Building Quantum Eyes: Dual-Mode Calorimetric SNSPD & Cryogenic Quantum Platforms at NTU

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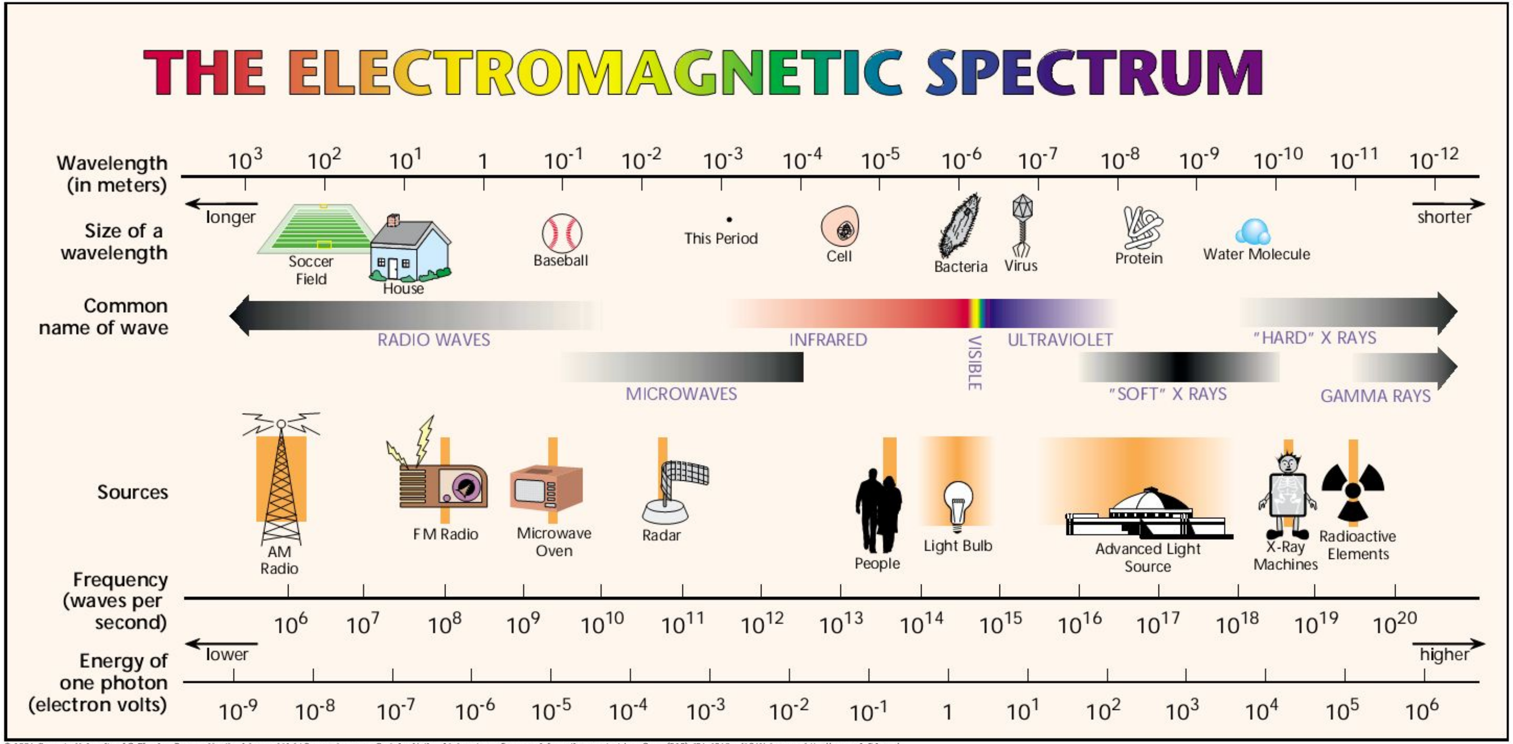
On behalf of the IQSens team

National Taiwan University

PPP16 Workshop

15 Jun, 2026

Photon detection



New quantum sensors

Typical HEP detectors

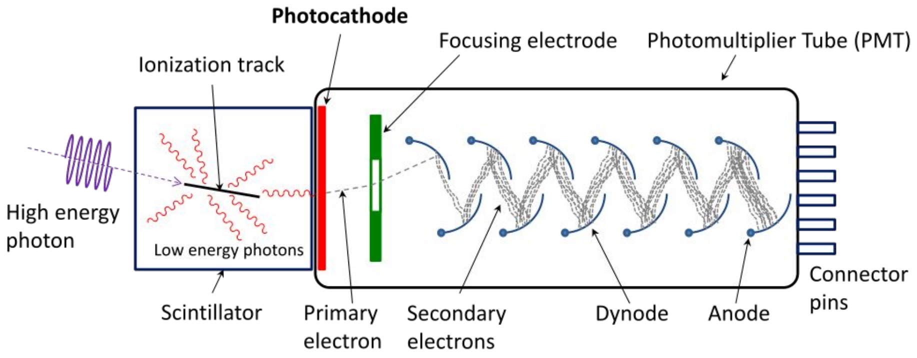
Rich spectrum of detectors for HEP

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

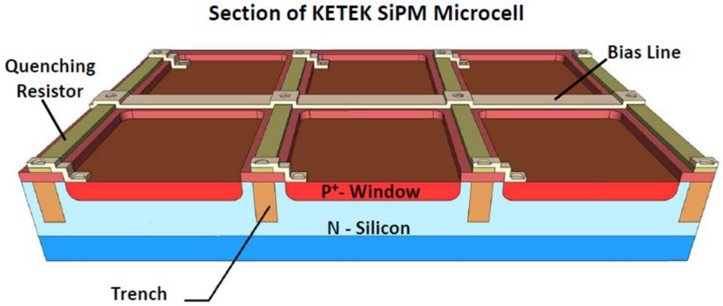
Semiconductor Single Photon Detectors

Photomultiplier Tubes (PMT)

Wikimedia Commons

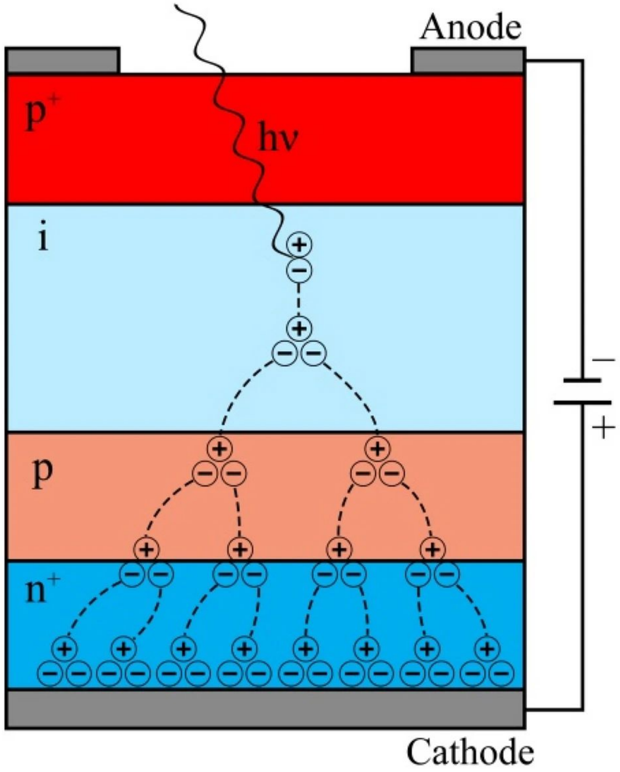


Silicon Photomultiplier (SiPM)



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

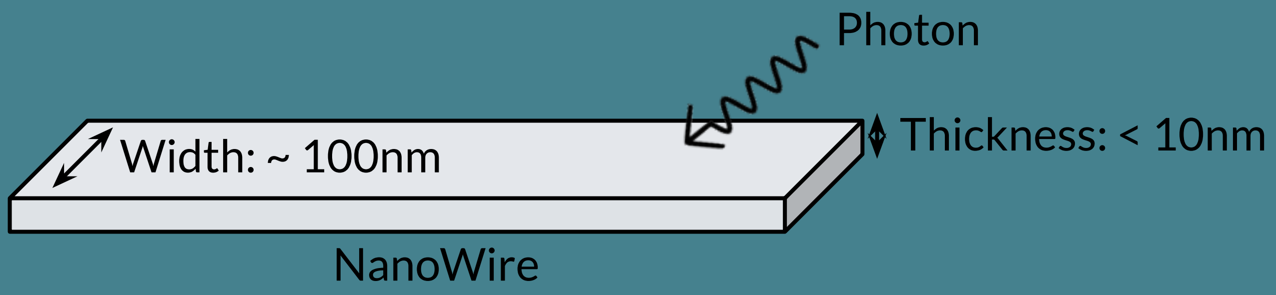
- Si: ~1.1eV (~1.1μm)
- Ge: ~0.7eV (~1.7μm)

Blocked impurity band solid-state photomultipliers.

- Large Dark Current

APPEC Communications

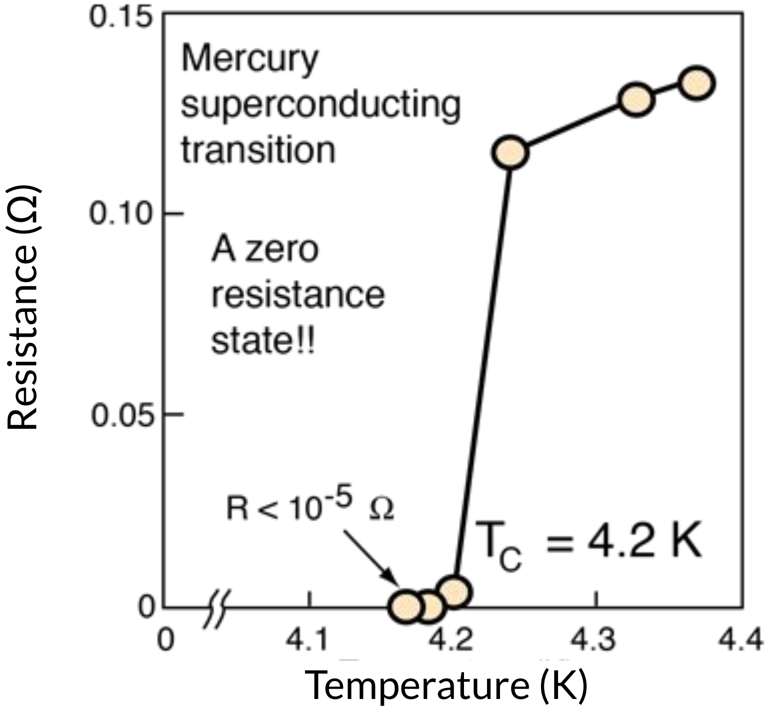
Izhnin, I.I., et al. Appl Nanosci 12, 253–263 (2022).



