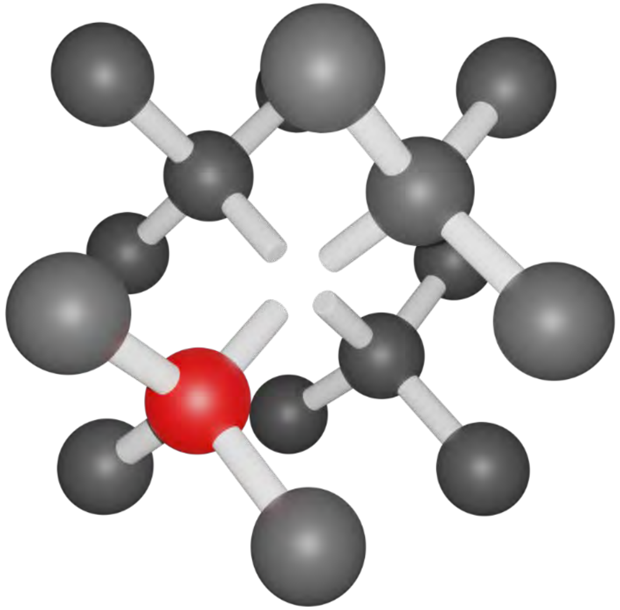
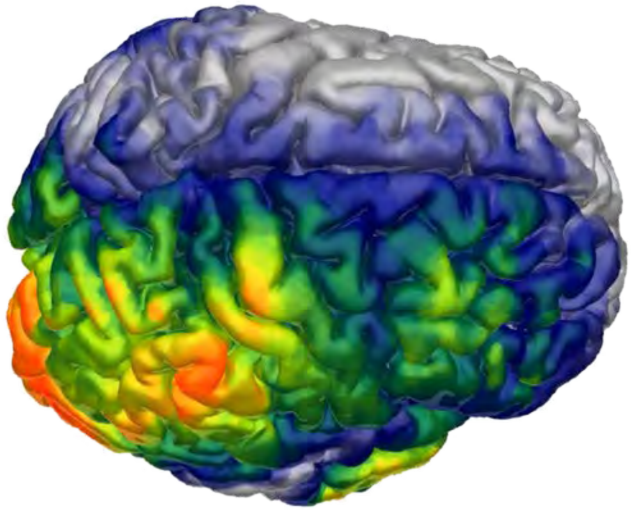
Diamond Quantum Sensors for Magnetoencephalography



Jonah A. Majumder

MIT ILP R&D Conference

14 November 2019



LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

This material is based upon work supported by the Under Secretary of Defense for Research and Engineering under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Under Secretary of Defense for Research and Engineering.

Outline

- **Magnetoencephalography (MEG)**
  - **Motivation**
  - **MEG Origin**
  - **Clinical Brain Imaging**
- **Diamond-Based MEG**
  - **The Nitrogen-Vacancy Center in Diamond**
  - **The MIT Lincoln Lab MEG System**

Brain Science

BRAIN INITIATIVE
BRAIN RESEARCH THROUGH ADVANCING INNOVATIVE NEUROTECHNOLOGIES

USA

China

Organization for Human Brain Mapping
Advancing Understanding of the Human Brain

International

EU

Human Brain Project

Brain/MINDS
Brain Mapping by Integrated Neurotechnologies for Disease Studies
能ネットワークの全容解明プロジェクト

Japan

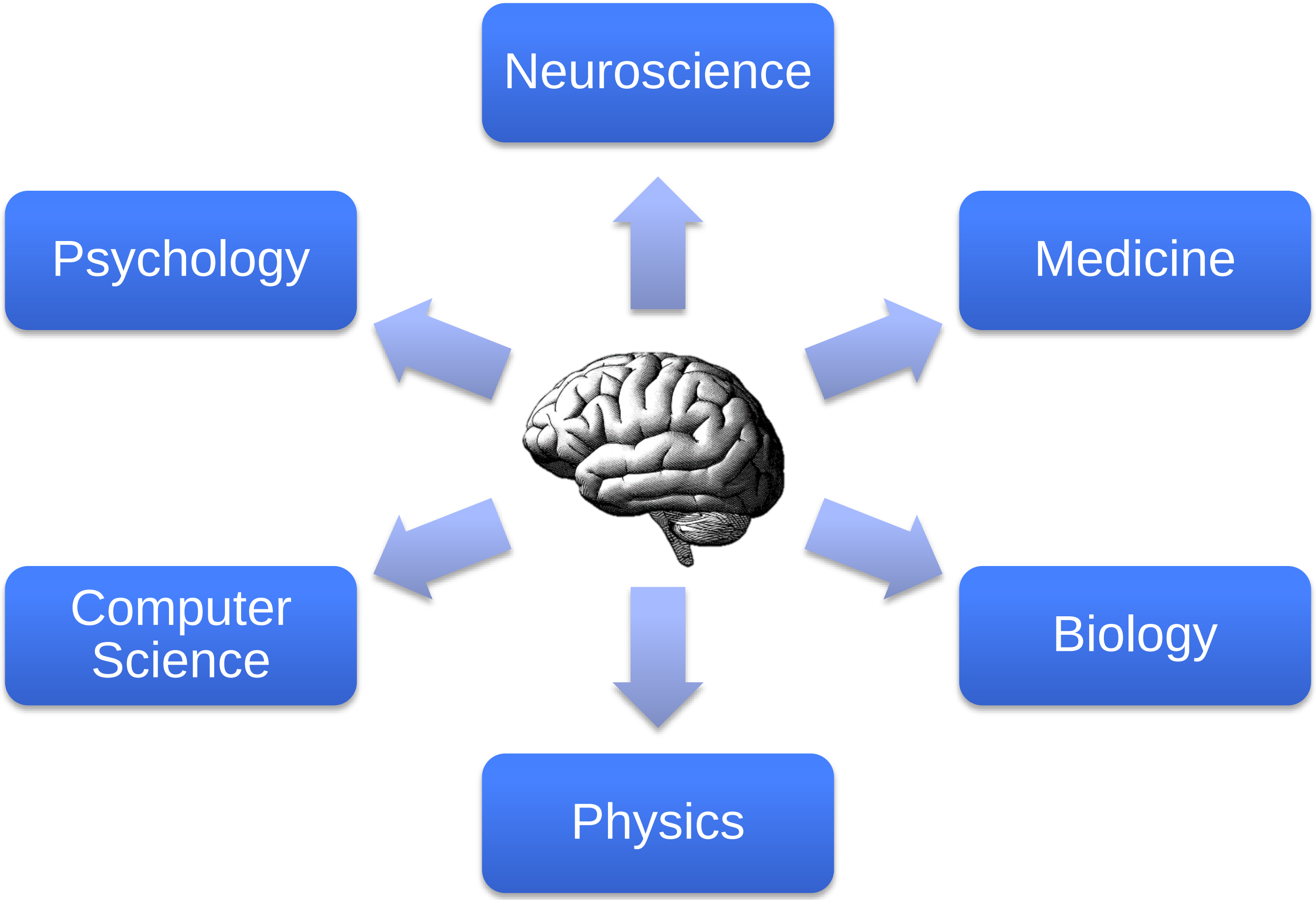
The 10th IBRO World Congress of Neuroscience
IBRO 2019
21-25 SEPTEMBER / DAEGU, KOREA

