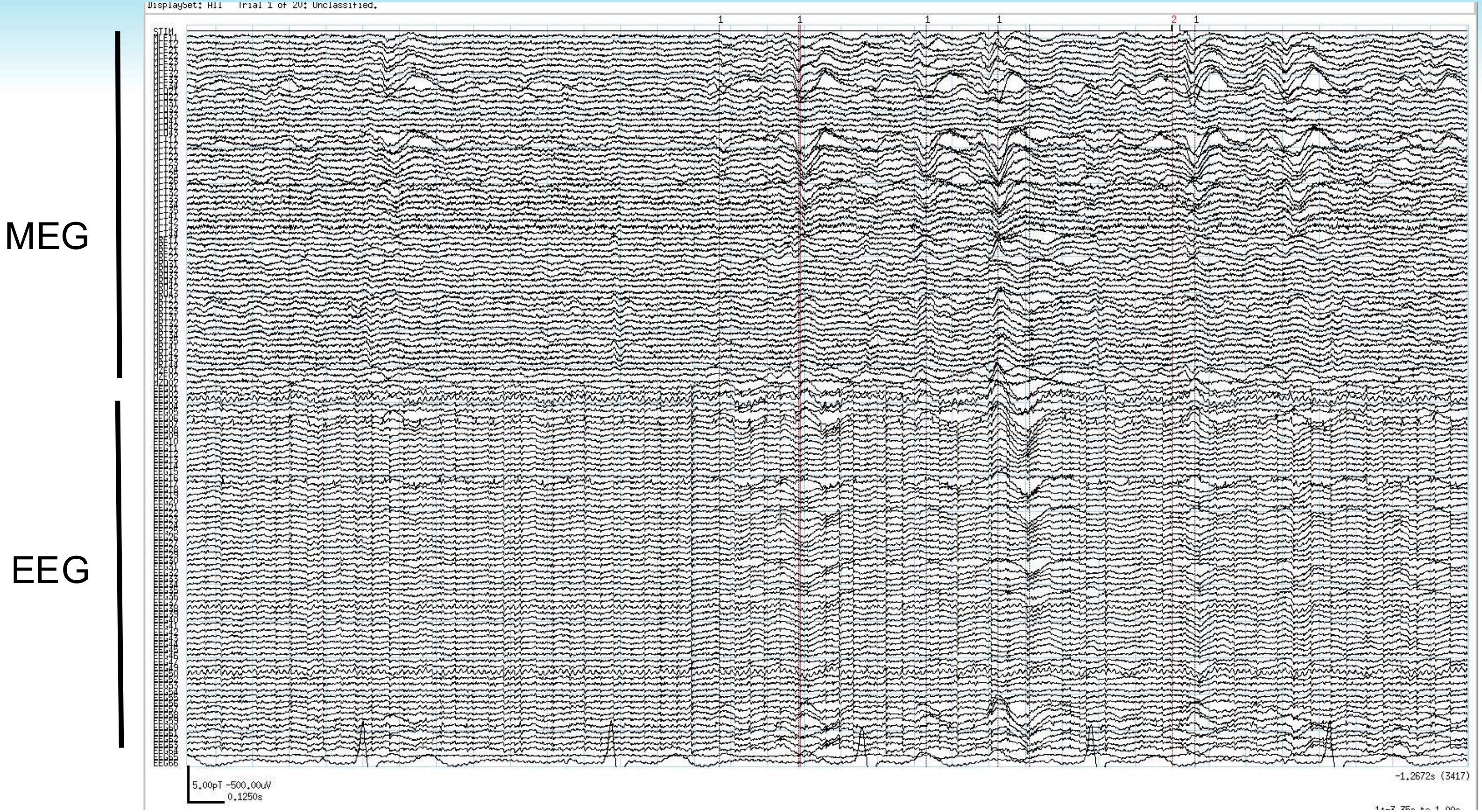
What is MEG?
What for?
MEG v. EEG?
OPM and perspective?

Institut de Neurosciences des Systèmes

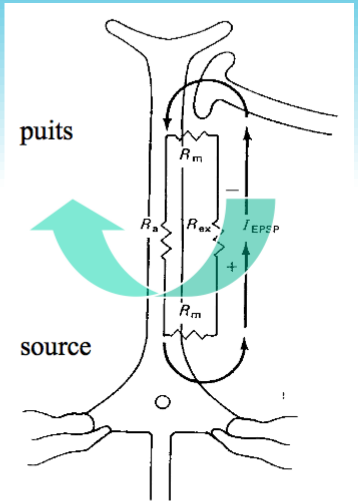
Jean-Michel Badier. AMU

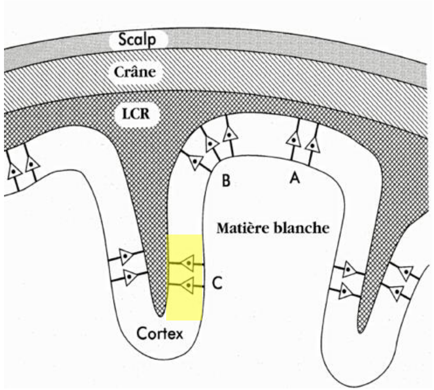
Fréjus 2025

MEG - EEG


DisplaySet: All   Trial 1 of 20: Unclassified.
MEG
EEG
5.00pT -500.00uV
0.1250s
-1.2672s (3417)

EEG et MEG : Origine ?

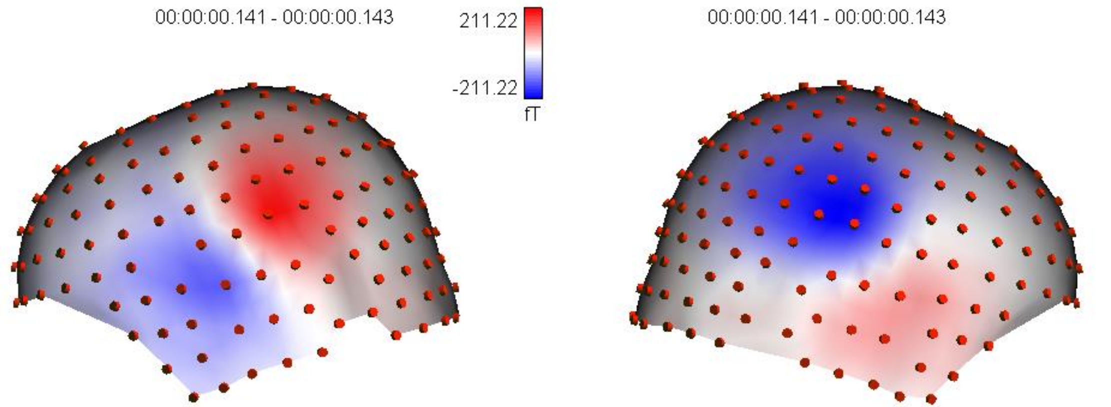


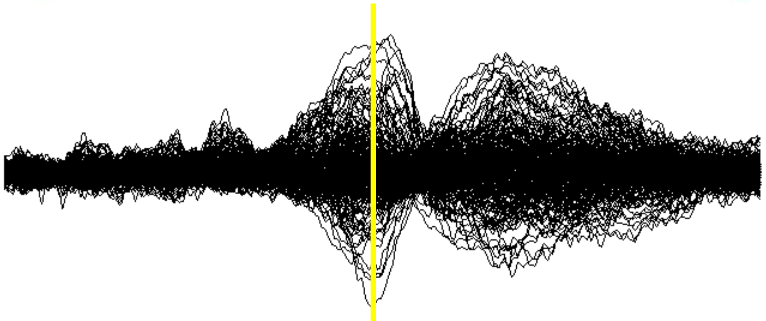


- EEG : courants extracellulaires
- MEG : champs magnétiques générés par les courants circulants, intra et extra-cellulaires
- Les courants électriques sont affectés par les différents milieux conducteurs (en particulier le crâne de conductivité plus faible)
- Les champs magnétiques ne sont pas affectés par les différents milieux traversés

