

Introduction to MEG and OPM analysis with the FieldTrip toolbox

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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

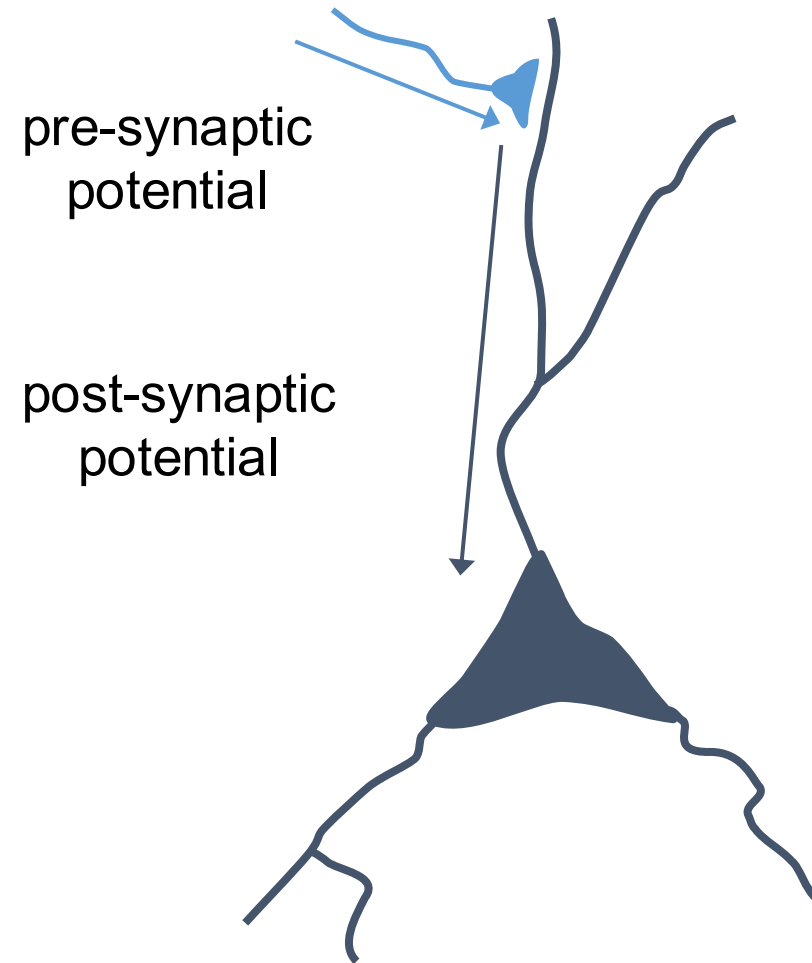
What kind of signals are generated in the brain

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

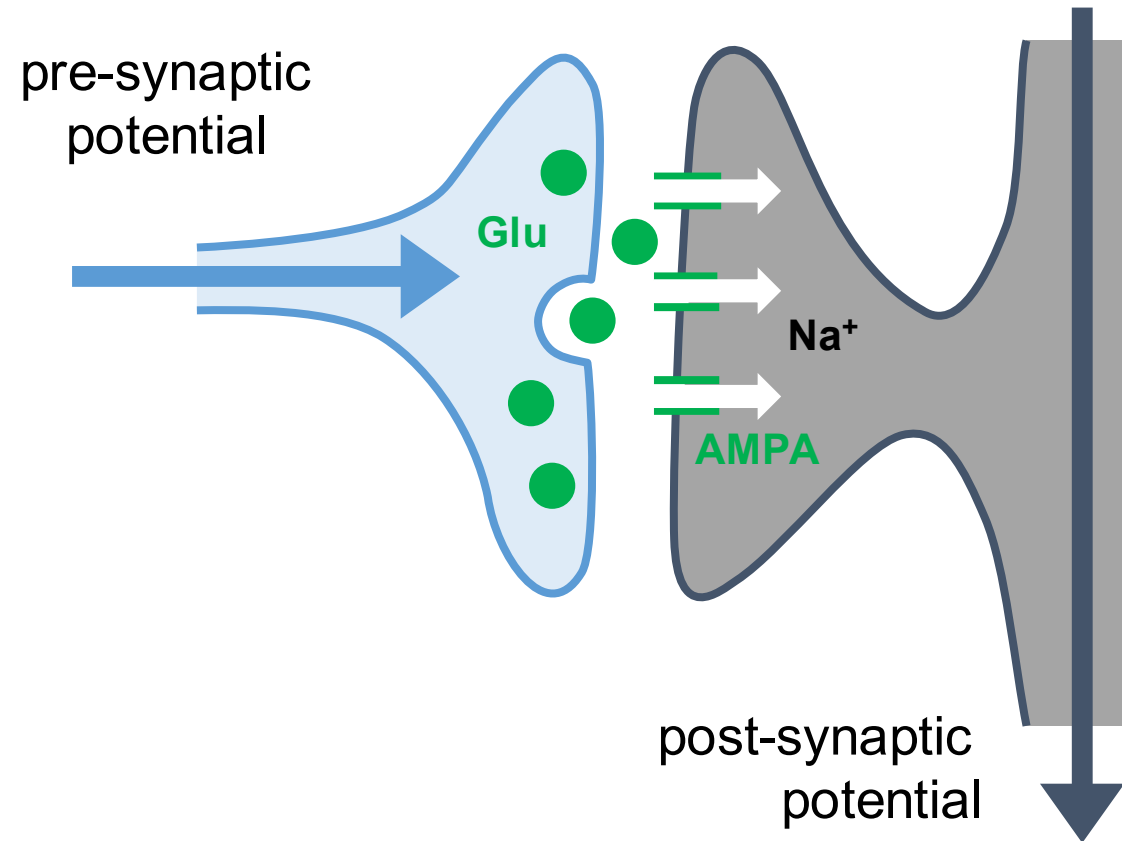
These PSPs represent the excitatory and inhibitory input that these neurons receive

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

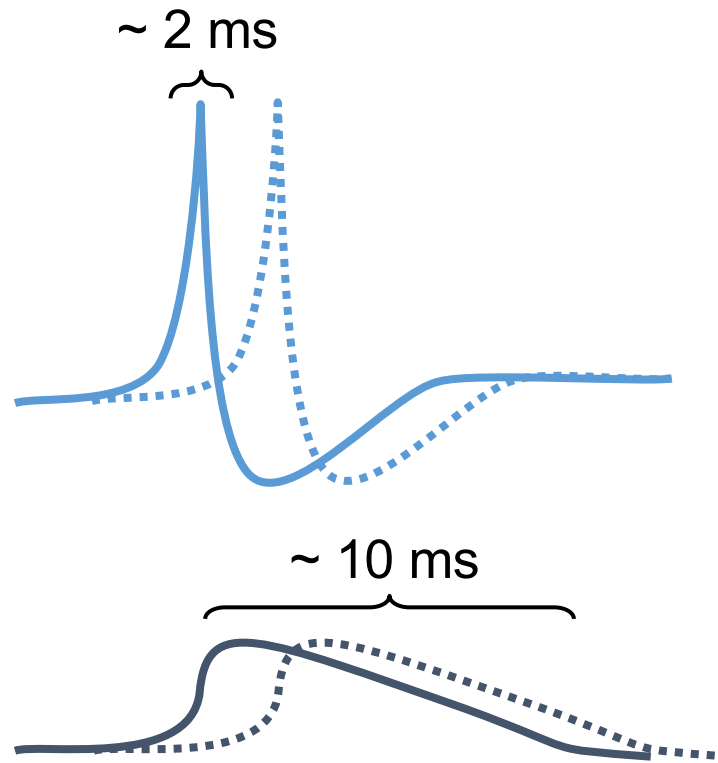
What generates the currents and fields



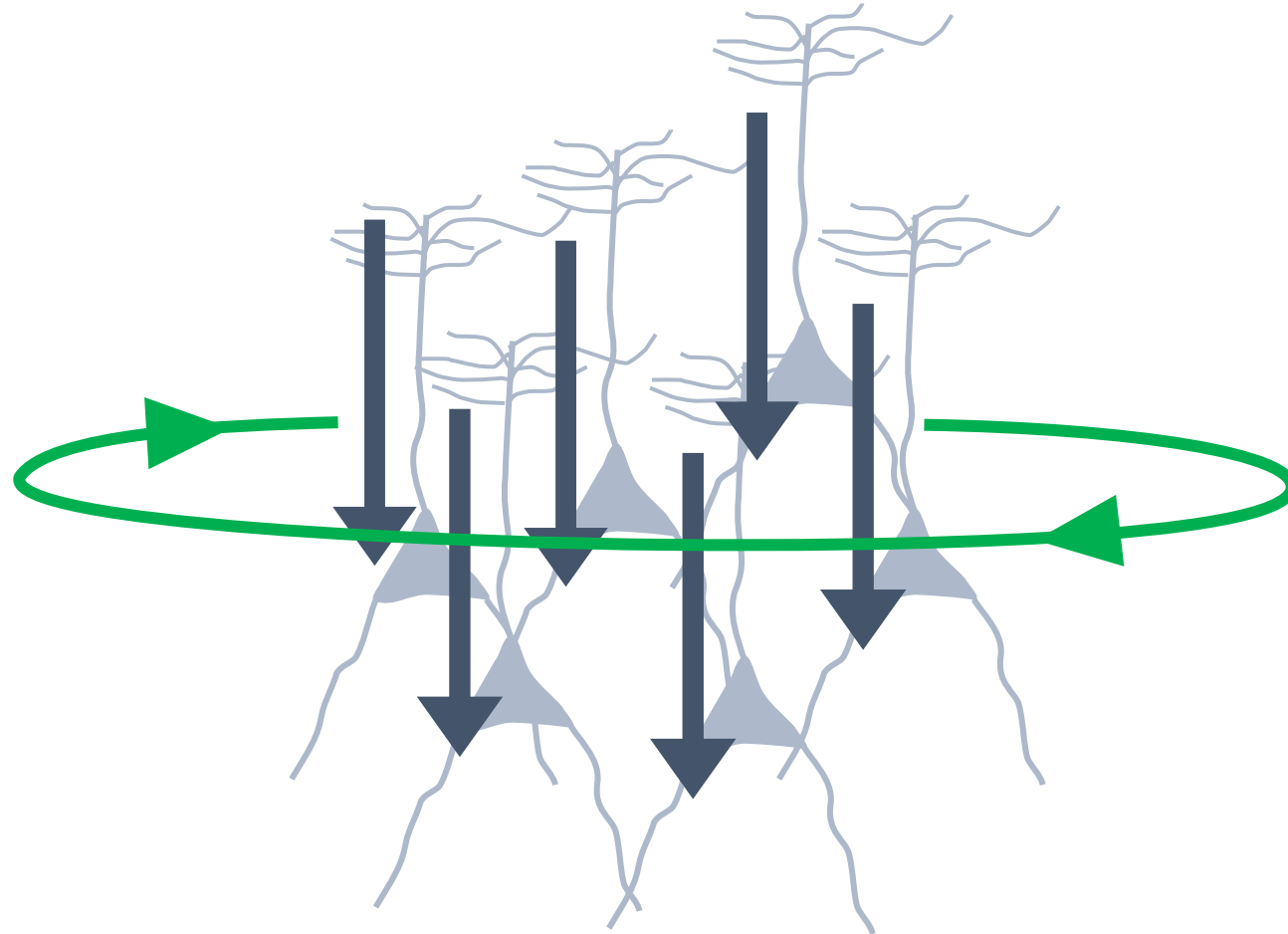
What generates the currents and fields



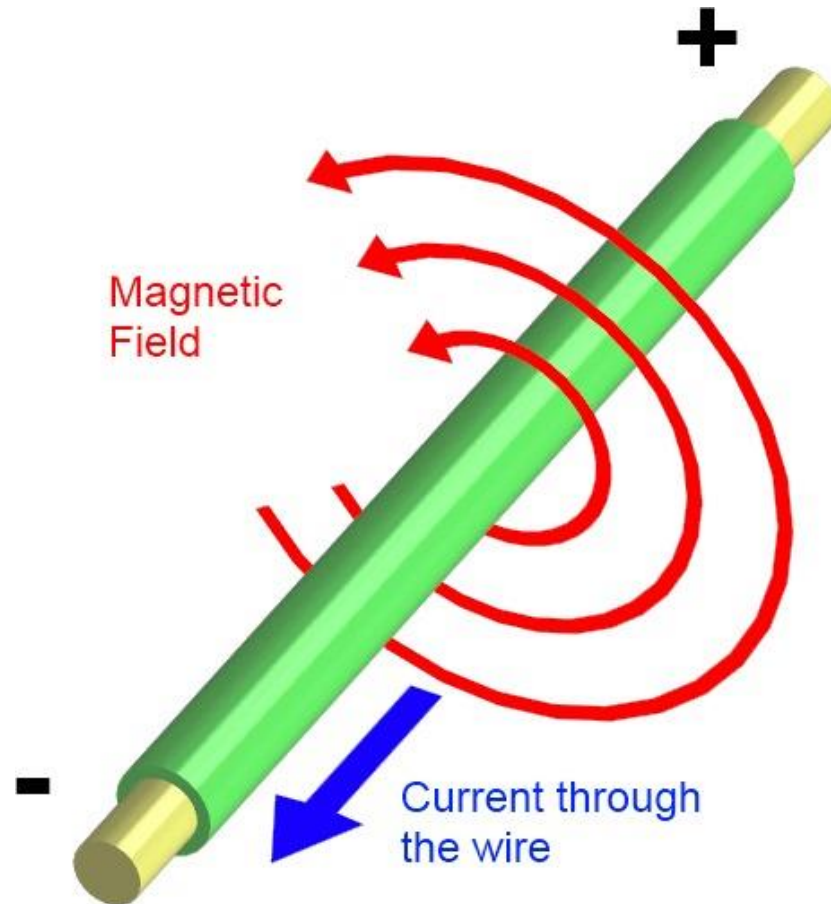
What generates the currents and fields



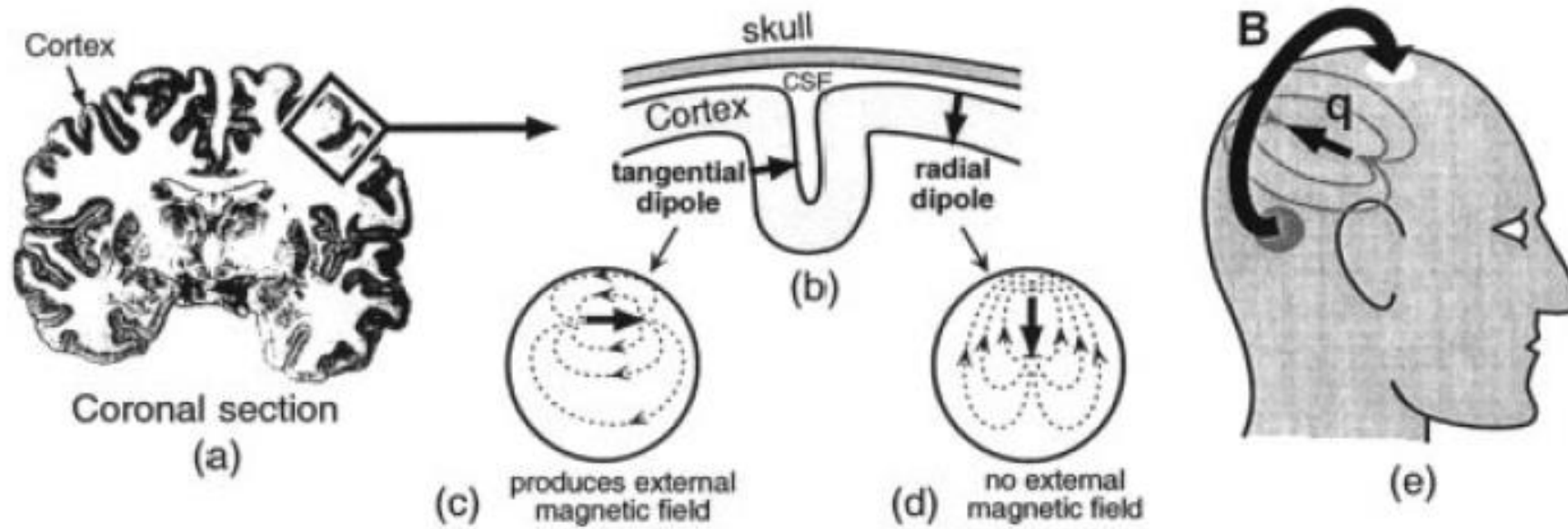
What generates the currents and fields



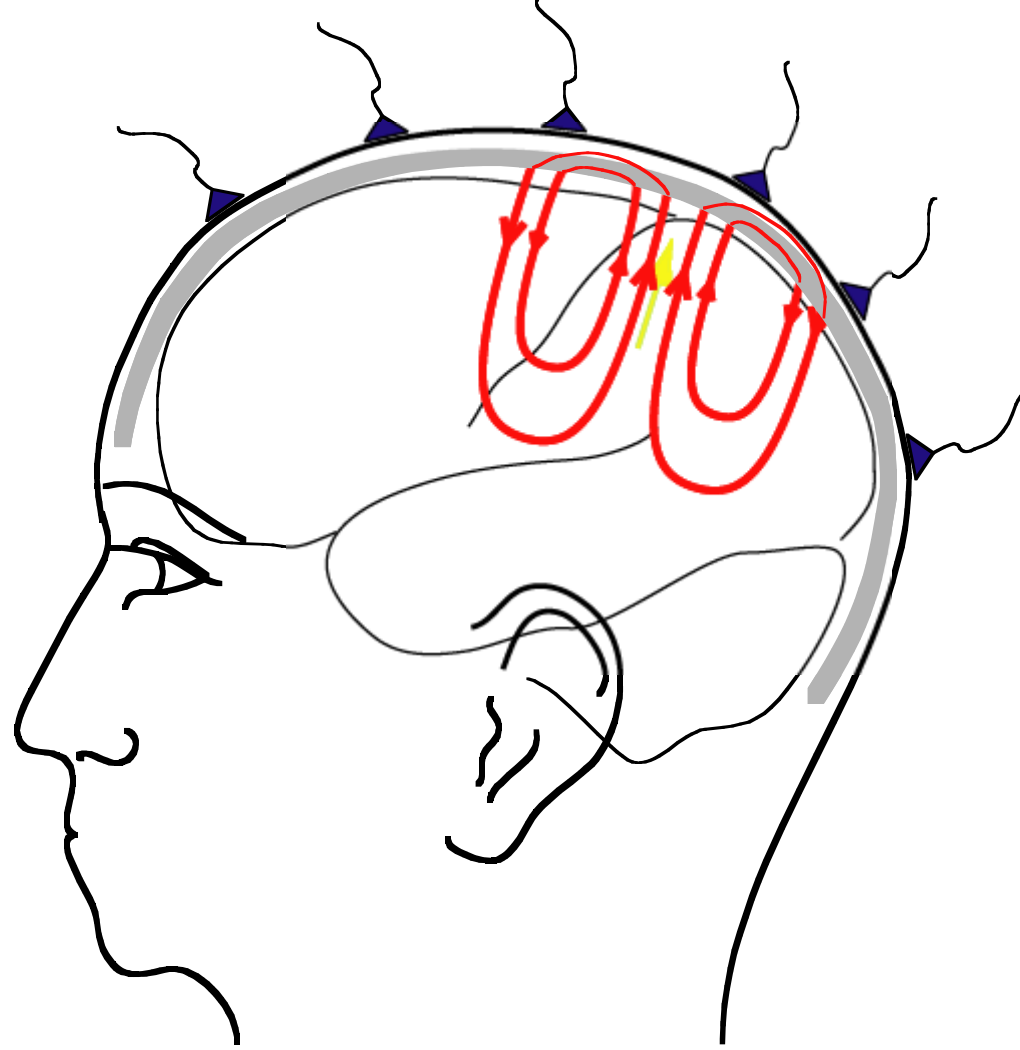
What generates the currents and fields



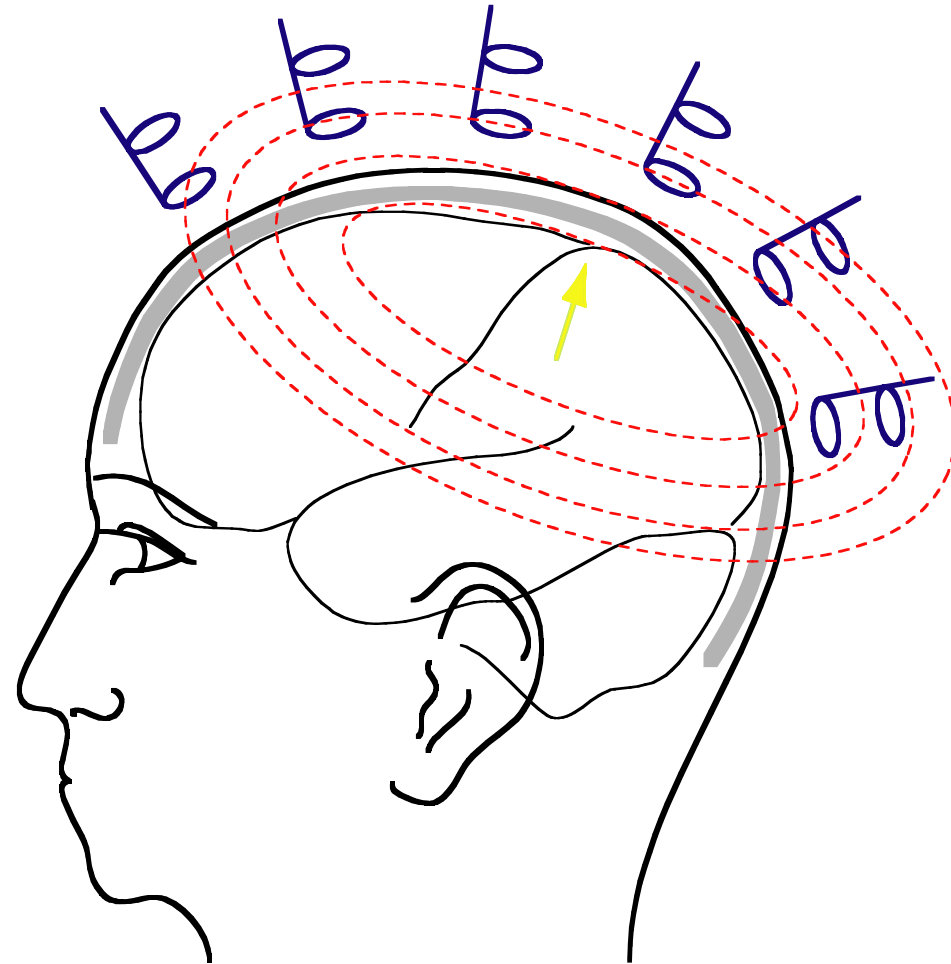
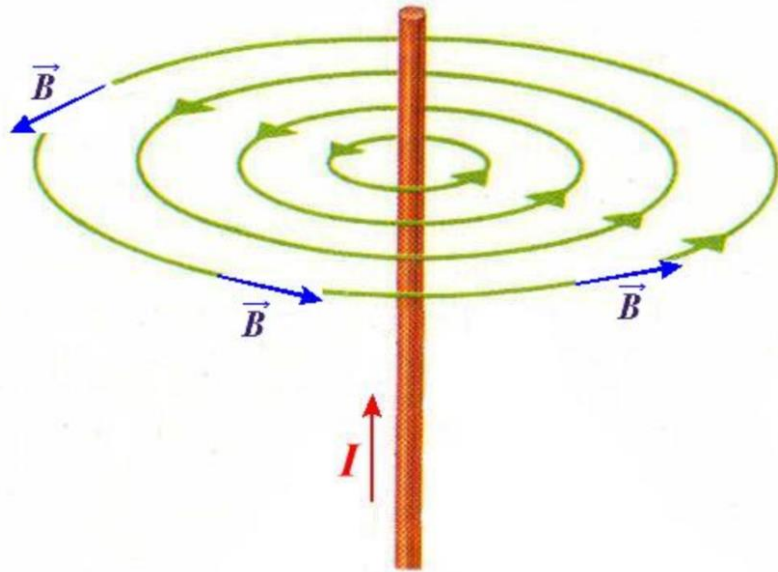
What generates the currents and fields



