Toward Directional Detection of Dark Matter Using Spectroscopy of Quantum Defects in Diamond

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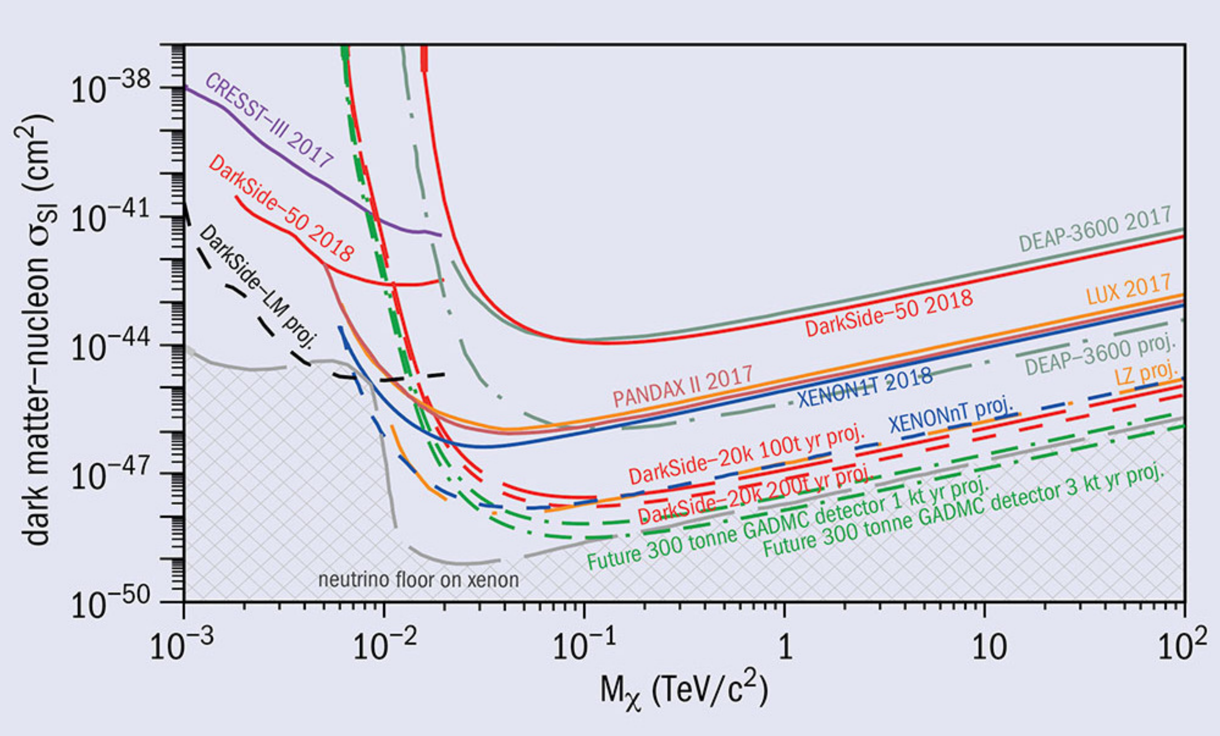
Diamond as a dark matter detector

- Solid-state density, semiconductor
- Low nuclear mass
- High sensitivity with scintillation, charge, or phonon collection

Kurinsky et al, Phys. Rev. D **99**, 123005

Long-term goal – direct detection below neutrino floor



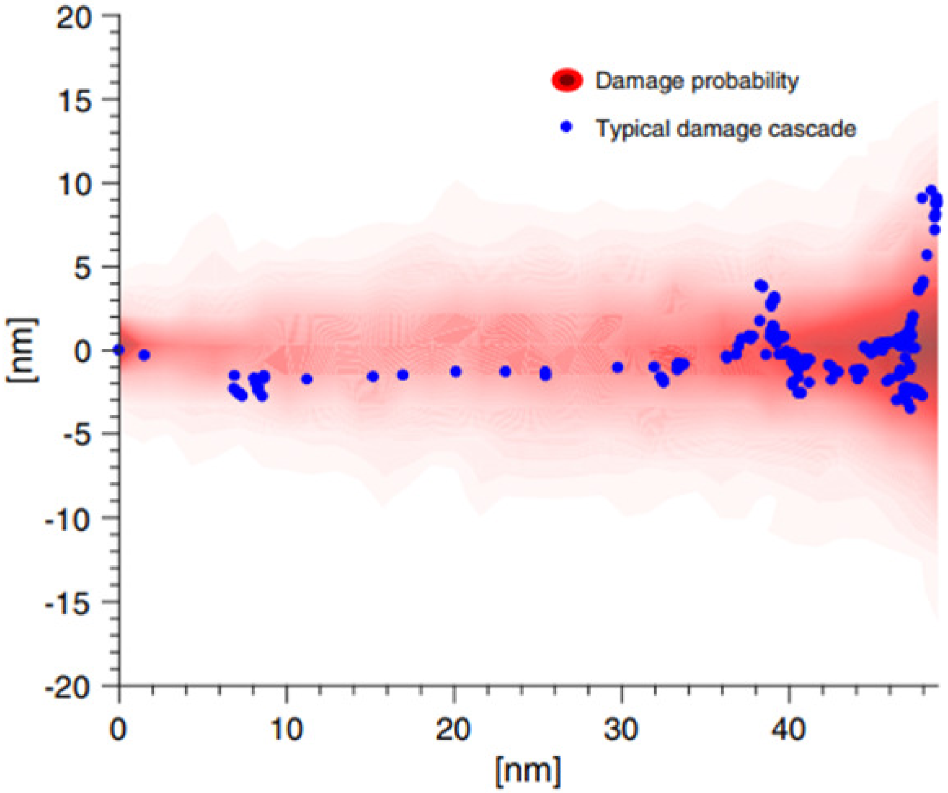
Cerncourier.com (2018)

Diamond as a *directional* dark matter detector

- Nuclear recoil creates charge, phonons, etc – plus damage to crystal lattice
- Damage track records direction
- Can be read out with spectroscopy of quantum defects

