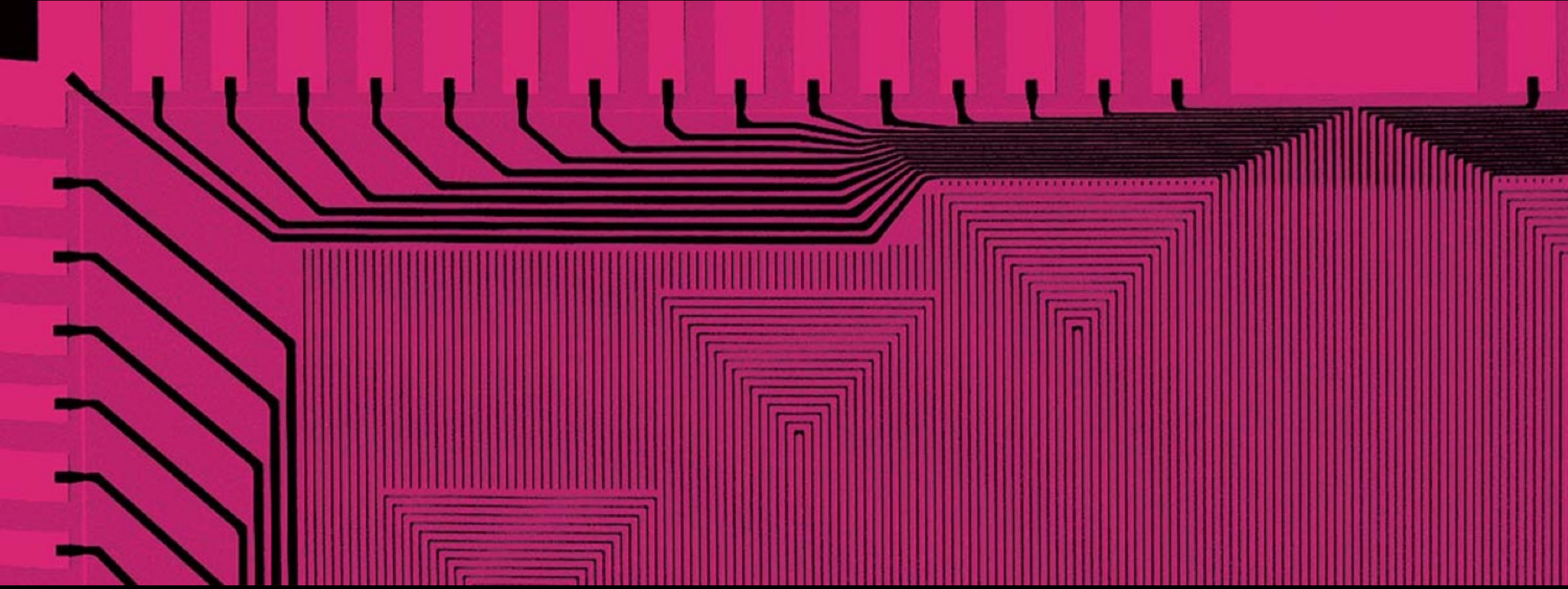


CPAD Workshop 2022

Superconducting nanowire single photon detectors for sub-GeV dark matter searches

Jamie Luskin

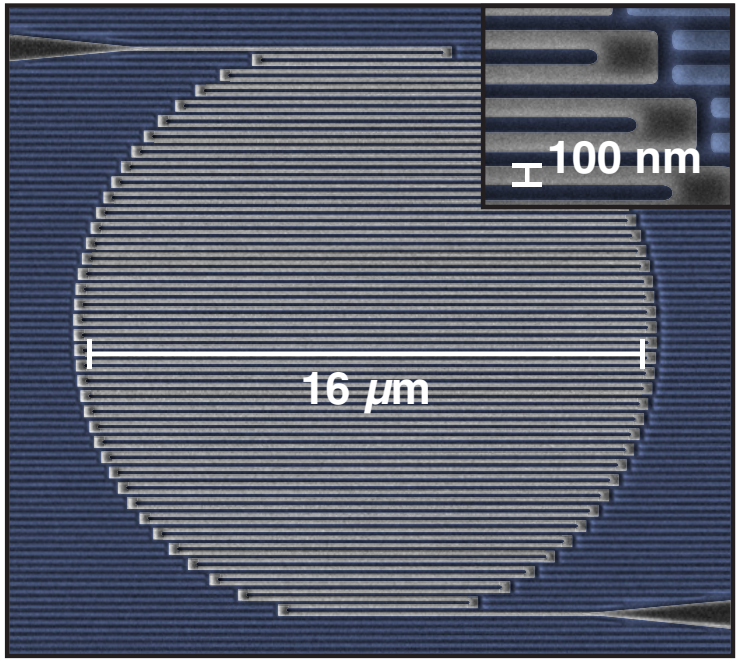
JPL, Caltech, University of Maryland

Jet Propulsion Laboratory
California Institute of Technology

Introduction to SNSPDs

- Thin film superconducting nanowire
  - Thickness: 2-10 nm
  - Width: 40-200 nm
  - Meandered active area
- Current-biased
- Cryogenic operation (1-4K)
- UV to mid-IR sensitivity

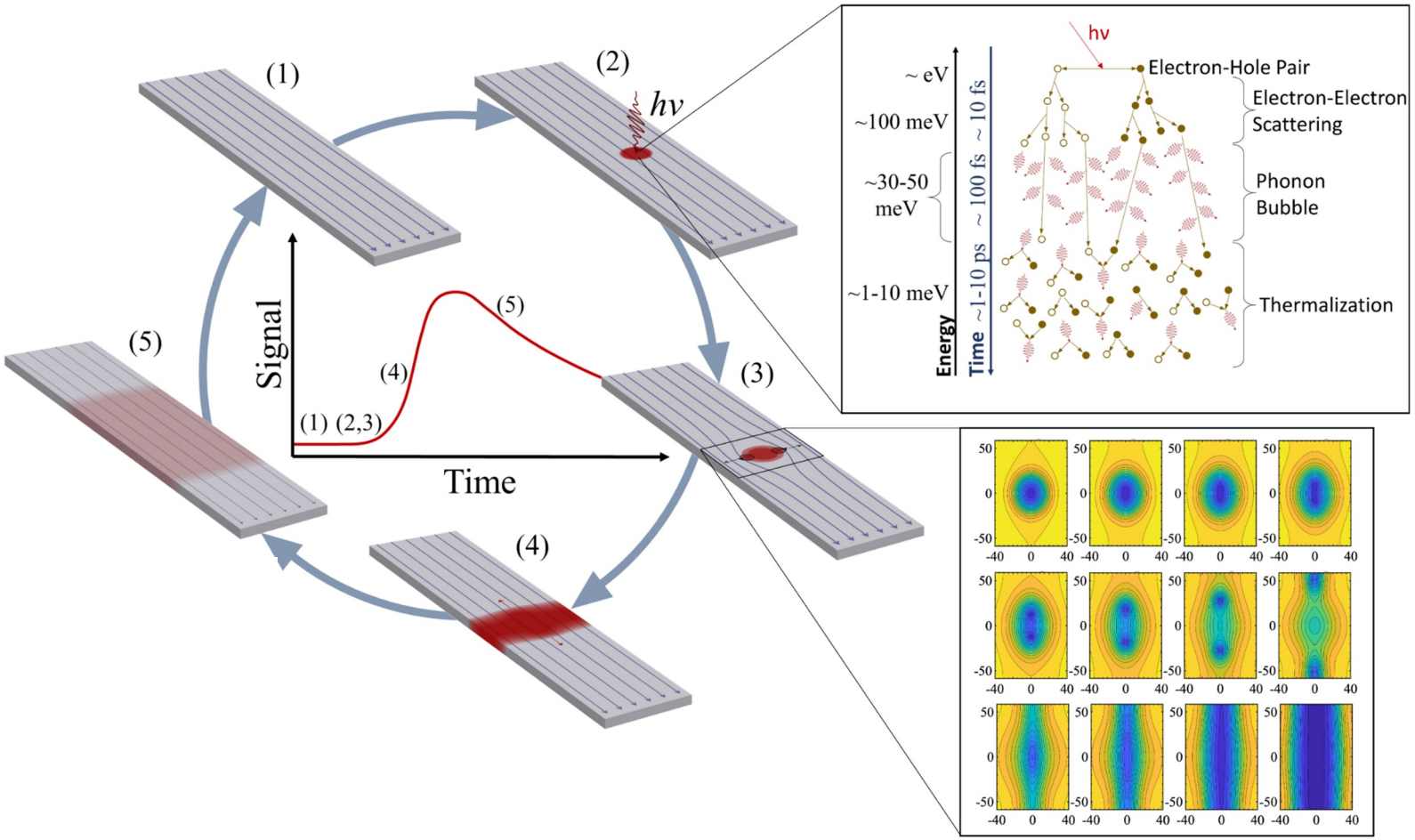
Typical SNSPD

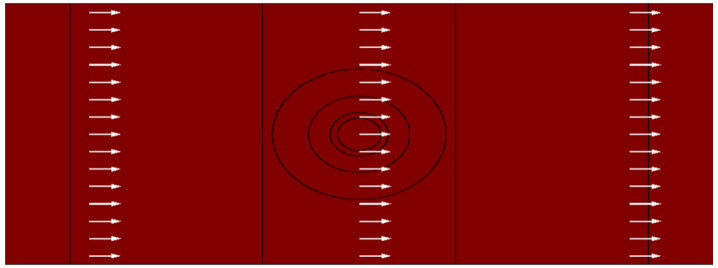


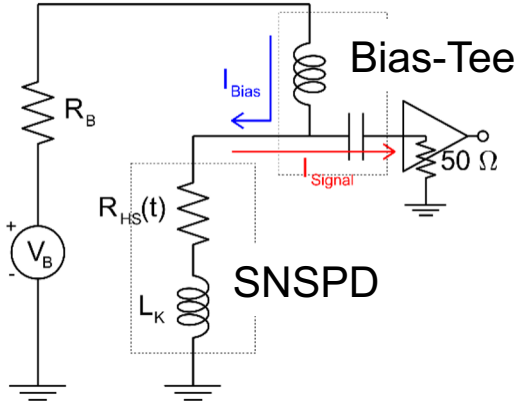
optical image

[1] Image from Wollman et al, J. of Astronomical Telescopes, Instruments, and Systems, 7(1), 011004 (2021). doi.org/10.1117/1.JATIS.7.1.011004

SNSPD Operation



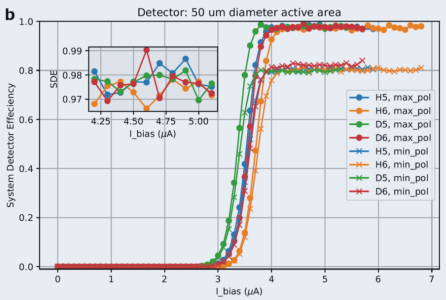




[2] J. Allmaras (2020) *Modeling and Development of Superconducting Nanowire Single-Photon Detectors.* Dissertation (Ph.D.), California Institute of Technology. resolver.caltech.edu/CaltechTHESIS:05312020-201105584

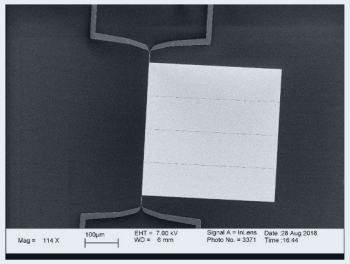
Current Status

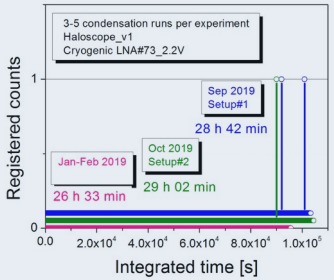
High Efficiency
98% SDE @ 1550 nm



[9] Reddy et al. Optica 7, 1649-1653 2020: doi.org/10.1364/OPTICA.400751

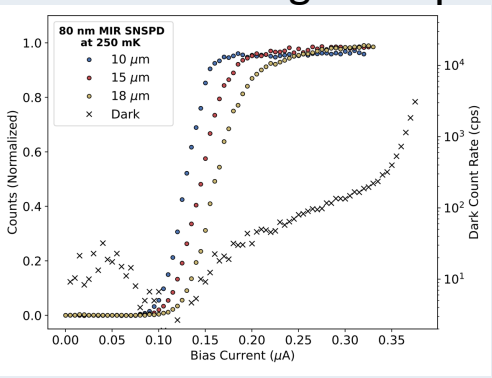
Low Dark Counts
~1e-5 cps



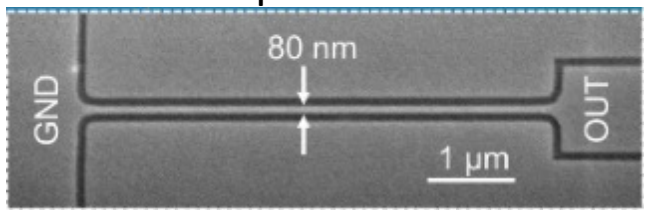


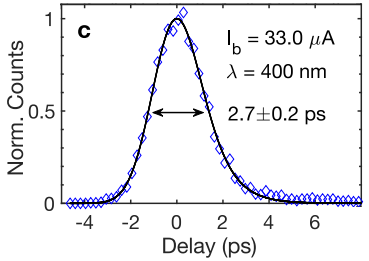
[10] Chiles et al. 2021 doi.org/10.48550/arXiv.2110.01582

