Directional dark matter detection in diamond: principles and experimental progress

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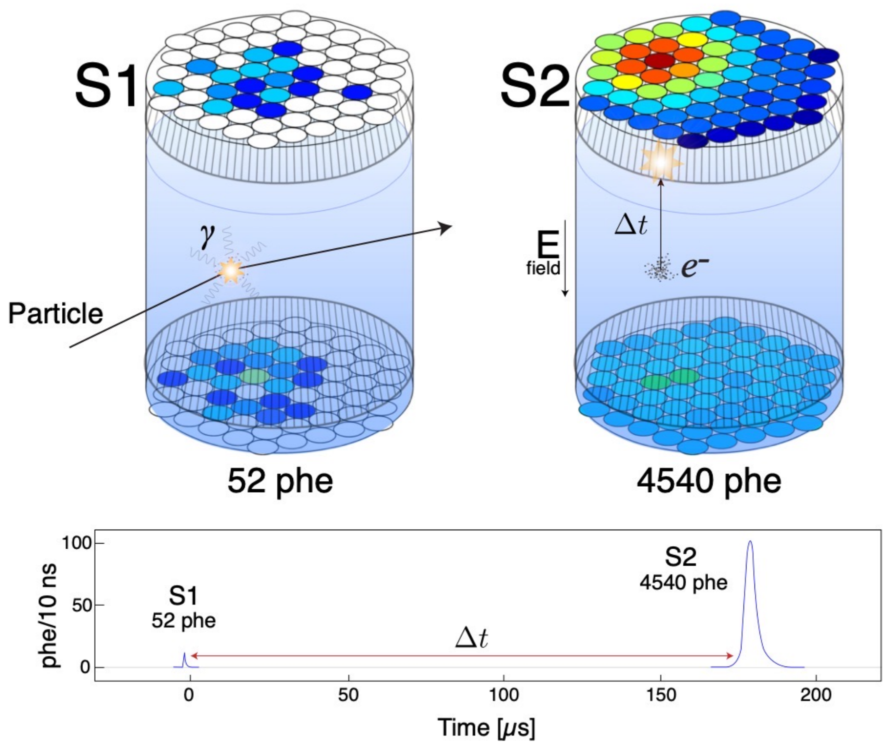
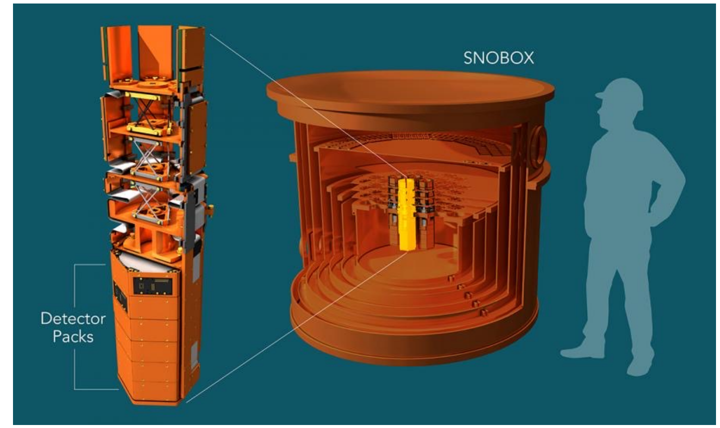
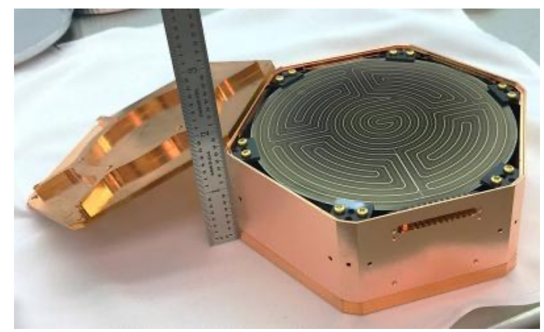
WIMP dark matter search



