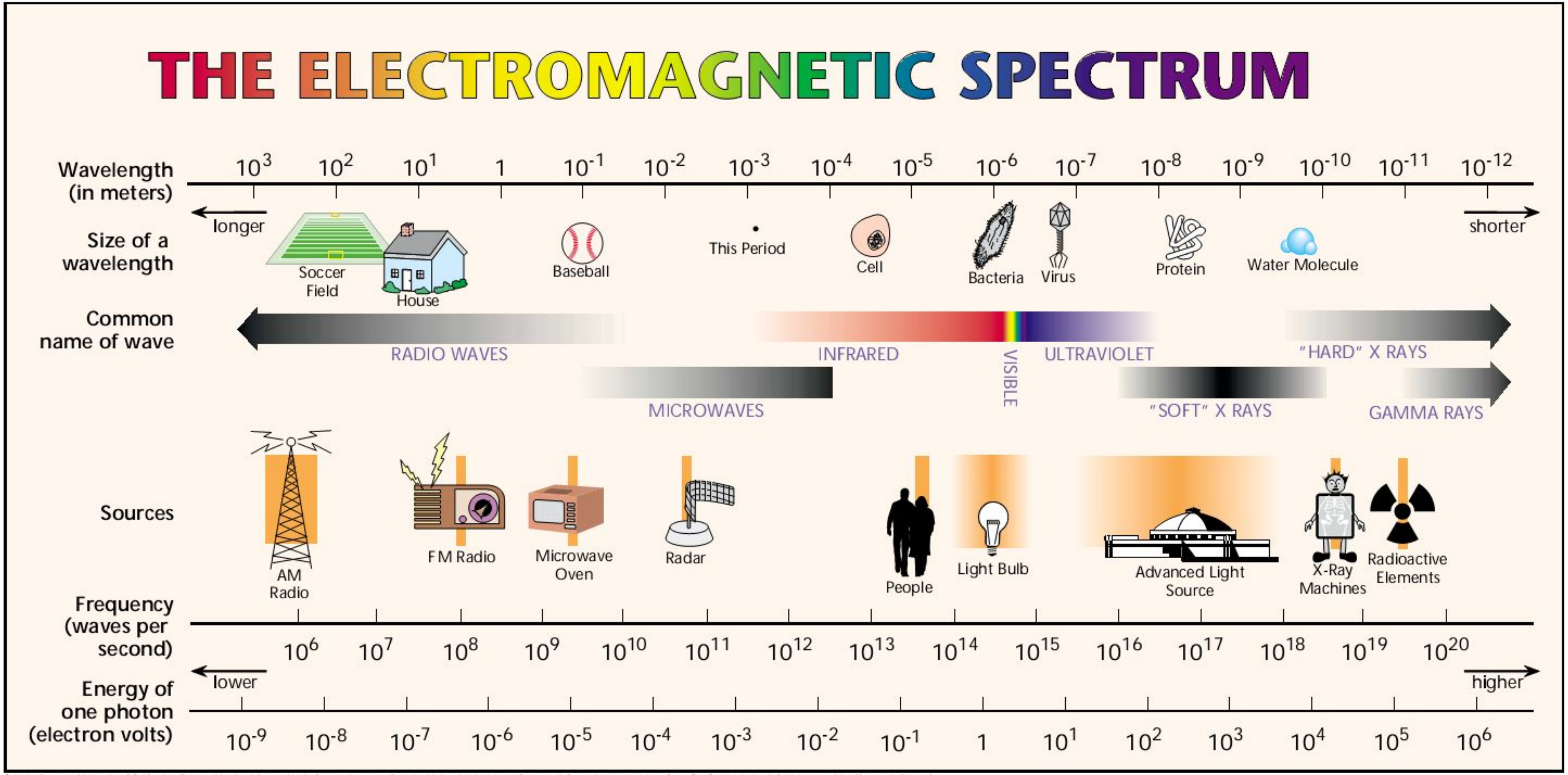
Superconducting Nanowire Single Photon Detector (SNSPD)

Hsin-Yeh Wu, Stathes Paganis

National Taiwan University

TIDC annual meeting

25 Nov, 2023

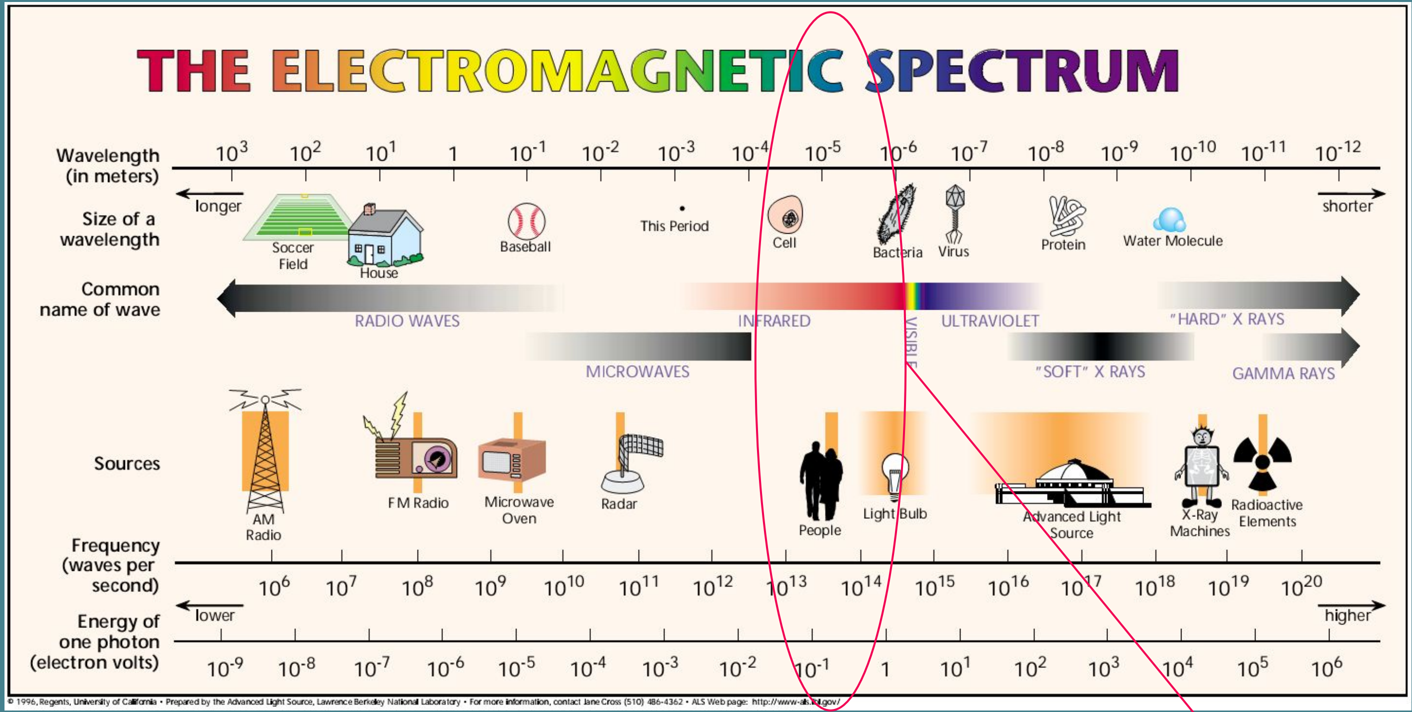


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^{3} 10^{2} 10^{1} 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
FM Radio
Microwave Oven
Radar
People
Light Bulb
Advanced Light Source
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}

Short Wavelength, High Energy

Rich spectrum of detectors for HEP

Source: Detector Technology Challenges – Ian Shipsey (15th Pisa meeting on Advanced Detectors)

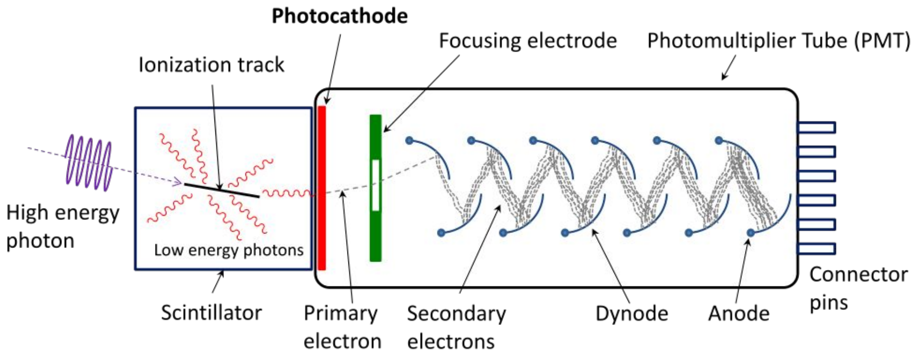


Let's extend to IR Single Photon!?

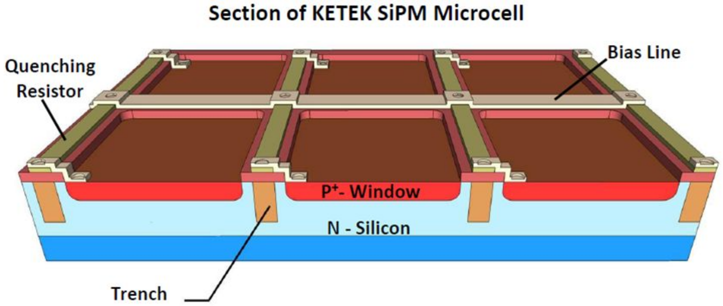
Semiconductor Single Photon Detectors

Photomultiplier Tubes (PMT)

Wikimedia Commons

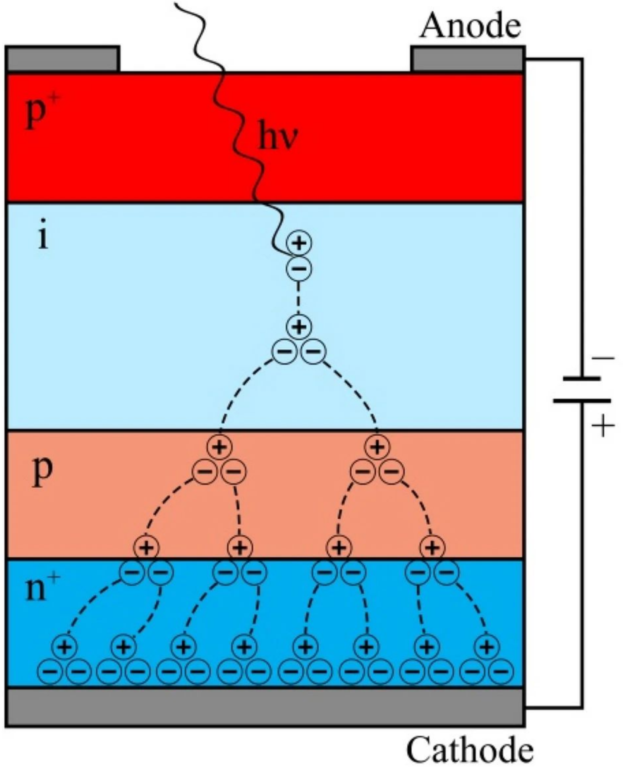


Silicon Photomultiplier (SiPM)



APPEC Communications

Single Photon Avalanche Diode (SPAD)



Izhnin, I.I., et al. Appl Nanosci 12, 253–263 (2022).

Semiconductor Single Photon Detectors

Photomultiplier Tubes (PMT)

Wikimedia Commons

Single Photon Avalanche Diode (SPAD)

Bandgap Threshold

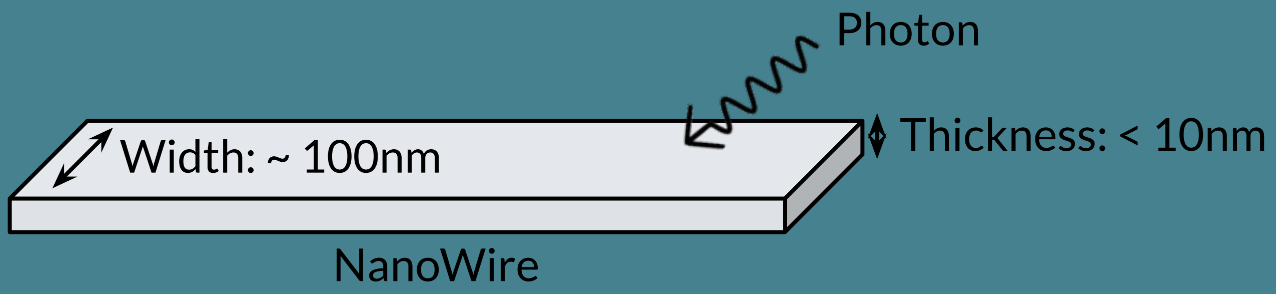
- Si: ~1.1eV (~1.1µm)
- Ge: ~0.7eV (~1.7µm)

Blocked impurity band solid-state photomultipliers.

- Large Dark Current

APPEC Communications

Izhnin, I.I., et al. Appl Nanosci 12, 253–263 (2022).



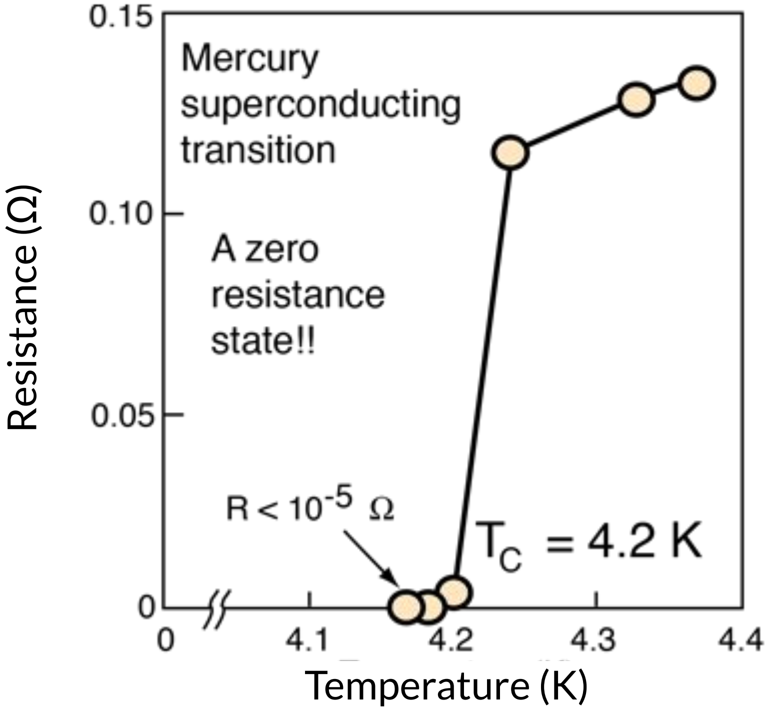
Superconductivity Nanowire Single Photon Detector (SNSPD)

Outline

SNSPD Intro
Fabrication and Characterization setup
First Prototypes results
Applications

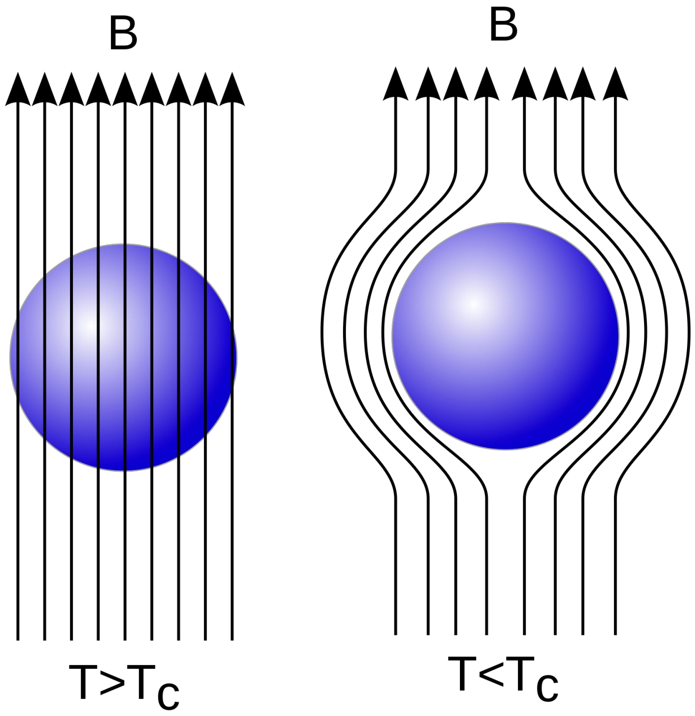
Superconductivity

Zero Resistance



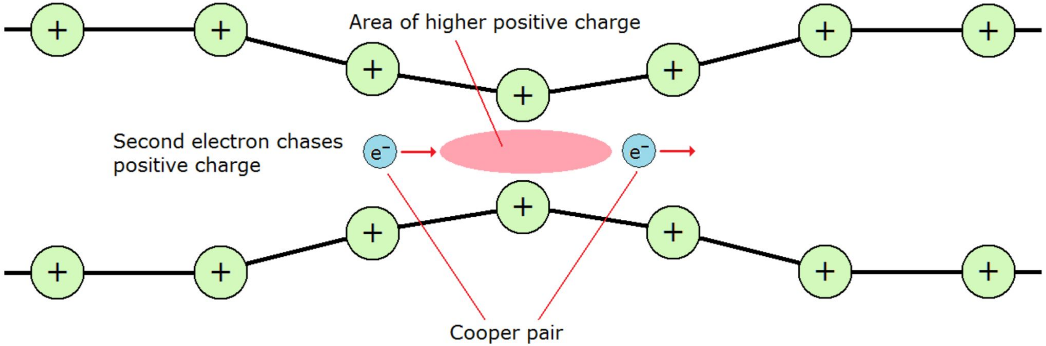
H. K. Onnes, Commun. Phys. Lab.12,120, (1911)

Meissner Effect Perfect diamagnetic (Superdiamagnetic)

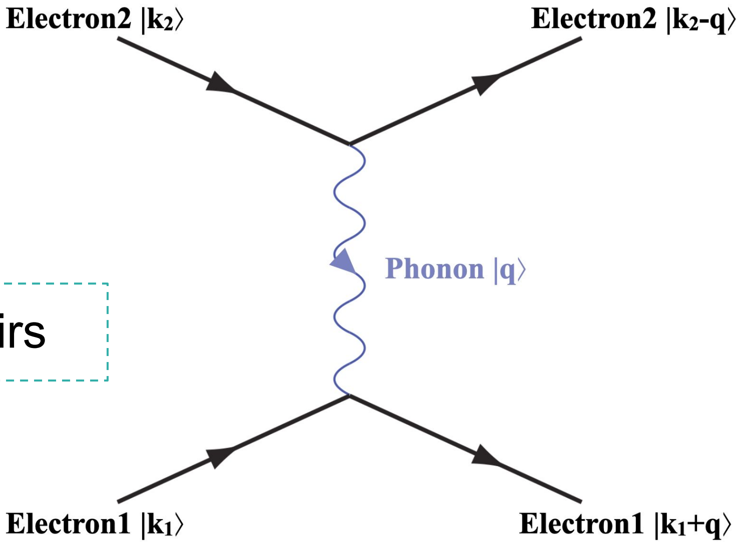


Wikimedia Commons

Cooper pairs (BCS mechanism)



$$\hat{H}\left|\vec{k_1} \pm \vec{q}\right\rangle = \epsilon_{k_1 \pm q}\left|\vec{k_1} \pm \vec{q}\right\rangle$$

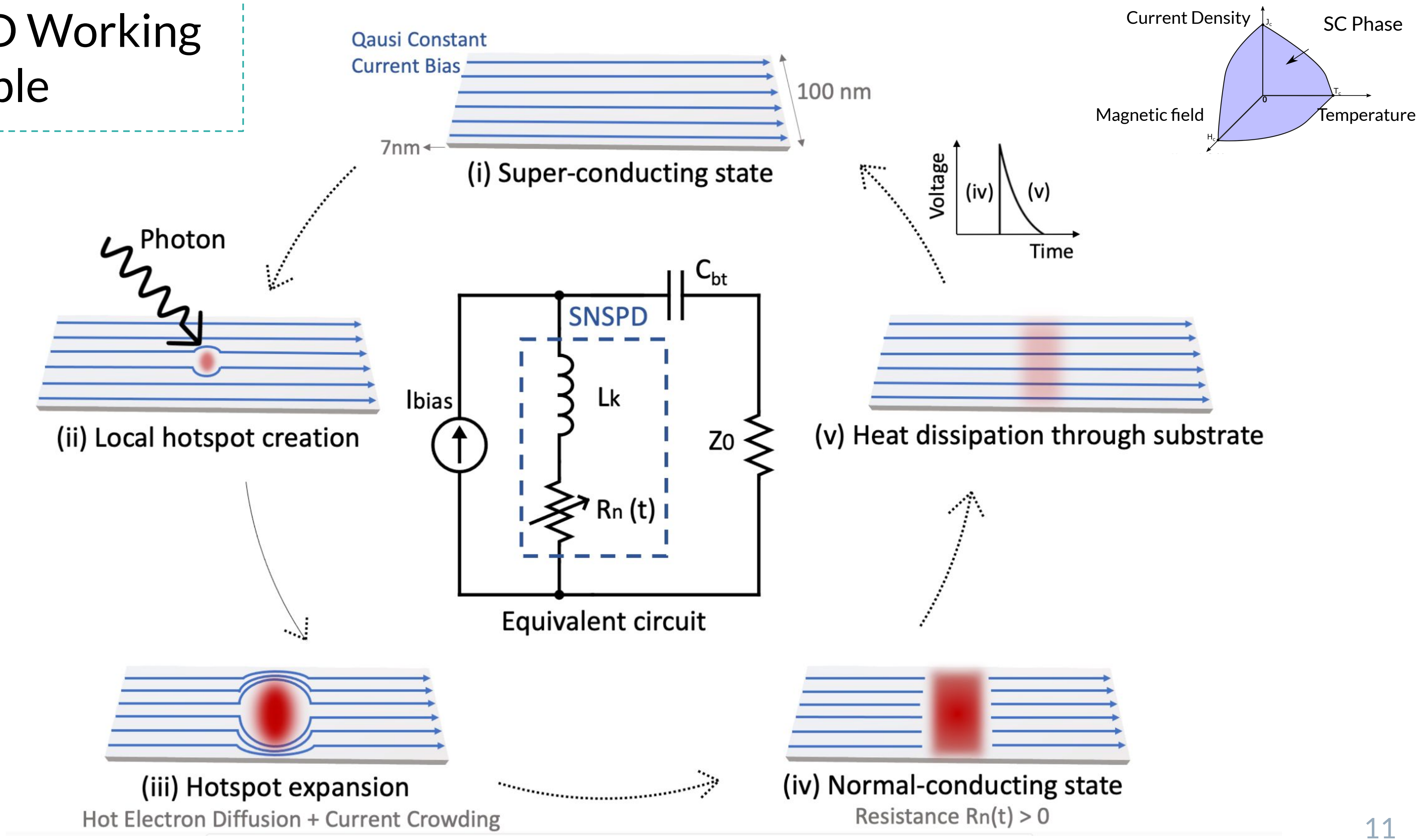


$V_{e\text{-}ph\text{-}e}$ (Attractive) > $V_{e\text{-}e}$ (Repulsive) → Cooper-Pairs

- Spin-0 composite particle (boson) → BEC Condensation
- Energy quantized → No random scattering → Zero Resistance
- Energy Gap Δ_{BEC} (~1meV) → 3 orders smaller than Δ_{Si} !

