Mid-Infrared SNSPDs for Exploring Dark Matter

BREAD Collaboration Workshop
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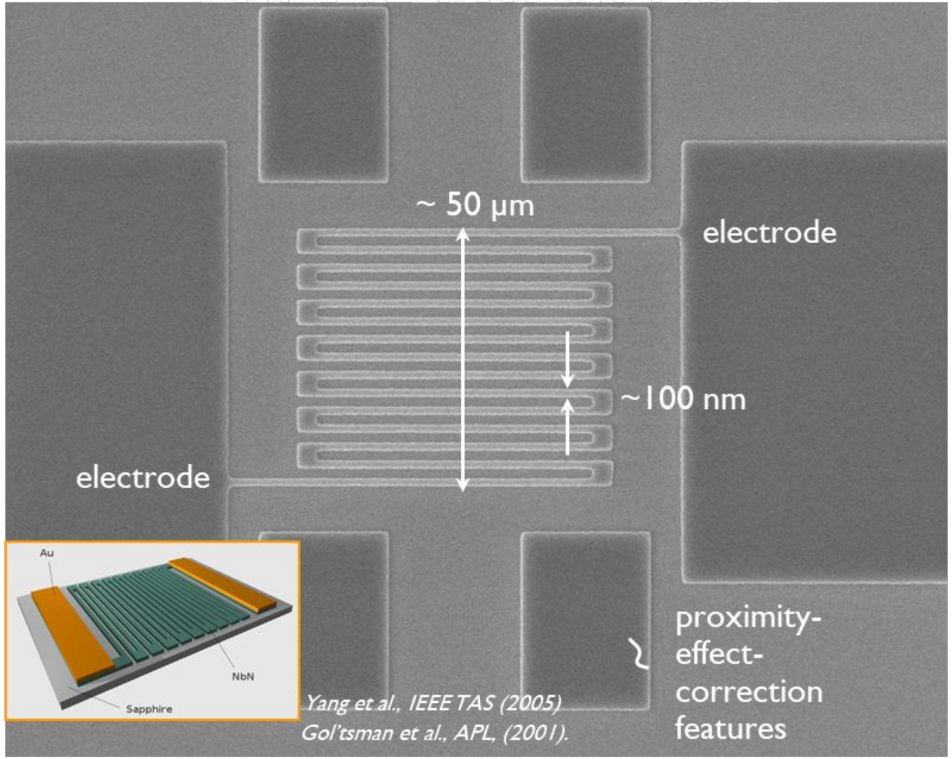
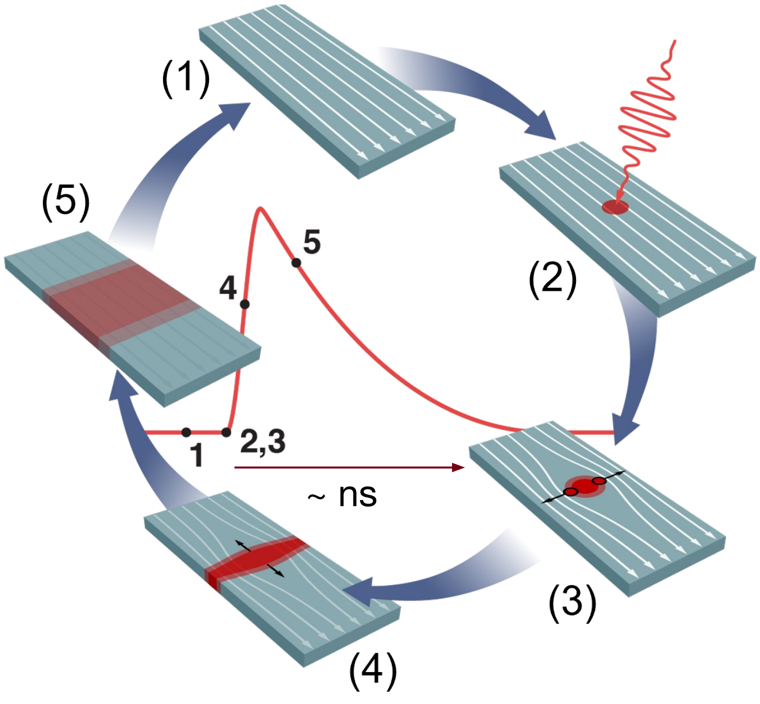
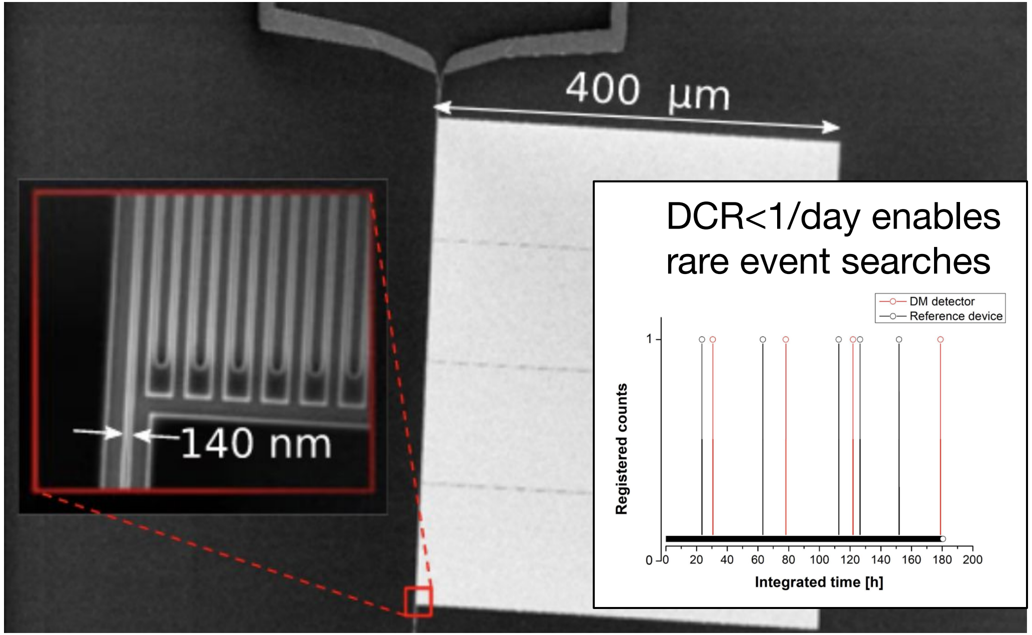
Superconducting Nanowire Single-Photon Detector (SNSPD)