Detection principle

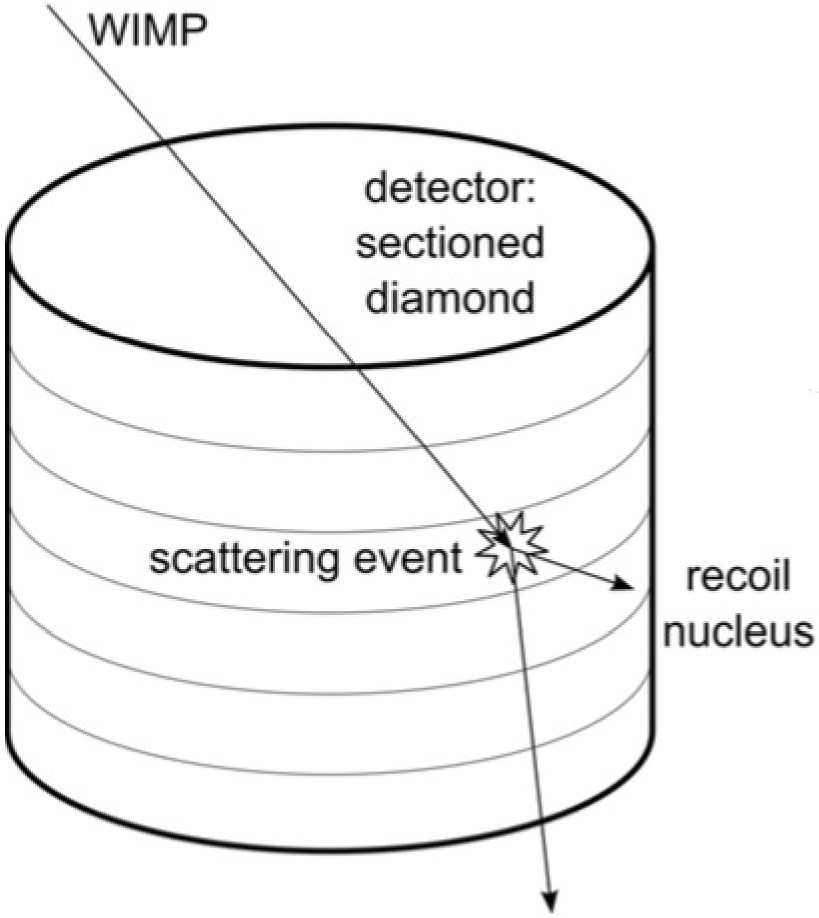
- Nuclear recoil – several keV C nucleus
- Initial nucleus cascades into others
- Asymmetric, oriented damage in crystal lattice



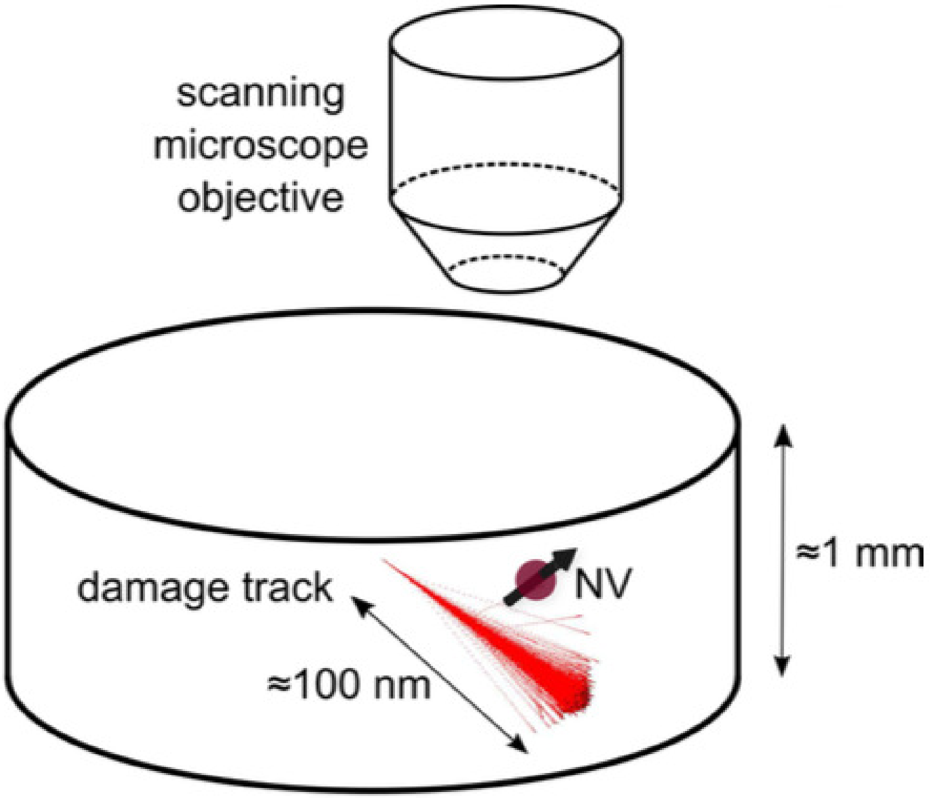
Rajendran et al, Phys. Rev. D **96**, 035009

Detection principle

- Detector: large array of CVD single-crystal diamonds
- Three length scales:
    - “detector scale”
    - “microscopy scale”
    - “atomic scale”
- “detector scale:”
    - Initial localization using scintillation, charge, etc



Detection principle



- Section with event removed from detector
- "microscopy scale": Defect spectroscopy to resolve event to ~1um
- "atomic scale": 3-D mapping to determine incident direction

Required capabilities

- High-resolution initial event localization in segmented diamond
- Micron localization of event within ~mm diamond segment
- Sub-100 nm mapping of damage tracks
- Demonstrating “low-background” diamonds
- Scaling production for a detector

