Single Photon Detection in GQuEST

Alex Ramirez
Caltech Graduate Student in Physics

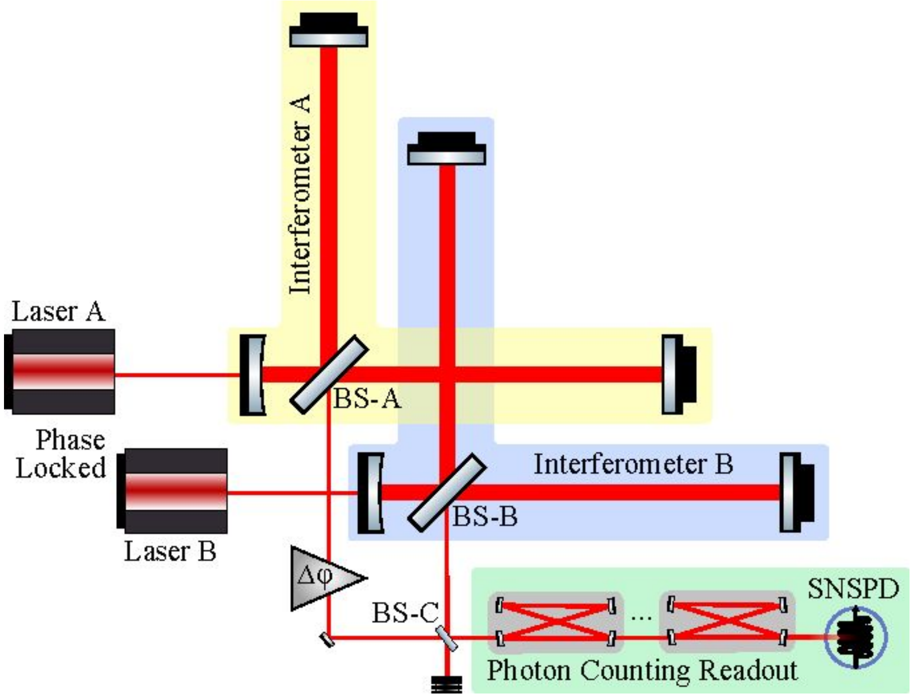
QuRIOS Collaboration Meeting
March 22nd, 2024

Agenda

- GQuEST detection requirements and readout
- Why SNSPD's, and what are they?
- SNSPD innovations and integrations in GQuEST
- Status of SNSPDs for GQuEST at Caltech
- Preliminary photon counting with avalanche photodiodes

GQuEST Goals for Detecting Quantum Gravity

- Searching for a signal on the order of $(10^{-22}\ \mathrm{m}/\sqrt{\mathrm{Hz}})^2$
- Sensitive at ~15 MHz
- Surpass SQL with integrated single photon detection $(6 \cdot 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}})^2$
- Cross correlate two interferometers



Benefits of Homodyne Fringe Readout vs Photon Counting

Homodyne Fringe Readout

- Measure of time-dependence (phase/freq)
- Quantum Shot noise $(3 \cdot 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}})^2$
- $\mathrm{SNR}^2=9$ or $\sigma = 3$ significance for $\alpha = 1$
  - **2 months** per single detection
- $$\mathrm{SNR}^2_{\mathrm{fringe}} \approx T\Delta f \left(\frac{\overline{S}^{\phi}_L}{\overline{S}^{q}_L}\right)^2$$

Photon Counting Readout

- Measure of the power in the optical sidebands
- Classical Noise limited $(3 \cdot 10^{-21}\ \mathrm{m}/\sqrt{\mathrm{Hz}})^2$
- $\mathrm{SNR}^2=9$ or $\sigma = 3$ significance for $\alpha = 1$
  - **28 hours** per single detection
- $$\mathrm{SNR}^2_{\mathrm{counting}} \approx \frac{T\Delta\epsilon}{4} \frac{\left(\overline{S}^{\phi}_L\right)^2}{\overline{S}^{q}_L \overline{S}^{c}_L}$$

$$\overline{S}^{\phi}_L \quad \left(3 \cdot 10^{-22}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\right)^2$$

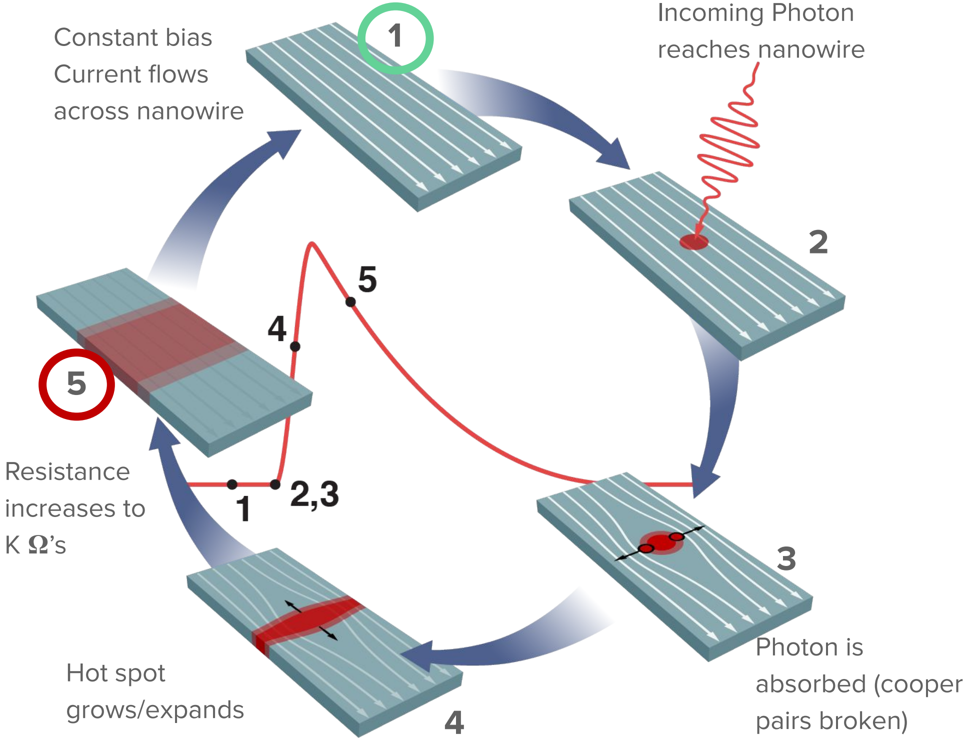
Motivation for Photon Counting with SNSPD's

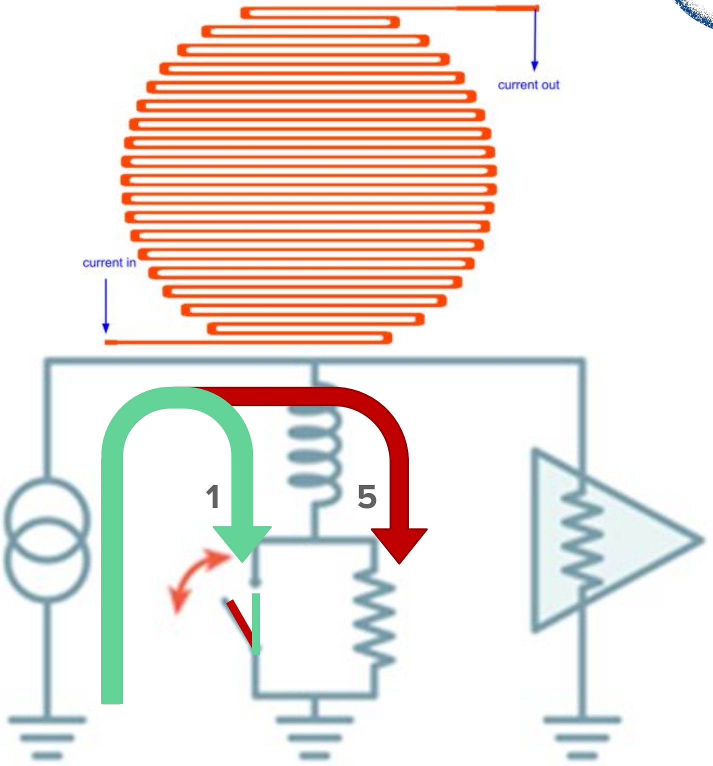
- SNSPD's offer a high speed and low noise approach to measuring photons
- Photon counting "avoids" quantum shot noise (but not classical noise)

Filtered signal photon flux	$\dot{N}^{\phi}_{\text{pass}}$	$1.4 \cdot 10^{-3}$ Hz
Filtered classical noise photon flux	$\dot{N}^{c}_{\text{pass}}$	$1.6 \cdot 10^{-2}$ Hz
Photon Detector Dark Count Rate	$\dot{N}^{d}$	$< 10^{-3}$ Hz

$$\mathrm{SNR}^2_{\text{counting}} = \int_0^T \frac{\left(\dot{N}^{\phi}_{\text{pass}}\,\mathrm{d}t\right)^2}{\left(\dot{N}^{\phi}_{\text{pass}} + \dot{N}^{c}_{\text{pass}} + \dot{N}^{d}\right)\mathrm{d}t}.$$

What are Superconducting Nanowire Single Photon Detectors?

