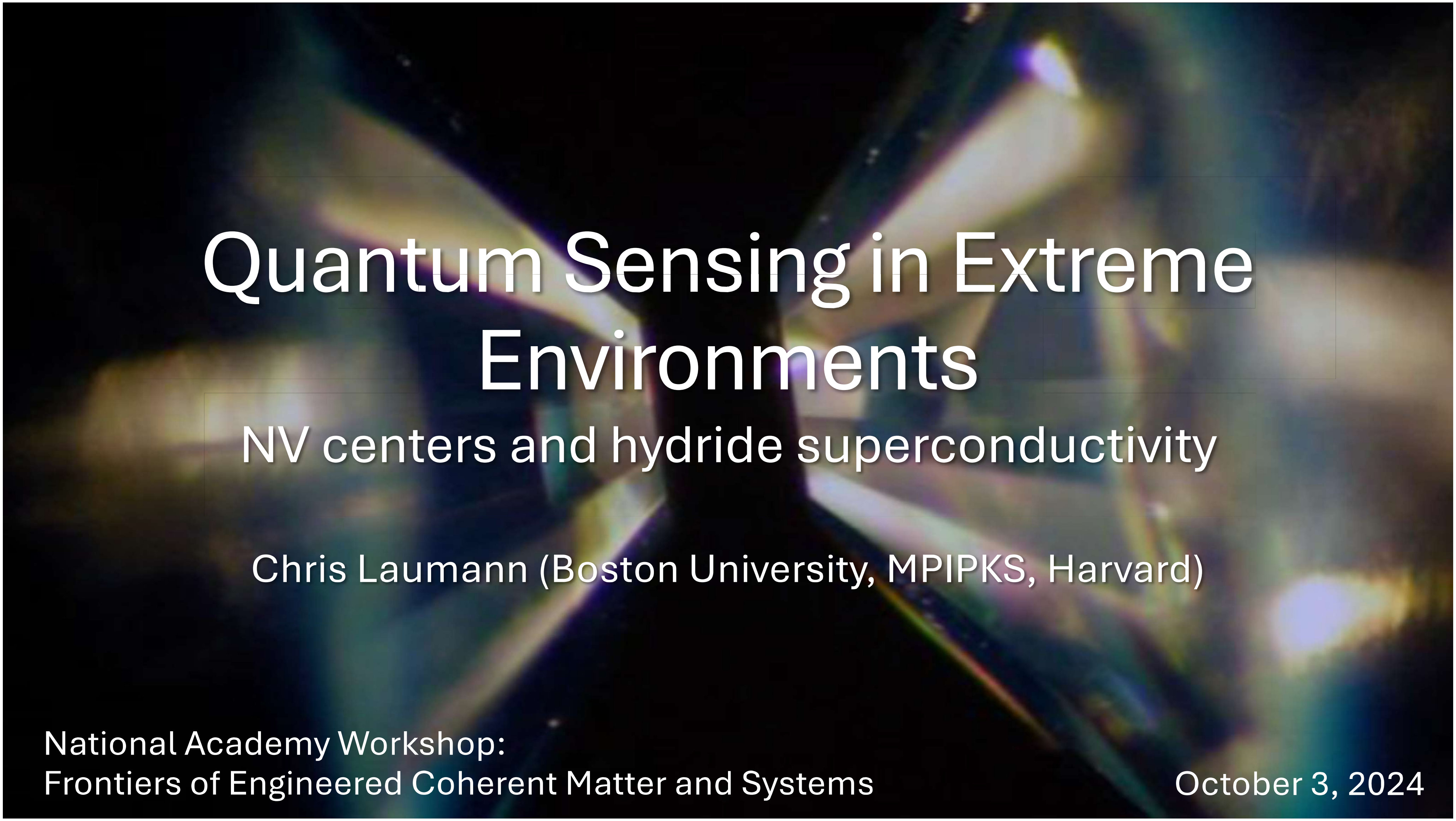


Quantum Sensing in Extreme Environments

NV centers and hydride superconductivity

Chris Laumann (Boston University, MPIPKS, Harvard)

National Academy Workshop:
Frontiers of Engineered Coherent Matter and Systems

October 3, 2024

Hydrogen under pressure

VOLUME 21, NUMBER 26 PHYSICAL REVIEW LETTERS 23 DECEMBER 1968

METALLIC HYDROGEN: A HIGH-TEMPERATURE SUPERCONDUCTOR?

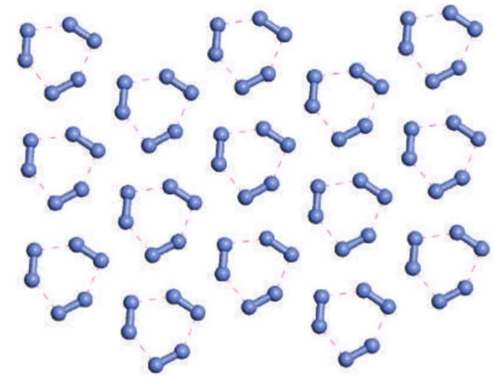
N. W. Ashcroft

Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850

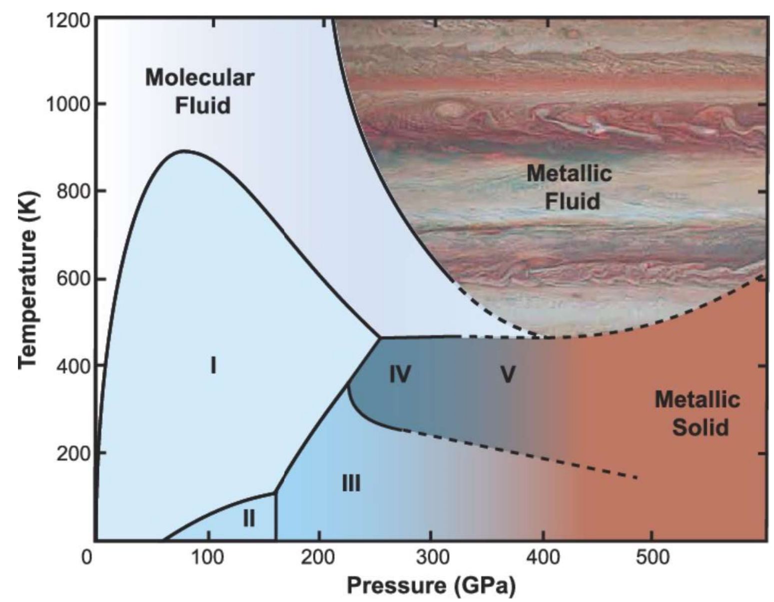
- BCS Superconductors:

$$T_c \sim \omega_D \exp\left[-\frac{1}{\lambda}\right]$$

- Low mass of Hydrogen
  - High phonon frequency
  - Strong phonon coupling
- High T_c!
- BUT: enormous pressure to break H_2



Pickard, Needs, *Nature Physics* (2007)



Gregoryanz, E. et al. *Matter and Radiation at Extremes* (2020)

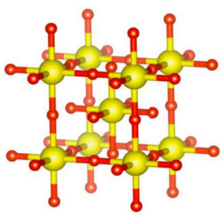
Hydrides under pressure

VOLUME 92, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 7 MAY 2004

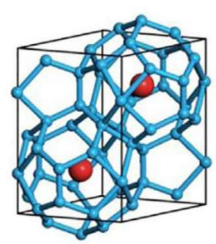
Hydrogen Dominant Metallic Alloys: High Temperature Superconductors?

N.W. Ashcroft

Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853-2501, USA
Donostia International Physics Center, San Sebastian, Spain



