

# Directional dark matter detection in diamond: principles and experimental progress

UCLA Dark Matter 2023 | March 31, 2023

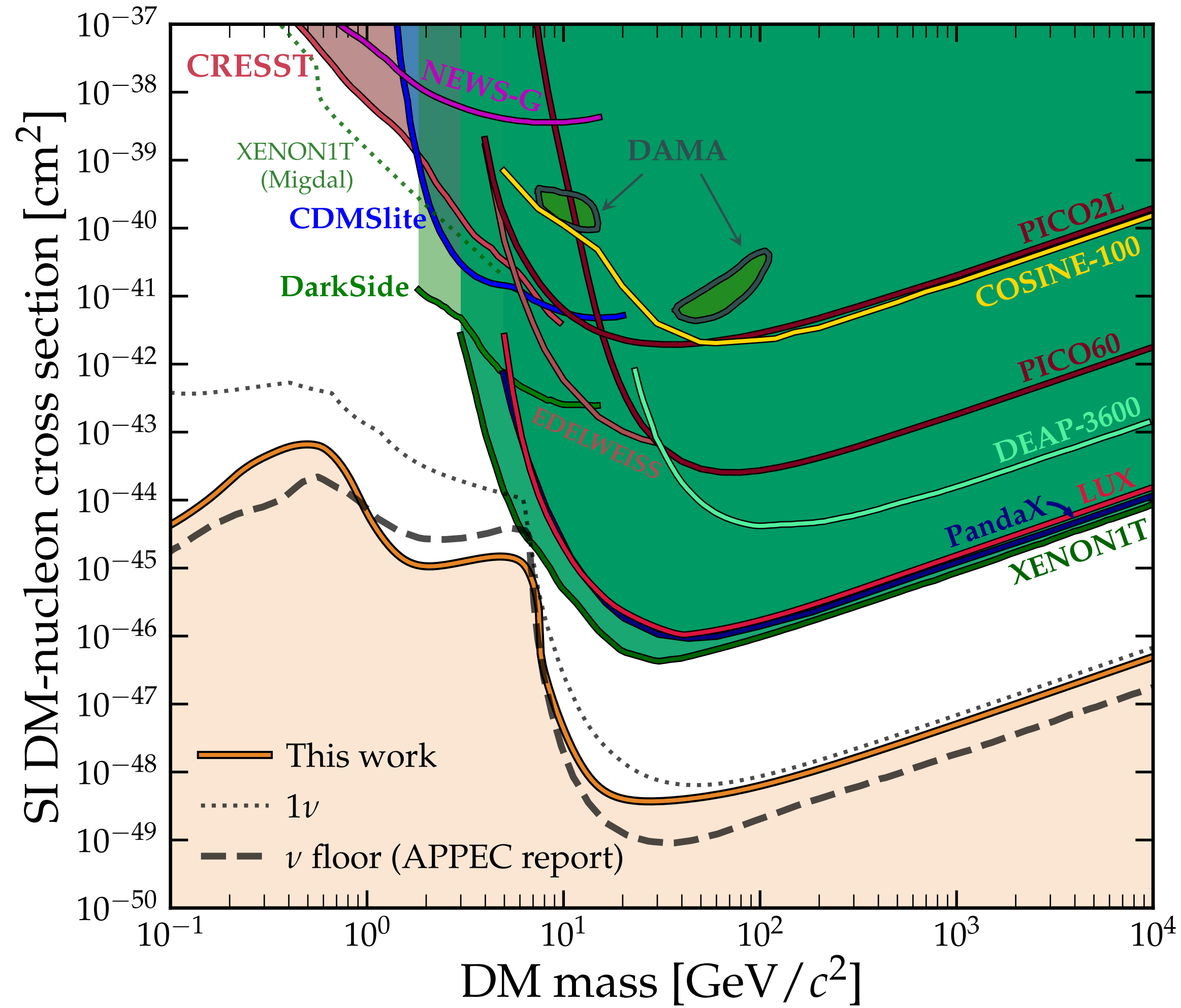
**Reza Ebadi**  
([ebadi@umd.edu](mailto:ebadi@umd.edu))

Based on:

[[2203.06037](#) hep-ex], [[2108.00304](#) quant-ph], [[2103.08388](#) physics.app-ph],  
[[2009.01028](#) physics.ins-det], and [[1705.09760](#) hep-ph]



# WIMP detection and neutrino fog



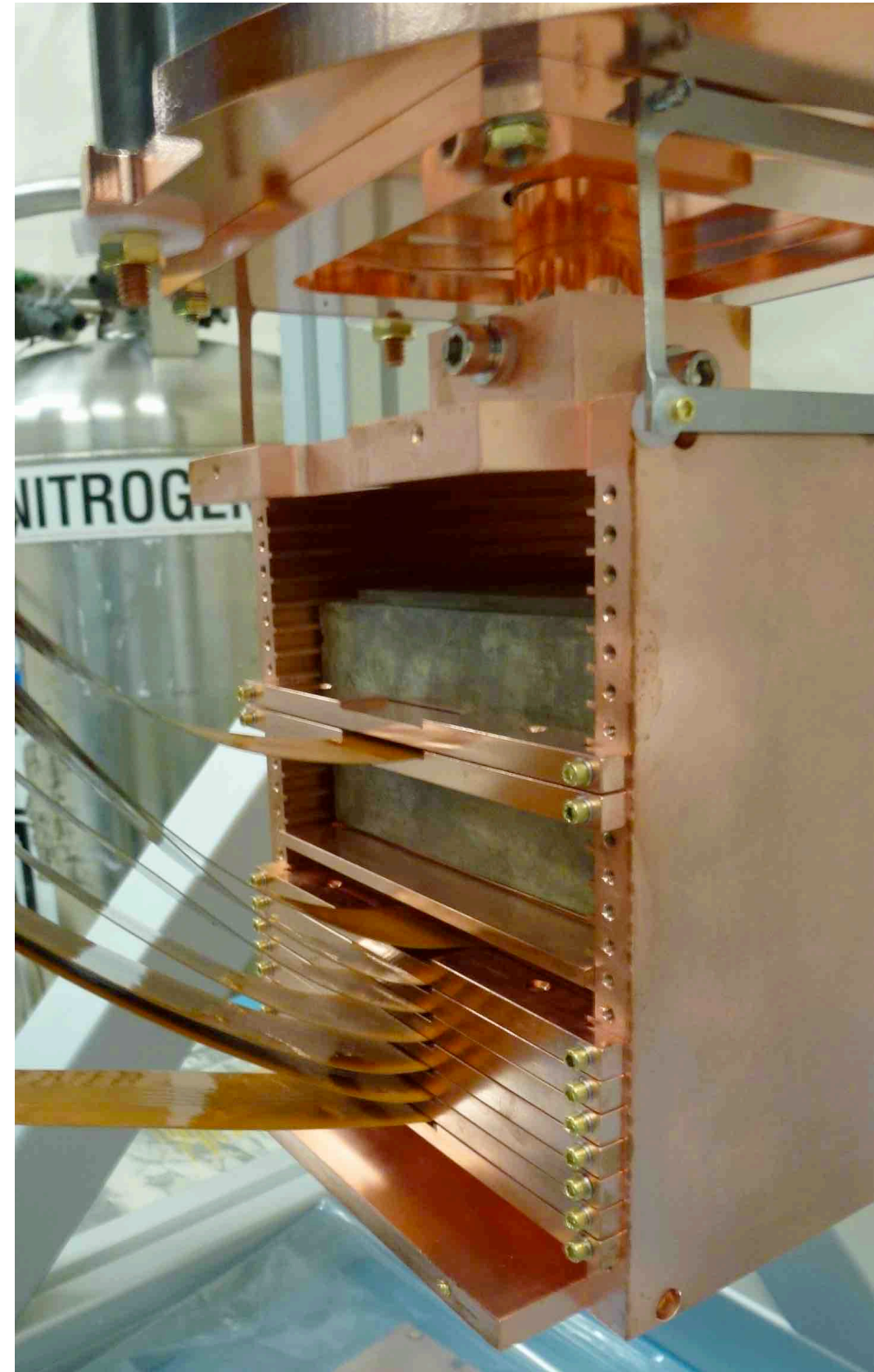
Direct detection searches reach increasingly stringent exclusion bounds, but after the next generation of detectors they will be limited by coherent neutrino scattering.

Phys. Rev. Lett. 127, 251802 (2021) [2109.03116]