Superconductivity Nanowire Single Photon Detector (SNSPD)

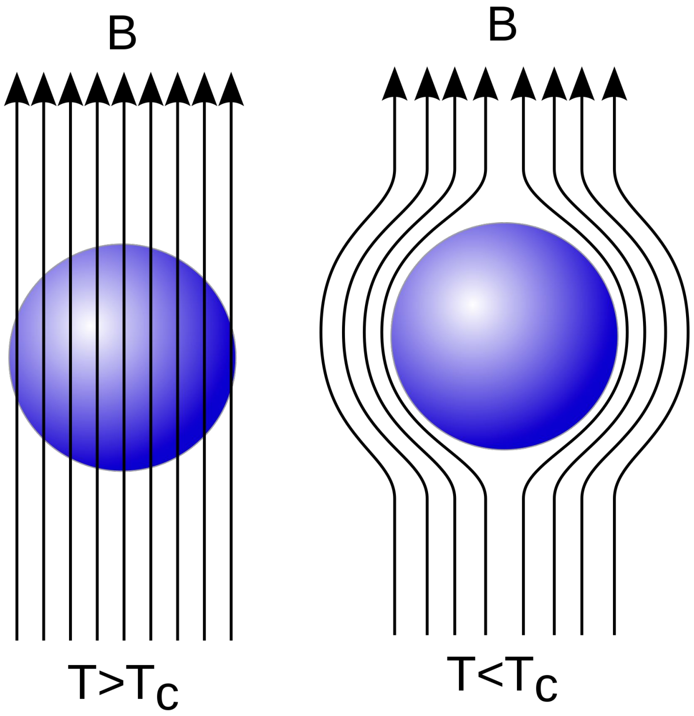
Superconductivity

Zero Resistance



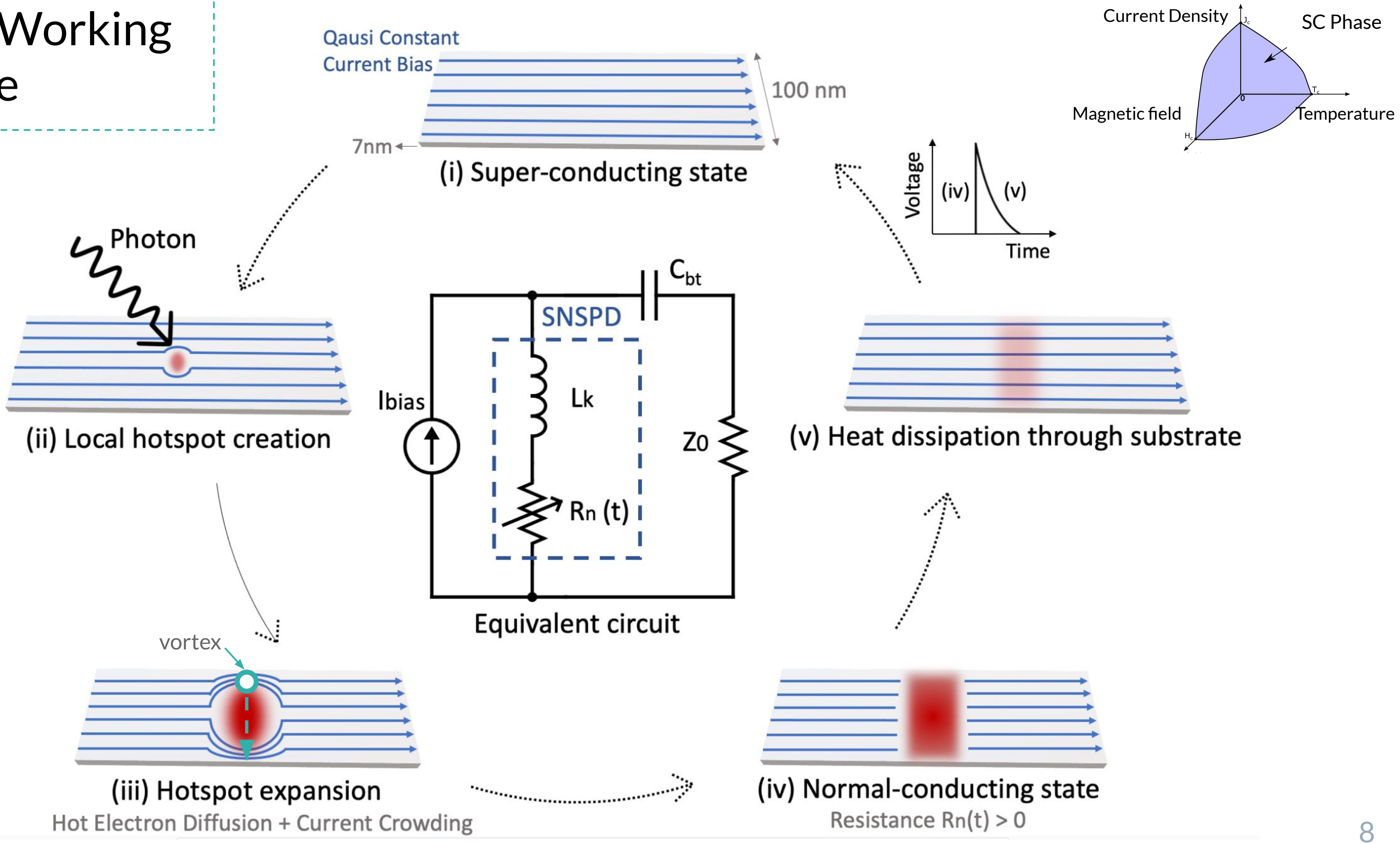
H. K. Onnes, Commun. Phys. Lab.12,120, (1911)

Meissner Effect
Perfect diamagnetic
(Superdiamagnetic)



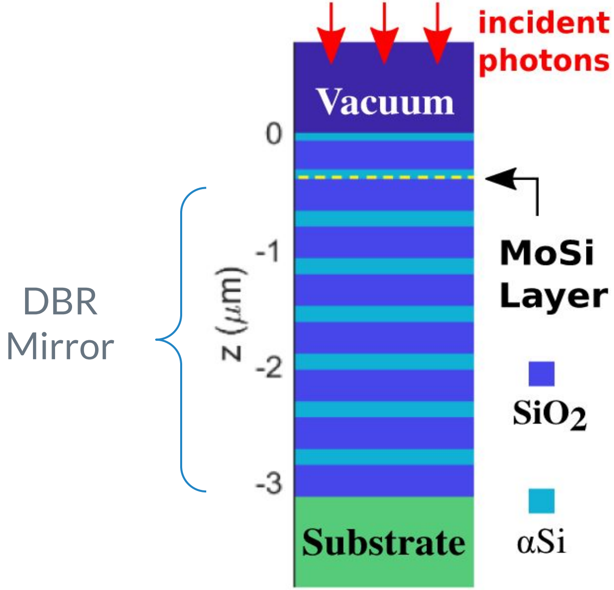
Wikimedia Commons

SNSPD Working Principle



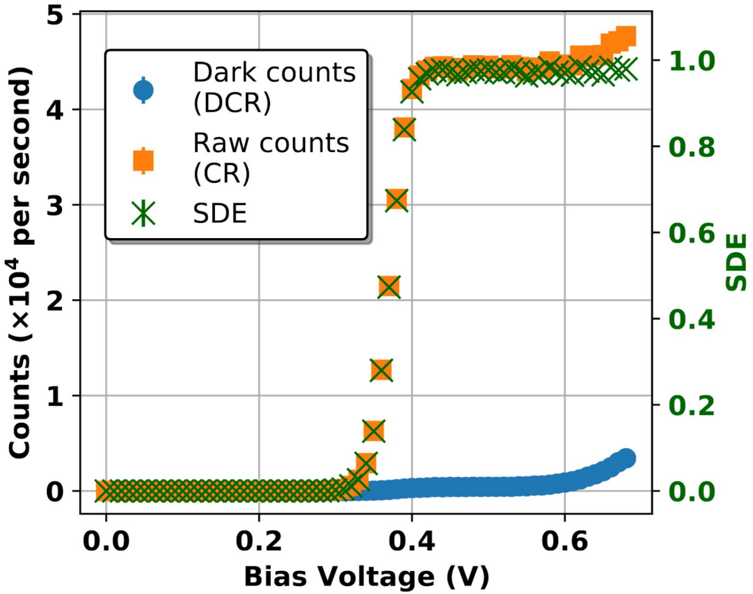
State-of-the-art SNSPDs @ 1550nm

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



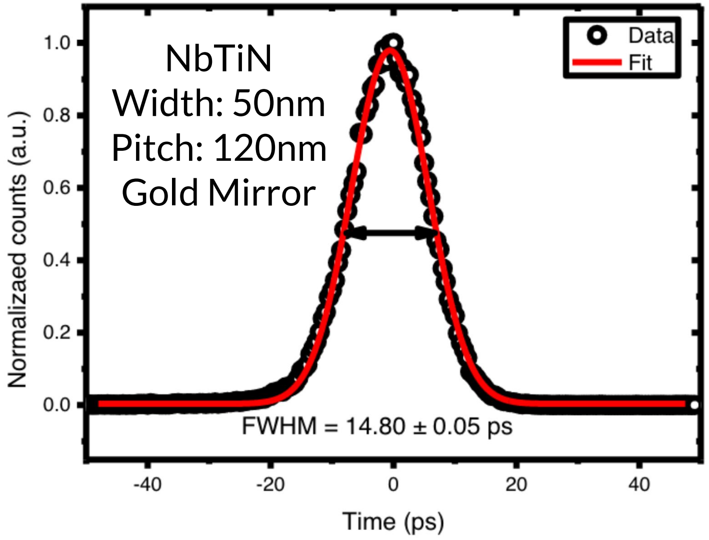
MoSi (Tc~5K)
Width: 80nm, Pitch: 140nm
Distributed Bragg Reflector Mirror
Measure Temperature ~750mK

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



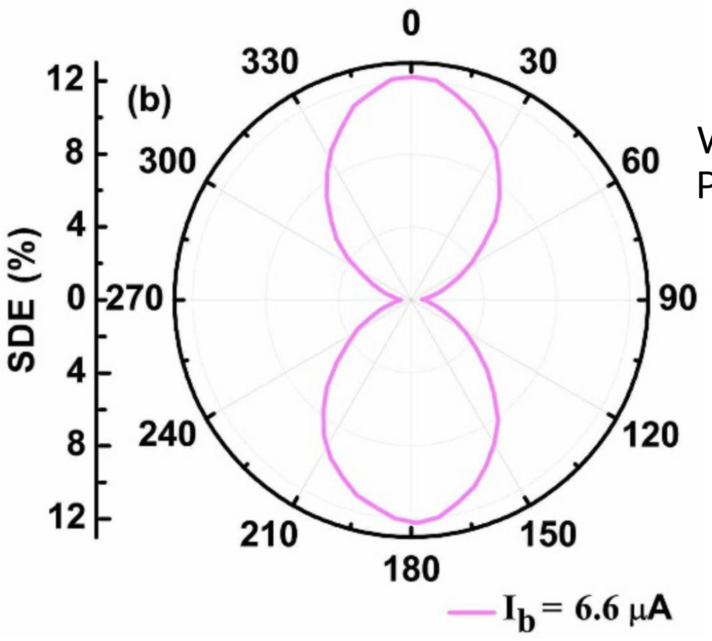
State-of-the-art SNSPDs @ 1550nm

Time Jitter < 15ps



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).

