Quantum Sensing for Precision Measurement

Applications to Physical and Life Sciences

Ronald Walsworth

Quantum Technology Center (QTC)

UNIVERSITY OF MARYLAND

A long game…with great opportunity

Precision measurement tools

High-impact applications

10 – 20 years

Publicly available image

Three illustrations…

Past

Present

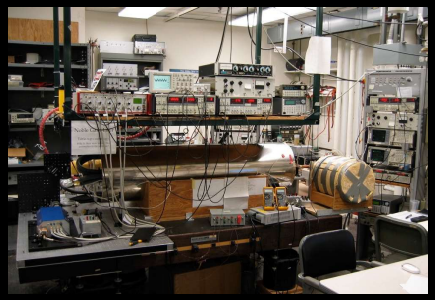
Future

Long game

Publicly available image

Three illustrations…

Past



Atomic test of
Lorentz symmetry

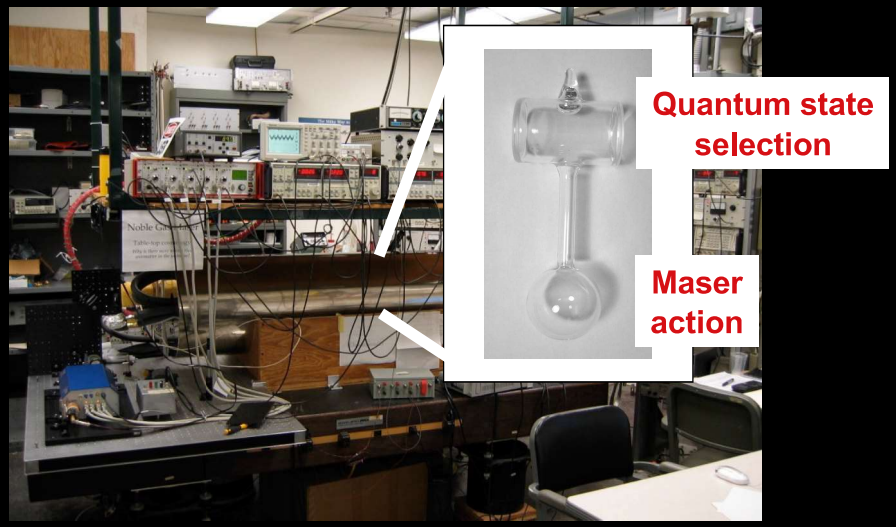
Portable
low-cost MRI

Long game

Images publicly available or from Walsworth & collaborators

Atomic test of Lorentz symmetry — 1990s

Co-located ^{3}He & ^{129}Xe NMR masers

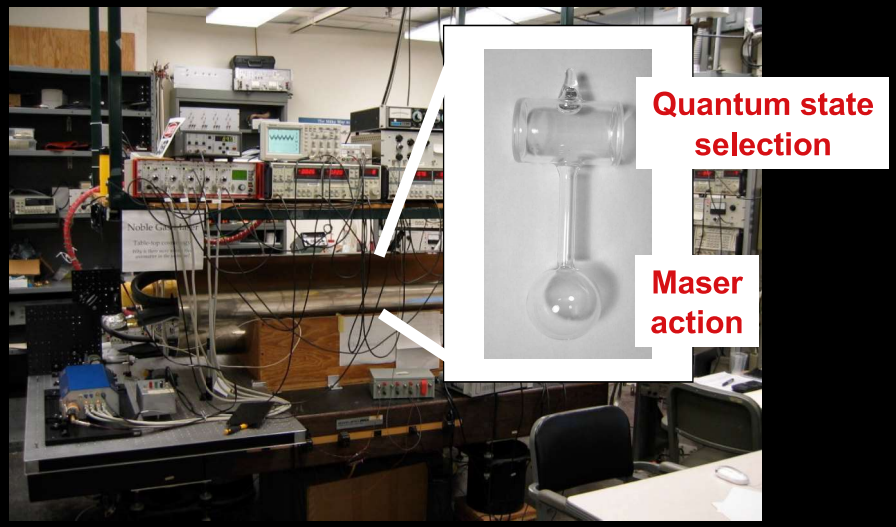


Nanohertz precision NMR
@ low magnetic field (0.2 mT)

Images from Walsworth & collaborators

Atomic test of Lorentz symmetry — 1990s

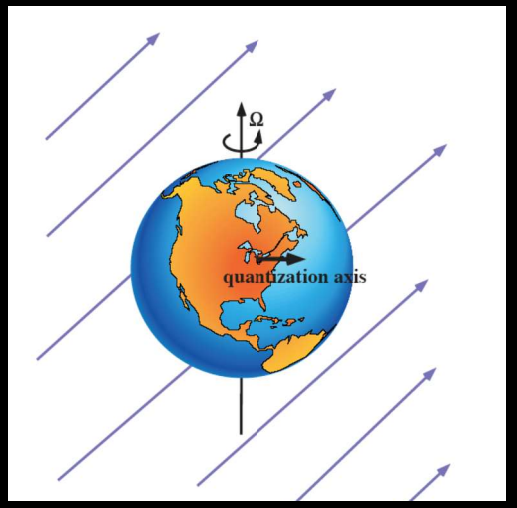
Co-located ^{3}He & ^{129}Xe NMR masers



Nanohertz precision NMR
@ low magnetic field (0.2 mT)

Images from Walsworth & collaborators

Monitor maser frequencies for sidereal modulation



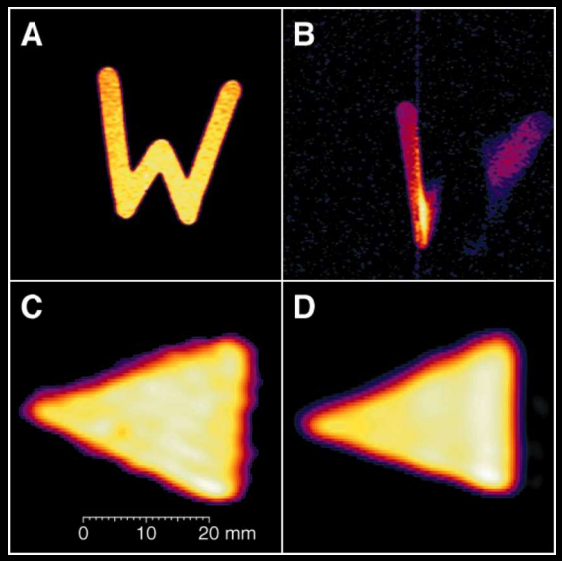
Limit of Lorentz violating coupling to neutron ~10^{-31} GeV

Physical Review Letters (2000)
Physical Review Letters (2004)

Demo high-resolution low-field MRI — late 1990s

At Brigham & Women's Hospital

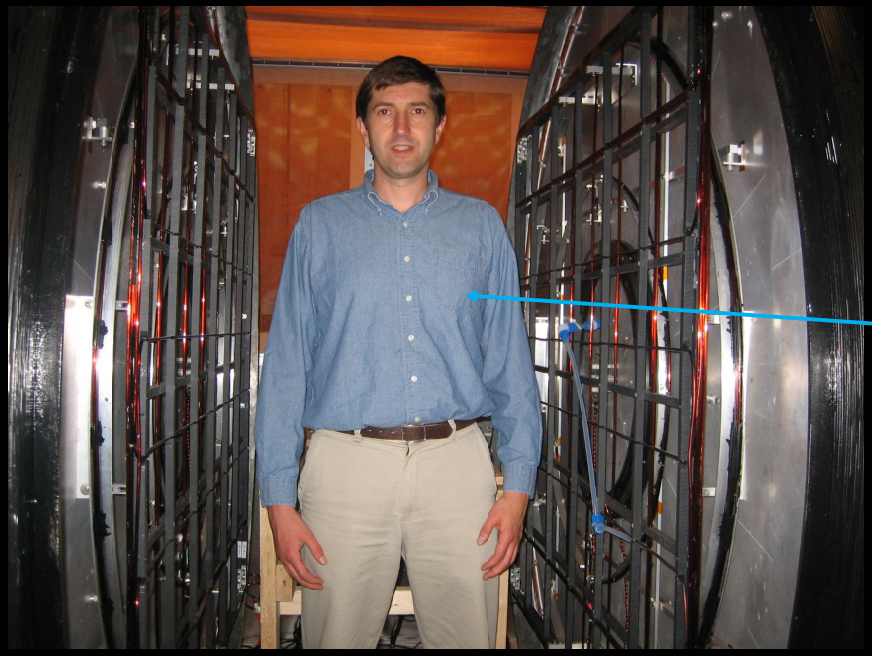
MRI of hyperpolarized ^{3}He gas @2 mT



Physical Review Letters (1998)