Seules techniques à même de suivre l'activité cérébrale à l'échelle temporelle appropriée

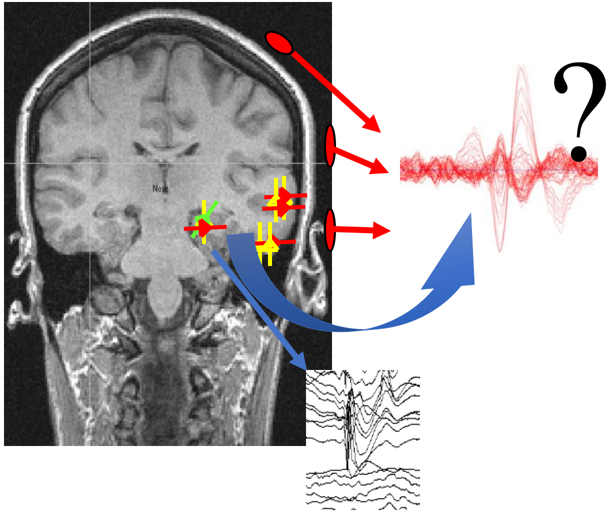
MEG → localisation



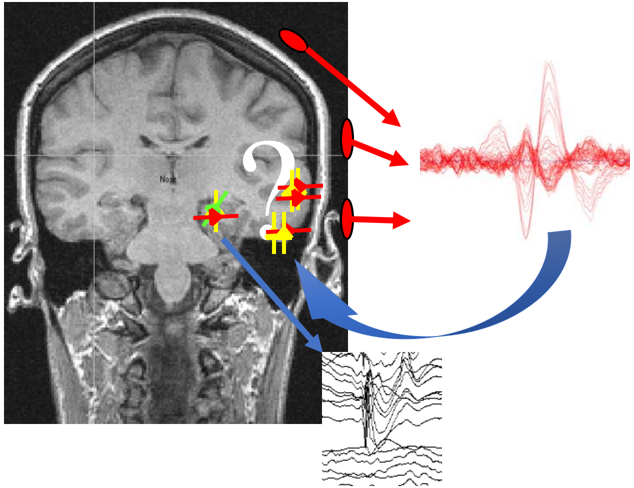


Stim audio
500Hz

Find the sources of MEG and EEG

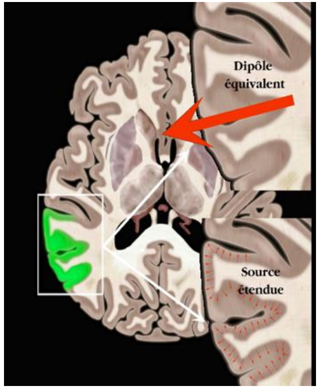


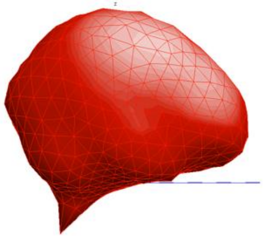
Forward problem (solution)



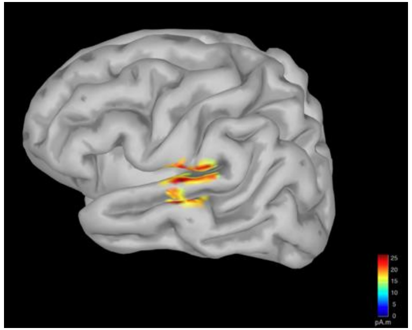
Inverse problem

Trouver les sources de la MEG et EEG





modèle de tête



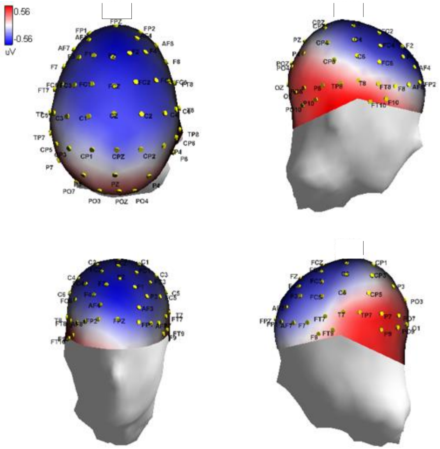
Modèle de source

Méthodes d'inversion

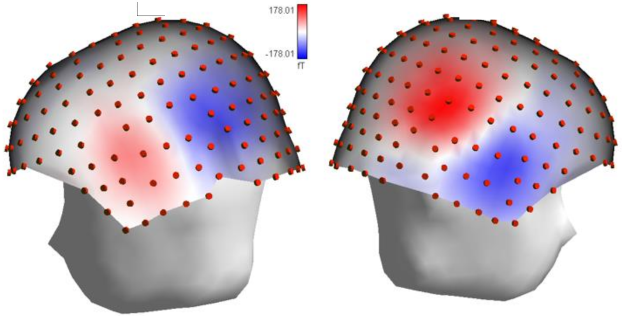
EEG/MEG Pourquoi payer plus ?

- Les sources radiales sont moins bien vues par la MEG

+ + + Il n’y a pas d’effet de lissage pour la MEG (effet dû au crâne).



