SNSPD & DRD5

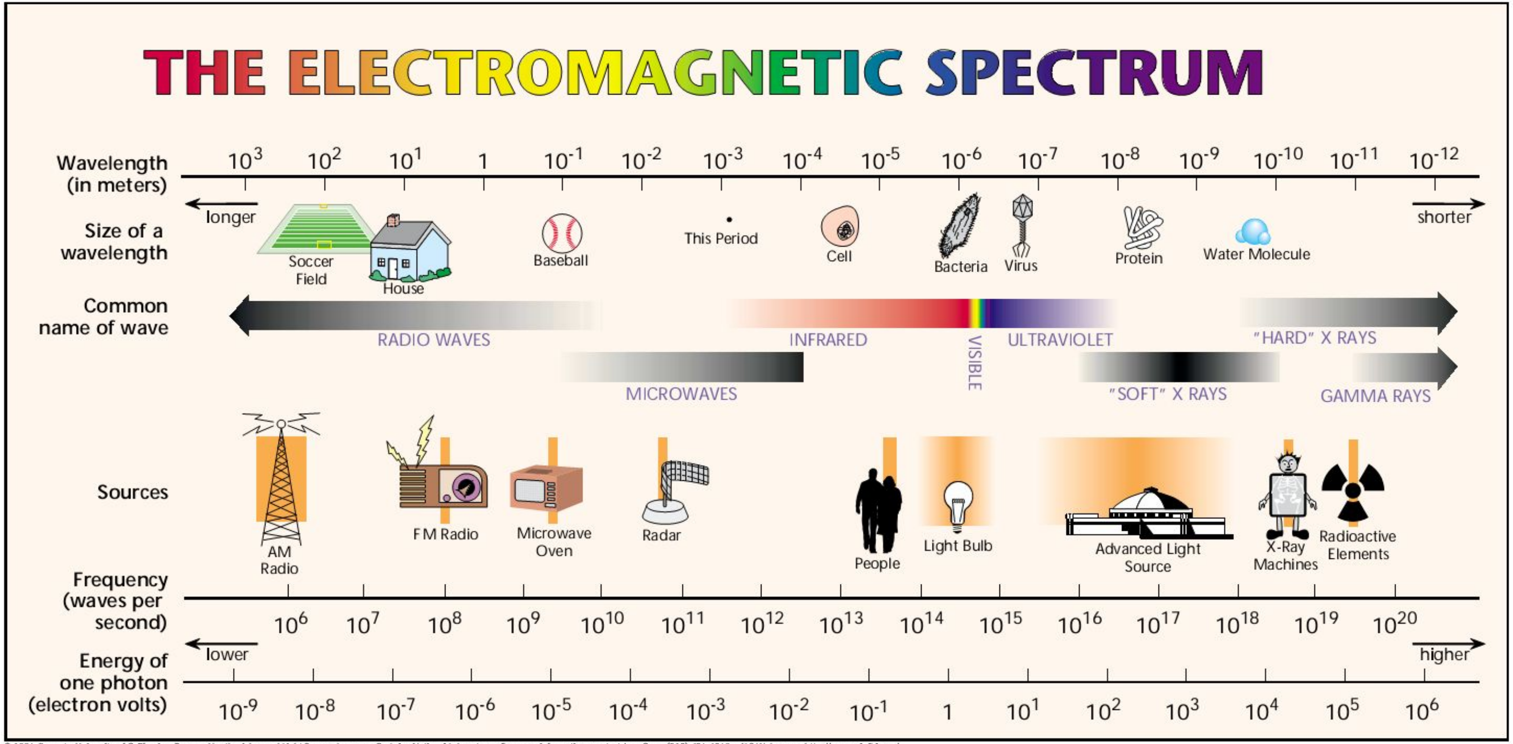
Hsin-Yeh Wu

National Taiwan University

TIDC annual meeting

22 Nov, 2024

Photon detection



New quantum sensors

Typical HEP detectors

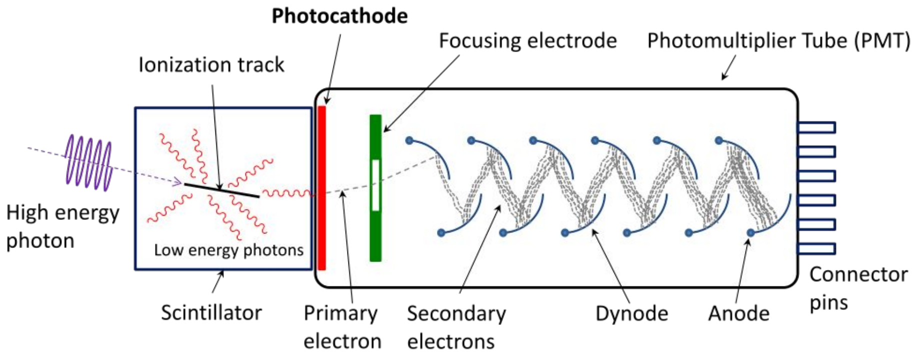
Rich spectrum of detectors for HEP

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

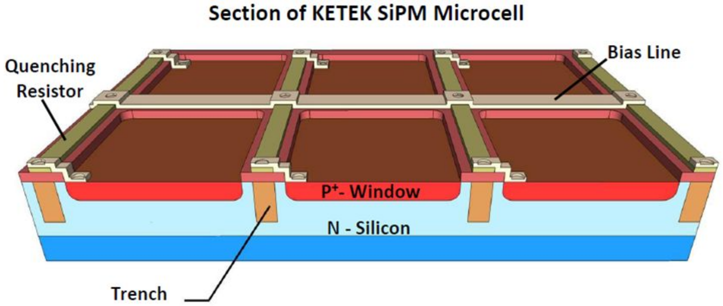
Semiconductor Single Photon Detectors

Photomultiplier Tubes (PMT)

Wikimedia Commons

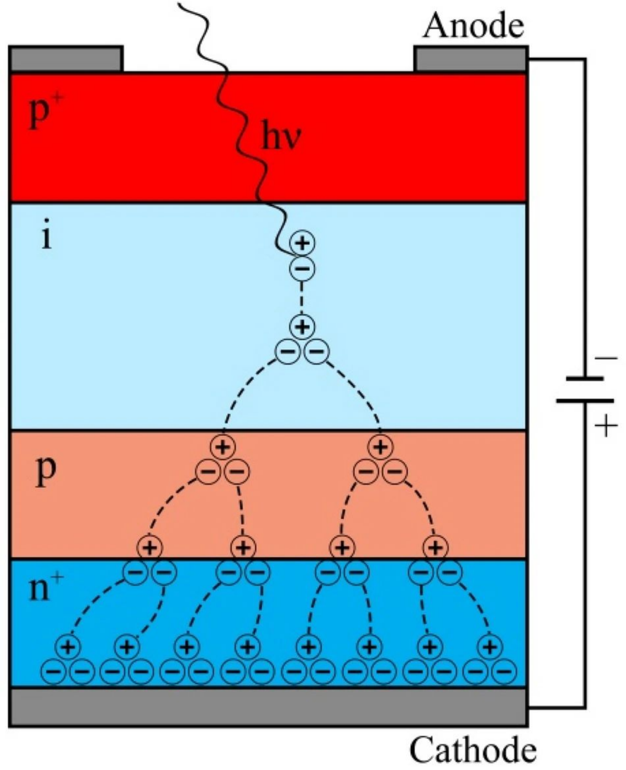


Silicon Photomultiplier (SiPM)



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

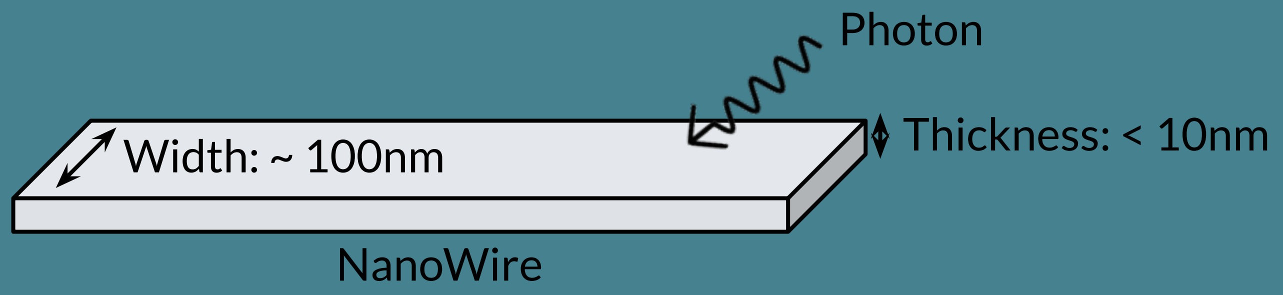
- Si: ~1.1eV (~1.1µm)
- Ge: ~0.7eV (~1.7µm)

Blocked impurity band solid-state photomultipliers.

- Large Dark Current

APPEC Communications

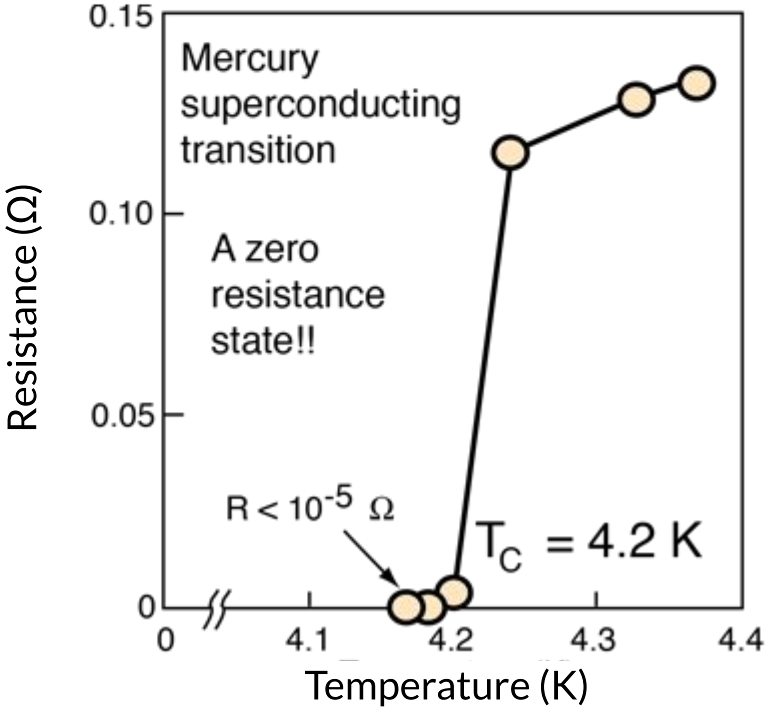
Izhnin, I.I., et al. Appl Nanosci 12, 253–263 (2022).



Superconductivity Nanowire Single Photon Detector (SNSPD)

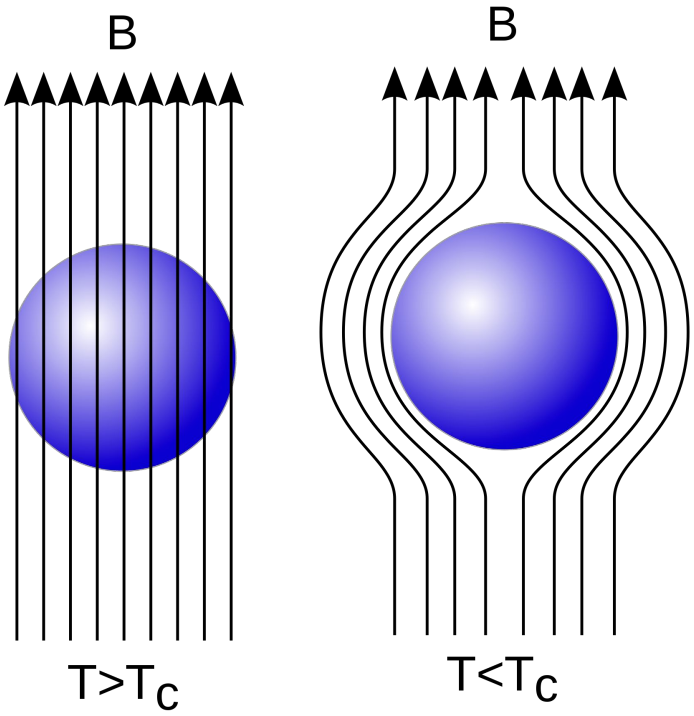
Superconductivity

Zero Resistance



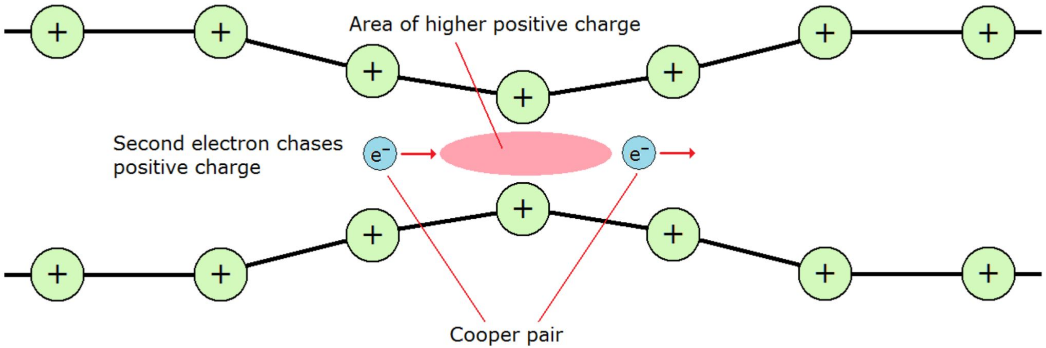
H. K. Onnes, Commun. Phys. Lab.12,120, (1911)

Meissner Effect
Perfect diamagnetic
(Superdiamagnetic)

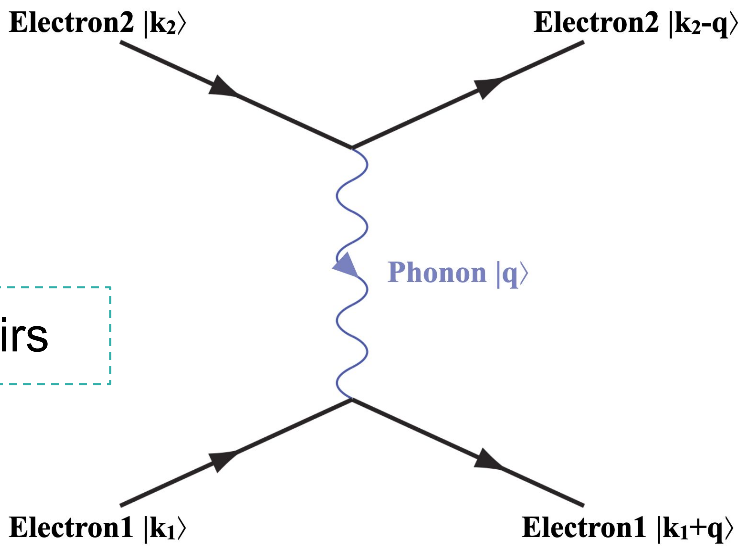


Wikimedia Commons

Cooper pairs (BCS mechanism)



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

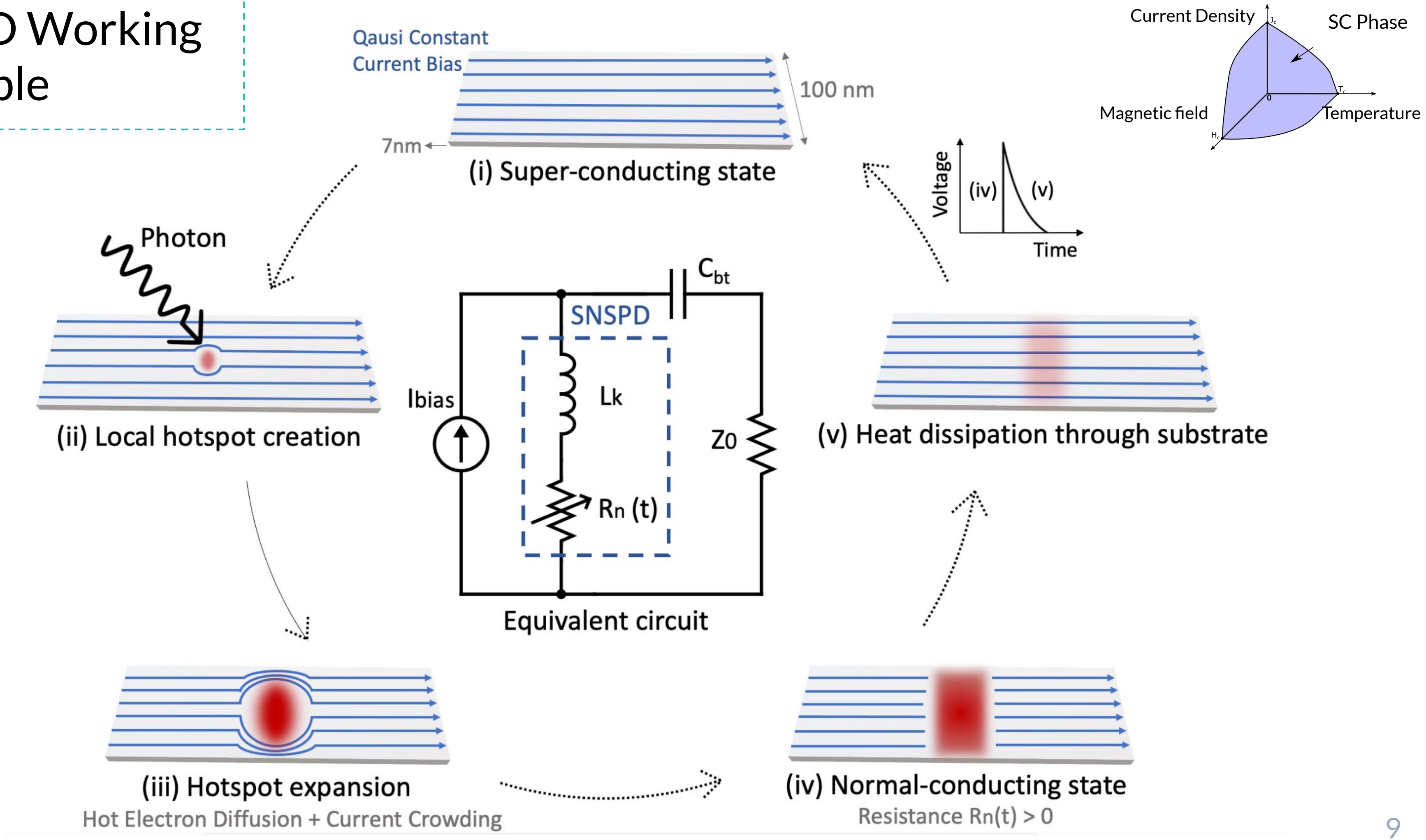


$V_{e\text{-}ph\text{-}e}$ (Attractive) > $V_{e\text{-}e}$ (Repulsive) → Cooper-Pairs

- 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} !

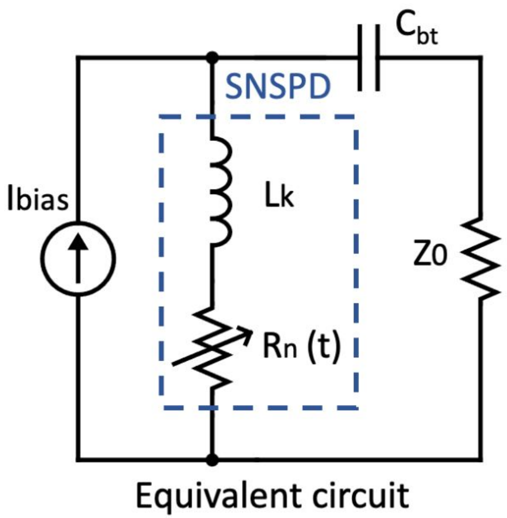
$$V = \frac{|M|^2}{(\epsilon_{\vec{k}} - \epsilon_{\vec{k}+\vec{q}})^2 - \hbar\omega_q{}^2}$$

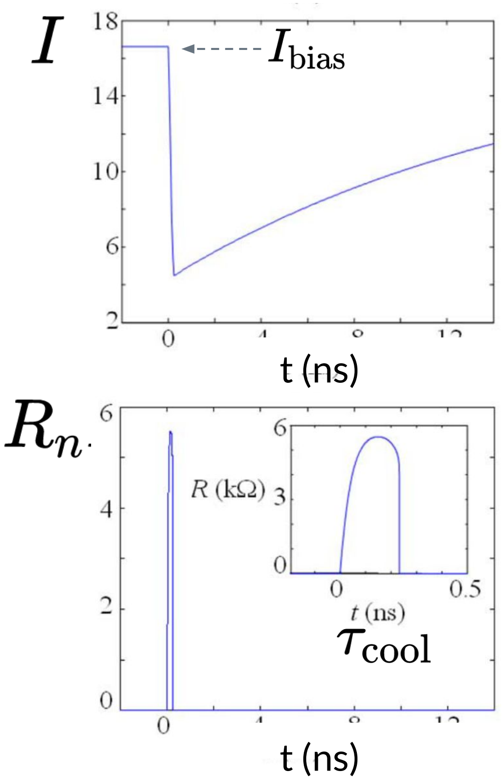
SNSPD Working Principle



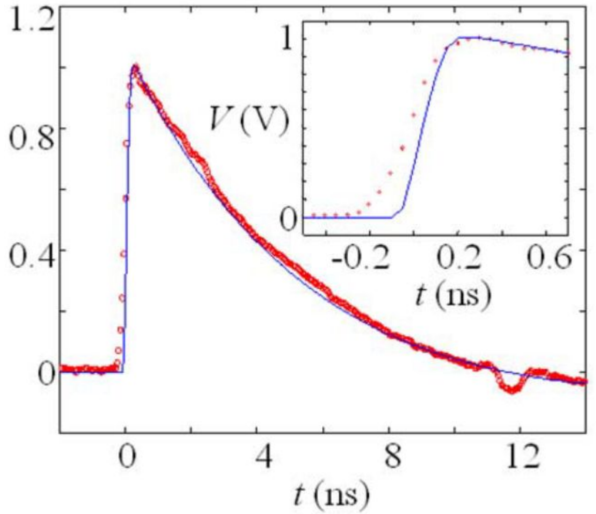
LCR Electric Circuit Model

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





Load(Z_0) Voltage



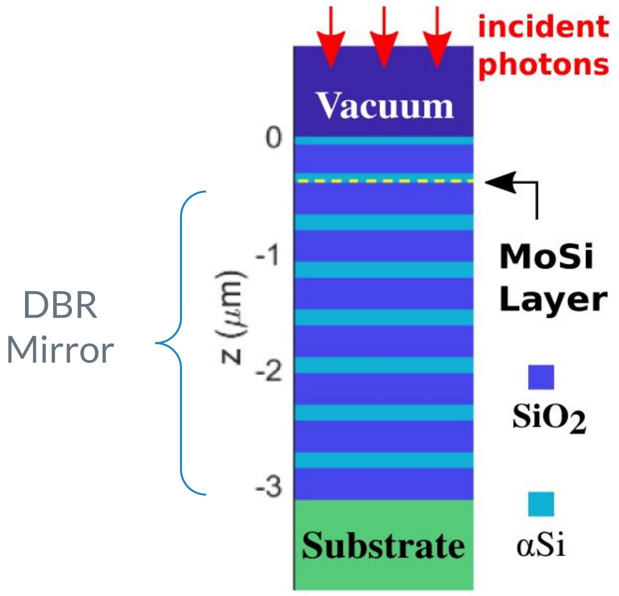
$$\tau_{\text{rise}} = \frac{L_k}{Z_0 + R_n(t)}$$

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

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

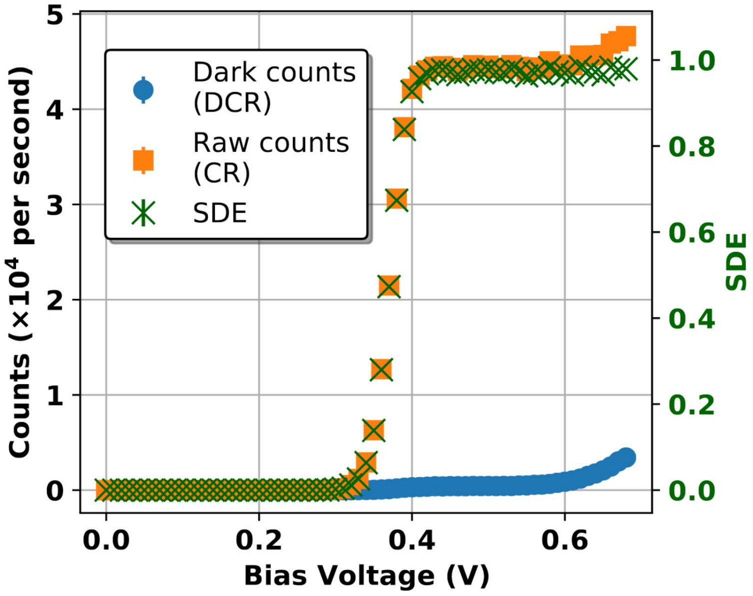
State-of-the-art SNSPDs @ 1550nm

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



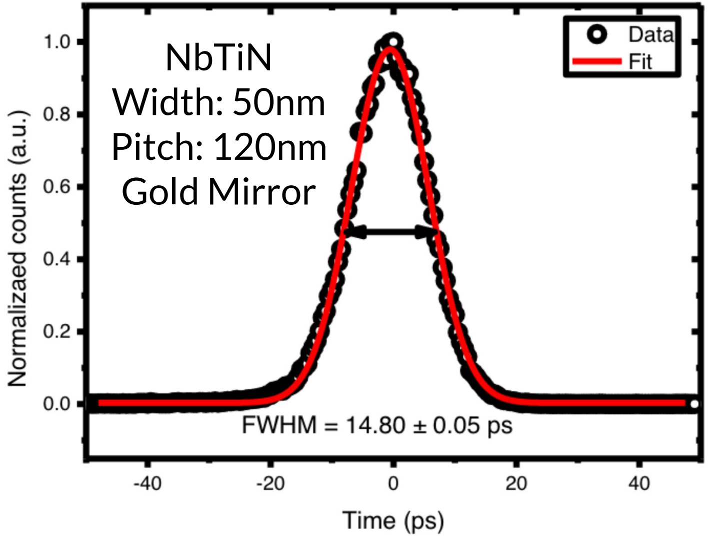
MoSi (Tc~5K)
Width: 80nm, Pitch: 140nm
Distributed Bragg Reflector Mirror
Measure Temperature ~750mK