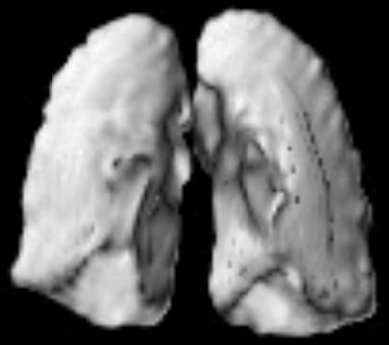
Images from Walsworth & collaborators

Human low-field MRI (physics lab) — 2000s



Walk-in MRI in physics lab

MRI of inhaled hyperpolarized ^{3}He gas @6.5 mT

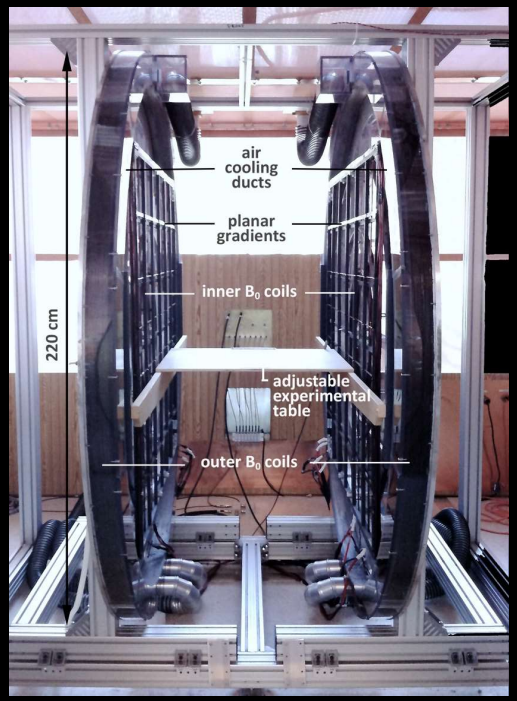


Magnetic Resonance in Medicine (2005)
Journal of Magnetic Resonance (2008)
Academic Radiology (2008)

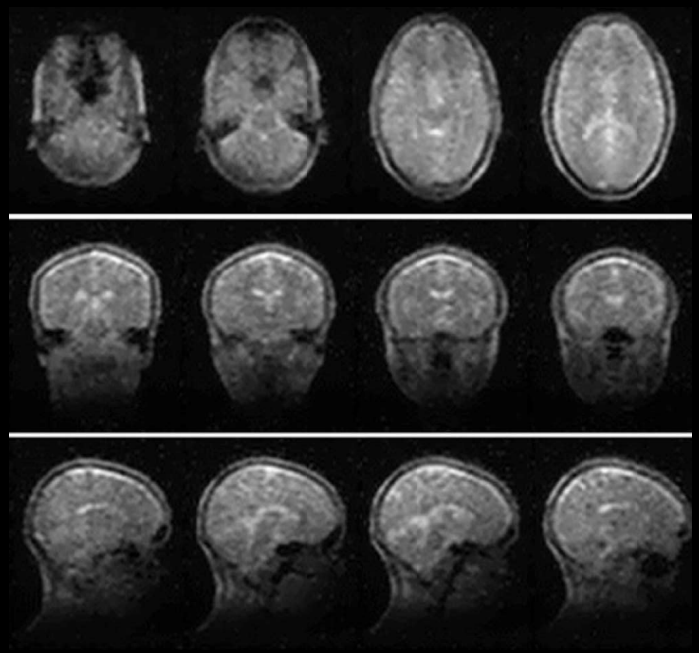
Images from Walsworth & collaborators

Low-field human brain MRI — mid 2010s

Matt Rosen



Walk-in MRI at Mass General Hospital



Scientific Reports (2015)

From institutional subscription

HYPERFINE

"Swoop"

Co-founders:

Jonathan Rothberg

Matt Rosen

Ron Walsworth

Portable low-field human MRI

FDA approved

10x lower cost

Publicly available image

2020 — COVID patients in ICU

Figure 1. Point-of-Care Magnetic Resonance Images (0.064 T) in an Intensive Care Unit Room

A Intensive care unit equipment

B Bedside point-of-care magnetic resonance imaging

All intensive care unit equipment, including ventilators, pumps, and monitoring devices, as well as the point-of-care magnetic resonance image operator and bedside nurse, remained in the room. All equipment was operational during scanning.

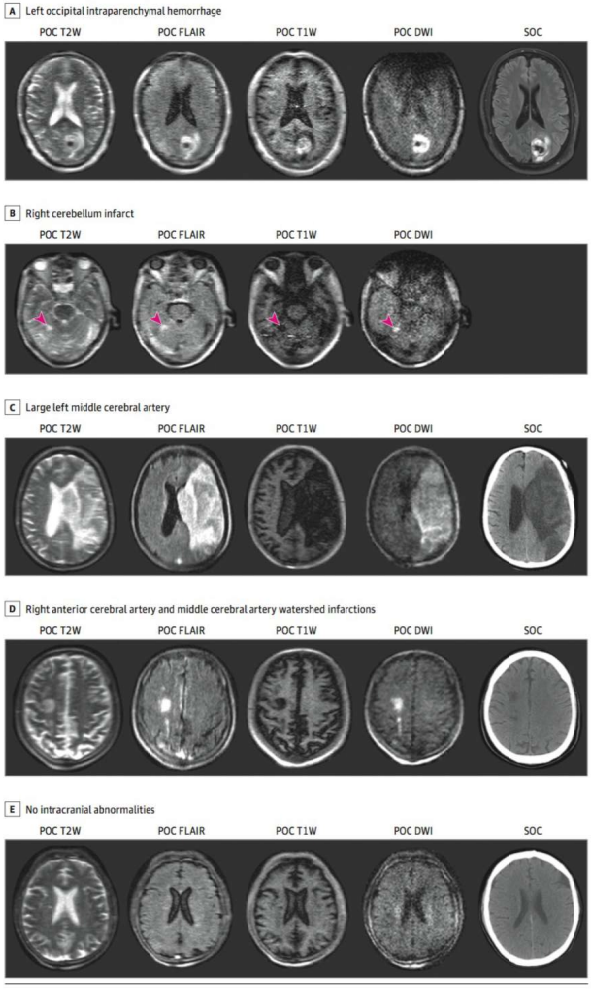
JAMA Neurology Published online September 8, 2020 jamaneurology.com

JAMA Neurology (2020)

From institutional subscription

COVID patients in ICU

Figure 2. Examples of Point-of-Care (POC) Magnetic Resonance Imaging (MRI) vs Standard-of-Care (SOC) Imaging in 5 Patients



) in an Intensive Care Unit Room

B Bedside point-of-care magnetic resonance imaging

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al during scanning.

jamaneurology.com

JAMA Neurology (2020)

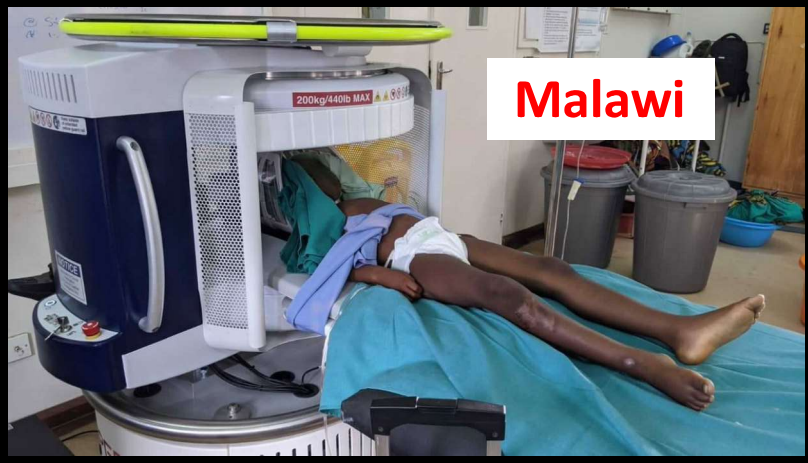
From institutional subscription

***Science* (2023)**

Hyperfine's Swoop, the first U.S. FDA–approved low-field brain scanner, can be wheeled to a patient's bedside.

