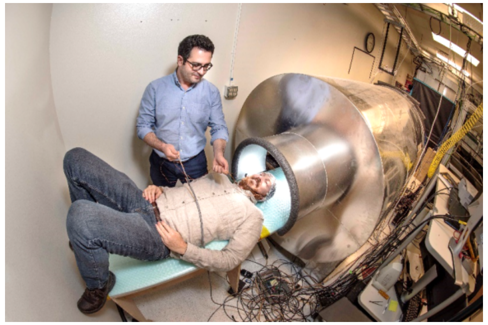
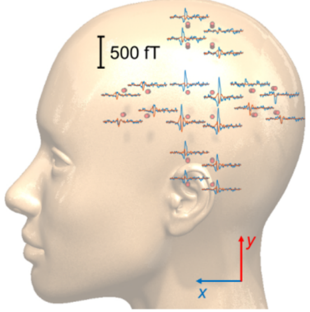
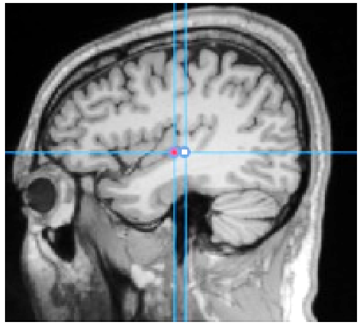
SAND2021-8019C

Sandia National Laboratories

Moving Closer to the Brain: Introduction to On-Scalp Magnetoencephalography







Peter D. D. Schwindt

Society for Brain Mapping and Therapeutics

2021

Outline

Magnetoencephalography

- What it is?
- What is it good for?

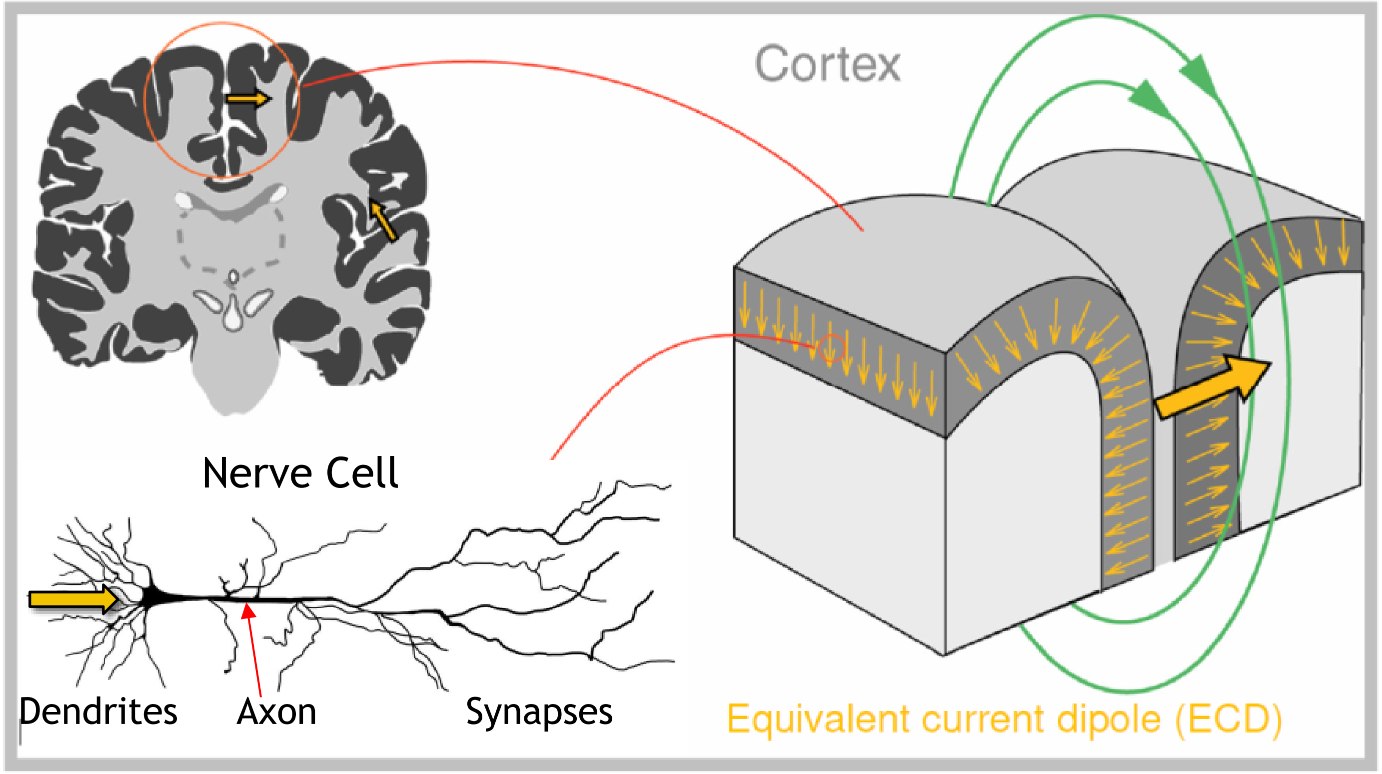
Next generation sensors

- Optically pumped magnetometers
- High T_C SQUID magnetometers

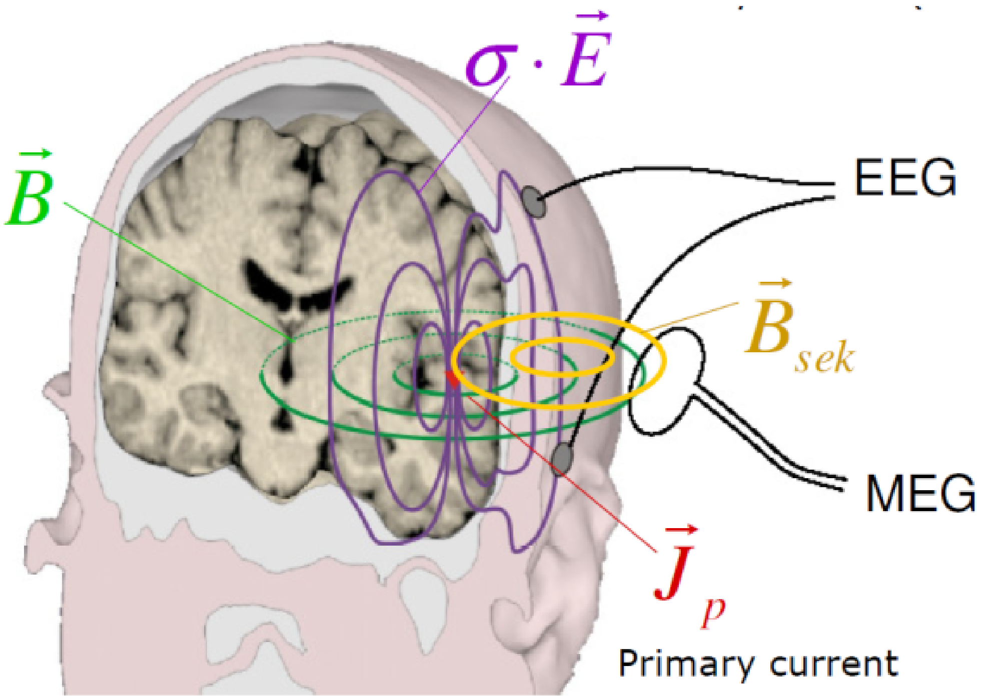
Measuring closer to the brain

- Primary advantages
- New applications

Magnetoencephalography (MEG)



B. Maess, MPI for Human Cognitive and Brain Sciences



Lauri Parkkonen (Aalto University)

- Postsynaptic currents flowing in the dendrites of the pyramidal neurons constitute the primary current ($\vec{J_p}$).
  - $< 10^{-13}$ T or 100 fT
- Both the primary and return currents contribute to the magnetic field sensed outside the subject's skull.

