Title: Quantum Sensing with Diamonds for Dark Matter Detection

Speakers: Reza Ebadi

Collection/Series: Particle Physics

Subject: Particle Physics

Date: December 06, 2024 - 1:00 PM

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Abstract:

Directional dark matter detectors using diamond as a target material offer a novel solution to overcome solar neutrino backgrounds. Sub-micron damage tracks from nuclear recoils can be read out via advanced quantum sensing techniques with nitrogen-vacancy (NV) centers. I will discuss recent advancements in strain-sensitive quantum interferometry that enable precise strain imaging, paving the way for directional particle detection. These developments highlight the potential of diamond-based detectors for advancing dark matter and neutrino physics, as well as material science applications.

Quantum Sensing with Diamonds for Dark Matter Detection

December 6, 2024 @ Perimeter Institute

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UNIVERSITY OF MARYLAND 1856

QUANTUM TECHNOLOGY CENTER

JOHN TEMPLETON FOUNDATION

Precision measurement

Ultraheavy dark matter search with electron microscopy of geological quartz
Phys. Rev. D 104 (2021) 1, 015041
High-Precision Mapping of Diamond Crystal Strain Using Quantum Interferometry
Phys. Rev. Applied 17 (2022) 2, 024041
Directional Detection of Dark Matter Using Solid-State Quantum Sensing
AVS Quantum Sci. 4, 044701 (2022)
GALILEO: Galactic Axion Laser Interferometer Leveraging Electro-Optics
Phys. Rev. Lett. 132 (2024) 10, 101001
Diamond Micro-Chip for Quantum Microscopy
e-Print: 2403.10414

Astrophysics

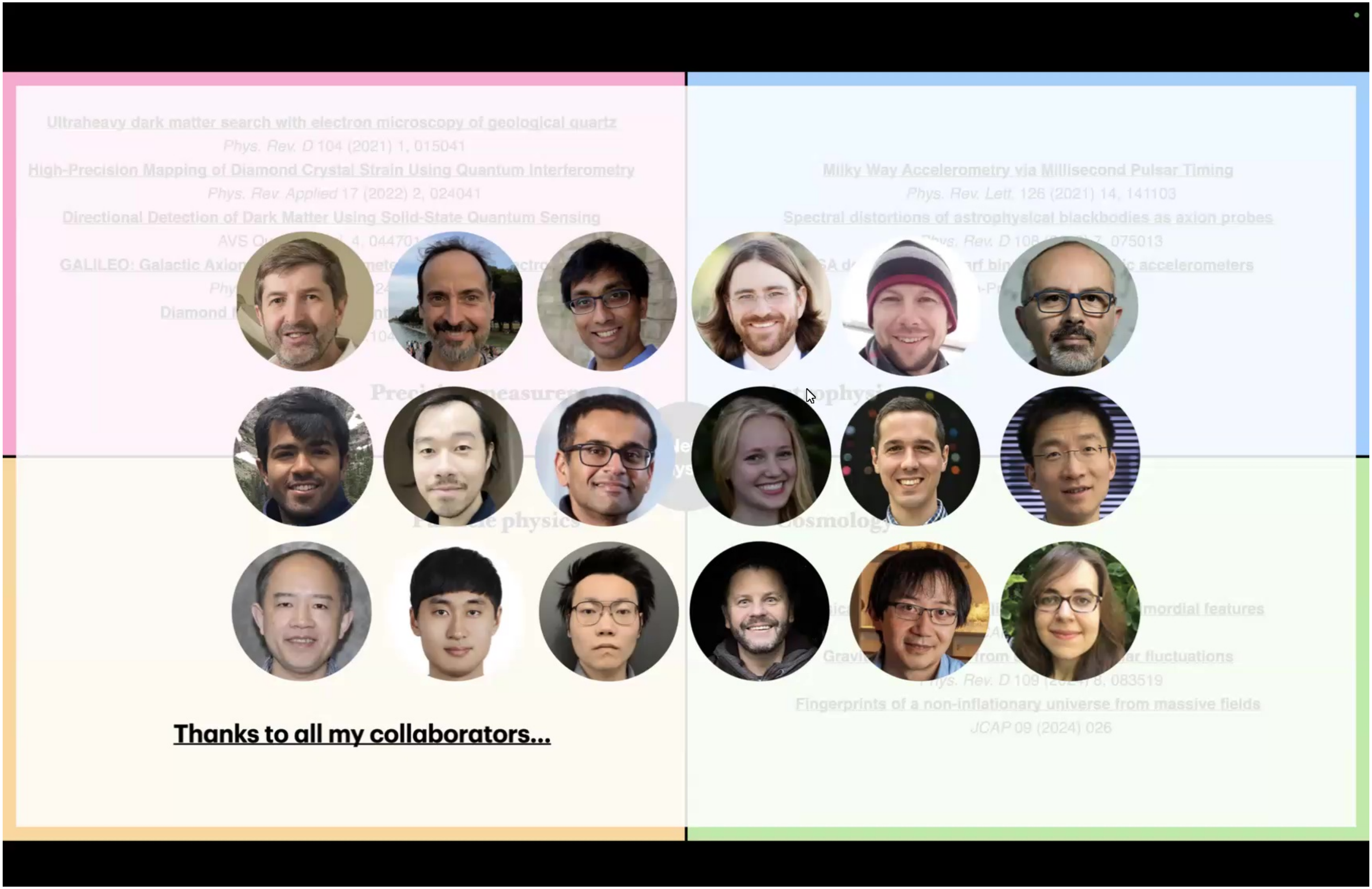
Milky Way Accelerometry via Millisecond Pulsar Timing
Phys. Rev. Lett. 126 (2021) 14, 141103
Spectral distortions of astrophysical blackbodies as axion probes
Phys. Rev. D 108 (2023) 7, 075013
LISA double white dwarf binaries as Galactic accelerometers
e-Print: 2405.13109

New Physics

Particle physics

Cosmology

Classical cosmological collider physics and primordial features
JCAP 08 (2022) 083
Gravitational waves from stochastic scalar fluctuations
Phys. Rev. D 109 (2024) 8, 083519
Fingerprints of a non-inflationary universe from massive fields
JCAP 09 (2024) 026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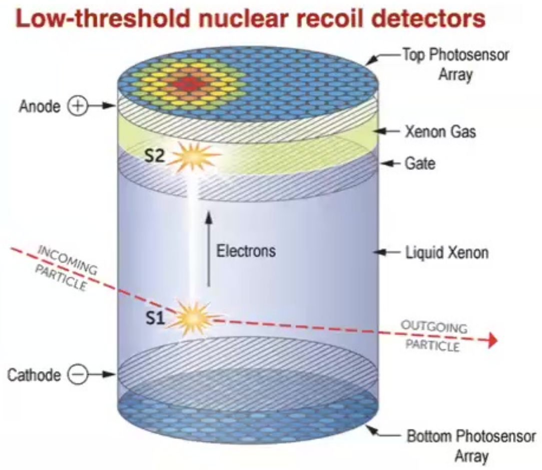
JCAP 09 (2024) 026
Thanks to all my collaborators...