UV – Mid-IR Operation
Photon counting to 18 μm

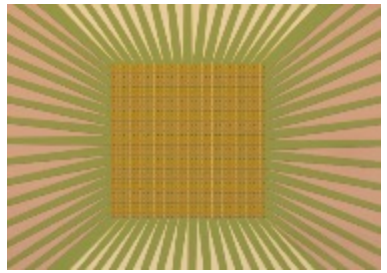


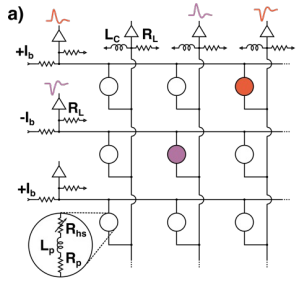
High Time Resolution
2.7 ps FWHM





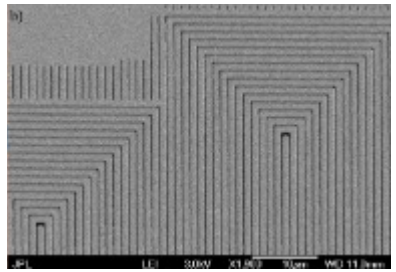
Kilopixel Array Formats
32x32 "row-column" array

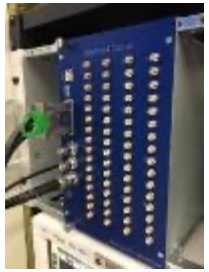




[12] Wollman et al. Opt. Express 27, 35279-35289 (2019) doi.org/10.1364/OE.27.035279

High Event Rate
1.2 Gcps in 64-element array





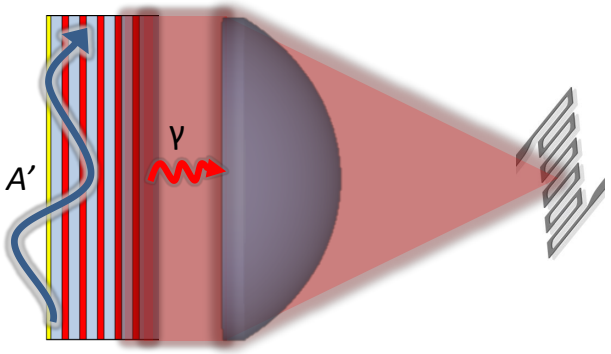
[13] M. Shaw, Proc. SPIE 11454, X-Ray, Optical, and Infrared Detectors for Astronomy IX, 1145411 (2020); doi.org/10.1117/12.2563483

Which metrics are important for dark matter searches?

[11] Korzh et al. 2020 *Nat. Photonics* **14,** 250–255: doi.org/10.1364/OPTICA.400751

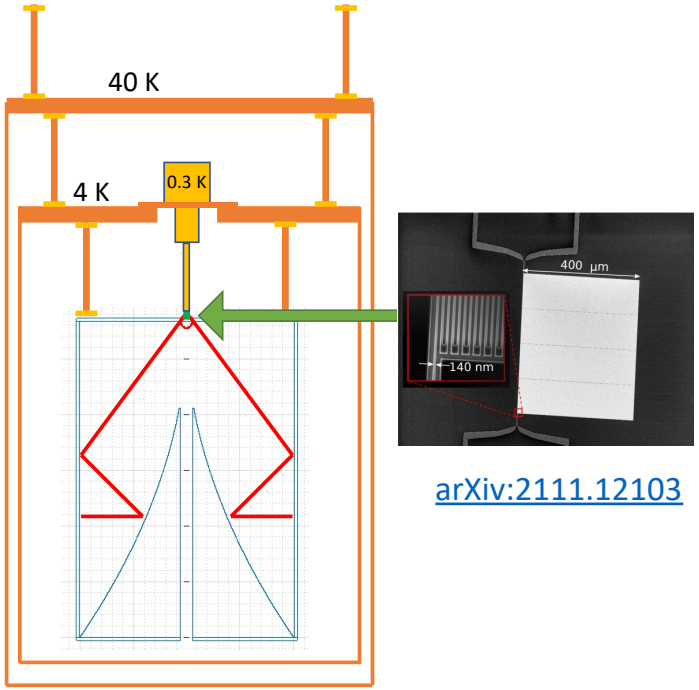
SNSPD for DM Detection

Light A' Multilayer Periodic Optical SNSPD Target (LAMPOST)

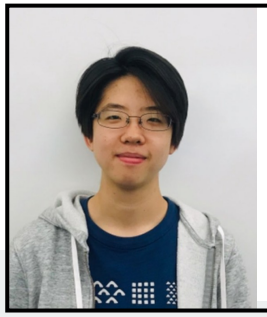


arXiv:2110.01582

Broadband Reflector Experiment for Axion Detection (BREAD)



arXiv:2111.12103



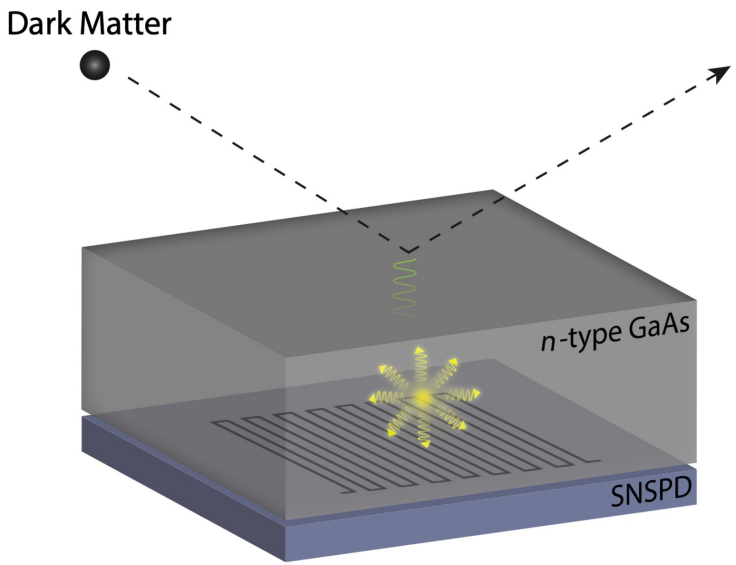
Christina Wang's talk

Nov 30, 2022, 1:55 PM

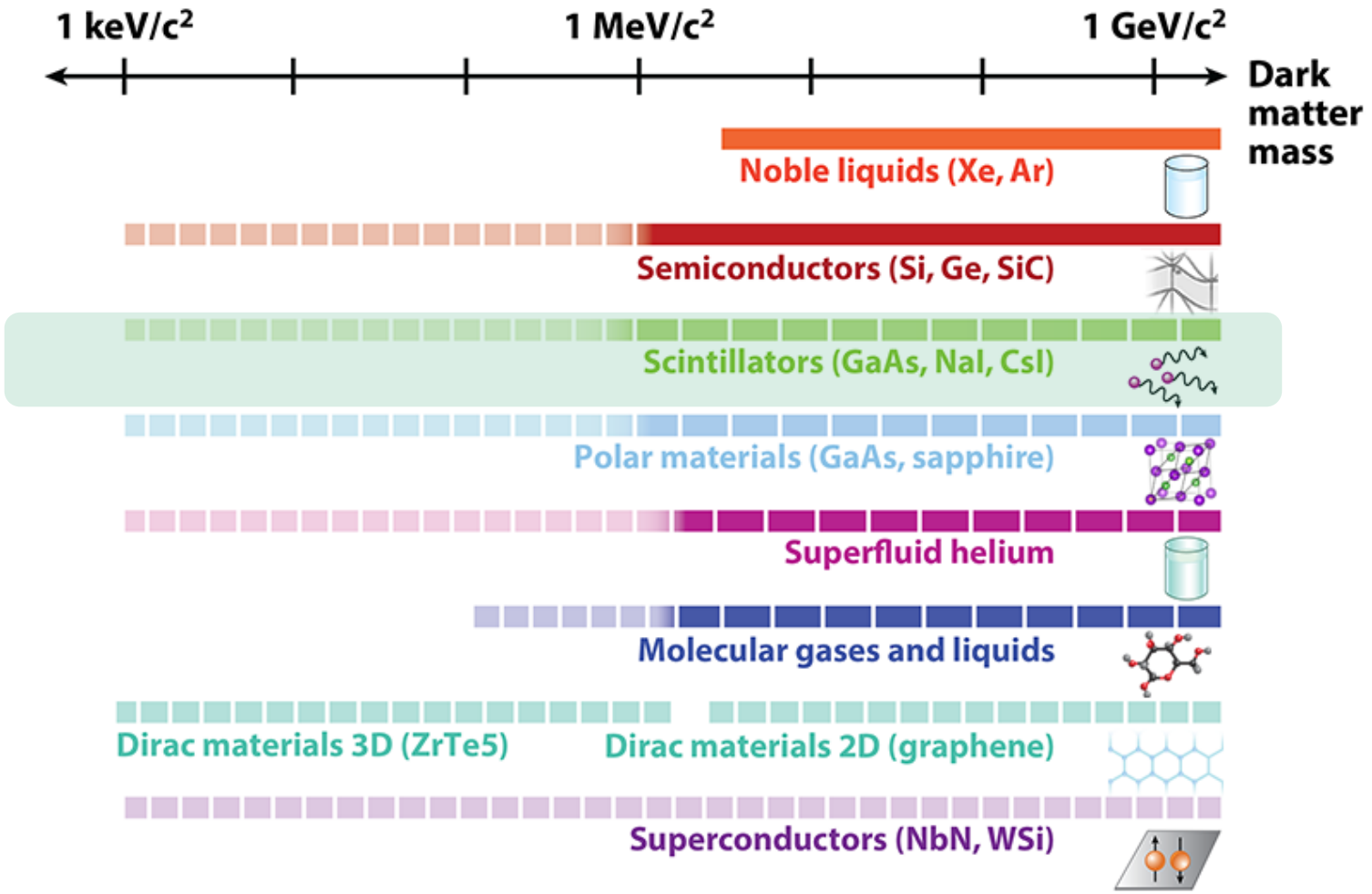
20m

Lecture Hall 2 (Wang Center)

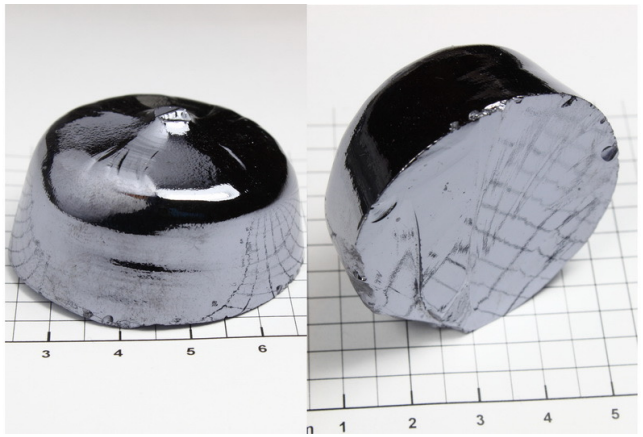
This Talk: My PhD Thesis Project

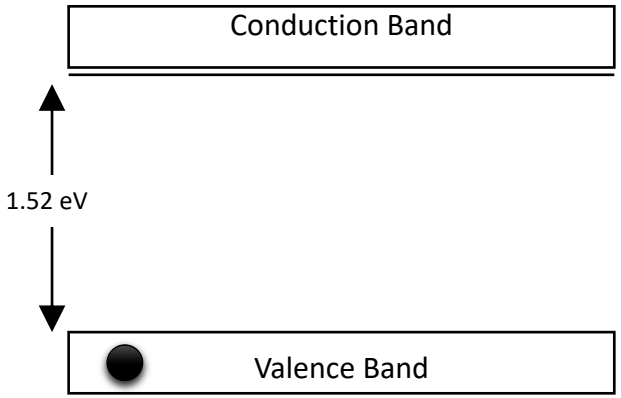


Scintillators for Sub-GeV Dark Matter Searches



n-type GaAs (Si, B)