Traditional MEG System:
Superconducting Quantum Interference Device (SQUID)

MEGIN® TRIUX

CTF cMEG

Tristan MAGViewTM

Mature technology

- Highly sensitive, 2-3 fT/rt-Hz
- High bandwidth
- Whole head coverage (> 300 channels)

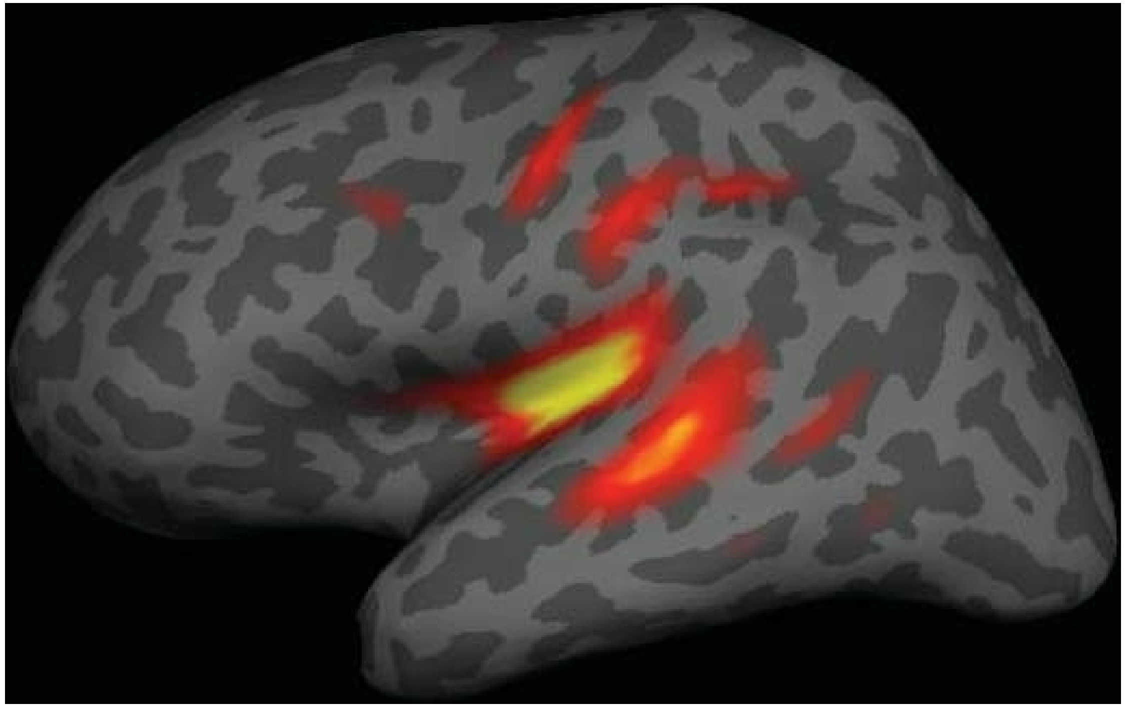
Disadvantages

- Low T_C superconductor: 4 K
- Helium is expensive, sources unreliable

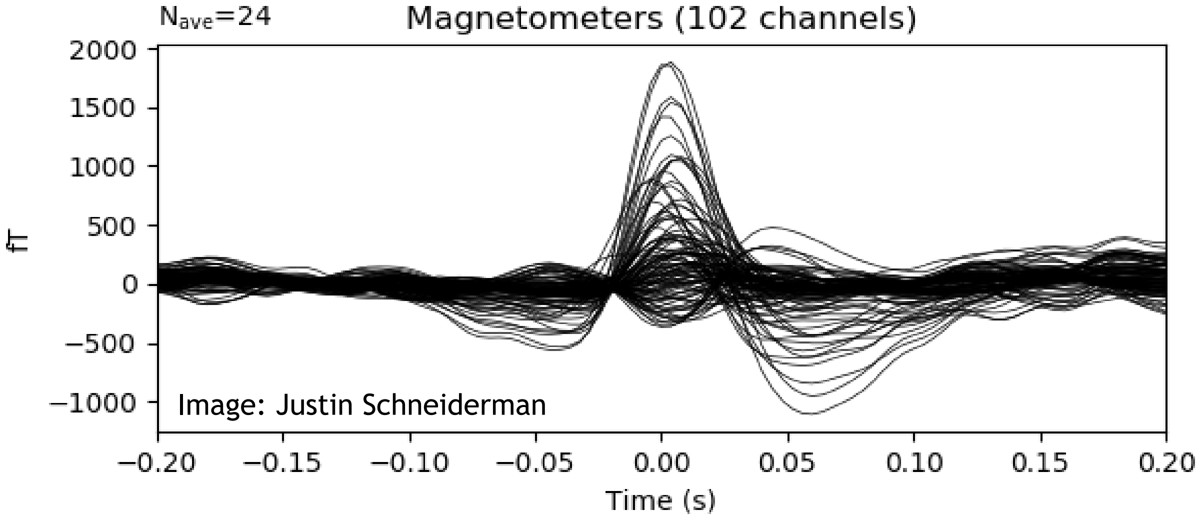
[1] Rainer Körber et al, "SQUIDs in biomagnetism: A roadmap towards improved healthcare," *in* Superconductor Science and Technology 29(11):113001, DOI: 10.1088/0953-2048/29/11/113001

What is it good for?

- Understand spatial/temporal brain function.
- Study psychological/neurological disorders.
- Localize a pathology (e.g. epilepsy).