South Korea

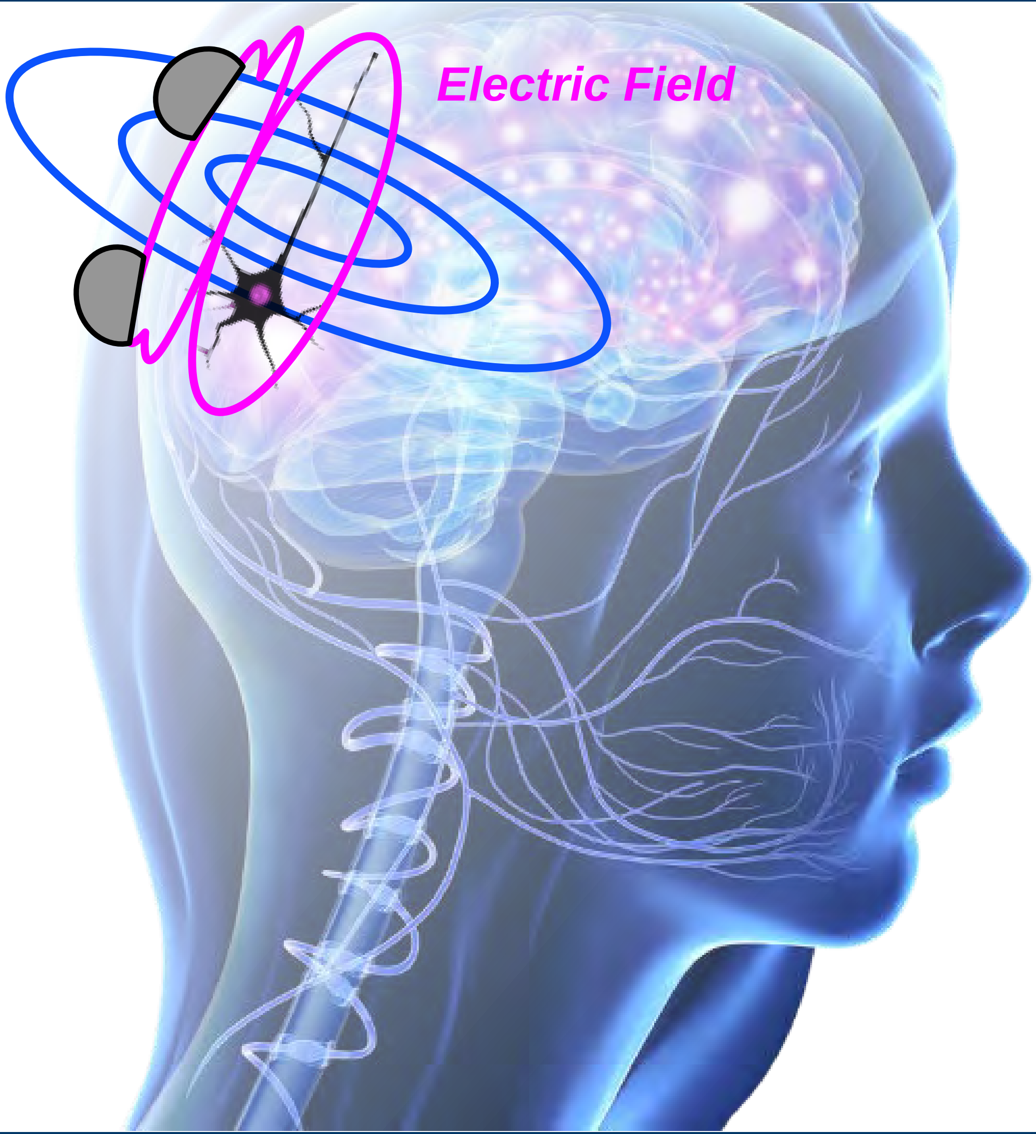
The human brain is the most complicated biological structure in the known universe. We've only just scratched the surface in understanding how it works – or, unfortunately, doesn't quite work when disorders and disease occur.

- NIH Director Francis S. Collins, M.D., Ph.D.

Brain Science



The Magnetoencephalography Signal



Neurons

- Neurons exist in complex networks throughout the brain.
- Neurons communicate via transient electrical signals.
- Bulk neuronal activity creates detectable signals.

Electrodes pick up voltage fluctuations

↓

Electroencephalography

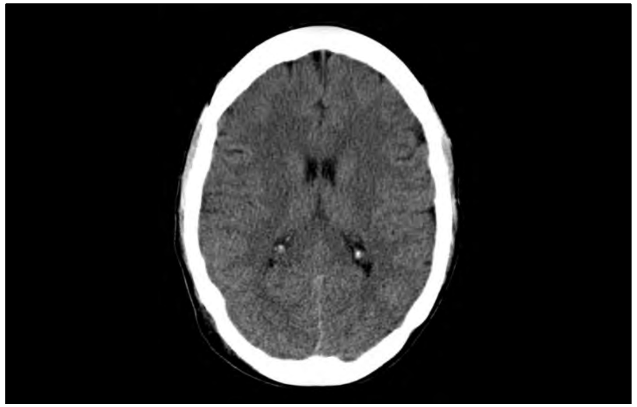
Sensitive magnetometers detect magnetic fields

↓

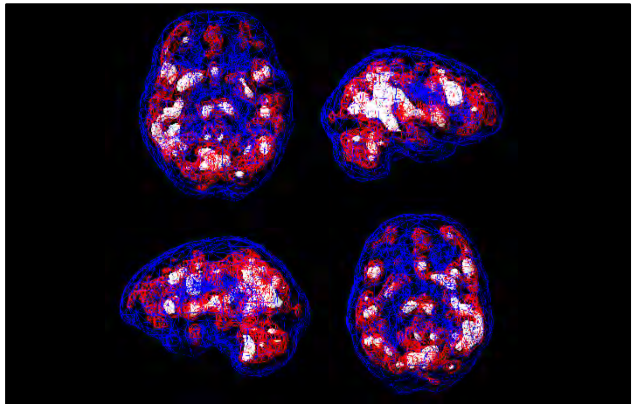
Magnetoencephalography

Clinical Brain Imaging Methods

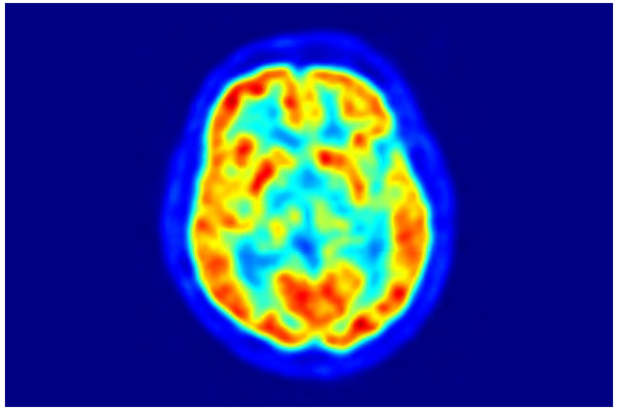
(Functional) Magnetic Resonance Imaging (fMRI/MRI)