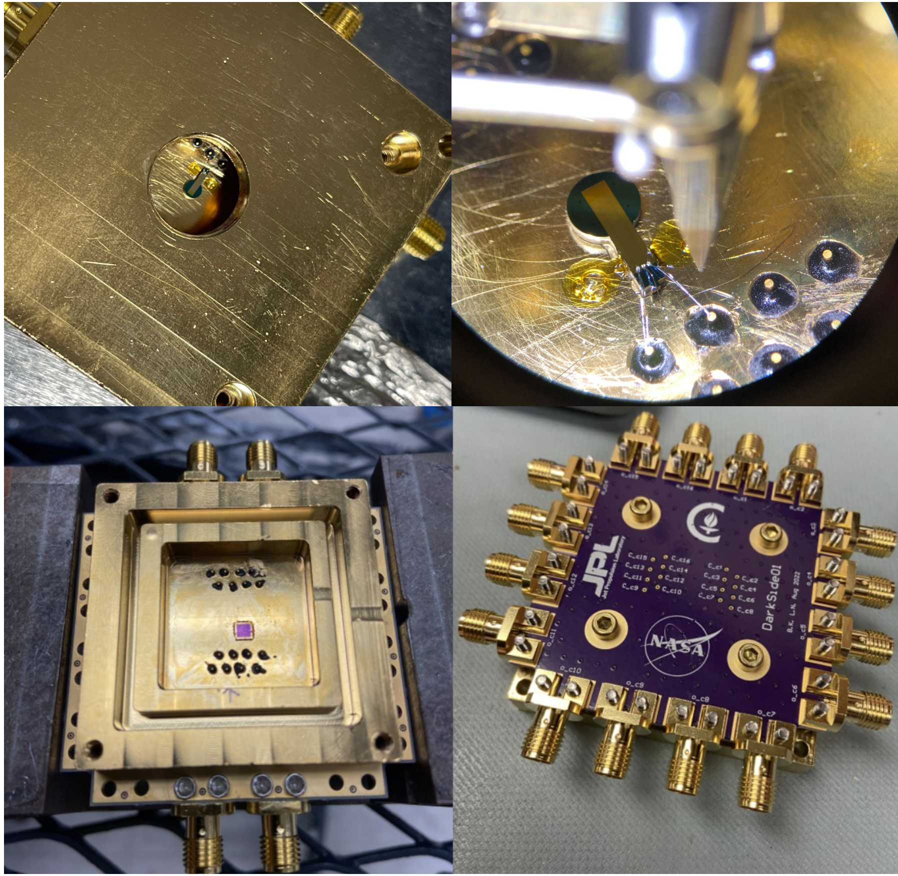




Lau, Jascha et al. (2023). Superconducting single-photon detectors in the mid-infrared for physical chemistry and spectroscopy. Chemical Society reviews. 52. 10.1039/d1cs00434

SNSPD Specs for GQuEST

- Specialized for 1550 nm
- Efficiency up to 83% ± 4.3% (1)
    - Efficiency Record 98% (2)
- Temporal Resolution: 13 ± 1 ps (1)
- Fast readout (10 ns / pulse)
    - 10^7 photons / second / pixel
    - Record 1.5 giga-counts/s (3)



GQuEST

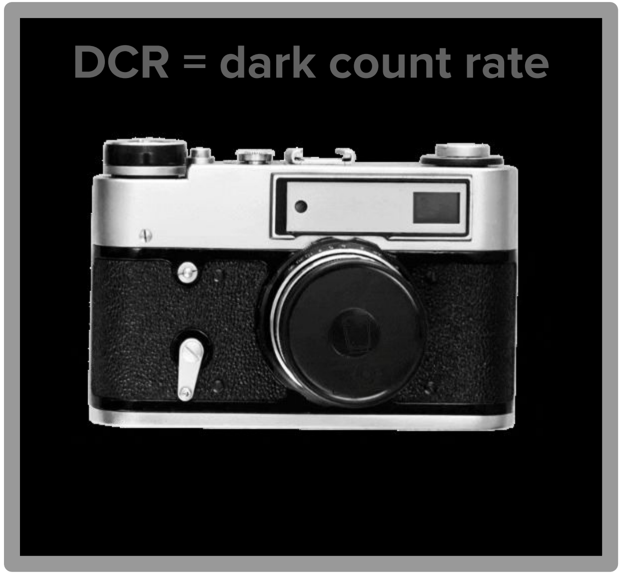
1. Marco Colangelo et al., “Impedance-Matched Differential Superconducting Nanowire Detectors”, Phys. Rev. Applied 19 (2023)
2. Dileep V. Reddy et. al, “Superconducting nanowire single-photon detectors with 98% system detection efficiency at 1550 nm”, Optica Vol. 7, Issue 12, pp. 1649-1653 (2020)
3. Ioana Craiciu et al. “High-speed detection of 1550 nm single photons with superconducting nanowire detectors”, Optica Vol. 10, Issue 2, pp. 183-190 (2023)

GQuEST SNSPD Hardware Requirements

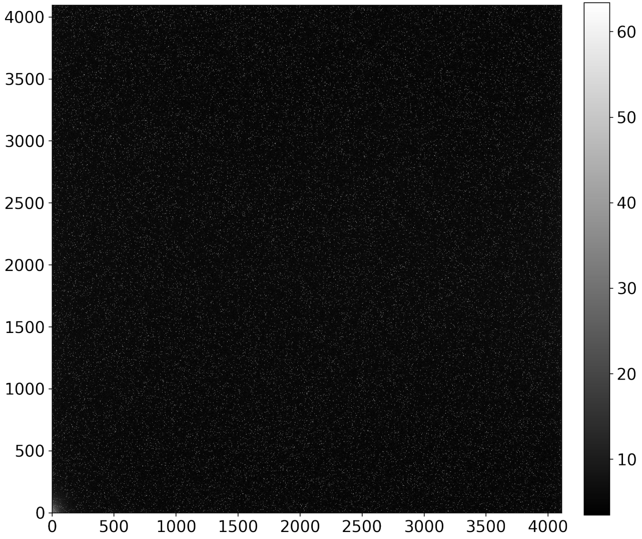
- High efficiency at 1550 nm
- Dark count rate of at least 10^{-4}
- Free space optics and bias electronics held at 4 K
- Fully differential readout electronics
- Long duty cycle for cryostat (order of 1 day)
- Single mode fiber connection between cryogenic filter cavity and SNSPD

What are Dark Counts?