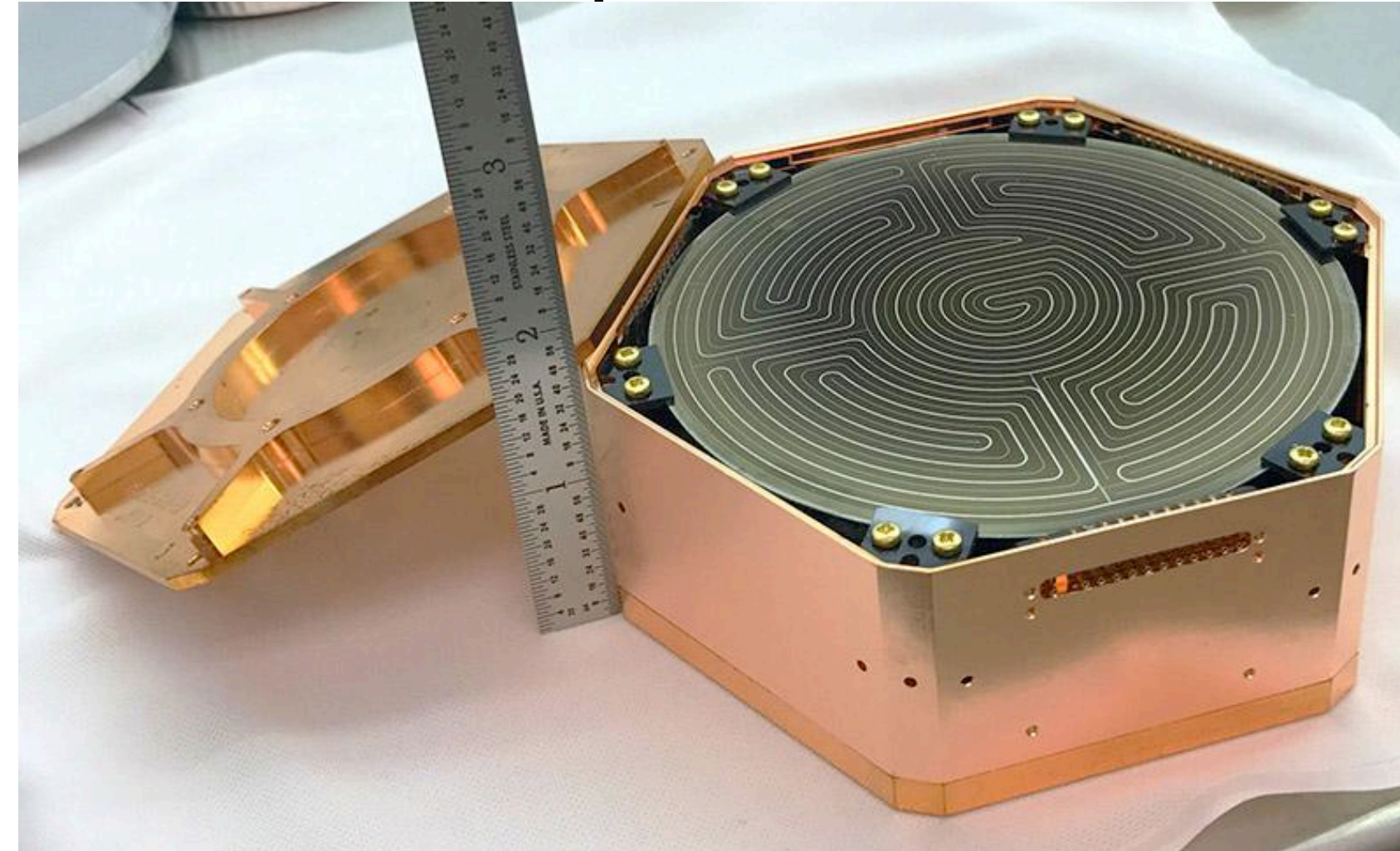


# Semiconductor-based direct detection

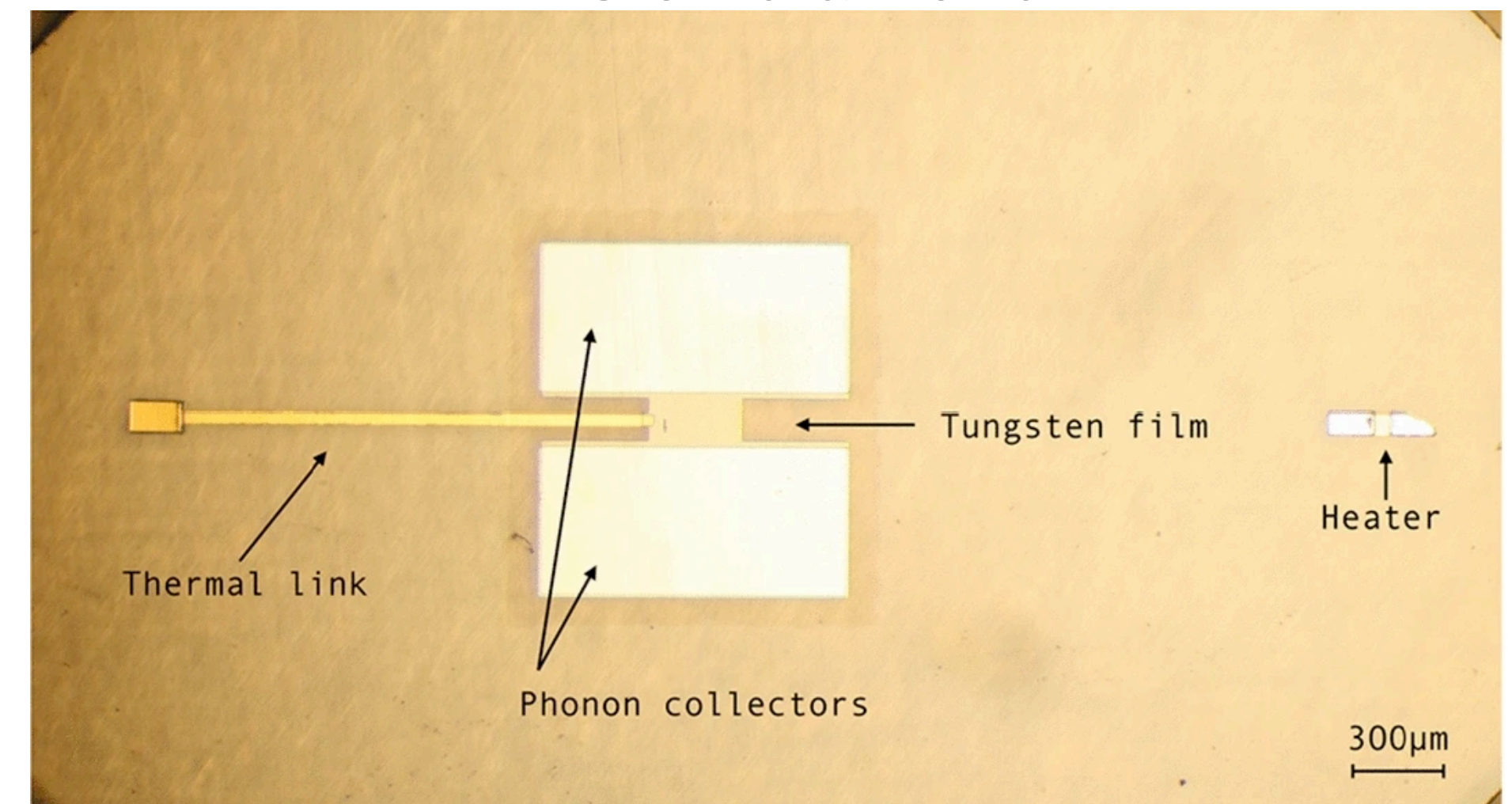
DAMIC



SuperCDMS



TES on diamond



SuperCDMS collaboration, e.g. PRL 120 061802

DAMIC collaboration, e.g. PRL 125 241803

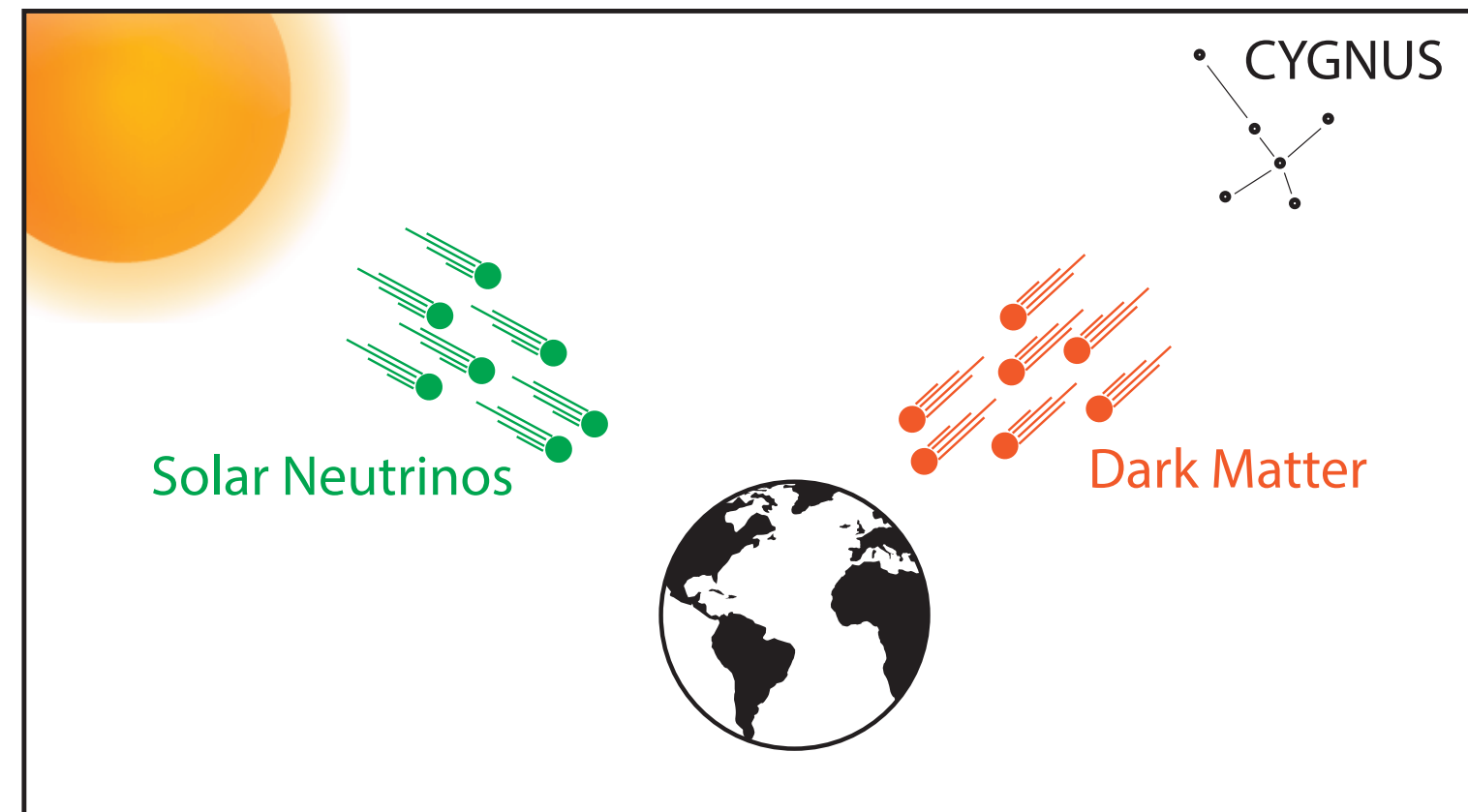
Diamond: Kurinsky et al, Phys. Rev. D 99, 123005

Diamond: Canonica et al, J. Low Temp. Phys. 199 606-613



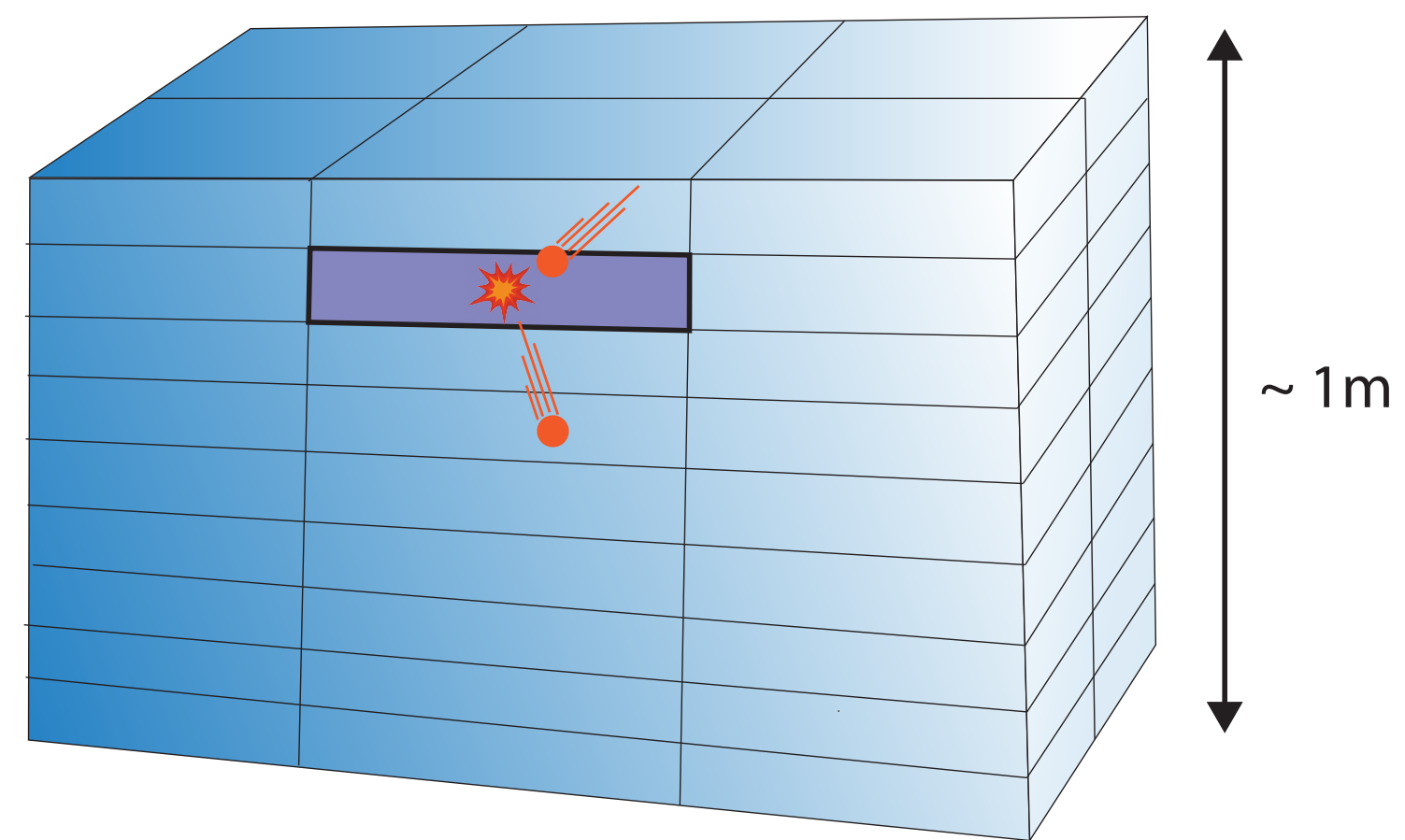
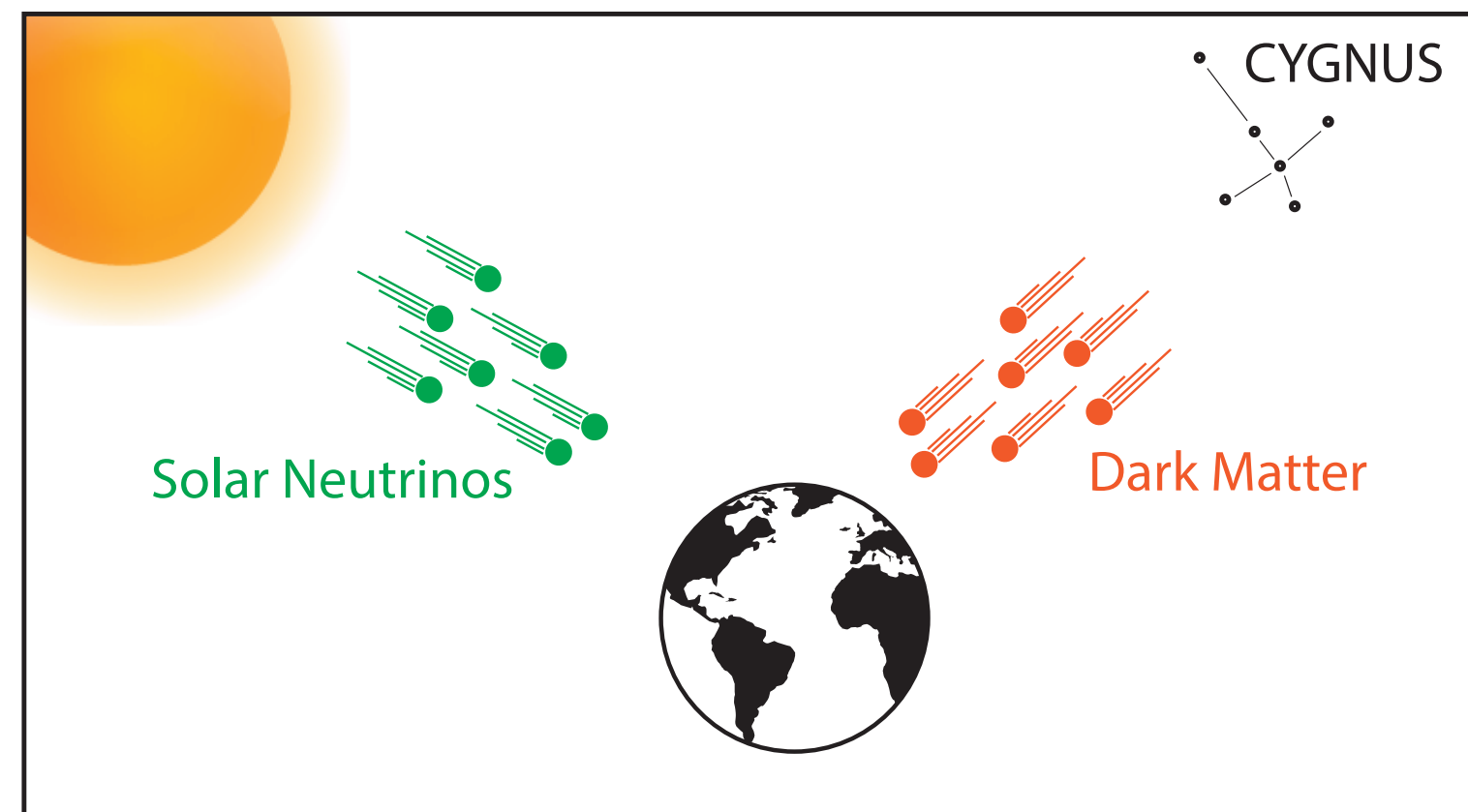
# Directional detection in diamond