R&D Goal

State-of-the-art SNSPD

Near-IR (0.8μm-2μm)

- ~100% efficiency @ 1550nm
- Low timing jitter (<15ps)
- Low Dark Count (<0.01Hz)
- Fast recovery (MHz rate)
- Multi Pixelated array

R&D Goal

Extend to Mid-IR (2μm-20μm)

- Energy resolving power
- Broadband spectrometry
- Polarization distinguishability

R&D Goal → Applications

State-of-the-art SNSPD

Near-IR (0.8μm-2μm)

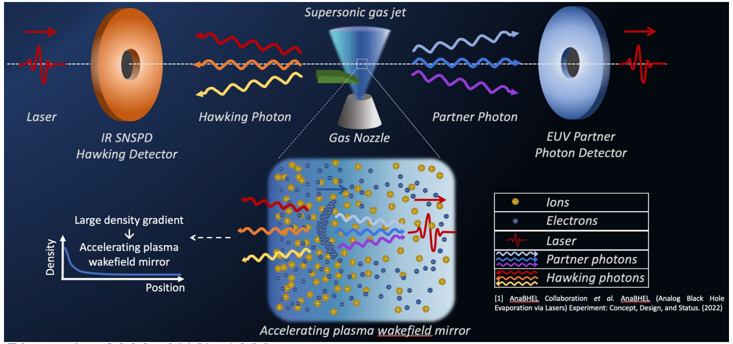
- ~100% efficiency @ 1550nm
- Low timing jitter (<15ps)
- Low Dark Count (<0.01Hz)
- Fast recovery (MHz rate)
- Multi Pixelated array

R&D Goal

Extend to Mid-IR (2μm-20μm)

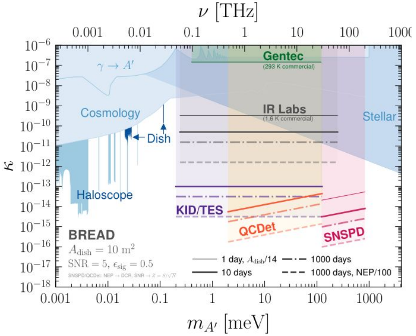
- Energy resolving power
- Broadband spectrometry
- Polarization distinguishability

Hawking radiation experiment



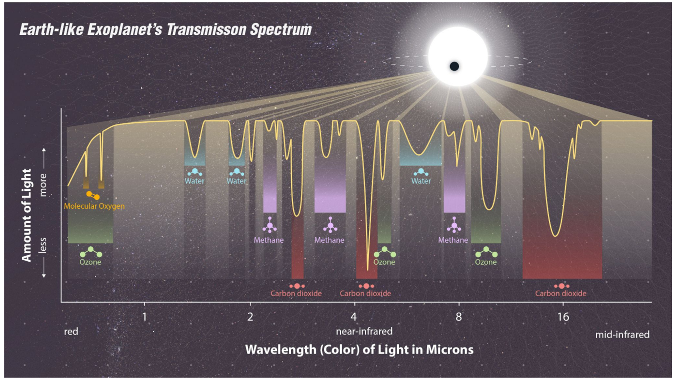
Photonics **2022**, *9*(12), 1003

Dark Matter/ Exotic Searches



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

Exoplanet Search

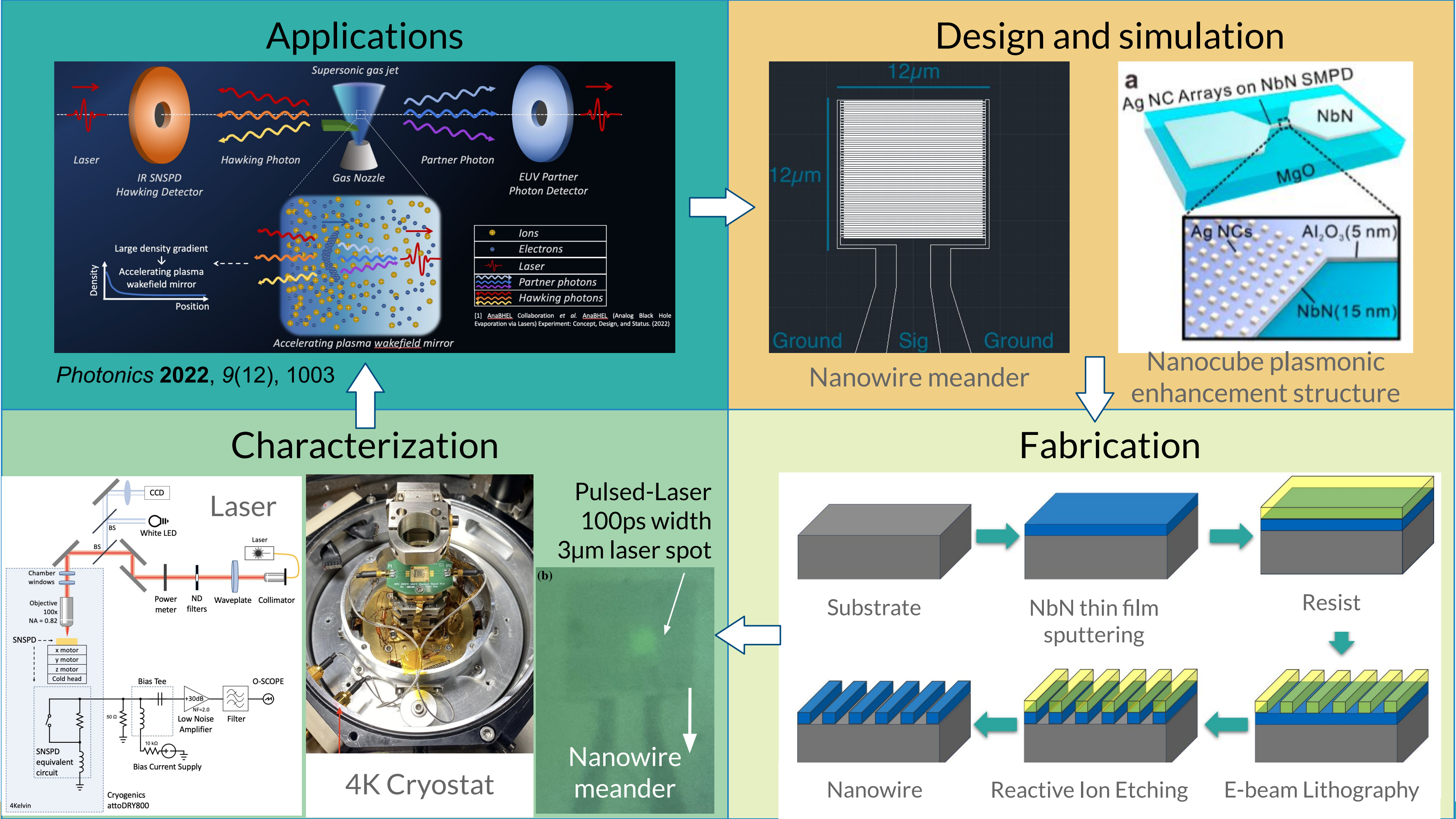


Credit: NASA, ESA, CSA, STScI, Joseph Olmsted (STScI)

CERN DRD5/RDq

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)				

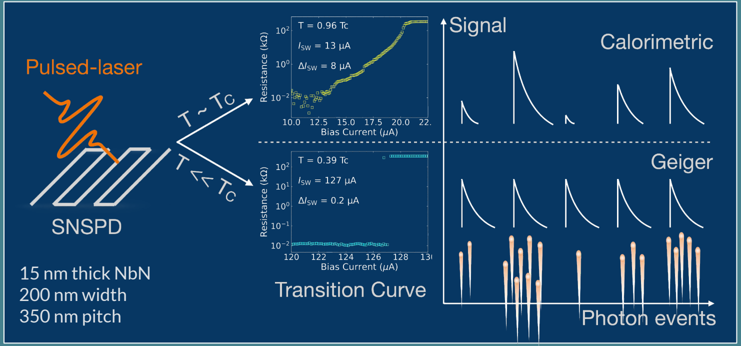
CERN-DRDC-2024-010, Michael Doser



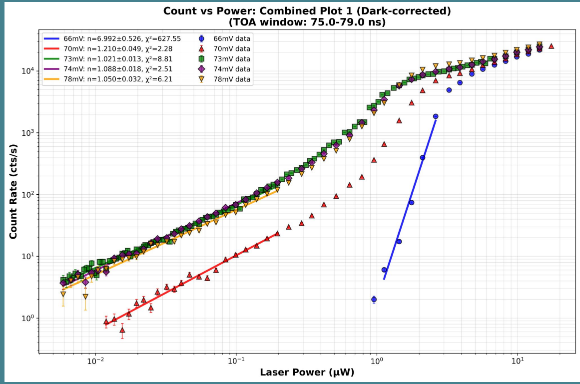
Applications
Supersonic gas jet
Laser
IR SNSPD
Hawking Detector
Hawking Photon
Gas Nozzle
Partner Photon
EUV Partner
Photon Detector
Large density gradient
Accelerating plasma
wakefield mirror
Density
Position
Ions
Electrons
Laser
Partner photons
Hawking photons
[1] AnaBHEL Collaboration et al. AnaBHEL (Analog Black Hole Evaporation via Lasers) Experiment: Concept, Design, and Status. (2022)
Accelerating plasma wakefield mirror
Photonics 2022, 9(12), 1003
Design and simulation
12μm
12μm
Ground
Sig
Ground
Nanowire meander
a
Ag NC Arrays on NbN SMPD
NbN
MgO
Ag NCs
Al2O3(5 nm)
NbN(15 nm)
Nanocube plasmonic
enhancement structure
Characterization
CCD
Laser
BS
White LED
BS
Laser
Chamber
windows
Objective
100x
NA = 0.82
SNSPD
x motor
y motor
z motor
Cold head
Power
meter
ND
filters
Waveplate
Collimator
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
4K Cryostat
Pulsed-Laser
100ps width
3μm laser spot
(b)
Nanowire
meander
Fabrication
Substrate
NbN thin film
sputtering
Resist
Nanowire
Reactive Ion Etching
E-beam Lithography

