Progress in directional DM detection with quantum diamond sensors

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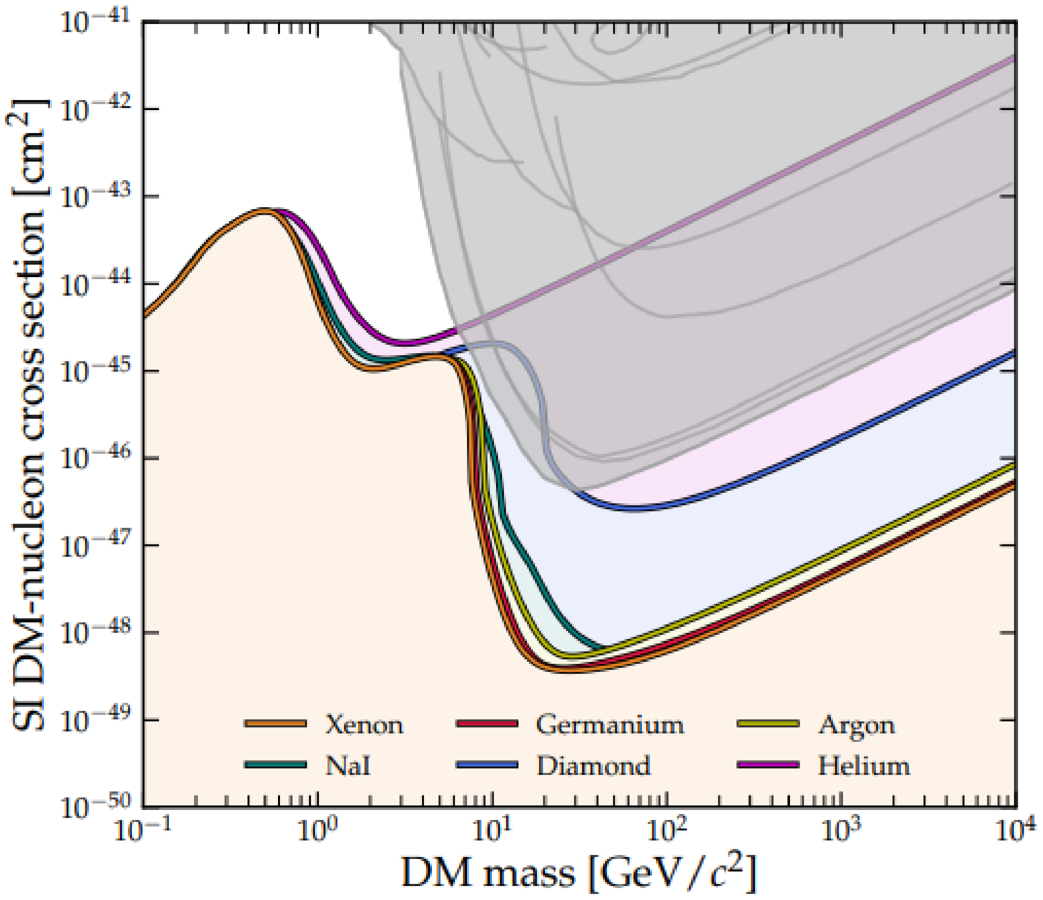
Introduction

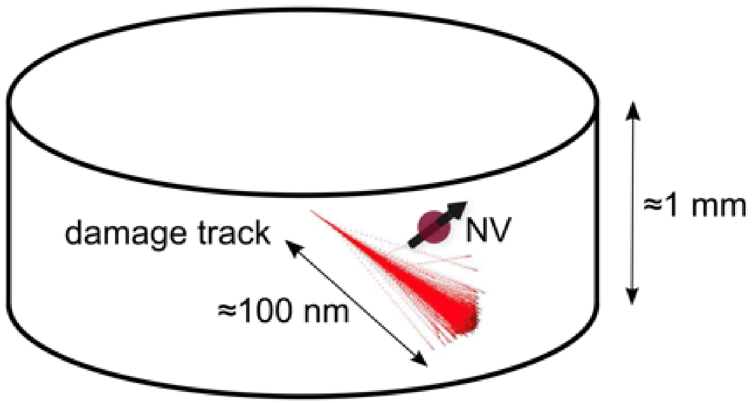
- Goal: overcome solar neutrino fog by using **nitrogen vacancy (NV) centers** in diamond as directional DM detector
- Strengths:
  - Solid-state → can pack more material in smaller volume
  - Complementary material to existing detectors
  - Can take advantage of state-of-the-art techniques in quantum sensing with NV centers

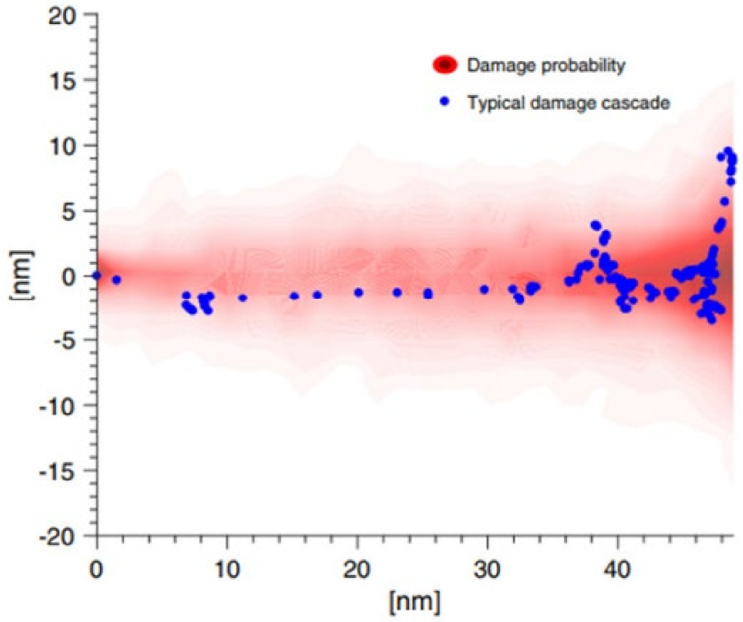


O'Hare, PRL **127**, 251802 (2021)
Ebadi et al., AVS Quant. Sci. **4,** 044701 (2022)

Detector principle

- 1-100 GeV WIMP → 10-100 keV nuclear recoil → 10-100 nm damage track in NV-enriched diamond
- Locate and characterize damage track w/ NV spectroscopy
- Deduce initial recoil direction and distinguish between solar neutrinos vs. DM



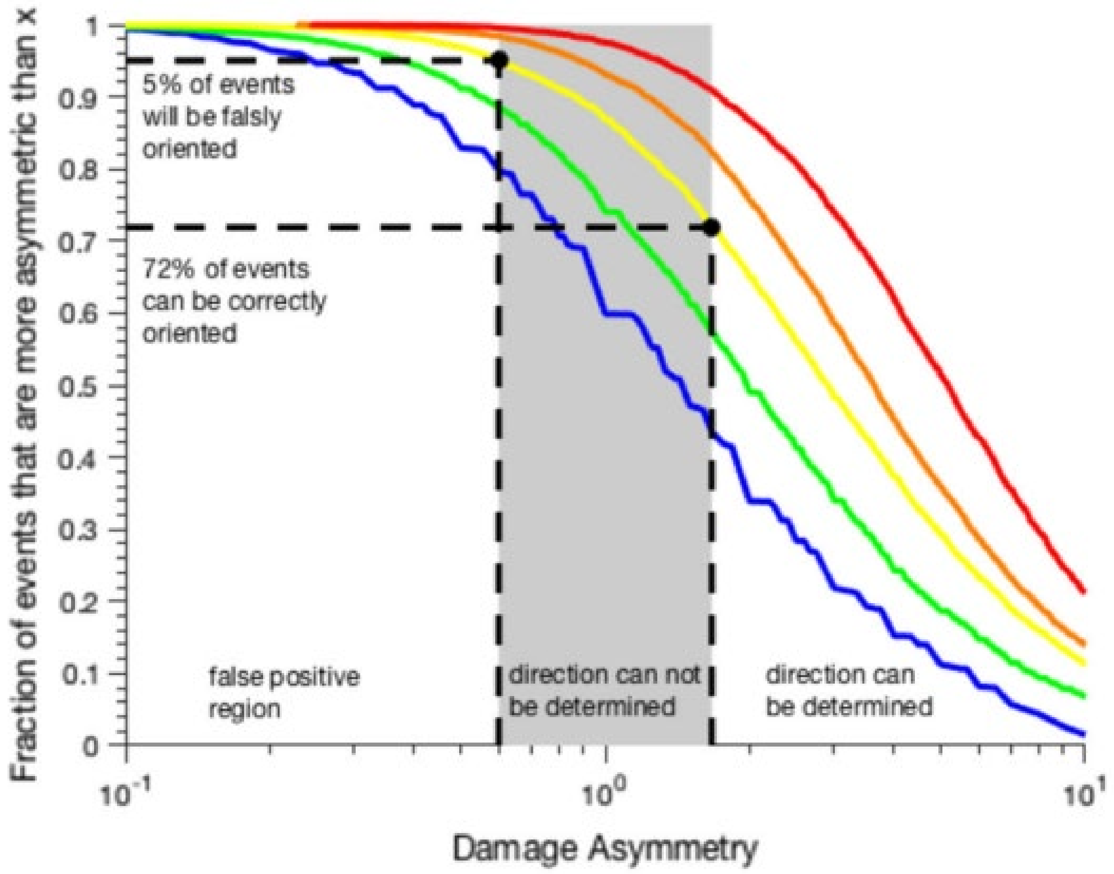


SRIM simulation for 30 keV recoil

Rajendran et al., PRD **9**, 035009 (2017)

