Deep-IR Sub-eV SNSPDs for Axion and Dark Matter Detection

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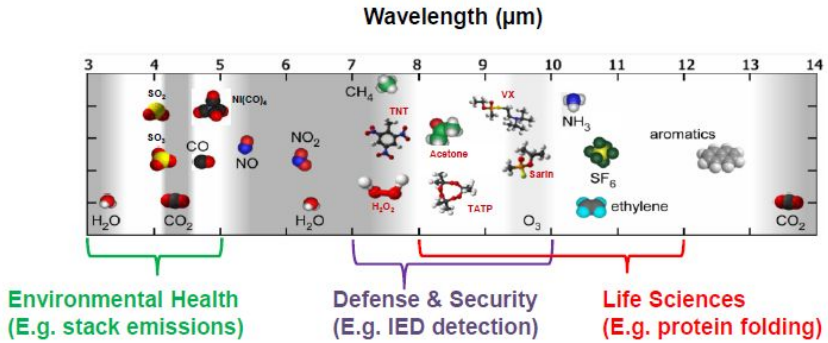
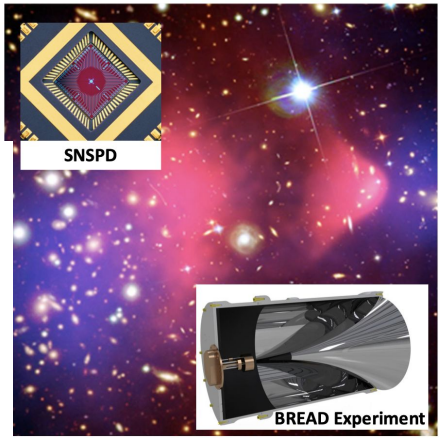
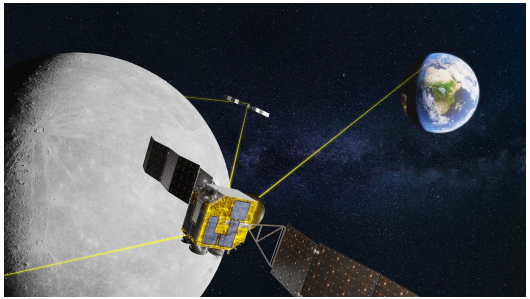
CPAD Meeting 2024

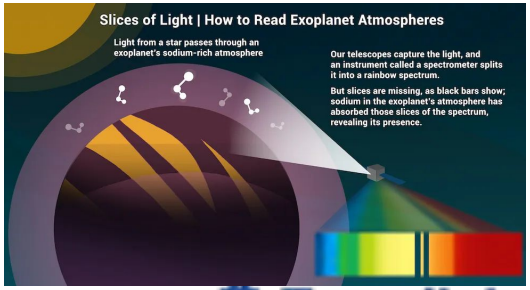
Deep-IR Sub-eV SNSPDs

- SNSPDs offer unique solution for efficient detection of deep-IR sub-eV photons
- Such photons play a key role in diverse areas of science including:
  - Axion and Dark Matter Detection
  - Deep-Space Communication
  - Exo-planet spectroscopy
  - Environmental Monitoring