Epileptic Waveforms



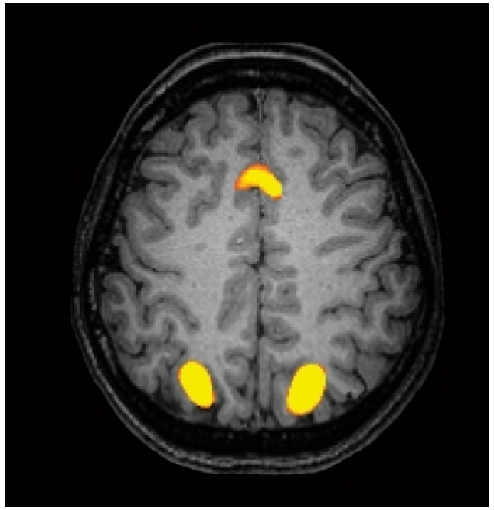
Medical Use of MEG

MEG can be used to diagnose conditions manifesting in *brain transient response*

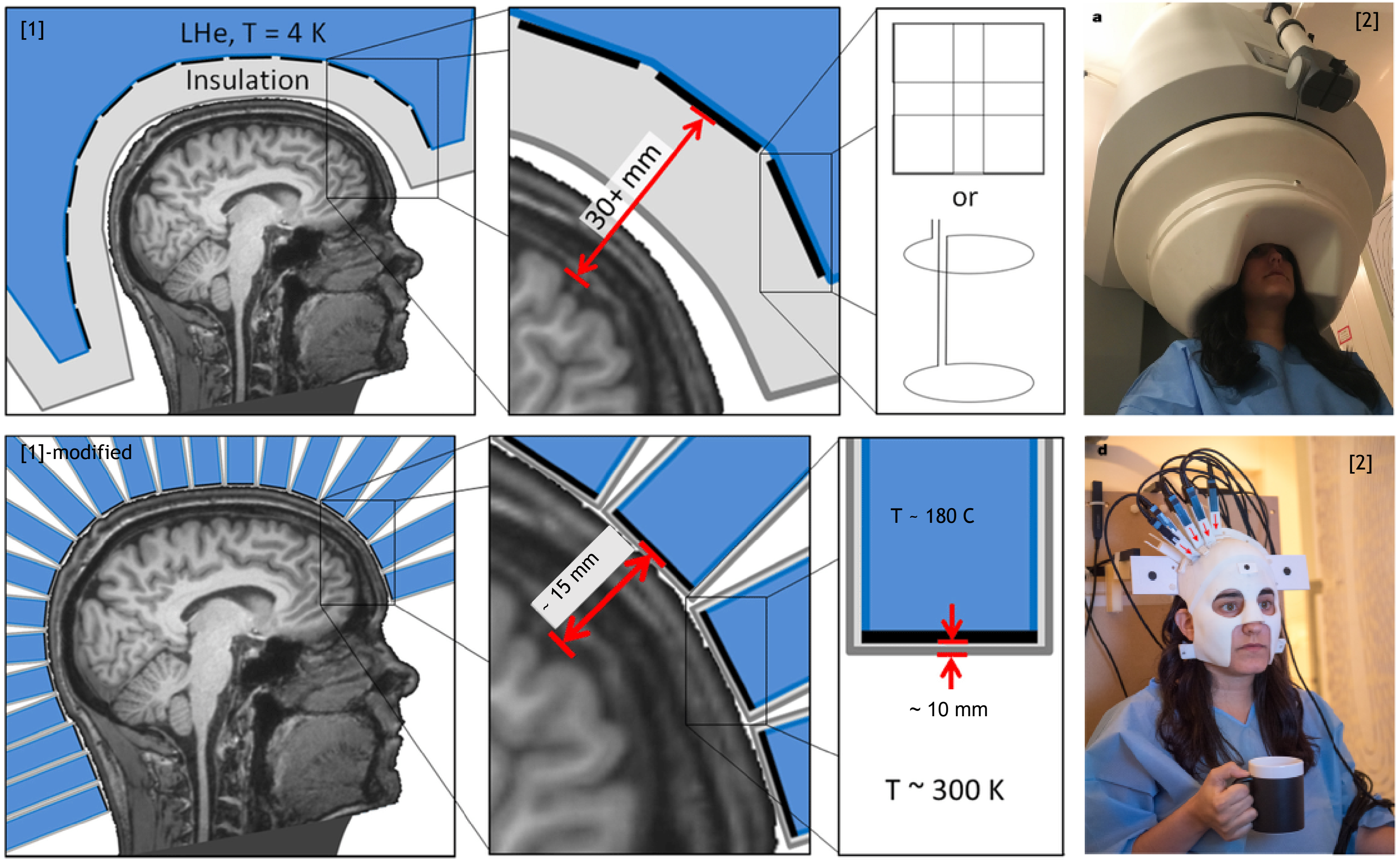
- **Pre-surgically locate the sources of epileptic seizures**
- **Presurgical Functional Mapping**
- Diagnose concussions
- Diagnose Traumatic Brain Injuries
- Post-traumatic Stress Disorder
- Schizophrenia
- Aging
- Alzheimer's Disease
- Attention Deficit and Hyperactivity Disorder
- Autism Spectrum Disorders
- Depression
- Dyslexia
- Migraine
- Multiple Sclerosis
- Neoplasms
- Pain
- Parkinson's Disease
- Stroke
- Tinnitus

MEG offers excellent spatial and temporal resolution.

	EEG	MEG	fMRI
Spatial Resolution	Poor (~cm)	Great (~mm)	Great (~mm)
Temporal Resolution	Great (~ms)	Great (~ms)	Poor (~s)
Cost	Low	High, but new sensors	High, but widespread



Traditional SQUID MEG vs. On-Scalp MEG



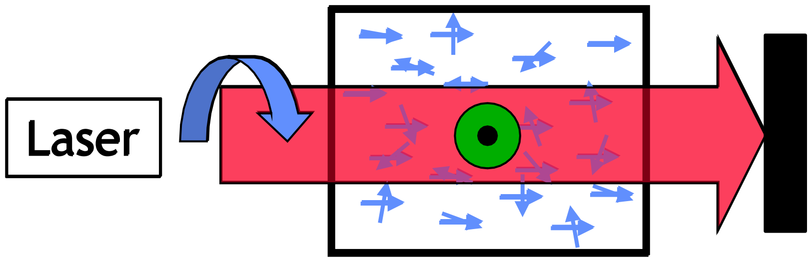
- SQUIDs require liquid He (4 K).
- Rigid helmet manufactured to fit 95% adult male subject's head size.
- Large sensor-source distance
  - Diminished signal
  - Less spatial complexity
- On-scalp MEG enhances spatial resolution
- Potentially wearable systems
- Applications:
  - Neuroscience research
  - Brain Computer Interface (BCI)
  - Clinical, e.g. epilepsy

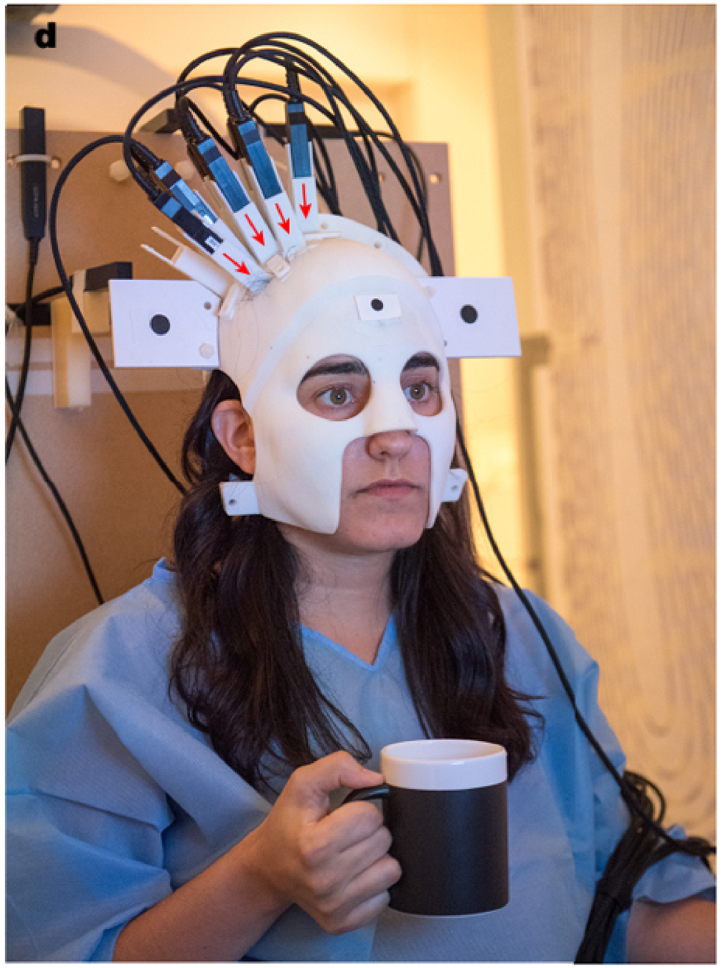
[1] Rainer Körber et al, "SQUIDs in biomagnetism: A roadmap towards improved healthcare," *in* Superconductor Science and Technology 29(11):113001, DOI: 10.1088/0953-2048/29/11/113001

[2] Boto E, Holmes N, Leggett J, Roberts G, Shah V, Meyer SS, et al. Moving magnetoencephalography towards real-world applications with a wearable system. Nature. 2018;555(7698):657.

On-scalp sensors: Optically Pumped Magnetometers

Use (rubidium) atoms to detect the magnetic field





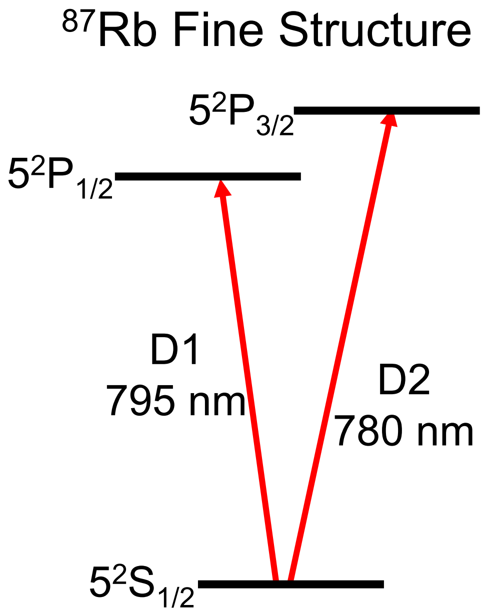
Boto E, Holmes N, Leggett J, Roberts G, Shah V, Meyer SS, et al. Moving magnetoencephalography towards real-world applications with a wearable system. Nature. 2018;555(7698):657.