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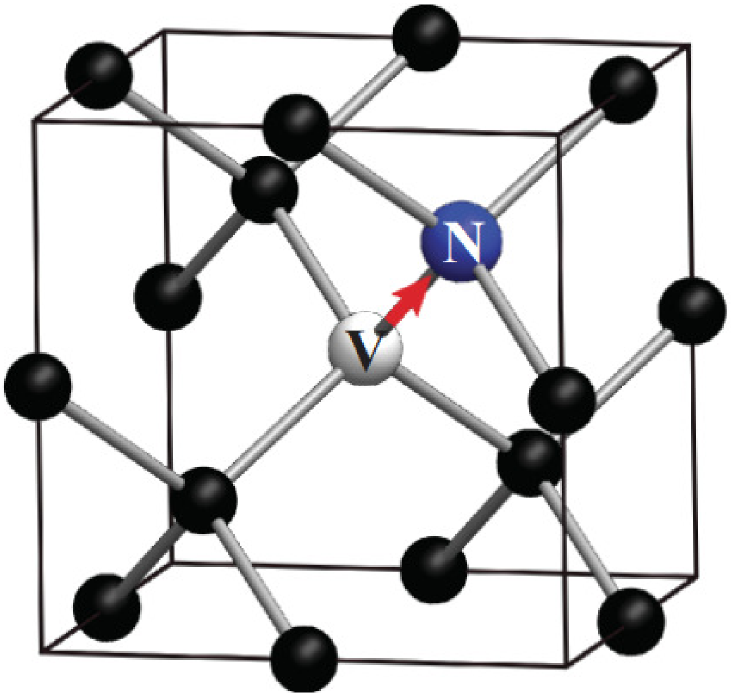
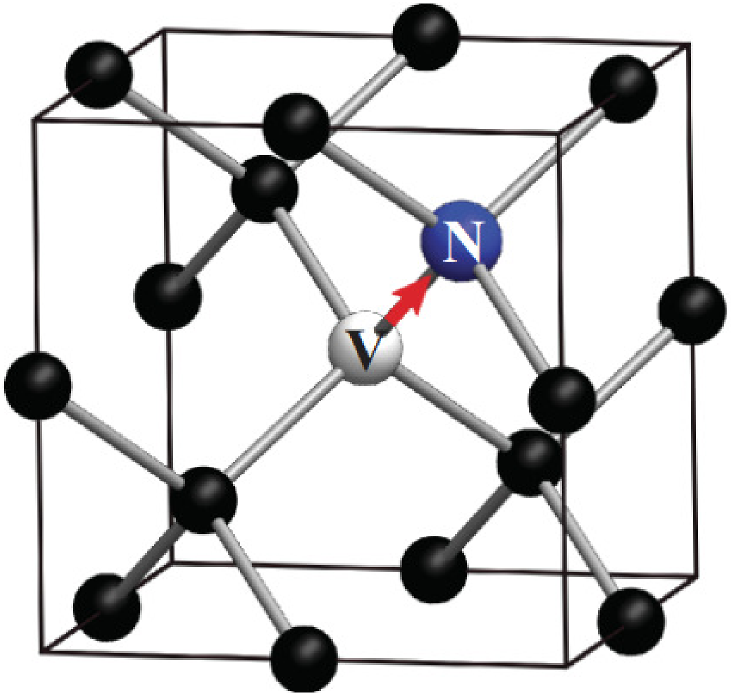
Quantum defect: nitrogen-vacancy center in diamond

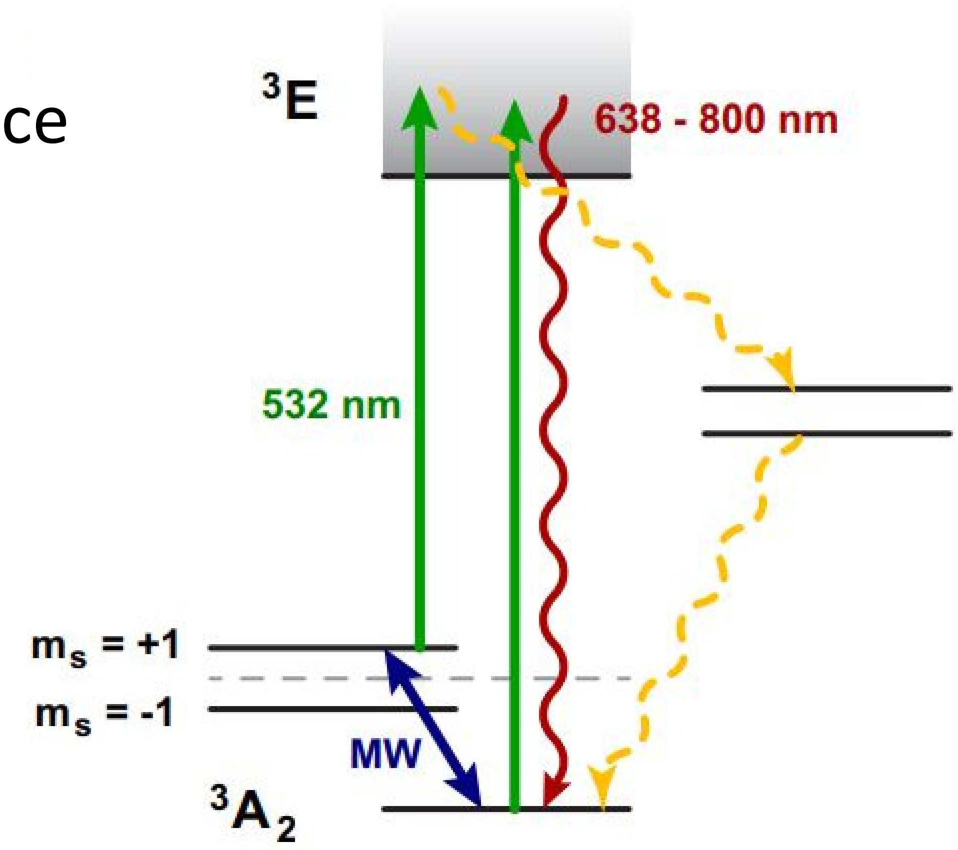
- Substitutional nitrogen and adjacent vacancy
- Electronic spin-1 system