MRI FOR ALL

3/4 of world does not have access to medical imaging



Images publicly available or from institutional subscription

Three illustrations…

Present

Quantum defects in solid-state host

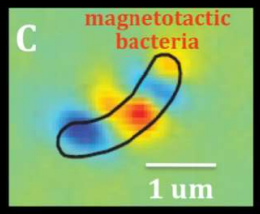
Nitrogen vacancy (NV) center in diamond

Long game

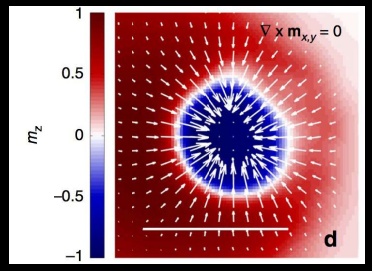
Publicly available images

NV-diamond sensing highlights

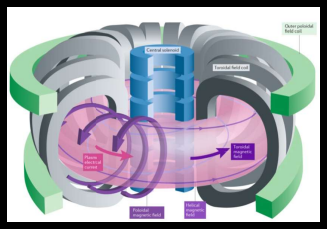
Live cell magnetic imaging



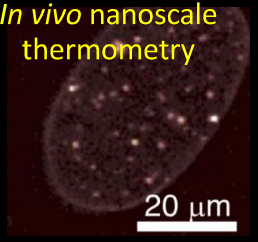
Materials science



Harsh environments



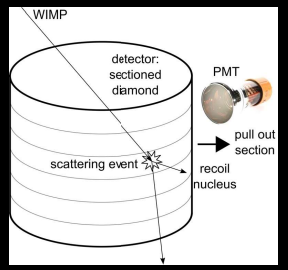
In vivo nanoscale thermometry



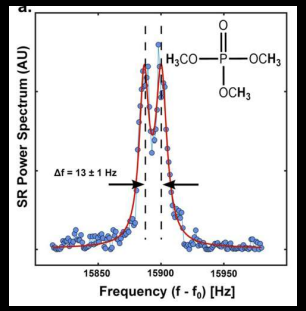
Platform quantum sensor

Object detection & GPS-free navigation

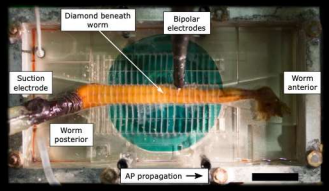
Rare particle detection



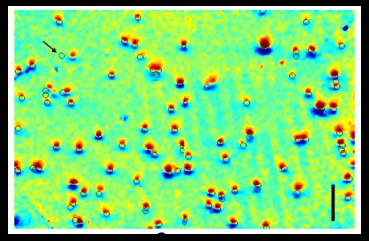
NMR/MRI of single cells and molecules



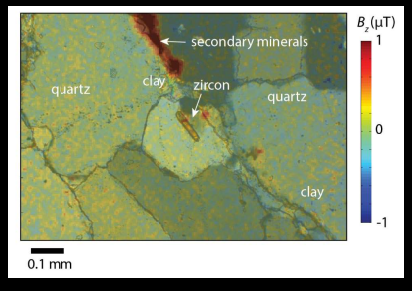
Neuroscience



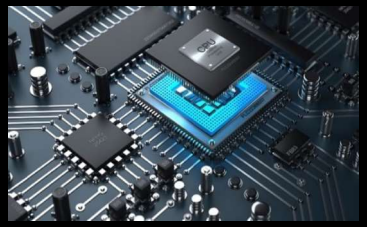
Clinical bioassay

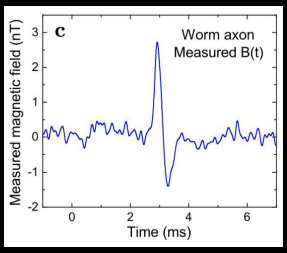


Geoscience

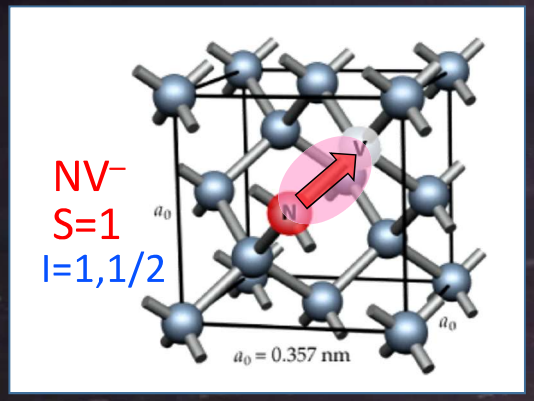


Electronics analysis





Images publicly available or from Walsworth & collaborators

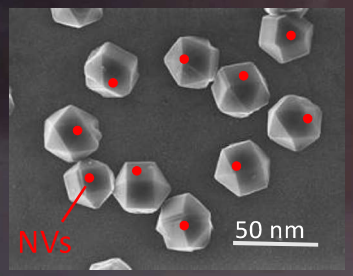


- Like an atom held in an inert solid
- Quantized energy levels
- Single-photon emitter
- Electronic & nuclear spin
- Operates at ambient & extreme conditions

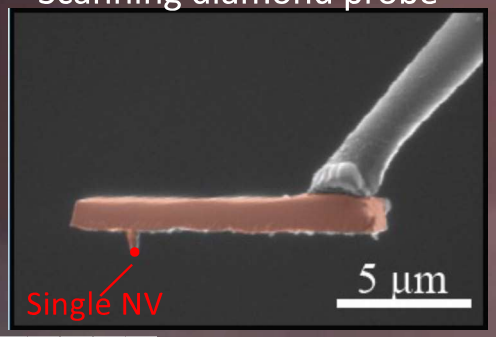
Nitrogen-Vacancy (NV)
color center

Bulk diamond

Nanodiamonds



Scanning diamond probe

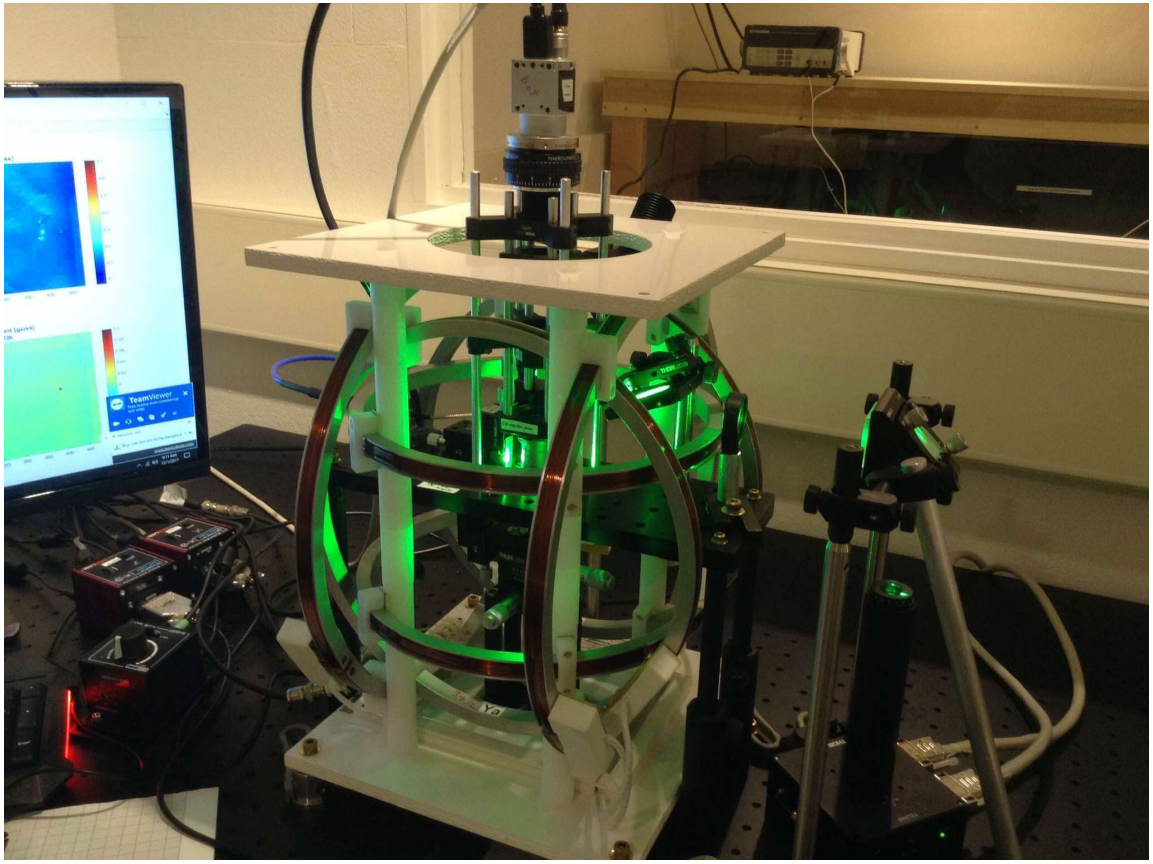


Red light emission =>

Sensitive probe of
magnetic & electric fields, temperature, pressure
with nanoscale resolution

Images publicly available or from Walsworth & collaborators

Quantum diamond microscope (QDM)