Directional information allows discrimination of neutrinos and WIMPs



# Directional detection in diamond

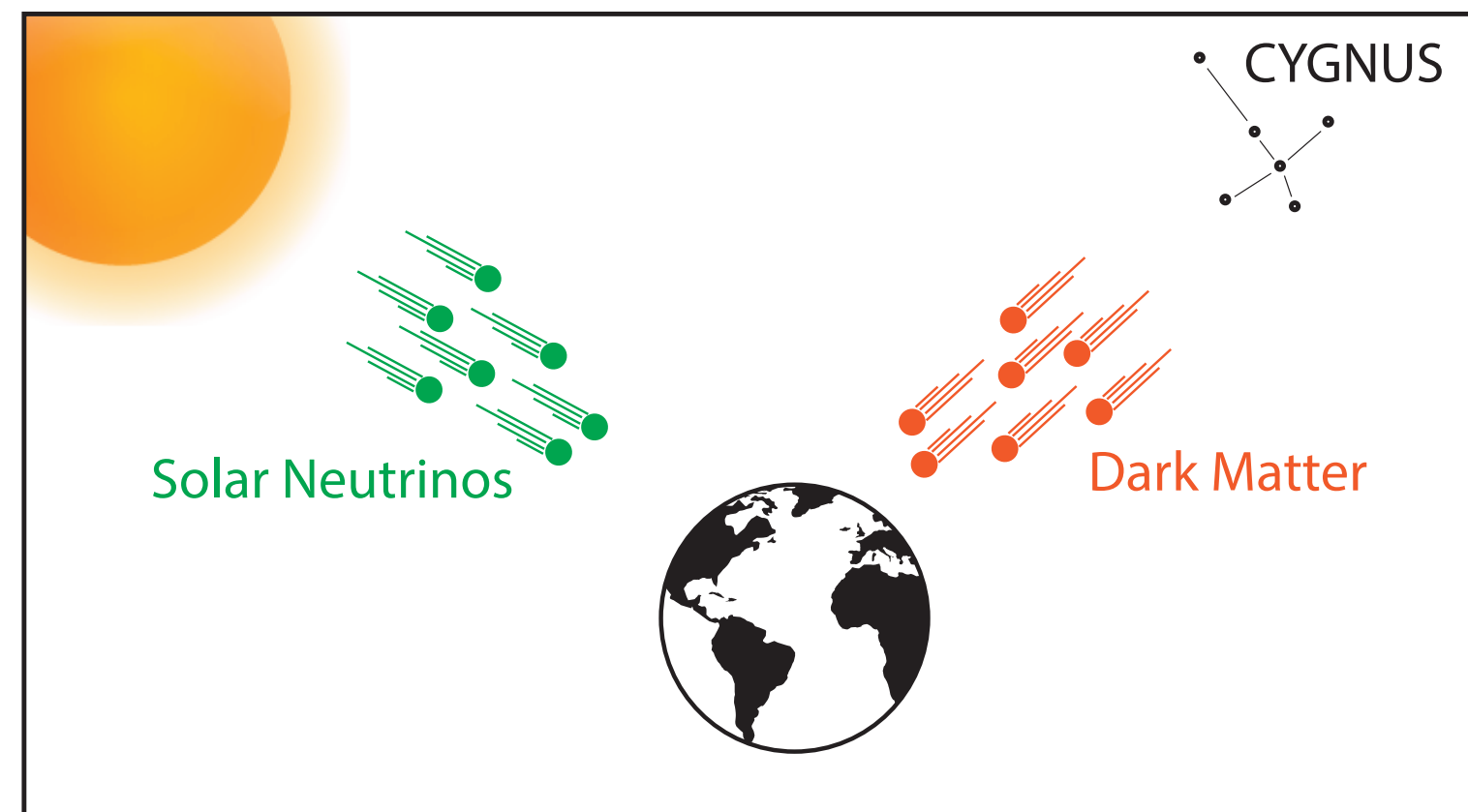
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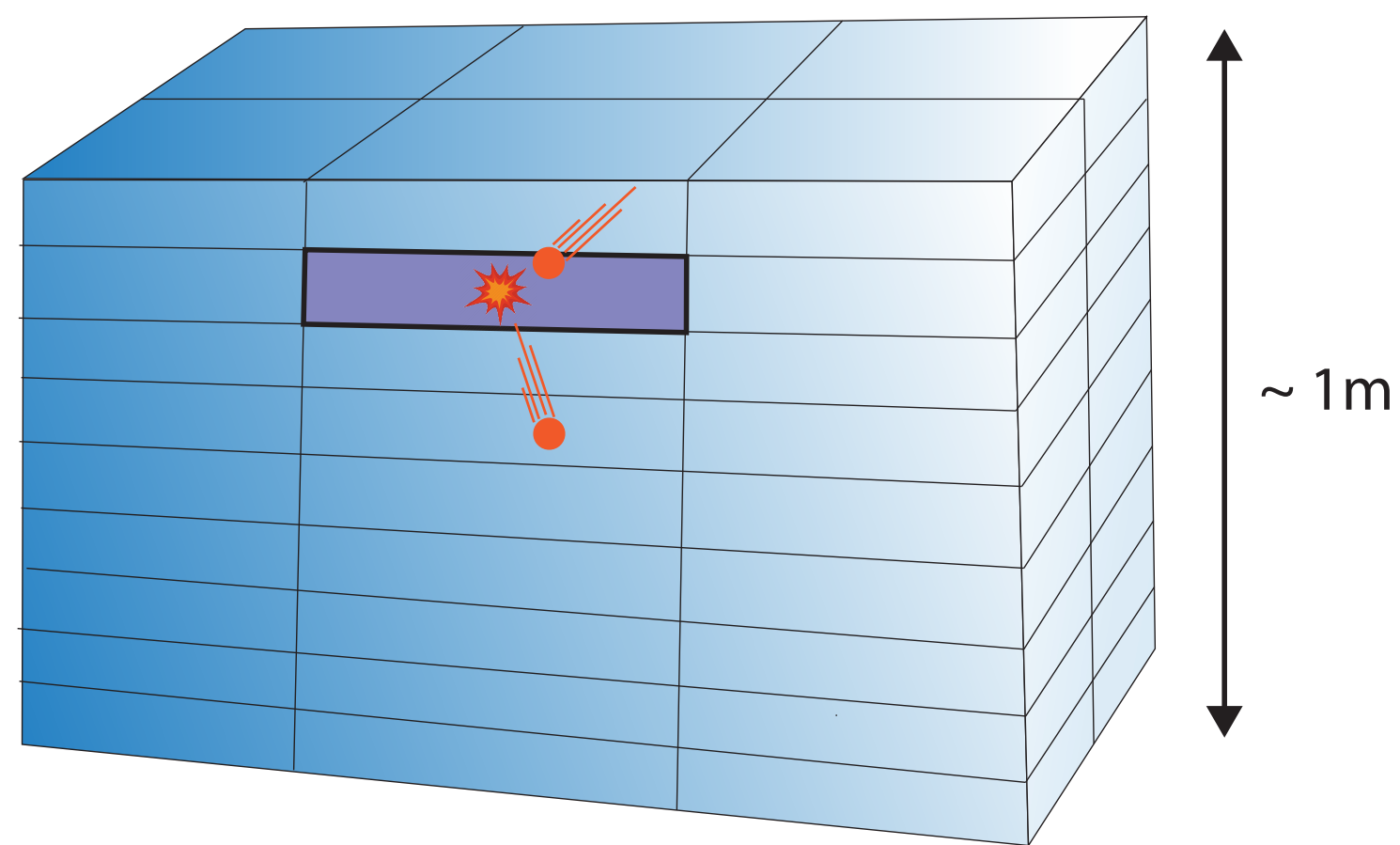
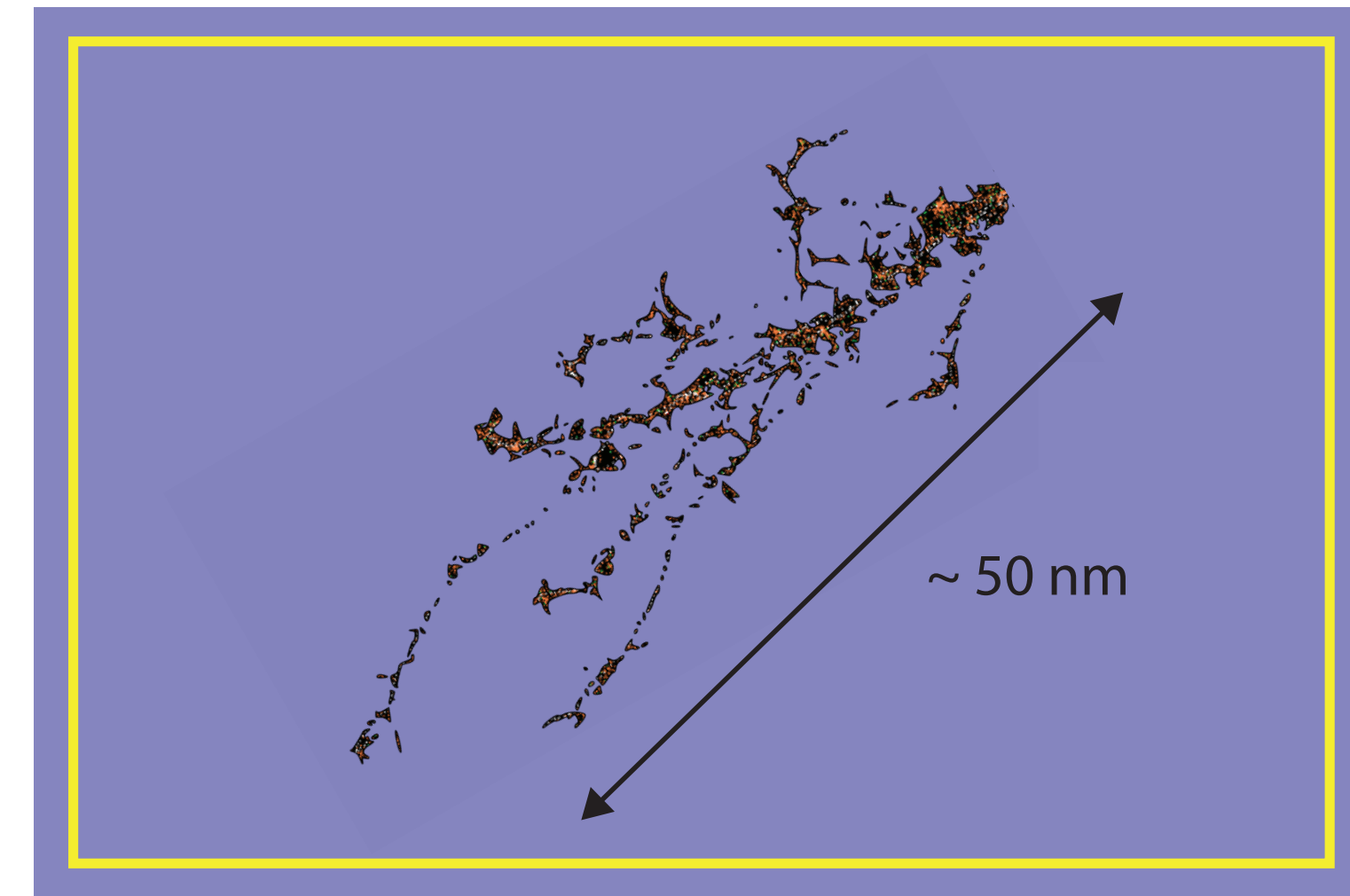
A diamond detector would consist of an array of lab-grown, instrumented diamond chips

# Directional detection in diamond

Directional information allows discrimination of neutrinos and WIMPs



In diamond or another crystalline target, a WIMP event would induce many secondary recoils, leaving a "track" of crystal damage