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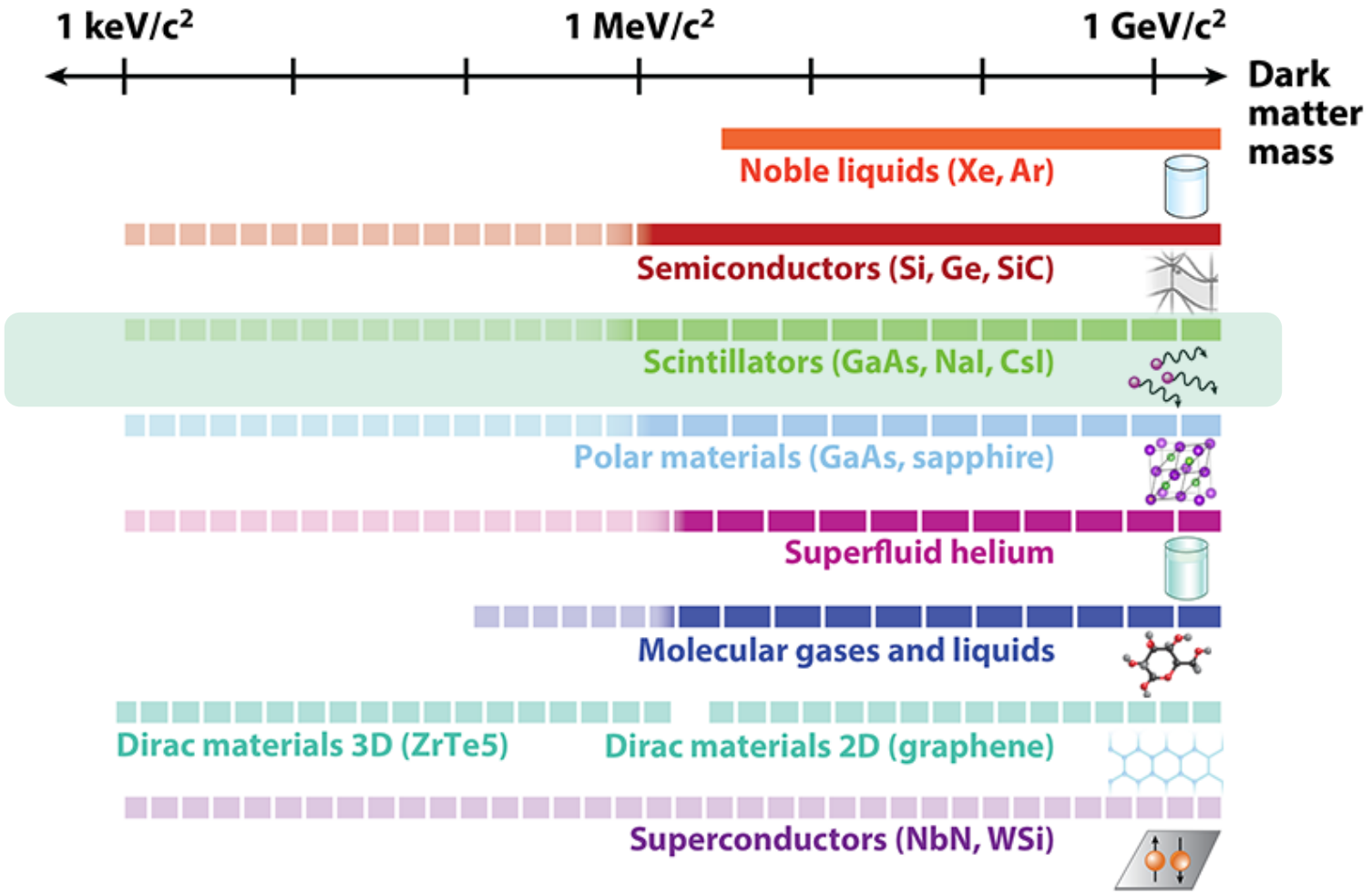

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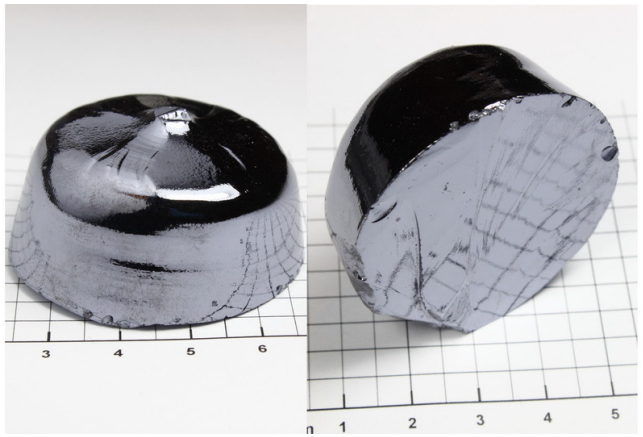
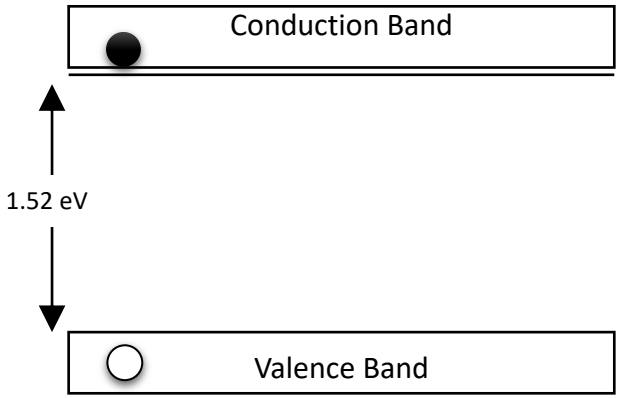
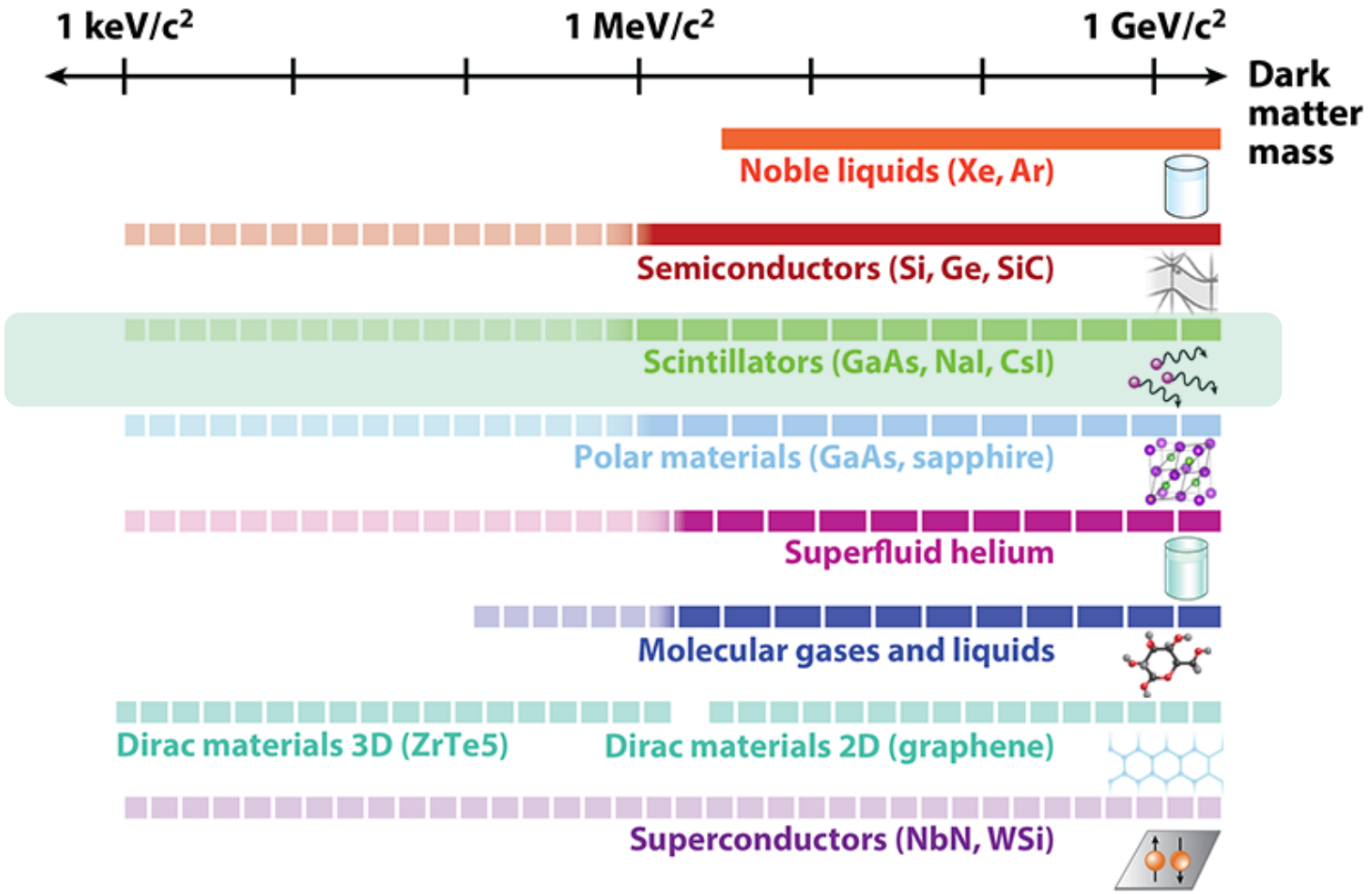
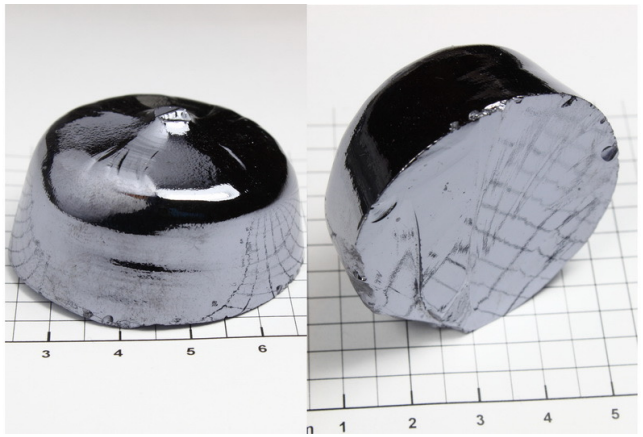


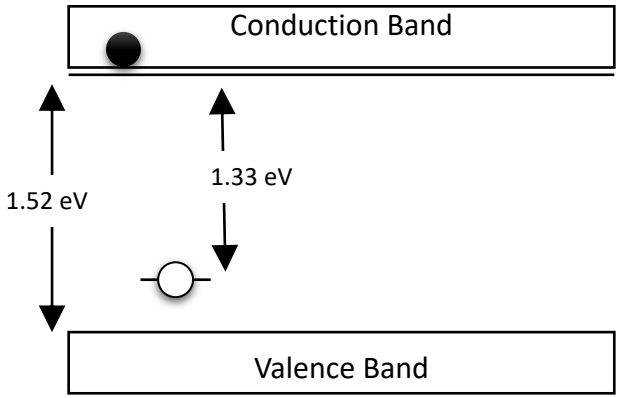


Scintillators for Sub-GeV Dark Matter Searches

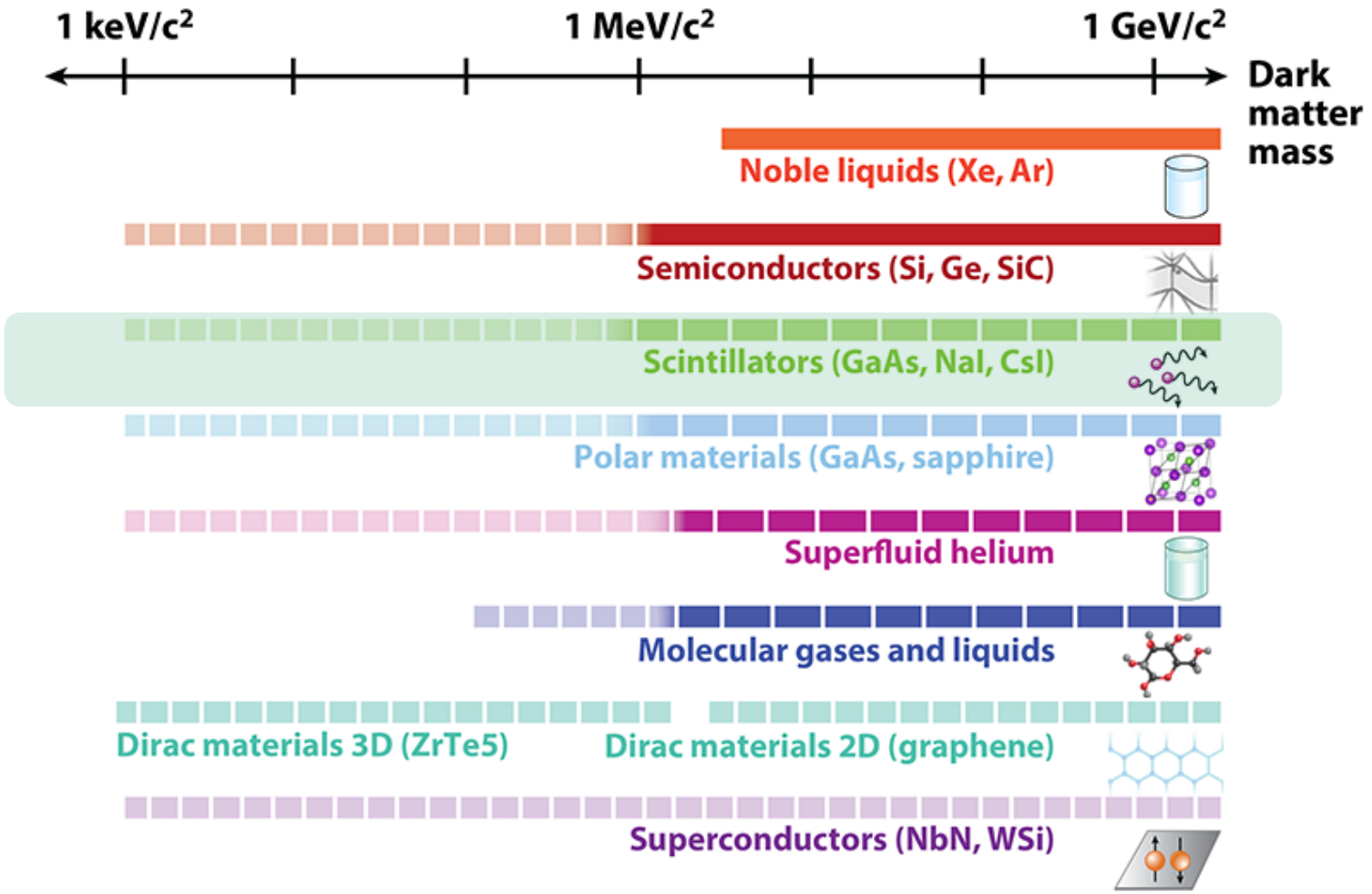


n-type GaAs (Si, B)