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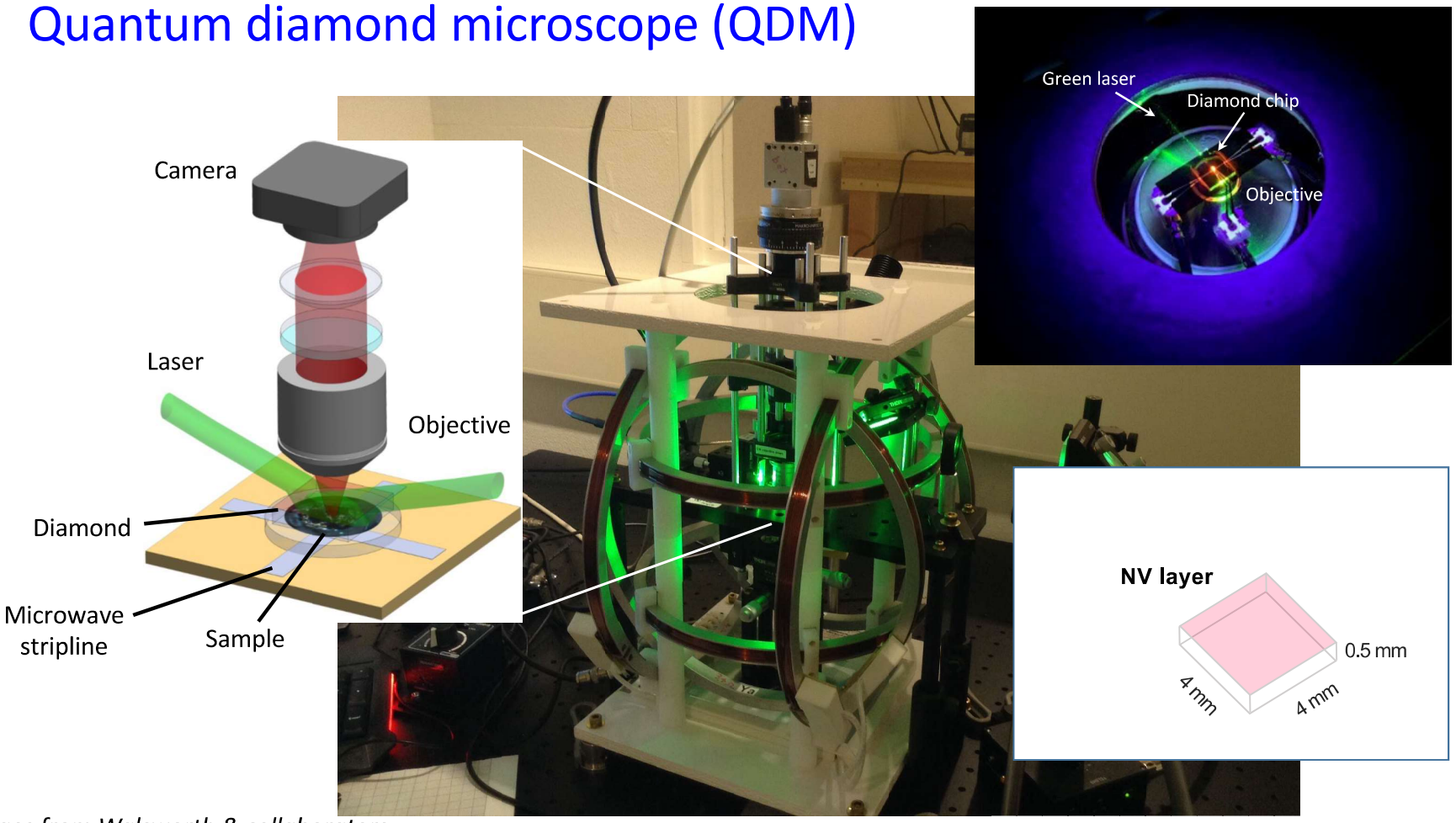

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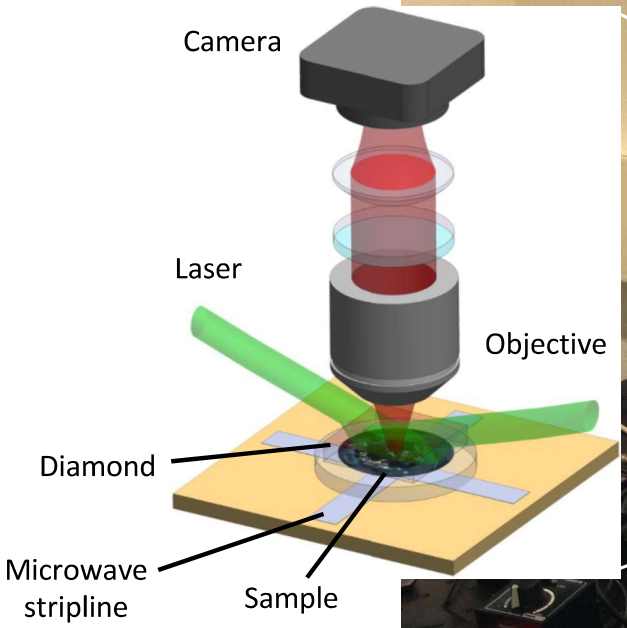
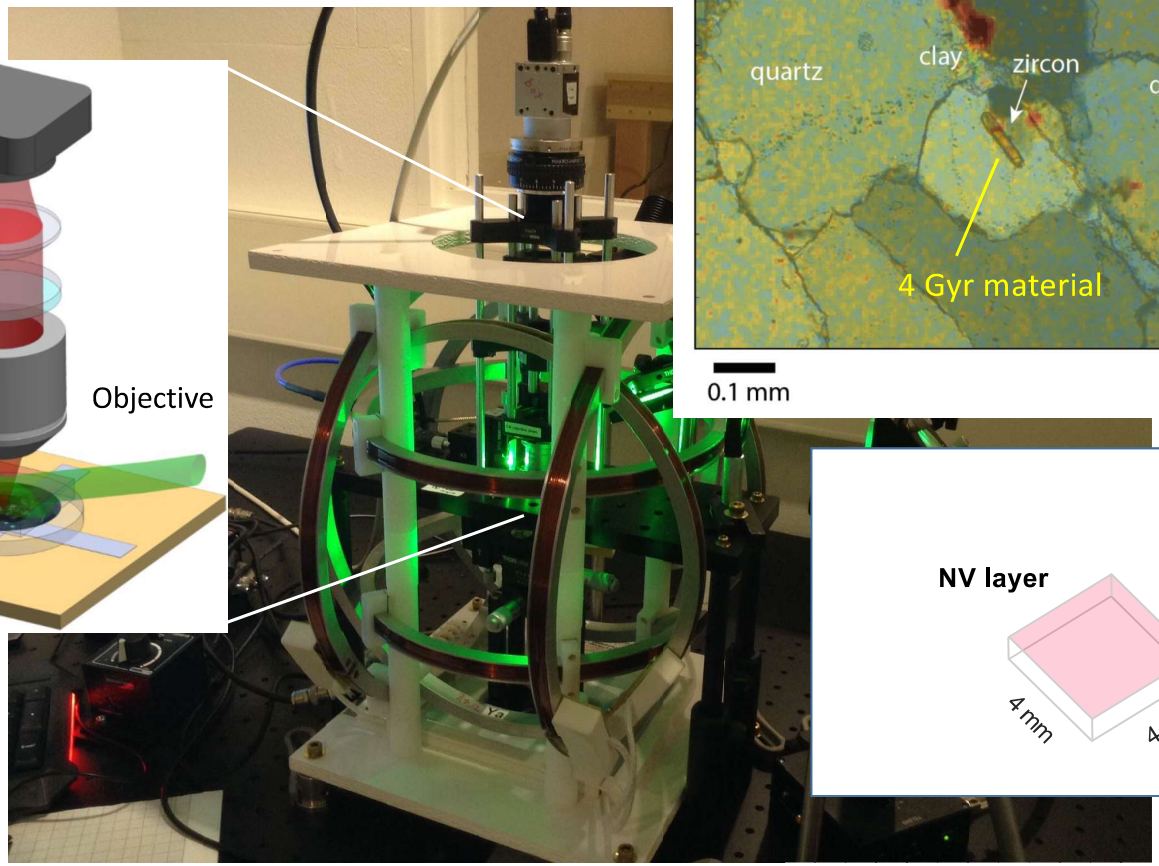
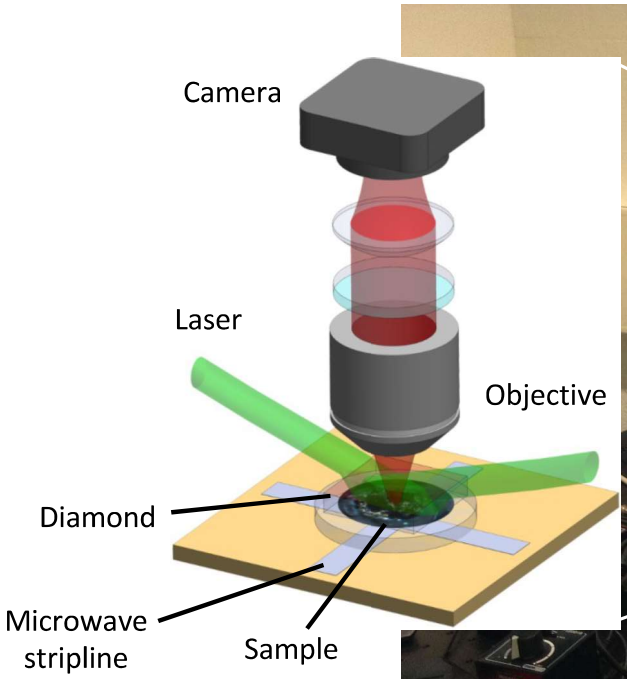