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

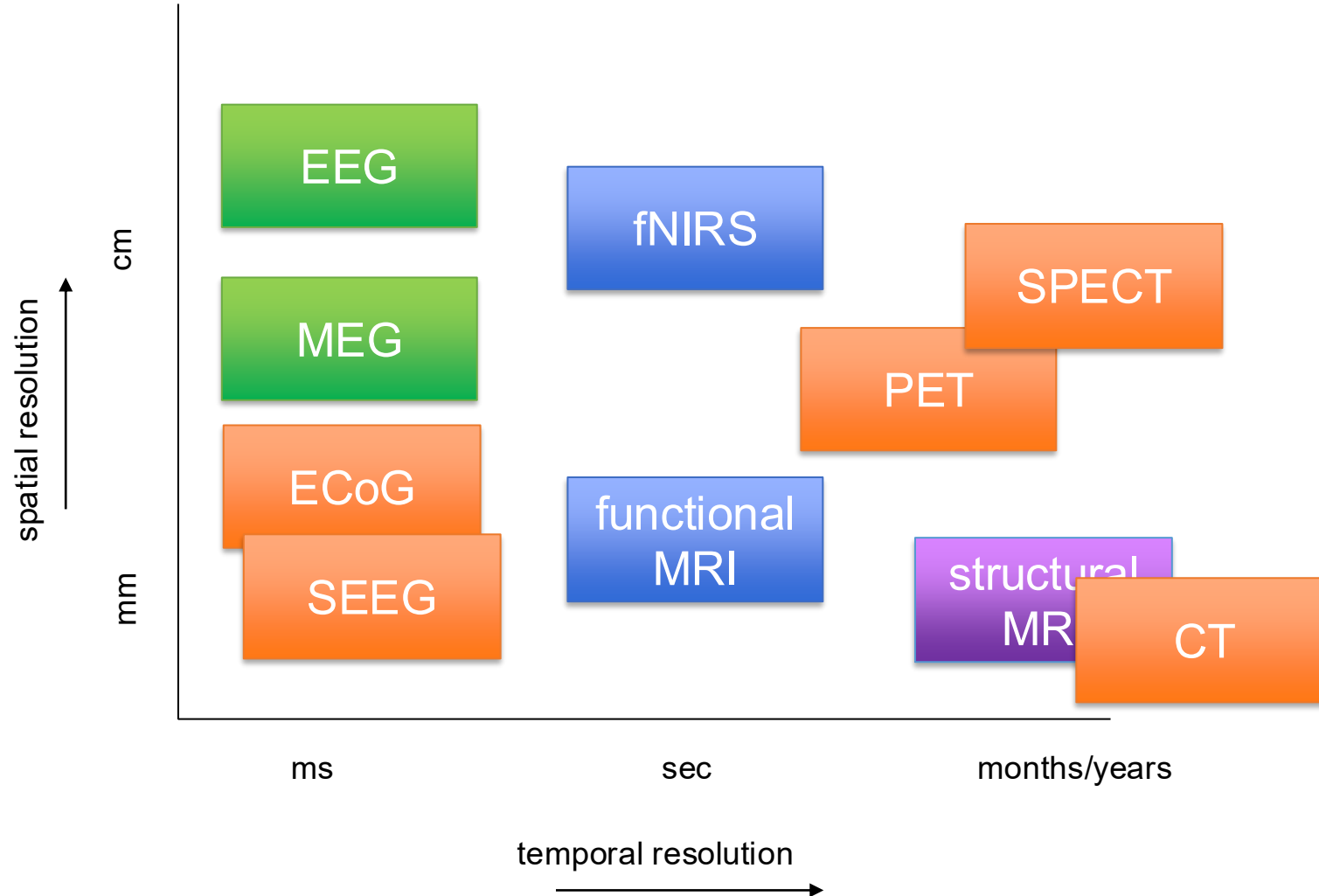
Analyzing those signals with FieldTrip

Background on the FieldTrip toolbox

How do we record these signals from the brain



These differ in their resolution, coverage & invasiveness



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 very sensitive magnetic detectors

- SQUIDs

- OPMs

Requires a magnetic noise-free environment

- Passive shielding with Mu-metal

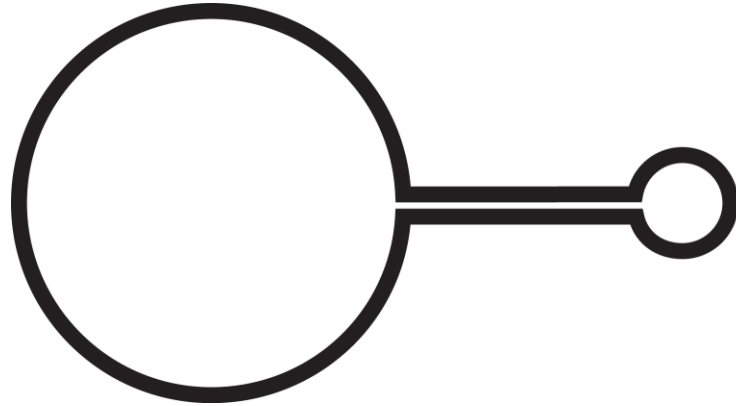
- Active shielding with Helmholtz-like coils

- Smart sensor design

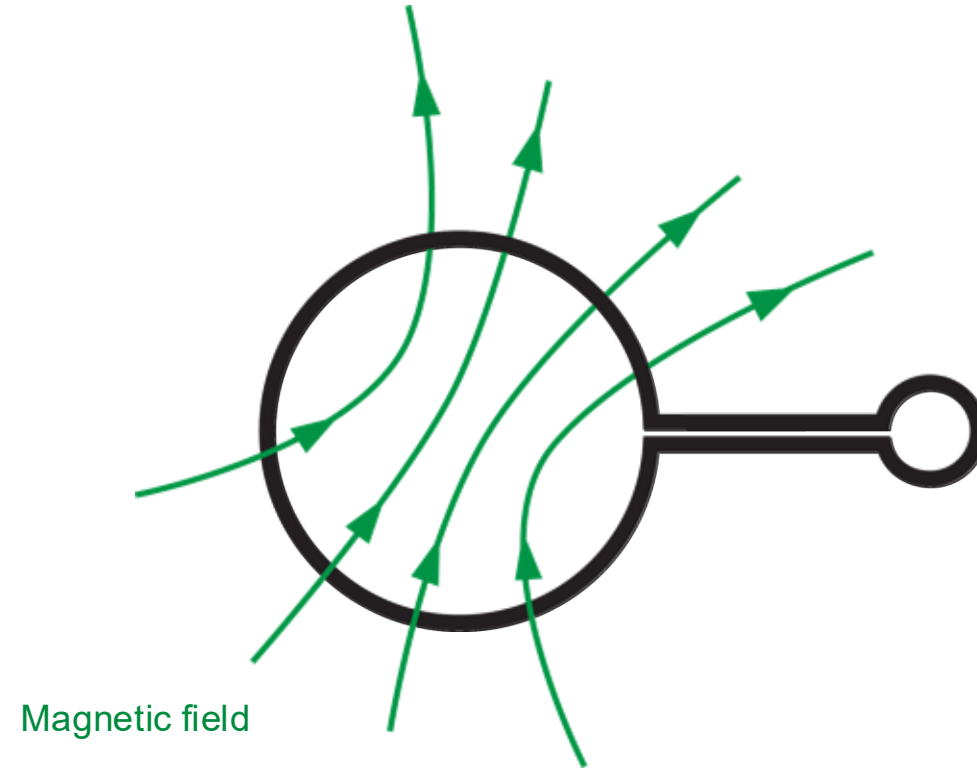
- Reference sensors for noise subtraction

- Off-line algorithmic denoising

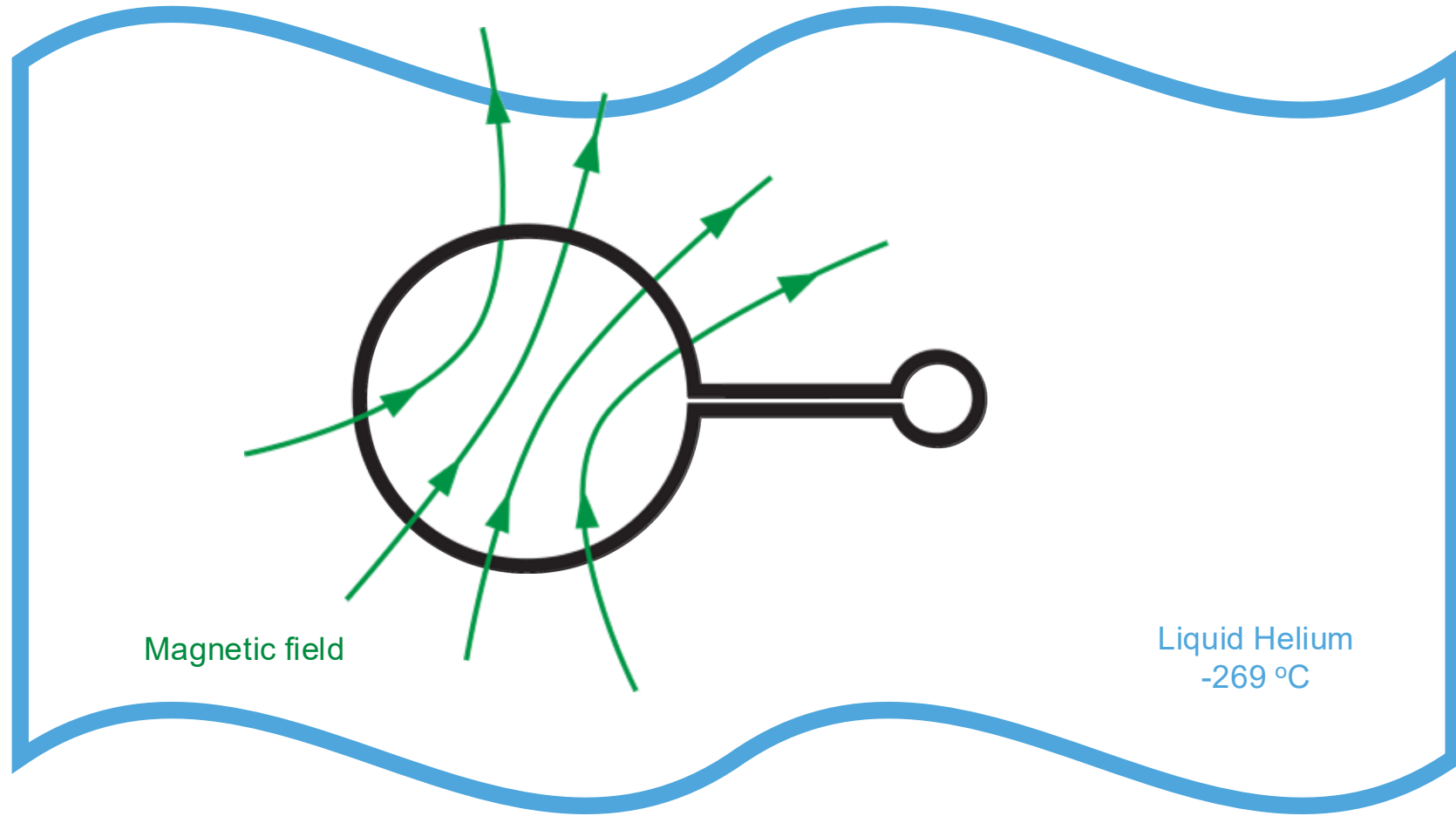
Recording small magnetic fields using SQUIDs



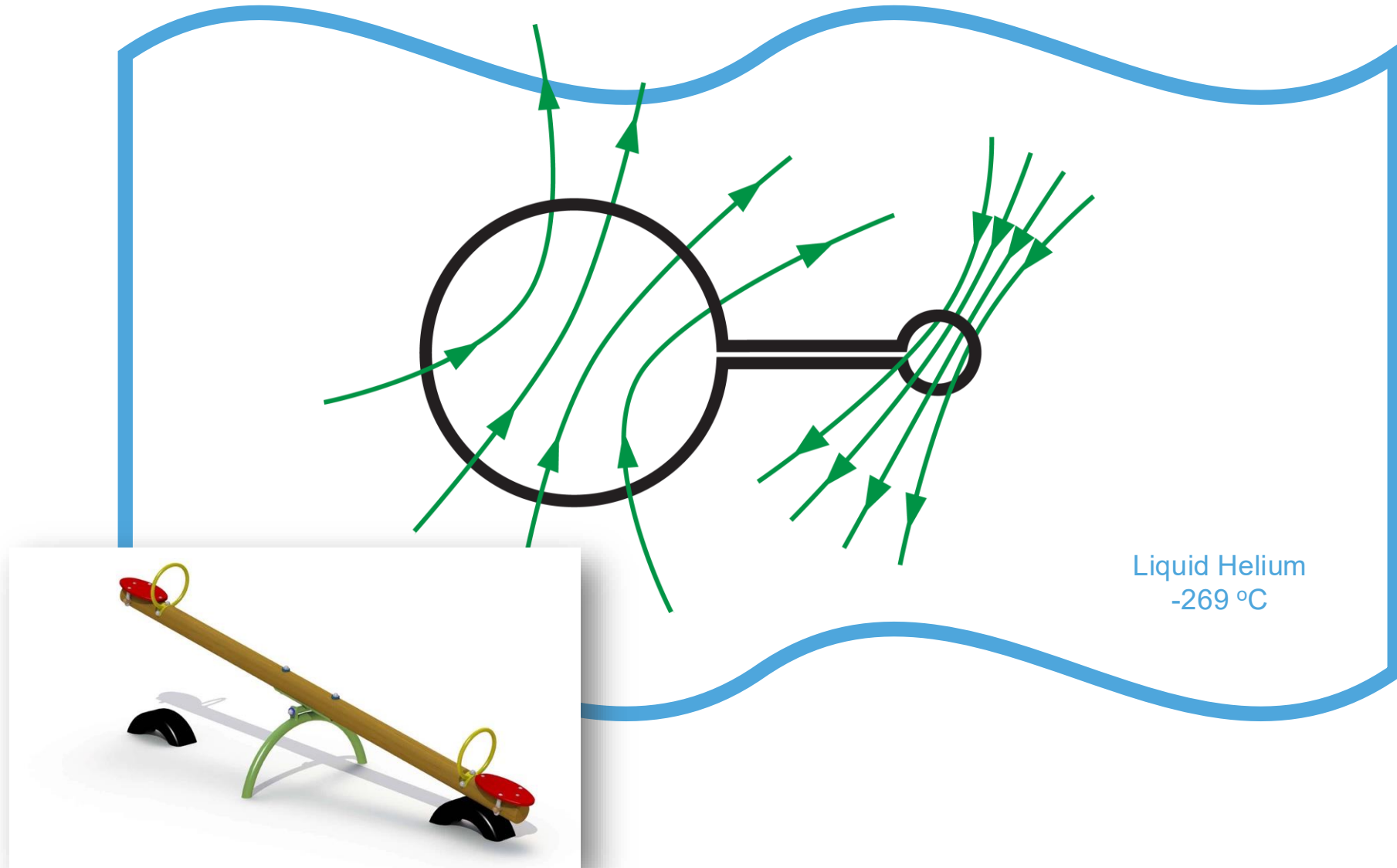
Recording small magnetic fields using SQUIDs



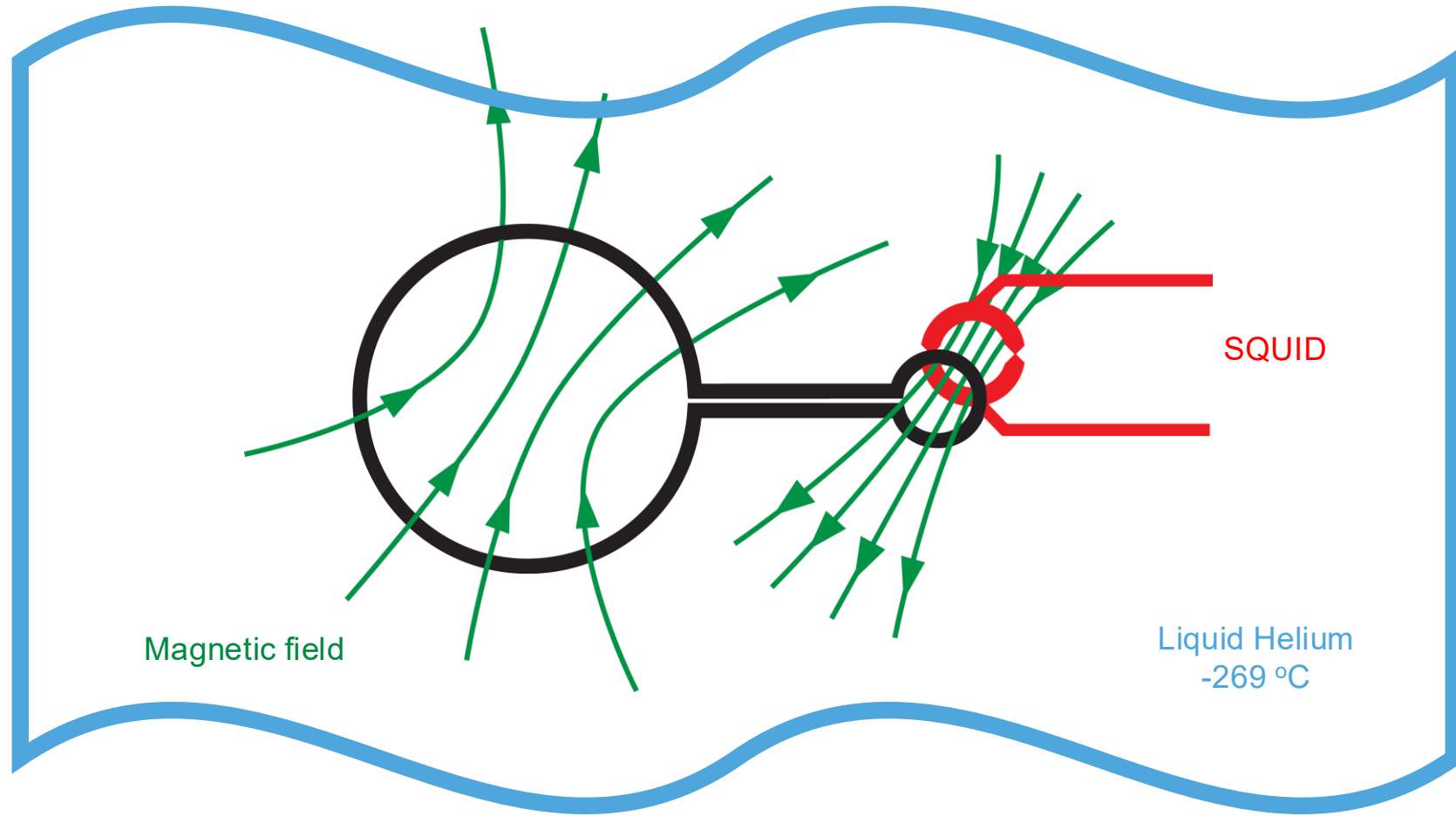
Recording small magnetic fields using SQUIDs