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



State-of-the-art SNSPDs @ 1550nm

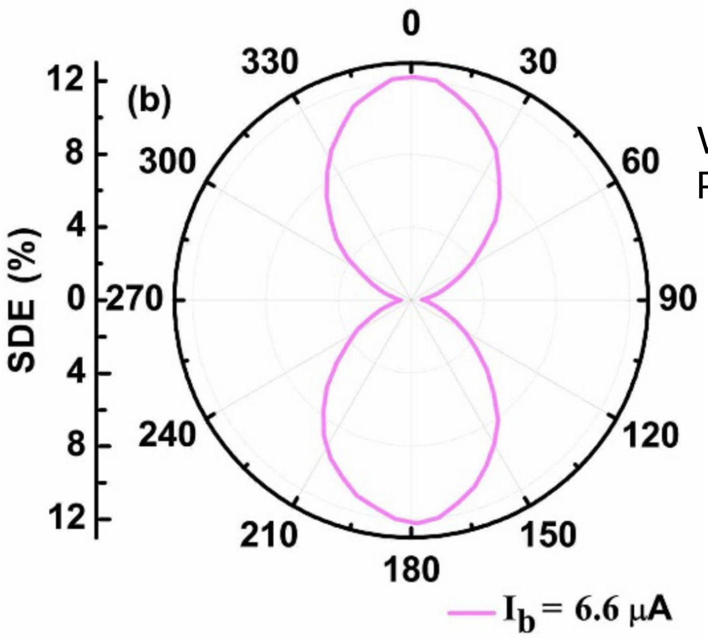
Time Jitter < 15ps



NbTiN
Width: 50nm
Pitch: 120nm
Gold Mirror

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

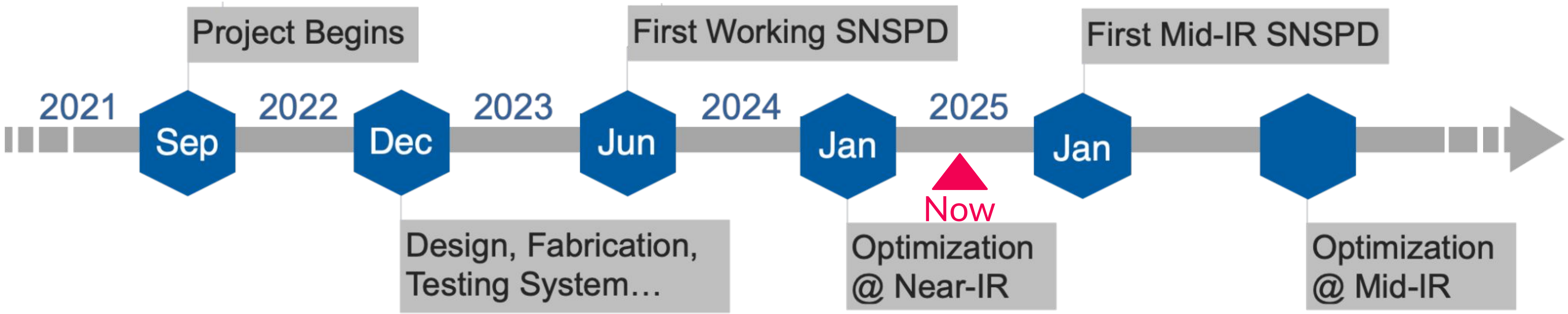
Excellent performance @ Near-IR (0.8μm-2μm)

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

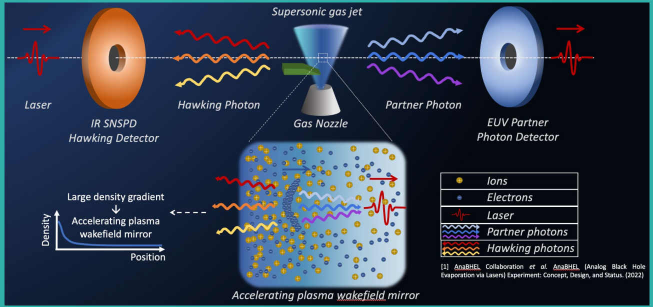
Goal

Extend to Mid-IR (2μm-20μm)

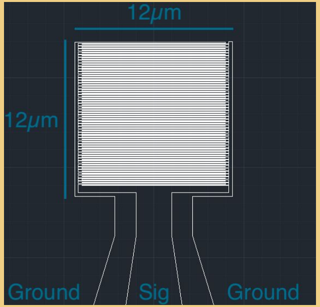
- All the excellent existing properties
- Energy resolving power
- Broadband
- Polarization distinguishability

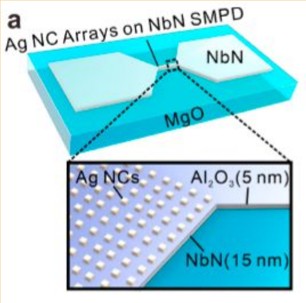


Applications

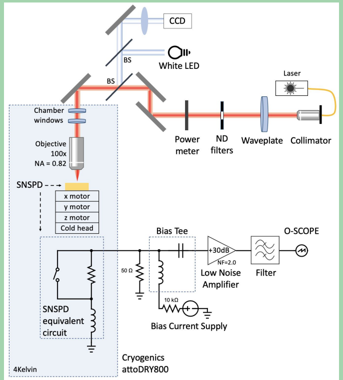


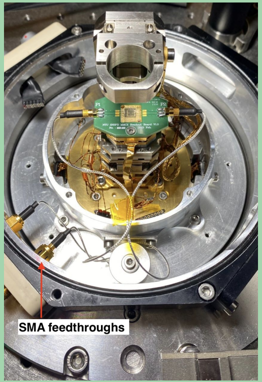
Design and simulation



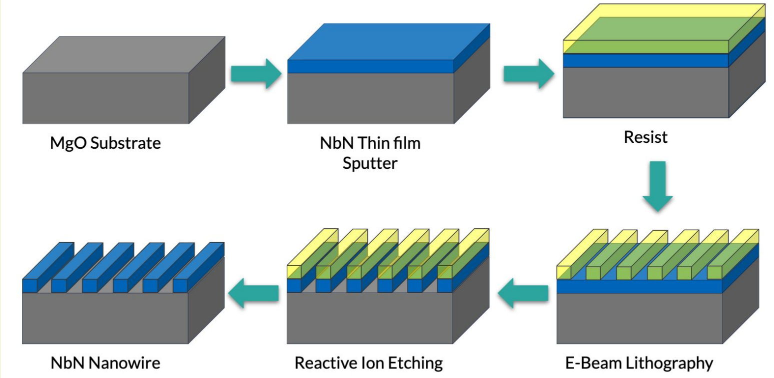


Characterization





Fabrication



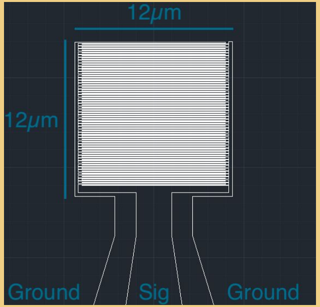
Special Thanks!

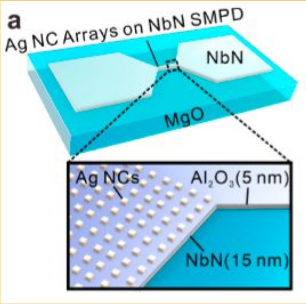
Active Plasmonics and Nanophotonics
Lu Research Lab @Academia Sinica
Feng-Yang Tsai, Shu-Xiao Liu, Jia-Wern Chen, Tzu-Yu Peng

TIDC
Jenny, OuChen, Yi-Ren Wu

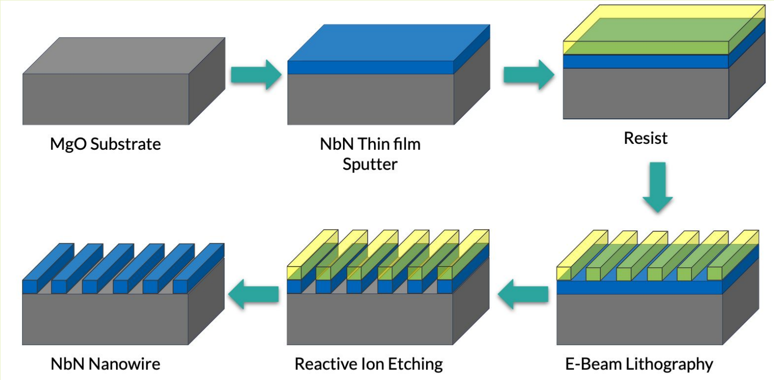
NSTC
Yi-Nan Chen

Design and simulation

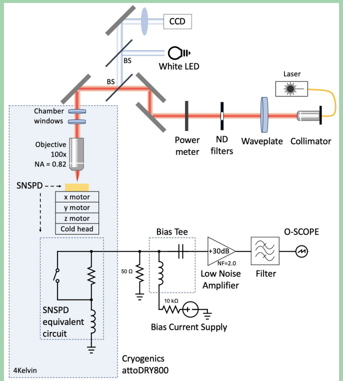


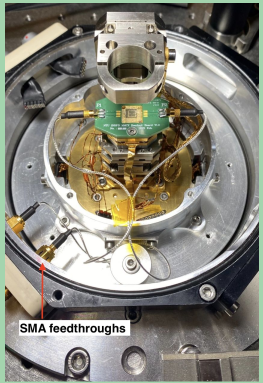


Fabrication



Characterization

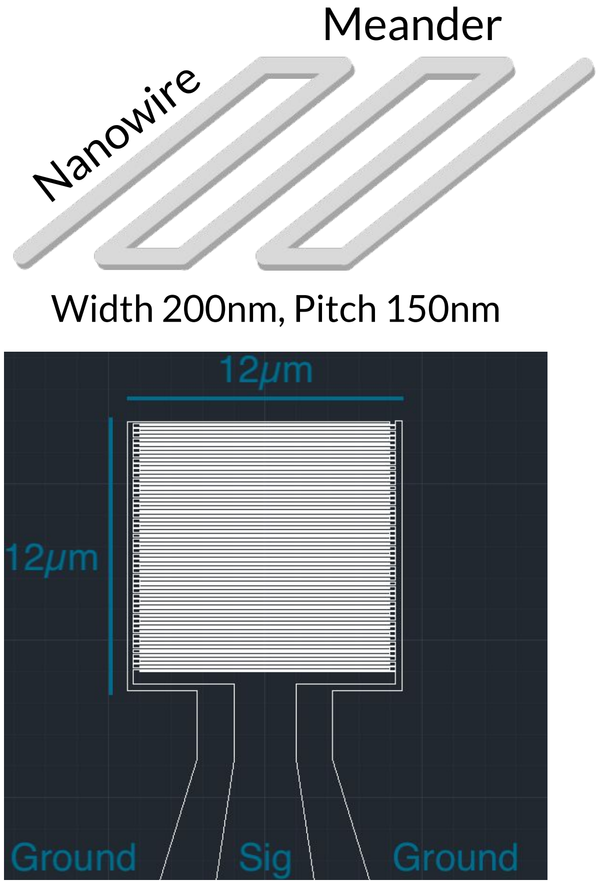




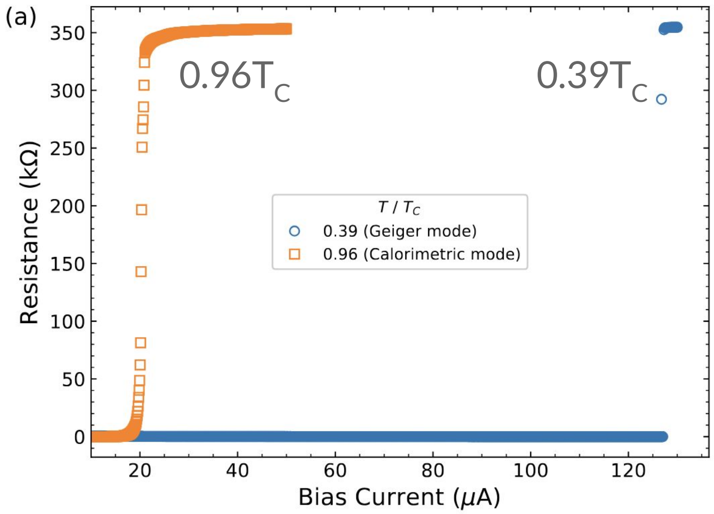
Dual-Mode Calorimetric SNSPD

Wu, H.-Y. et al. Dual-Mode Calorimetric Superconducting Nanowire Single Photon Detectors. Preprint at https://doi.org/10.48550/arXiv.2410.10280 (2024).

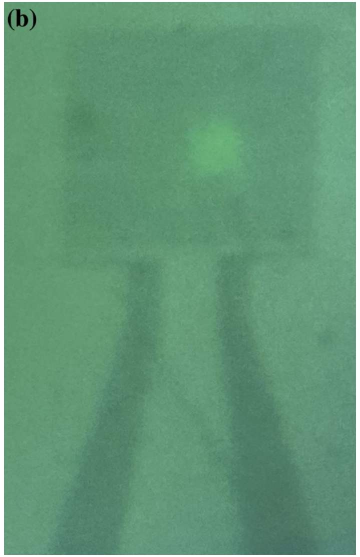
Experiment setup



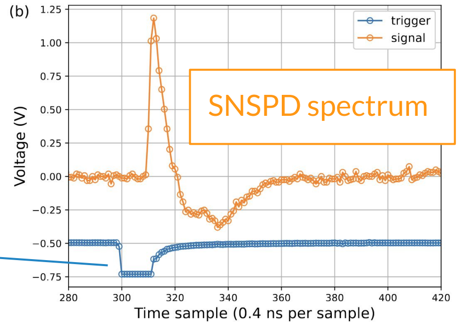
Resistance-Current Diagram @ Different Operating Temperature



515nm Pulsed-Laser
100ps width
3μm laser spot

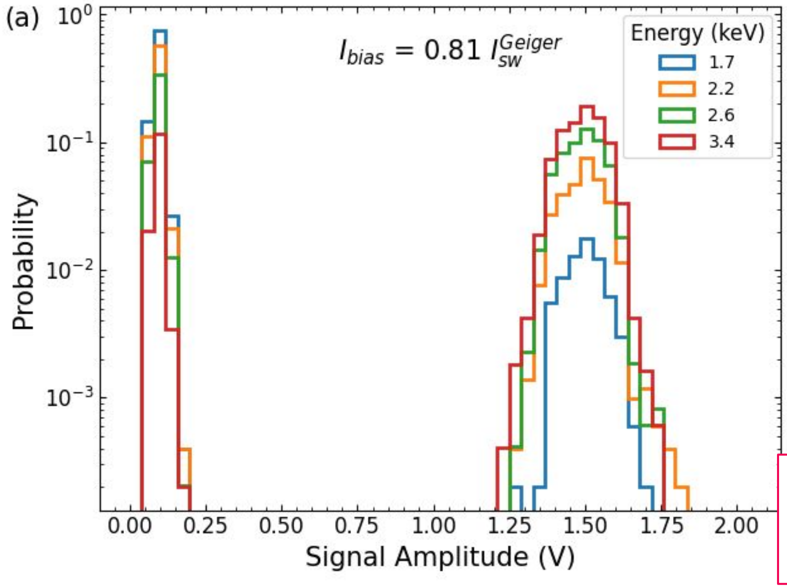


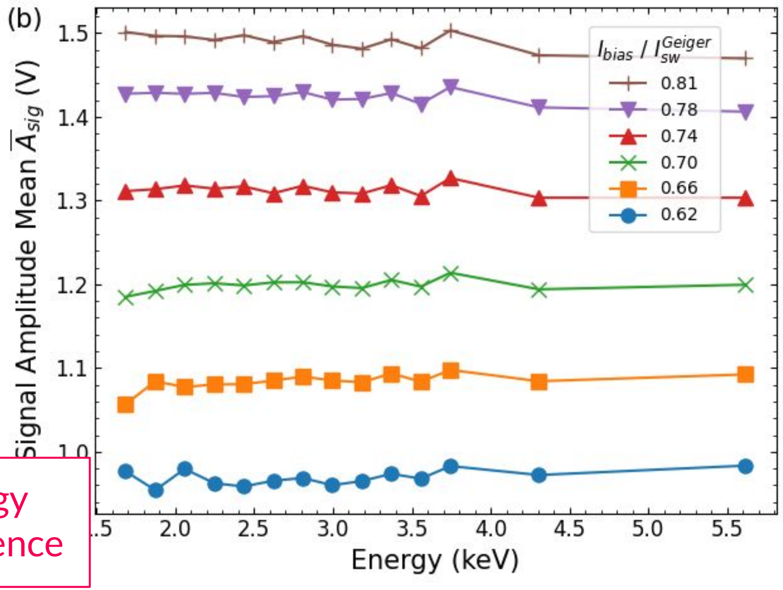
Geiger mode (Operating @ 0.39T_C)



1 pulsed-laser event trigger

- 10000 pulsed-laser events are recorded
- Measure the peak-to-peak amplitude of the spectrum
- Modulate input photon number per laser pulse
- Operating in the normal Geiger mode does not show energy dependence in the signal amplitude

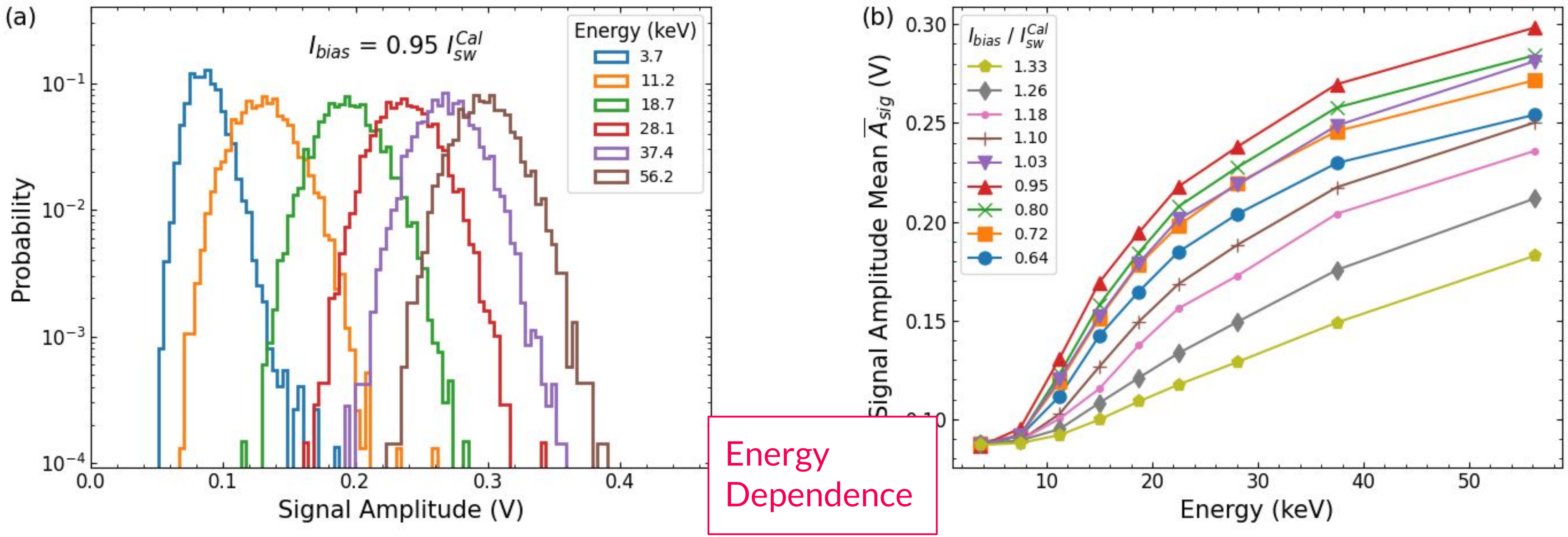




No Energy Dependence

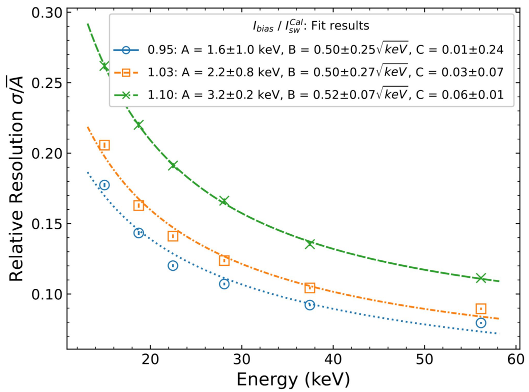
Calorimetric mode (Operating @ 0.96T_c)

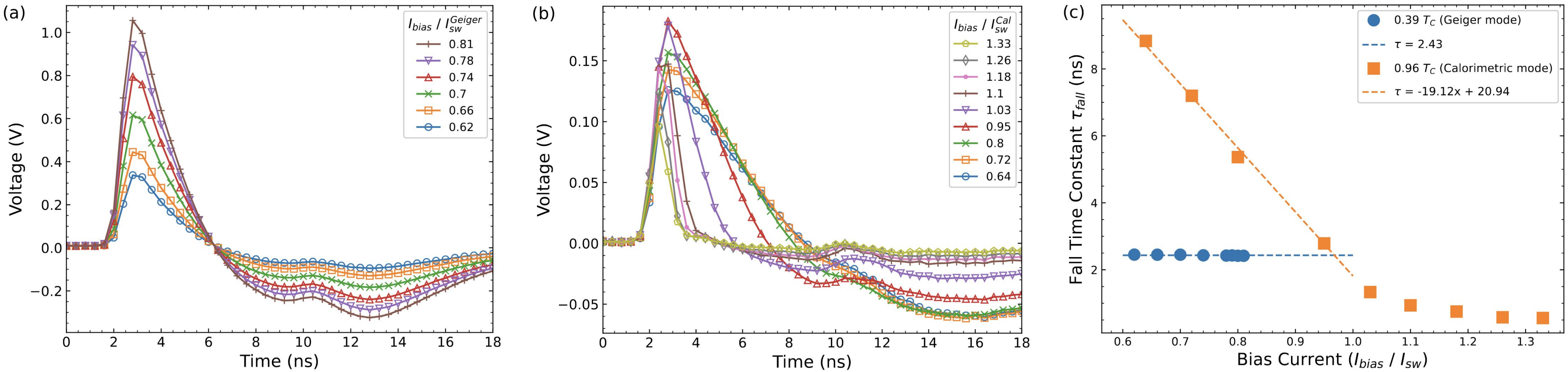
- Signal amplitude depend on absorbed photon number
- SNSPD becomes partially resistive (i.e. does not transit totally) while absorbing photons
- Other effects: Faster timing recovery, steadier operation without dark count and latching, etc ...



Some other features for Calorimetric SNSPD

- Timing
  - Falling time constant depends on bias current
  - Reaches 560 ps falling time constant, faster than Geiger mode (2.2ns)
- Stable operation
  - No Dark count (Geiger mode around 1Hz)
  - No latching effect (Geiger mode latches at around $0.81I_C$)
- Energy resolution around 6% constant term (Dominated by the noise term)





Still a long way to go...

- Many issues with the device and experiment setup
  - Low efficiency
  - Noise
  - Fabrication / Characterization setup systematic uncertainties not controlled
  - Detection Mechanism unclear
  - ...
- There is a potential to build a single photon detector with properties:
  - High efficiency
  - Fast
  - Low noise
  - Calorimetric/Spectroscopy
  - Infrared sensitivity (sub-eV)
  - Polarization sensitivity

Detectors	σ/E	τ_{fall}	Timing Jitter
TES[11,21]	0.06% (@1 keV)	87 µs	10-100 ns
MKID[12,22]	1.8% (@3 eV)	32 µs	-
NTD-Ge[14,23]	0.1% (@6 keV)	7 ms	-
Calorimetric SNSPD	<6% const. term	560 ps	< 108 ps

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What can we do with such detector?

