
```

```
cfg = []
cfg.method = 'mtmfft'
cfg.foilim = [1 120]
...
freqdata = ft_freqanalysis(cfg, rawdata)
```

```
cfg = []
cfg.method = 'montecarlo'
cfg.statistic = 'indepsamplesT'
cfg.design = [1 2 1 2 2 1 2 1 1 2 ... ]
...
freqstat = ft_freqstatistics(cfg, freqdata)
```

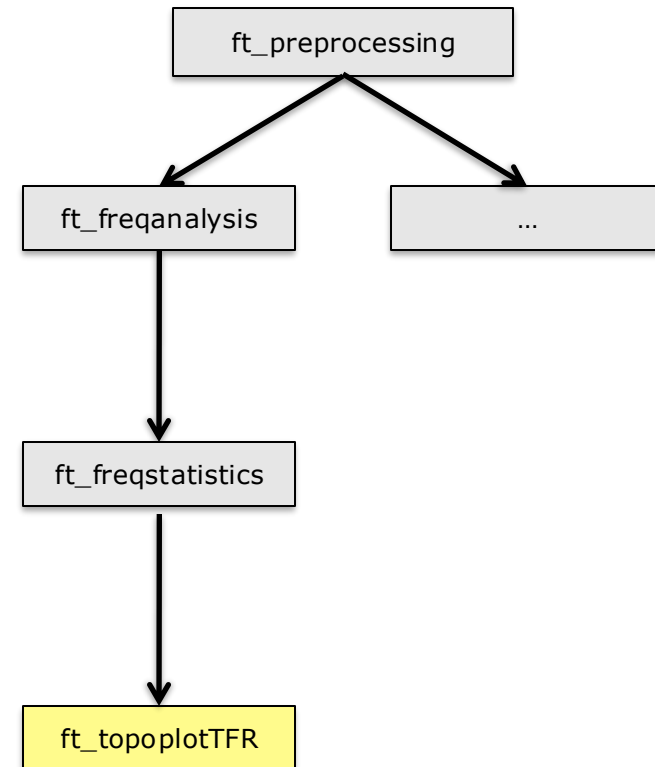


Example use in scripts

```
cfg = []
cfg.dataset = 'Subject01.ds'
cfg.bpfiler = [0.01 150]
...
rawdata = ft_preprocessing(cfg)
```

```
cfg = []
cfg.method = 'mtmfft'
cfg.foilim = [1 120]
...
freqdata = ft_freqanalysis(cfg, rawdata)
```

```
cfg = []
cfg.method = 'montecarlo'
cfg.statistic = 'indepsamplesT'
cfg.design = [1 2 1 2 2 1 2 1 1 2 ... ]
...
freqstat = ft_freqstatistics(cfg, freqdata)
```

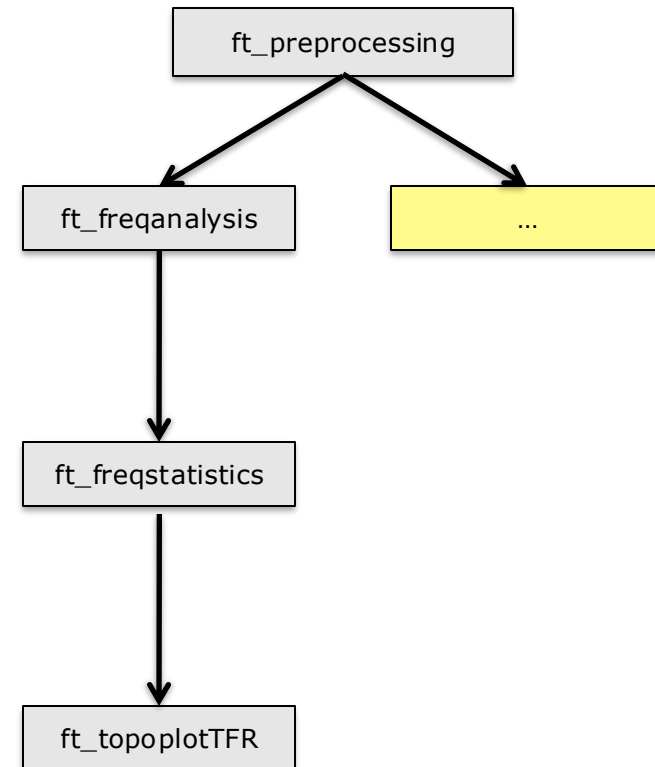


Example use in scripts