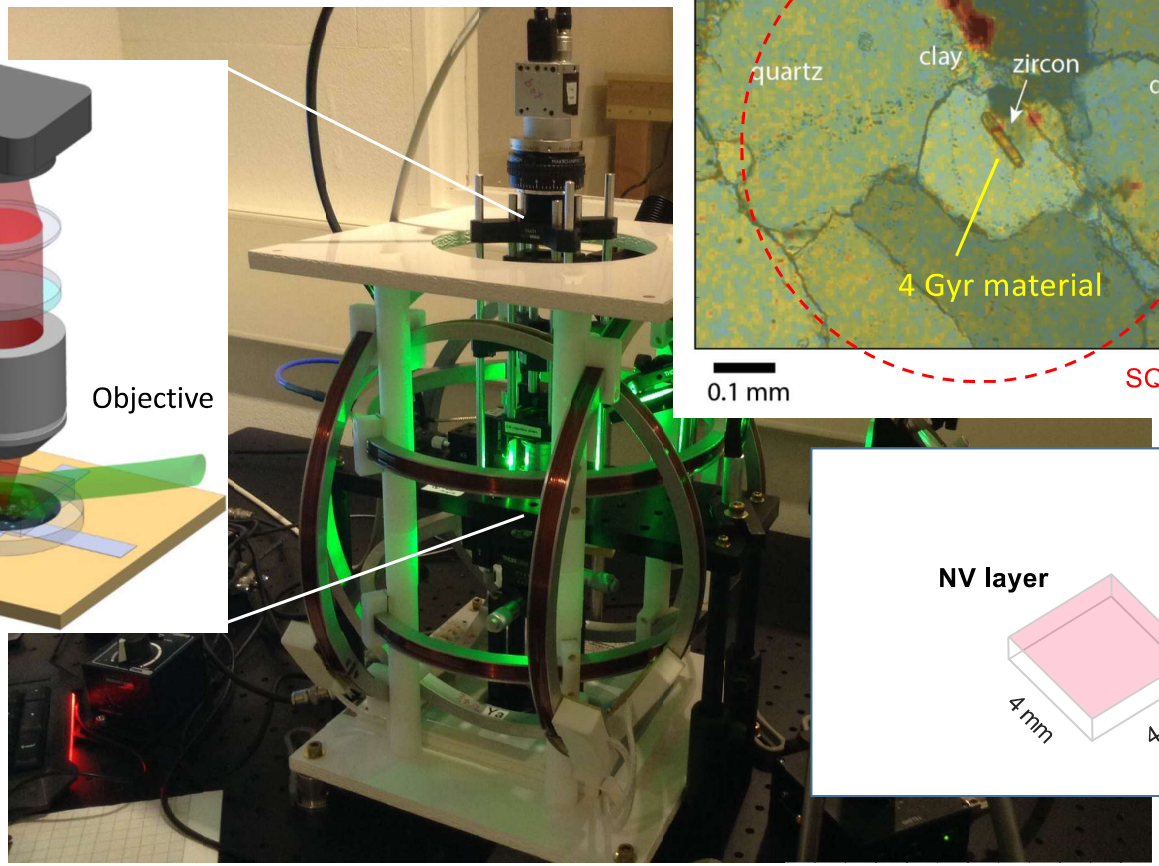


Ancient rocks & meteorites

Images from Walsworth & collaborators

Quantum diamond microscope (QDM)

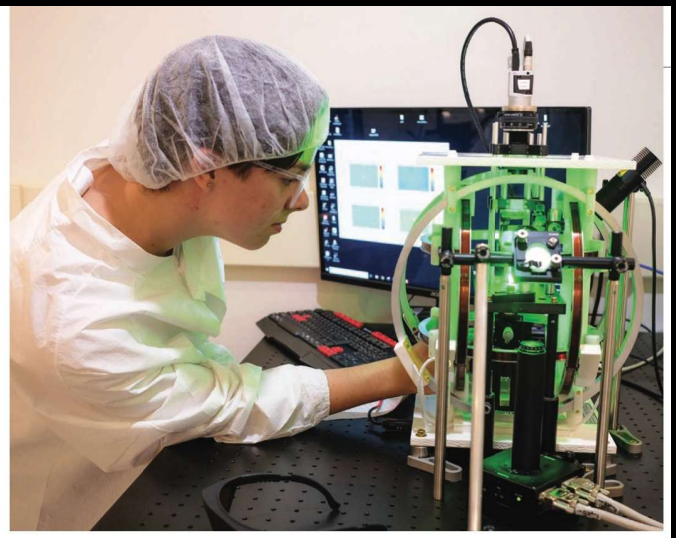




Ancient rocks & meteorites

Images from Walsworth & collaborators

Science (2020)



EARTH SCIENCE

Diamond microscope unlocks ancient rocks' magnetic secrets

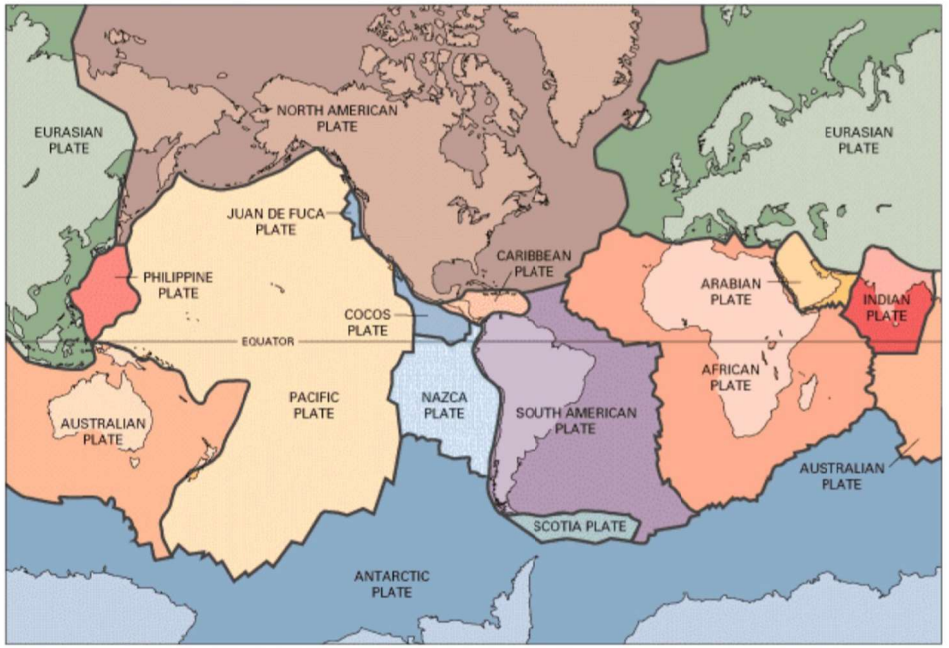
Quantum sensor reveals clues about plate tectonics, planet formation, and climate change with exquisite resolution

From institutional subscription

Harvard researchers find evidence of tectonic plates billions of years ago

By Martin Finucane Globe Staff, Updated October 26, 2022, 8:10 a.m.