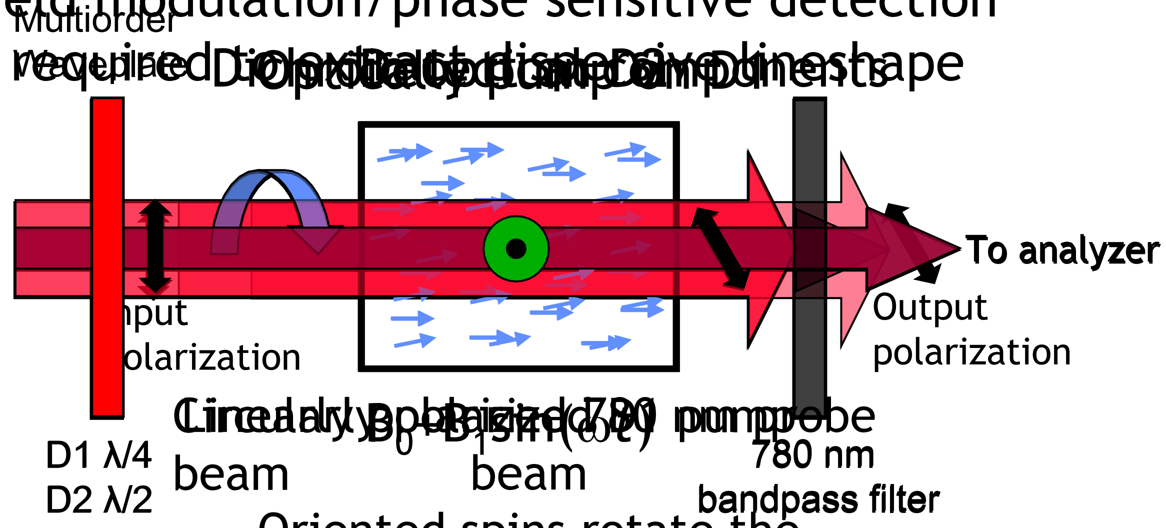
Two-color pump/probe scheme

Two optical resonances in Rubidium (fine structure)

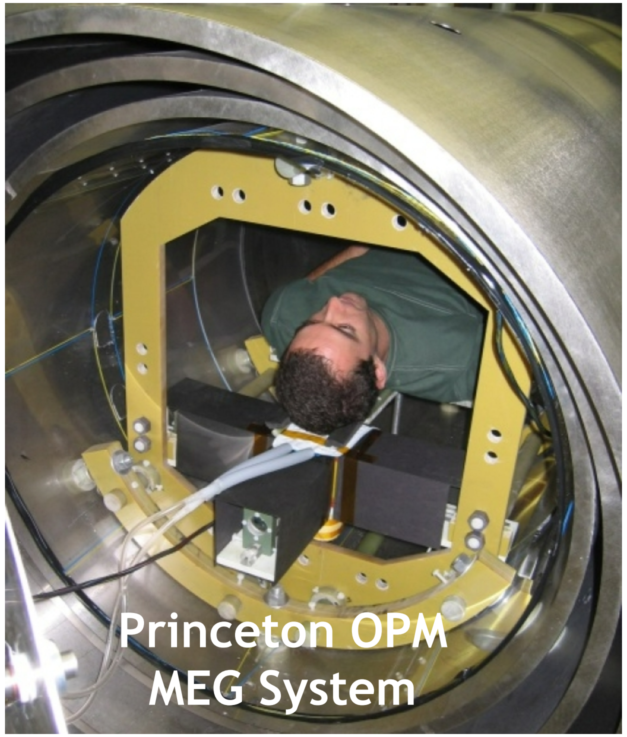
- Use D1 for optical pumping and D2 for probing

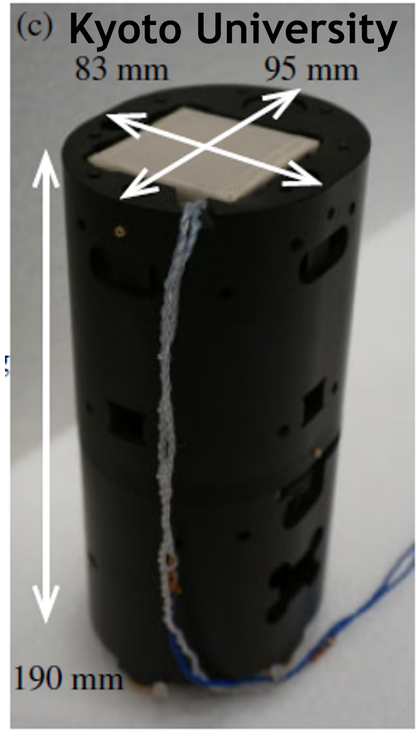
Based on: V. Shah and M. V. Romalis, PRA 80, 013416 (2009)