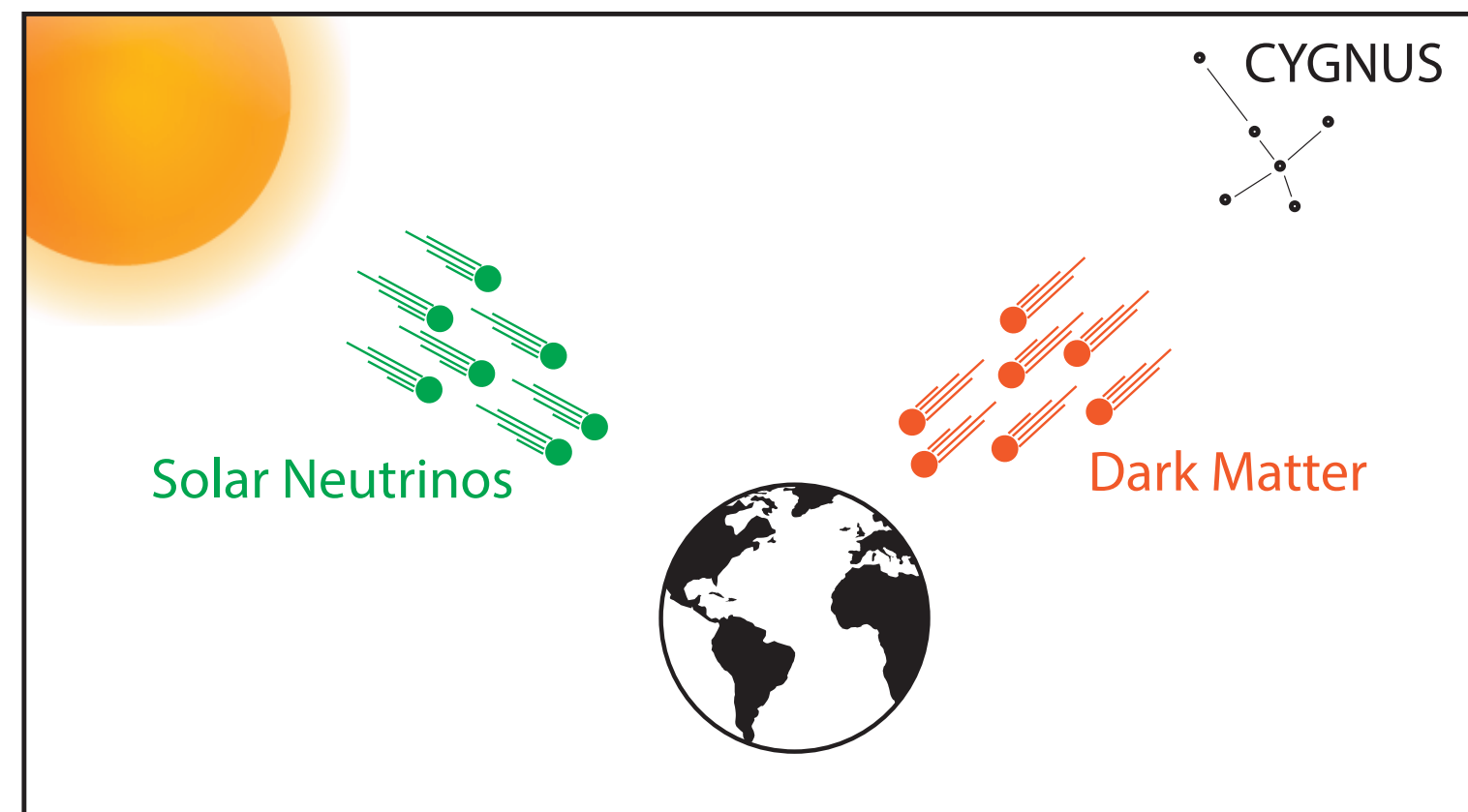


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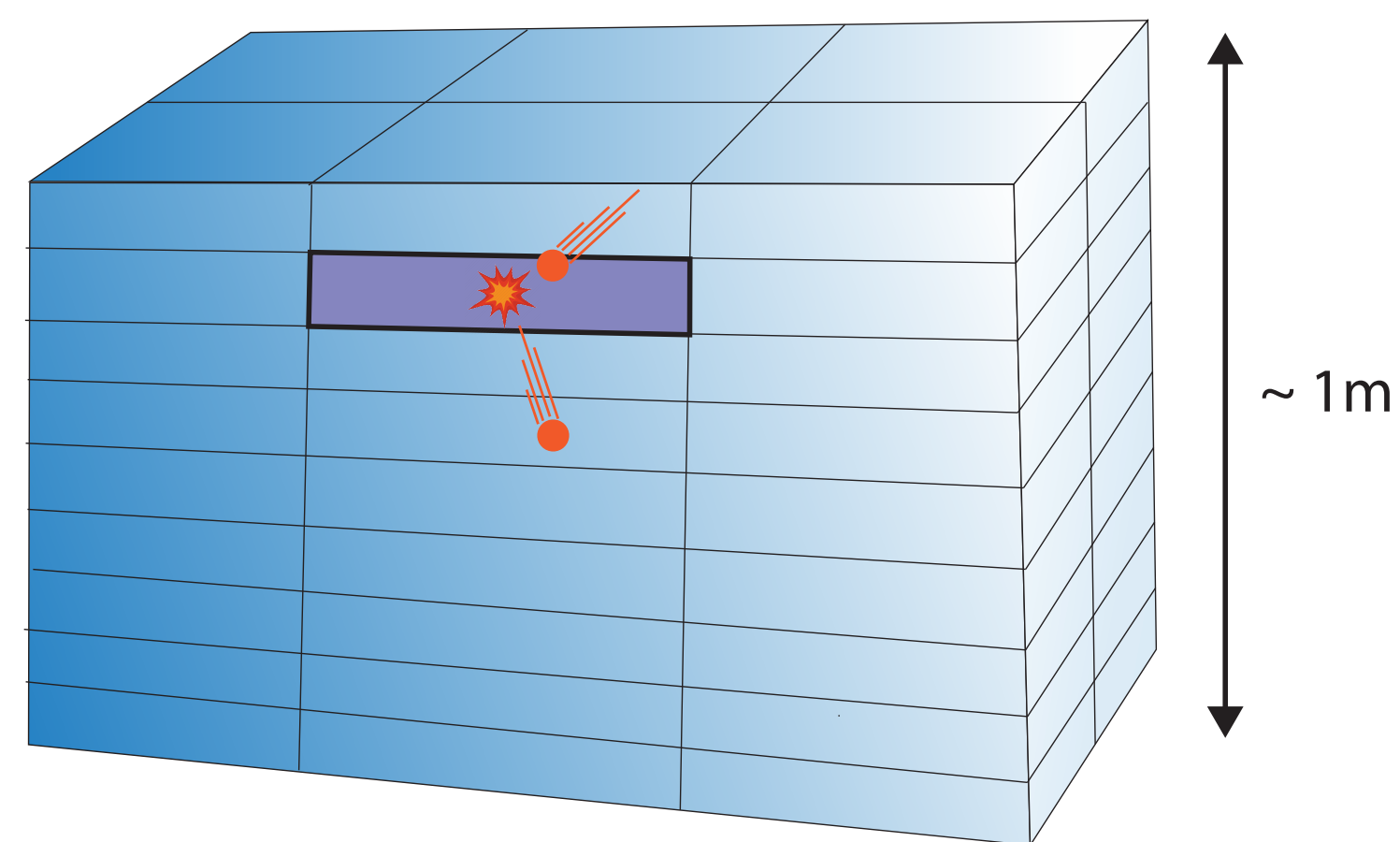
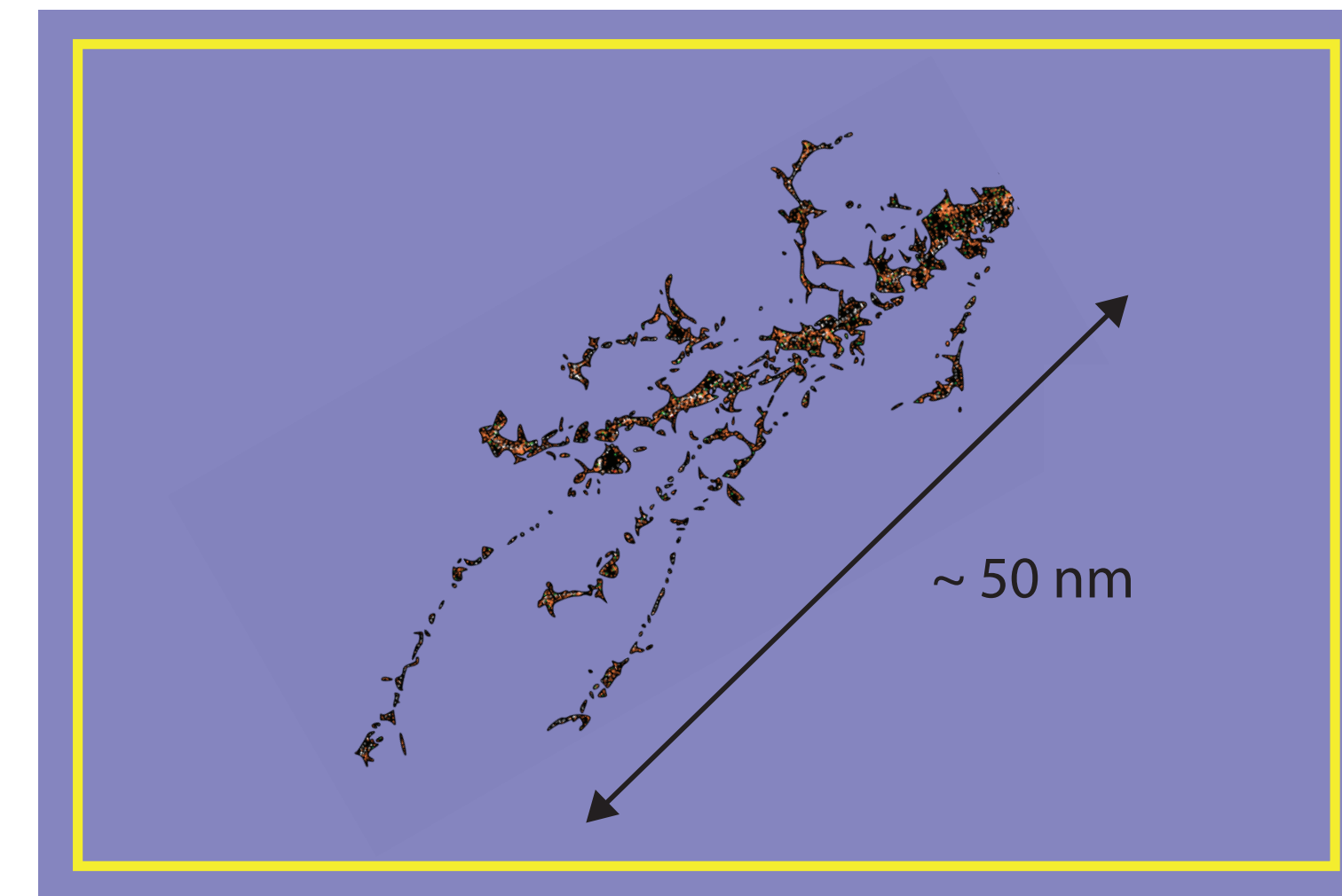


# Directional detection in diamond

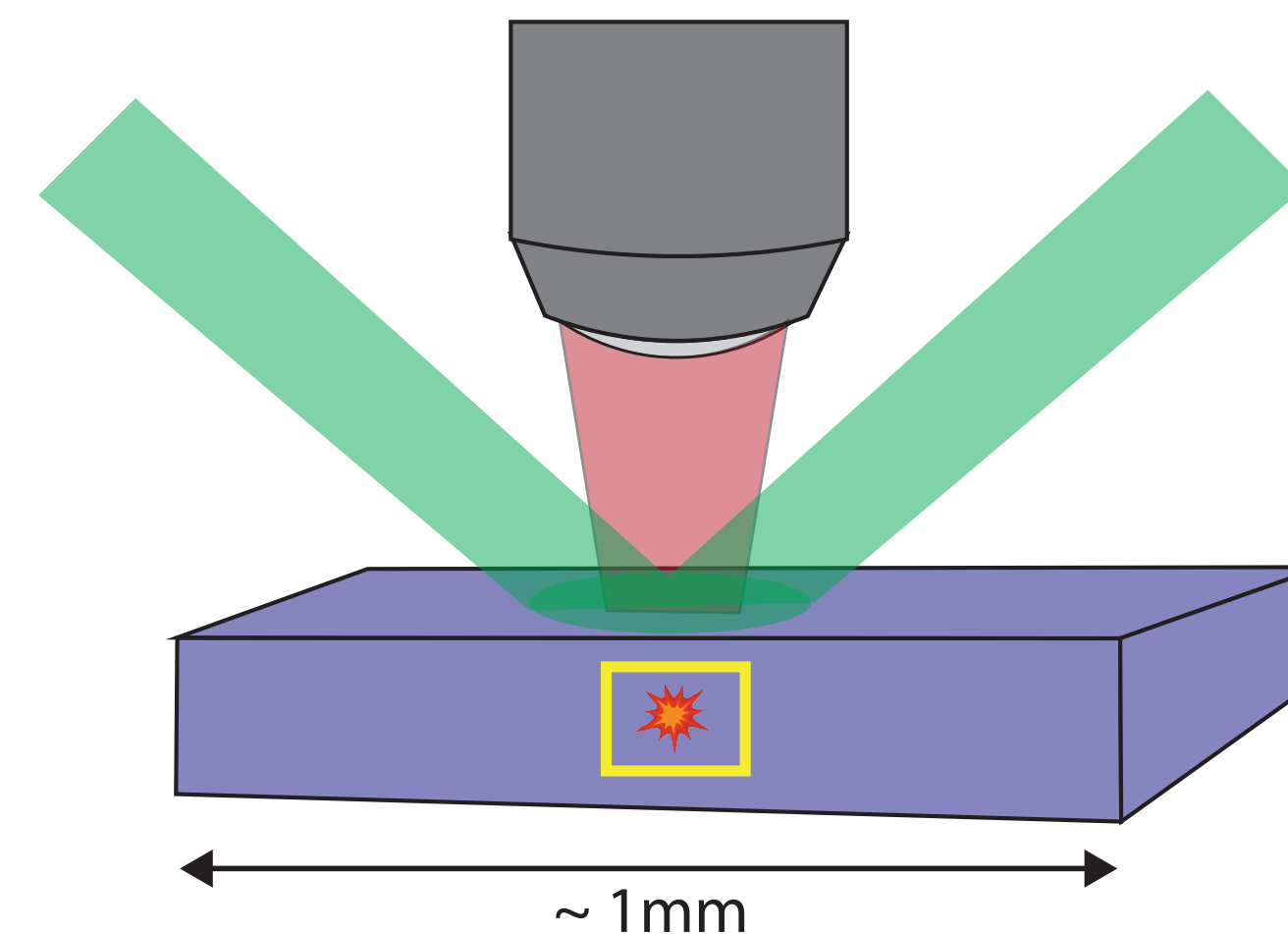
Directional information allows discrimination of neutrinos and WIMPs



In diamond or another crystalline target, a WIMP event would induce many secondary recoils, leaving a “track” of crystal damage



A diamond detector would consist of an array of lab-grown, instrumented diamond chips



After an event is detected in a chip, that chip would be removed; the damage track located; and the direction read out.

