Snowmass2021 - Letter of Interest

# *Direct Detection of Spin-independent and Spin-dependent Nuclear Scattering of Sub-GeV Dark Matter Using Molecular Excitations and Superconducting Nanowire Single-Photon Detectors*

**Thematic Areas:**

■ (CF1) Dark Matter: Particle Like
■ (Other) IF1: Quantum Sensors
■ (Other) IF2: Photon Detectors

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**Abstract:** Dark matter with mass $\sim$100 keV to 100 MeV and with spin-independent or spin-dependent interactions with nuclei can scatter off and excite a molecule, which subsequently relaxes to its ground state, emitting multiple infrared photons. These photons can be detected with an array of ultra-low-noise Superconducting Nanostrip Single-Photon Detectors (SNSPDs). The SNSPDs can also be used directly as the target to probe DM with mass $\sim$100 keV to GeV that scatters off electrons in the SNSPDs and bosonic DM with sub-eV masses that is absorbed in the SNSPDs. We detail the R&D needed to experimentally realize this detection concept, which can probe orders of magnitude of unexplored dark matter parameter space.

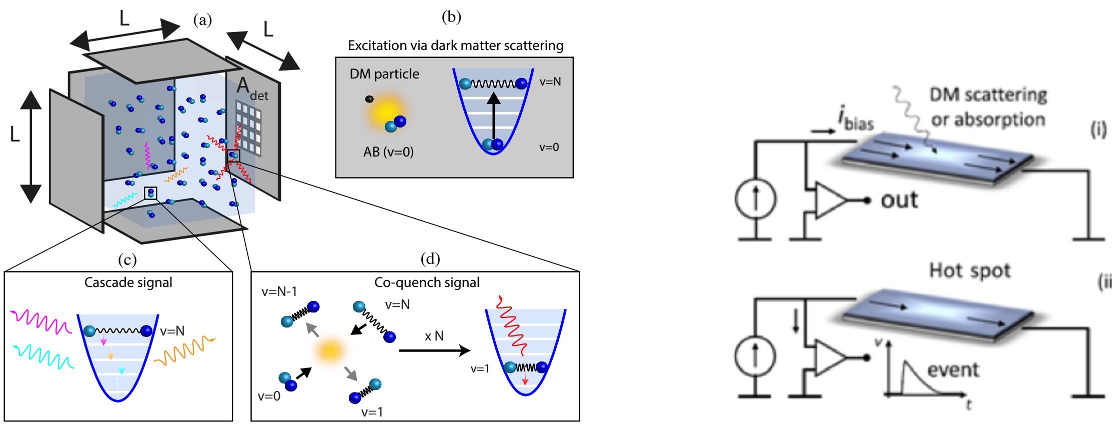


Figure 1: DM detection concept schematic. **Left:** A DM particle interacts with a low-pressure, low-temperature molecular target, such as carbon monoxide (CO), exciting a ro-vibrational molecular mode. The excited state relaxes to the ground state (bottom panels), emitting several photons that are then absorbed by the SNSPDs. **Right:** The absorption and scattering of DM directly in an SNSPD: (i) An SNSPD under voltage bias is kept close to some critical point. (ii) Energy from a DM interaction is absorbed, driving a phase transition and leading to a sudden, measurable voltage change.

# 1 Physics Goals

The past few years have seen many dark matter (DM) direct-detection concepts emerge, see *e.g.*[1–4] and references therein. Here we highlight the role played by a molecular gas target coupled to an array of ultra-low-noise Superconducting Nanostrip Single-Photon Detectors (SNSPDs). Such a detector is sensitive to several types of DM signals:

- DM with mass $\sim$100 keV to 100 MeV can scatter off and excite a molecule to probe spin-independent and spin-dependent interactions (Fig. 1 (**left**))[5]. The excited molecule relaxes to the ground state by emitting multiple photons of energy $\mathcal{O}$(200 meV). The reach of the proposed experiment is shown in Fig. 2 (**top**) for spin-independent scattering (for both heavy (**top left**) and light (**top right**) mediators).
- The SNSPDs can be used directly as the target (Fig. 1 **right**). DM with mass $\sim$100 keV to GeV can scatter off electrons in the SNSPDs, while DM with sub-eV masses can be absorbed in the SNSPDs[6]. This deposits energy above the superconducting gap, breaking Cooper pairs in the SNSPDs and creating an observable signal in the device. The reach for DM-electron scattering and for relic dark photon absorption are shown in Fig. 2 in the **bottom left** and **bottom right** panels, respectively.

The low-energy-sensitivity threshold ($<$100 meV) of SNSPDs is a key enabler of our approach. The development of unique wide-band low-energy SNSPDs would also open up a range of detection possibilities in, *e.g.*, DM science, imaging, and in enabling atmospheric spectroscopy of planets.

# 2 Required R&D, Status, and Plans

The near-term R&D goals of our proposed effort are to build a working prototype detector, before scaling it up. This includes:

- Build a high-reflectivity cavity that contains the gas target and that can efficiently capture photons and focus them onto SNSPDs; integrate different subsystems to make a working prototype.
- Build a large-area array of SNSPDs sensitive to 5-micron infrared photons w/ $\mathcal{O}$(1) efficiency.