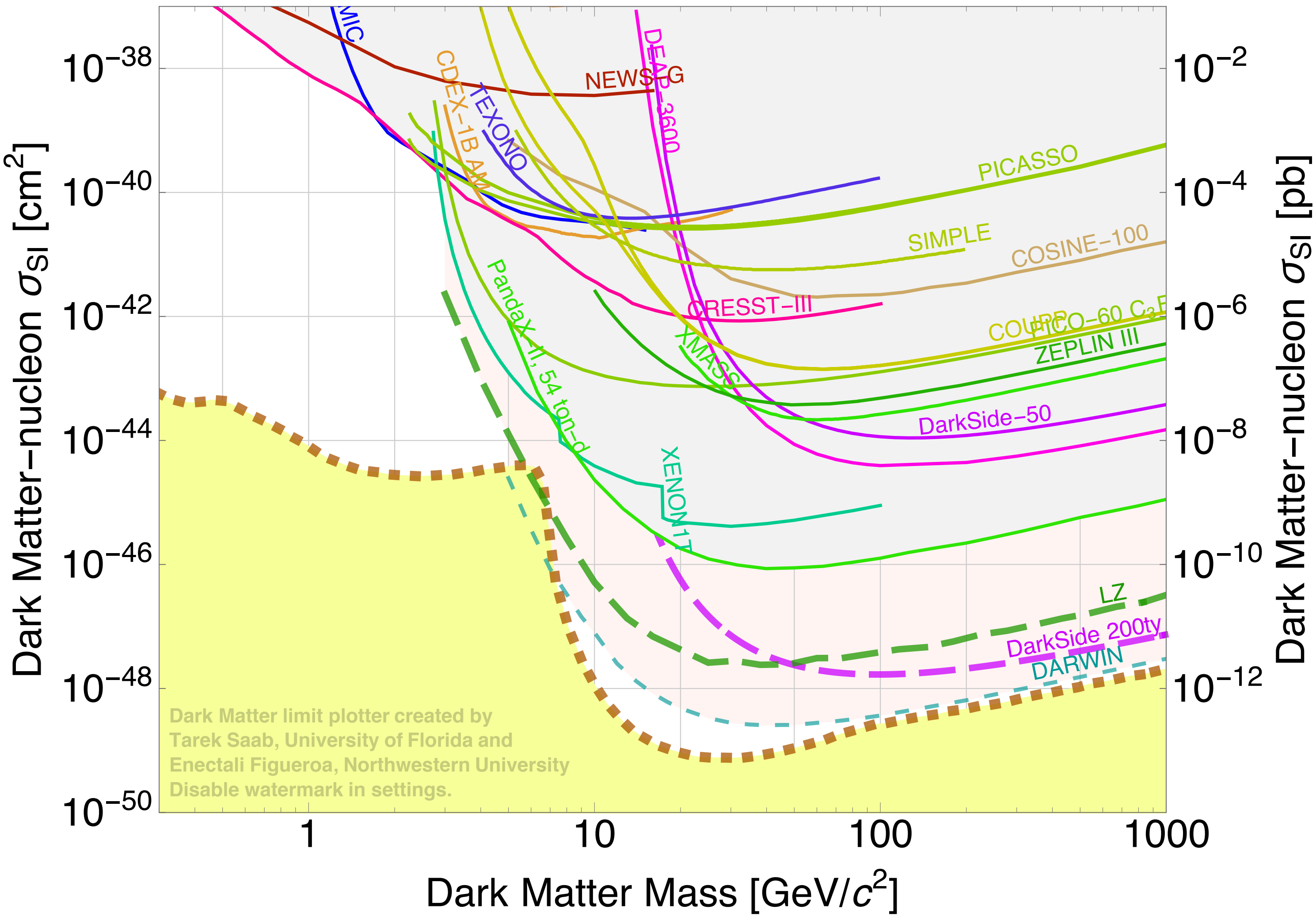




XENON, LUX, DarkSide, LZ, …

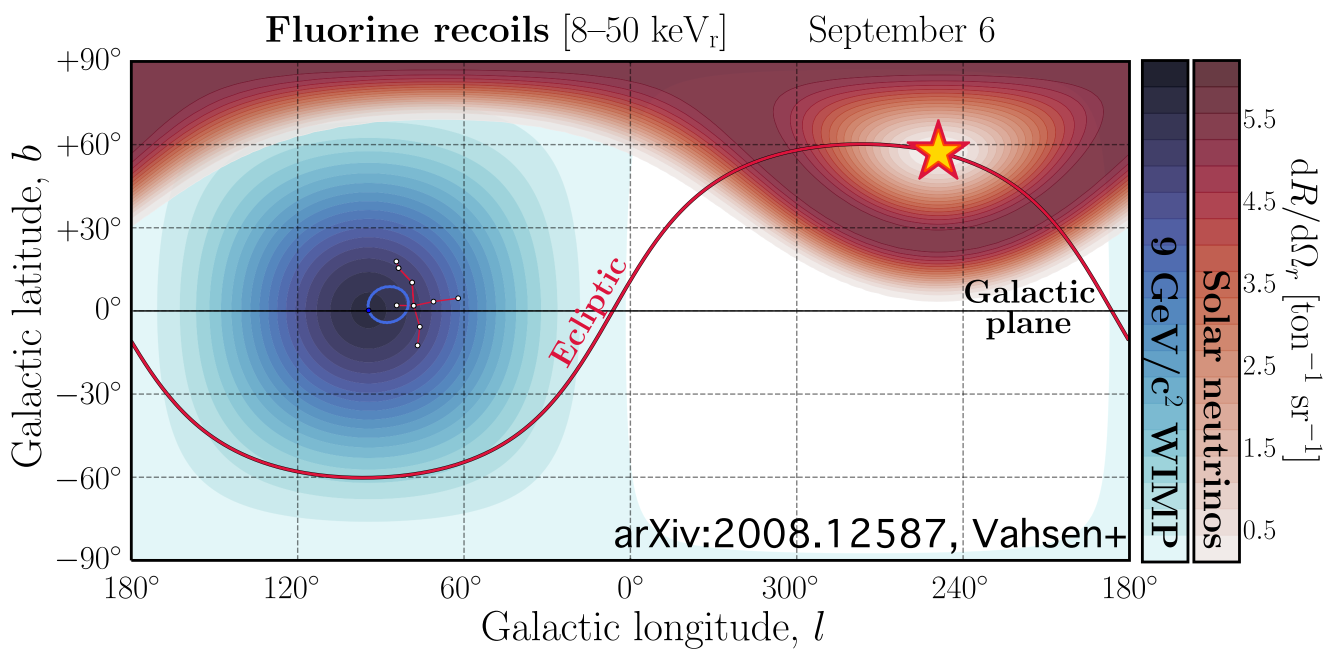
CDMX, …

WIMP searches approaching neutrino floor



Directional detection

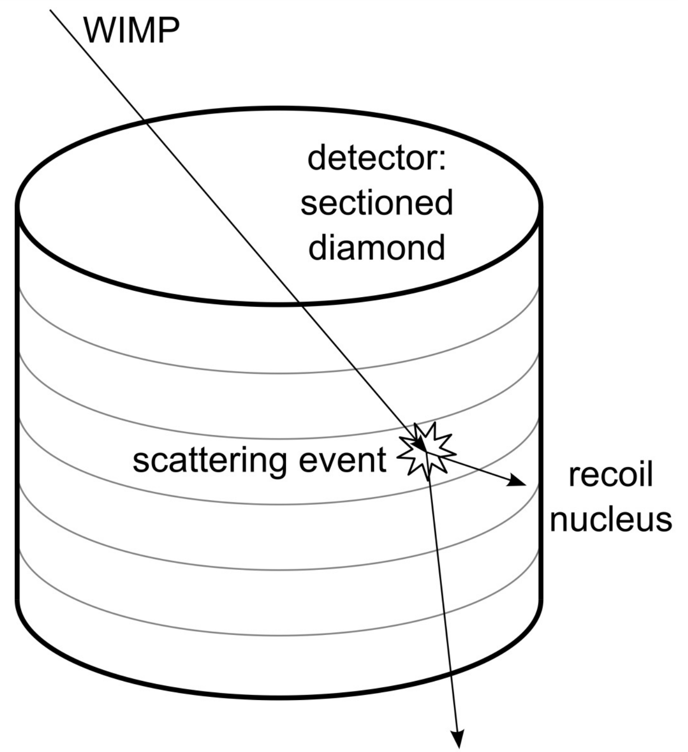
- ❑ Reject solar neutrinos
- ❑ DM astronomy
  - ❑ Background discrimination
  - ❑ Out-of-equilibrium Galactic DM components
- ❑ Neutrino physics