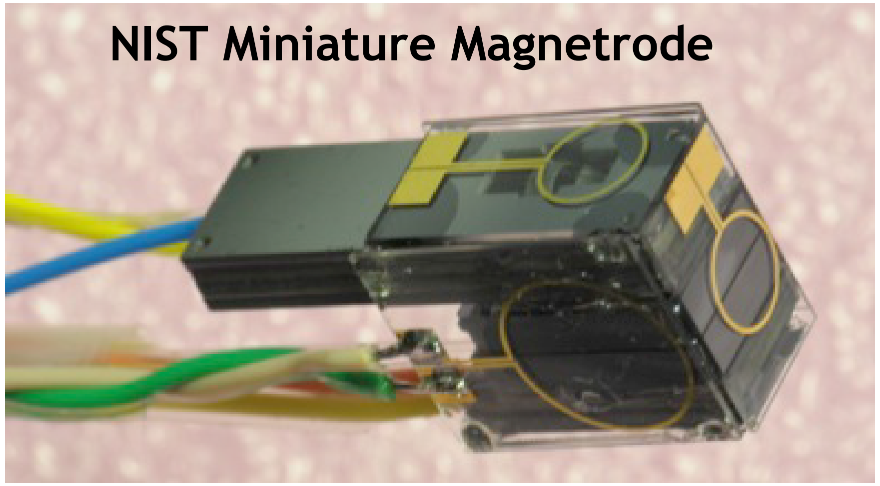




Early Groups Working on OPM MEG







Emerging Companies

QUSPIN
AN ATOMIC DEVICES COMPANY

cerca
Magnetics Limited

FieldLine

kernel

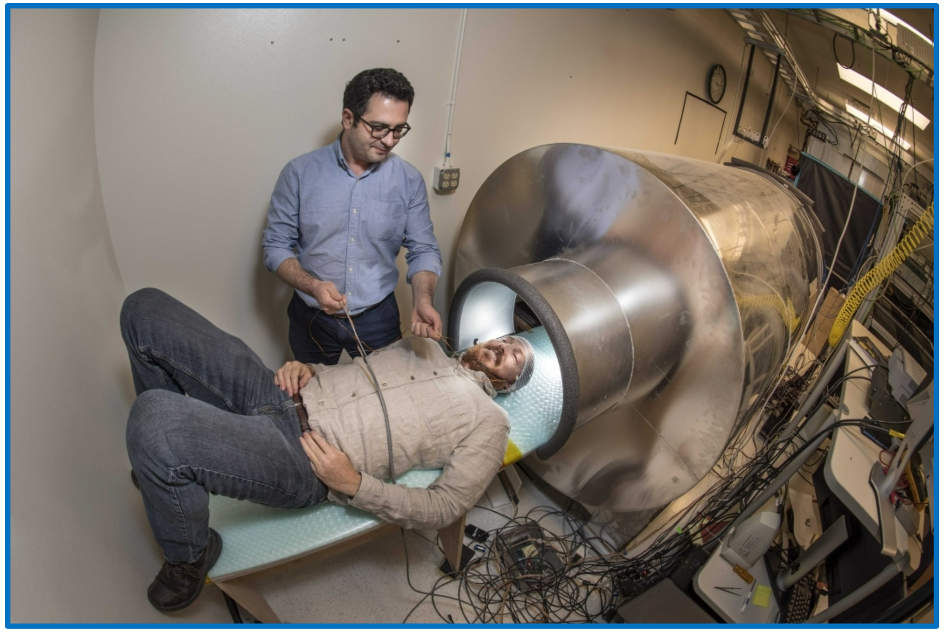
MAG 4He alth

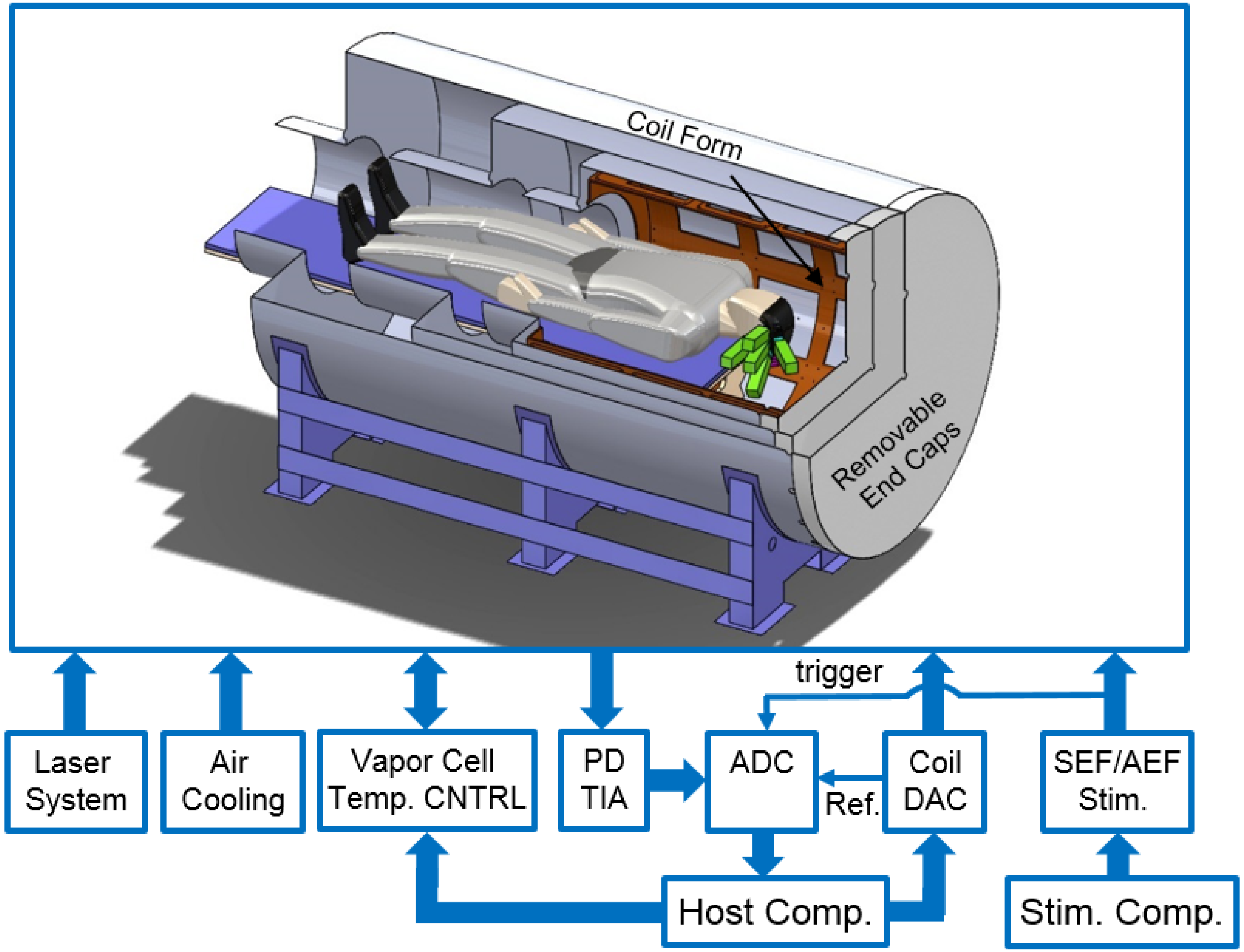
Potentially less costly systems

Cost savings in the sensor system (no cryogenics)

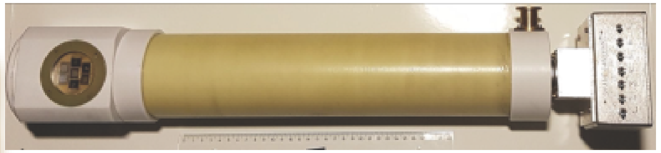
- Can by individual sensors or whole head systems
- Smaller initial investment