X-ray Computed Tomography (X-ray CT)

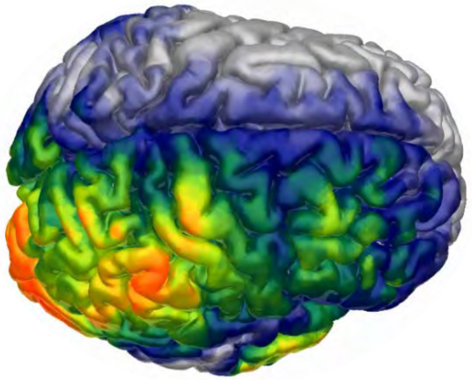


Single-Photon Emission Computed Tomography (SPECT)



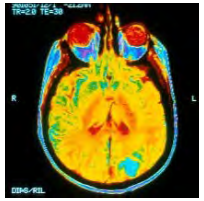
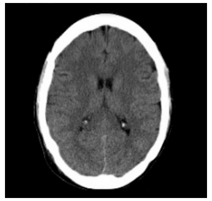
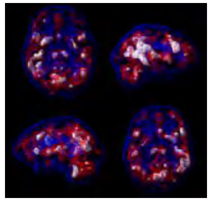
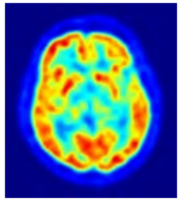
Positron Emission Tomography (PET)

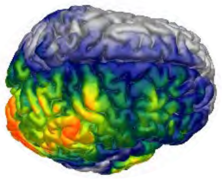
Electroencephalography (EEG)



Magnetoencephalography (MEG)

Brain Imaging Method Comparison

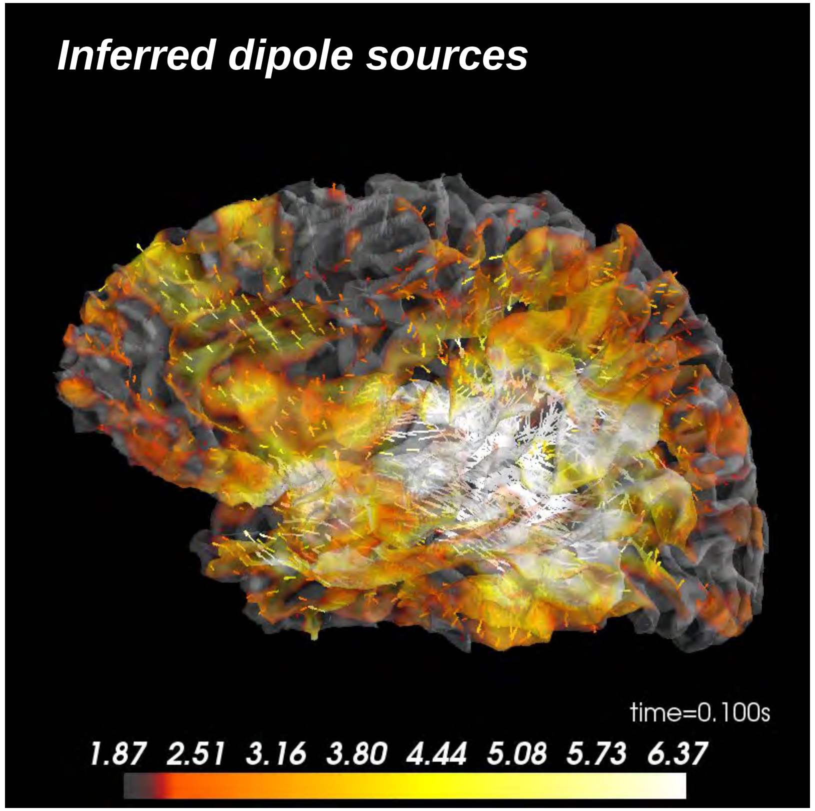







	(f)MRI	X-ray CT	SPECT	PET	EEG	MEG
Safety and Comfort	–	✗	✗	✗	–	✓
Spatial Localization	✓	✓	–	✓	–	✓
Direct Measurement of Neural Activity	–	–	–	✗	✓	✓
Full-Brain Imaging	✓	✓	✓	✓	–	–
Time Resolution	–	✗	✗	–	✓	✓

E. Lin and A. Alessio, Journal of Cardiovascular Computed Tomography 3, 403 (2009).

MEG Visualized



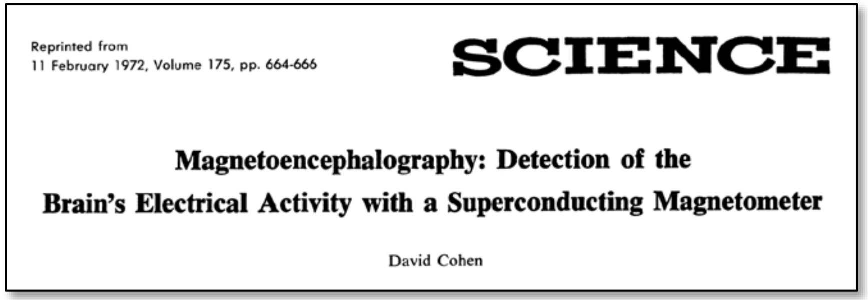
Data and visualization from MNE software package using sample data (citation below).

Courtesy of S. Pursiainen, Inverse Problems research group at Tampere University of Technology. Created using *Zeffiro Interface* ©.

A. Gramfort, M. Luessi, E. Larson, D. Engemann, D. Strohmeier, C. Brodbeck, R. Goj, M. Jas, T. Brooks, L. Parkkonen, M. Hämäläinen, MEG and EEG data analysis with MNE-Python, Frontiers in Neuroscience, Volume 7, 2013, ISSN 1662-453X

The History of Magnetoencephalography (at MIT)

Dr. David Cohen, MIT
“The Father of Biomagnetometry”



Reprinted from
11 February 1972, Volume 175, pp. 664-666

SCIENCE

Magnetoencephalography: Detection of the Brain’s Electrical Activity with a Superconducting Magnetometer

David Cohen

Superconducting quantum interference device (SQUID)

