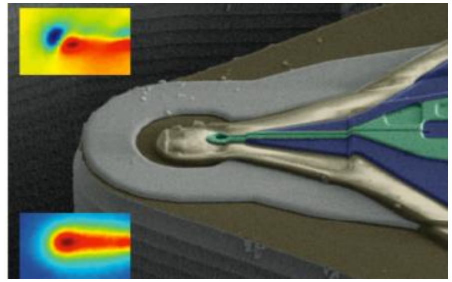
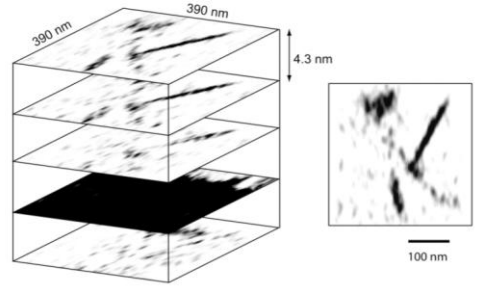
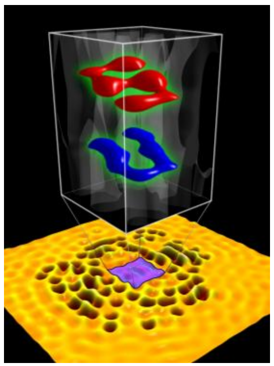
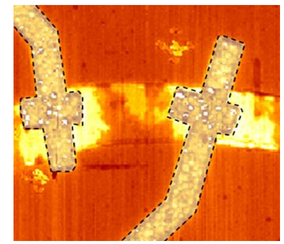
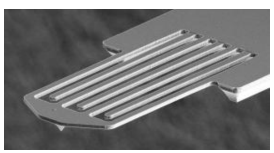


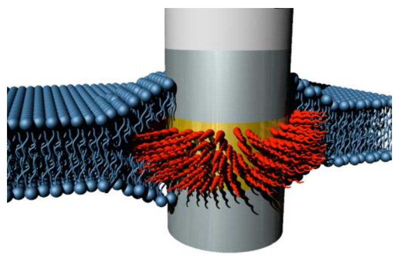


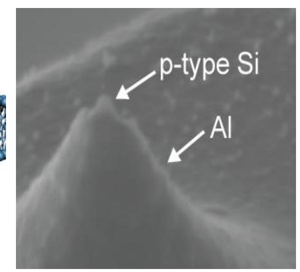


CPN









Characterization Needs for Manufacturable Integrated Nanosystems

Kathryn A. Moler
Director, Center for Probing the Nanoscale, Stanford University
kmoler@stanford.edu

CPN is supported by the National Science Foundation under Award PHY-0830228

"One must be able to measure and quantify phenomena in order to understand and use them, which is true also for nanoscale phenomena."

Small Wonders, Endless Frontiers: Review of the National Nanotechnology Initiative, report from the National Research Council, June 2002

CPN
An NSF Nanoscale Science and Engineering Center

About the Center for Probing the Nanoscale

Founded in 2004 by Stanford and IBM research

Supported by the National Science Foundation as a Nanoscale Science and Engineering Center

Goals:

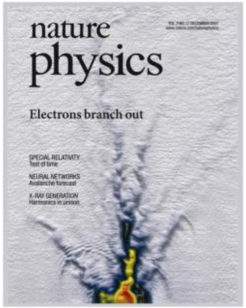
- ***To develop novel probes*** that dramatically improve our capability to observe, manipulate, and control nanoscale objects and phenomena.
- ***To educate*** the next generation of scientists and engineers regarding the theory and practice of these probes.
- ***To apply these novel probes*** to answer fundamental questions and to shed light on technologically relevant issues.
- ***To disseminate*** our knowledge and to transfer our technology so that other research scientists and engineers can make use of our advances, and so that corporations can manufacture and market our novel probes.
- ***To inspire*** thousands of middle school students by training their teachers at a Summer Institute.

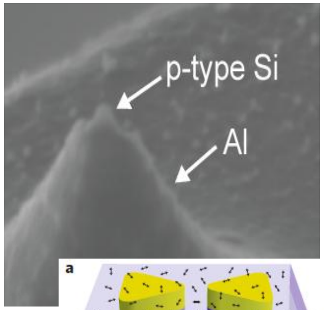
http://cpn.stanford.edu

CPN Research Themes

Nanoscale Electrical Imaging

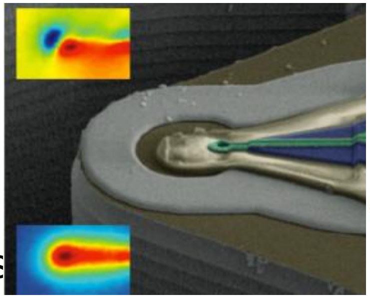
- Measure electronic properties at the 10 nm scale
  - Scanning Microwave Microscopy, Scanning Gate Microscopy, Novel Cantilever Design and Fabrication

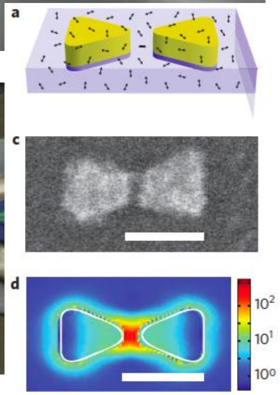




Individual Nanomagnet Characterization

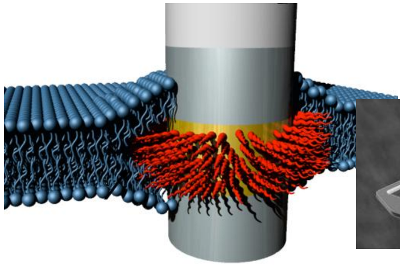
- Magnetic sensitivity and spatial resolution for nm magnet characterization
  - Scanning SQUID Microscopy, Polar Kerr-effect Measurements combined with bowtie nanoantennas





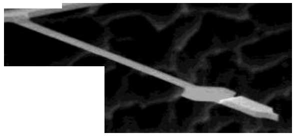
Bio-Probes

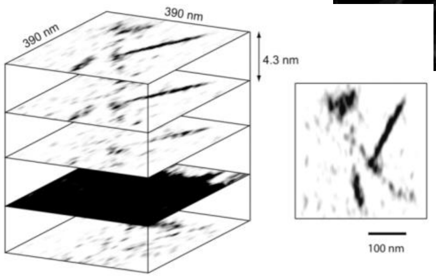
- Understand biological processes that take place in cell membranes
  - Bio-functionalized probe tips combined with ultra-fast probe sensors



Nanoscale Magnetic Resonance Imaging

- Molecular structure microscope with chemical sensitivity
  - Magnetic force detection from nuclear spin flips





General considerations for nanosensors

- spatial resolution
- sensitivity to quantity of interest
    - magnetic field
    - spin
    - capacitance
    - dielectric constant
- bandwidth
- invasiveness
- interpretability
- ease of use
- temperature range

Signal-to-Noise at the Nanoscale

Less stuff => less signal

Fewer particles
=>
more fluctuations
=>
more noise

What do you want in 10 years?

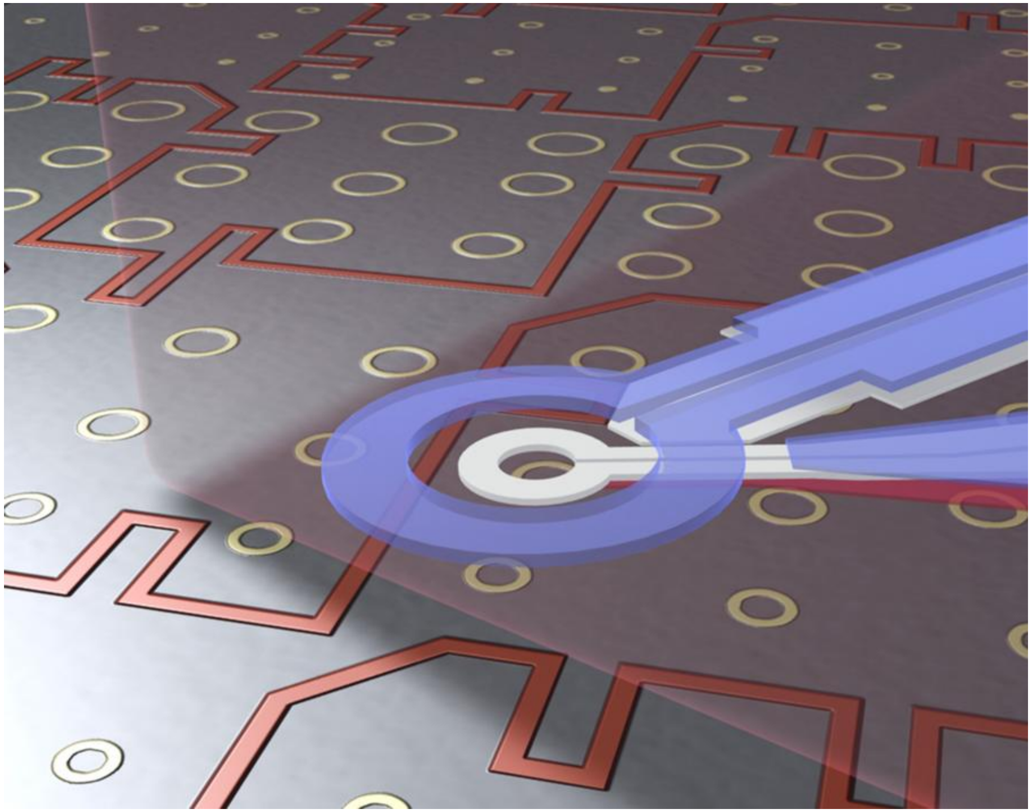
I want 1 nm spatial resolution.

I want 1 μ_B spin sensitivity.

I want 1 ns time resolution.