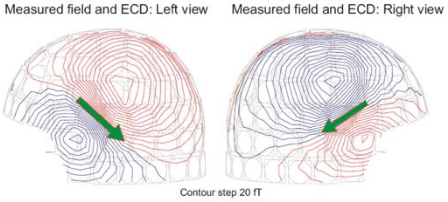
EEG



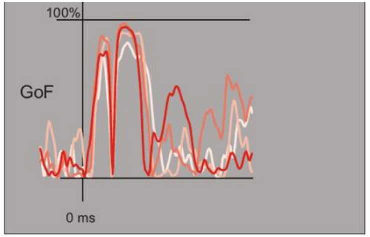
MEG

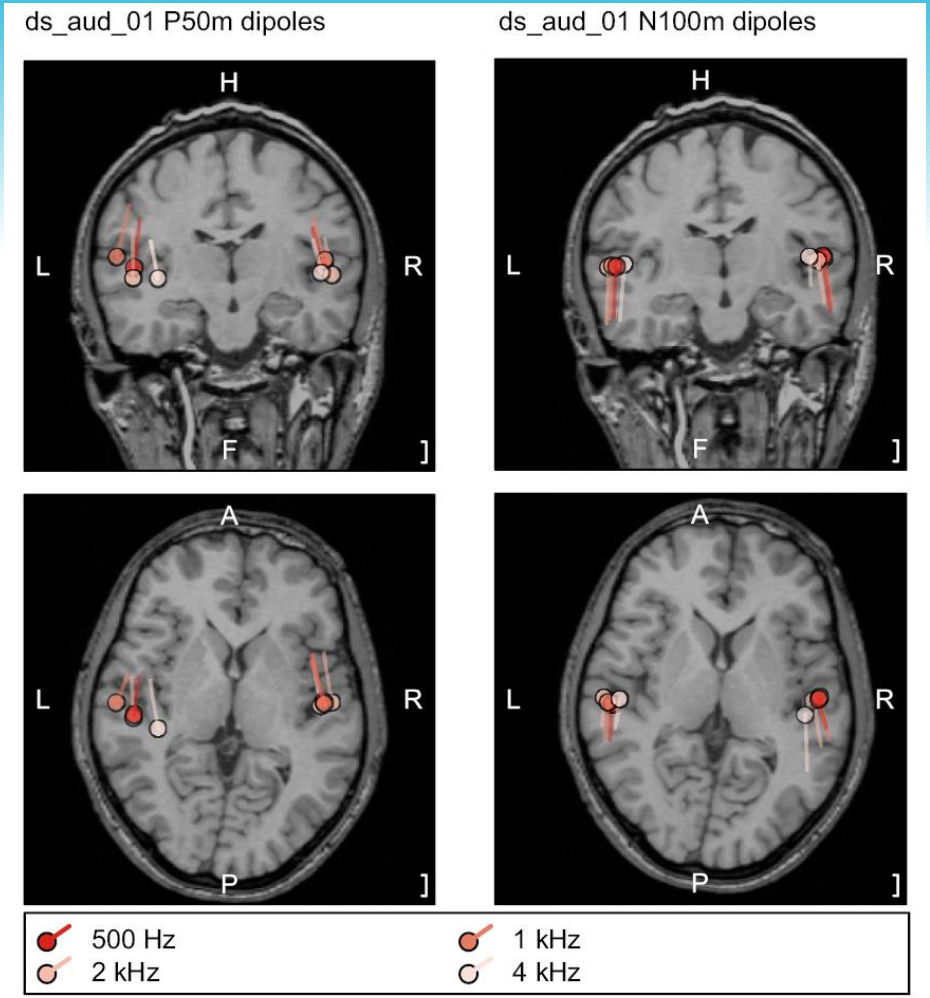
Evoked activity by pure tone (750Hz)

« dipole fit » Tonotopie

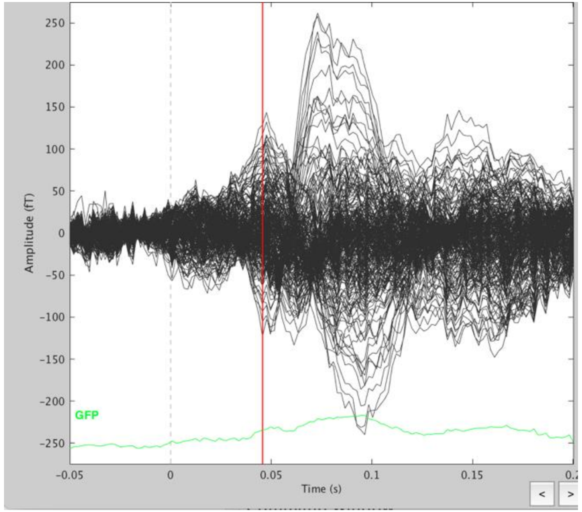


1kHz – 100ms

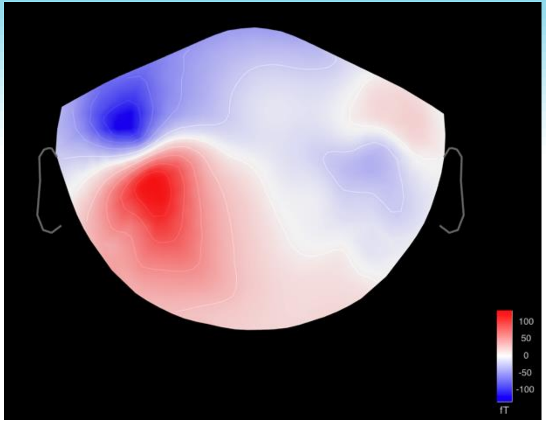


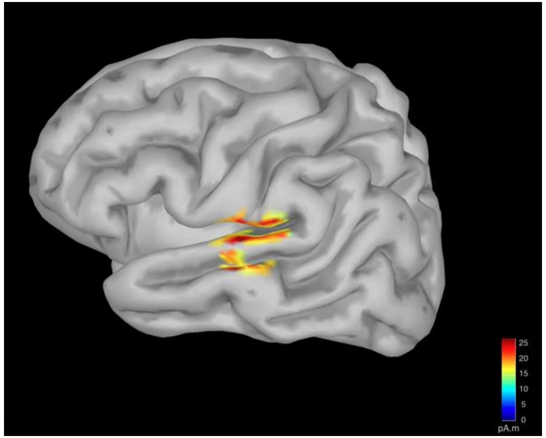


Minimum Norm Estimate (MNE)