[1] J. P. Allmaras, *PhD Thesis Caltech (2020)*

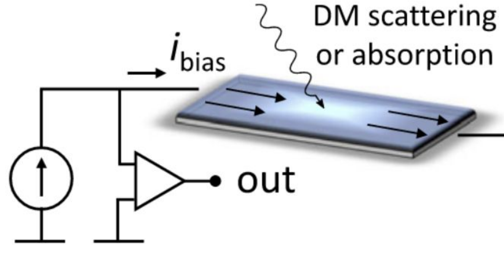
SNSPDs for Dark Matter Search



- Single photon sensitivity at 1550 nm
- Large detector area (400 um^2 x 400 um^2)
- Convenient fabrication, shielding, amplification, operating temperature (≥ 1 K)

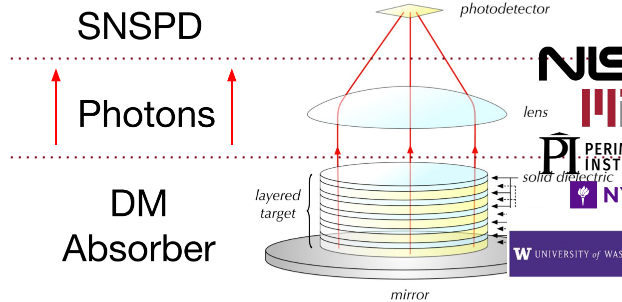
Direct Detection

Hochberg et al, Phys. Rev. Lett. 123, 151802



Indirect Detection (LAMPOST)

Chiles et al, Phys. Rev. Lett. 128, 231802, 2022



SNSPDs for Axion and Dark-Photon DM Search

1. For non-relativistic light dark matter, haloscope convert dark matter into photons with wavelengths set by the dark-matter mass

$$m_{DM} \approx 1 / \lambda$$

2. Previous experiment at 1550 nm corresponds to $m_{DM} \sim 0.8 - 1$ eV
3. Mid-IR (5–30 μm) SNSPDs enable sensitivity to $m_{DM} \sim 50 - 250$ meV
4. However, expected photon rates can be extremely low ($\ll$ 1 photon/s)
5. **SNSPD requirements for axion and dark-photon haloscopes**:
    a. Mid-IR sensitivity with ultra-low background count rate and saturated detection efficiency
    b. Maintain detection sensitivity in strong magnetic fields (for axions)

NIST and JPL have shown Saturated Single-Photon Detection at 29 μm

1. arXiv:2308.15631 [pdf, other] quant-ph cond-mat.supr-con physics.ins-det

Low-noise single-photon counting superconducting nanowire detectors at infrared wavelengths up to 29 μm

Authors: Gregor G. Taylor, Alexander B. Walter, Boris Korzh, Bruce Bumble, Sahil R. Patel, Jason P. Allmaras, Andrew D. Beyer, Roger O'Brient, Matthew D. Shaw, Emma E. Wollman