PNAS (2022)

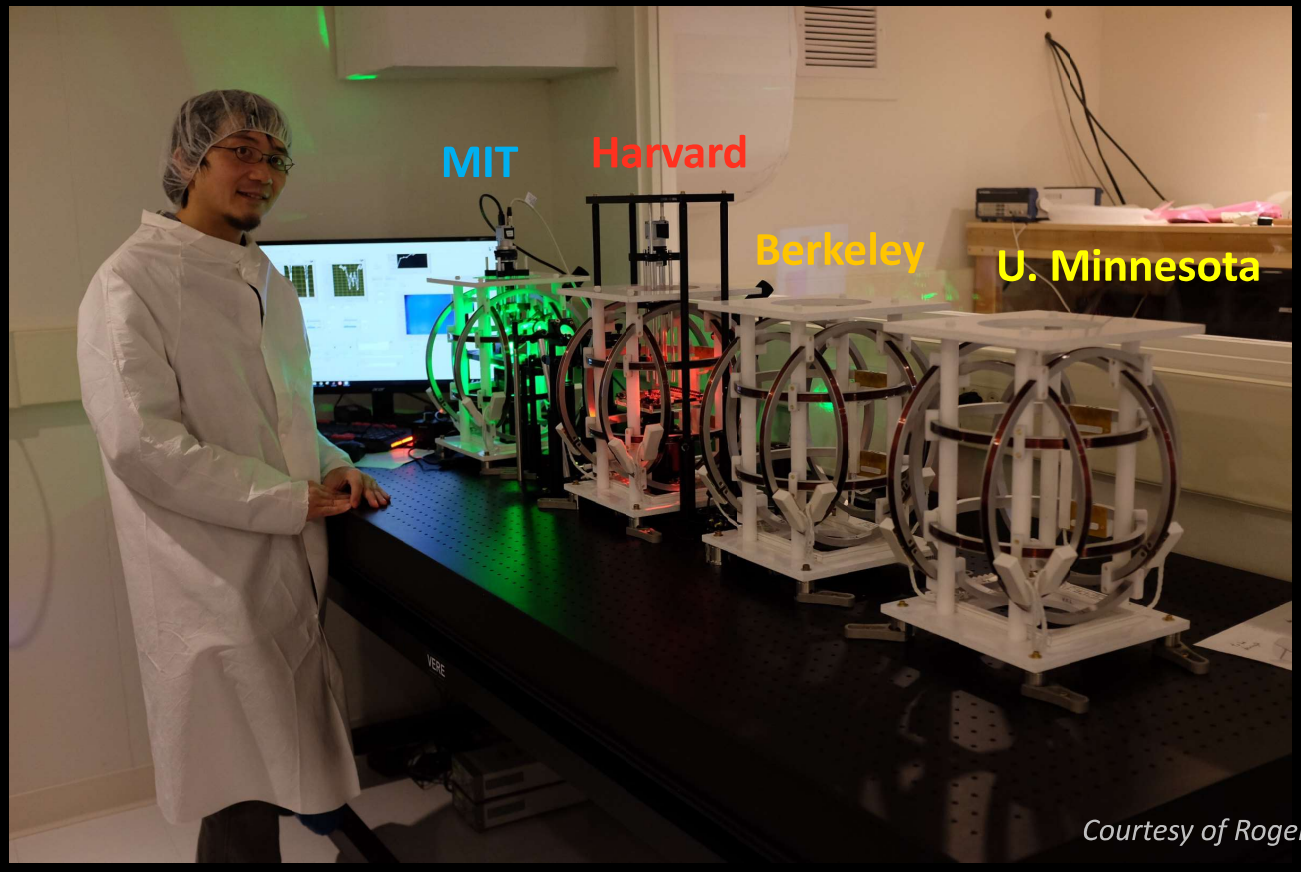


A US Geological Survey map of the Earth's tectonic plates. Scientists believe there may have been a time when there was only a single plate covering the planet. But a study from Harvard has found evidence of tectonic plates as far back as 3.25 billion years ago. USGS

From personal subscription

NSF Support => Disseminate QDM technology

Roger Fu
Harvard

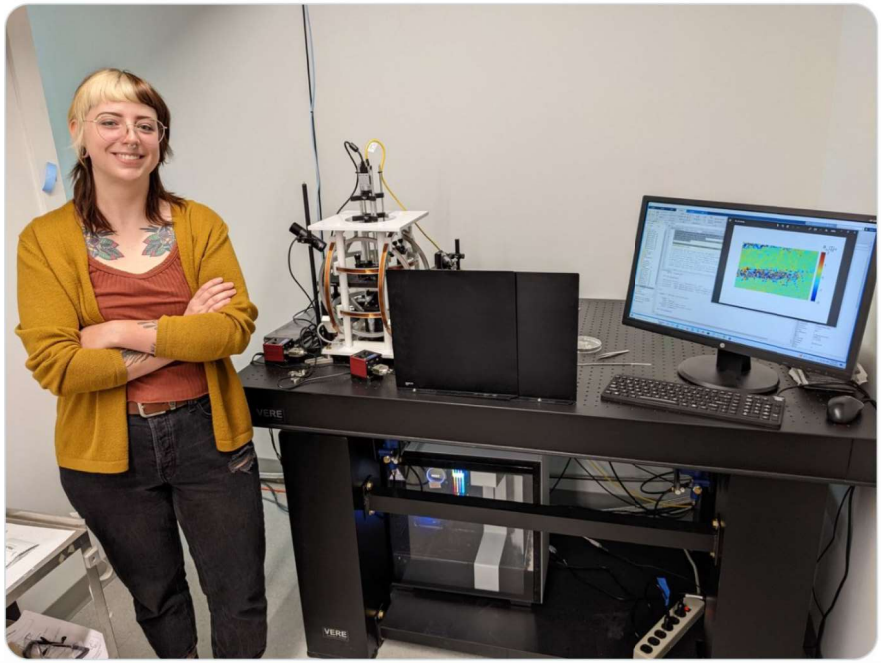


Courtesy of Roger Fu, Harvard

U. Minnesota

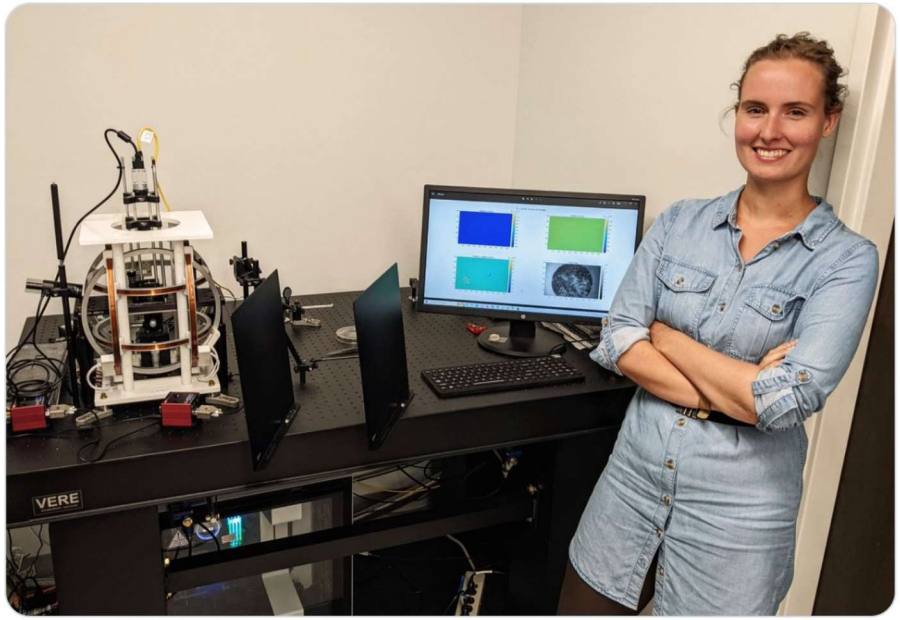
Institute for Rock Magnetism
@irm_umn

Visiting Fellow, Katie Bristol, a graduate student from U. Florida, using the IRM's Quantum Diamond Microscope (QDM) to look at the magnetic properties clinkers. #NSFfunded @irm_umn @UMNEarthScience @UMNCSE