Quantum defect: nitrogen-vacancy center in diamond

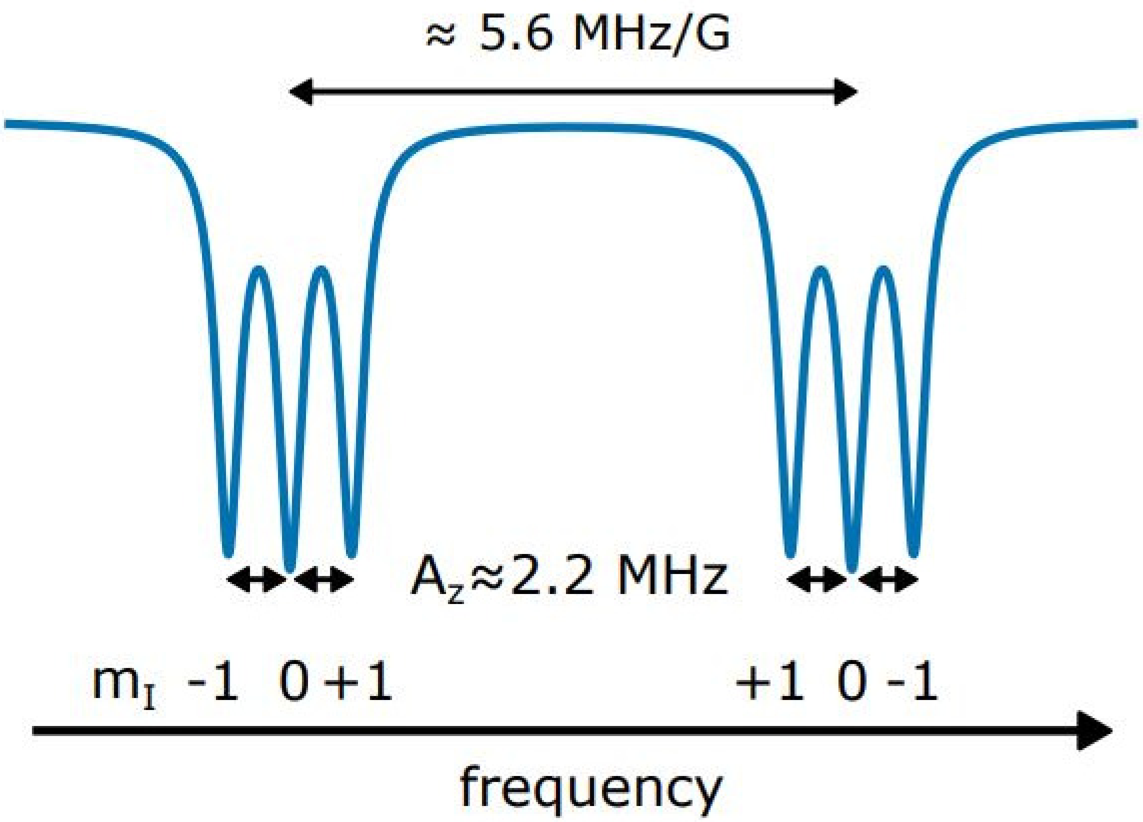
- Substitutional nitrogen and adjacent vacancy
- Electronic spin-1 system
- Spin-dependent fluorescence





Optically Detected Magnetic Resonance in NVs

Microwave spectroscopy of ground-state spin



Optically Detected Magnetic Resonance in NVs

Hamiltonian in low bias field

$$
\begin{aligned}
H_{\mathrm{LF}}/h = {} & \left(D + \mathcal{M}_z + d_{||} E_z\right) S_z^2 + \frac{g_e \mu_B}{h} B_{0,z} S_z \\
& + \left(\frac{d_\perp E_x}{h} + \mathcal{M}_x\right)\left(S_y^2 - S_x^2\right) \\
& + \left(\frac{d_\perp E_y}{h} + \mathcal{M}_y\right)\left(S_x S_y + S_y S_x\right).
\end{aligned}
$$

NV magnetometry

- Sensitive; high spatial resolution; bio-compatible

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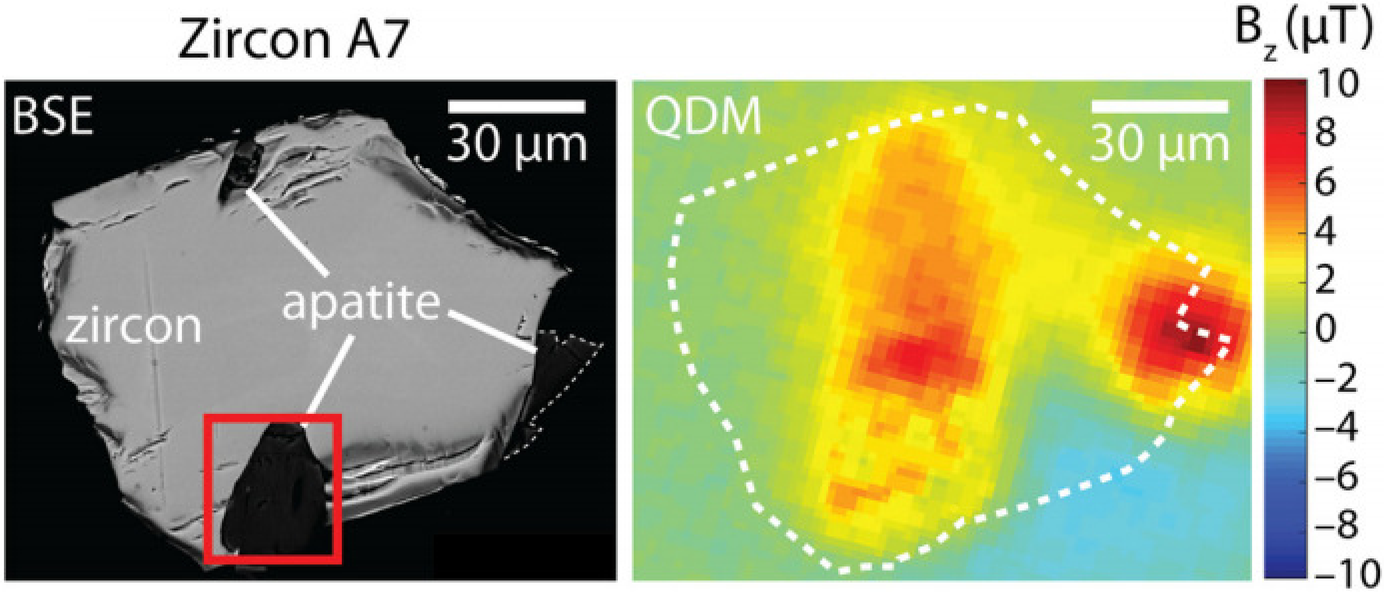
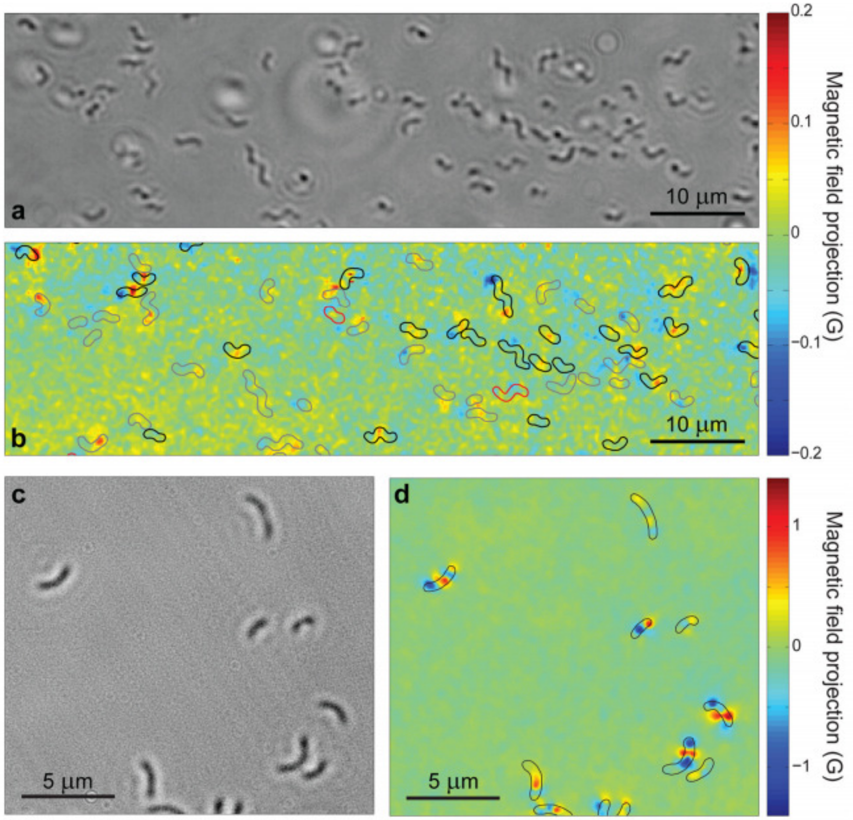