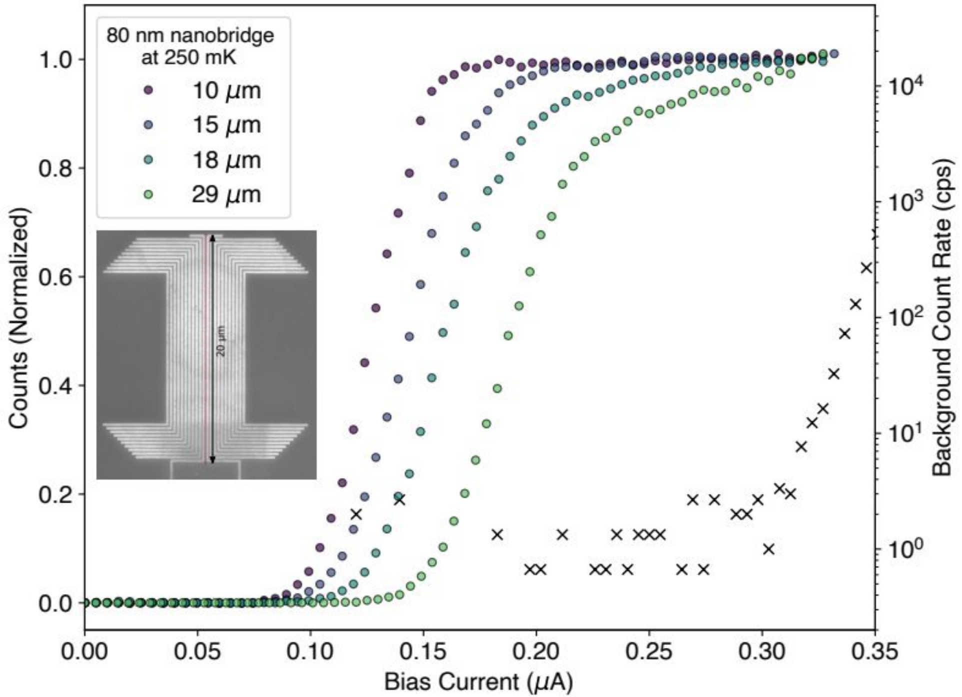
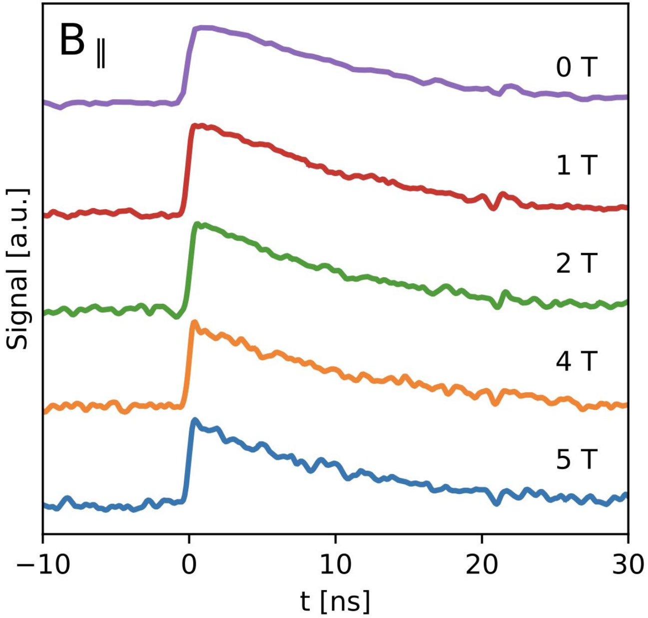
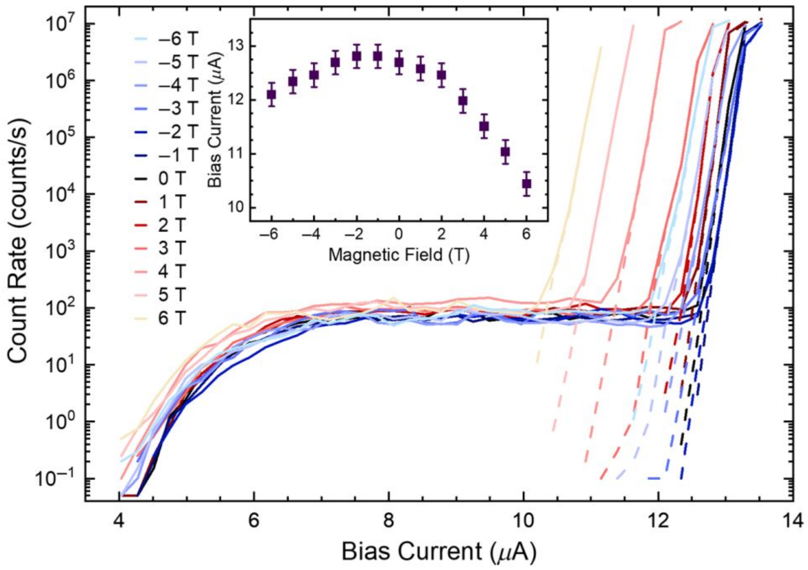


FIGURE 2. Normalized PCR curves for 80 nm wide nanobridge at 250 mK for wavelengths of 10 μm, 15 μm, 18 μm and 29 μm. The saturated count rates were 6 kcps, 12 kcps, 7 kcps and 8 kcps for each wavelength respectively. BCR is shown in black ×'s on the right y-axis. The inset shows an SEM of the device with the active area highlighted in red. The remaining structures visible are for proximity error correction during the electron beam lithography.