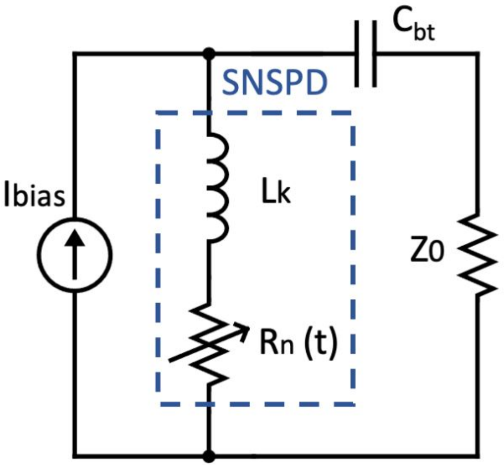
$$V = \frac{|M|^2}{(\epsilon_{\vec{k}} - \epsilon_{\vec{k}+\vec{q}})^2 - \hbar\omega_q{}^2}$$

SNSPD Working Principle

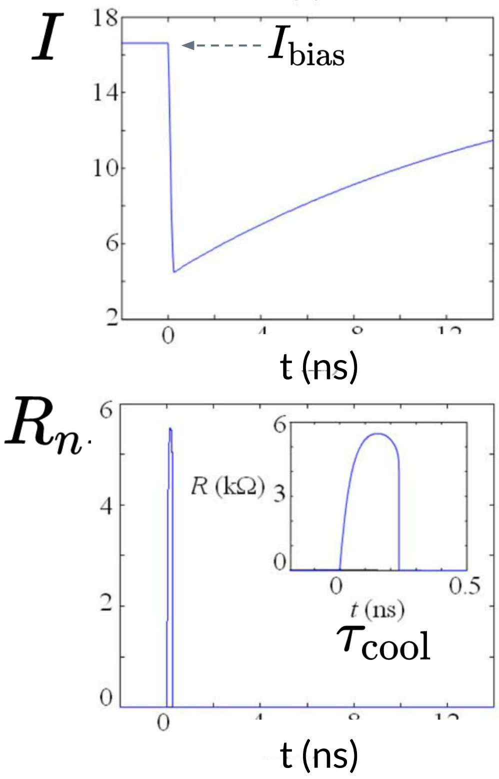


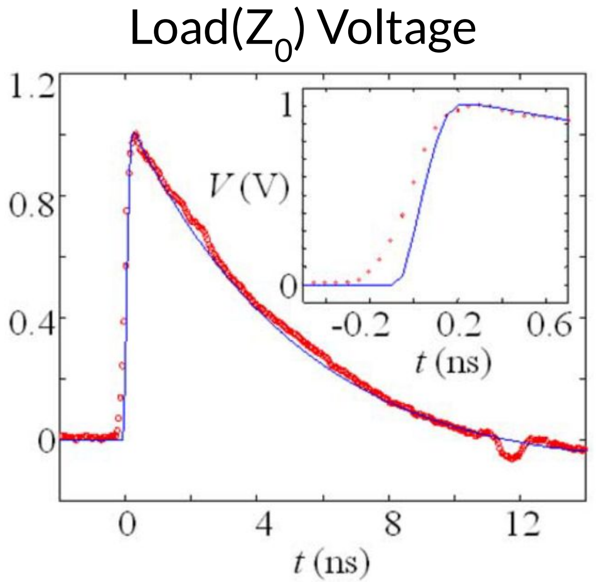
LCR Electric Circuit Model

Yang, J. K. W. et al. IEEE Transactions on Applied Superconductivity 17, 581–585 (2007)



Equivalent circuit





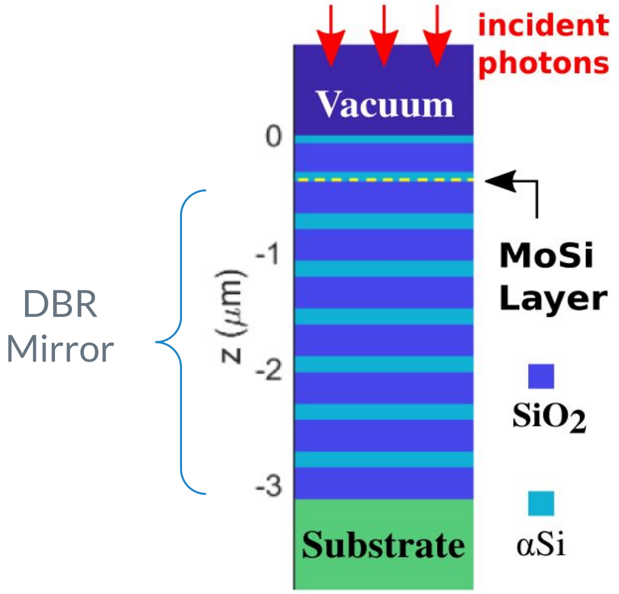
$$\tau_{\text{rise}} = \frac{L_k}{Z_0 + R_n(t)}$$

$$\tau_{\text{fall}} = \frac{L_k}{Z_0}$$

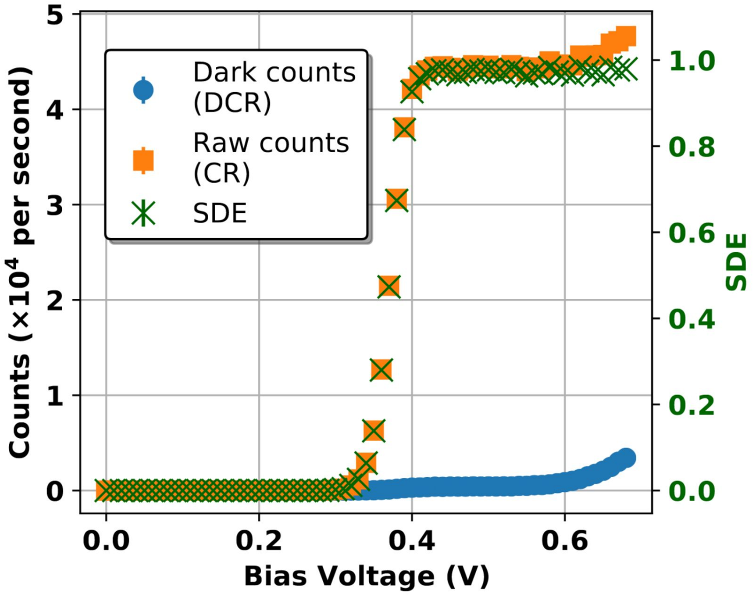
$$C_{bt}\left(L_k I'' + Z_0 I' + (R_n I)'\right) = I_{\text{bias}} - I$$

State-of-the-art SNSPDs @ 1550nm

Reddy, D. V. et al. Optica 7, 1649 (2020).



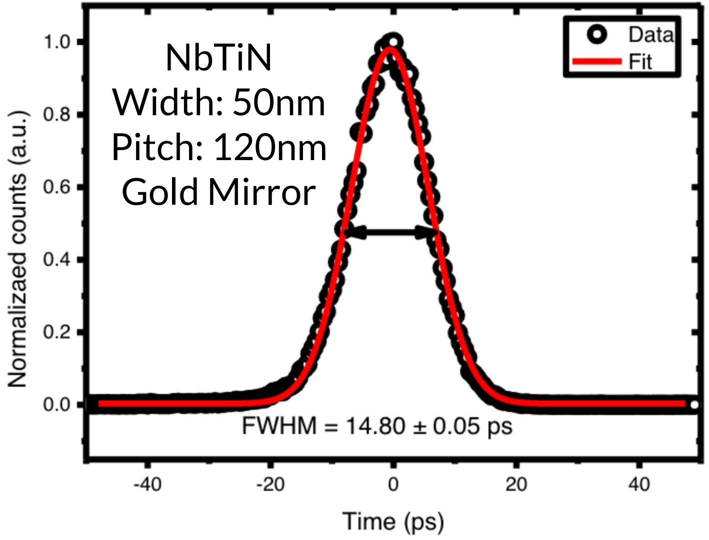
98% System Detection Efficiency
High Count Rate
Low Dark Count Rate



MoSi (Tc~5K)
Width: 80nm, Pitch: 140nm
Distributed Bragg Reflector Mirror
Measure Temperature ~750mK

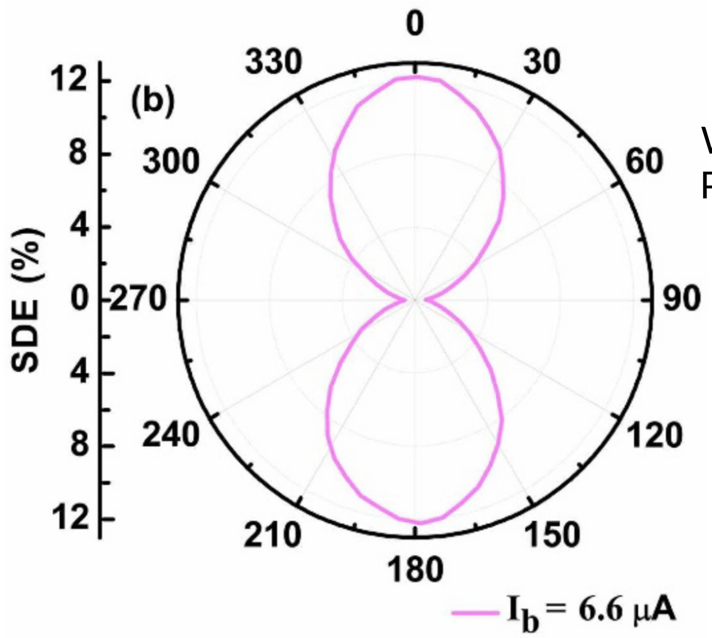
State-of-the-art SNSPDs @ 1550nm

Time Jitter < 15ps



Esmaeil Zadeh, I. et al. APL Photonics 2, 111301 (2017).

Polarization Sensitive



NbN
Thick: 7nm
Width: 50nm
Pitch: 100nm
No Mirror

Guo, Q. et al. Sci Rep 5, 9616 (2015).

Our Roadmap

State-of-the-art

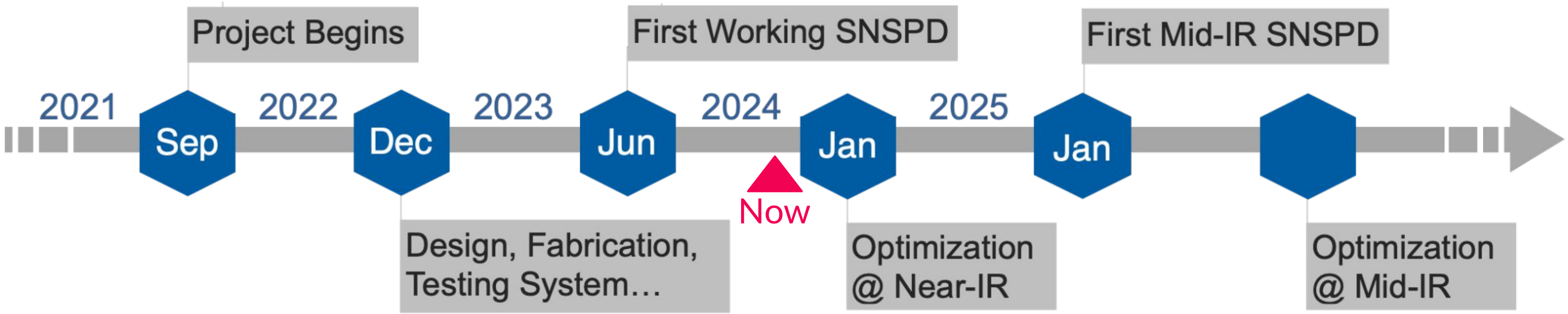
Excellent performance @ Near-IR (0.8μm-2μm)

- ~100% single photon efficiency @ 1550nm
- Low timing jitter (<15ps)
- Low Dark Count (<0.01Hz)
- Fast recovery (MHz readout rate)
- Polarization sensitive
- Multipixelized array

Goal

Extend to Mid-IR (2μm-20μm)

- All the excellent existing properties
- Broadband
- Polarization distinguishability



SNSPD Fabrication

SC Material Choice

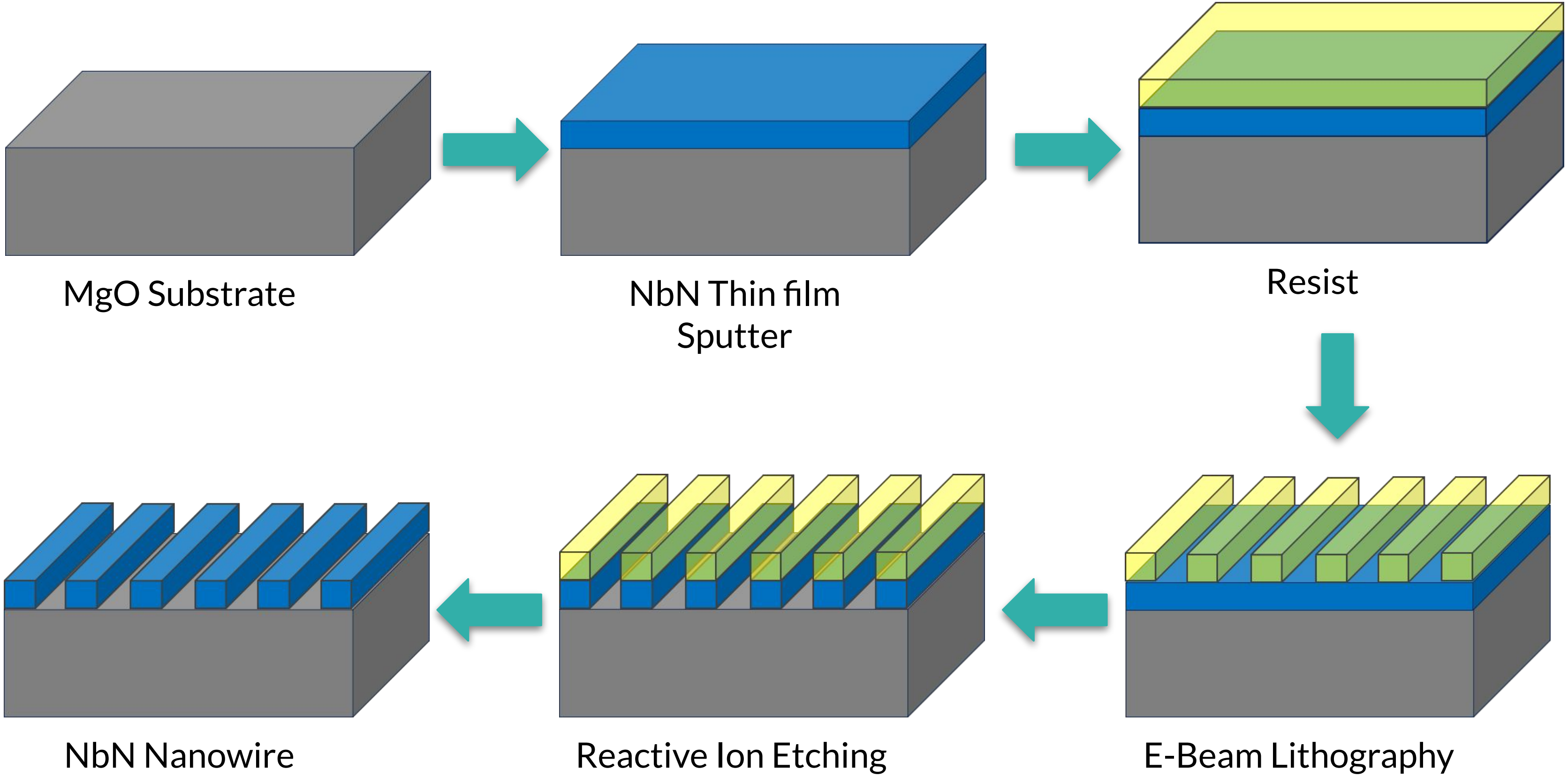
Material	Tc*, K	Δ(BCS), meV	Nqp** (3μm photon)
Nb	4.15	0.63	~600
✅ NbN	8.6	1.3	~300
NbTiN	9.6	1.46	~300
WSi	3.7	0.56	~700
MoSi	4.3	0.65	~600
MoGe	4.4	0.66	~600
TiN	0.4 - 4.5	0.06 – 0.68	~6000 - 600
SC-diamond	2 - 4.2	0.3 – 0.63	~1300 - 600

* Data for thin film

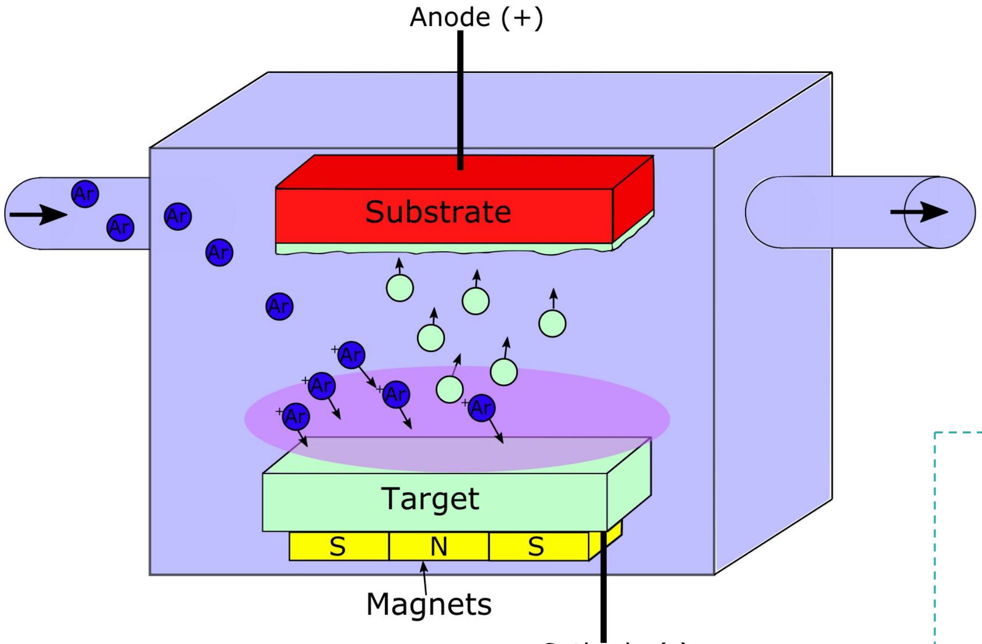
** Number of quasi-particles

Dmitry Morozov et. al, Proc. SPIE 10659, Advanced Photon Counting Techniques XII, 106590G (14 May 2018)

Fabrication Flow

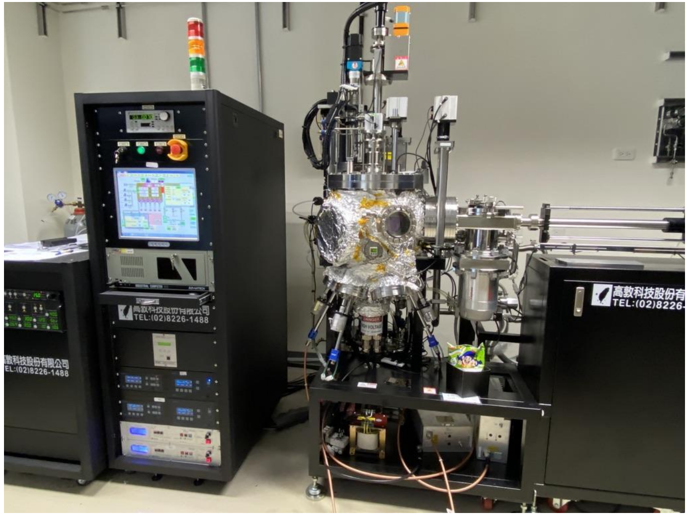


Reactive Magnetron Sputter



Taylor, G. G. glathesis:2021-82501

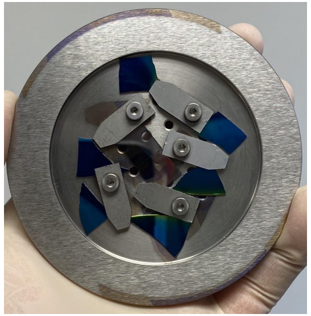
Sputter @ Prof. Yu-Rong Lu's Lab (AS)



7nm NbN Recipe

- Target=NbN
- UHV=10^{-9} Torr
- RF Power=130 W
- Ar:N_2=36:0.1 sccm
- APC=0.9 mTorr
- Temperature=900°C
- Rate=0.3 Å/s (260s)

NbN Thin film

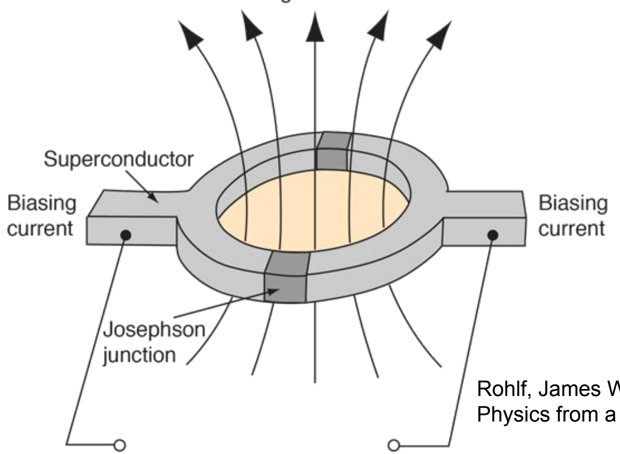


Jing-Wei Yang

Thin film quality characterization

Magnetic susceptibility χ_V @ 2-20K

→ Critical Temperature



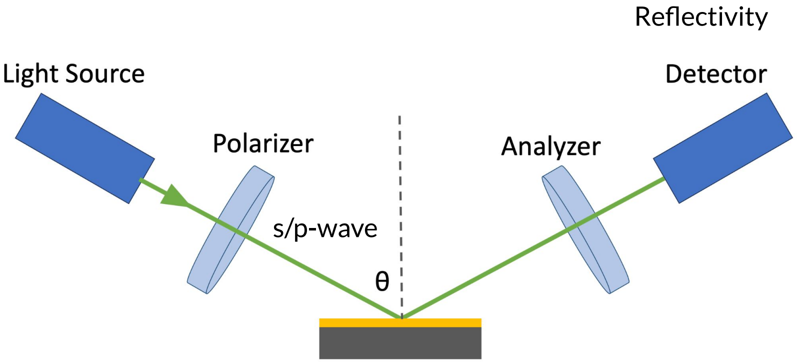
Rohlf, James William, Modern Physics from a to Z0, Wiley 1994

Superconducting Quantum Interference Device (SQUID)

Measured by Instrumentation Center, Chen, I-Nan

Electric susceptibility χ_e @ 300K

→ Metallic Property



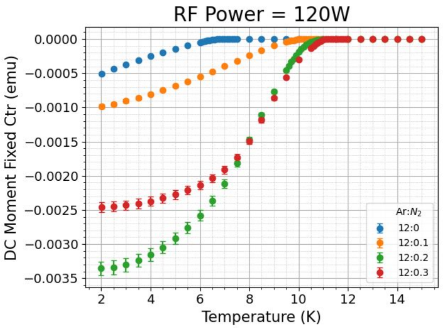
Ellipsometry

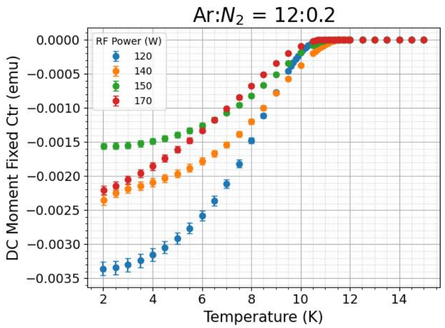
Measured by Lu's Lab, Jing-Wei Yang

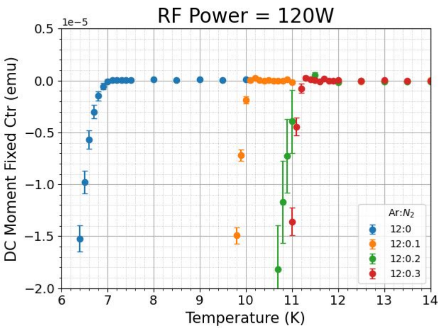
NbN Thin Film Optimization with Sputter Parameters

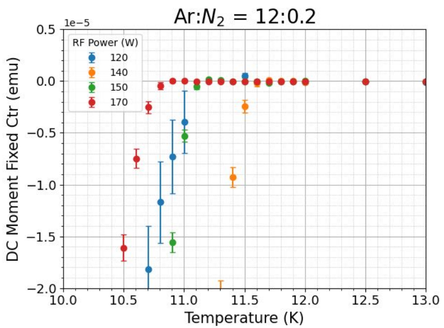
RF Power & Ar:N_2 Flow rate

SQUID → Higher Tc (Better crystallized)