H_3S



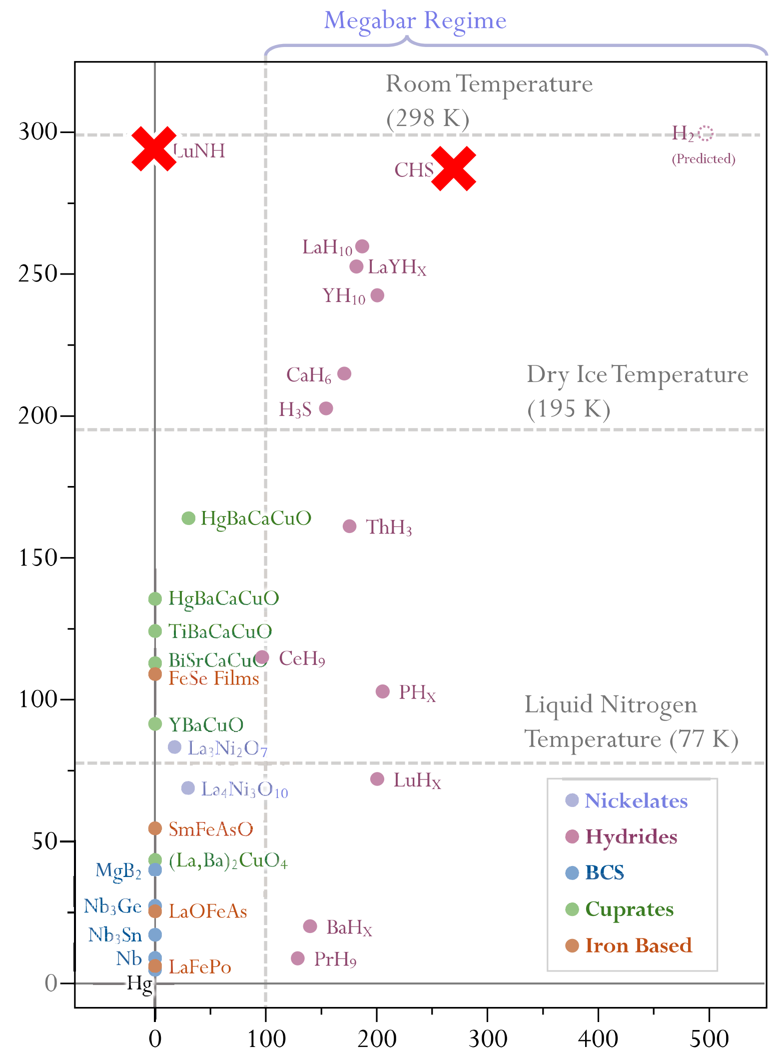
CeH_9

LETTER

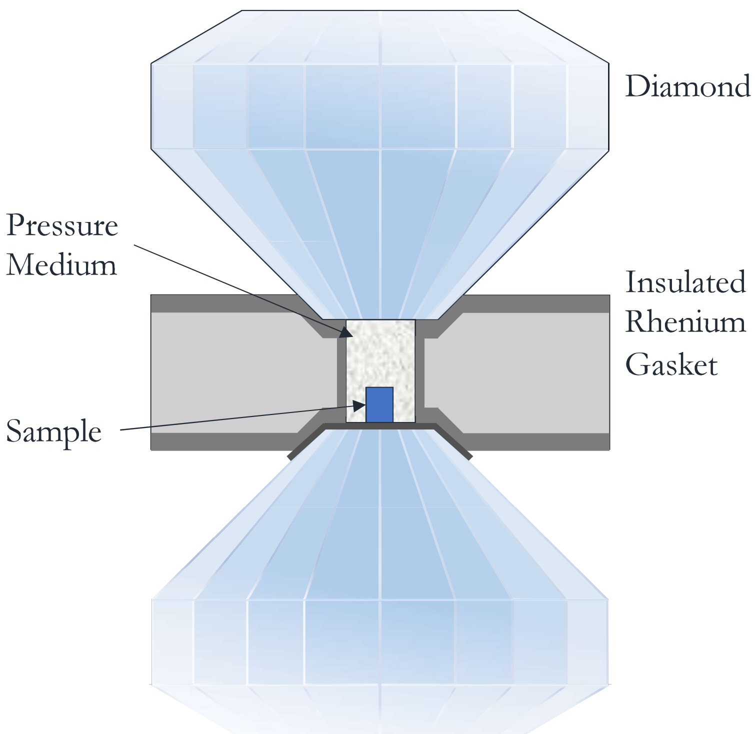
doi:10.1038/nature14964

Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

A. P. Drozdov[1]*, M. I. Eremets[1]*, I. A. Troyan[1], V. Ksenofontov[2] & S. I. Shylin[2]

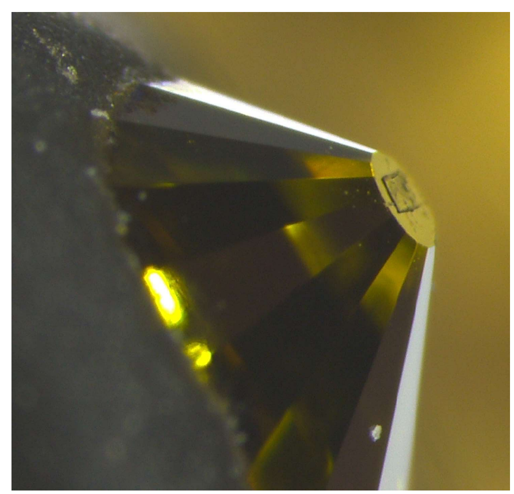


Working under pressure: diamond anvil cells



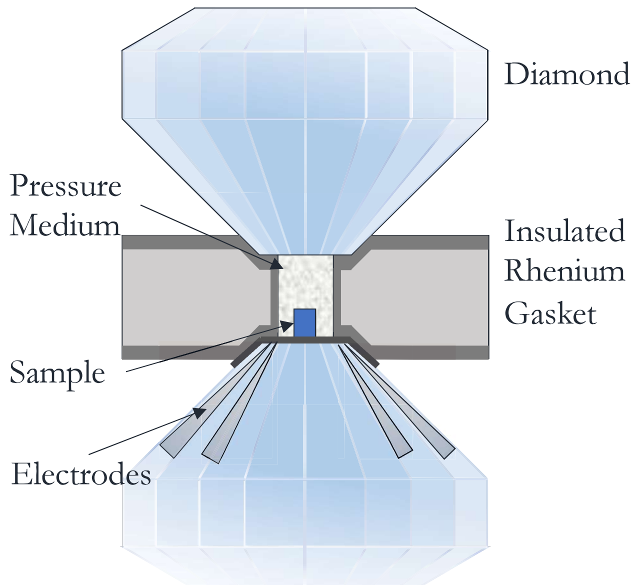
Review: Mau, Hemley. *Rev. Mod Phys.* (1994)

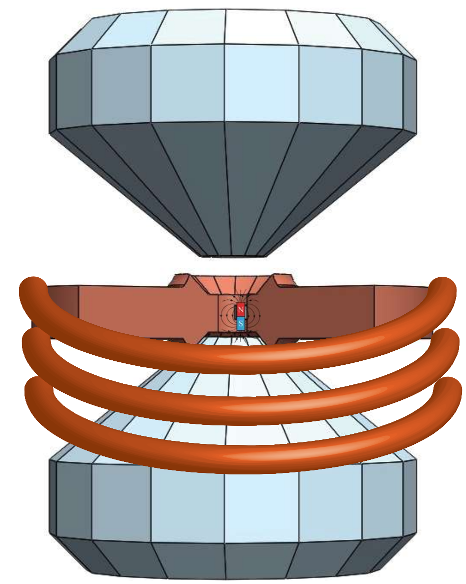
- Hydrides require high pressure!
  - Synthesized at pressure
  - None yet stable at ambient
- **Challenge:** Can't open cell to probe



The High-P_c Superconductor Challenge

Observe simultaneous transition in electrical resistance and diamagnetic response (Meissner effect)





Electrical Resistance from 4-Terminal Measurement

Bulk Diamagnetism from Coils

Challenge 1: Resistance may drop sharply from other transitions (structural, thermal deformation)
Challenge 2: Coils typically outside cell – huge background from leads, screws, …
Challenge 3: Transport and magnetic measurements typically performed in **different cells**

Strategy: Embed shallow layer of NV centers in DAC

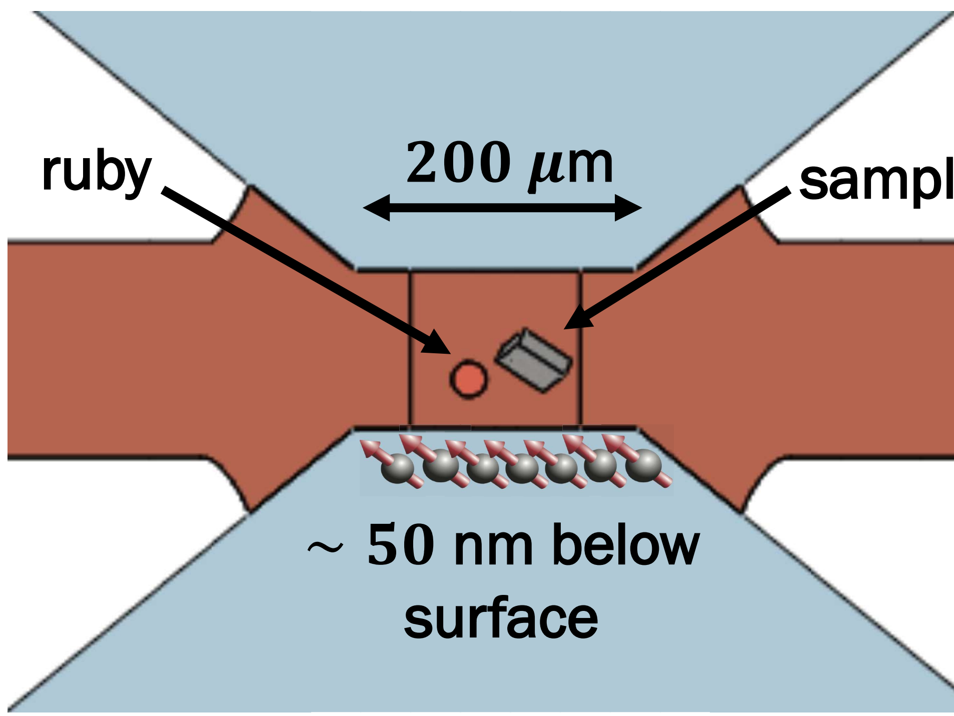
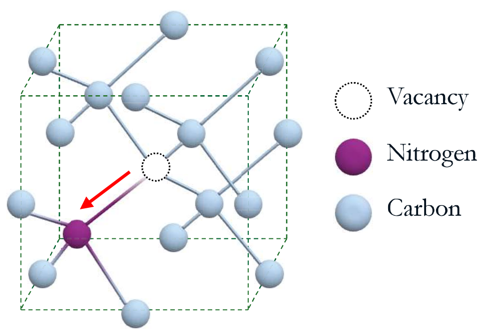


Image magnetic response locally!