- Dark counts are false detection events often generated by black body radiation
- Characterized by the average number of counts when no signal is applied

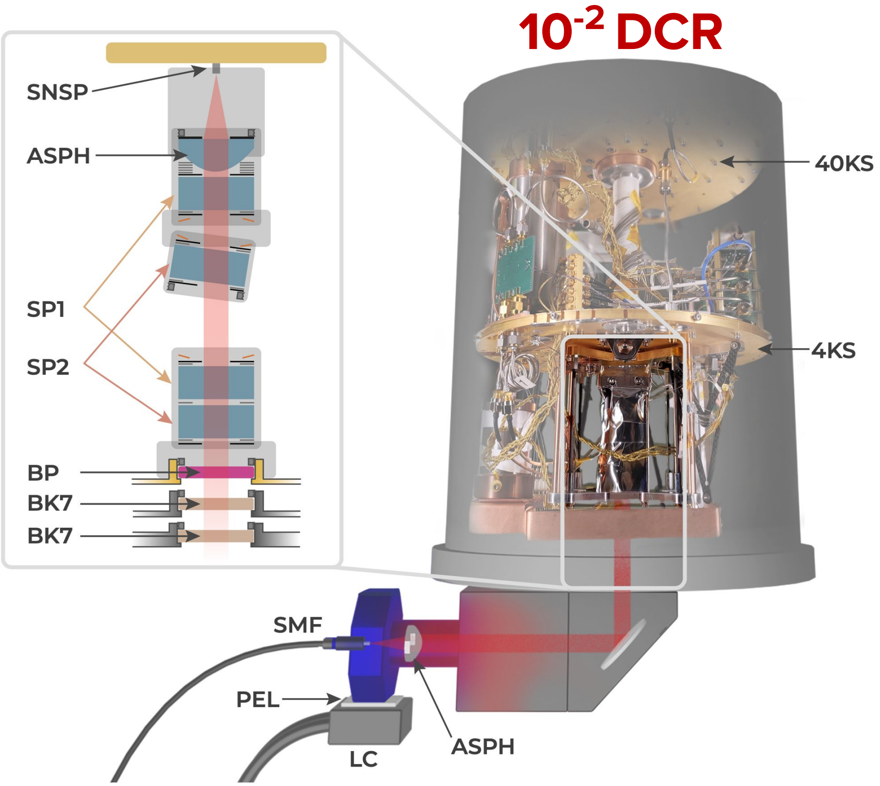


“Dark Box”

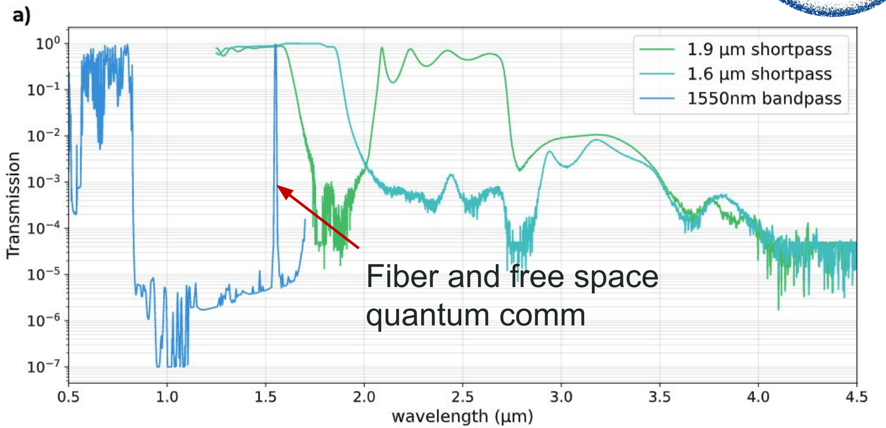


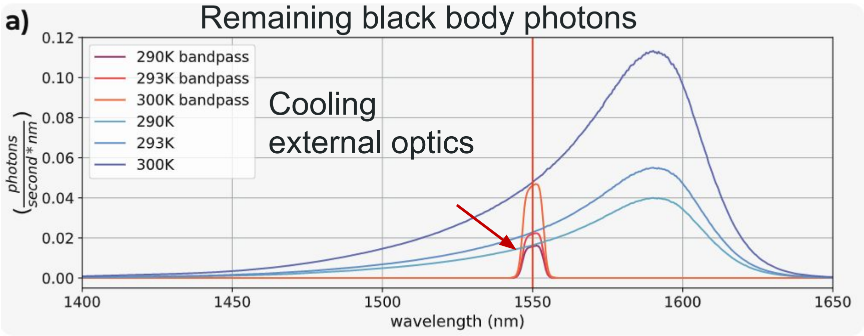
“Dark Count” Image

Free-space coupled SNSPD to room temperature



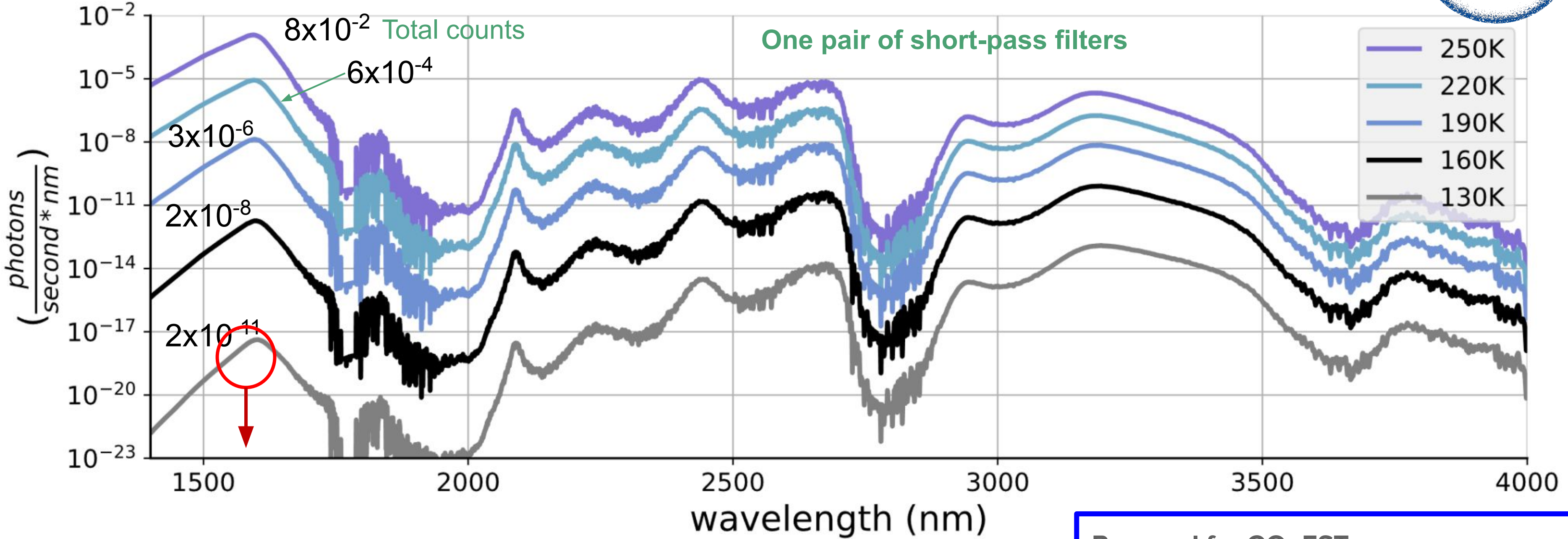
Modified PhotonSpot Inc. Cryostat





Mueller, Korzh *et al*, **Optica 8,** 1586 (2021)