Recording small magnetic fields using SQUIDs

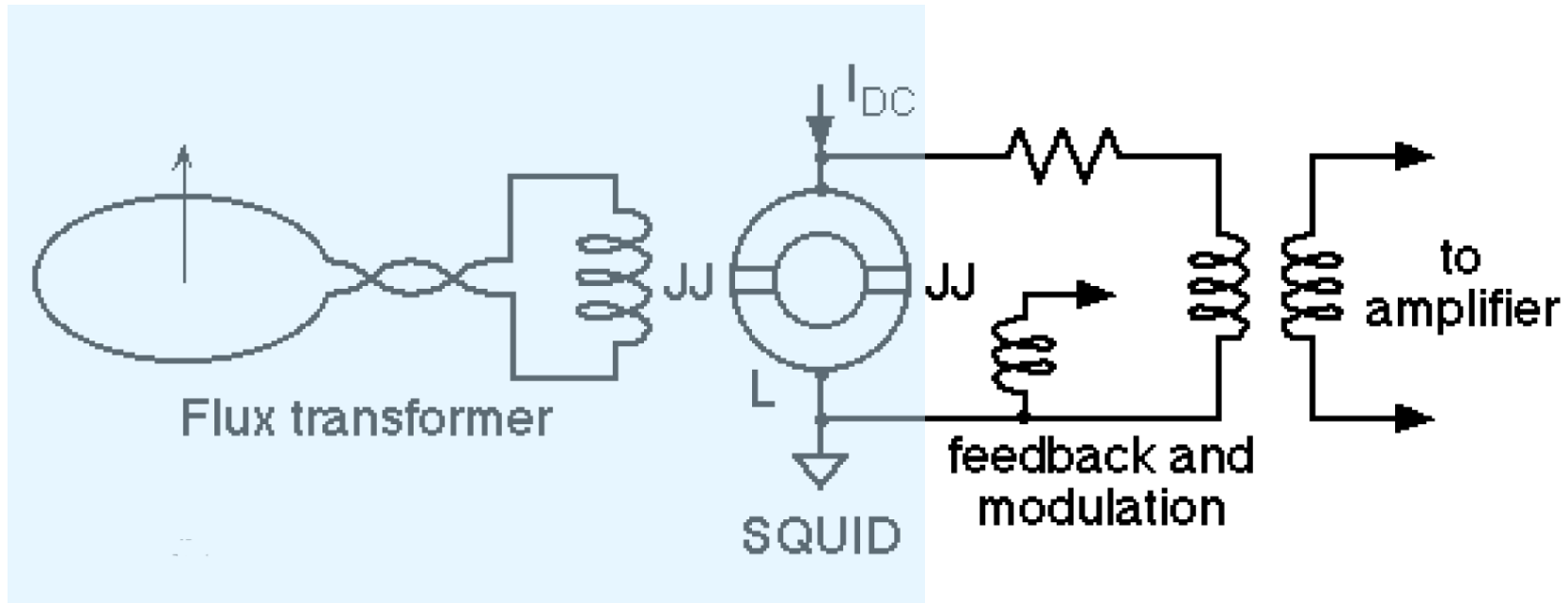
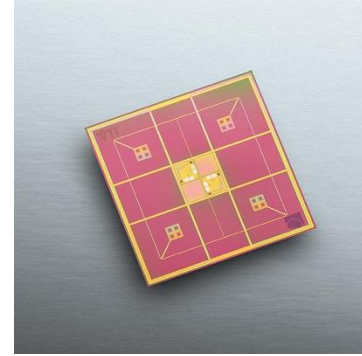


Recording small magnetic fields using SQUIDs

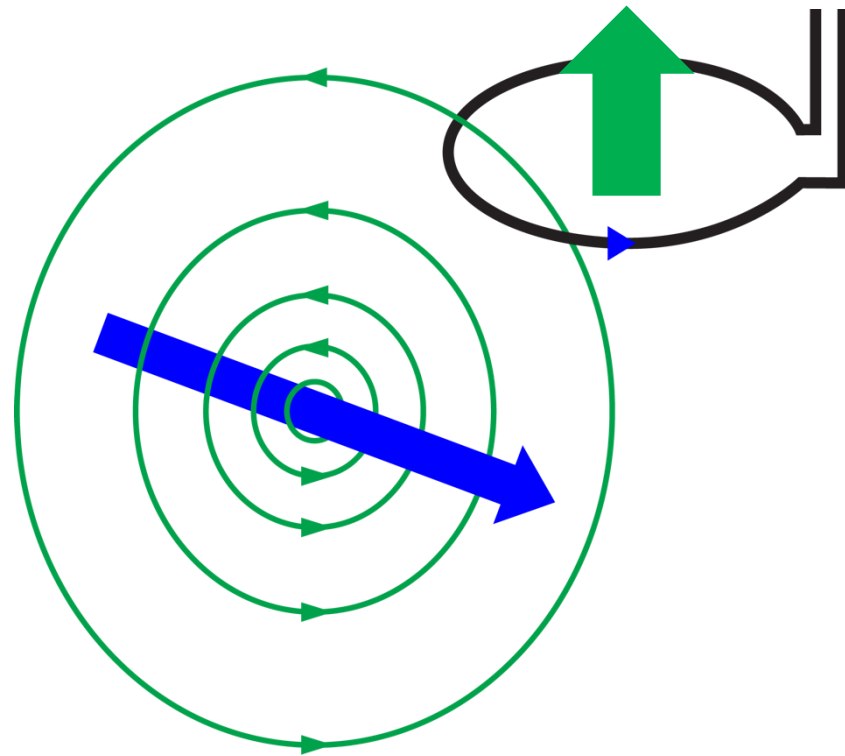


Magnetic field detectors

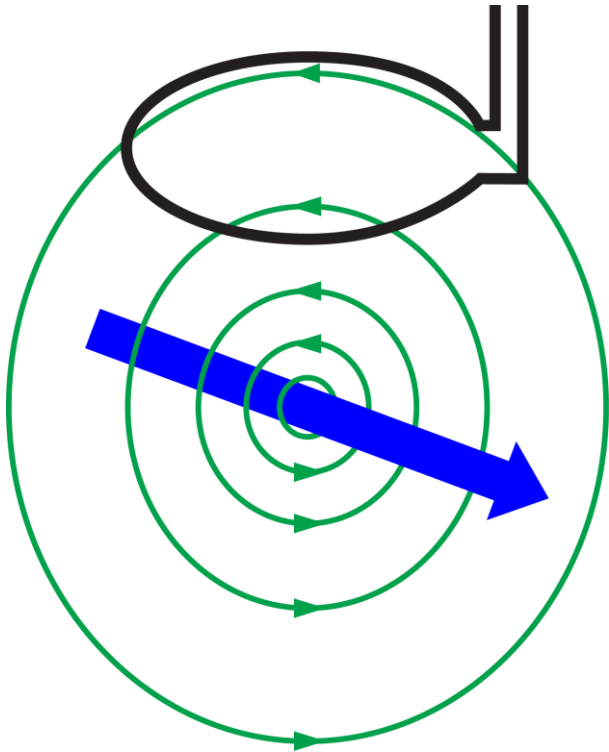
Superconducting **QU**antum Interference **D**evice