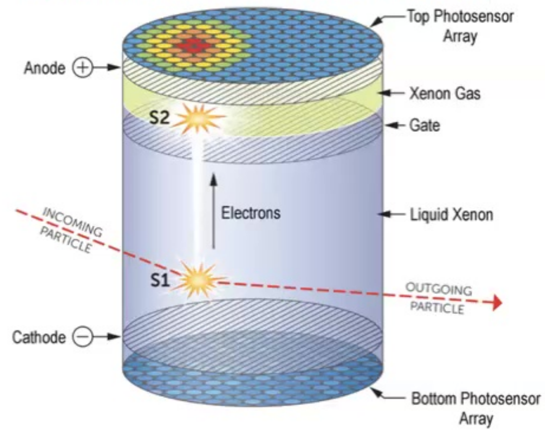
WIMP DM detection



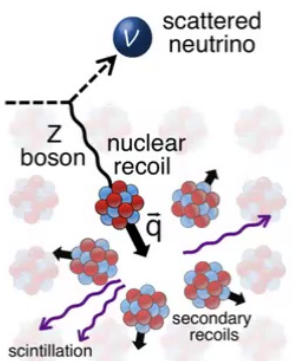
Goodman, Witten [Phys. Rev. D 31, 3059 (1985)]
Drukier, Stodolsky [Phys. Rev. D 30, 2295 (1984)]
Freedman [Phys. Rev. D 9, 1389 (1974)]

WIMP DM detection

Low-threshold nuclear recoil detectors



Coherent elastic neutrino-nucleus scattering (CEvNS)



PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

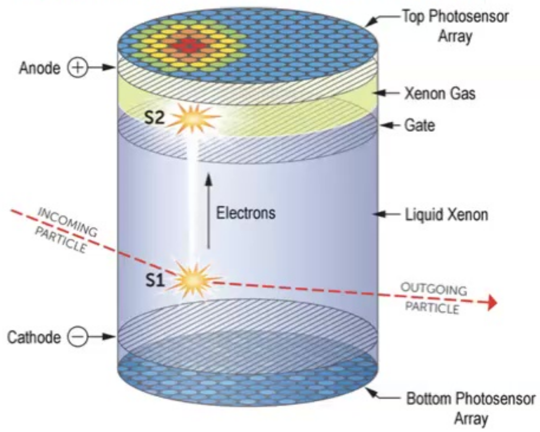
The DM signal has not yet been observed…

but the original concept of neutrino detection is starting to be realized

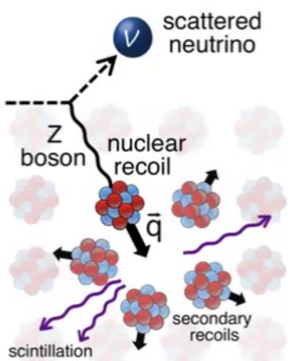
Goodman, Witten [Phys. Rev. D 31, 3059 (1985)]
Drukier, Stodolsky [Phys. Rev. D 30, 2295 (1984)]
Freedman [Phys. Rev. D 9, 1389 (1974)]

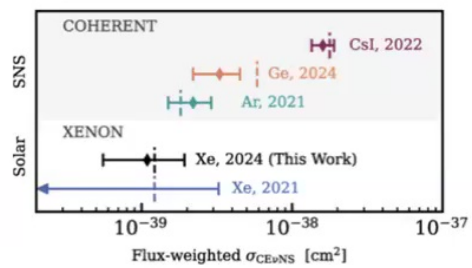
WIMP DM detection

Low-threshold nuclear recoil detectors



Coherent elastic neutrino-nucleus scattering (CEvNS)





PHYSICAL REVIEW LETTERS **133**, 191001 (2024)

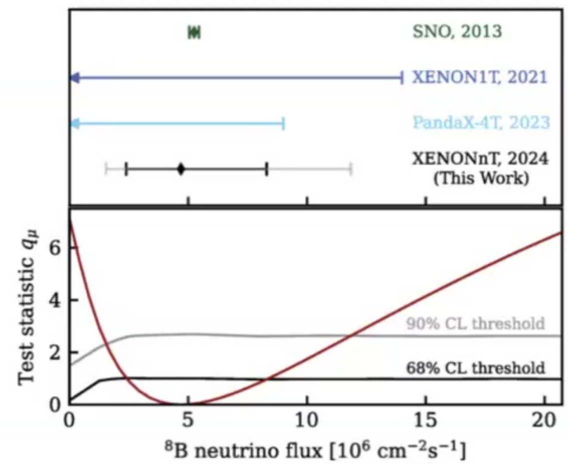
Editors' Suggestion | Featured in Physics

First Indication of Solar ^{8}B Neutrinos through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T

PHYSICAL REVIEW LETTERS **133**, 191002 (2024)

Editors' Suggestion | Featured in Physics

First Indication of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT

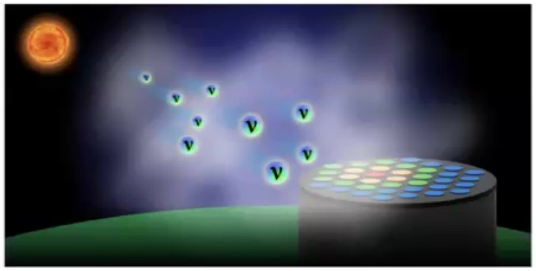


Neutrino observatory

Goodman, Witten [Phys. Rev. D 31, 3059 (1985)]
Drukier, Stodolsky [Phys. Rev. D 30, 2295 (1984)]
Freedman [Phys. Rev. D 9, 1389 (1974)]
PandaX Collaboration [Phys. Rev. Lett. 133, 191001 (2024)]
XENON Collaboration [Phys. Rev. Lett. 133, 191002 (2024)]
COHERENT Collaboration [Phys. Rev. Lett. 126, 012002 (2021)]
COHERENT Collaboration [Science 357, 1123 (2017)]

Neutrino fog

The end of the "zero background" era

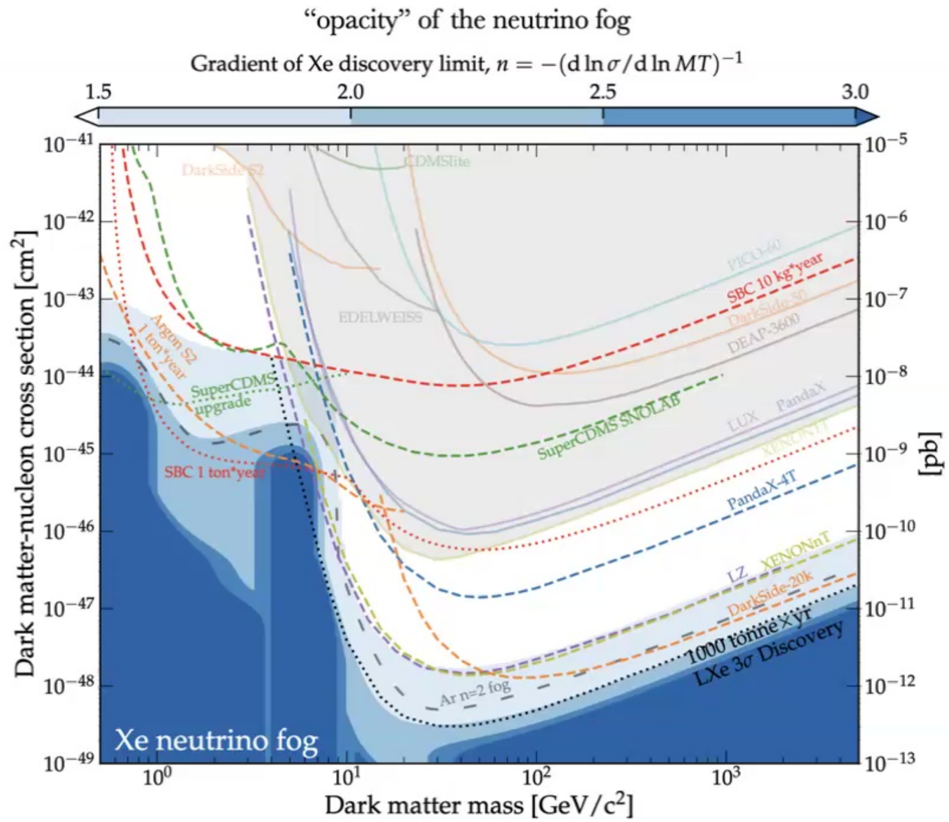


Neutrino fog instead of neutrino floor

With sufficient statistics, it is possible to separate the background from the signal.