S. Hsieh et al. *Science* **366** 1349-1354 (2019); see also related work by Roch group and Yang group (Science 2019)

The Local Sensor: Nitrogen-Vacancy Center

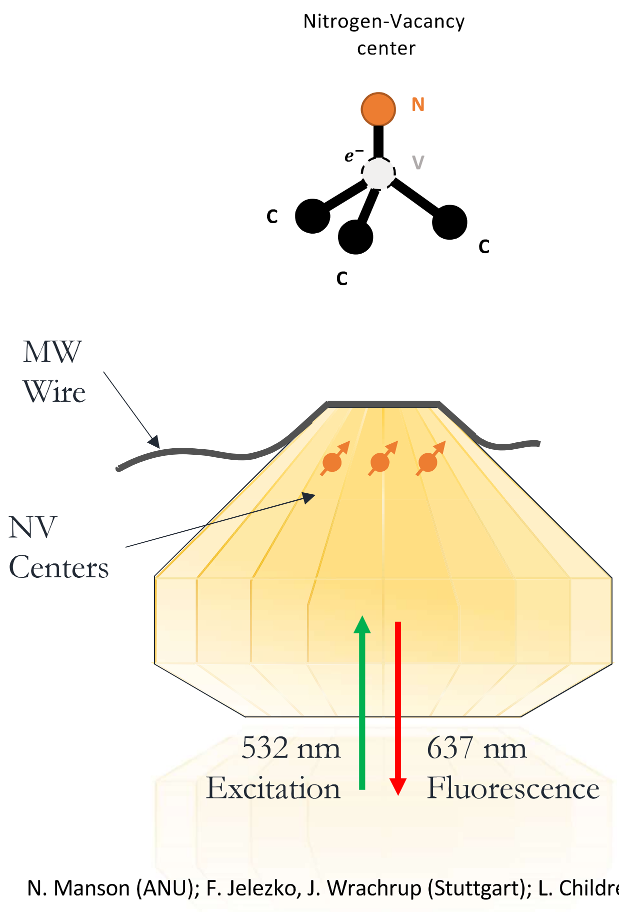


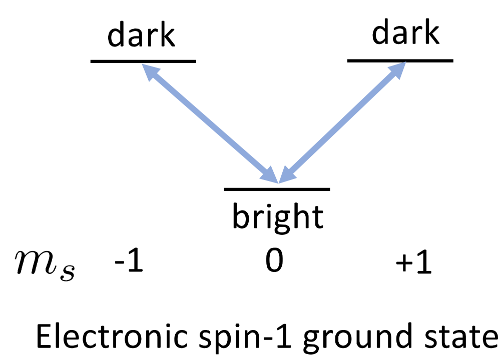
- One of many defects in diamond
- A natural spin qubit
- Workhorse for quantum sensing and quantum networks
- C.f. David Awshalom's talk next

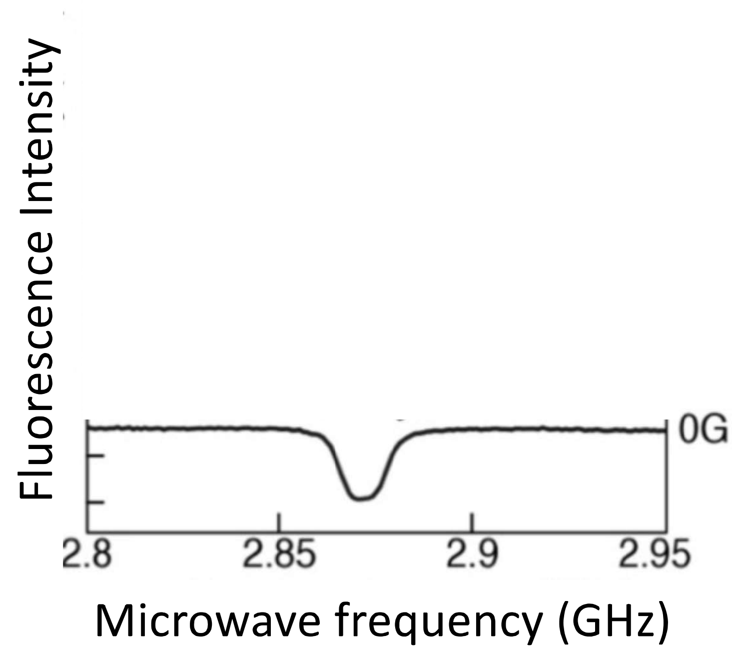
- Key Features for Today
  - Sensitive to local magnetic fields
  - Optical control and readout
  - Operates in wide range of temperature and pressure

N. Manson (ANU); F. Jelezko, J. Wrachrup (Stuttgart); L. Childress et al (Harvard); D. Awschalom (UCSB); review Physics Reports 528.1 (2013): 1-45.

How to use the NV to sense magnetic fields?







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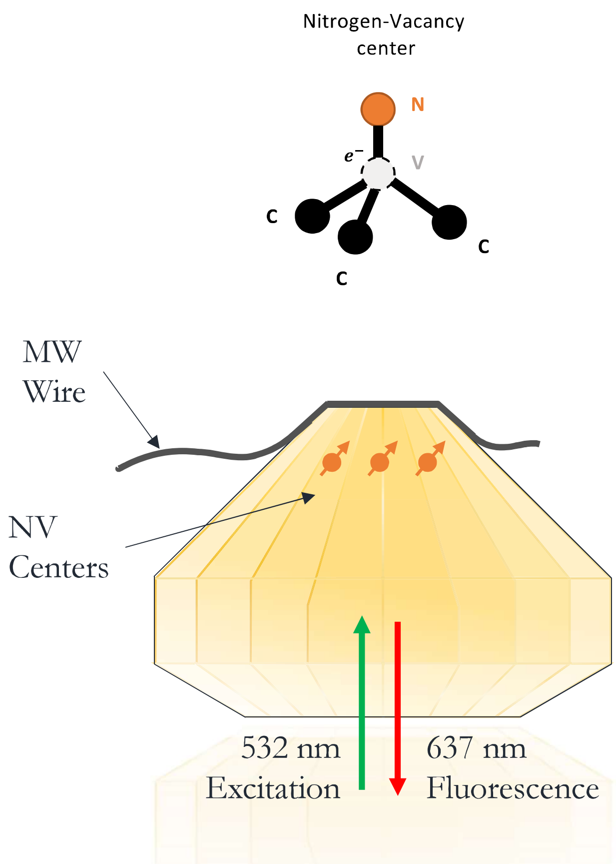
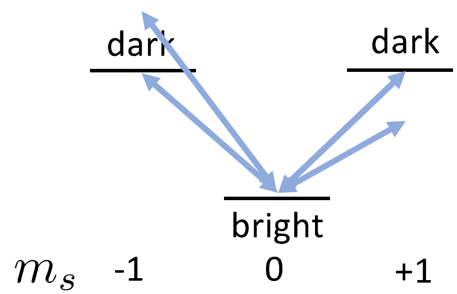
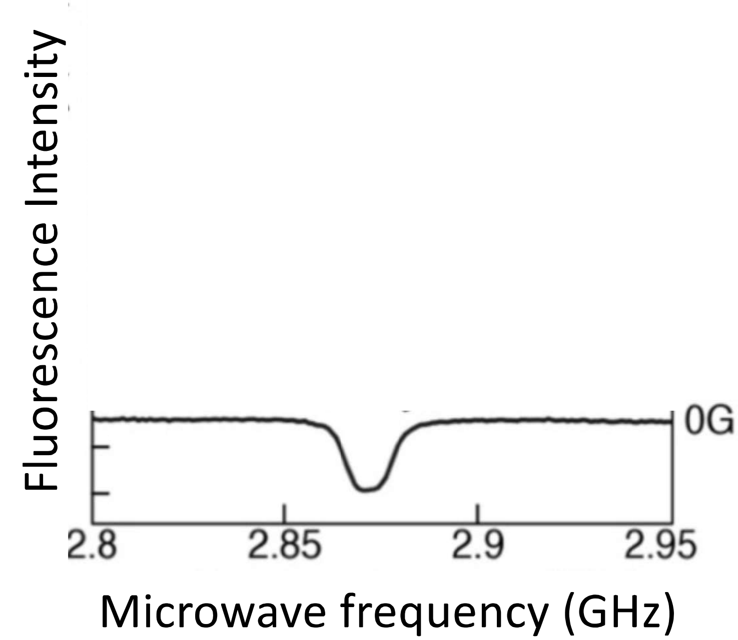