Smaller magnetic shielding systems

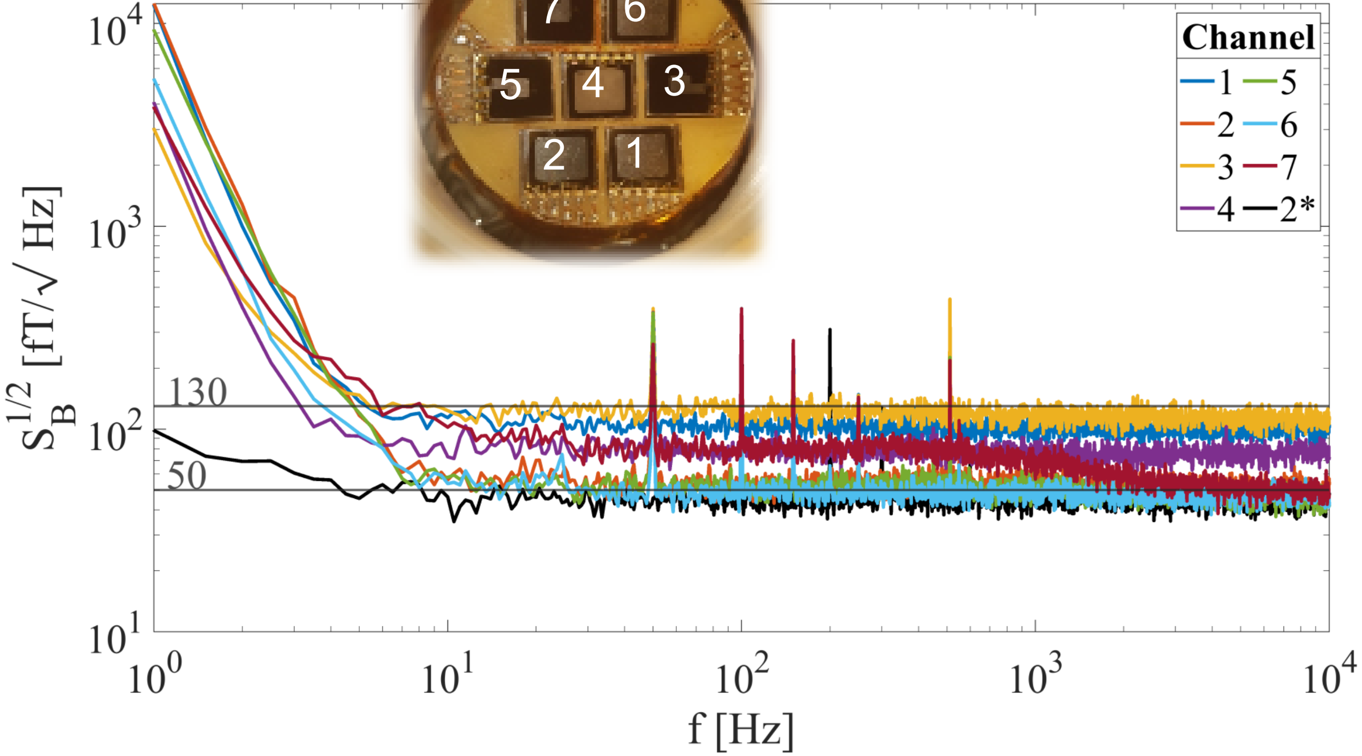




On-scalp MEG with high-T_c SQUIDs



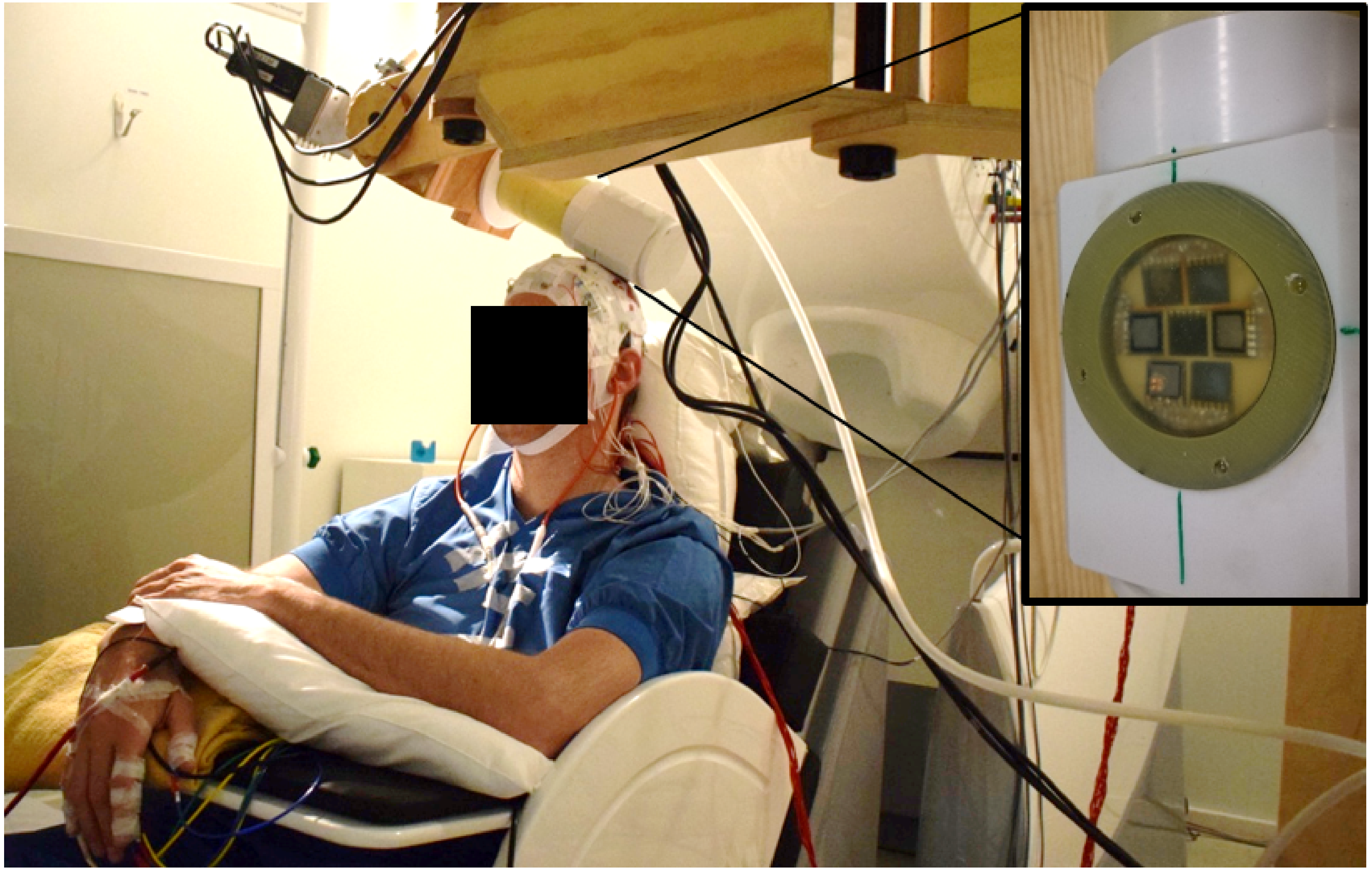
- White magnetic field noise: 50-130 fT/√Hz to < 10 Hz
- Bandwidth: > 10 kHz
- Temperature independent calibration (stable within 0.5%)
- Sensor-to-sensor crosstalk problem solved (< 0.5%)
- Scalp standoff: approaches 1 mm



* → Channel 2 magnetometer in dipstick at 78 K with superconducting shield for comparison

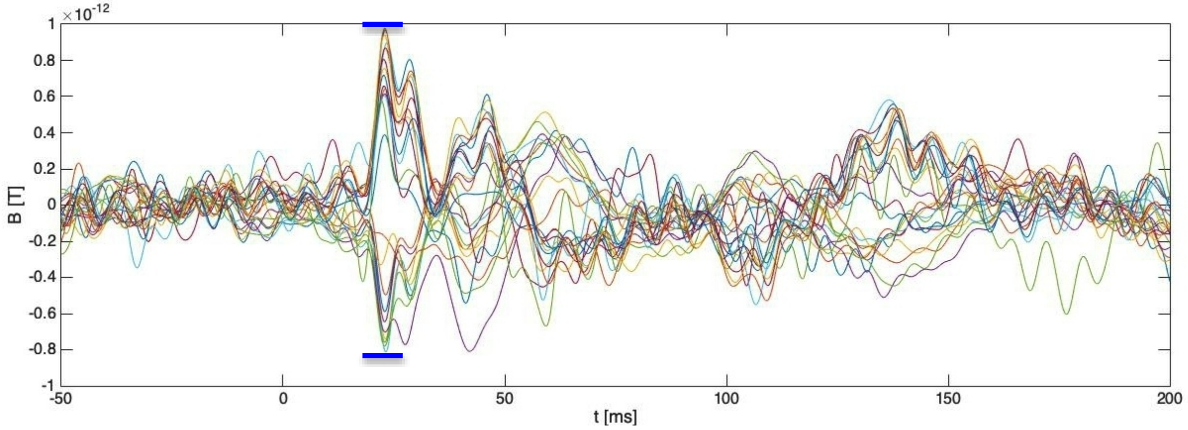
[Pfeiffer et al. *IEEE Trans. Biomed. Eng.* **67**, 5 (2020)]
[Ruffieux et al. *Supercond. Sci. Technol.* **33**, 025007 (2020)]
[Ruffieux et al. *Supercond. Sci. Technol.* **30**, 054006 (2017)]
[Ruffieux. PhD Thesis. Chalmers University of Technology (2020)]

Benchmarking: seven high-T_c SQUIDs vs Elekta (KI NatMEG)