Increased exposure ↓

Zero background	$\sigma \propto 1/N$
Poissonian background subtraction	$\sigma \propto 1/\sqrt{N}$
Background fluctuations-limited	$\sigma \propto \sqrt{(1 + N\delta\Phi)/N}$
Poissonian background subtraction	$\sigma \propto 1/\sqrt{N}$

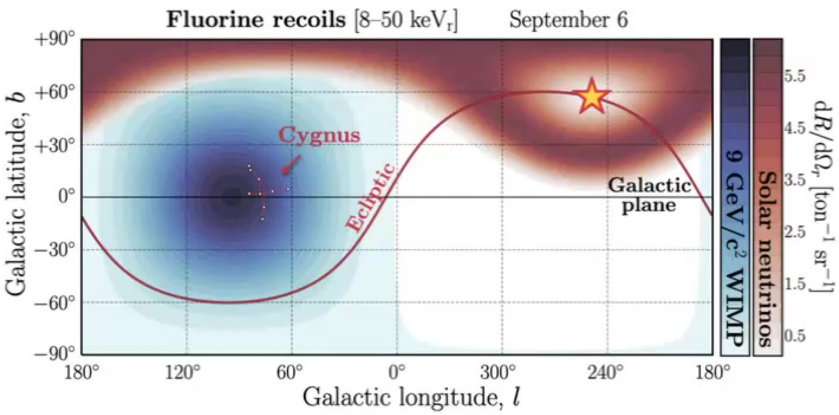


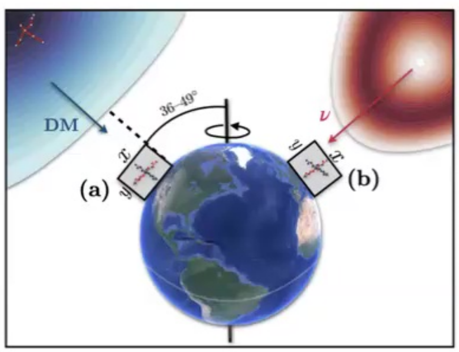
O'Hare [arXiv:2109.03116]

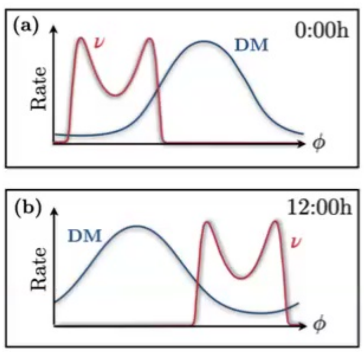
Akerib et al. (including **RE**) [arXiv:2203.08084]

Directional detection

A method for mitigating the neutrino background







THIRD SERIES, VOLUME 37, NUMBER 6 15 MARCH 1988

Motion of the Earth and the detection of weakly interacting massive particles

David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

If the galactic halo is composed of weakly interacting massive particles (WIMP's), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP's. Earth's motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP's. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.

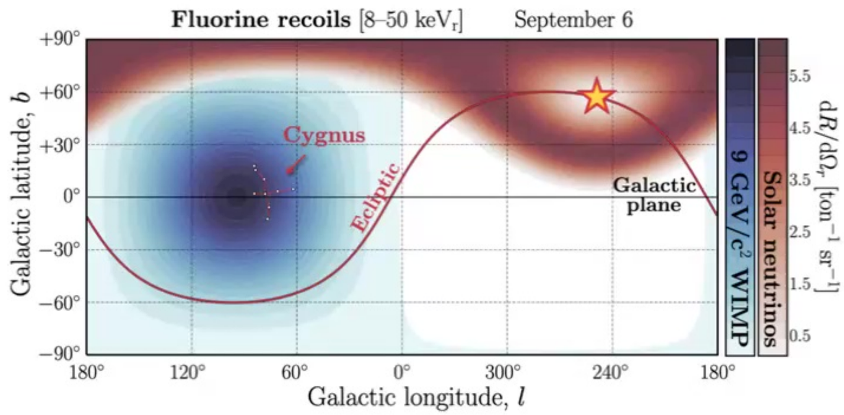
We would have liked to be building directional detectors to confirm the DM signal, but that is not the case

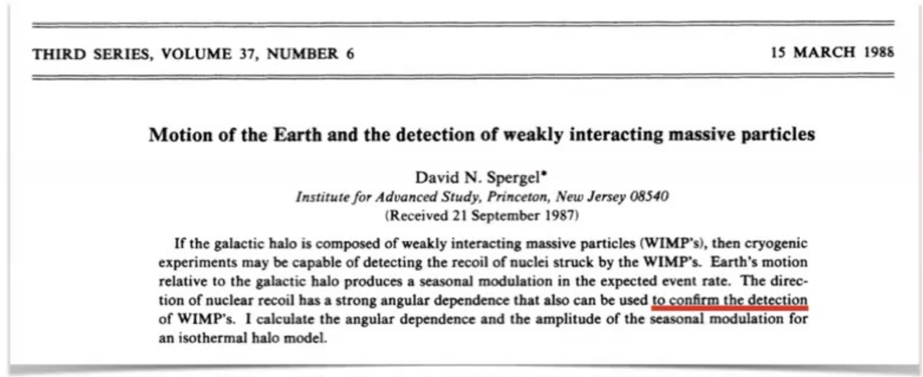
- Counting
- Energy
- Time
- Direction (1d, 2d, 3d)
- Head/tail asymmetry

Spergel [Phys. Rev. D (1988)]
Vahsen et al. [arXiv:2008.12587]
Vahsen, O'Hare, Loomba [arXiv:2102.04596]

Directional detection

A method for mitigating the neutrino background





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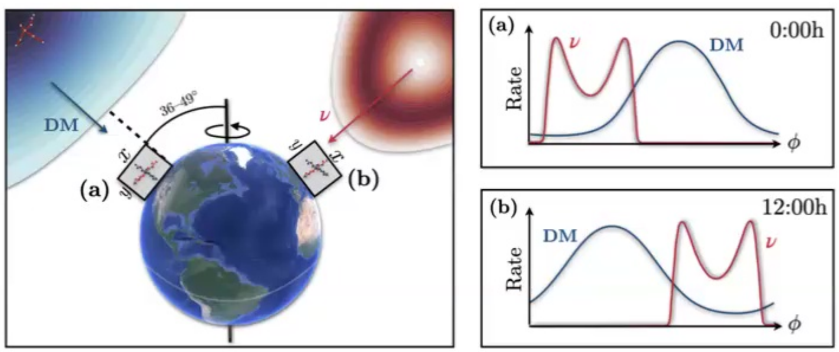


- Counting
- Energy
- Time
- Direction (1d, 2d, 3d)
- Head/tail asymmetry

CYGNUS Collaboration

Gas time projection chambers (TPCs)

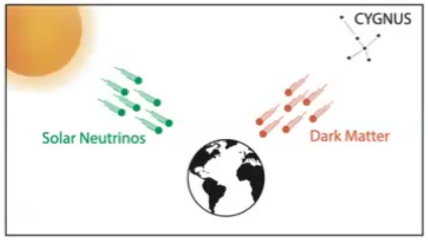
✔ Mature technology, demonstrated directional detection

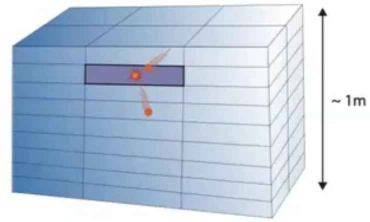
✘ Extremely large volume and challenging instrumentation

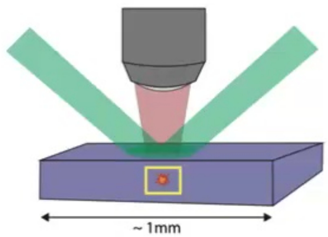
Spergel [Phys. Rev. D (1988)]
Vahsen et al. [arXiv:2008.12587]
Vahsen, O'Hare, Loomba [arXiv:2102.04596]