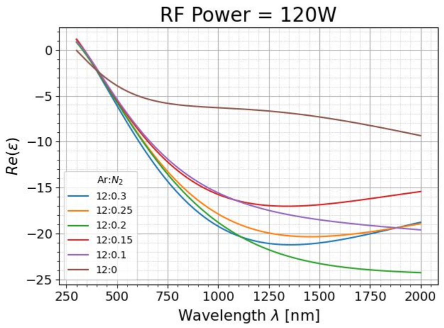


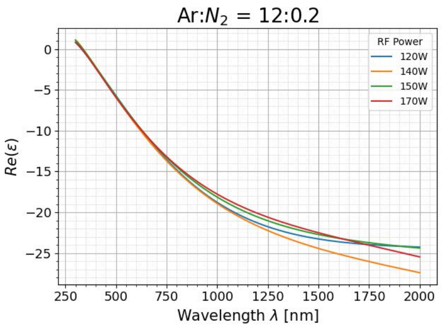


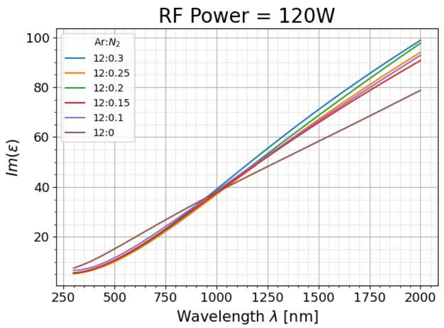
👑 12:0.2 or 12:0.3

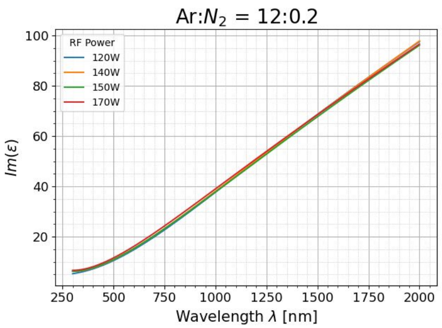
👑 140W

Ellipsometry → Re(ε) more negative (More metallic)
Im(ε) larger (Higher absorption)





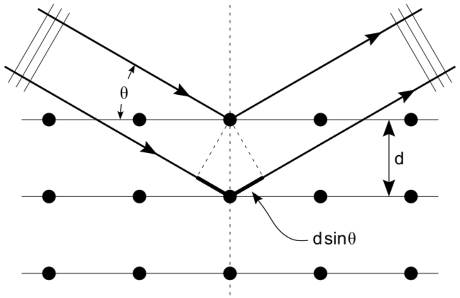




👑 12:0.2 or 12:0.3

👑 140W

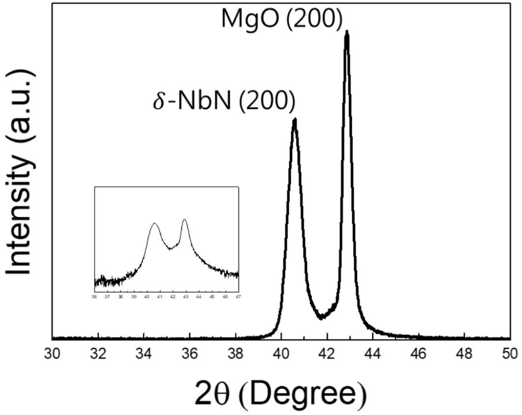
Inpurities – X-Ray Diffraction



Wikimedia Commons

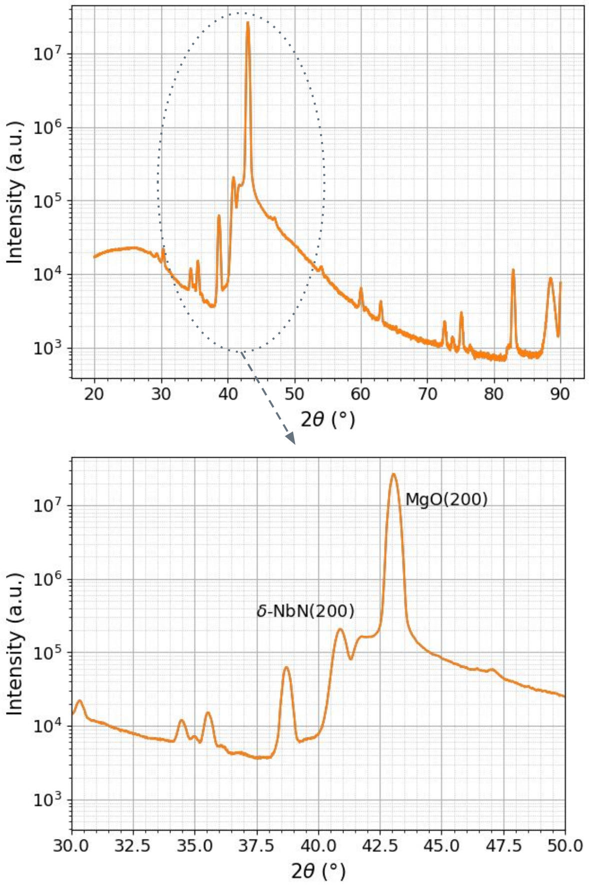
Crystal Structure

2022 Measured



Jing-Wei Yang, https://hdl.handle.net/11296/5376n3

2023 Measured

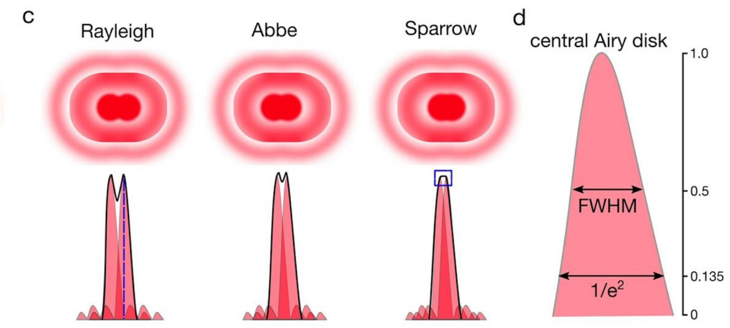


E-Beam Lithography

Abbe's Diffraction Limit

$$d = \frac{\lambda}{2\mathrm{NA}}$$

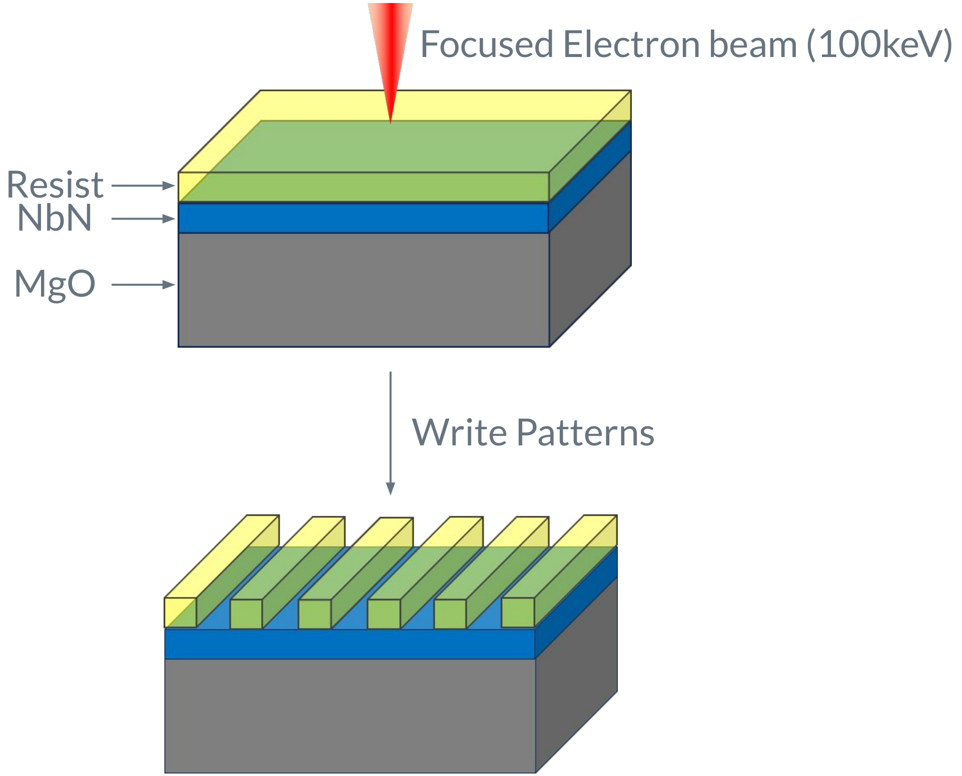
Lithography Resolution



©Erdinc Sezgin. J. Phys.: Condens. Matter 29 (2017) 273001

PhotoLithography with UV(400nm) → d~200nm

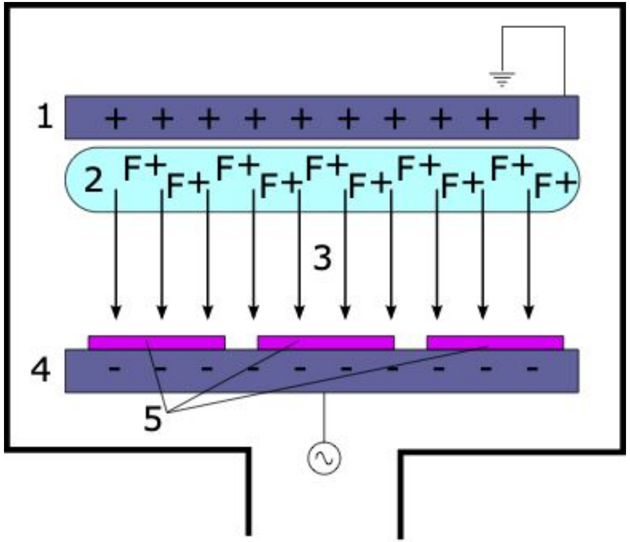
Nanowire width: 100nm → E-Beam Lithography



Reaction Ion Etching

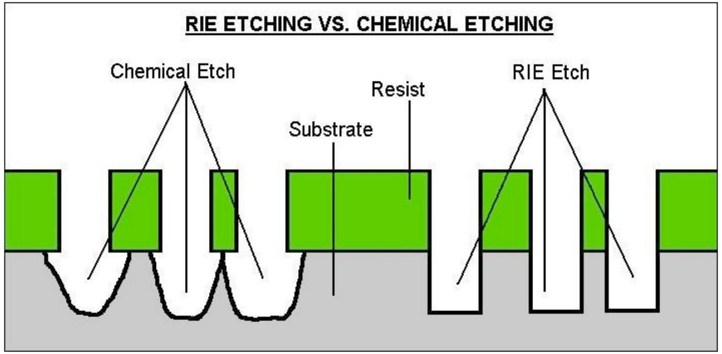
RIE Principle similar to Sputter →

Ion acceleration bombardment

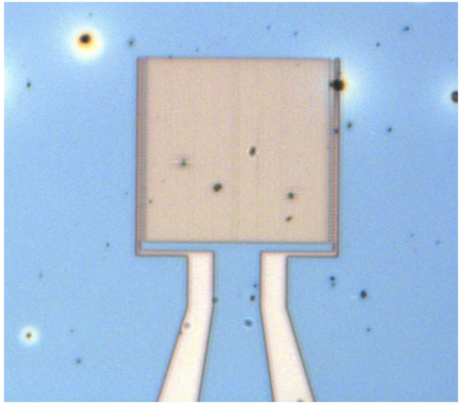


By Dollhous, modified by Adove1018 to show correct electric charges. - https://en.wikipedia.org/wiki/File:Riediagram.gif#file, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=29191041

Higher precision compared to traditional chemical etch

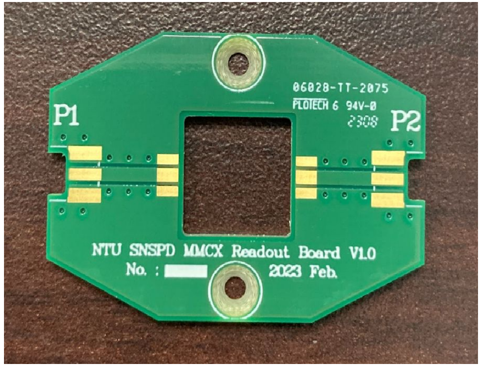


After Etching → NbN Nanowire



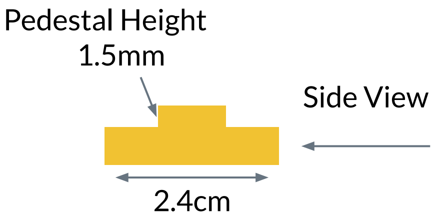
SNSPD Characterization Setup

SNSPD Device Preperation

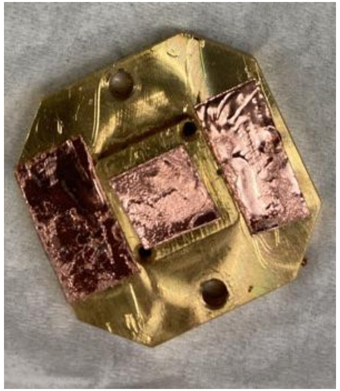


2 Channel SNSPD Readout PCB

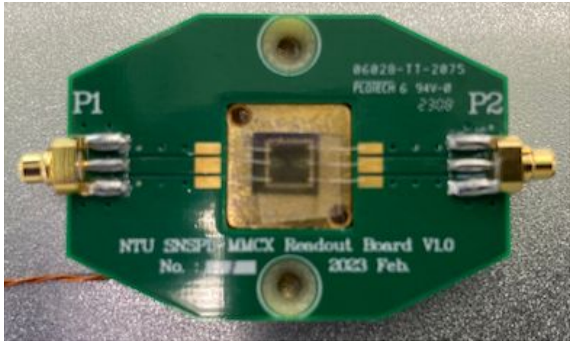
Grounded Coplanar Waveguide (GCPW)
MMCX connector
Designer: Hsin-Yeh, Wu
Drawn by: Jenny Huang
Fabrication: Plotech



Gold-plated Mount



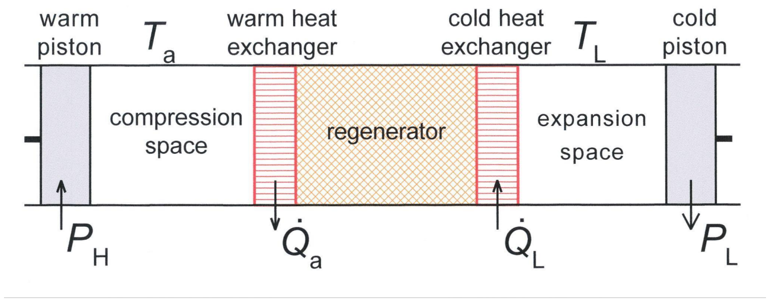
SNSPD Device



Wirebond: Ouchen

Cryogenics

Cryocooler: Stirling Refregirator

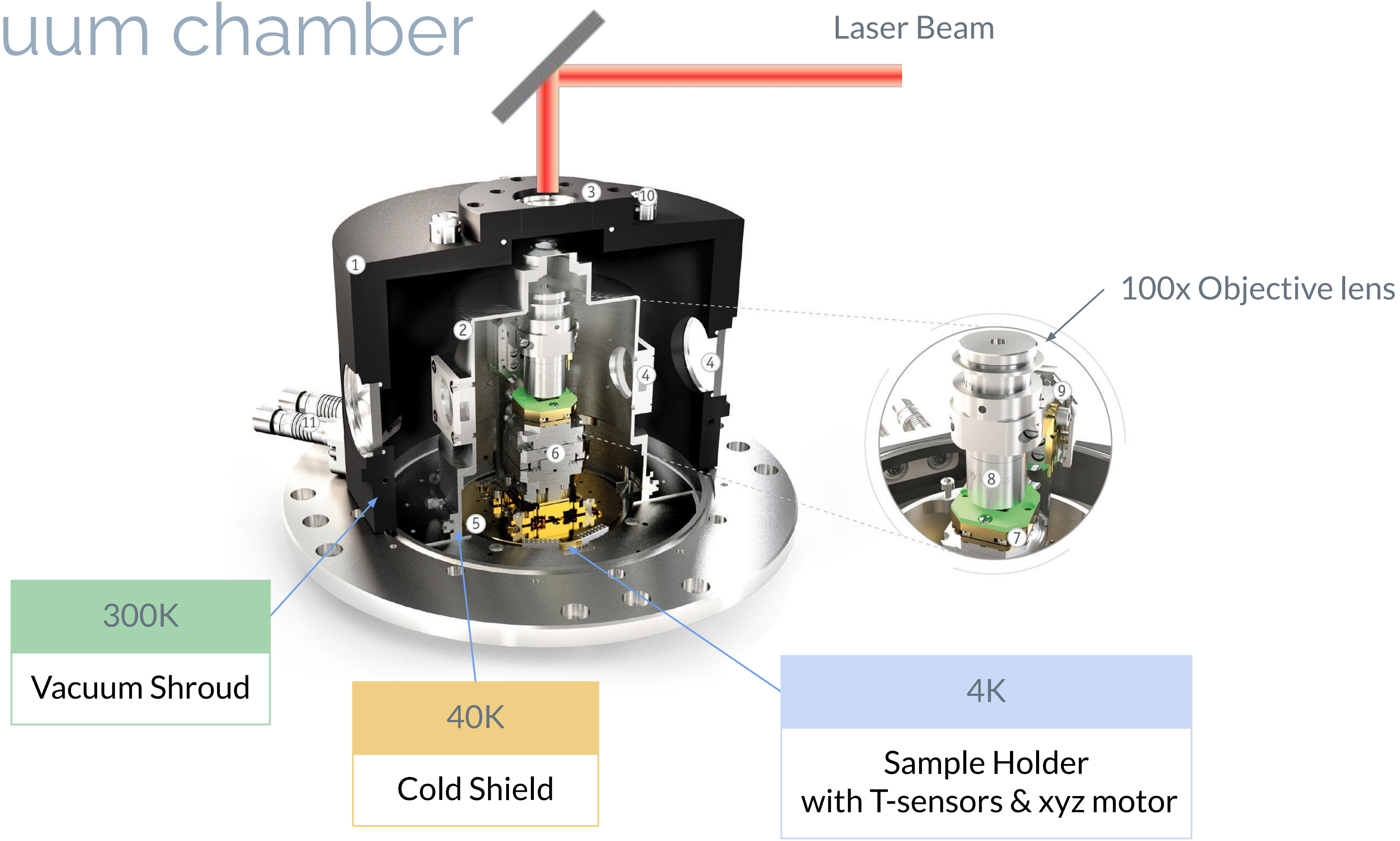


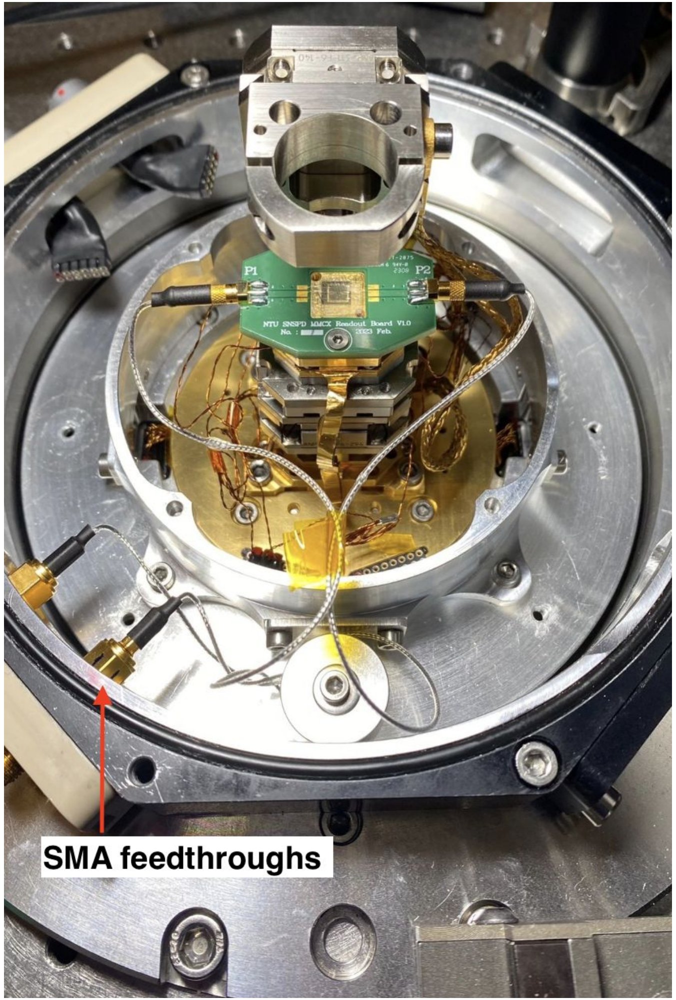
By Adwaele - Made by SliteWrite, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=124814496

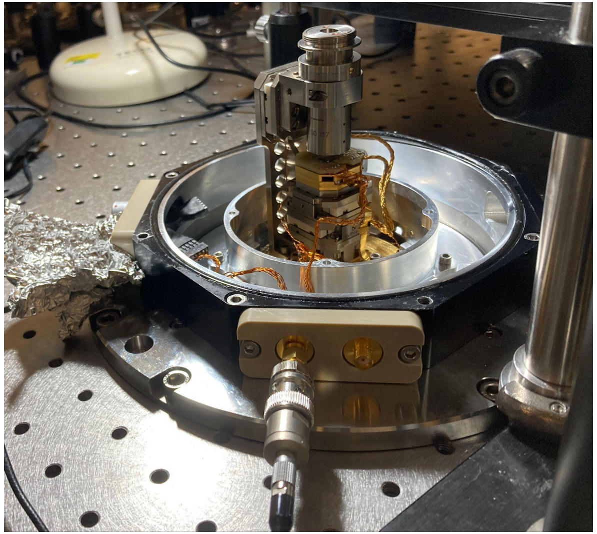
attoDRY800
Pulsetube Optical table implemented @ Prof. Yu-Rong Lu's Lab (AS)

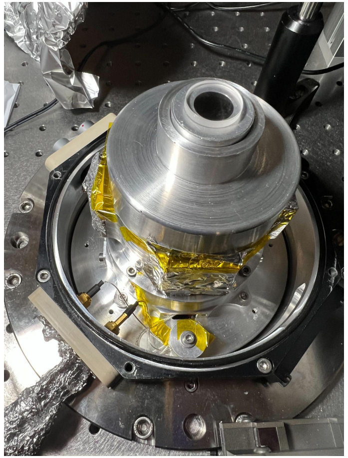
01 optical table (included)
02 cryocooler
03 cold breadboard
04 customizable vacuum shroud
05 touchscreen user interface
06 obstruction free work space