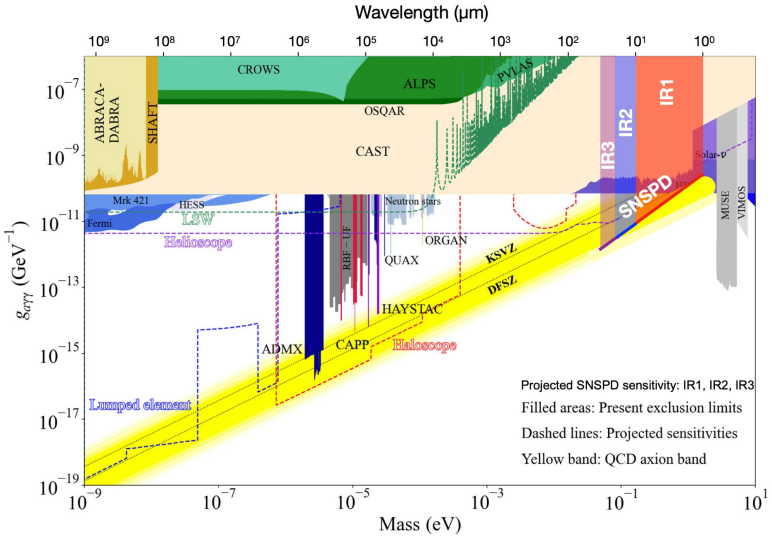


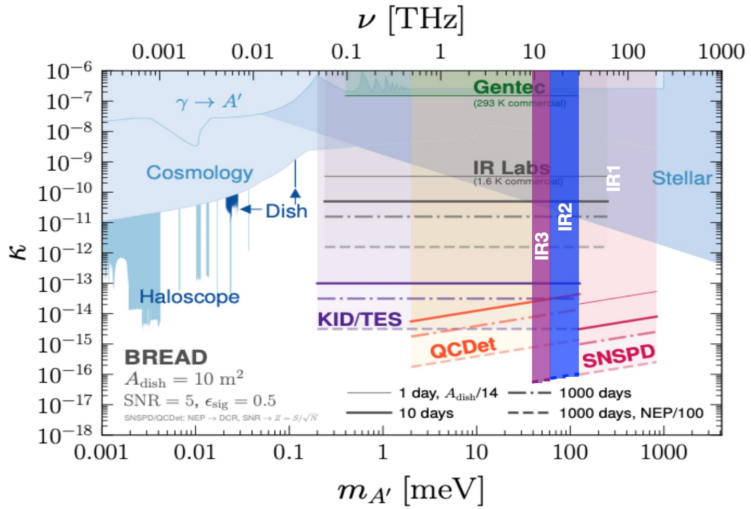




Axion and Dark Matter Searches

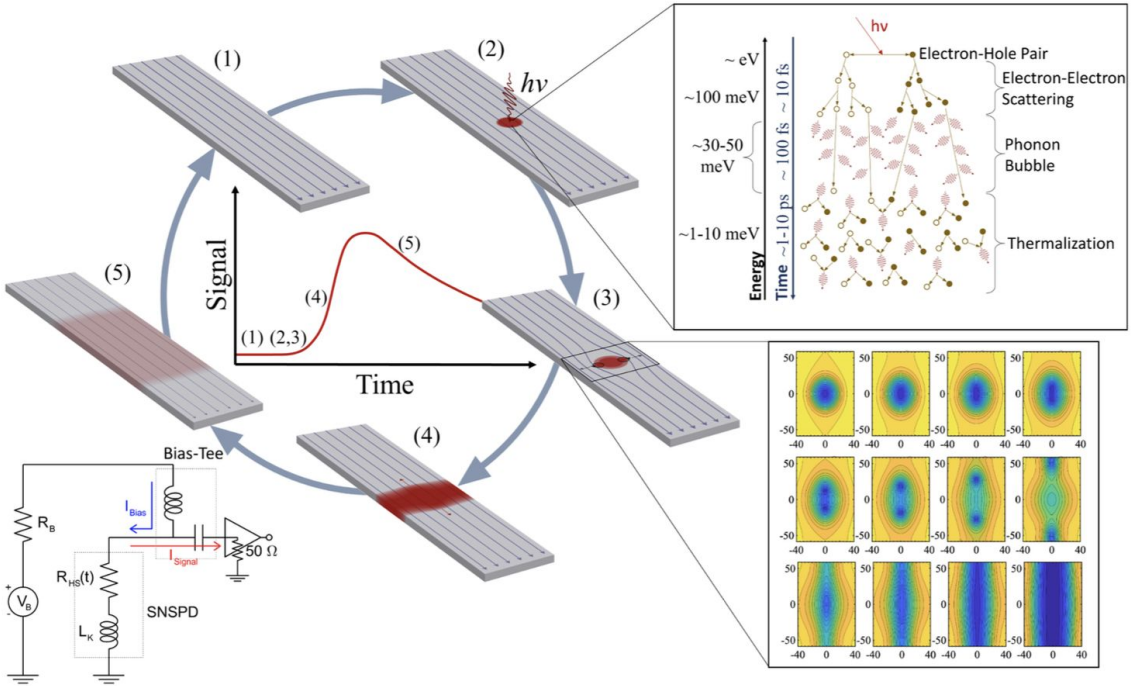
- SNSPDs cover a key range in axion and dark matter searches below 1eV
- Conventional SNSPDs optimized for 0.8 eV for quantum communication
- Goal: extend the coverage down towards 0.01 eV !