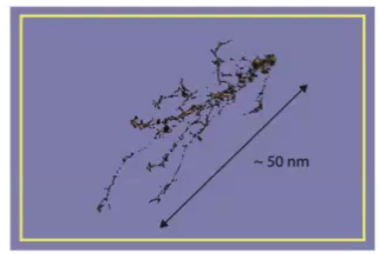
Directional detection in diamond

A solid state directional detector









RE et al. [AVS Quantum Sci. 4, 044701 (2022)]
Marshall et al. [Quantum Sci. Technol. 6 024011 (2021)]
Rajendran et al. [Phys. Rev. D 96, 035009 (2017)]

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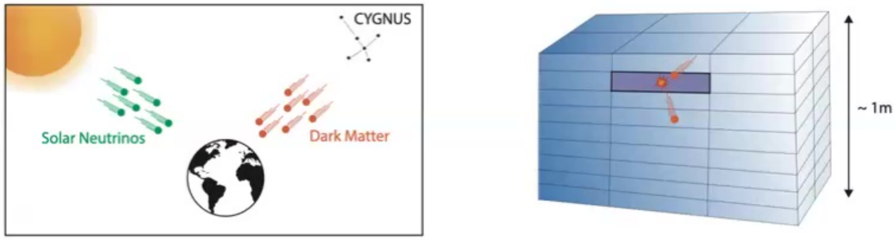

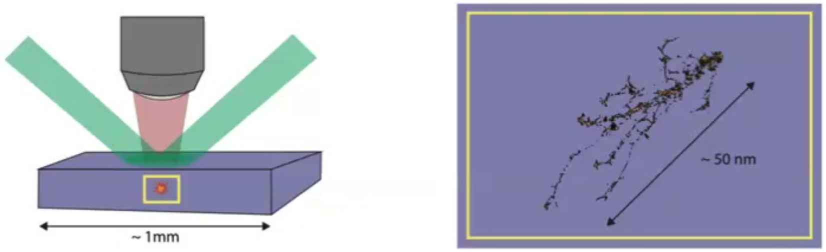

STEP I: Event detection and localization at the mm scale using charge, phonon, or photon collection. The event time is recorded to determine the absolute orientation of the specific mm-scale chip in which the event occurred.

STEP II: Damage track localization at the micron scale using optical-diffraction limited techniques utilizing quantum defects in the solid.

STEP III: Mapping damage tracks at the nanoscale using either superresolution optical methods or x-ray microscopy. The meter-scale detector continues operation during steps II and III.

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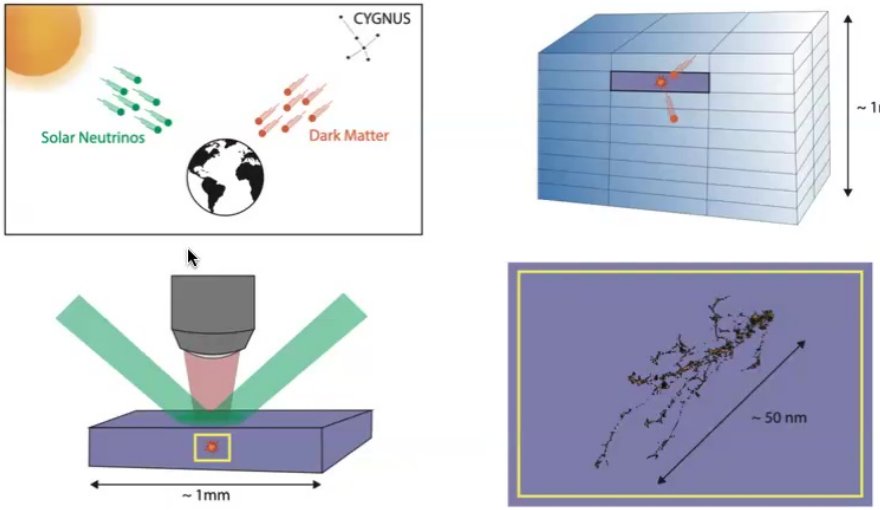

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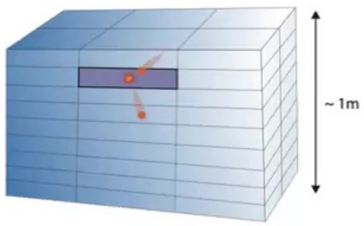
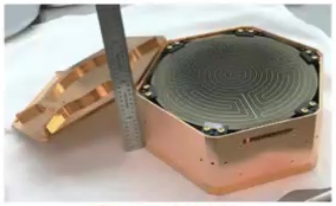
Why diamond?

RE et al. [AVS Quantum Sci. 4, 044701 (2022)]
Marshall et al. [Quantum Sci. Technol. 6 024011 (2021)]
Rajendran et al. [Phys. Rev. D 96, 035009 (2017)]

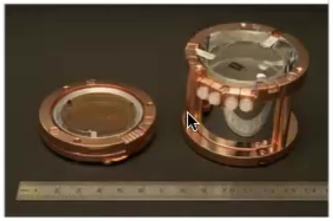
Directional detection in diamond

STEP I

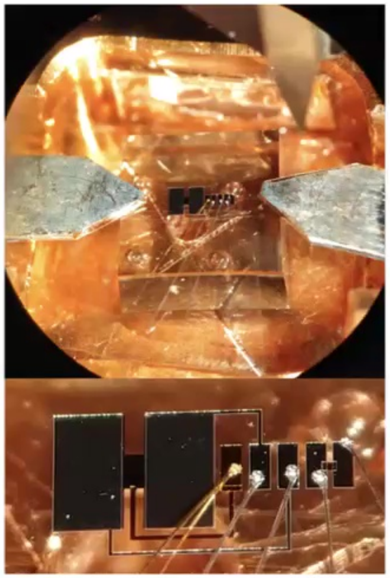




SuperCDMS



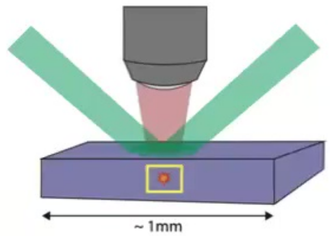
CRESST



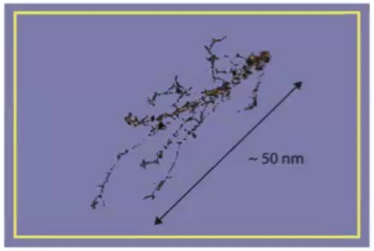
Low-threshold TES on diamond

What we have focused on…

STEP II



STEP III



Kurinsky et al. [arXiv:1901.07569]

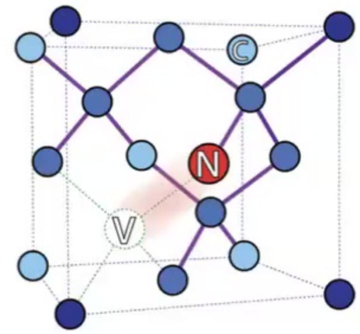
Abdelhameed [*Eur.Phys.J.C* 82 (2022) 9, 851]

Canonica et al. [*J Low Temp Phys* 199, 606–613 (2020)]

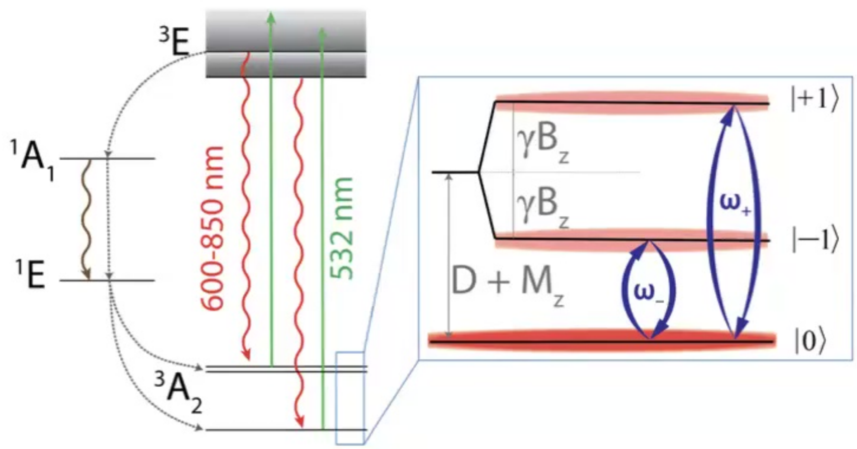
Questions?