Highlights of our current results

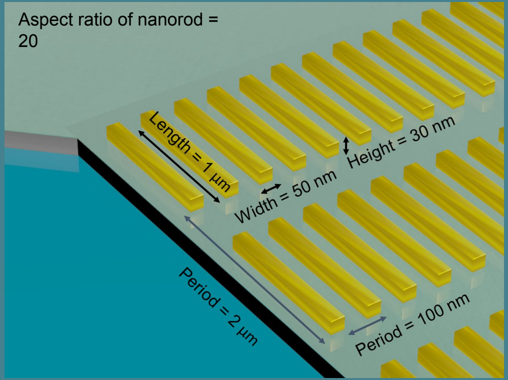
Dual Mode Calorimetric SNSPD



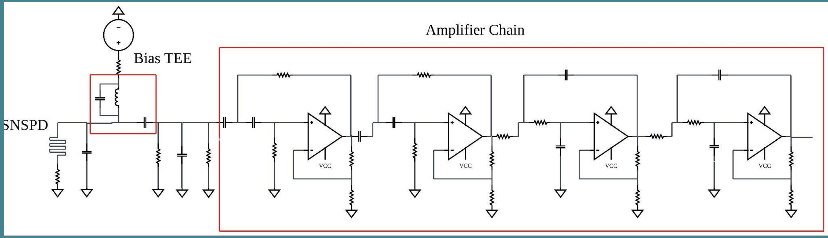
Single photon sensitivity demonstration



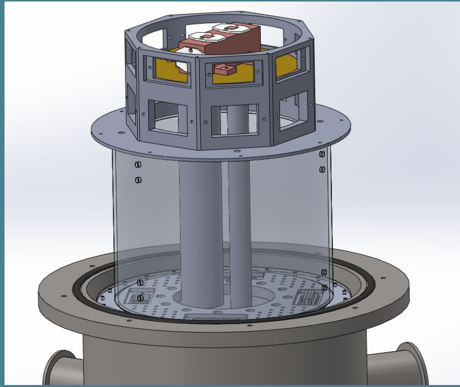
Plasmonic SMSPD



LTSPICE simulation

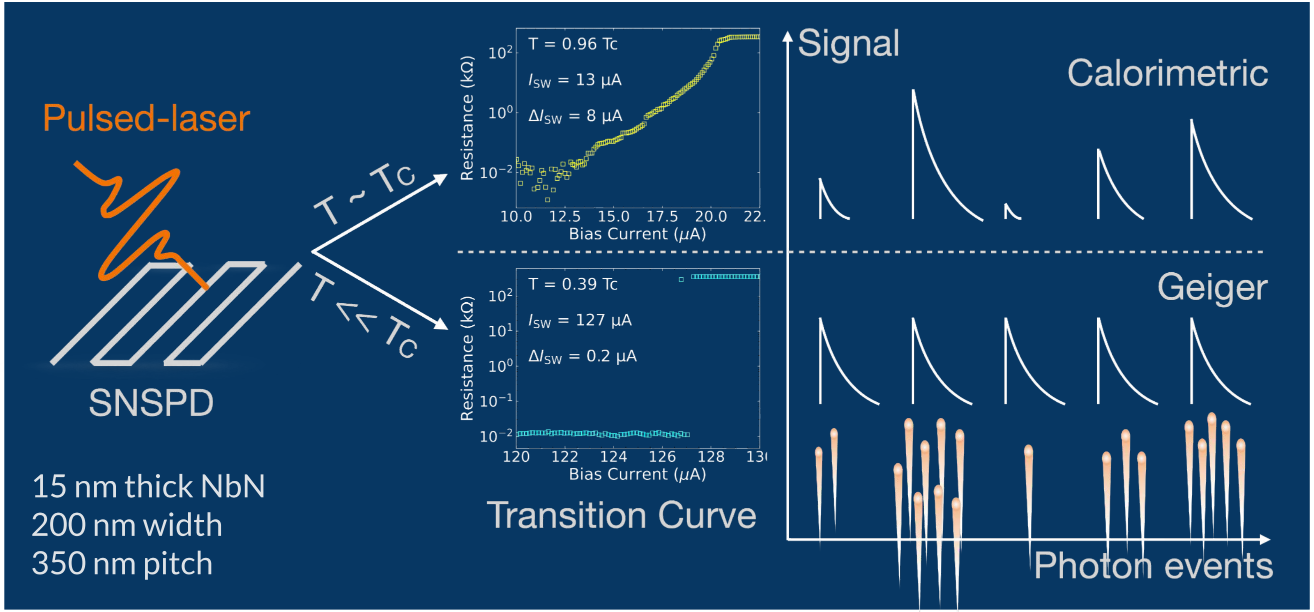


New Cryostat



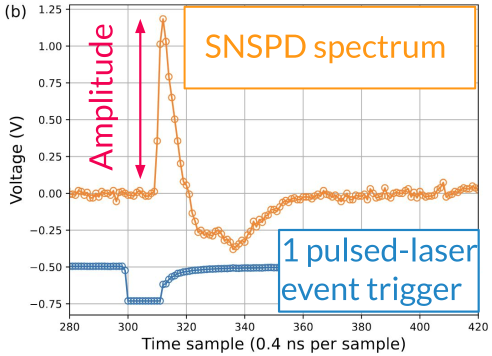
Dual-operation mode SNSPD

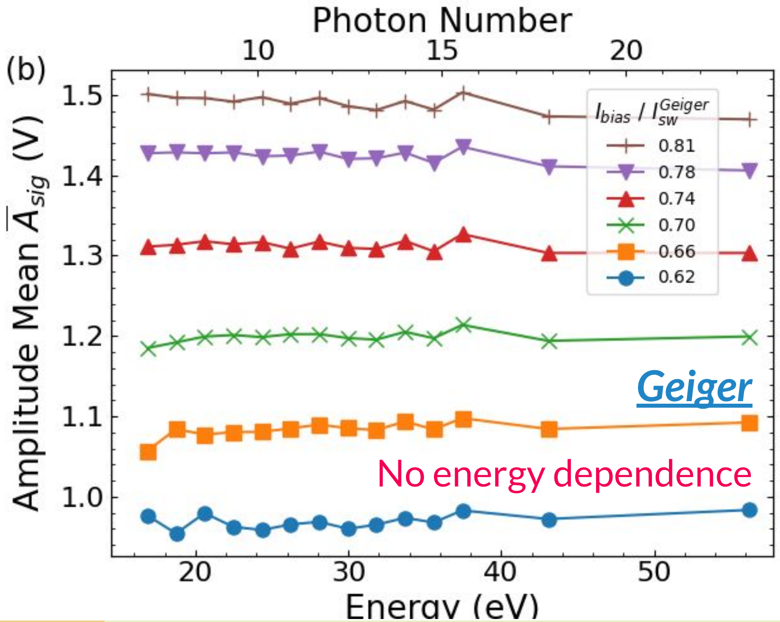
- Paper published at [APL Quantum 2, 026118 (2025)]
  - Switch between conventional event counting and energy measurement by adjustment of operating temperature and bias current
  - Geiger mode @ 4.7 K (0.39 Tc) ↔ Calorimetric mode @ 11.5 K (0.96 Tc)

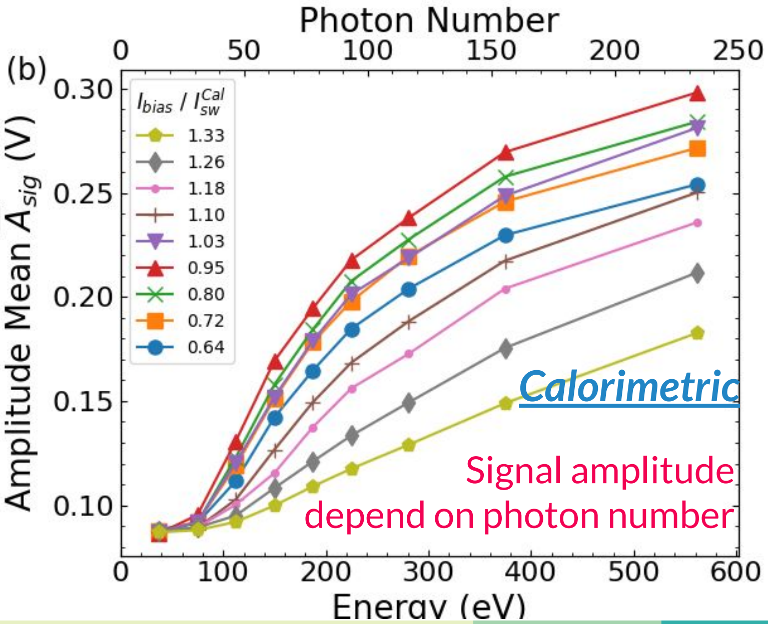


Results Highlight

- Geiger ↔ Calorimetric
  - Vortex-crossing-induced full transition ↔ Joule heating partial transition
  - No energy dependence in signal amplitude ↔ depend on N(absorbed photon)
  - Fast event counting ↔ Potential fast photon number resolving spectroscopy

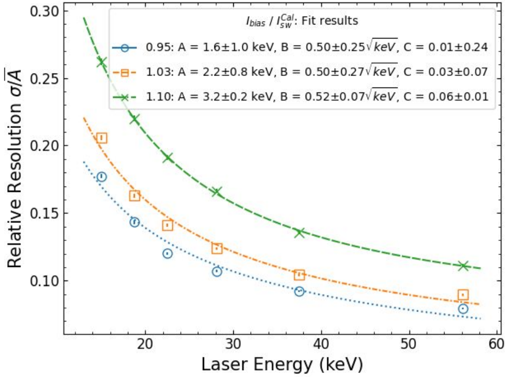


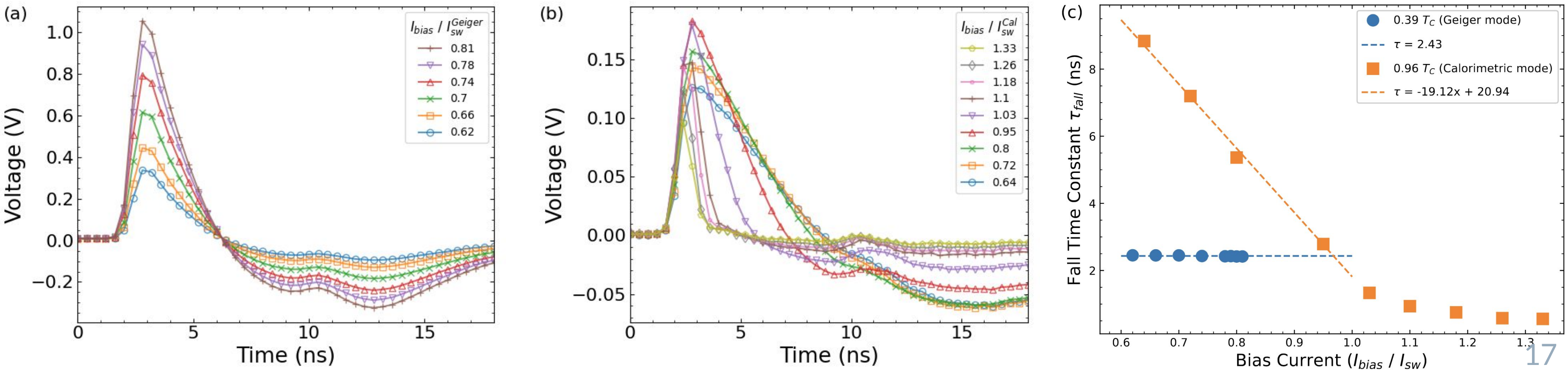




Features of Calorimetric SNSPD

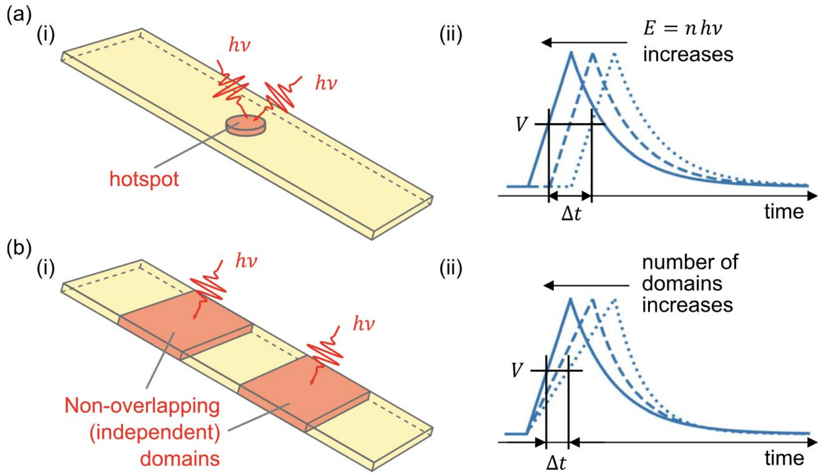
- Timing
  - Falling time constant depends on bias current
  - Reaches 560 ps falling time constant, faster than Geiger mode (2.2ns)
- Stable operation
  - No Dark count (Geiger mode around 1Hz)
  - No latching effect (Geiger mode latches at around $0.81I_C$)
- Energy resolution around 6% constant term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