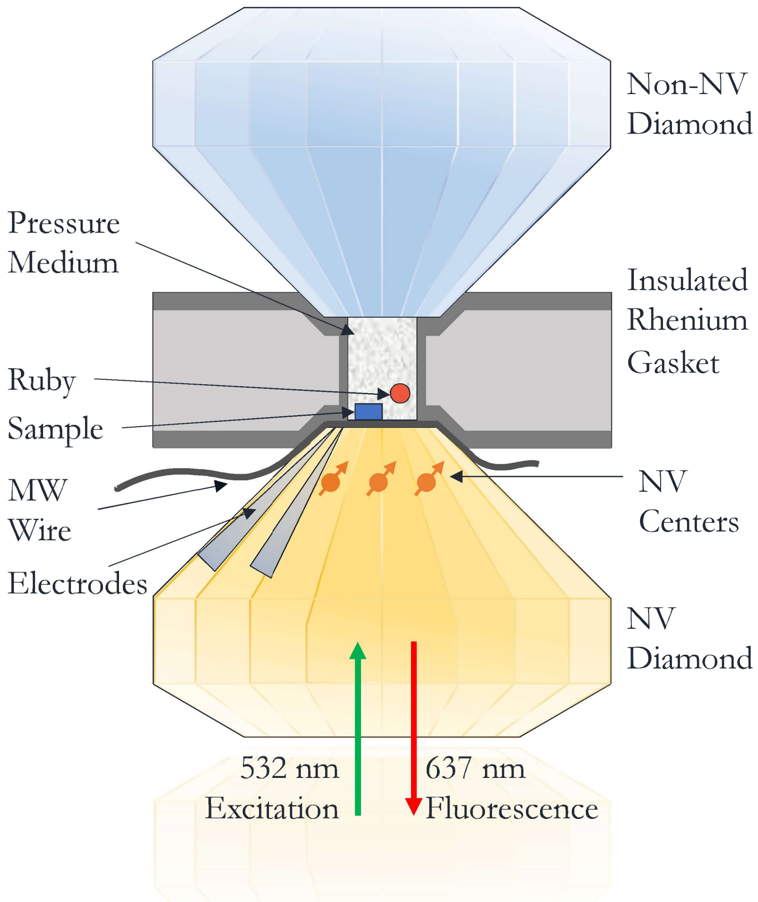


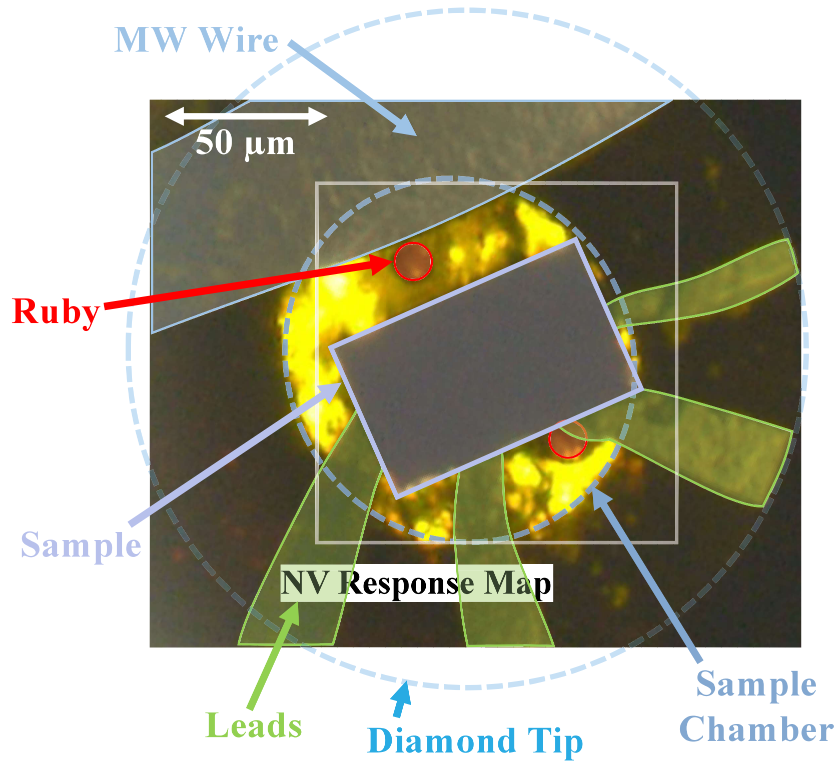
Electronic spin-1 ground state



N. Manson (ANU); F. Jelezko, J. Wrachrup (Stuttgart); L. Childress et al (Harvard); D. Awschalom (UCSB); review Physics Reports 528.1 (2013): 1-45.

Geometry of a high pressure experiment



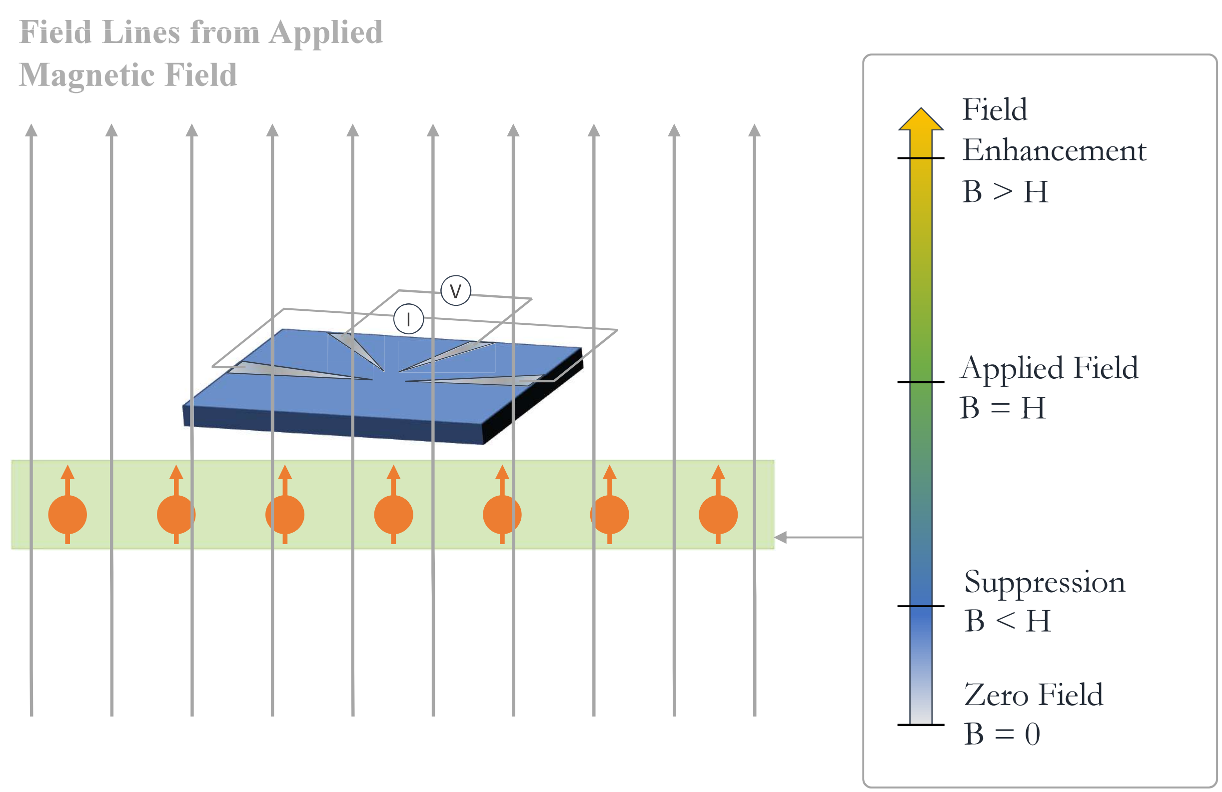


BSCCO Under Pressure: 5 GPa

Bhattacharya, … *Nature* (2024); Hsieh, … *Science* (2019); Roch group and Yang group (*Science* 2019)

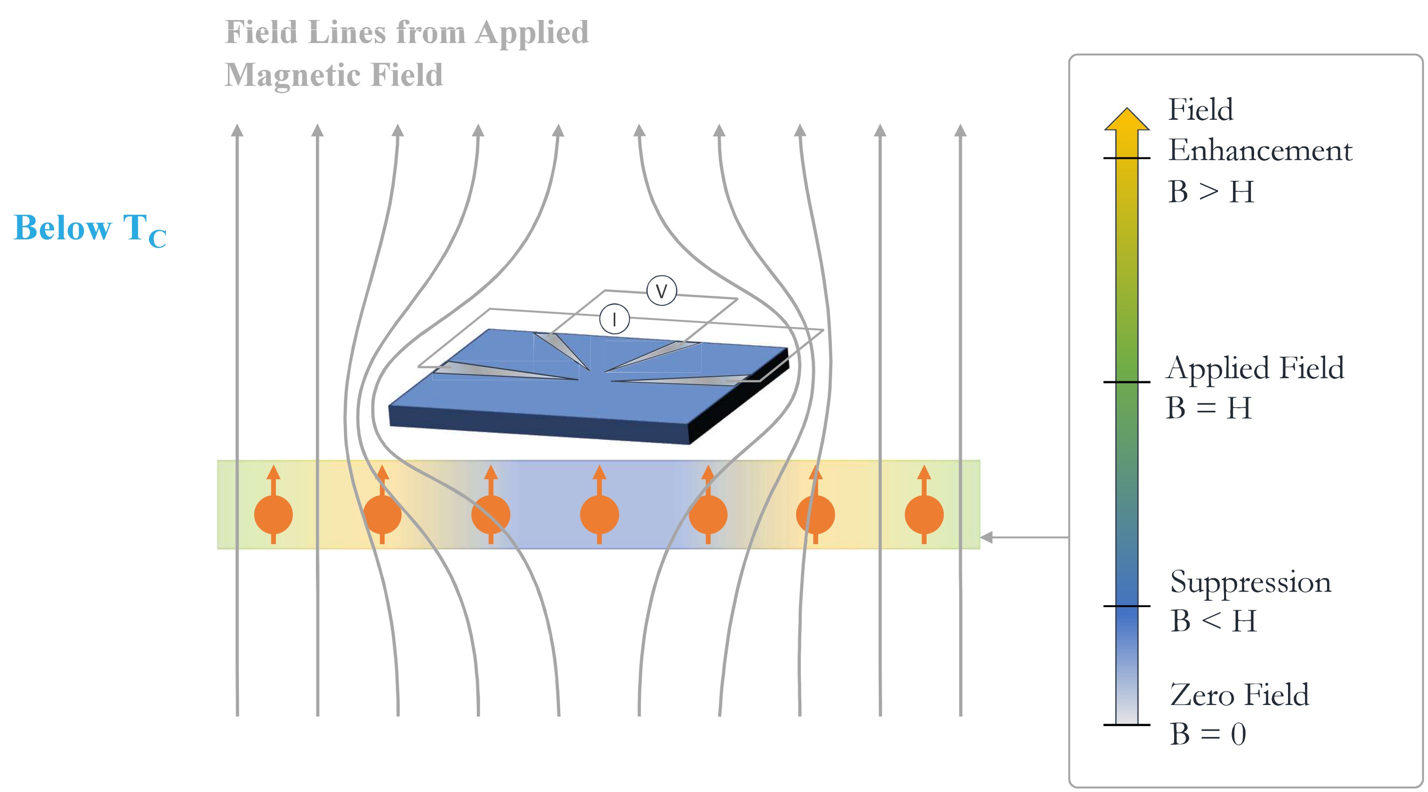
What should we expect from a superconductor?