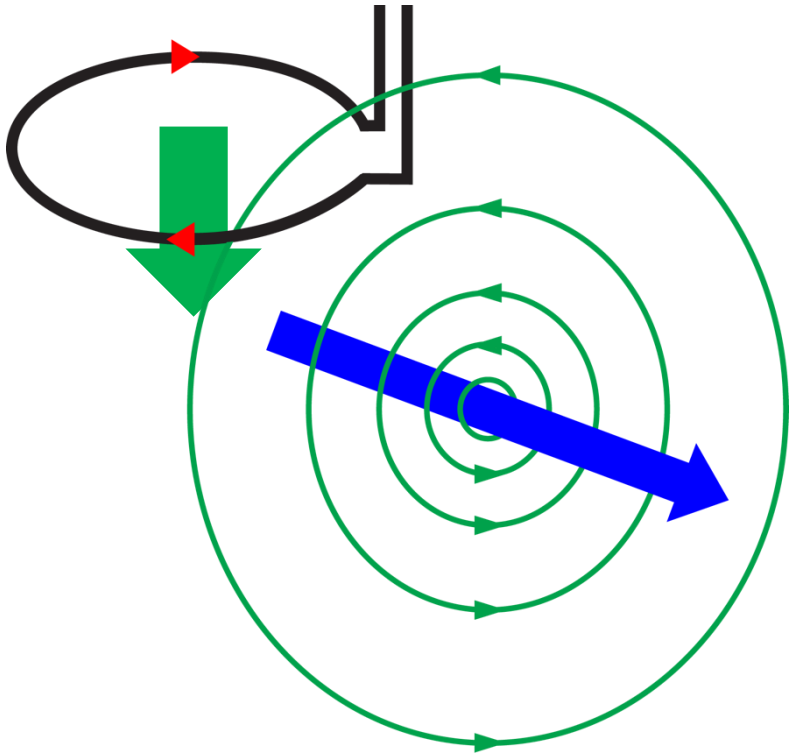
Magnetometer



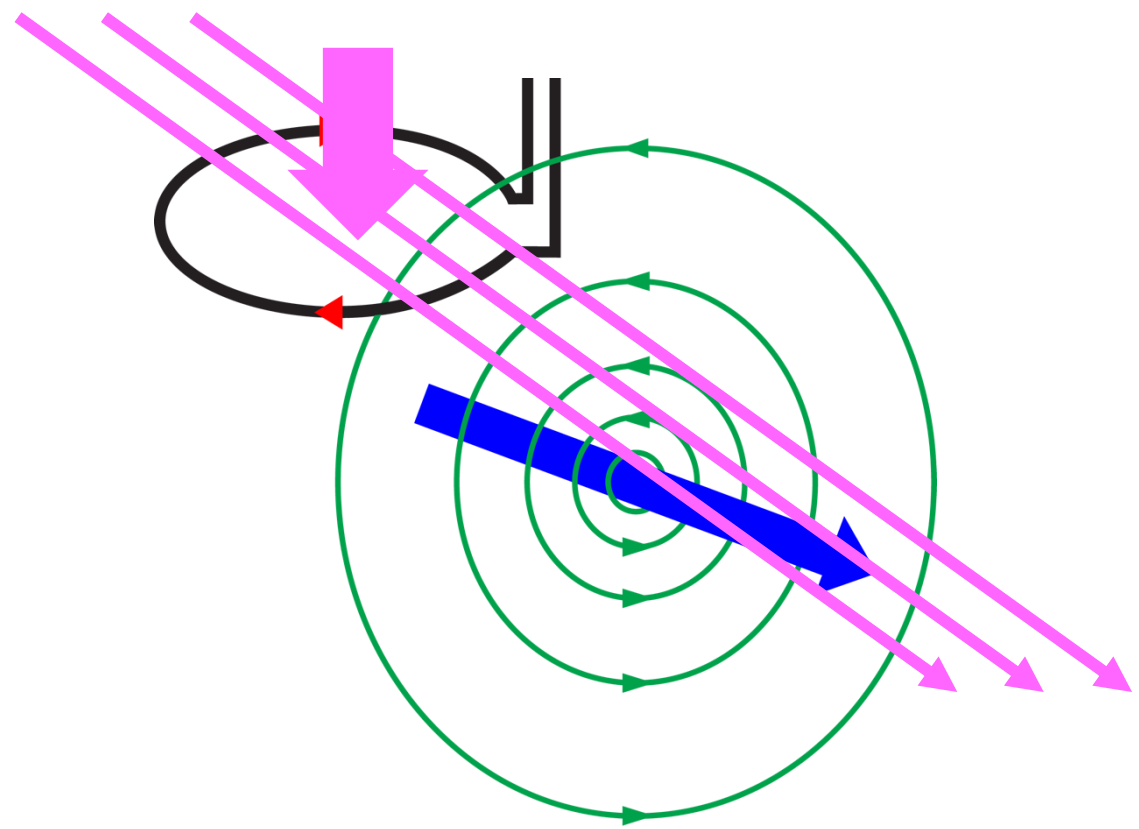
Magnetometer



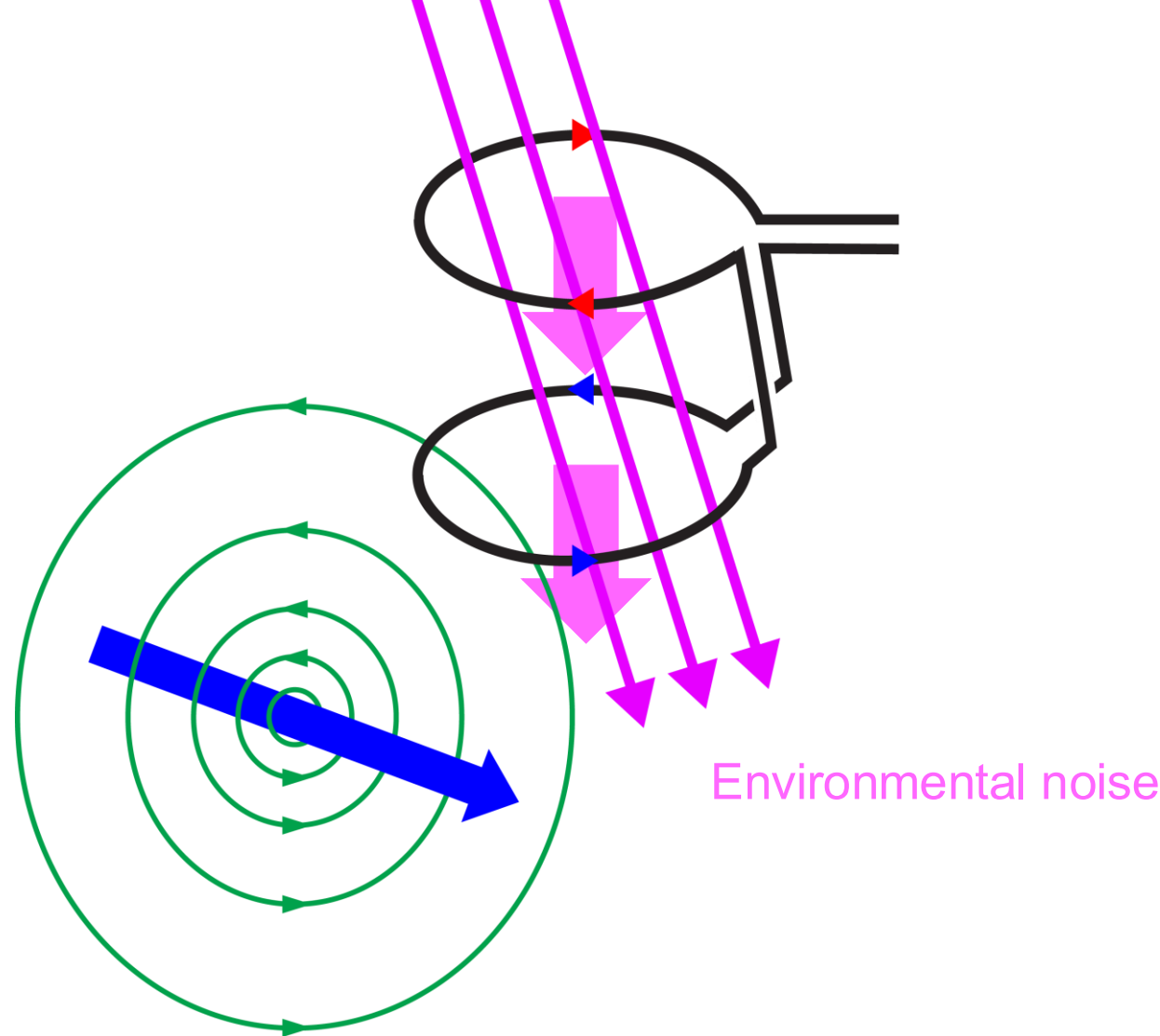
Magnetometer



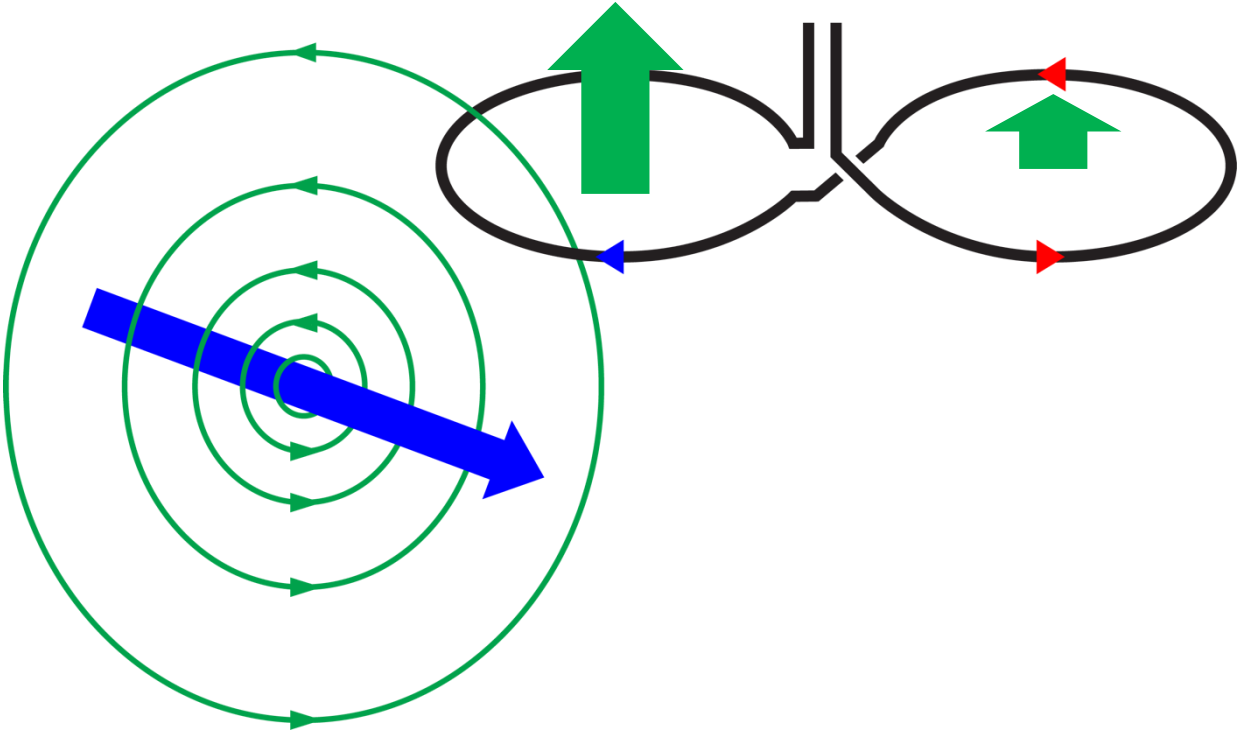
Magnetometer



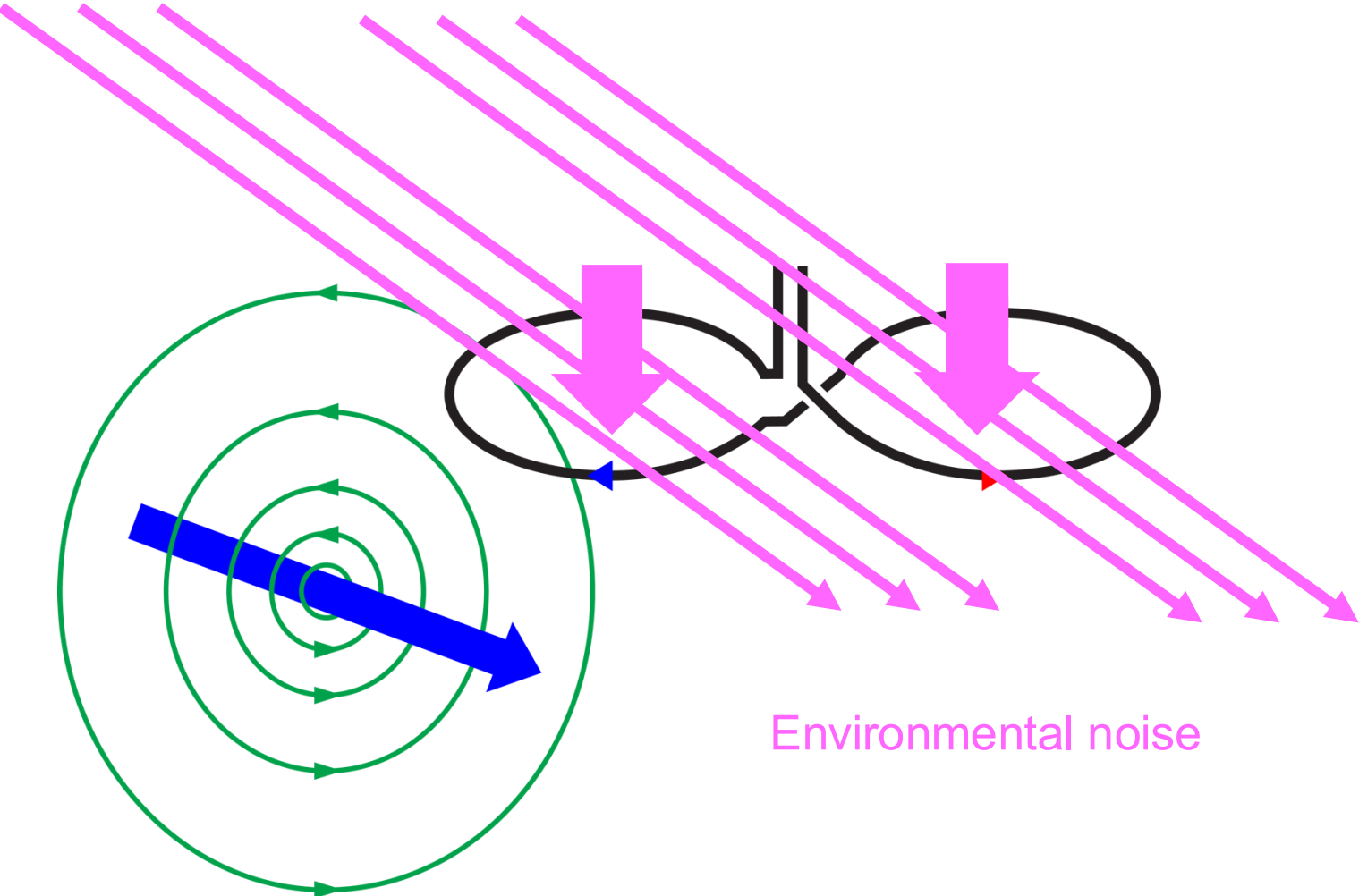
Axial gradometer



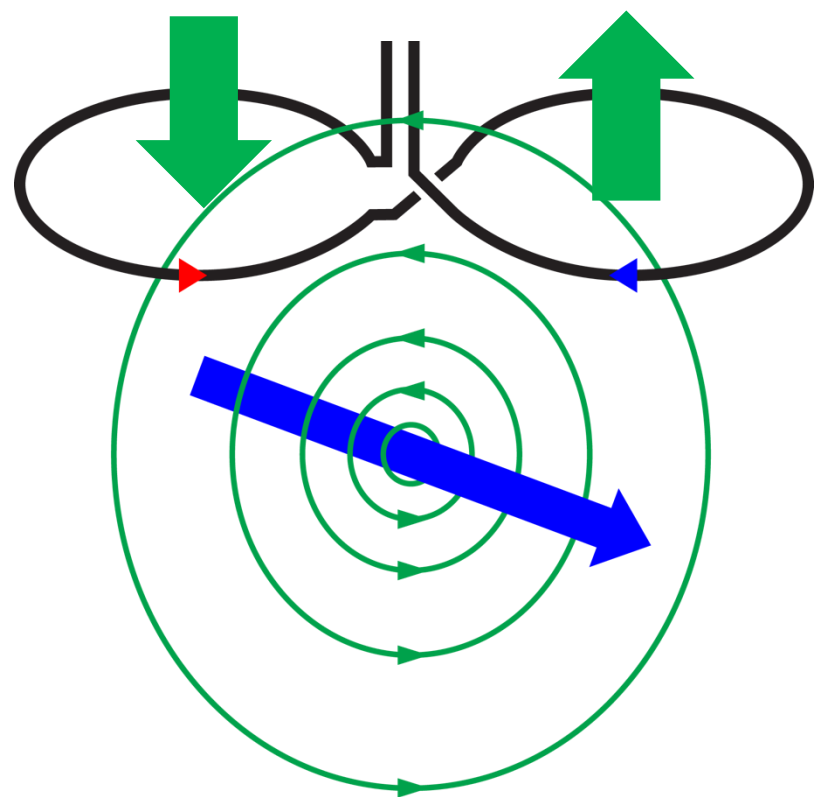
Planar gradiometer



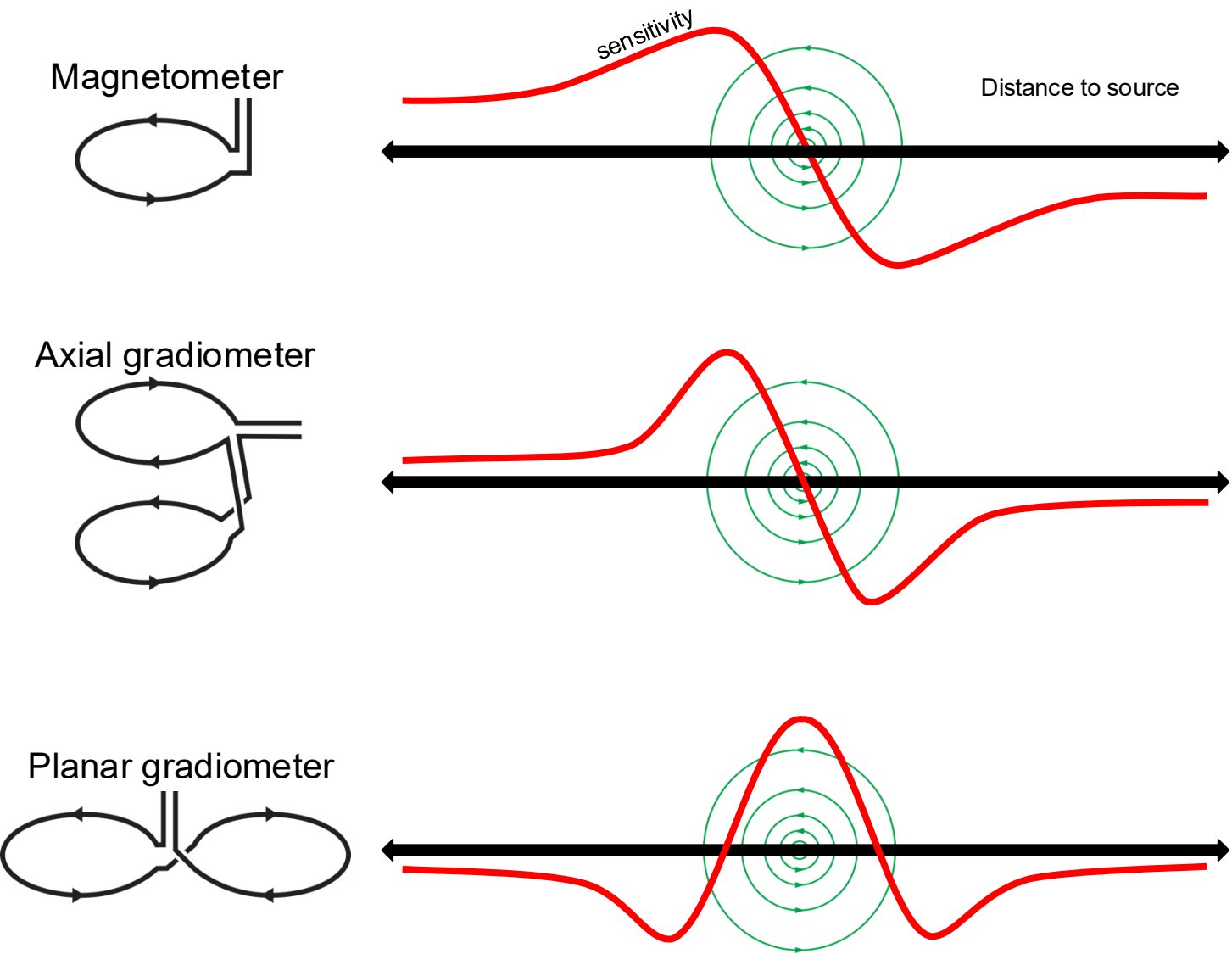
Planar gradiometer

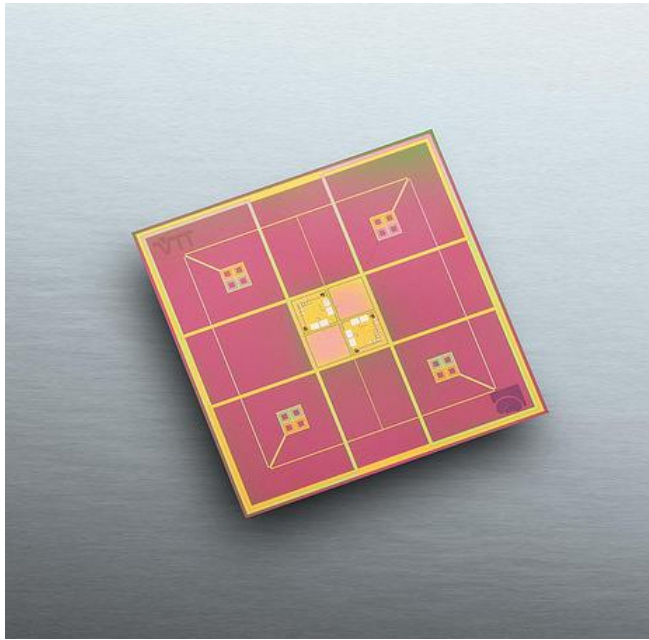


Planar gradiometer



MEG sensor – sensitivity profile



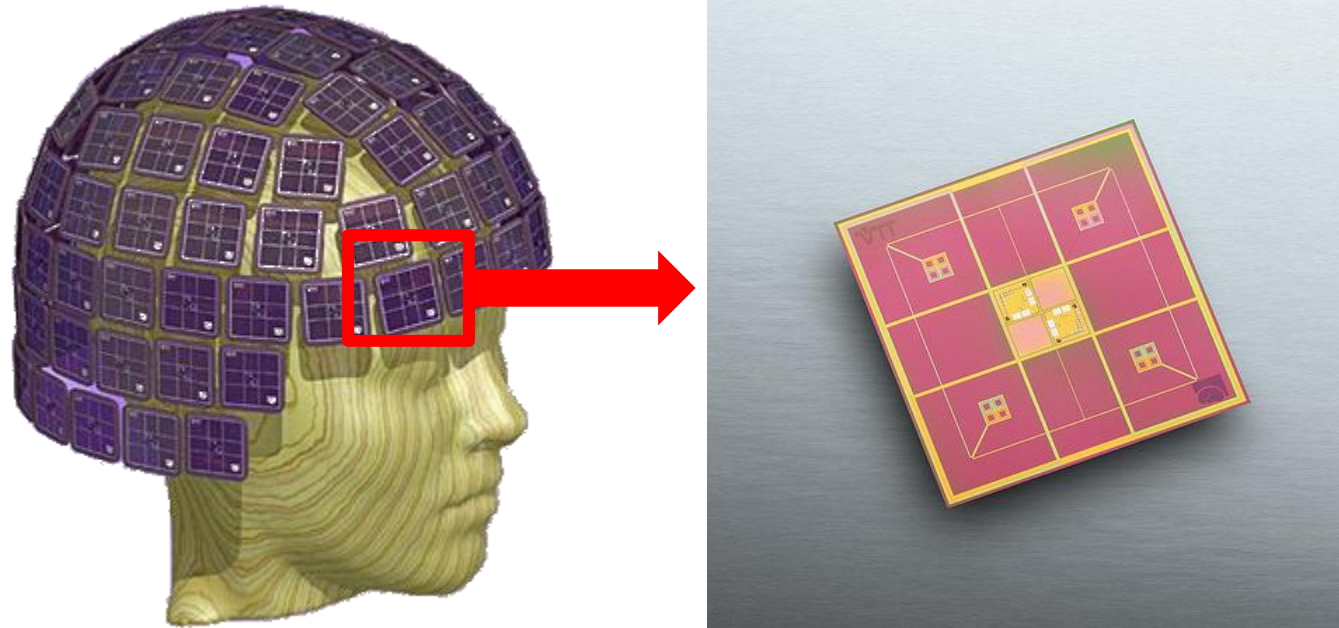


Neuromag/Elekta/Megin

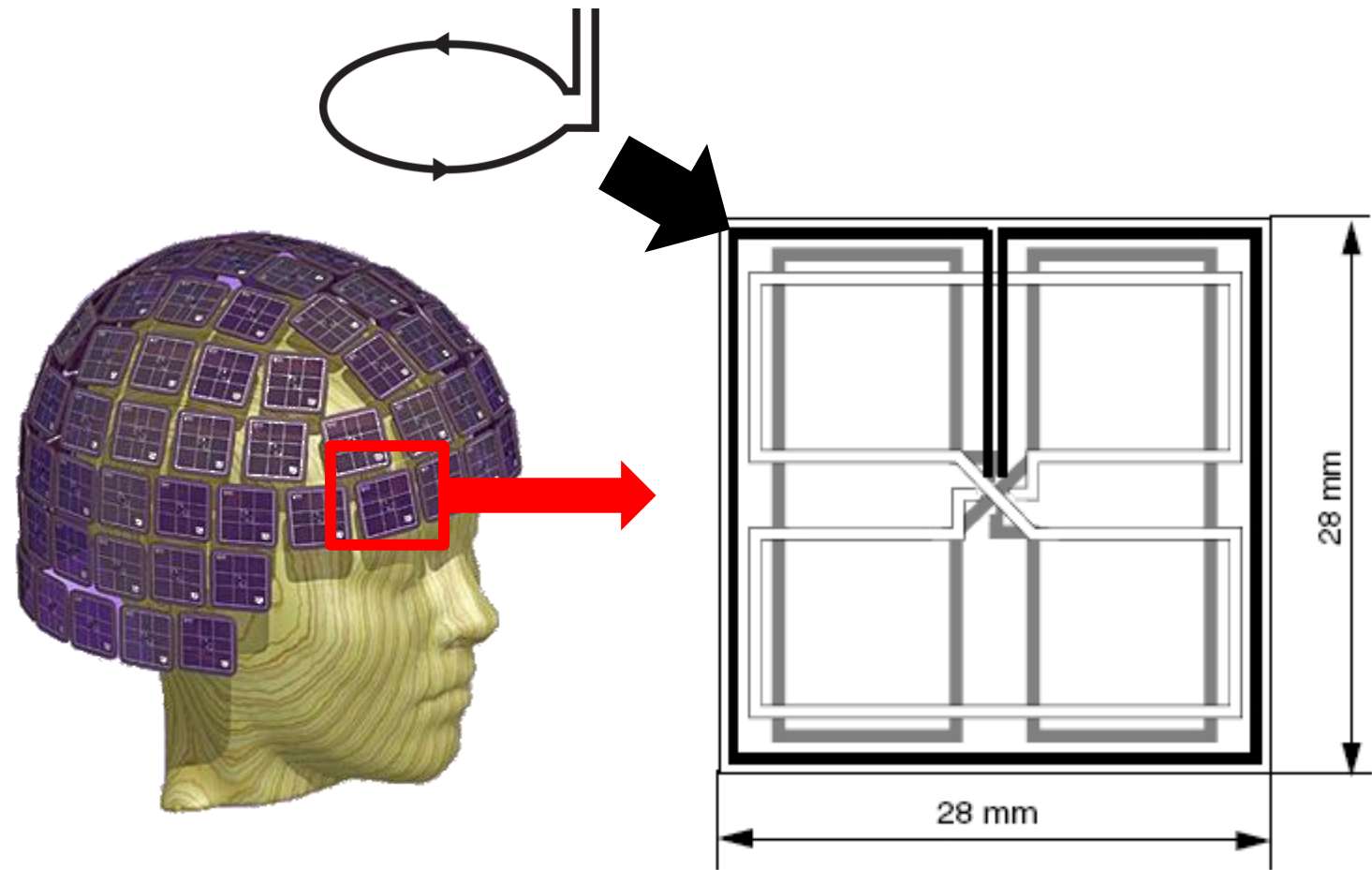
102 magnetometers
204 planar gradiometers
306 channels total