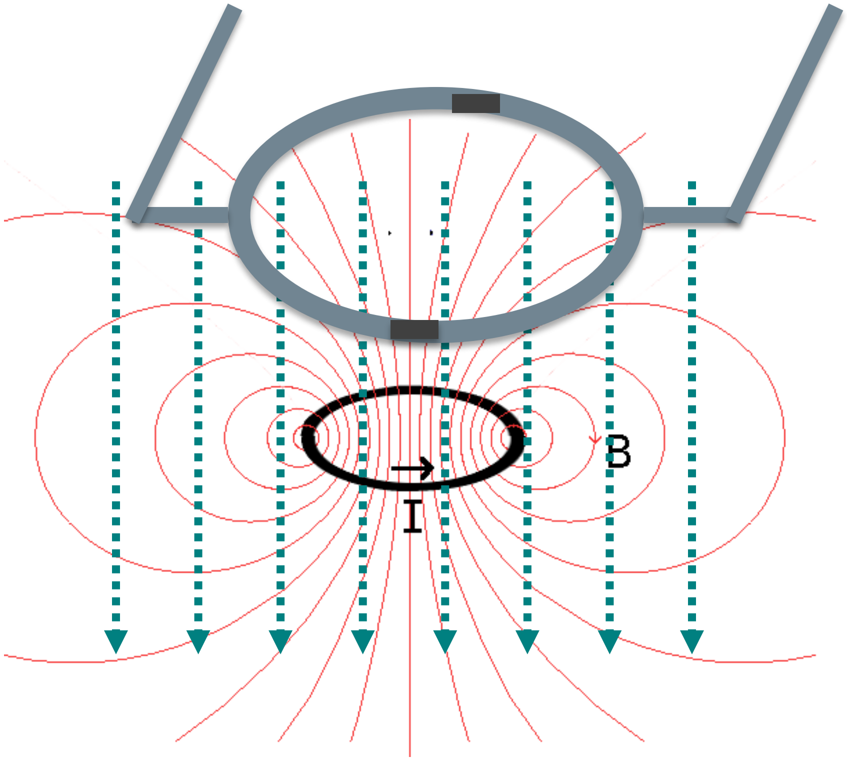
I want it all at once at room temperature next to a real production line.

Scanning SQUID Microscopy



Moler Group

Magnetic Measurements



Goal:

Measure the magnetic moment and magnetic susceptibility of a nanoscale system.

Superconducting Quantum Interference Device (SQUID)

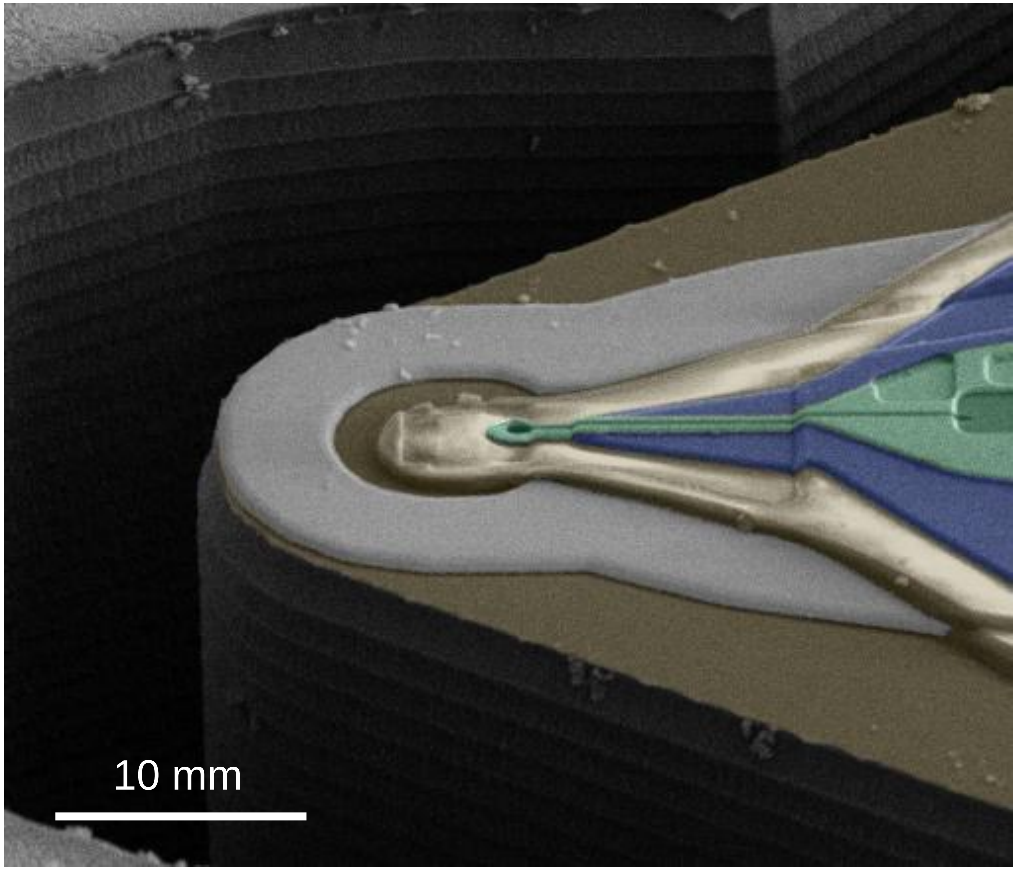
Current SQUIDs

Design

- Produced by 12-layer optical lithography process
- Pickup loops as small as 500 nm defined by FIB
- Terraced tips allow positioning of pickup loop 300 nm from sample

Performance demonstrated

- Spin sensitivity < 100 μ_B/rt-Hz

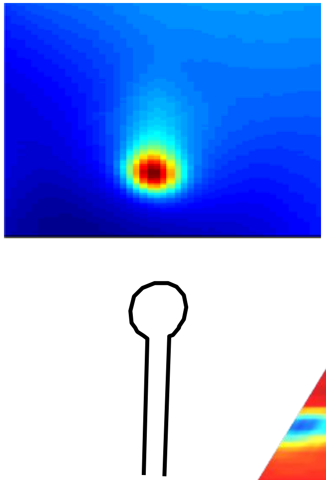


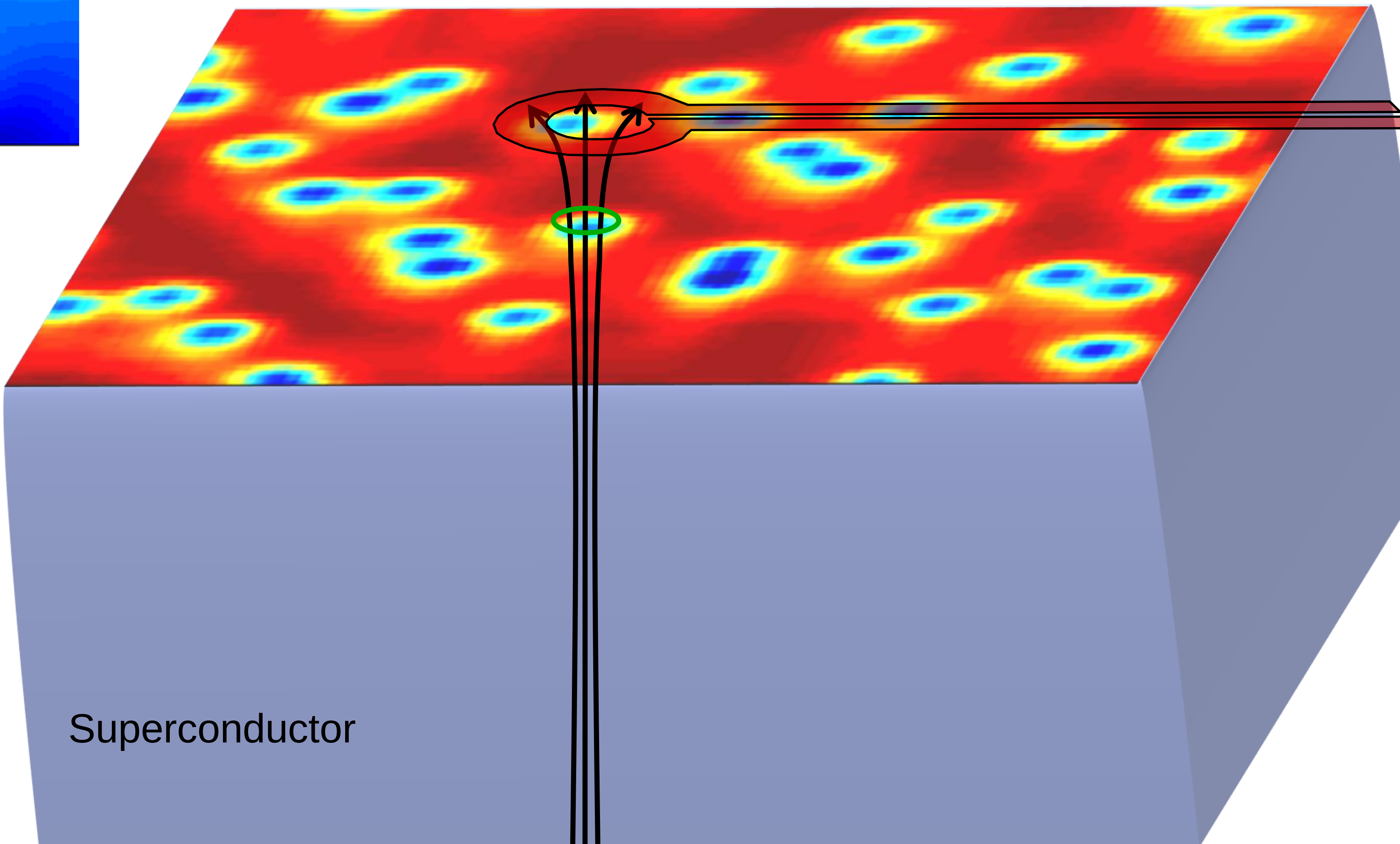
Koshnick, *et al.*, *APL* **93** (2008)

Scanning SQUID Microscopy - Magnetometry

Operate as Magnetometer without field coil

- DC measurement of flux captured by pickup loop.