Above T_C



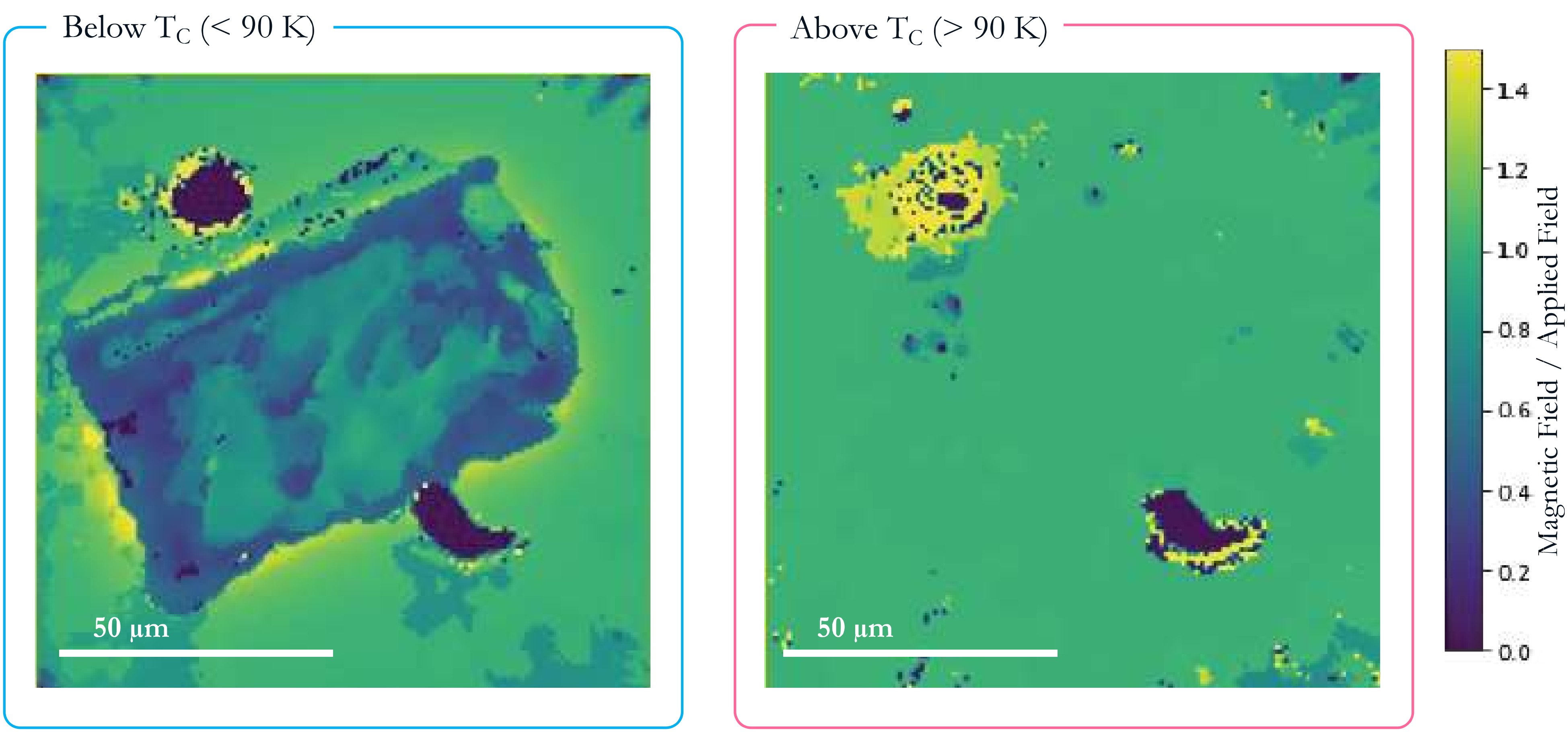
Normal State

What should we expect from a superconductor?



Meissner State

Seeing the Meissner effect in BSSCO



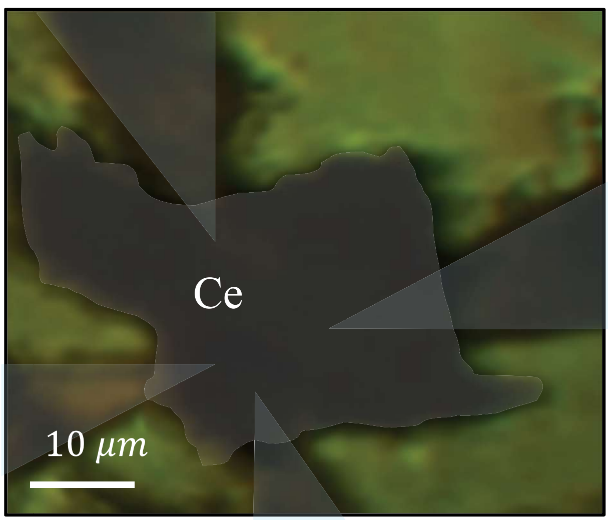
PHYSICAL REVIEW LETTERS **127,** 117001 (2021)

High-Temperature Superconducting Phases in Cerium Superhydride with a T_c up to 115 K below a Pressure of 1 Megabar

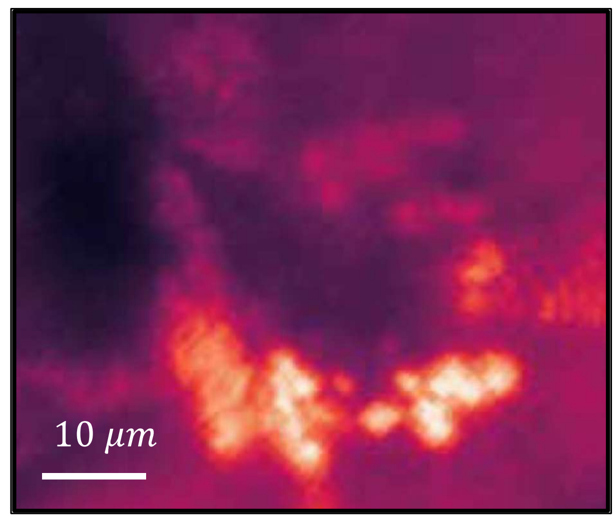
Wuhao Chen,[1] Dmitrii V. Semenok,[2] Xiaoli Huang,[1,*] Haiyun Shu,[4] Xin Li,[1] Defang Duan,[1] Tian Cui,[3,1,†] and Artem R. Oganov[2]

Laser heat up to ~ 1500 K above ~ 140 GPa

$$\mathrm{Ce} + \mathrm{NH_3BH_3} \rightarrow \mathrm{CeH_9} + \mathrm{cBN}$$



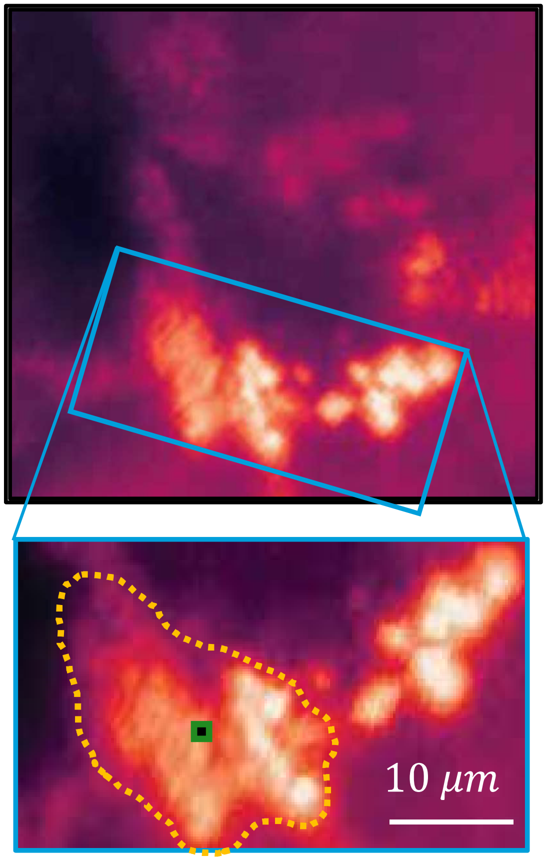
White light



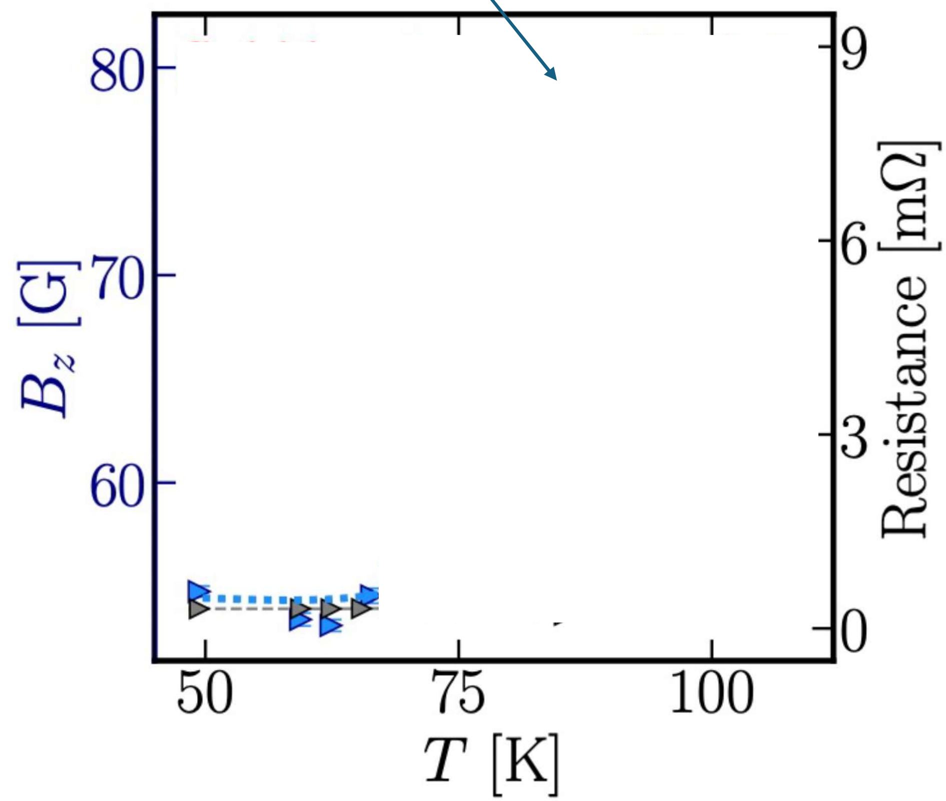
NV Fluorescence

Bhattacharya, … Nature **627**, 73–79 (2024)