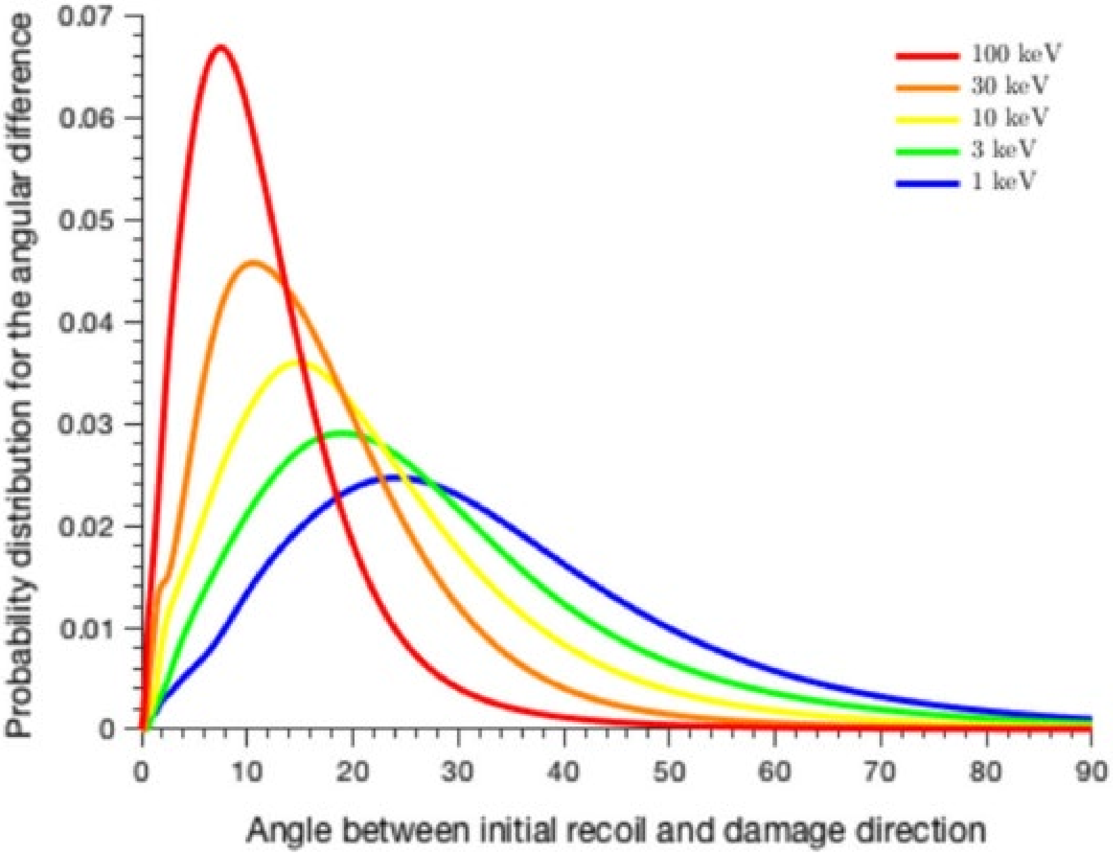
Estimated directional performance

Based on SRIM simulations



Head/tail identification

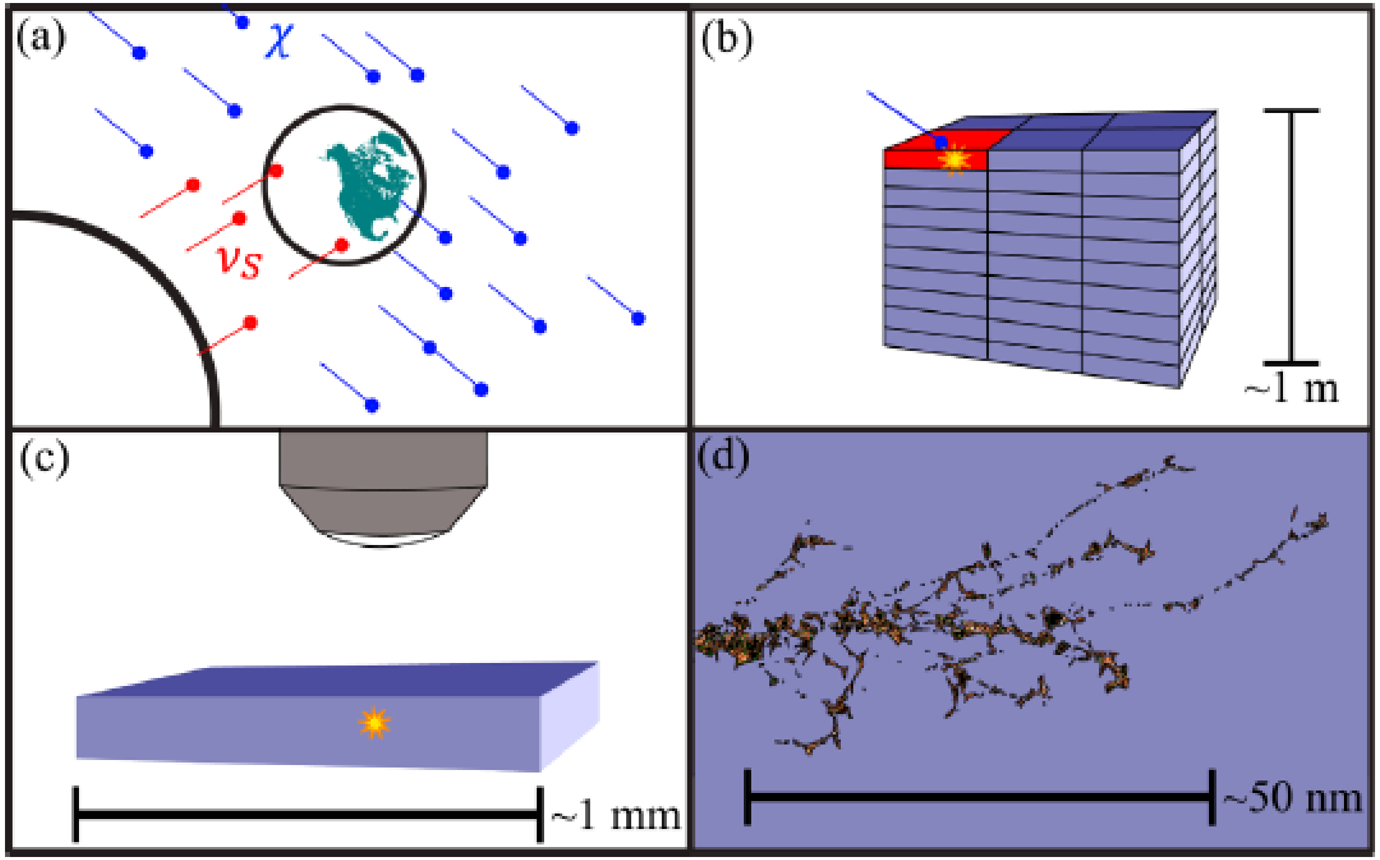
Angular difference to initial recoil



Rajendran et al., PRD **9**, 035009 (2017)

Detector scheme

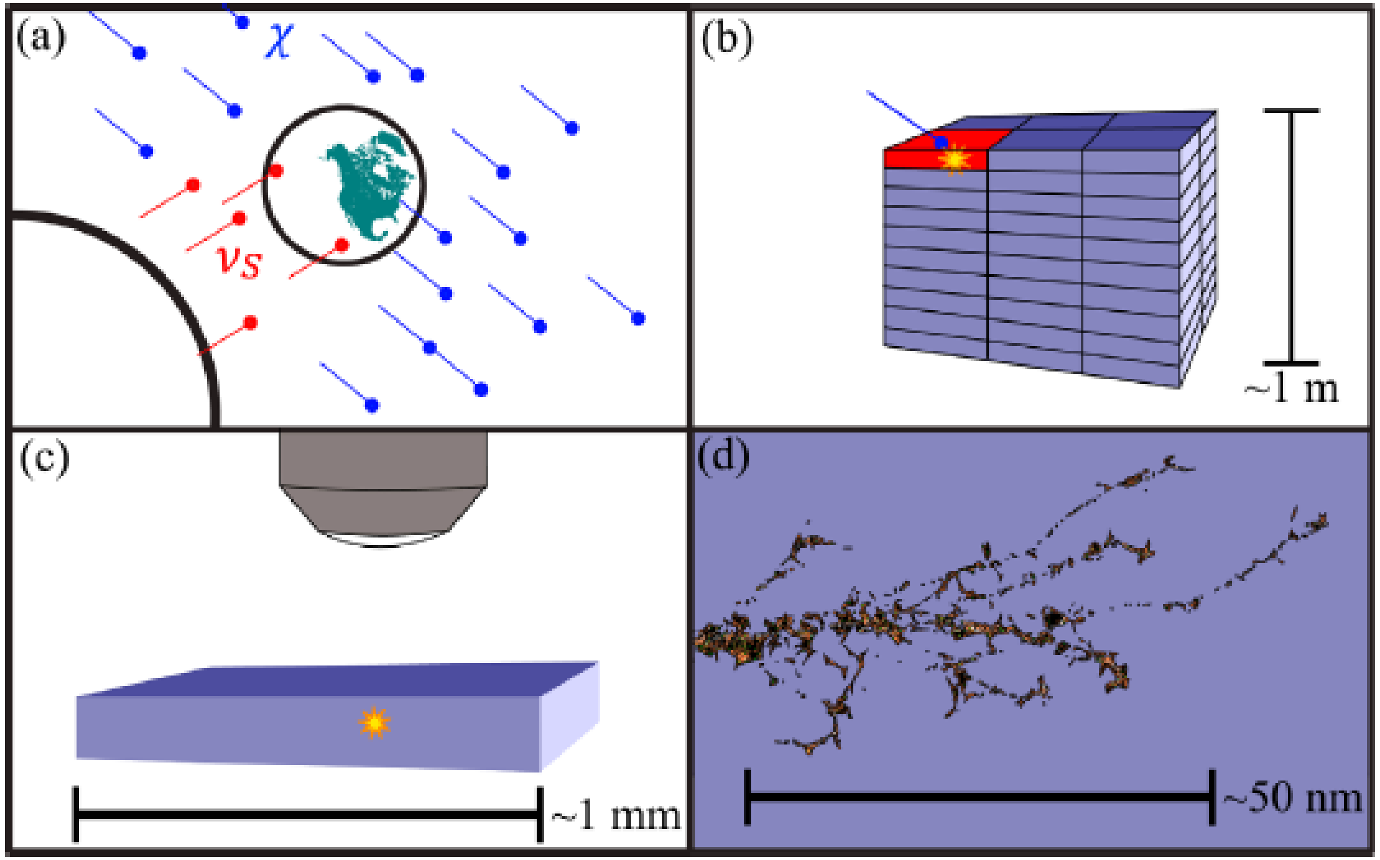
- m^3 scale detector consisting of many mm-scale NV-enriched diamond chips
- Expect O(30) solar neutrino events per ton year
- Diamond cost predicted to be comparable to current large-scale DM experiments
- Multi-stage detection