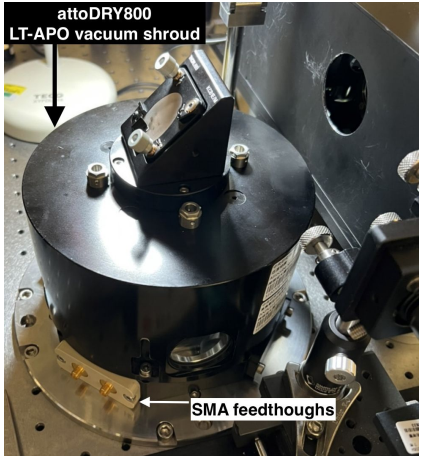
Vacuum chamber



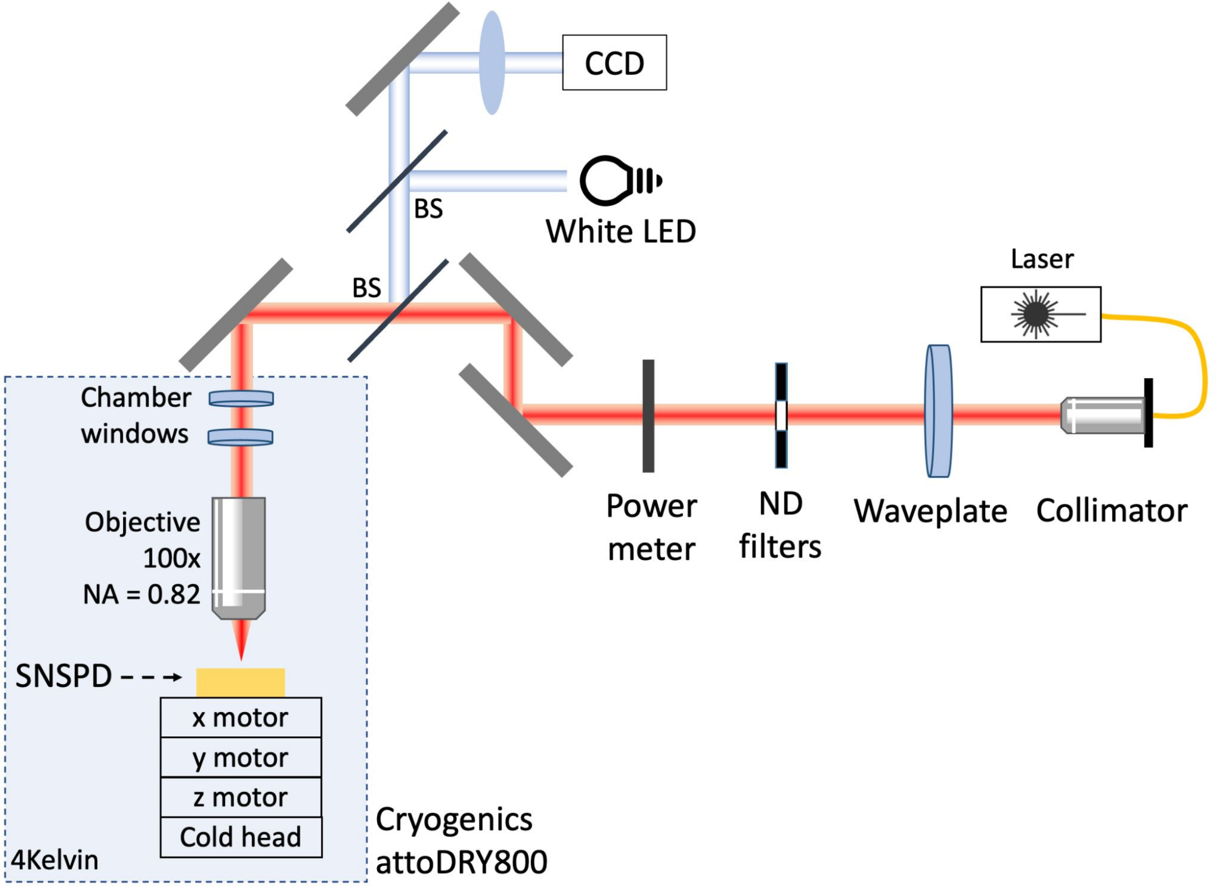

NTU SNSPD MMCX Readout Board V1.0
P1
P2
SMA feedthroughs



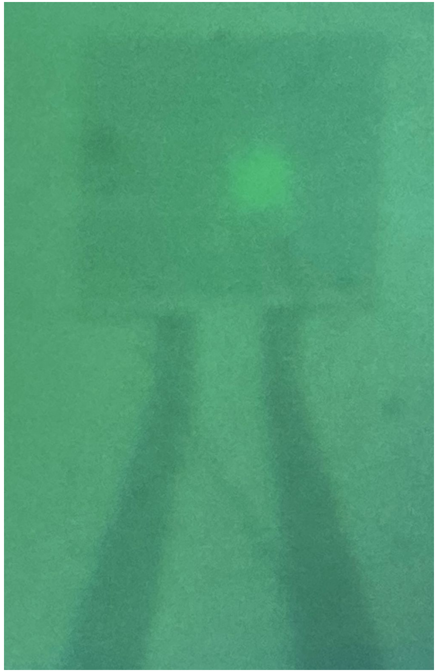



attoDRY800
LT-APO vacuum shroud
SMA feedthoughs

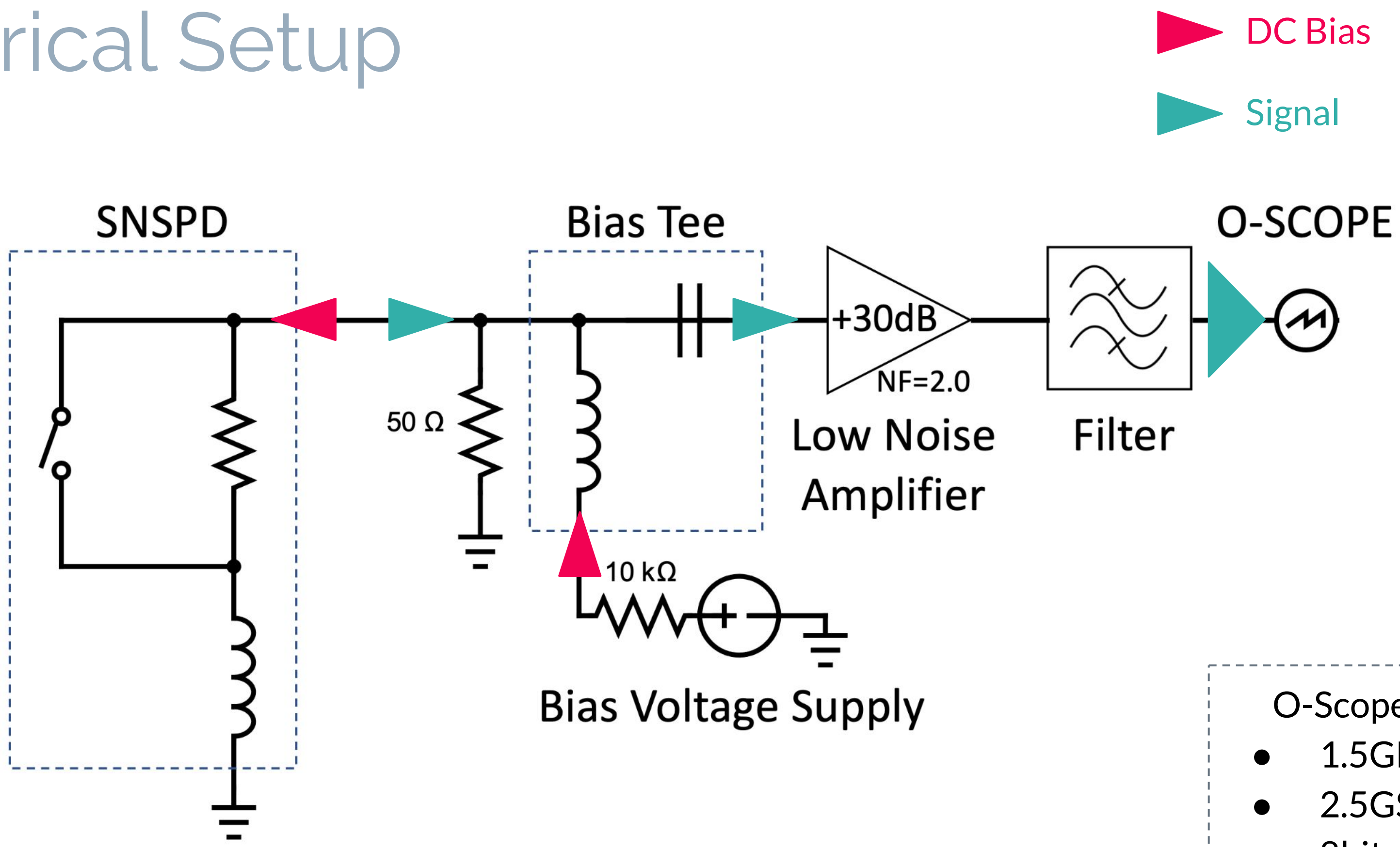
Optical Setup – Open-Air Coupling



CCD Image

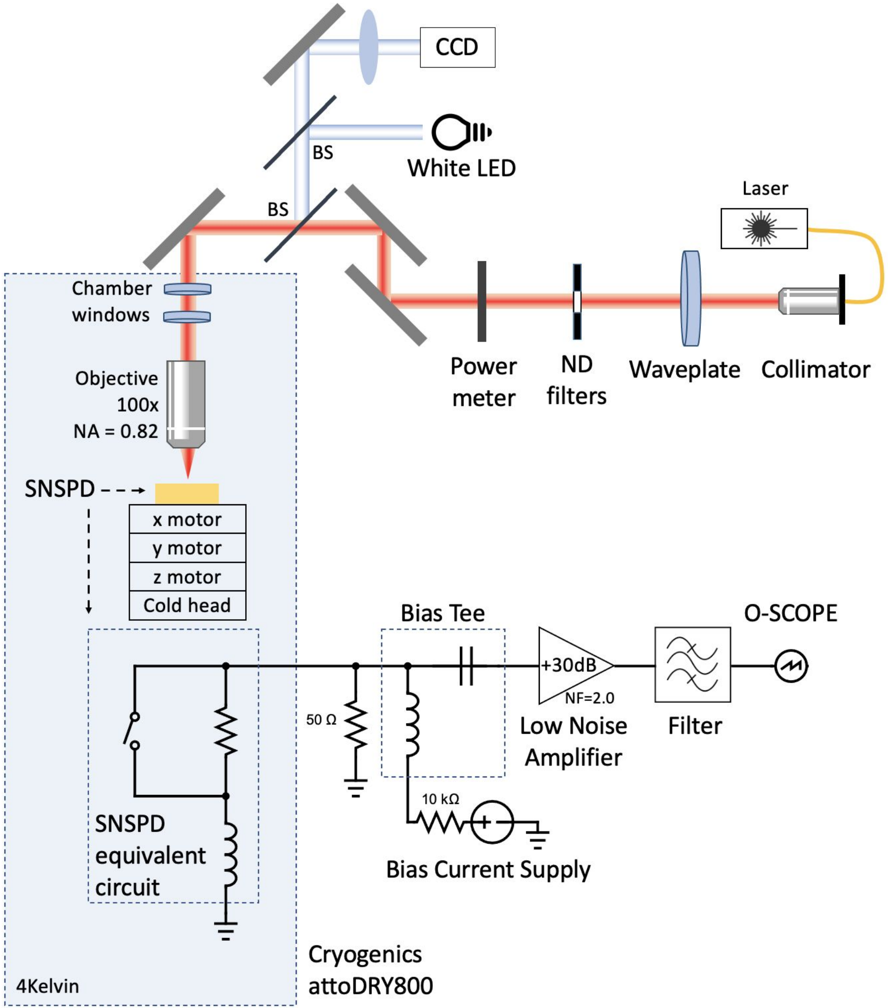


Electrical Setup



O-Scope

- 1.5GHz
- 2.5GS/s
- 8bits


CCD
BS
White LED
BS
Laser
Chamber windows
Objective 100x NA = 0.82
Power meter
ND filters
Waveplate
Collimator
SNSPD
x motor
y motor
z motor
Cold head
Bias Tee
O-SCOPE
+30dB
NF=2.0
50 Ω
Low Noise Amplifier
Filter
10 kΩ
SNSPD equivalent circuit
Bias Current Supply
4Kelvin
Cryogenics attoDRY800

CW Laser Configuration

Laser

- 532nm CW
- 100μW

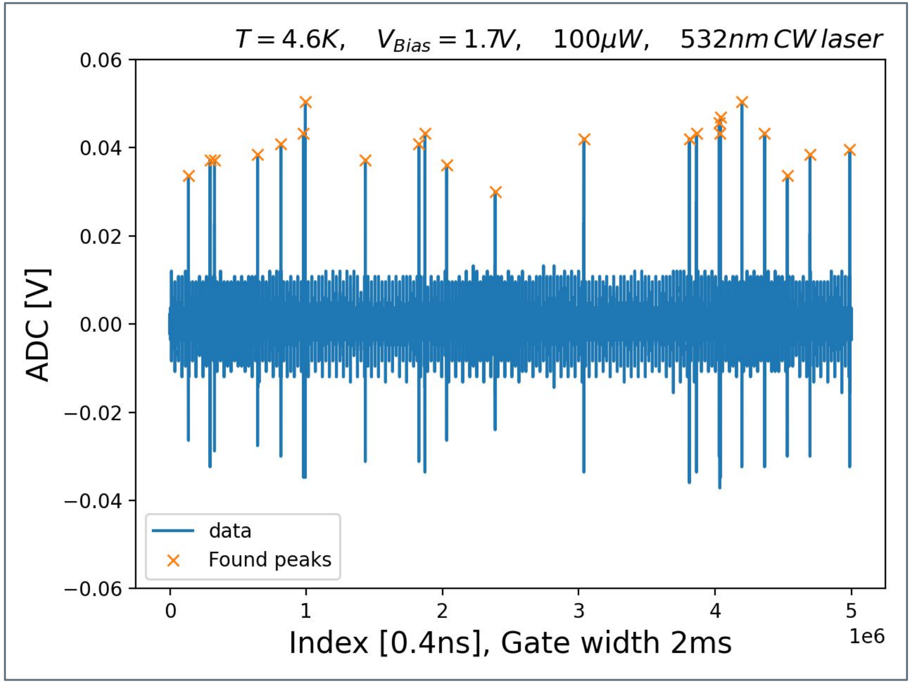
Oscilloscope

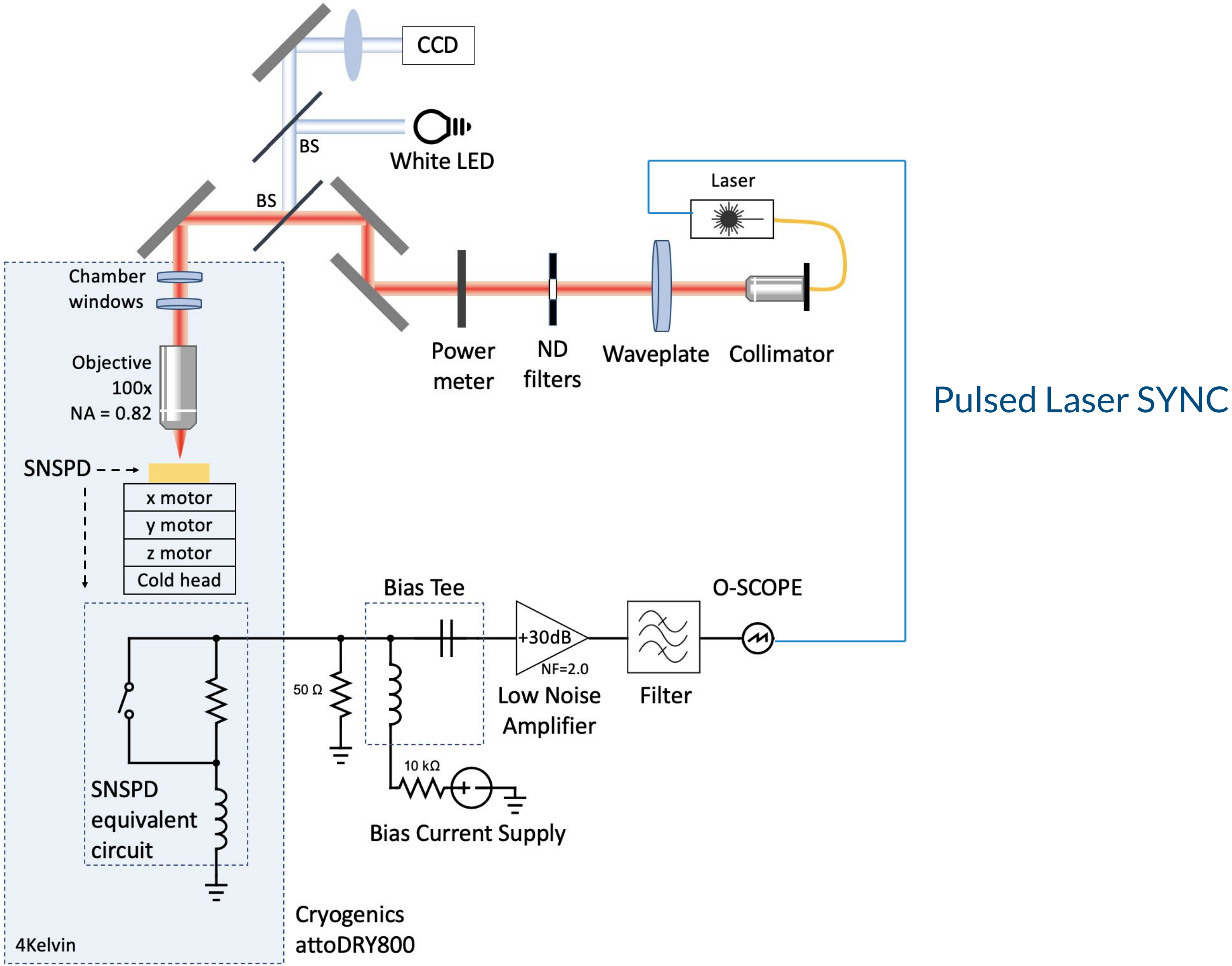
- Sampling Rate: 2.5GS/s (0.4ns)
- Time Gate: 5M Samples → 2milisecond

Counting

- Peak finding
- Threshold: 20mV
- Peak Minimum Distance: 40ns

1 Oscilloscope Time Gate

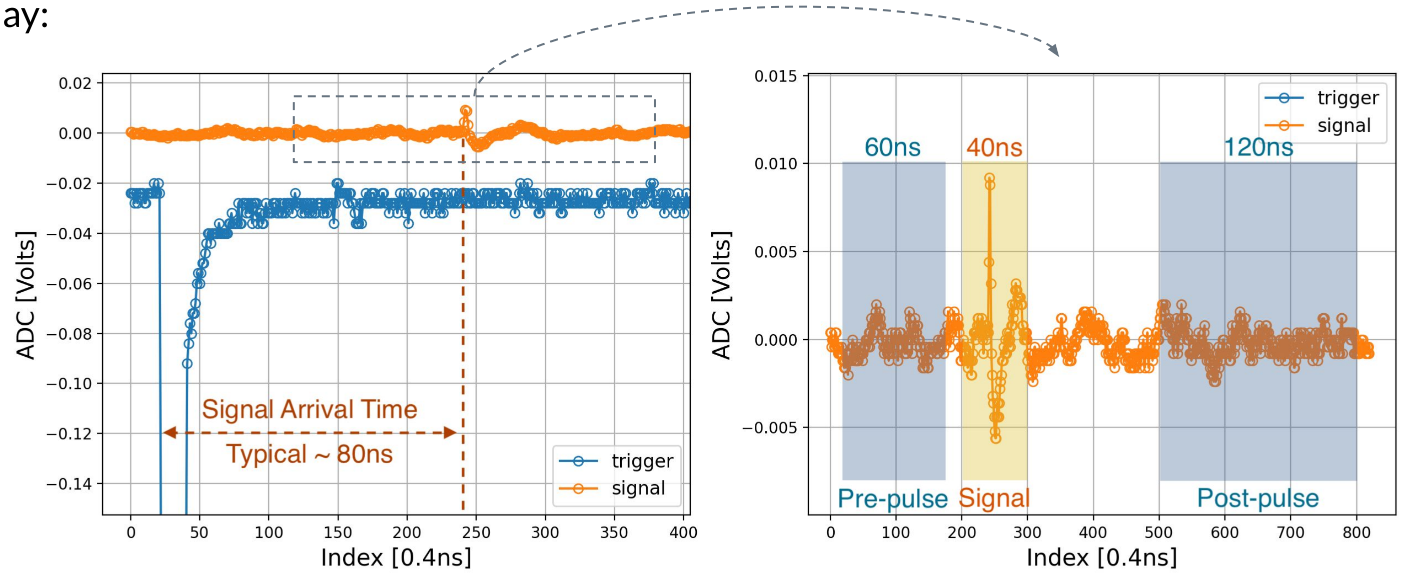



CCD
White LED
BS
BS
Laser
Chamber windows
Objective 100x NA = 0.82
Power meter
ND filters
Waveplate
Collimator
Pulsed Laser SYNC
SNSPD
x motor
y motor
z motor
Cold head
Bias Tee
O-SCOPE
+30dB
NF=2.0
50 Ω
Low Noise Amplifier
Filter
10 kΩ
SNSPD equivalent circuit
Bias Current Supply
4Kelvin
Cryogenics attoDRY800

Pulse Data Taking

Pulse Laser Repetition Rate: 2.5MHz (400ns)
Pulse Laser Width: 100ps
Oscilloscope Sampling Rate: 2.5GHz (0.4ns)
Trigger: Laser Sync
Signal: Amplified SNSPD output

Event Display:



Sub-window of

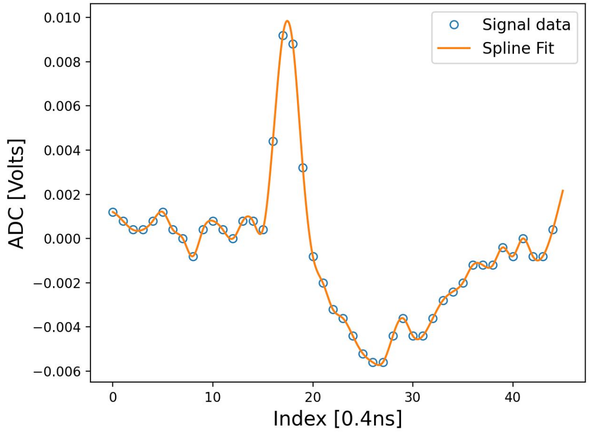
1 Laser Trigger

Define Signal &

Sideband Region

Event Selection & Signal Reconstruction

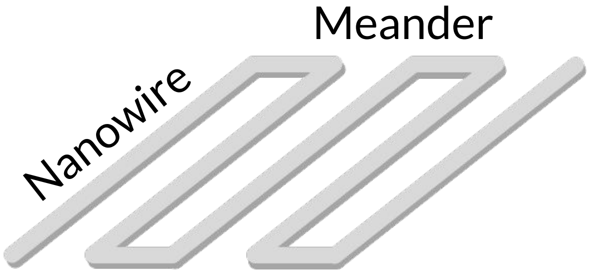
- Signal Reconstruction within the Signal Region
  - Cubic spline fit → turn the discrete data points into continuous function
  - Differentiate the spline function → Find turning points
- Variables
  - Amplitude = Voltage range (including overshoot)
  - Pulse arrival time = time of 50% voltage level of rising slope
  - Rise time = Time interval between 10%-90% of rising slope
- Event Selection
  - Signal Amplitude > 3mV
  - Voltage Differentiate at rising slope > 2mV/sample



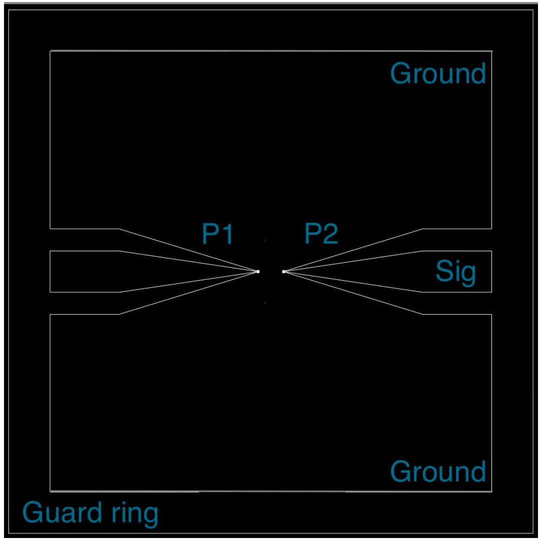
$$\text{Detection Efficiency} = \frac{N_{Event\ Selection}}{N_{Event\ PreSelection}}$$

SNSPD Characterization w/ 532nm Pulsed Laser

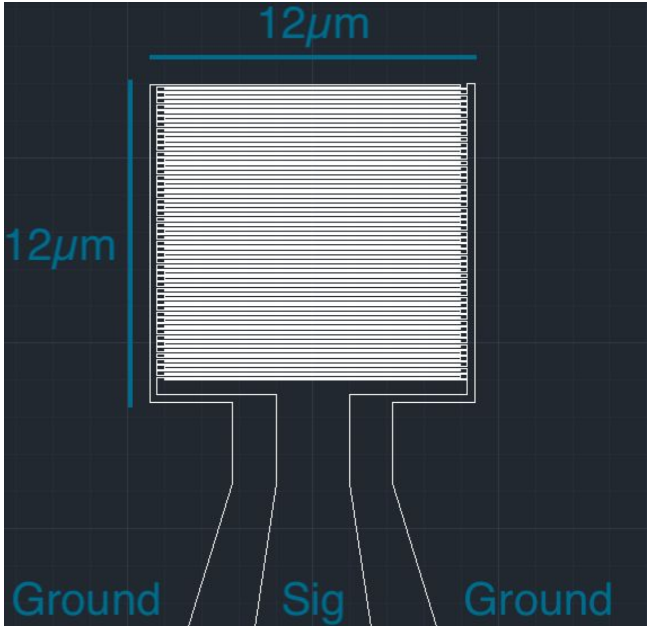
SNSPD Pattern Design



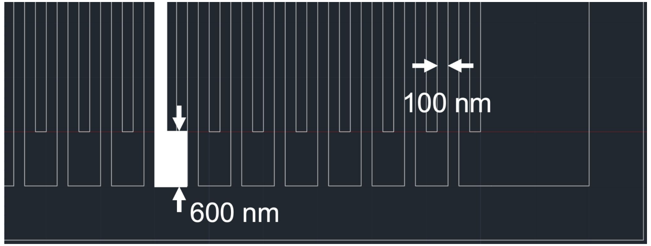
2 unit SNSPD with coplanar waveguide readout



Nanowire meander (Total Length 720μm)