Simultaneous Meissner and Transport



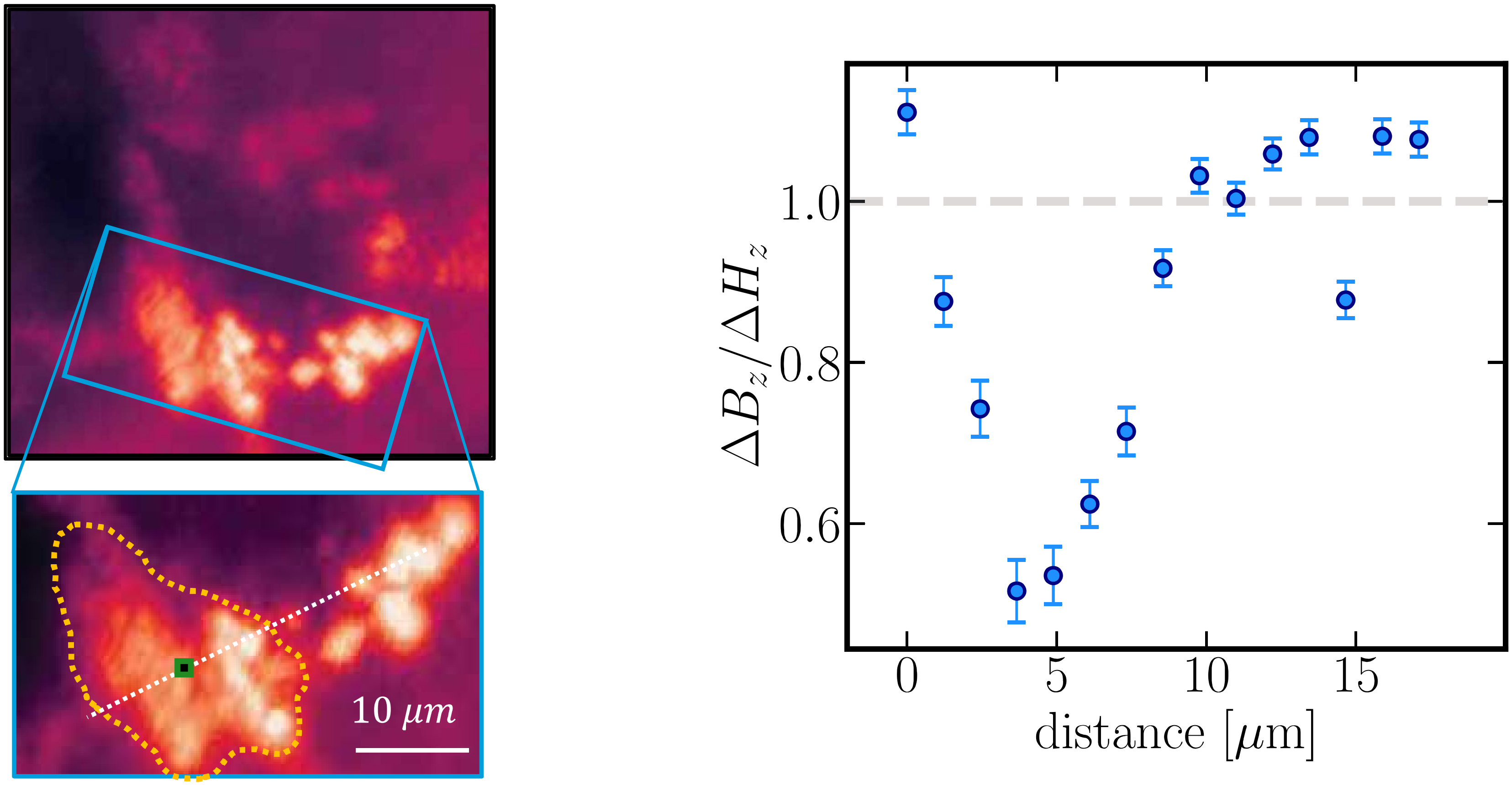
Transitions measured simultaneously in one run



Zero-field cool, turn on 80G and measure B field at point.

Bhattacharya, … Nature **627**, 73–79 (2024)

Imaging Superconducting Grains

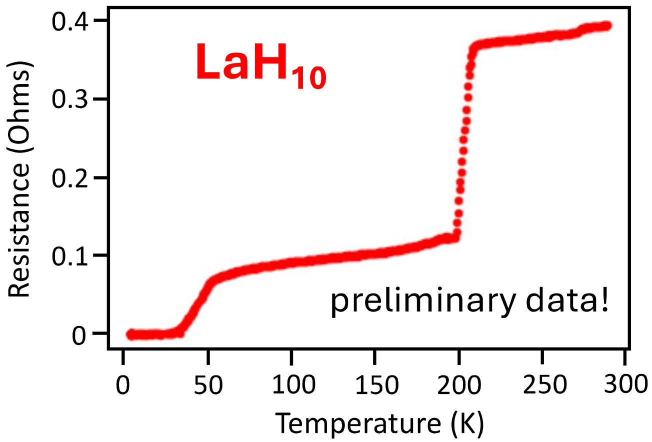


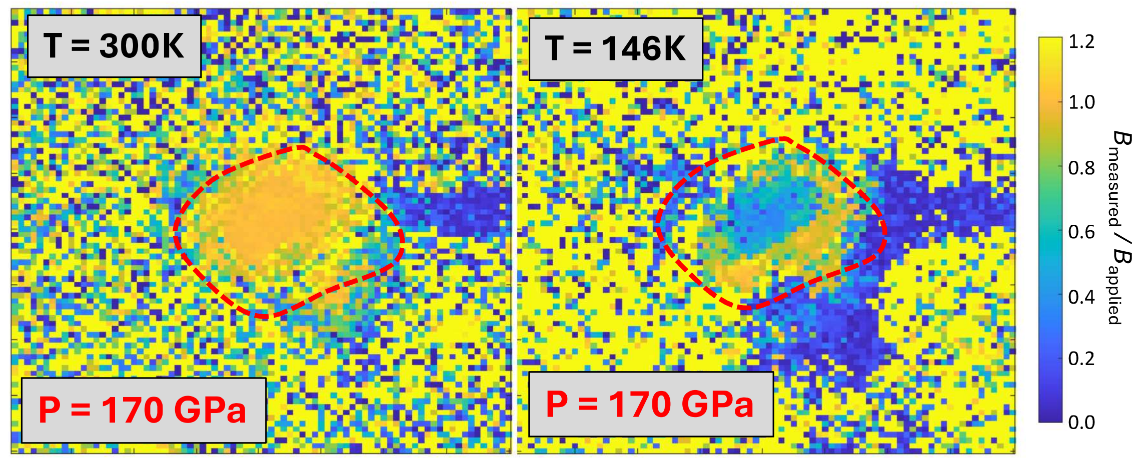
Superconducting grains of order 5-10 μm. Not all laser-heated regions superconducting.