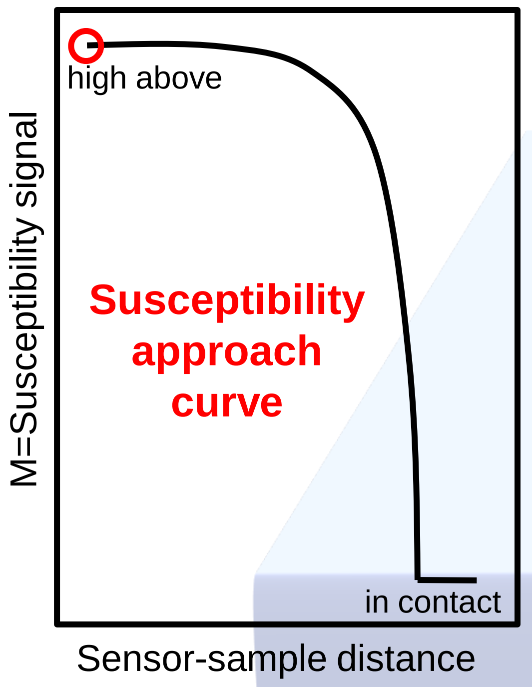


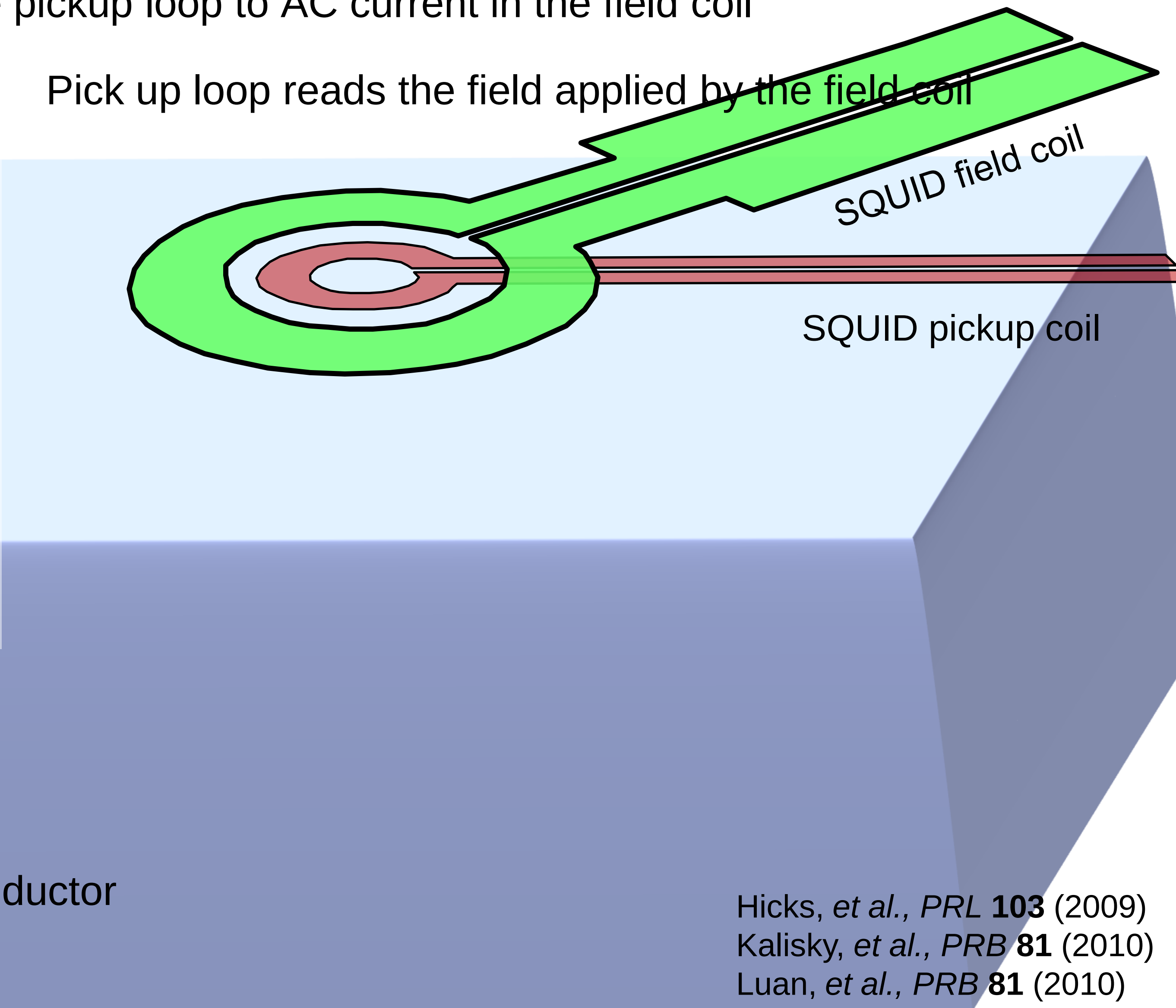


Scanning SQUID Microscopy - Susceptometry

Operate as Susceptometer with field coil

– Response in the pickup loop to AC current in the field coil

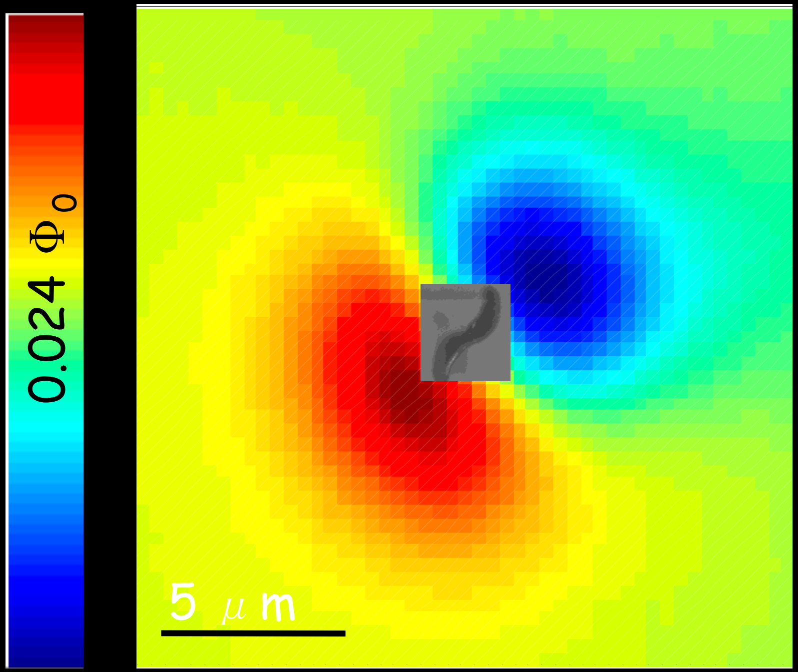




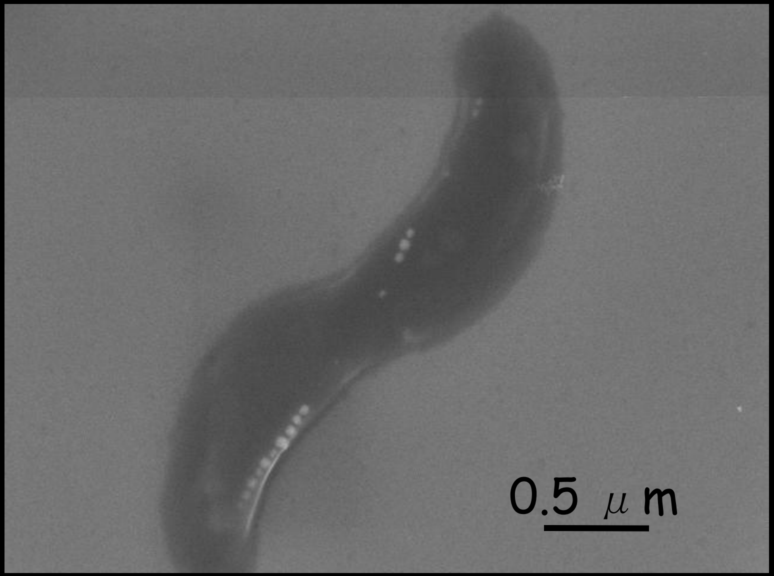
Hicks, *et al.*, *PRL* **103** (2009)
Kalisky, *et al.*, *PRB* **81** (2010)
Luan, *et al.*, *PRB* **81** (2010)