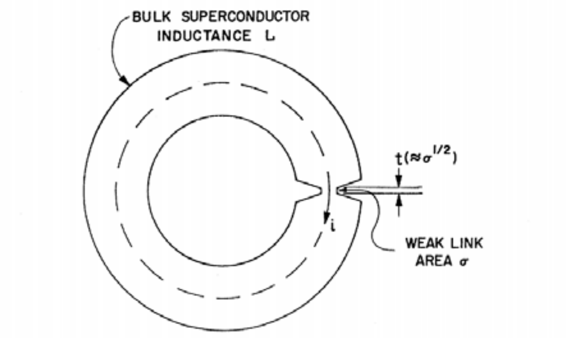
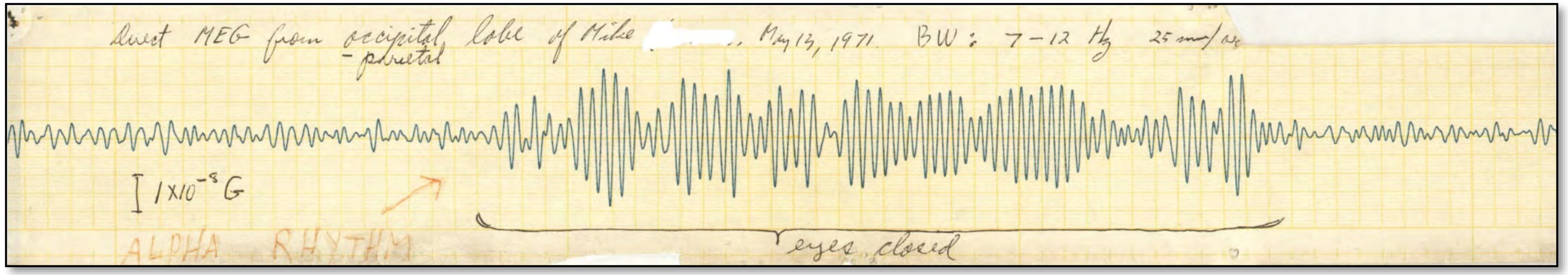


FIG. 1. Topology of a weakly connected superconducting ring. The inductance of the ring is L and the weak link has a length t, cross section σ, and maximum supercurrent i_c.



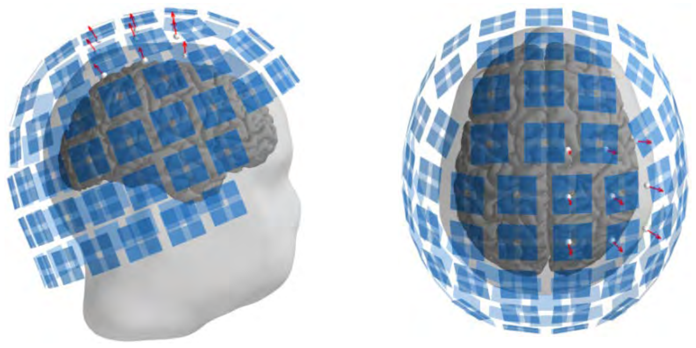
Early magnetoencephalography (1971) seen by Cohen et al.

D. Cohen, Science 175, 664 (1972).; A. H. Silver and J. E. Zimmerman, Physical Review 157, 317 (1967). www.davidcohen.mit.edu.

Magnetoencephalography Today

Elekta Neuromag® TRIUX™

SQUID Sensor Array



Less than 200 clinical MEG facilities exist worldwide.

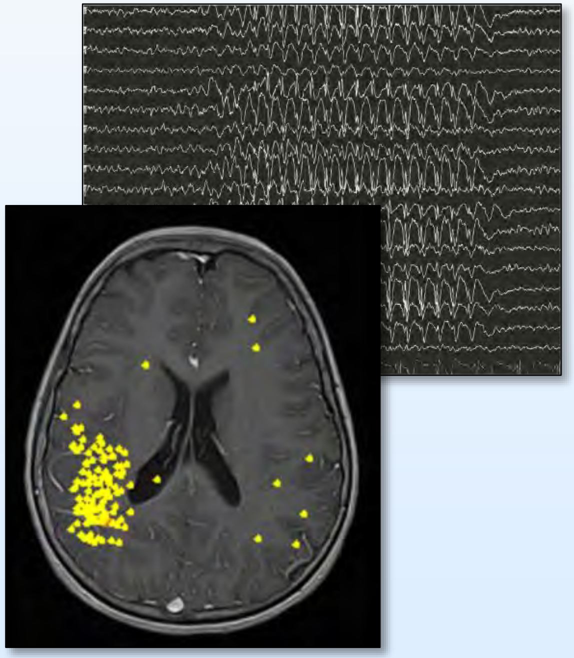
Magnetically Shielded Room

SQUID: Superconducting Quantum Interference Device

Clinical MEG

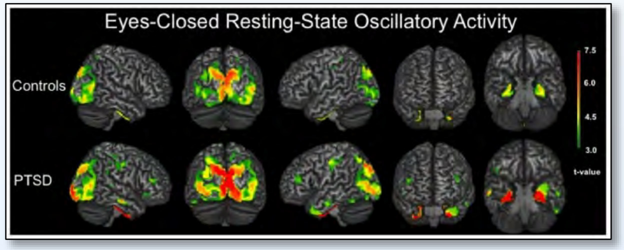
Epilepsy

Localization of Epileptic Spikes within the Brain



Post-Traumatic Stress Disorder

Disease Identification and Localization




SCIENTIFIC AMERICAN.

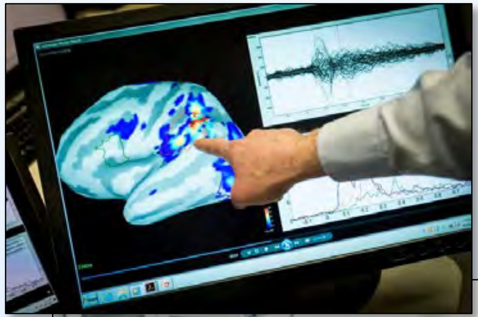
HEALTH

Brain Scan Offers First Biological Test in Diagnosis of Post-Traumatic Stress Disorder

Researchers use a brain-scanning technique to find differences in the neural connections of PTSD patients that could help researchers understand and treat the disorder

Presurgical Functional Mapping

Identification of Abnormally Functioning Areas



S. M. Stufflebeam, Neurosurgery Clinics of North America 22, 153 (2011). S. P. Ahlfors and M. Mody, Organizational Research Methods 22, 95 (2016).

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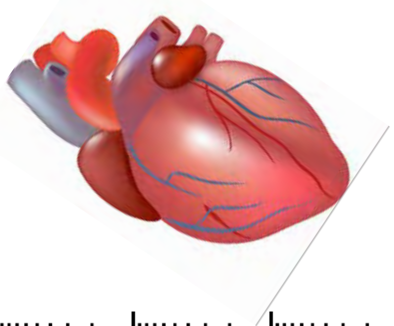
Magnetic Field Scales