Bhattacharya, … Nature **627**, 73–79 (2024)

The Hydride Outlook

Short-term challenge: **directly image and characterize superconductivity in near room-temperature materials**





The Hydride **Outlook**

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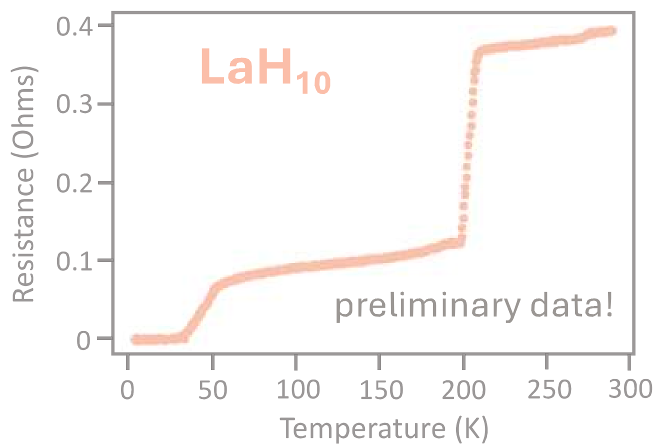
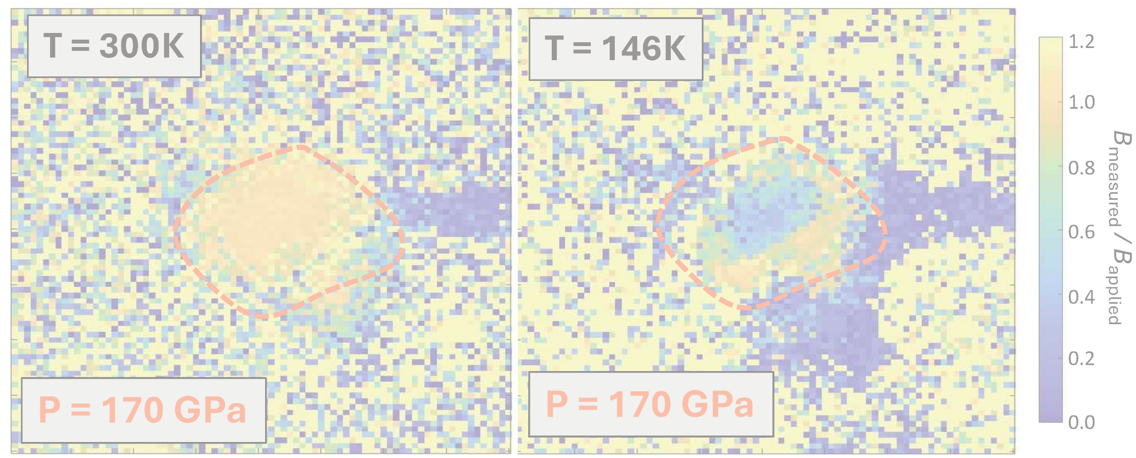
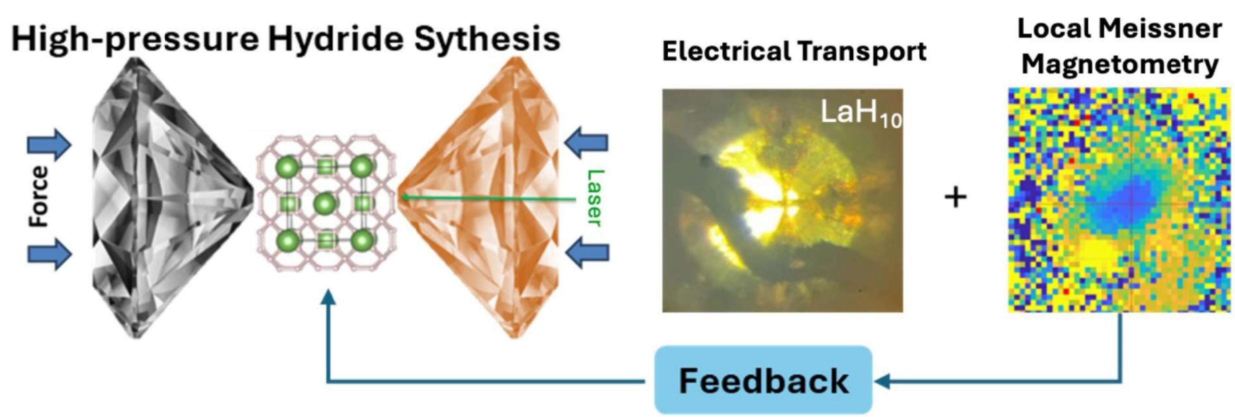


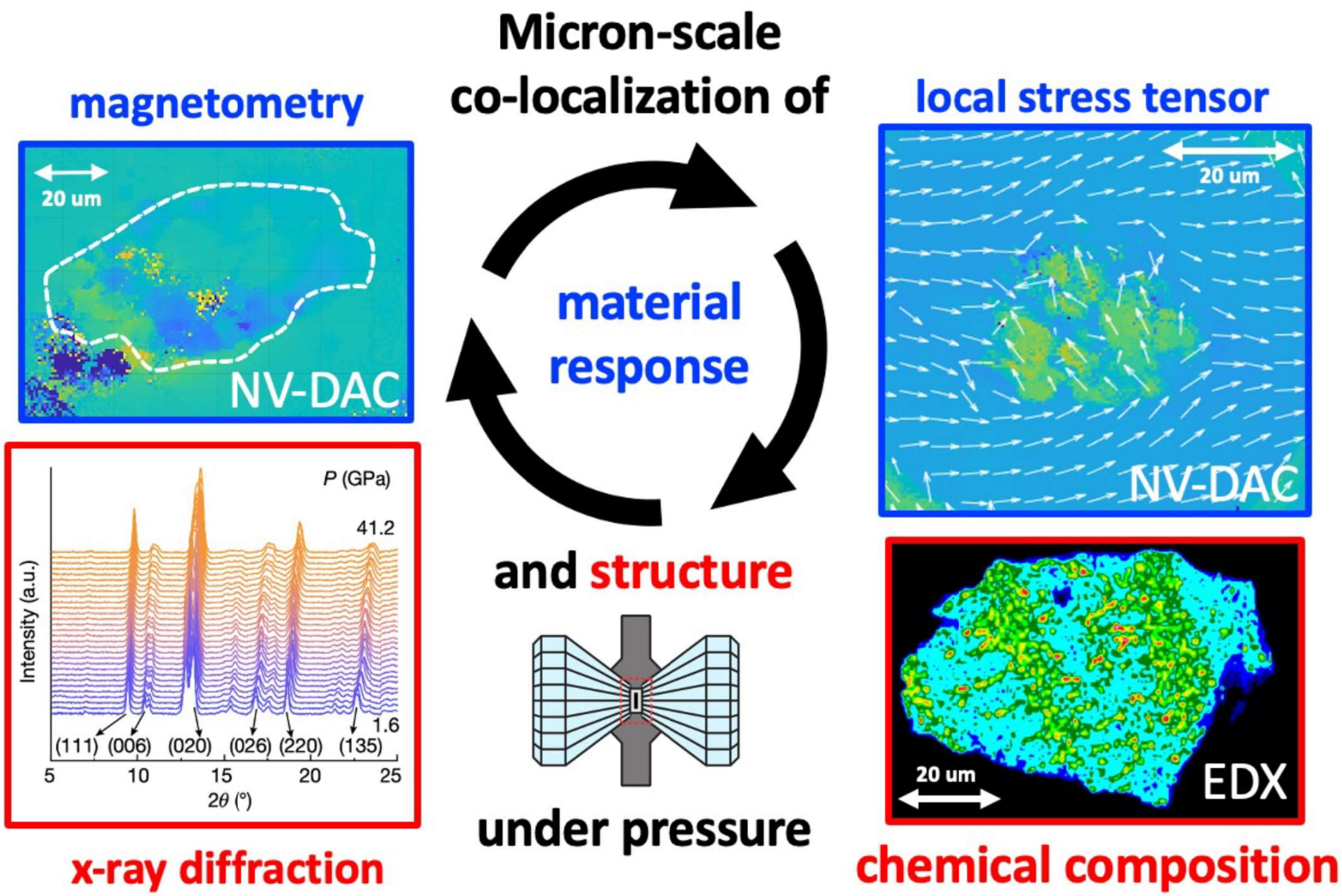


Long-term challenge:

Toward metastable, ambient-recoverable, high-Tc superconductor



The Hydride **Outlook**



The NV Center **Outlook: Coherent Networks**

How do hydrodynamic descriptions arise from interacting quantum systems?