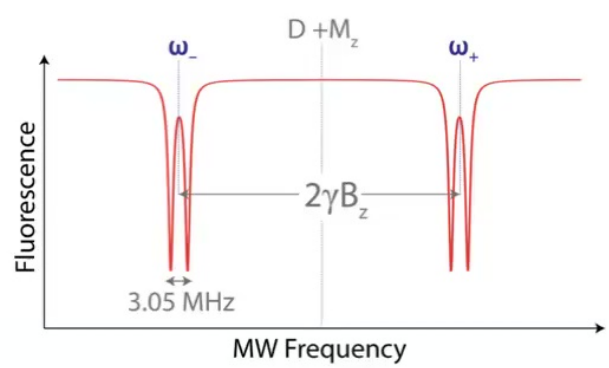
Nitrogen-vacancy center and spin dependent readout

- Spin-1 point defects in diamond
- Spin-dependent intersystem crossing allows optical initialization and readout
- Spin precession frequencies sensitive to strain



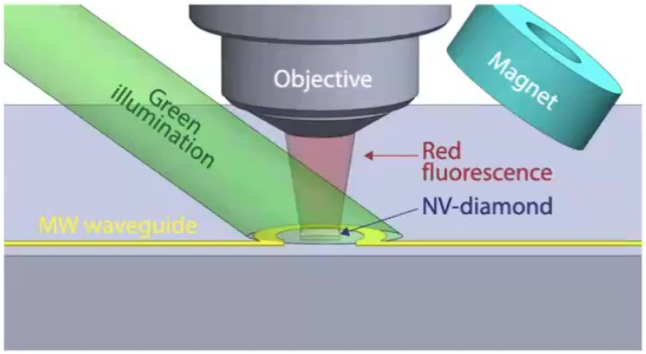
$$H \simeq (D + M_z)S_z^2 + \gamma B_z S_z$$

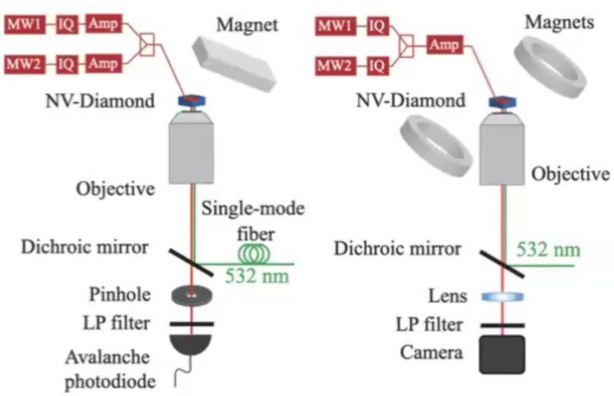




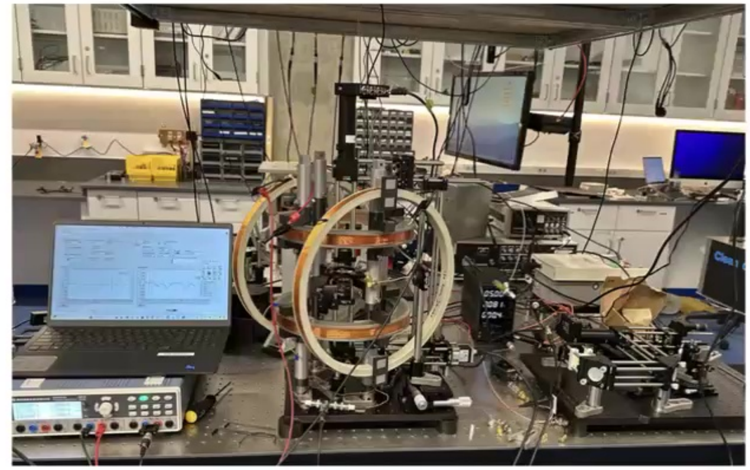
RE et al. [AVS Quantum Sci. 4, 044701 (2022)]
Barry et al. [Reviews of Modern Physics 92 (1), 015004]

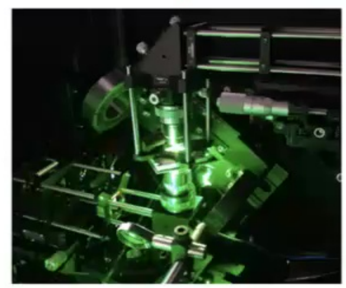
Quantum diamond microscope (QDM)