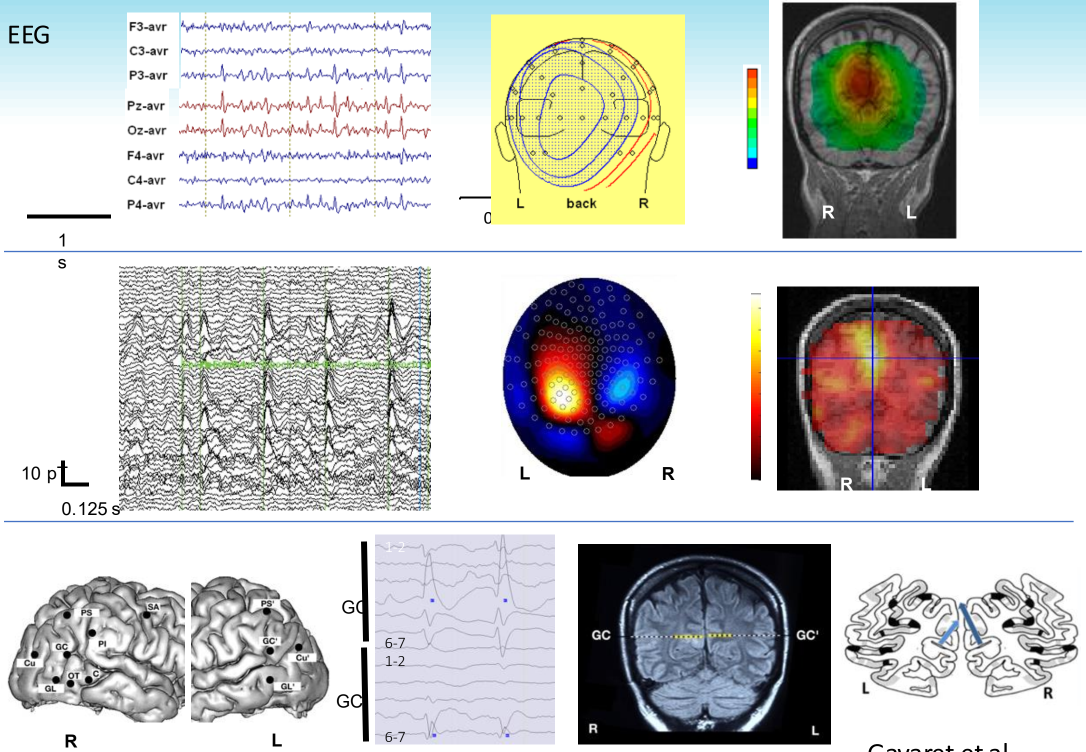


Champ évoqué auditif





DYNAMAP



Gavaret et al. 2014

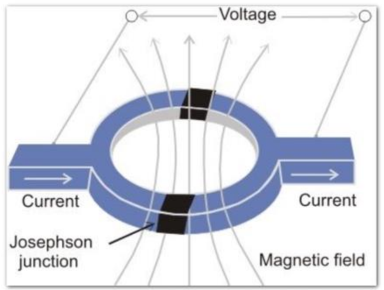
Institut de Neurosciences des Systèmes

AMU

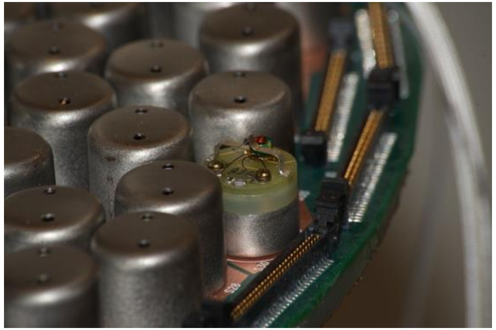
AP HM

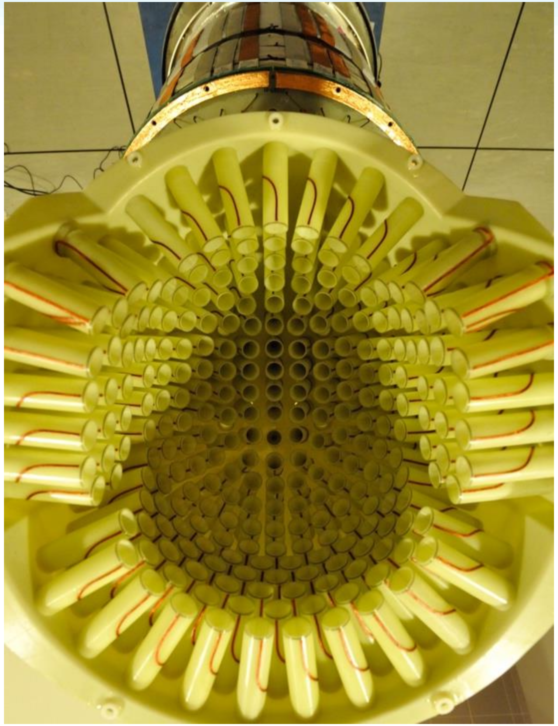
EEG	MEG
• Lissage dû au crâne • Très influencé par la géométrie de la tête • Sensibilité aux sources profondes à déterminer • Mouvement de la tête possibles	• Pas d'effet de lissage • Résolution spatiale supérieure • Sensibilité faible au sources radiales. • Sources profondes détectables avec traitement. • Pas de mouvement de la tête • Résolution temporelle supérieure

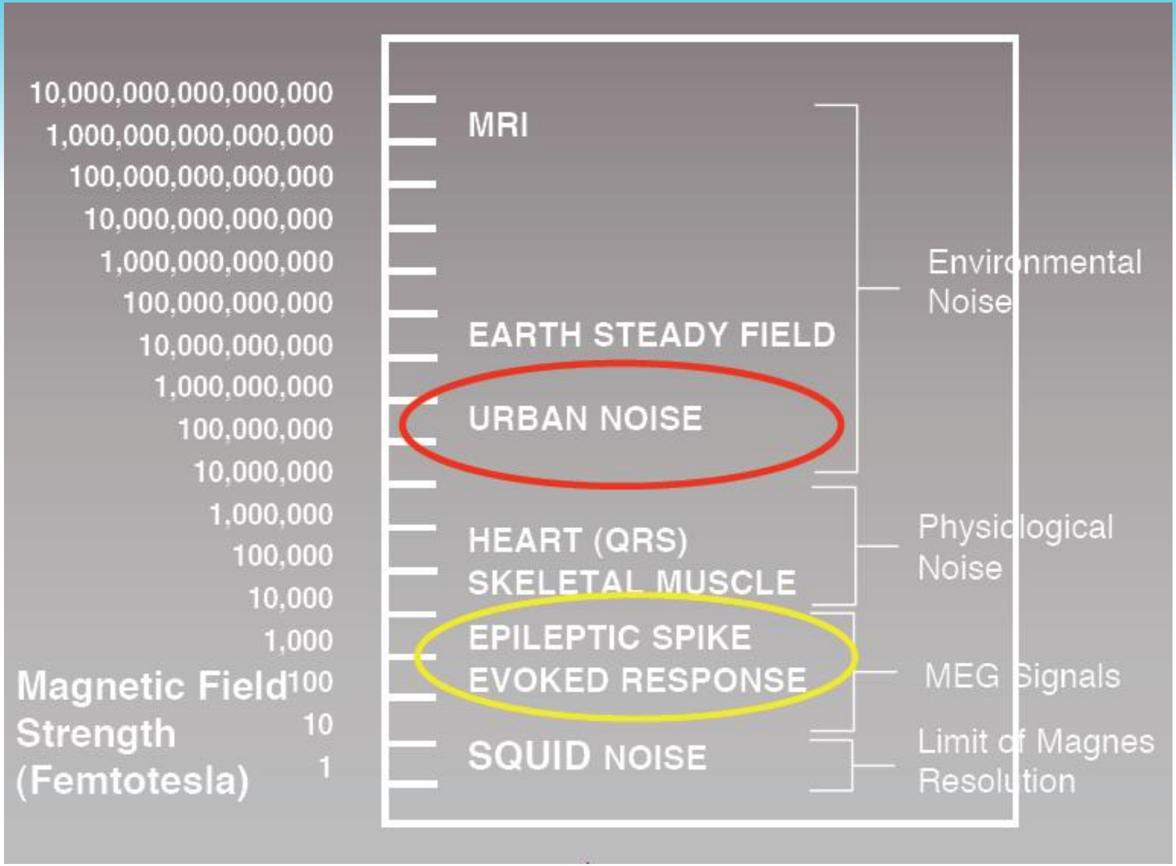
Current sensor: Superconducting QUantum Interference Device (SQUID)



A basic SQUID Magnetometer. (Image: Adapted from DOI:10.13140/RG.2.2.17984.66564)



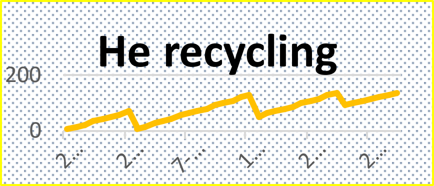




Amplitudes des signaux

Pourquoi si peu d'équipements MEG ?

- Recours à la cryogénie :
  - Maintenance complexe
  - Utilisation de l'hélium liquide (problème écologique et économique).