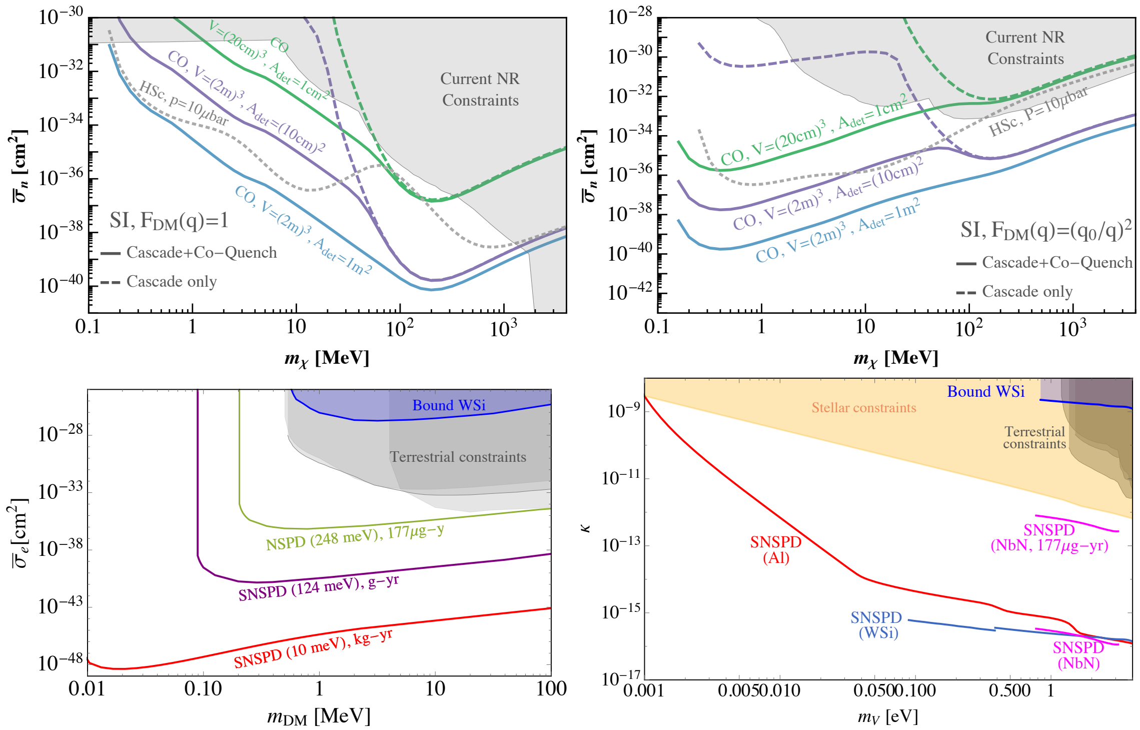


Figure 2: **Top:** Expected reach assuming zero background events for DM spin-independent nuclear scattering off CO molecules at a partial pressure of 5 mbar and a temperature of 55 K, for various tank volumes $V$ and photodetector areas $A_{\rm det}$, a 1-year exposure, and a heavy (light) mediator in the left (right) plot. Colored dashed (solid) curves correspond to CO cascade (cascade+co-quench) photons (see [5]). The gray dotted curve corresponds to a cascade photon signal from an HSc gas at a pressure of 10 $\mu$bar and at a temperature of 46 K. Current constraints are shown with gray shaded regions. **Bottom:** Expected reach of SNSPDs as simultaneous 'target + sensor' for DM-electron scattering in the SNSPD via an ultralight scalar mediator (left) and absorption of relic kinetically mixed dark photon DM (right). The solid colored curves indicate 95% C.L. expected sensitivity through SNSPD targets (Al, WSi, NbN or others), assuming no backgrounds and for kg-year exposure (unless otherwise stated) with various energy thresholds. For clarity, 177 $\mu$g corresponds to a 10 by 10 cm-squared area of NbN at 4 nm thickness and a 50% fill factor, and 248 (124) meV threshold corresponds to a 5 (10) $\mu$m wavelength. Also shown are existing terrestrial and stellar constraints, including from a prototype WSi SNSPD that was not designed for DM detection.

- Operate the SNSPDs at sub-K temperatures while maintaining the molecular gas target at a colder temperature (*e.g.*, for CO at around 50 K).
- Verify experimentally several key properties of the gas that are only known theoretically.
- Characterize possible radioactive backgrounds events that can mimic a DM signal.
- Derive the first bounds on data collected from the prototype.

Our proposal is complementary to already existing efforts, and is unique among other proposals. In particular, we will probe DM interactions with electrons for DM masses below $\sim$1 MeV, a mass range that is difficult to probe with other mature proposals that use semiconductor or noble liquid targets. We would also, for the first time, probe spin-independent (spin-dependent) interactions between DM particles and nuclei for DM masses $\sim 0.1$ MeV $- 1$ MeV ($\sim 0.1$ MeV $- 100$ MeV). Finally, our proposal will also probe bosonic DM below 1 eV, which is below the silicon band gap and hence also inaccessible with other mature proposals that rely on semiconductor or noble-liquid targets.

## References


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[5] R. Essig, J. Pérez-Ríos, H. Ramani and O. Slone, *Direct Detection of Spin-(In)dependent Nuclear Scattering of Sub-GeV Dark Matter Using Molecular Excitations*, *Phys. Rev. Research.* **1** (2019) 033105, [1907.07682].

[6] Y. Hochberg, I. Charaev, S.-W. Nam, V. Verma, M. Colangelo and K. K. Berggren, *Detecting Dark Matter with Superconducting Nanowires*, 1903.05101.