Free-space filtering of cryogenic environment

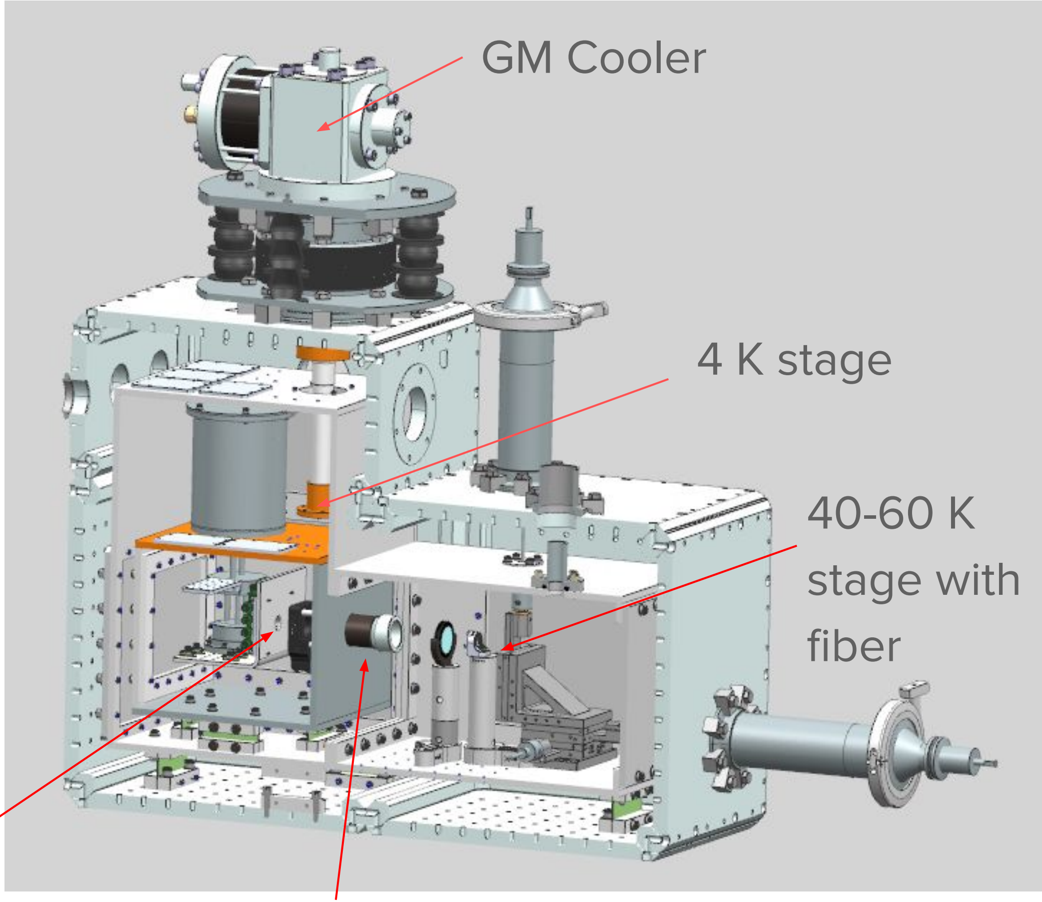


Proposal for GQuEST

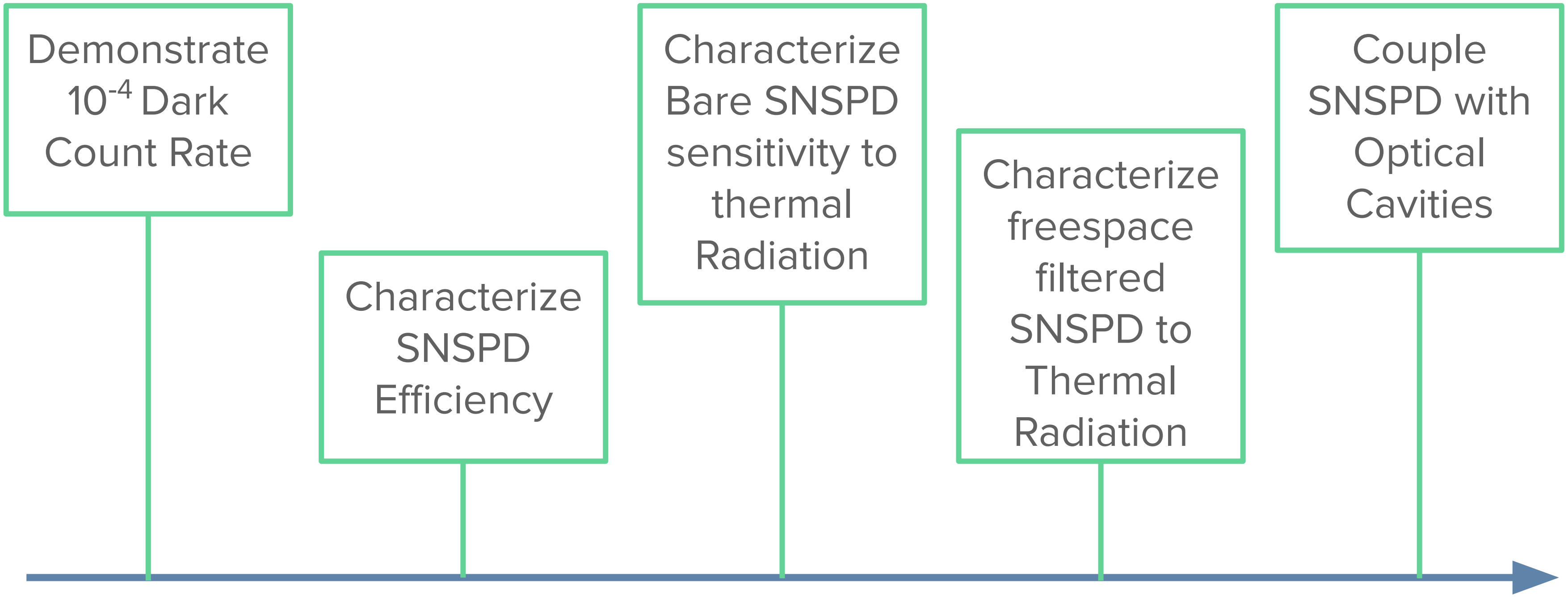
- 1 pair of short-pass filters
  - 2 x 0.5 inch of BK7 glass
- Optional: 3 nm bandpass filter

Cryogenic Cooling For Single Photon Detection

- 3 Stage Cryostat
  - Fiber held at 40-60 K
  - Free Space Optics @ 4 K
  - SNSPD @ 1 K
- 10^{-2} DC rate w/o cooled fiber
- 10^{-5} DC rate w/ cooled fiber

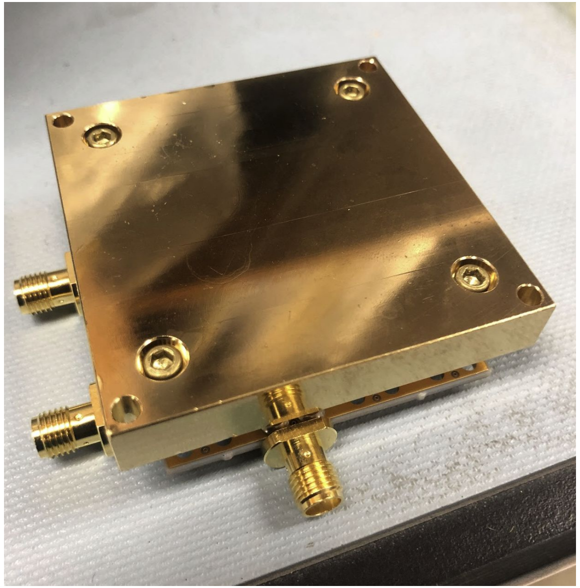
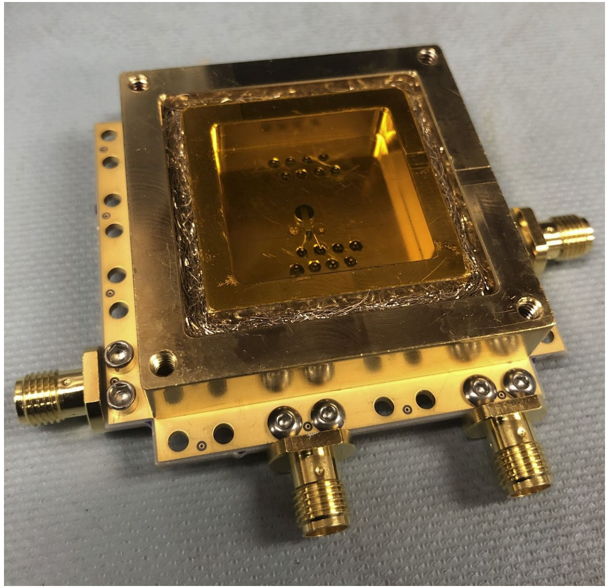
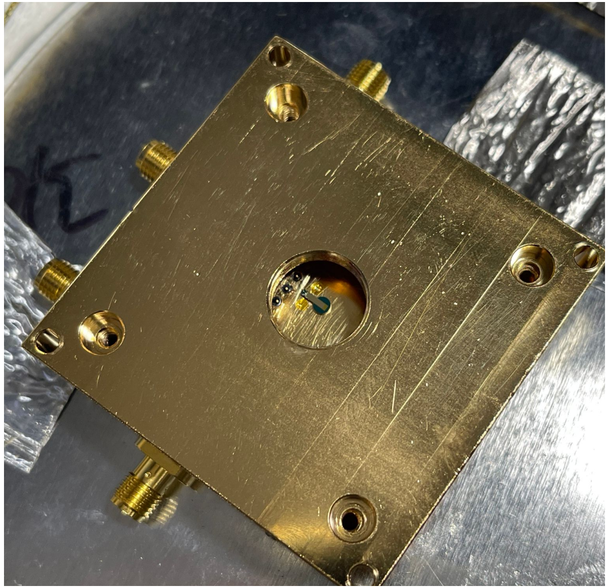