# Directional detection in diamond

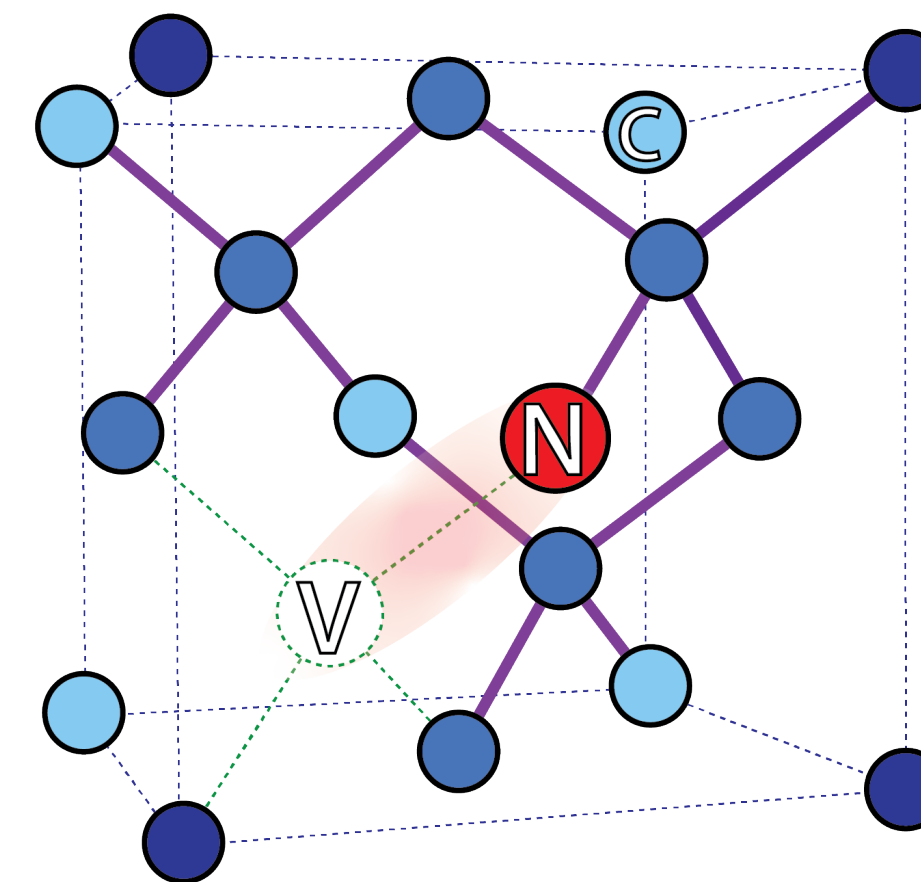
**STEP I:** Event detection and localization at the **mm scale** using charge, phonon, or photon collection. The event time is recorded to determine the absolute orientation of the specific mm-scale chip in which the event occurred.

**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.

# Nitrogen vacancy centers as quantum crystal-damage sensors

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

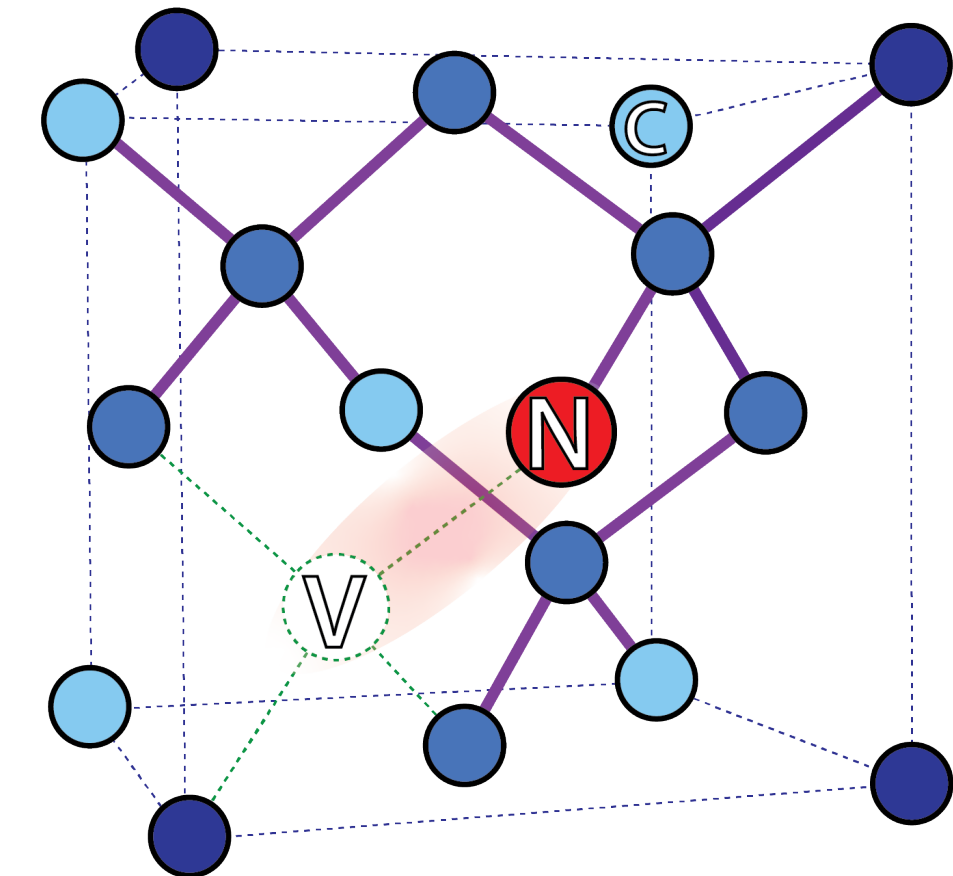
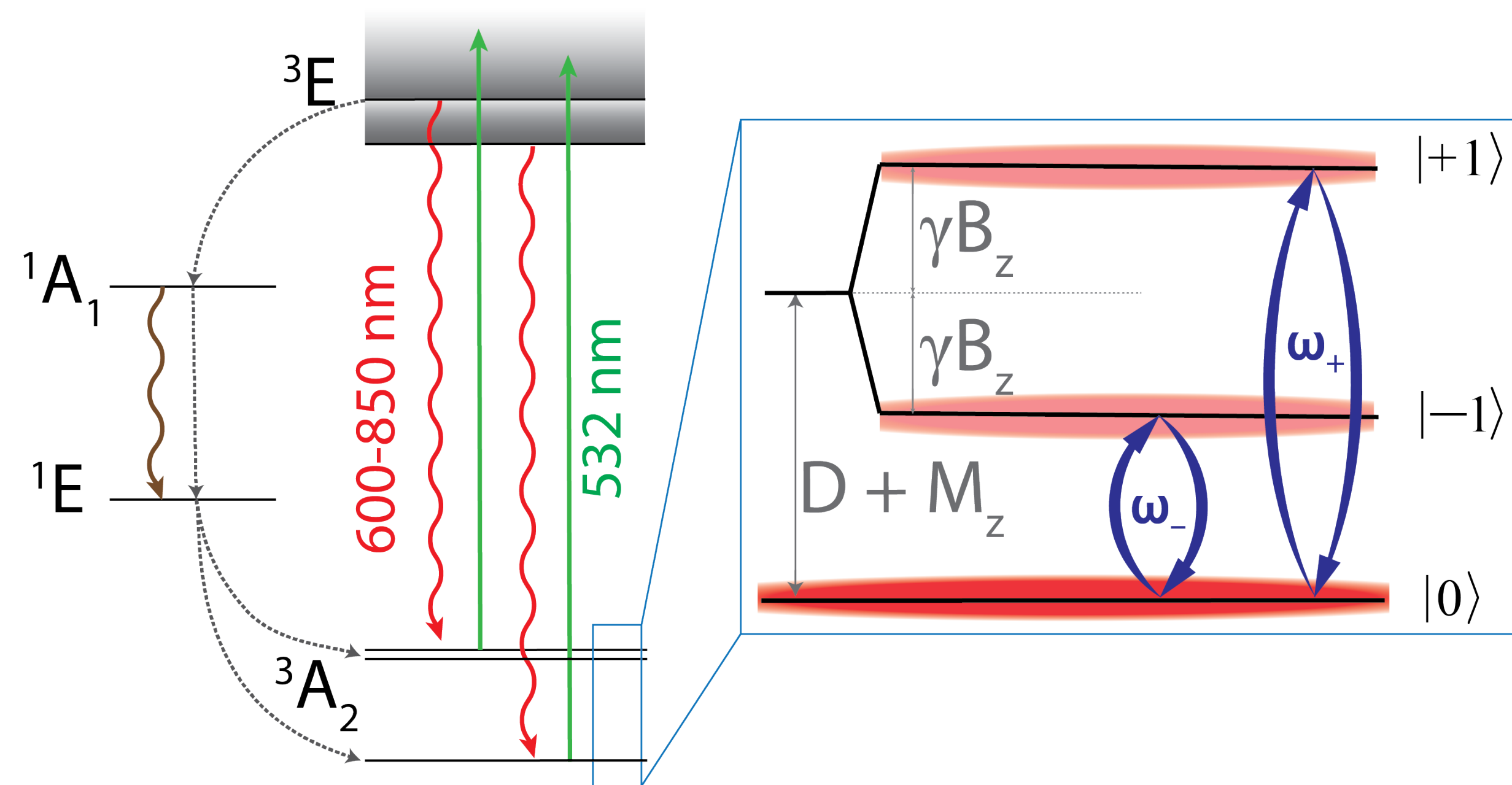