Detector scheme

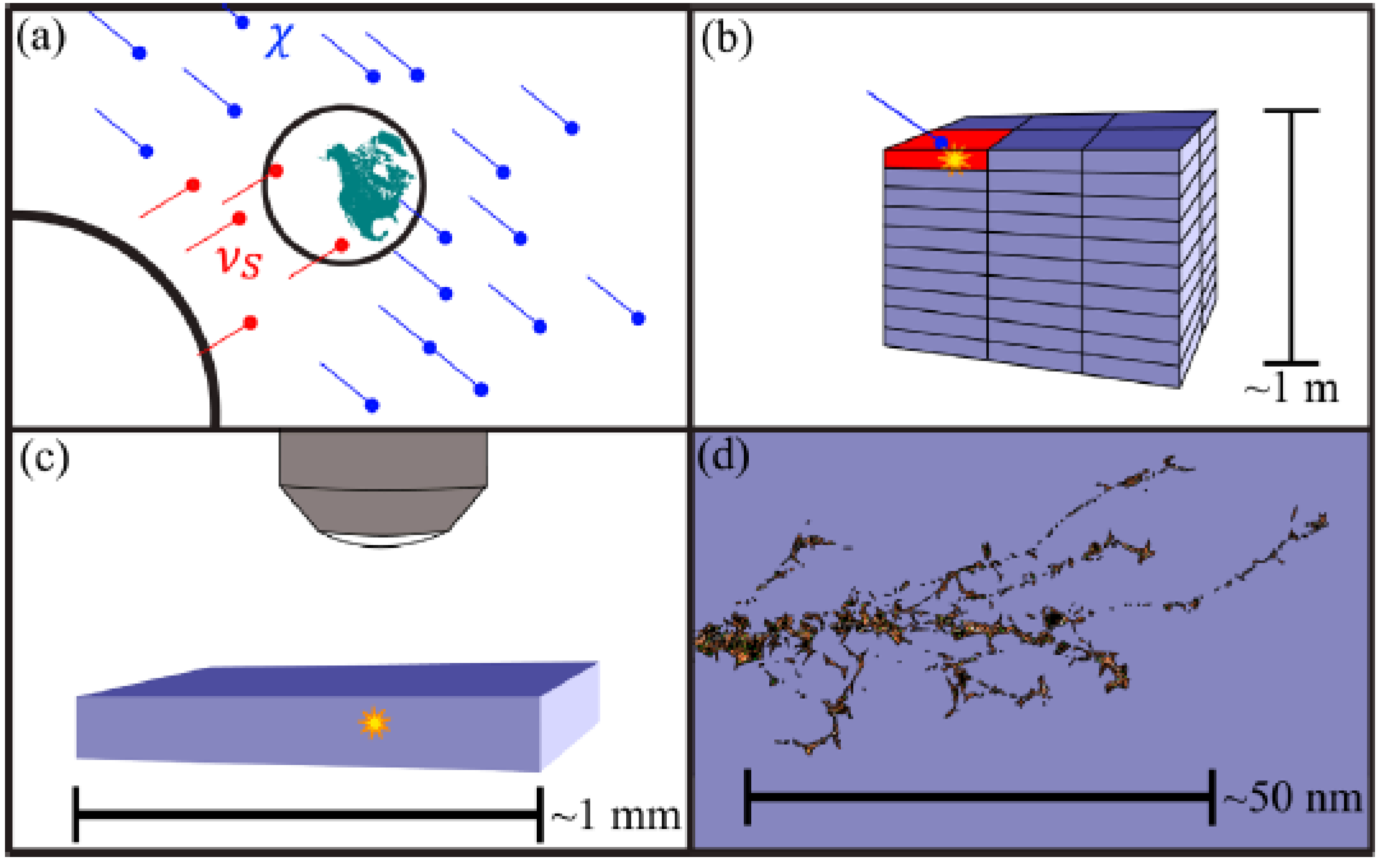
Stage 1: mm-scale real time detection

- **Stage 1: real-time event detection**
- Similar working principle as conventional DM detector
- Charge, phonon, or photon collection
- Localize event to mm-scale chip within detector
- Extract chip of interest



Detector scheme

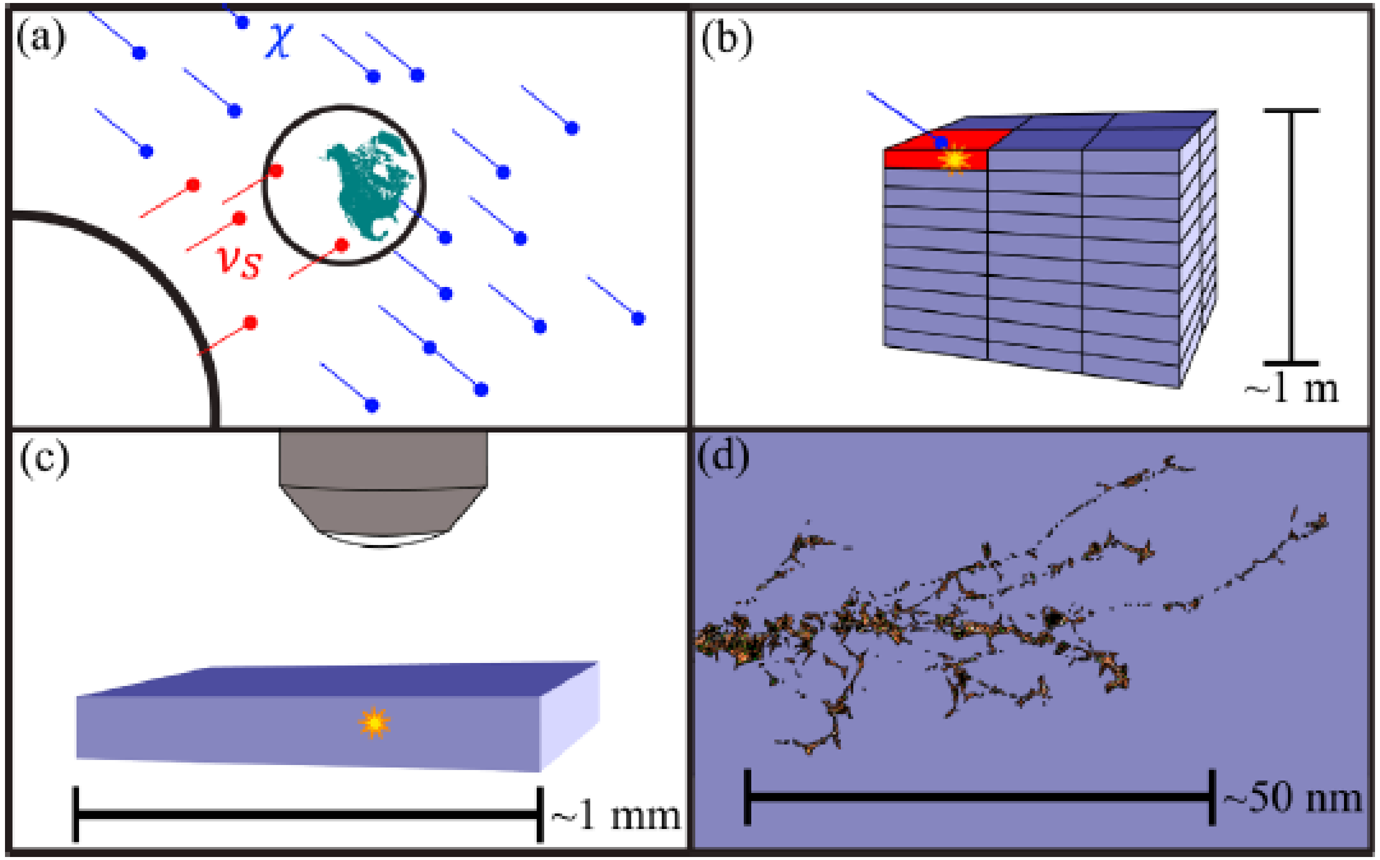
- **Stage 2: um-scale localization**
- Examine diamond chip of interest with quantum diamond microscope (QDM)
- Use NV centers to rapidly localize event within $\sim 1\ \mu m^3$ voxel



Stage 2: um-scale localization

Detector scheme

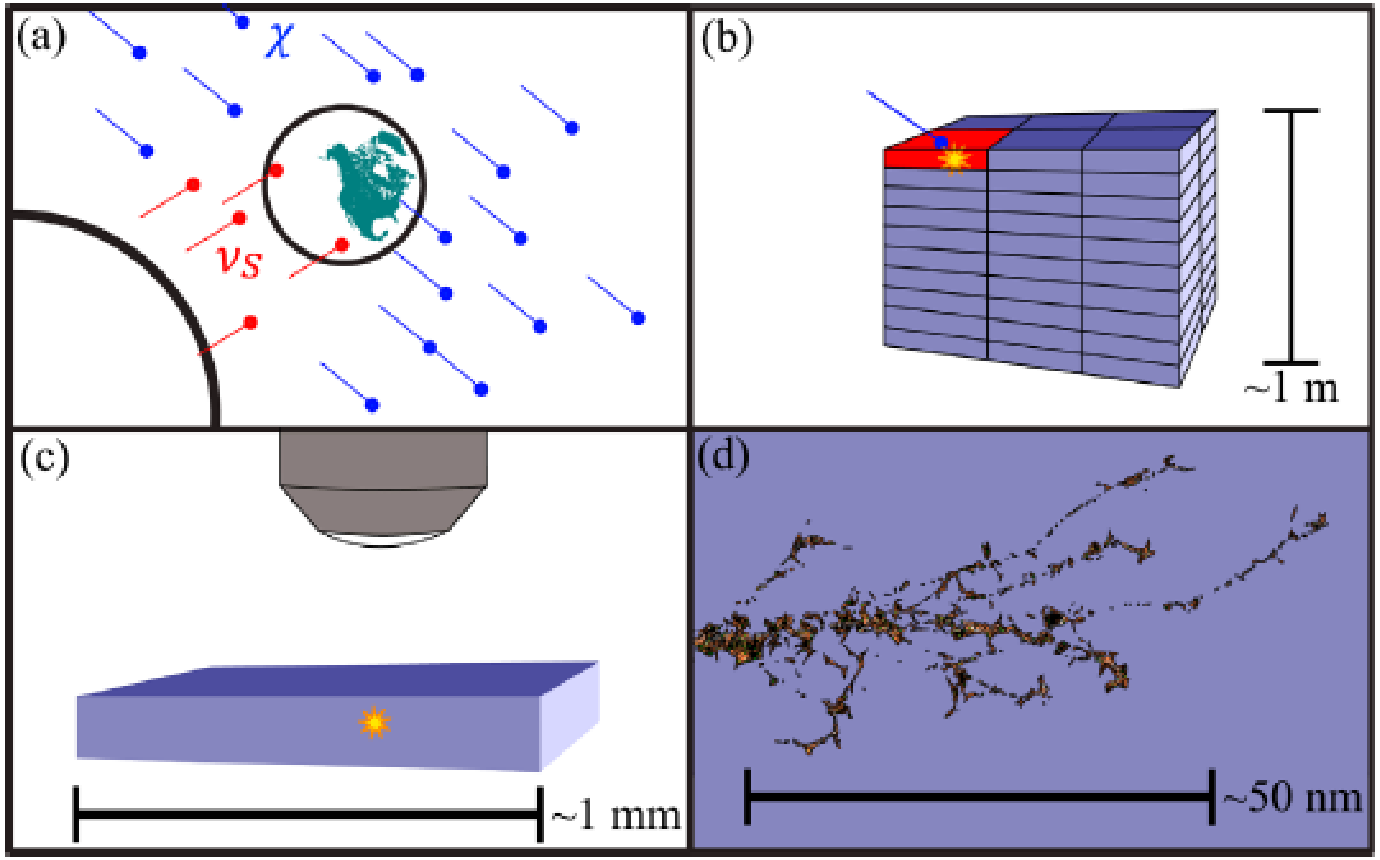
- **Stage 3: nm-scale characterization**
- Scan 1 μm^3 voxel with high-resolution techniques to determine shape, size, and orientation of damage track
- Deduce initial recoil direction
- Correlate with recorded event time to determine event origin



Stage 3: nm-scale characterization

General detector requirements

- Low background diamonds
  - No pre-existing features that resemble WIMP tracks
- Imaging with high resolution
- Fast and efficient scanning to keep up with event rate
  - Goal: complete stages 1-3 in < 3 days