Geological paleomagnetism

R.R. Fu et al, EPSL **458**, 1-13

NV magnetometry

- Sensitive; high spatial resolution; bio-compatible

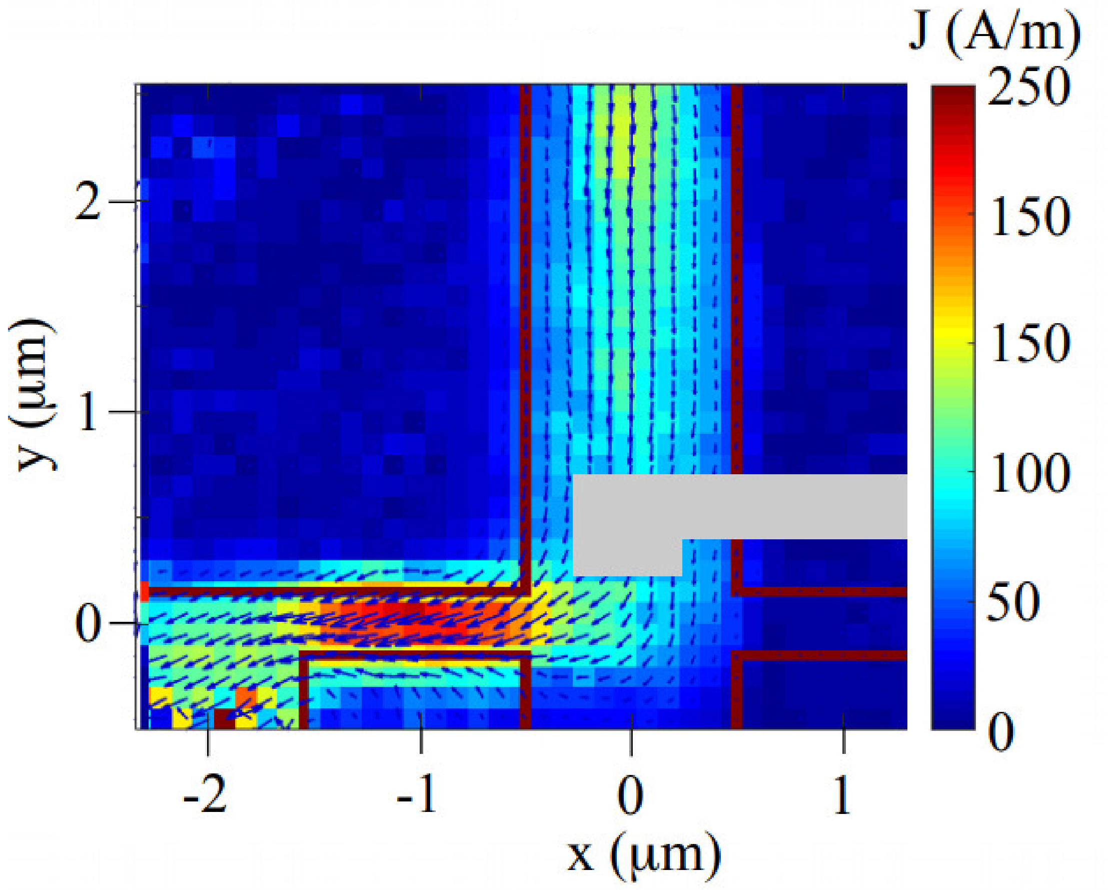


Optical imaging of magnetic bacteria

D. LeSage et al, Naure **496**, 486-489

NV magnetometry

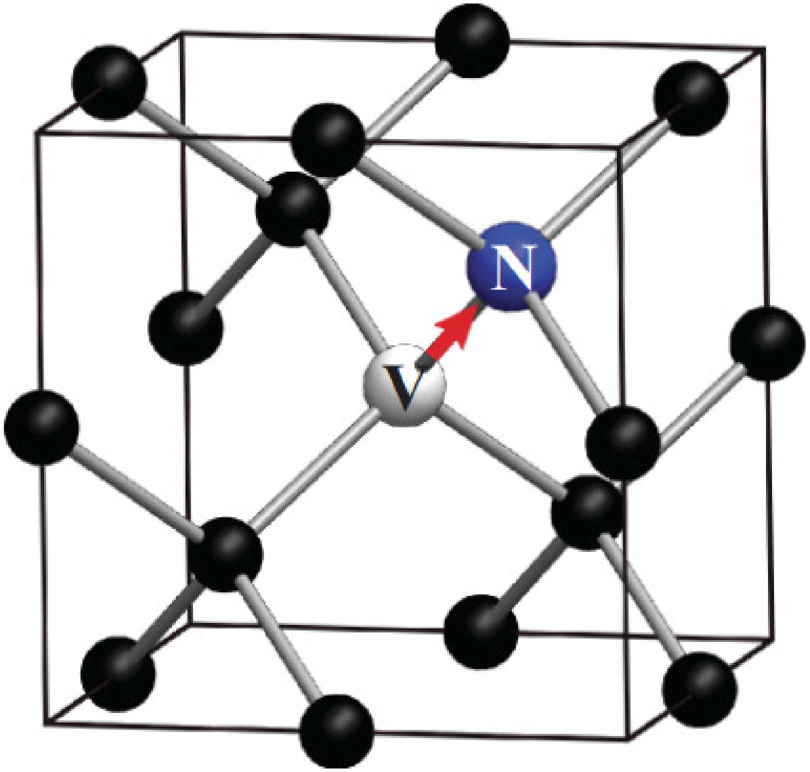
- Sensitive; high spatial resolution; bio-compatible