Superconducting MRI[1] magnet

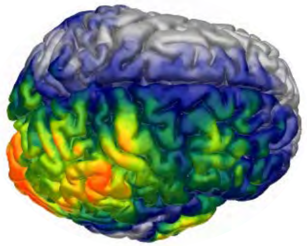
Earth's (core) magnetic field

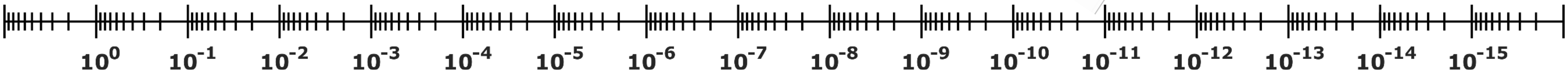
Urban magnetic noise

Magneto-cardiography



Magneto-encephalography





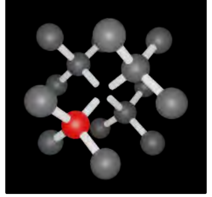
← **Magnetic Field (Tesla)** →

Commercially available magnetometers by minimum detectable field

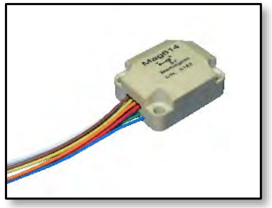
Hall Effect Sensor

Magnetoresistor

NV[2] Diamond



Fluxgate



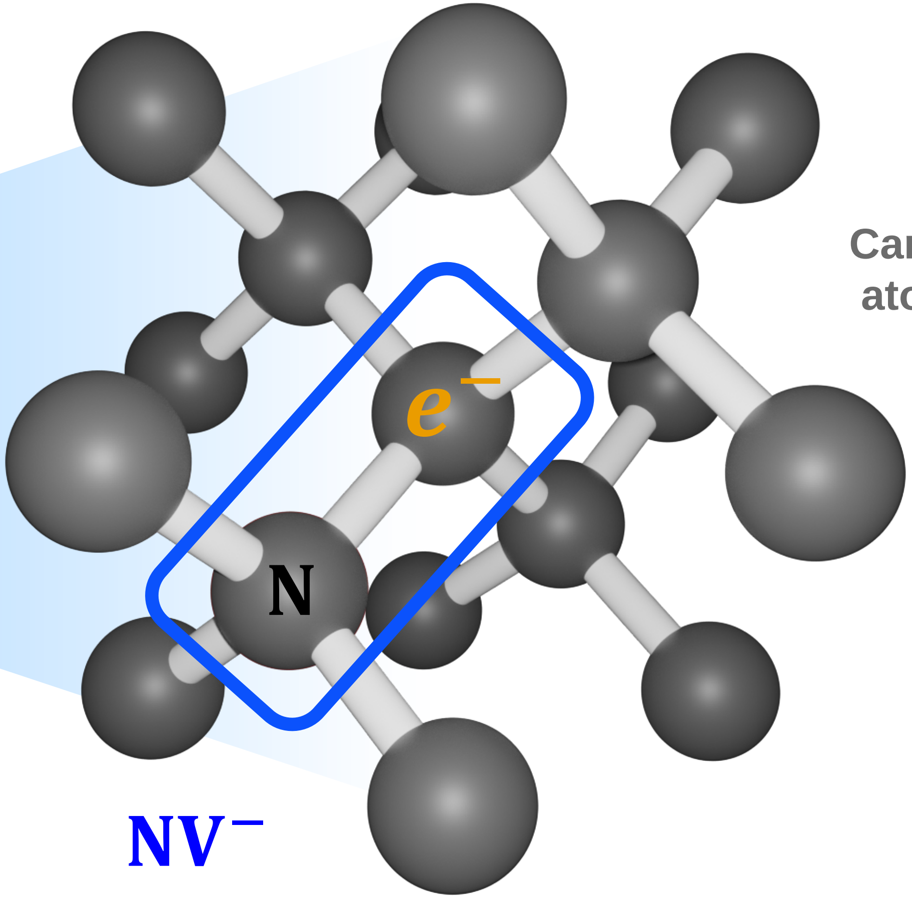
Atomic Vapor Cell

SQUID[3]

[1]MRI: Magnetic Resonance Imaging; [2]NV: Nitrogen Vacancy; [3]SQUID: Superconducting Quantum Interference Device

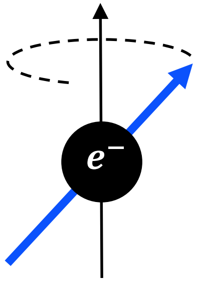
Quantum Sensors: Nitrogen-Vacancies in Diamond

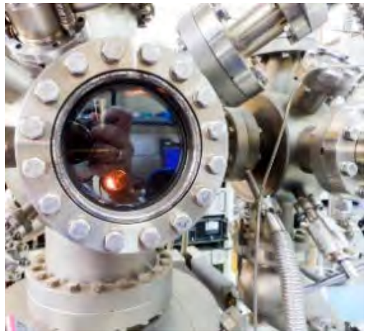
Diamond



Advantages of a Solid State Device

Measurements Tied to Fundamental Constants



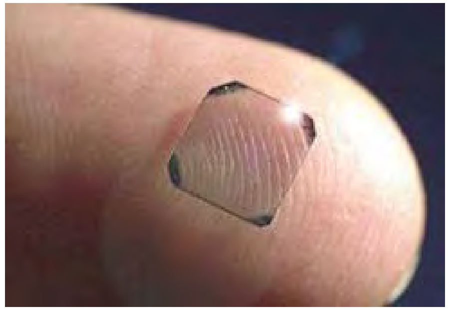


No Vacuum

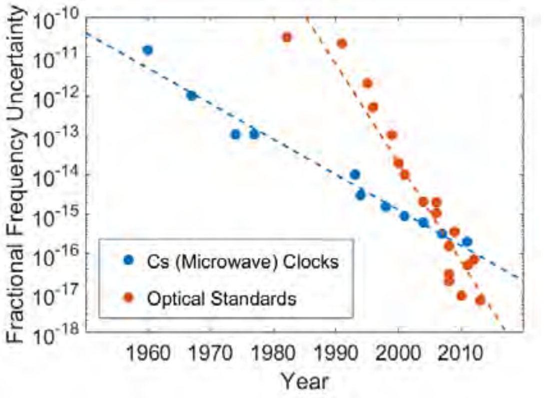
No Fancy Lasers

No Cryogenics

Sub-centimeter Scale

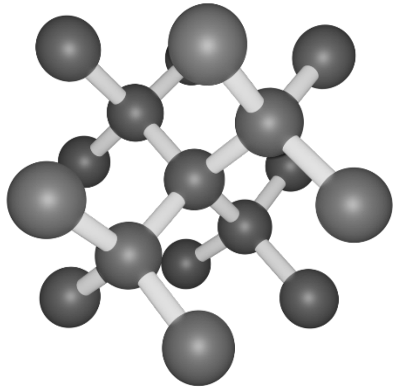


Superb Precision Measurement Capability



Mature Semiconductor Processes

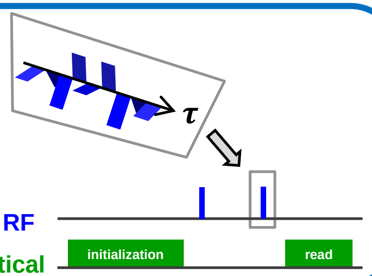
Fixed Crystallographic Axes (Reliable Vector Sensitivity)



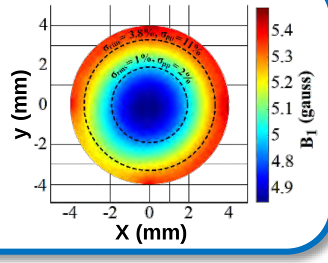
N. Poli, C. W. Oates, P. Gill, and G. M. Tino, La Rivista Del Nuovo Cimento 036, 555 (2013).