SNSPDs in Strong Magnetic Fields





Polakovic, Tomas et al. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 959 (2020): 163543.

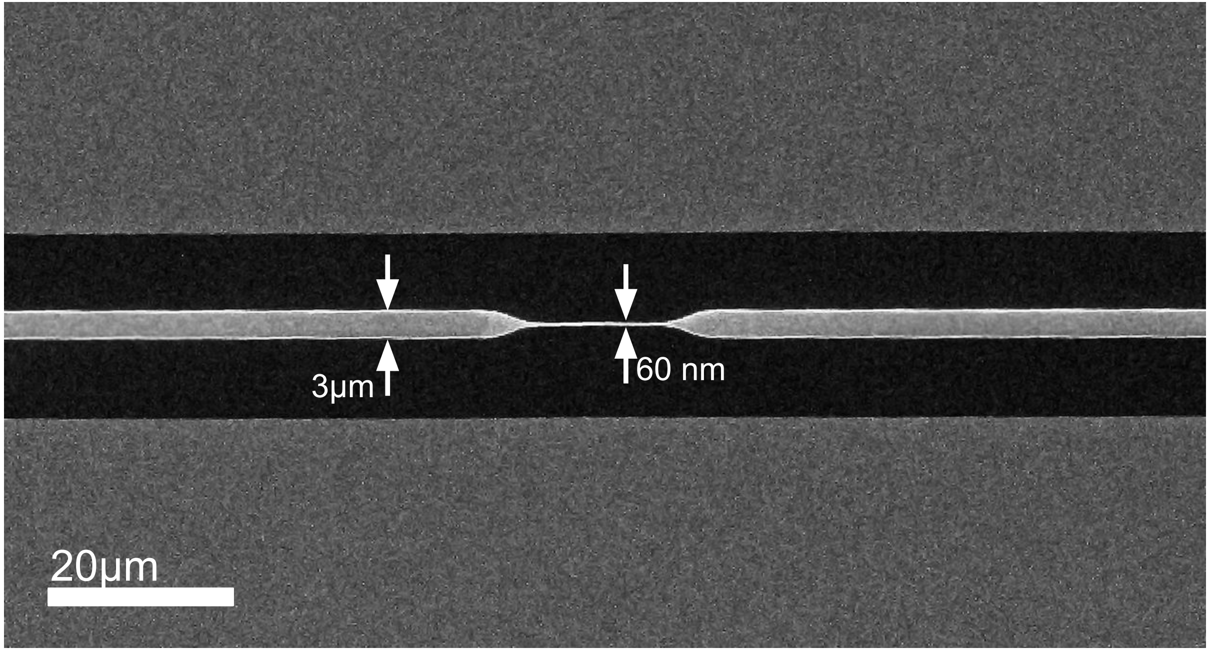
Benjamin J. Lawrie, et. al., “Multifunctional Superconducting Nanowire Quantum Sensors,” Phys. Rev. Applied 16, 064059 (2021)