Imaging electron flow in graphene

Ku et al, arXiv:1905.10791 (2019)

Strain effects on NV centers



Stress/strain on crystal lattice – shift in effective electric field

Strain effects on NV centers

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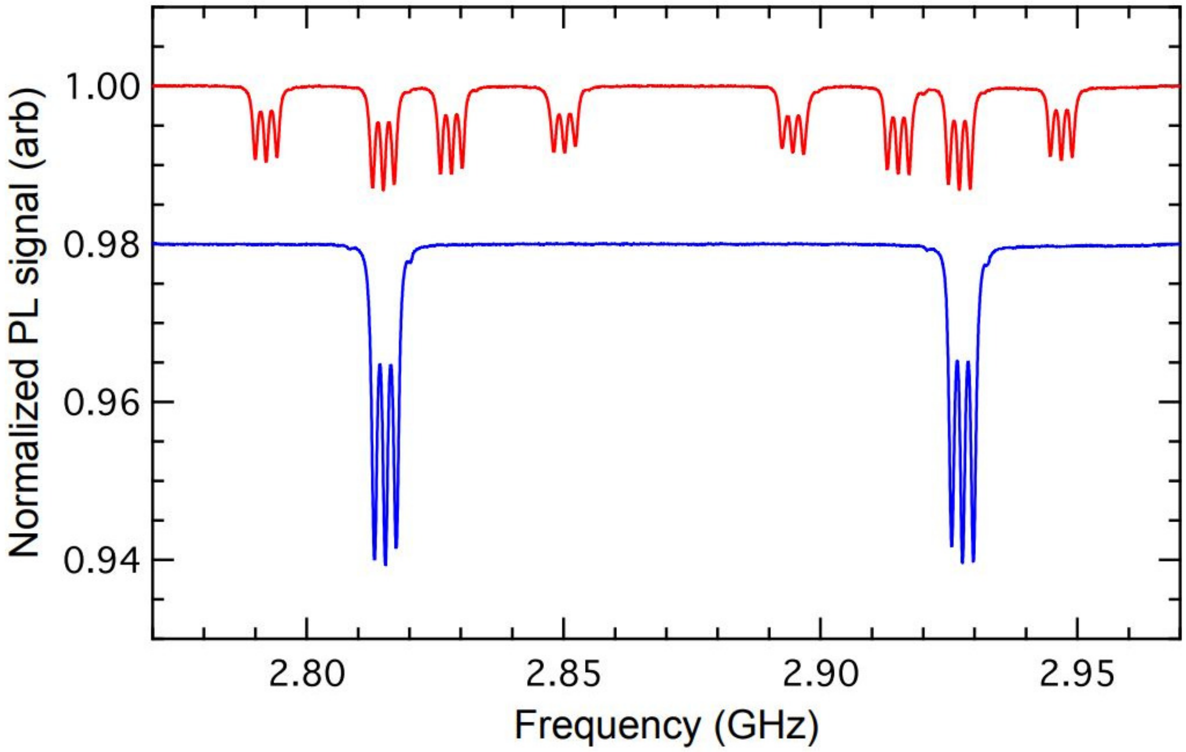
\begin{aligned}
H_{\mathrm{LF}}/h = &\left(D + \mathcal{M}_z + d_{\|} E_z\right) S_z^2 + \frac{g_e \mu_B}{h} B_{0,z} S_z \\
&+ \left(\frac{d_{\perp} E_x}{h} + \mathcal{M}_x\right) \left(S_y^2 - S_x^2\right) \\
&+ \left(\frac{d_{\perp} E_y}{h} + \mathcal{M}_y\right) \left(S_x S_y + S_y S_x\right) .
\end{aligned}
$$