Wide variety of applications

Particle Physics

Cosmology

Astroparticle physics

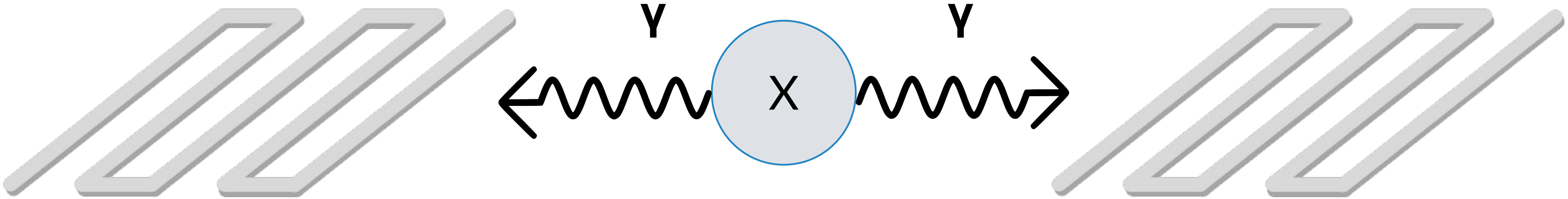
Quantum communication/information

Ultra-Fast Calorimetry/Spectroscopy

- Diphoton coincidence measurements
  - Bell type entanglement experiments / Vacuum fluctuations
  - Remove background events
  - Reconstruct diphoton mass spectrum

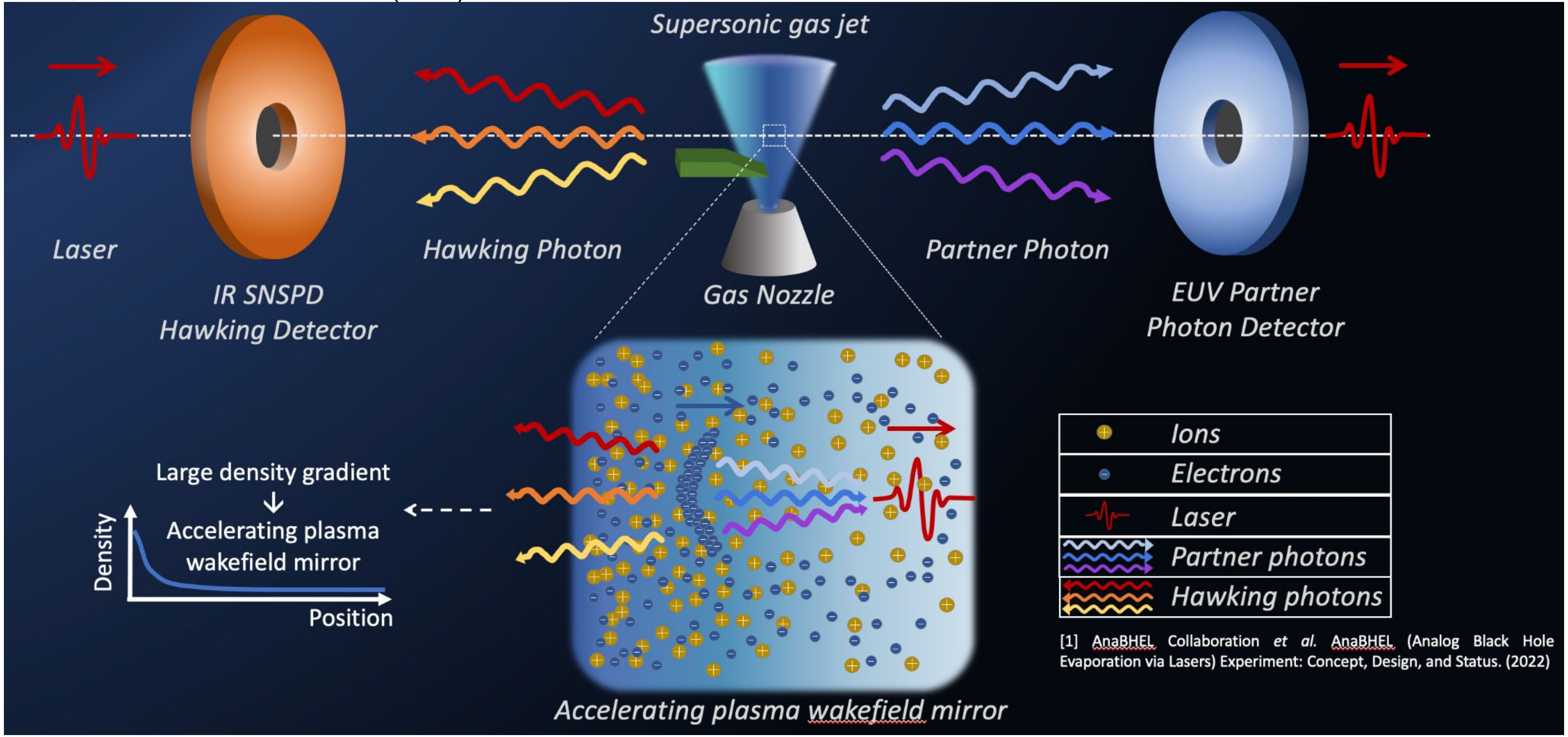
- Trigger-type experiments
  - Fast pulsed-laser

- High signal/background rate experiment
  - Remove pile-up (Pulsed-laser, plasma, radioactive source)



AnaBHEL (Analog Black Hole Evaporation via Lasers) Experiment

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

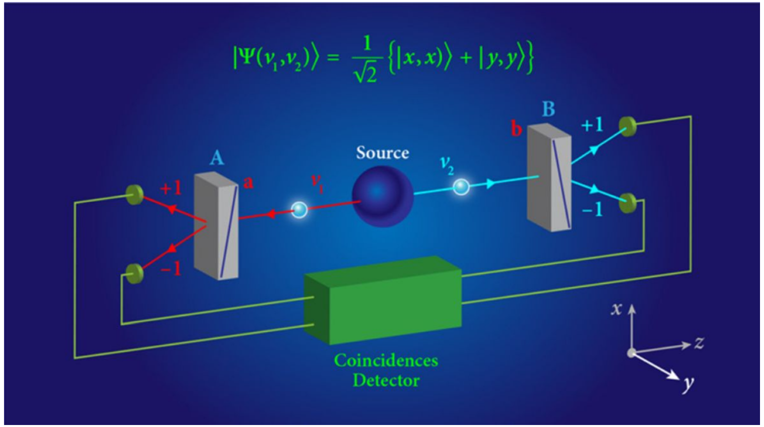


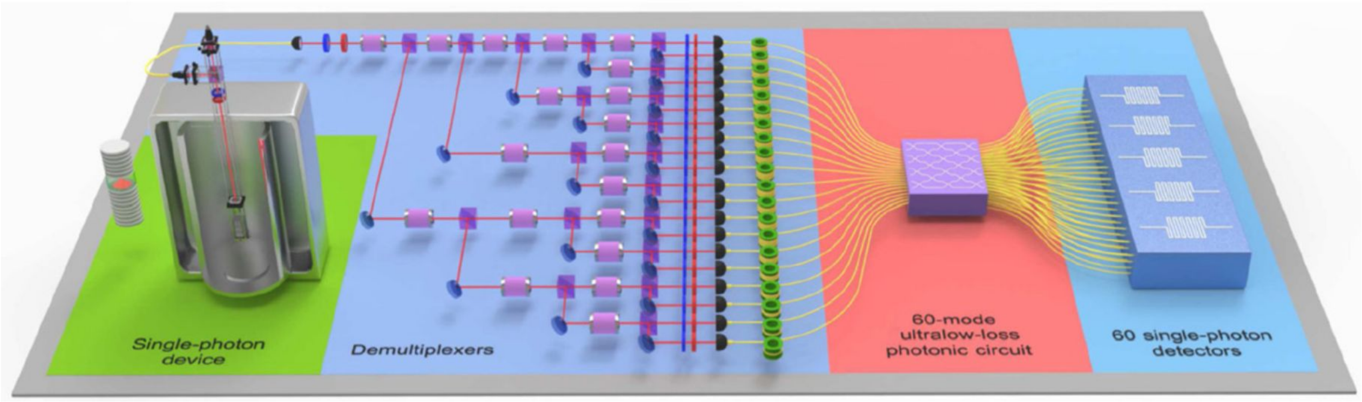
Requirements:

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

Quantum information

You, L. Superconducting nanowire single-photon detectors for quantum information. Nanophotonics 9, 2673–2692 (2020).



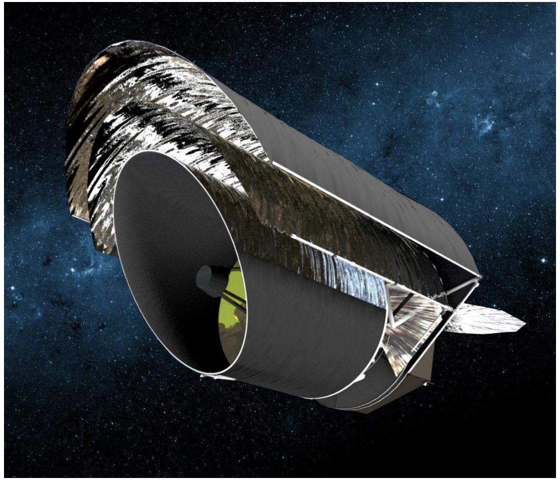


Exoplanet search

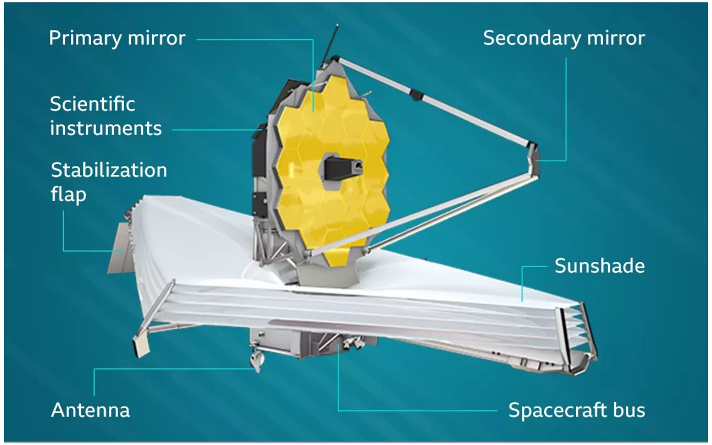
JATIS 7, 011004 (2021).

- 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

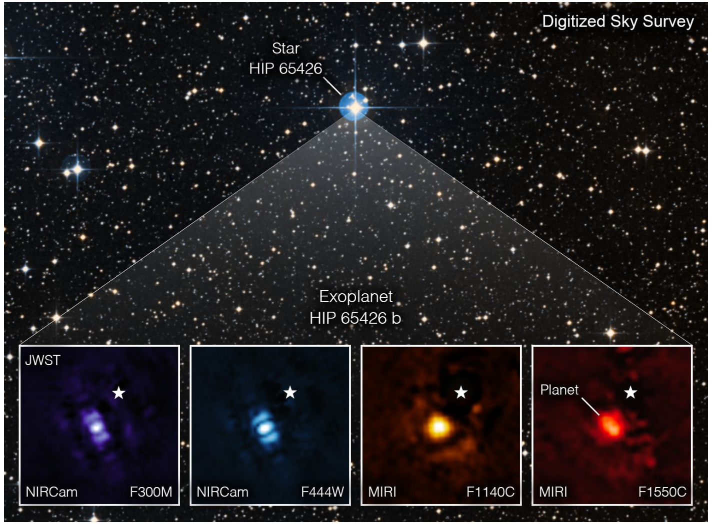
Origins Space Telescope Proposal



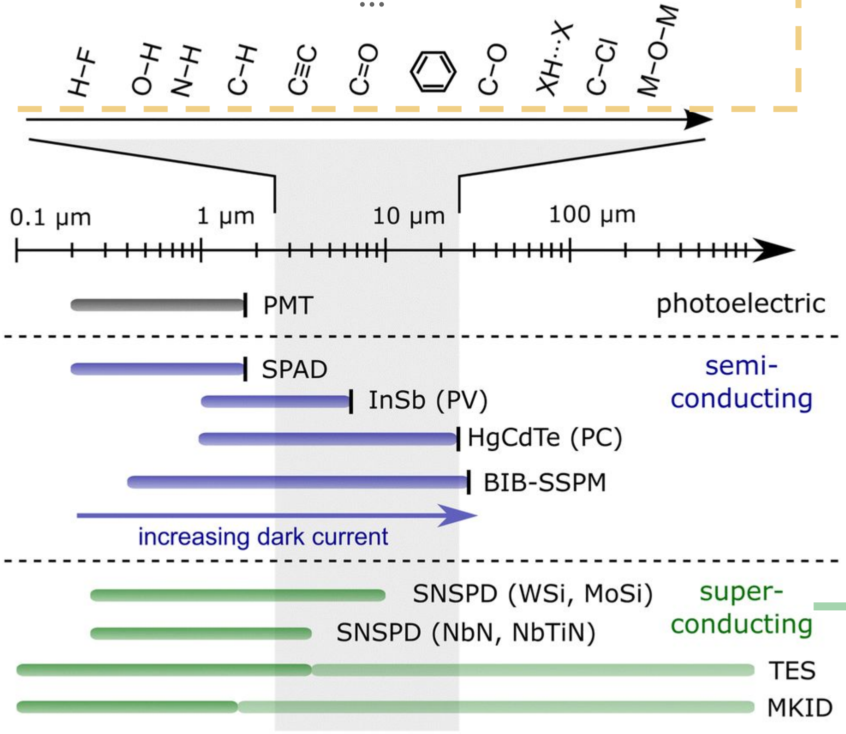
James Webb Space Telescope



Source: Nasa



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



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

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

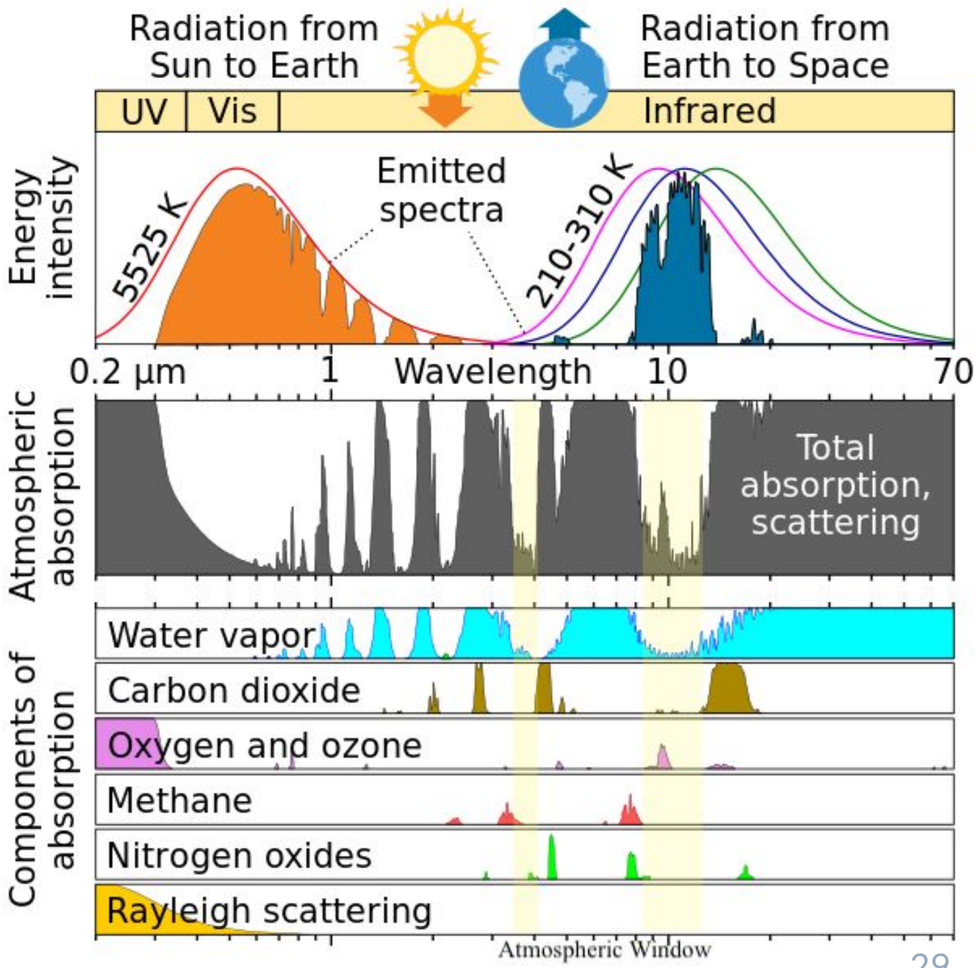
SNSPD can be the detector to meet all stringent requirements in these applications

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

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 Observetory



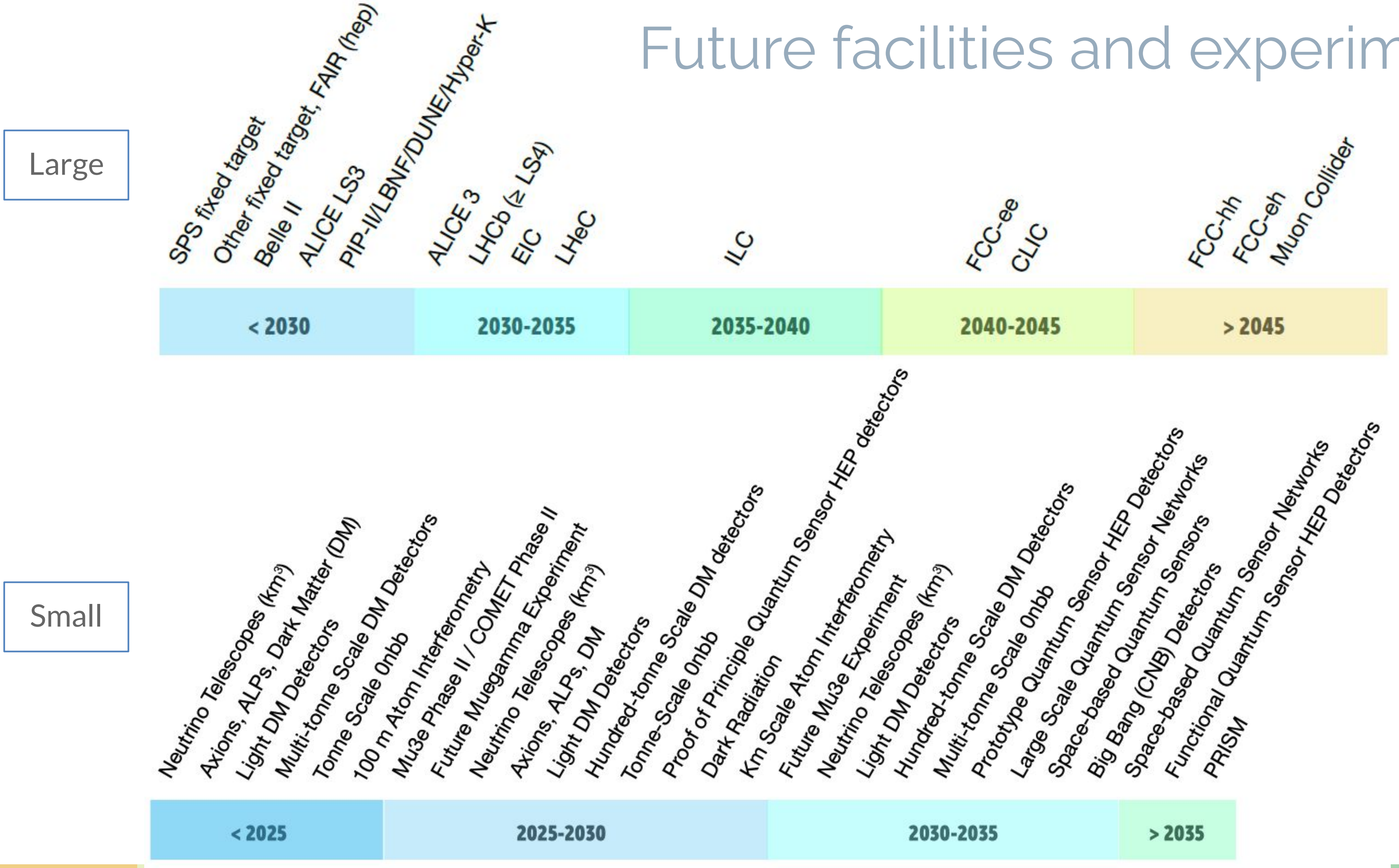
CERN
DRD5 / RDq
R&D on quantum sensor

1. ECFA Detectors R&D Roadmap Process Group. The 2021 ECFA detector research and developement roadmap. Preprint at https://doi.org/10.17181/CERN.XDPL.W2EX (2021).

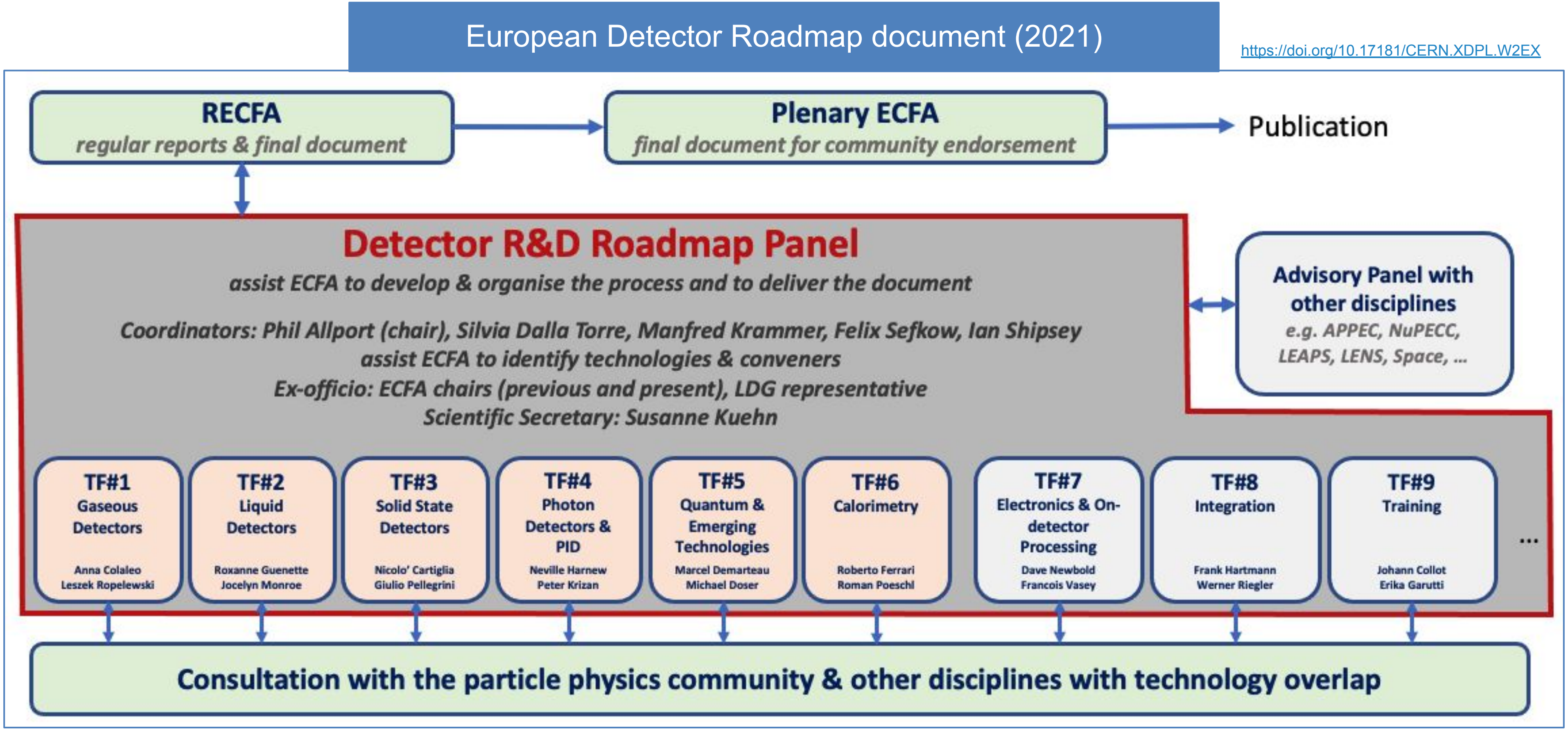
2. The European Strategy and Detector R&D Program. https://arxiv.org/html/2408.17094v1 (2024).

3. Doser, M. & Demarteau, M. Proposal on R&D on quantum sensors: the DRD5/RDq proto-collaboration. https://cds.cern.ch/record/2901426 (2024).