Magnetotactic bacteria

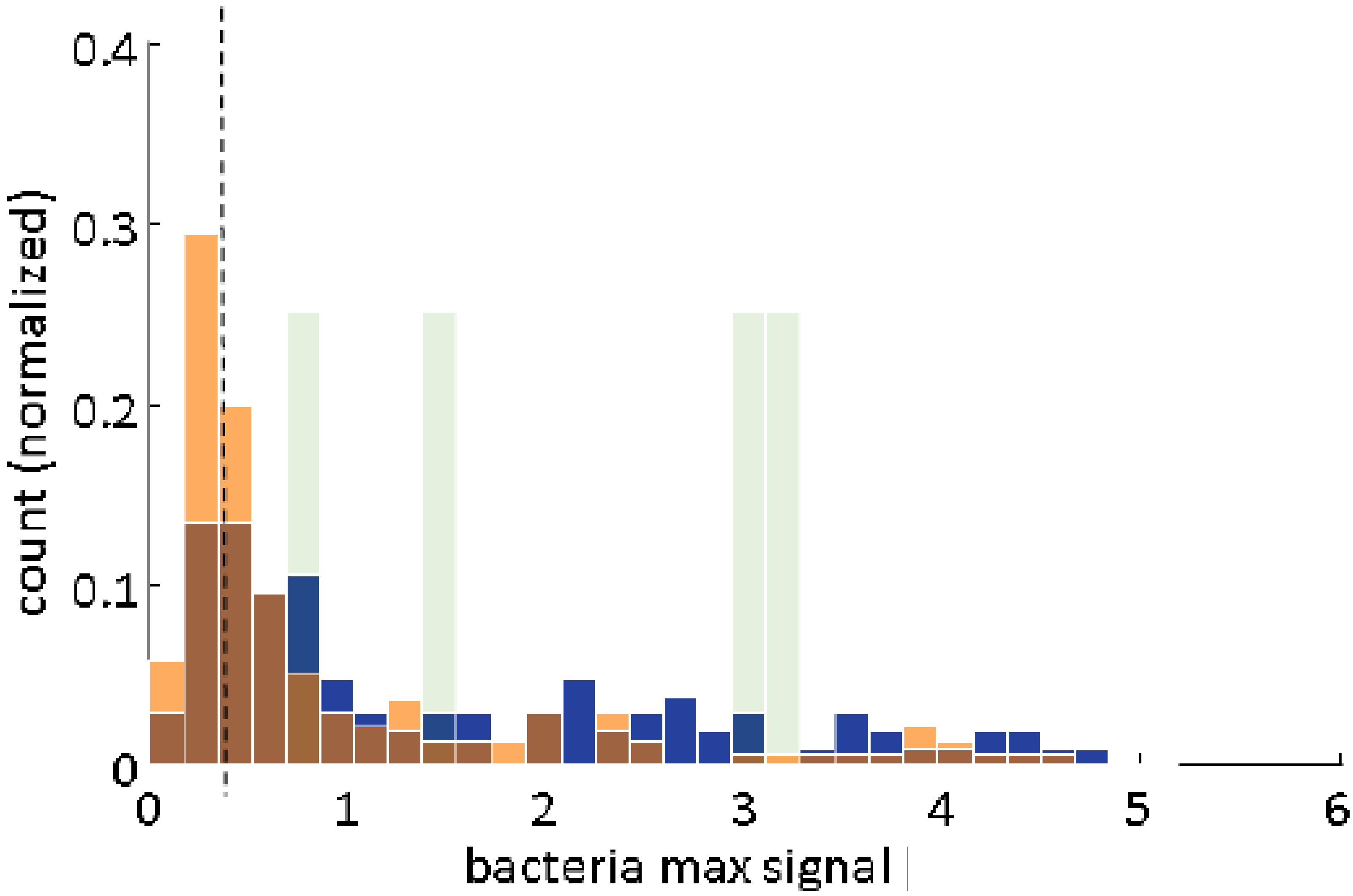
Magnetometry image



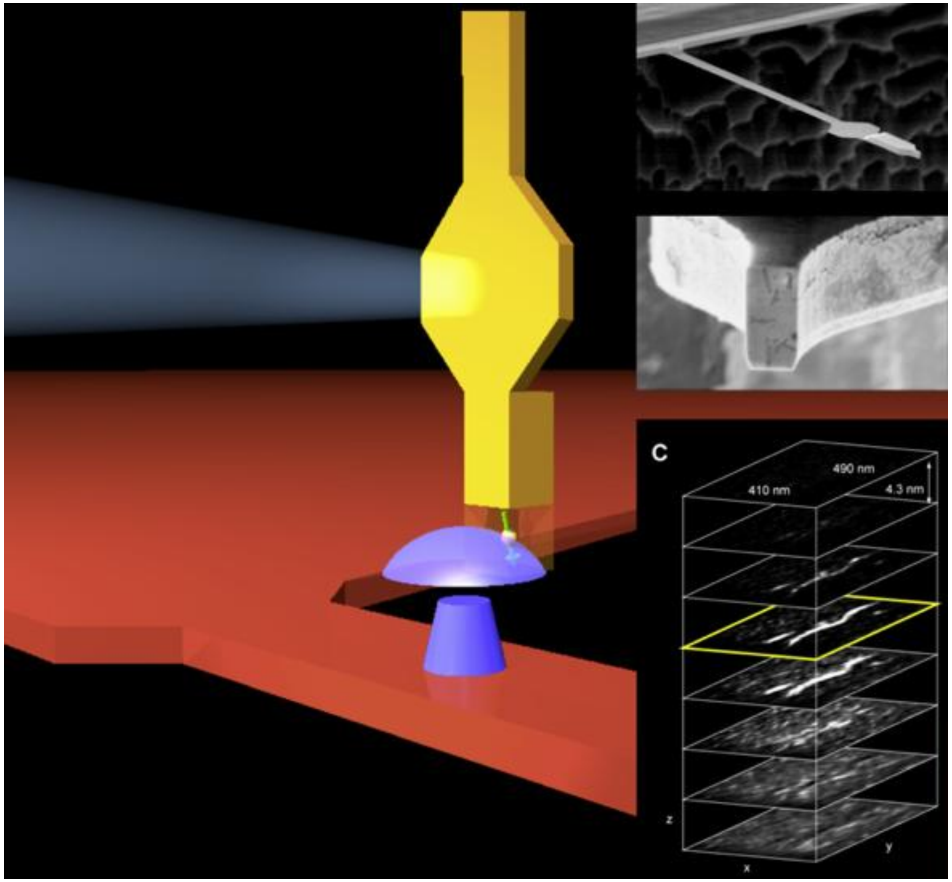
SEM image



Distribution of Magnetic Moments In Populations of Magnetotactic Bacteria



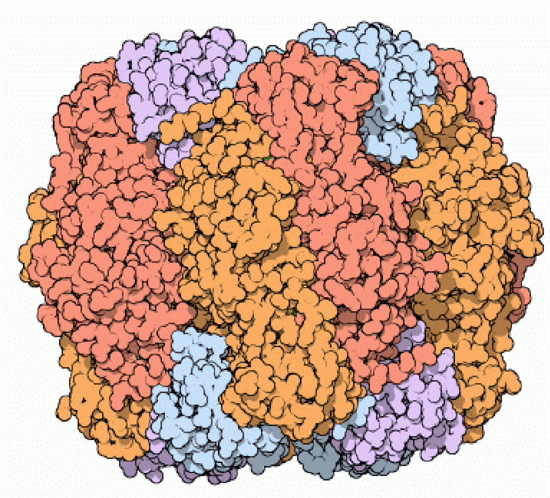
Nanoscale MRI



Rugar Group (IBM/Stanford)

Nanoscale Magnetic Resonance Imaging (MRI)

The Quest for a Molecular Structure Microscope



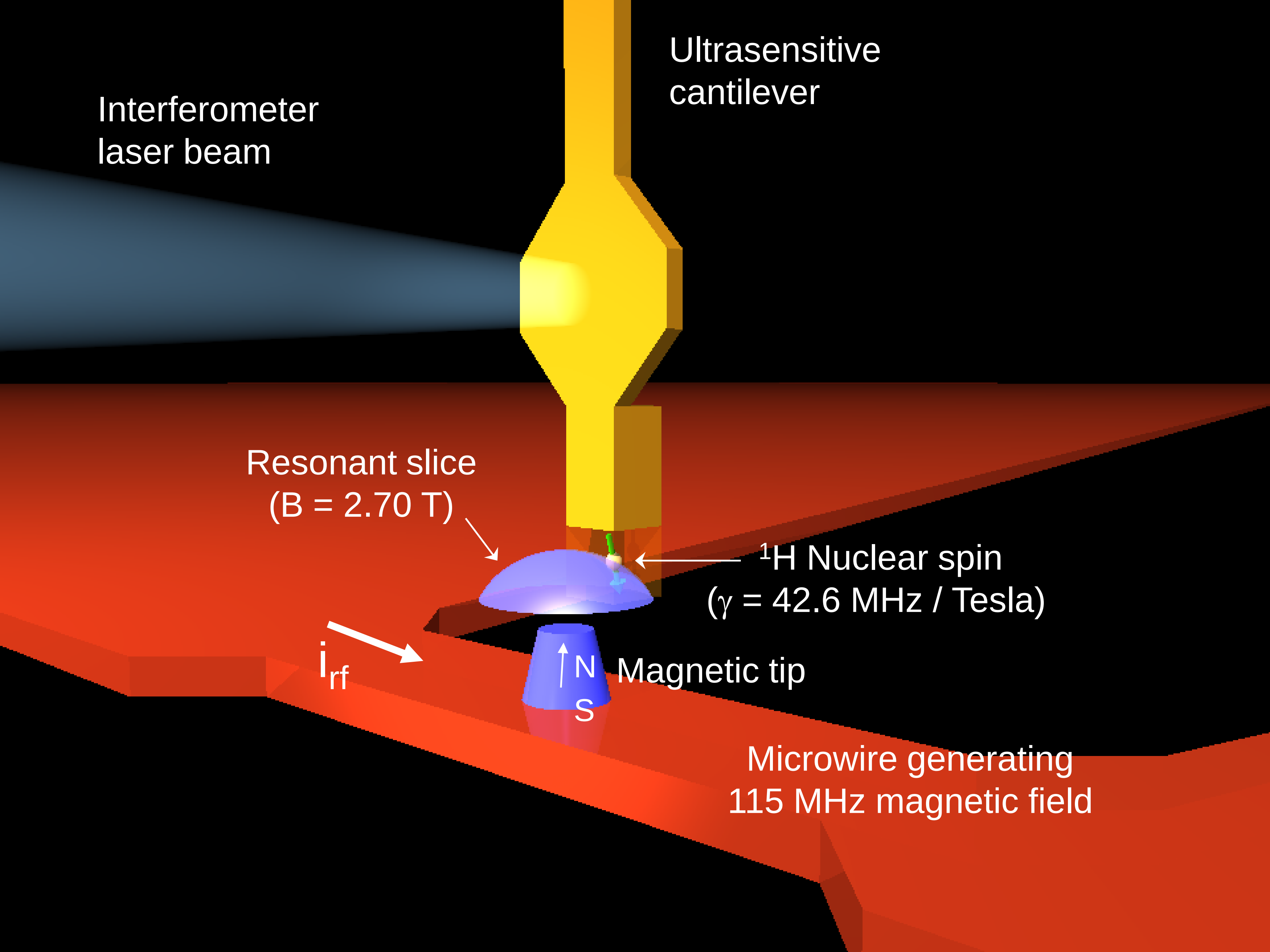
- Molecular structure is key to understanding function
- Most proteins in your body have no known structure due to limitations of current techniques (radiation damage, crystallization…)
- Can a microscope be built that can directly image the 3D structure of molecules?