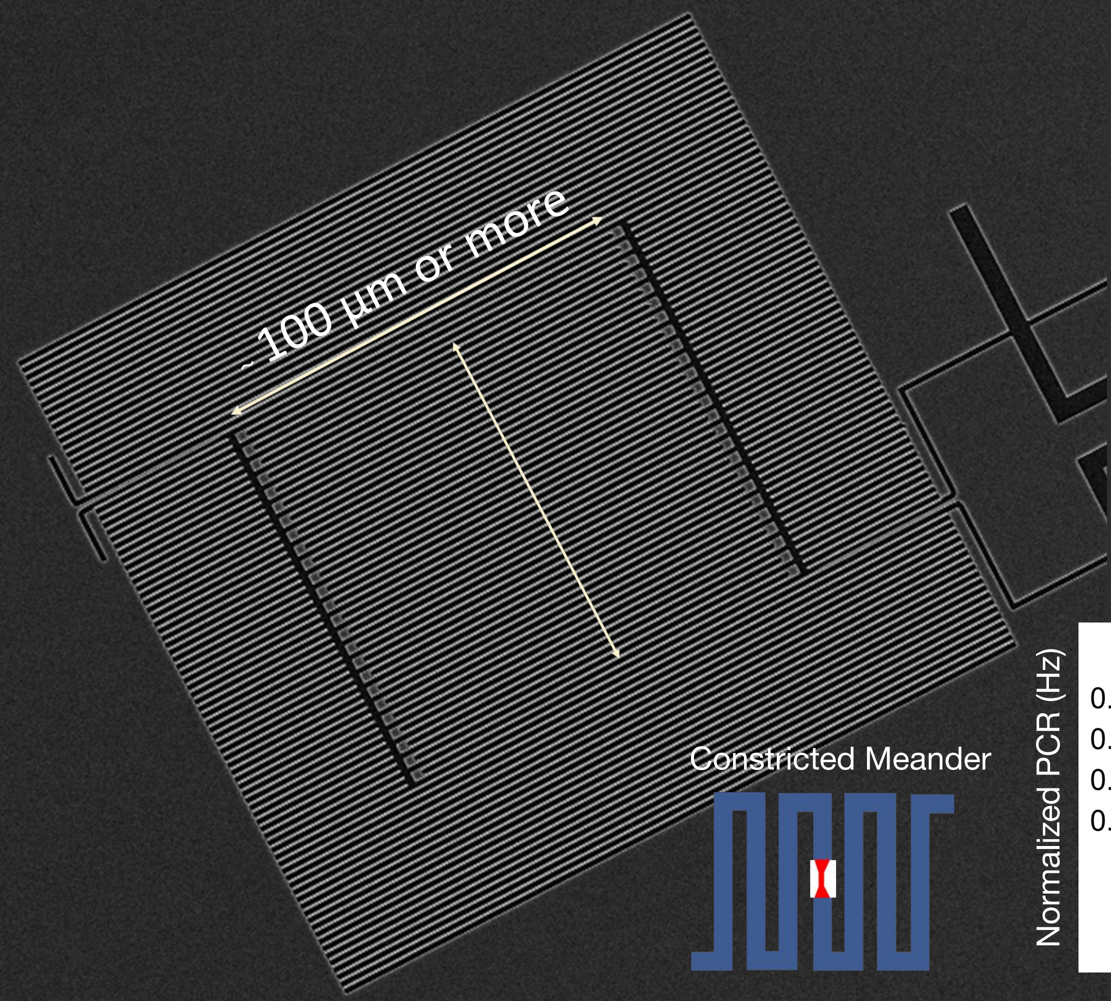
Mid-IR SNSPDs: Current Status and Outlook

Performance Metrics	Current Status	Near-term (~2-3 years)	Aspirational Targets
Minimum Energy Detection Threshold	λ = 29 μm (~40 meV) *[Taylor et al. 2023]*	λ = 50 μm (~25 meV)	λ = 80 μm (~15 meV)
Detection Area (Single-Pixel)	10x11 μm^2 @29 μm *[Taylor et al. 2023]*	1x1 mm^2 @29 μm	1x1 cm^2
Optical Absorption Efficiency (η)	~ 3% @29 μm (Estimation from optical simulations)	> 60% @29 μm	> 80%
Dark Count Rate (DCR)	10^{-2} cps @29 μm *[Taylor et al]* *$6x10^{-6}$ cps* @1.5 μm *[Chiles et al]*	10^{-2} cps @29 μm	Background Vetoing 10^{-6} cps @29 μm
NEP = (hν/η)·√(2·DCR)	$2x10^{-20}$ W/√Hz @29 μm	$1.6x10^{-21}$ W/√Hz @29 μm	-
Operating Temperature	250 mK @29 μm *[Taylor et al. 2023]*	-	1 K
Tolerance to Magnetic Fields	B|| = 5 T @λ = 400 nm (3K) *[Polakovic et al. 2020]*	B|| = 1 T @29 μm	B|| = 10 T

Improving Energy-Detection Threshold

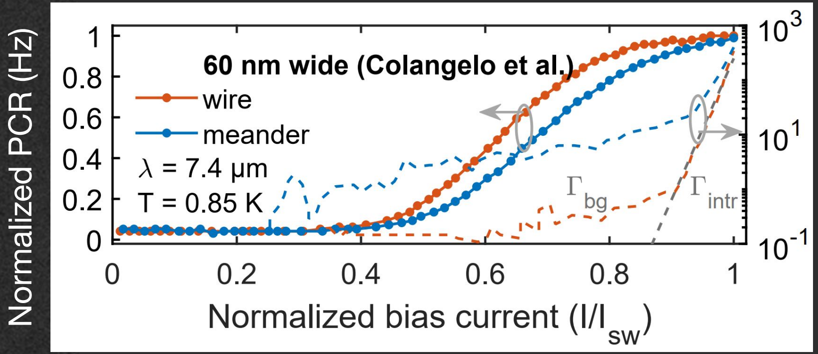
1. Reducing T_C of the superconducting film ($E_{detect,min} \propto N_0\Delta(0)^2wd(1 - I_{sw}/I_{dep})$)
2. Reduce nanowire cross-sectional area → facilitates hotspot formation and detection of lower-energy photons