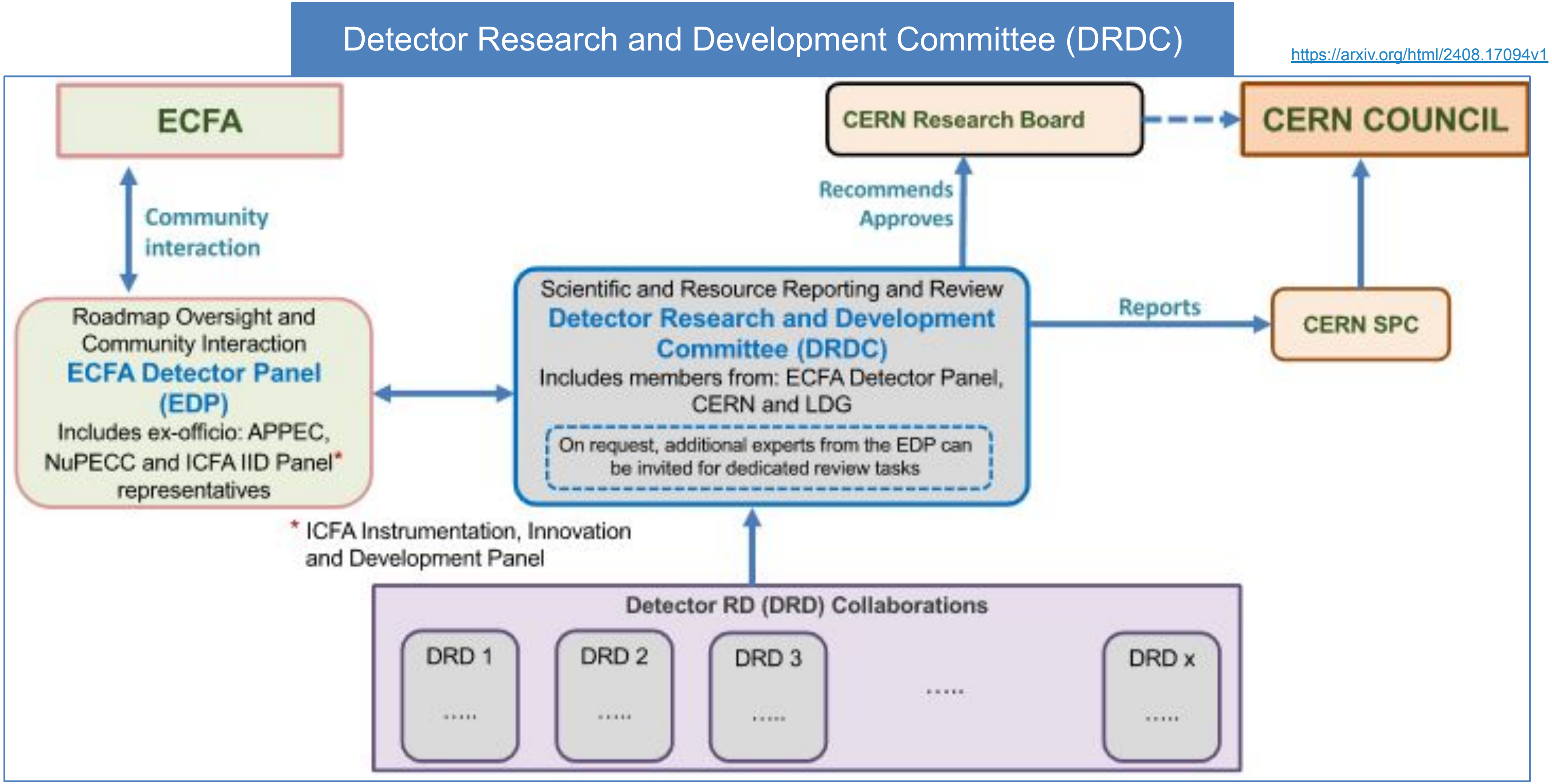
Future facilities and experiments



European Committee for Future Accelerators (ECFA)



New CERN committee



DRD5 / DRq : R&D on Quantum Sensor

Sensor family → Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials

- Quantum technologies are advancing rapidly with unprecedented sensitivity and precision.
- Focusing area
  - Exploring foundational physics questions (e.g., symmetry violations, interactions).
  - Enhancing extreme-sensitivity measurements.
  - Applying new materials and phase transitions to detector technologies.
- Community Building
  - No membership fees or common funds.
  - Lightweight joining process via request to the collaboration board.
  - 94 groups (338 individuals) expressed interest in signing the proposal submitted in February 2024.

DRD5 Work packages

Sensor family → Work Package ↓	clocks & clock networks	superconducting & spin-based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto-mechanical sensors	nano-engineered / low-dimensional / materials
WP1 *Atomic, Nuclear and Molecular Systems in traps & beams*	X			X	(X)	
WP2 *Quantum Materials (0-, 1-, 2-D)*		(X)	(X)		X	X
WP3 *Quantum superconducting devices*		X				(X)
WP4 *Scaled-up massive ensembles* (spin-sensitive devices, hybrid devices, mechanical sensors)		X	(X)	X	(X)	X
WP5 *Quantum Techniques for Sensing*	X	X	X	X	X	
WP6 *Capacity expansion*	X	X	X	X	X	X

HEP function / Work package	Tracking	Calorimetry	Timing	PID	Helicity
WP 1 (Quantum systems in traps and beam)	Rydberg TPC	BEC WIMP scattering (recoil)	O(fs) reference clock for time-sensitive synchronization (photon TOF)	Rydberg dE/dx amplifiers	
WP2 (Quantum materials: 0-, 1- and 2-D)	"DotPix"; improved GEM's; chromatic tracking (sub-pixel); active scintillators	Chromatic calorimetry	Suspended / embedded quantum dot scintillators	Photonic dE/dx through suspended quantum dots in TPC	
WP 3 (Superconducting quantum devices)	O(ps) SNSPD trackers for diffractive scattering (Roman pot)	FIR, UV & x-ray calorimetry	O(ps) high Tc SNSPD	Milli- & microcharged particle trackers in beam dumps	
WP 4 (scaled-up bulk systems for mip's)	Multi-mode trackers (electrons, photons)	Multi-mode calorimeters (electrons, photons, phonons)	Wavefront detection (e.g. O(ps) embedded devices)		Helicity detector via ultra-thin NV optically polarized scattering / tracking stack
WP 5 (Quantum techniques)				Many-to-one entanglement detection of interaction	
WP 6 (capacity building)	Technical expertise of future workforce (detector construction); broadened career prospects and thus enhanced attractiveness; cross-departmental networking and collaboration; broadened user base for infrastructure (beam tests, dilution refrigerators, processing technologies)				

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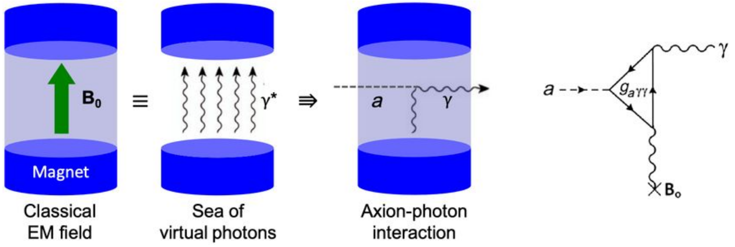
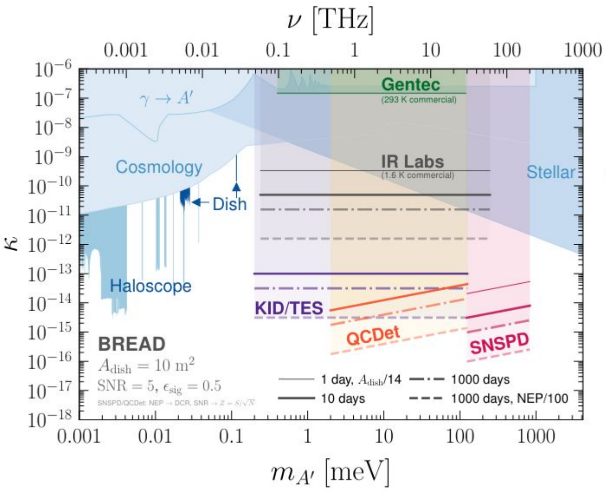
Dark Matter Searches

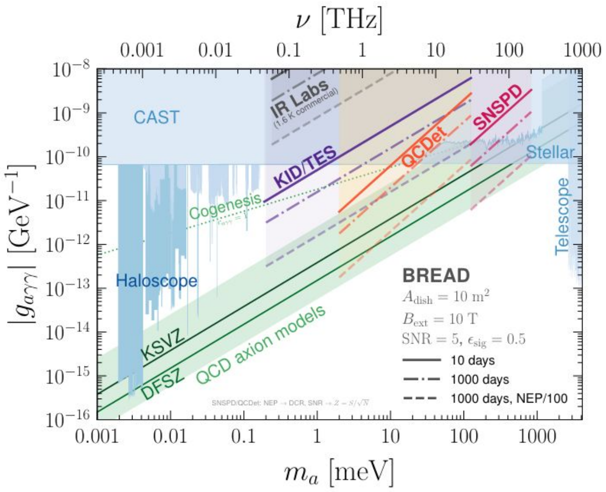


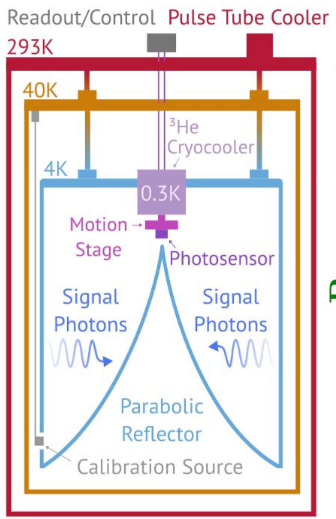
arXiv.2104.14831 (2021)

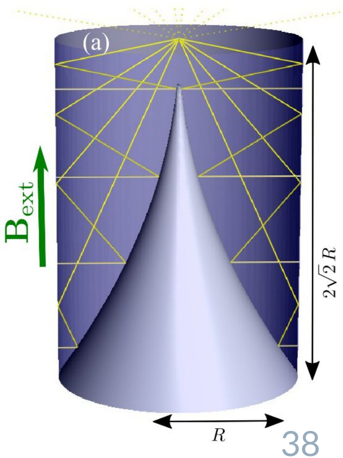
- Dark matter candidates with m_{DM} < 1 eV
  - QCD Axions (*a*)
  - Dark Photons (*A'*)
- Non-zero DM-photon couplings → lab detection through EM interactions

Broadband solenoidal haloscope for terahertz axion detection (BREAD) Phys. Rev. Lett. 128, 131801 (2022).



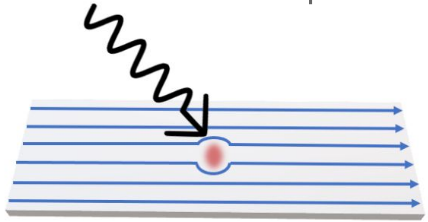


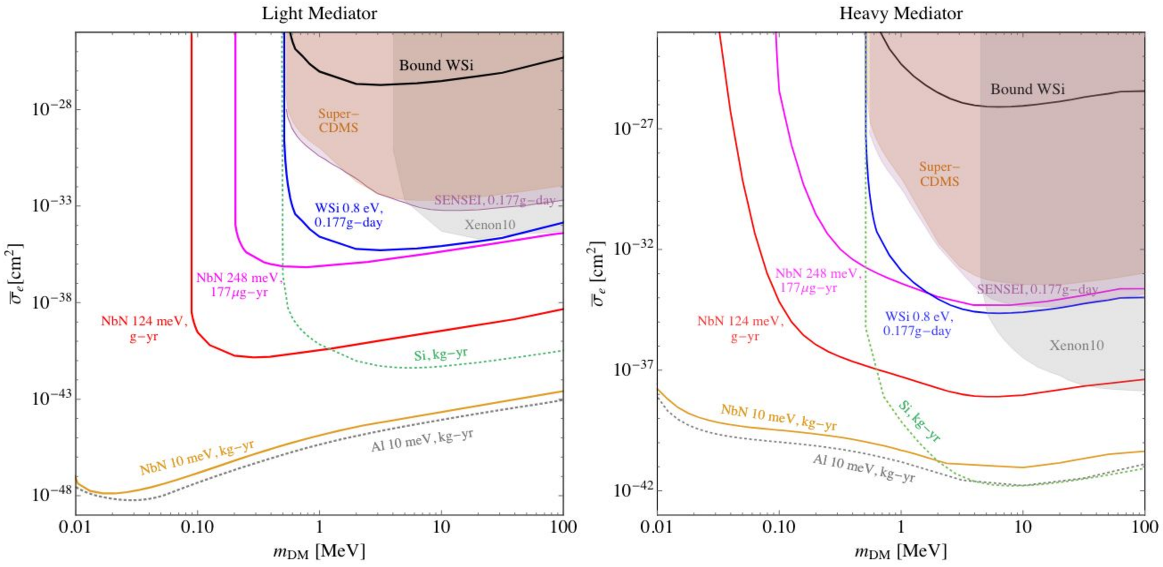




Dark Matter Searches – Direct interaction

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





- Requires stable and low Dark Counts

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

HEP function / Work package	Tracking	Calorimetry	Timing	PID	Helicity
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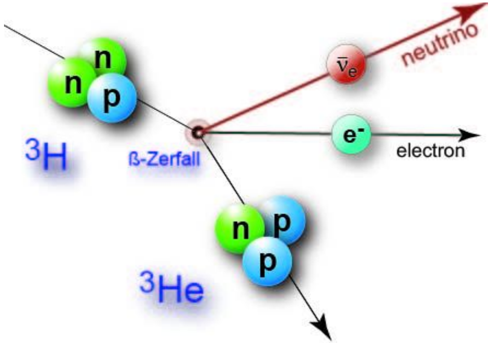
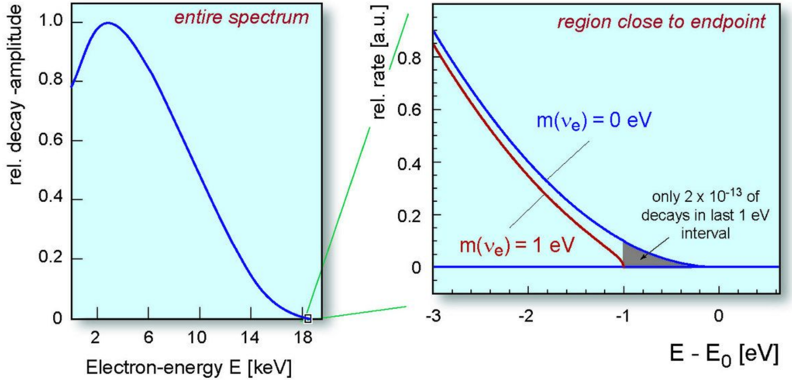
Direct neutrino mass measurement

https://www.katrin.kit.edu/79.php





G Drexlin, Direct neutrino mass measurements

	$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$	$^{187}Re \rightarrow {}^{187}Os + e^- + \bar{\nu}_e$
half life $t_{1/2}$	12.3 years	43.2 Gyears
end-point energy E_0	18.57 keV	2.47 keV
decay mode	super-allowed	unique first forbidden
electron shell	simple (H-like)	complex
ß-source	gaseous / quench-condensed	metallic Re / dielectric $AgReO_4$
total ß-activity	high: $\sim 10^{11}$ ß/s	low: $< 10^5$ s^{-1}
detector specific ß-rate	4.7 Ci s^{-1} injection (KATRIN)	~ 1 Bq / mg Re (MARE)
systematic effects	electron scattering in ß-source	surface / solid state effects

Direct neutrino mass measurement

	electrostatic spectrometer	cryogenic micro-bolometer
detector response	kinetic energy of ß-electron	entire energy
ß-energy interval	narrow interval at E_0	entire spectrum
ß-spectroscopy	integral spectrum	differential spectrum
experimental set-up	integral design	modular design (arrays)
energy resolution	$\Delta E = 0.93$ eV (100%)	$\Delta E > 5\text{-}10$ eV (FWHM)
systematic effects	HV fluctuations, scattering	energy calibration, surface effects

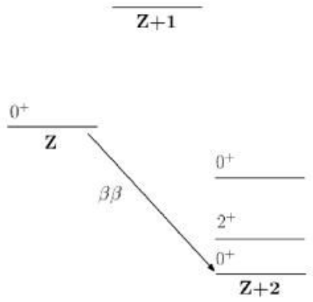
- KATRIN 2024 upper limit of $m_\nu < 0.45$ eV at 90 % confidence level (259 days)

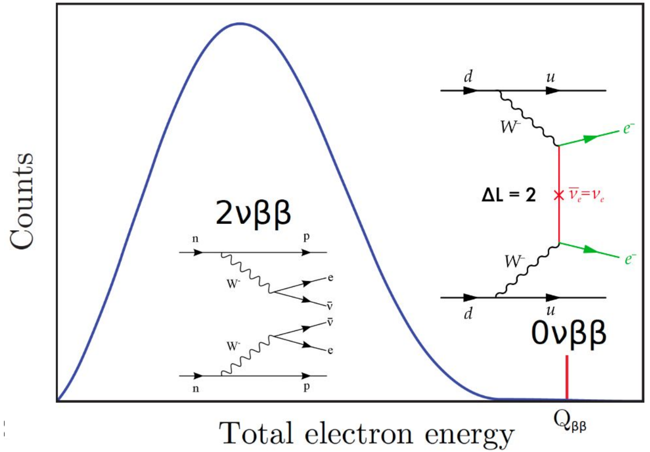
  Aker, M. et al. Direct neutrino-mass measurement based on 259 days of KATRIN data. Preprint at https://doi.org/10.48550/arXiv.2406.13516 (2024).

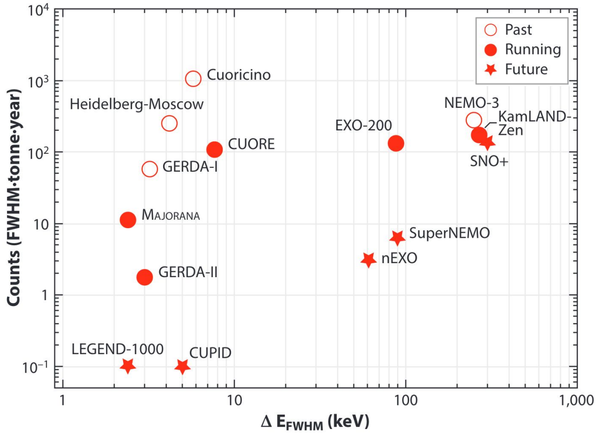
- Expect with 1000 days of measurement to reach target sensitivity of 0.2 eV
- Neutrino oscillation data have 1-2 order less delta mass

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





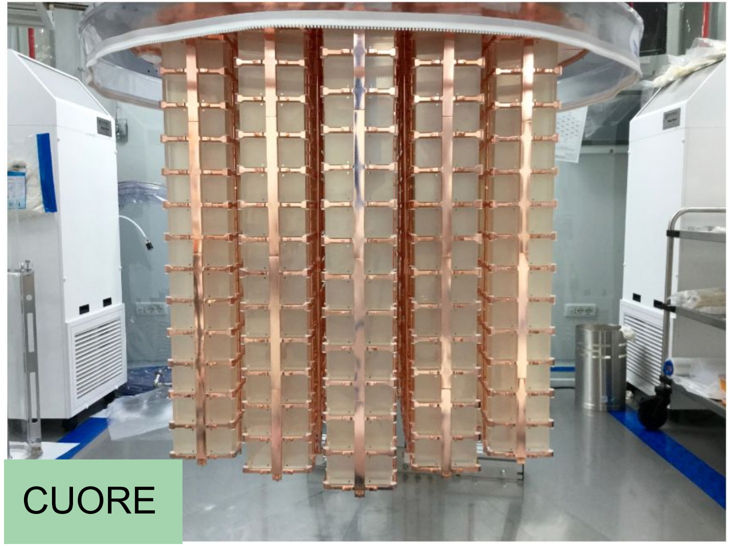


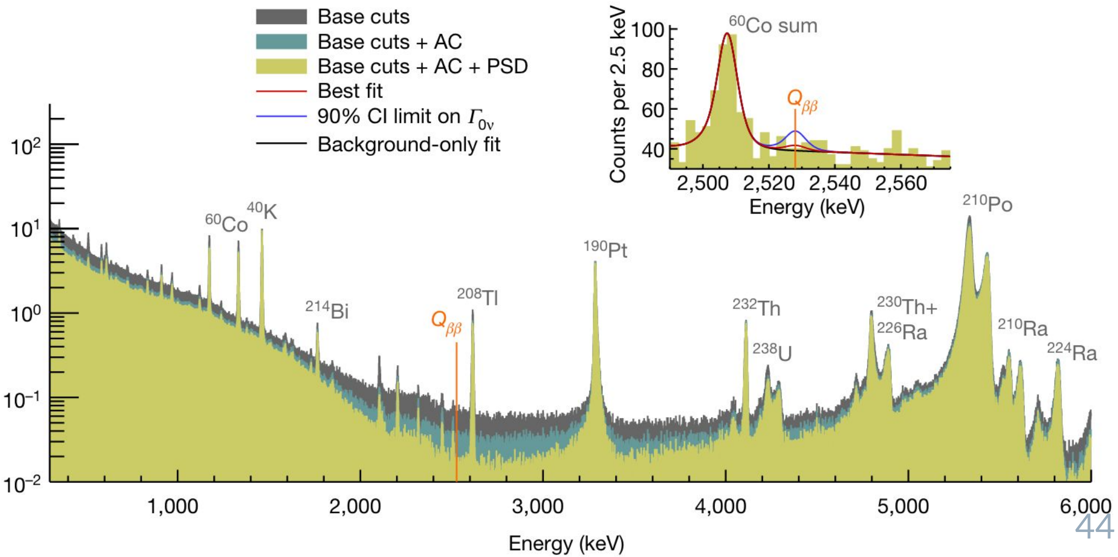
Bradford Welliver (15th Pisa meeting on Advanced Detectors) Annual Review of Nuclear and Particle Science 69, 219–251 (2019).

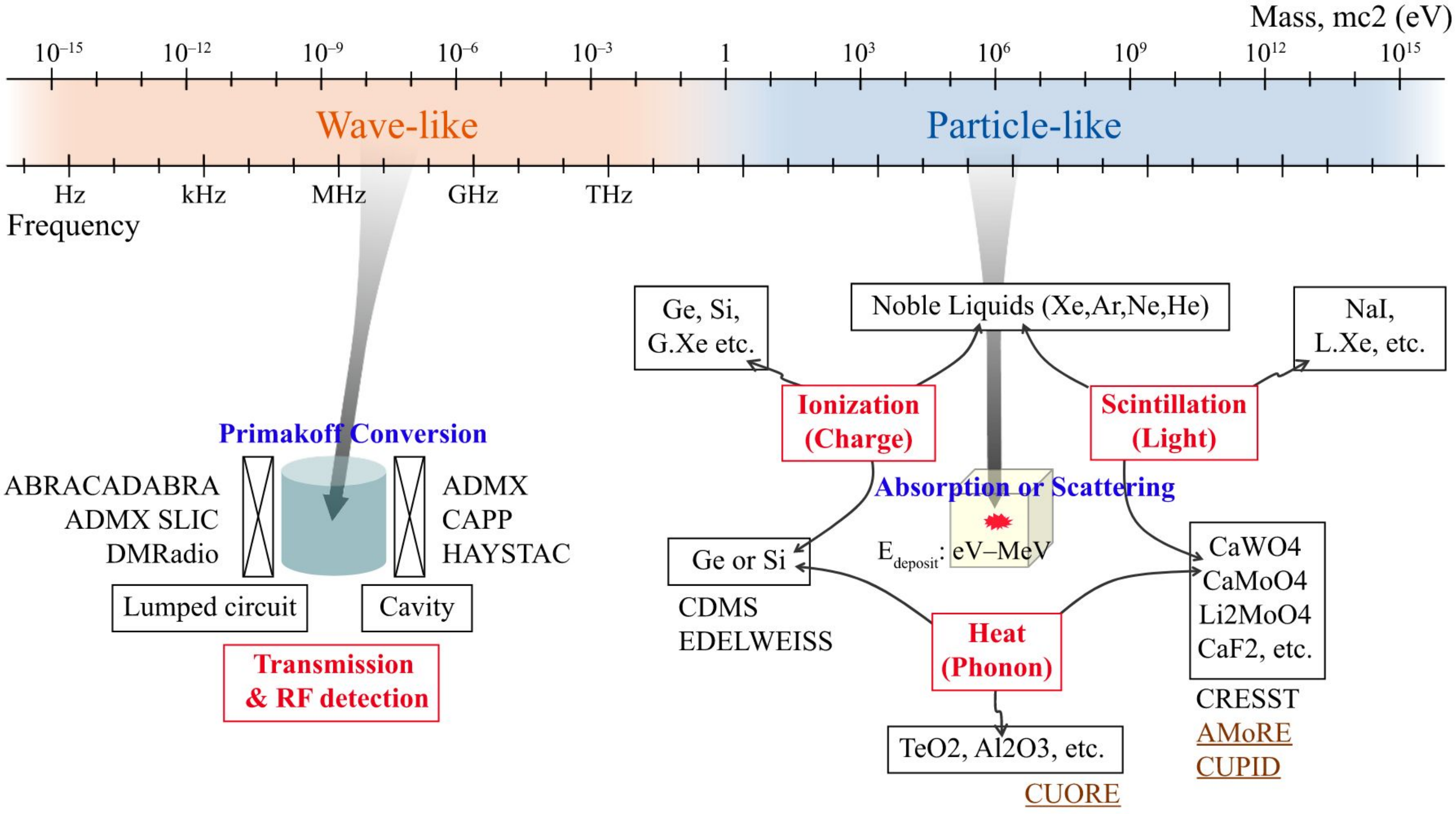
Neutrinoless double beta decay

- 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).







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

Summary

- Ongoing development of a mid-to-far IR SNSPD
  - Dual-Mode Calorimetric operation is observed which could lead to ultra-fast spectroscopy
  - Enhancing the performance of the SNSPD with state-of-the-art optical structures
  - Testing plasmonic structures, new materials, new designs…
  - System updates to minimize electric noise and laser coupling
  - Still a lot of work to be carried out

- Joined CERN DRD5/RDq
  - No immediate task or responsibility
  - Try to discuss and see where we can contribute
  - Find new application opportunities for the SNSPD R&D

Thanks to all the collaborators!!