Extend Magnetic Resonance Imaging (MRI) to the Nanoscale

- Features
  - True 3D imaging, chemically selective, non-destructive

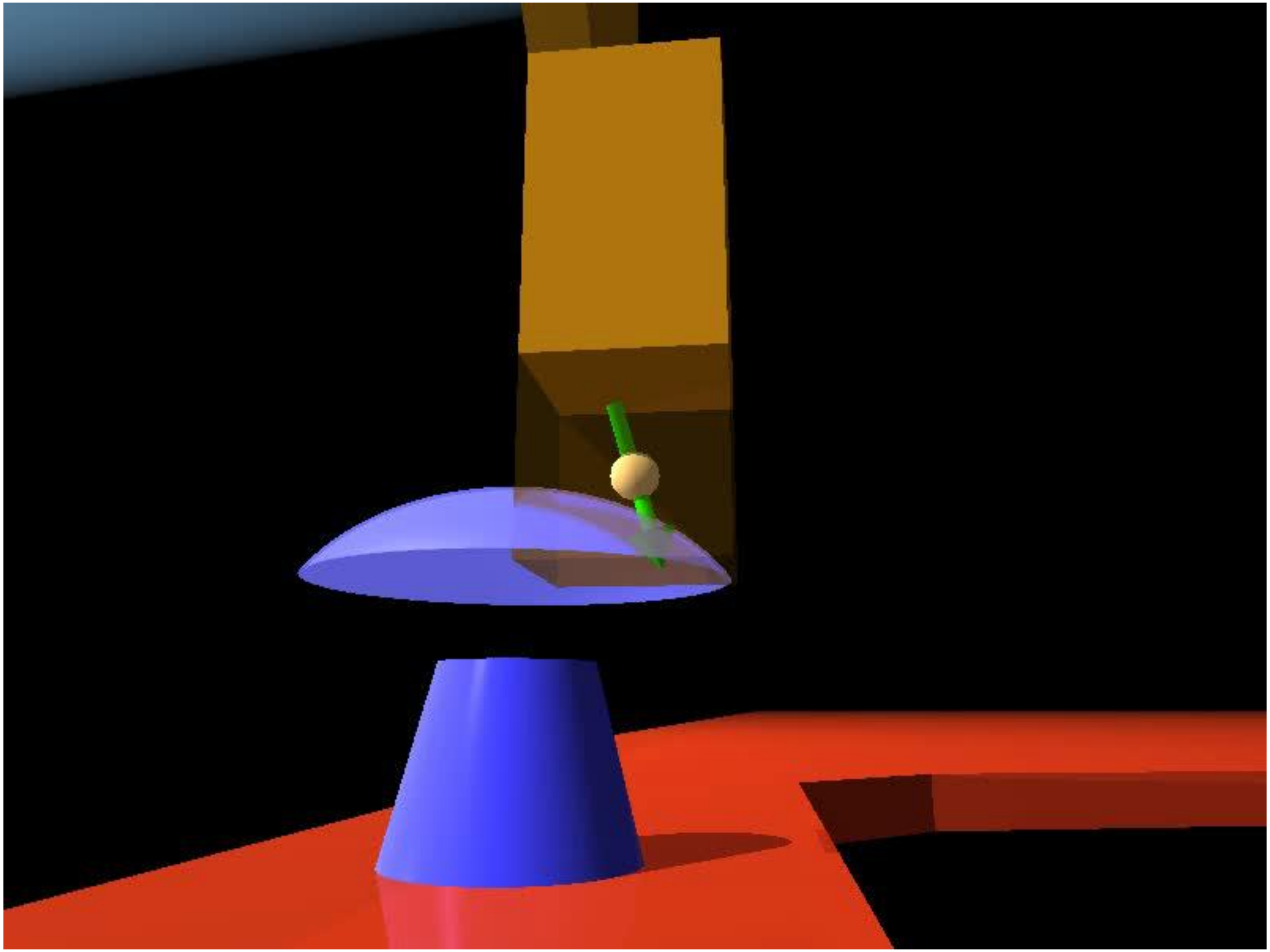
But ...

- Conventional MRI requires 10^{12} - 10^{18} nuclear spins per voxel and is limited to resolution of $(3\ \mu m)^3$

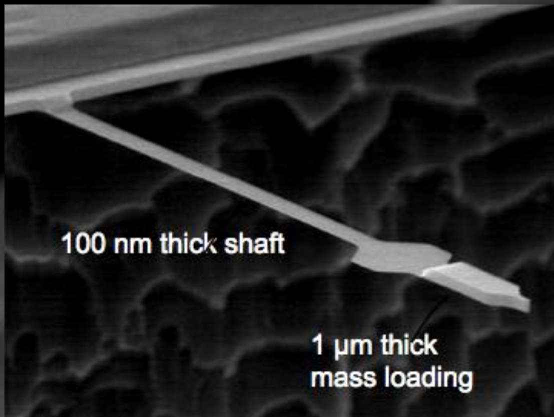


Ultrasensitive cantilever
Interferometer laser beam
Resonant slice (B = 2.70 T)
¹H Nuclear spin (γ = 42.6 MHz / Tesla)
i_{rf}
N
S
Magnetic tip
Microwire generating 115 MHz magnetic field

Nanoscale MRI Schematic



First MRFM Images of a Biological Sample

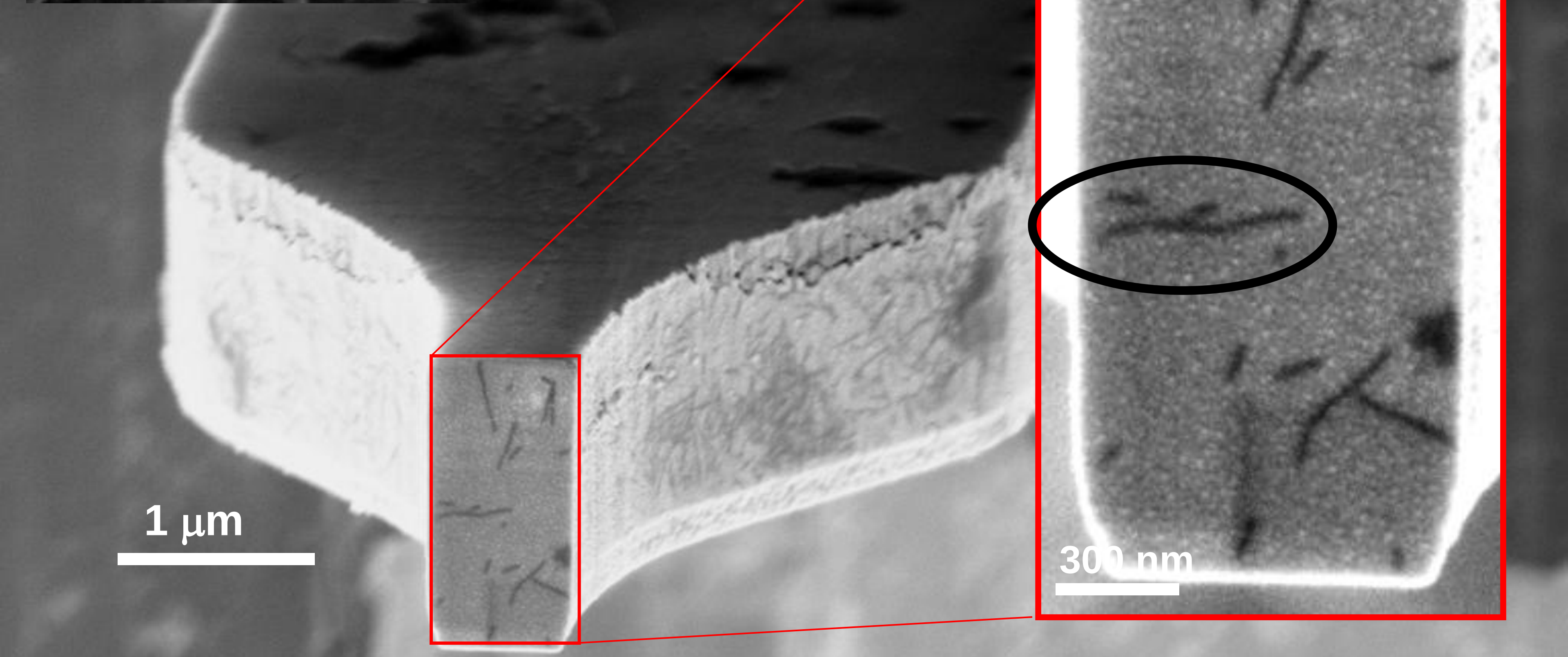


Tobacco Mosaic Virus

TMV particle size:

18 nm diameter

Up to 300 nm long



C. L. Degen et al., Proc. Natl. Acad. Sci USA **106**, 1313 (2009)

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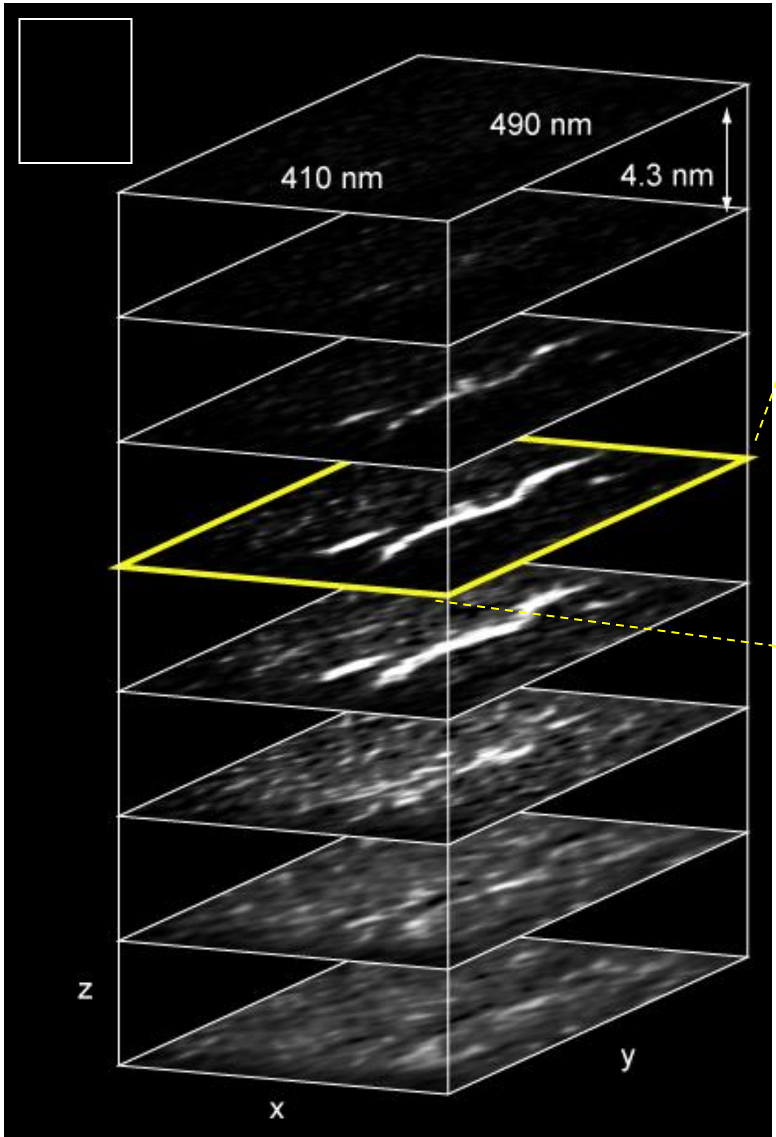
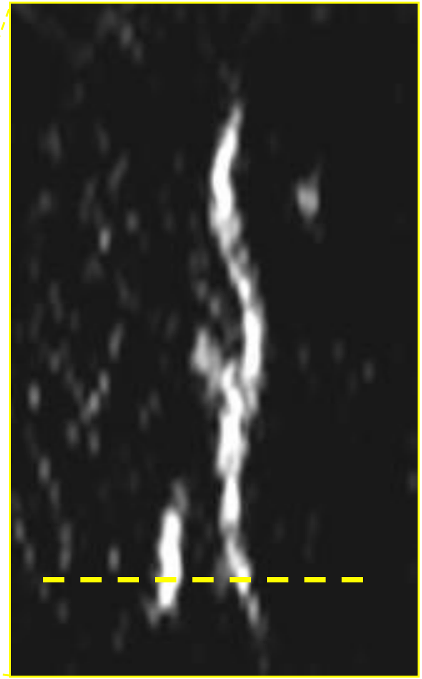
3D reconstruction of proton density