Testing our SNSPD for GQuEST

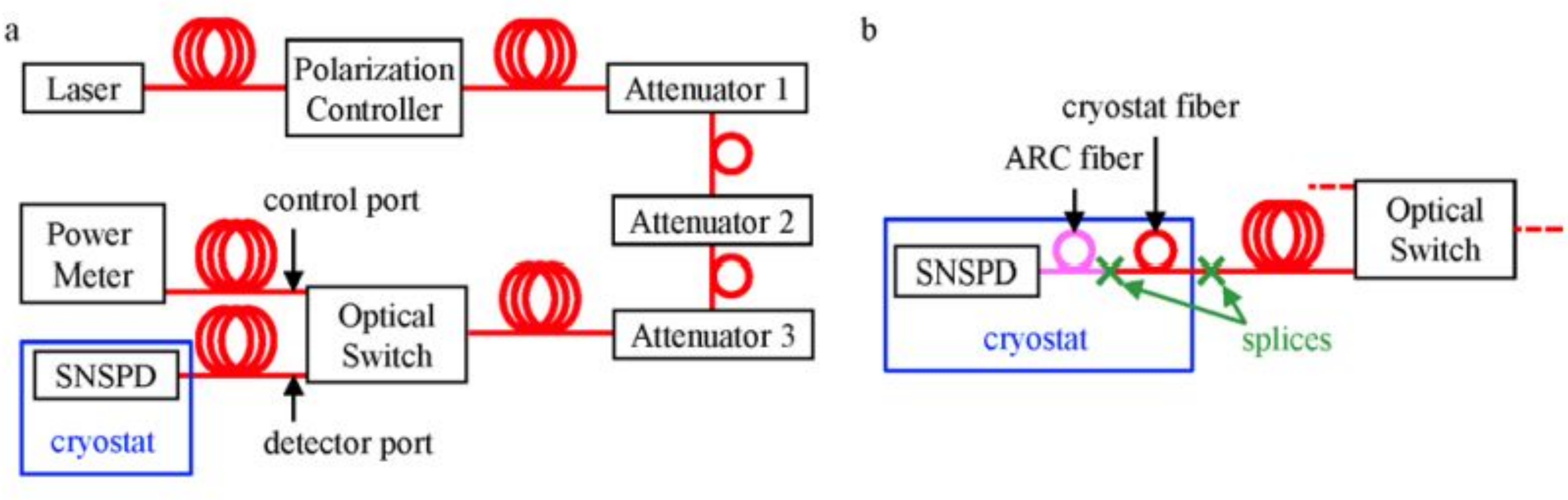


SNSPD Housings

GQuEST

Dark Box Enclosure	SNSPD Casing + PCB	Open Fiber Lid
		

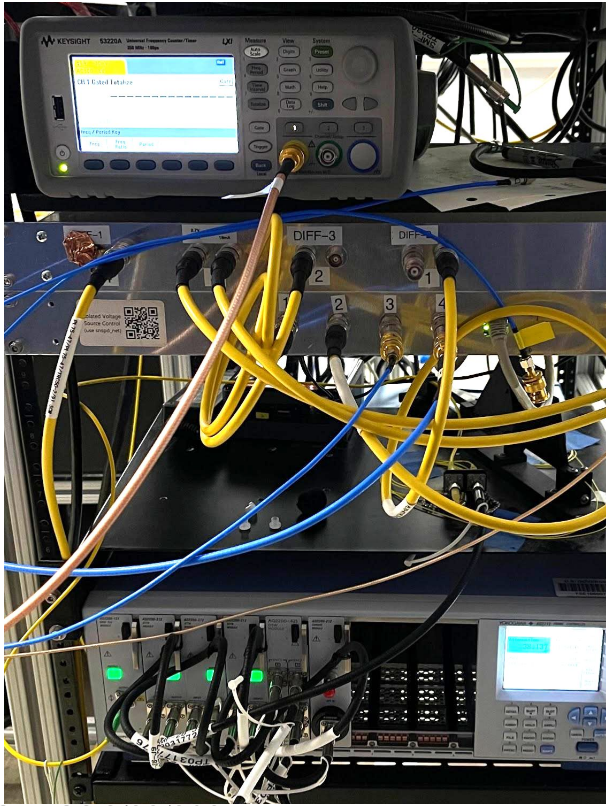
SNSPD Efficiency Experimental Setup

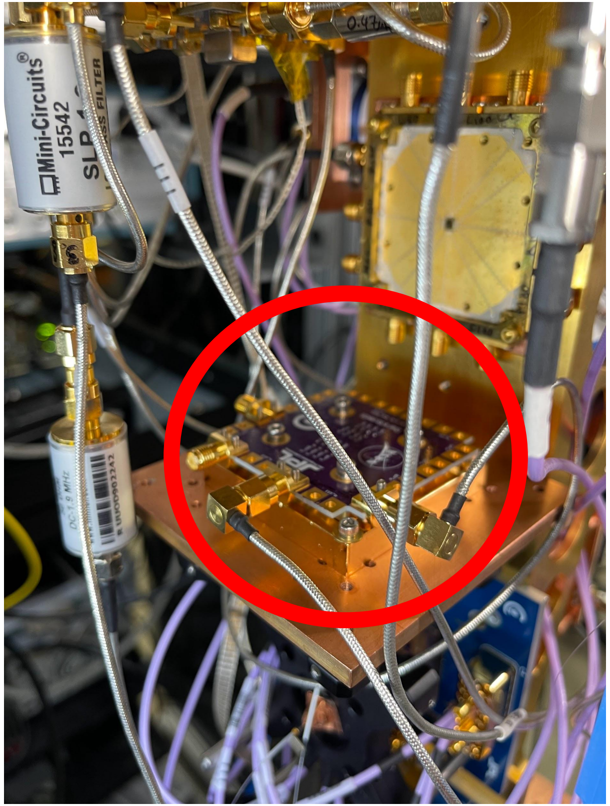


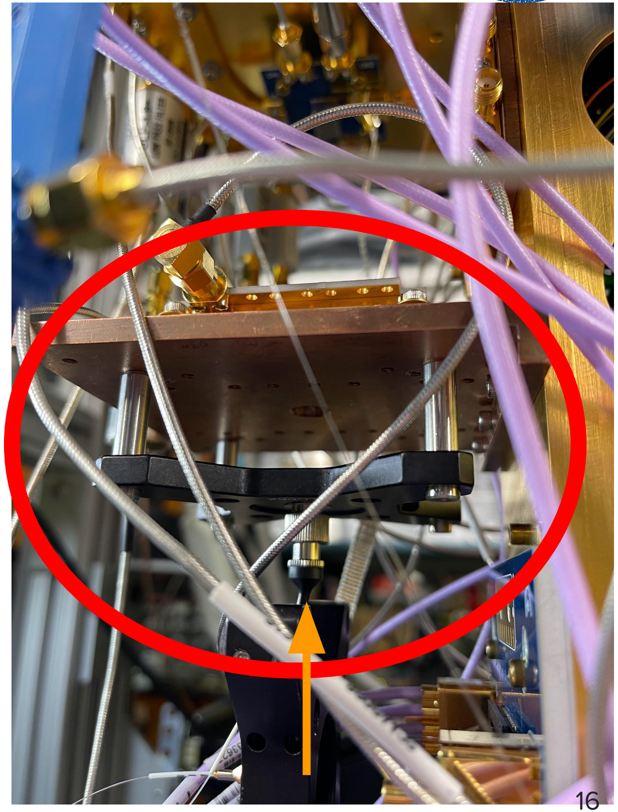
F. Marsili, Et al., 2013, *Detecting Single Infrared Photons with 93 % System Efficiency: Supplementary Information*