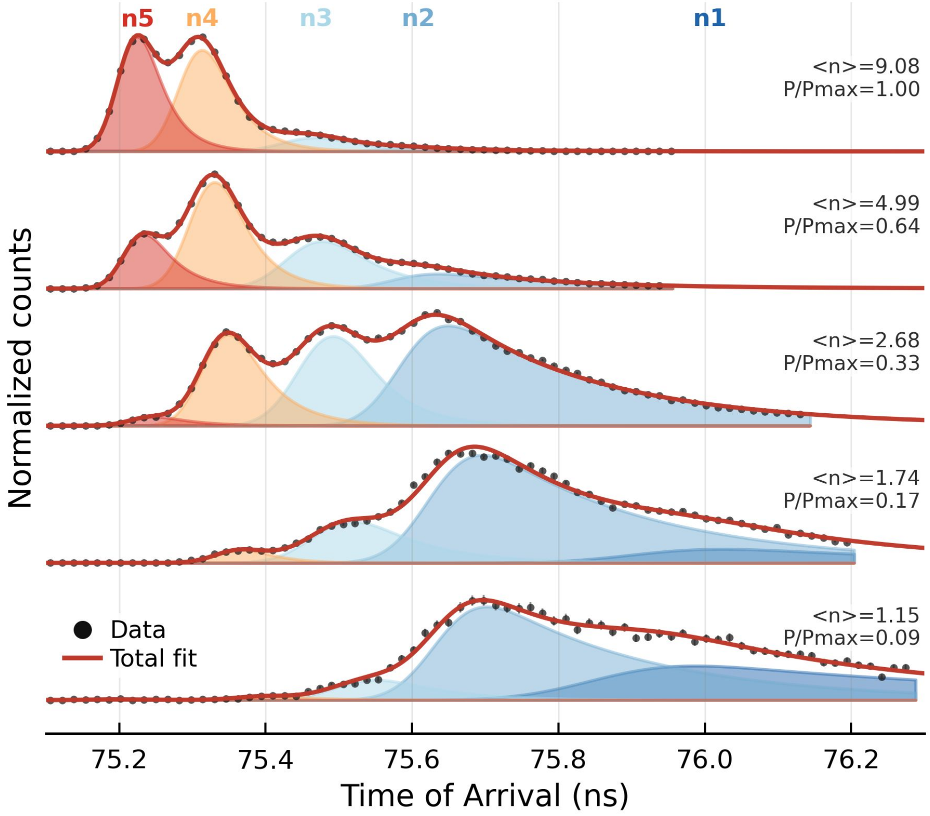


Photon number resolution with TOA

- Time of Arrival (TOA)
- PNR capability demonstration
  - Agree with poisson statistics
- Potential revealing position information or vortex mechanism



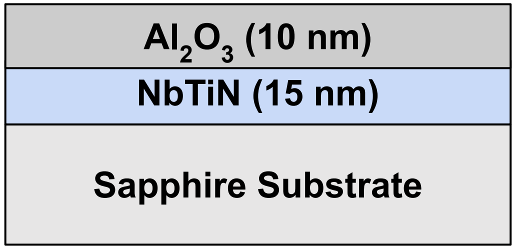
Sidorova, M. et al. APL Photonics 10, (2025).



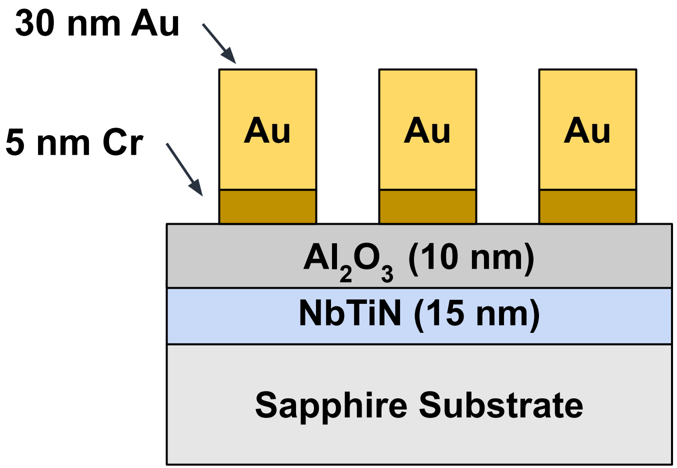
Plasmonic nanocube structure

Shu-Xiao Liu

Pristine SMSPD

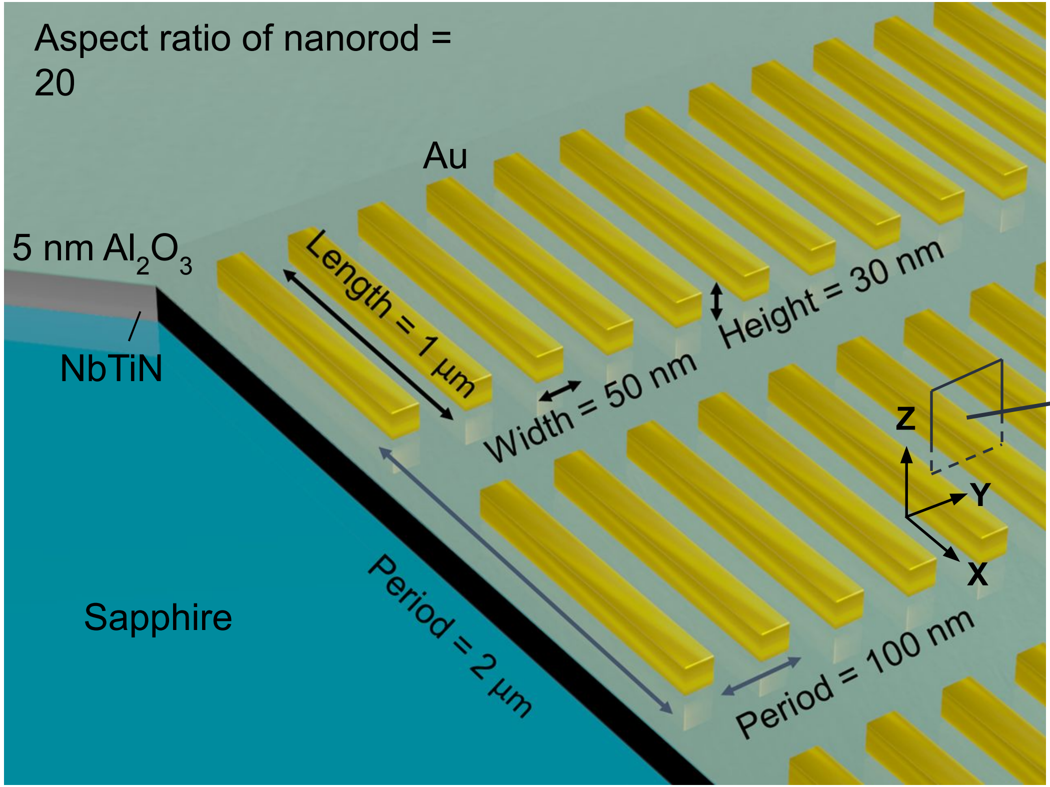


Plasmonic SMSPD

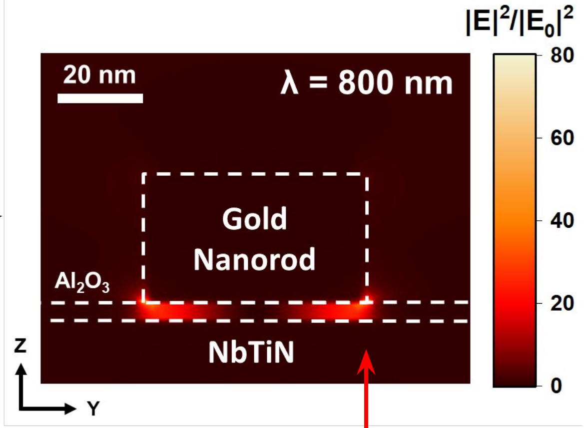


Gold nanostructure on NbTiN SMSPD

Shu-Xiao Liu



Finite-Difference Time-Domain (FDTD) Simulation



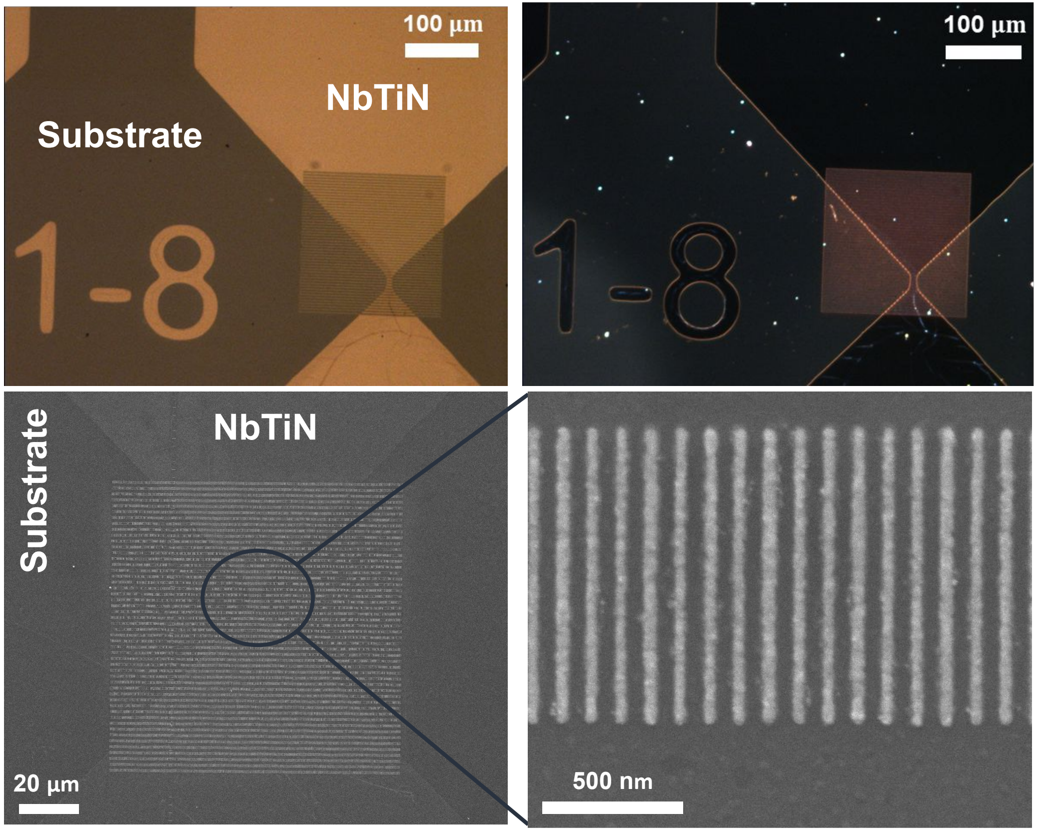
Gap-plasmon resonance

Shu-Xiao Liu

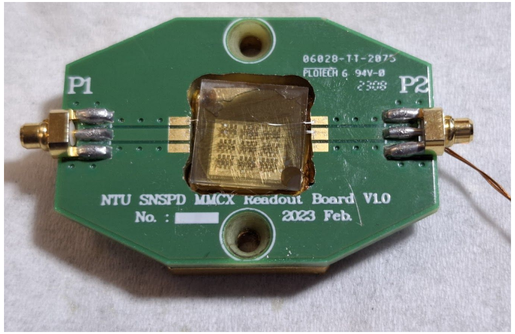
Plasmonic nanostructure fabrication

OM Images

SEM Images



SMSPD on PCB Stage



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

What can we do with such detector?