SNSPDs

- Bias current through superconductor until impinging photon deposits enough energy to break superconductivity
- Signal read out through a shunted parallel circuit



Reducing Energy Detection Threshold

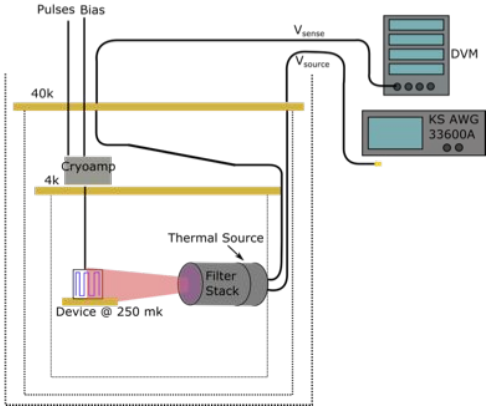
- Detection threshold roughly behaves like: $\sqrt{D} \times w \times d \times T_c^{3/2}$

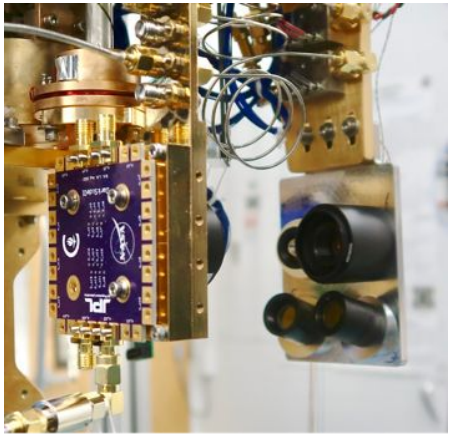
- Three main factors to reduce threshold:
  - (1) Decreasing thickness (d) and width (w) of the nanowire
  - (2) Reducing diffusion coefficient D
  - (3) Lowering Tc by reducing nanowire gap energy

- We have had the most success with strategy (3) by tuning the silicon content of WSi material in fabrication process
  - Operating temperature must be reduced accordingly, to ~100 mK

IR Photon Sources

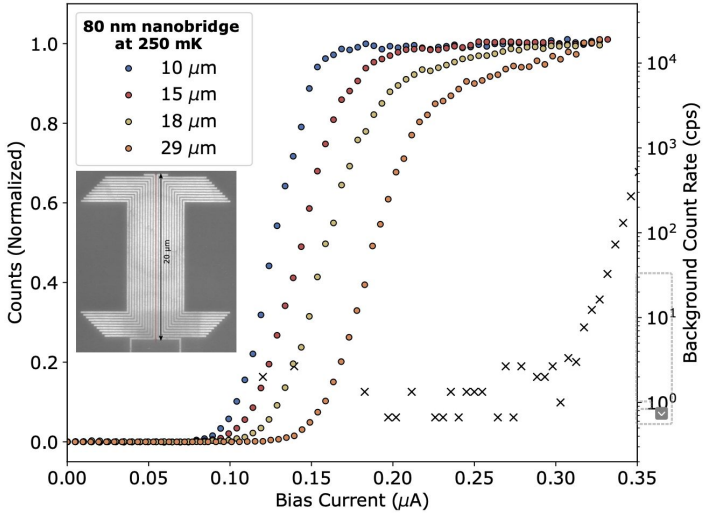
- A key challenge for testing is to produce a pure source of IR photons in the 10 - 50 μm range
- We employ broad spectrum thermal photon sources, coupled with IR optical filters to generate photons with a peak wavelength ranging between 10 to 42 μm

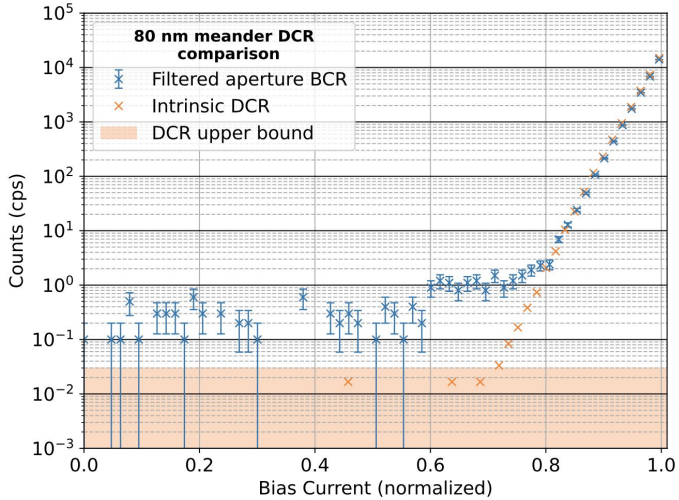




Detection Efficiency and Dark Counts

- Verified full detection efficiency saturation of prototypes between 10-29μm
- At dark counts below 0.1 Hz using custom designed copper dark enclosure