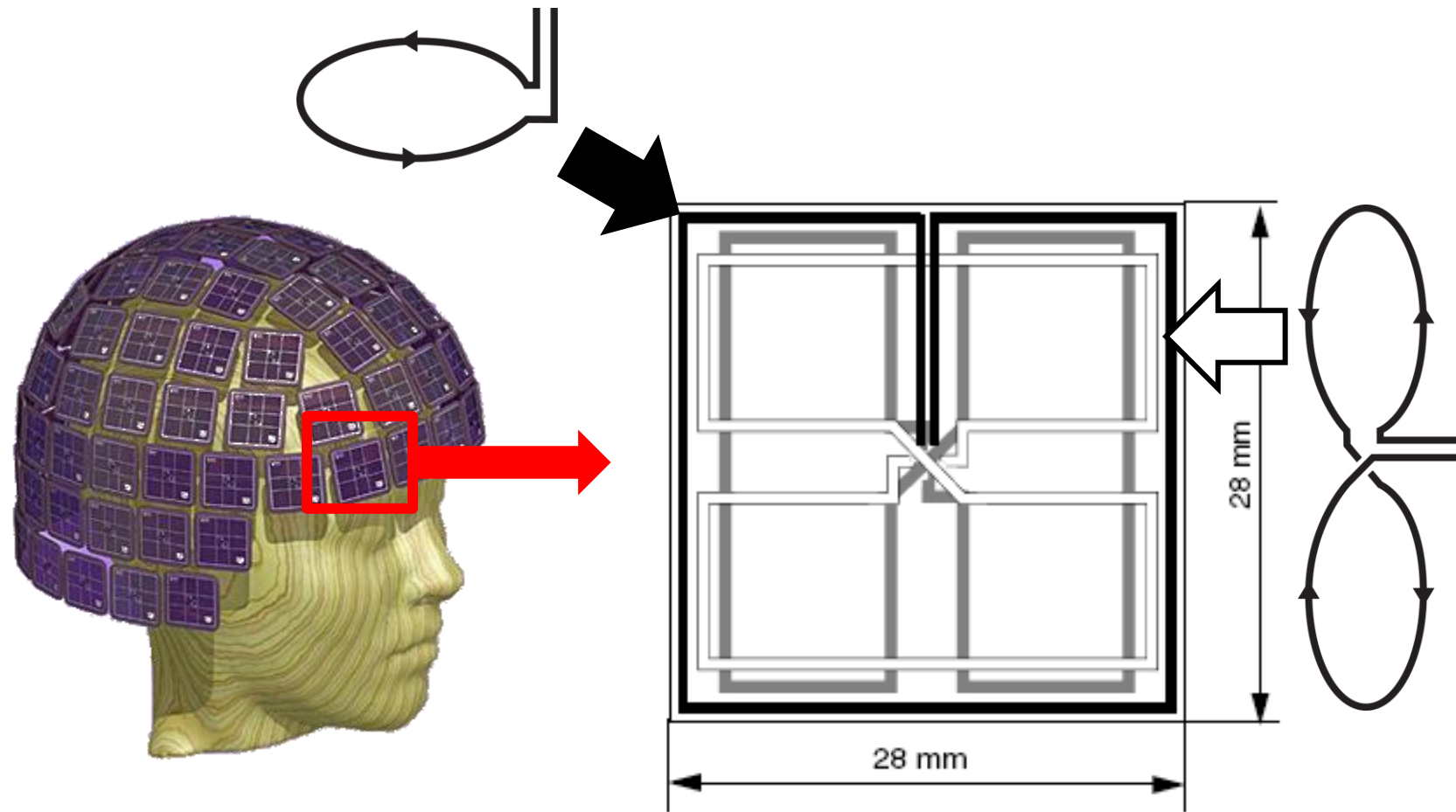
Neuromag/Elekta/Megin



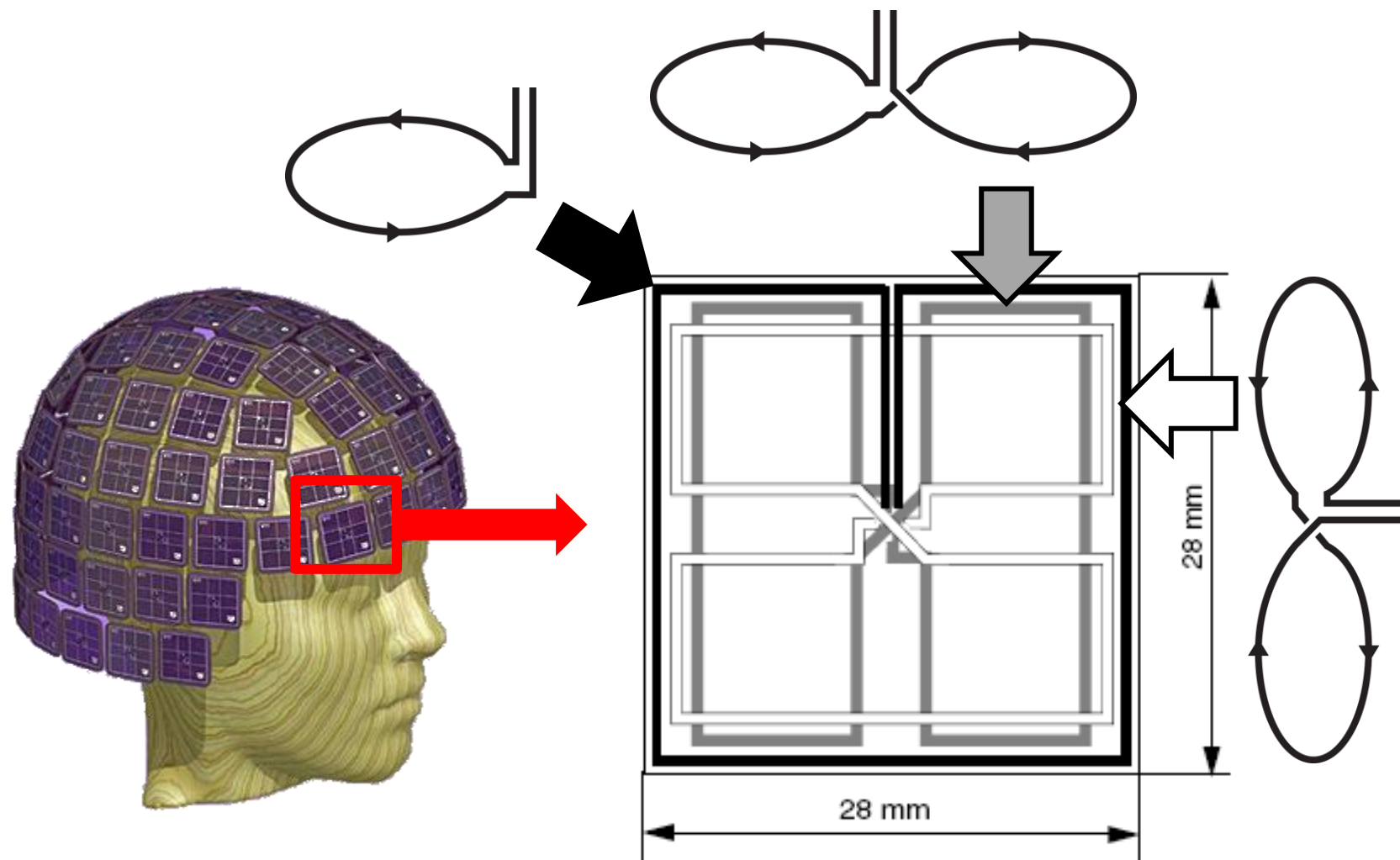
Neuromag/Elekta/Megin



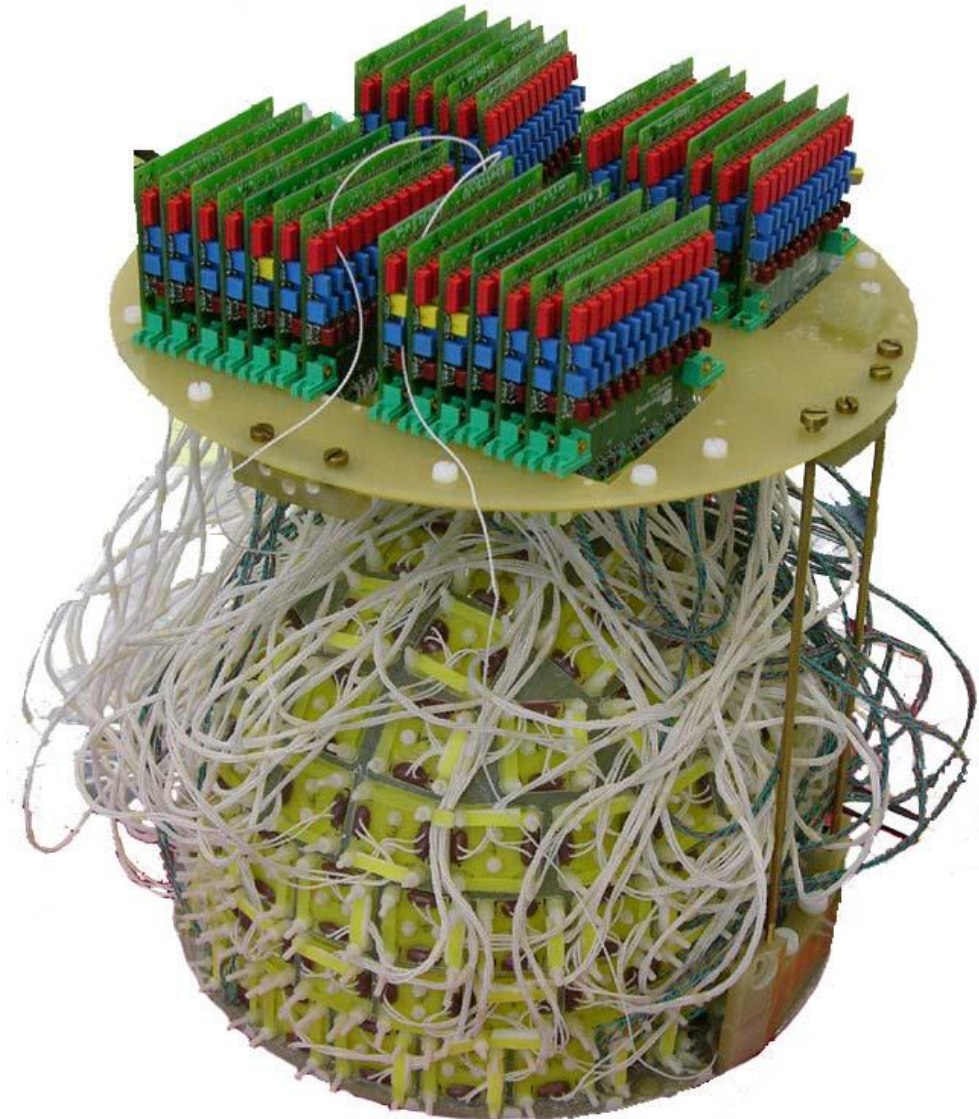
Neuromag/Elekta/Megin



Neuromag/Elekta/Megin

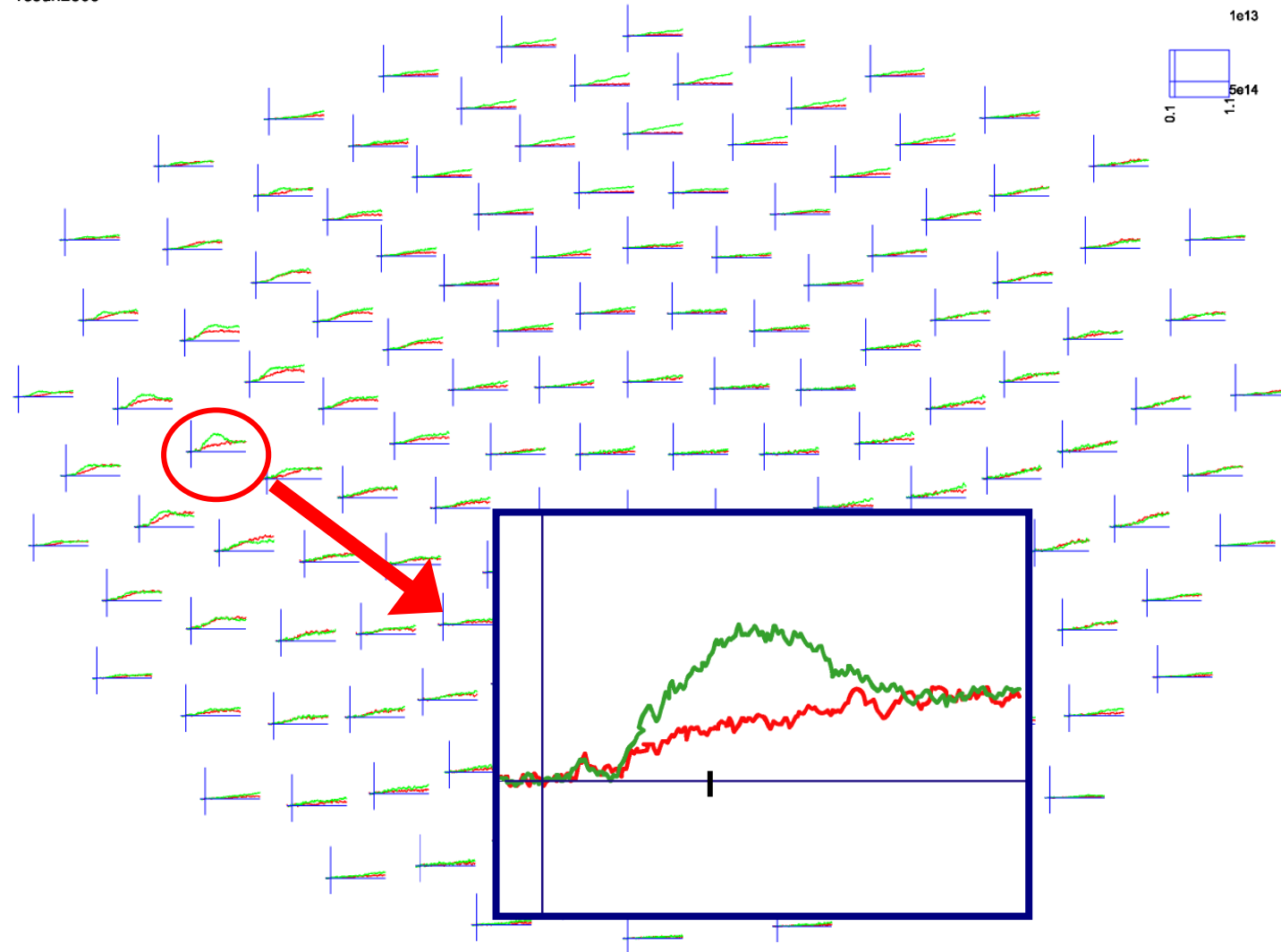


Neuromag/Elekta/Megin

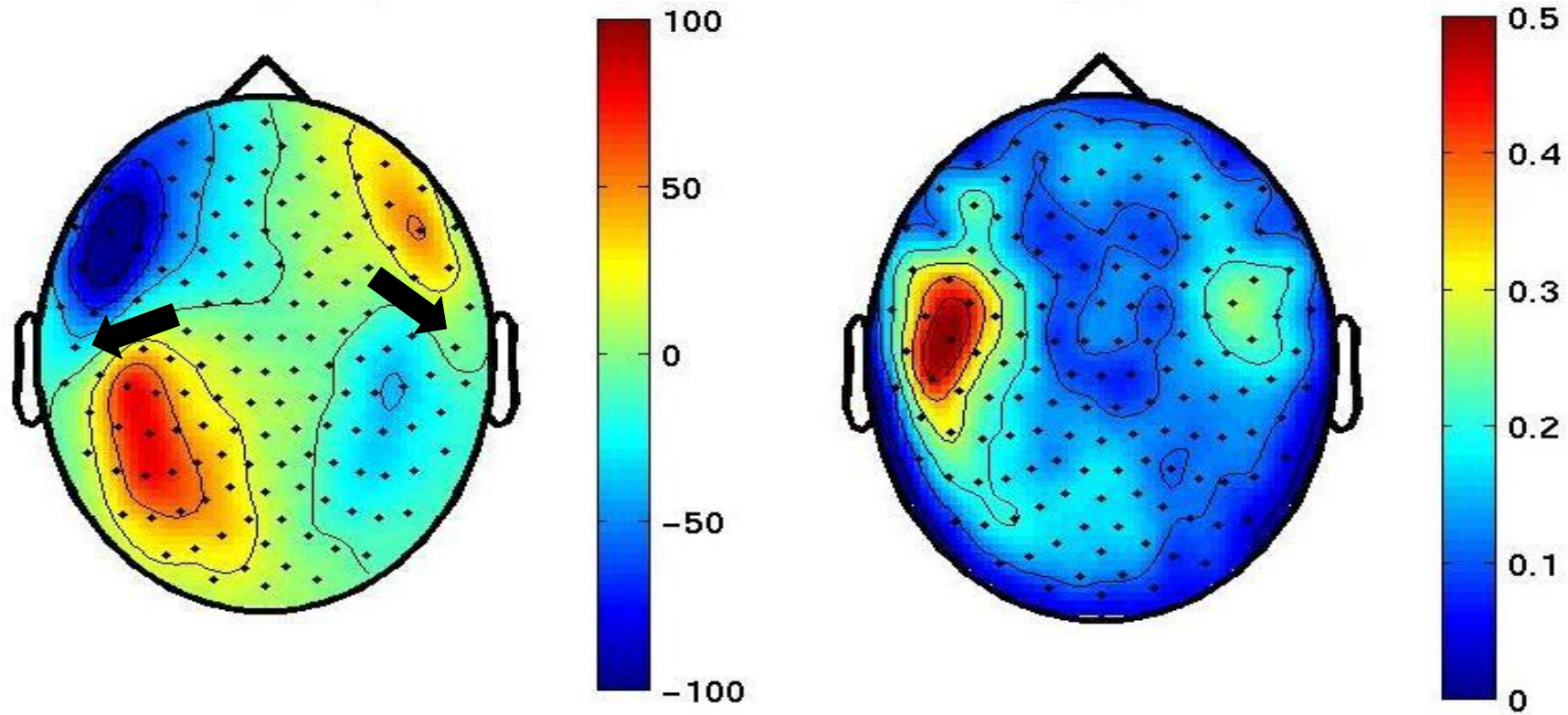


N400 response in MEG

18Jun2003



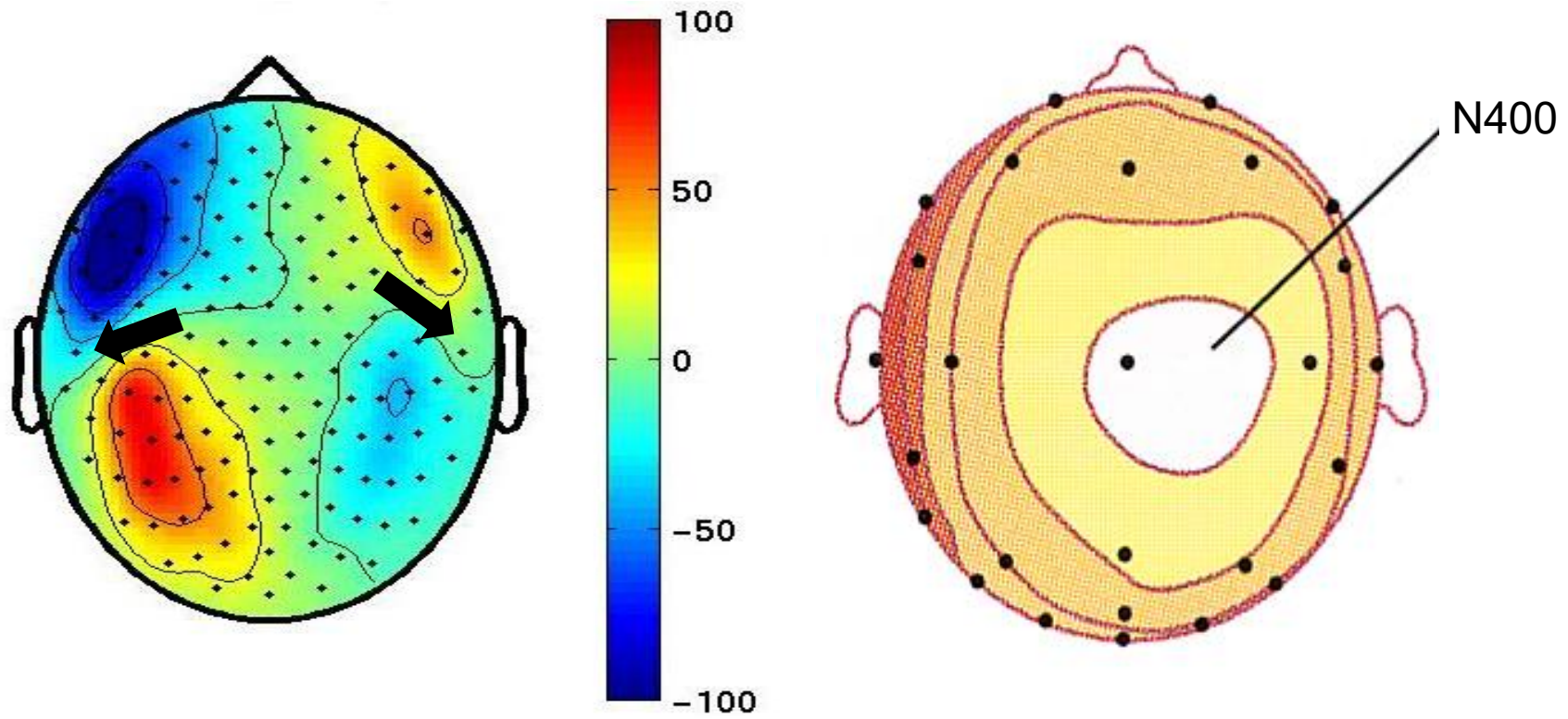
N400 response - compared between MEG systems



axial magnetic field

planar gradient

N400 response - compared between MEG and EEG



axial magnetic field

potential distribution

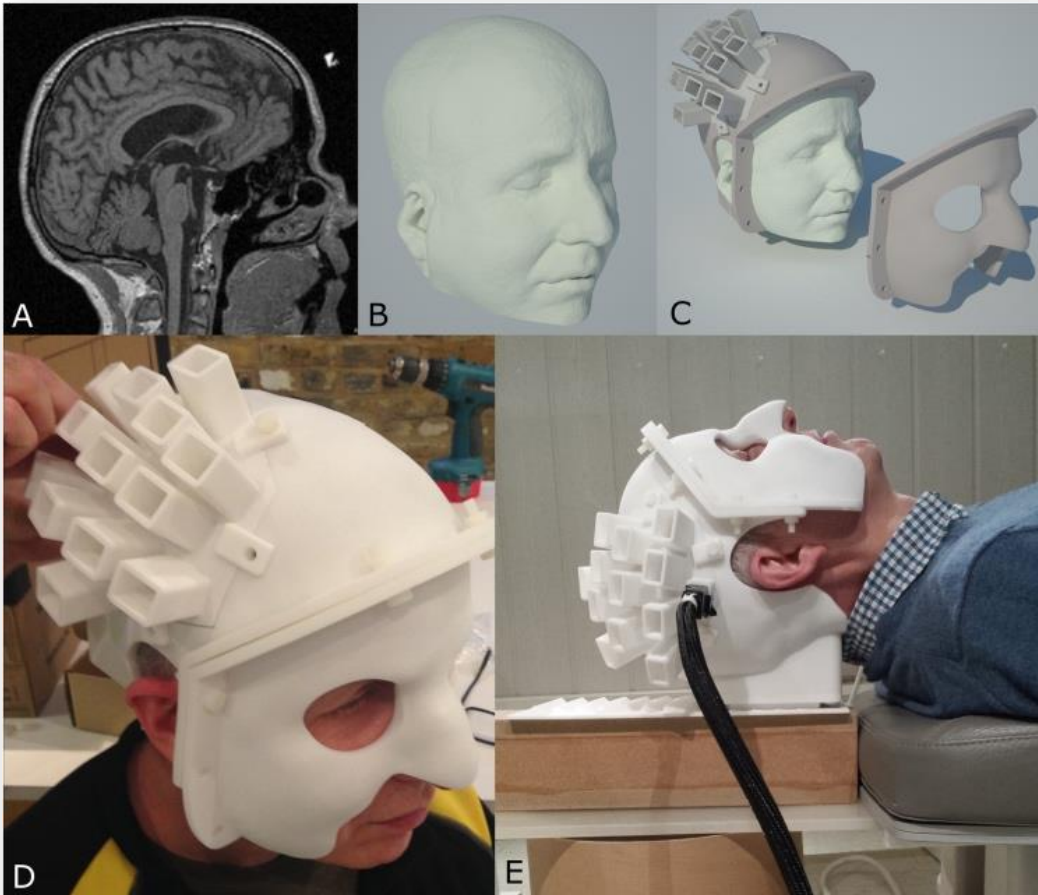
Optically Pumped Magnetometers

LETTER

doi:10.1038/nature26147

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^{3,6}, Gareth R. Barnes³, Richard Bowtell¹ & Matthew J. Brookes¹

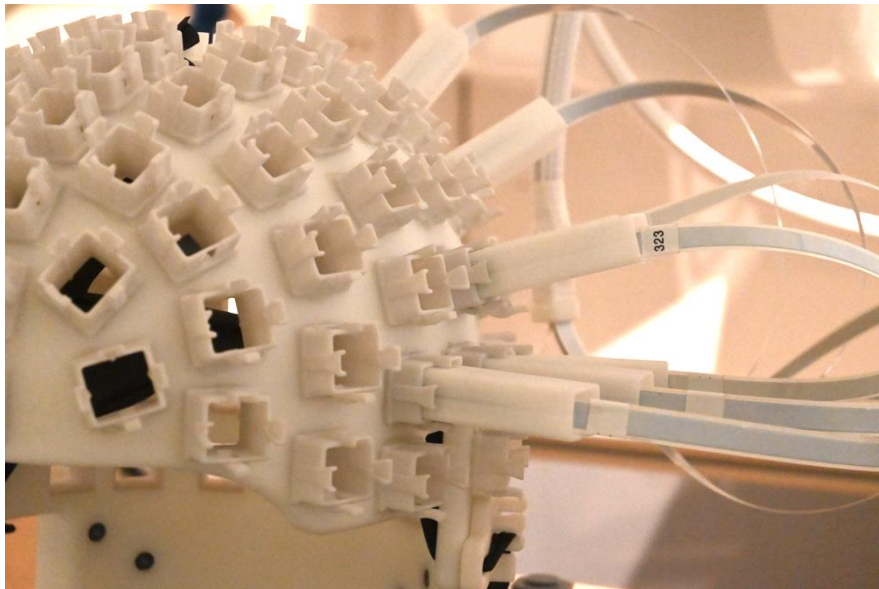
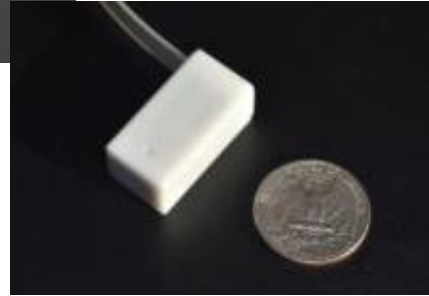


Boto, Barnes, Brookes, et al. (2017) Neuroimage



Boto, Barnes, Brookes, et al. (2018), Nature

FieldLine OPM system in Stockholm



Cercamagnetics OPM system installed in Cardiff



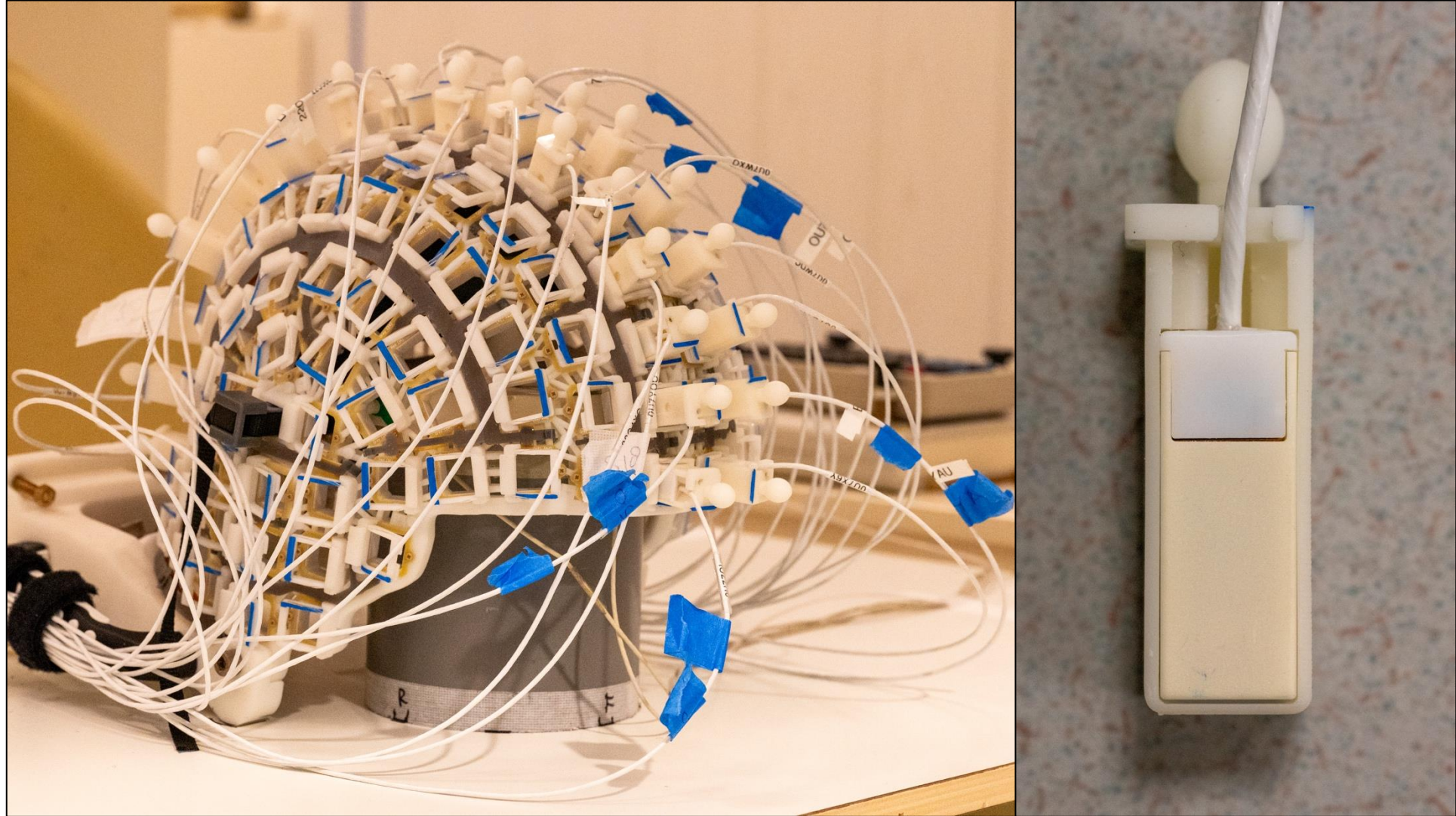
Different Optically Pumped Magnetometers (OPMs)