Scintillators for Sub-GeV Dark Matter Searches



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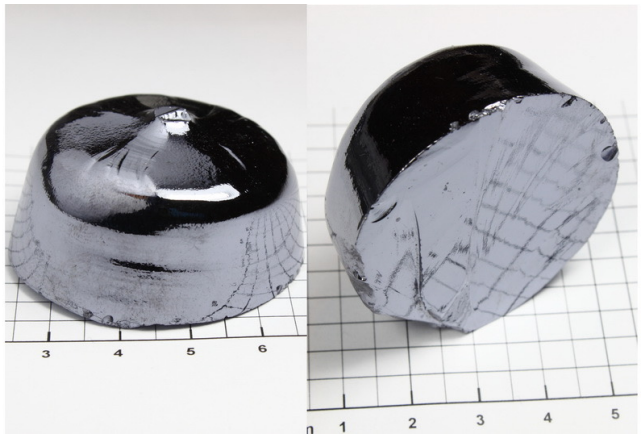
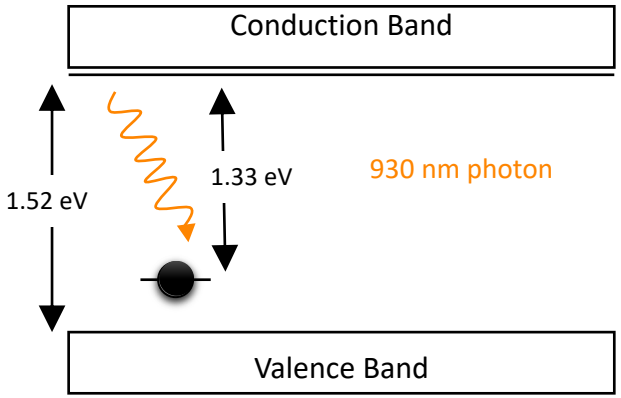
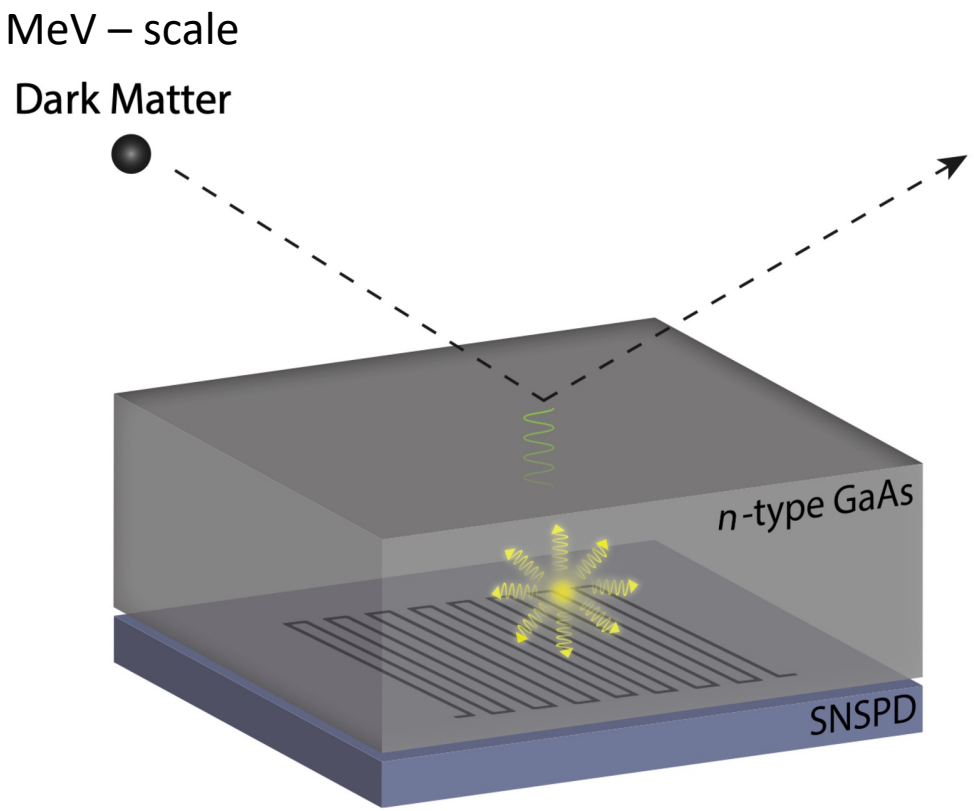
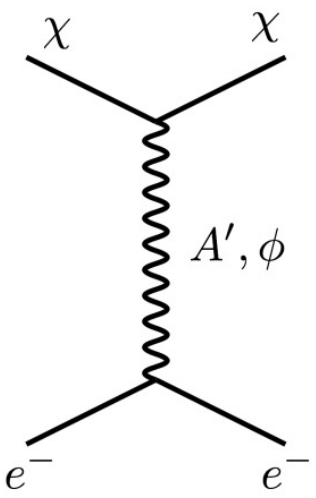


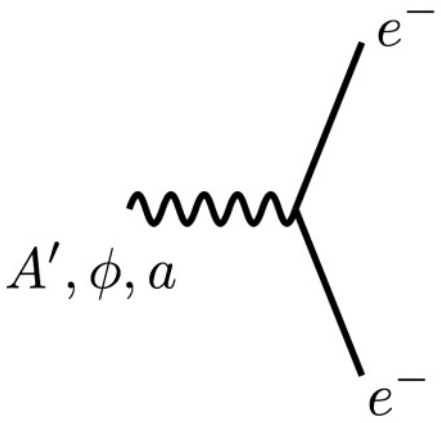


Detection Concept



- Interactions probed
  - *Absorption* – DM mass $m_x\, c^2$ deposited
  - *Scattering* – DM kinetic energy $m_x\, v^2$ deposited



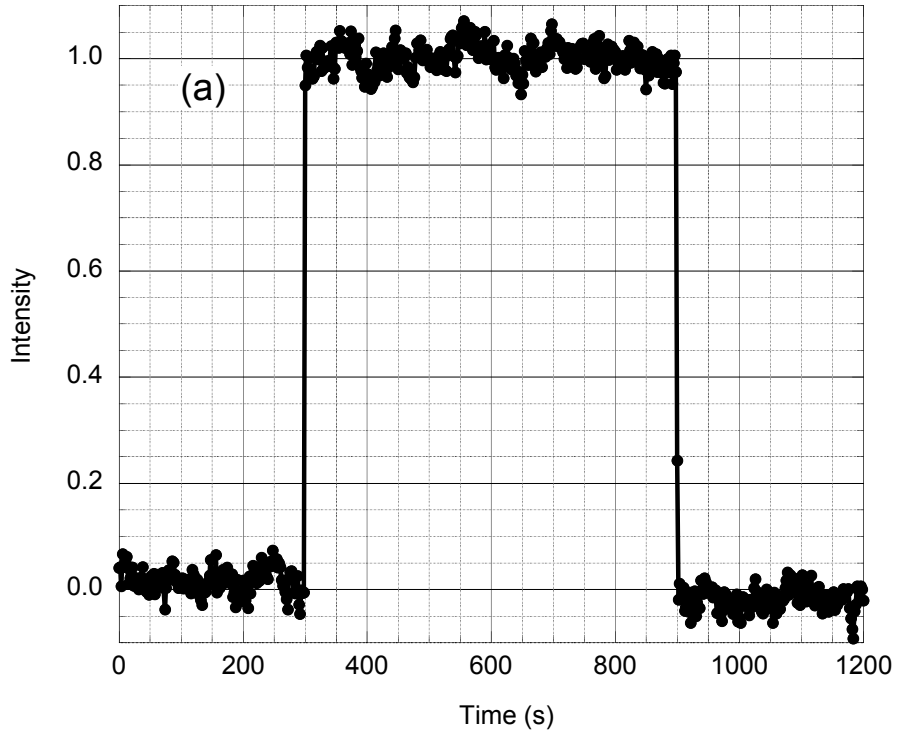


[14] Battaglerieri et al. 2017 doi.org/10.48550/arXiv.1707.04591

Advantages of this Approach

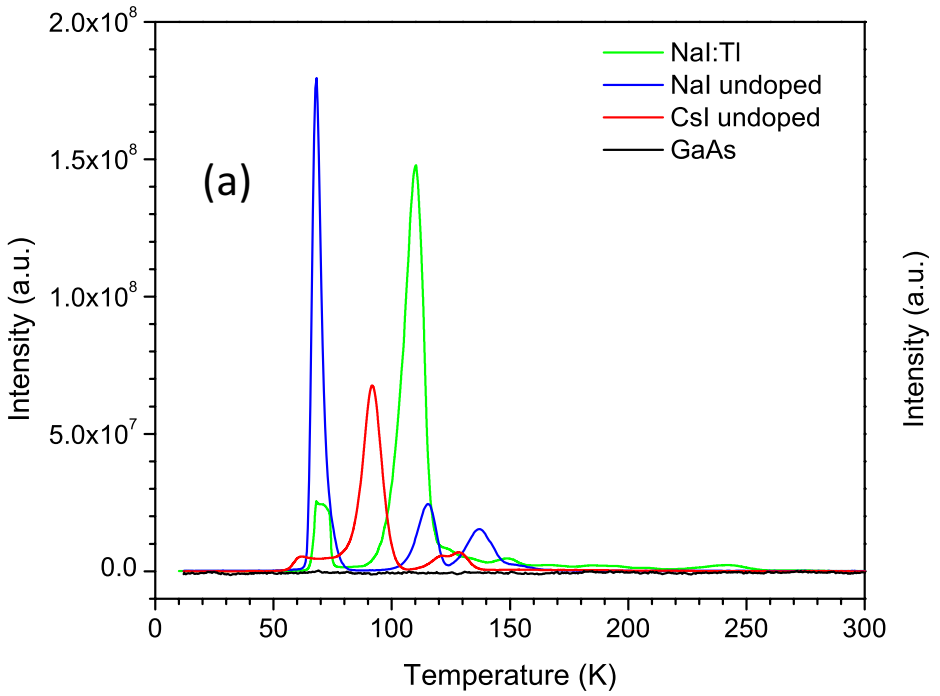
n-type GaAs

- Commercially available
- No afterglow
- Luminosities >100 photons/keV observed without anti-reflective coatings **at 10K**



Large-area SNSPDs

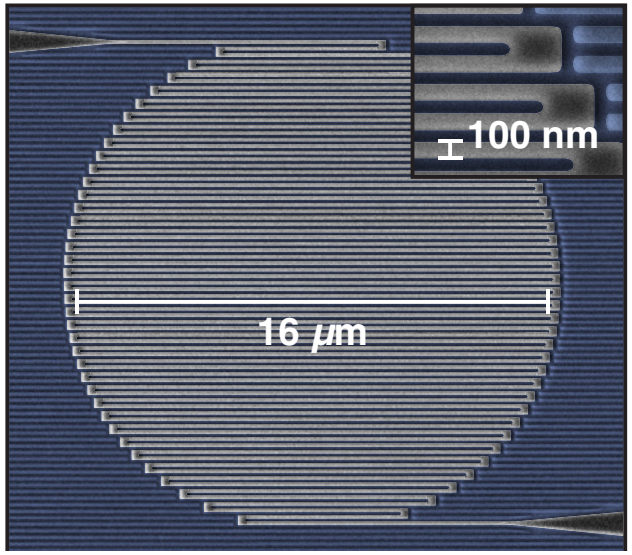
- Low intrinsic dark count rate
- Near IR operation
- Cryogenic operation