Institute for Rock Magnetism
@irm_umn

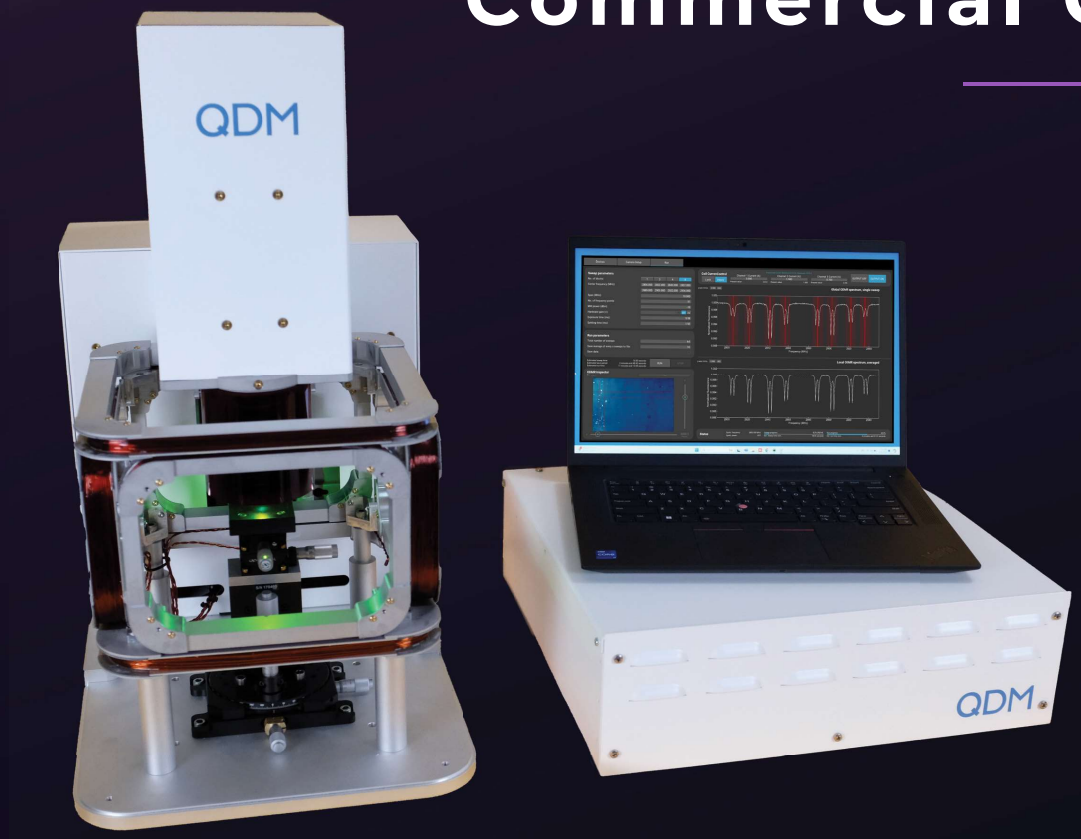
Our first Magnetic Microscopy Visiting Fellow, Rosa de Boer from Utrecht University, using the IRM's Quantum Diamond Microscope (QDM). #NSFfunded @UMNEarthScience @UMNCSE @deboeretal



1:11 PM · Aug 10, 2022

Publicly available images

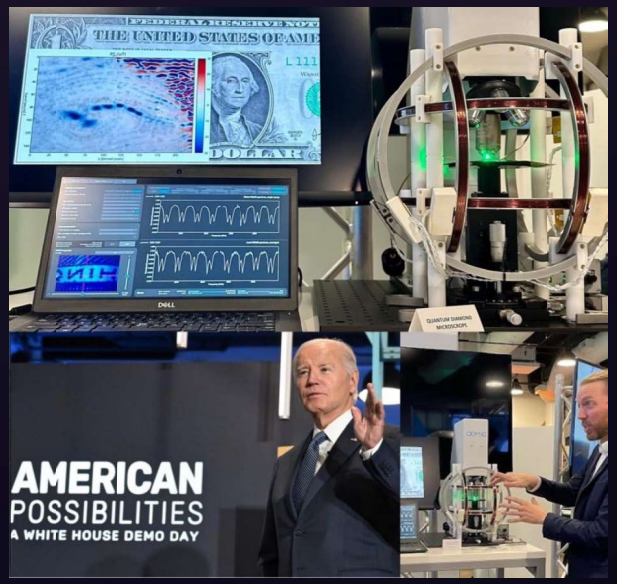
Commercial QDM



Publicly available image

QDM Demos for US Government

Congress, Spring 2024
with NSF Director



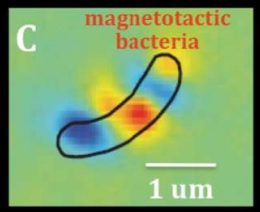
White House, Fall 2023

Images publicly available or from Walsworth & collaborators

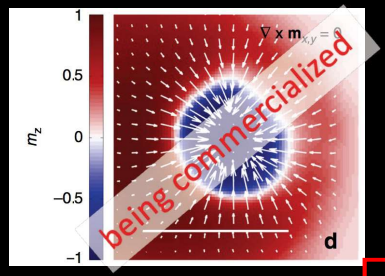
QUANTUM CATALYZER

NV-diamond sensing highlights

Live cell magnetic imaging



Materials science



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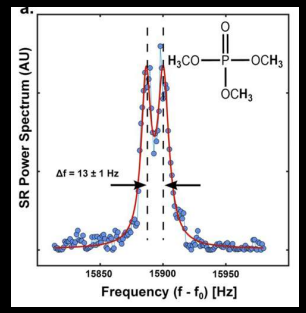
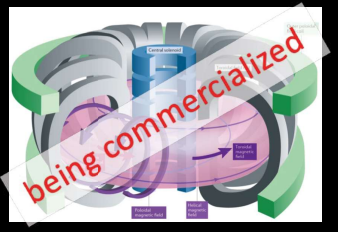
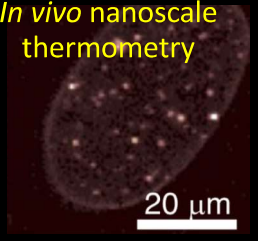


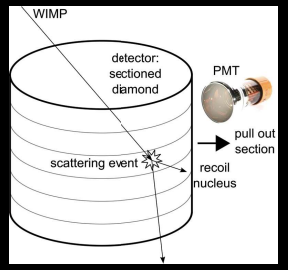
Harsh environments



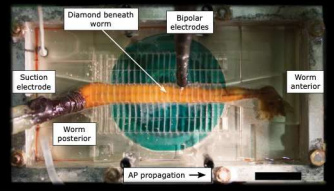
In vivo nanoscale thermometry



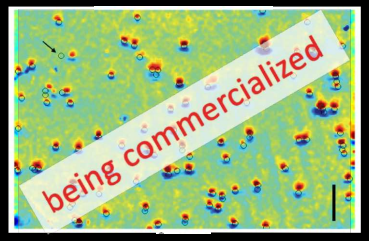
Rare particle detection



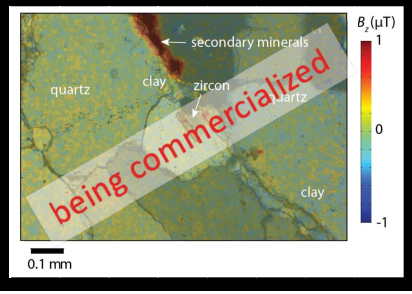
Neuroscience



Clinical bioassay



Geoscience



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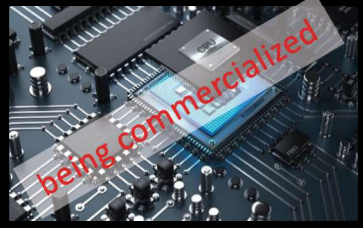
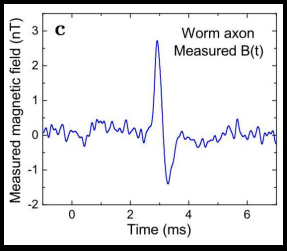