Stress/strain on crystal lattice – shift in effective electric field

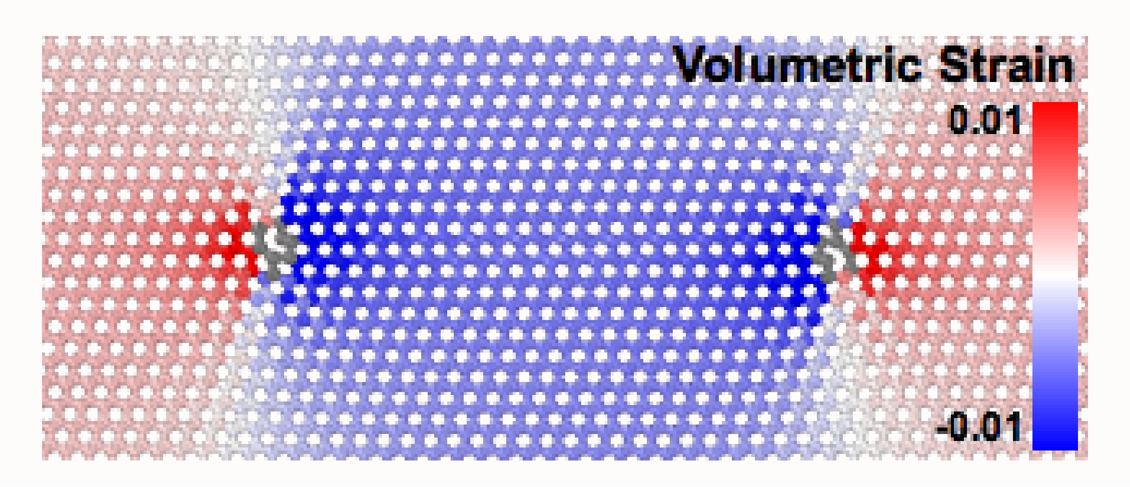
Strain effect on NV centers



Stress/strain on crystal lattice – shift in effective electric field

Strain effect on NV centers

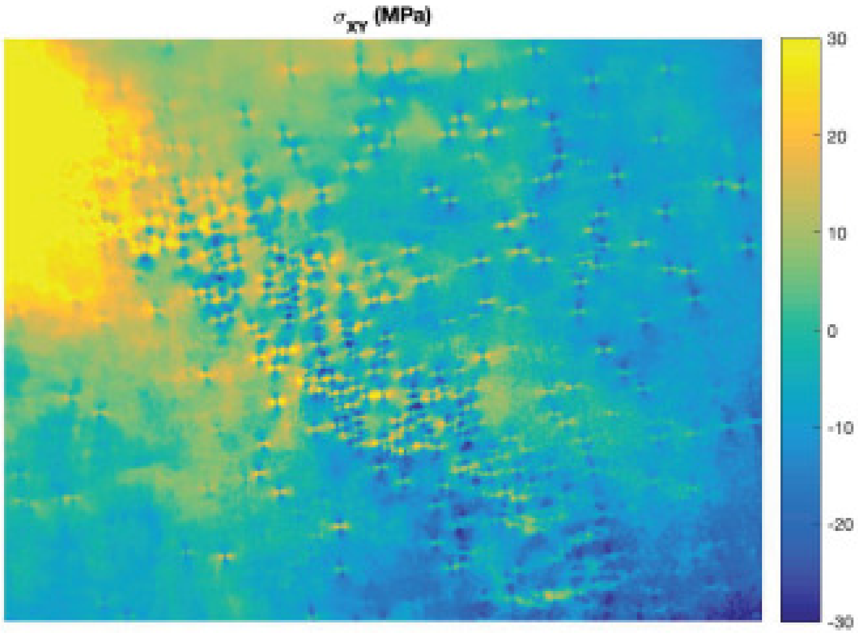
- Strain from local dislocations propagates through diamond lattice

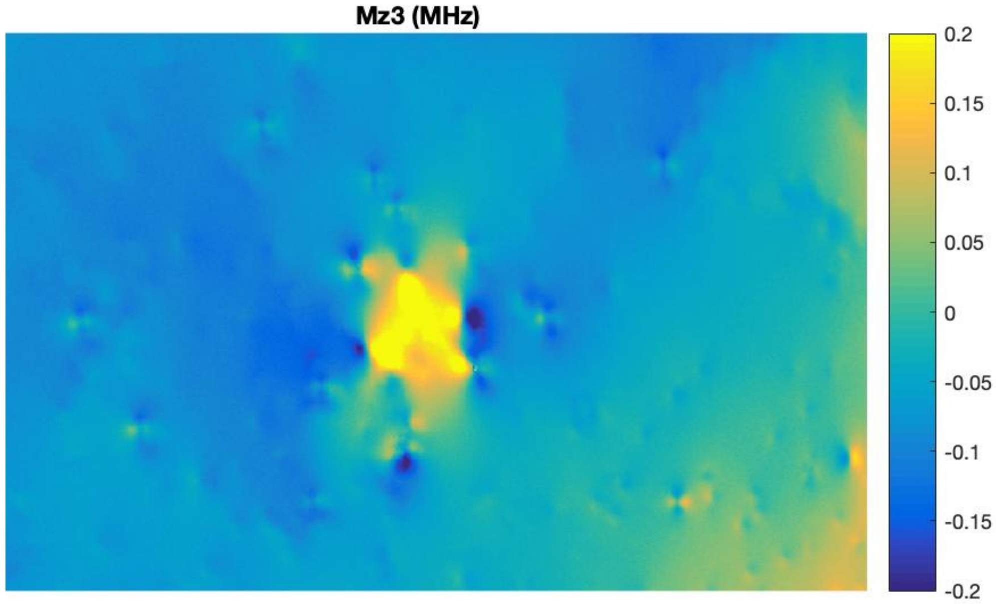


OVITO atomic simulator, strain analysis modifier, © 2017 Alexander Stukowski

“Microscopy scale”: optical strain mapping

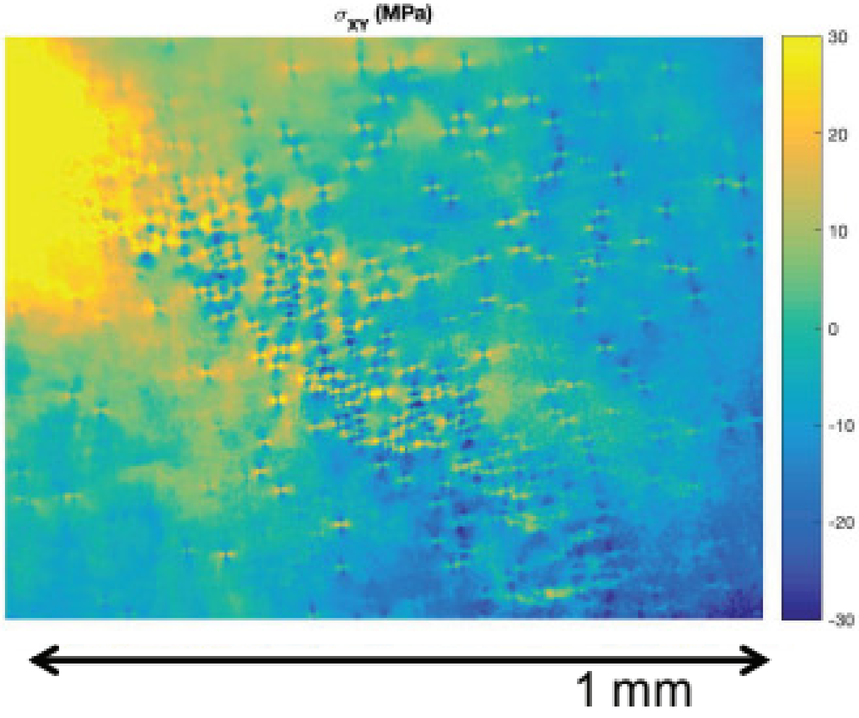
- Strain from local dislocations propagates through diamond lattice
- Wide-field optical spectroscopy maps strain features