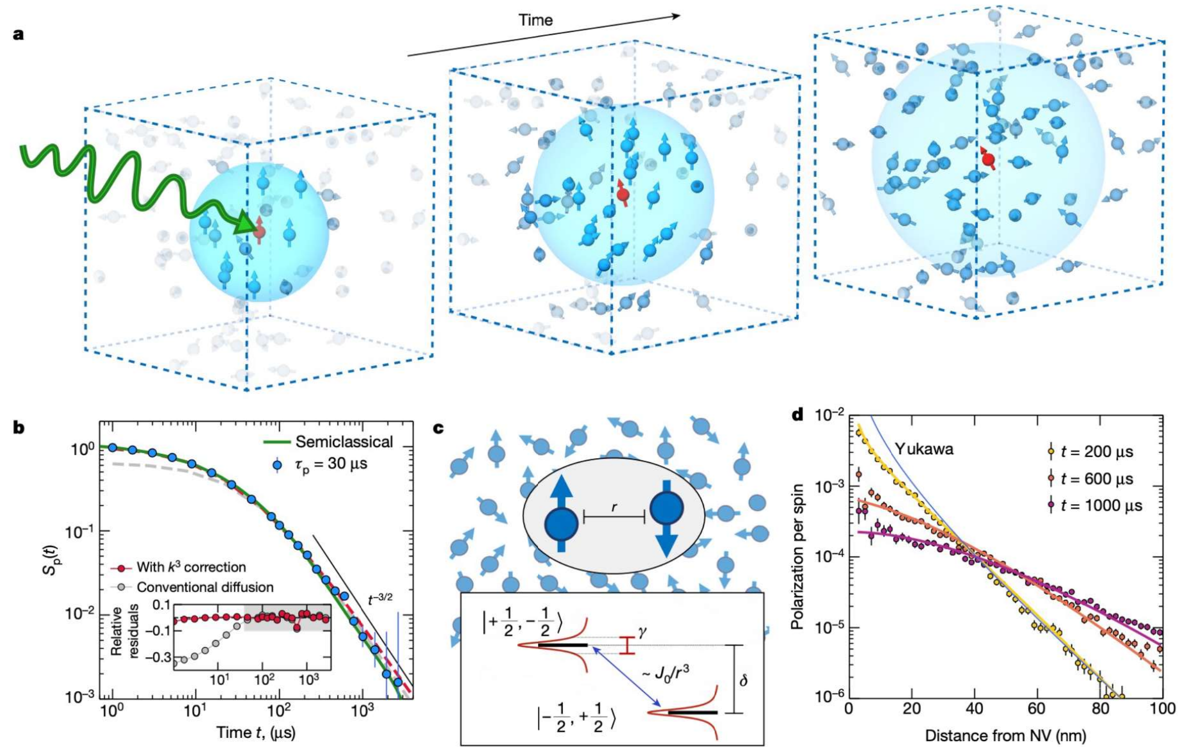
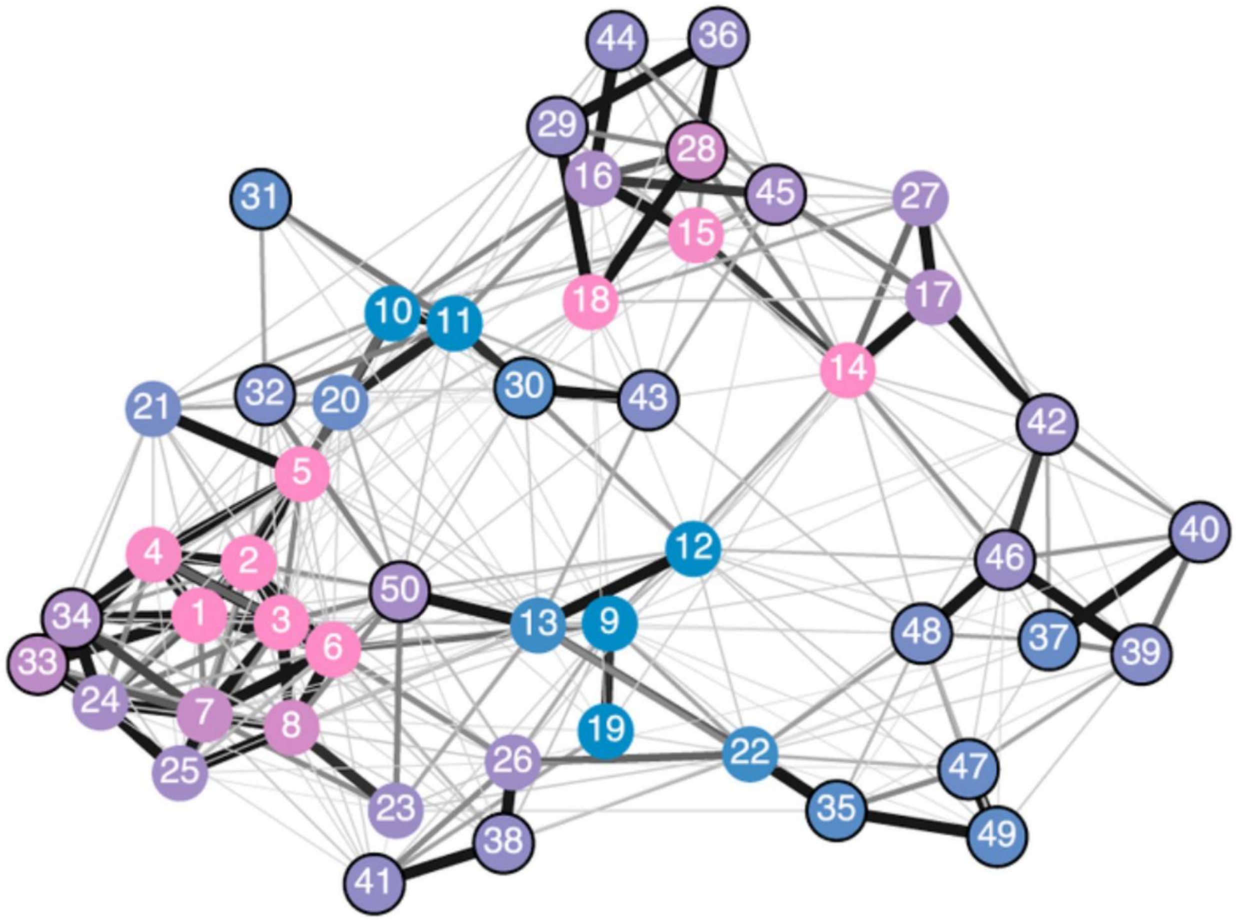


Fig. 1 | Nanoscale spin diffusion in a long-range interacting quantum system. Inset: relative residuals for the two spin diffusion models. In the hydrodynamical

Zu, et al. **Emergent hydrodynamics in a strongly interacting dipolar spin ensemble** Nature (2021)

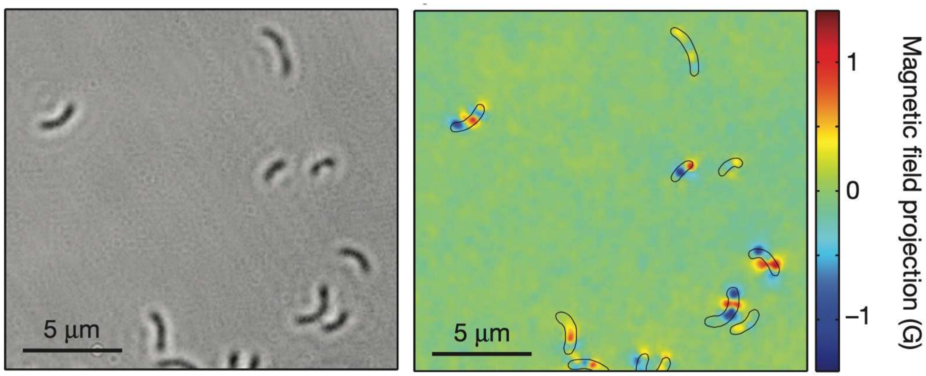
The NV Center **Outlook: Coherent Networks**



Taminiau Group (Delft)

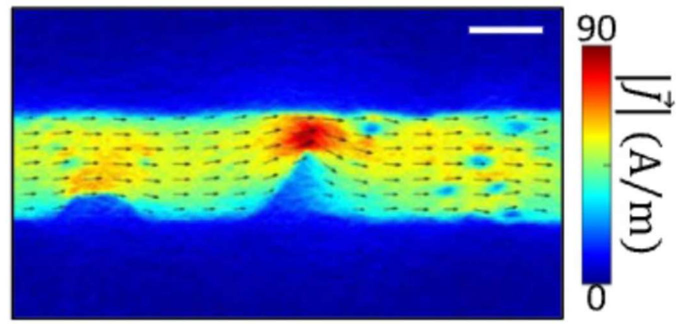
The NV Center Outlook: The Case of Metrology

Magnetotactic bacteria



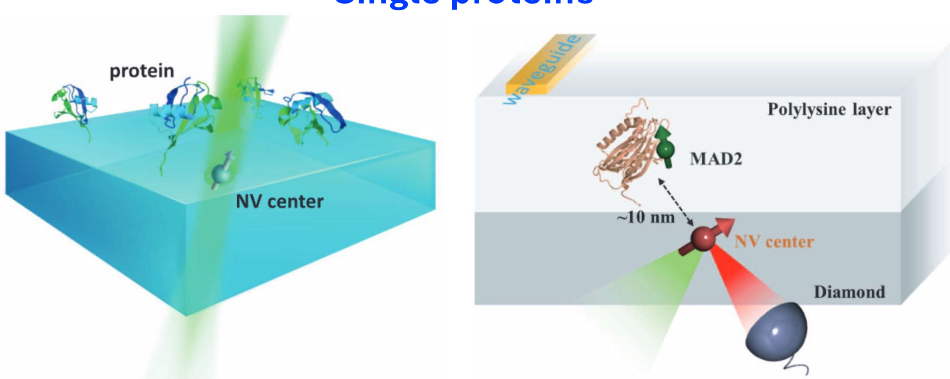
Nature **496**, 486–489 (2013)

Current flow in graphene



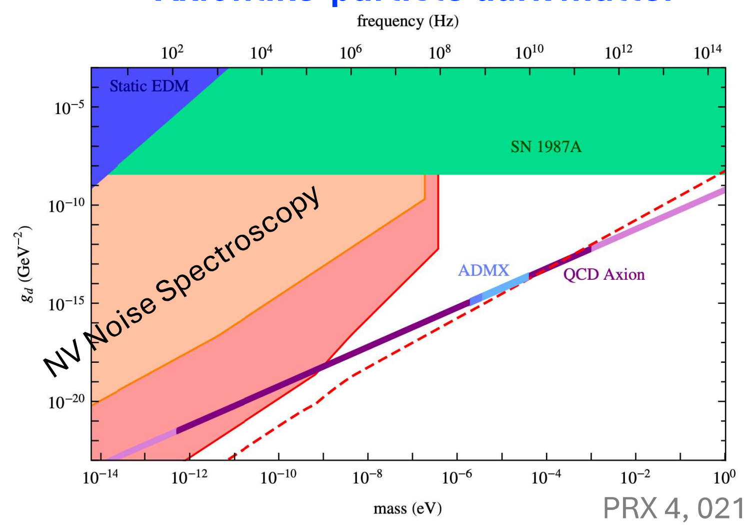
Sci Adv. 3, e1602429 (2017)

Single proteins



Science **347**,1135-1138 (2015) Science **351**, 836-841 (2016)

Axionlike-particle dark matter



PRX 4, 021030 (2014)

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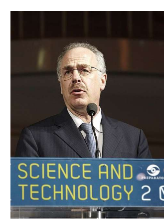
Prabudhya Bhattacharyya

Wuhao Chen

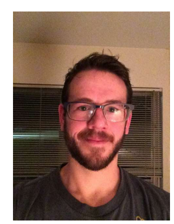
Zachary Geballe

Shubhayu Chatterjee

Xiaoli Huang



Raymond Jeanloz



Tom Smart

Bert Halperin