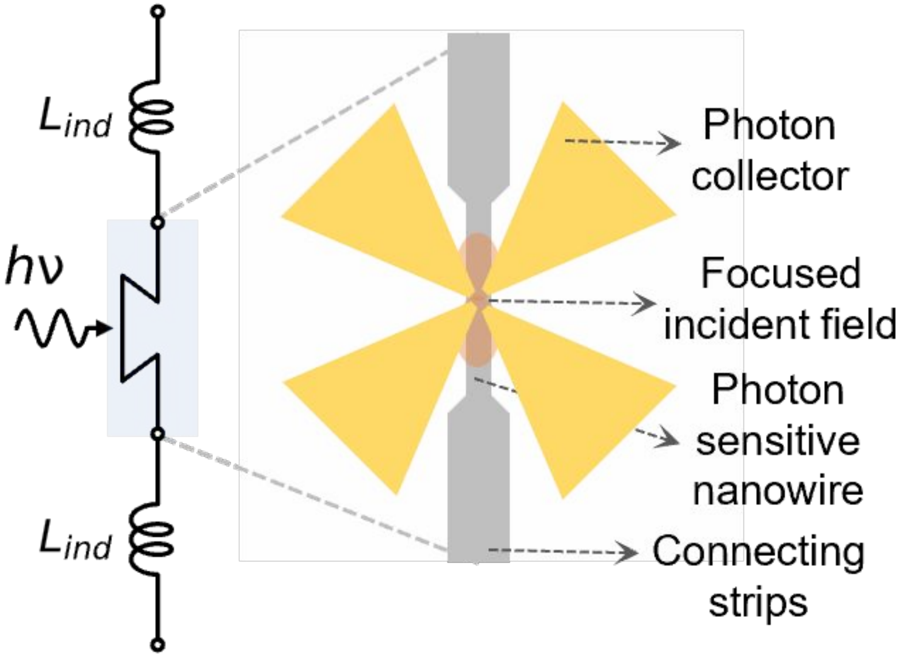
Nanowire width ~ 60 nm, thickness ~ 3nm. Extreme dimensionality scaling of superconducting nanowires leads to

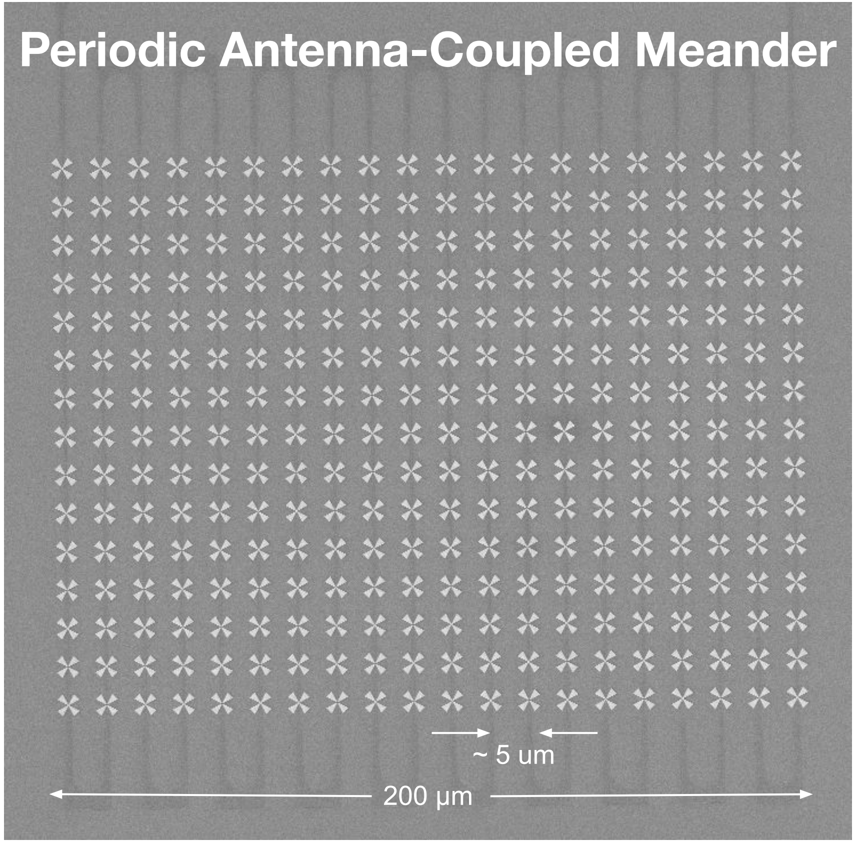
- Low photon collection efficiency
- Reduced fabrication yield
- Challenges in scaling to large active-area detectors