National Taiwan University
High Energy Physics Group

奈米機電系統研究中心
半導體製程重點技術平台
Nano-Electro-Mechanical-Systems (NEMS) Research Center

NSTC 國家科學及技術委員會
National Science and Technology Council

Extra Slides

SNSPD Fabrication

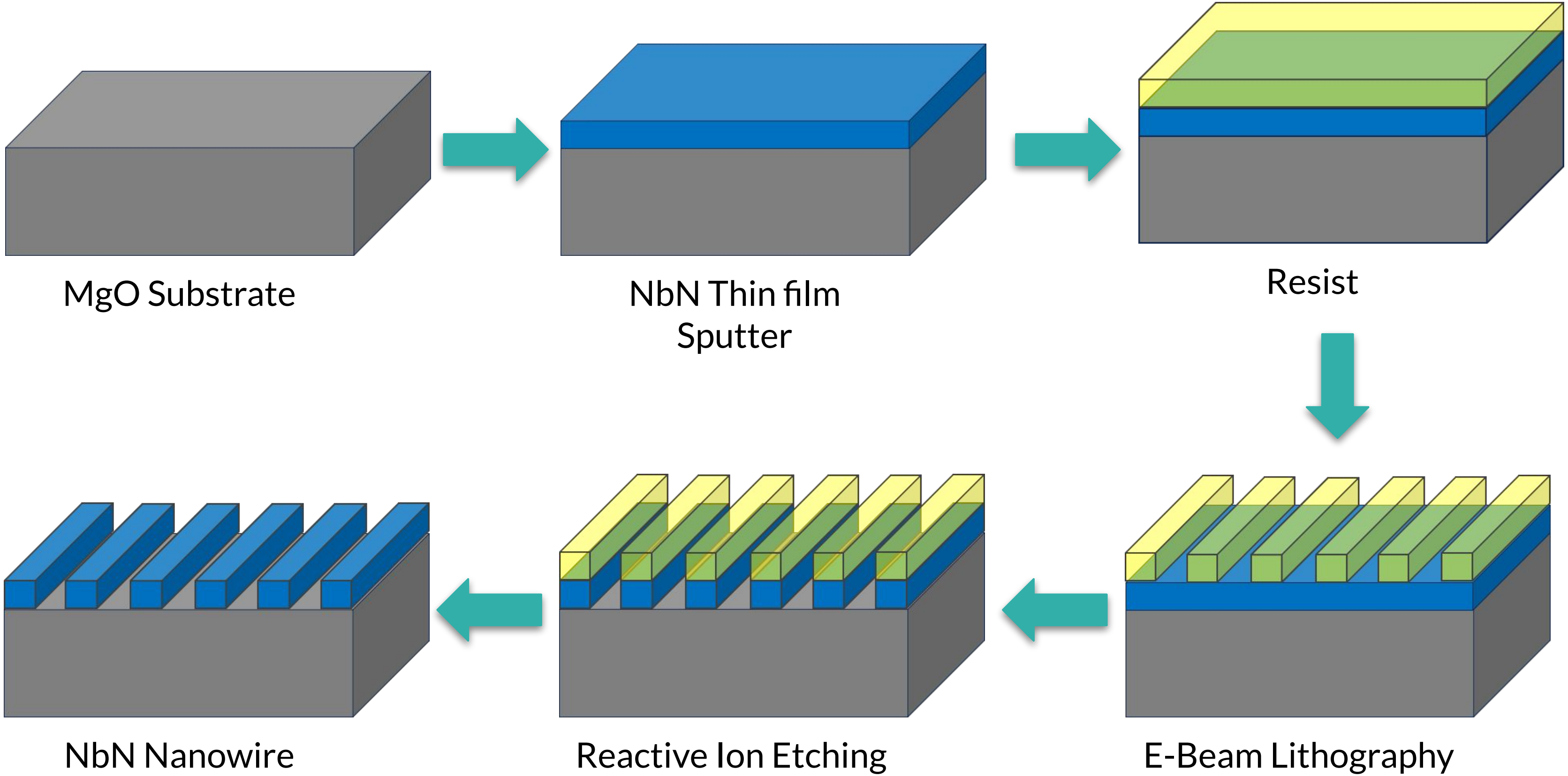
SC Material Choice

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

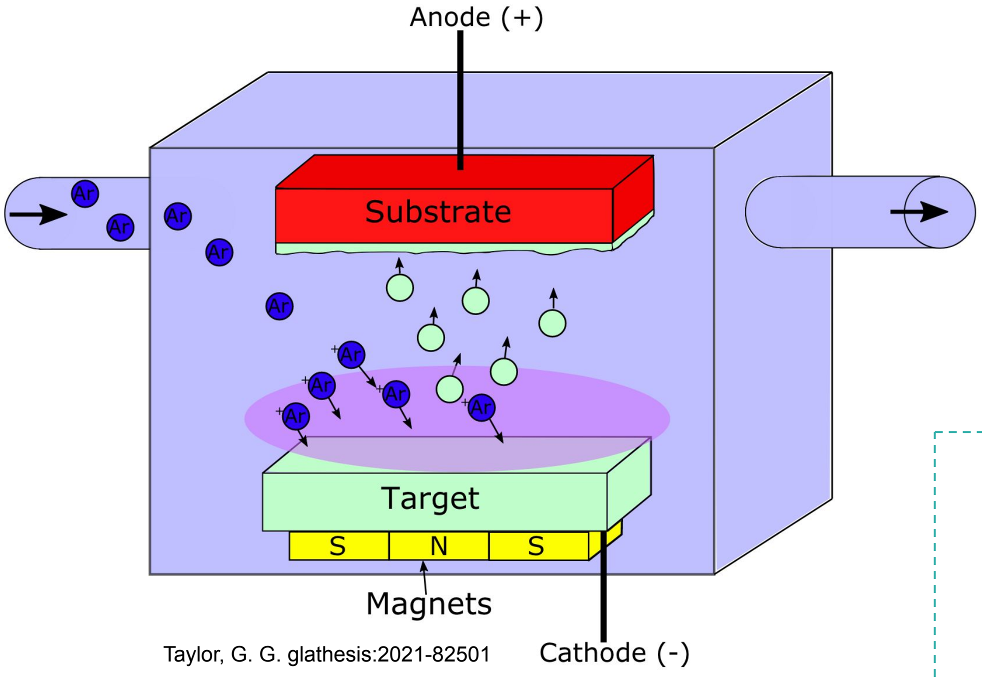
* Data for thin film
** Number of quasi-particles

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

Fabrication Flow

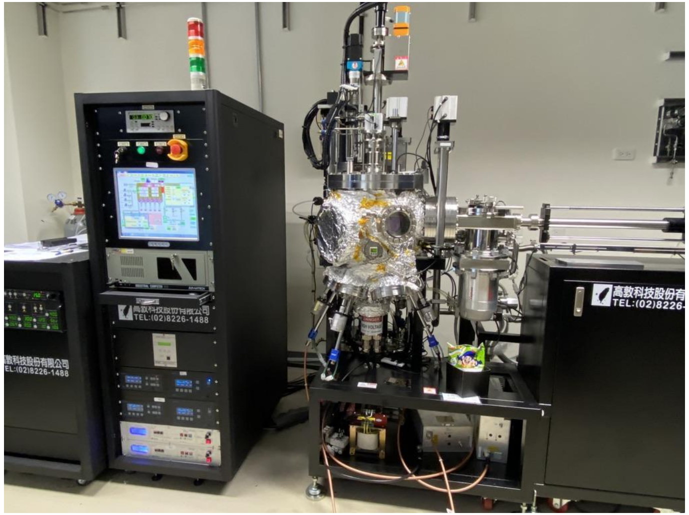


Reactive Magnetron Sputter



Taylor, G. G. glathesis:2021-82501

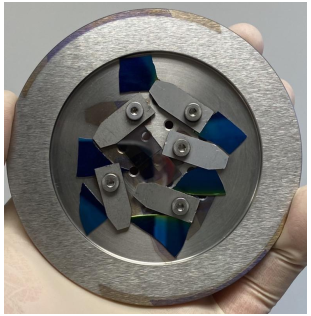
Sputter @ Prof. Yu-Rong Lu's Lab (AS)



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)

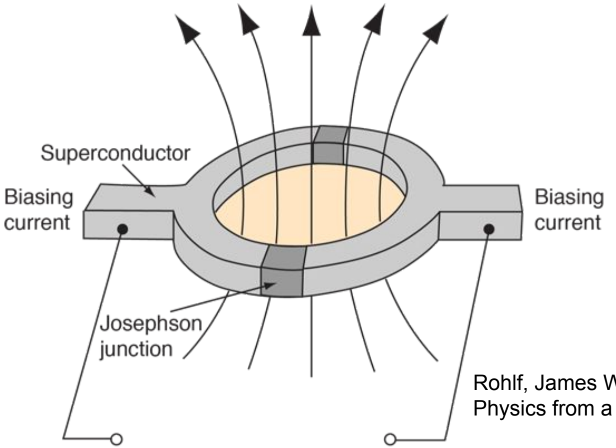
NbN Thin film



Thin film quality characterization

Magnetic susceptibility χ_V @ 2-20K

→ Critical Temperature



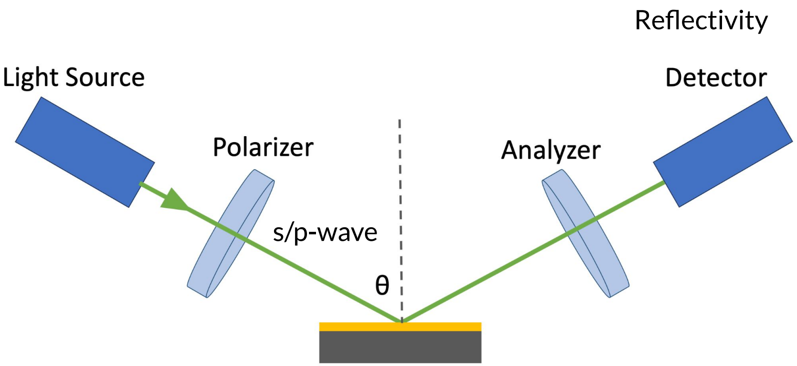
Rohlf, James William, Modern Physics from a to Z0, Wiley 1994

Superconducting Quantum Interference Device (SQUID)

Measured by Instrumentation Center, Chen, I-Nan

Electric susceptibility χ_e @ 300K

→ Metallic Property



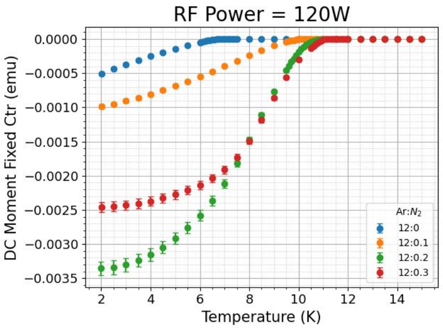
Ellipsometry

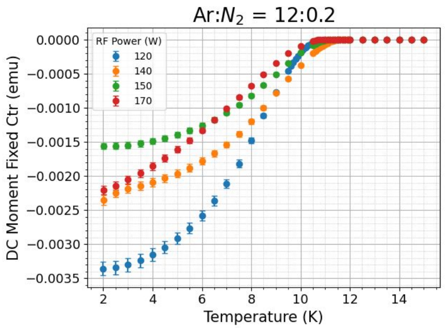
Measured by Lu's Lab, Jing-Wei Yang

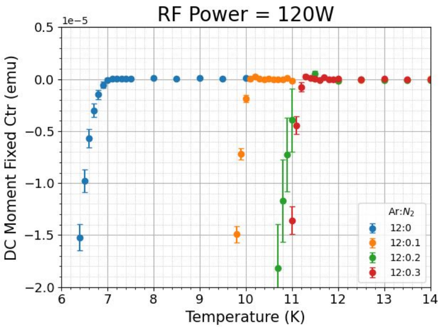
NbN Thin Film Optimization with Sputter Parameters

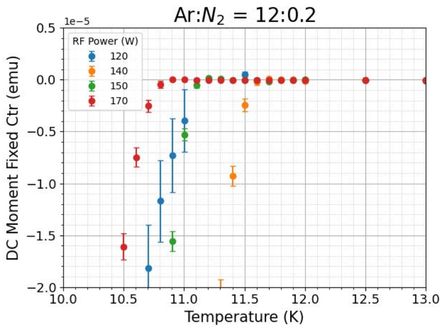
RF Power & Ar:N_2 Flow rate

SQUID → Higher Tc (Better crystallized)





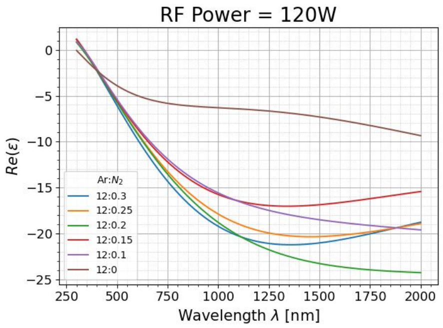


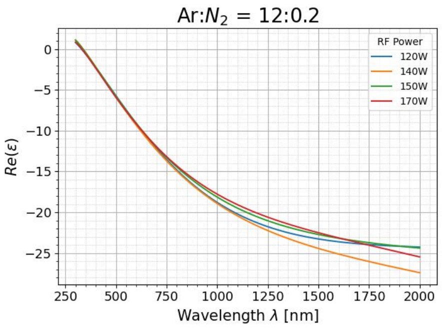


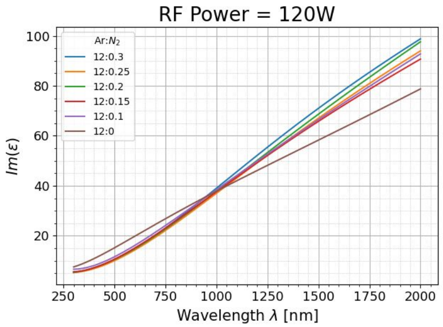
12:0.2 or 12:0.3

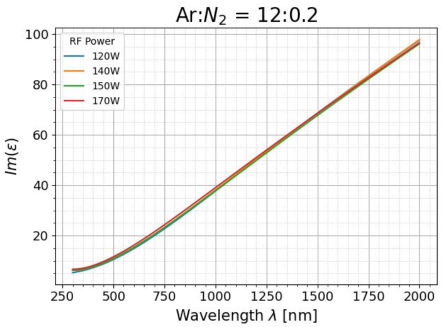
140W

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





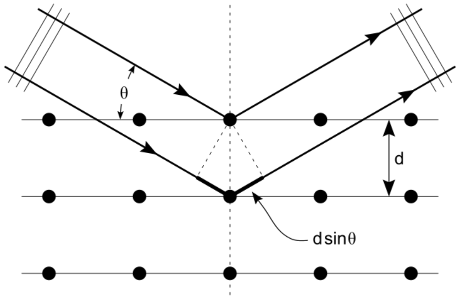




12:0.2 or 12:0.3

140W

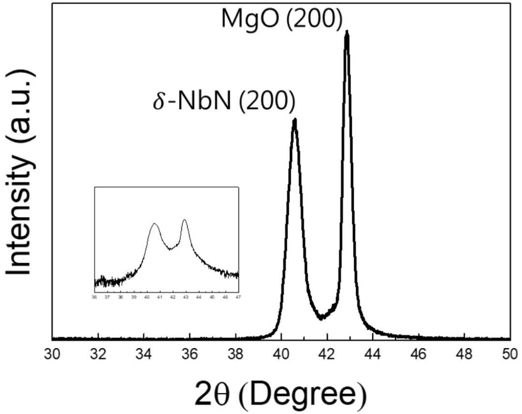
Inpurities – X-Ray Diffraction



Wikimedia Commons

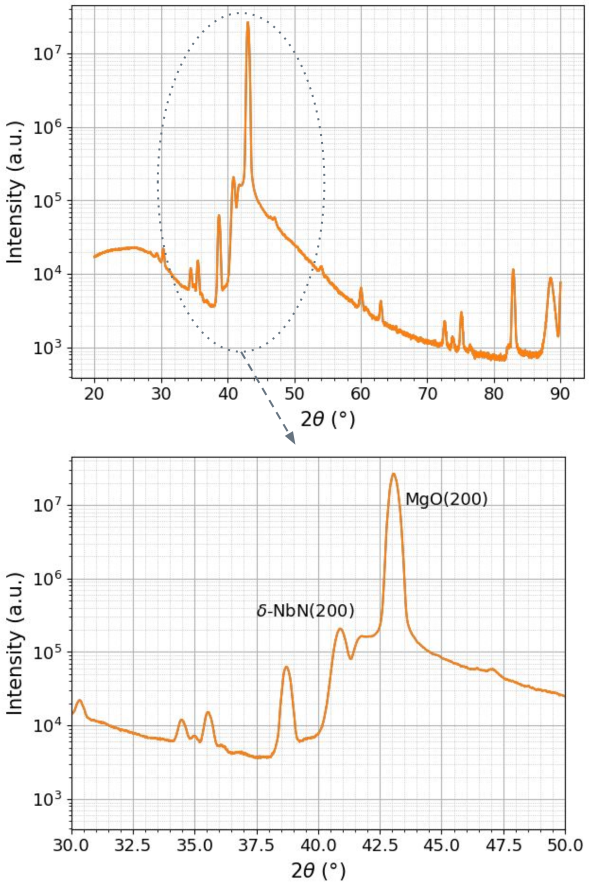
Crystal Structure

2022 Measured



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

2023 Measured

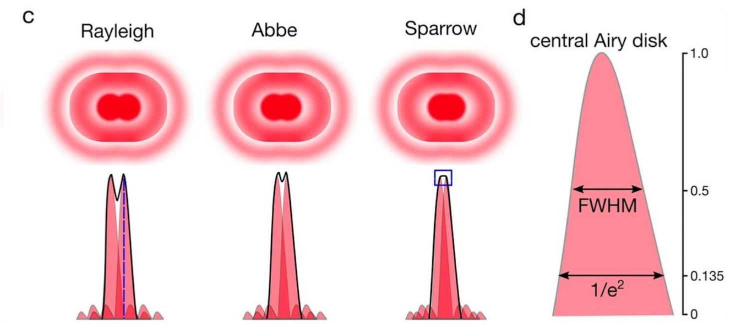


E-Beam Lithography

Abbe's Diffraction Limit

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

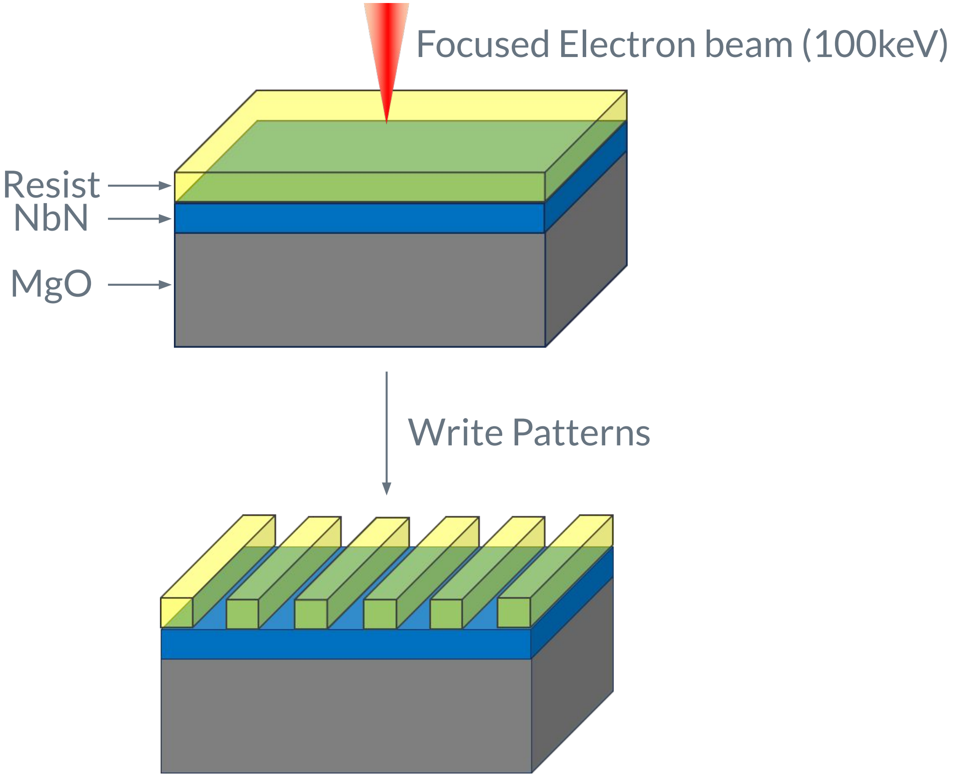
Lithography Resolution



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

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

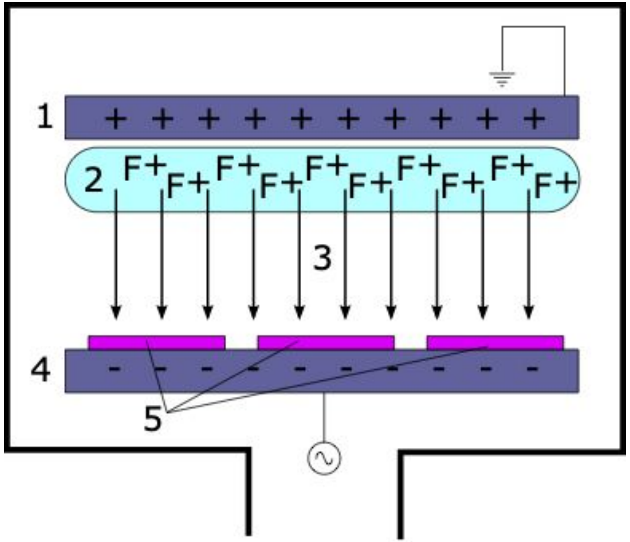
Nanowire width: 100nm → E-Beam Lithography



Reaction Ion Etching

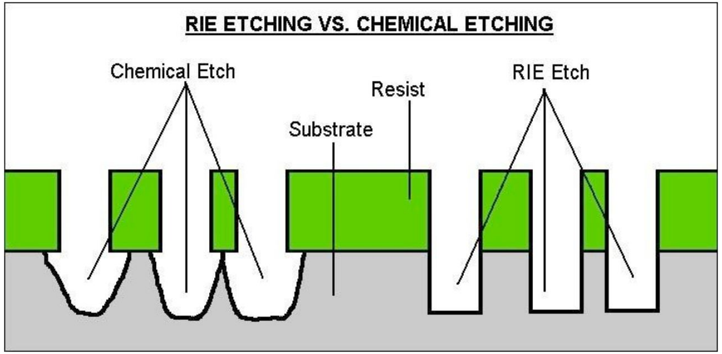
RIE Principle similar to Sputter →

Ion acceleration bombardment

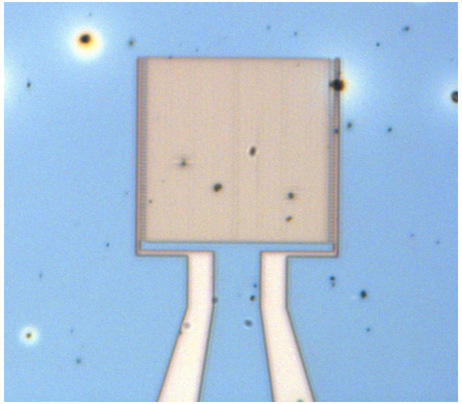


By Dollhous, modified by Adove1018 to show correct electric charges. - https://en.wikipedia.org/wiki/File:Riediagram.gif#file, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=29191041

Higher precision compared to traditional chemical etch

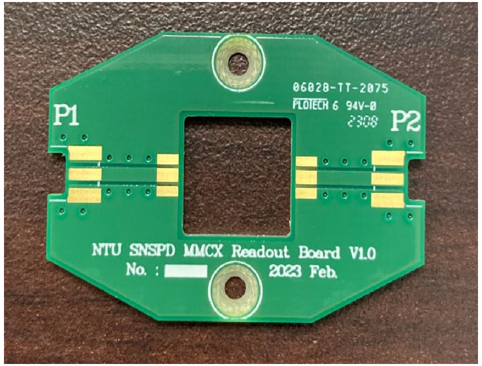


After Etching → NbN Nanowire

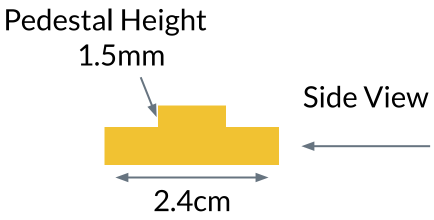


SNSPD Characterization Setup

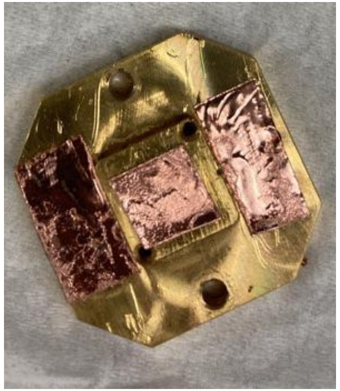
SNSPD Device Preperation



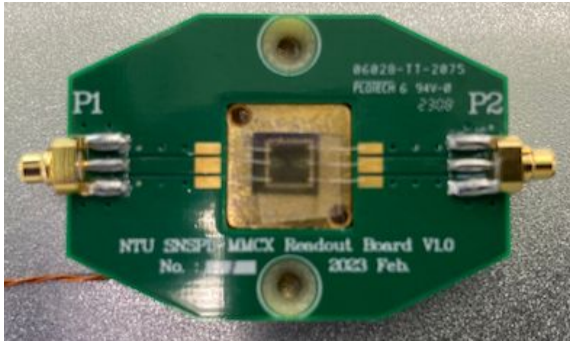
2 Channel SNSPD Readout PCB
Grounded Coplanar Waveguide (GCPW) MMCX connector Designer: Hsin-Yeh, Wu Drawn by: Jenny Huang Fabrication: Plotech