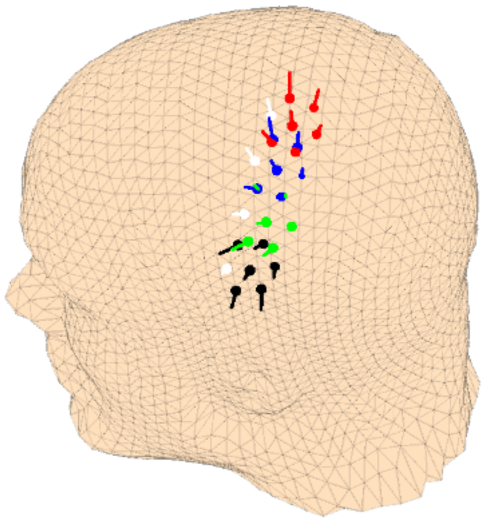


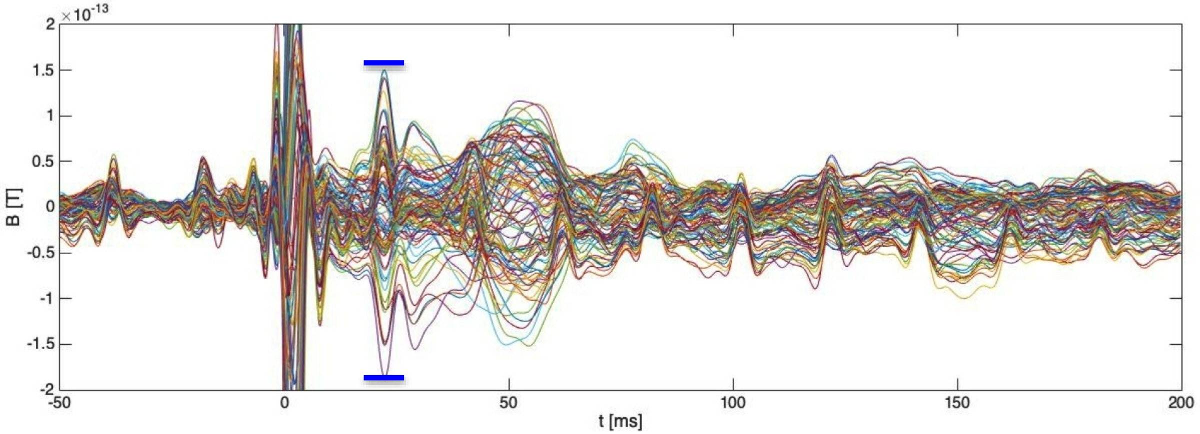
Benchmarking: seven high-T_c SQUIDs vs Elekta (KI NatMEG)

- Somatosensory evoked fields: shallow sources, strange results



4x7-channel (24 channels)
N20m ~1.8 pT peak-to-peak





TRIUX (102 channels)
N20m ~350 fT peak-to-peak

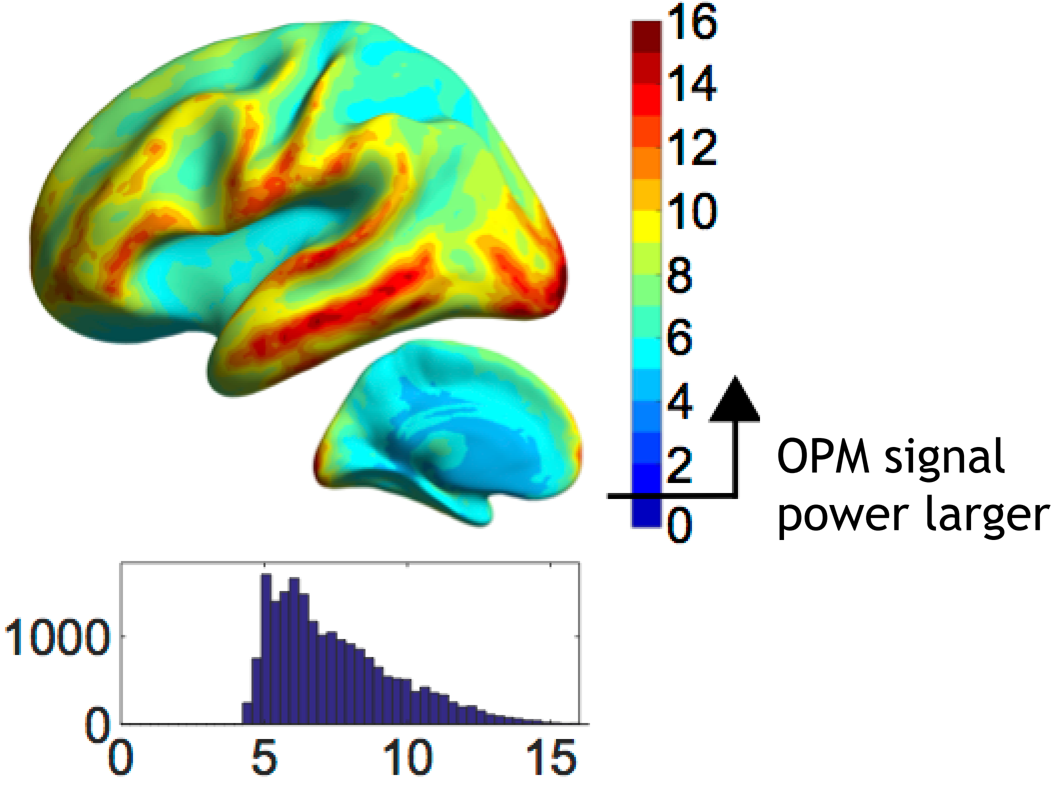
Xie et al, Benchmarking for on-scalp MEG sensors, *IEEE Trans. In Biomed. Eng.* 2016 DOI: 10.1109/TBME.2016.2599177
C Pfeiffer et al., *IEEE Trans. On Biomed. Eng.* **67**(5), 1483-1489

Moving closer to the brain: Benefits of OPM-MEG

Closer proximity to brain means increases in
- **Sensitivity** (larger signals)
- Spatial resolution (more detail)
- Information

Simulation
- 102 OPMs vs. 102 SQUIDs
- OPM noise 6 fT/rHz
- SQUID 3 fT/rHz

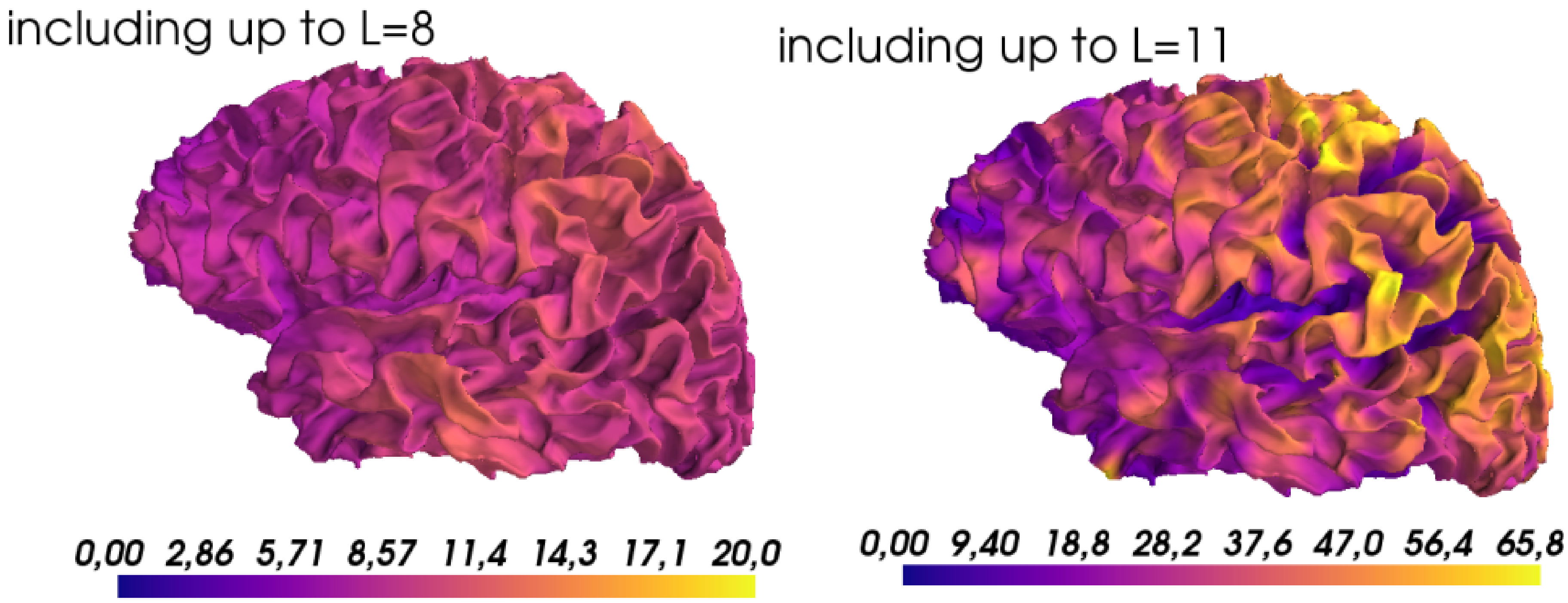
Relative signal power (OPM / SQUID)