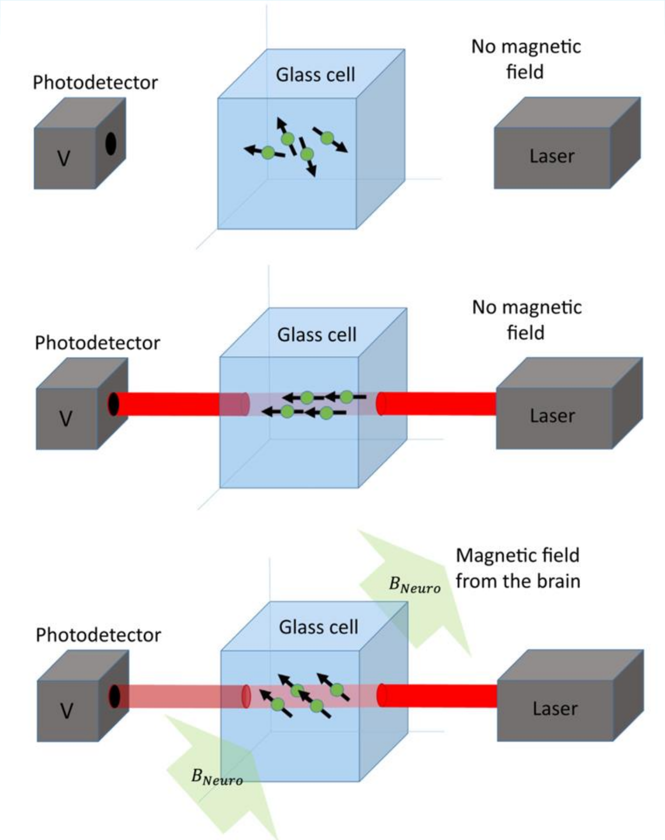


-> Coût élevé

- Capteur de taille fixe
- Pas de mouvement durant l'enregistrement

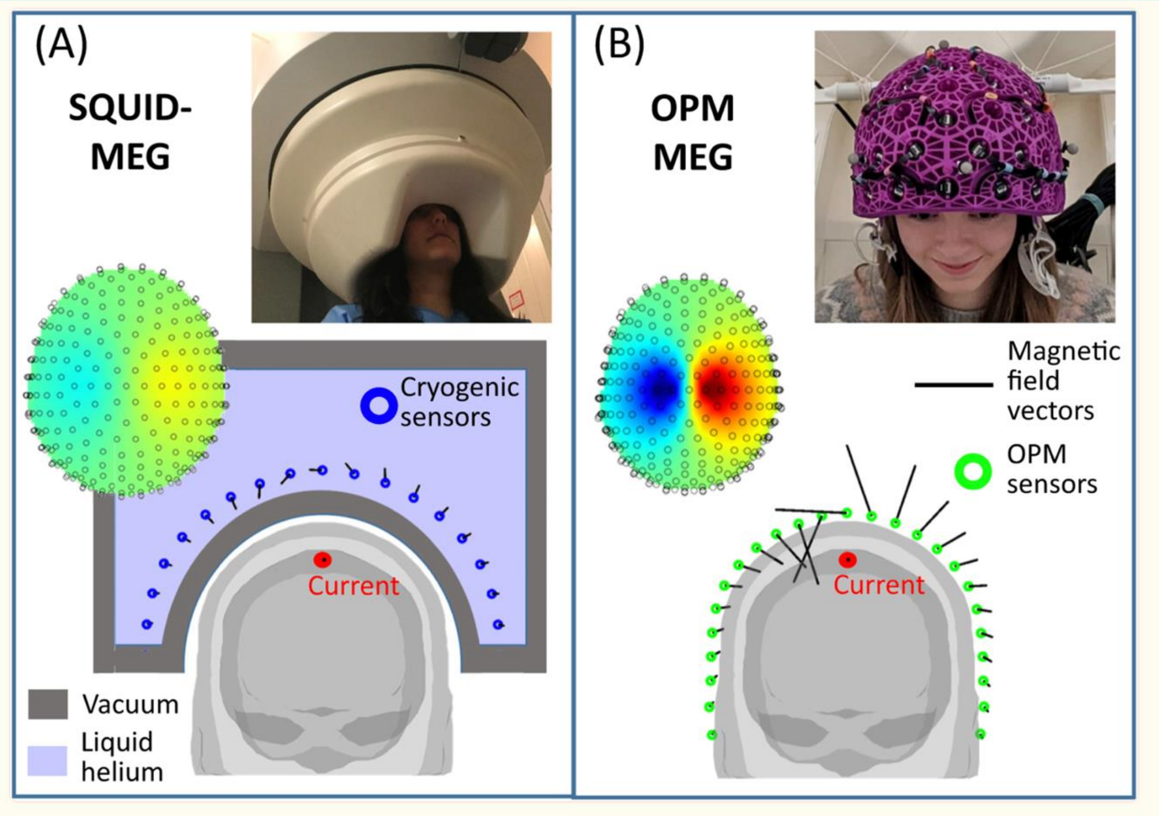
Optically Pump Magnetometer
Simple description for non-physicists

Alkali OPMs (rubidium)



Brookes et al. 2022

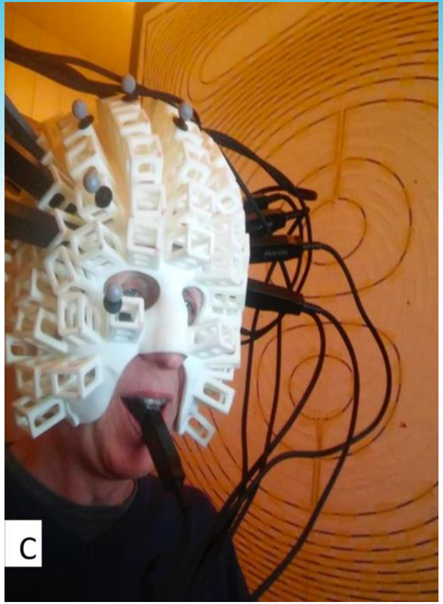
OPM v. SQUID. Amplitude of the fields



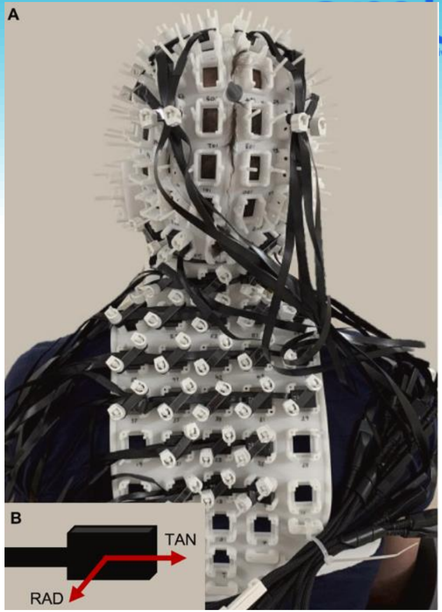
Brookes et al. 2022

New advances:

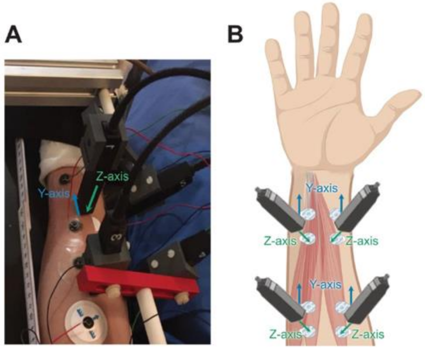
- Epilepsy. Vivekananda et al. 2020. Mellor et al. 2021. Feys et al. 2022. Badier et al. 2023.
- Pédiatric applications. Feys et a. 2021. Boto et al. 2022.
- Portable systems. Boto et al. 2018. Pedersen et al. 2022. Seymour et al. 2022. Rhodes et al. 2023.
- Peripheral nerves. Bu et al. 2022, Greco et al. 2023, Mardel et al. 2024.
- Neuromuscular pathologies. Sometti et al. 2021. Semeia et al. 2022.
- …



Tierney et al. 2021

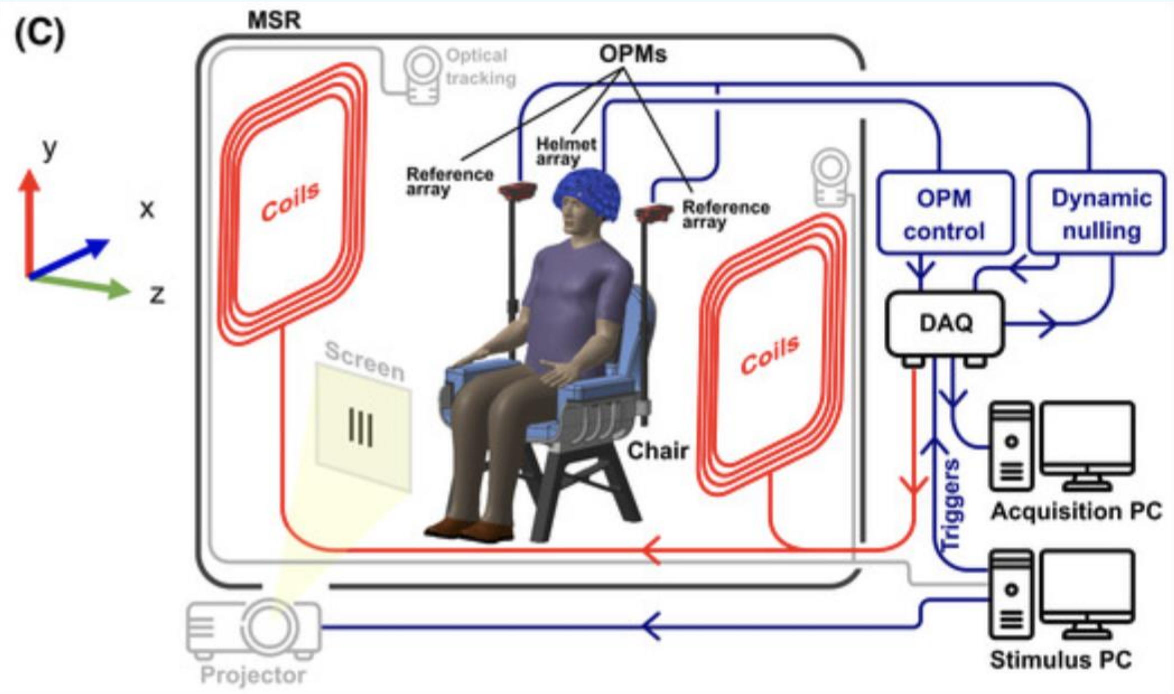


Mardell et al. 2024



Greco et al. 2023

Zero-field-> compensation coils

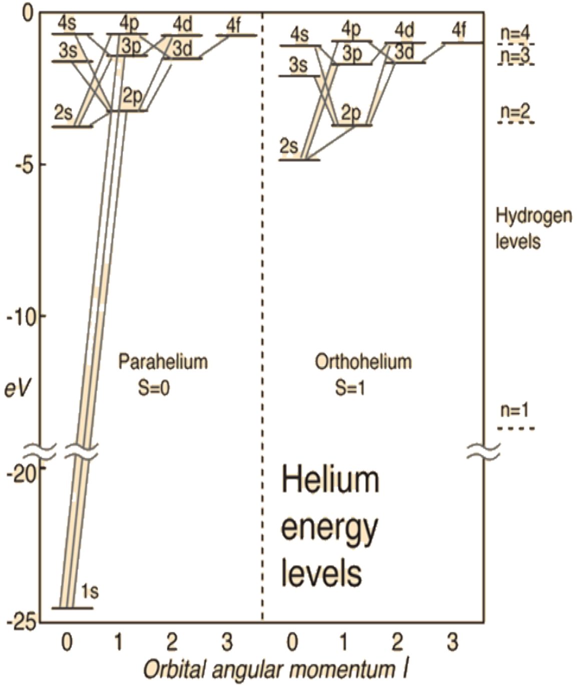


Rea et al. 2022

^{4}He OPM

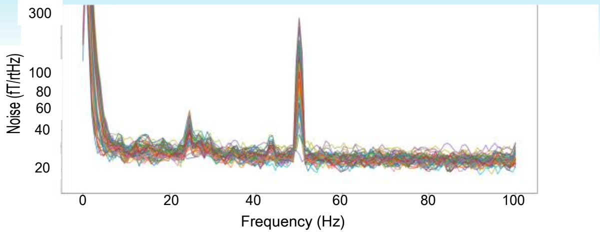
- Developed by CEA Leti for European Space Agency Swarm mission : still functional up there after >10 years of continuous operation

- Helium-4 needs to be brought to an excited level for measuring the magnetic field
  - Requires plasma excitation, dissipating ~10 mW.
  - Working at any temperature, **no noticeable heating**

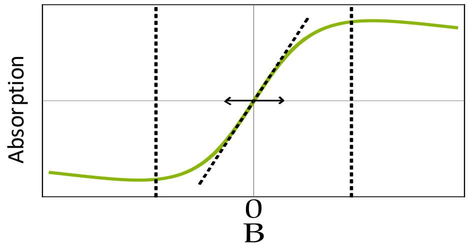


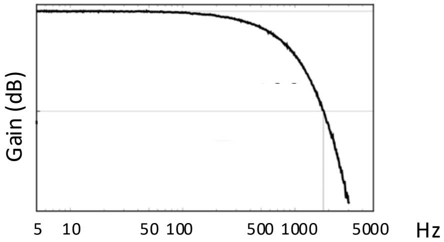
^{4}He OPM

no denoising



Parametric resonance curve:





- Sensitivity: 30 fT/√Hz (on two axes)
- Close loop dynamic range: ±200 nT

  Do not require active shielding in the MSR
- Bandwidth: 2 kHz

Fourcault et al, Opt. Express 29, 14467 (2021).

OPMs and OPMs !

Alkali

- Limited dynamic ± 1.5 nT
- Requires compensation to obtain a field close to zero
- Sensitivity < 15-23 fT/√Hz
- Limited bandwidth: < 100 Hz
- Vectorial measurement possible
- Heat dissipation (150°c) !

https://quspin.com/products-qzfm/

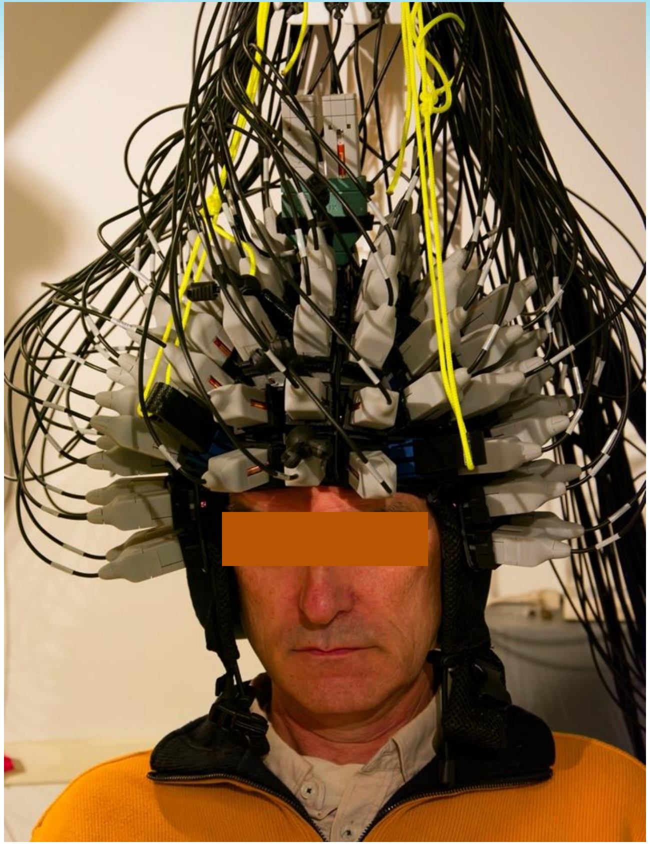
^{4}He

- Higher dynamic ±125 nT
- No need for compensation coils.
- Sensitivity <30 fT/√Hz
- High bandwidth: DC-2 kHz
- Current sensor size
- Vectorial measurement by construction
- Operation at room temperature

Mag4Health

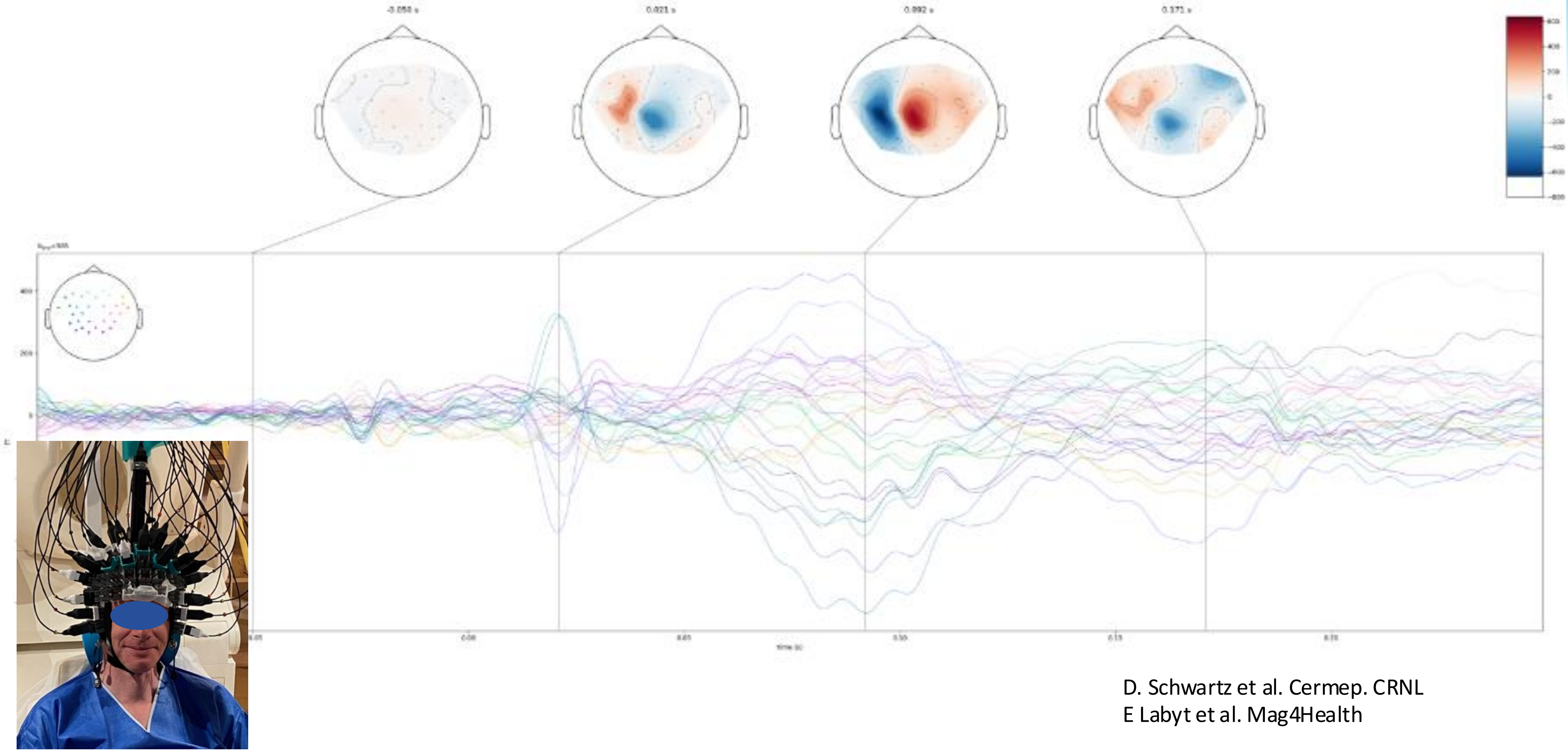
Squid:
- Dynamic: 16 nT
- Sensitivity: 5 fT/√Hz

Capteur tête entière ^4He OPM



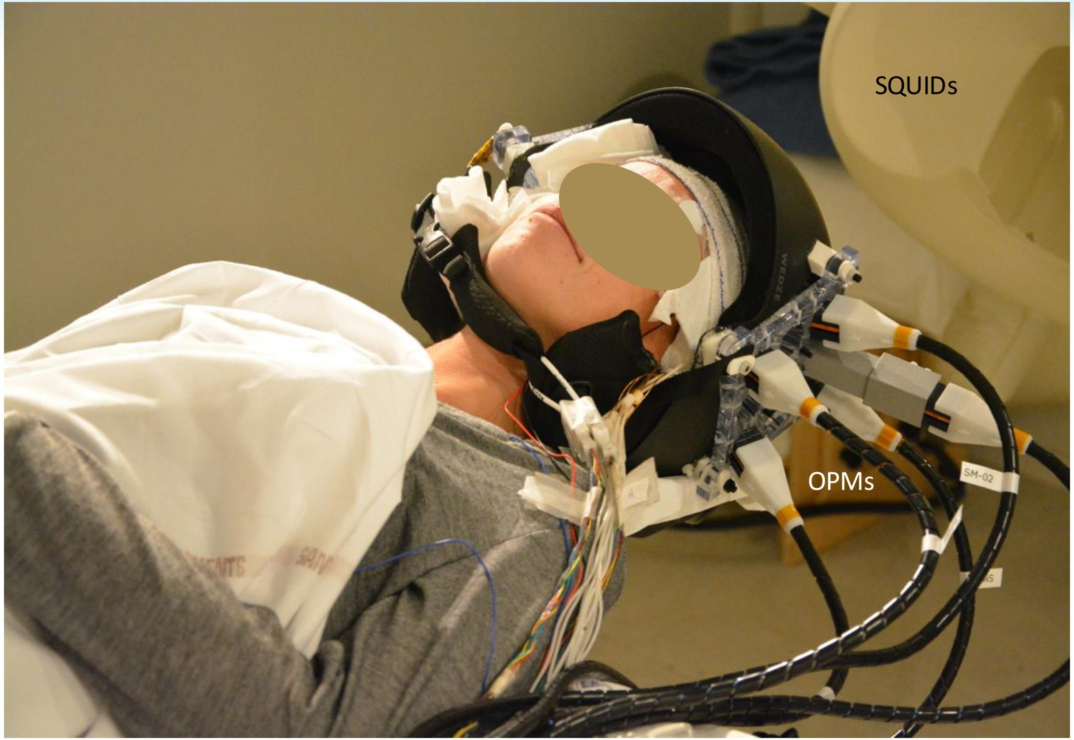
96 capteurs -> 288 canaux par mesure sur chaque axe

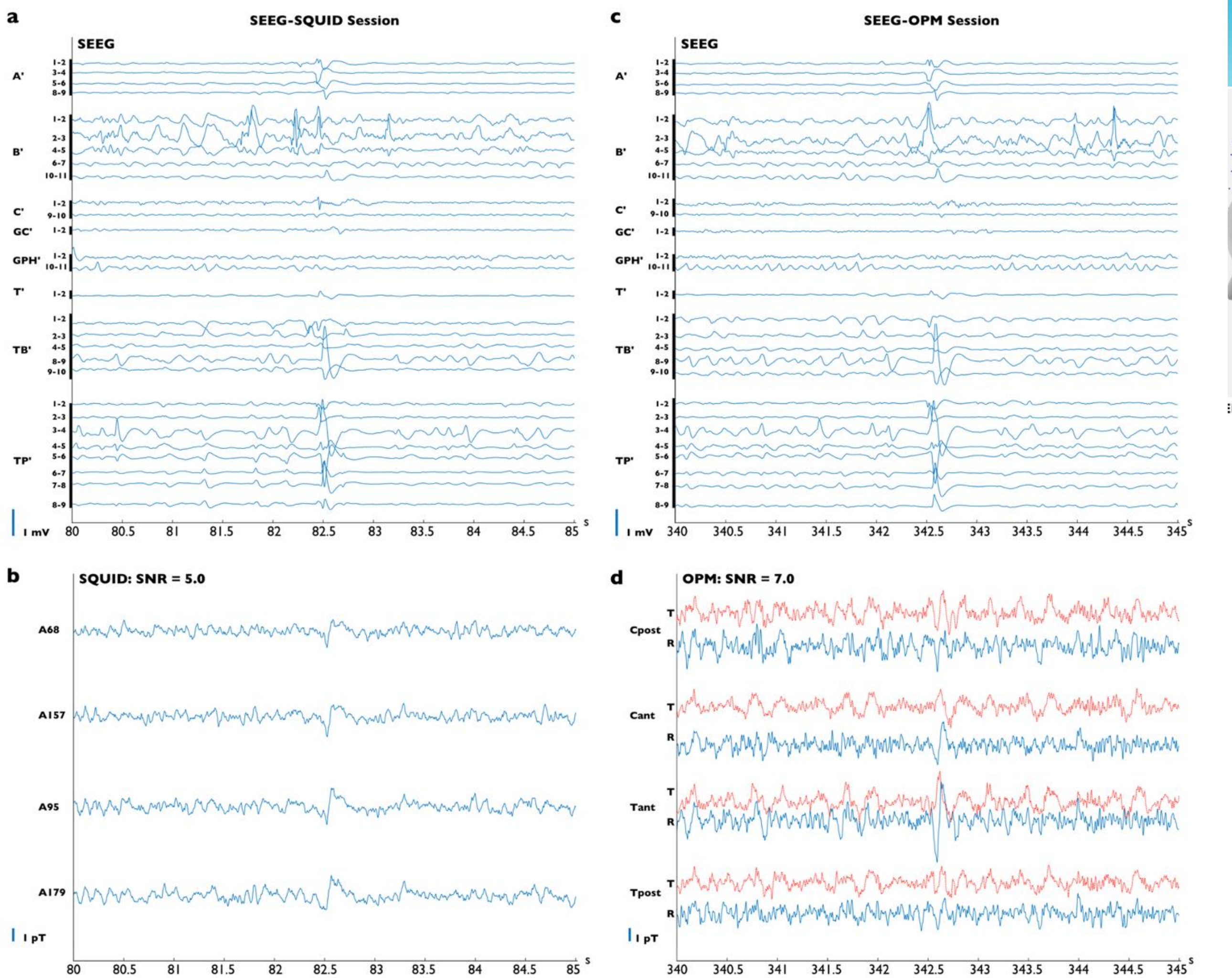
Capteur tête entière ^{4}He OPM

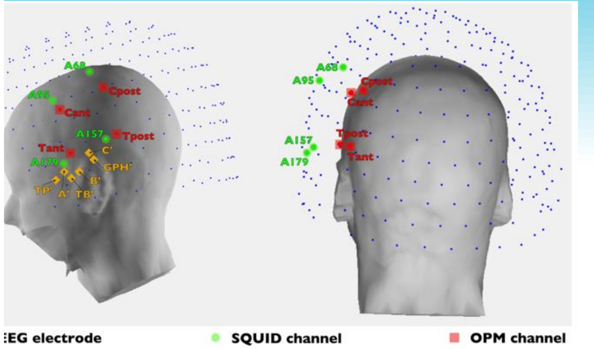


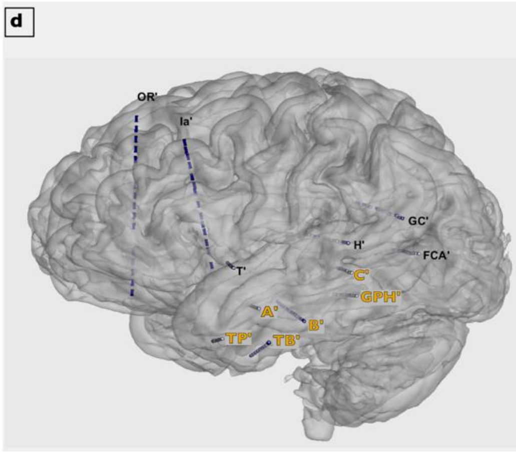
D. Schwartz et al. Cermep. CRNL
E Labyt et al. Mag4Health

OPM versus SQUIDs ?
-> Enregistrements simultanés





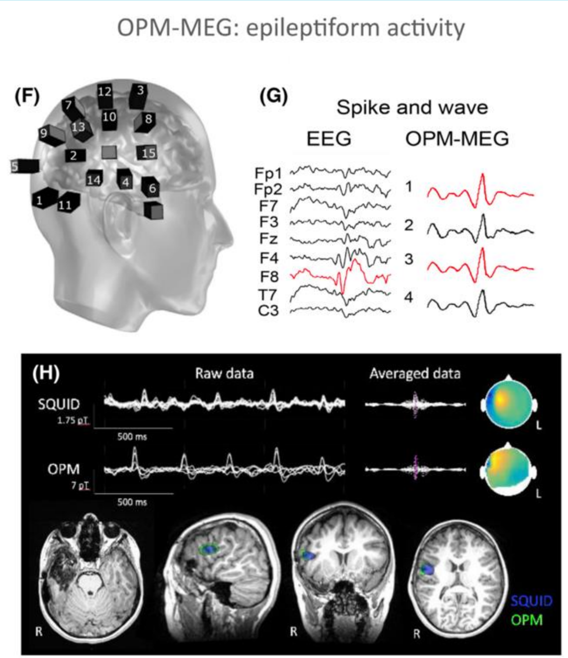




Badier et al. 2023

OPM le plus :

- Amplitude des signaux plus forte
- Fréquence spatiale plus élevée (distinctions des sources)
- Mesures tangentielles pour un meilleurs échantillonnage des champs magnétiques
- Miniaturisation
- Mouvements possibles -> enregistrement des crises
- Taille du capteur adaptable -> enregistrement chez l'enfant



Feys et al. 2022

OPM le plus. OPM quand ?

- Amplitude des signaux plus forte
- Fréquence spatiale plus élevée (distinctions des sources)
- Mesure de capteurs tangentielles pour un meilleurs échantillonnage des champs magnétiques
- Miniaturisation
- Mouvement possibles -> enregistrement des crises
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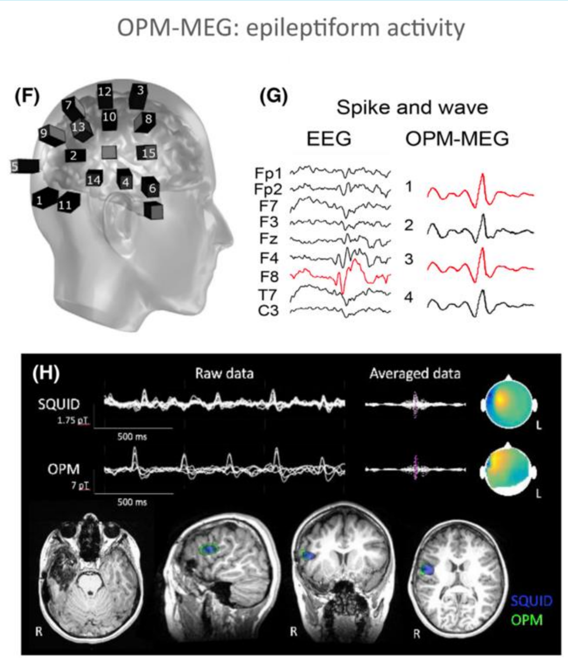
- Systèmes tête entière disponibles (4 sociétés)
- Coût << 1M€. Coût de maintenance faible
- Recherches cliniques pour l'épilepsie

-> Nouvel élan pour la MEG y compris clinique



Feys et al. 2022