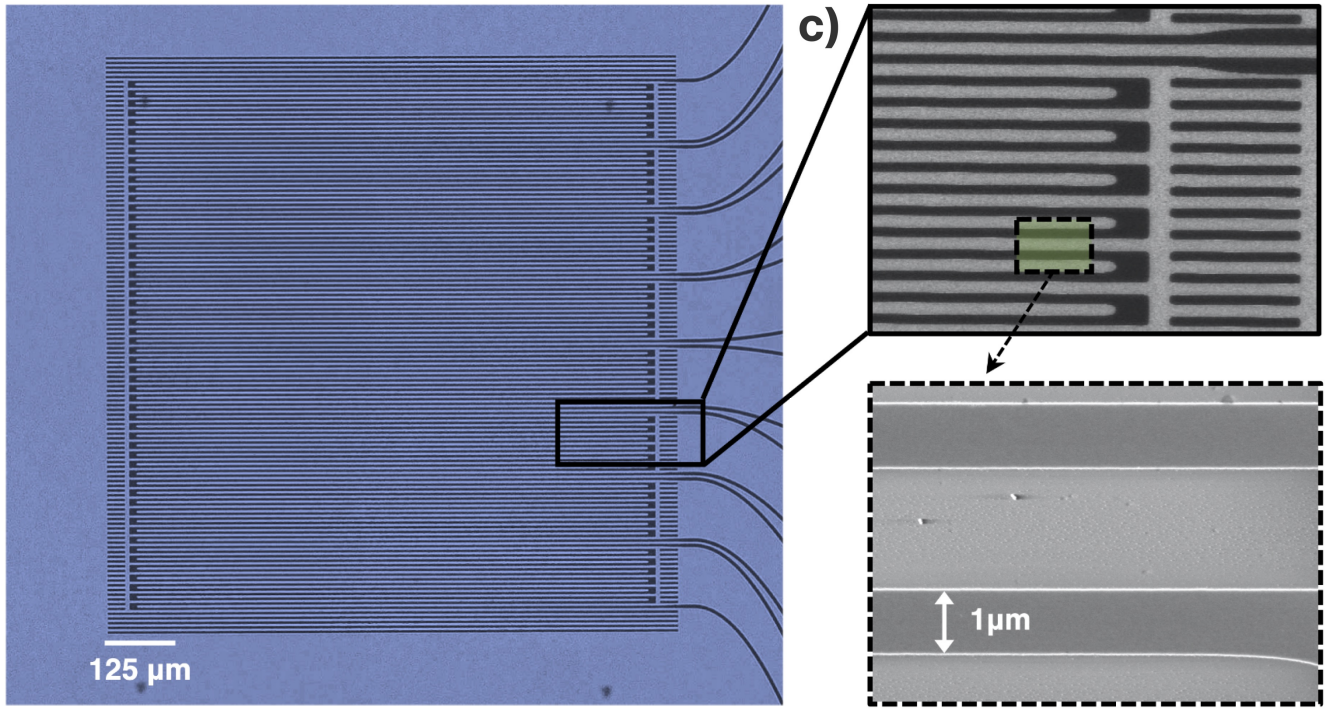


[19] Derenzo et al. Journal of Applied Physics **123**, 114501 (2018); https://doi.org/10.1063/1.5018343

Large Active Area SNSPDs

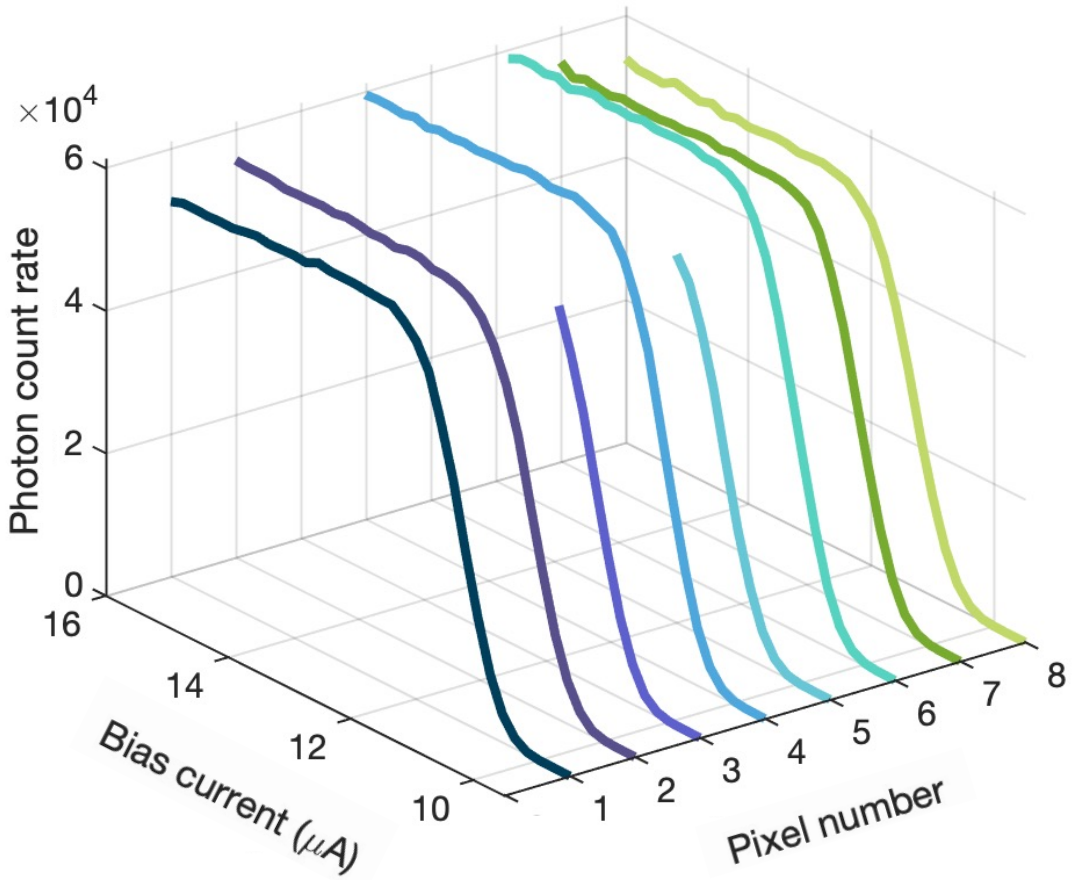
- WSi (silicon rich)
- **1mm^2 active area**; 8 pixels
- Wire width: 1µm (novel regime)
- Fill factor = 0.25
- Electron beam and Photolithography





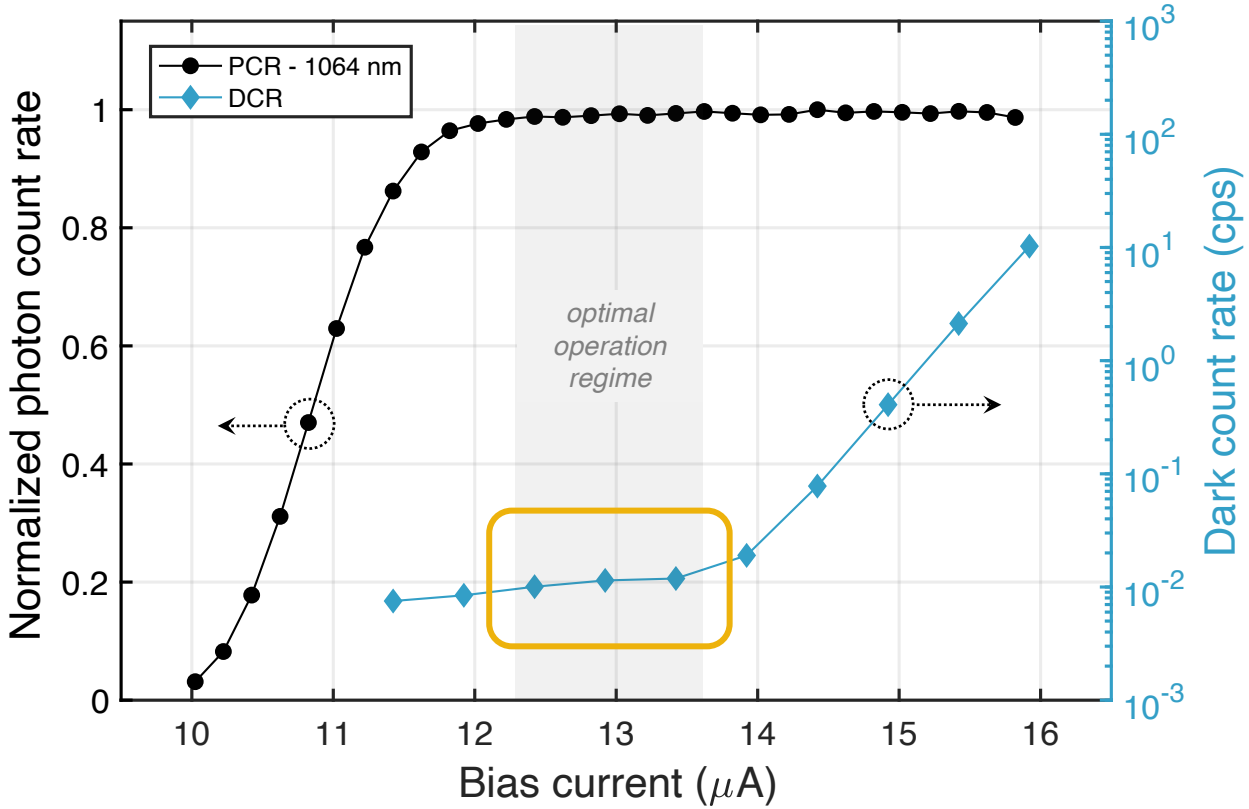
[22] Luskin et al. 2022: Large active-area superconducting microwire detectors for sub-GeV dark matter searches; manuscript in preparation

Photoresponse and Dark Count Rate



800 mK

λ = 1064 nm



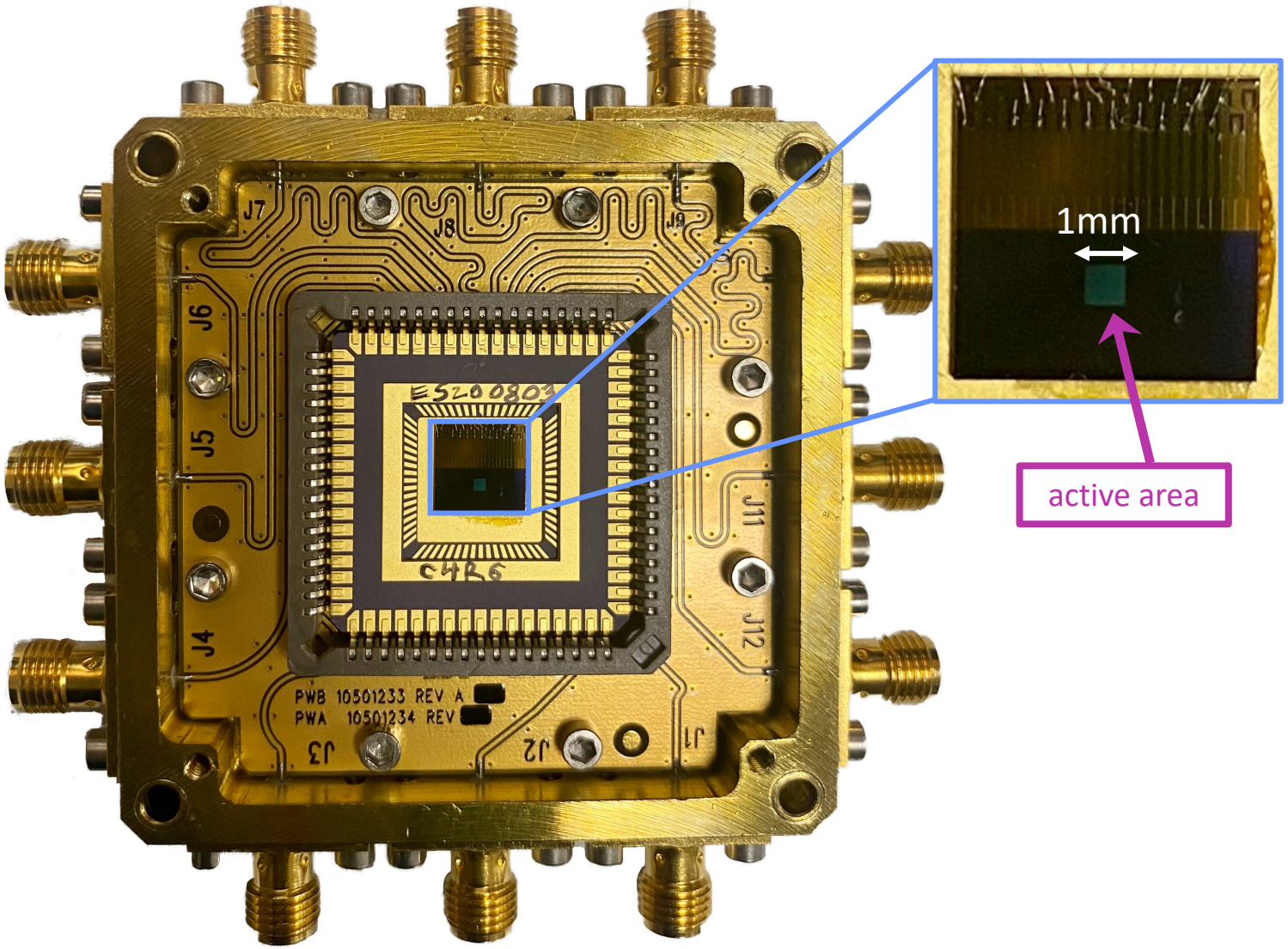
- ✓ *Single photon sensitivity in all pixels*
- ✓ *Saturated internal detection efficiency in 6/8*