Simplified ground state spin Hamiltonian

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

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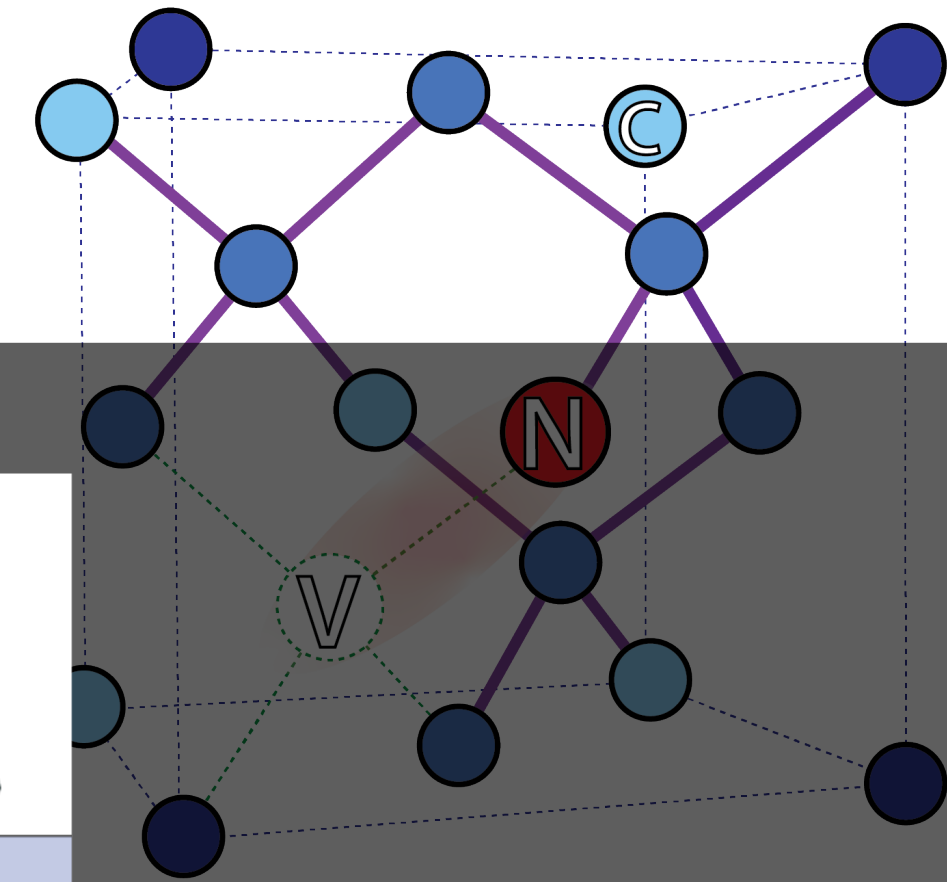
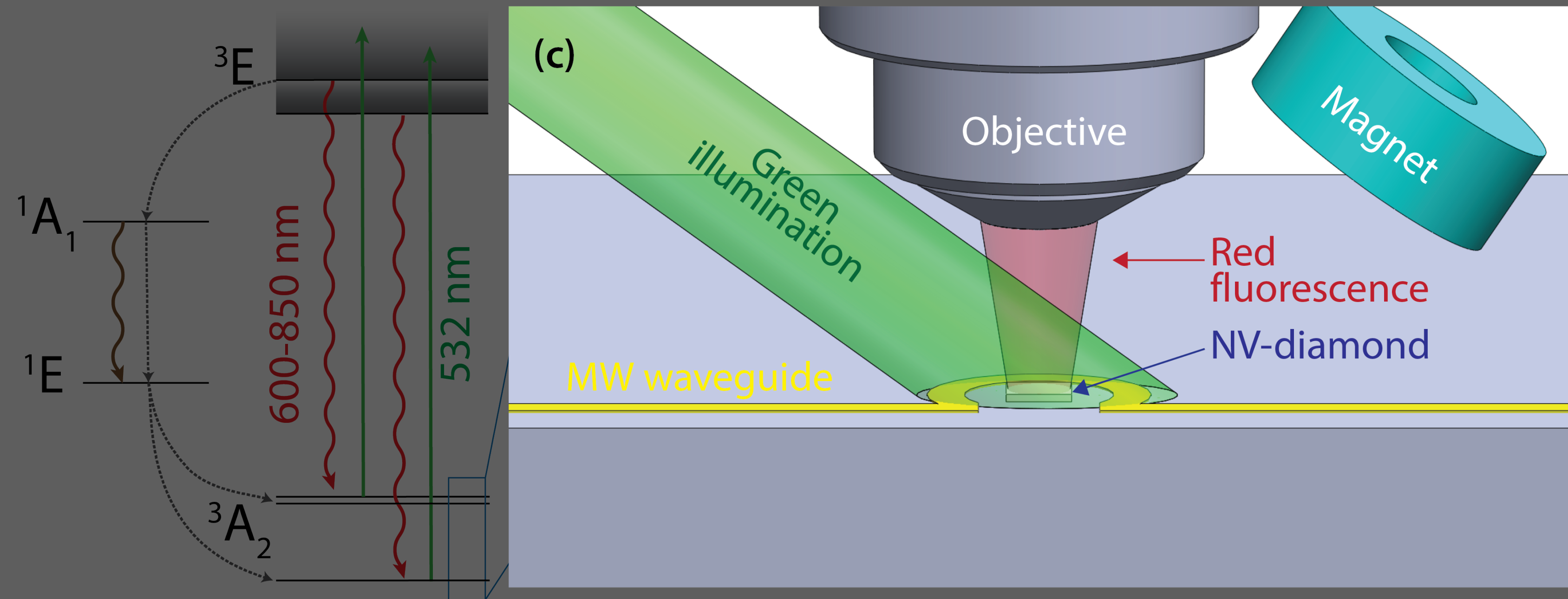
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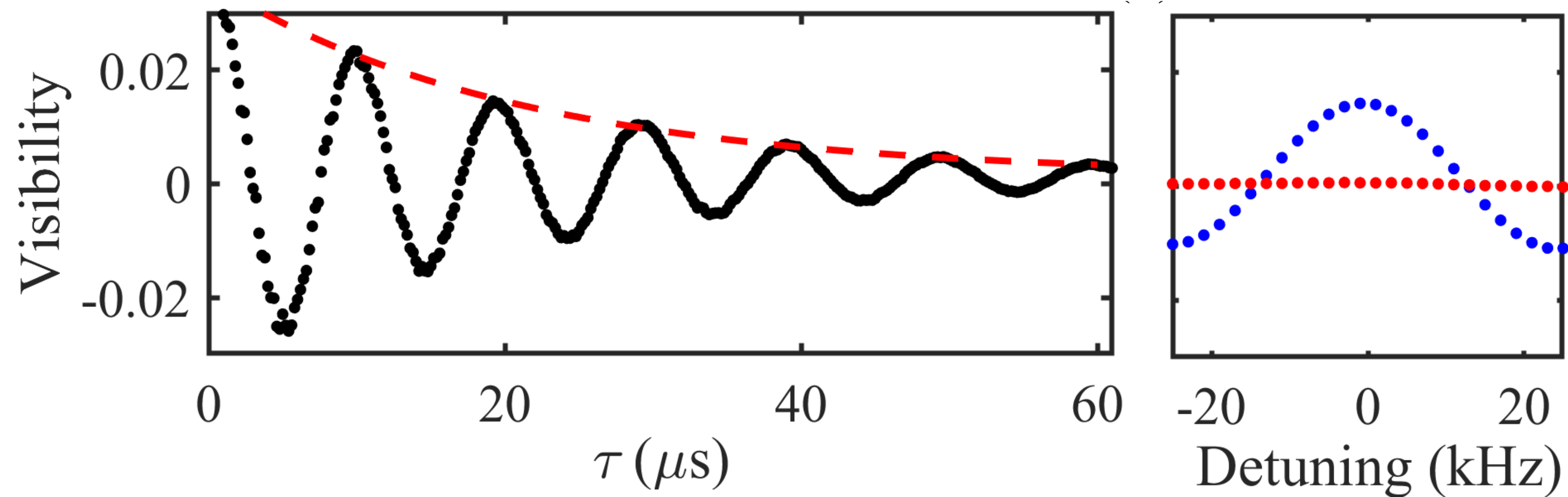
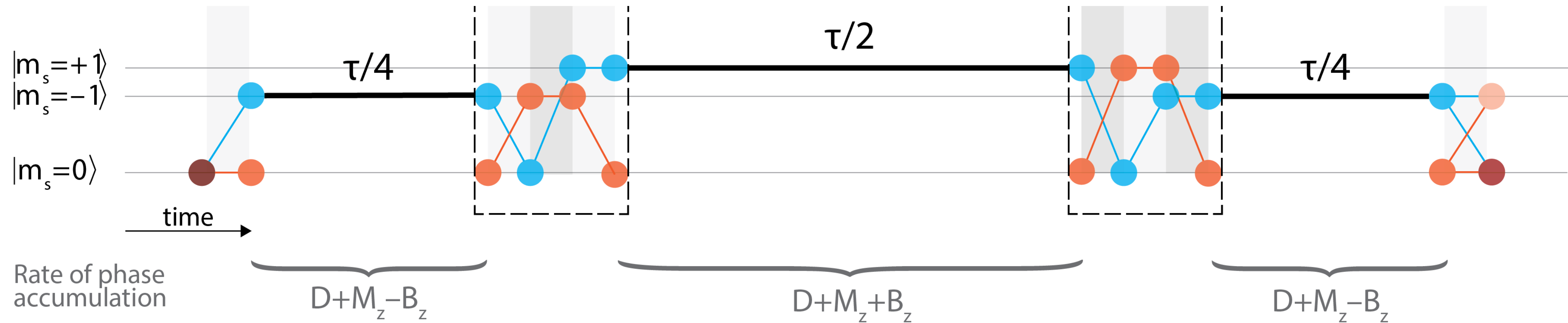
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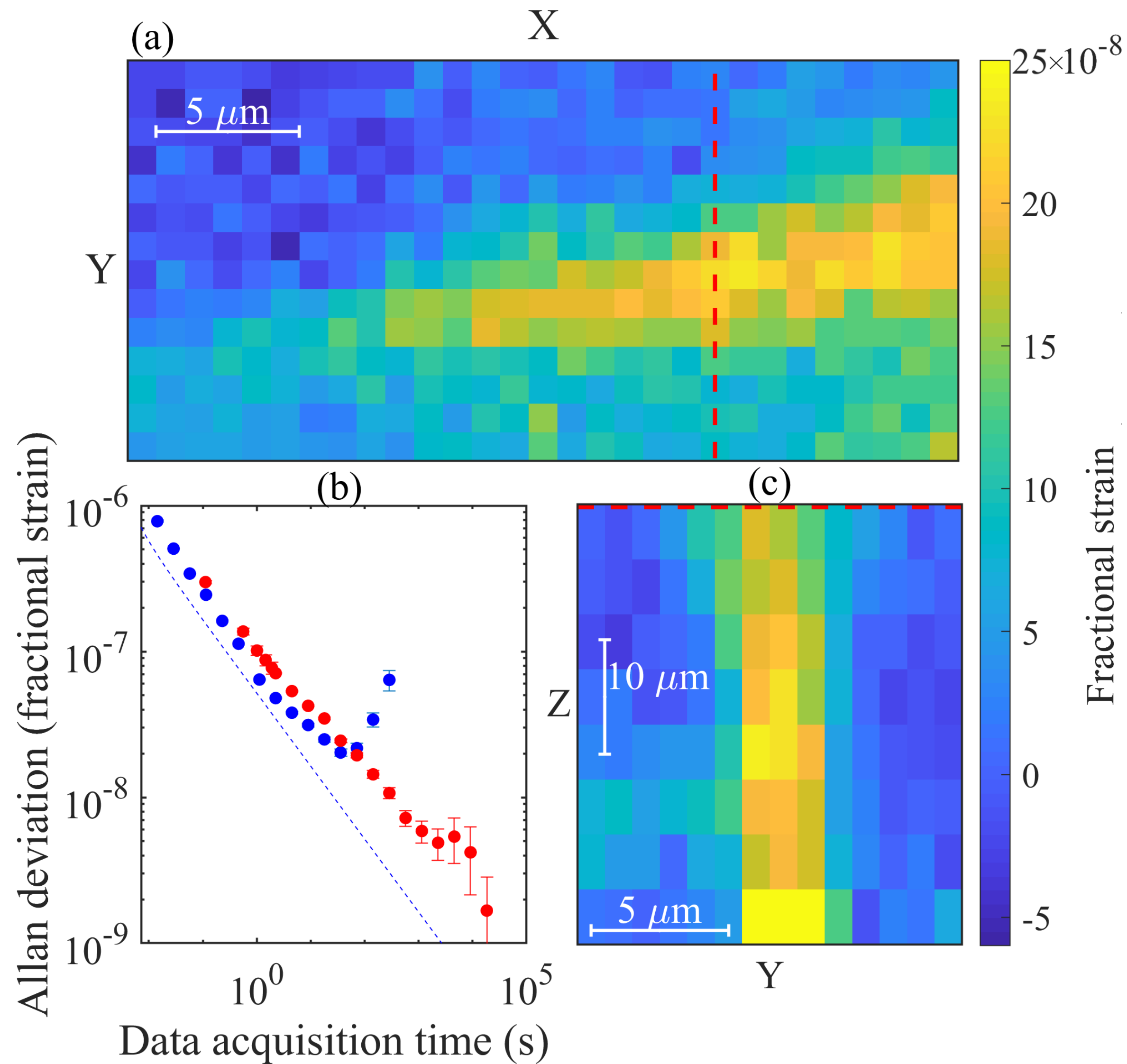
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# Strain-CPMG: spin-1 enhanced strain sensing