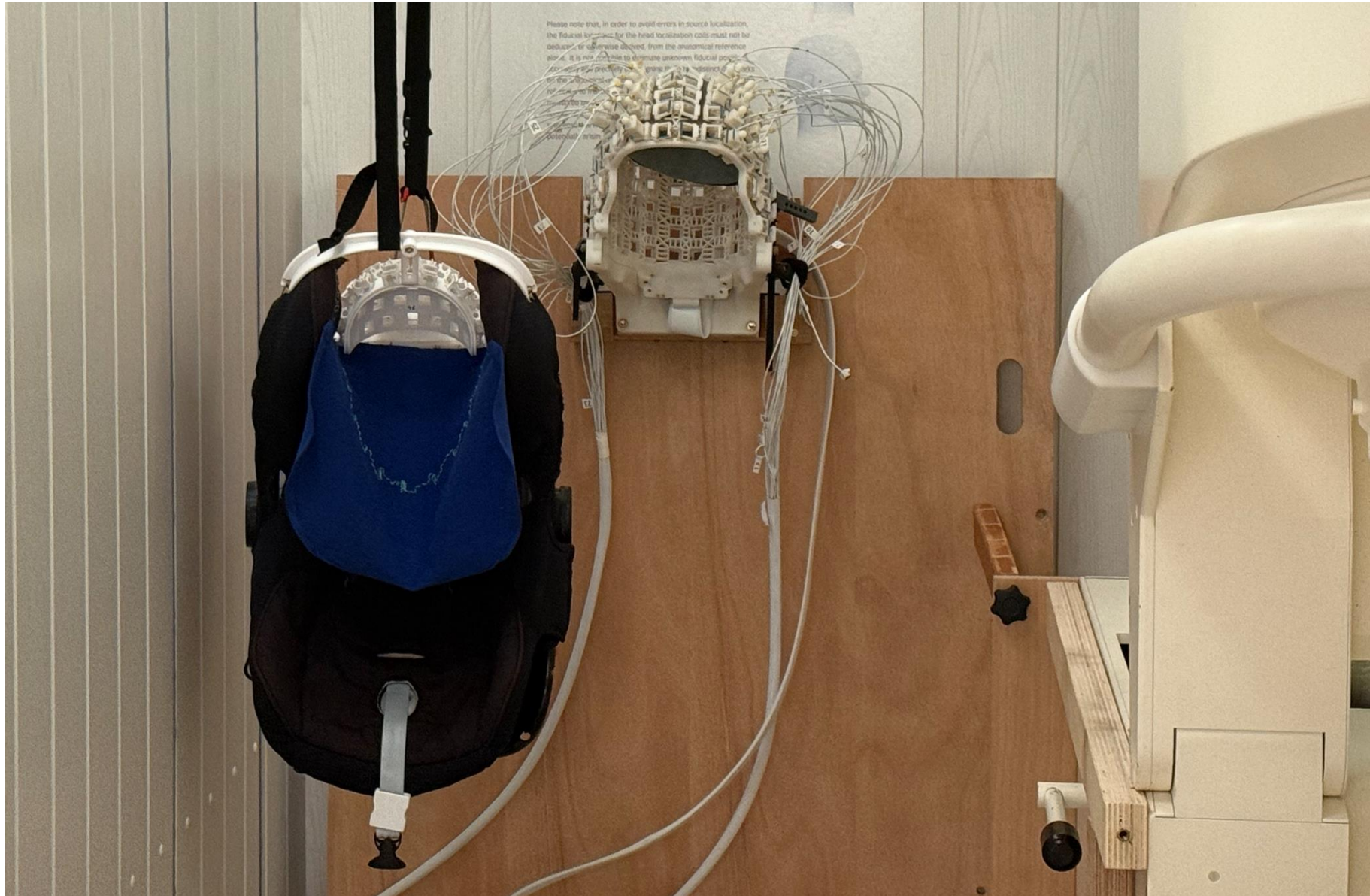
32 sensor FieldLine system installed at DCCN



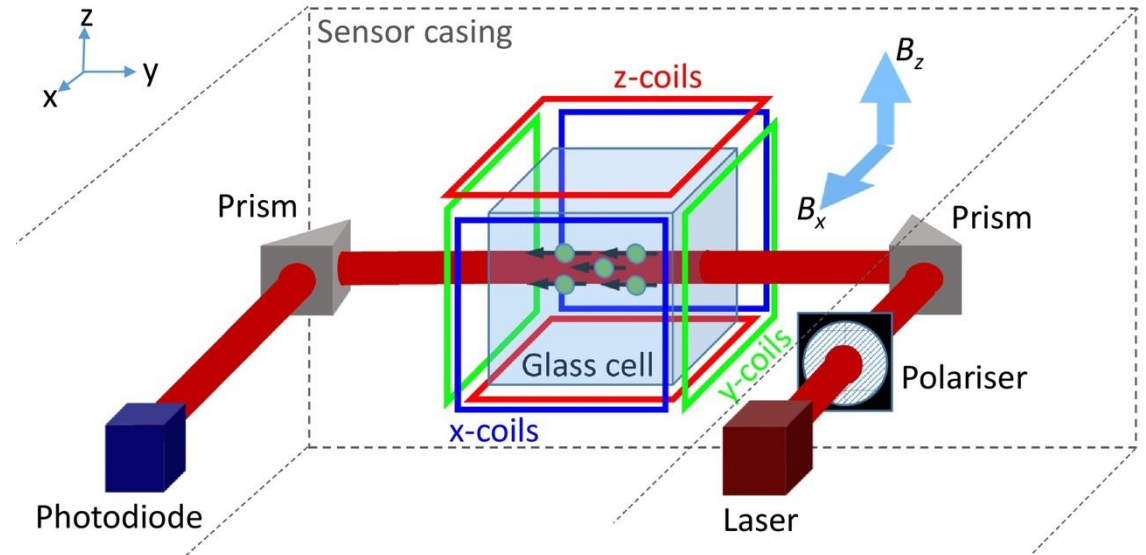
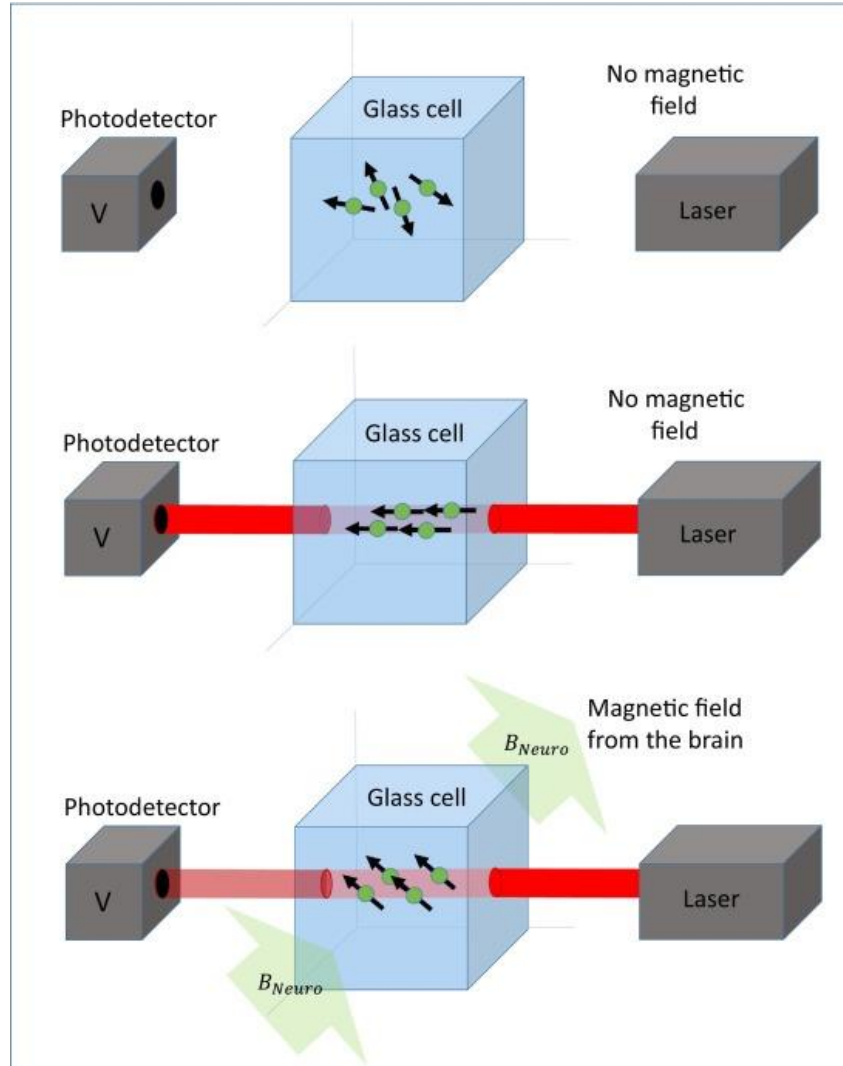
FieldLine "Smart Helmet"



Baby and adult OPM systems



How do Optically Pumped Magnetometers (OPMs) work?



OPMs versus SQUIDs - advantages

No Helium, hence lower operational costs

Closer to the scalp and smaller spacing

Higher spatial resolution

Flexible sensor placement

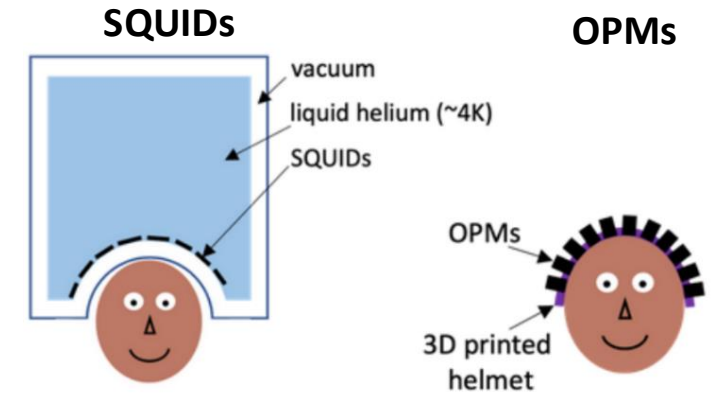
- Wearable helmets for head-free recordings

- Can be adapted to infants/children

- Custom helmets provide tight fit, no head-to-helmet movements

- Custom helmets can be combined with TUS transducer or VR headset

- Sensors can be distributed over multiple “helmets” for hyperscanning



OPMs versus SQUIDs - disadvantages

Limited operating range, from ± 5 nT up to ± 150 nT

Limited bandwidth, from 1-100 up to 1-300 Hz

More noise than SQUIDs: 15 fT/sqrt(Hz) compared to 7 fT/sqrt(Hz)

Not really room temperature, except for the He4 ones

Fragile due to glass cell and limited life-span due to overheated laser

Separate sensors rather than fixed array requires sensor positioning system

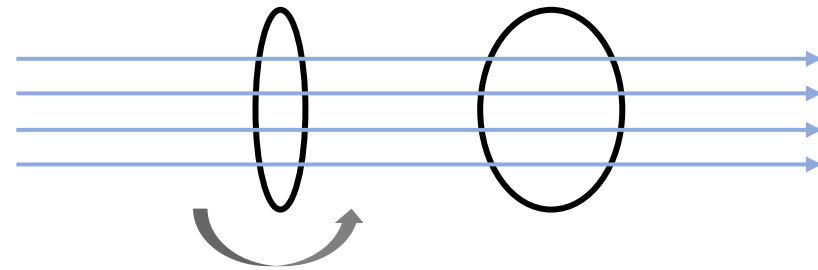
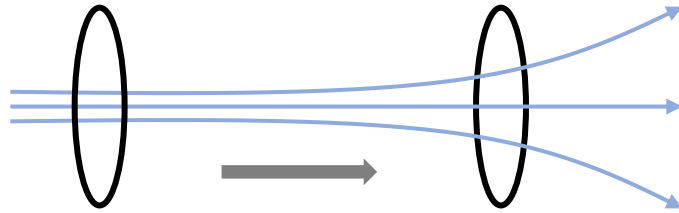
Imprecise hardware calibration/fabrication

Swapping between helmets is time consuming

Cables are cumbersome

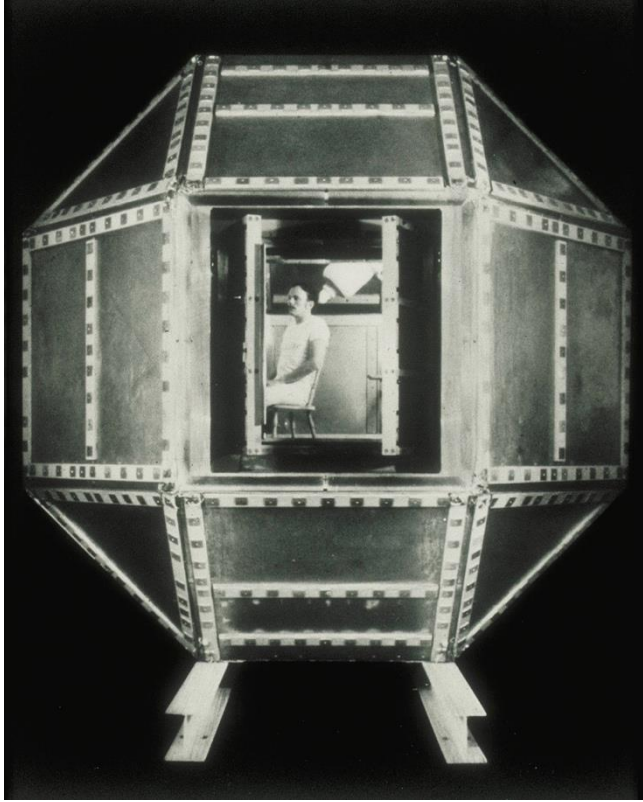
Magnetometers, so they see all the noise

OPM movements pick up residual magnetic fields and gradients

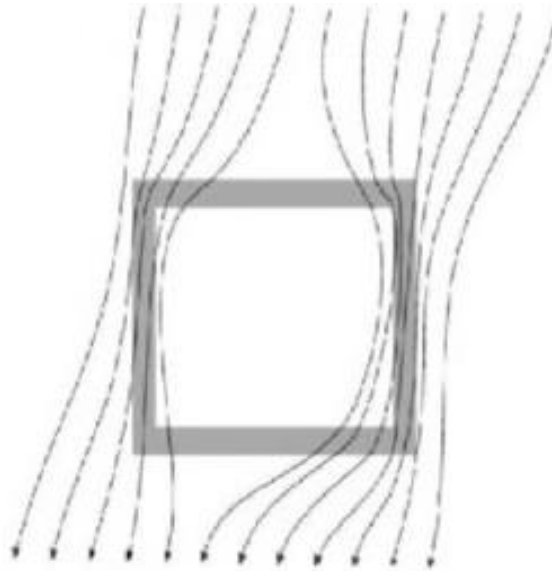


Magnetically shielded room (MSR)

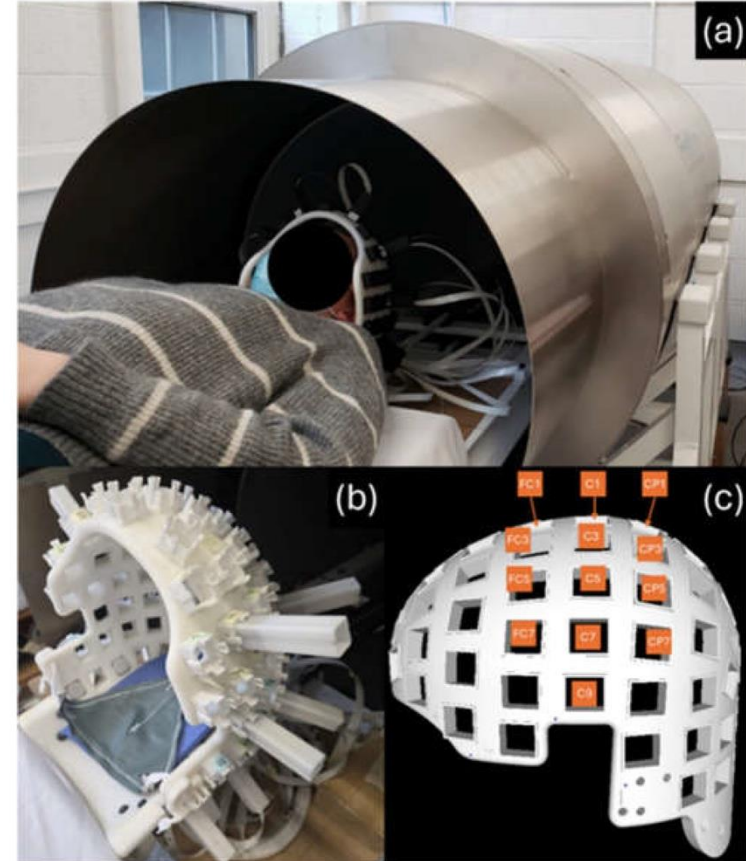
these had to be large for SQUID systems



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



OPMs allow for small person-sized magnetic shields
at a fraction of the weight and cost