“Microscopy scale”: optical strain mapping

- Ongoing work:
  - Demonstrate strain resolution required to detect DM track
  - Increase spatial resolution to ~1um level
  - Detect implanted tracks
  - Prototyping 3-dimensional strain mapping

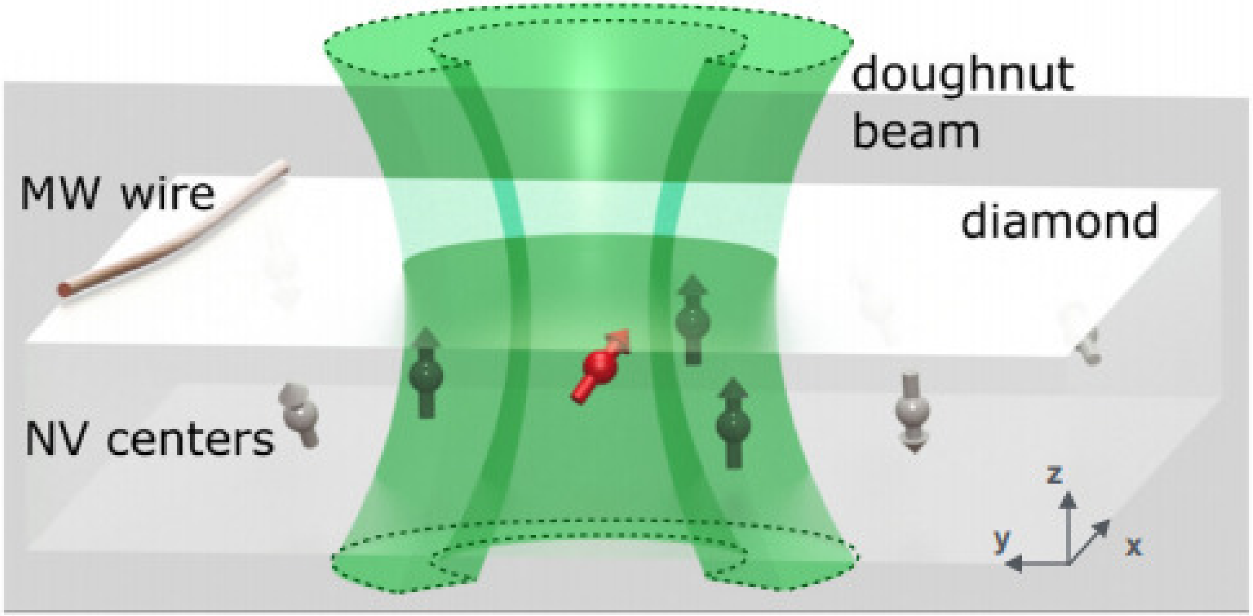


“Microscopy scale”: defect creation

- High-N, low-V diamond
- DM candidate impact creates vacancies
- Anneal, measure newly created NV centers
- Caveat – must preserve direction!

“Atomic scale”: damage track reconstruction

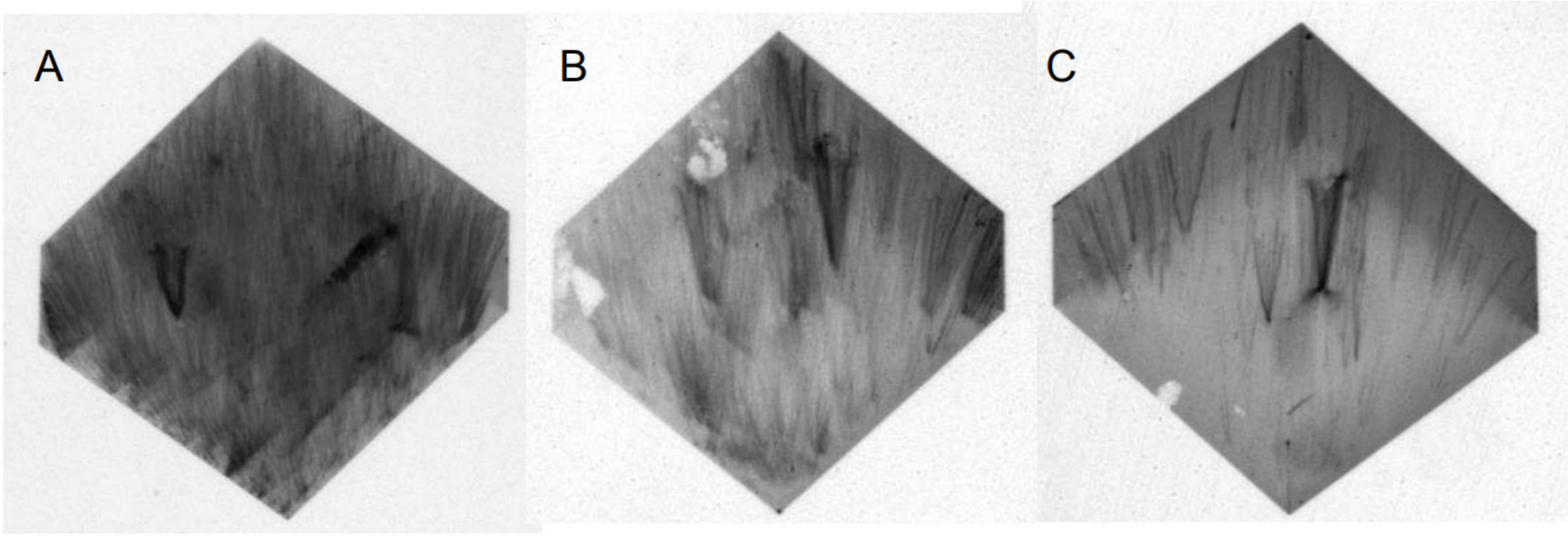
- Option A: superresolution NV microscopy



J. Jaskula et al, Optics Express 25, 10 (2017)

“Atomic scale”: damage track reconstruction

- Option A: super-resolution NV microscopy
- Option B: x-ray tomography



I. Friel et al, Arxiv:0909.1200 (2009)

Conclusion

- Diamond – promising detector candidate for low-mass DM
- Crystal lattice damage preserves direction
- Using AMO techniques, propose to measure direction using defect spectroscopy
- Promising first steps, many challenges remain

Thanks!

- Walsworth group at Harvard-Smithsonian CFA
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