Gold-plated Mount



SNSPD Device



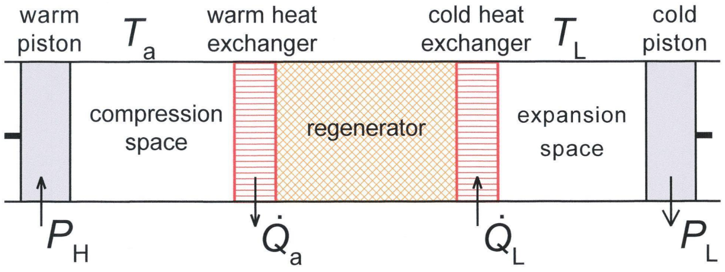
Wirebond: Ouchen

Cryogenics

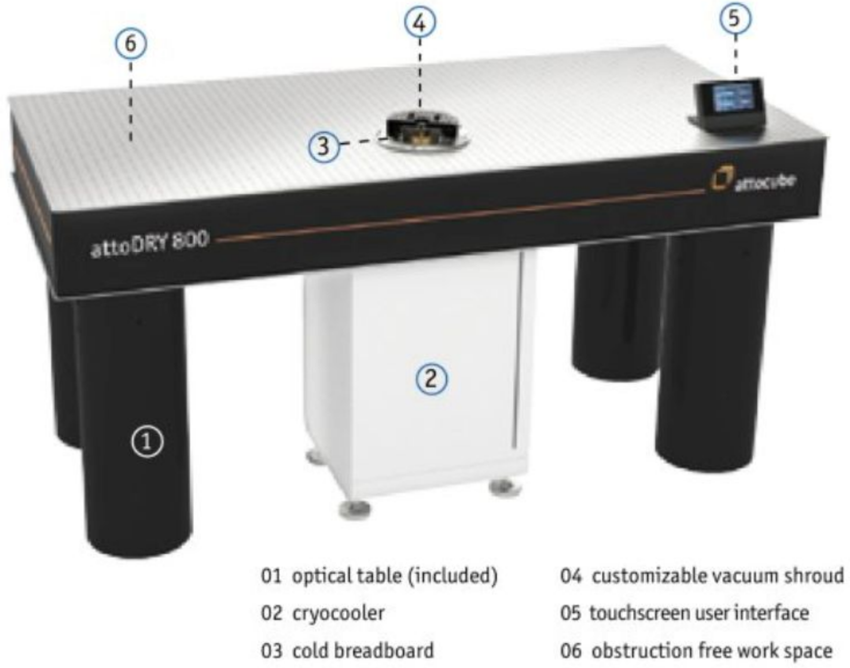
attoDRY800

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

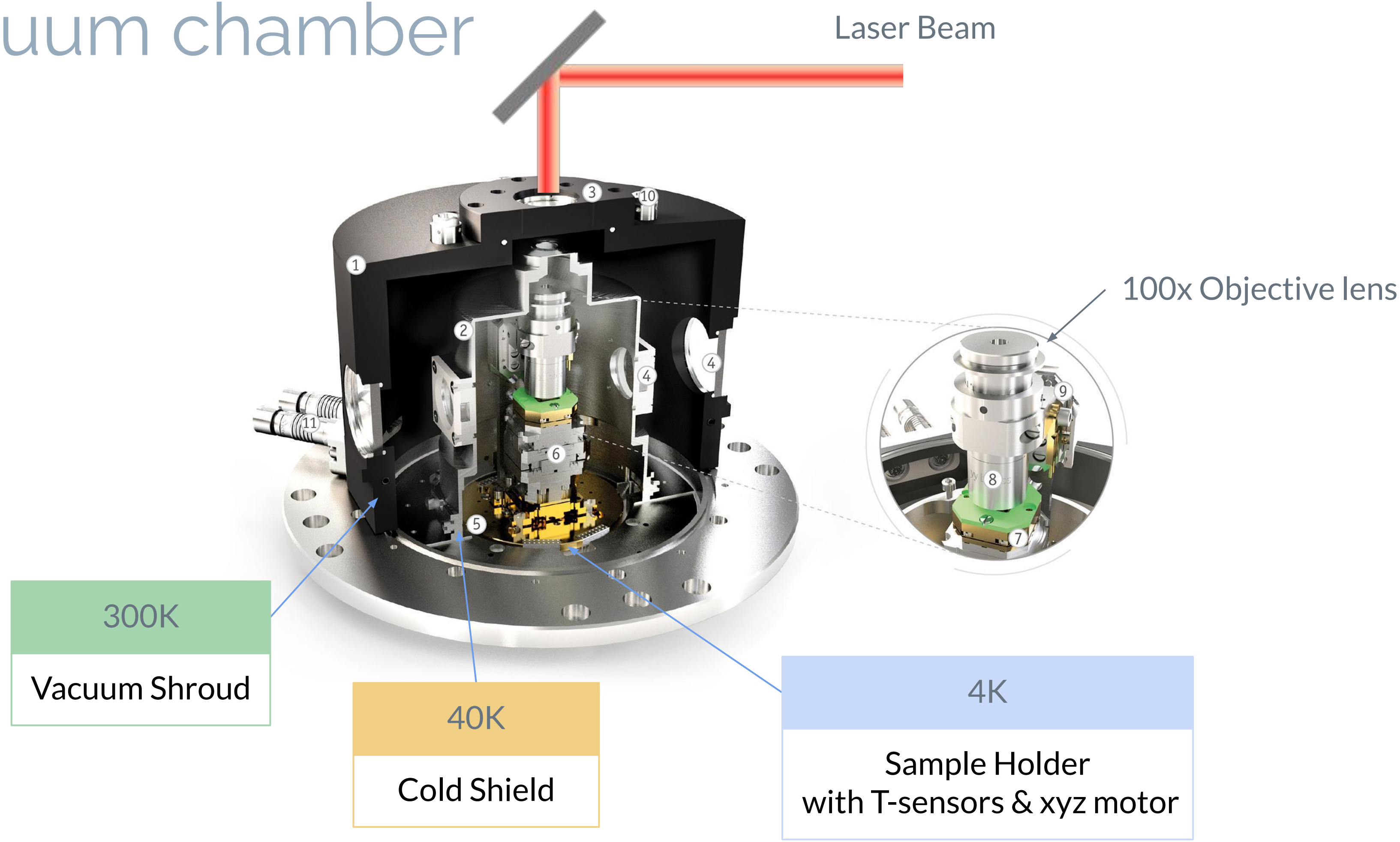
Cryocooler: Stirling Refregirator

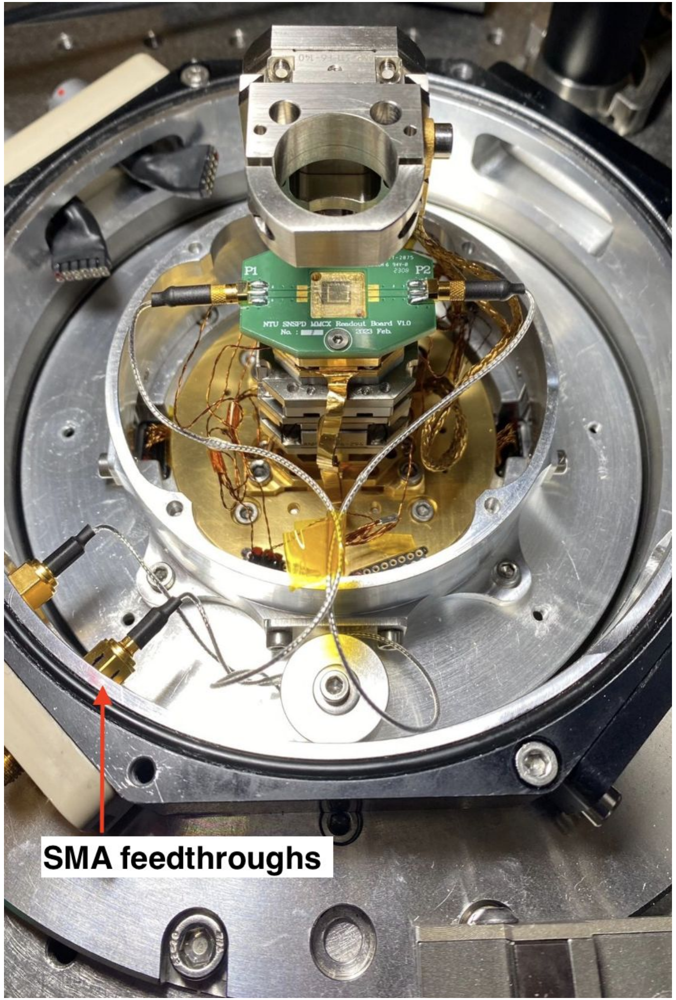


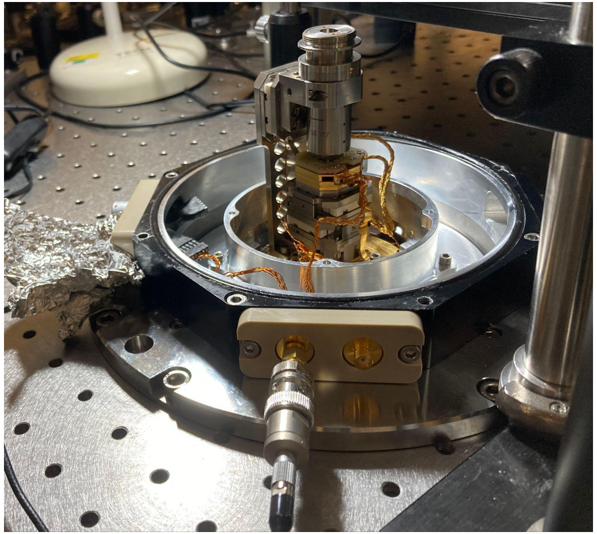
By Adwaele - Made by SliteWrite, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=124814496

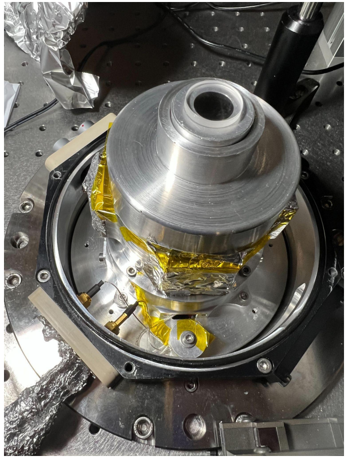


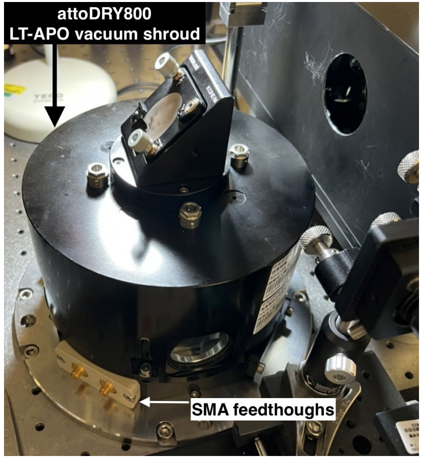
Vacuum chamber



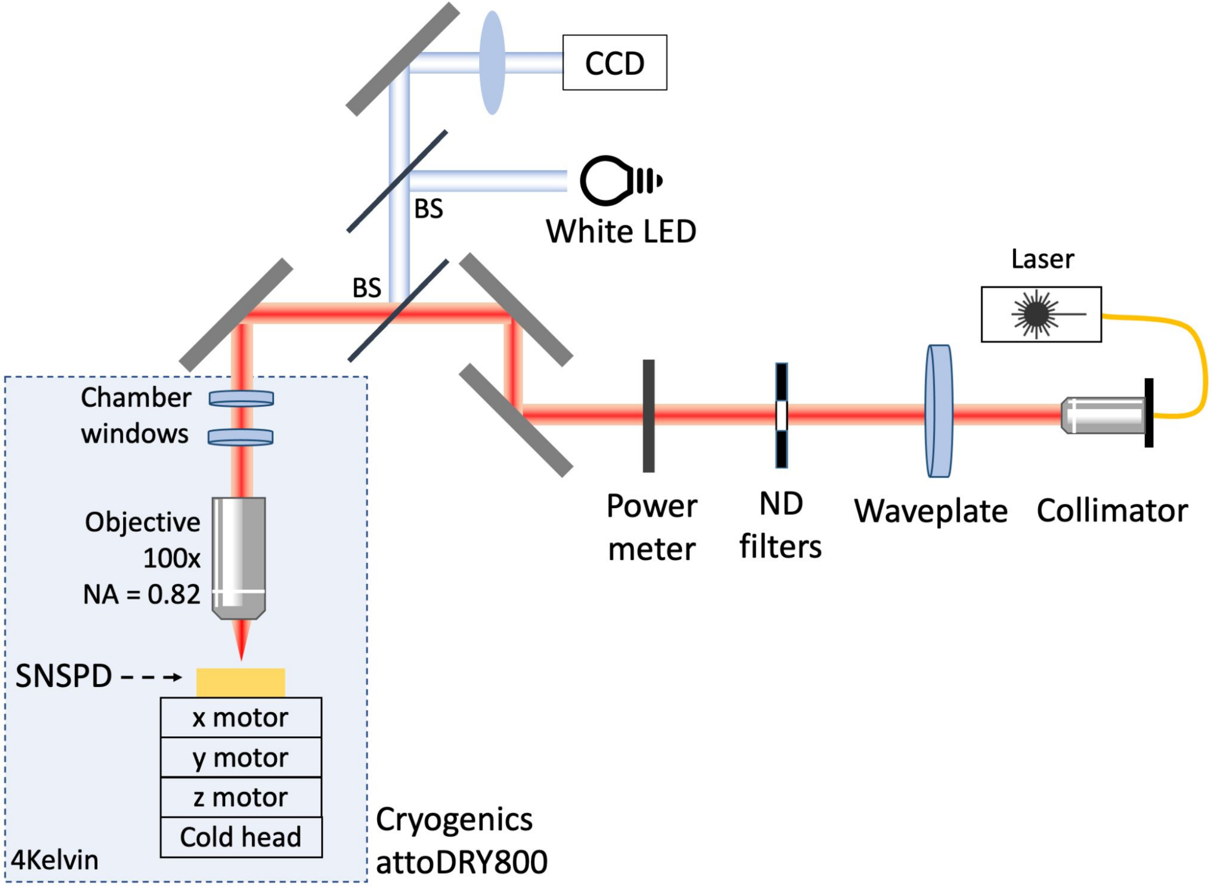

P1
P2
NTU SNSPD MMCX Readout Board V1.0
SMA feedthroughs



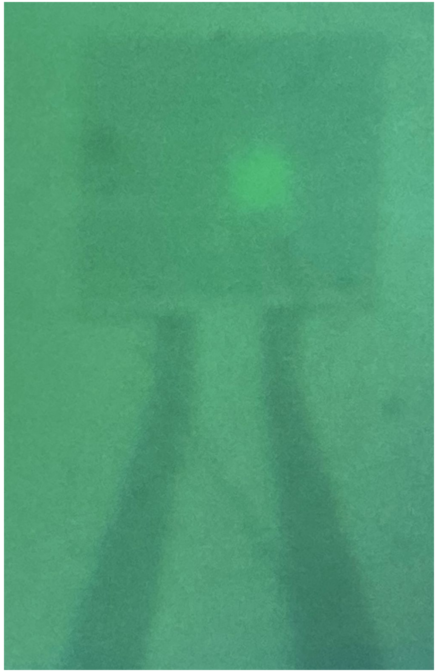



attoDRY800
LT-APO vacuum shroud
SMA feedthoughs

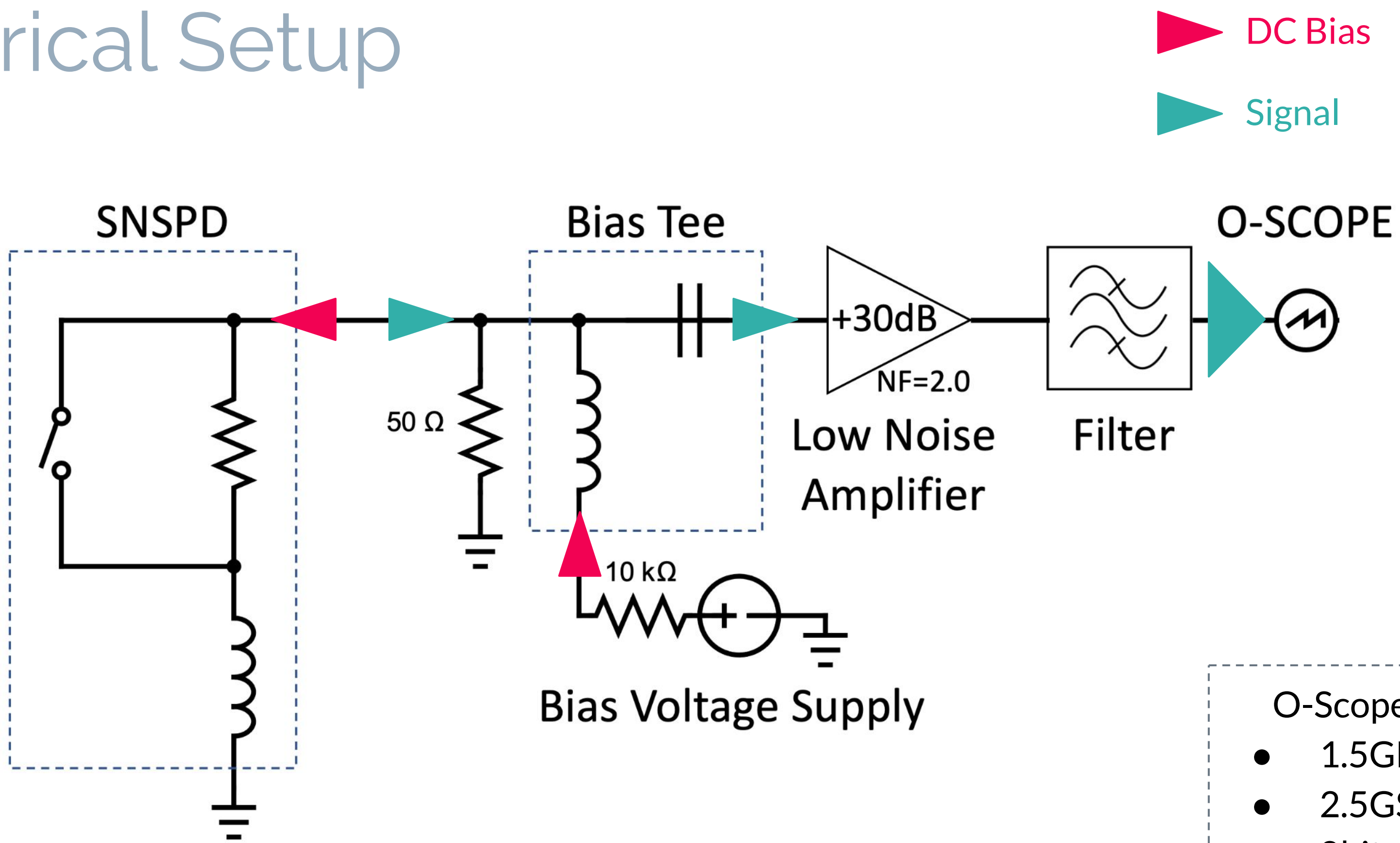
Optical Setup – Open-Air Coupling



CCD Image

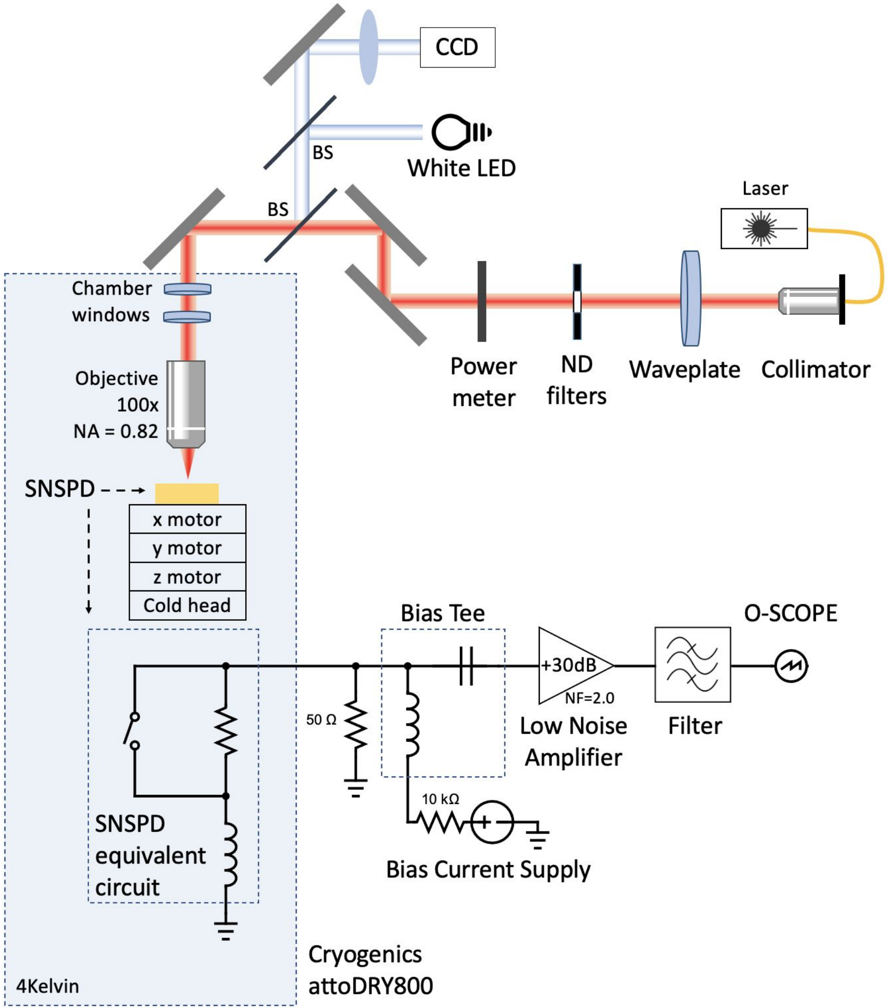


Electrical Setup



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

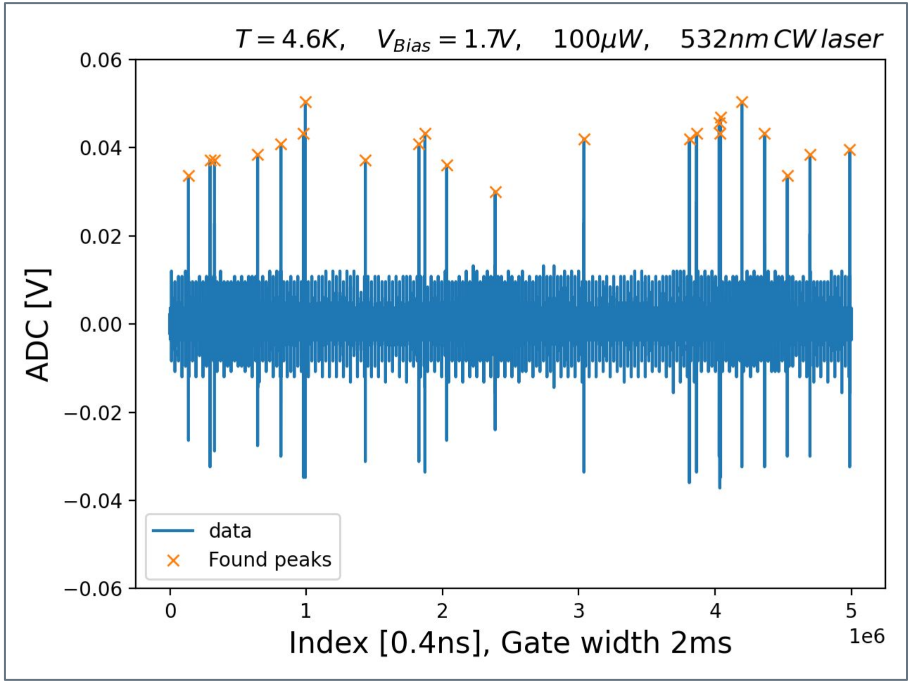
Oscilloscope

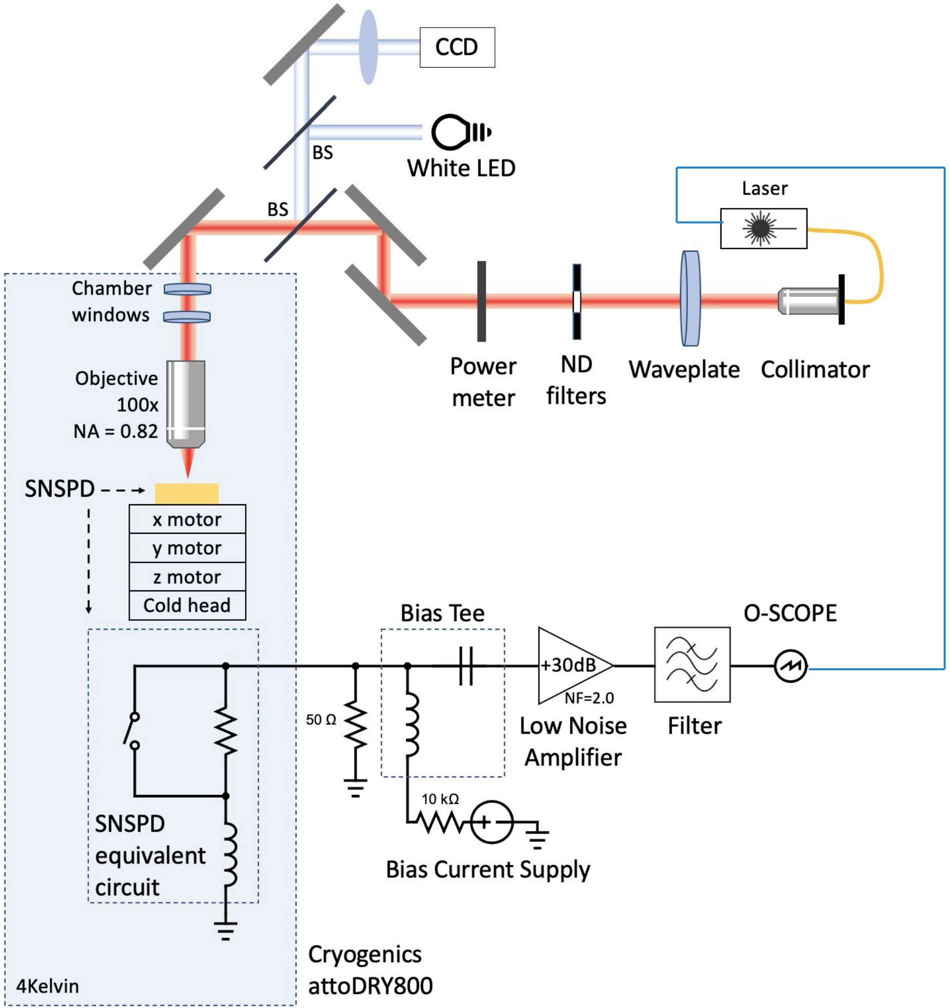
- Sampling Rate: 2.5GS/s (0.4ns)
- Time Gate: 5M Samples → 2milisecond