Dark count rate: 10^{-2} cps

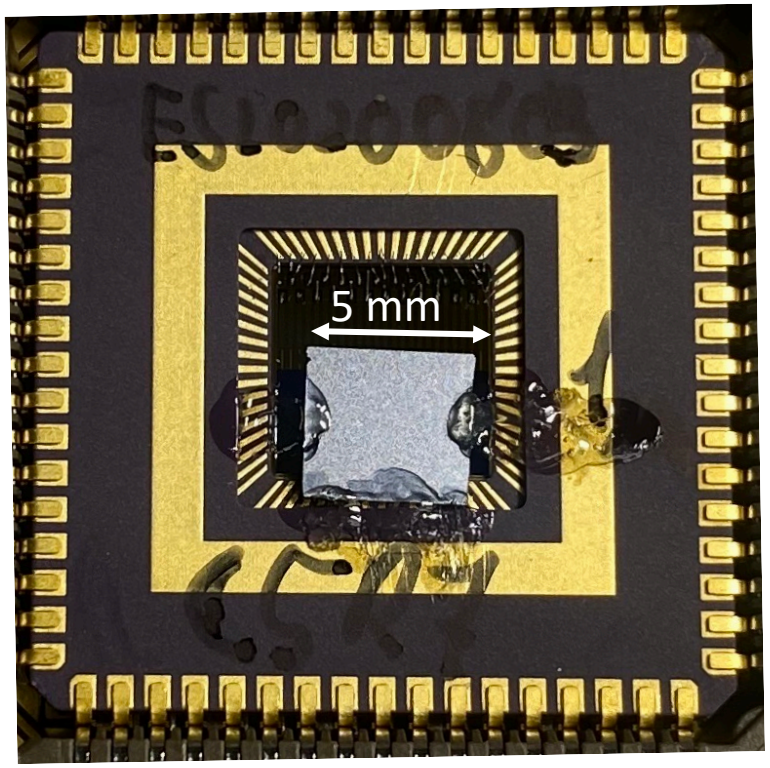
[22] Luskin et al. 2022: Large active-area superconducting microwire detectors for sub-GeV dark matter searches; manuscript in preparation

Proof-of-Concept System

1 mm² SNSPD array

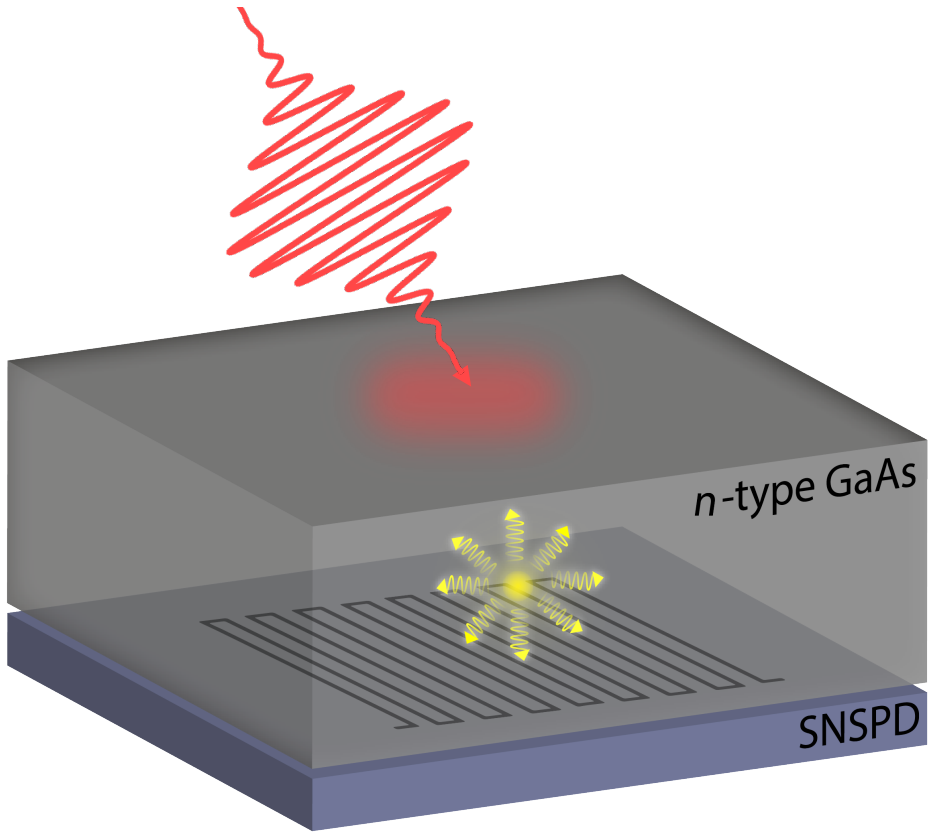


5 x 5 x 0.625 mm³ n-type GaAs



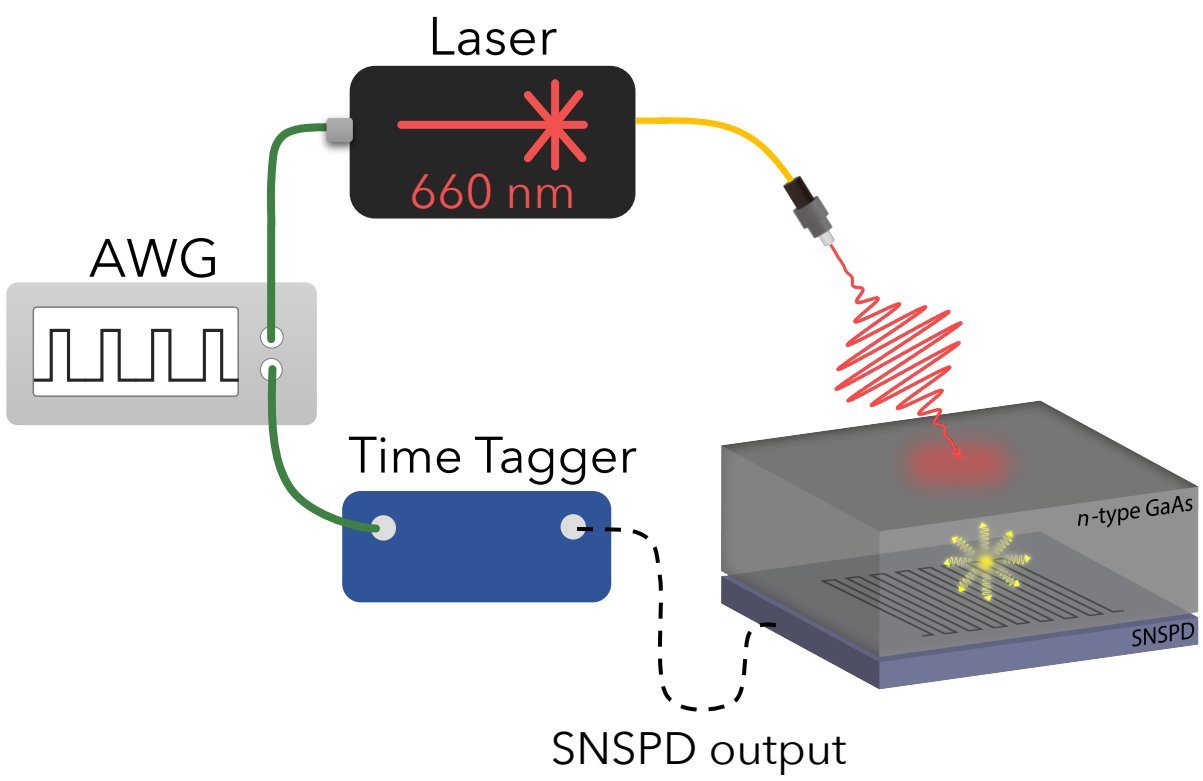
Target mass: 83 mg

Optical Excitation Experiments



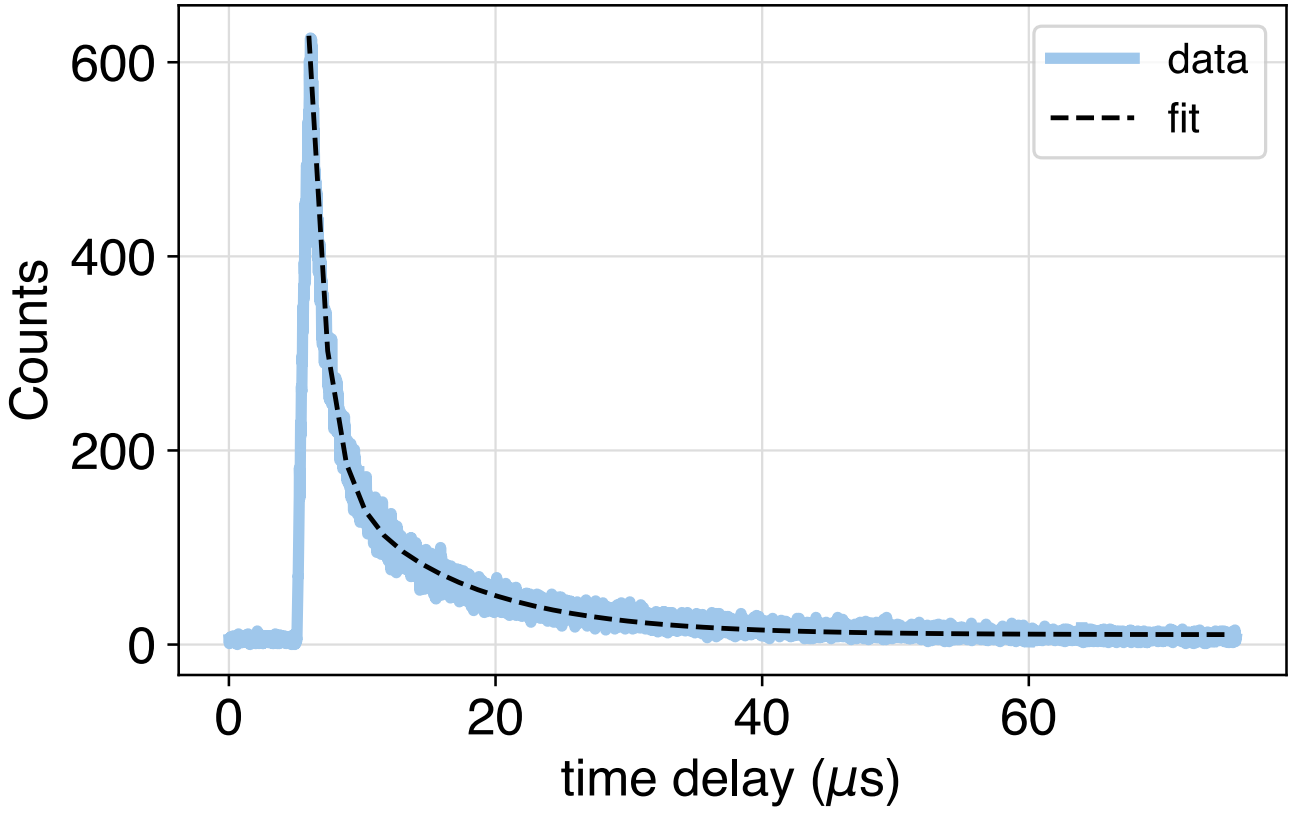
- Excite *n*-type GaAs with pulsed 660nm laser
- Detect scintillation photons with SNSPD using time tagger
  - Timescale measurements
  - Calibrated light yield measurements:
    - *in progress*

Optical Characterization: Timescale Measurement

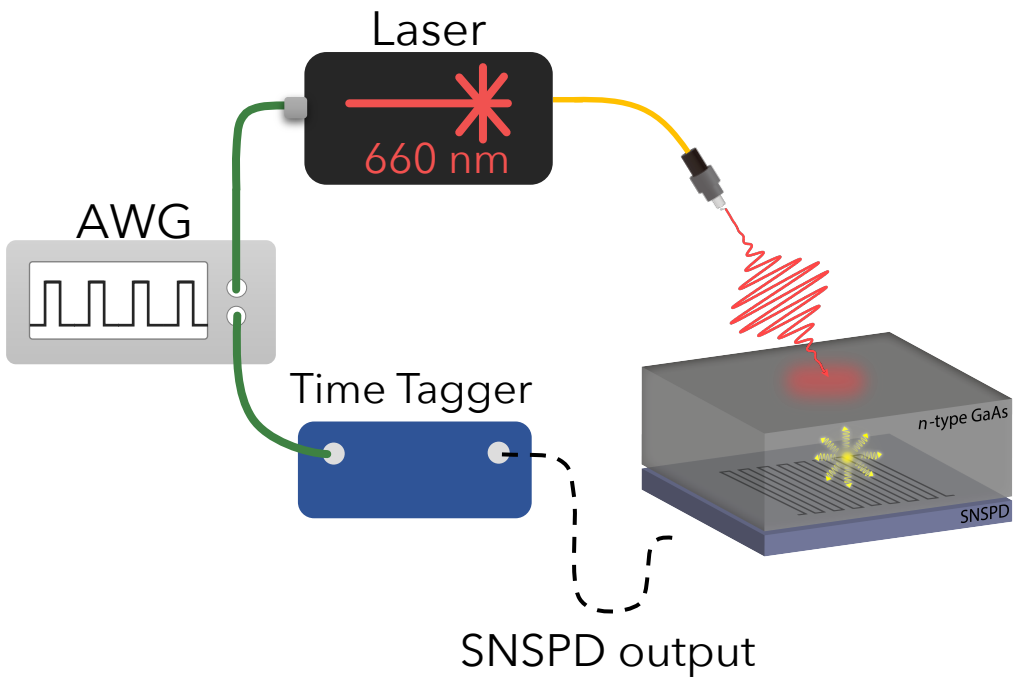


- Optical excitation w/ pulsed **660 nm** laser
- Rep. rate **10 kHz**, ns width
- Histogram time delay between laser pulse and SNSPD pulse