GQuEST

Laboratory Setup

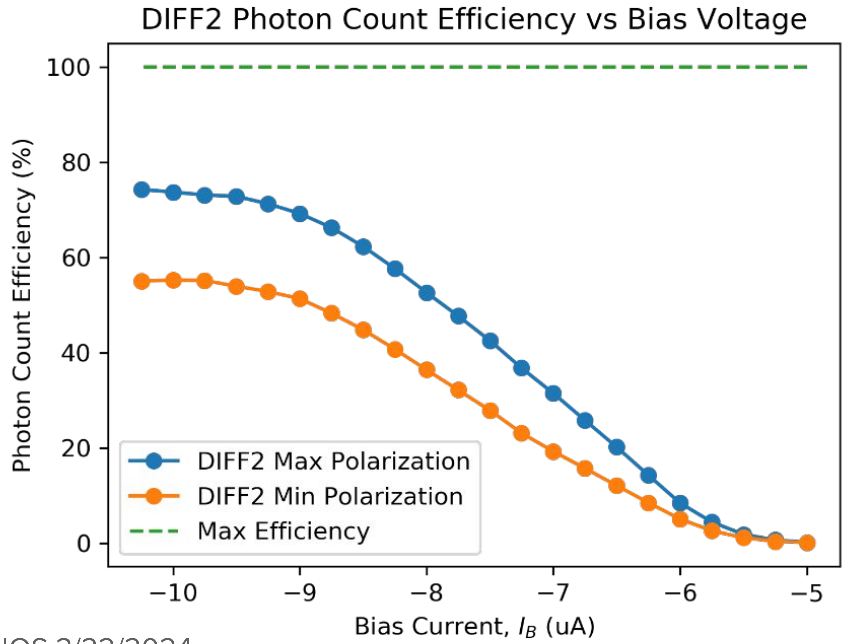


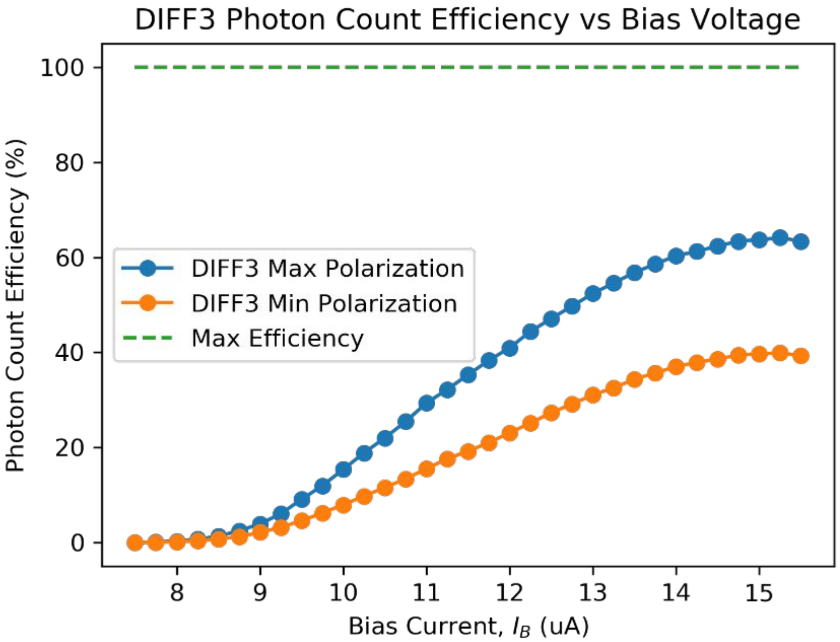




Initial SNSPD Measurements

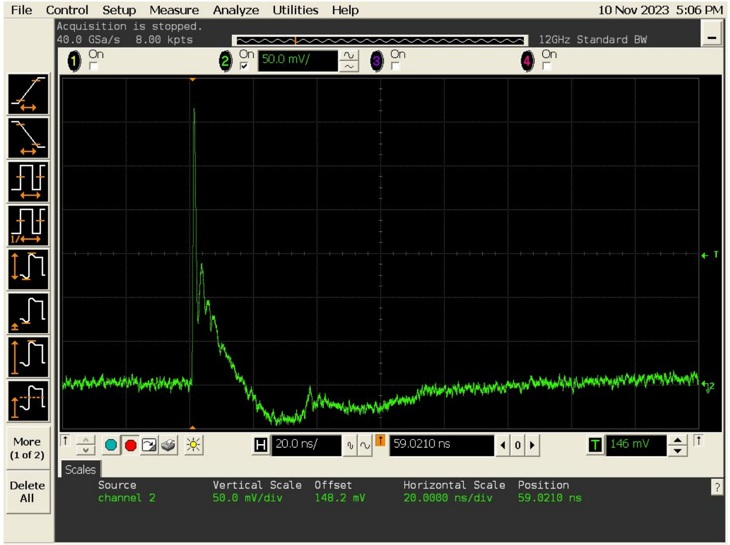
Current Efficiency measurements taken with GQuEST SNSPD

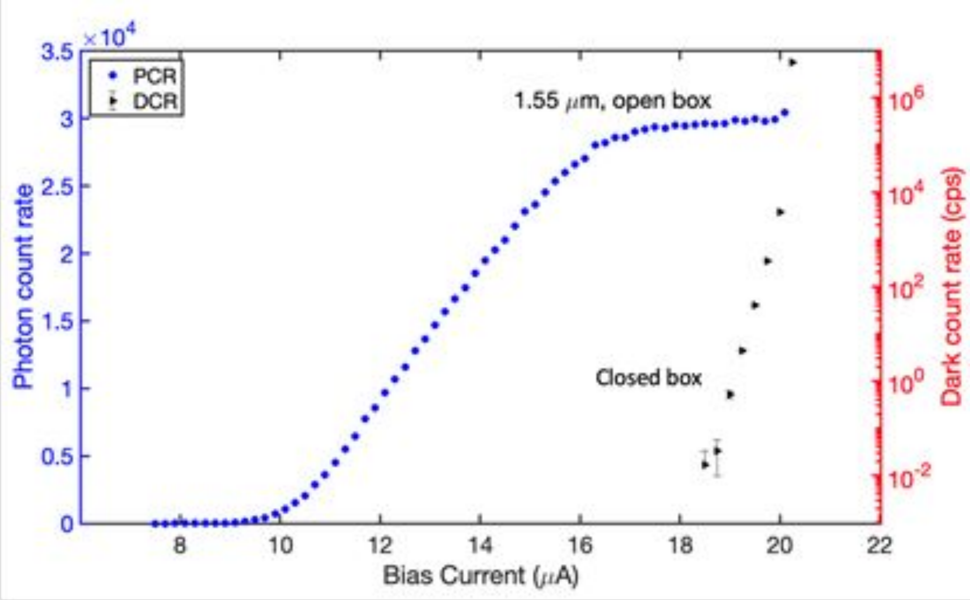




PCR Curve of GQuEST SNSPD

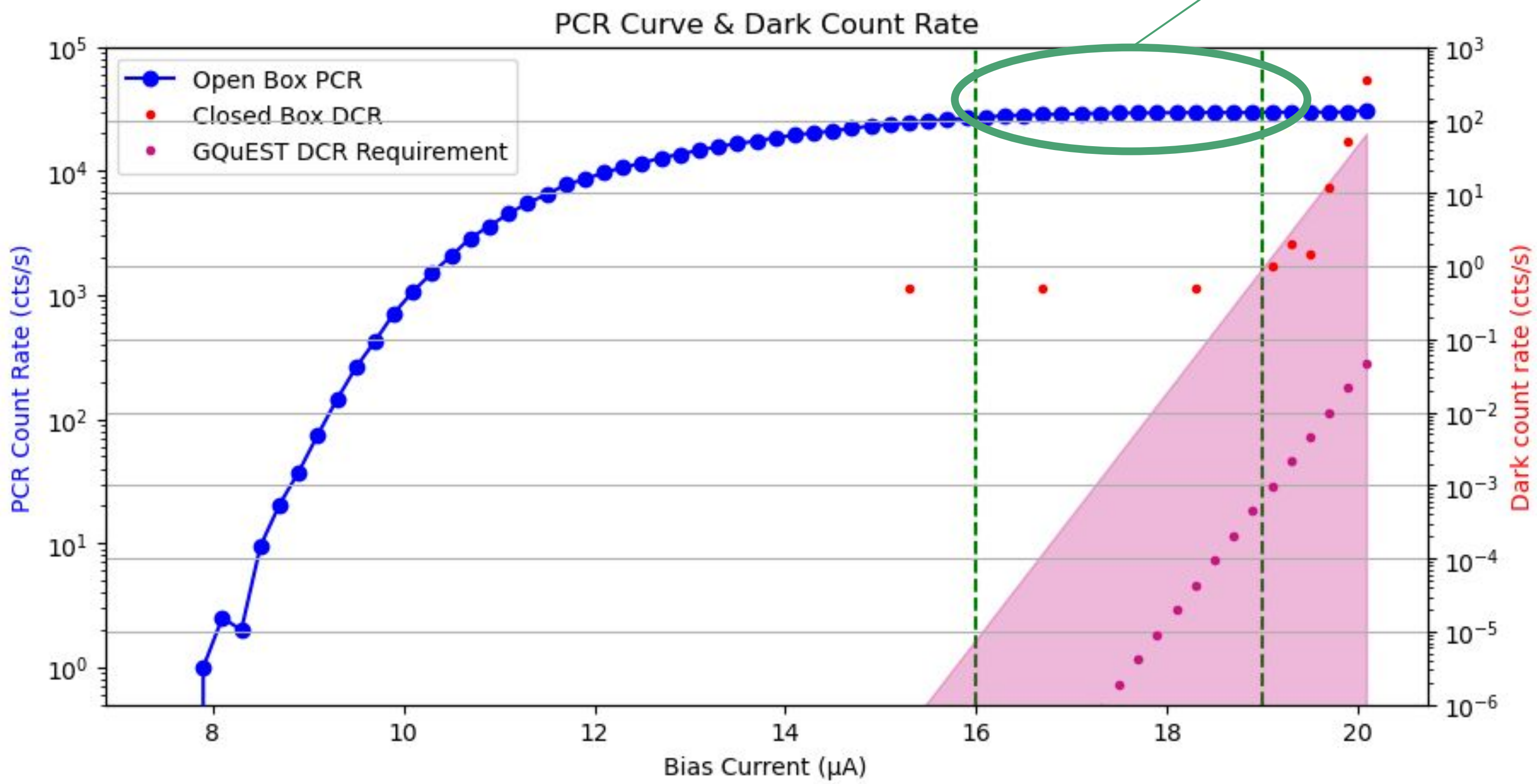
Photon Count Rate with respect to input Bias Current