Group of Lauri Parkkonen, Aalto University

Iivanainen et al. NeuroImage 2017

Subspace angles SQUID vs. OPM



Benefits of OPM-MEG

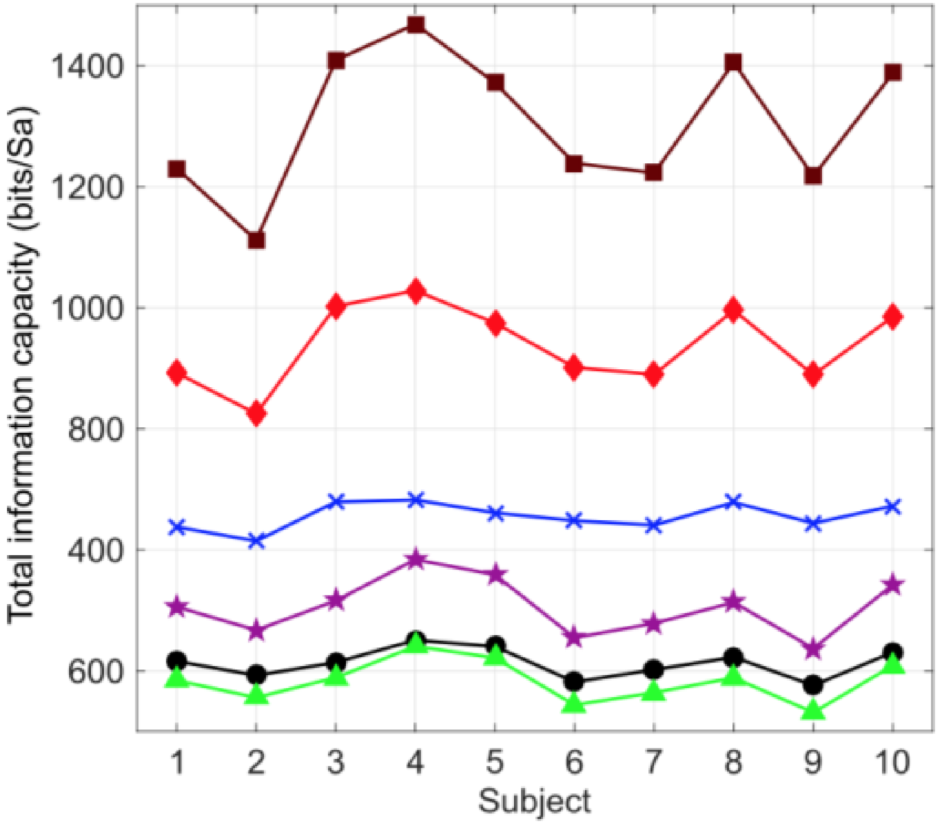
Closer proximity to brain means increases in

- Sensitivity (larger signals)
- Spatial resolution (more detail)
- **Information**

Simulation

- 102 OPMs vs. 102 SQUIDs
- OPM noise 6 fT/rHz
- SQUID 3 fT/rHz

Label	Array	Number of sensors	Average (bits/Sa)	Normalized (bits/Sa/ch)
■	aOPM	306	1307	4.3
◆	tOPM	204	939	4.6
×	nOPM	102	656	6.4
★	aSQUID	306	506	1.7
●	mSQUID	102	413	4.0
▲	gSQUID	204	383	1.9



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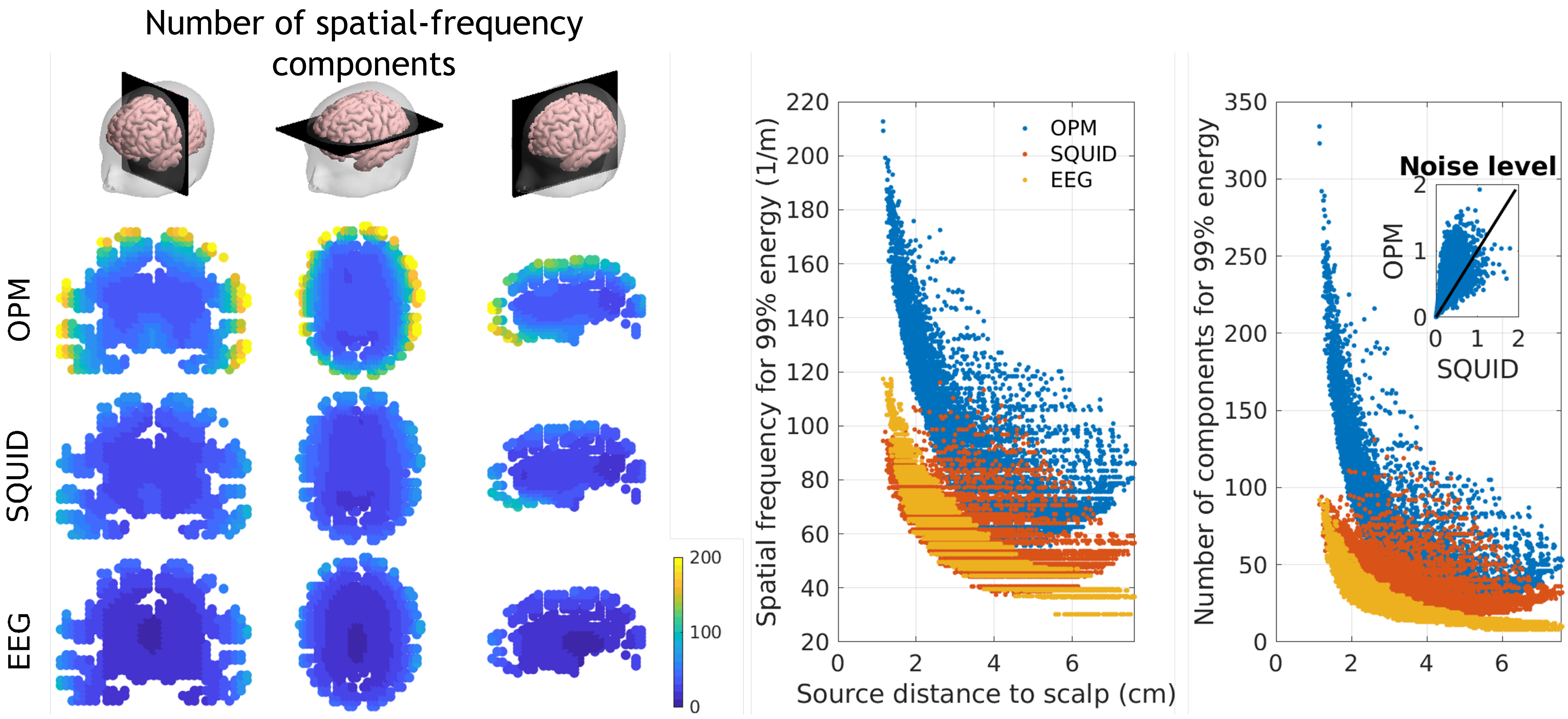
Iivanainen et al. NeuroImage 2017

Spatial-frequency basis (uniform sampling)



Group of Lauri Parkkonen, Aalto University

Iivanainen, Mäkinen et al. in preparation

Conclusion

Next generations sensors

- Optically pumped magnetometers
- High Tc SQUIDs

Multiple research groups and companies

Advantages

- **Sensitivity** (larger signals)
- Spatial resolution (more detail)
- Information

New applications

- New neuroscience paradigms with wearable systems
- Brain computer interface
  - Larger information volume