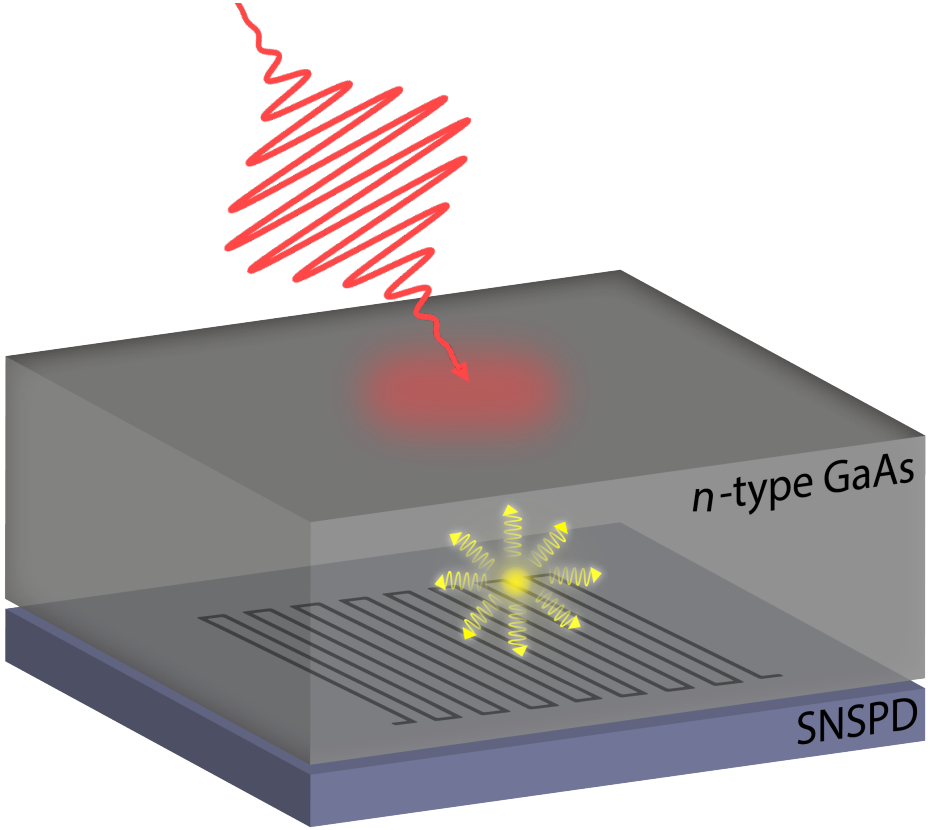
Optical Characterization: Timescale Measurement



- Optical excitation w/ pulsed **660 nm** laser
- Rep. rate **10 kHz**, ns width

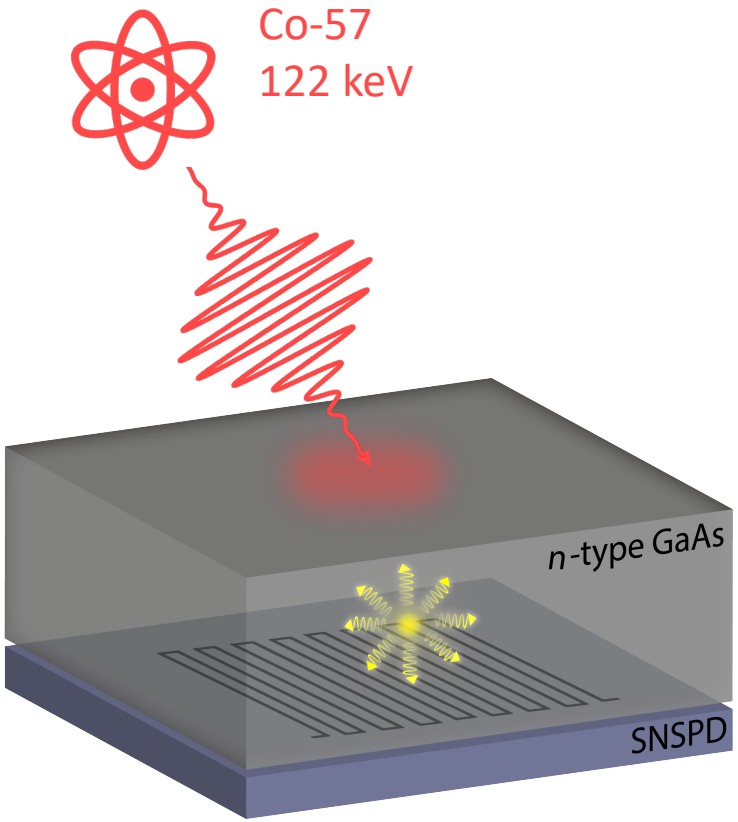


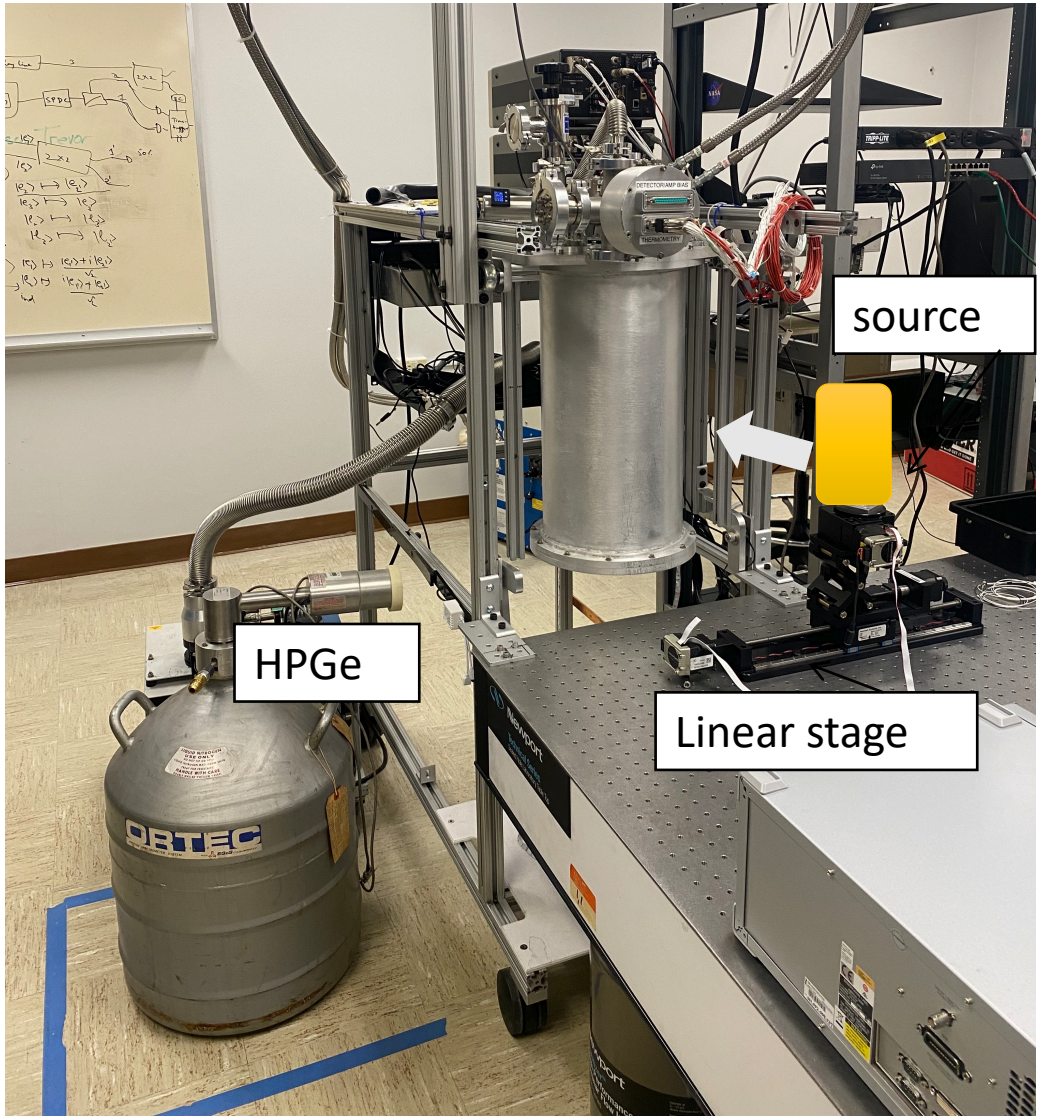
Optical Excitation Experiments



- Excite *n*-type GaAs with pulsed 660nm laser
- Detect scintillation photons with SNSPD using time tagger
  - Timescale measurements
  - Calibrated light yield measurements: upcoming

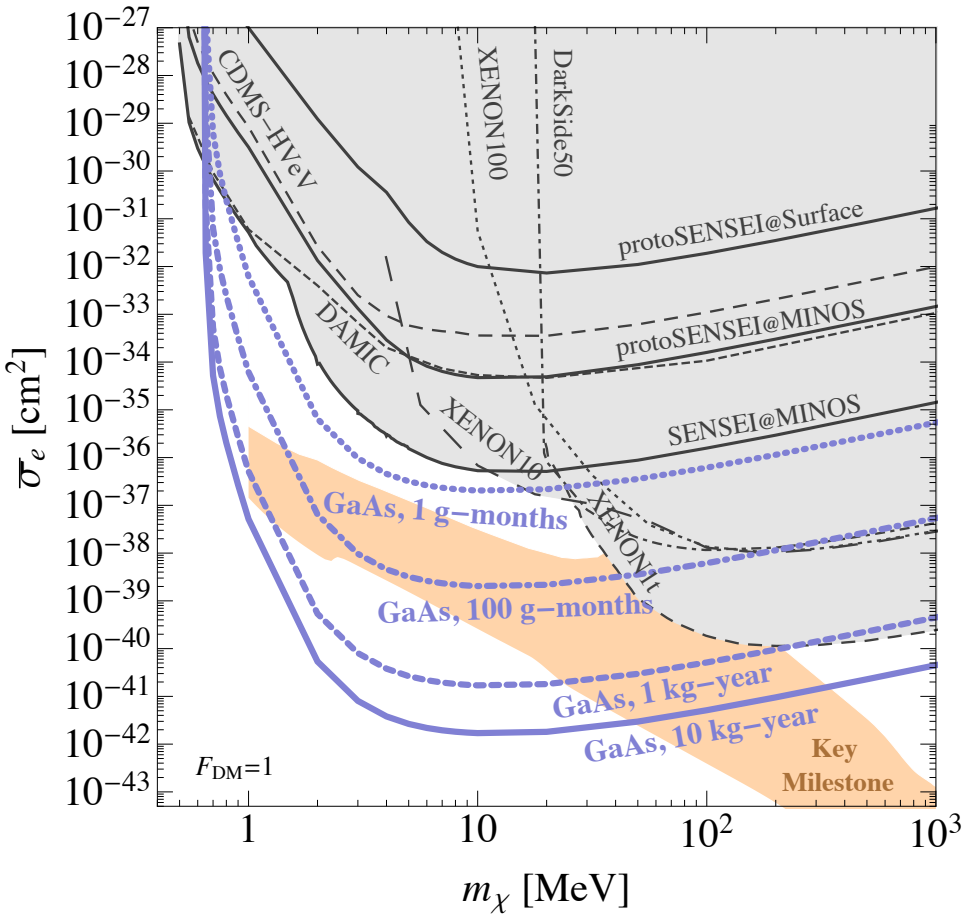
Energy-tagged X-ray Excitation: Next Steps





- Light yield measurement
  - Instead of X photons out per 660nm photon in
  - X photons out per keV in
- Digitizer readout

Scaling the experiment



Enabling Developments
- Optical lithography
- Multiplexing techniques

- **<u>1g target mass</u>**
  GaAs thickness: 0.5 cm
  SNSPD pixel size: 1mm^2
  → approx. 38 SNSPD pixels needed
  doable now