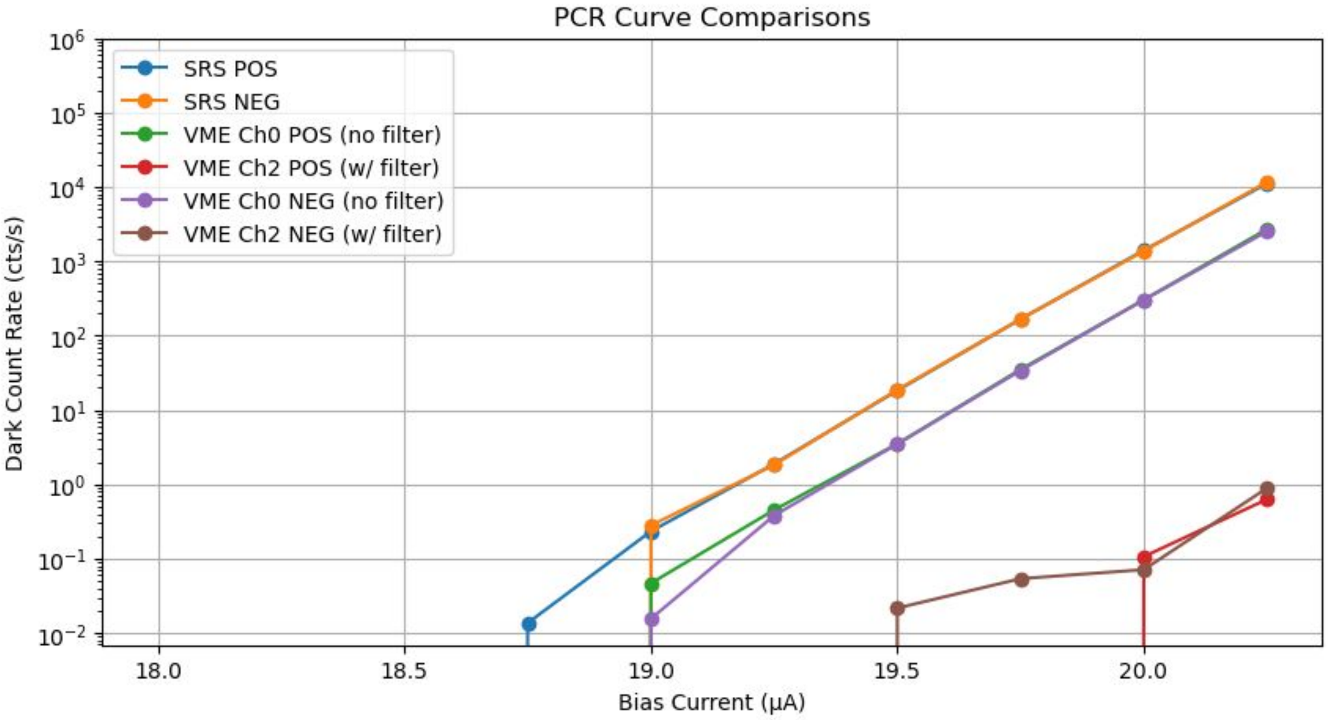
10^{-4} Measurements with Dark Box

Highest Efficiency



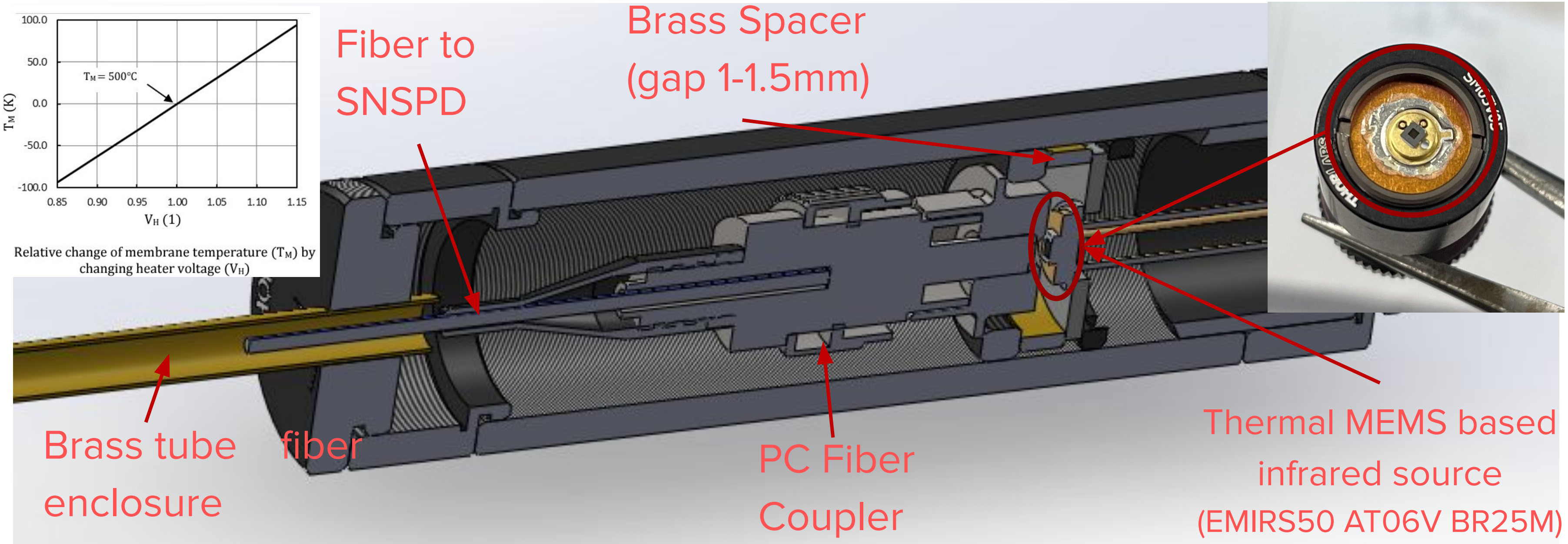
Voltage Supply Noise Comparison (Dark Box)

Comparison of SRS Voltage supply and the new DAC VME (built by Lautaro)