Detail from one horizontal slice



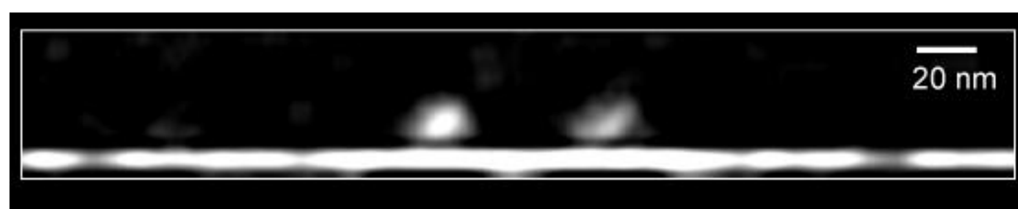
Combined ultrasensitive MRFM detection with 3D image reconstruction delivers < 10 nm voxel resolution

100 millionfold improvement in volume resolution over conventional MRI

Elementally selective imaging

No radiation damage

Cross-section - showing depth resolution



C. L. Degen et al., *Proc. Natl. Acad. Sci* **106**, 1313 (2009)

Spin Measurements - Nitrogen-Vacancy Center

- Small changes in sample's magnetic field gives rise to variations in fluorescence intensity
- Technique can work under ambient conditions (no cryo, no vacuum)

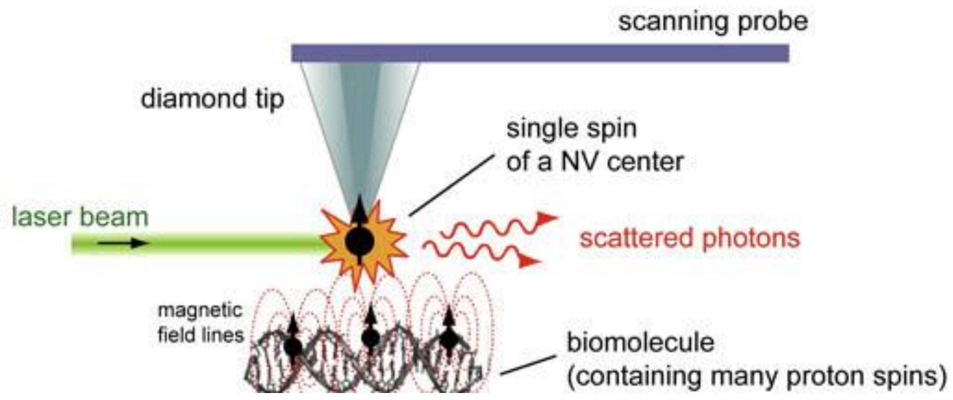
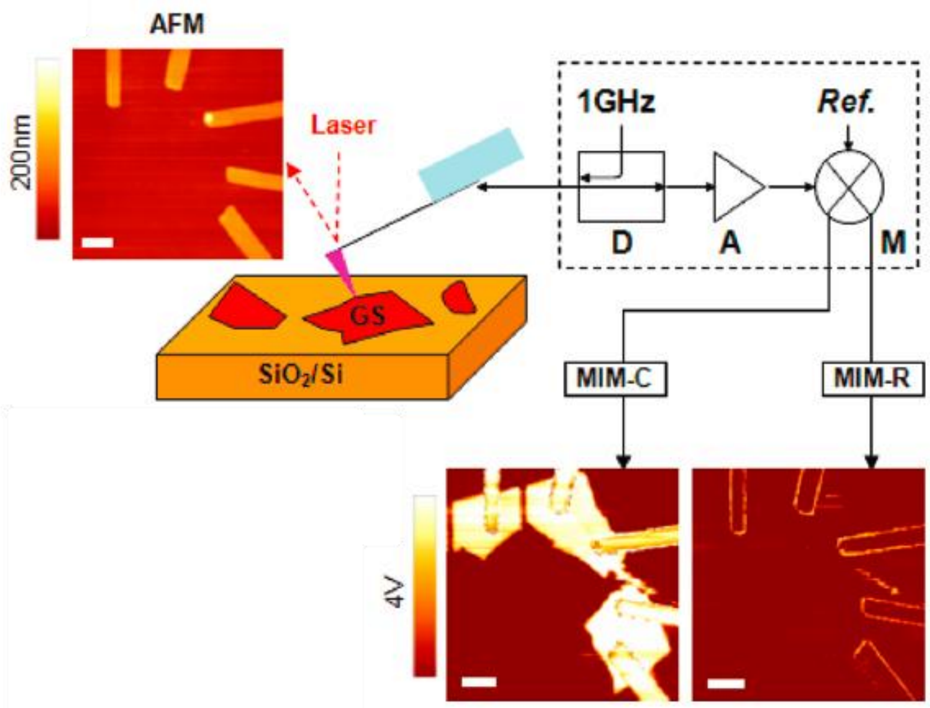


Image taken from Degen lab

Theoretical estimates suggest that NV centers will enable imaging of both magnetic fields and spins at room temperature comparable to what MRFM and SQUID microscopy can do at low temperature.

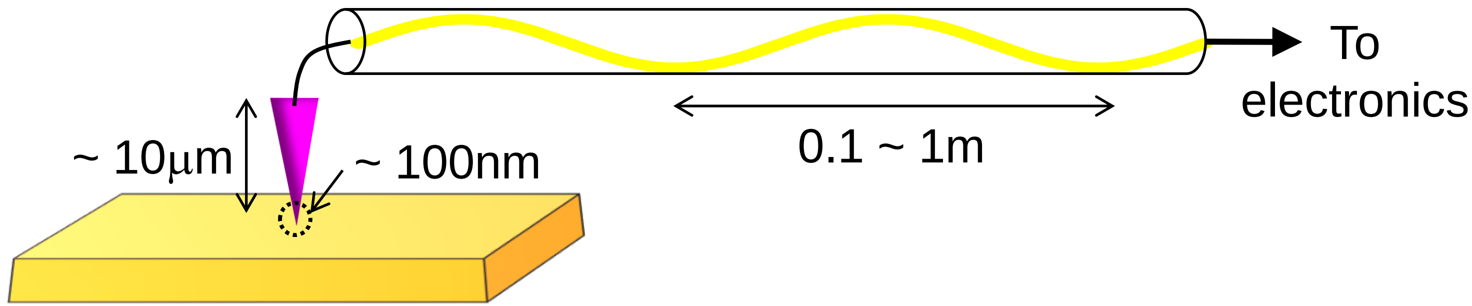
Nanoscale Microwave Impedance Microscopy



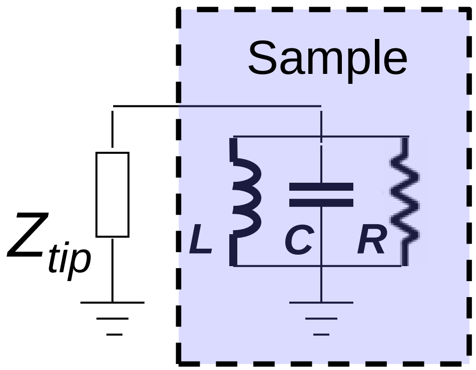
Keji Lai and Michael Kelly, Zhi-Xun Shen Group

Near-field microwave imaging

How…



What…



Finite element analysis → Local dielectric constant and conductivity (ε, σ)

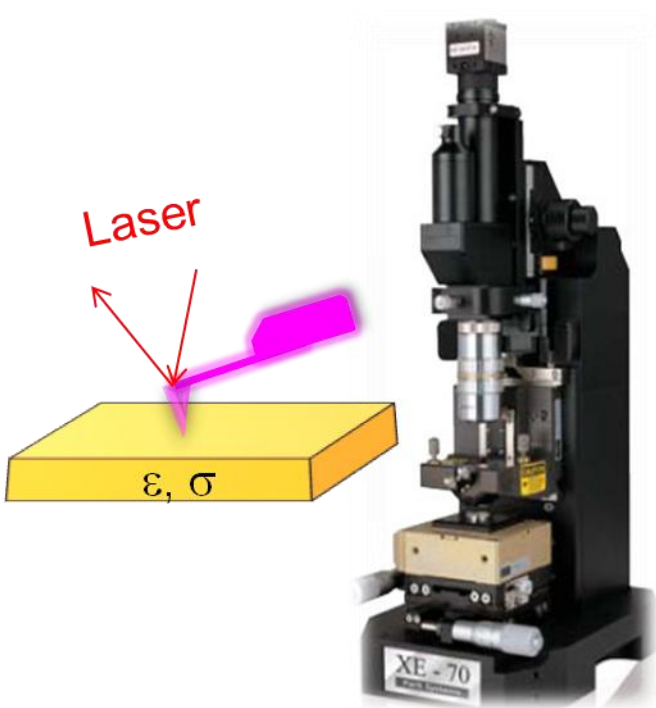
Microwave impedance microscopy (MIM)

Why… For microwave frequency:

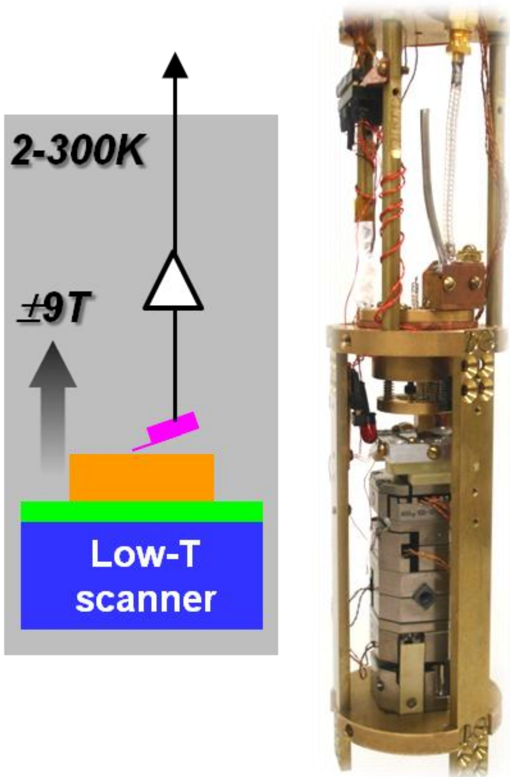
- Big contrast between metal & insulator
- f >> DC, therefore no electrodes required
- f << optic, energy small, therefore no inter-band transitions

Instrumentation

Commercial
atomic-force microscope



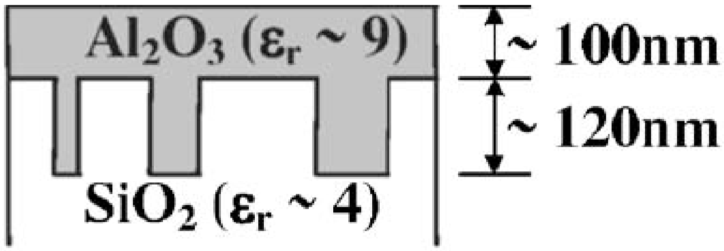
Customized
cryogenic / magnet system

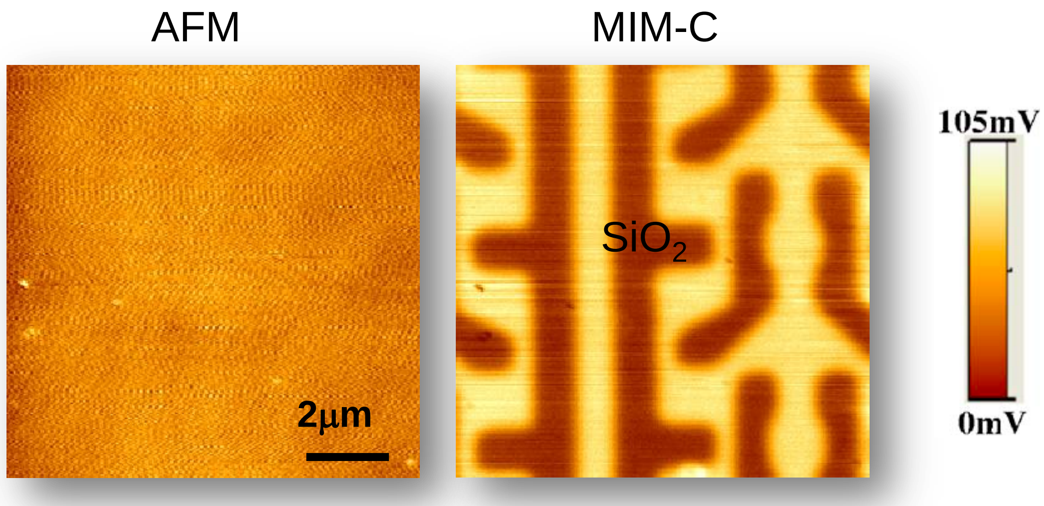


Imaging Electronic Devices

Sub-surface imaging

- a layer of Al_2O_3 is sputtered onto a SiO_2 sample and then the surface is polished

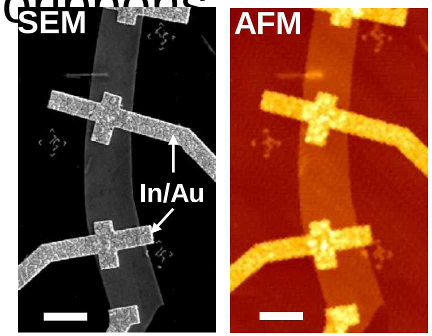


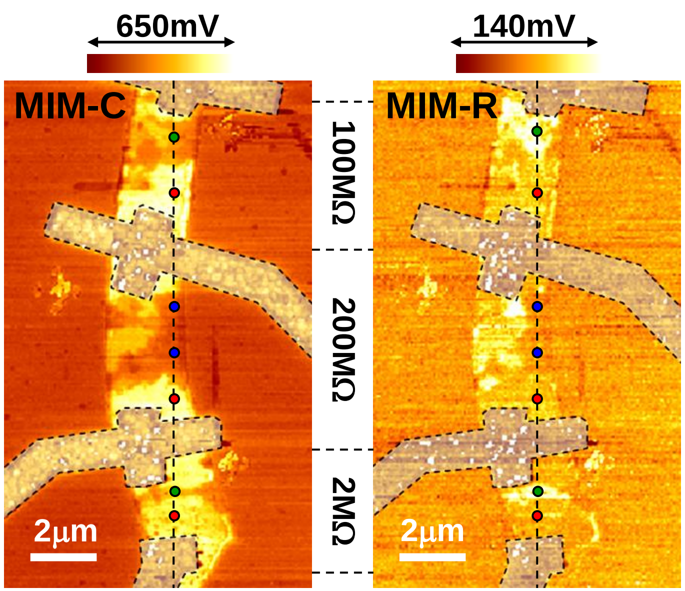


K. Lai *et al., Rev. Sci. Instrum.* **78** (2007)

Material Science Applications

Electronic Inhomogeneity in Phase-change In_2Se_3 nanoribbons

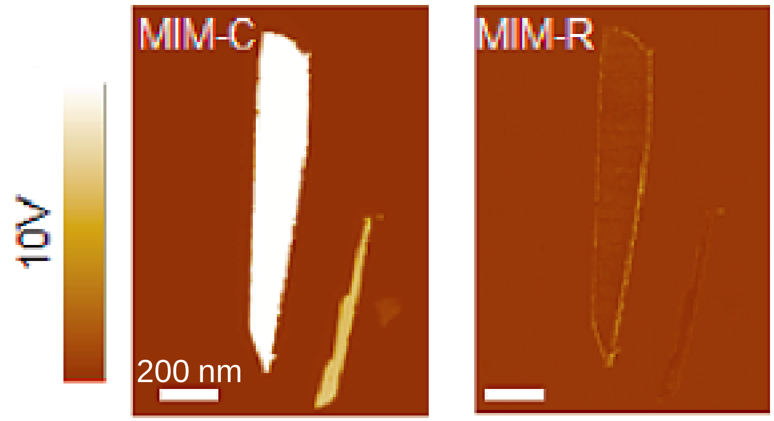




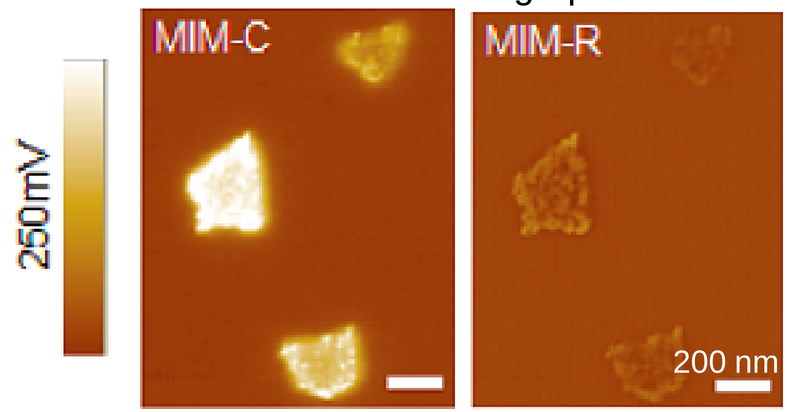
K. Lai *et al.*, *Nano Lett.* **9** (2009)

Graphene derived from various sources

Peel-off graphene



Annealed graphene sheets, chemically derived from graphite



W. Kundhikanjana *et al.*, *Nano Lett.* **9** (2009)

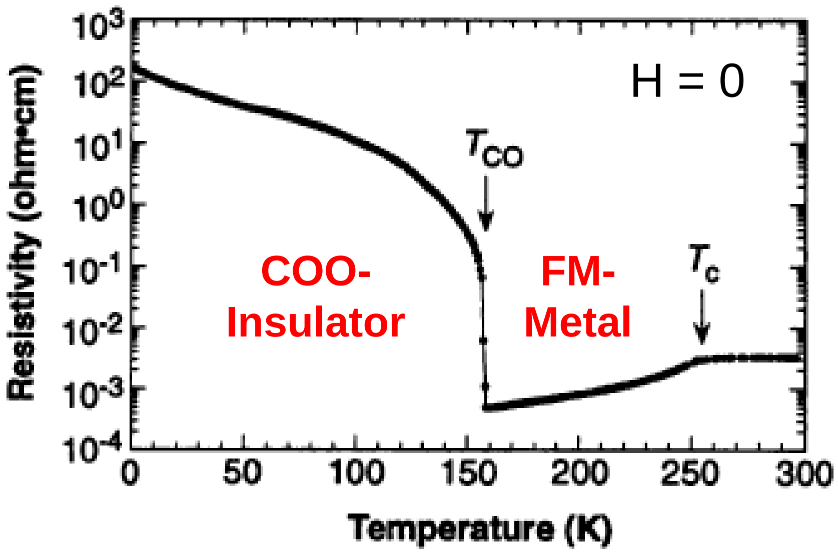
Colossal Magnetoresistance $Nd_{1/2}Sr_{1/2}MnO_3$ Phase Transitions