```
cfg = []
cfg.dataset = 'Subject01.ds'
cfg.bpfiler = [0.01 150]
...
rawdata = ft_preprocessing(cfg)
```

```
cfg = []
cfg.method = 'mtmfft'
cfg.foylim = [1 120]
...
freqdata = ft_freqanalysis(cfg, rawdata)
```

```
cfg = []
cfg.method = 'montecarlo'
cfg.statistic = 'indepsamplesT'
cfg.design = [1 2 1 2 2 1 2 1 1 2 ... ]
...
freqstat = ft_freqstatistics(cfg, freqdata)
```



Example use in scripts

```
subj = {'S01.ds', 'S02.ds', ...}
trig = [1 3 7 9]

for s=1:nsubj
    for c=1:ncond

        cfg = []
        cfg.dataset = subj{s}
        cfg.trigger = trig(c)
        rawdata{s,c} = ft_preprocessing(cfg)

        cfg = []
        cfg.method = 'mtmfft'
        cfg.foilim = [1 120]
        freqdata{s,c} = ft_freqanalysis(cfg, rawdata{s,c})

    end
end
```

Example use in scripts

```
subj = {'S01.ds', 'S02.ds', ...}
trig = [1 3 7 9]

for s=1:nsubj
    for c=1:ncond

        cfg = []
        cfg.dataset = subj{s}
        cfg.trigger = trig(c)
        rawdata = ft_preprocessing(cfg)

        filename = sprintf('raw%s_%d.mat', subj{s}, trig(c));
        save(filename, 'rawdata')

    end
end
```

Example use in distributed computing

```
subj = {'S01.ds', 'S02.ds', ...}
trig = [1 3 7 9]

for s=1:nsbj
    for c=1:ncond

        cfgA{s,c} = []
        cfgA{s,c}.dataset      = subj{s}
        cfgA{s,c}.trigger      = trig(c)
        cfgA{s,c}.outputfile = sprintf('raw%s_%d.mat', subj{s}, trig(c))

        cfgB{s,c} = []
        cfgB{s,c}.dataset      = subj{s}
        cfgB{s,c}.trigger      = trig(c)
        cfgB{s,c}.inputfile    = sprintf('raw%s_%d.mat', subj{s}, trig(c));
        cfgB{s,c}.outputfile = sprintf('freq%s_%d.mat', subj{s}, trig(c));

    end
end

dfeval(@ft_preprocessing, cfgA)
dfeval(@ft_freqanalysis,  cfgB)
```


Example use in distributed computing

```
subj = {'S01.ds', 'S02.ds', ...}
trig = [1 3 7 9]

for s=1:nsbj
    for c=1:ncond

        cfgA{s,c} = []
        cfgA{s,c}.dataset      = subj{s}
        cfgA{s,c}.trigger      = trig(c)
        cfgA{s,c}.outputfile = sprintf('raw%s_%d.mat', subj{s}, trig(c))

        cfgB{s,c} = []
        cfgB{s,c}.dataset      = subj{s}
        cfgB{s,c}.trigger      = trig(c)
        cfgB{s,c}.inputfile    = sprintf('raw%s_%d.mat', subj{s}, trig(c));
        cfgB{s,c}.outputfile = sprintf('freq%s_%d.mat', subj{s}, trig(c));

    end
end

qsubcellfun(@ft_preprocessing, cfgA)
qsubcellfun(@ft_freqanalysis,  cfgB)
```

Talk outline

What kind of signals are generated in the brain

How do we record those signals

Analyzing those signals with FieldTrip

Background on the FieldTrip toolbox

FieldTrip is a toolbox

the data and the separate functions are in
your hands

the scripts depend on the data properties,
your computer and on your programming
skills and style

scripts correspond to analysis protocols

- scripts can be reviewed by supervisors

- scripts are often shared with colleagues

- scripts can be published/released

Finding your way around in the FieldTrip toolbox

Matlab

help functionname

edit functionname

Website

<http://www.fieldtriptoolbox.org>

Email discussion list

Expertise in your local group

Introduction to EEG, MEG and analysis with the FieldTrip toolbox

Robert Oostenveld

*Donders Institute, Radboud University, Nijmegen, NL
NatMEG, Karolinska Institute, Stockholm, SE*