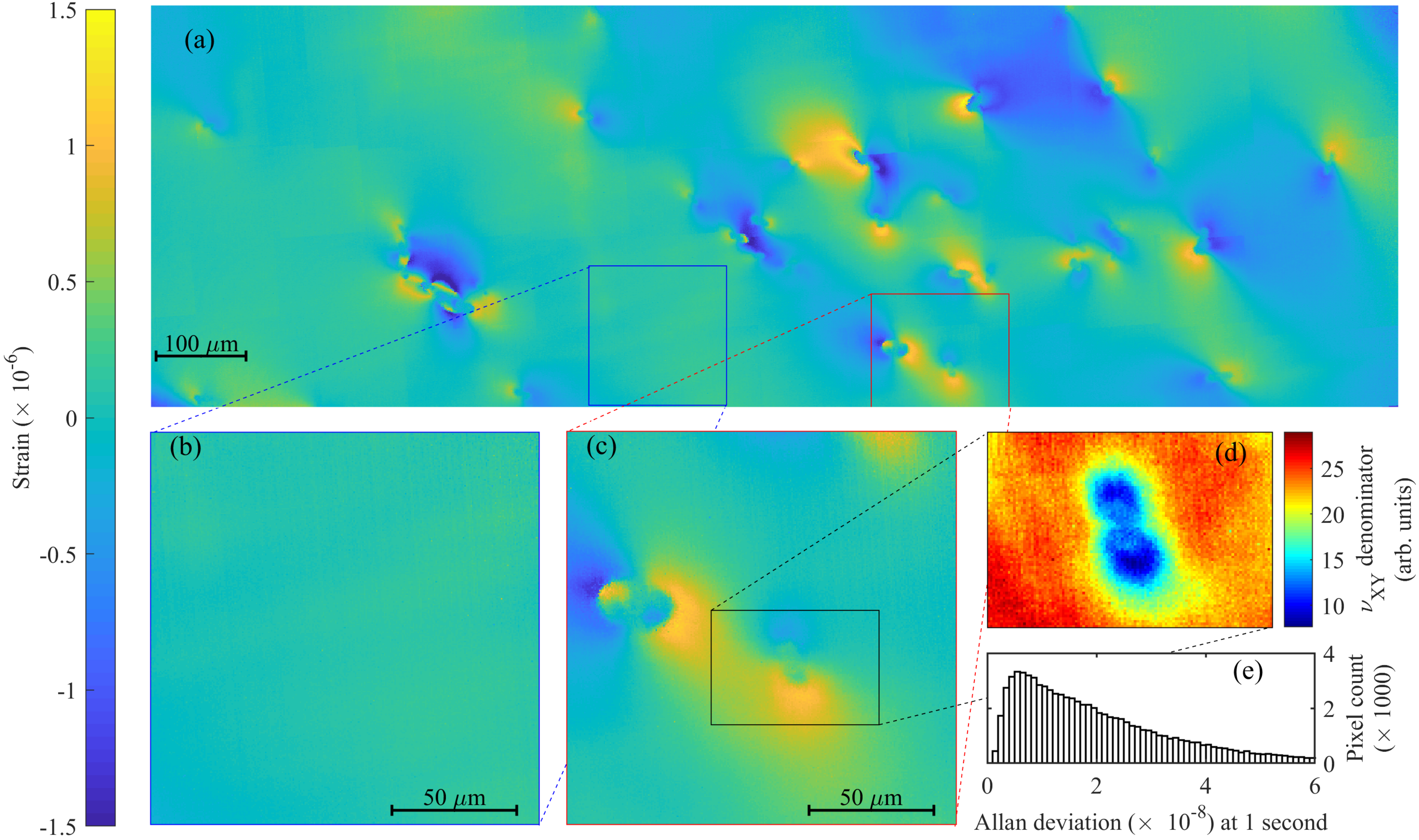
# Strain-CPMG results: sensitivity



$$5 \times 10^{-8} \frac{1}{\sqrt{\text{Hz} \cdot \mu\text{m}^3}}$$



# Strain-CPMG results: fast, widefield strain imaging





# Directional detection in diamond

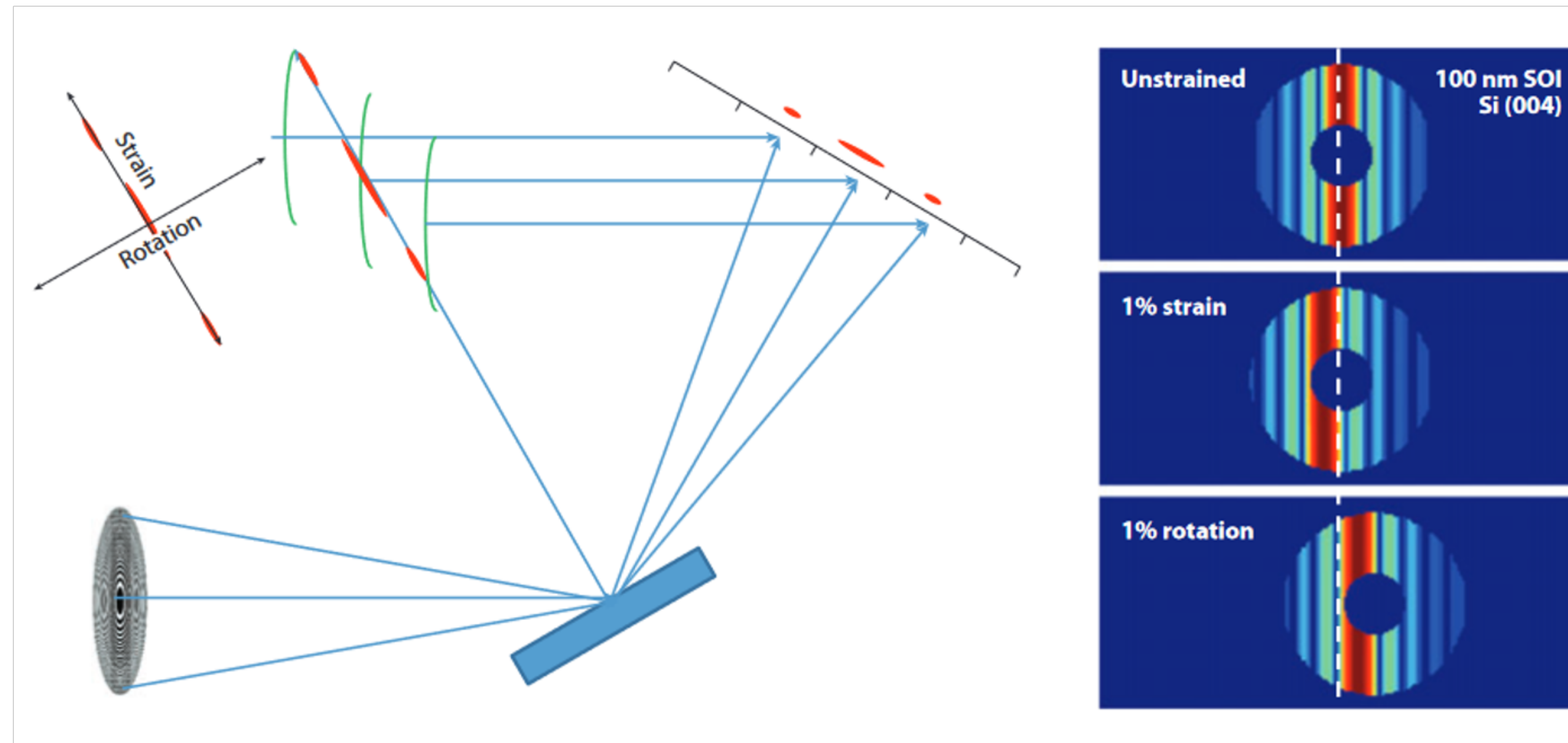
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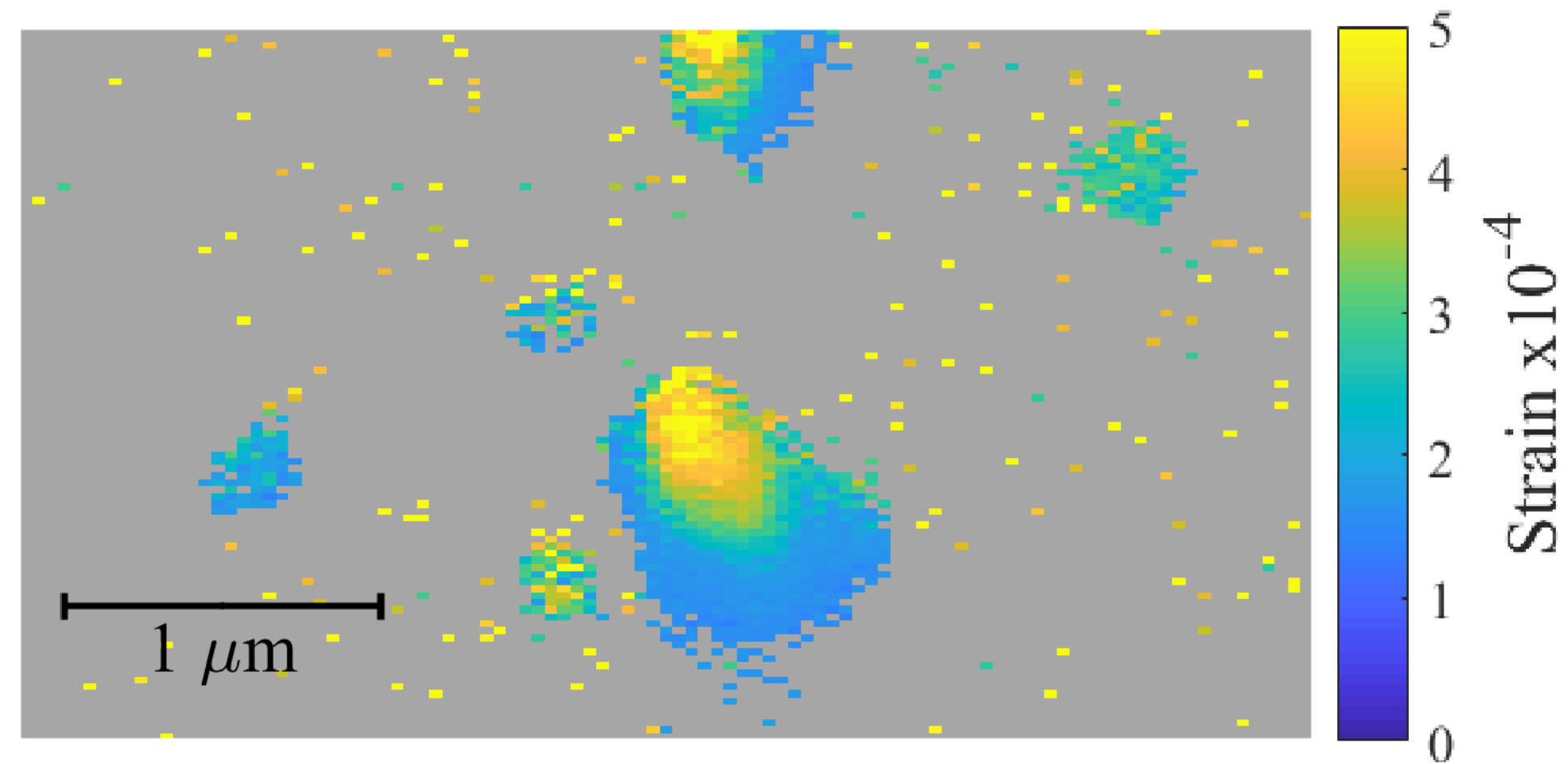
# Nanoscale track mapping with X-ray microscopy



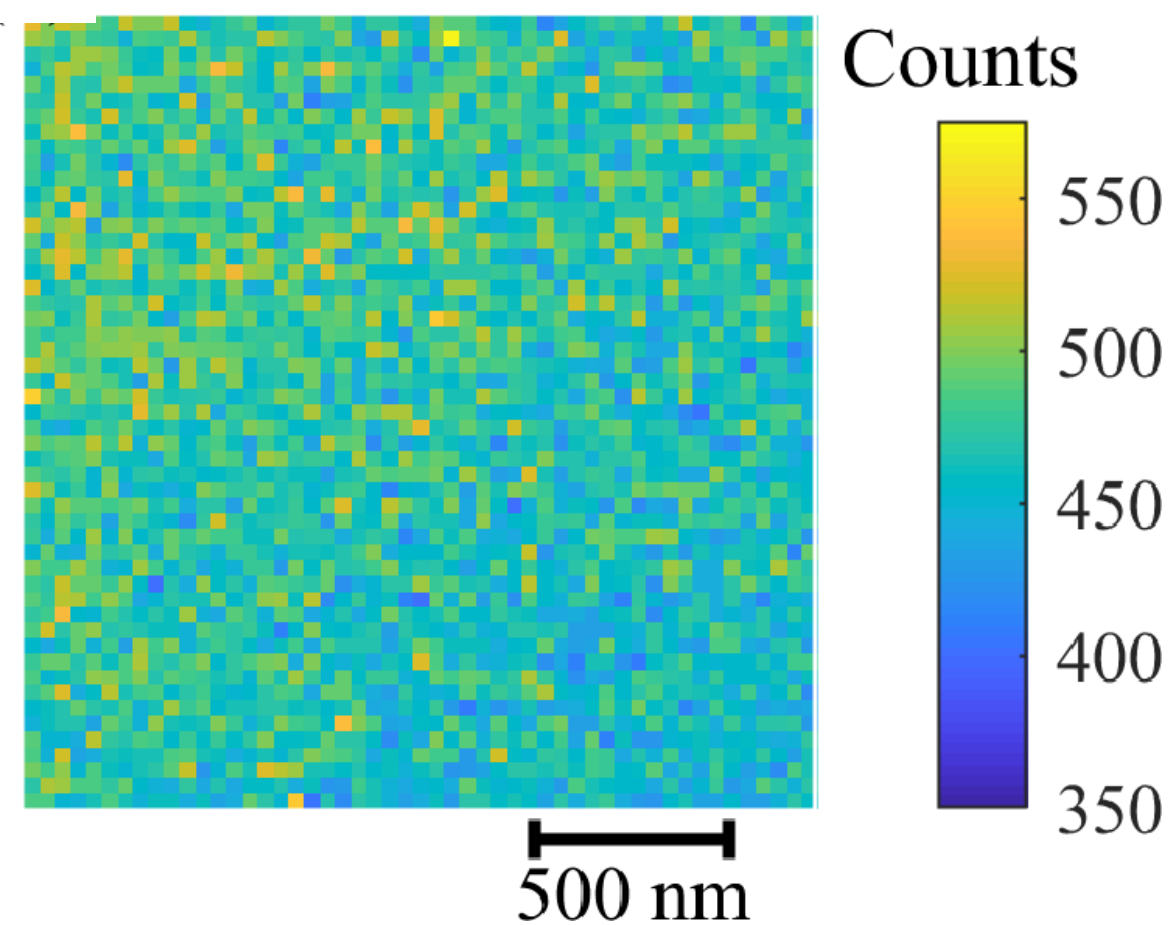
Holt et al., Annu. Rev. Mat. Res. 48:183-211

