# Snowmass2021—Letter of Interest

# *Solid-state directional detection of massive dark matter particles via spectroscopy of quantum defects*

**Thematic Areas:** (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (IF1) Quantum Sensors

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**Abstract:** Limits on WIMP dark matter will, in the coming decade, approach the neutrino floor — the sensitivity level at which detection of solar neutrinos represents an irreducible background. Directional detection methods will allow WIMP searches to continue below the neutrino floor; but existing directional techniques feature low target densities, requiring very large volumes and making the neutrino floor difficult to reach. Wide-bandgap semiconductors such as diamond offer a path to directional detection with solid-state densities: in addition to charge carriers, phonons, and photons which can be detected using established techniques, a WIMP event in such a crystal also leaves behind a characteristic damage track in the crystal lattice. Using a variety of methods from atomic physics, this crystal damage can be identified and mapped, and thus, the direction of the incoming particle determined.

## Introduction

Results from upcoming generations of WIMP detectors are likely to approach the "neutrino floor", where coherent scattering of solar neutrinos will be detected[1]. Like WIMPs, solar neutrinos induce nuclear recoils in a target. They scatter at energies relevant to WIMP searches, meaning standard background-discrimination techniques cannot reject them. Without discrimination between WIMP and solar neutrino events, identifying WIMPs below the neutrino floor will require detecting annual modulation atop the neutrino background, demanding dozens of events to achieve a 5 sigma discovery. Detecting the direction of an incoming particle would enable rejection of solar neutrinos, as well as reveal a WIMP signal's cosmological origin[2]. A solid-state directional detector is especially attractive for probing WIMP cross-sections below the neutrino floor. Their high target density[3] contrasts well to existing directional detection methods with gaseous and emulsion targets[4].

## Detector Principle

Wide-bandgap semiconductors such as diamond and silicon carbide have been proposed as a target for solid-state WIMP detection[3,5,6]. Their good semiconductor properties and lower-mass nuclei provide an advantageous sensitivity profile compared to existing detectors. These materials can be lab-grown with high purity and homogeneous crystal structure[7]; a WIMP event in such a crystal would leave a characteristic track of damage, with the crystal acting as a "frozen bubble chamber" recording the direction of the incident particle. The crystal damage track results from the cascade of secondary nuclear recoils initiated when a WIMP (or neutrino) impacts a target nucleus; simulations for a diamond target indicate measurable orientation and head-tail asymmetry down to 1–3 keV of recoil energy[3]. The shape and orientation of this damage track can be read out via spectroscopy of quantum point defects in the crystal such as Nitrogen-Vacancy (NV)[8,9] and Silicon-Vacancy (SiV)[10] defects in diamond, and divacancies in silicon carbide[11,12].

A directional detector based on solid-state point defects in a semiconductor could take advantage not only of a large target mass, but also of intensive development of instrumentation for WIMP detectors based on silicon or germanium. Detector segments could be instrumented with charge or phonon collectors such as transition edge sensors, or scintillation photons could be collected from the detector bulk. When a crystal segment triggers one of these detection methods, it would be removed from the detector for directional analysis, while the remainder of the detector continues to accumulate exposure.

Damage tracks from WIMP events will be tens or hundreds of nanometers long[3], requiring a two-step process to extract the directional information. Fortunately, both steps can be built upon techniques established in the fields of solid-state quantum sensing and quantum information processing[13]. First, diffraction-limited optics can be used to resolve the position of the damage track to a sub-micron voxel within the millimeter-scale detector segment. Second, optical superresolution techniques or high-resolution x-ray nanoscopy can be used to measure the damage track structure at the nanometer scale.

## Readout Technologies

Initial simulations and experimental demonstrations of these techniques have focused on the nitrogen vacancy (NV) center in diamond, as it is the most widely used and best-characterized quantum emitting defect[8,9]. Consisting of a lattice site vacancy adjacent to a substitutional nitrogen defect, the NV is a spin-1 system featuring optical initialization and readout, and a microwave transition frequency sensitive to local crystal strain (as well as magnetic and electric fields). The damage track from a WIMP-induced recoil cascade would induce significant strain on nearby NV centers, which can be measured via shifts in their spin transition frequencies. Diffraction-limited strain imaging could be used to localize damage tracks at the micron scale; sensitive, widefield strain imaging has been the subject of much recent work[14,15]. Furthermore, techniques used to sense magnetic fields could bring wide-field strain sensing to the level required to detect WIMP tracks[13]. Superresolution microscopy and spectroscopy using NV centers has been extensively developed as well[16]. Spatially-resolved, subdiffraction strain sensing is a plausible avenue for nanoscale readout of damage track direction. These same methods are applicable to other color centers in diamond such as the silicon vacancy center[10], or to divacancies in silicon carbide[11,12].

Alternatively, defects can be created from recoil-induced lattice site vacancies generated during a WIMP interaction with the diamond (or other crystal). A nitrogen-rich diamond could be annealed to induce these vacancies to form new NV centers[17] or other color centers. In silicon carbide, the single silicon vacancy is itself a quantum emitting defect at room temperature[18]. In crystals with few pre-existing emitters, this represents a near-background-free method of damage track localization. The direction can then be extracted either via strain spectroscopy of the created color centers, or by superresolution spatial mapping of the defect positions. Scanning X-ray nanobeam diffraction measurements present a non-defect-based method for damage track direction measurement – instruments at synchrotron facilities can detect strains at the level predicted for a WIMP damage track, and can be performed with nanometer spatial resolution[19,20].

All of the techniques outlined above require that optical measurements be performed on-site to avoid cosmic ray exposure during transit. Additionally, detector segments may require etching to bring the damage track close to the surface for nanometer-scale measurements, but appropriate techniques enable this without introducing additional strain or distorting the WIMP signal[21].

## Outlook

In the near term, work towards such a solid-state, WIMP detector with directional sensitivity is centered around demonstrating the capability to locate and determine the direction of nuclear recoil damage tracks in diamond or other crystals. This requires adaptation and development of existing techniques, but the current state of the art is not far from the requisite sensitivity and resolution. In the medium term, such a detector will require position-sensitive instrumentation with spatial resolution at the millimeter scale, as well as development of crystal growth techniques to create large volumes of radiopure, structurally homogeneous crystals. With appropriate development, this approach offers a viable path towards directional WIMP detection with sensitivity below the neutrino limit.

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