Mapping out the residual field in our MSR

Outside

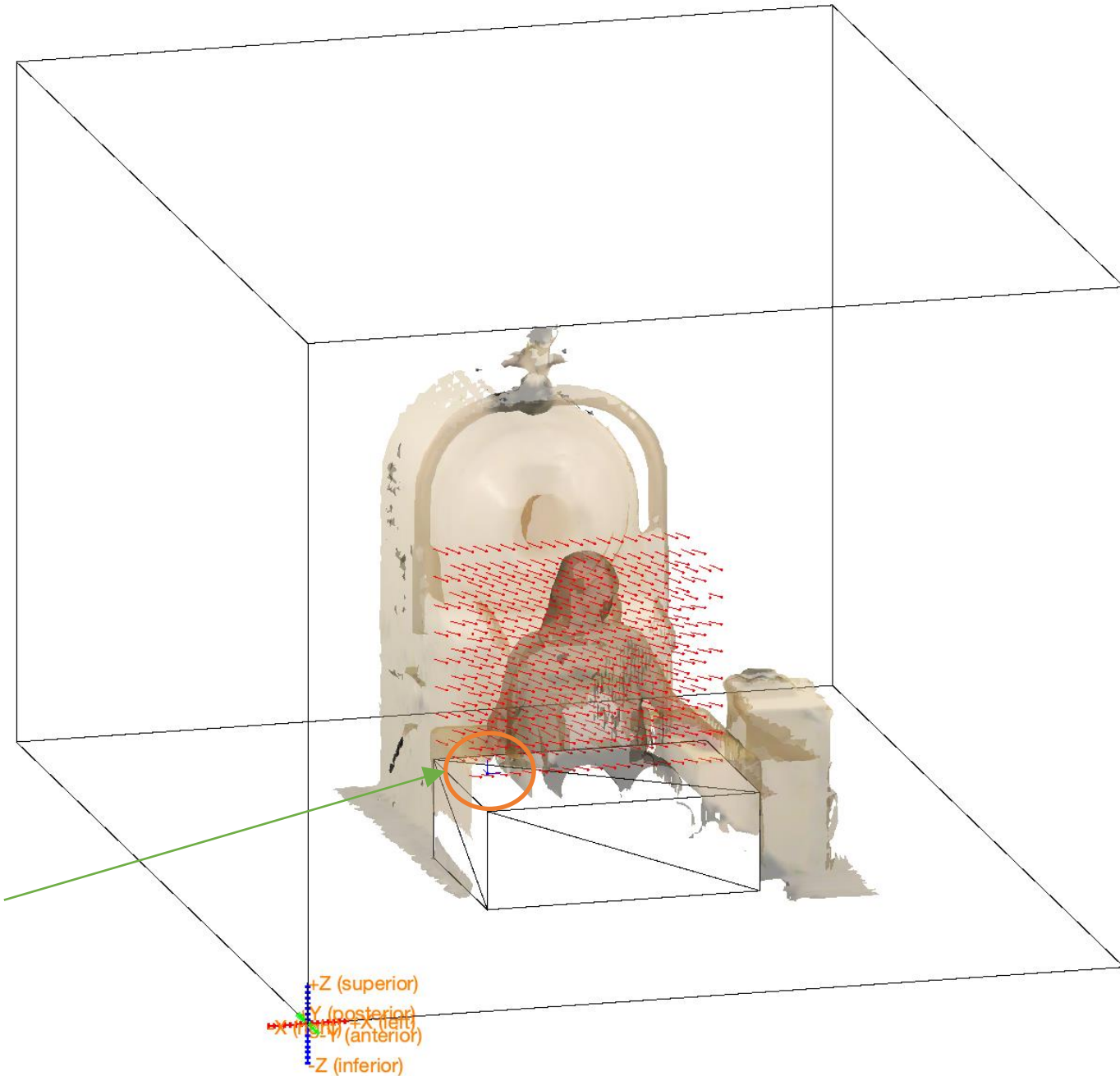
50 μT

50 000 nT

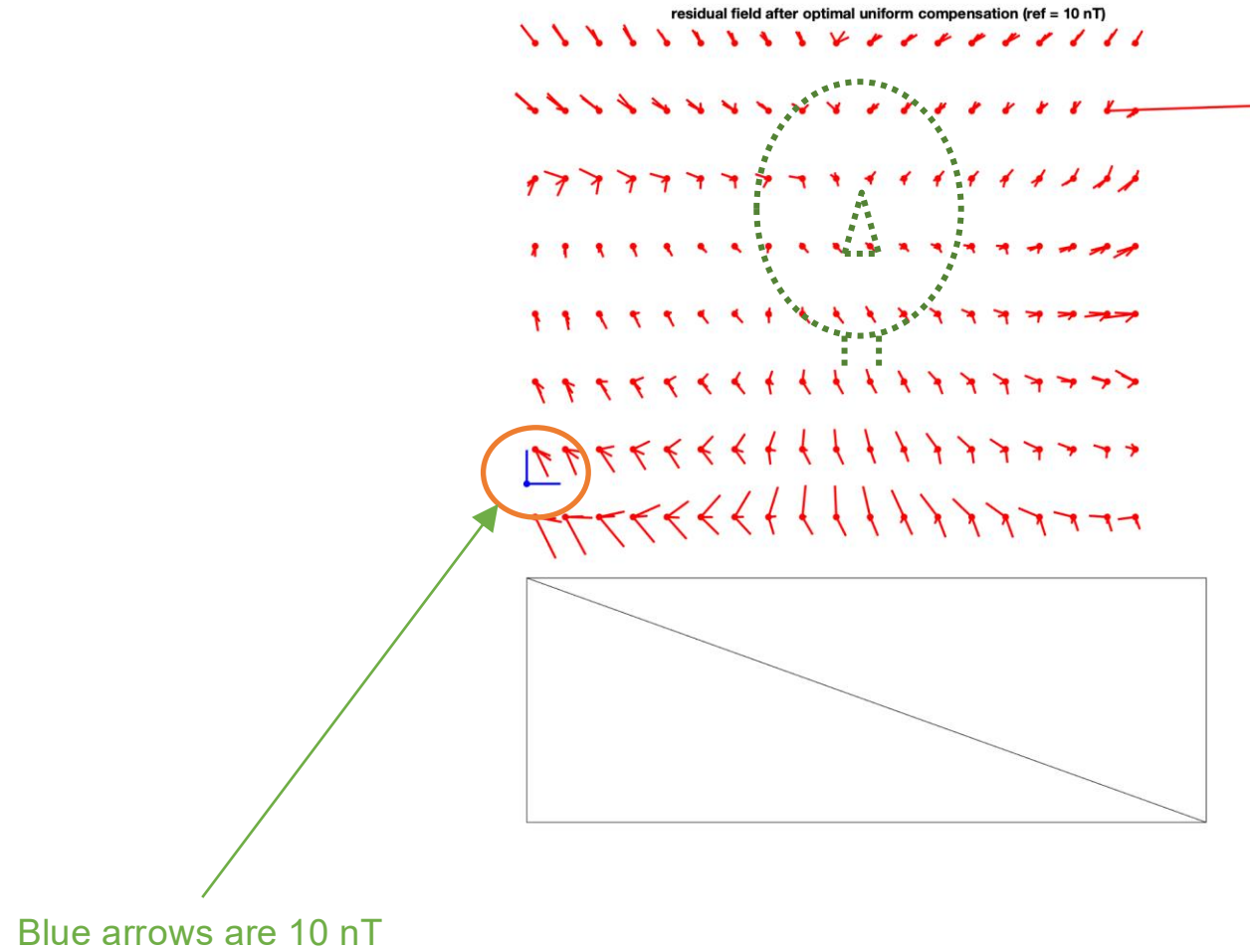
Inside

50-60 nT

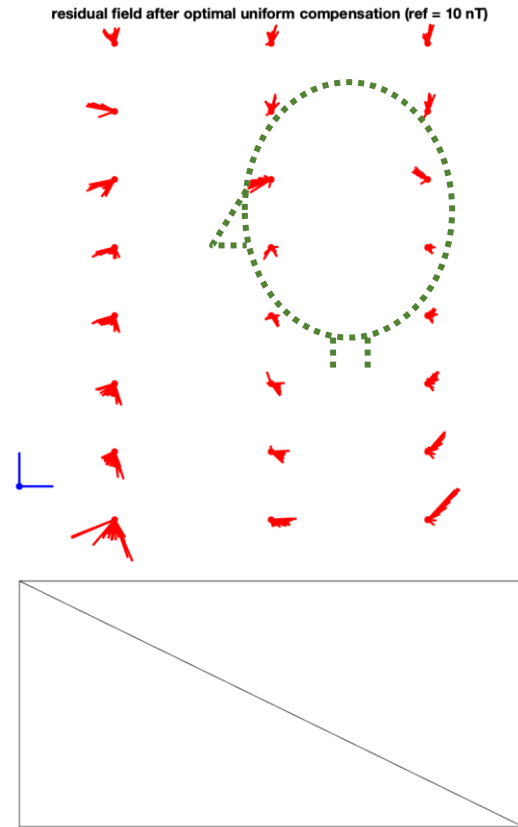
Blue arrows are 50 nT



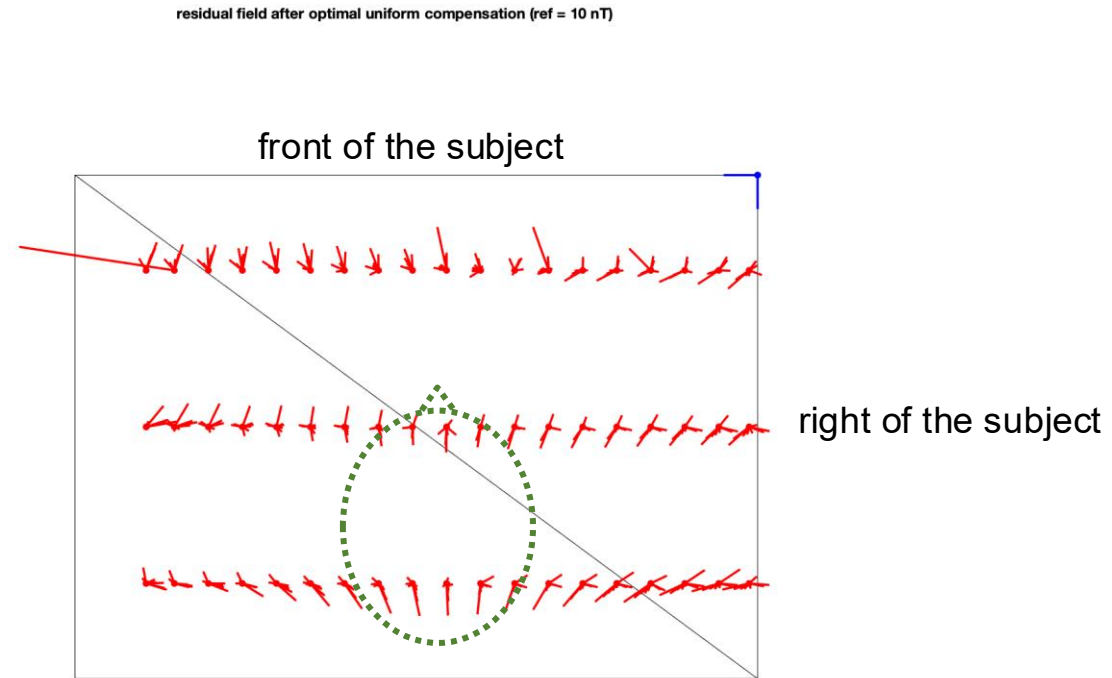
Residual gradient – seen from front



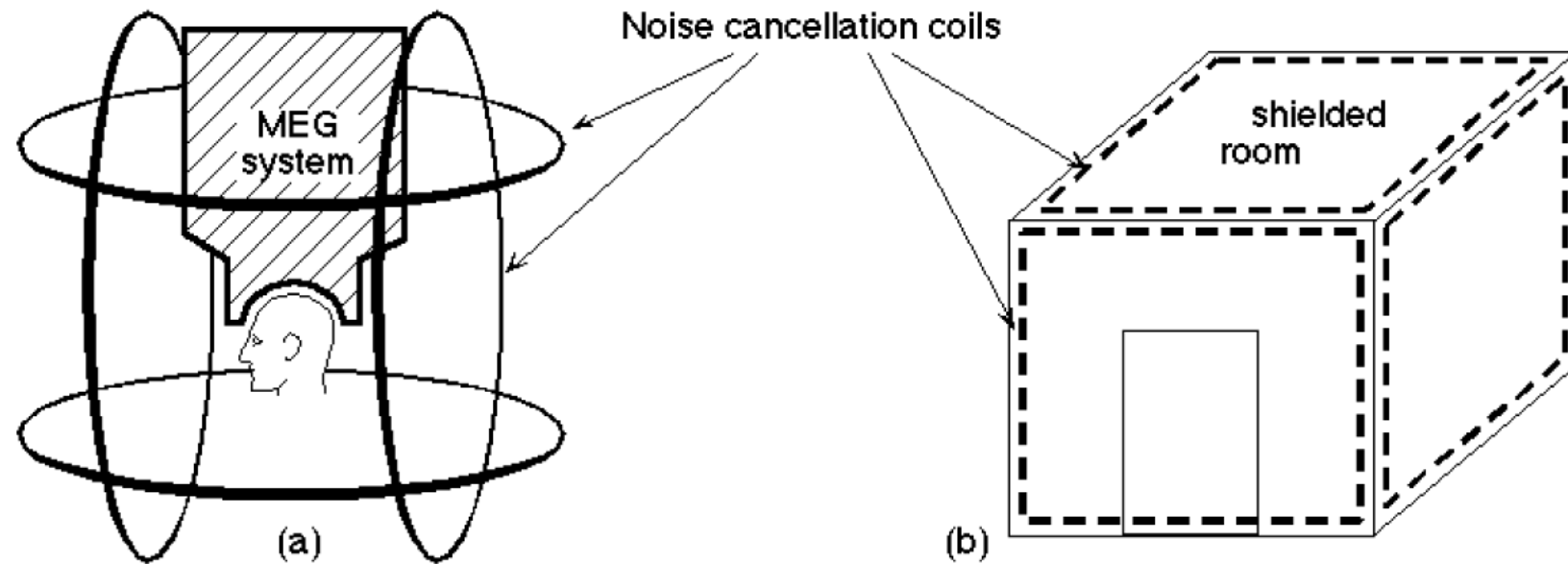
Residual gradient – seen from left



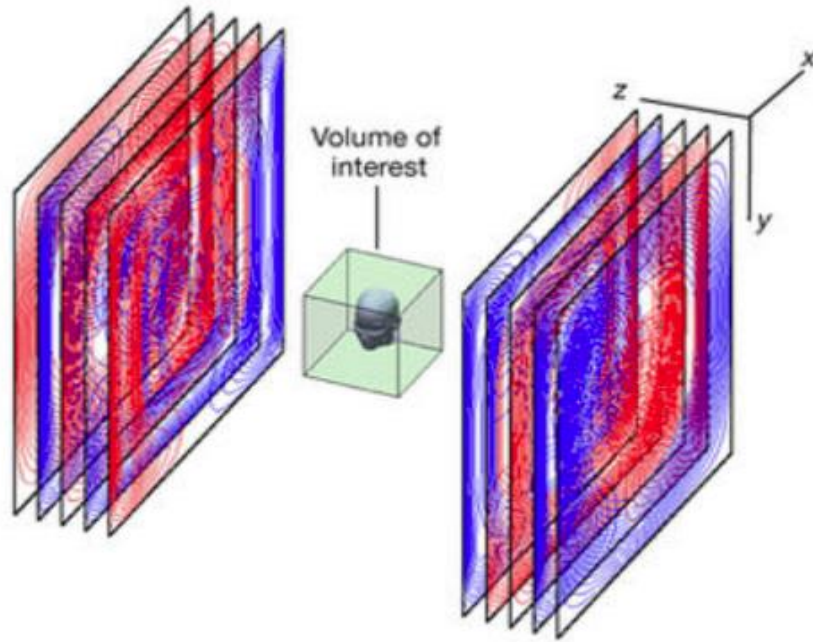
Residual gradient – seen from top



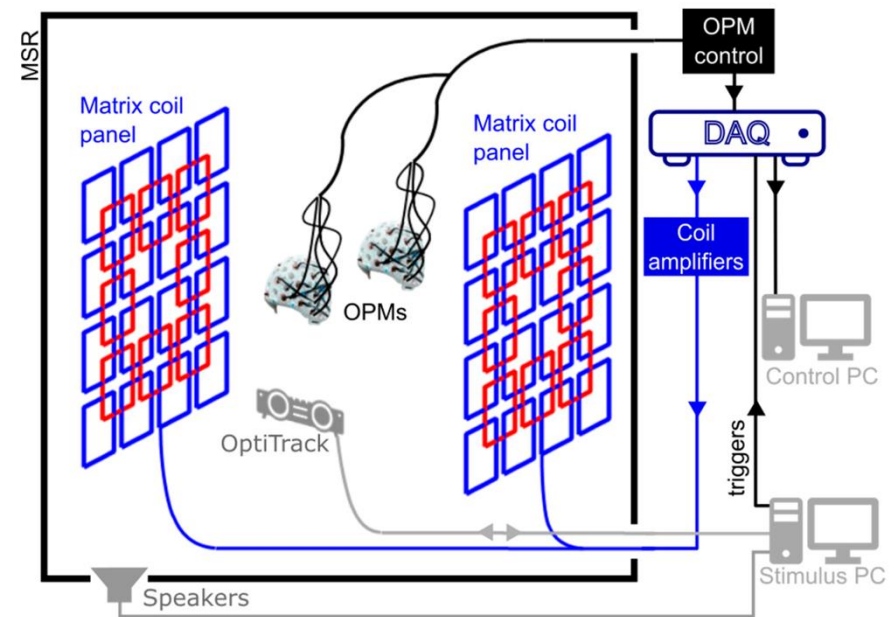
Shielding - active



Ambient field nulling coils



Bi-planar coils



Matrix coils

Simple Helmholtz-style coils in our MSR



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How do we record those signals

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Background on the FieldTrip toolbox

M/EEG signal characteristics considered during analysis

timecourse of activity

-> ERP

spectral characteristics

-> power spectrum

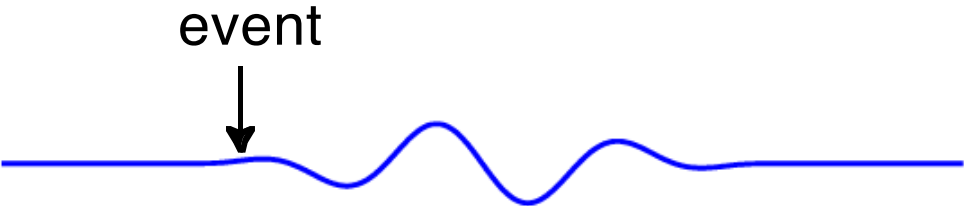
temporal changes in power

-> time-frequency response (TFR)

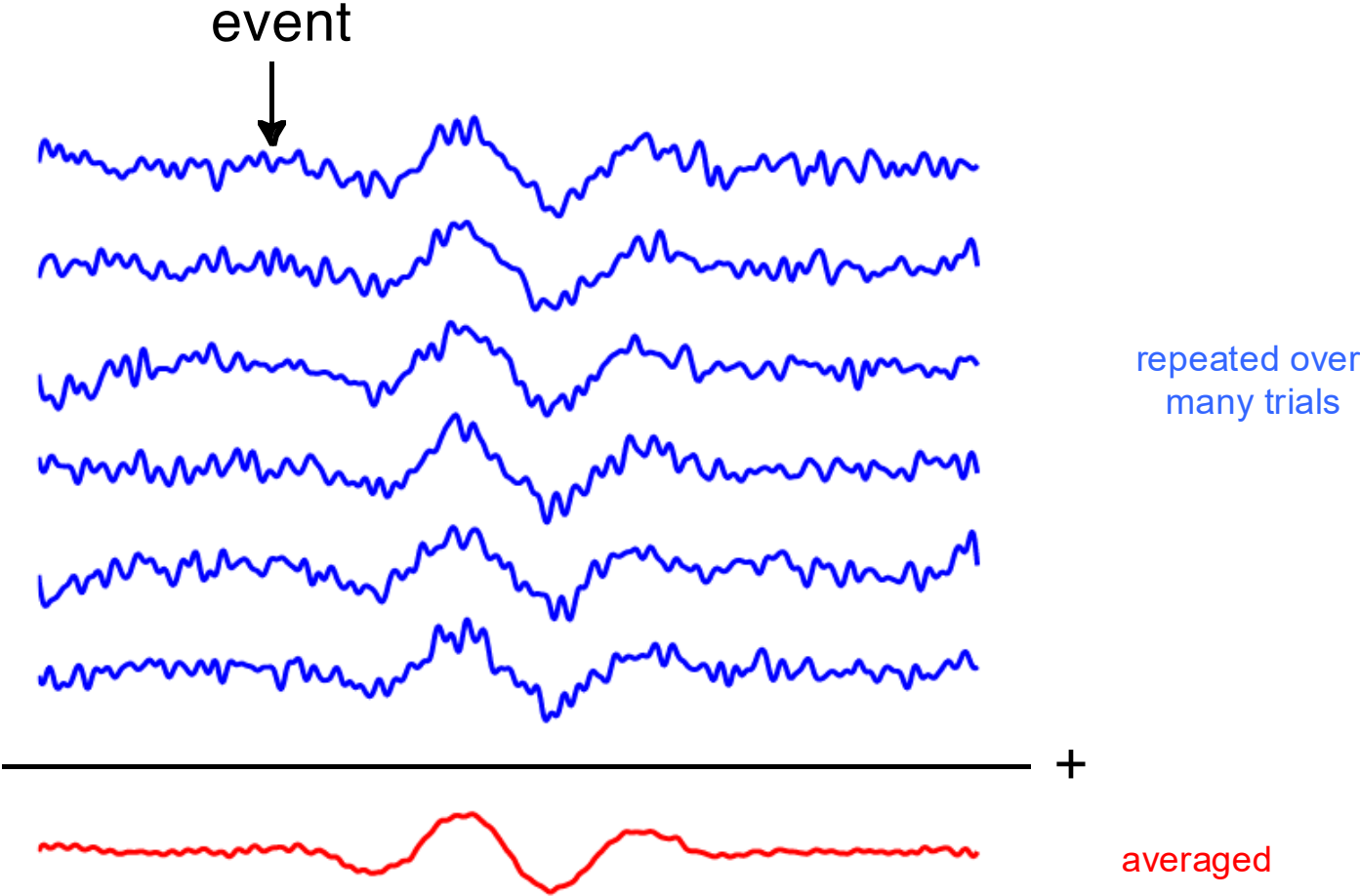
spatial distribution of activity over the head