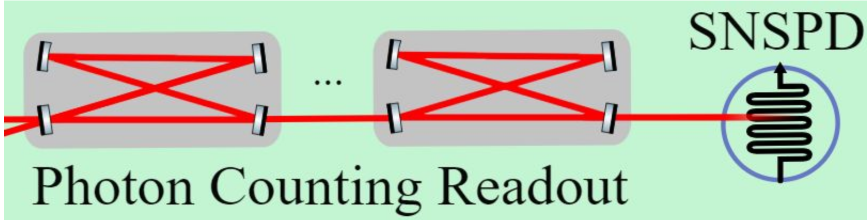
Thermal Source Measurements with SNSPD

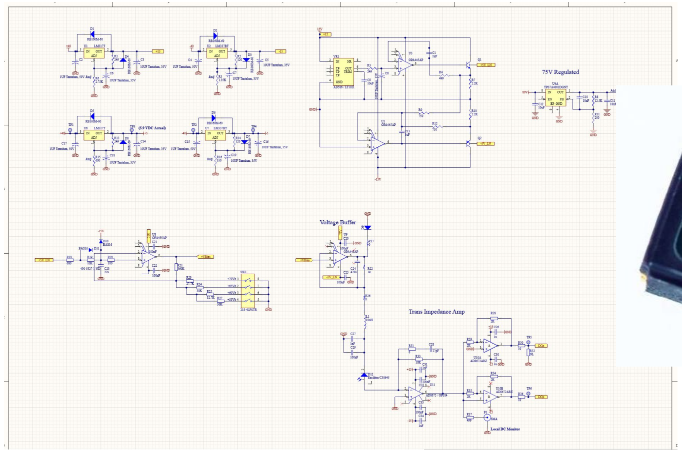
Measuring SNSPD response to thermal excitation via radiating thermal source

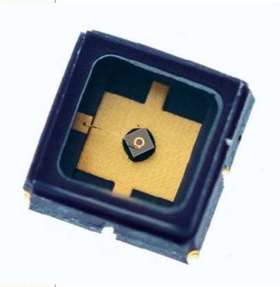


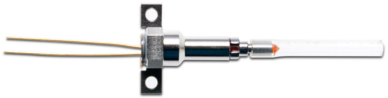
Low-noise Avalanche Photodiodes

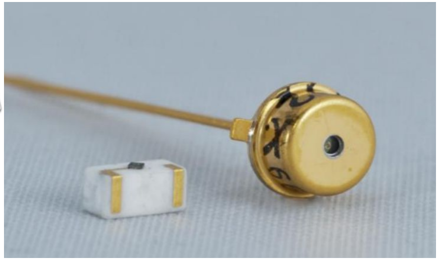
- Sub-pico-watt noise floor @ 293 K
- Preliminary testing with 1-2 cavities
- 60-120 db of attenuation
- 10^{12} p/s - 10^{6} p/s or 100 nW - 100fW
- Exponential gain in avalanching mode
- Previously: 1 count/sec achieved with 10% efficiency [1]











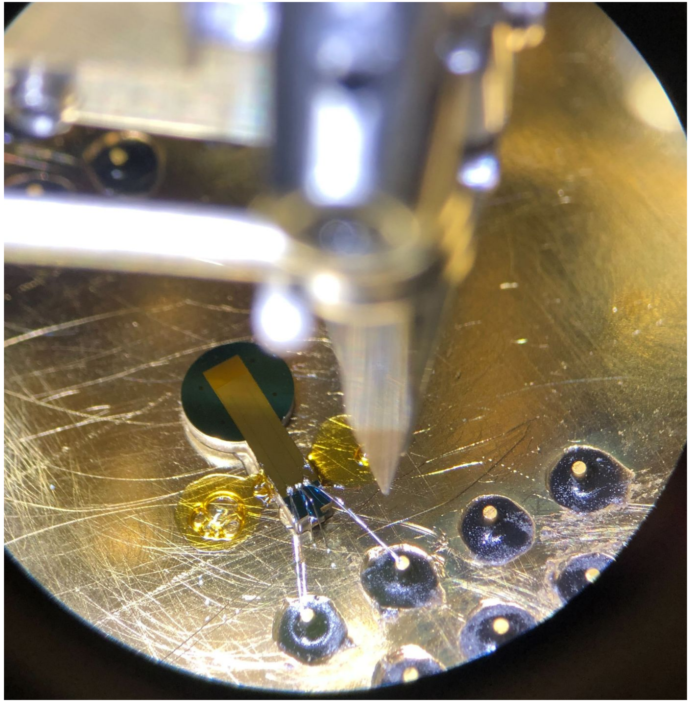
1. Boris Korzh et al., “Free-running InGaAs single photon detector with 1 dark count per second at 10% efficiency”, Appl. Phys. Lett. 104, 081108 (2014)

Next Steps

- Test and verify SNSPD Dark Count Rate with the new voltage source
- Characterize the SNSPD response with the radiative thermal source
- Utilize Avalanche Photodiodes to calibrate and measure the outputs of the filter cavities
- Assemble and install cryostat from Fermilab in Bridge
- Begin SNSPD testing with filter cavities

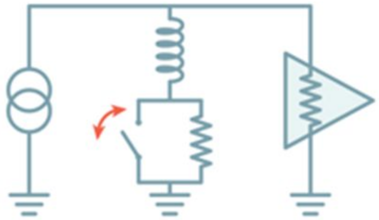
Conclusion

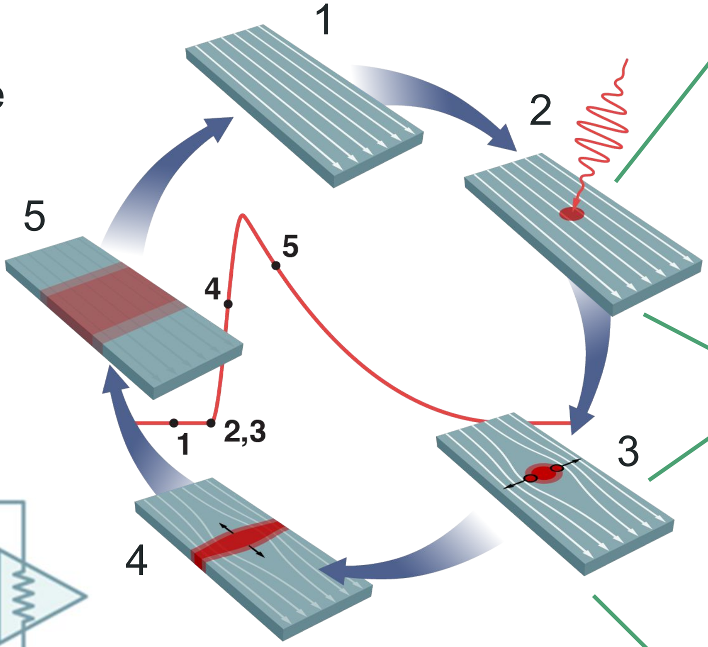
- Our SNSPD can achieve low dark count rates of at least 10^{-4} (a precedent for the 1550 nm detector)
  - An order of magnitude smaller than our signal
- Reach efficiencies of 80+ %
- Improving upon previous designs by cooling the incoming fiber from filter cavities

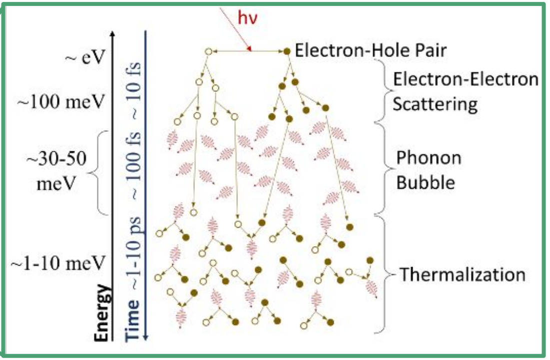


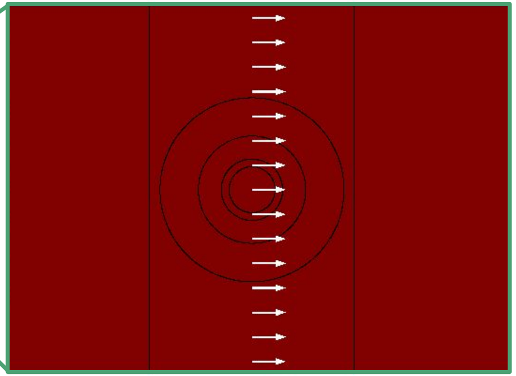
Superconducting Nanowire Single Photon Detector

1. Current-biased superconducting nanowire
2. Photon absorption & Hotspot formation
3. Suppression of superconductivity
4. Normal domain growth - ***internal gain***
5. Recovery









Typically operating at 1-4 kelvin

G. Goltsman, et al., **APL** 79, 705 (2001)
J.P. Allmaras, A.G. Kozorezov, B.A. Korzh, K.K. Berggren, and M.D. Shaw, ***PRApplied* 11** 034062 (2019)
J.P. Allmaras, *Modeling and Development of Superconducting Nanowire Single-Photon Detectors.* **Ph.D. Dissertation**, Caltech (2020)