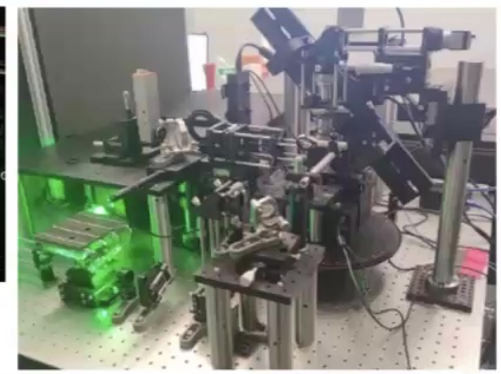


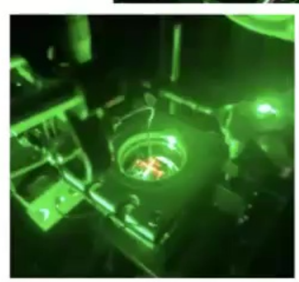


Confocal **Widefield imager**

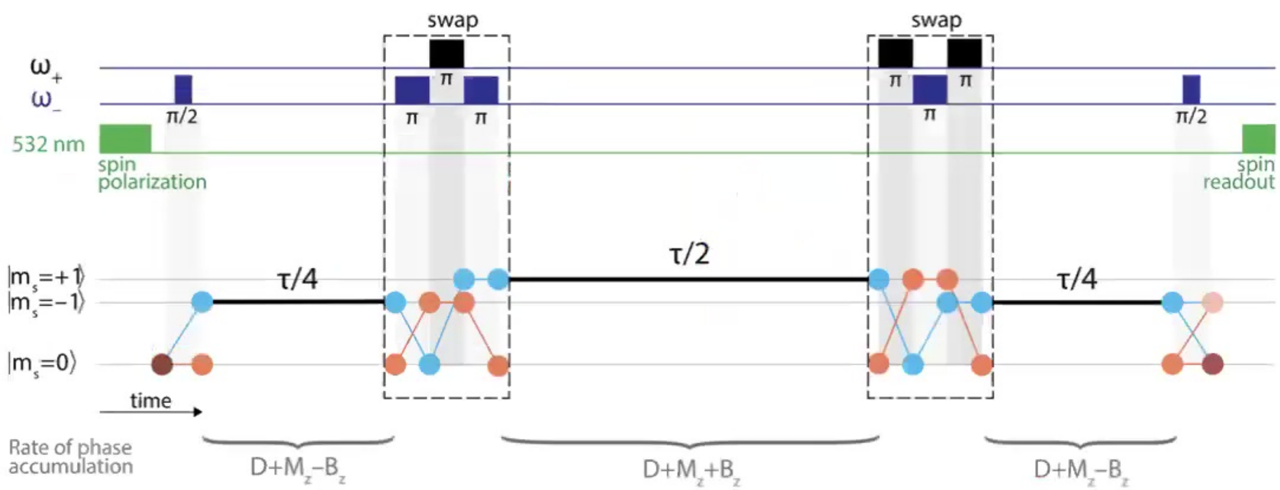








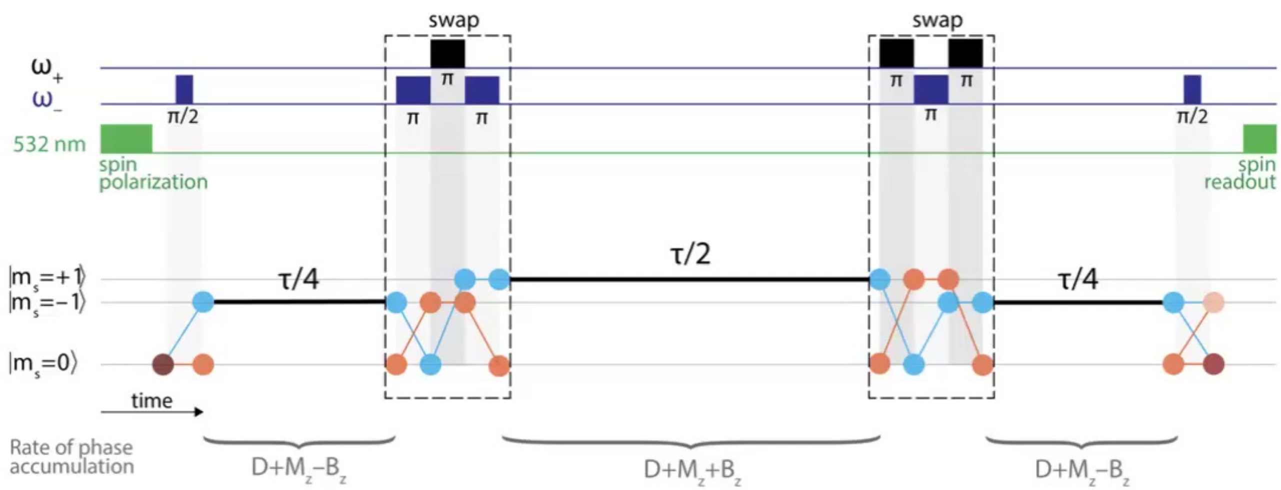
Strain-CPMG: spin-1 enhanced strain sensing



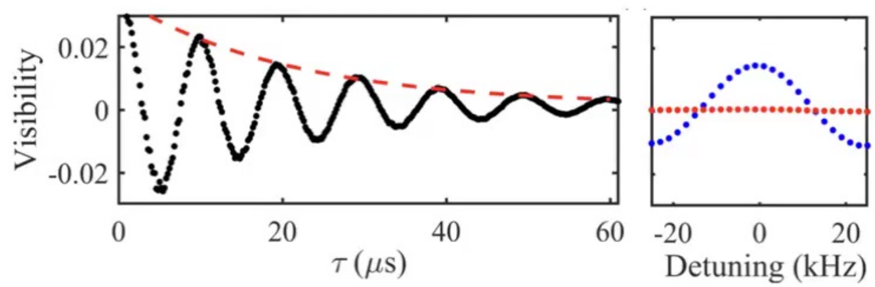
Spending equal time on both the + and - states cancels out the magnetic contribution.

Marshall, **RE** et al. [Phys. Rev. Applied 17 (2022) 2, 024041]

Strain-CPMG: spin-1 enhanced strain sensing



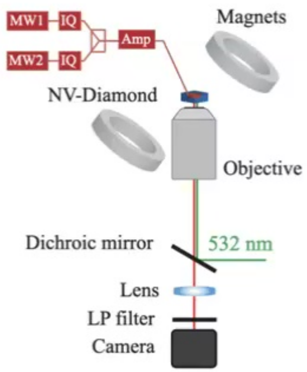
Spending equal time on both the + and - states cancels out the magnetic contribution.



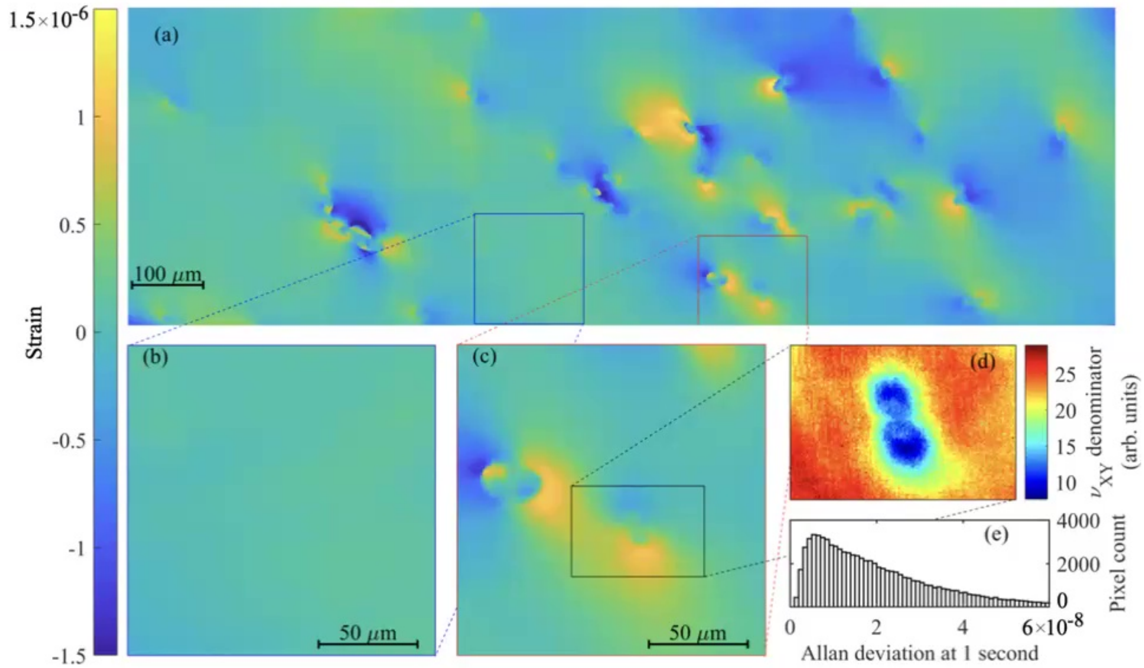
3x improvement in dephasing time (7 μs to 20 μs)

Marshall, **RE** et al. [Phys. Rev. Applied 17 (2022) 2, 024041]

Strain-CPMG: Widefield imaging



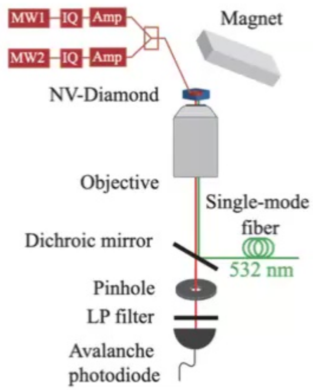
- Sensitivity: ~1e-8 Hz^(- 1/2)
- Estimated required sensitivity for DM track localization: 1e-7 to 3e-6
- Each FOV (100 μm x 100 μm): 1 second of data acquisition
- Showcasing low-strain samples
- ✗ Z-sectioning is absent

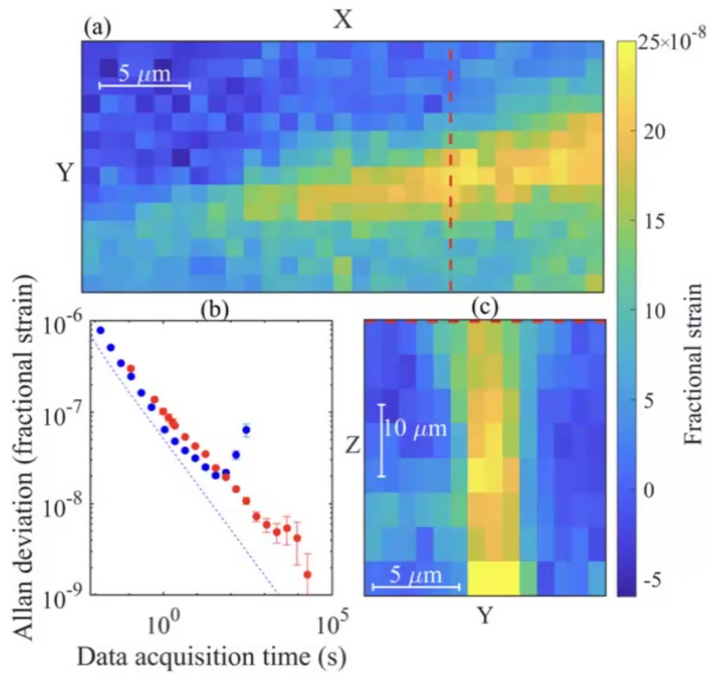


Sample:
CVD bulk diamond material, grown by Element Six; isotopically purified 12C;
[N] = 3 ppm;
e-irradiated and annealed to form NV centers.