# X-ray microscopy performance

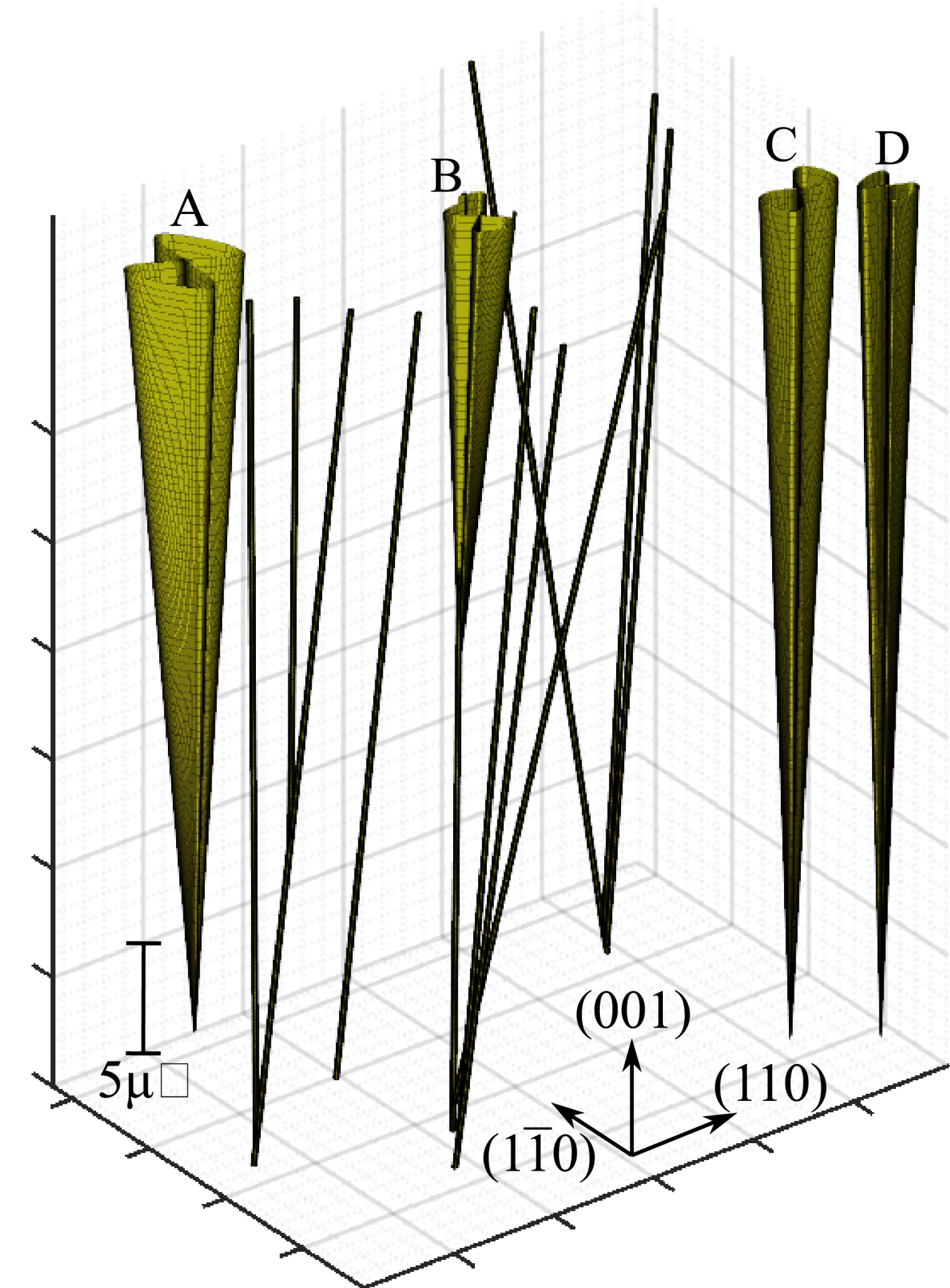
Sub-micron strain features are resolved



No observed backgrounds



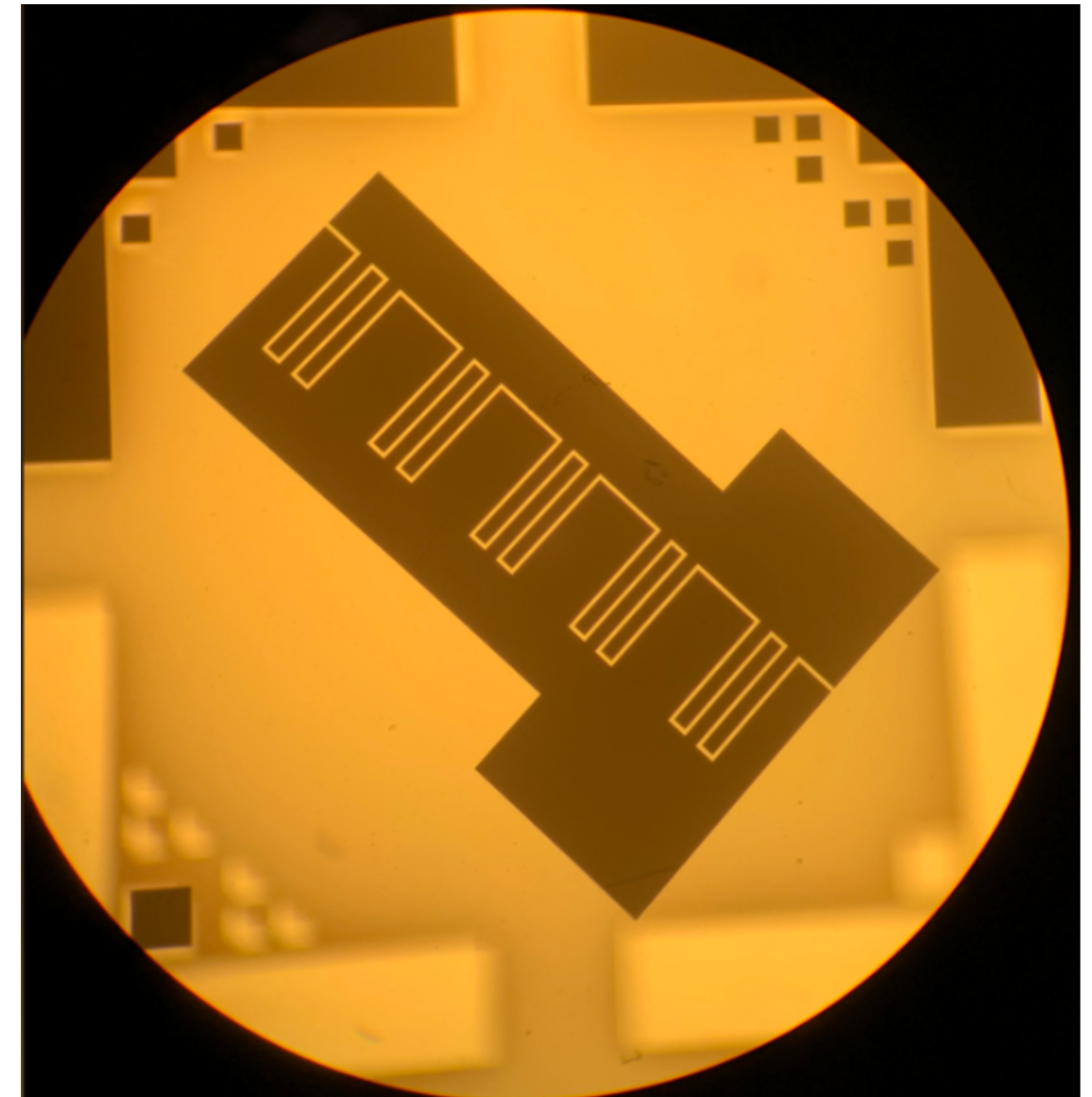
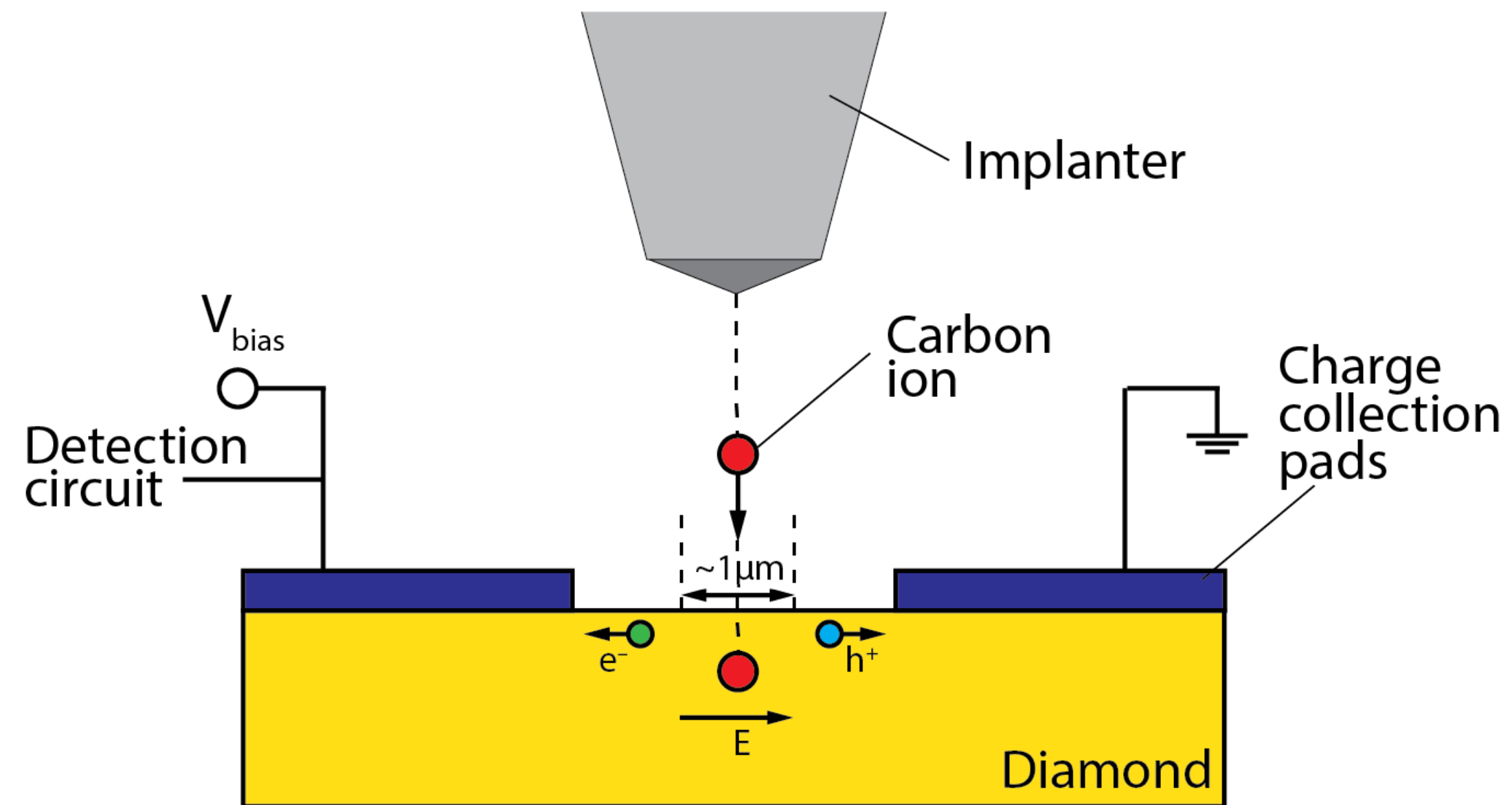
Three dimensional reconstruction





# Towards detecting injected signals

Deterministic single-ion implantation:  
Collect charges released by ion implantation between two gold pads



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



**JHU**



Surjeet Rajendran

**Dark matter team**



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(now at NIST)



David Phillips  
(now at MIT Lincoln  
Labs)



Daniel Ang



Aakash Ravi  
(now at Q-Cat)

**PI**



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**ANL**

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Nazar Deegan

**Sandia**

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Pauli Kehayias  
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**WPI**

Raisa Trubko

**BU**

Alex Sushkov

**Walsworth group collaborators**



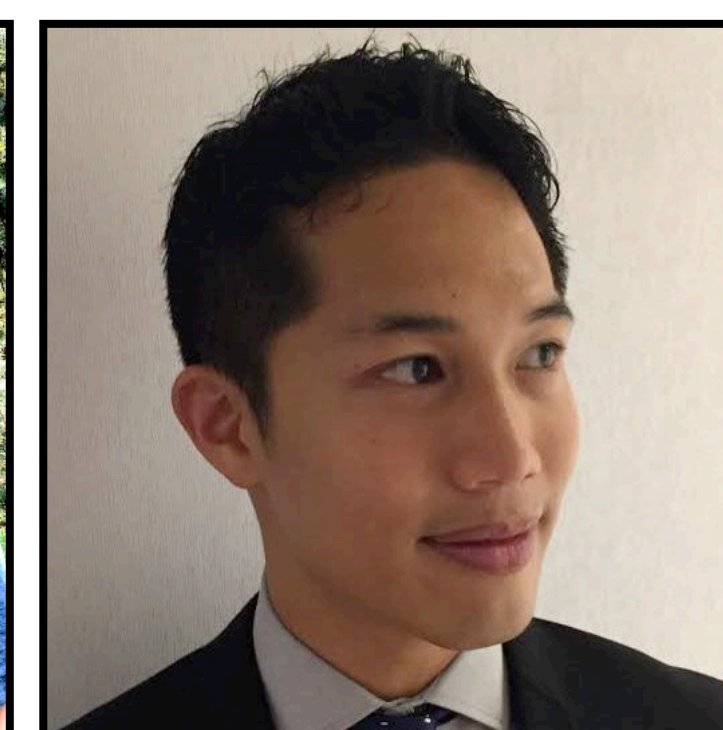
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Connor Hart



Matthew Turner  
(now at Booz Allen  
Hamilton)



Mark Ku  
(now at UDel)