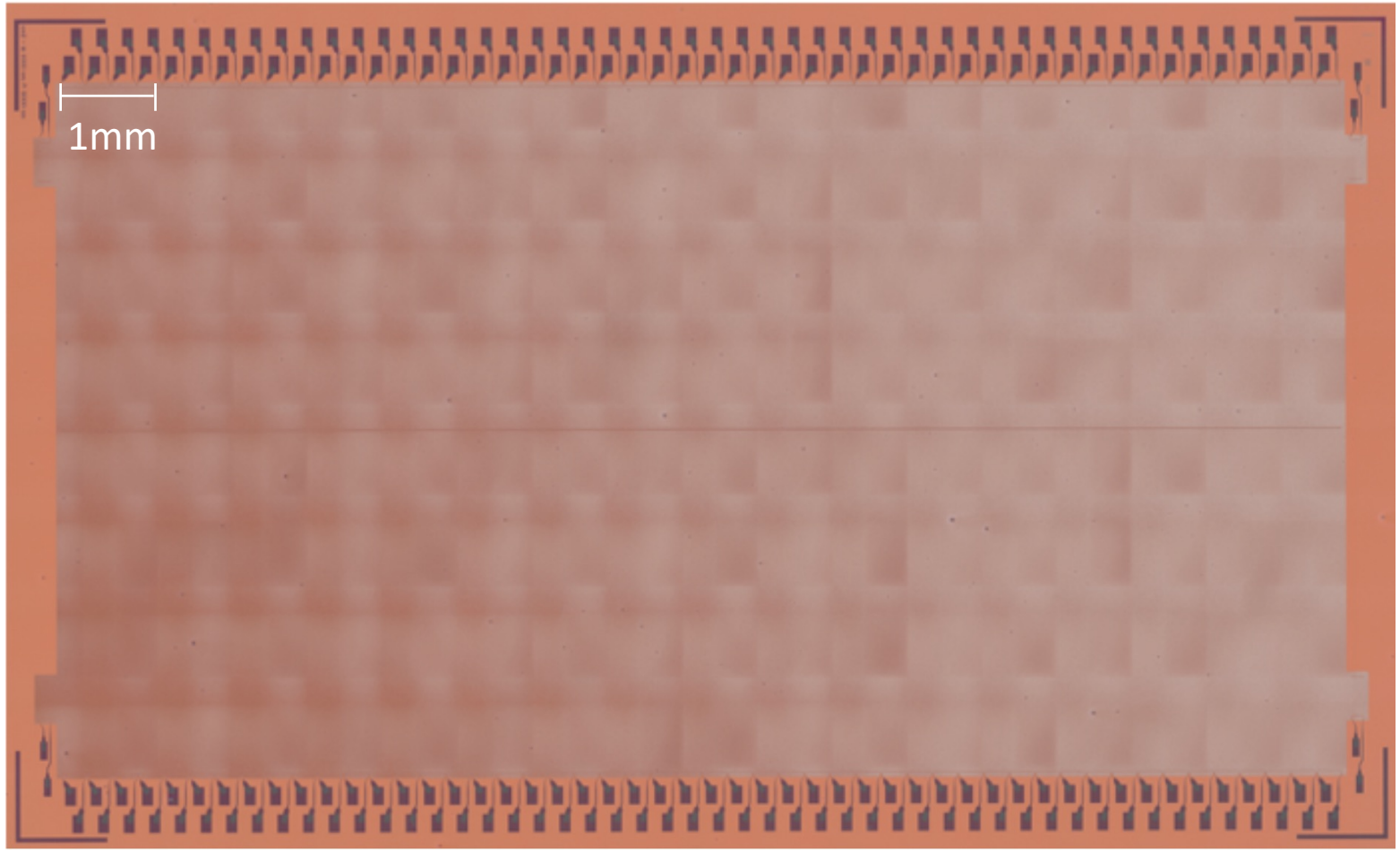
- **<u>1 kg target mass</u>**
  GaAs thickness: 10 cm
  SNSPD module-size 1cm^2
  (100 pixels/module)
  → approx. 19 modules
  1900 pixels

- **<u>10 kg target mass</u>**
  GaAs thickness: 10 cm
  SNSPD module-size of 2cm^2
  (100 pixels/module)
  → approx. 47 modules
  4700 pixels

How to efficiently fabricate this many large pixels?

How to scalably readout this many pixels?

Scaling SNSPD Active Areas



- New 100 pixel arrays
- 1µm-width WSi wires
- Active area: 1.05 cm^2
- Test yield

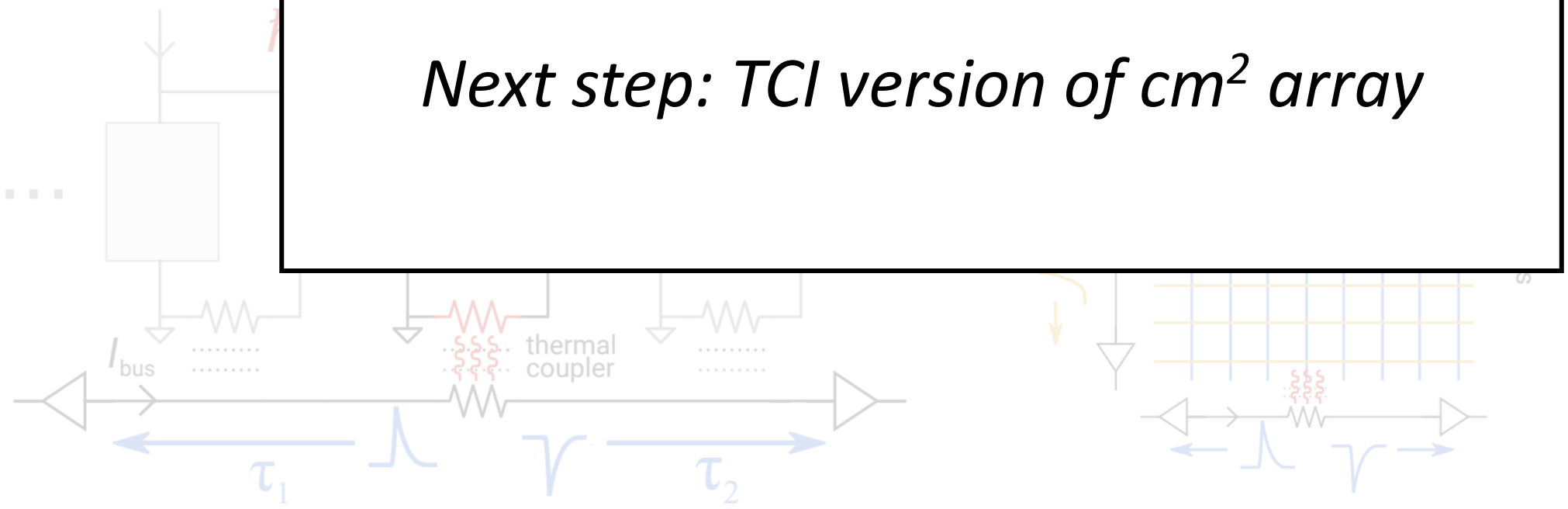
L_k proportional to (length/width) of device

TCI Multiplexing: *Path to cm² Active Area*

Thermal Coupled Imager (TCI)

- Combination of time-of-flight delay lines and thermal couplers
- Demonstrated on 32 x 32 array with 1um-wide WSi wires

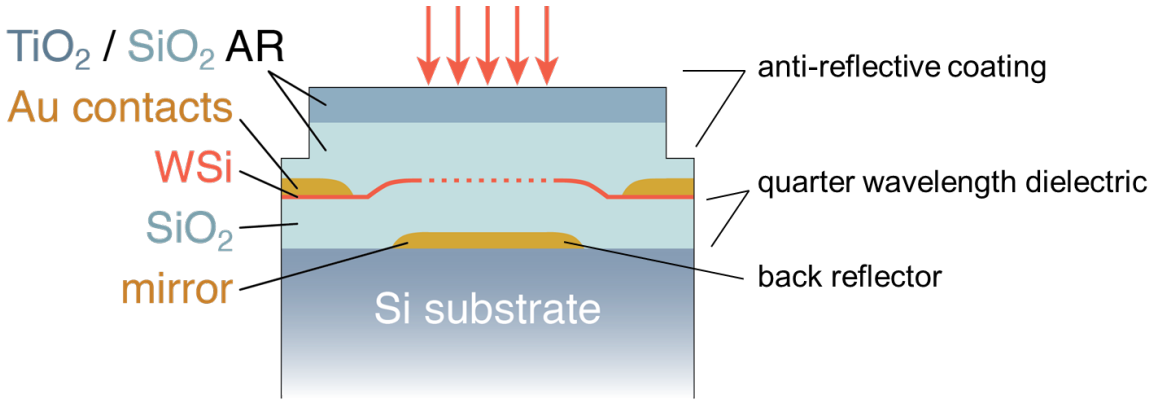
Next step: TCI version of cm² array

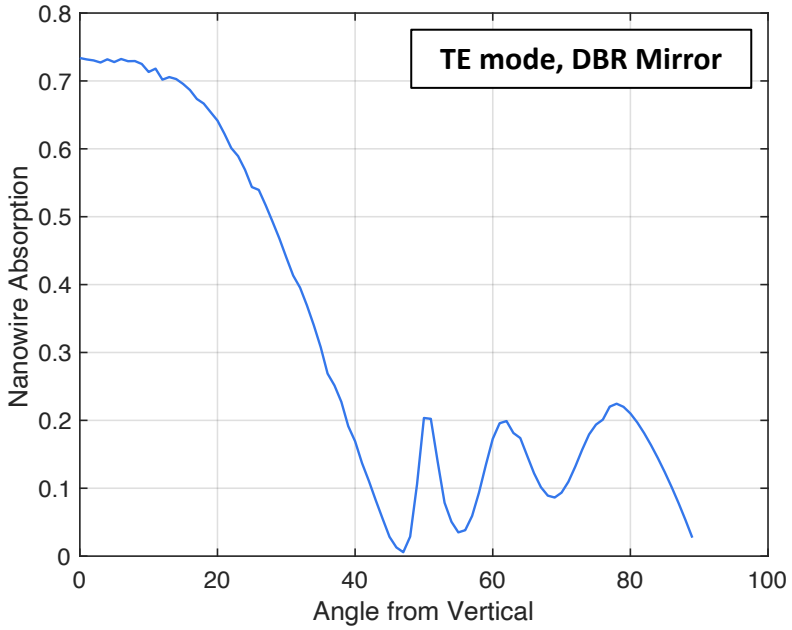


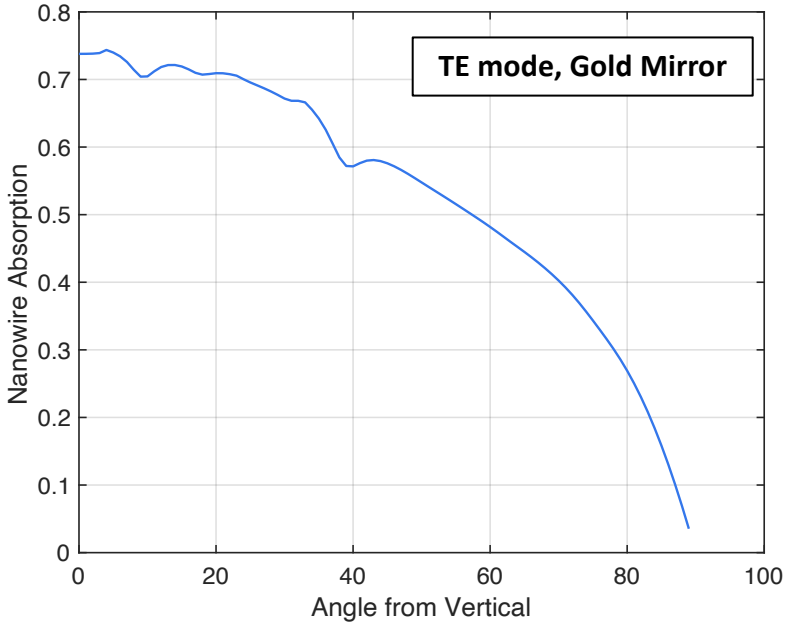
[27] McCaughan et al. 2022 doi.org/10.48550/arXiv.2112.04705

Increasing Efficiency: Optical Stack Design

- Designing with rigorous coupled-wave analysis (RCWA)
- Goal: maximize absorption of 930nm in nanowire
  - *No stack*: ~5% efficiency for FF 0.25







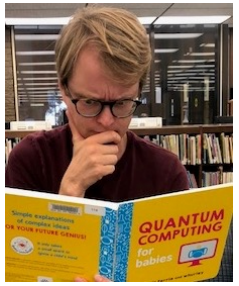
[5] J. Allmaras (2020) *Modeling and Development of Superconducting Nanowire Single-Photon Detectors.* Dissertation (Ph.D.), California Institute of Technology. resolver.caltech.edu/CaltechTHESIS:05312020-201105584

Summary

- *n*-type GaAs as a cryogenic scintillator + SNSPDs as a novel sub-GeV DM experiment
  - Optical characterization
  - Scaling from proof-of-concept stage to robust experiment
- Applications in low mass dark matter detection are driving the SNSPD development
  - Reaching larger active areas

JPL SNSPD Development Team

JPL Staff



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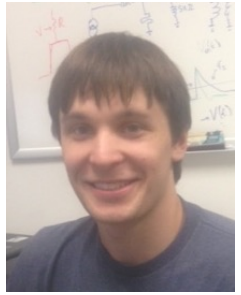
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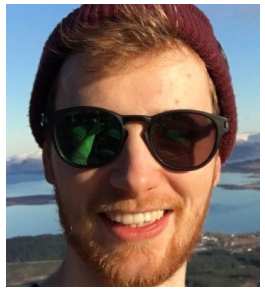
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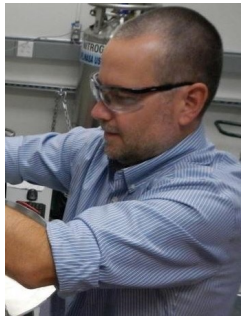
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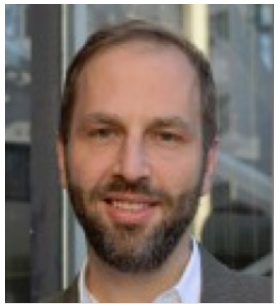
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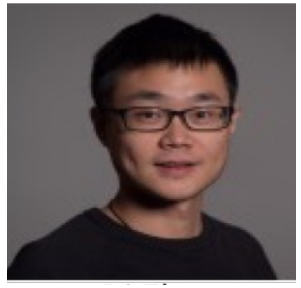
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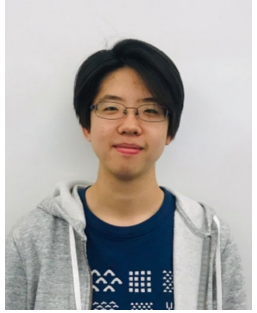
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