Marshall, **RE** et al. [Phys. Rev. Applied 17 (2022) 2, 024041]

Strain-CPMG: Scanning confocal microscope





✔ Volume-normalized sensitivity: 5e-8 Hz^(- 1/2) μm^(3/2)

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

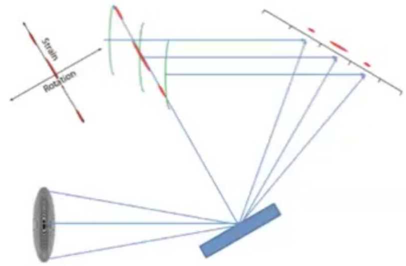
Assuming same sensitivity for widefield imager: full mm-scale chip can be imaged in ~ 13 hours

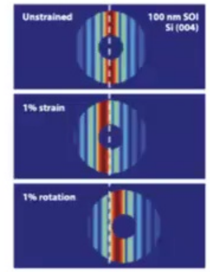
Sample:
CVD bulk diamond material, grown by Element Six; isotopically purified 12C;
[N] = 3 ppm;
e-irradiated and annealed to form NV centers.

Marshall, **RE** et al. [Phys. Rev. Applied 17 (2022) 2, 024041]

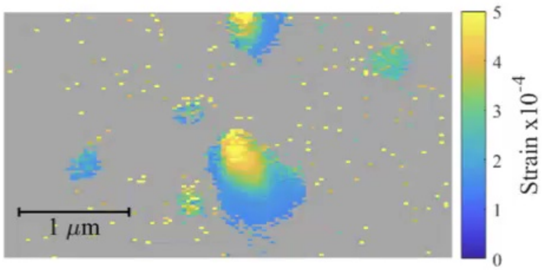
Nanoscale track reconstruction

Scanning X-ray diffraction microscopy



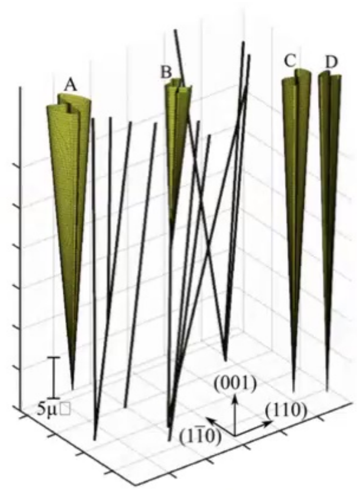


Argonne NATIONAL LABORATORY

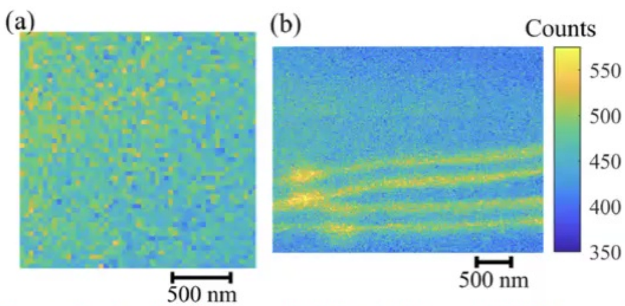


Resolution: ~10 nm

Sensitivity: ~ 1.6E-4



✓ Strain features similar to the expected signal



✓ 3D reconstruction of the strain features

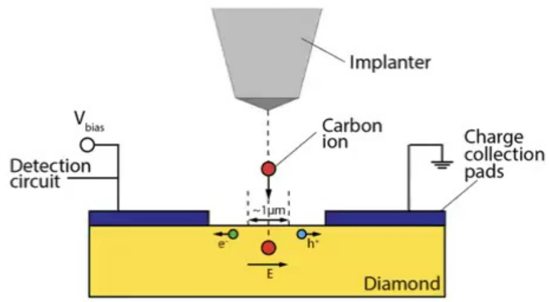
✓ No confusion background detected in an initial search

Mason Marshall

Marshall et al. [Phys. Rev. Appl. (2021)]

Holt et al. [Annu. Rev. Mater. Res. (2013)]

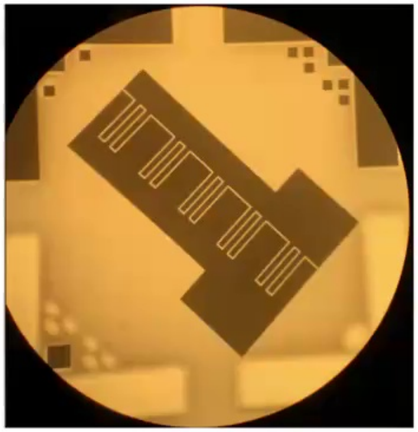
Ongoing work: injected signal

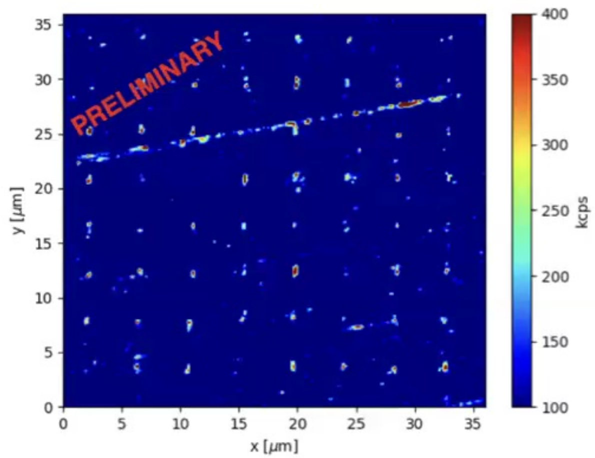


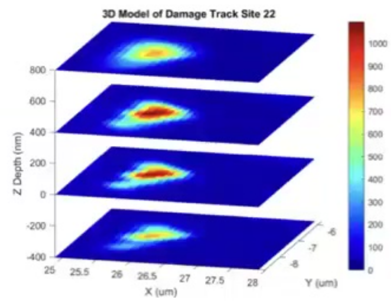
Single ion implantation

Carbon ion implantation @ few MeV

NV creation after annealing at high temperatures





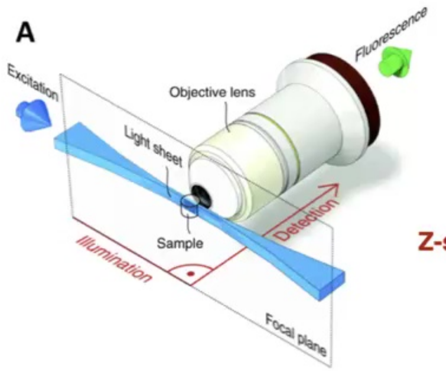


Jiashen Tang Daniel Ang

Titze et al [Nano Lett. 22, 3212-3218]