D. N. Spergel, *Phys. Rev. D* (1988)

Diamond detector

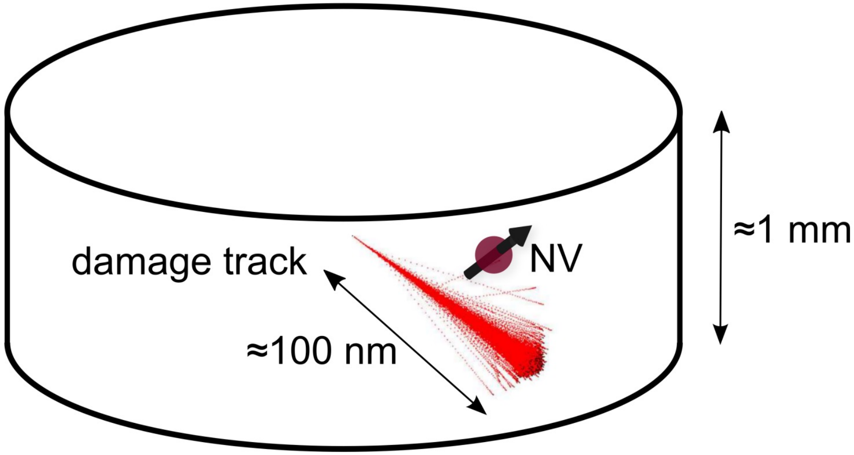
- Carbon – complementary sensitivity to existing detectors
- High detection efficiency possible – phonon, charge and scintillation photon collection
- Sensitive to nuclear recoil, electron recoil, and DM absorption



Kurinsky *et al.*, Phys. Rev. D (2019)
Rajendran *et al.*, Phys. Rev. D (2017)

Directional detection principle

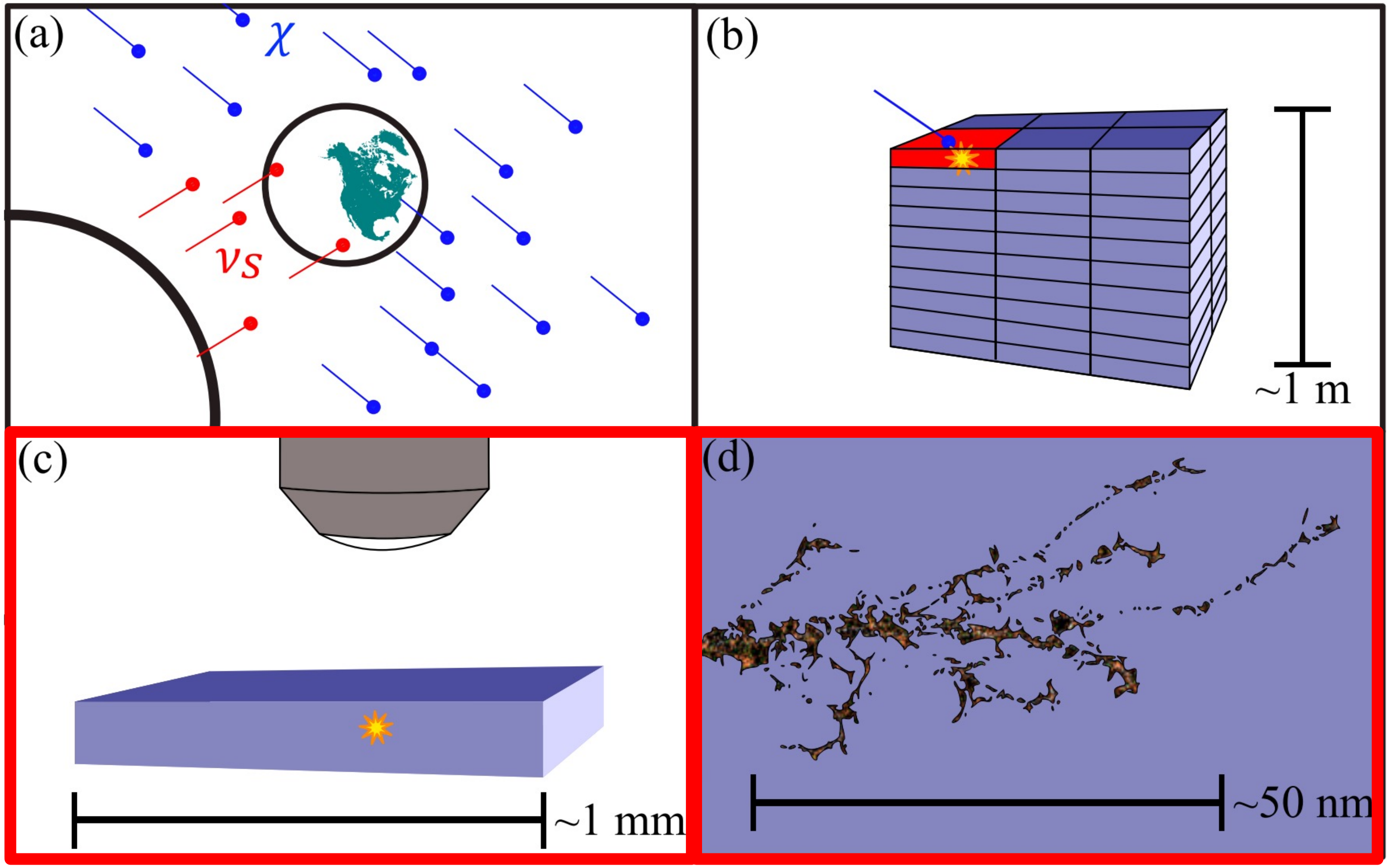
- ❑ WIMP event initiates recoil cascade → damage track
- ❑ Crystal damage track preserves particle direction



<u>Use AMO physics techniques to measure track direction</u>

Rajendran *et al.*, Phys. Rev. D (2017)

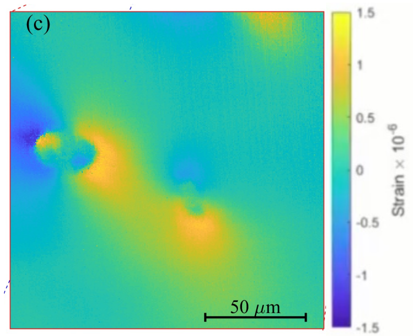
Directionality readout



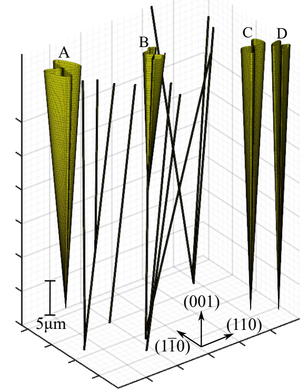
1. **Identify an event** in a mm-scale segment of a large detector.
2. **Localization down to a ~µm voxel** within the mm-scale diamond segment.
3. **Track reconstruction** within the ~µm voxel

M. Marshall *et al.* Quantum Sci. Technol. (2021)

	Micron-scale localization	Nanoscale track mapping
METHOD I	**Strain spectroscopy.** Detect damage-induced shifts of order 10-100 kHz in NV spin precession frequency.	**X-ray tomography.** Scanning x-ray diffraction microscopy.

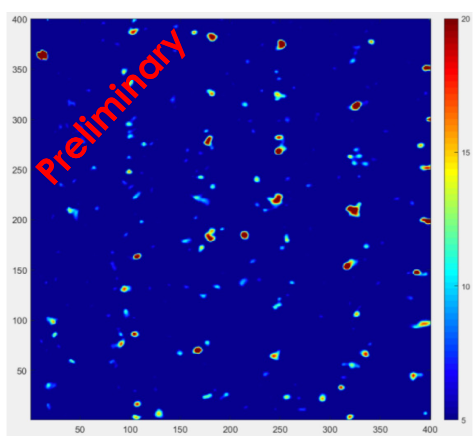


M. Marshall, **RE** *et al.*, arXiv:2108.00304

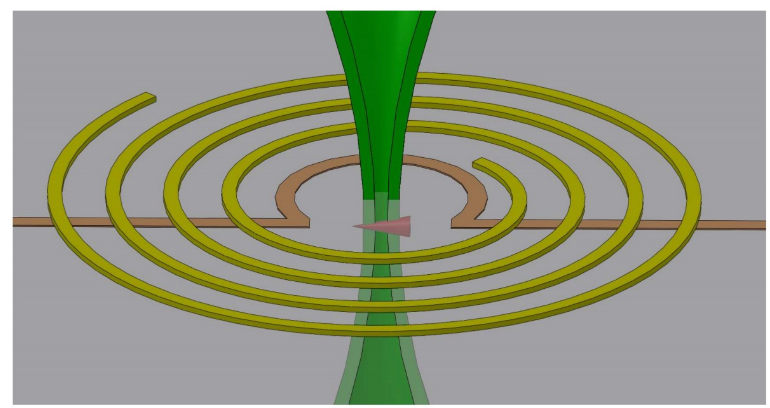


M. Marshall *et al.* Phys. Rev. Appl. (2021)

	Micron-scale localization	Nanoscale track mapping
METHOD II	**Defect creation.** Create fluorescent defects at damage sites.	**Superresolution spectroscopy.**



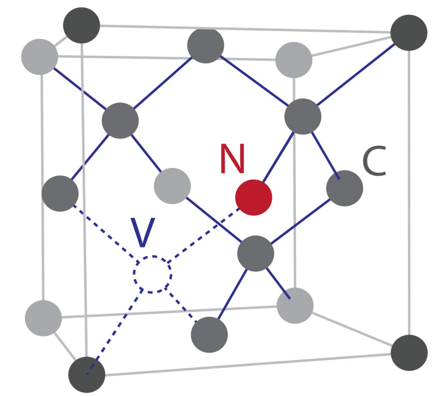
Ongoing work

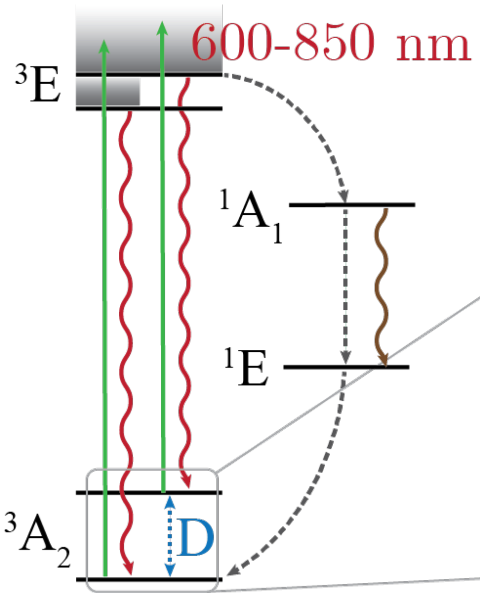


Future work

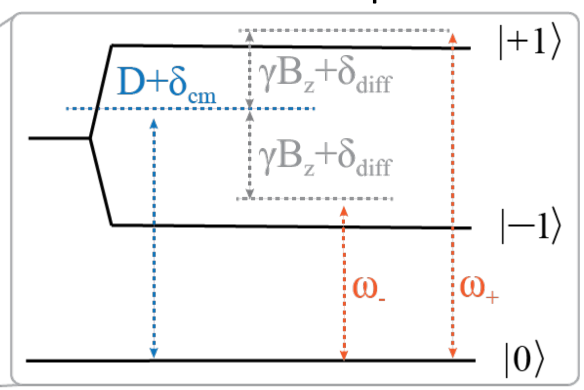
Nitrogen-vacancy centers

- Optical initialization/readout and microwave manipulation
- Sensitive to magnetic fields, strain, electric fields, and temperature
- Room temperature operation
- Vectorial information





Ground state spin = 1



$D \simeq 2.87$ GHz

Simplified GS spin Hamiltonian when a bias magnetic field is aligned with one of the NV classes:

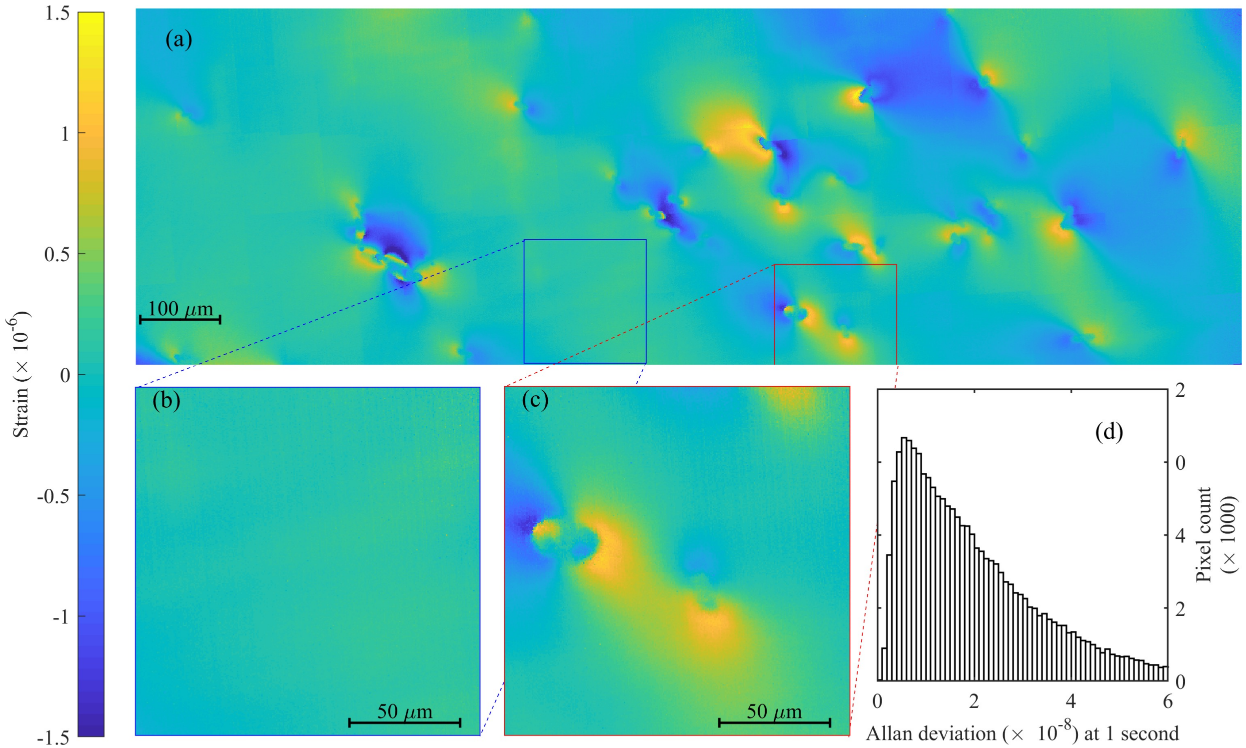
$$H \simeq (D + M_z)S_z^2 + \gamma B_z S_z$$

Micron-scale localization

Strain spectroscopy

M. Marshall, **RE** *et al.*, arXiv:2108.00304

- Ensemble NV spectroscopy
- Widefield quantum diamond microscope (QDM)



- Improved sensitivity via dynamical decoupling sequences (Strain-CPMG)
- Volume-normalized sensitivity: $5\times10^{-8}\ Hz^{-\frac{1}{2}}\ \mu m^{\frac{3}{2}}$

- Required sensitivity for DM track localization: $1\times\ 10^{-7}$ to 3×10^{-6}
- Each FOV (100 μm x 100 μm): 1 second of data acquisition
- Scanning full mm-scale chip: $\sim$ 13 hours

Nanoscale track mapping

X-ray tomography

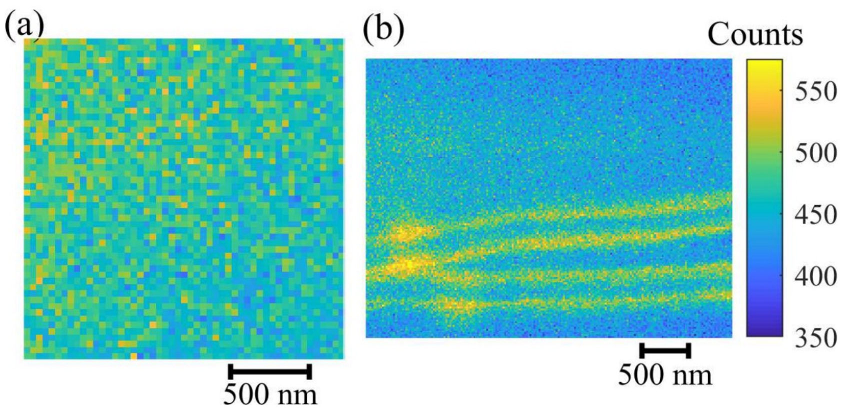
M. Marshall *et al.* Phys. Rev. Appl. (2021)

Scanning X-ray diffraction microscopy

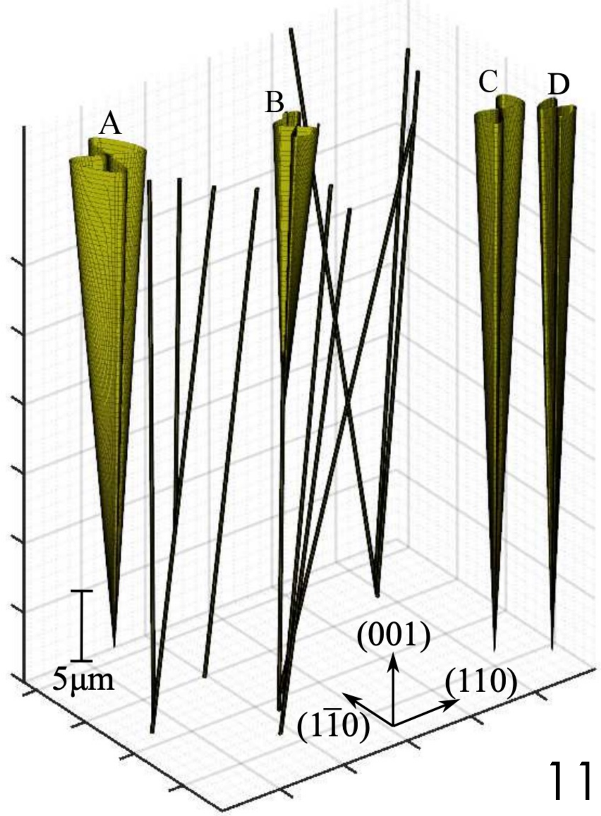
Argonne NATIONAL LABORATORY

Hard X-ray Nanoprobe

Initial background scans



3D reconstruction of known strain features



- No confusion background detected in an initial background search.

- Resolution: ~ 10 nm
- Sensitivity: ~ 1.6×10^{-4} (in a non-optimized diamond sample)

Micron-scale localization

Defect creation

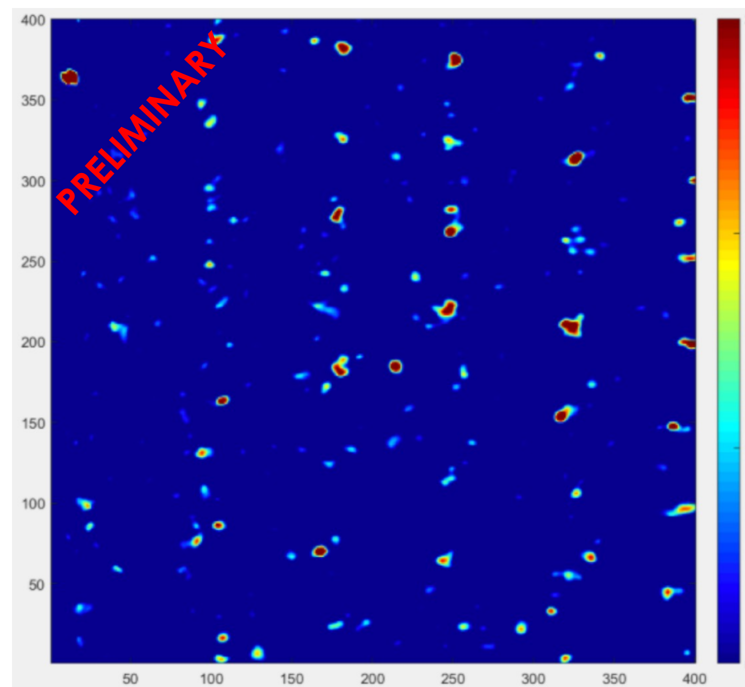
Ongoing work

Ion Beam Laboratory

Diamond sample with low NV density, but high N density

- Annealing makes implantation-induced vacancies mobile → NV creation → fluorescent detection

- Single ion implantation
- Across energy range



Summary and Outlook

Preliminary measurements are optimistic for WIMP detection proposal.

- Strain spectroscopy
  - ✓ Sensitivity to voxel-averaged DM-induced strain
  - ✓ Fast enough localization possible
  - ❑ Detection of the injected signals (ion implantation-induced damage track)
  - ❑ 3D localization at µm scale

- NV center creation
  - ✓ Fluorescence detection of several-ion impact sites
  - ❑ Single ion implantation at a range of energies

- X-ray diffraction
  - ✓ Sensitivity to DM-induced strain at ∼10 nm scale
  - ❑ Direction measurement of injected signals

- Damage track simulations
  - ❑ Molecular dynamics simulations

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JHU
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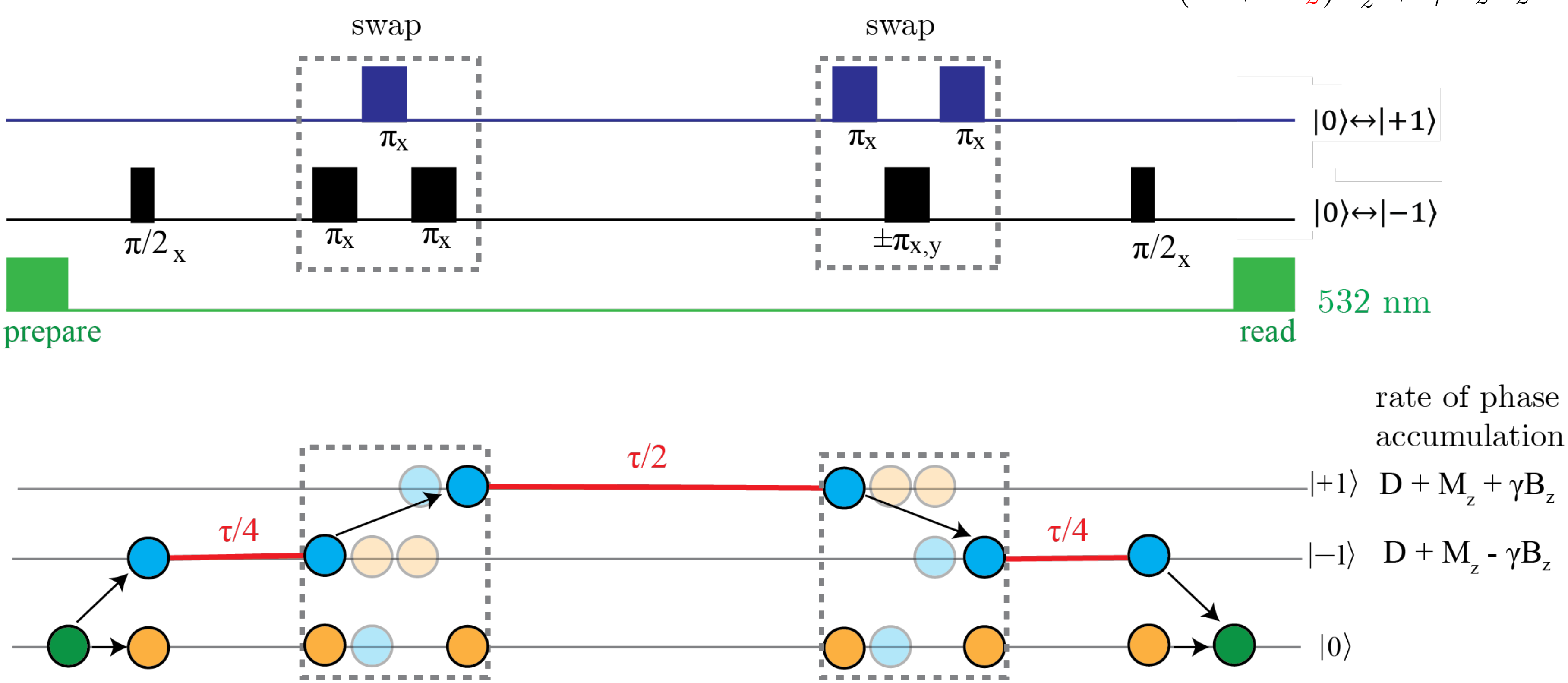
UDel
Mark Ku

Backup slides

Strain sensing protocol

- TCPMG: thermal-CPMG
- Used for nanoscale thermometry using single NV centers

$$H \simeq (D + M_z)S_z^2 + \gamma B_z S_z$$



M. Marshall, **RE** *et al.*, arXiv:2108.00304

G. Kucsko et al. (Nature 2013); D. M. Toyli et al. (PNAS 2013);
P. Neumann et al. (Nano Lett. 2013)

Micron-scale localization

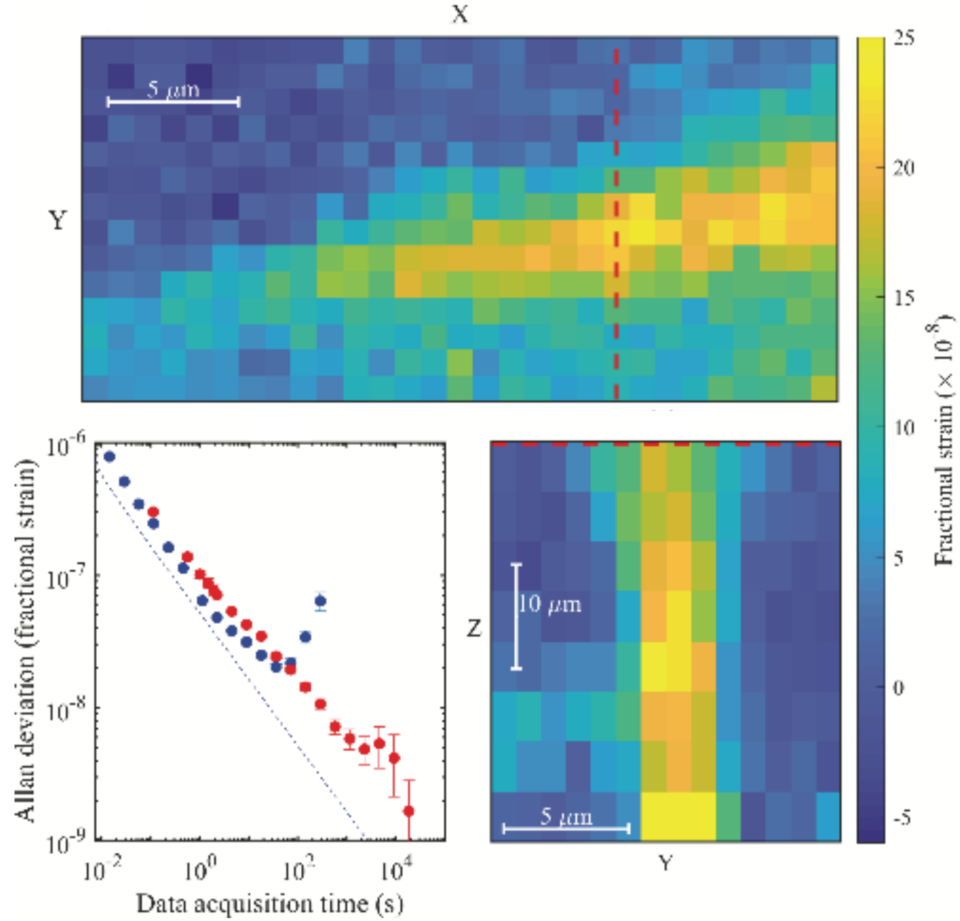
Strain spectroscopy

M. Marshall, **RE** *et al.*, arXiv:2108.00304

- Scanning confocal microscope
- Volume-normalized sensitivity:

$$5\times10^{-8}\,Hz^{-\frac{1}{2}}\,\mu m^{\frac{3}{2}}$$

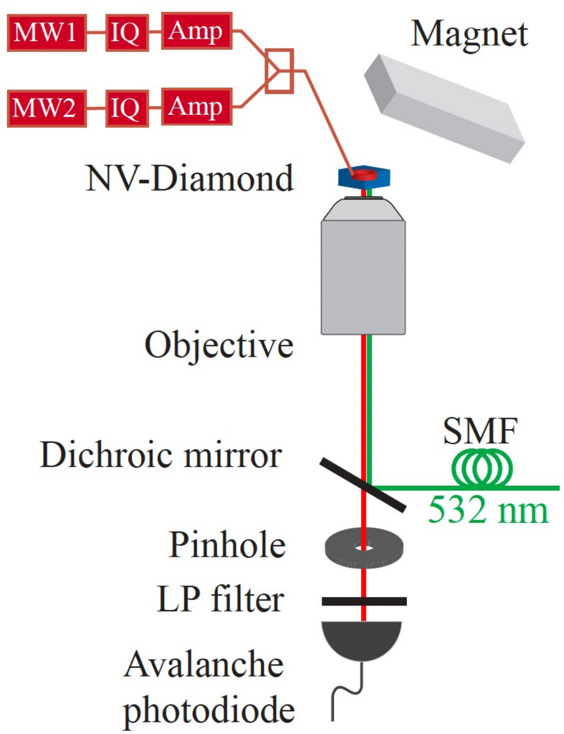
Not fast enough for scanning the mm-scale diamond chip.



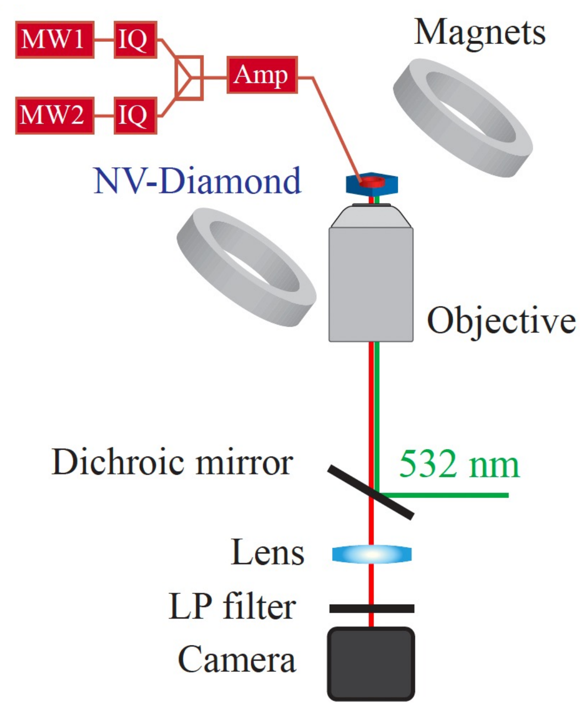
Sample:
CVD bulk diamond material, grown by Element Six; isotopically purified ^{12}C; [N] = 3 ppm; e-irradiated and annealed to form NV centers.

Apparatus schematic

Confocal microscope



Widefield quantum diamond microscope (QDM)



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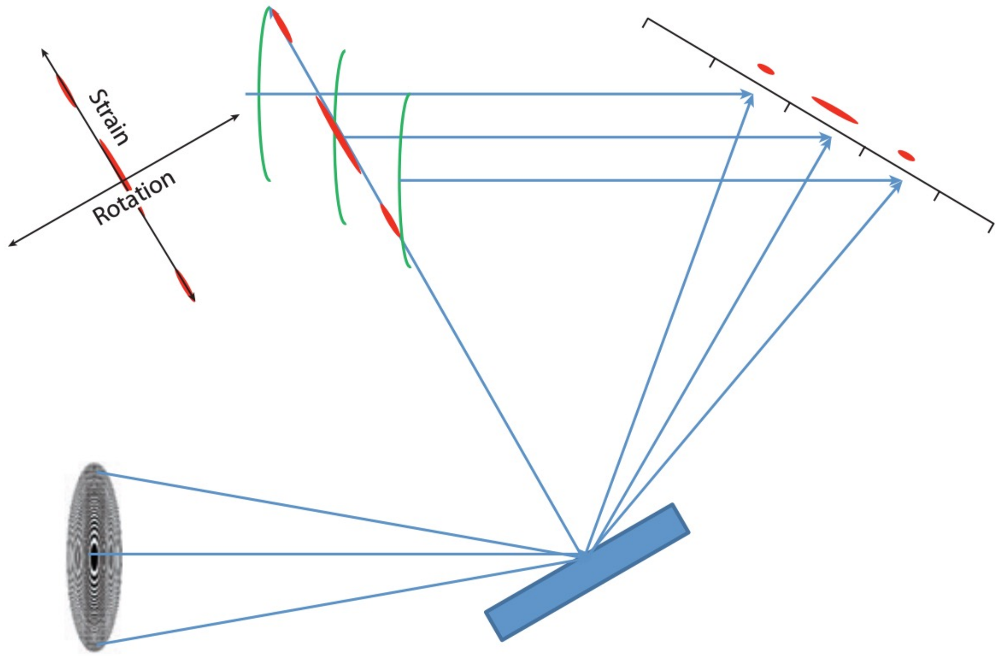
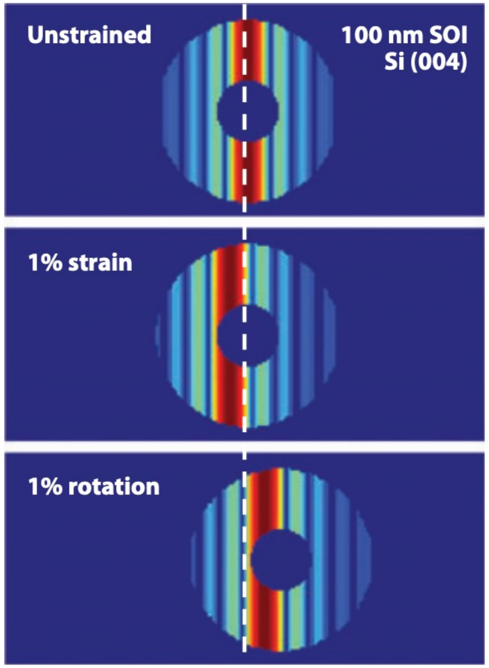
Scanning X-ray diffraction microscopy

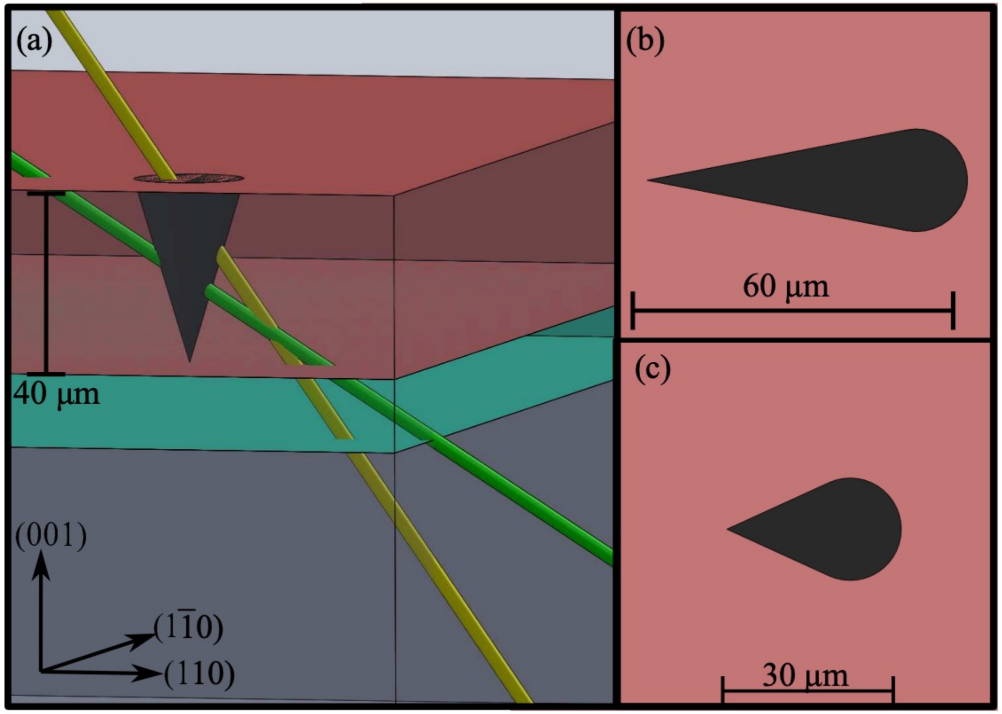




M. Holt *et al.* Annu. Rev. Mater. Res. (2013)

Scanning X-ray diffraction microscopy

Schematic of the measured CVD diamond sample and strain features projected onto measurement surfaces



- high-purity CVD substrate (gray)
- polishing damage layer at substrate surface (green)
- NV-doped CVD overgrowth layer (red)

M. Marshall *et al.* Phys. Rev. Appl. (2021)