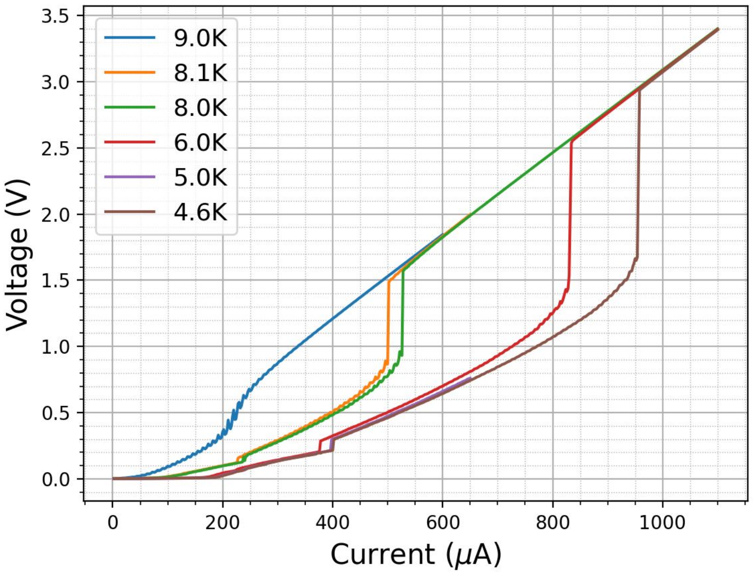


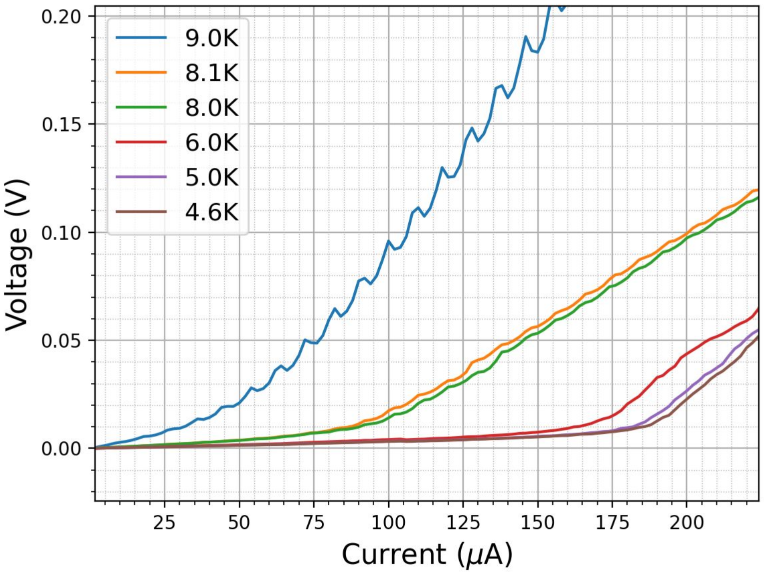
Width 100nm, Pitch 200nm



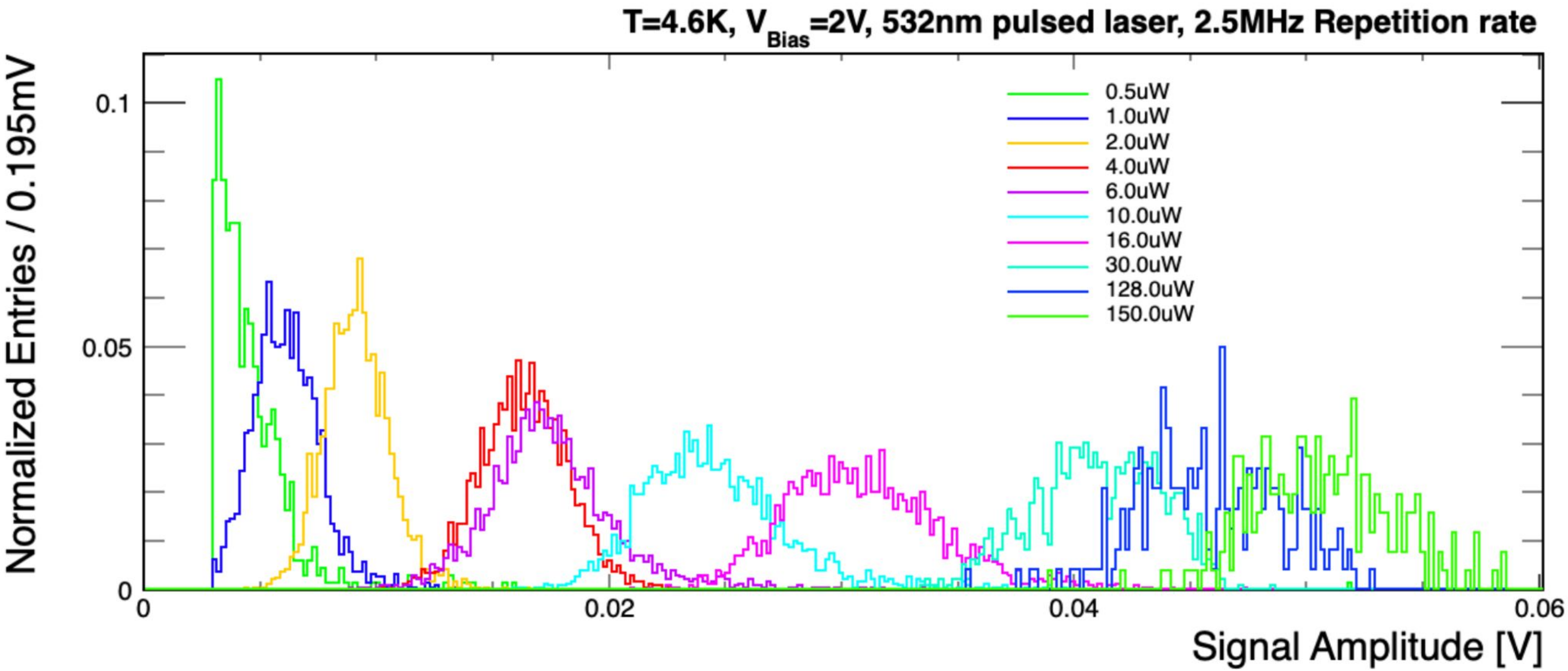
IV Curve

- Critical Current @ 4.6K ~ 180μA
- Critical Temperature ~ 9K
- Wide Transition Width ~ 800μA

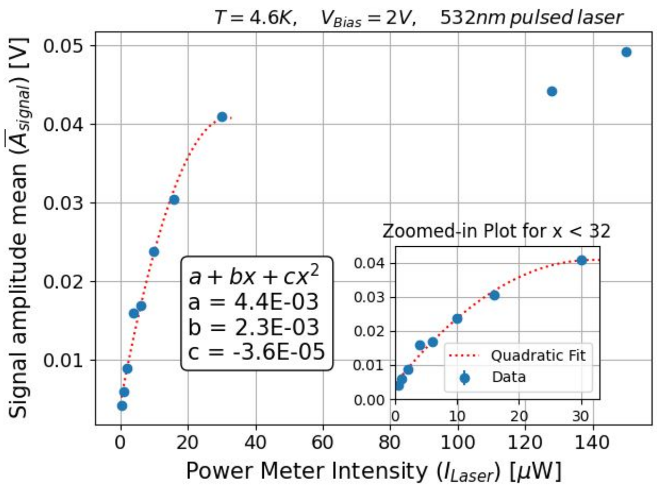


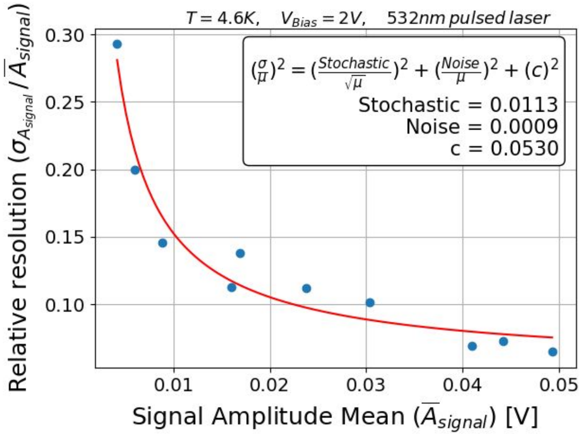


Laser Power Sweep



Preliminary Results

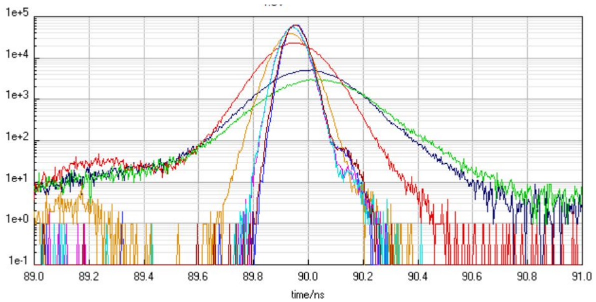




- 1% stochastic term
- 5% constant term

- $I_{Laser} < 30\mu W \rightarrow \bar{A}_{signal}$ has a quadratic gain
- $I_{Laser} > 30\mu W \rightarrow \bar{A}_{signal}$ slowly rises / saturates

Light Intensity Dependance!!



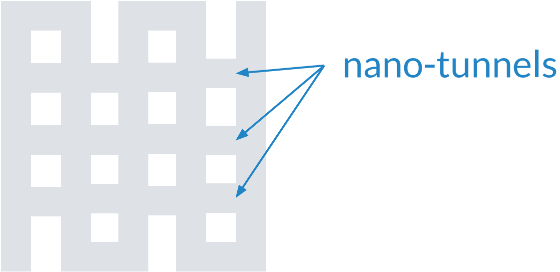
- TCSPC module (4ps)
- Time jitter ~ 100ps

SEM image

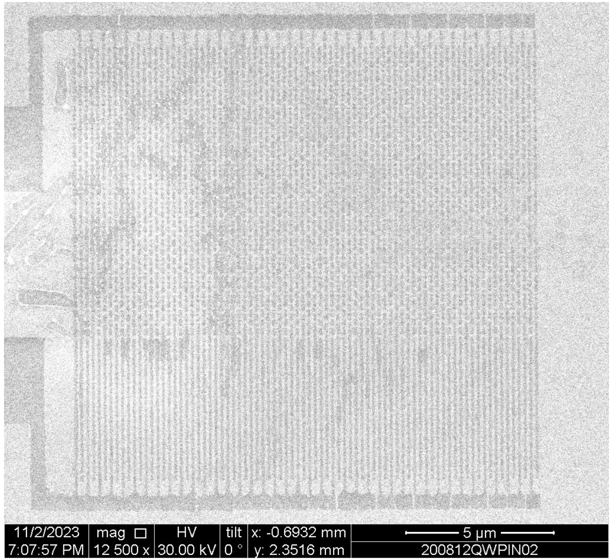
- Mesh-like structure
  - Nano-tunnels dimension around 10-100nm
  - Reason of the wide transition and kinks in IV Curve
  - Currently retuning EBL parameters

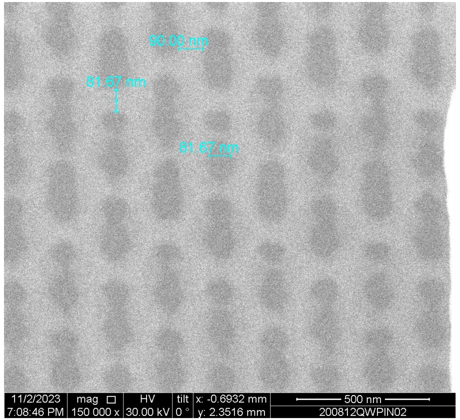
- This accident may lead us to SNPSD calorimeters!
  - Very fast response (100ps level)
  - Wide dynamic range
  - Good energy resolution

Original design



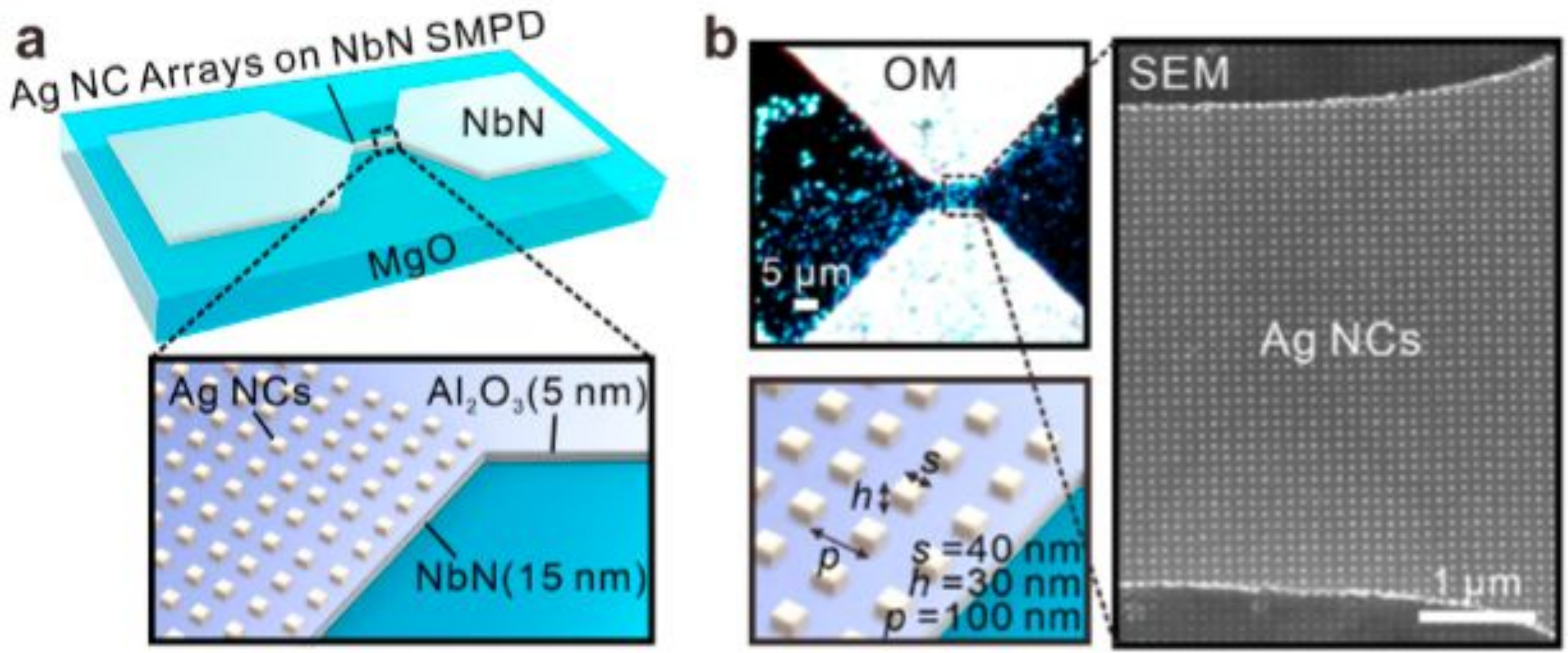
SEM image





Gap-plasmon Superconducting "Microwire" Single Photon Detector

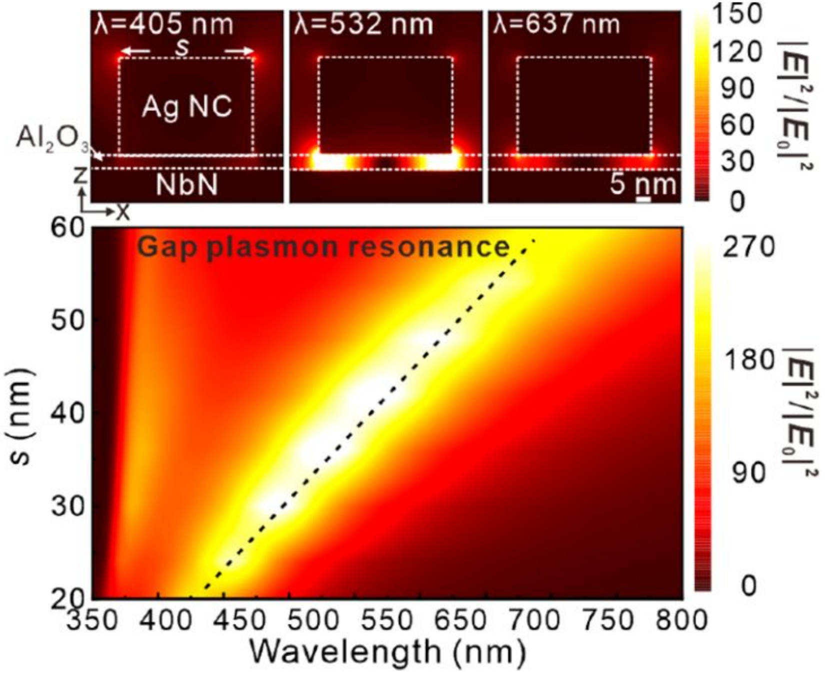
Gap-Plasmon-Enhanced SC Microwires



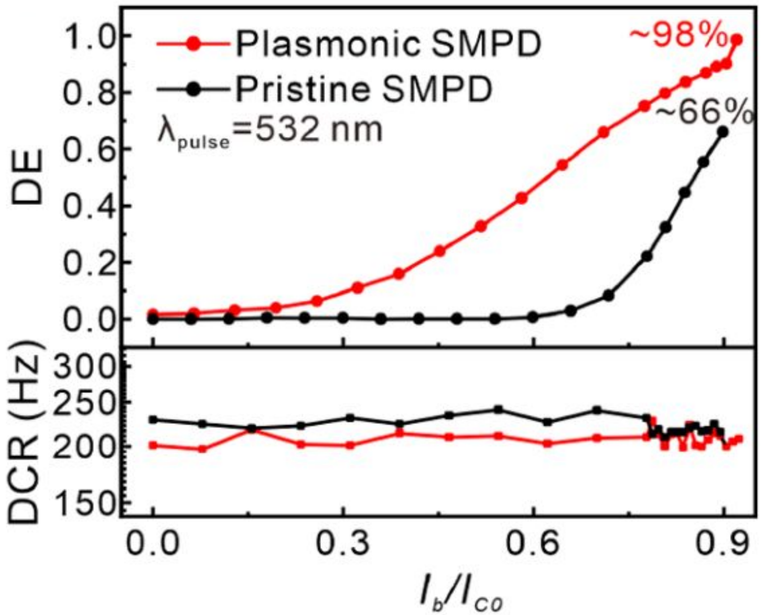
Yang, J.-W. et al. Nanoscale Gap-Plasmon-Enhanced Superconducting Photon Detectors at Single-Photon Level. Nano Lett. (2023).

Results

FDTD Simulation



Detection efficiency



Gap-plasmonics nanocubes may lead us to sensitivity in longer wavelengths!

Why do we need SC IR single photon detectors?

Wide variety of applications

Particle Physics

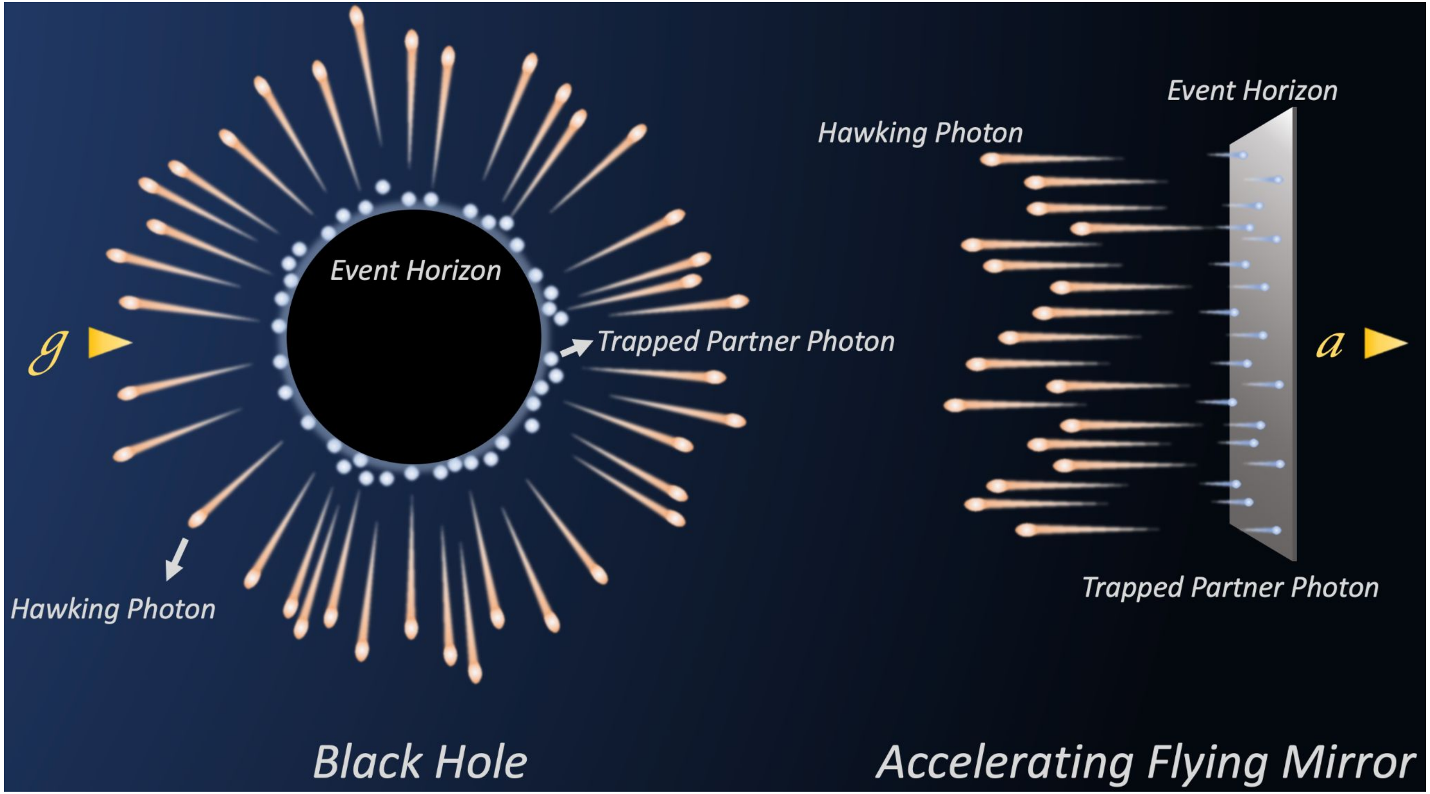
Cosmology

Astroparticle physics

Quantum communication/information

Analog Black Hole

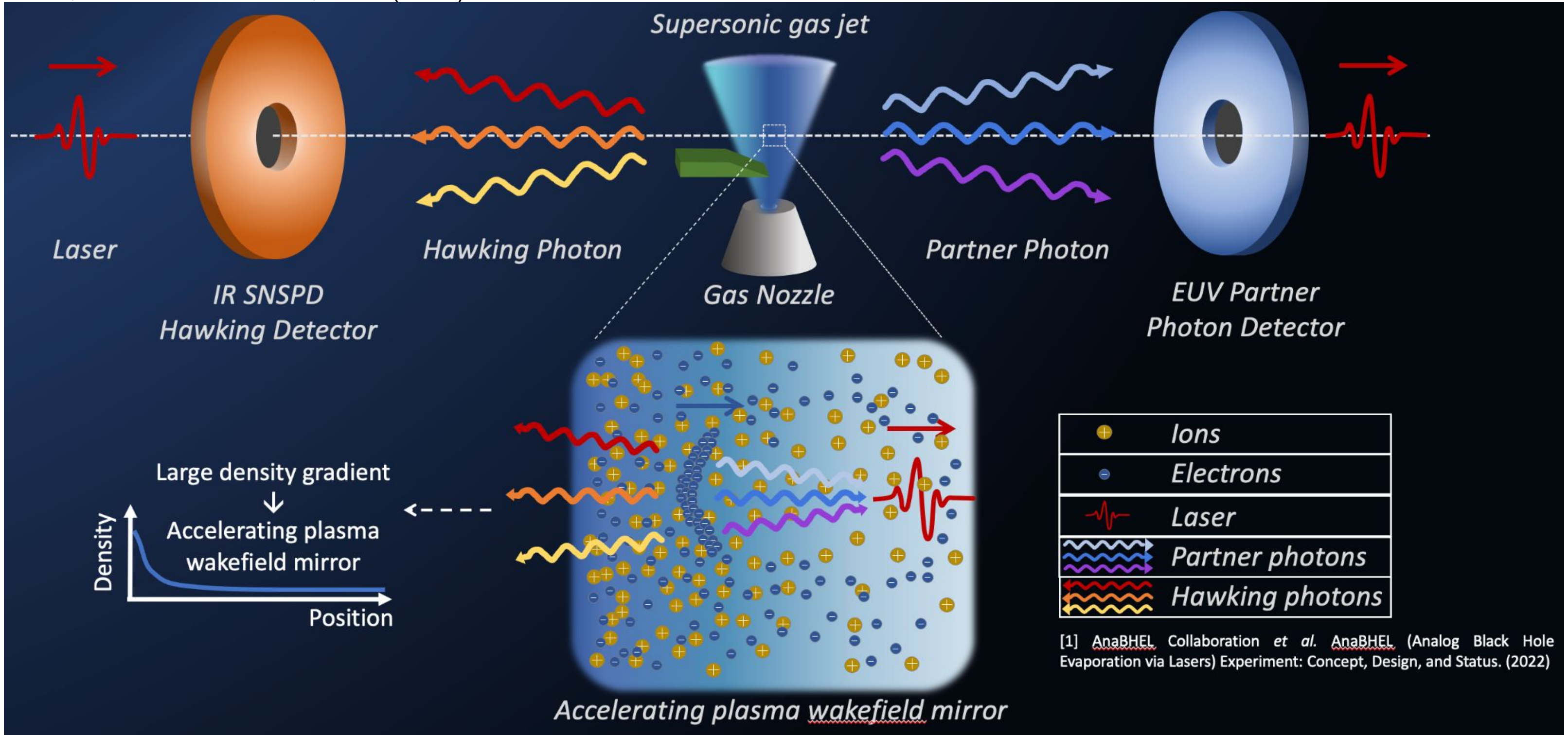
Chen, P. & Mourou, G. Phys. Rev. Lett. 118, 045001 (2017).