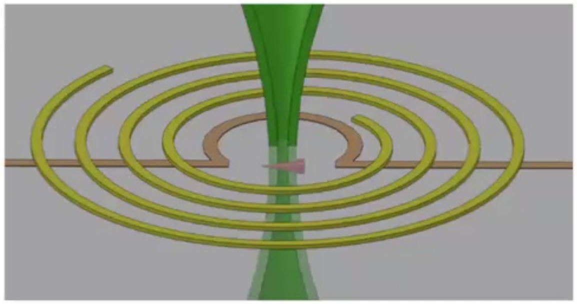
Ongoing work

Light sheet microscopy



Z-sectioning for strain imaging

Nanoscale strain spectroscopy

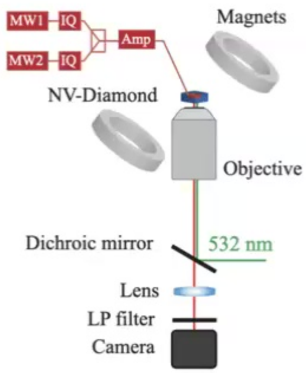


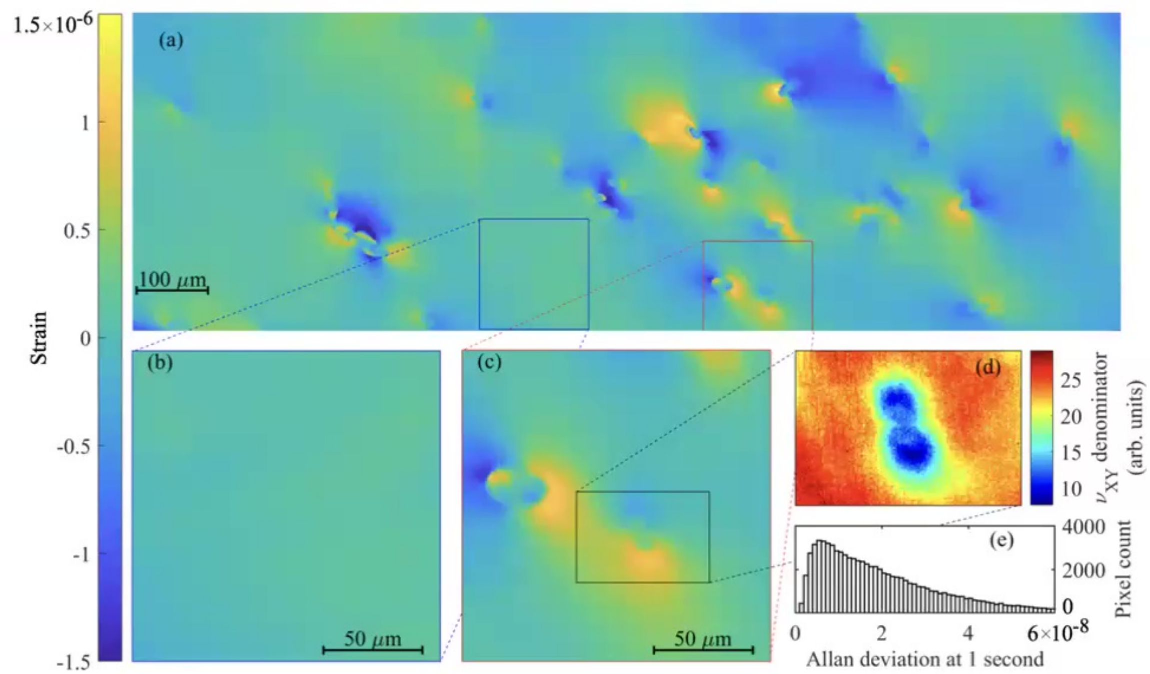
In-house nanoscale track reconstruction

Molecular dynamics simulations

Accurate signal simulation

Strain-CPMG: Widefield imaging





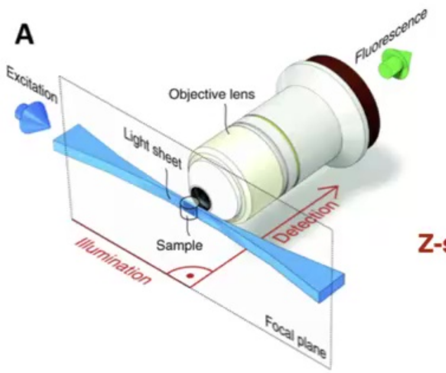
- ✓ Sensitivity: ~1e-8 Hz^(- 1/2)
- ✓ Estimated required sensitivity for DM track localization: 1e-7 to 3e-6
- ✓ Each FOV (100 μm x 100 μm): 1 second of data acquisition
- ✓ Showcasing low-strain samples
- ✗ Z-sectioning is absent

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

Marshall, **RE** et al. [Phys. Rev. Applied 17 (2022) 2, 024041]

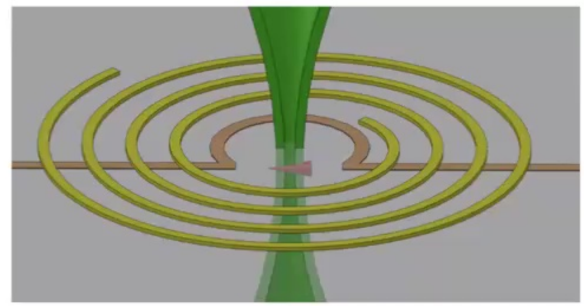
Ongoing work

Light sheet microscopy



Z-sectioning for strain imaging

Nanoscale strain spectroscopy



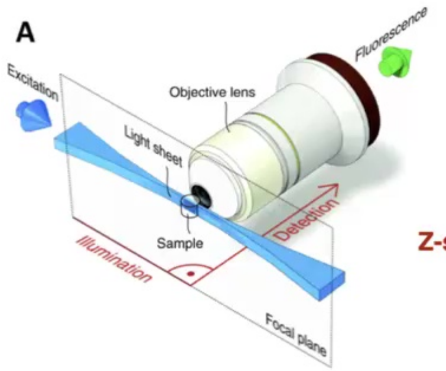
In-house nanoscale track reconstruction

Molecular dynamics simulations

Accurate signal simulation

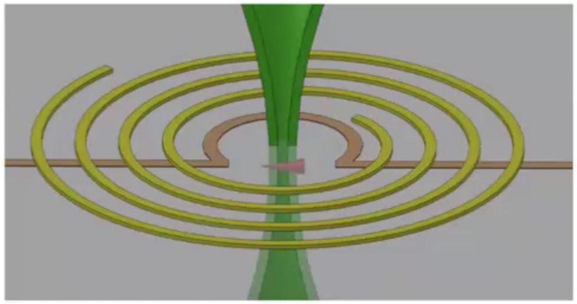
Ongoing work

Light sheet microscopy



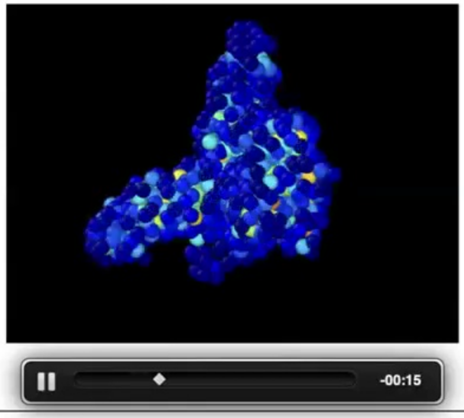
Z-sectioning for strain imaging

Nanoscale strain spectroscopy



In-house nanoscale track reconstruction

Molecular dynamics simulations



Accurate signal simulation

Summary

Basic idea

Neutrino fog and directional detection

Multi-stage directional detection in diamond

Nitrogen-vacancy centers as quantum sensors

NV center as a point defect and it's spin-dependent fluorescence

Quantum interferometry — Ramsey sequence

Strain-CPMG — an optimized quantum protocol for strain sensing

Experimental progress so far

Strain imaging using quantum interferometry

X-ray diffraction microscopy for nanoscale strain reconstruction

Ongoing work

Injected signals via ion implantation; Light sheet microscopy; Nanoscale strain spectroscopy; Molecular dynamics simulations

Thank you for listening!