-> source reconstruction

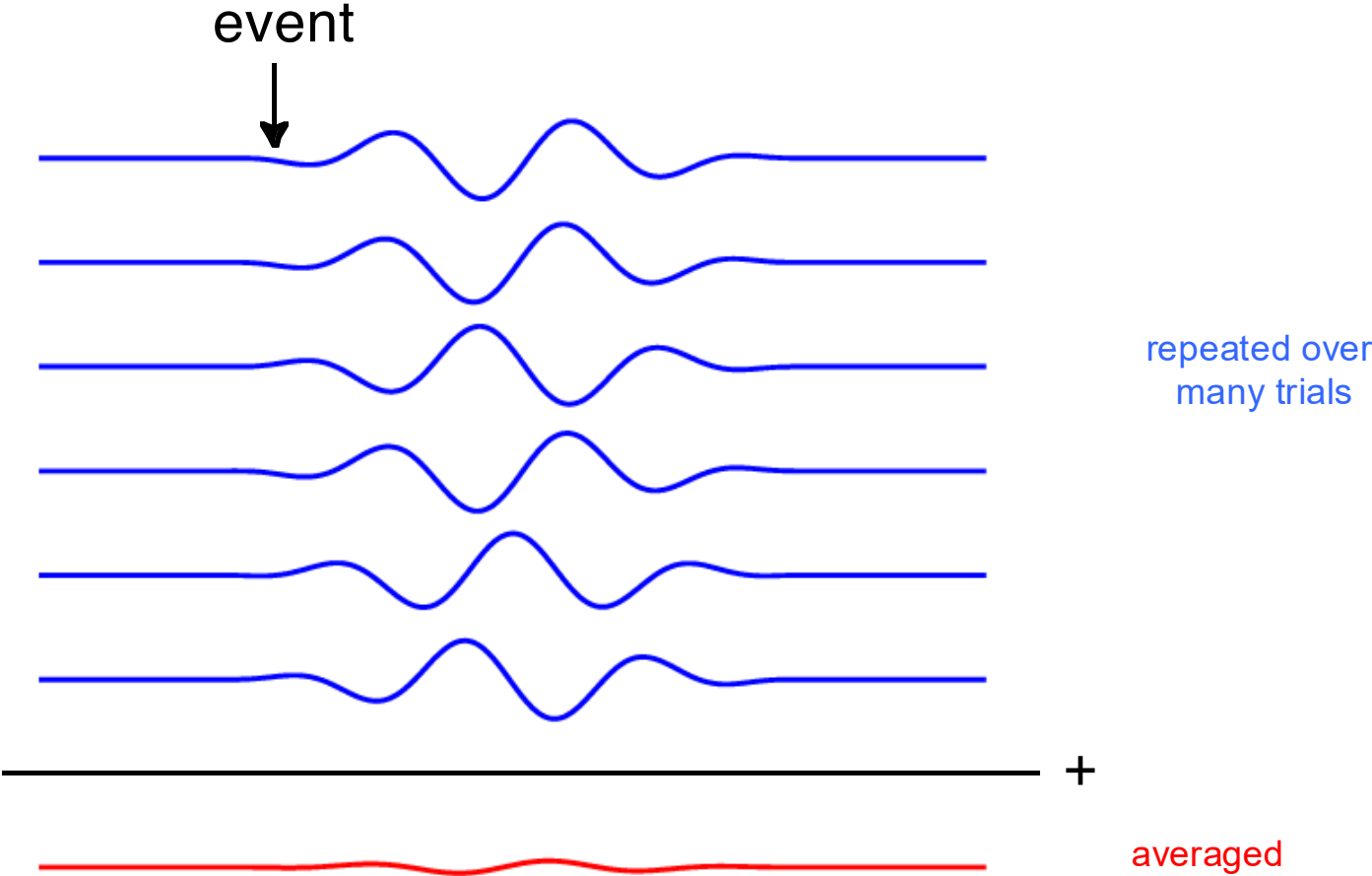
Evoked activity



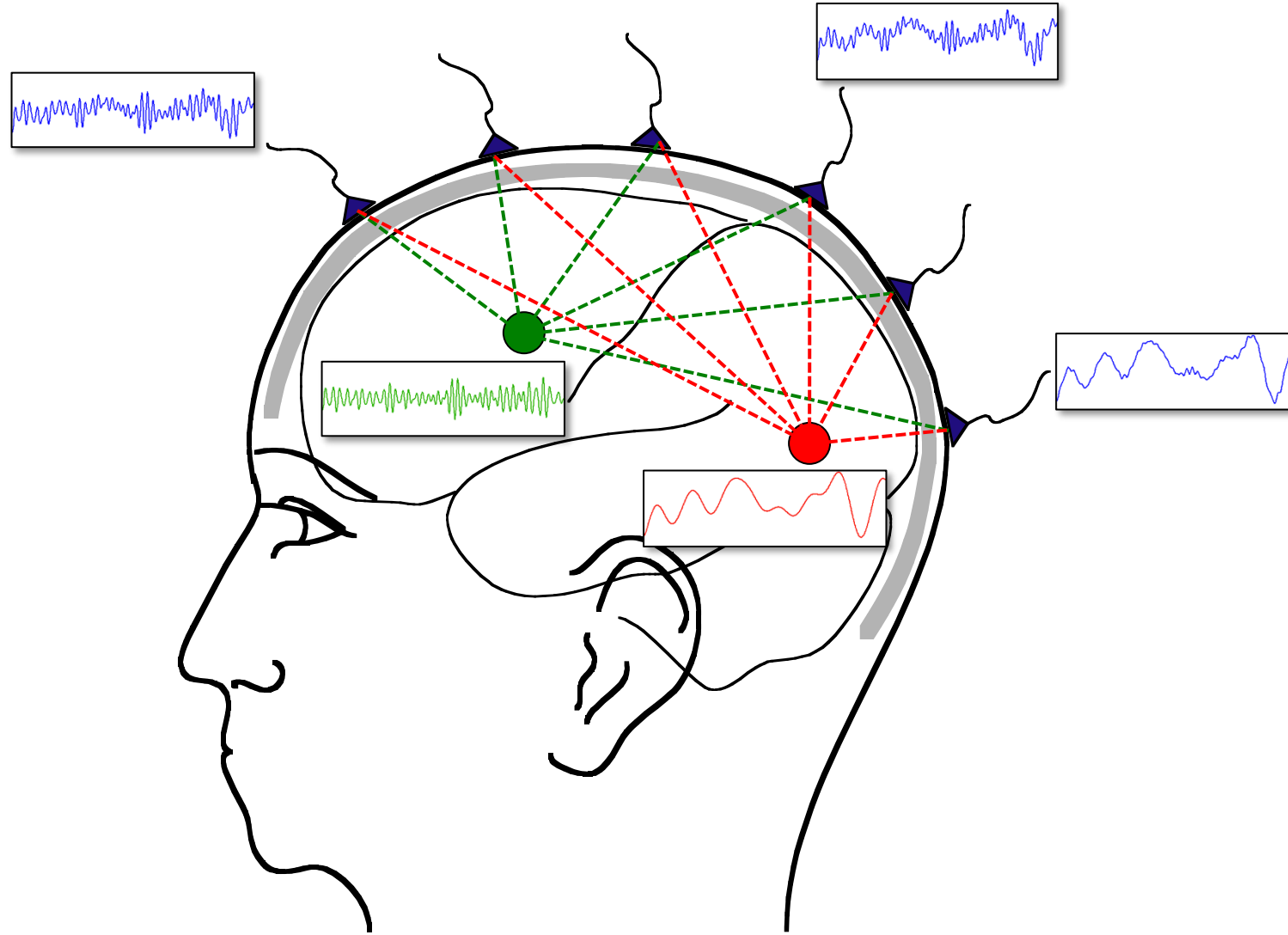
Evoked activity



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(cfg, datain
```

```
dataout = functionname(
```



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

```
cfg.channel = {'C3', 'C4', 'F3', 'F4'}  
cfg.foylim = [1 70]
```

FieldTrip v.s. default Matlab

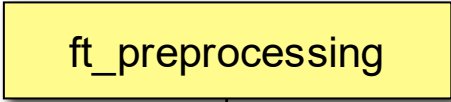
```
dataout = functionname(cfg, datain, ...)
```

```
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)
```

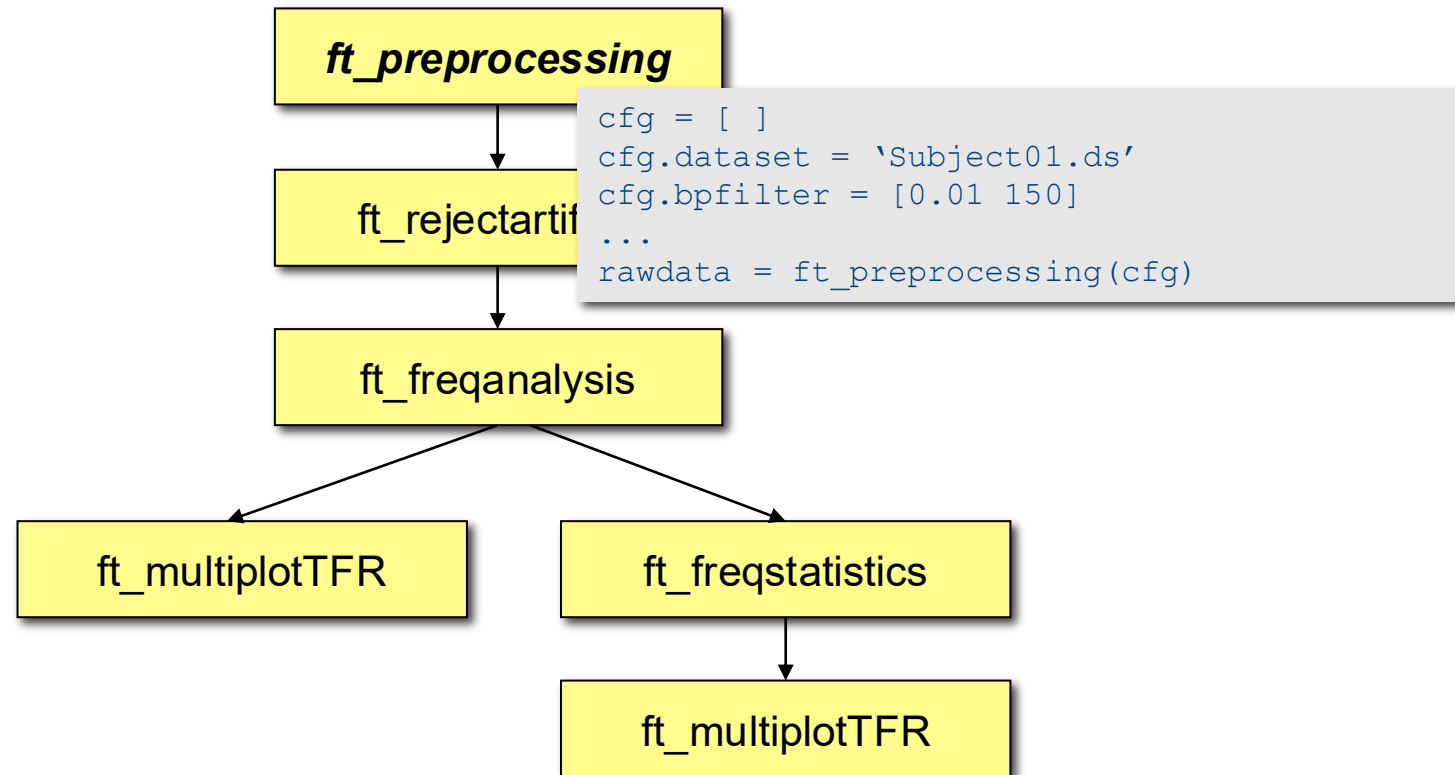
or

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

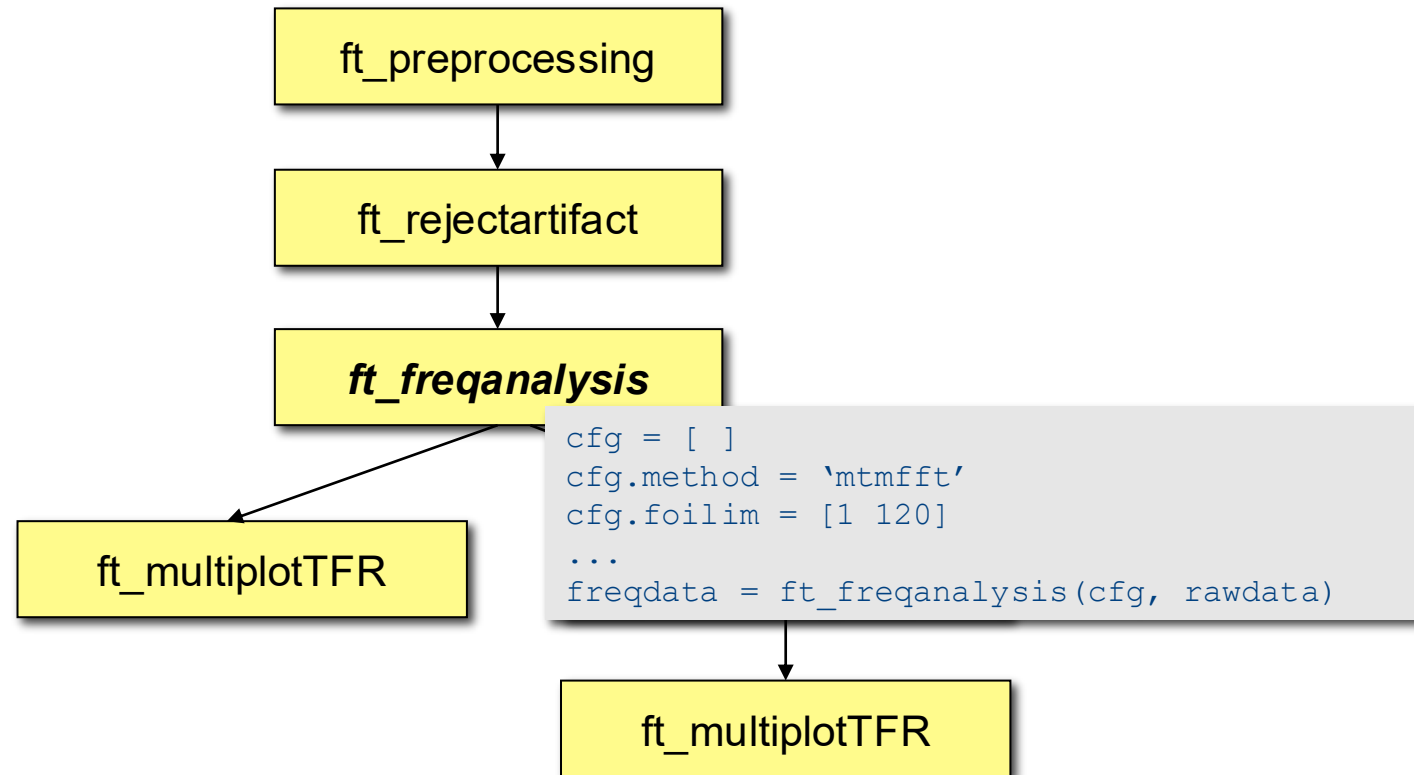
The first input argument "cfg" is the configuration structure, which contains all details for the dataset filenames, trials and the preprocessing options. You can only do preprocessing after defining the segments of data to be read from the file (i.e. the trials), which is for example done based on the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

...

Using functions in an analysis protocol



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

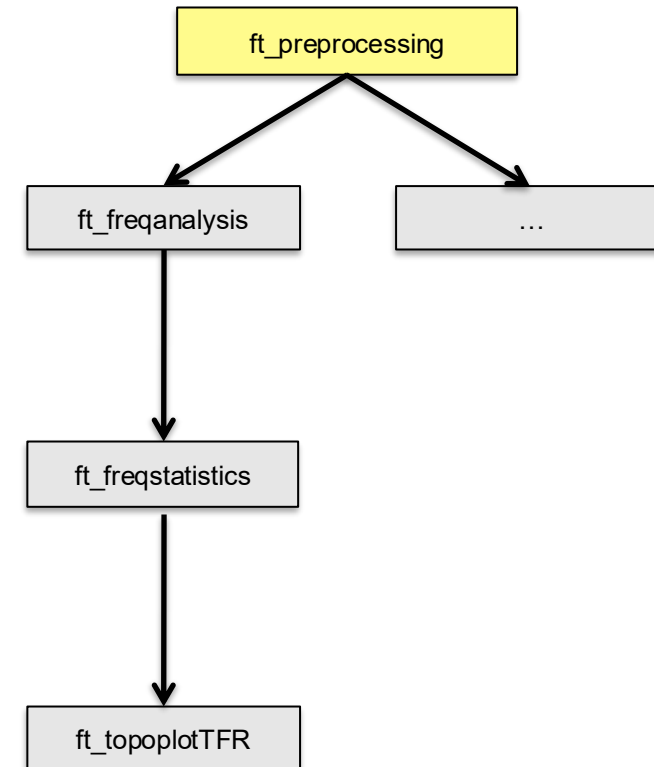
```
timelockData =  
    label: {151x1 cell}  
    avg: [151x900 double]  
    var: [151x900 double]  
    time: [1x900 double]  
dimord: 'chan_time'  
    cfg: [1x1 struct]
```

Example use in scripts

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

```
cfg = []  
cfg.method = 'mtmfft'  
cfg.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)
```

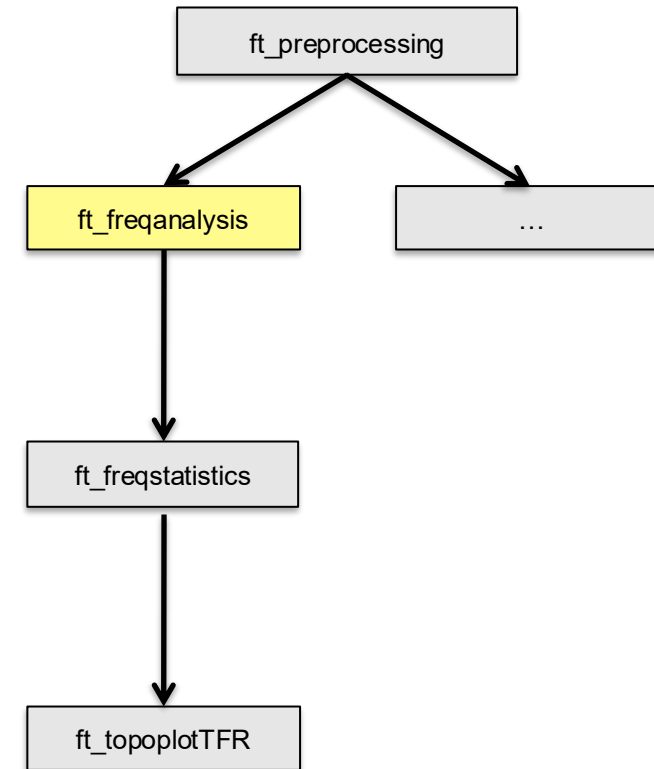


Example use in scripts

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

```
cfg = []
cfg.method = 'mtmfft'
cfg.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)
```

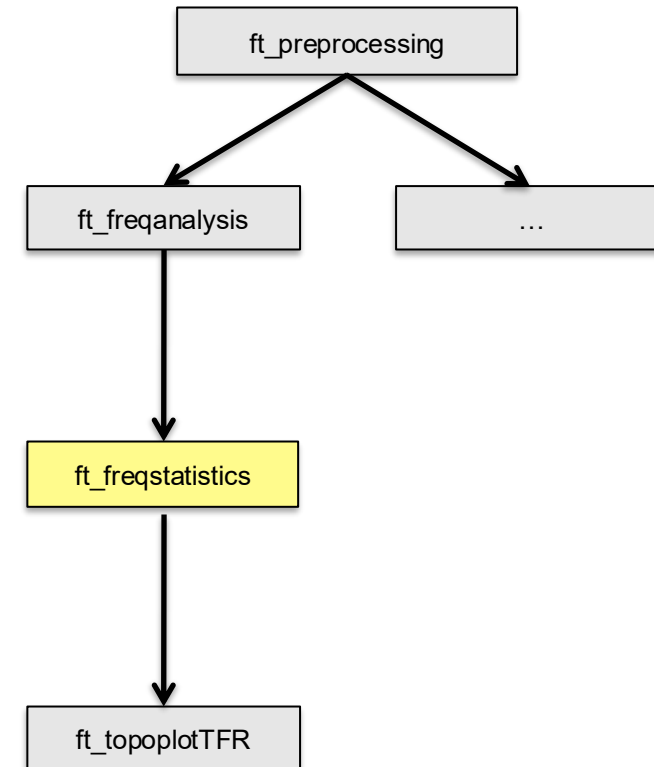


Example use in scripts

```
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)
```

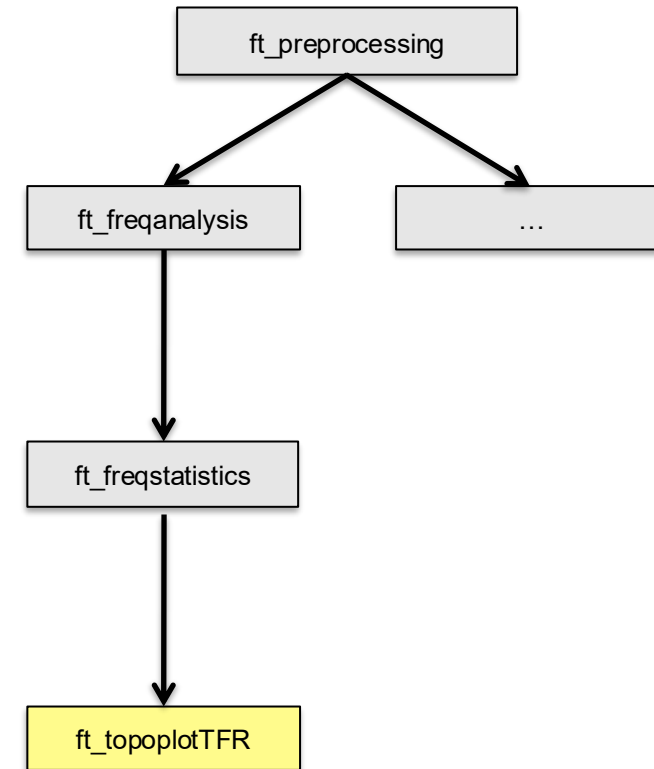


Example use in scripts

```
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)
```

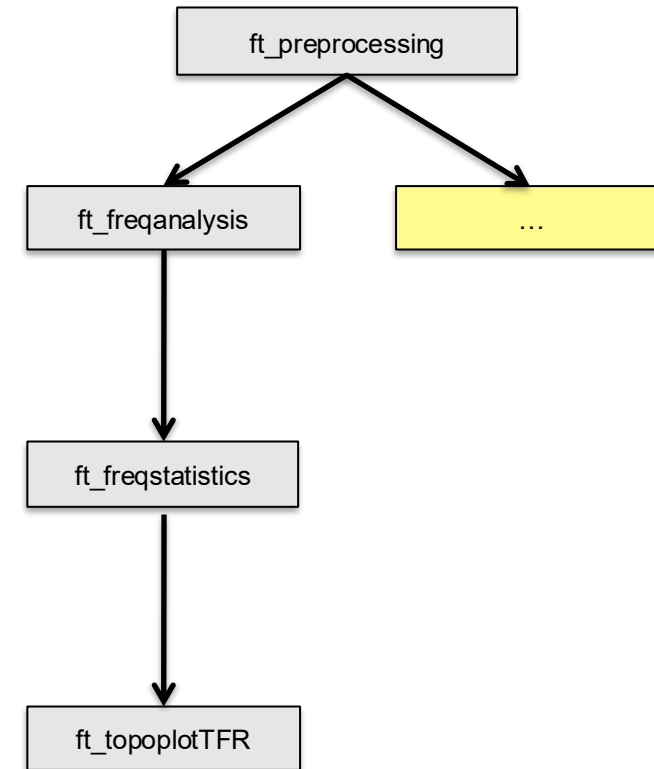


Example use in scripts

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

```
cfg = []  
cfg.method = 'mtmfft'  
cfg.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

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

for s=1:nsbj
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:nsbj
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 lab and among your peers



Radboud University



Introduction to MEG and OPM analysis with the FieldTrip toolbox

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