Particle Physics

Cosmology

Wide variety of applications

Astroparticle physics

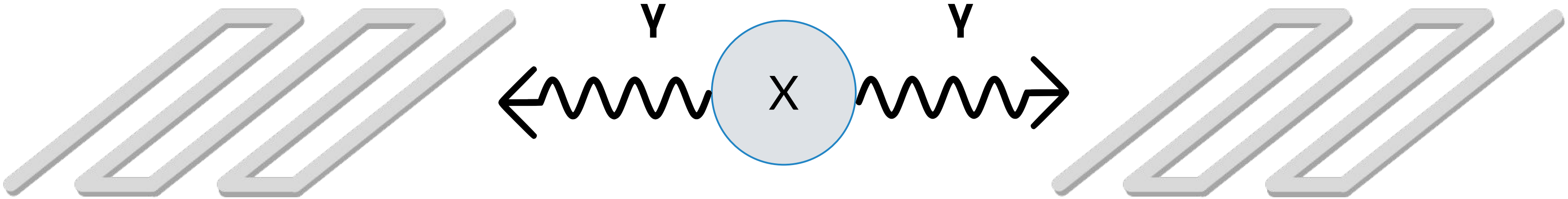
Quantum communication/information

Ultra-Fast Calorimetry/Spectroscopy

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

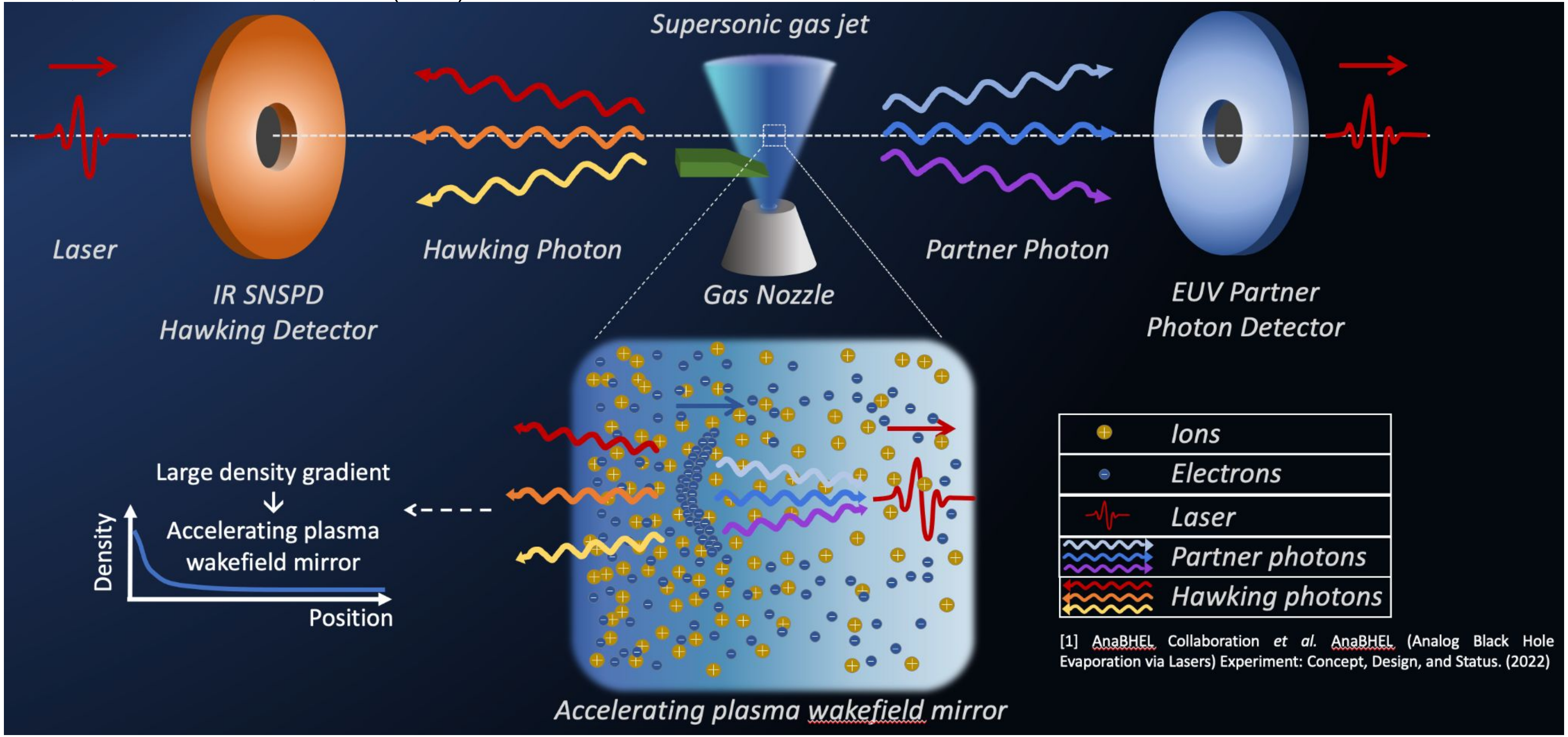
- Trigger-type experiments
  - Fast pulsed-laser

- 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).

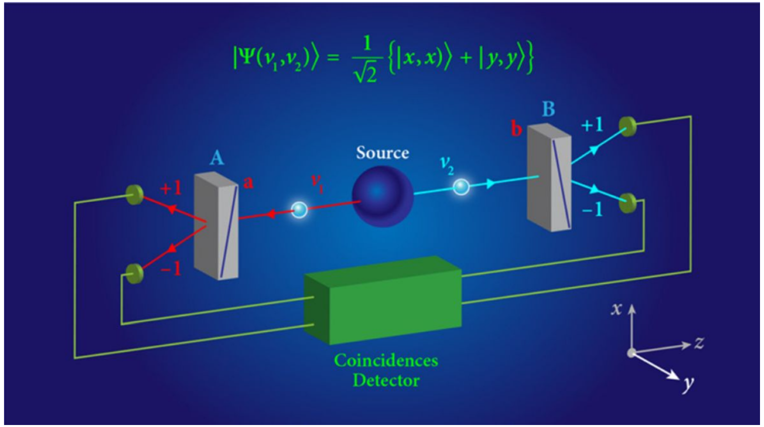


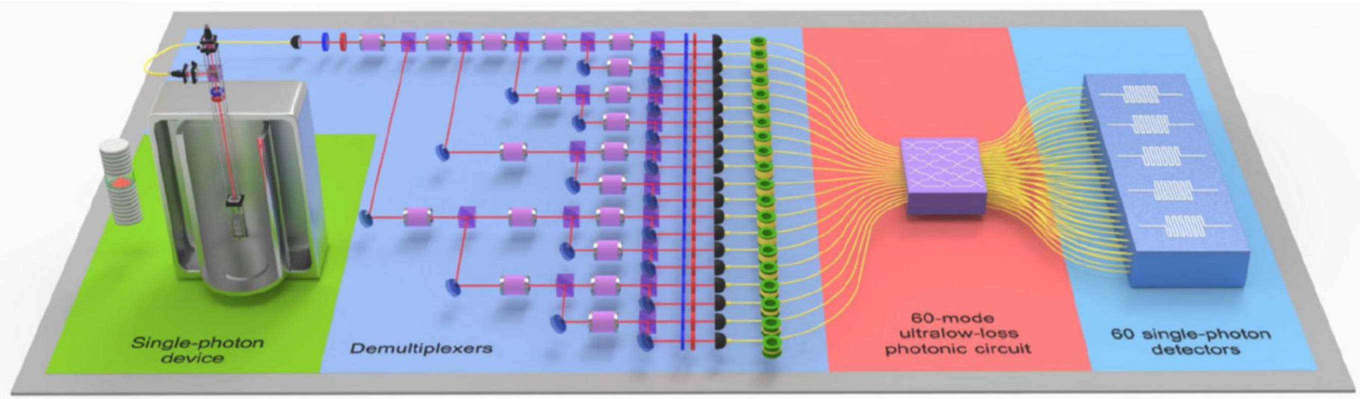
Requirements:

- 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).

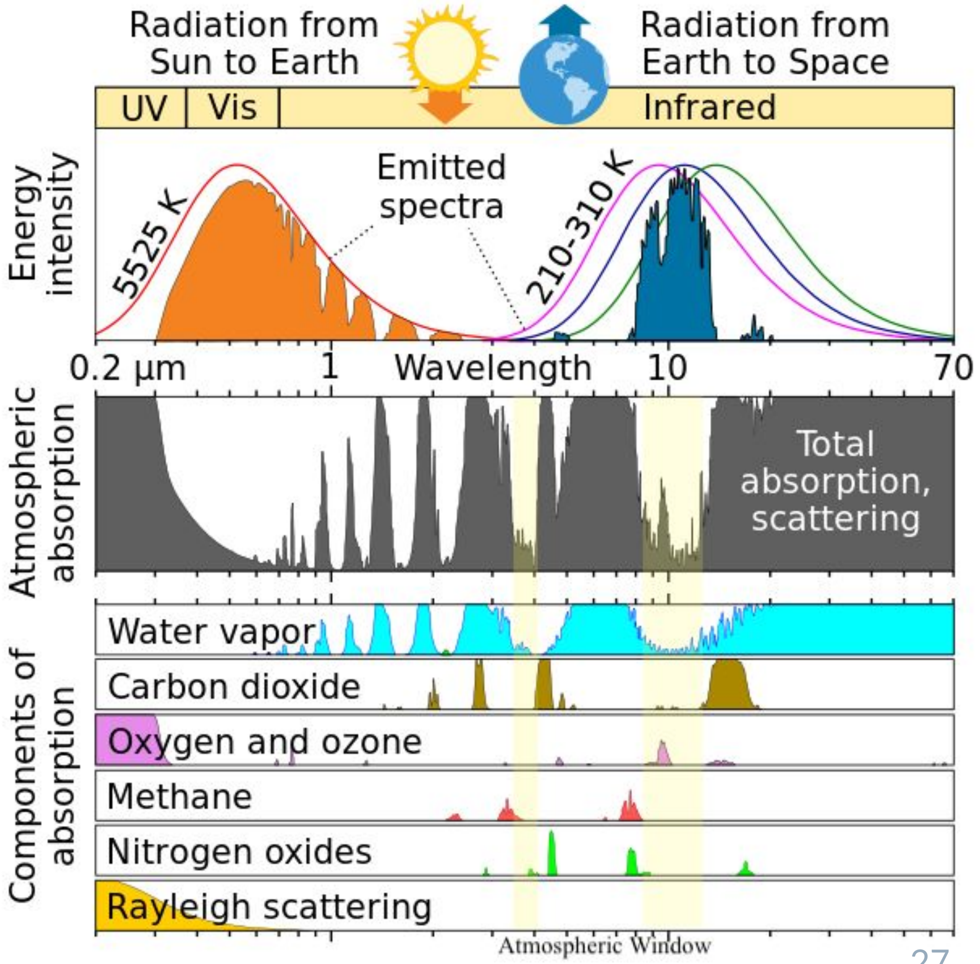




Atmospheric Window

- 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

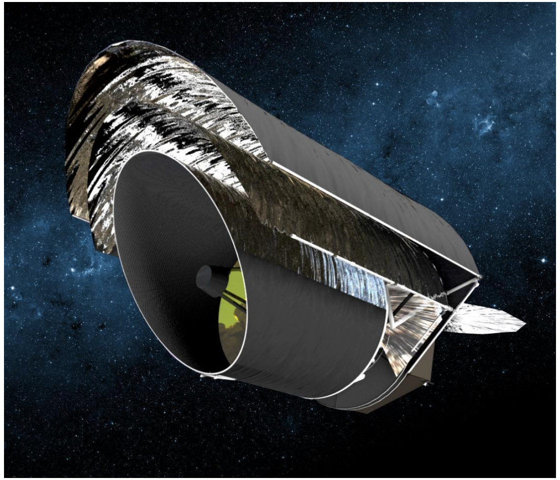


Exoplanet search

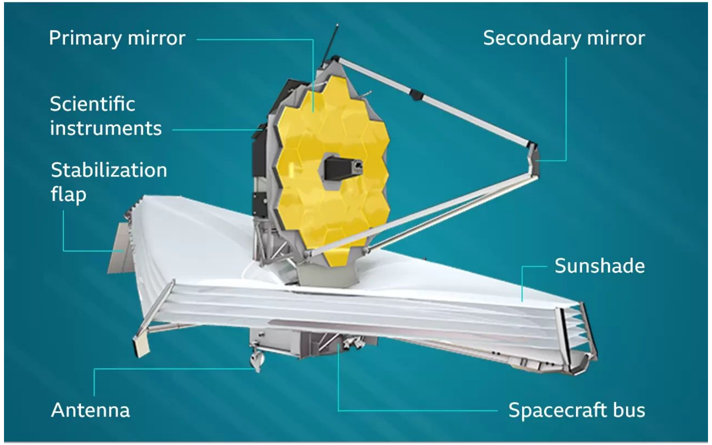
JATIS 7, 011004 (2021).

- 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

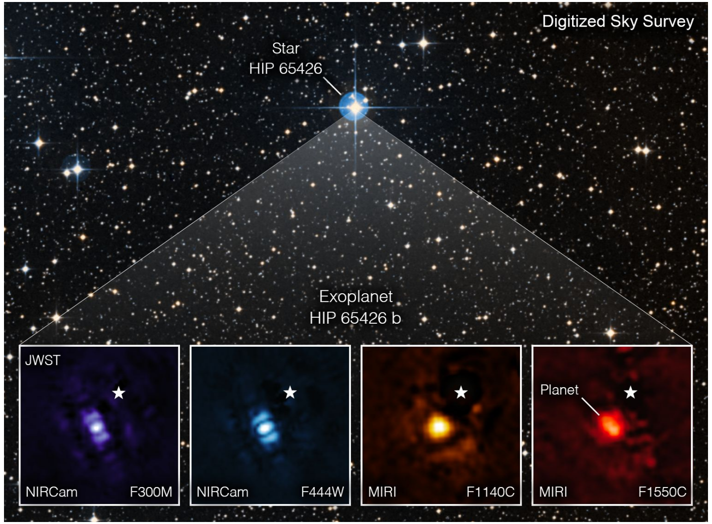


James Webb Space Telescope



Source: Nasa

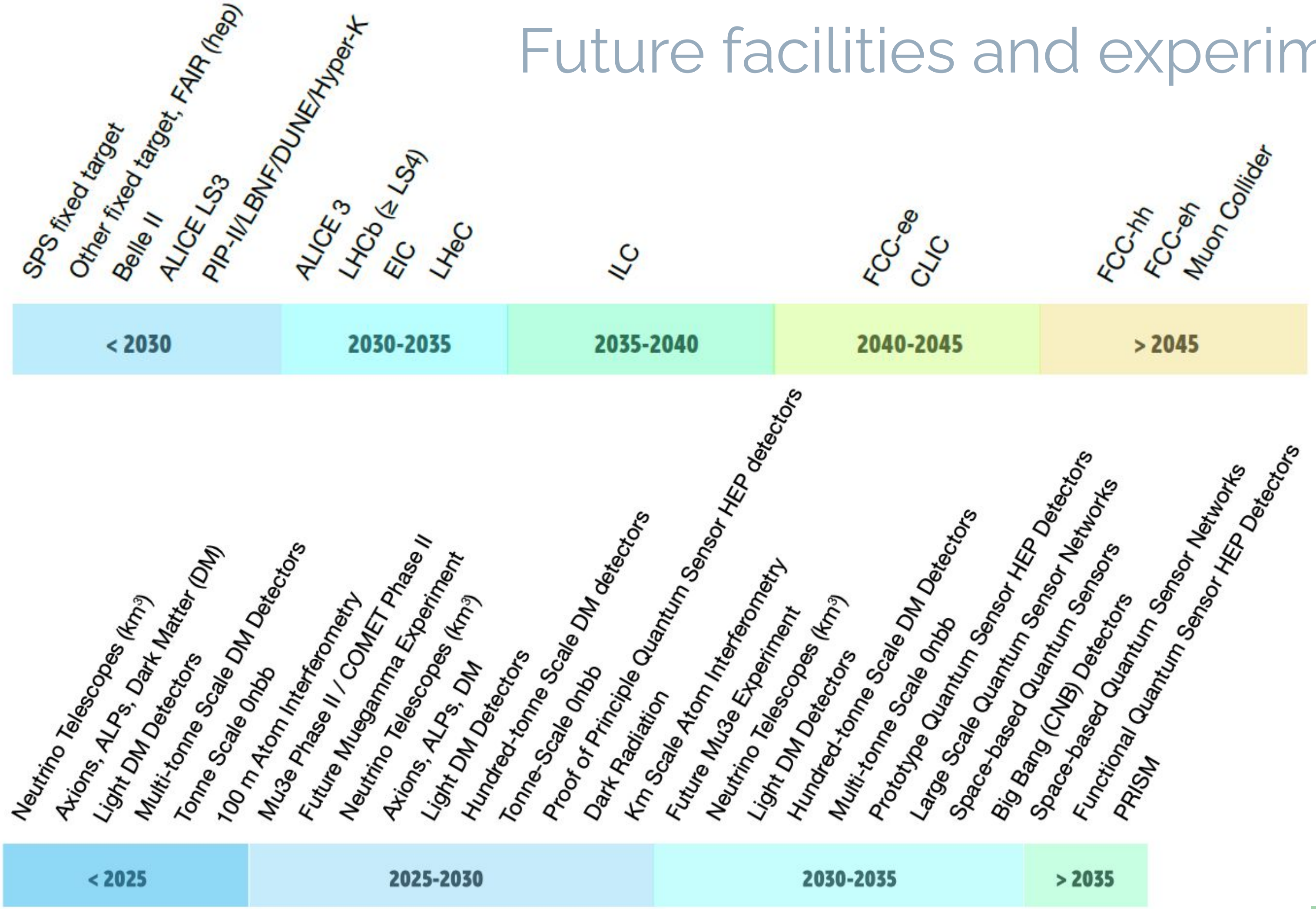
BBC



Future facilities and experiments

Large

Small



CERN 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)				

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	
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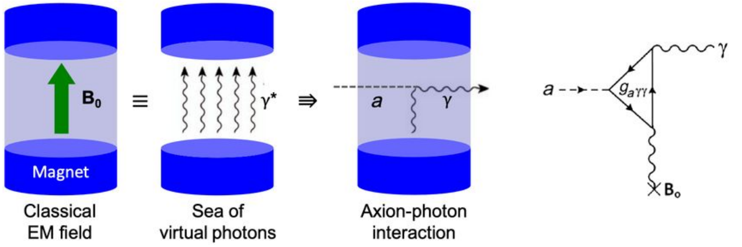
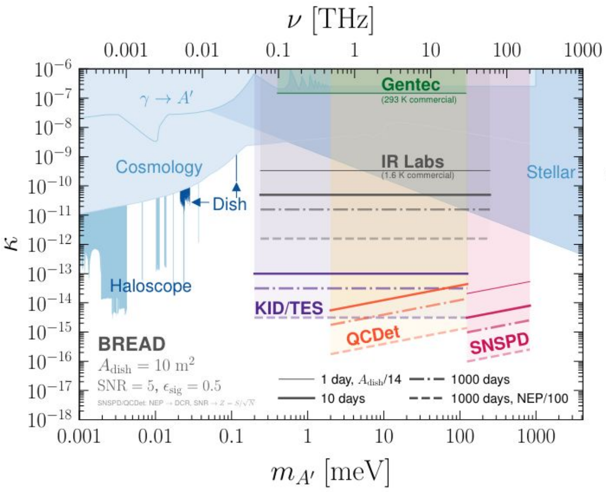
Dark Matter Searches

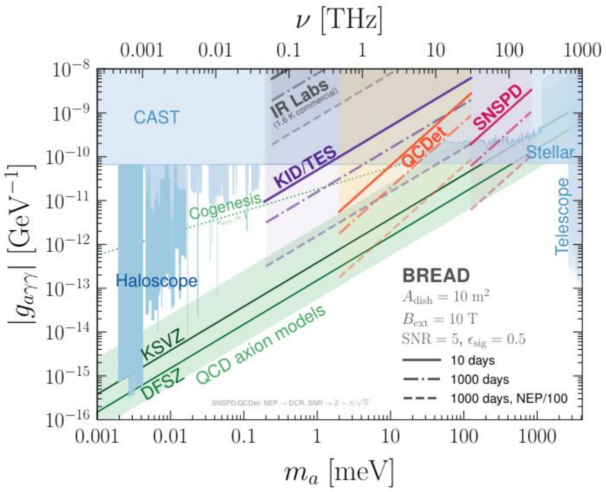


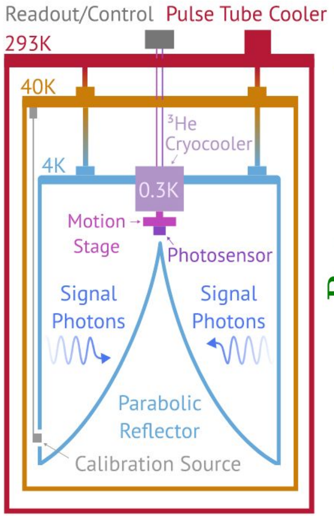
arXiv.2104.14831 (2021)