Counting

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

1 Oscilloscope Time Gate



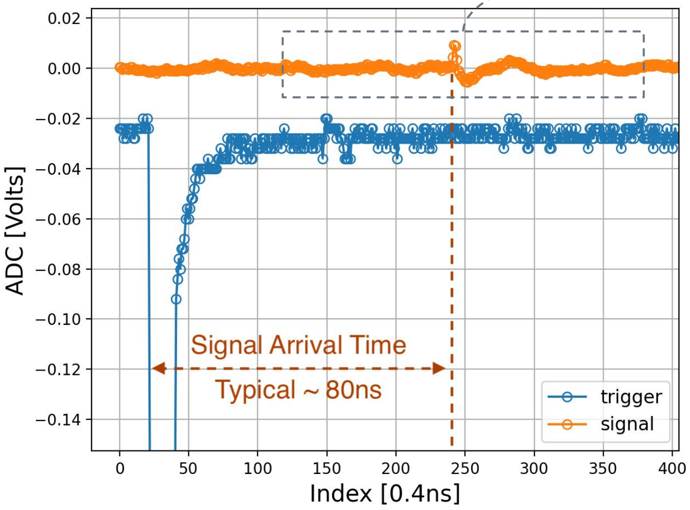


Pulsed Laser SYNC

Pulse Data Taking

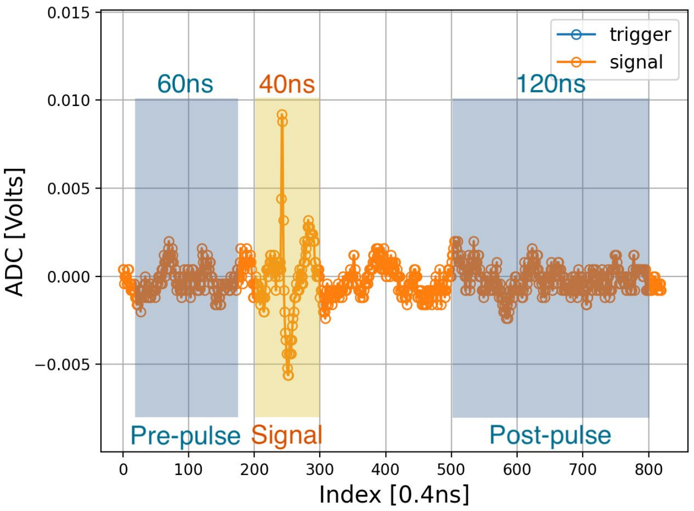
Pulse Laser Repetition Rate: 2.5MHz (400ns)
Pulse Laser Width: 100ps
Oscilloscope Sampling Rate: 2.5GHz (0.4ns)
Trigger: Laser Sync
Signal: Amplified SNSPD output

Event Display:



Sub-window of

1 Laser Trigger



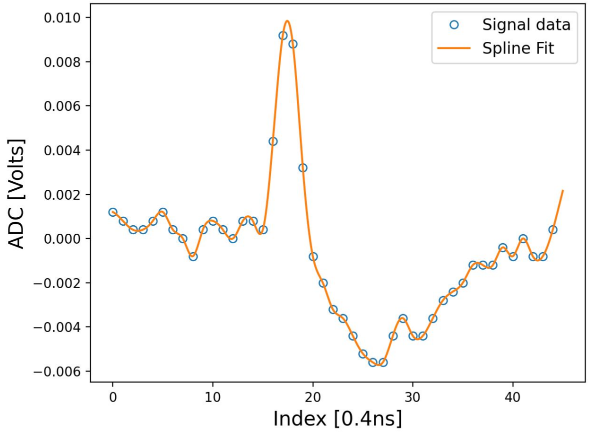
Define Signal &

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

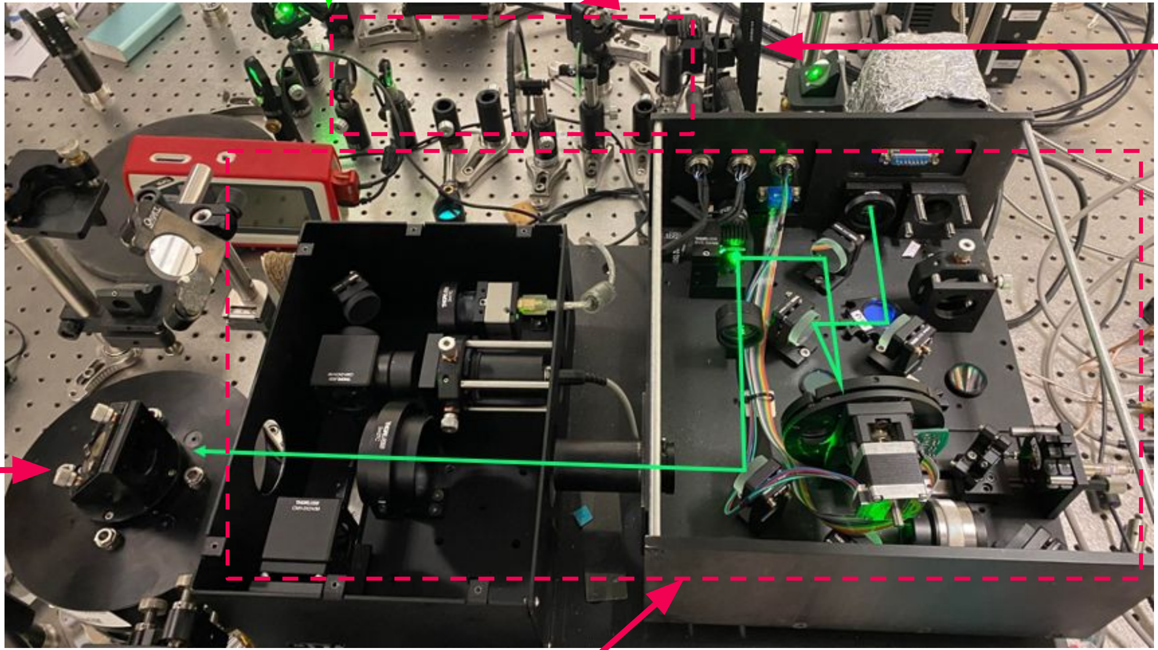
$$\text{Detection Efficiency} = \frac{N_{Event\ Selection}}{N_{Event\ PreSelection}}$$



(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

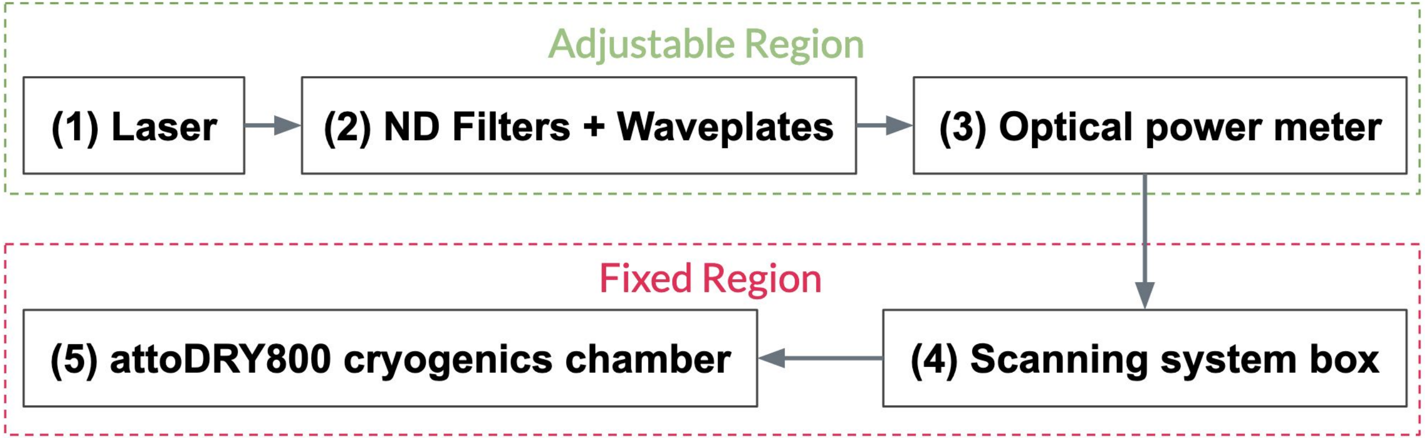


(5) attoDRY800 cryogenics chamber

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

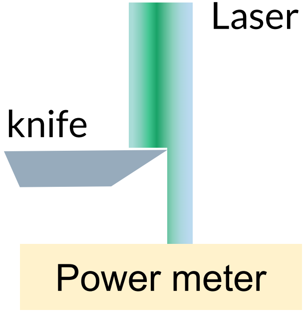
Transmission Factor Tests

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



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

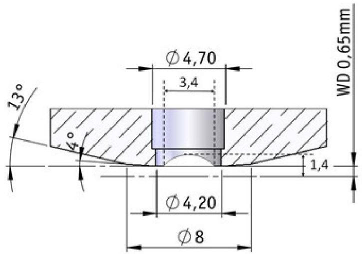
Laser beam size - Knife Edge technique

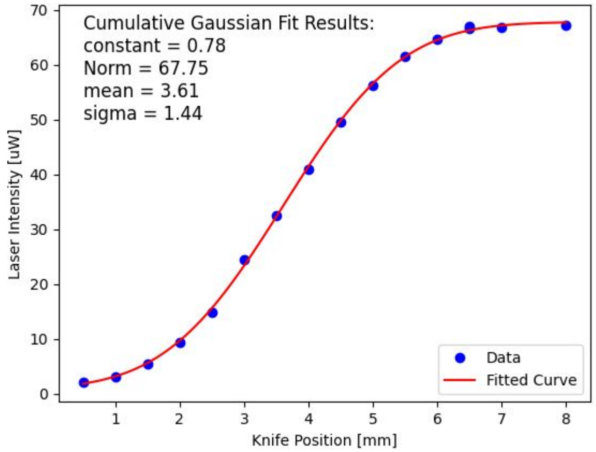


- Laser beam size is broadened by a laser beam expander in the black box. The size will be larger than the objective lens clear aperture, so laser will be blocked partially Currently the exapander is fixed and cannot be removed.

- 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%





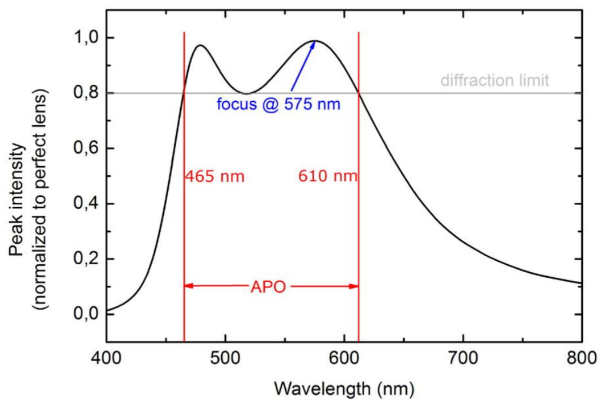
Transmission calibration

- $T_{black\ box}$ 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

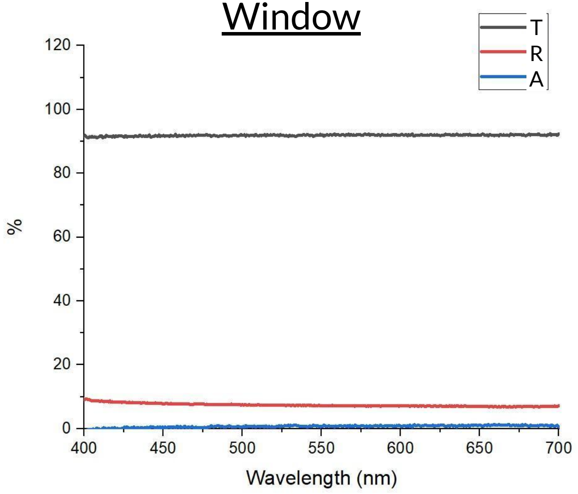
$T_{chamber + black\ box} = T_{black\ box} \times 2T_{window} \times T_{objective\ lens} \times A_{objective\ lens} \times A_{sample}$

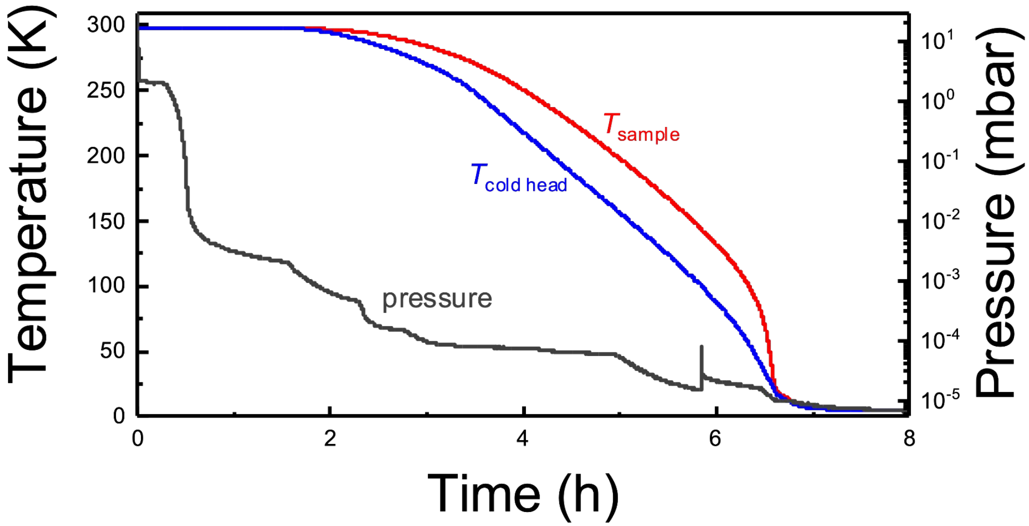
→ $T_{chamber + black\ box} = 46\%$

Objective lens

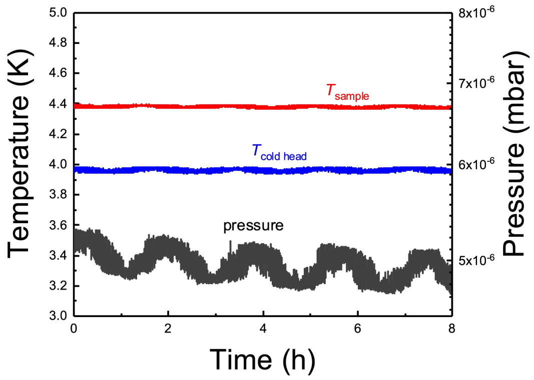


Window

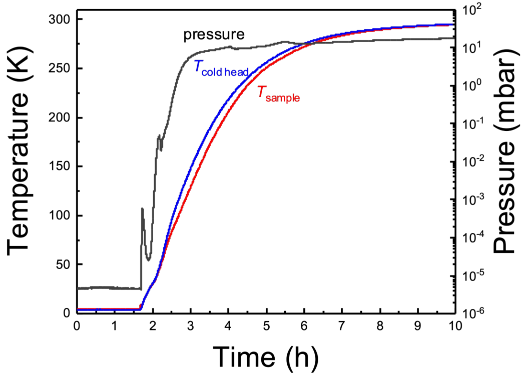




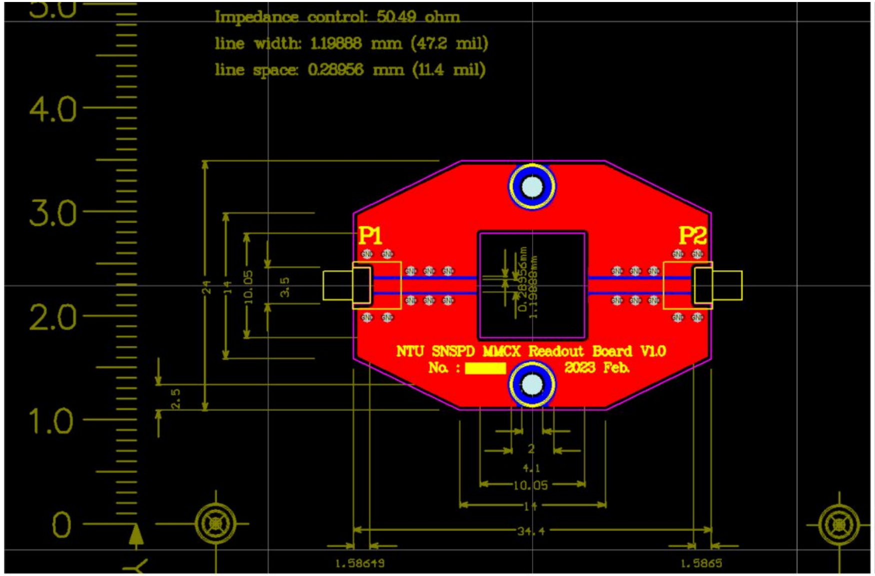
Temperature (K)
300
250
200
150
100
50
0
0
2
4
6
8
Time (h)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Pressure (mbar)
T_{sample}
$T_{cold\ head}$
pressure

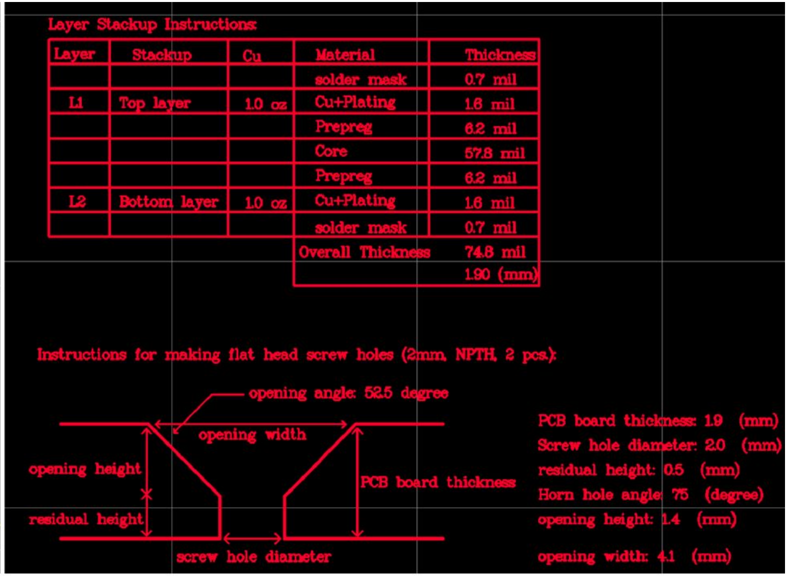


Temperature (K)
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
0
2
4
6
8
Time (h)
$8x10^{-6}$
$7x10^{-6}$
$6x10^{-6}$
$5x10^{-6}$
Pressure (mbar)
T_{sample}
$T_{cold\ head}$
pressure

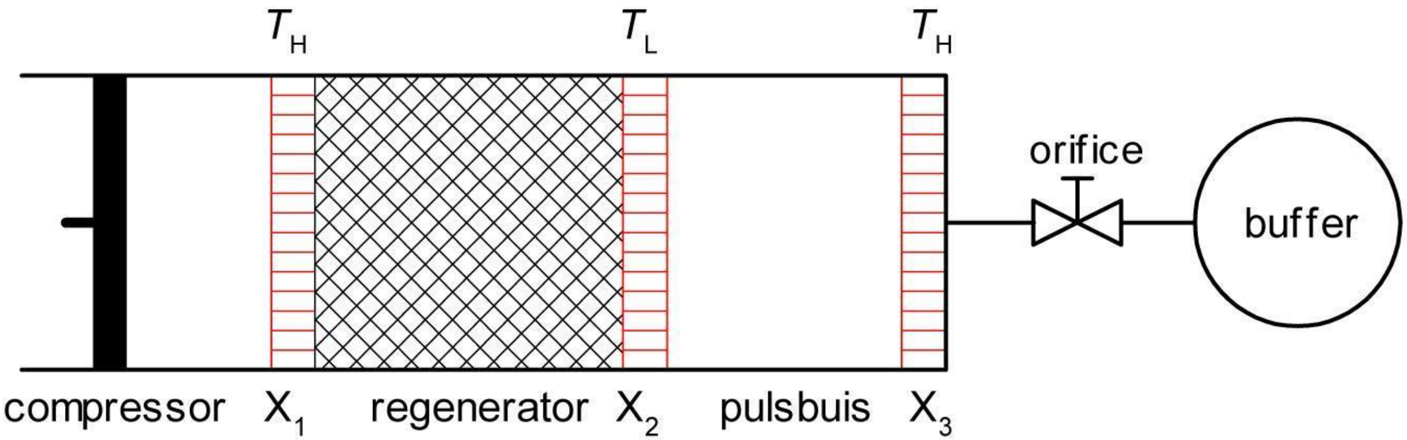


Temperature (K)
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
Time (h)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Pressure (mbar)
pressure
$T_{cold\ head}$
T_{sample}


Impedance control: 50.49 ohm
line width: 1.19888 mm (47.2 mil)
line space: 0.28956 mm (11.4 mil)
P1
P2
NTU SNSPD MMCX Readout Board V1.0
No. :
2023 Feb.
24
14
10.05
3.5
2.5
2
4.1
10.05
14
34.4
1.58649
1.5865
5.0
4.0
3.0
2.0
1.0
0


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.):
opening angle: 52.5 degree
opening width
opening height
residual height
PCB board thickness
screw hole diameter
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

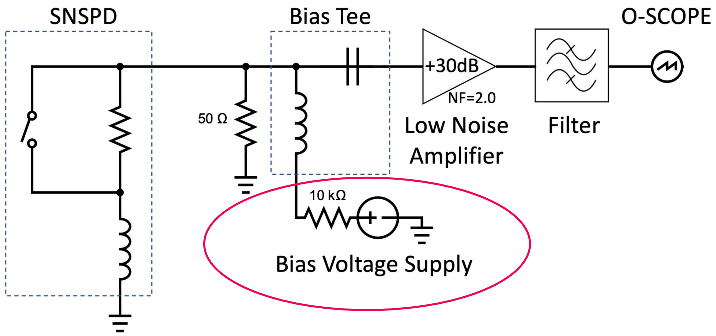
- Inductance is the tendency of an electrical conductor to oppose a change in the electric current flowing through it.
- Kinetic inductance originates from the inertial mass of mobile charge carriers
- Kinetic inductance is observed in high carrier mobility conductors (e.g. superconductors)

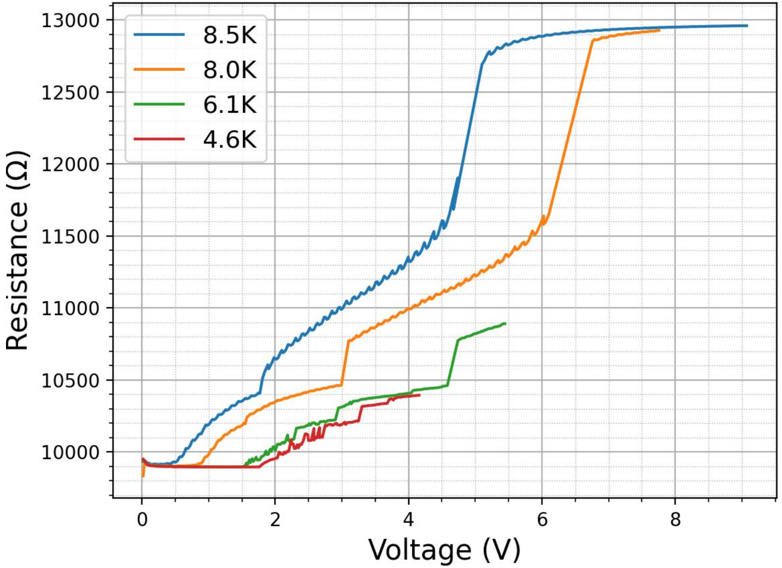
$$\frac{1}{2}(2m_e v^2)(n_s l A) = \frac{1}{2} L_K I^2$$