MIT LL Unique Diamond Technology Platform

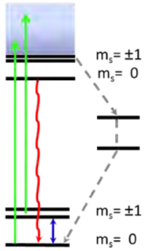
Pulse Sequence Design

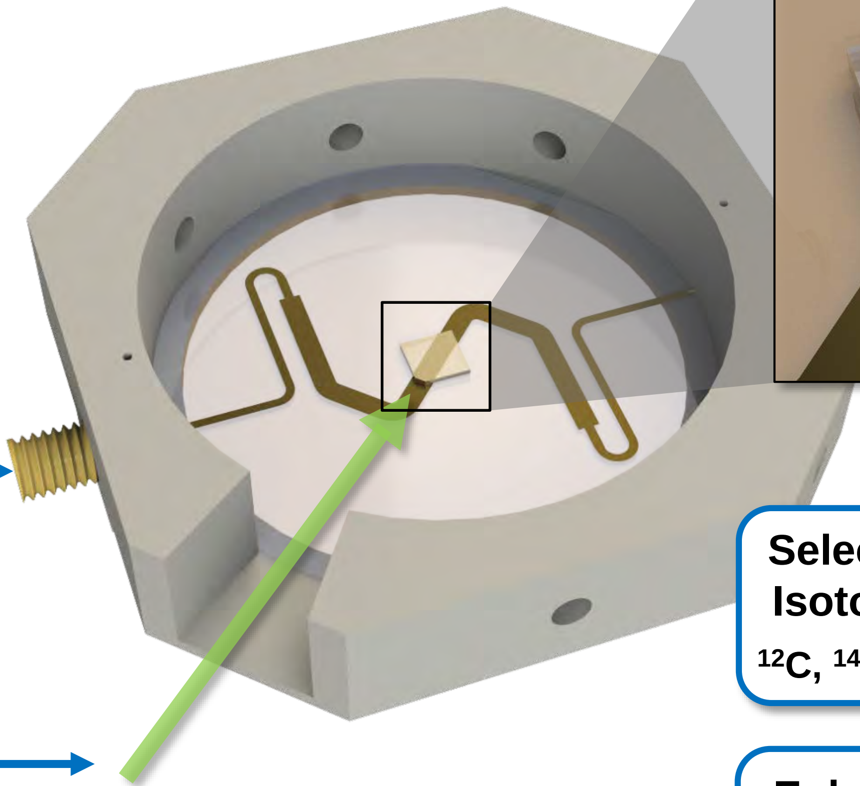


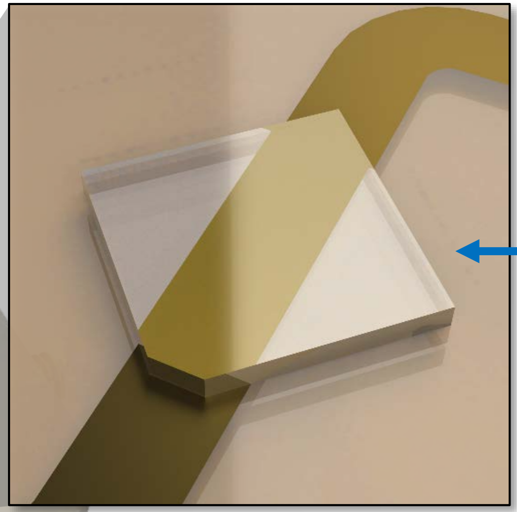
RF Engineering



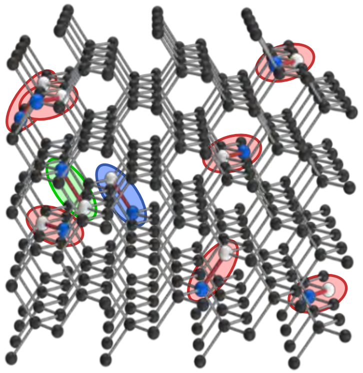
Quantum State Preparation & Measurement





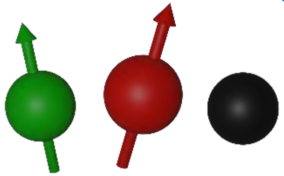


Tailored Diamond Growth

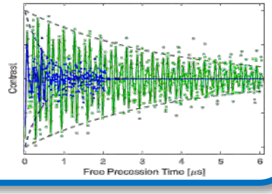


Selective Isotopes

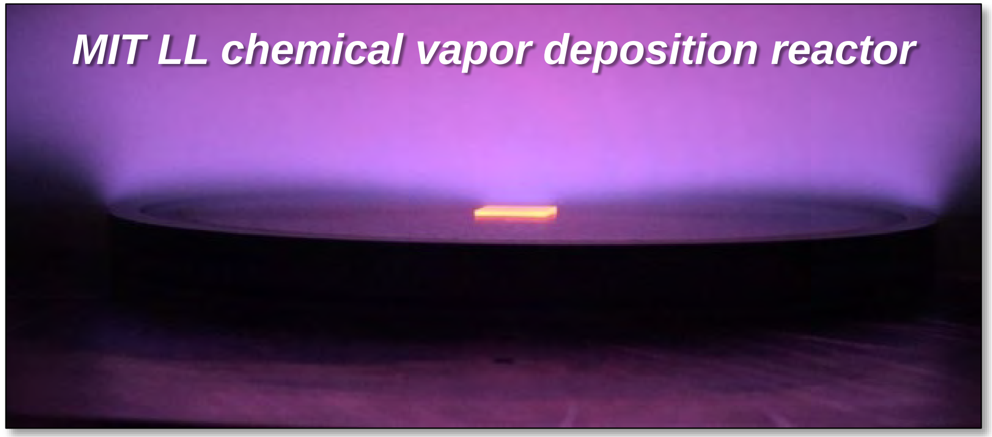
^{12}C, ^{14}N, ^{15}N



Enhanced Quantum Coherence

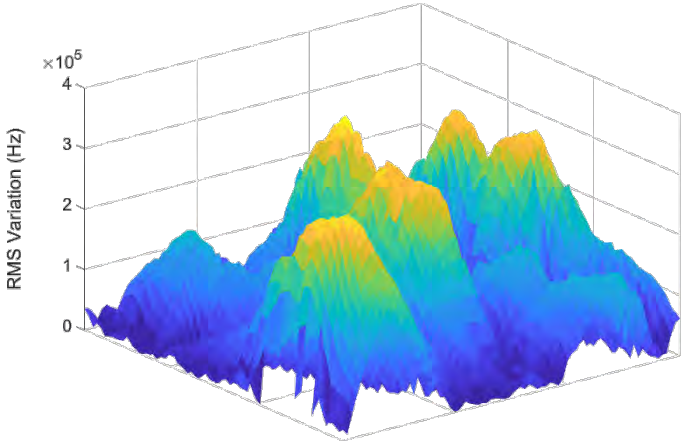


Diamond Engineering



In-House Characterization Capabilities

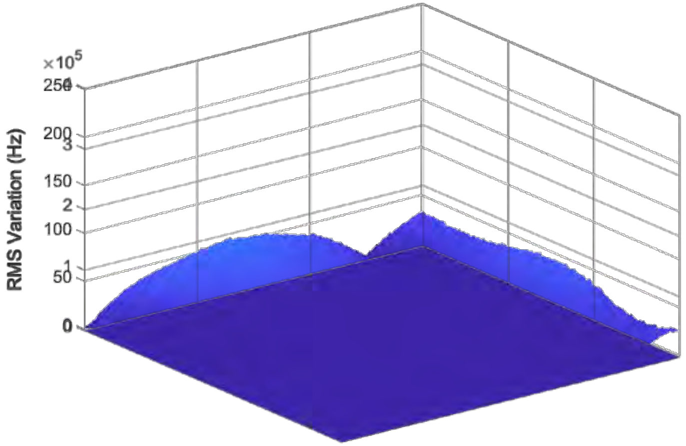
Commercial Diamond



Inhomogeneous Strain Degrades Sensor Performance

Optimized growth and processing

MIT LL Diamond