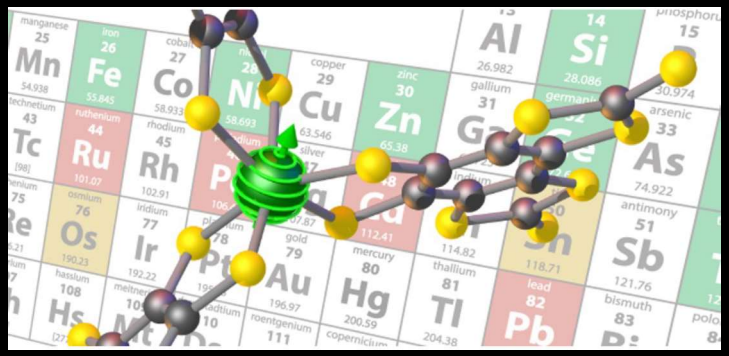


Images publicly available or from Walsworth & collaborators

Three illustrations…

Future

Designer quantum sensors, built from the bottom-up

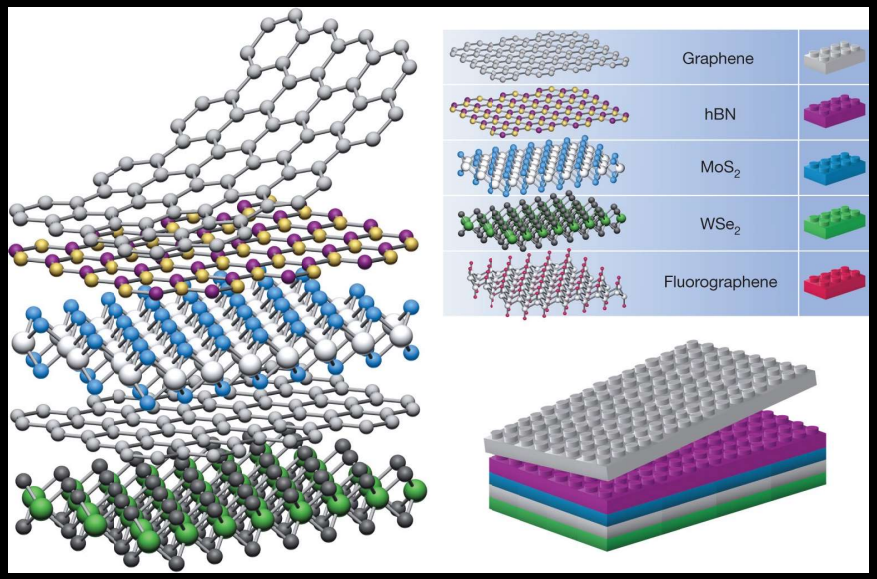


Long game

Images publicly available or courtesy of Danna Friedman, MIT

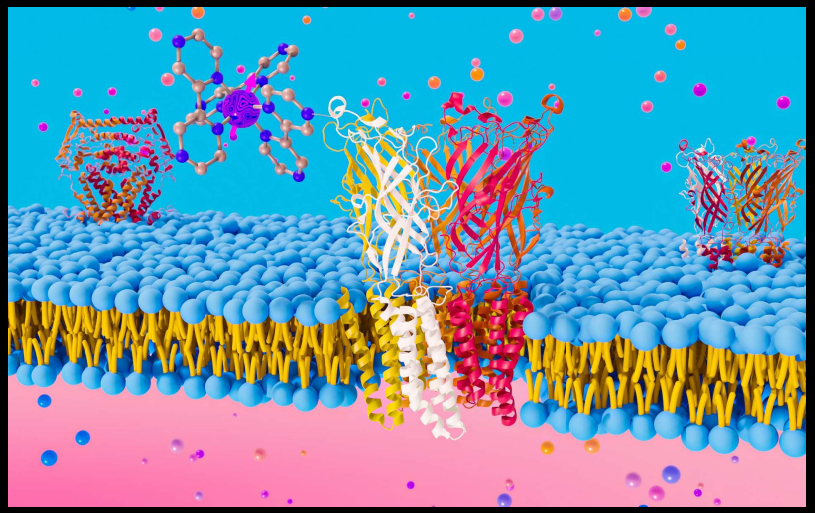
Quantum sensors tailored for targeted applications

Quantum defects in 2D materials



Geim, Nature (2013)
From institutional subscription

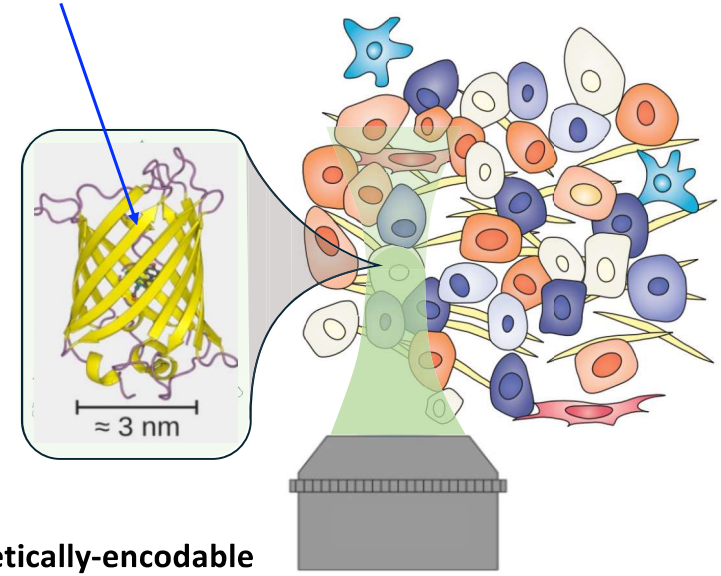
Chemically synthesized qubits



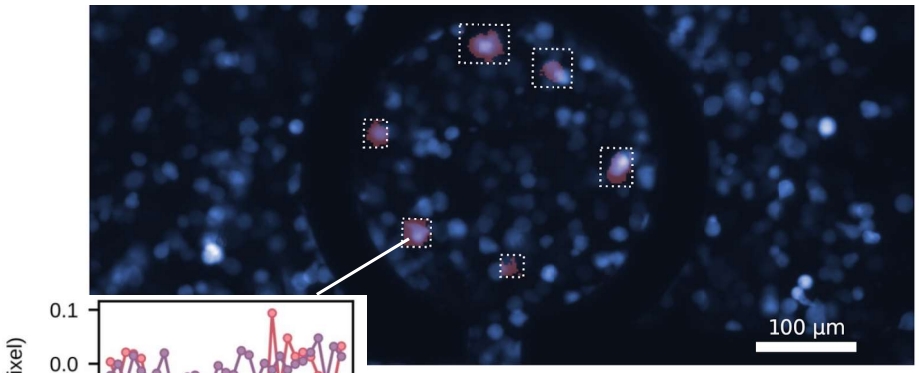
Courtesy of Danna Friedman, MIT

Quantum sensors in fluorescent proteins

Optically-addressable spin qubit
in yellow fluorescent protein



Genetically-encodable
=> Easily integrated
with biomolecules, cells



ODMR signals from proteins expressed in human (HEK) cells

$B_{DC} \approx 100$ pT mol$^{1/2}$ Hz$^{-1/2}$ (at room T)

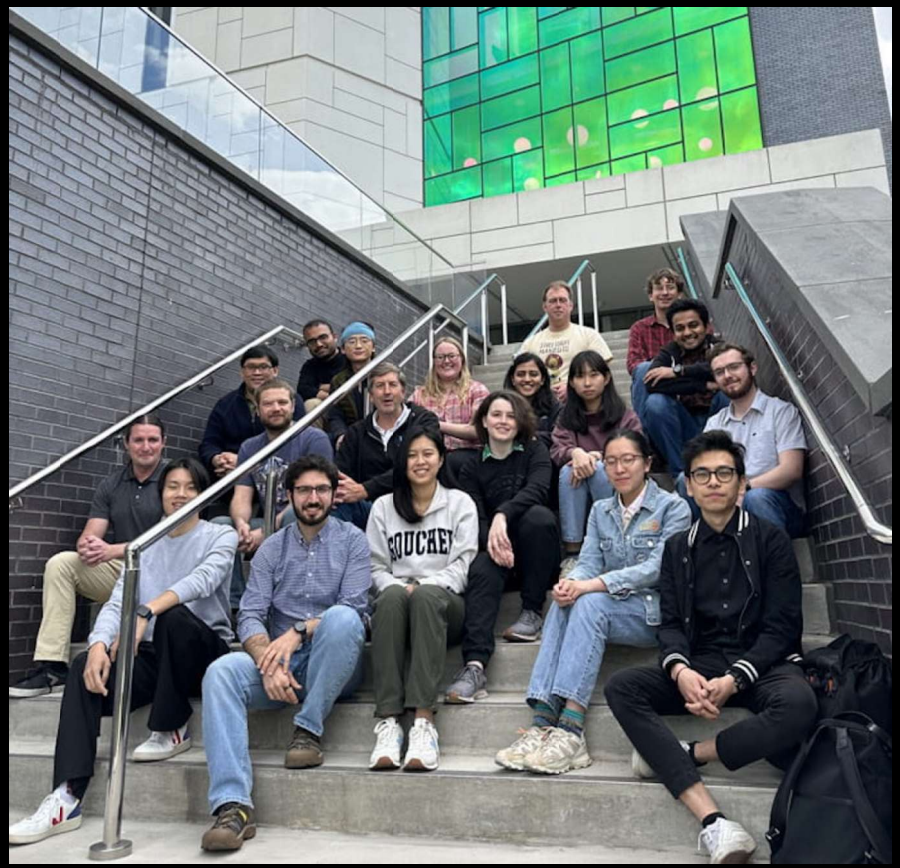
Courtesy of Peter Maurer, UChicago
arXiv:2411.16835

Maurer Awschalom Gagliardi Esser-Kahn

Quantum Sensing for Precision Measurement
Applications to Physical and Life Sciences

- Long game: 10+ years (Focus)
- Initial driver usually from fundamental physics
- Interdisciplinary collaborations key
  to impact in other fields (Openness)
- Tech translation often aided by commercialization
- Burgeoning QIS field can help sustain support
  & attract/build next generation

Publicly available image



http://walsworth.umd.edu/

Publicly available image

Thank you

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Ronald Walsworth's contribution to this presentation related to companies was not part of his University of Maryland duties or responsibilities