Stage 1: Diamond as a general DM detector

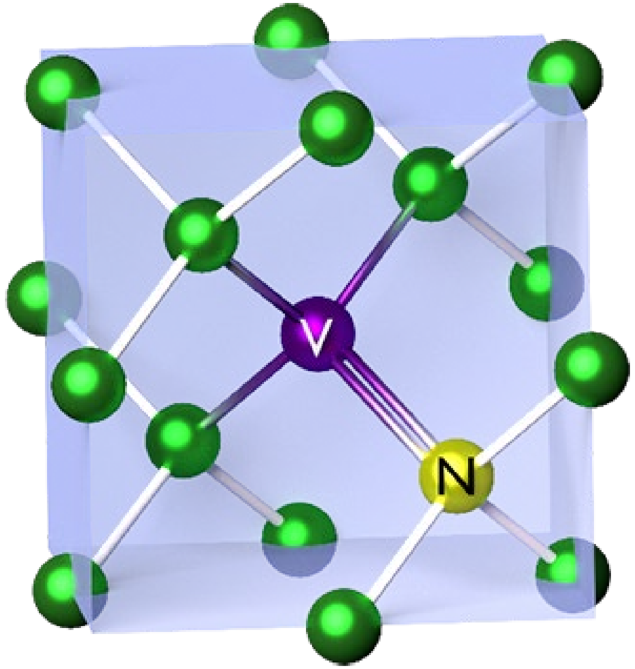
- Several favorable properties (Kurinsky et al., PRD **99**, 123005 (2019))
  - Semiconductor with wide bandgap (5.4 eV)
  - Lower mass compared to other solid-state detectors
  - Can be manufactured with high purity
- High detection efficiency possible via charge, photon, or phonon collection
- Can be used as a DM detector via nuclear recoil, electron recoil, or absorption
- Active research efforts in other groups (e.g. CRESST collaboration)

Abdelhameed et al., Eur. Phys. J. C 28:851 (2022)
G. Angloher et al., arxiv:2310.05815 (2023)

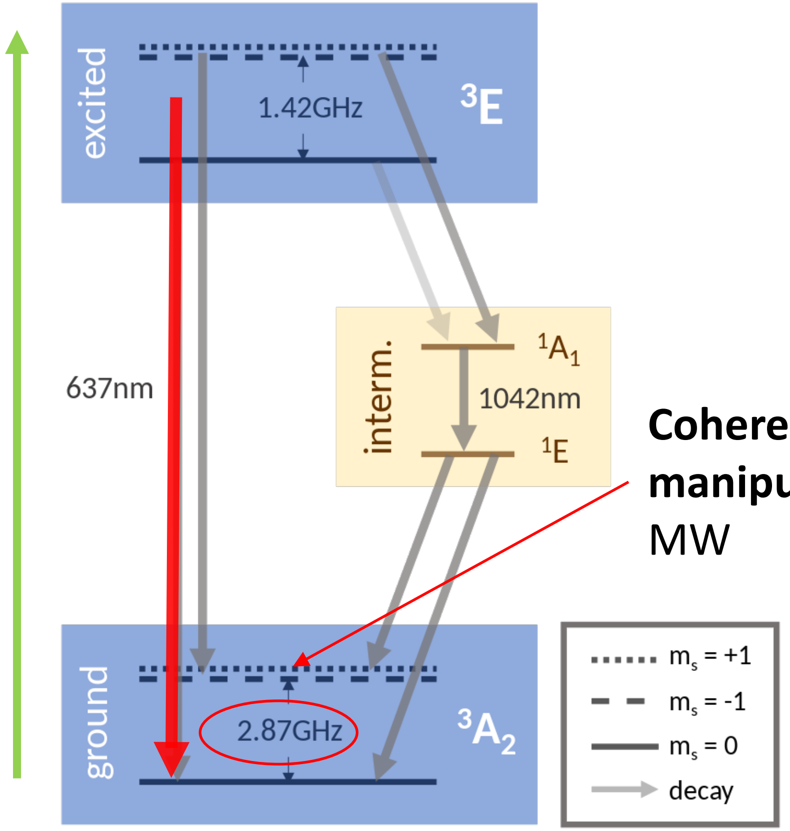
Stage 2: micron scale localization

- **Method 1:** Use diamonds with pre-existing NV centers
  - Measure strain shift caused by damage track
- **Method 2:** Use diamonds with low NV density, high N concentration
  - Detect new NVs created by damage track
- **NV centers are key component!**

Nitrogen vacancy centers in diamond



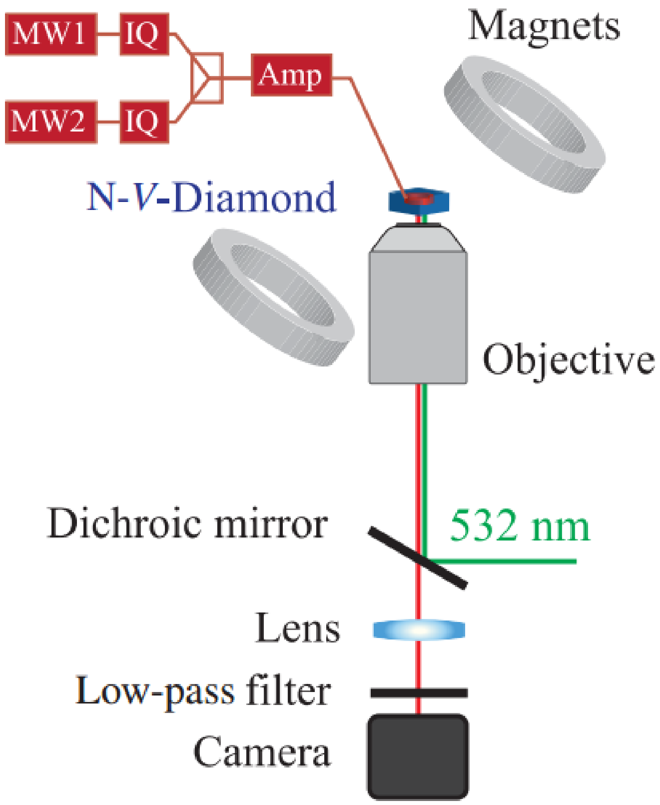
Optical initiation/readout:
532 nm excitation
640-800 nm emission



Coherent state manipulation
MW

Spin-1 ground state

Nitrogen vacancy centers in diamond



Quantum diamond microscope (QDM)

Simplified Hamiltonian when bias field B_z is aligned with one of the 4 diamond crystal axes

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

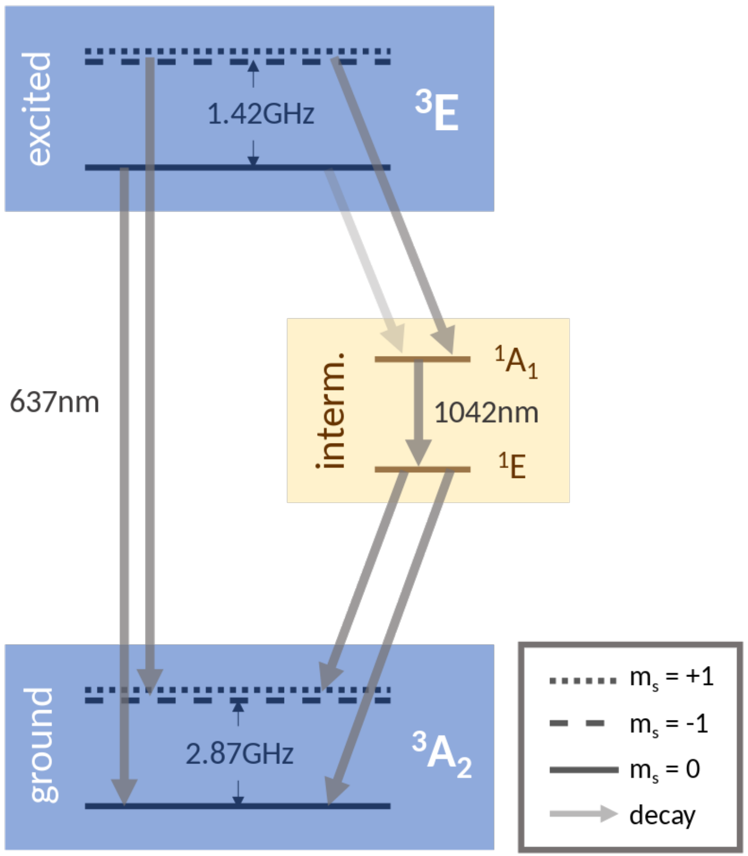
Temperature-dependent (D)

Crystal strain (M_z)

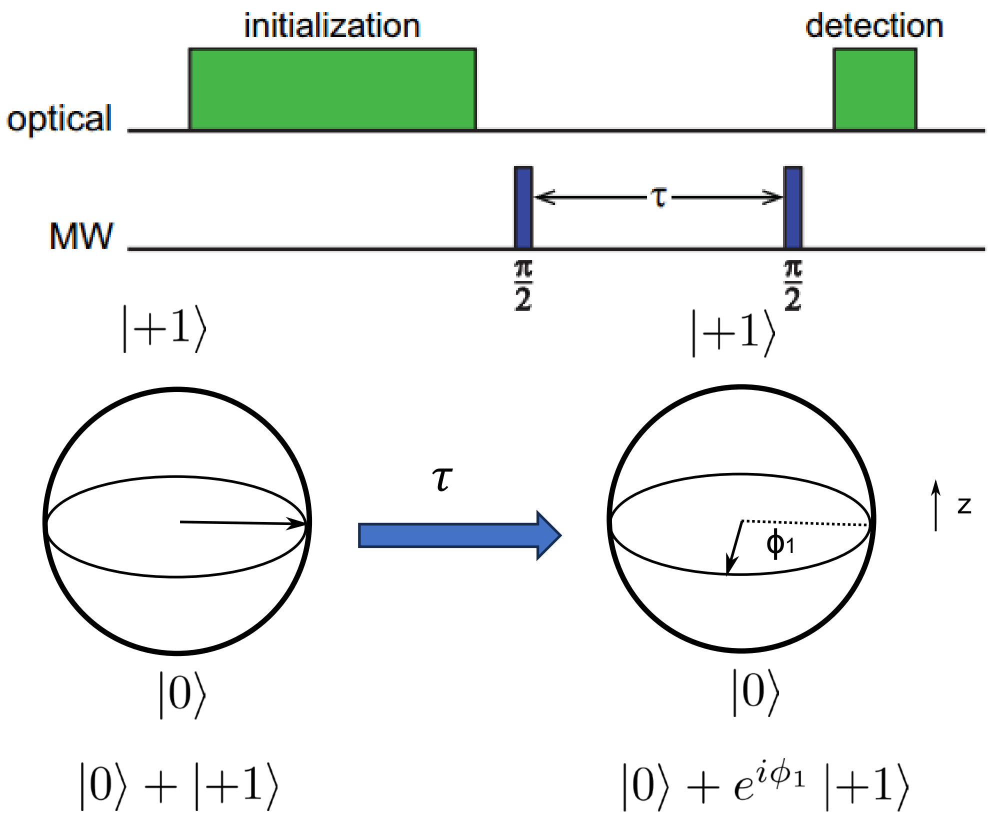
Magnetic field (B_z)