Scaling to Large Detection Area

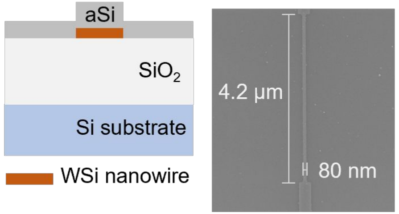
Metallic Antenna in mid-IR



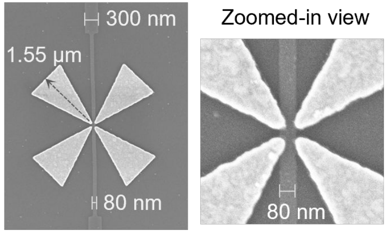


Detection Area Scaling with Antennas

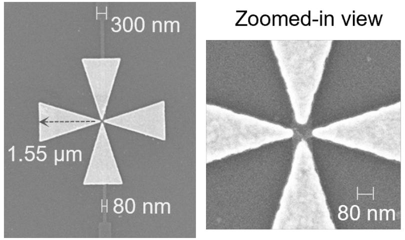
Nanowire without antenna



Nanowire with cross-shaped antenna

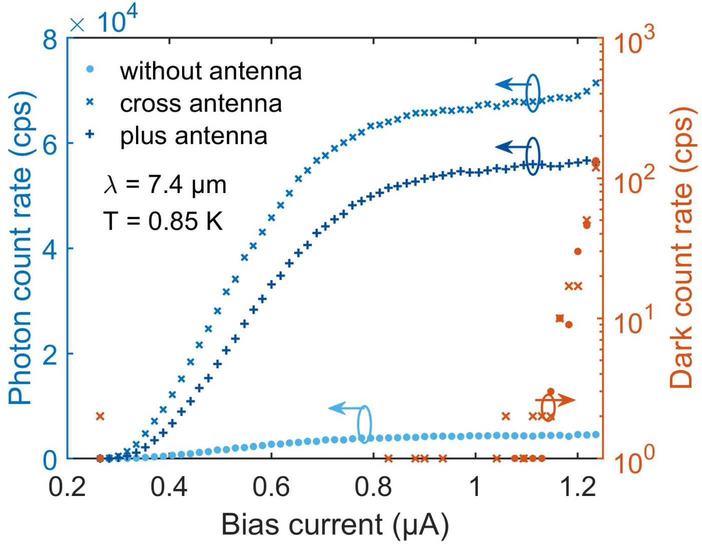


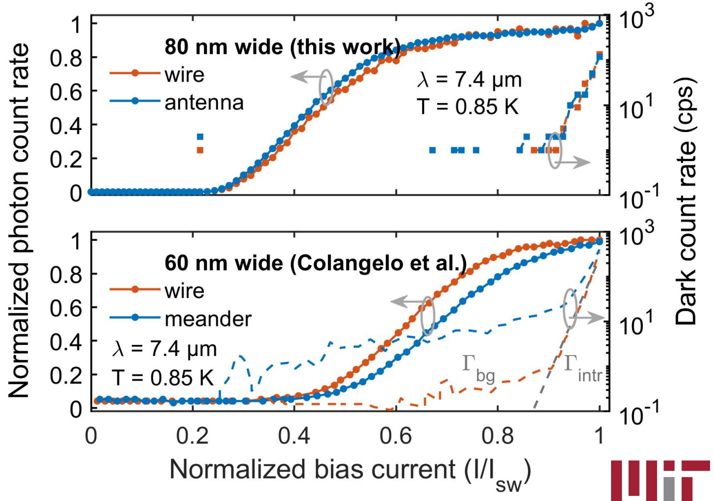
Nanowire with plus-shaped antenna



3 nm-thick WSi nanowire, 80 nm width, 4.2 μm long:

1. 15.5x improvement in PCR using antenna coupling at 7.4 μm
2. DCR remained same, so PCR/√DCR increased by antenna coupling



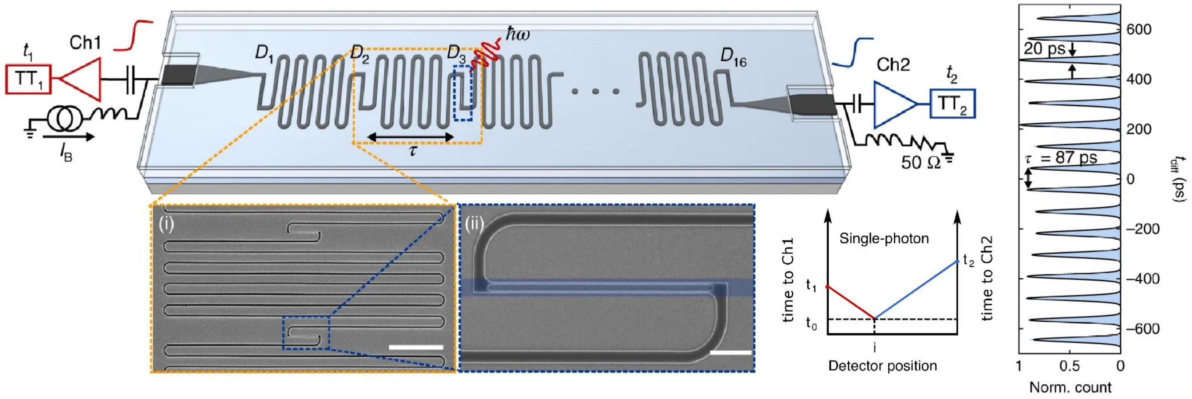


[1] *Paul, Dip Joti, et al. manuscript in revision*

Vetoing Strategy of the Background Events

Dark counts (i.e. background events) in SNSPDs originate from

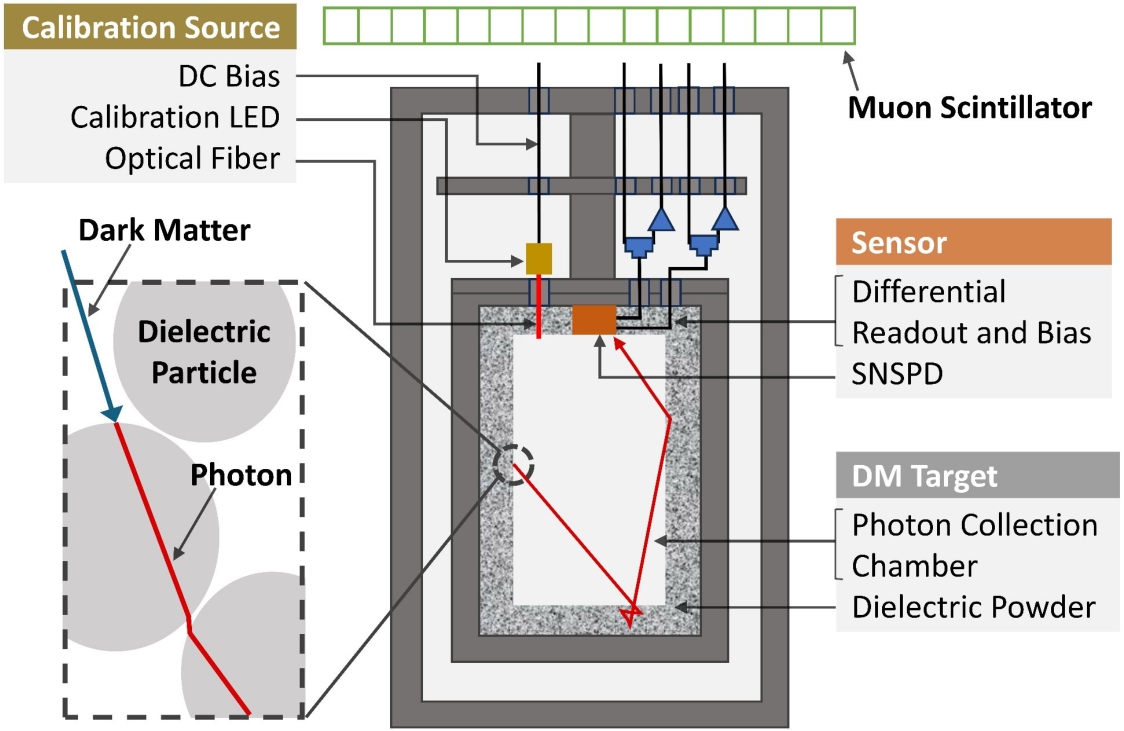
- Intrinsic dark counts: fluctuations at weak points or constrictions in SNSPDs
  - Vetoing by identifying the location of detection events
- Extrinsic backgrounds: thermal radiation and energetic cosmic particles
  - Vetoing using scintillation detectors and event-timing correlations



Background Events Vetoing by Impedance Matched Tapers and Differential Readout

[1] D. Zhu et al., Nature nanotechnology 13 no. 7, (2018) 596–601.

Disordered Dielectric Haloscope: DPHaSE



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[1] *Koppell, Stewart, et al., arXiv preprint arXiv:2506.00115 (2025)*

Outlook & Future Directions

1. **State-of-the-art mid-IR SNSPDs (29 µm)** enable sensitivity to dark-matter masses of m_{DM} ~ 40 meV
2. **Axion haloscope experiments** require demonstrated mid-IR SNSPD performance in strong magnetic fields, or alternatively, haloscope designs that efficiently couple axion-induced photons to SNSPDs outside the magnetic field region
3. **Resonant metallic antenna structures** offer a promising route to enhanced optical absorption efficiency and scalable active detector area
4. **Scaling to mm^2-scale detector areas** is feasible with current technology; **cm^2-scale arrays** will require row–column multiplexing and integrated readout electronics
5. **Achieving ultra-low background rates and operation at elevated temperatures** for mid-IR SNSPDs remain key areas for further investigation

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Thank You