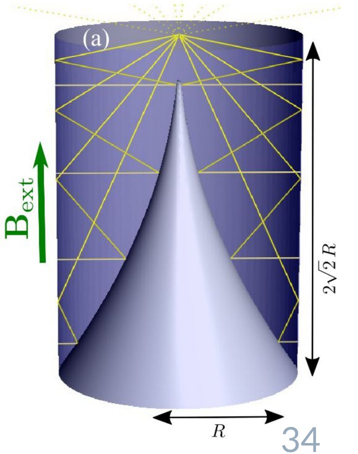
- Dark matter candidates with m_{DM} < 1 eV
  - QCD Axions (*a*)
  - Dark Photons (*A'*)
- Non-zero DM-photon couplings → lab detection through EM interactions

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



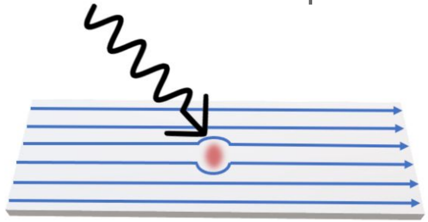






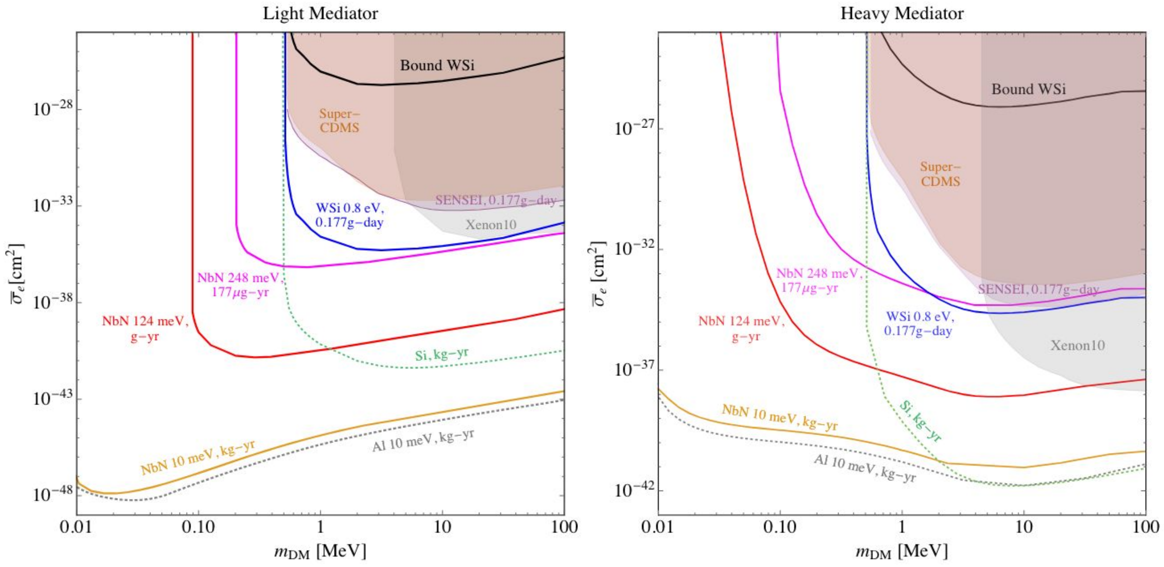
Dark Matter Searches – Direct interaction

DM Scattering
or Absorption



- Requires stable and low Dark Counts

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



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

Pu-Kai Wang

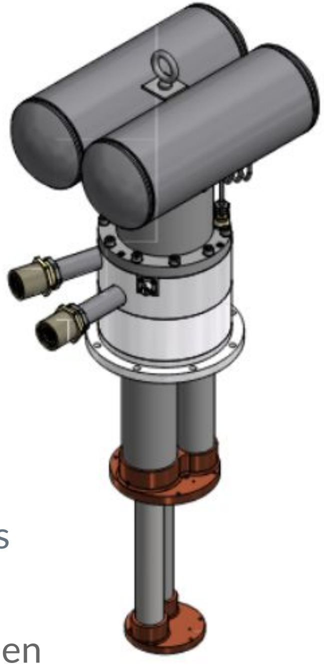
Cryogenics

New cryogenics setup @ NTU

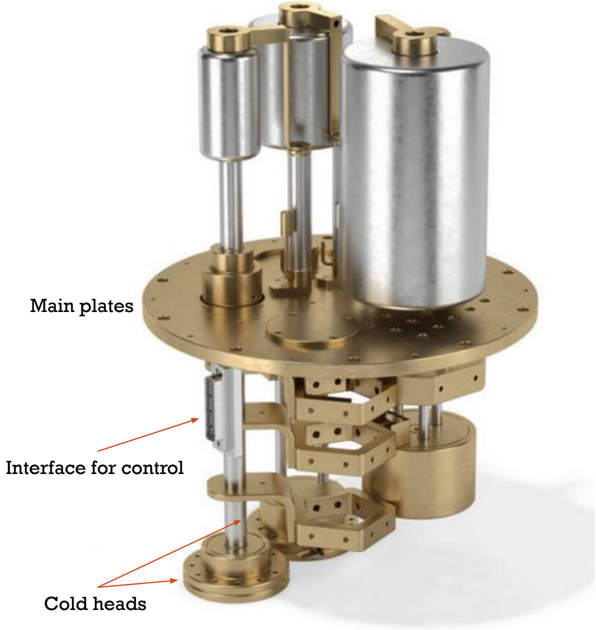
Pu-Kai Wang

- Motivation
  - Dedicated cryogenics for SNSPD
  - Lower temperature
  - Platform for new exotic searches
- Design Goal
  - Larger working space
  - More types of feedthroughs
  - Noise shielding
  - Temperature extend to 300 mK
- Intermediate step
  - Small size for conceptual test
  - Still provide SNSPD testing capabilities
- Pulse tube and sorption cooler from Pisin Chen

Pulse tube
(PT420 from Cryomech)



sub-Kelvin sorption coolers
(GL10 from Chase Research Cryogenics)



GL10-018

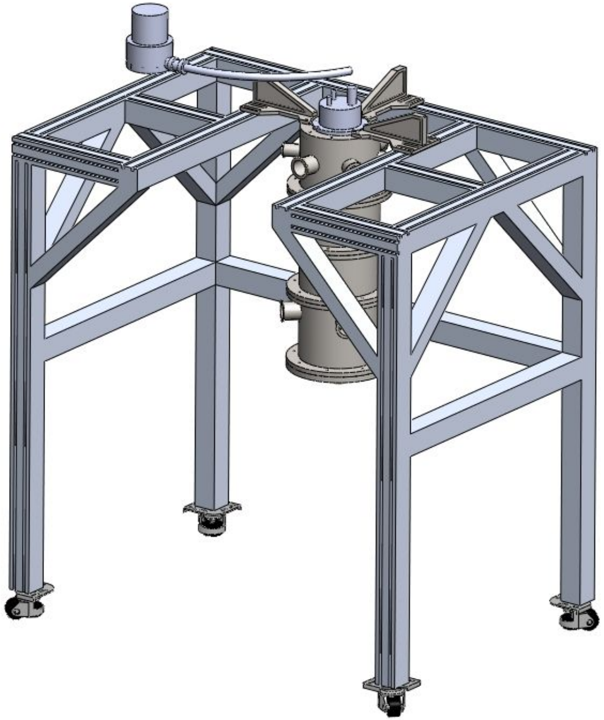
Dimension ~ 15 * 15 *15 cm^3

Cryogenic quantum platform @ NTU

Pu-Kai Wang

Cryostat deployment

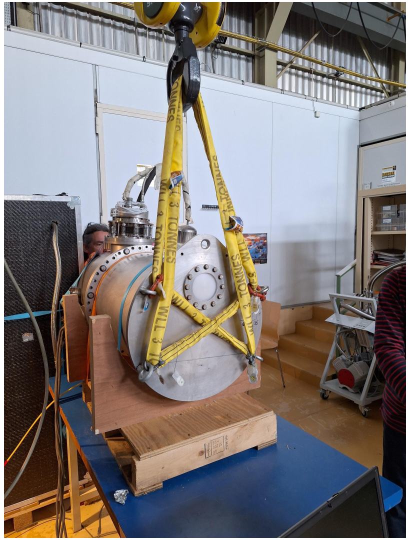
Structure design

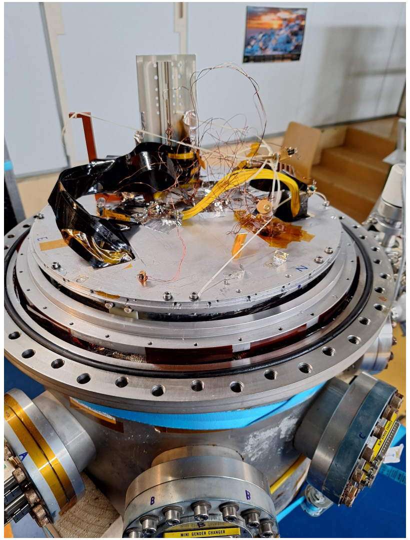


Cryogenics setup at CEA Saclay

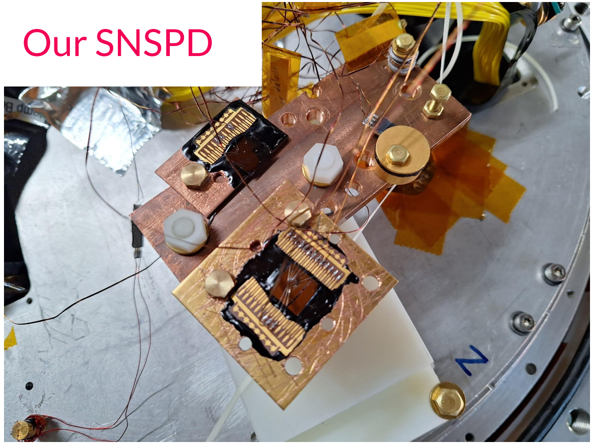
Xavier-Francois Navick

- Dedicated to Analog Black Hole experiment
- Reaches ~ 250mK, sustains for ~ 20hrs
- Retired cryogenics from other experiments
- Extensive rework of the cryostat ongoing





Our SNSPD



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Lecospa
Pisin Chen, Yung-Kun Liu

IoP, Academia Sinica
Pu-Kai, Wang

CEA Saclay
Marc Besançon, Jean-François Glicenstein, Xavier-François Navick, Boris Tuchming

Thanks to all the collaborators!!

TIDC

National Taiwan University
High Energy Physics Group

LeCosPA

75 Re Rhenium 186.207 | 6 C Carbon 12.011 | 33 As Arsenic 74.922 | 71 Lu Lutetium 174.967 | 57 La Lanthanum 138.905 | 5 B Boron 10.811

奈米機電系統研究中心
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cea Irfu

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

Conclusion

- TIDC/NTU demonstrated **dual-mode operation** of a single NbN SNSPD
  - switching between Geiger (event counting)
  - Calorimetric (energy-resolving) modes by adjusting temperature and bias current
- **Plasmonic SMSPD** with Au nanocube structures on NbTiN is under development, targeting broadband mid-IR sensitivity via gap-plasmon resonance
- A new **sub-Kelvin cryogenic platform** (target 300 mK) is being commissioned at NTU
- A second setup at CEA Saclay reaches ~250 mK for the AnaBHEL experiment
- Such detectors open a **broad physics reach**: dark matter searches, exoplanet spectroscopy, quantum information, and Hawking radiation analogues
- Challenges in efficiency, noise, and fabrication systematics remain — but the path toward a fast, calorimetric, polarization-sensitive, mid-IR single-photon detector is clear