Equivalence Principle

AnaBHEL (Analog Black Hole Evaporation via Lasers) Experiment

Chen, P. et al. Photonics 9, 1003 (2022).

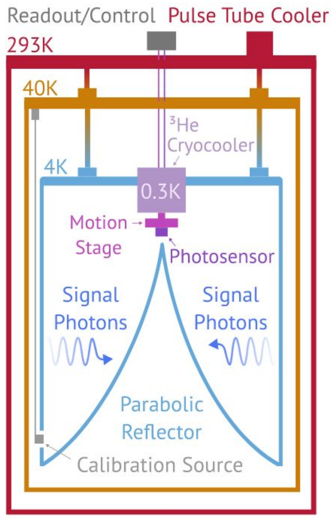


Requirements:

- Broadband 10-100μm single photon sensitivity
- High efficiency, High speed, Low Timing Jitter, Low Dark Count
- Polarization distinguishability

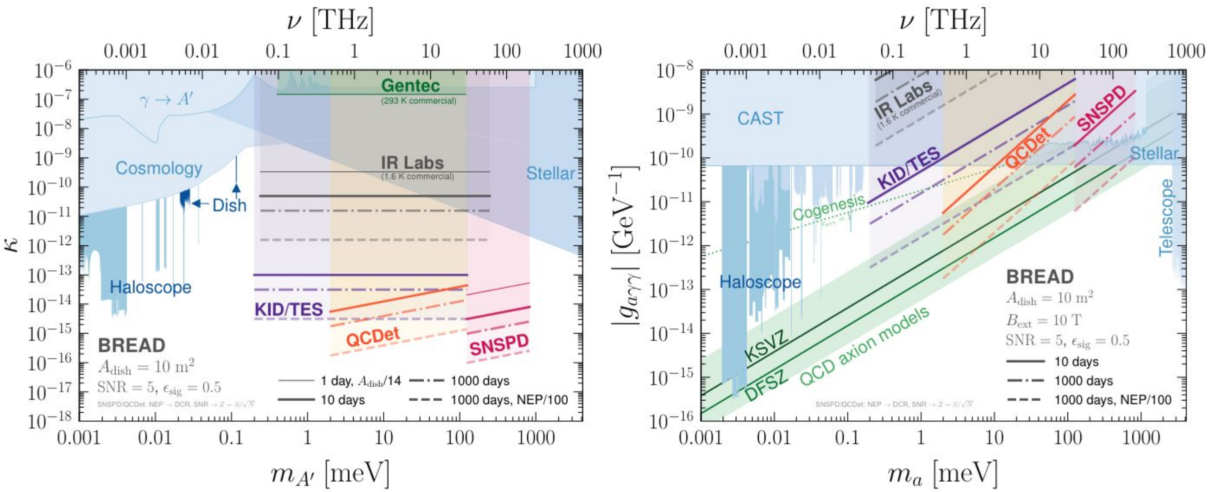
Dark Matter Searches

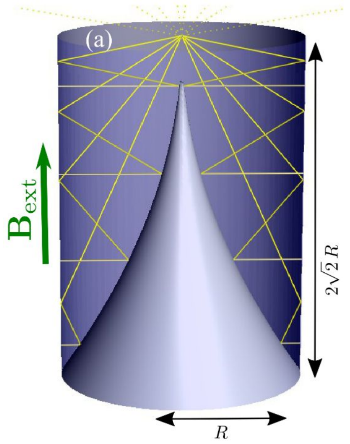
- Dark matter candidates with m_{DM} < 1 eV
  - QCD Axions (*a*)
  - Dark Photons (*A'*)
- Non-zero DM-photon couplings → lab detection through EM interactions



Broadband solenoidal haloscope for terahertz axion detection (BREAD)

Phys. Rev. Lett. 128, 131801 (2022).

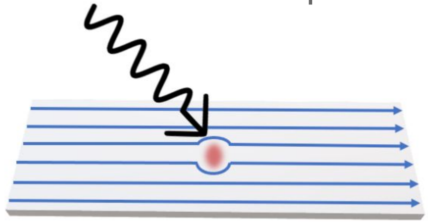


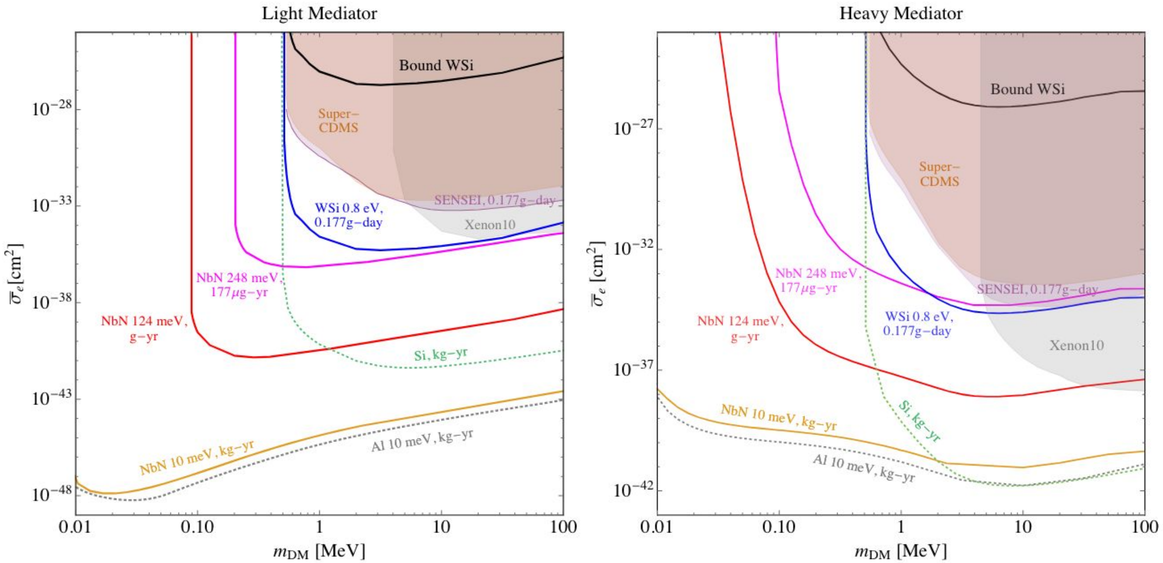


Dark Matter Searches – Direct interaction

Phys. Rev. Lett. 123, 151802 (2019).

DM Scattering
or Absorption



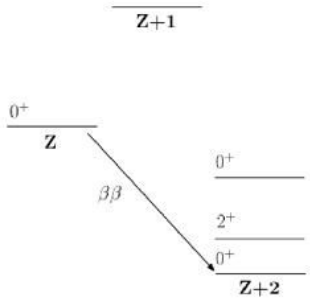


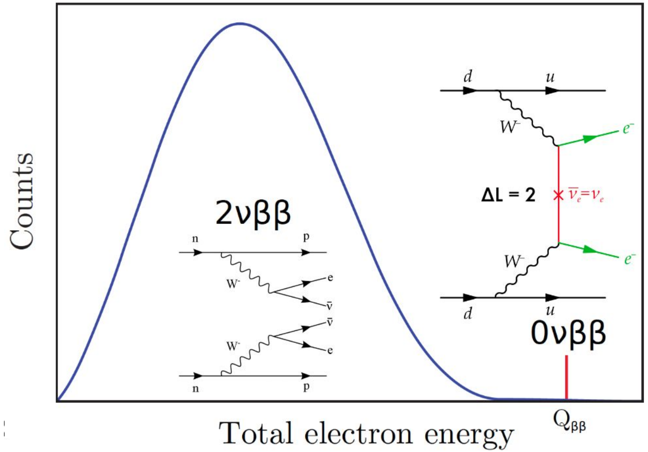
- Requires stable and low Dark Counts

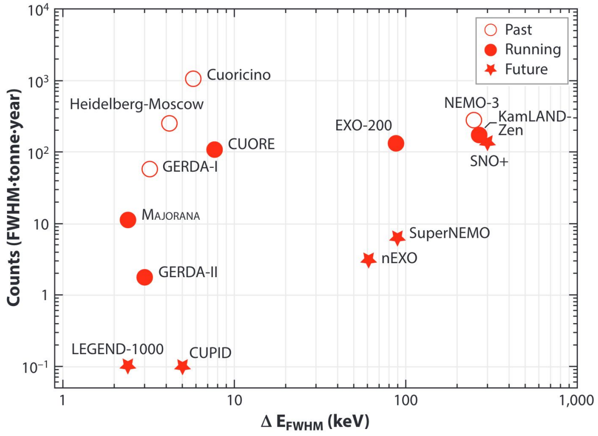
Lower energy/wavelength threshold can lead to larger DM detection phase space!

Neutrinoless double beta decay

- 2νββ is a rare SM radioactive decay process
- 0νββ is a theoretical, experimentally unobserved process
- Implys ΔL ≠ 0
  - Lepton number violation = new physics!
  - Prove the Majorana nature of neutrino → Majorana mass
  - Connection to baryon asymmetry







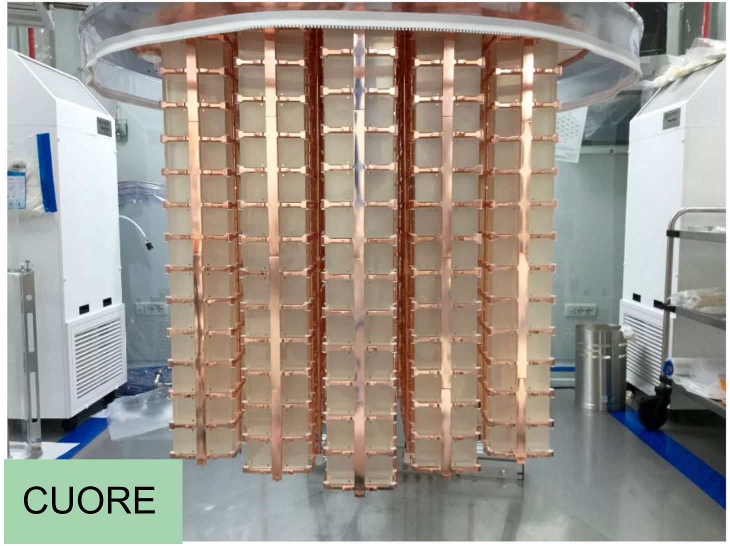
Bradford Welliver (15th Pisa meeting on Advanced Detectors)

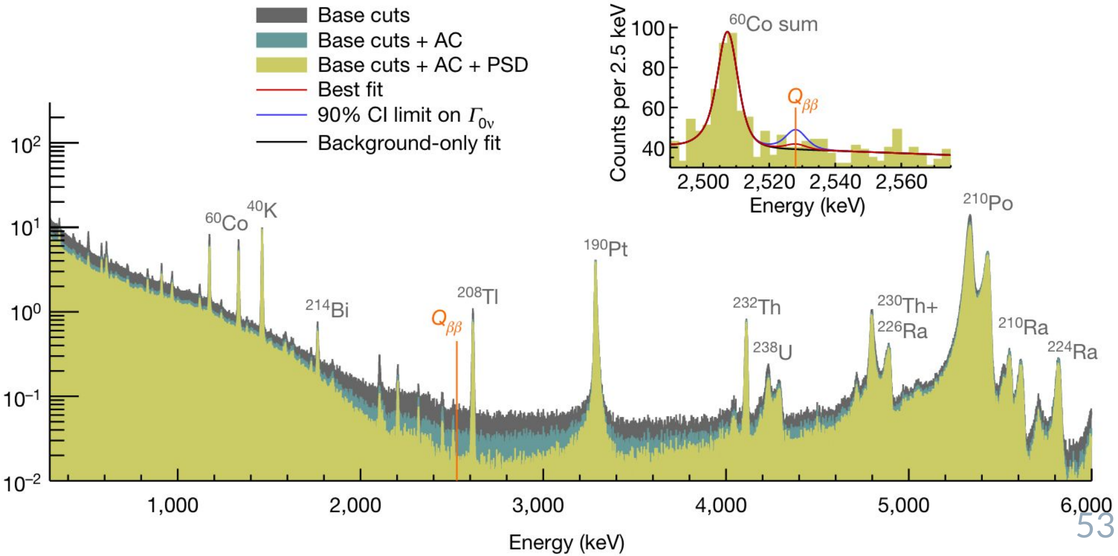
Annual Review of Nuclear and Particle Science 69, 219–251 (2019).

Neutrinoless double beta decay

- Planning upgrades: CUPID-1T
  - 1 Ton of ^{100}Mo
  - Irreducible background from 2νββ → Pileup becomes important with large amount of source
  - Implementation of TES → Low Dark Count, 10us timing resolution, good energy resolution
- SNSPD calorimeter may be an even better option!

Nature 604, 53–58 (2022).



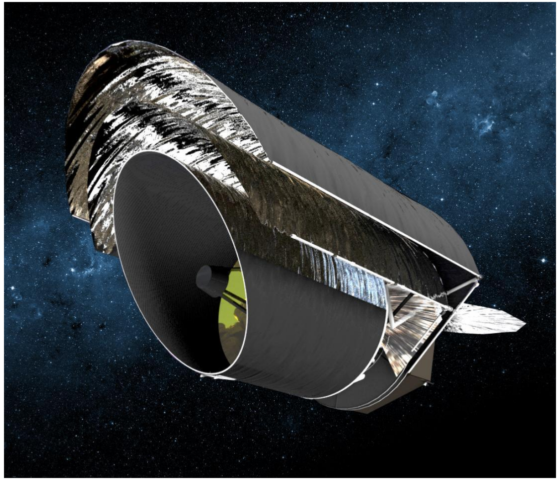


Exoplanet search

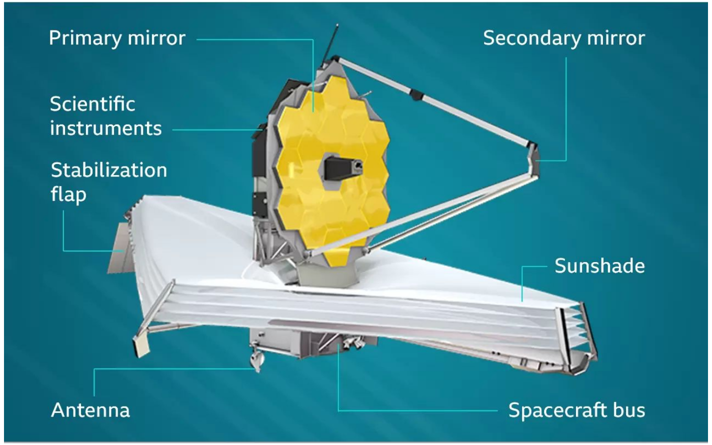
JATIS 7, 011004 (2021).

- Planetary science (Outside the solar system)
- Search for Earth-like, habitable planets
- Future: Origins Space Telescope(OST) (2035)
    - Targetting mid to far-infrared (5-600 μm)
    - Actively cooled to 4.5K → SC detectors

Origins Space Telescope Proposal

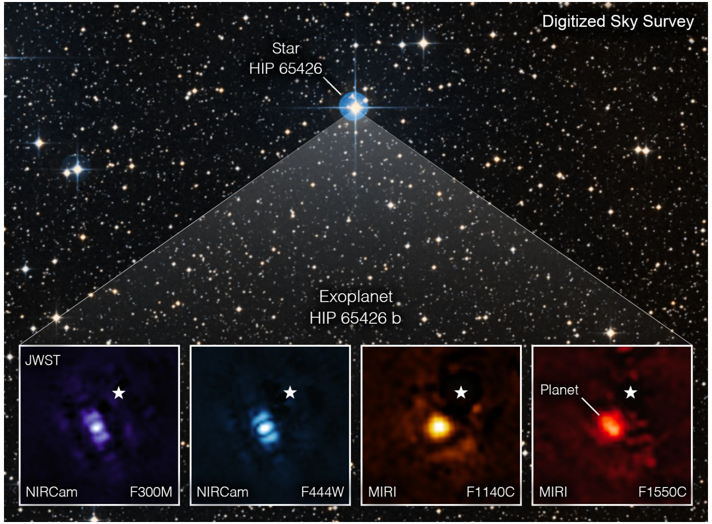


James Webb Space Telescope



Source: Nasa

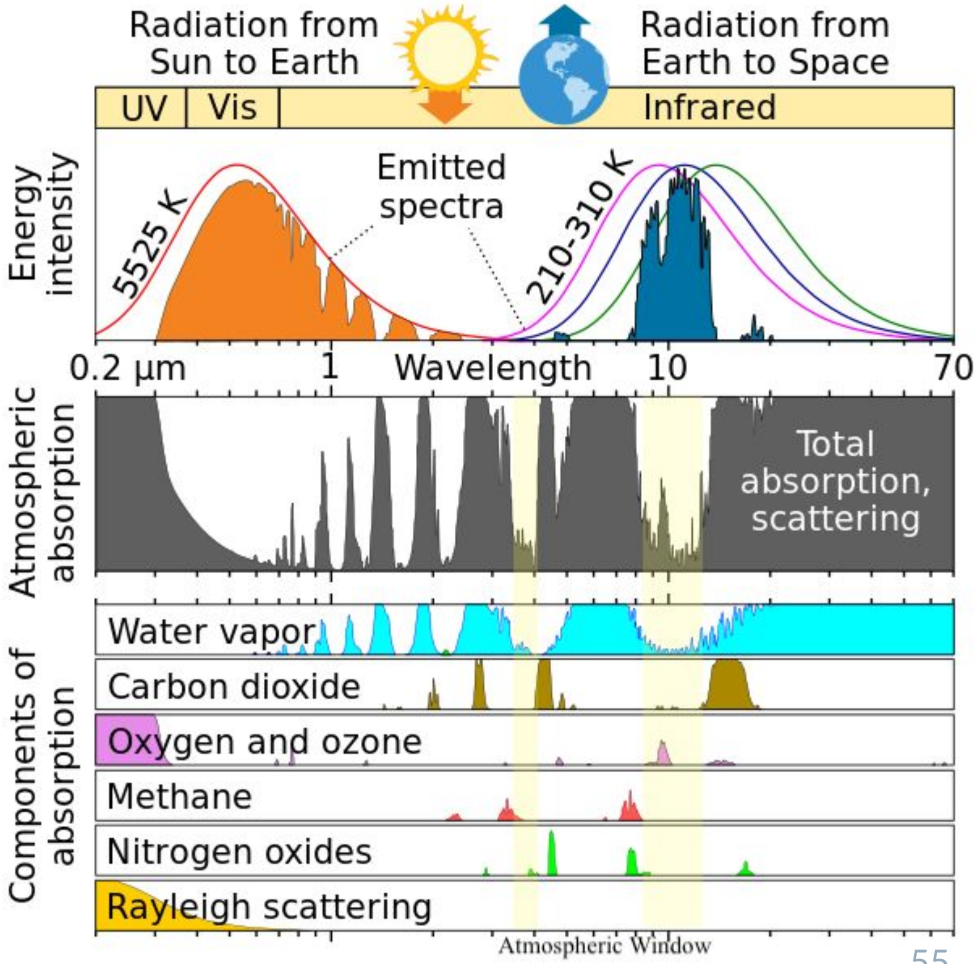
BBC



Atmospheric Window

- No sun radiation & atmospheric absorption
- At around 3-4μm & 8-10μm

- Ground-to-Satellite/Space Applications
  - Free space optical (FSO) communication
  - Quantum secure keys
  - Space Observatory

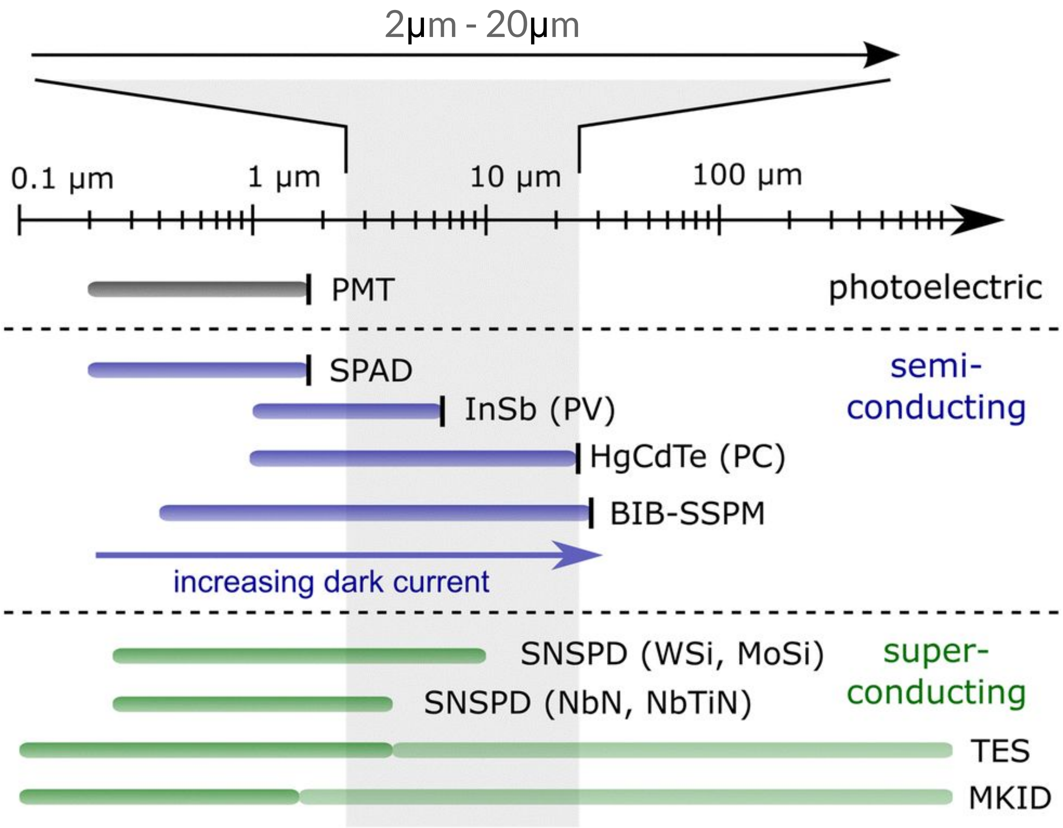


Comparing SC Single Photon Detectors @1550nm

Figure of Merit	SNSPD	TES	MKID	STJ
Efficiency	99.5%	98%	17%	20%
Number resolution	5	29	7	/
Recovery time	80ps	75ns	50μs	20μs
Timing jitter	2.6ps	30ns	1μs	1μs
Dark counts (Hz)	0.01	0.0086	/	/
Maximum count rate	1.5×10^9	10^5	2×10^3	10^4
Number of “pixels”	1024	36	20440	120

Optimal detector for quantum communication with fiber optics

Wavelength Sensitivity Range Comparison



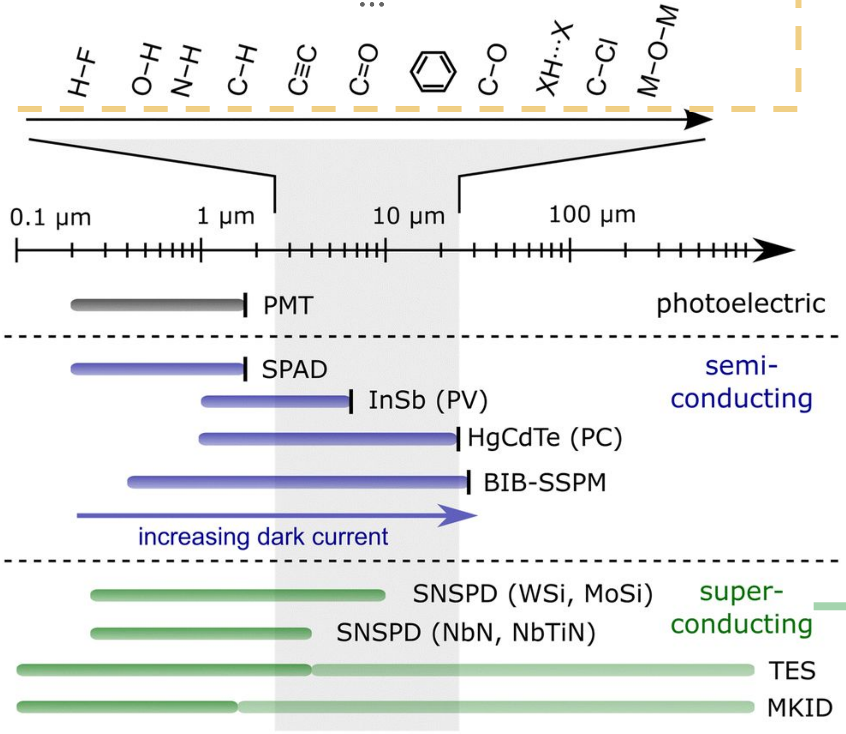
Chemical Society Reviews 52, 921–941 (2023).