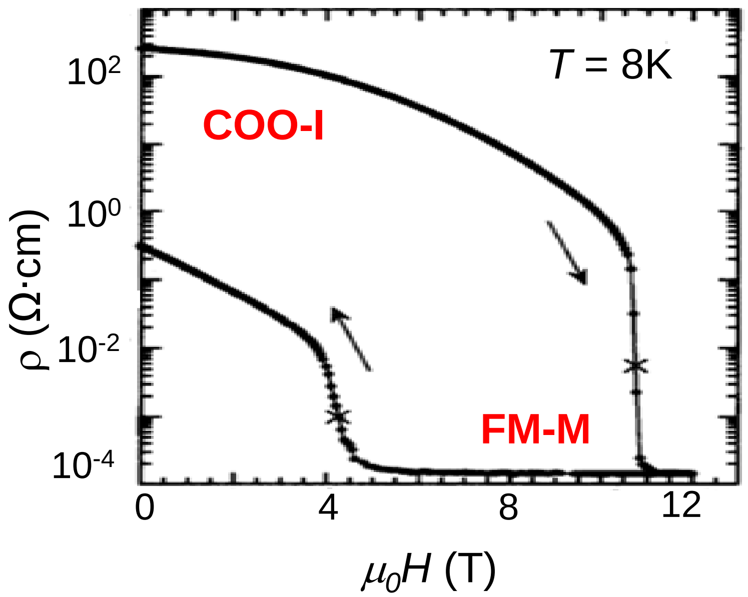
Temperature-driven phase transitions

- T_{curie} ~ 250K: paramagnetic to ferromagnetic
- T_{coo} ~ 160K: charge/orbital-order

Magnetic field driven phase transition below T_{coo}

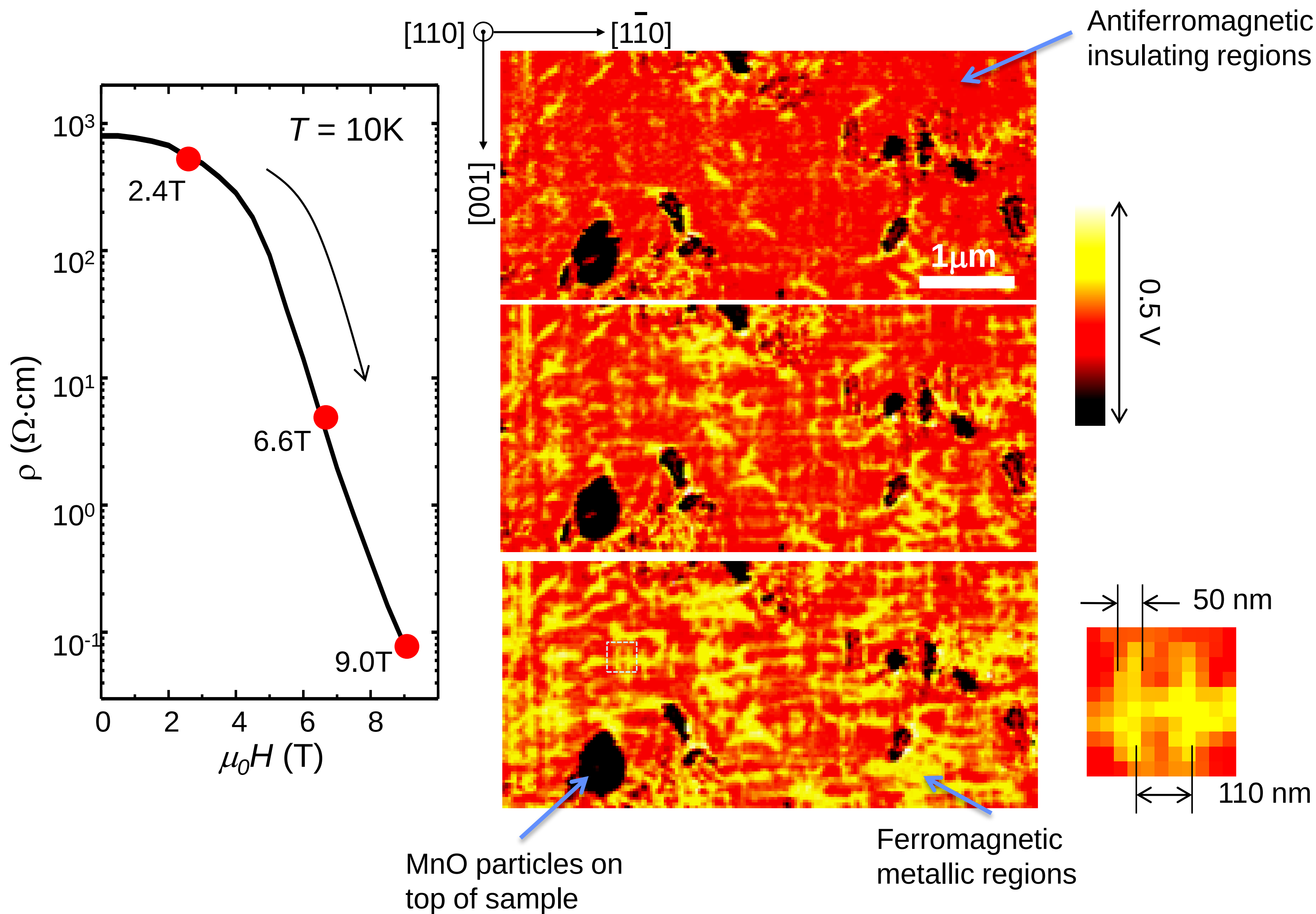
- From antiferromagnetic COO insulating to ferromagnetic metallic
- Hysteresis below T_{coo}





Science 270, 961 (1999)

Microwave Imaging of CMR



K. Lai *et al.*, *Science* **329**, 190 (2010)

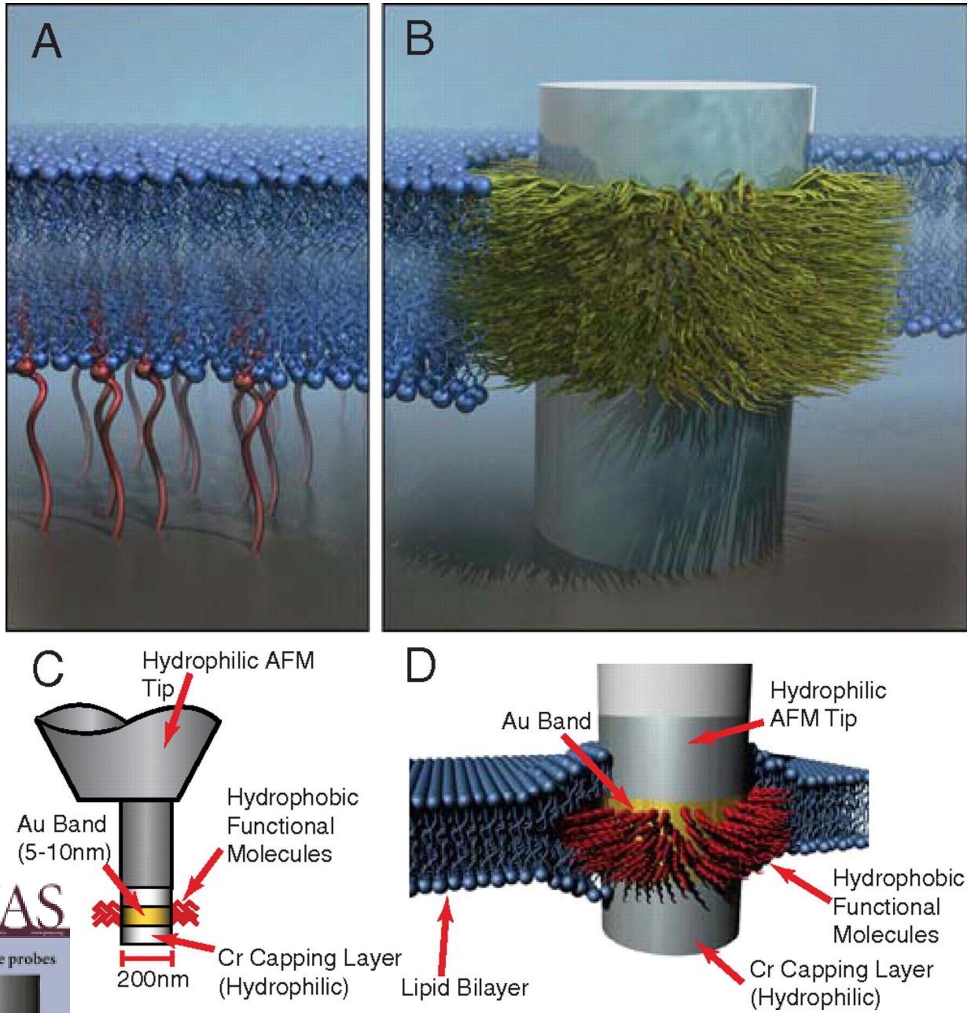
Biomimetic Stealth Probes

Motivation

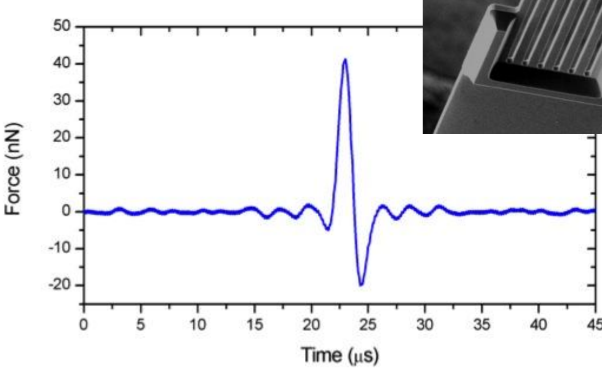
– Create an **access port** to study cell activity and transport mechanisms through cell membranes

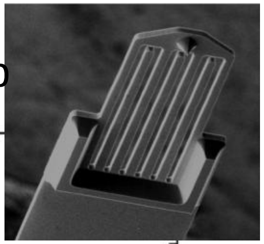
Technology

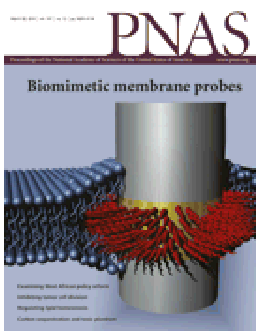
– Use a bio-functionalized probe tip to mimic membrane proteins and insert into the cell membrane's lipid bi-layer



Prof. Solgaard Group







B.D. Almquist and N.A. Melosh, *PNAS*. **107** (2010)

Where Do We Go from Here?

Sensitivity, Resolution …

- Continued research into new measurement techniques
- Improvements of current techniques to push spatial and temporal resolution, sensitivity, …

Multi-modality characterization

- Simplified construction and advances in nanofabrication are enabling characterization techniques that can probe several physical properties at the same time in one instrument, especially important for integrated nanosystems

Ease of Use

Synergy between characterization research and design & manufacture of integrated nanosystems

Thank You!