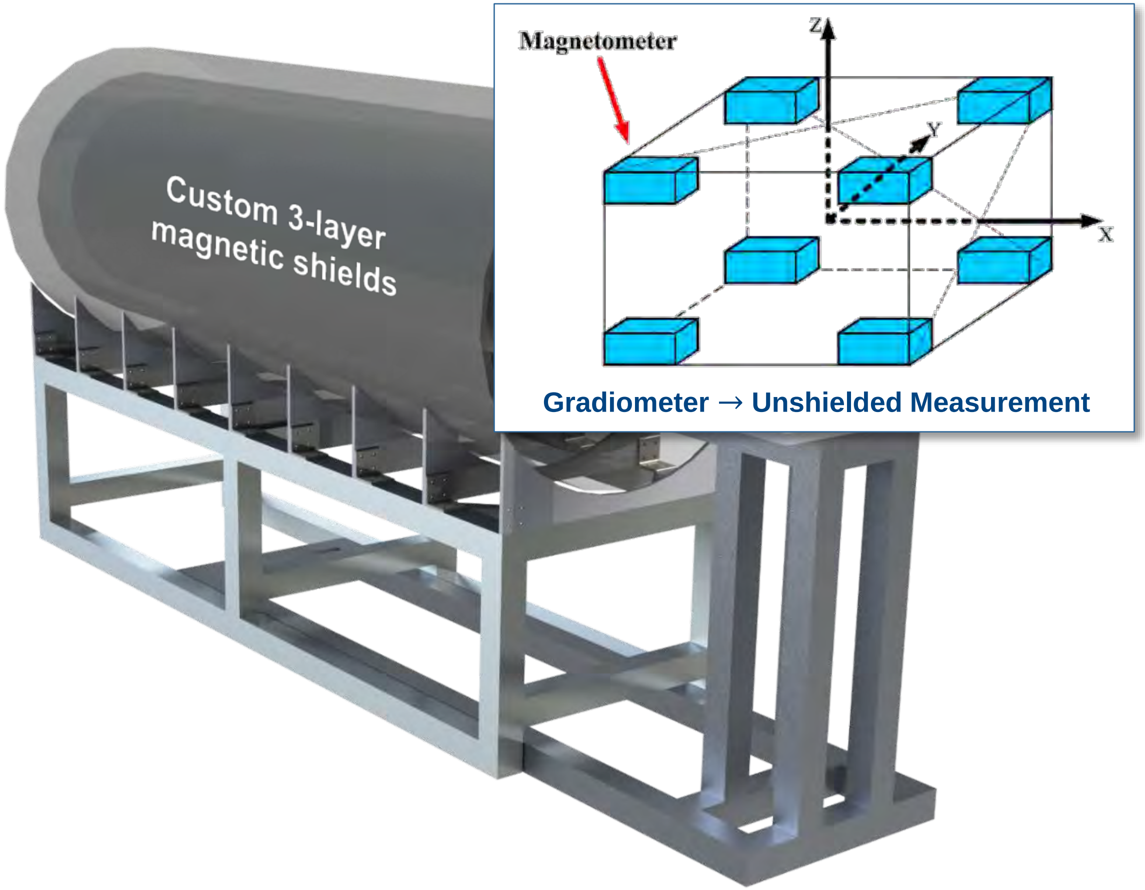


[1]EPR: Electron paramagnetic resonance spectroscopy; [2]PL: Photoluminescence spectroscopy; [3]FTIR: Fourier-transform infrared spectroscopy

MIT LL Shield System

Shielded Room: $1M

MIT LL Shields: < $50k



C. Wang, X. Zhang, X. Qu, X. Pan, G. Fang, and L. Chen, Sensors 16, 2168 (2016).

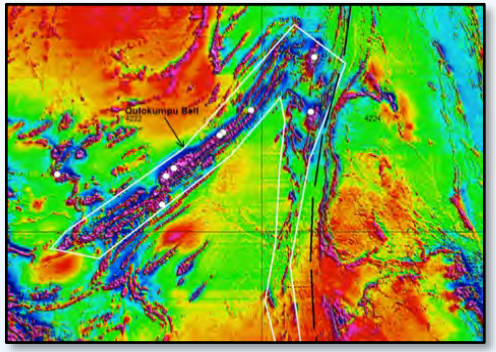
Technology Outlook

NV Diamond Biomagnetometry

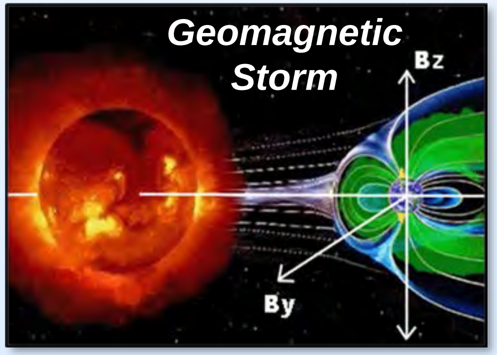
Magneto-cardiography

Single-sensor MEG

Potential New Applications



Navigation via Magnetic Maps



Space Weather Sensing

Acknowledgements

MIT LL Quantum Sensing Team

Back: John Barry, Alex Zhang, Erik Eisenach, Matt Steinecker, Mike O'Keeffe

Front: Linh Pham, Jonah Majumder, Erik Thompson, Danielle Braje, Alexandra Day, Chuck Wuorio

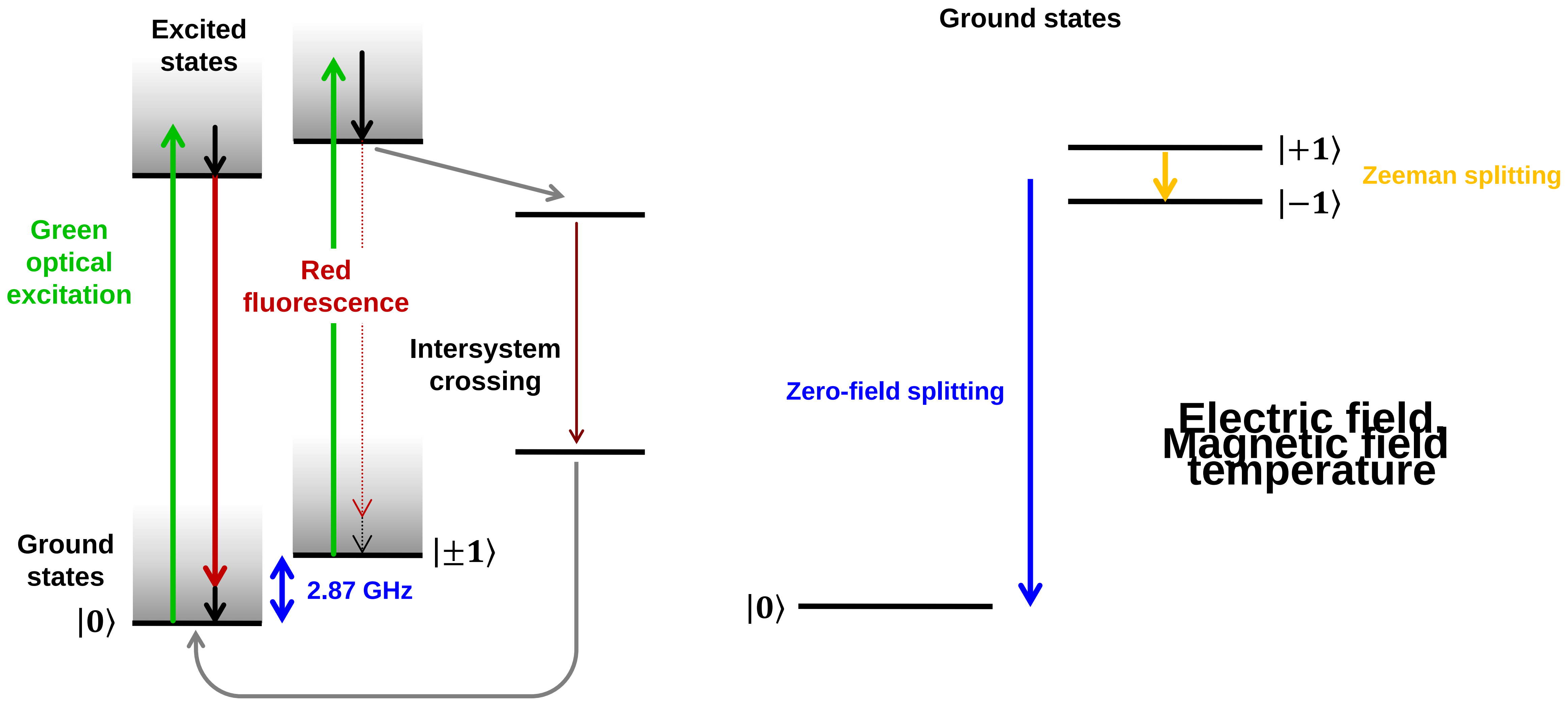
Not pictured: Christopher Foy, Scott Alsid, Reggie Wilcox

Mass General Hospital

Matti Hämäläinen

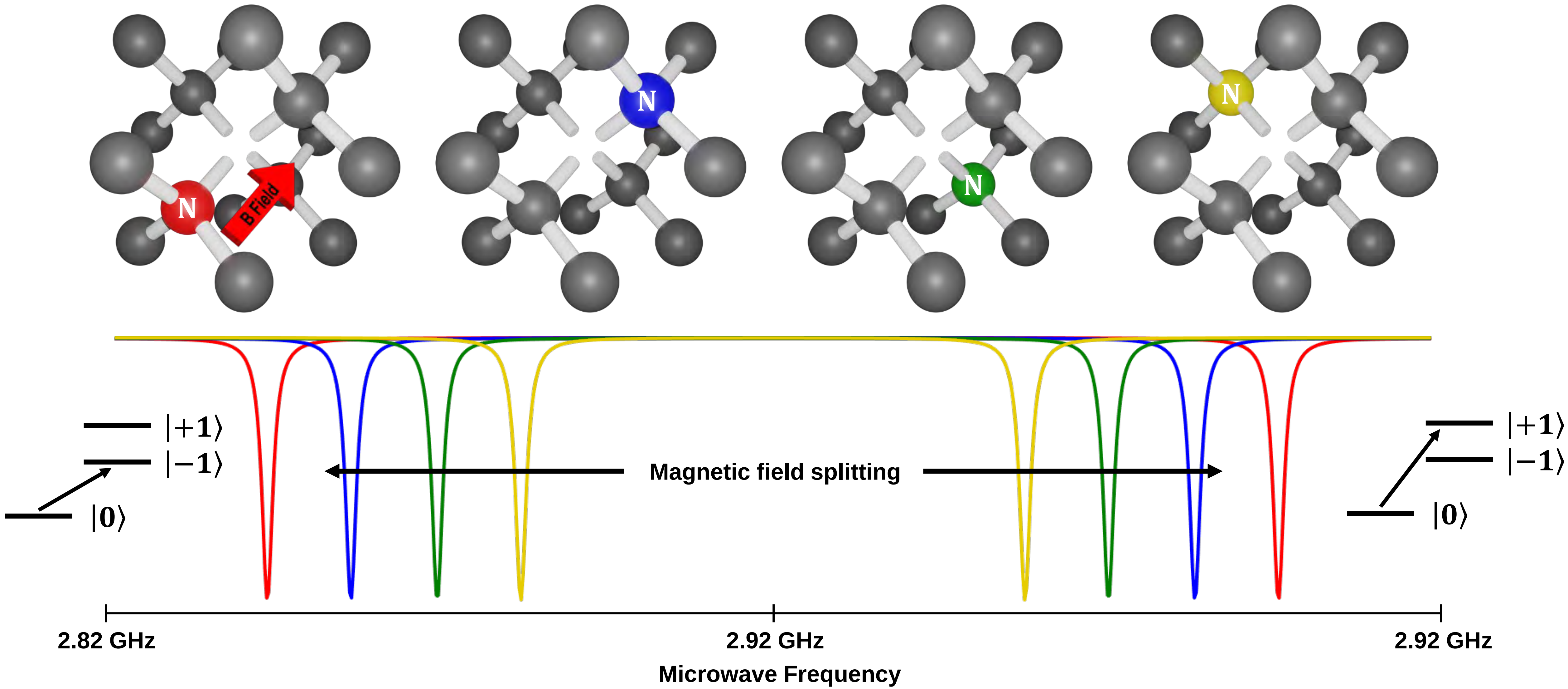
Seppo Ahlfors

Energy Levels of the Nitrogen-Vacancy Center



Electric field, Magnetic field temperature

Inherent Vector Sensitivity



Pushing the Nitrogen-Vacancy's Sensitivity

$$\underset{\text{(optical shot noise)}}{B_{min}} = \underbrace{\frac{\hbar}{g_e \mu_B}\left(\frac{1}{\Delta m_s \sqrt{N\tau}}\right)}_{\text{Spin-projection noise}} \times \boxed{\underbrace{\frac{1}{e^{-\left(\frac{\tau}{T_2^*}\right)^p}}}_{\text{Inhomogeneous dephasing}}} \times \underbrace{\frac{1}{\mathcal{F}_R}}_{\text{Readout fidelity}} \times \underbrace{\sqrt{\frac{t_{over}+\tau}{\tau}}}_{\text{Measurement overhead}}$$