Large Dark Current

Haven't reach theoretical limit

Quantum Communication @ Atmospheric Window
Analog Black Hole
Exoplanet Search
Dark matter search
...

Mid - Far Infrared is a golden wavelength band for next generation measurements!

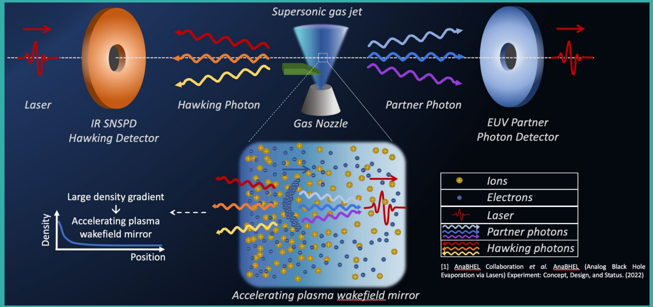


Chemical Society Reviews 52, 921–941 (2023).

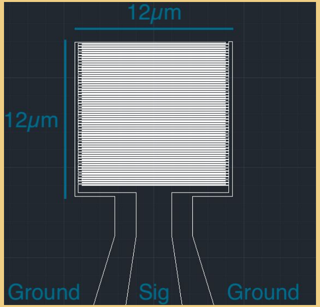
SNSPD can be the detector to meet all stringent requirements in these applications

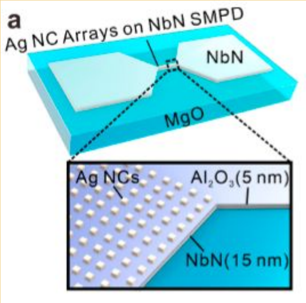
Shown sensitivity in MIR
Potential calorimetery
Very fast timing
Low dark count
...

Applications

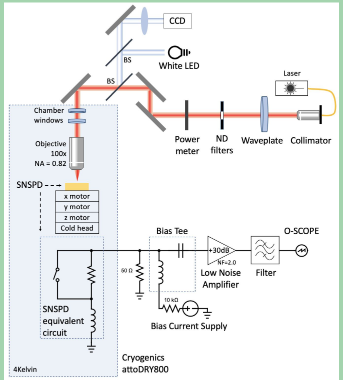


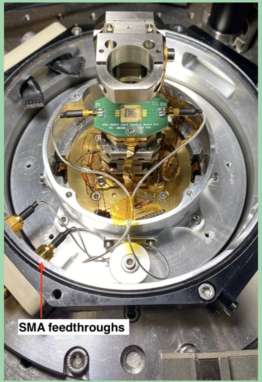
Design and simulation



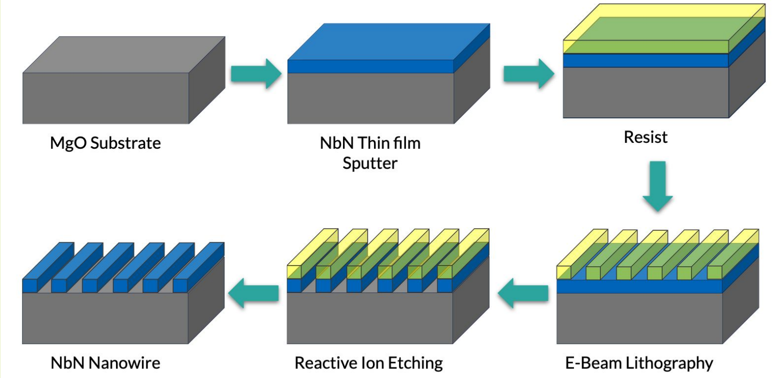


Characterization

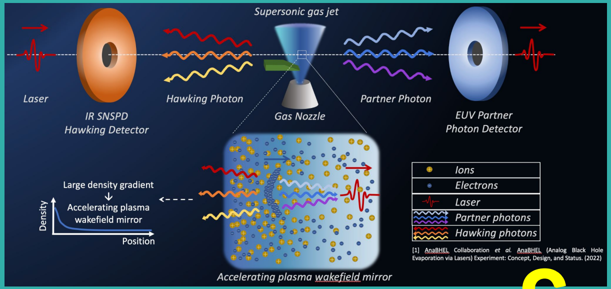




Fabrication

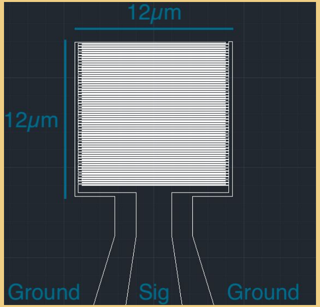


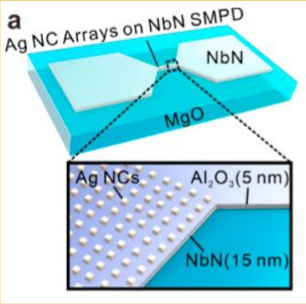
Applications



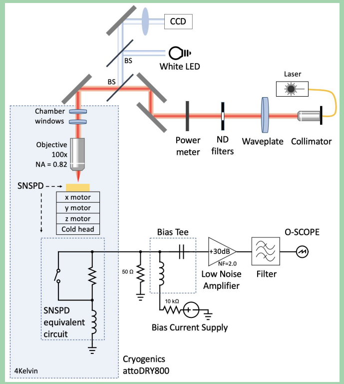
& More!

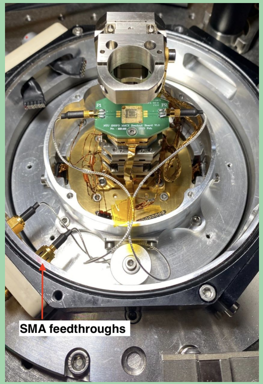
Design and simulation



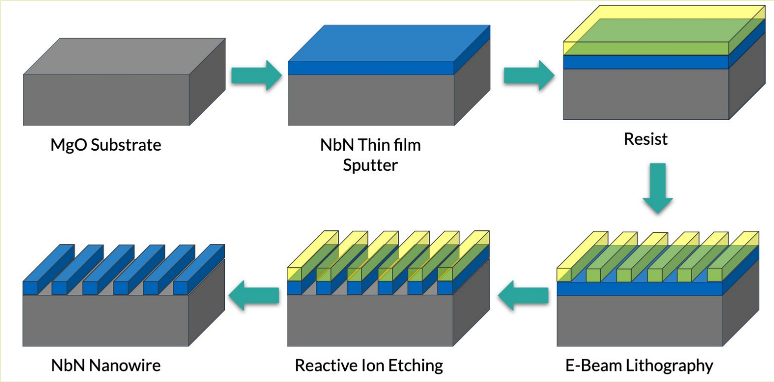


Characterization

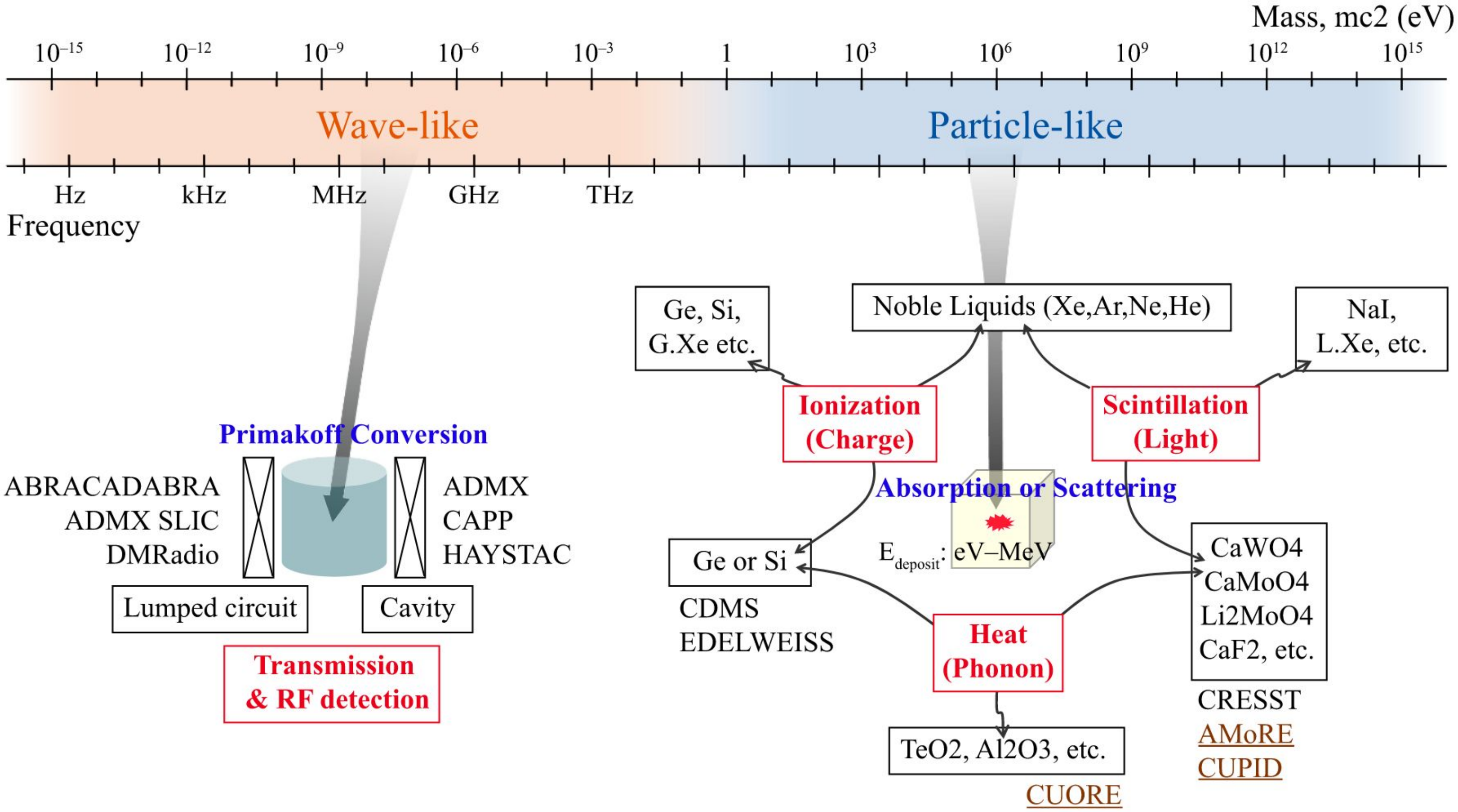




Fabrication



Extra Slides

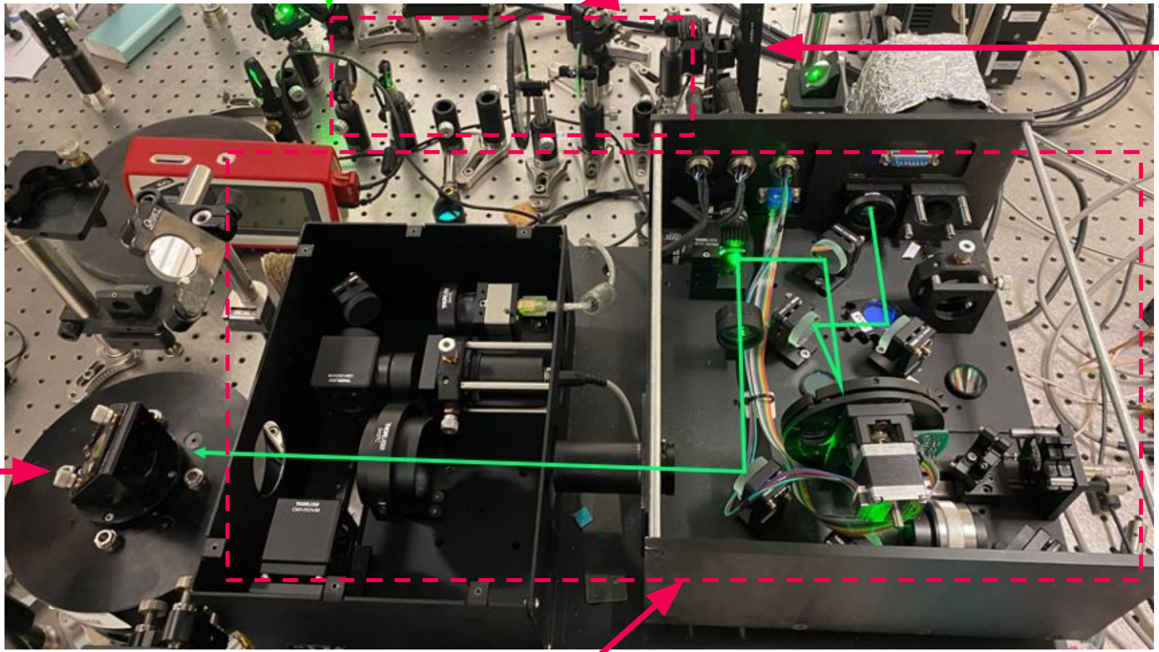


Kim, Y.-H., Lee, S.-J. & Yang, B. Superconducting detectors for rare event searches in experimental astroparticle physics. Supercond. Sci. Technol. 35, 063001 (2022).

(1) Lasers:
Switch input source manually with blocks and mirrors

(2) ND Filters Series:
Including fixed & variational ND filters

(3) Optical power meter:
Mounted on a 90° Manual Flip Mount

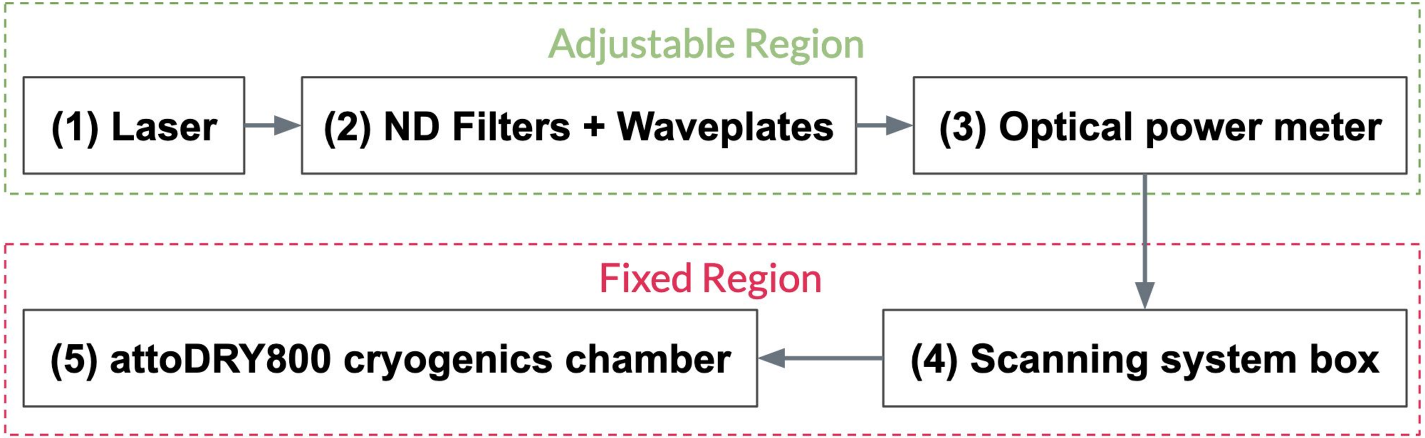


(5) attoDRY800 cryogenics chamber

(4) Scanning system box
(actual use irrelevant to us, but it contributes to power attenuation)

Transmission Factor Tests

$$P_{\text{sample}} = P_{laser} \times T^{\lambda}_{total} = P_{\text{Power meter}} \times T^{\lambda}_{\text{Fixed Region}}$$



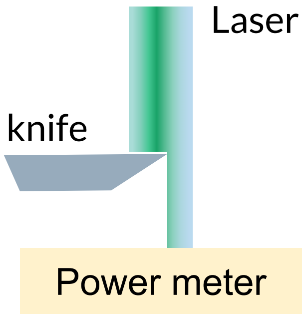
$$T_{\text{Fixed Region}} = T_{\text{ScanningBox}} \times 2T_{\text{window}} \times T_{\text{objective lens}} \times A_{\text{objective lens}} \times A_{\text{sample}}$$

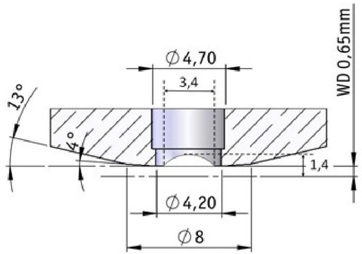
Laser beam size - Knife Edge technique

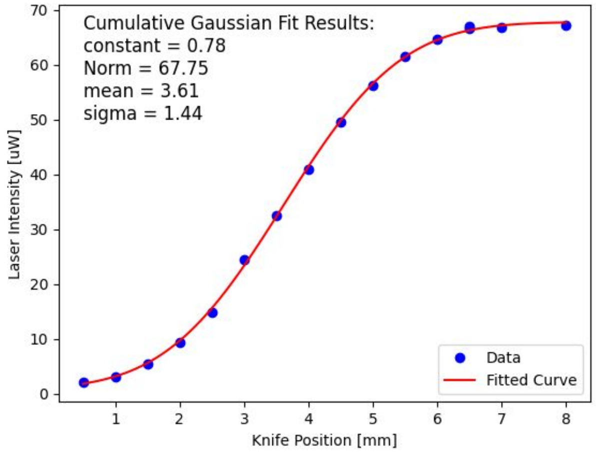
- Laser beam size is broadened by a laser beam expander in the black box. The size will be larger than the objective lens clear aperture, so laser will be blocked partially Currently the exapander is fixed and cannot be removed.

- LT-APO/VIS/0.82 Objective lens apperature : 4.7mm

- Assuming the laser is collimated to the center of the objective lens
  → Laser within apperature 4.7mm (±1.63sigma) : 89.68%







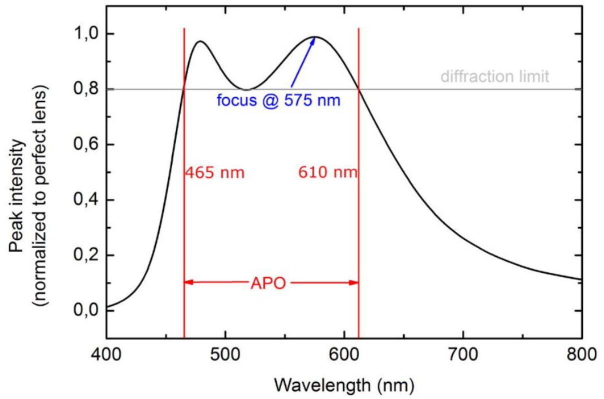
Transmission calibration

- $T_{black\ box}$ calibrated with 532 pulse laser → 80%
- $T_{Objective\ lens}$ from spec @~532 → 80%
- T_{Window} 90% at visible light
- A_{sample} corresponds to how well we focus the laser to the sample. Since the Rayleigh length after the objective lens is very short (several nm) and we see a clear image of the laser beam focused in the center of the sample → We assume now that A_{sample} is 1

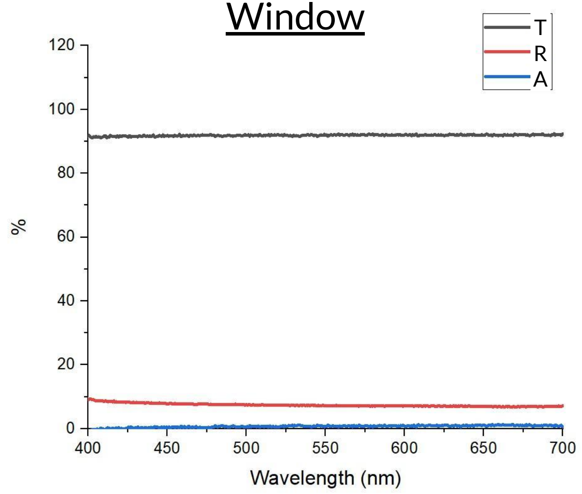
$T_{chamber + black\ box} = T_{black\ box} \times 2T_{window} \times T_{objective\ lens} \times A_{objective\ lens} \times A_{sample}$