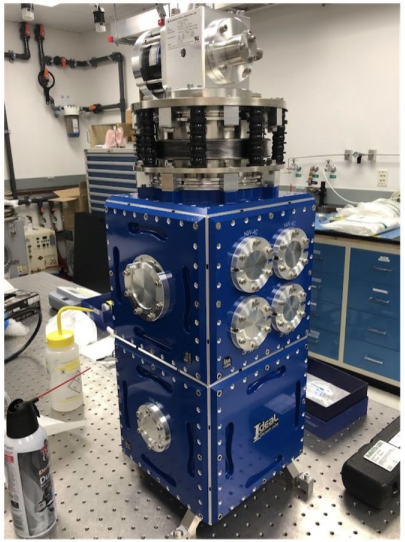




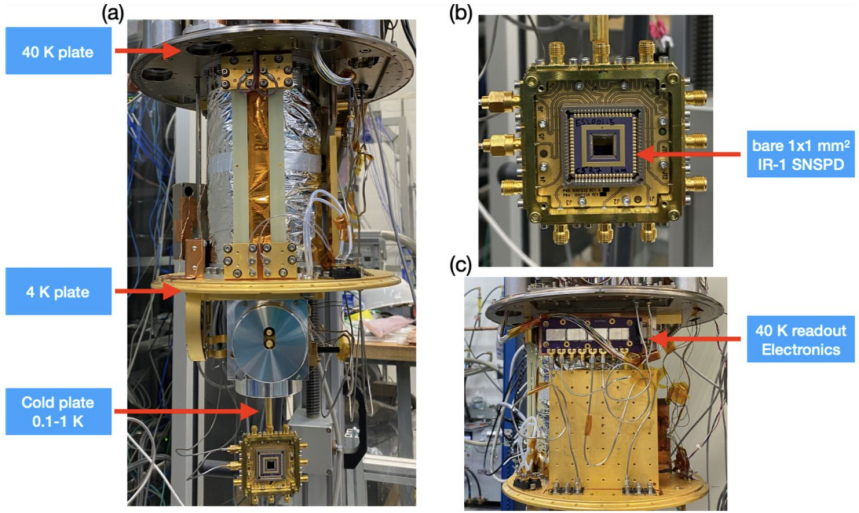
Gregor G. Taylor, et al, "Low-noise single-photon counting superconducting nanowire detectors at infrared wavelengths up to 29 μm," Optica 10, 1672-1678 (2023)

Cryogenic Testing Infrastructure

- Availability of multiple of sub-K cryogenic sensor testing stations to parallelize testing efforts



Left: Sensor Testing Station @ JPL

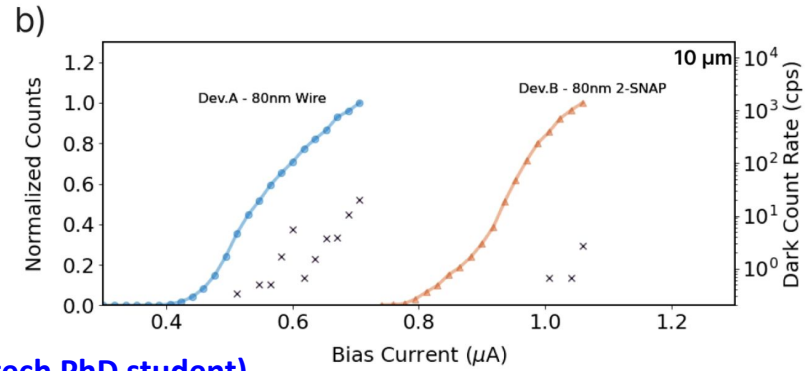


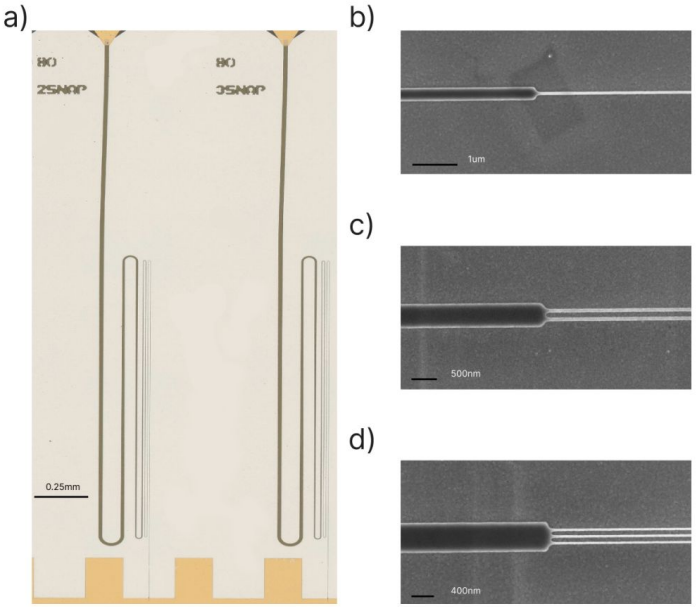
Right: SNSPD integration and characterization system (SIACS) @ Fermilab

Recent improvements to SNR

- Enhancing single wires with 2 or 3 parallel wires to form SNAPs (Superconducting nanowire avalanche photodetector) improves SNR by factor 2-3

Sahil Patel (Caltech PhD student)



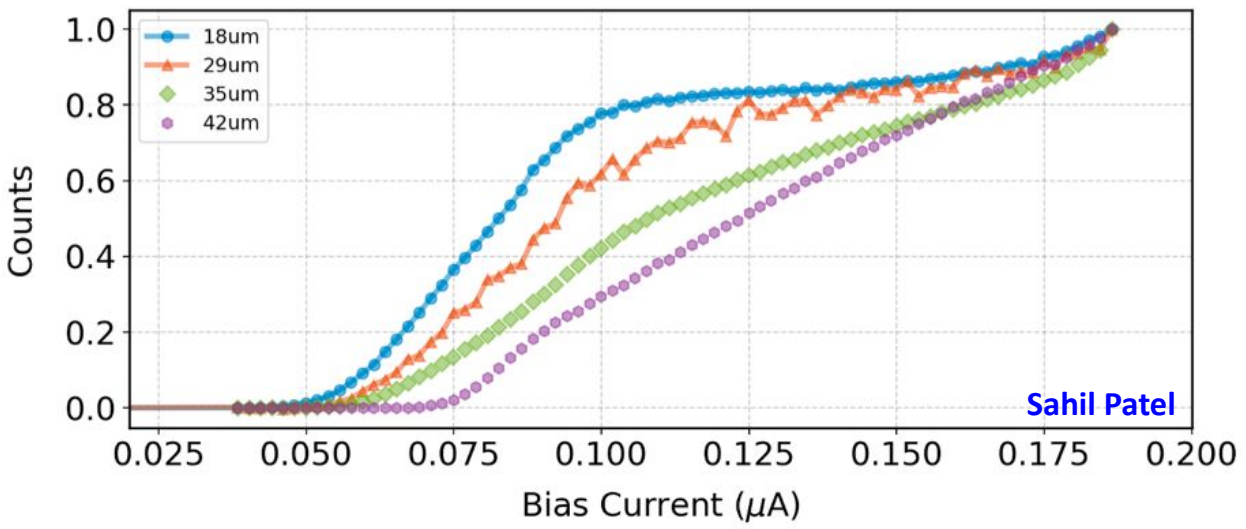


Sahil Patel, et al, "Improvements of readout signal integrity in mid-infrared superconducting nanowire single-photon detectors", Appl. Phys. Lett 124, 162604 (2024).

Pushing to Lower Energy Threshold

- Further attempts at engineering the superconducting material has been successful at reducing the Tc accordingly

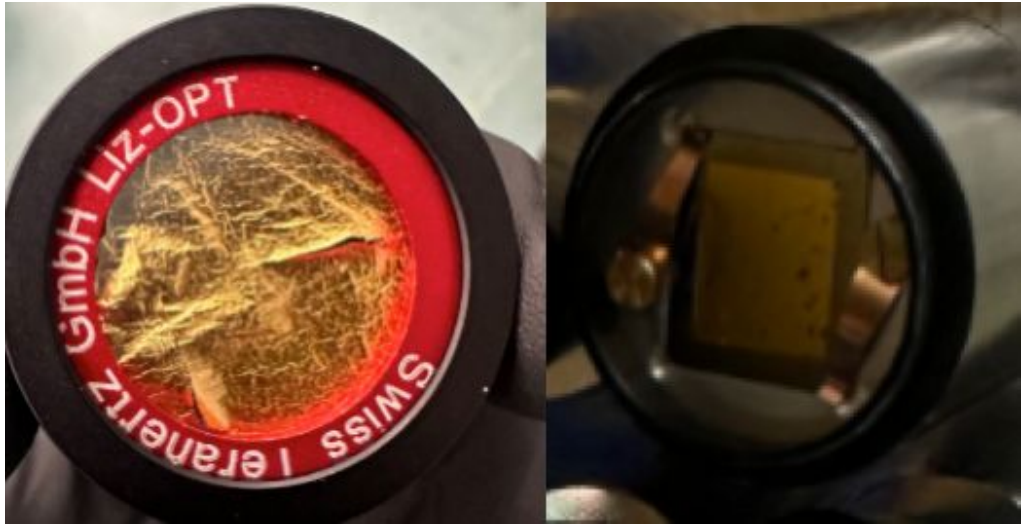
- But we're observing unusual shape in efficiency saturation curve
- Suspect imperfect filtering of the IR photons



Improving Deep-IR photon source

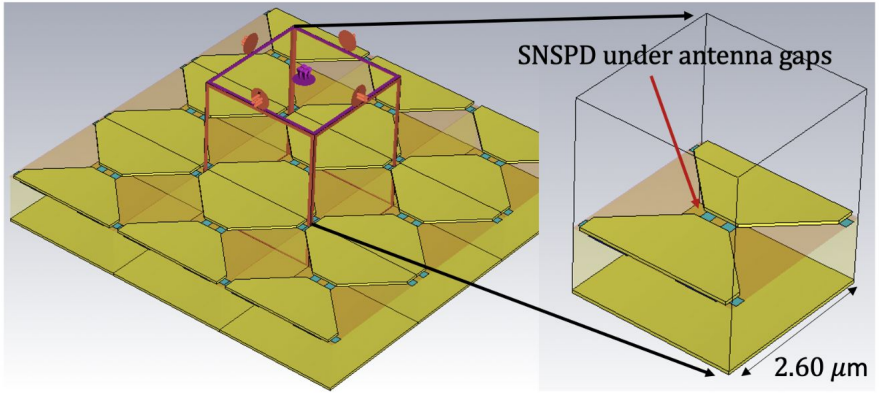
- Have observed some mechanical issues with current filters
- Thermal cycling of the cryostat have induced wrinkling in some filters

- Investigating alternative filter vendors and alternative mechanical support solutions
- Also investigating quantum cascade lasers for deep-IR photon source

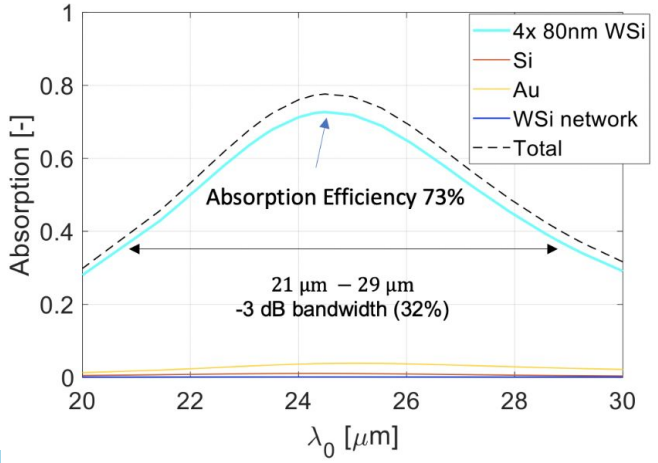


Antenna-Coupled Structures

- Working on extending the sensitive area of the sensor to mm^2 scale
- For wavelengths above ~20μm, efficient antenna coupled structures have been produced for TES in the past
- Simulations show high efficiency structures are promising
- Work ongoing on fabrication and testing



Sven van Berkel (JPL), et al



Summary

- Presented preliminary results and ongoing work on IR-sensitive SNSPDs
- Successfully achieved sensors with sensitivity down to 29μm

- Work ongoing to:
  - Push sensitivity down further towards 50μm
  - Fabricate and test antenna coupled structures to achieve sensors with mm^2 scale active area needed for axion and dark matter experiments such as BREAD

Backup