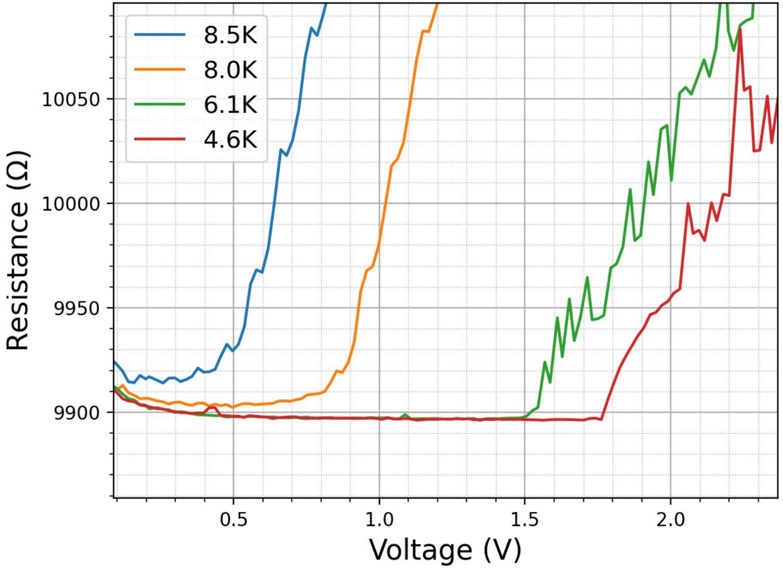
$$L_K = \left(\frac{m_e}{2n_s e^2}\right)\left(\frac{l}{A}\right)$$

VR Curve w/ 10kΩ

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

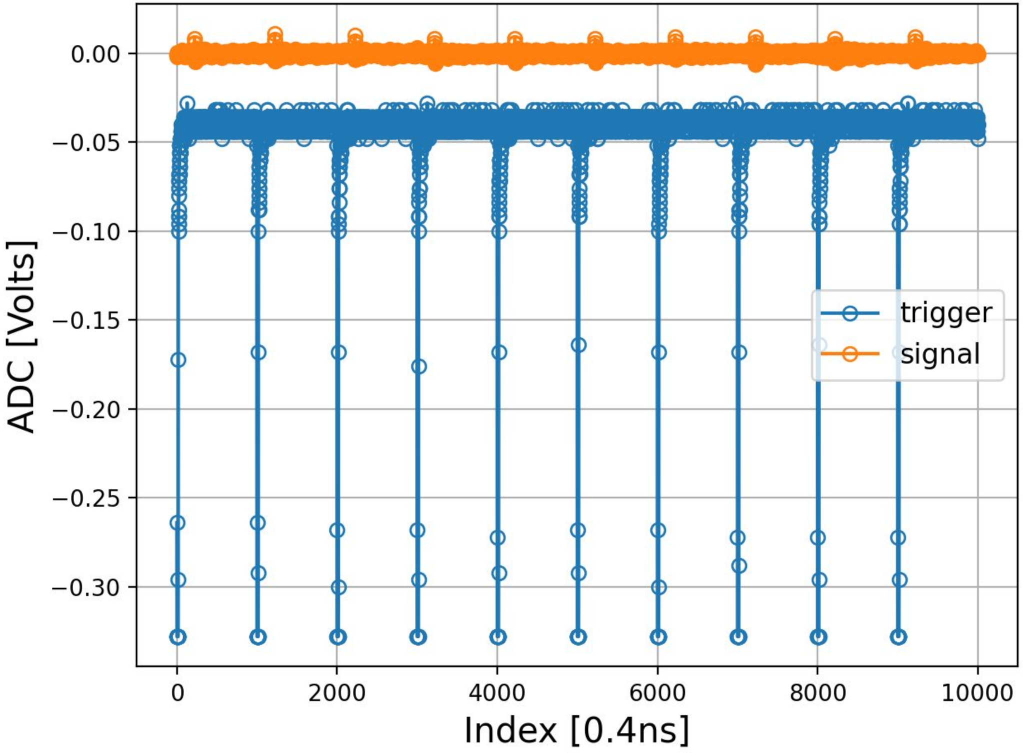






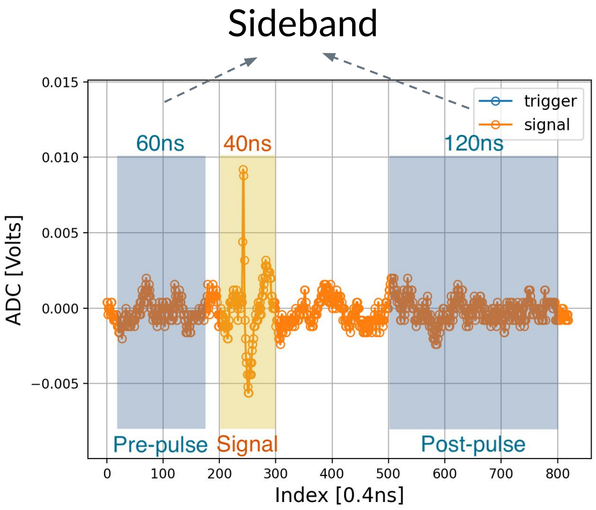
1 Oscillscope Event

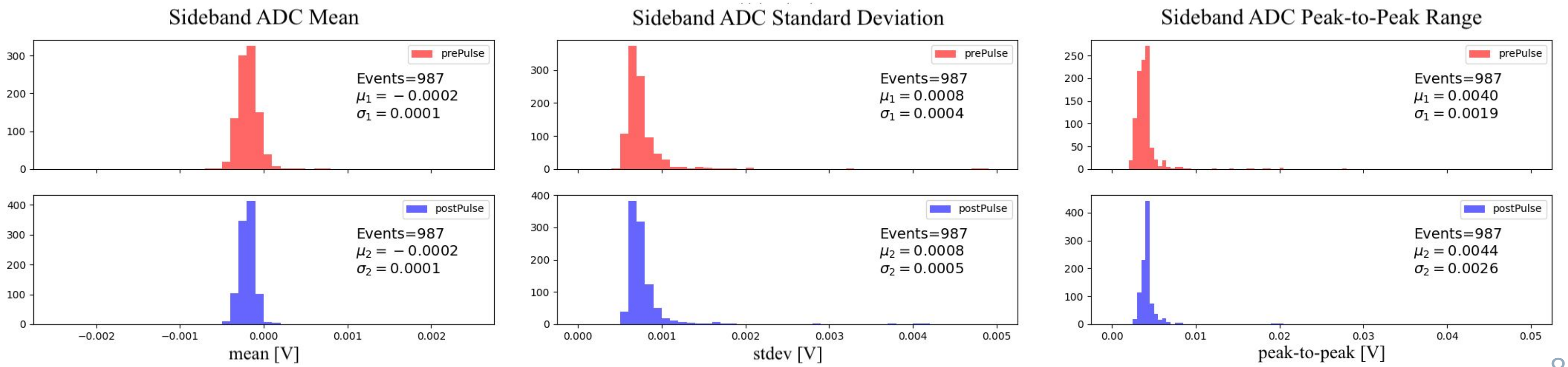
4μs Window → 10 Laser Triggers



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

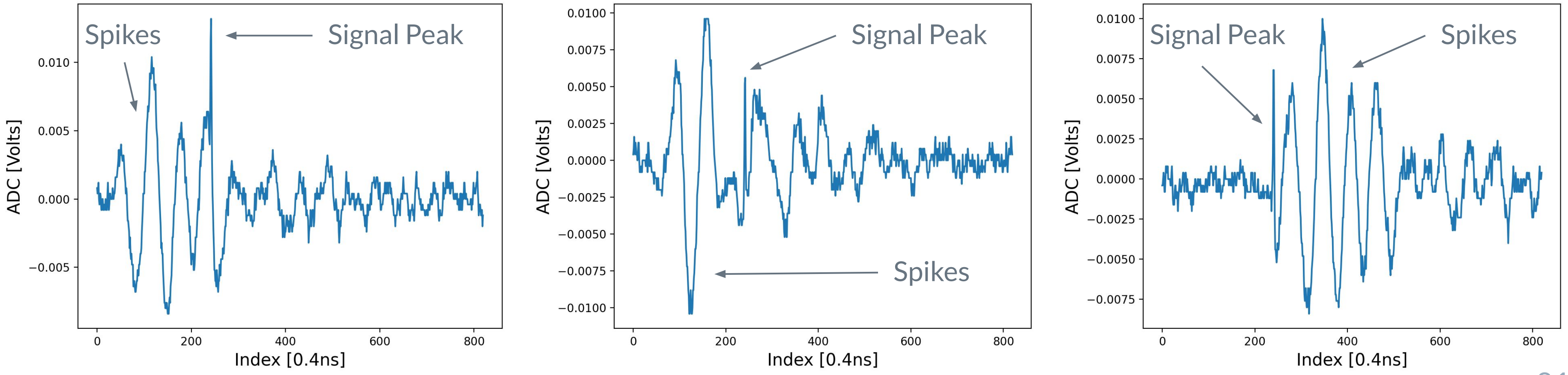


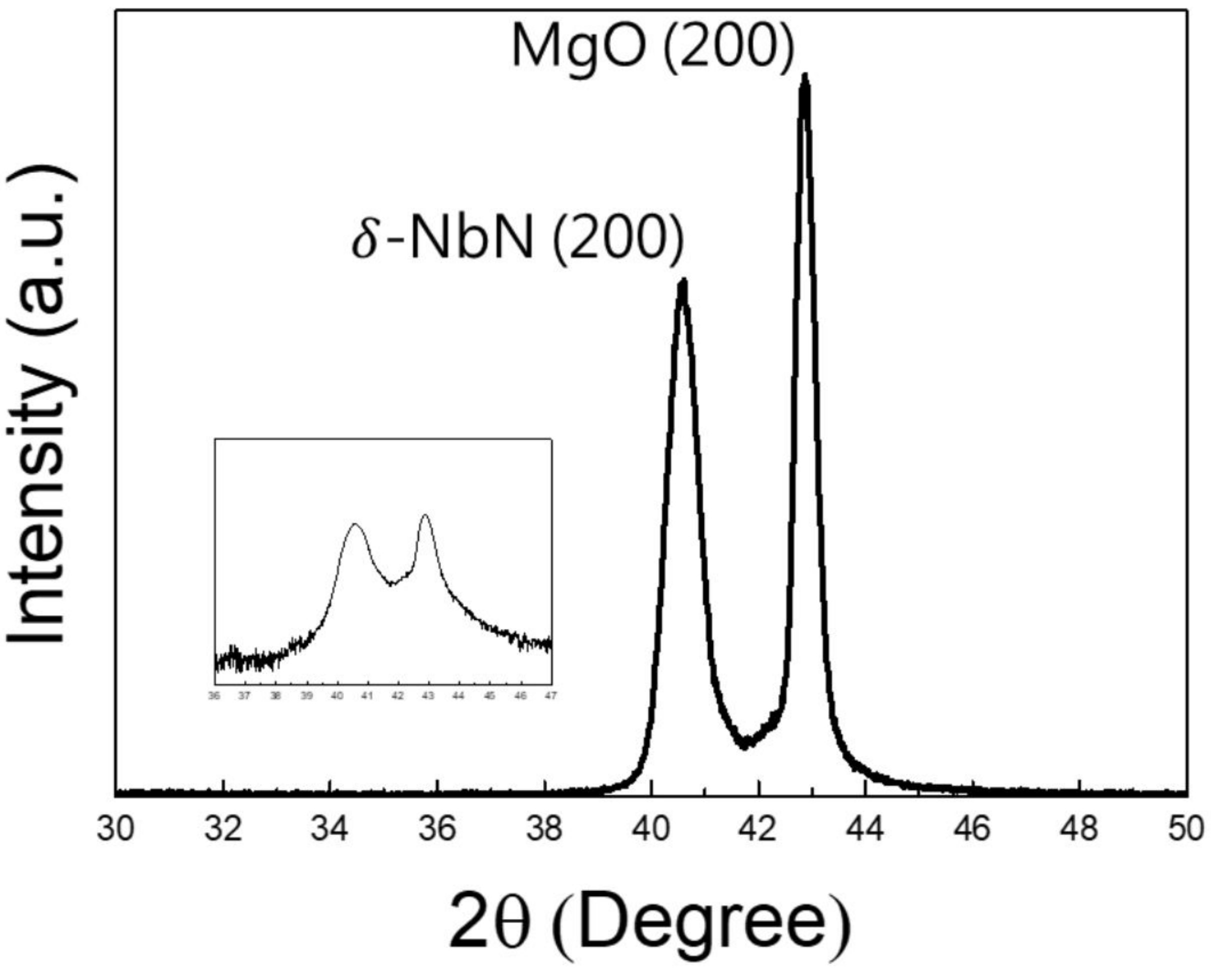


Event Pre-Selection

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

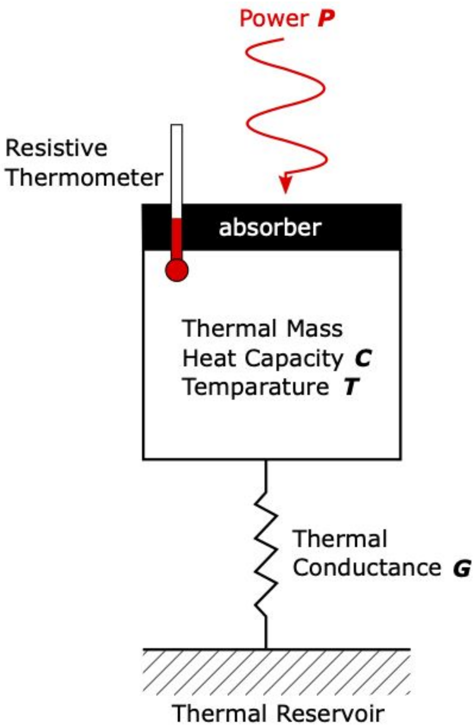
<u>Remove laser events with large noise/spikes</u>



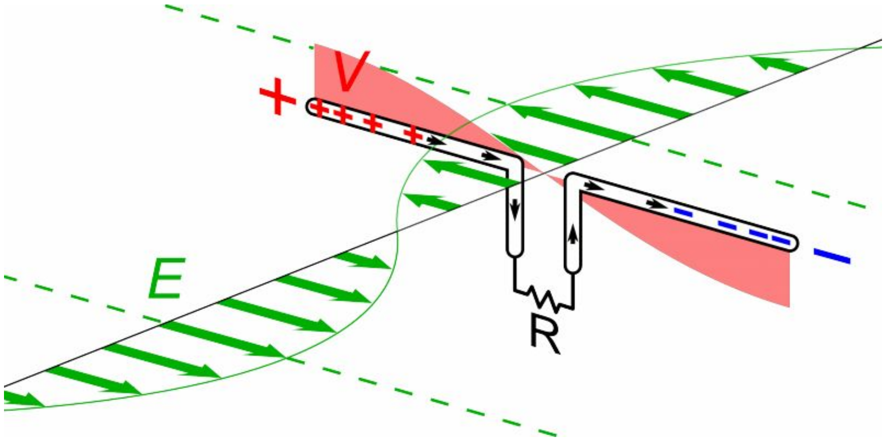

MgO (200)
δ-NbN (200)
Intensity (a.u.)
2θ (Degree)
30
32
34
36
38
40
42
44
46
48
50

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

Comparing SC Single Photon Detectors @1550nm

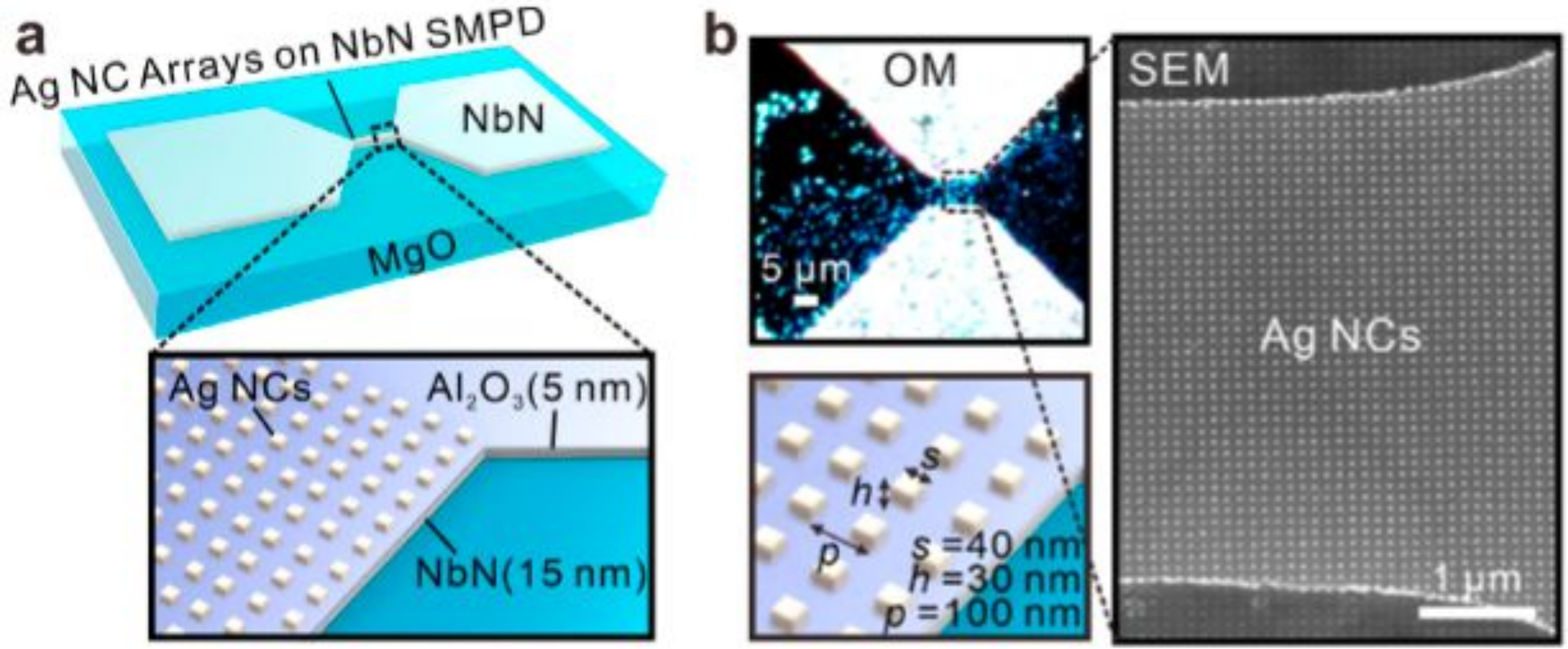
Journal of Lightwave Technology 40, 7578–7597 (2022).

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

Gap-plasmon Superconducting “Microwire” Single Photon Detector

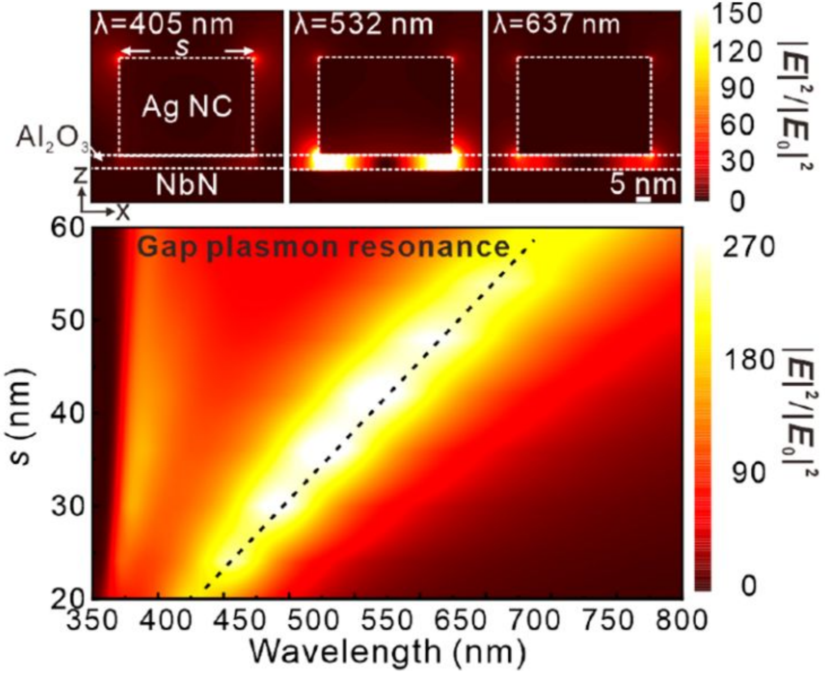
Gap-Plasmon-Enhanced SC Microwires



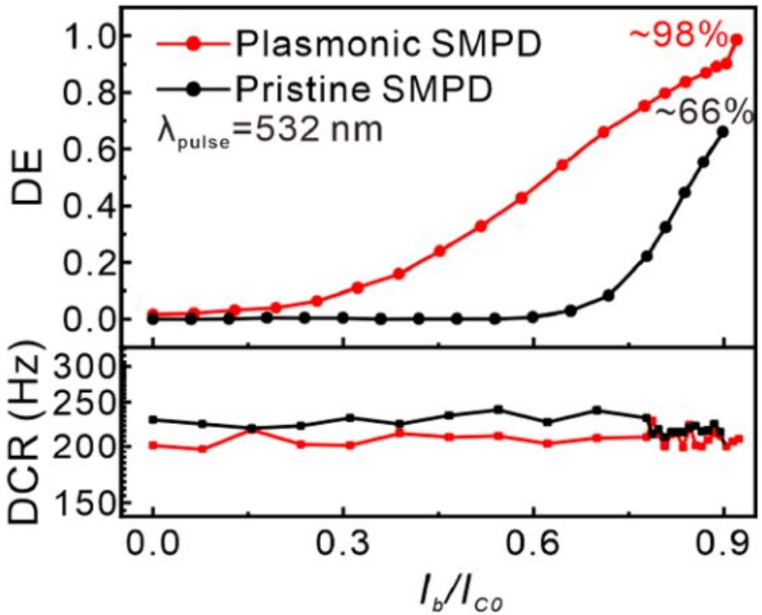
Yang, J.-W. et al. Nanoscale Gap-Plasmon-Enhanced Superconducting Photon Detectors at Single-Photon Level. Nano Lett. (2023).

Results

FDTD Simulation



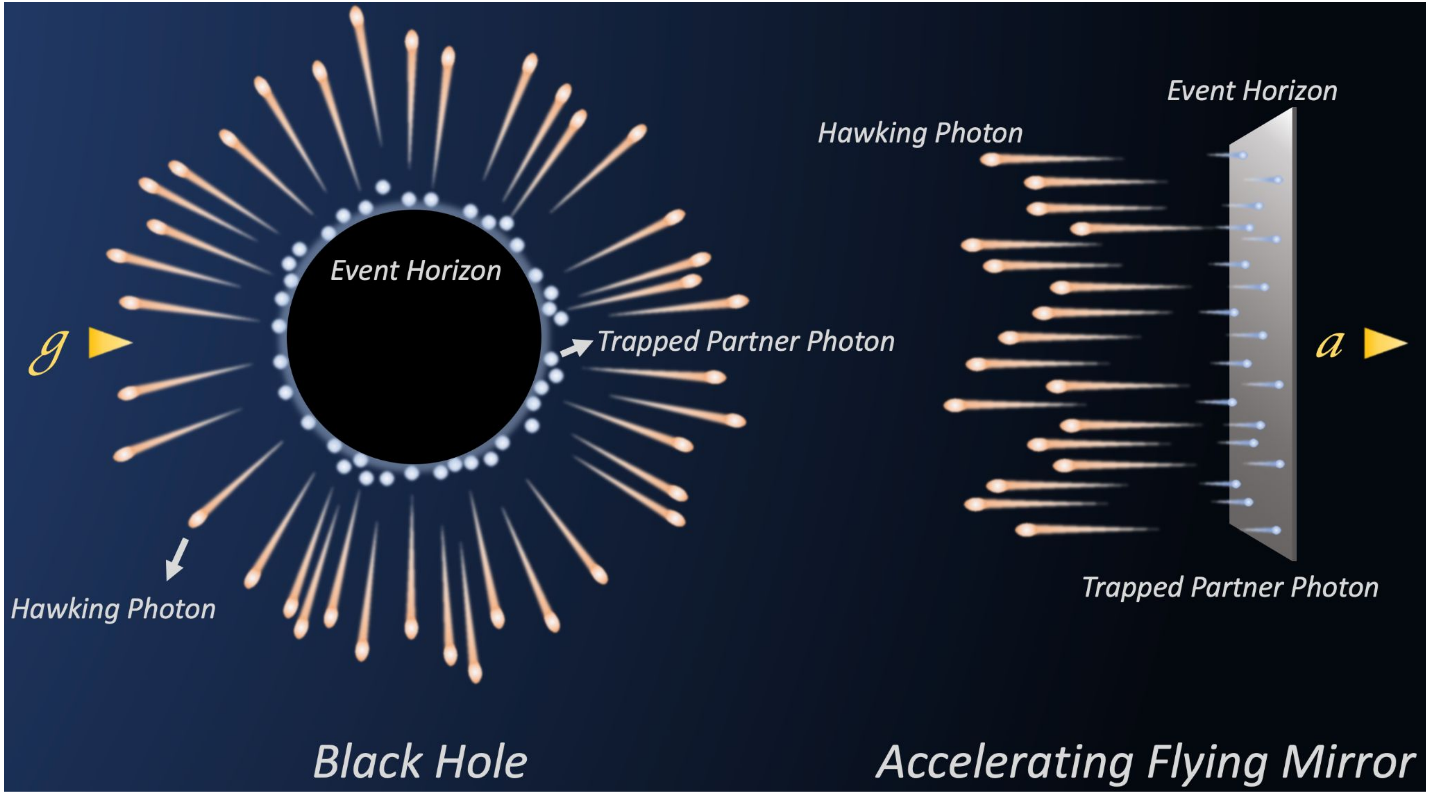
Detection efficiency



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

Analog Black Hole

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



Equivalence Principle