Example of quantum sensing with NVs

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

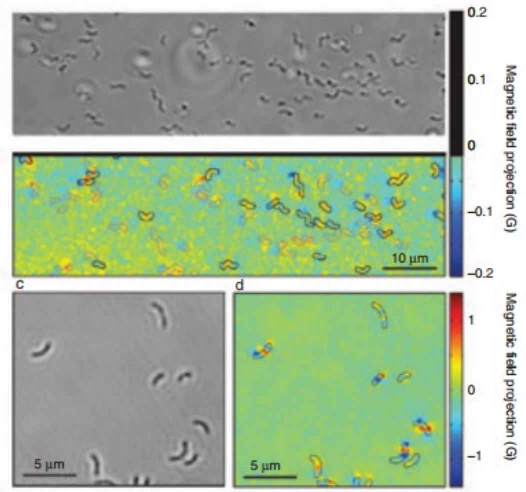


Ramsey DC magnetometry

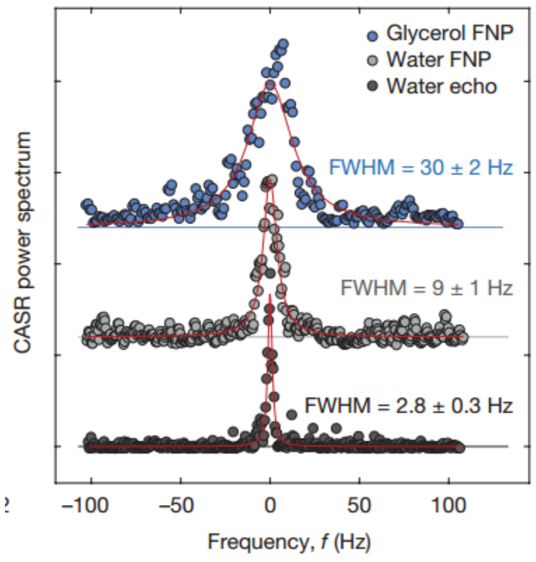


$$\phi_1 \propto \gamma B_z S_z \tau$$

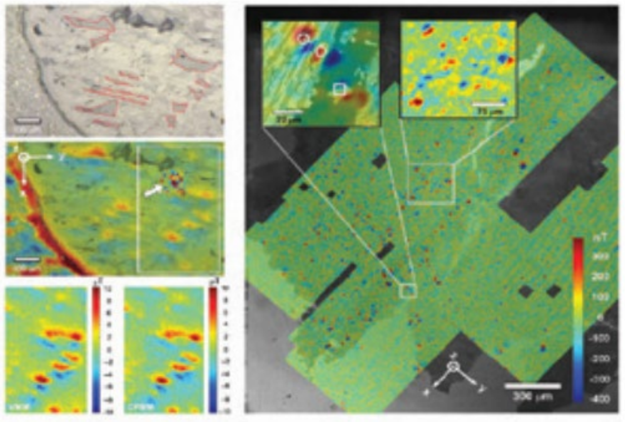
Diverse applications of NVs



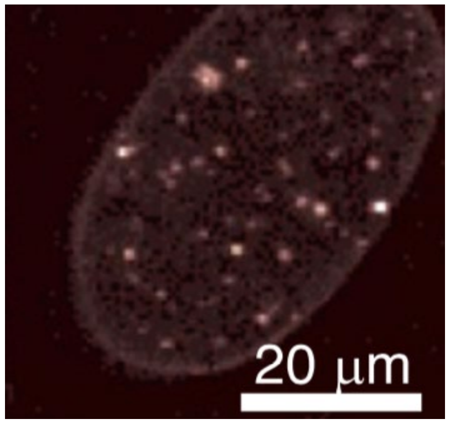
Bio-imaging



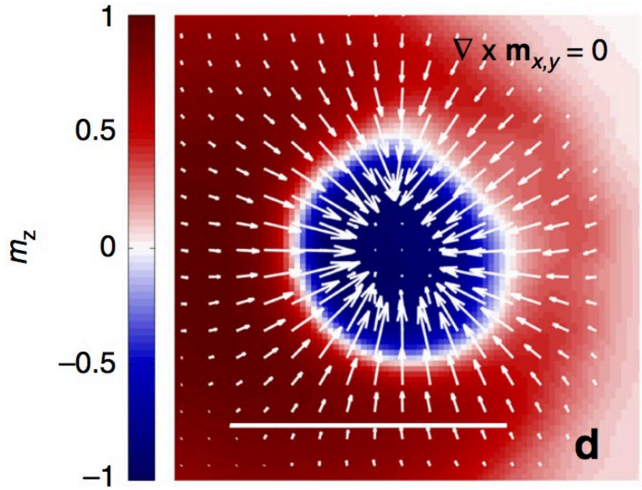
NMR



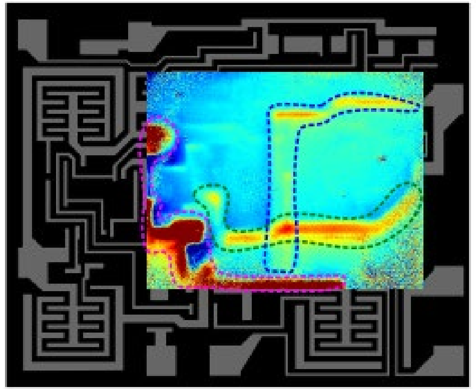
Geoscience



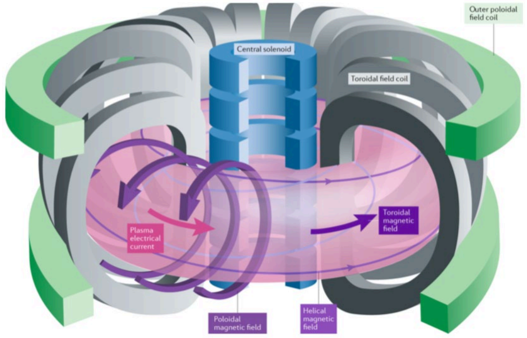
Nanoscale in situ thermometry



Condensed matter physics



IC imaging



Extreme environment sensing

Levine et al., Nanophotonics 8 (11): 1945-1973 (2019)
Glenn et al., Nature 555, 351–354 (2018)

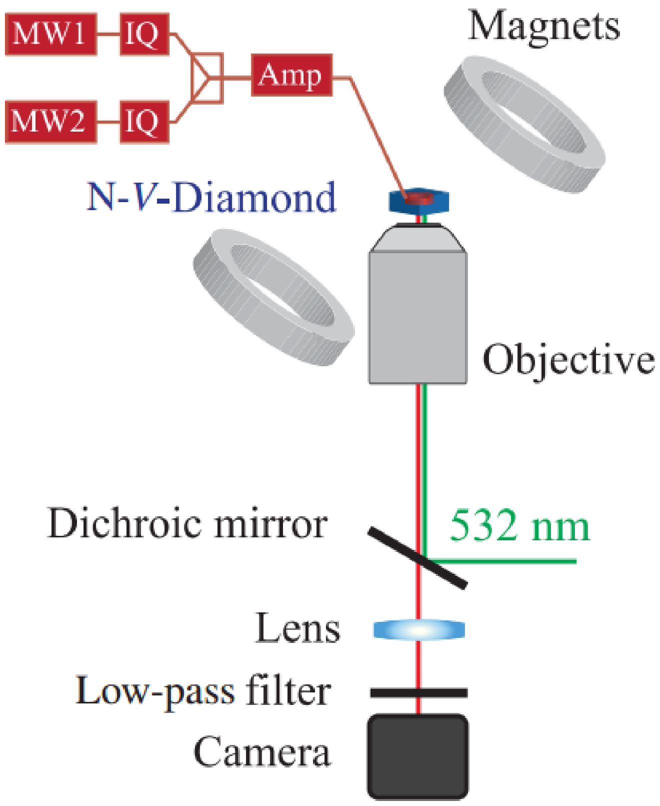
Stage 2 detection, method 1: NV strain sensing

- Use low-strain diamond grown via chemical vapor deposition (CVD) with ~0.5-3 ppm NV
- WIMP damage track results in strain shift of NV centers in its vicinity ($1/r^3$ decay)

Strain shift

$$H = (D + \boxed{M_z}) S_z^2 + \gamma B_z S_z$$

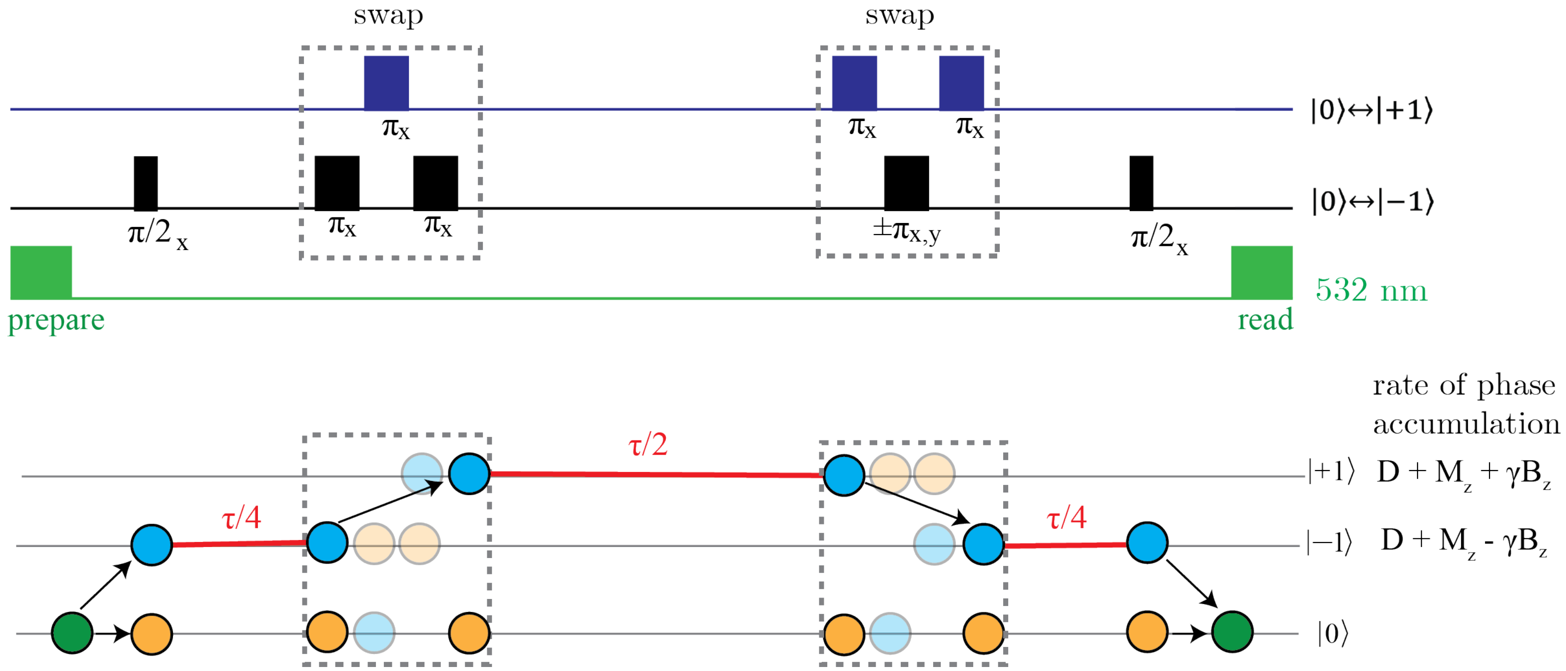
- Perform high-resolution NV strain spectroscopy with $\sim 1\ \mu\mathrm{m}^3$ resolution on a QDM
- Detect 10^{-7} average strain shift caused by damage track



Widefield QDM

Strain CPMG pulse protocol

- By spending equal time in $|\pm 1\rangle$ states, B_z term is cancelled out
- Need to ensure temperature is constant



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

$$M_z = A_1\epsilon_{zz} + A_2(\epsilon_{xx} + \epsilon_{yy})$$

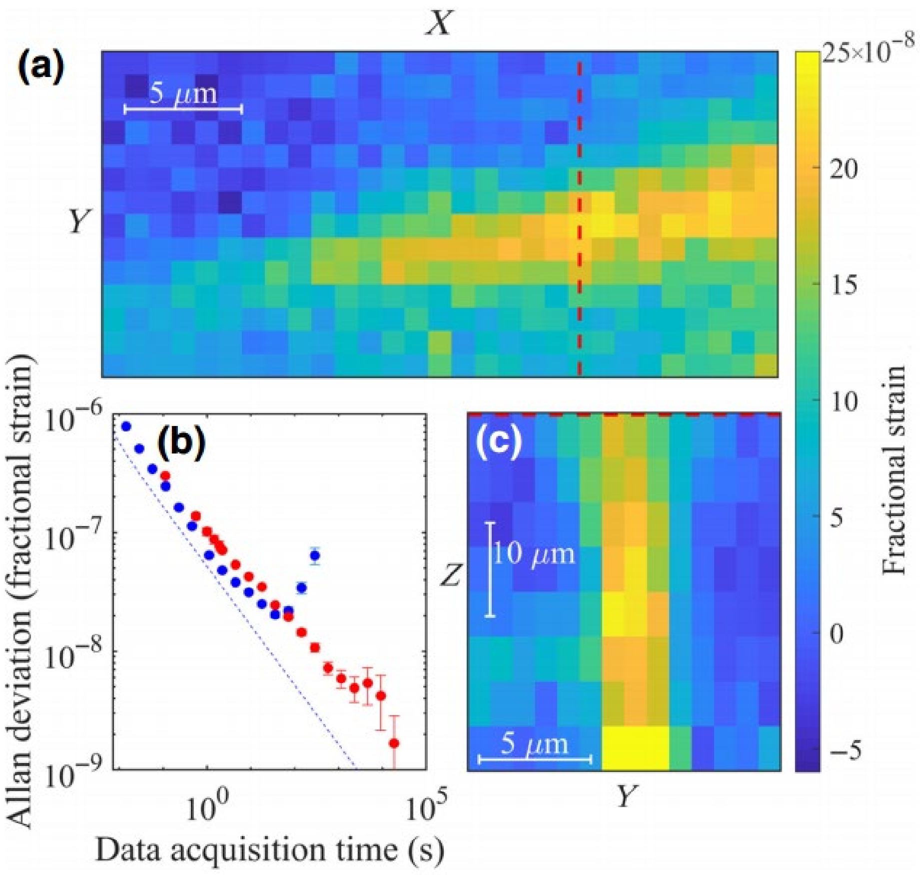
M. Marshall et al., PR Applied **17**, 02401 (2022)

3D strain imaging with confocal microscope

- 2020-21: strain imaging tests with confocal and widefield QDM
- Strain sensitivity (confocal):

$$5(2) \times 10^{-8}/\sqrt{Hz\ \mu m^{-3}}$$

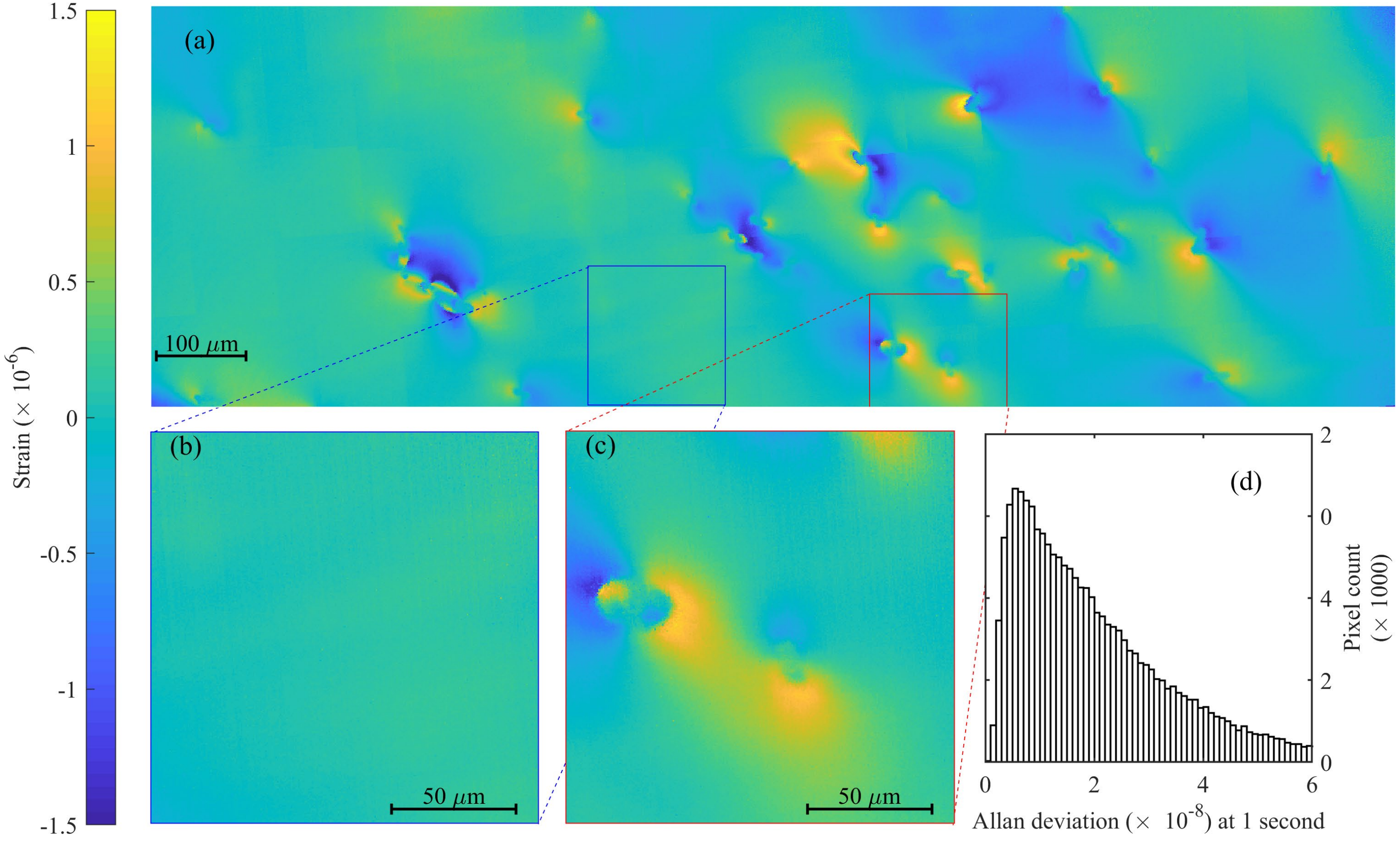
- Fulfills DM requirement
- Technical challenges:
  - Temperature fluctuations
  - Microwave power inhomogeneity at different depths from the diamond surface
  - Confocal scanning speed is too slow for actual DM experiment



M. Marshall et al., PR Applied **17**, 02401 (2022)

Widefield strain imaging

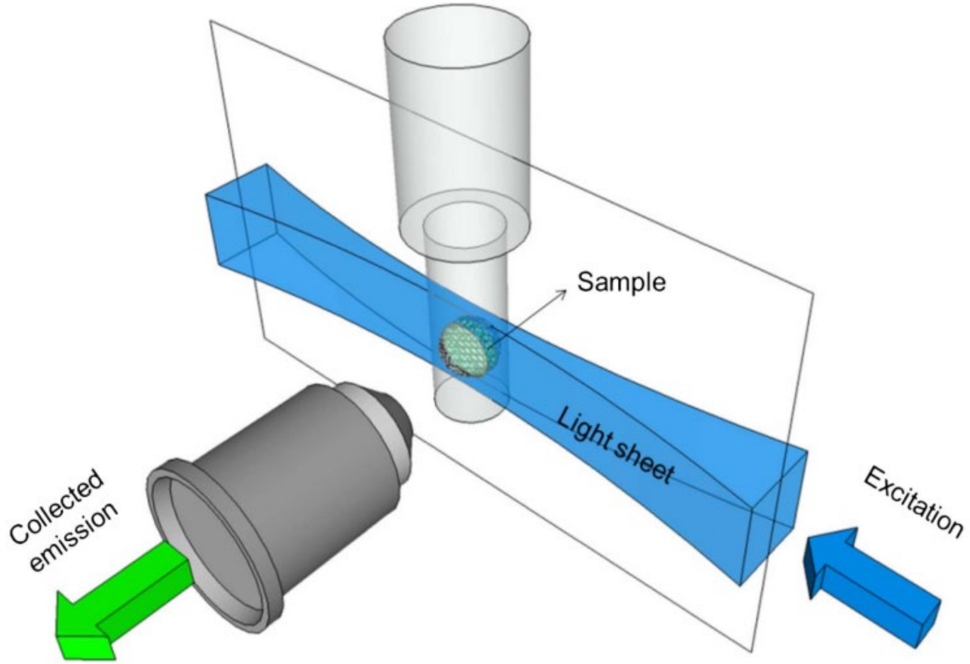
- Widefield strain imaging with similar level of strain sensitivity
- 150 x 150 um^2 FOV, 1 s averaging time
  - ~2 days to scan whole diamond volume
- Observed natural strain features (50-100 um length scales)
- Limitation: only 2D



M. Marshall et al., PR Applied **17**, 02401 (2022)

Towards rapid 3D strain imaging

- **Light sheet microscopy** (optical sectioning)
- State-of-the-art LSMs can achieve ~1 um axial resolution and mm-scale FOVs
- Already used in DM searches with color centers in other solid-state detectors (PALEOCCENE collaboration)
- Currently building a prototype LSM @ UMD for 3D NV strain imaging
- Developing custom resonators w/ ARL to improve MW homogeneity



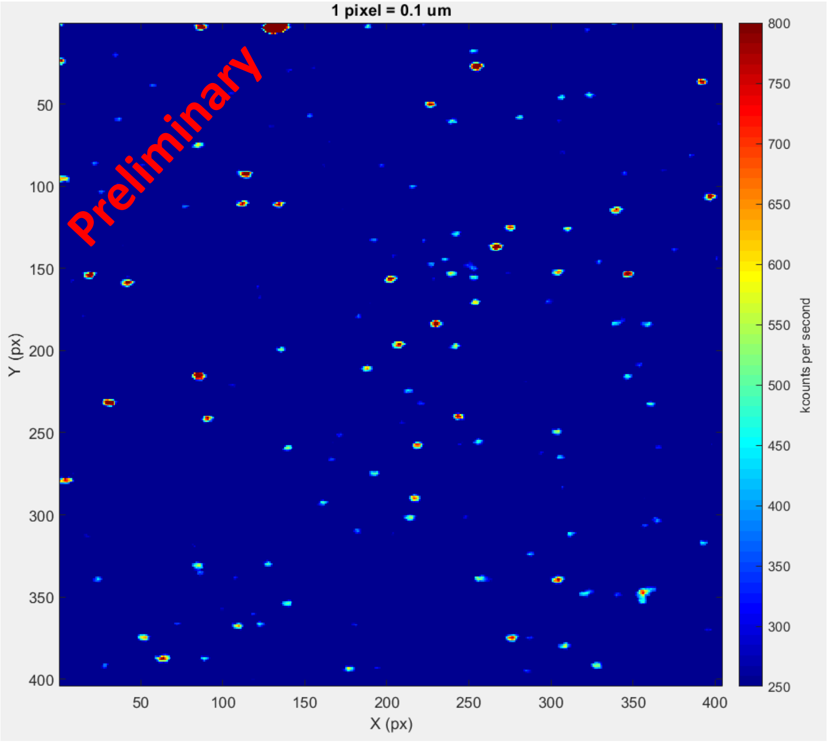
Vladimirov et al., doi:10.1101/2023.06.16.545256 (2023)
Alfonso et al., arXiv:2203.05525 (2023)
Olarte et al., Adv. Opt. Phot. **10** (1), 111-179 (2018)

Stage 2, Method 2: Fluorescence from created NVs

- Use HPHT diamonds with ~200 ppm nitrogen
  - Low number of pre-existing NVs
- WIMP damage track creates vacancies
- Annealing at high temperature (800 C) results in some vacancies attaching to nitrogen atoms and becoming NVs
- Identify damage track location by detecting optical fluorescence from NVs

Stage 2, Method 2: Fluorescence from created NVs

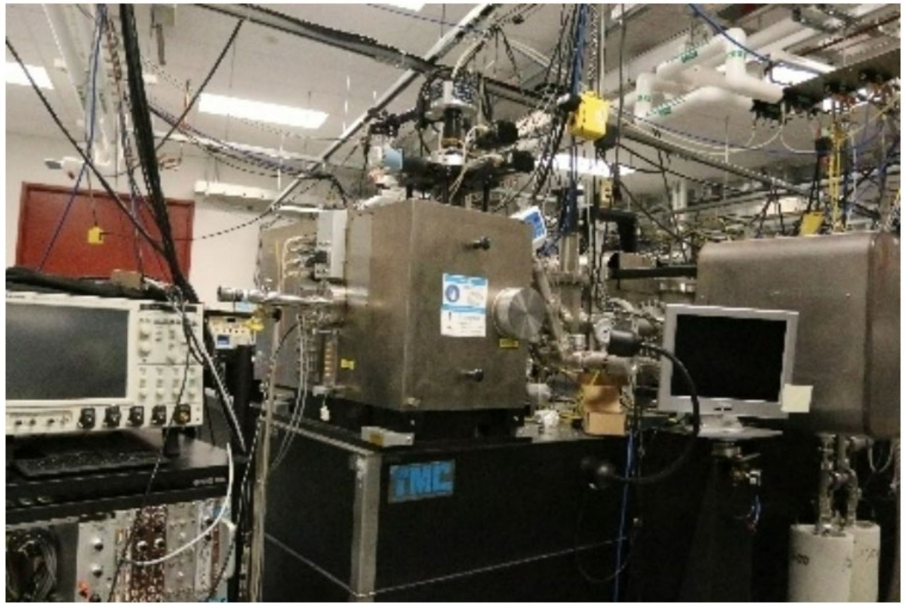
- Advantages:
  - HPHT diamond is cheaper
  - Detect fluorescence only - no quantum sensing techniques required (simpler)
- Disadvantages:
  - Annealing may affect directional detection performance
  - Higher impurities may make charge collection (stage 1) more difficult
- Further studies required to determine best method



NVs created as result of 385 keV ion implantation @ Innovion

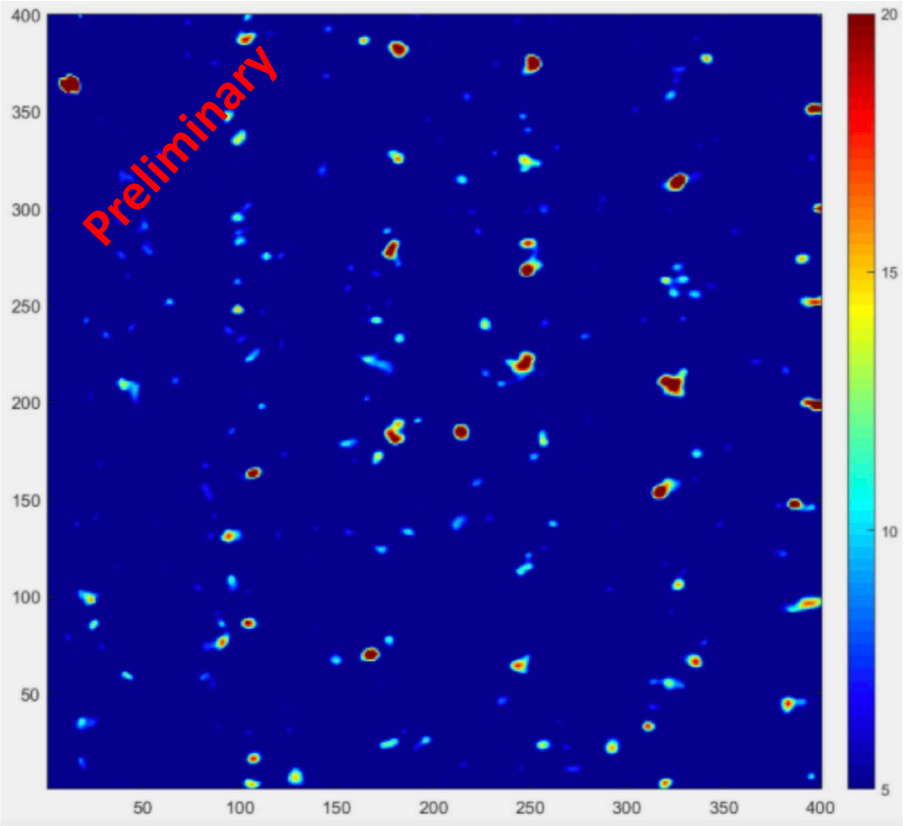
Artificial signal injection

- Active research cooperation with Ion Beam Laboratory in SNL
- Microbeam facility:
  - Can inject single carbon ions into diamond sample
  - Minimum energy of 800 keV
  - 3 um spatial resolution



Artificial signal injection

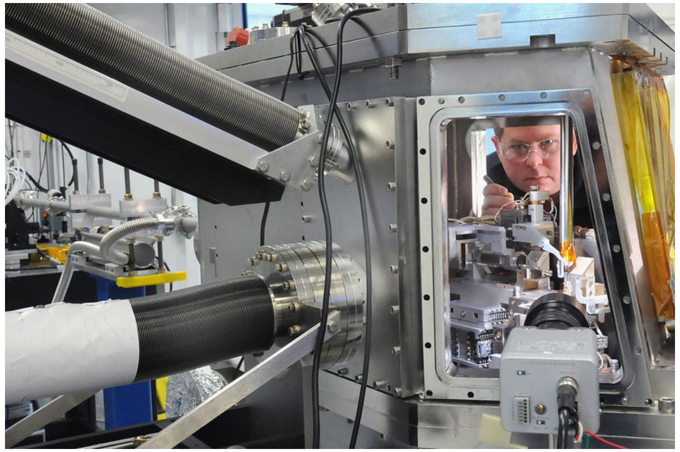
- Spring 2021 implantation:
  - HPHT sample (method 2)
  - Observed created NVs in a grid pattern as expected
  - High background due to sample prep
  - Ion beam not optimized
- Fall 2023 implantation: currently analyzing data
- Further implantations planned:
  - Use CVD samples to look for strain shift (method 1)
  - Nanobeam facility: <25 keV energy

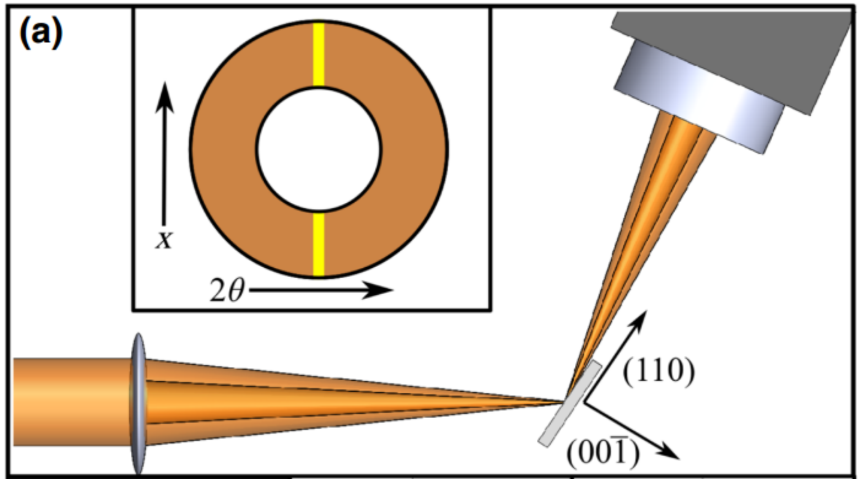


HPHT (method 2) implantation result, 2021

Stage 3: nm scale scanning

- Scanning X-ray diffraction microscopy @ ANL Hard X-Ray Nanoprobe
- X-ray beam focused to ~10 nm spot
- Detect Bragg diffraction pattern which encodes local crystal structure
- Extract strain by comparing readings from nearby positions in the sample
- Scans at different sample angles allow for 3D reconstruction
- $\sim 1.6 \times 10^{-4}$ strain sensitivity
  - 10 keV WIMP expected to produce similar strain levels

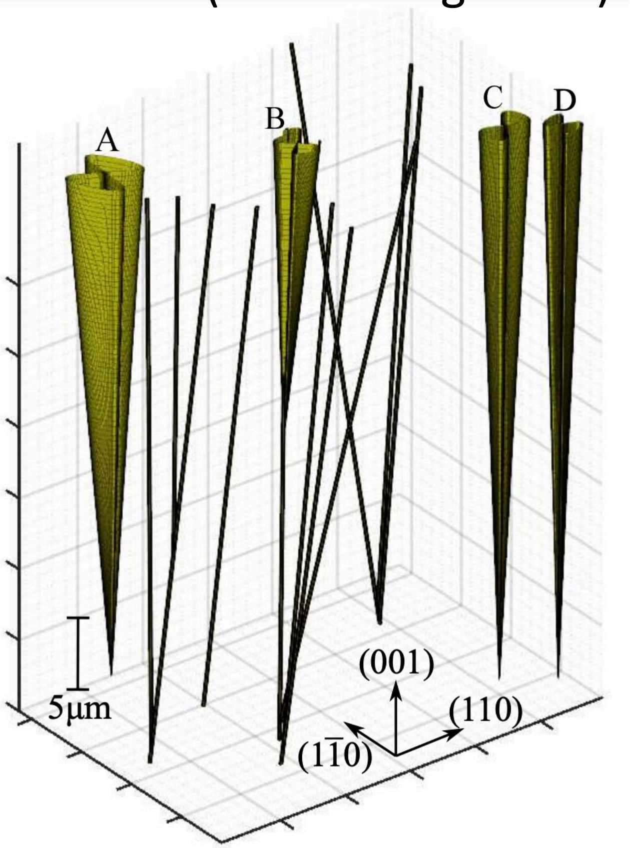


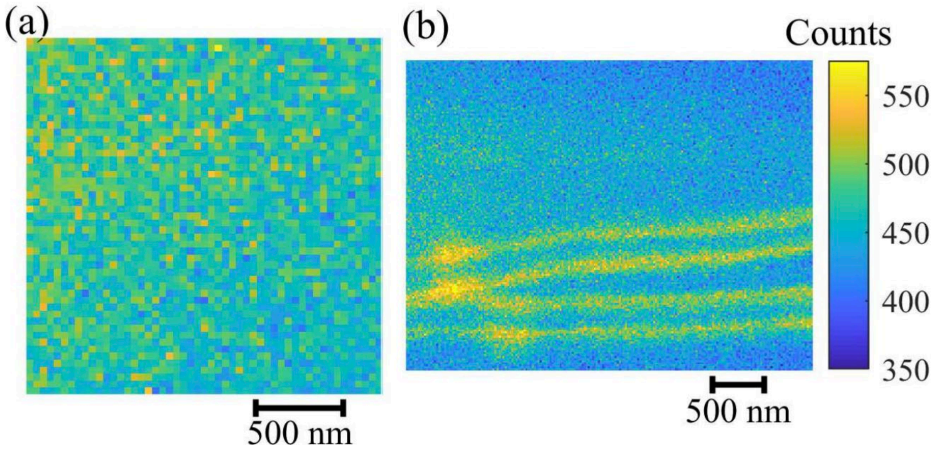


Marshall et al., PR Applied **16**, 054032 (2021)

- Low strain regions exhibit no natural features that could be mistaken for WIMP damage tracks
- Future: repeat SXDM scans with implanted samples
- Con: only a few SXDM facilities available in the world

3D reconstruction of pre-existing strain features (from CVD growth)





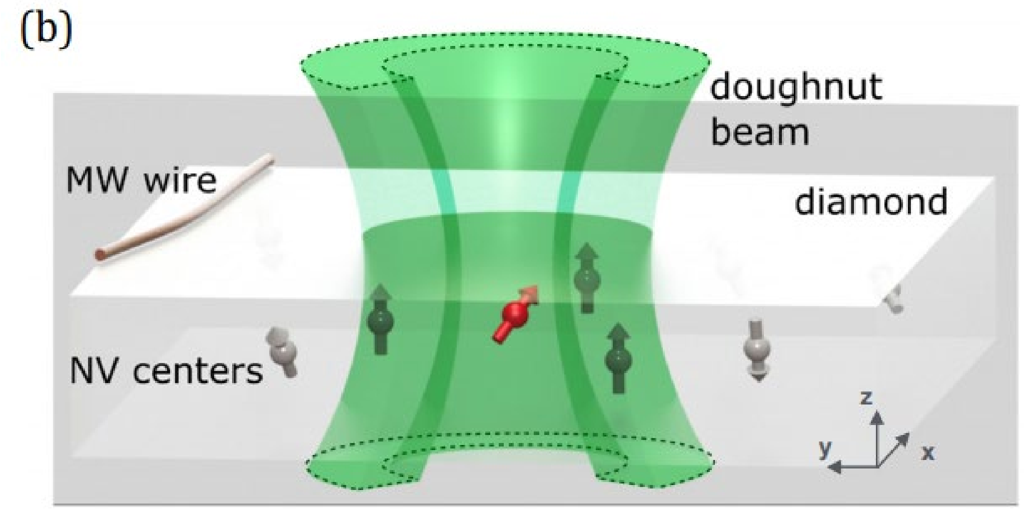
Low strain regions

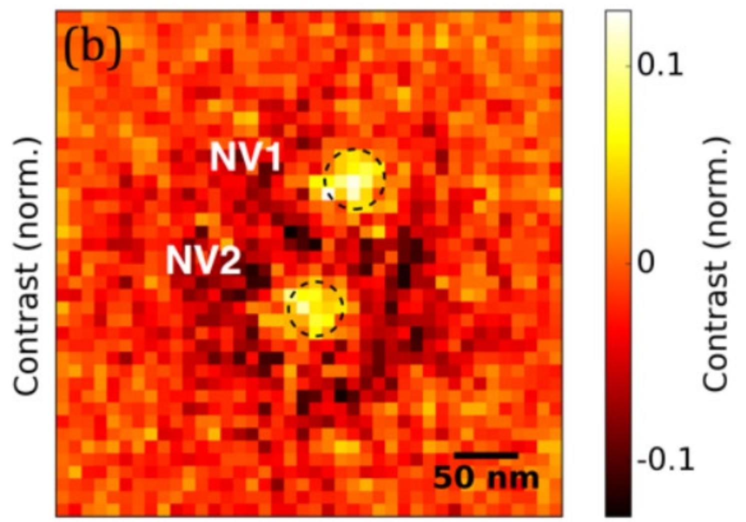
Marshall et al., PR Applied **16**, 054032 (2021)

Stage 3 alternative method: super-resolution spectroscopy of NV centers

- Image damage track by looking at strain shift on single NVs in its vicinity
  - Employ pattern recognition/machine learning techniques to determine initial recoil detections
  - Optimize density of NVs (typically $1/(30\ \mathrm{nm})^3$) based on damage track size
- Requires optical microscopy below the diffraction limit
  - Super-resolution NV imaging techniques have been previously developed in our group
- Advantage: setup could be deployed locally near DM detector

- Spin-RESOLFT: "turn off" signal from all except single NV by using doughnut laser beam
- Localized NV position to 5 nm uncertainty
- Imaged magnetic fields to 20 nm lateral resolution
- Can be straightforwardly extended to image strain
- Limitation: only 2D imaging of near-surface NVs

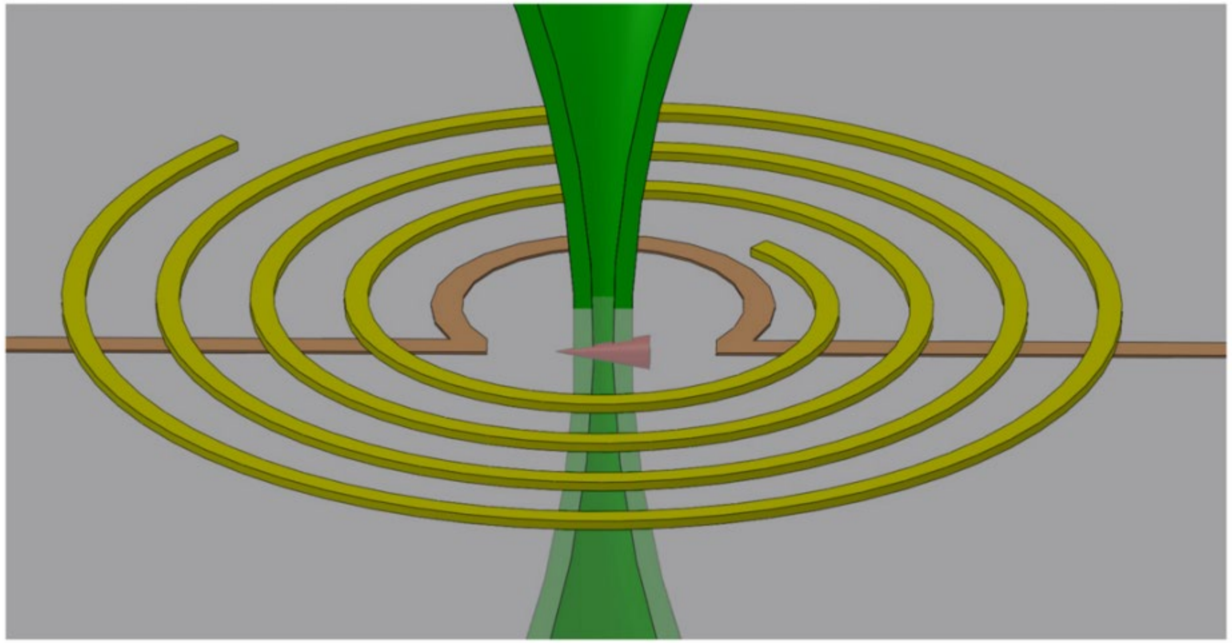




Jaskula et al., Opt. Express **25**, 11048 (2017)

Proposal to achieve 3D super-resolution

- Lateral 2D imaging using doughnut beam (spin-RESOLFT)
- Add z-resolution by applying magnetic field gradient along z
- Zeeman shift gradient created: selectively address z by tuning MW frequencies
- Etching techniques can also be used to make damage track closer to surface



Arai et al., Nat. Nano. **10**, 859–864 (2015)
Marshall et al., Quantum Sci. Tech. **6,** 024011 (2021)

Molecular dynamics simulations

- Earlier work used SRIM to model WIMP damage tracks
- Currently performing new simulations with LAMMPS
    - Classical n-body simulation
    - Keeps track of all atoms in the lattice
    - Use REBO interaction potentials known to be empirically accurate for diamond lattice
- Will allow more accurate prediction of directional detection performance and imaging capabilities required

Preliminary result from a 30 keV nuclear recoil

Rajendran et al., PRD **9**, 035009 (2017)
Image credit: Max Shen

Progress and future plans

- 2017: initial proposal (Rajendran et al., PRD **9**, 035009)
- 2019-22: experiments at Harvard University
  - Marshall et al., PR Applied **16**, 054032 (2021): Demonstrated nm-scale X-ray diffraction spectroscopy at required sensitivity
  - Marshall et al., PR Applied **17**, 02401 (2022): Demonstrated um-scale confocal and widefield strain spectroscopy at required sensitivity
  - Marshall et al., Quantum Sci. Tech. **6,** 024011 (2021): development roadmap

Progress and future plans

- 2023: move to Quantum Technology Center, University of Maryland
    - New personnel
    - Rebuilding strain imaging capabilities
    - Pursuing further research: LSM, ion implantation, improved simulations, …

32

Progress and future plans

- 2024 main research goals:
  - Demonstrate first step towards full 3D widefield strain spectroscopy with $1\ \mu\text{m}^3$ spatial resolution and 10^{-7} strain resolution (stage 2)
  - Detect artificial damage tracks from ion implantation
- Longer term goals:
  - Superresolution spectroscopy and SXDM of implanted samples (stage 3)
  - Stage 1 (real time detection) research: possibly collaborate with other groups
  - Determine which method for each stage is most promising
  - Build prototype directional DM detector

Summary and conclusion

- NV centers in diamond are a new, promising method of directional detection of WIMPs that can potentially overcome the neutrino fog
- Required imaging techniques for each stage are either already demonstrated or all within reach
- Substantial experimental progress has been made on demonstrating required strain sensitivity:
  - Stage 2: strain imaging
  - Stage 3: X-ray diffraction imaging
- Clear development path for the next few years

QTC Dark Matter team

Prof. Ron Walsworth (PI)

Daniel Ang
(QTC staff scientist)

Other collaborators

- Smriti Bhalerao (UMD)
- Michael Titze, Ed Bielejec (Sandia)
- Johannes Cremer, Mason Marshall, Mark Ku, David Phillips, Pauli Kehayias (Harvard)
- Martin Holt, Nazar Delegan, F. Joseph Heremans (Argonne)

Graduate students:

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Jiashen Tang

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Max Shen

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