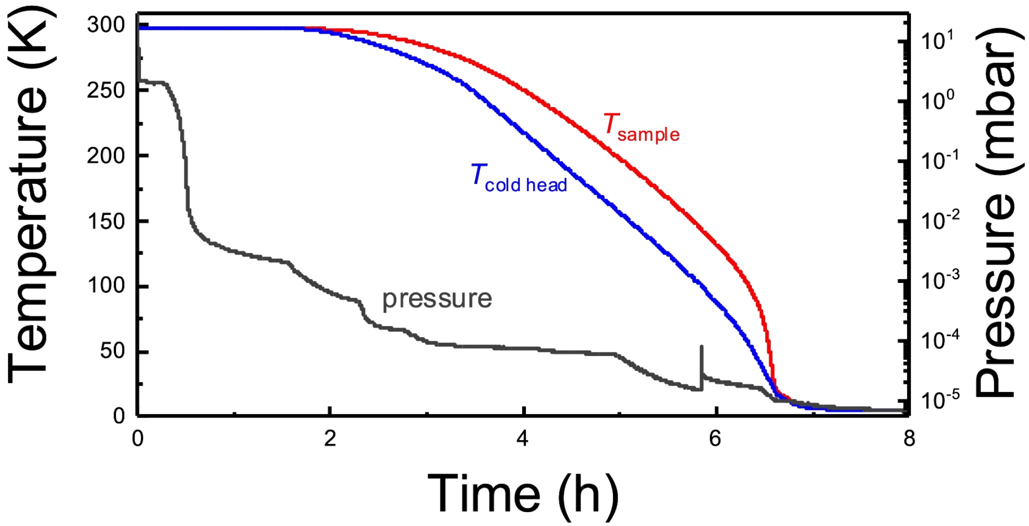
→ $T_{chamber + black\ box} = 46\%$

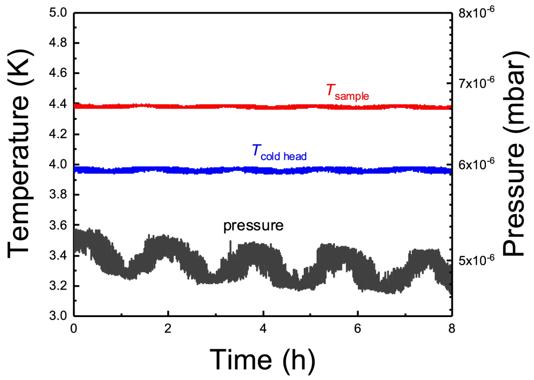
Objective lens

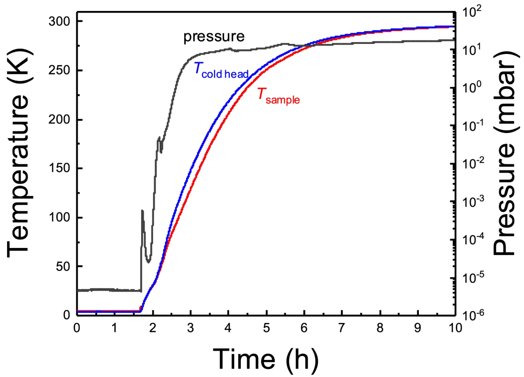


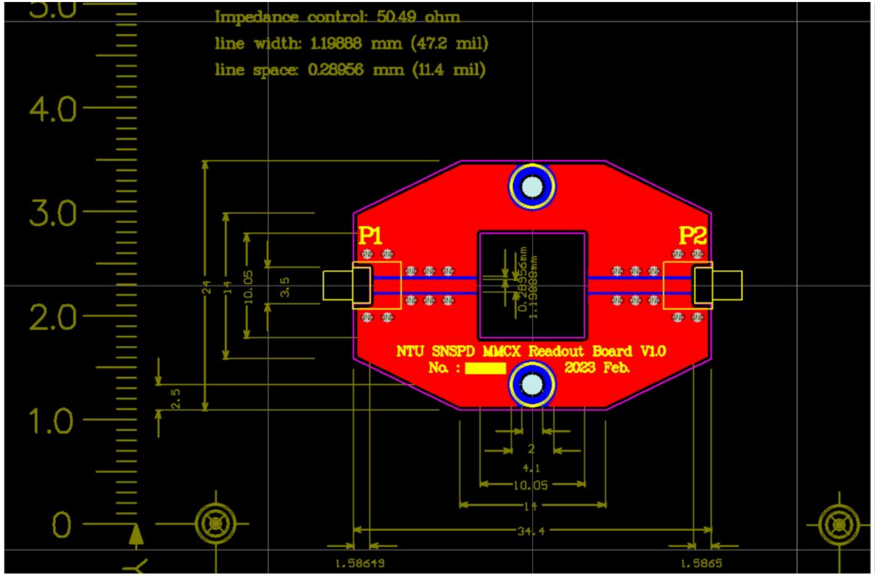
Window




Temperature (K)
Pressure (mbar)
Time (h)
T_{sample}
$T_{cold\ head}$
pressure


Temperature (K)
Pressure (mbar)
Time (h)
T_{sample}
$T_{cold\ head}$
pressure

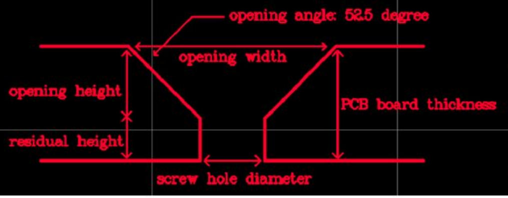

Temperature (K)
Pressure (mbar)
Time (h)
pressure
$T_{cold\ head}$
T_{sample}



Layer Stackup Instructions:

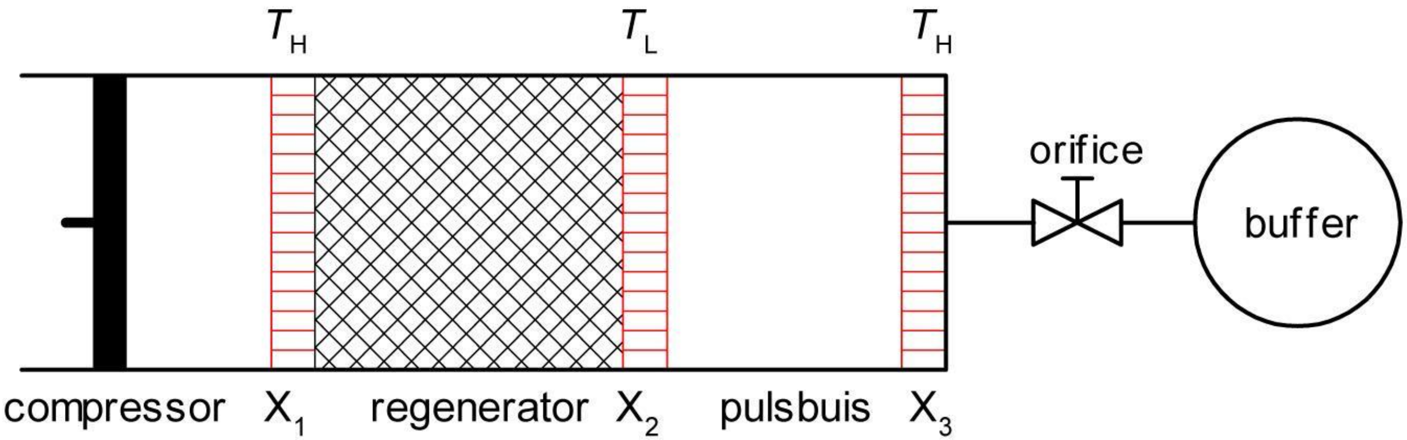
Layer	Stackup	Cu	Material	Thickness
			solder mask	0.7 mil
L1	Top layer	1.0 oz	Cu+Plating	1.6 mil
			Prepreg	6.2 mil
			Core	57.8 mil
			Prepreg	6.2 mil
L2	Bottom layer	1.0 oz	Cu+Plating	1.6 mil
			solder mask	0.7 mil
			Overall Thickness	74.8 mil
				1.90 (mm)

Instructions for making flat head screw holes (2mm, NPTH, 2 pcs.):



PCB board thickness: 1.9 (mm)
Screw hole diameter: 2.0 (mm)
residual height: 0.5 (mm)
Horn hole angle: 75 (degree)
opening height: 1.4 (mm)
opening width: 4.1 (mm)

Pulsetube


T_H
T_L
T_H
orifice
buffer
compressor
X_1
regenerator
X_2
pulsbuis
X_3

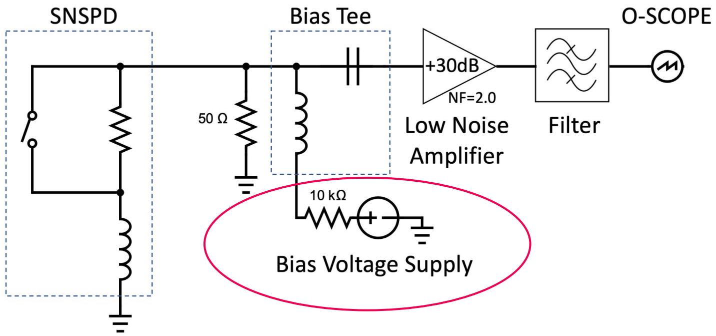
- Inductance is the tendency of an electrical conductor to oppose a change in the electric current flowing through it.
- Kinetic inductance originates from the inertial mass of mobile charge carriers
- Kinetic inductance is observed in high carrier mobility conductors (e.g. superconductors)

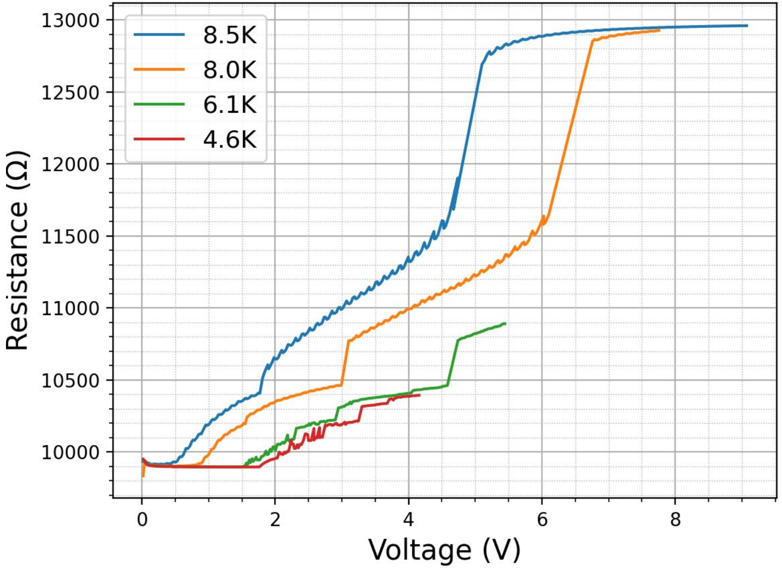
$$\frac{1}{2}(2m_e v^2)(n_s l A) = \frac{1}{2} L_K I^2$$

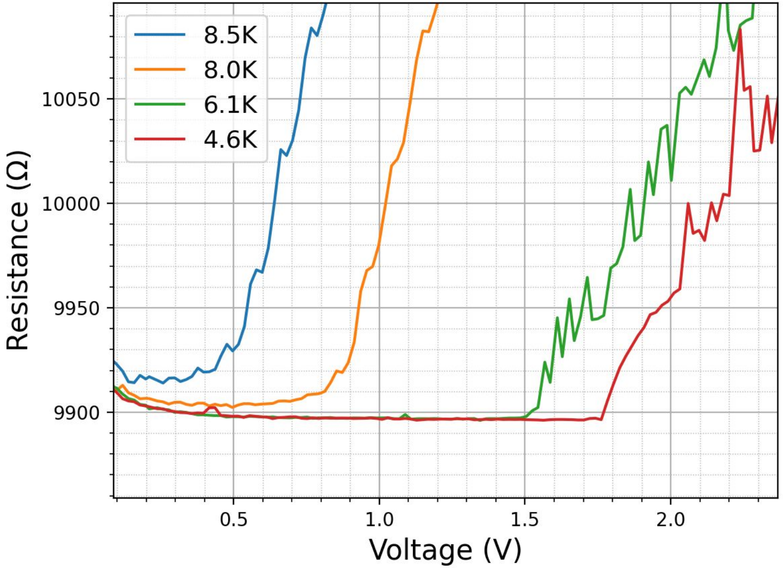
$$L_K = \left(\frac{m_e}{2n_s e^2}\right)\left(\frac{l}{A}\right)$$

VR Curve w/ 10kΩ

- 10kΩ resistor in series with bias voltage source
- Translate bias current to voltage
- Critical Voltage @ 4.6K ~ 1.76V

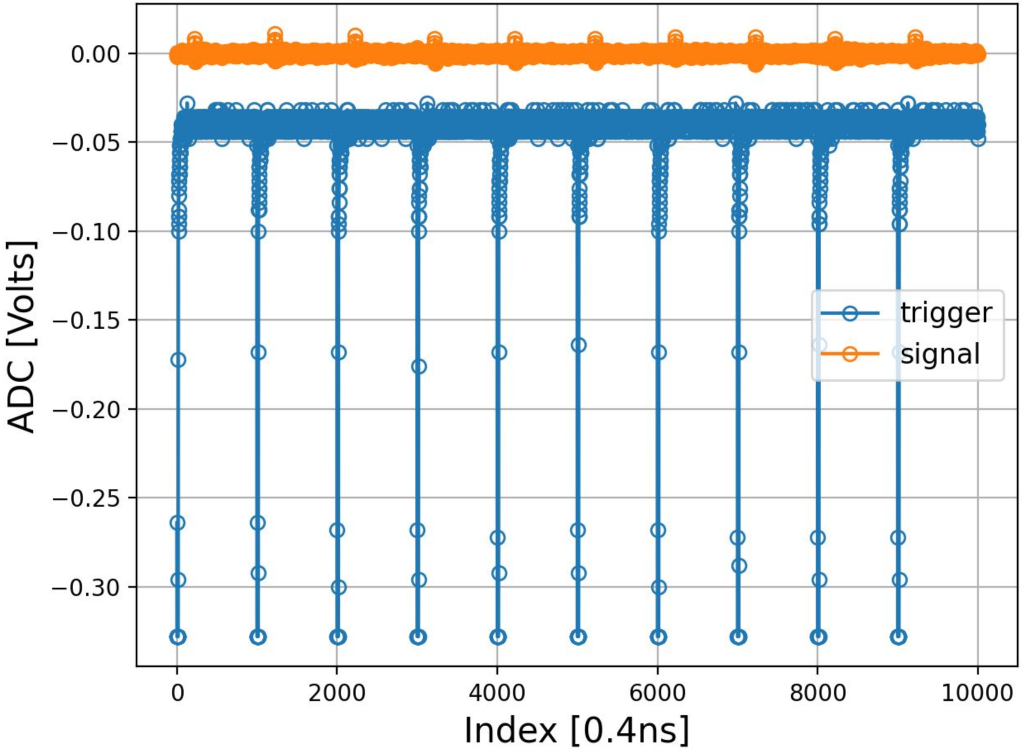






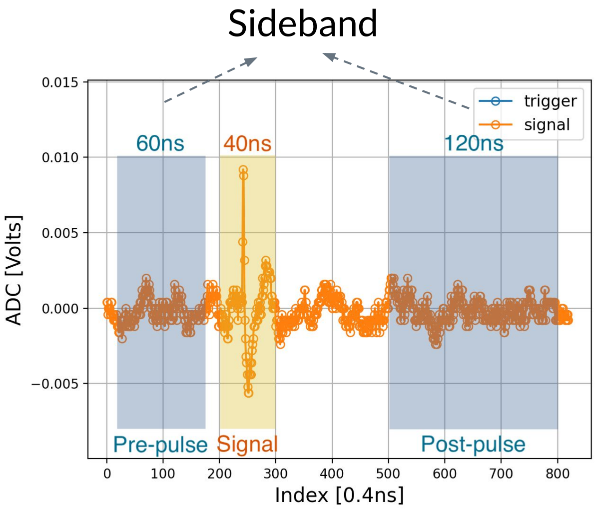
1 Oscillscope Event

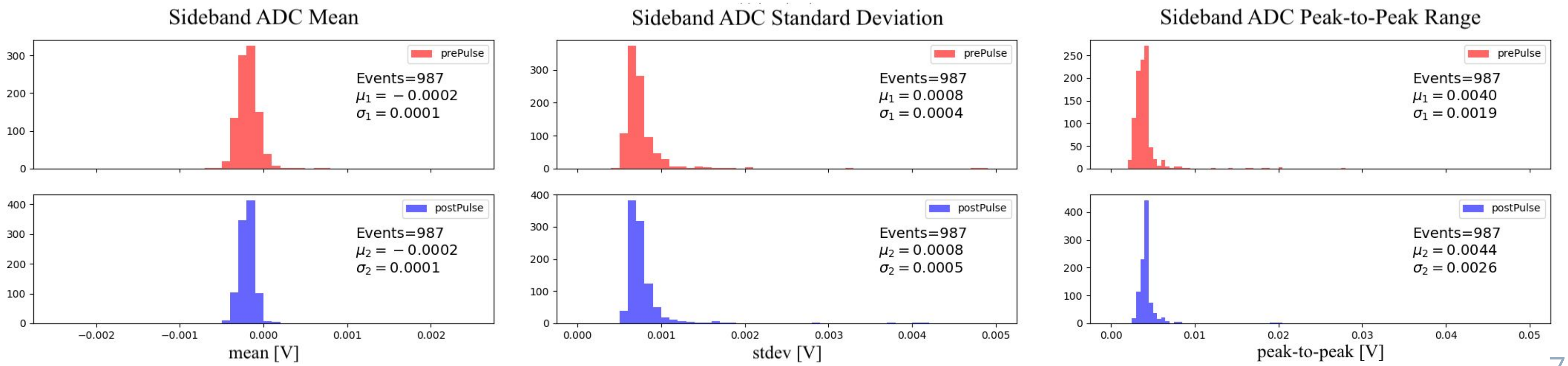
4μs Window → 10 Laser Triggers



Sideband Analysis

- Baseline Voltage (Mean) : -0.2mV ± 0.1mV
- Average Noise (Std): 0.8mV ± 0.4mV
- Noise Peak-to-Peak / Random Spikes (Range): 4mV ± 2mV
- Sideband analysis with and without signal
  - Similar results → Noise is uncorrelated to the signal

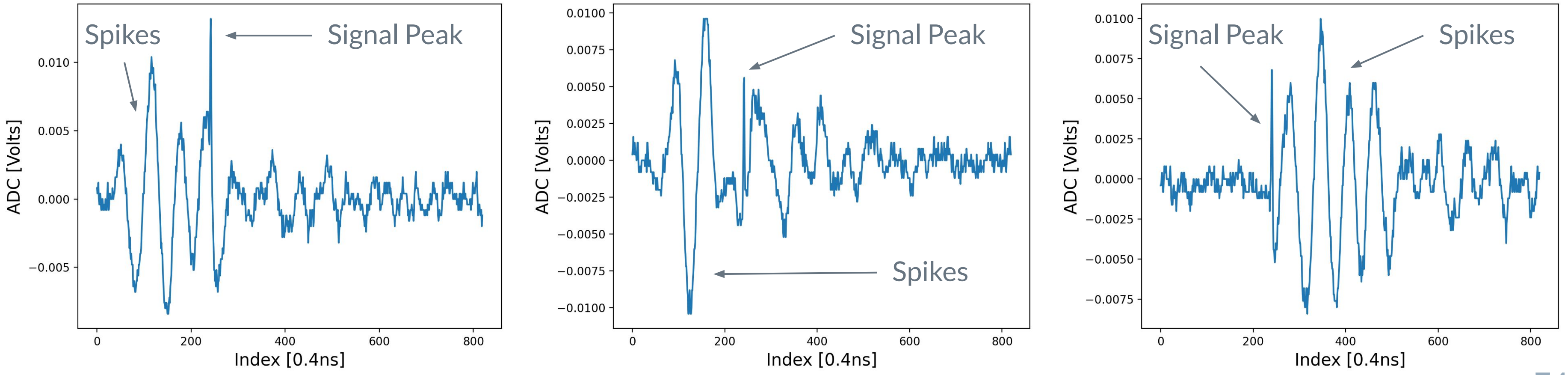


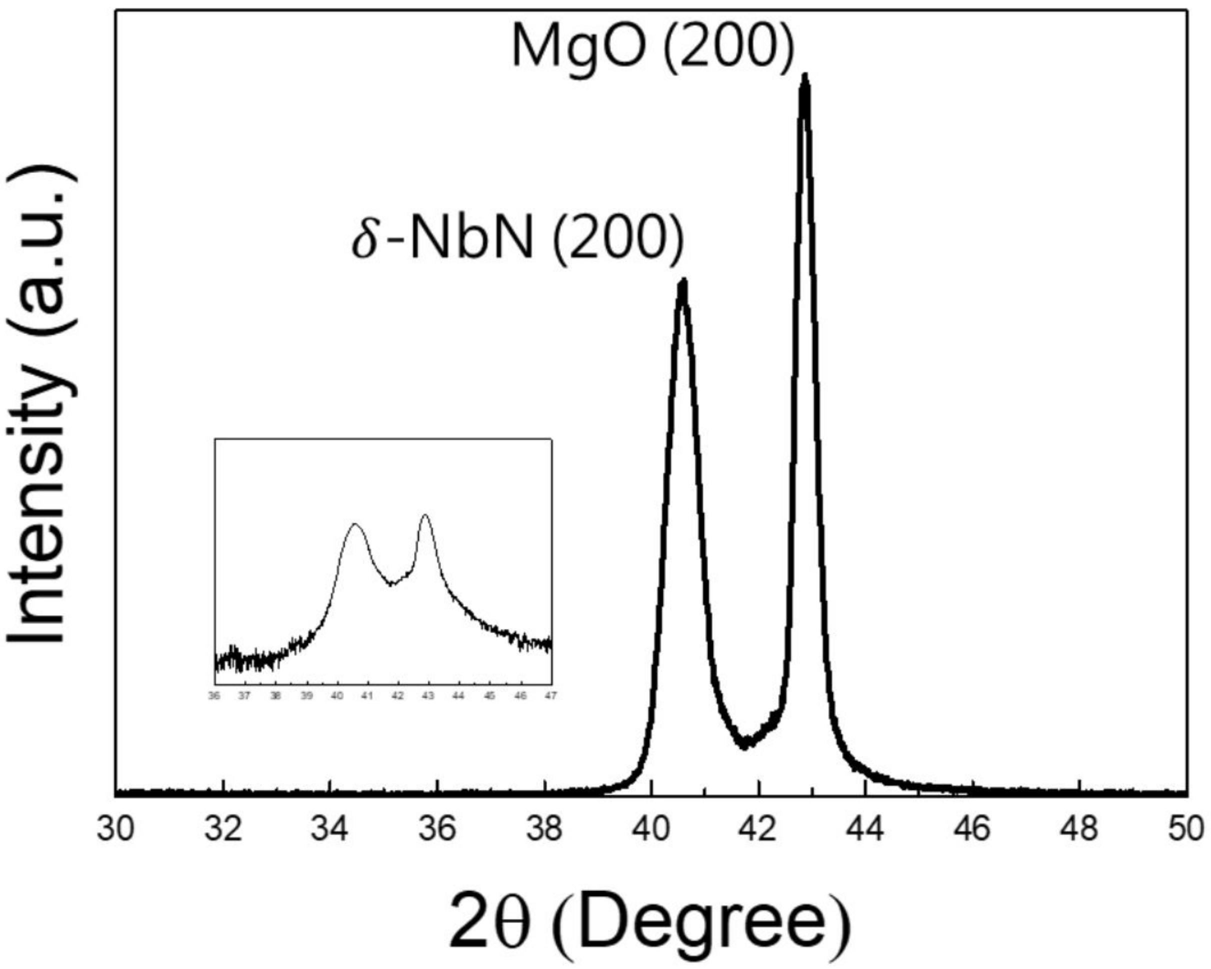


Event Pre-Selection

- Sideband Peak-to-Peak Range < 3mV
- Sideband Average Noise < 2mV

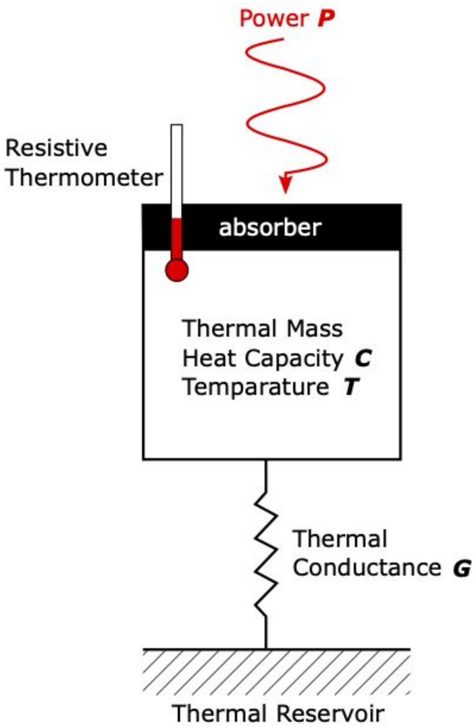
Remove laser events with large noise/spikes



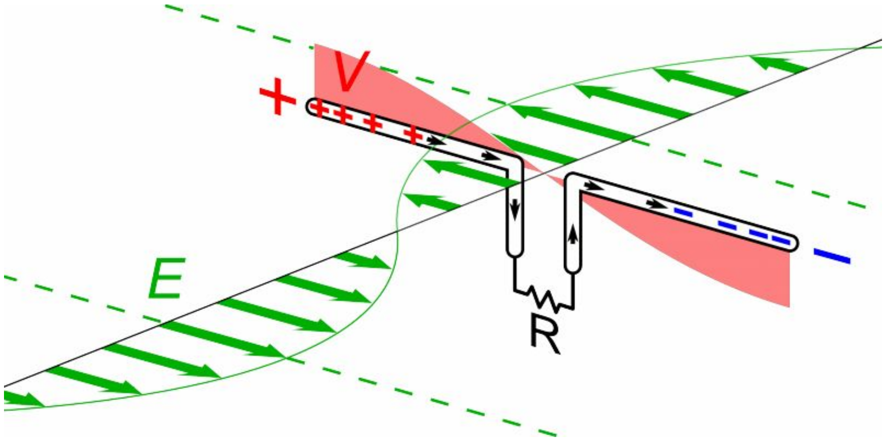

MgO (200)
δ-NbN (200)
Intensity (a.u.)
2θ (Degree)
30
32
34
36
38
40
42
44
46
48
50

Collective Detection → Electromagnetic wave

Bolometer



Antenna



Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	
AGS BNL (1960)	π N interactions	
FNAL Batavia (1970)	Neutrino Physics	
SLAC Spear (1970)	ep, QED	
ISR CERN (1980)	pp	
PETRA DESY (1980)	top quark	
Super Kamiokande (2000)	Proton Decay	
Telescopes (2000)	SN Cosmology	

Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z,W
AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy