Photon Detection with Superconducting Detectors from Millimeter-Wave to Gamma-Ray

Presented by:

OSA Photonic Detection Technical Group

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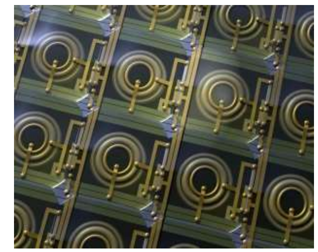
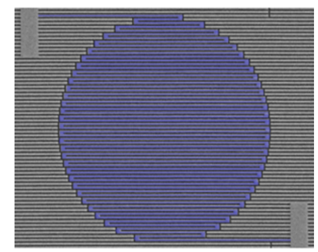
About Us



The Photonic Detection technical group is part of the Photonics and Opto-Electronics Division of the Optical Society. This group focuses on the detection of photons as received from images, data links, and experimental spectroscopic studies to mention a few. Within its scope, the PD technical group is involved in the design, fabrication, and testing of single and arrayed detectors.

This group focuses on materials, architectures, and readout circuitry needed to transduce photons into electrical signals and further processing. This group's interests include: (1) the integration of lens, cold shields, and readout electronics into cameras, (2) research into higher efficiency, lower noise, and/or wavelength tunability, (3) techniques to mitigate noise and clutter sources that degrade detector performance, and (4) camera design, components, and circuitry.

Executive Board

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OSA Photonic Detection Technical Group

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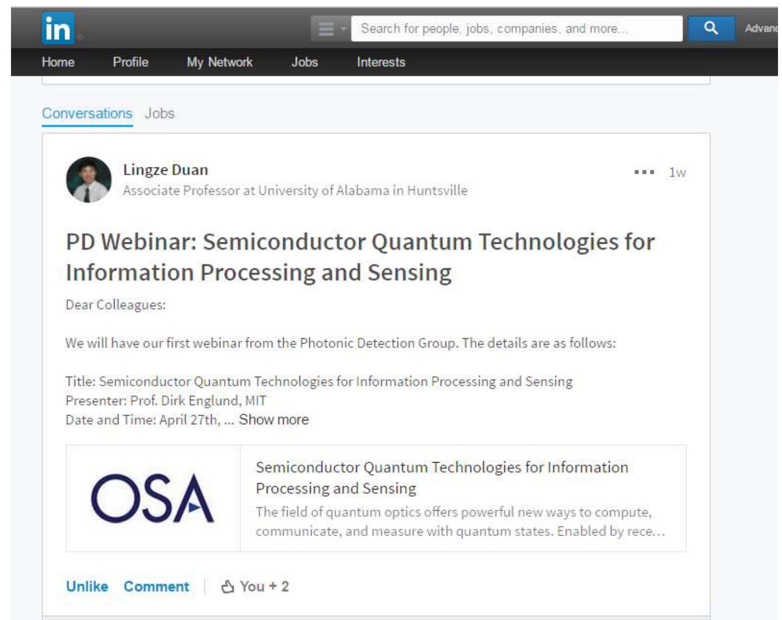


Photonic Detection Technical Group

Planned Technical Group Activities

Our activities include:

- Special sessions at leading OSA conferences. We had a successful panel discussion at OSA FiO 2015.
- Webinars. We have planned about 3-4 webinars for 2016.
- Proposal on a journal special issue covering PD activities.
- Interaction with local sections and student chapters. We are in the process of setting this up.
- Proposal for the creation of student poster awards at OSA meetings.
- Road map towards solving outstanding research problems.

Outreach:

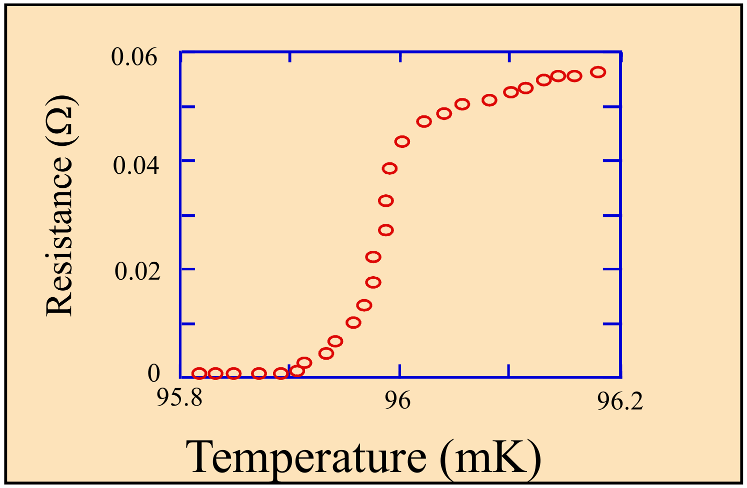
- Regular communications (distribution list announcements and listservs)
- Create and maintain an active/engaged social media/networking functions (e.g., SharePoint, Google Plus, Twitter, Facebook, and/or LinkedIn).

Detecting photon with superconducting detectors from millimeter-wave to gamma-ray

Jiansong Gao
Quantum Sensors Group
National Institute of Standards and Technology
Boulder, CO

OSA webinar, 9/28/2016

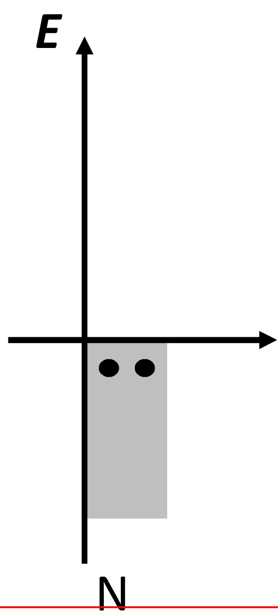
Superconductivity

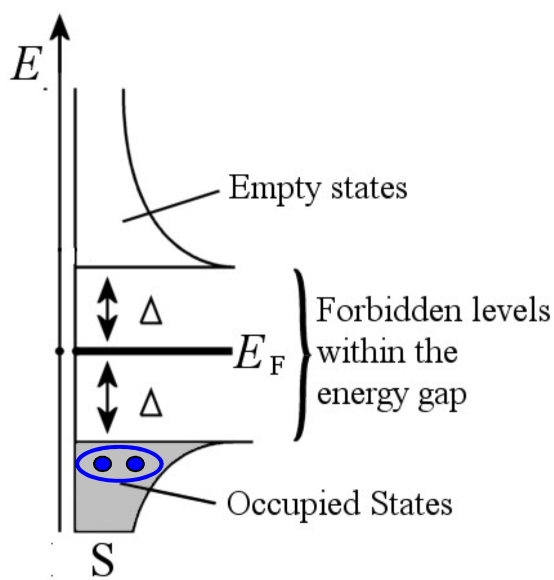


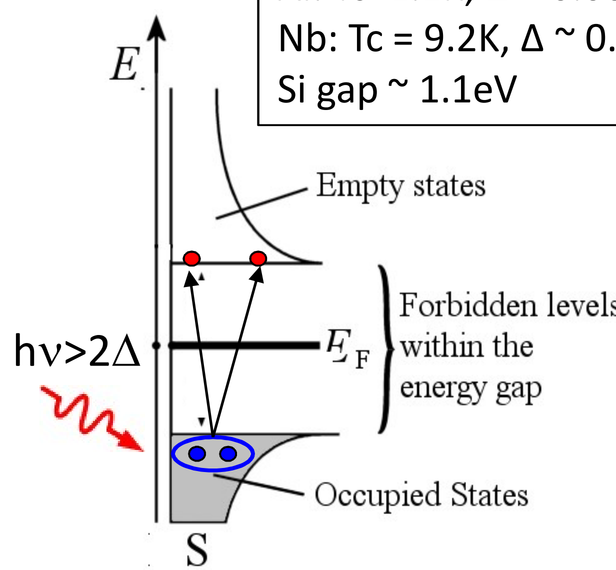
- Electrical resistance goes to zero at a critical temperature Tc
- Critical Current Ic or density Jc above which there is resistance
- Electrons in the superconducting ground state form Cooper pairs
- Excitations above the ground state are known as quasi-particles, energy ~ 2Δ

Operating at T~Tc, it is an extremely sensitive thermometer.

Al: Tc=1.2K, Δ ~ 0.0002 eV
Nb: Tc = 9.2K, Δ ~ 0.0014 eV
Si gap ~ 1.1eV



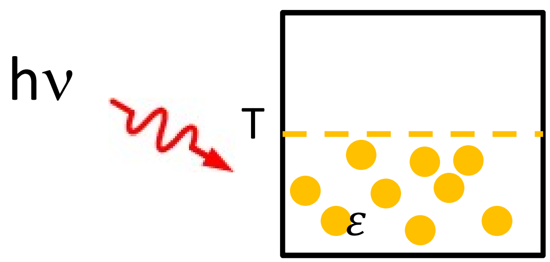




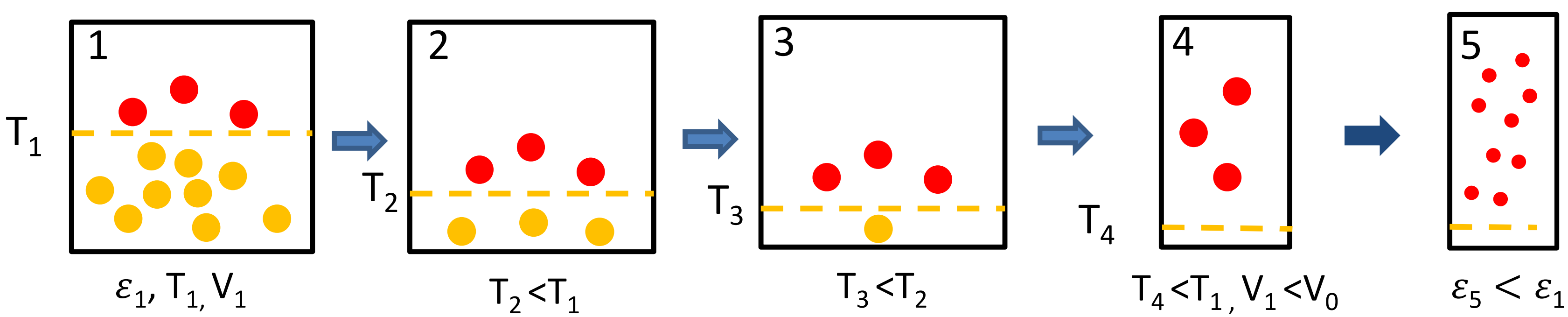
Operating at T<<Tc, it is like a "semiconductor" with extremely small gap

Why superconducting detectors

- Low noise
  - Johnson noise: 4kTR
- High sensitivity, low cutoff frequency
  - Superconductor gap ~1 meV v.s. semiconductor gap ~1eV
  - We are effectively using a ruler with finer mark.
- In quantum picture, most detectors works by counting some kind of quanta (e.g., phonons or electron excitations) in a system.



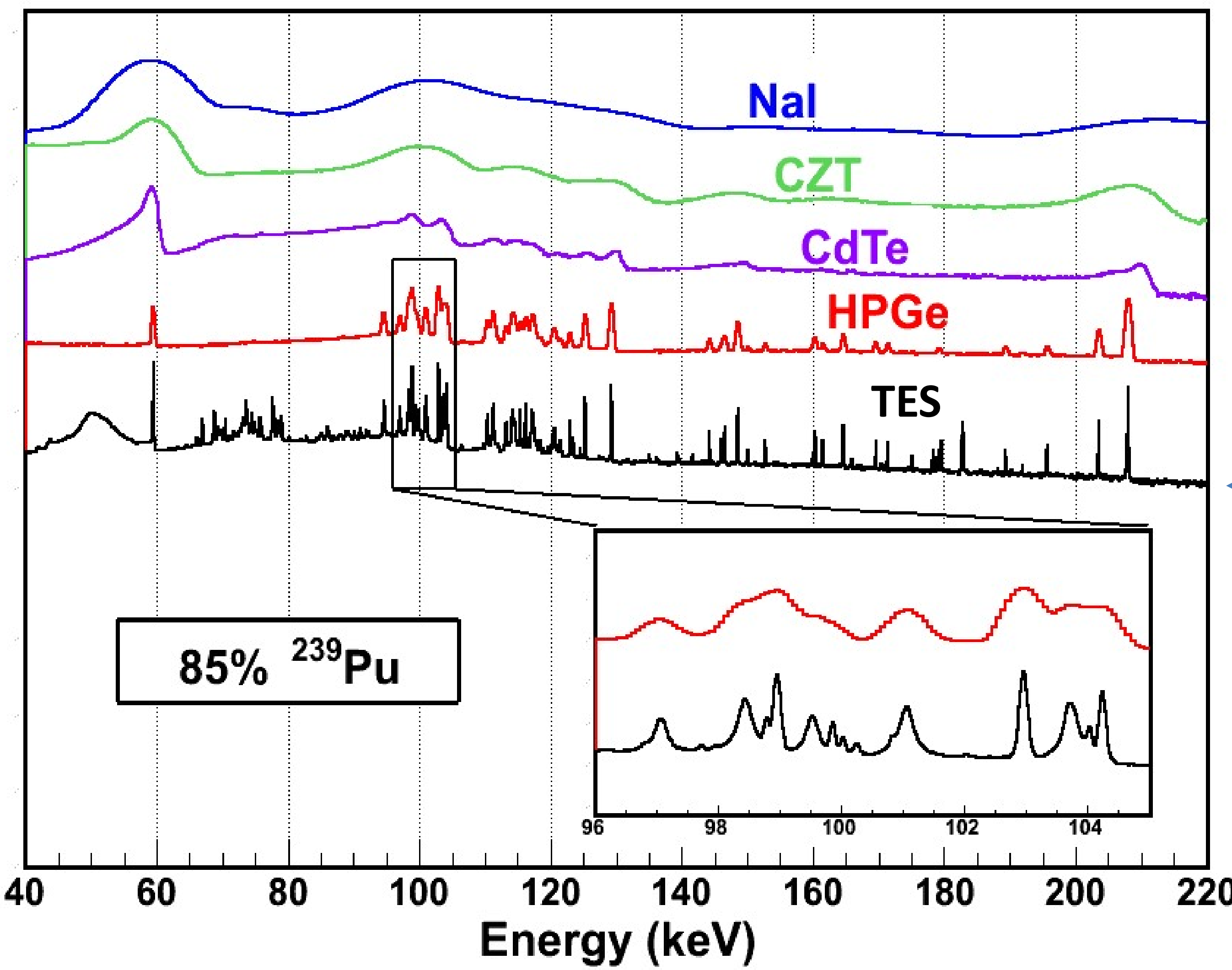
$$SNR \propto \frac{N_{ex}}{\sqrt{N_{tot}}} \sim \frac{\frac{h\nu}{\varepsilon}}{\sqrt{\frac{h\nu}{\varepsilon} + N_{th}(T)}}$$



Smallest size of quanta, smallest volume, lowest temperature = Highest sensitivity

Superconducting v.s. conventional detectors: an example

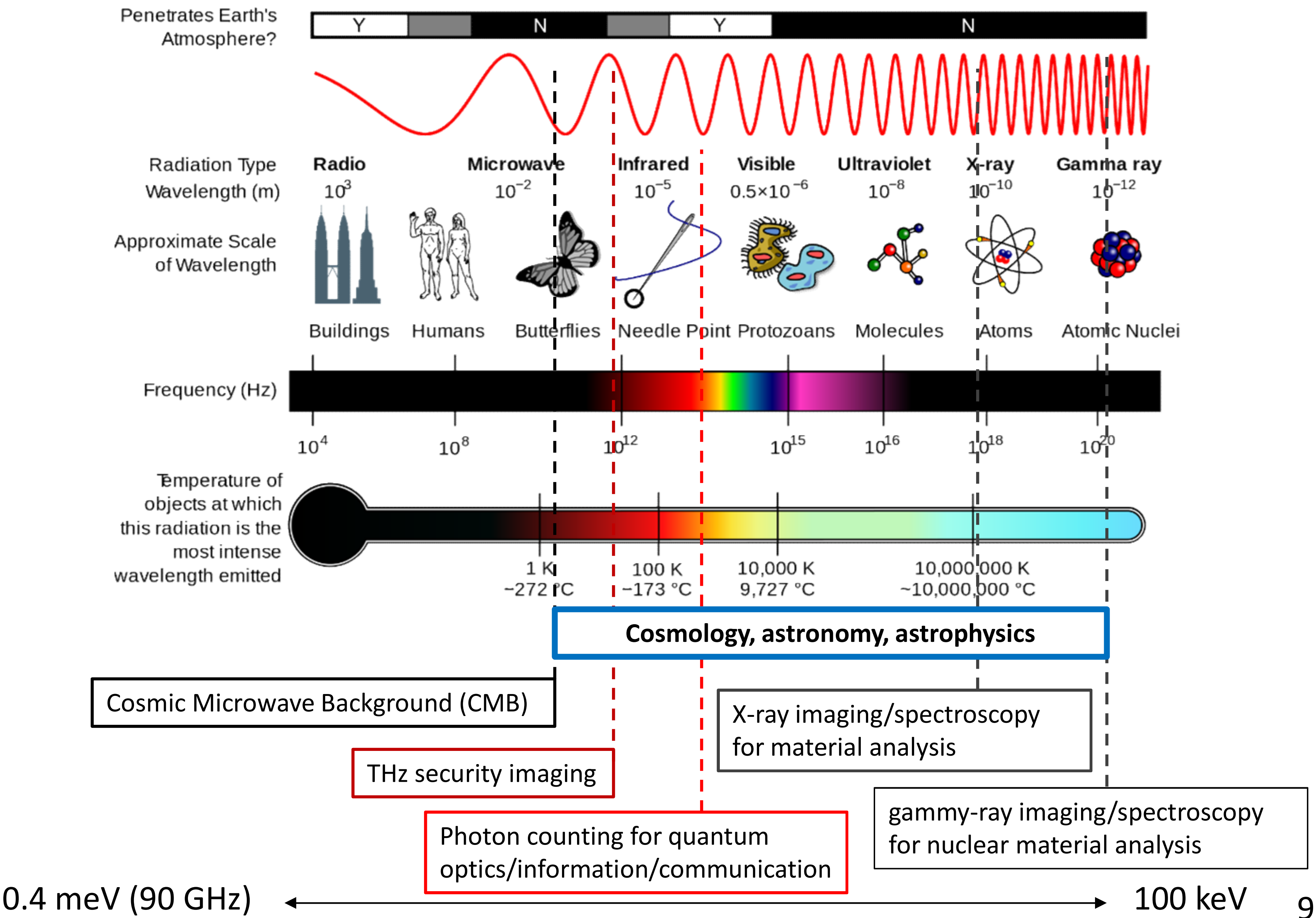
Energy-dispersive gamma-ray detectors



conventional Semiconductor detectors

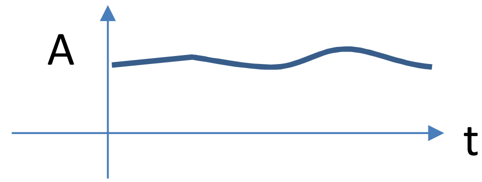
Superconducting transition edge sensors (TES)

Superconducting photodetectors – by wavelength



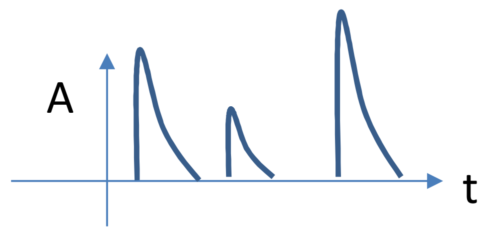
Superconducting detectors - by mode of operation

- Bolometer - measuring power



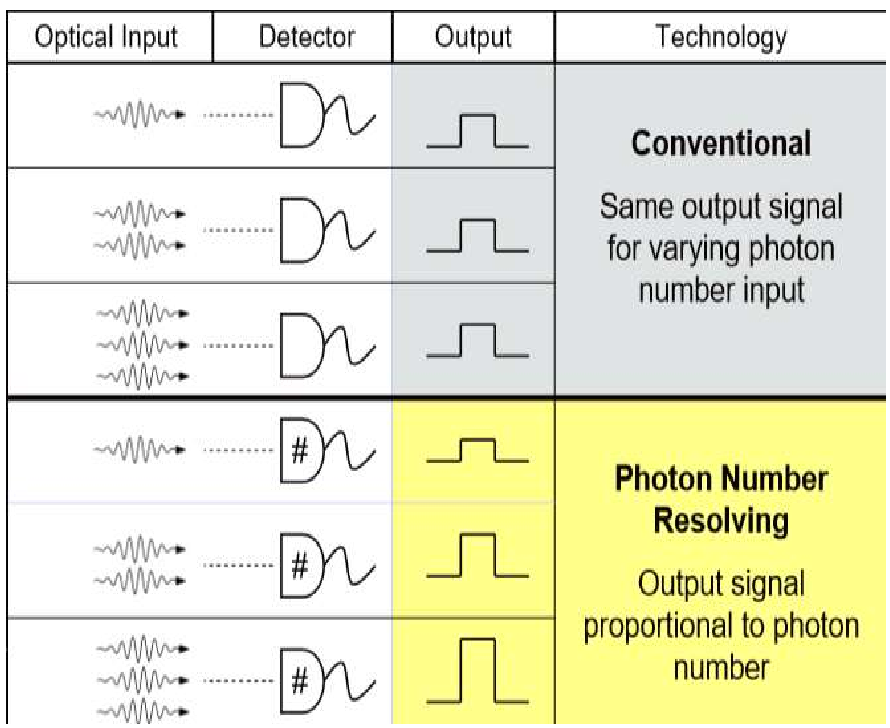
NEP: Noise equivalent power

- Calorimeter – counting photons
  - Energy not resolved



ΔE: Energy resolution

  - Energy resolving (photon number resolving)

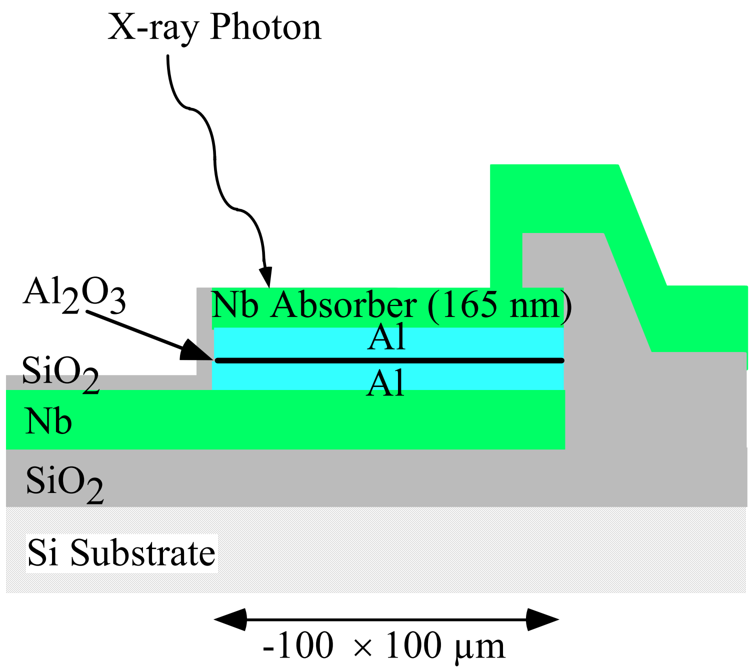


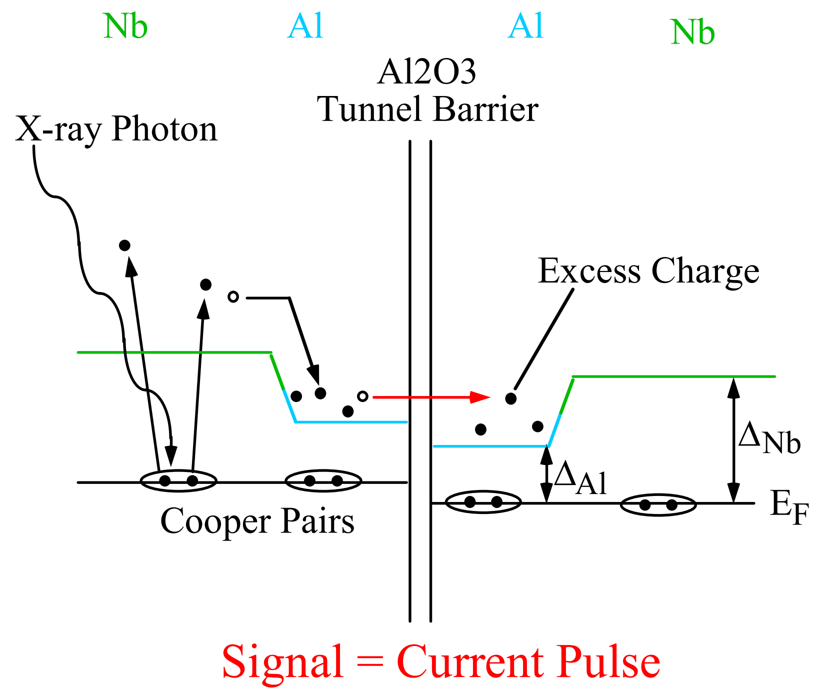
Superconducting detectors — by technology

- Superconducting tunnel junction detector (STJ)
- Superconducting nanowire single photon detector (SNSPD)
- **Superconducting transition edge sensor (TES)**
- Microwave kinetic inductance detector (MKID)

Most of the detectors shown in this talk are developed at NIST (Boulder)
***Quantum Sensors** (Joel Ullom): MM, THz, X-ray, Gamma-ray TES and MKID*
Single Photonics and Quantum Information (Sae Woo Nam)***:** NIR, optical TES and SNSPD*

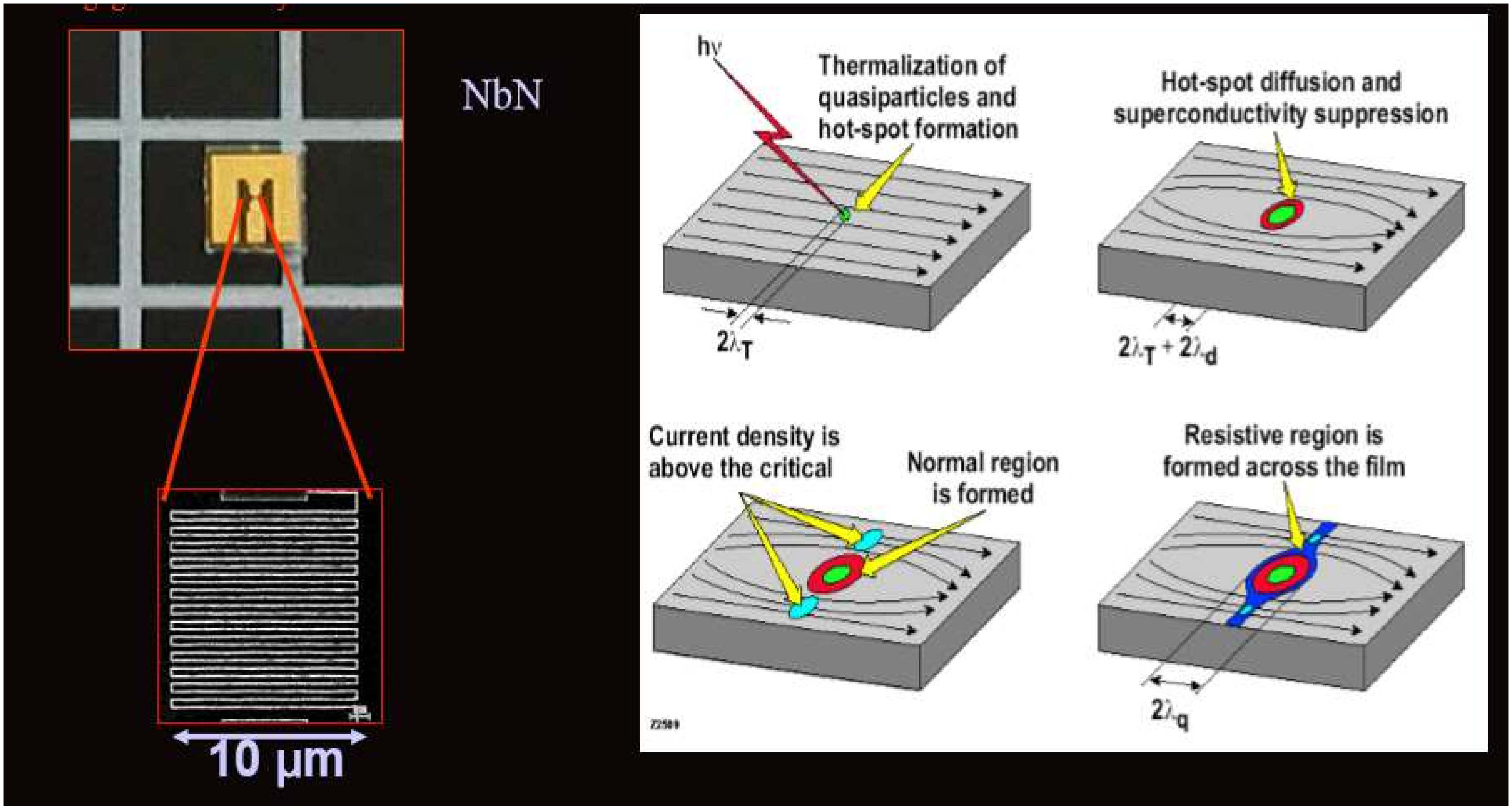
Superconducting tunnel junction detector (STJ)





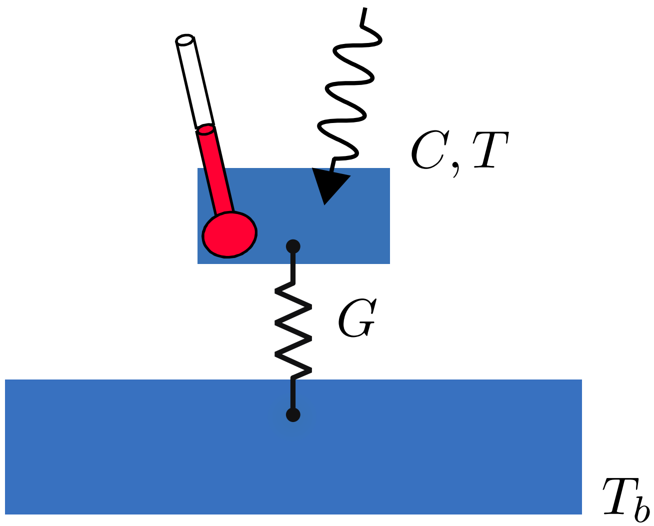
- Analogous to a semiconductor detector
- Energy resolving
- Al – AlOxide – Al junctions
- JJ not popular as detector – hard to scale to a large array
- building block for SQUIDs and quantum bits (qubits)

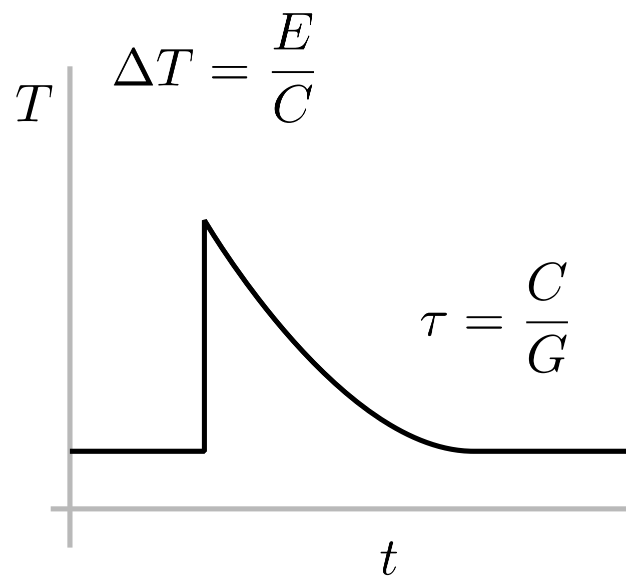
Superconducting nanowire single photon detector (SNSPD)



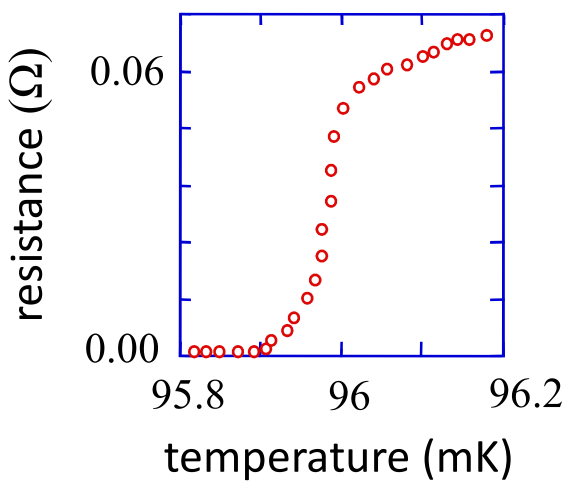
- NbN, Wsi, … 4nm thick, <50nm wide
- Current bias, voltage pulse
- Photon counting, but not energy resolving
- Fastest superconducting detector, ~50ps jitter

Transition Edge Sensors (TES)

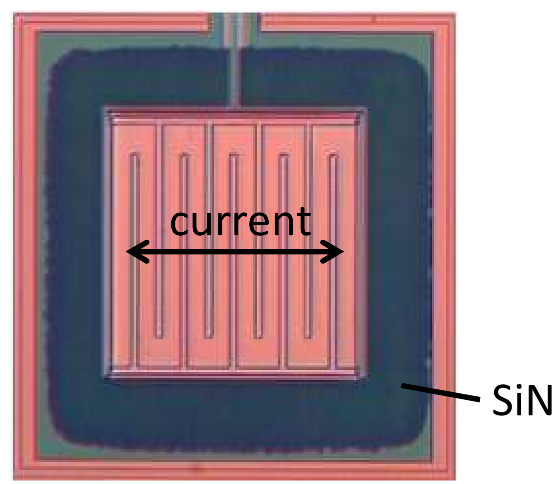




thin-film thermometer

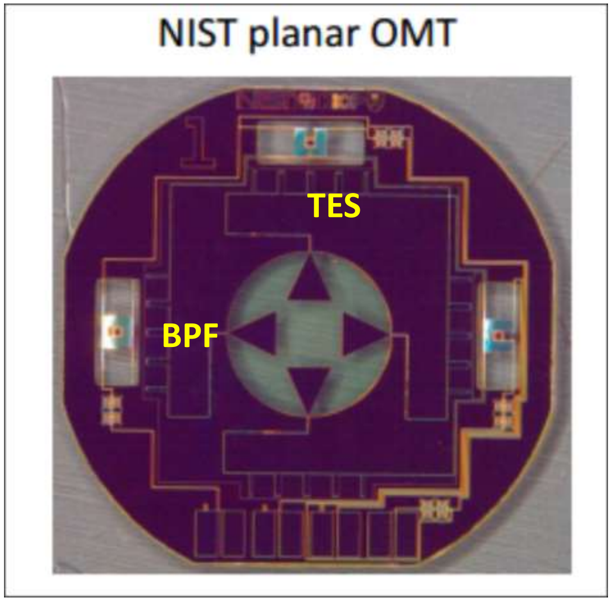


TES micrograph

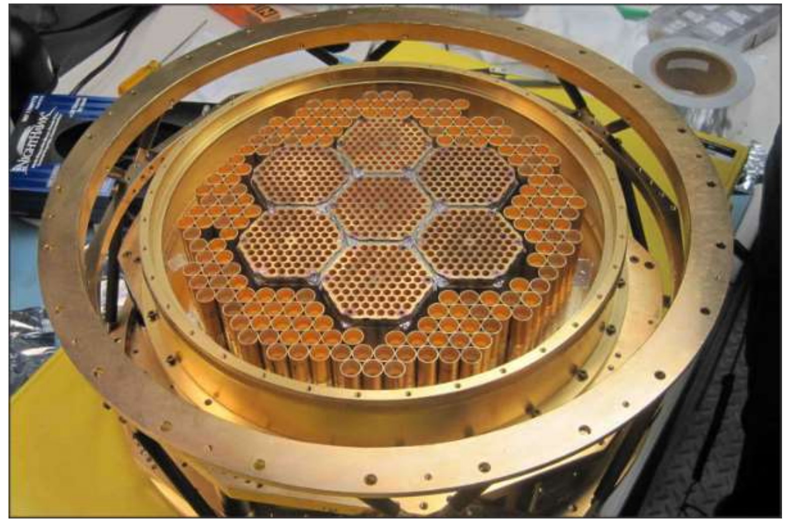


TES bolometer for cosmic ray background (CMB)

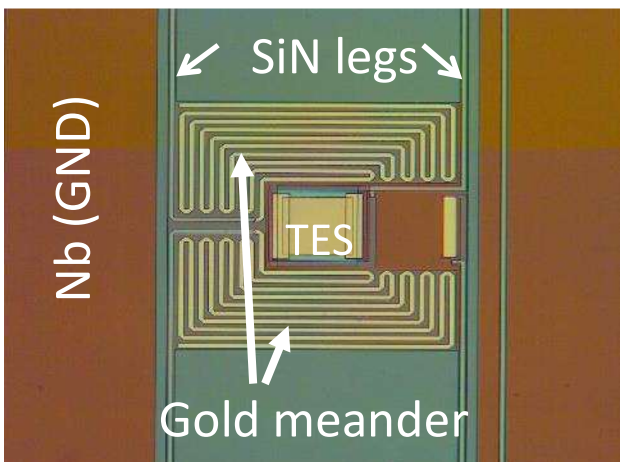
NIST dual polarization TES for ABS, SPTPol, ACTPol



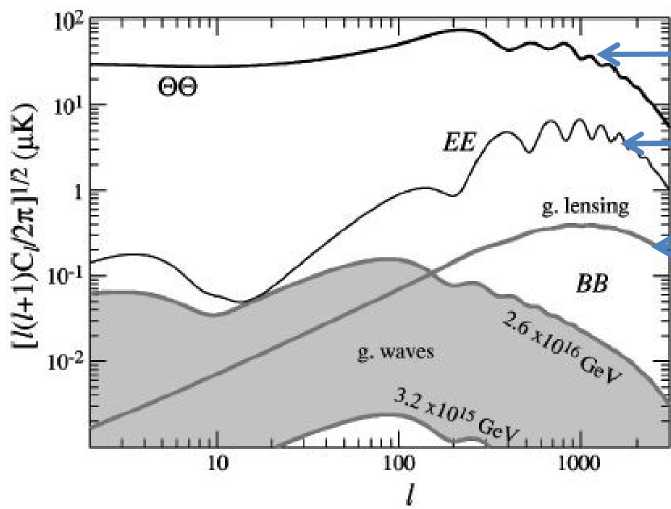
Feedhorn array



TES: AlMn (Tc~500mK), MoCu (Tc~150mK), feedhorn-coupled

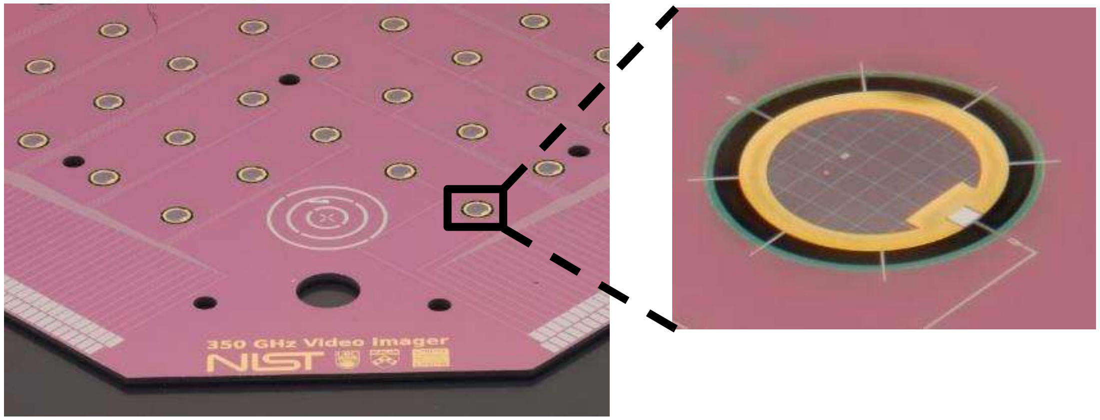


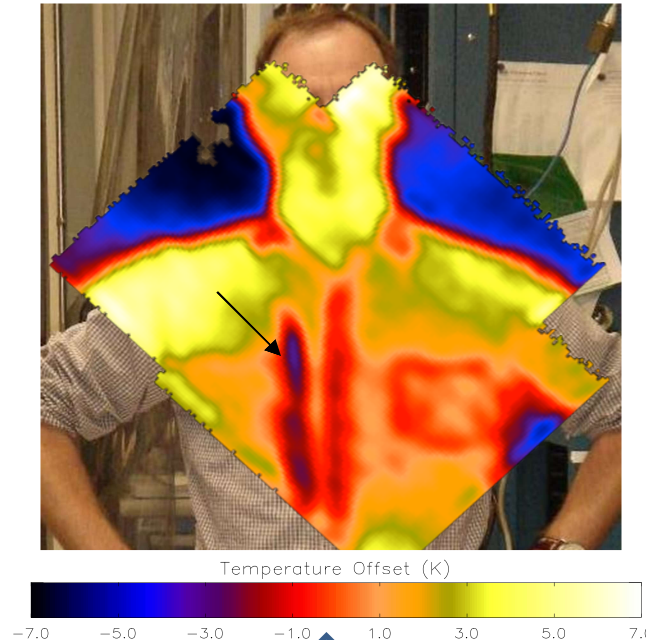
B-mode polarization in the CMB is a signature of gravity waves and the energy scale of inflation.



Application - Cosmology

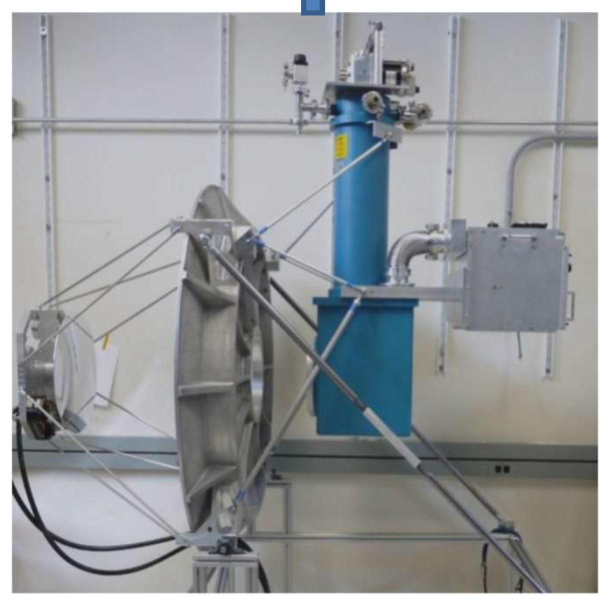
TES for THz imaging





- TES: Al (Tc~1.2K), feedhorn-coupled
- Passive thermal imaging at 350GHz
- 17 m standoff distance
- 6 fps video for live imaging
- 1 cm spatial and 0.1 K temperature resolution

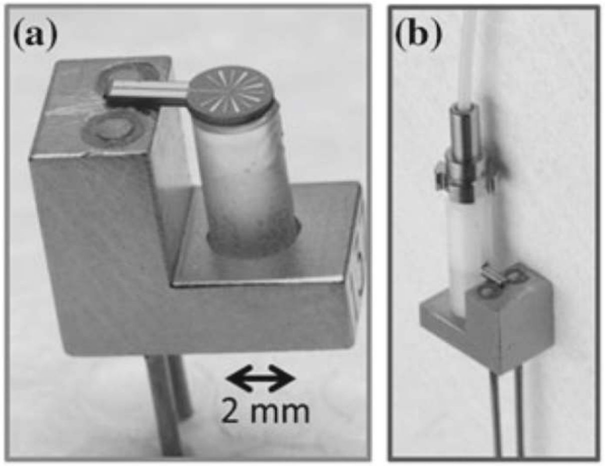
17 m



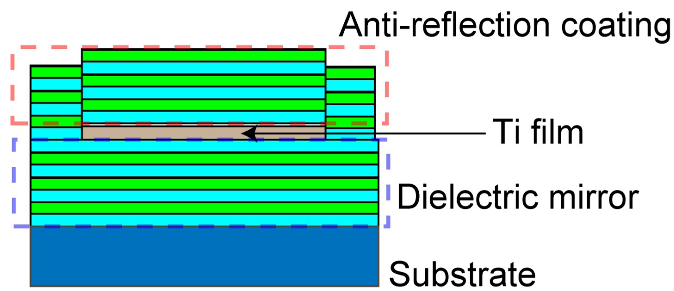
Application - Security

Credit: Dan Becker

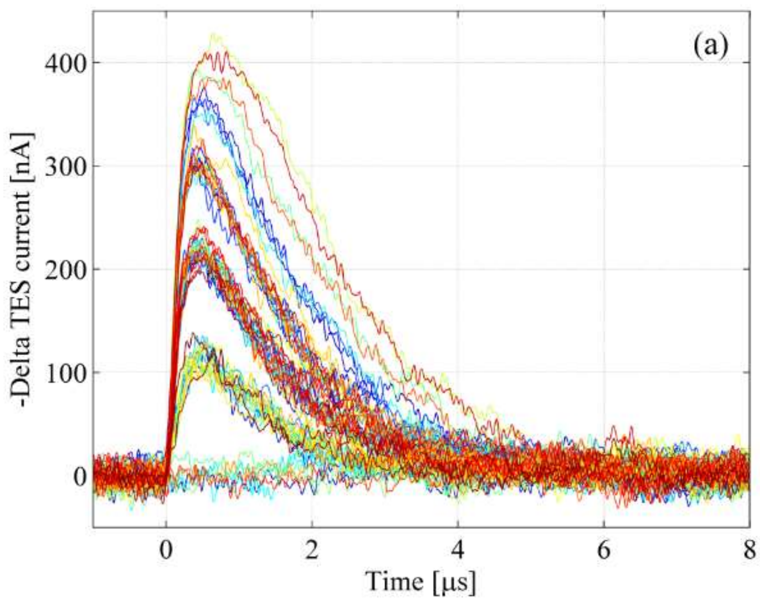
Visible/IR single photon counting TES

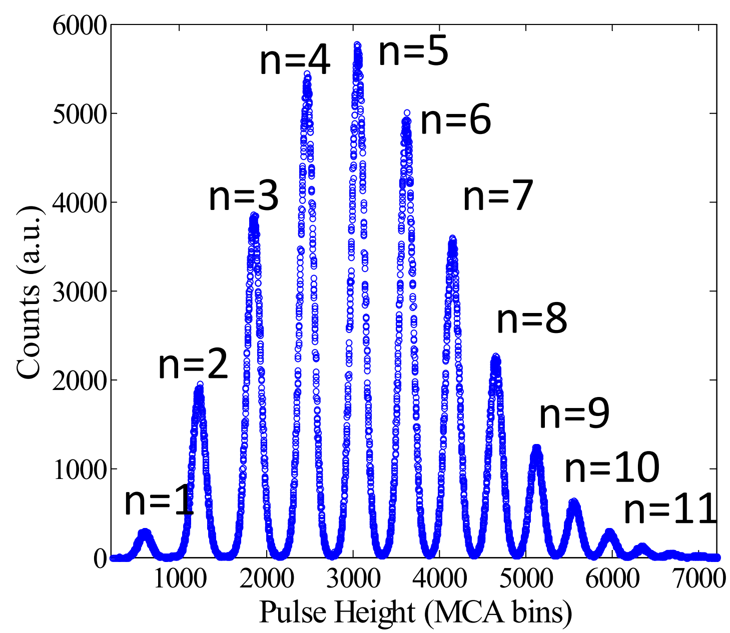


TES: W (Tc~100 mK), fiber coupled



- Photon Number Resolution
- >95% end-to-end measured efficiency at 1550nm



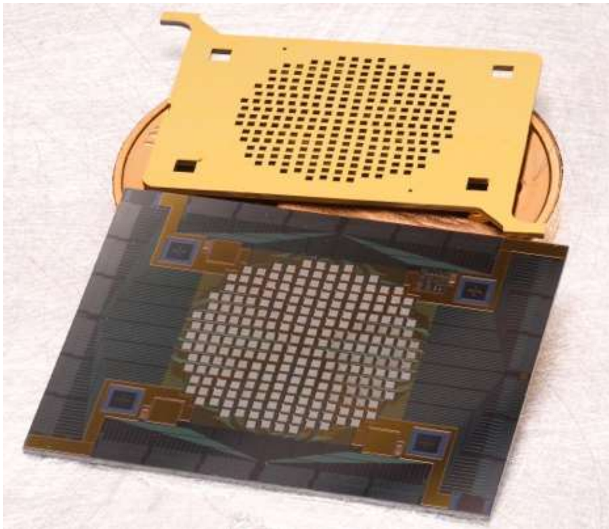


Application – Quantum information

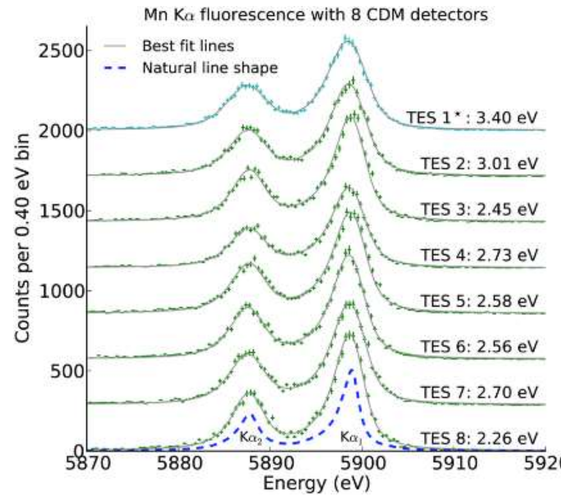
Credit: Sae Woo Nam, Adriana Lita

TES X-ray spectroscopy

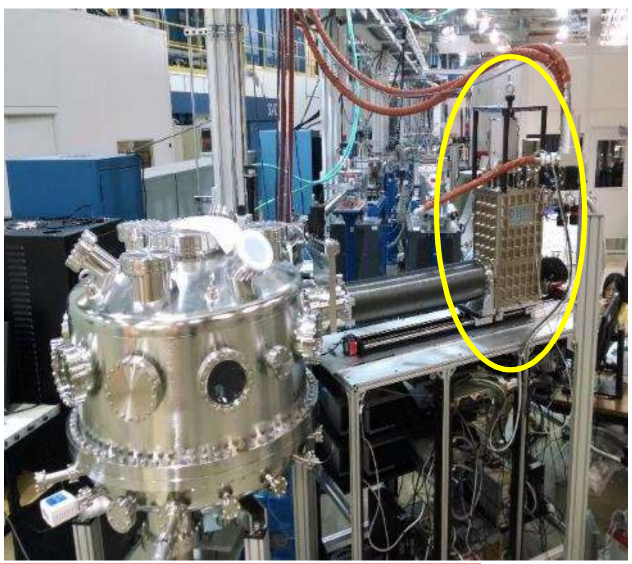
- X-ray TES, MoCu 100mK, Au or Bi



- 2.5 eV resolution at 6 keV

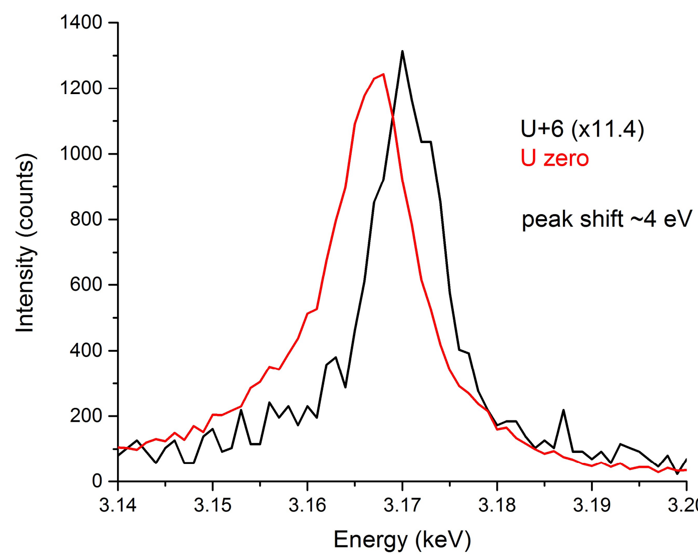


- 240 TES instrument installed at APS



- Uranium chemical shifts

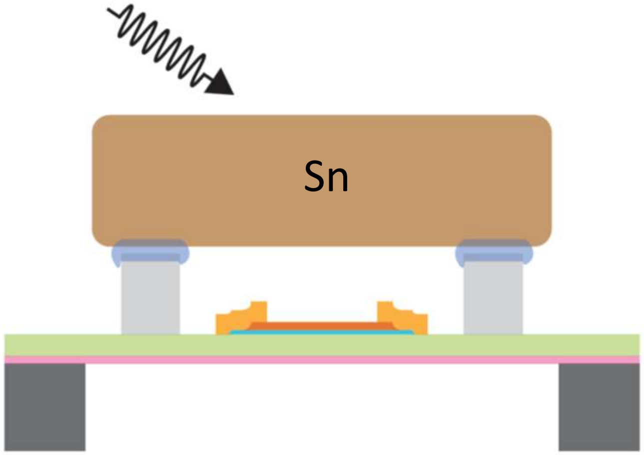
(Los Alamos/STAR Cryo commercial system)

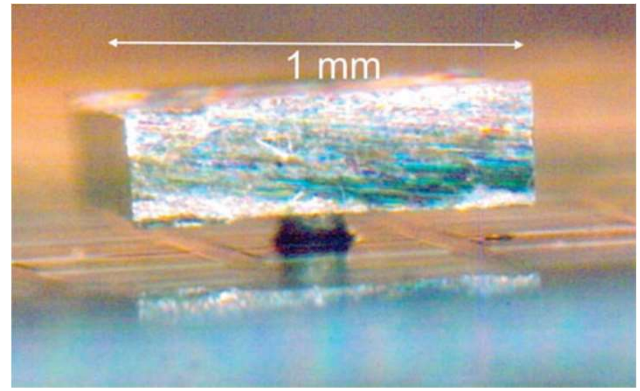


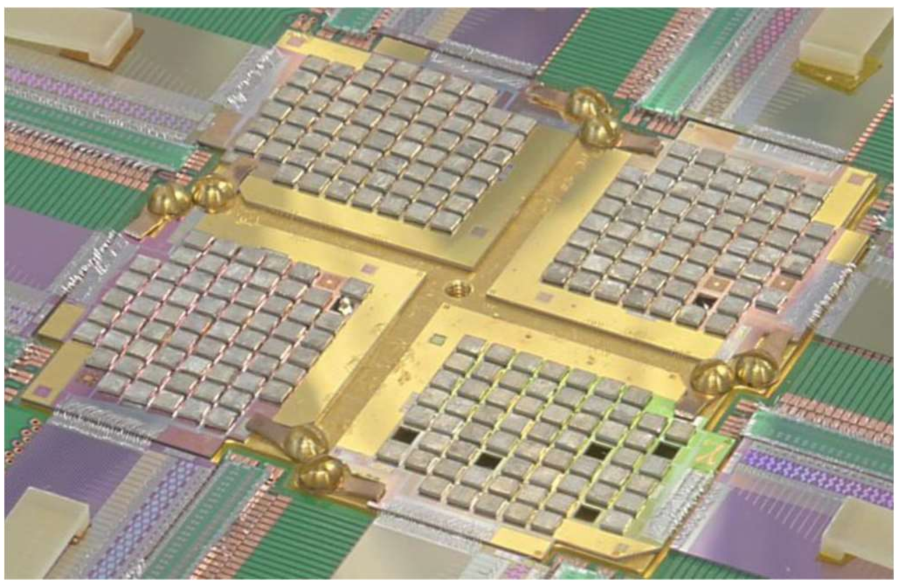
Application – Material analysis

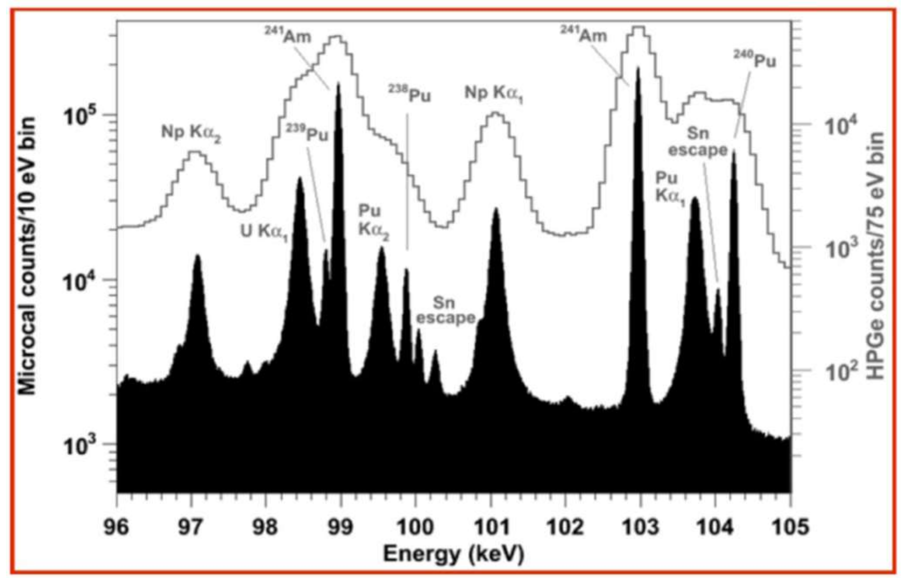
TES γ-ray spectroscopy

TES: MoCu (Tc~150mK), Sn absorber





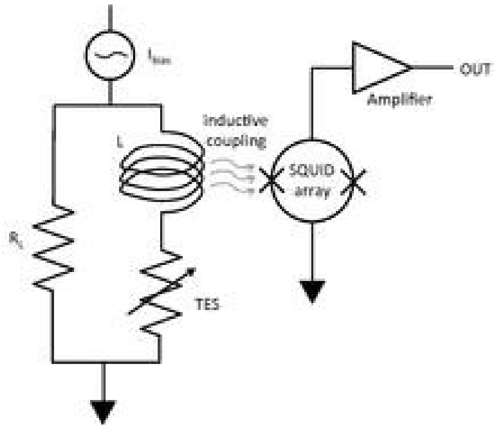




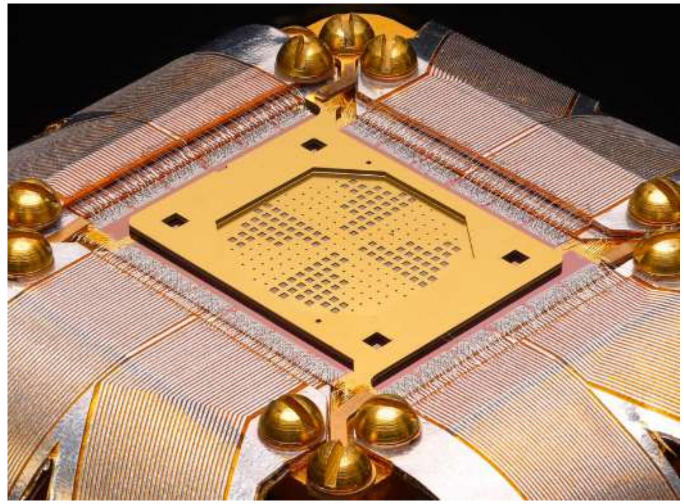
Application – Nuclear material analysis

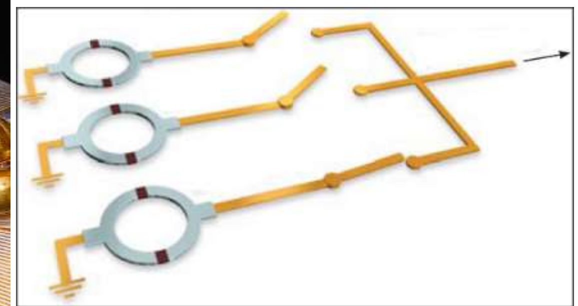
TES γ-ray spectroscopy: high res., fast, in-situ
to replacing mass spectrometry: slow, destructive

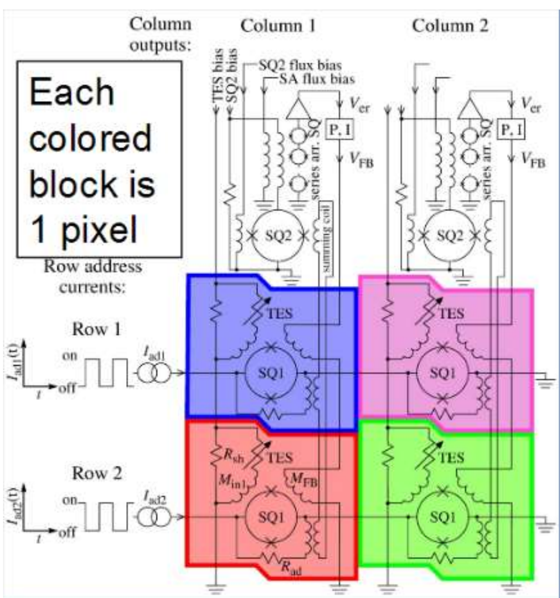
TES readout and scaling to large arrays



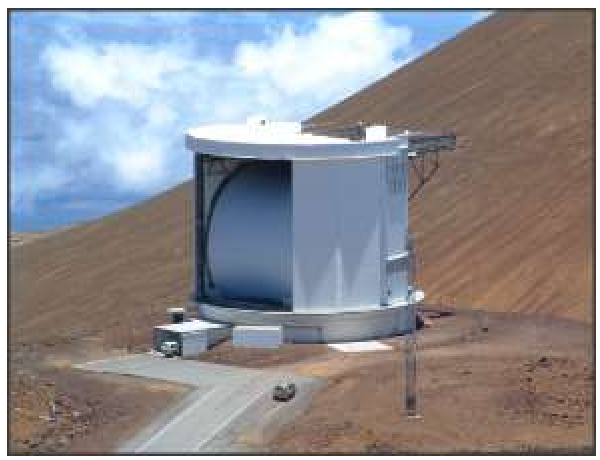
bias wire + SQUID readout wire







Time Domain SQUID Multiplexer



Largest TES instrument
SCUBA-2: 10,000 TES
TDM readout, still >2500 wires

- Currently TDM, FDM, CDM utilizes MHz bandwidth

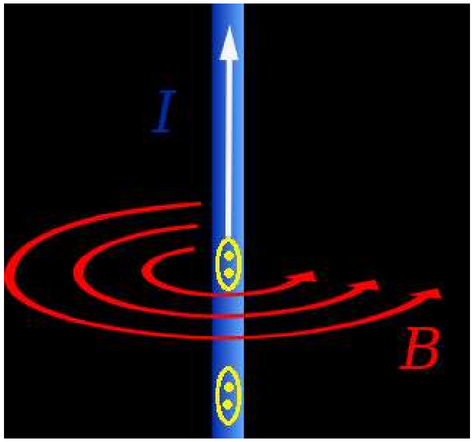
To scale to large detector array

- Less wires
- More bandwidth

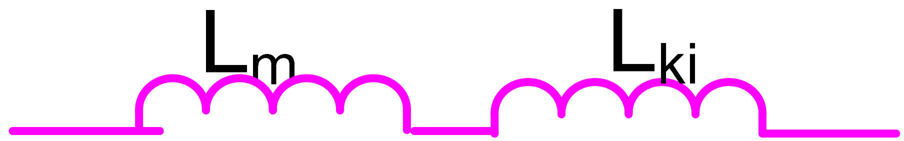
$\Rightarrow$ Microwave readout

Microwave Kinetic Inductance Detectors (MKIDs)

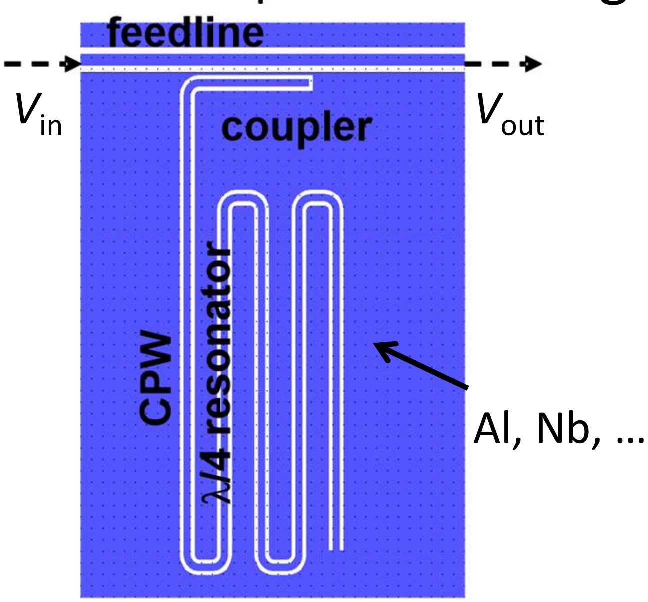
- Kinetic Inductance of superconductor



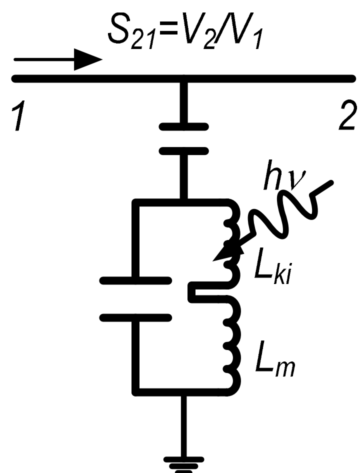
$$E = E_m + \int \frac{1}{2} n^* m^* v^2 d\vec{r} = \frac{1}{2} L_m I^2 + \frac{1}{2} L_{ki} I^2$$

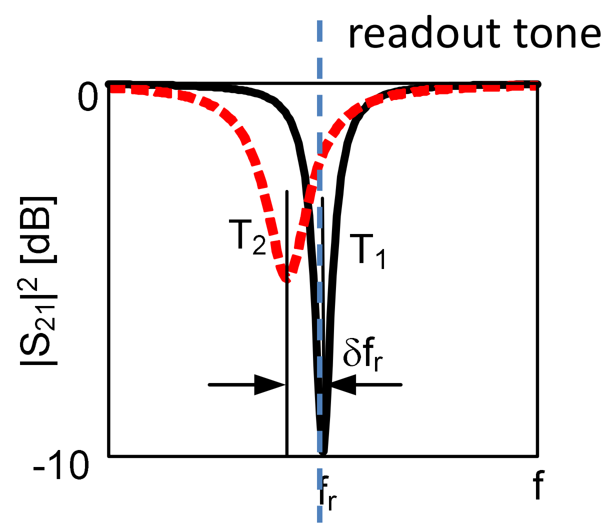


- Use superconducting resonators to sense quasiparticles



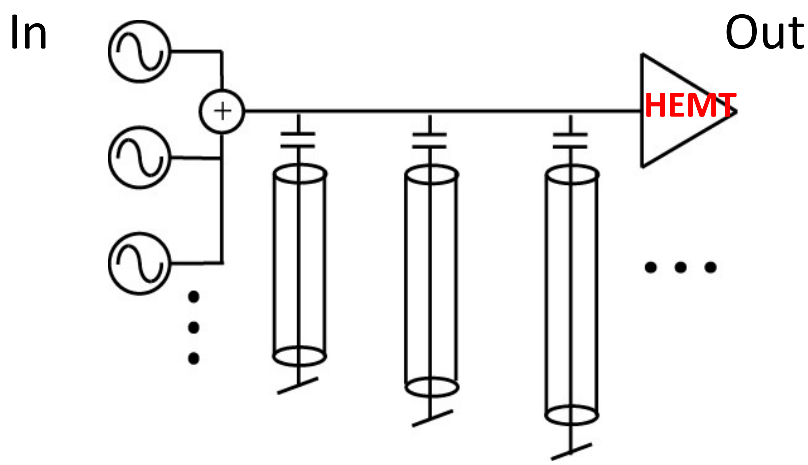
CPW: coplanar waveguide

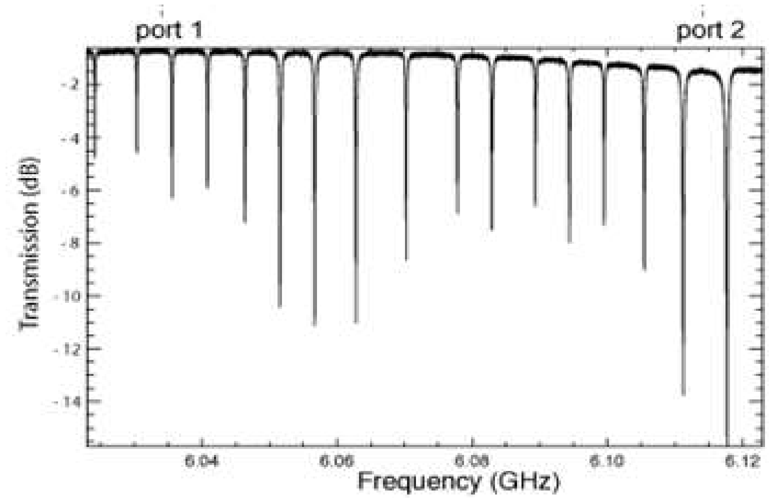


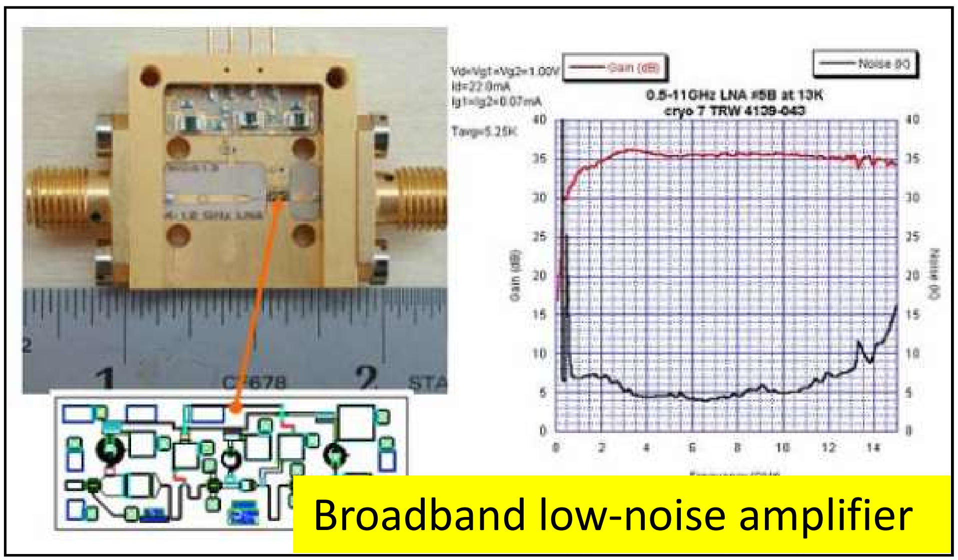


Invented by J. Zmuidzinas and H. Leduc at Caltech/JPL in 2000

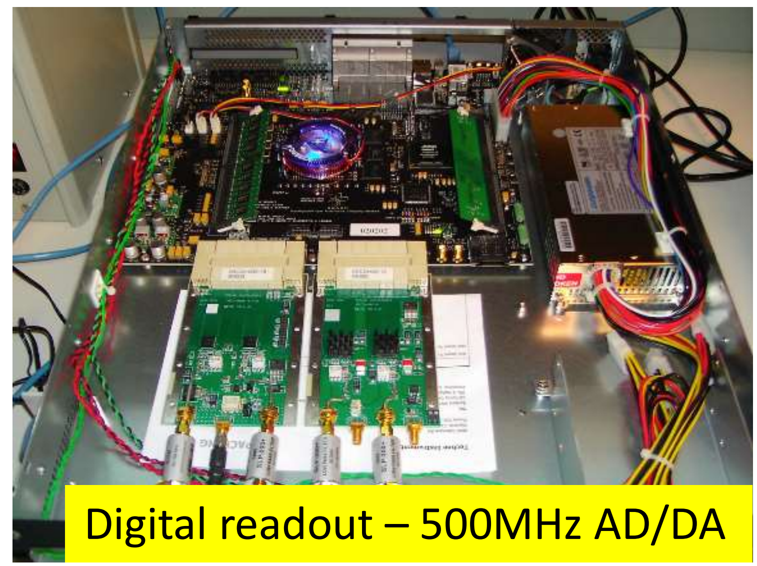
Frequency domain multiplexing







Broadband low-noise amplifier



Digital readout – 500MHz AD/DA

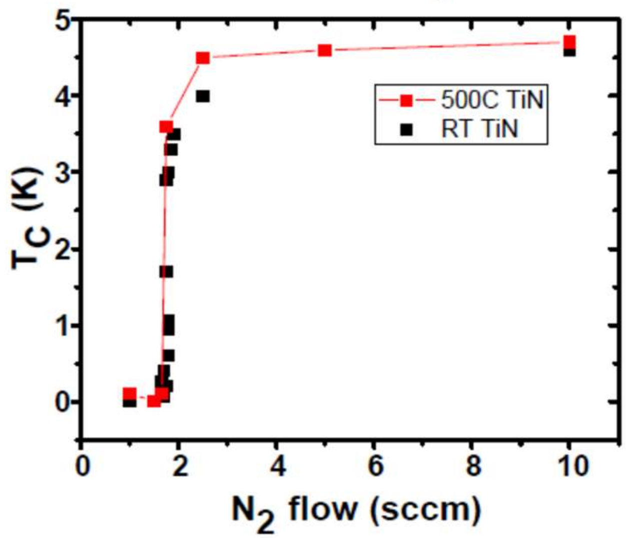
GHz bandwidth, 1000s of MKIDs needs one HEMT and one pair of coaxial cables!

TiN film ideal for MKID

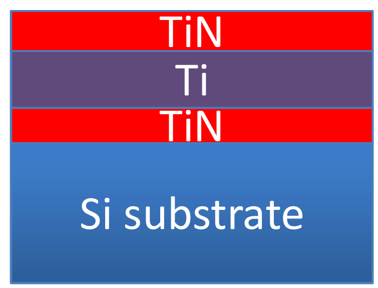
Advantages:

- High kinetic inductance (100 times Al) -> responsivity
- Low loss, $Q_i > 10^7$ -> multiplexing
- High normal resistivity, $\rho_n \sim 100\ \mu\Omega\cdot cm$ -> good absorber
- Tunable Tc (0 – 5K) -> gap engineering

TiN tunability

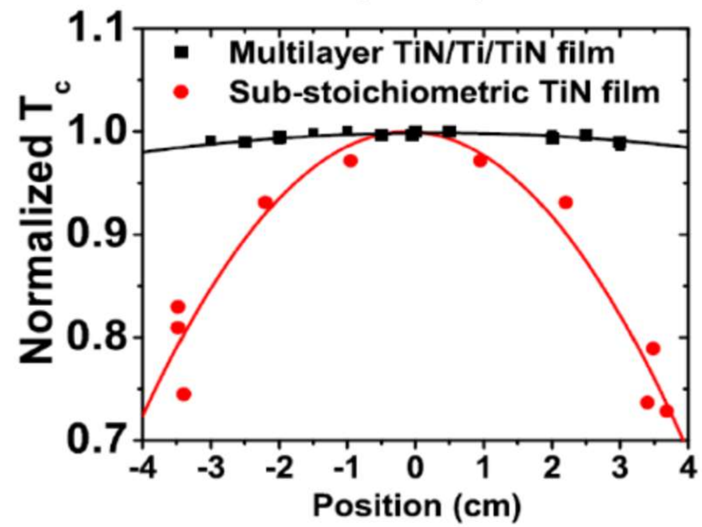


TiN trilayer



Credit: Mike Vissers

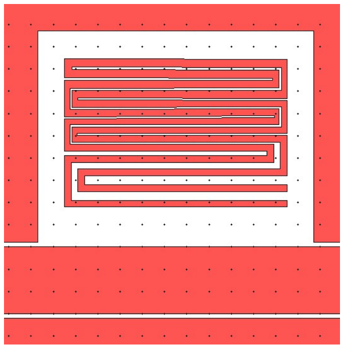
uniformity comparison



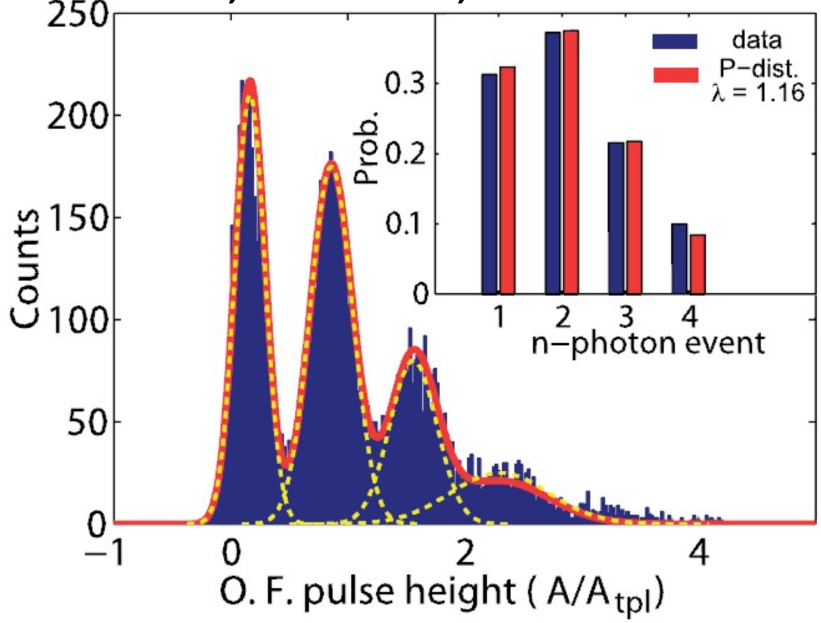
Leduc, etal, APL **97**, 102509 (2010), Vissers, etal , APL **97**, 232509 (2010)

TiN MKID photon counting at 1550 nm

2012

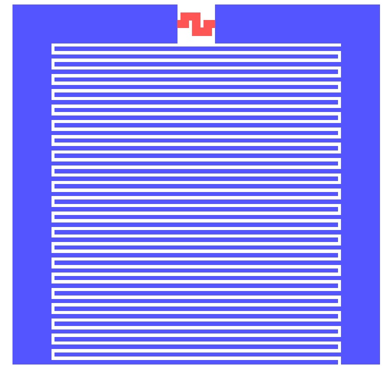


TiN, Tc~0.9K, ΔE ~ 0.4 eV

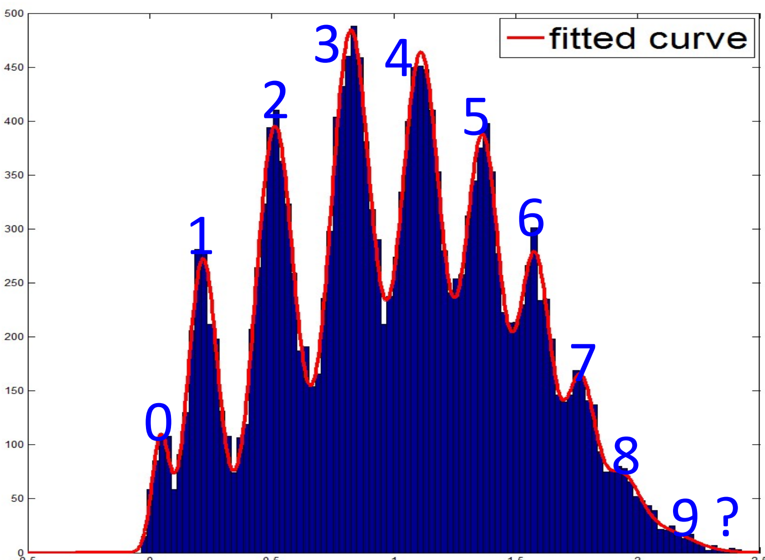


J. Gao et al., APL 101, 142602 (2013)

2016



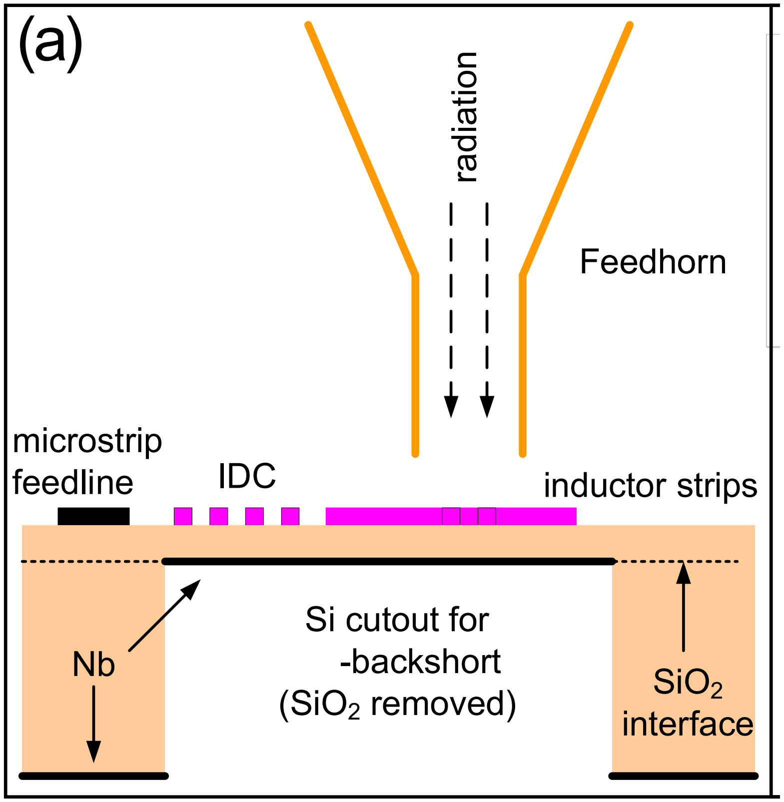
TiN/Ti/TiN, Tc~1.4K, ΔE ~ 0.25 eV



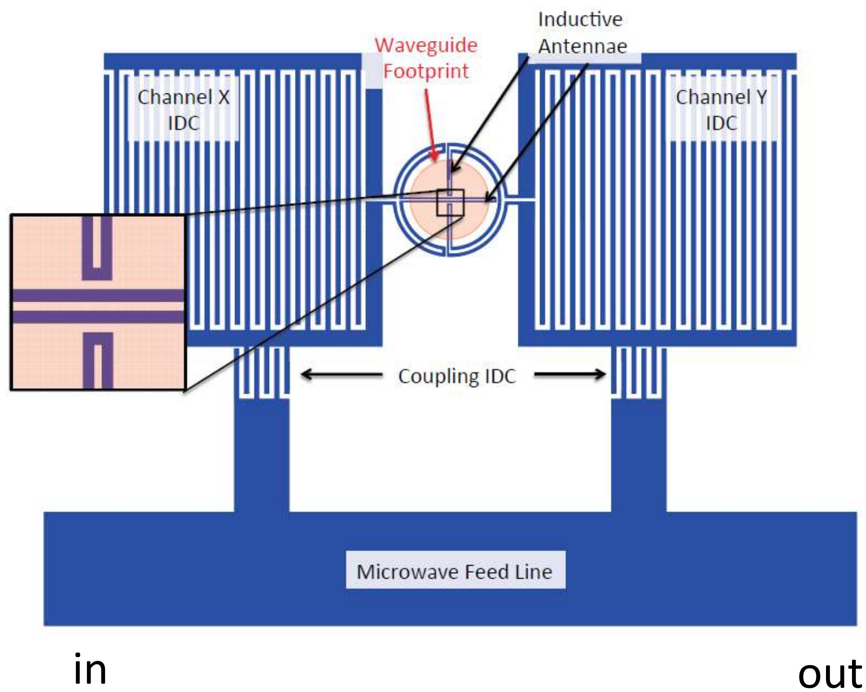
Credit: Yiwen Wang (unpublished)
Southwest Jiaotong University, China

Feedhorn-coupled MKID polarimeters/bolometers

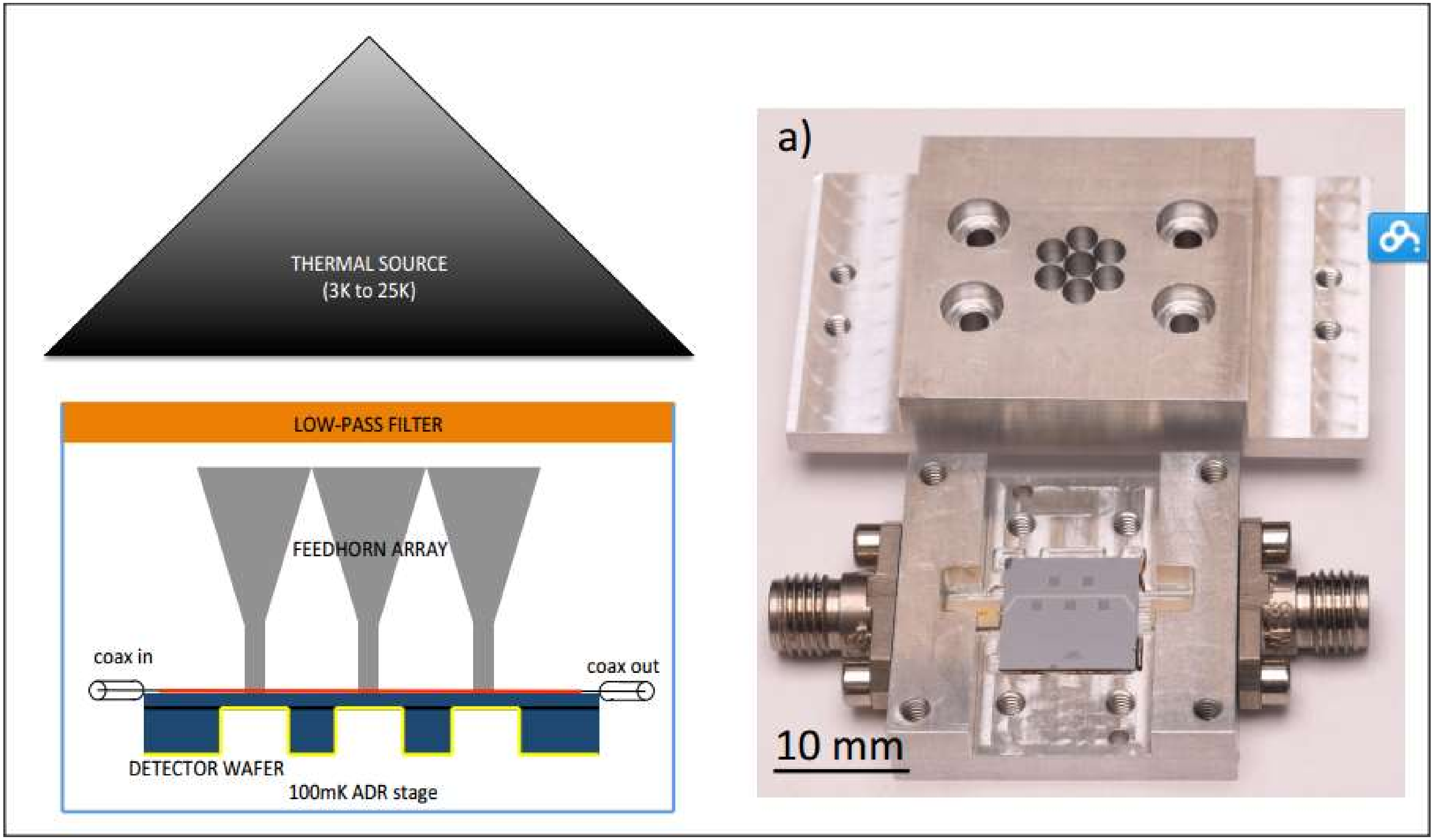
- Feedhorn-coupled, dual-polarization sensitive.



- Dual polarization



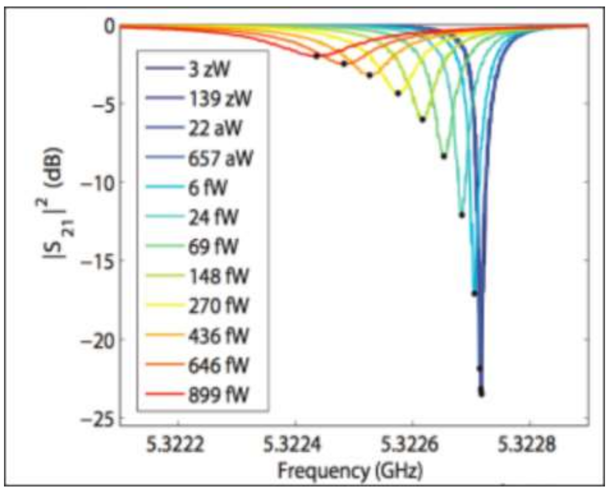
Lab test using blackbody source



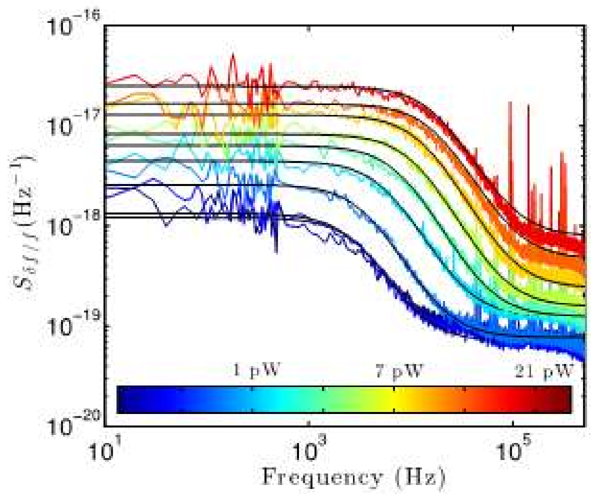
Detector sensitivity

- Lab blackbody load test has demonstrated photon-noise limited sensitivity at 1.2 THz (250 μm).

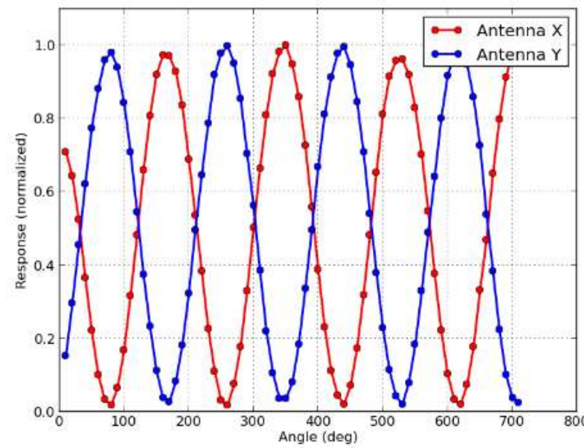
- Response to THz photon



- Photon (shot) noise



- Excellent cross-pol rejection



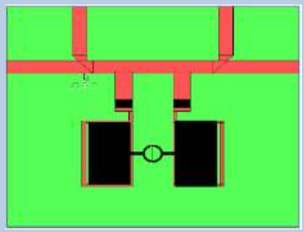
Credit: Johannes Hubmayr

Hubmayr et al, APL 106, 073505 (2015).

MKID array fabrication

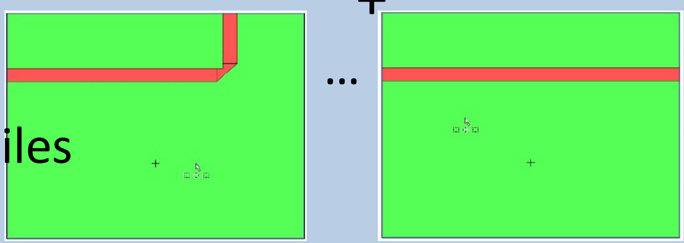
- New "tiling and trimming" layout/fabrication scheme efficiently uses the stepper to produce arbitrary-size (number of pixels, wafer size, pixel placement) high quality MKID arrays

template pixel tile



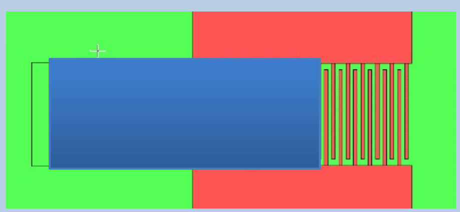
+

feedline winding tiles

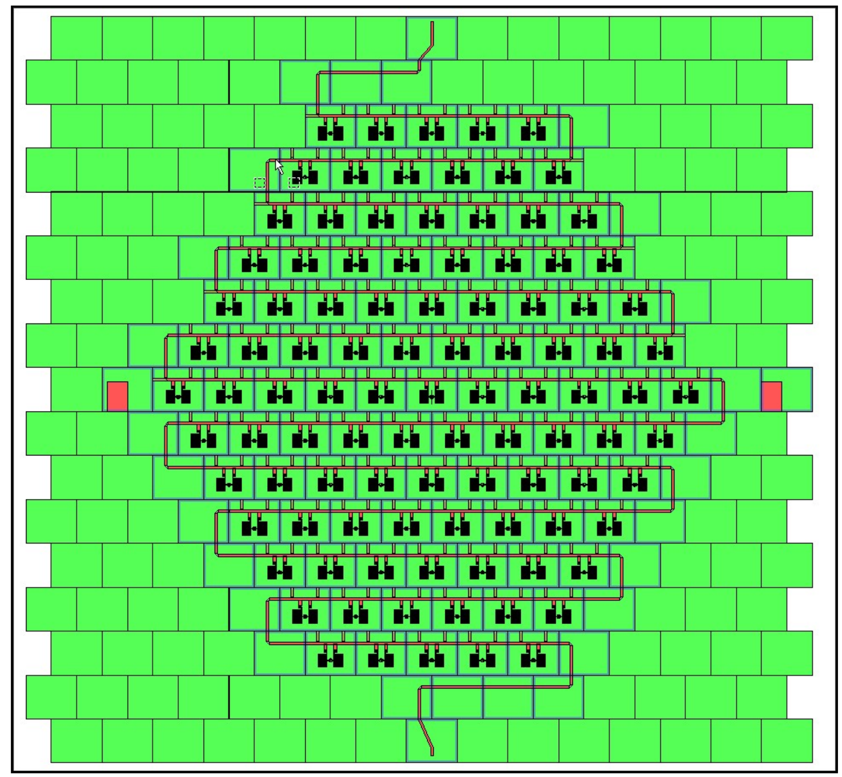


+

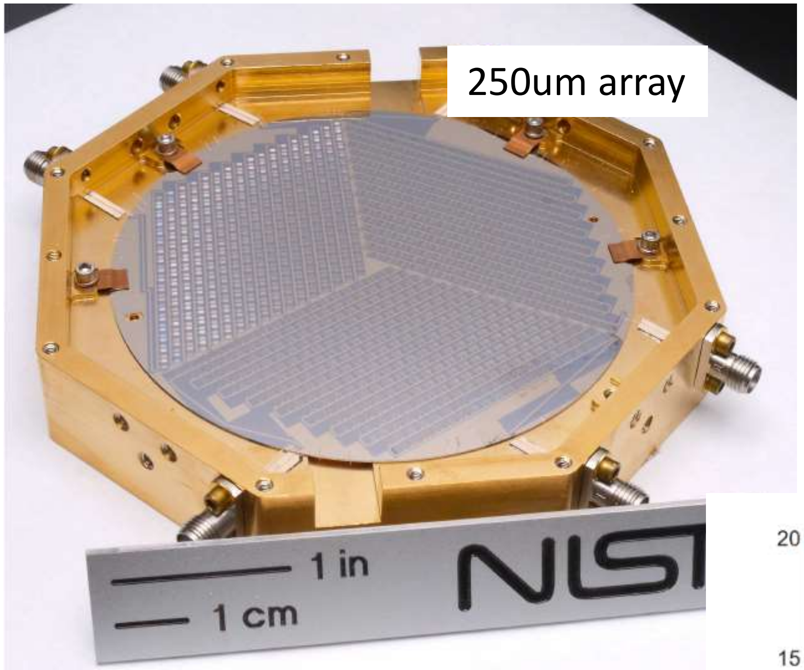
IDC triming mask



MKID array design kit

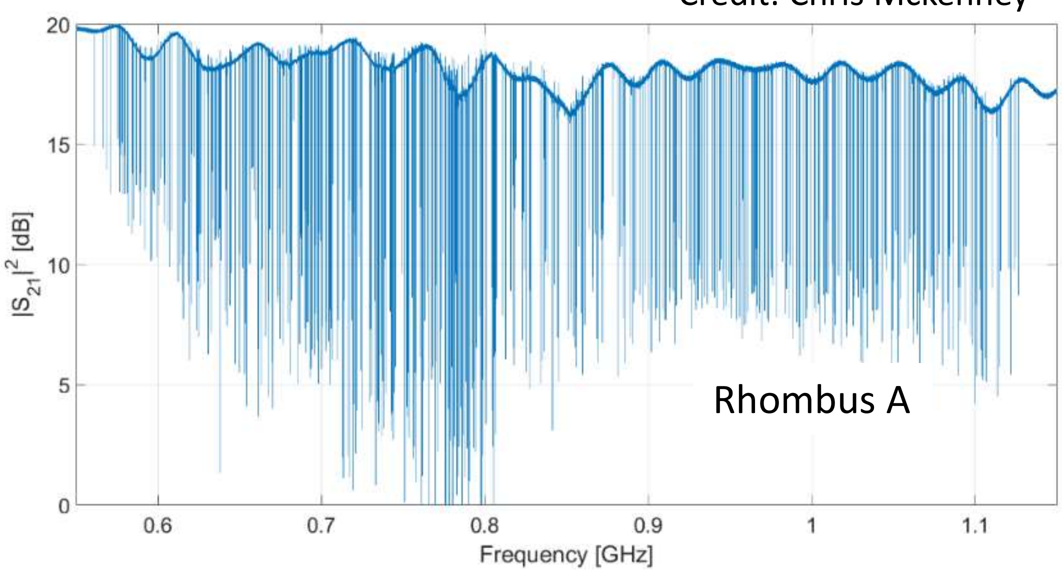


MKID arrays for BLAST



3 rhombuses, 306 pixels/rhombus
1812 MKIDs

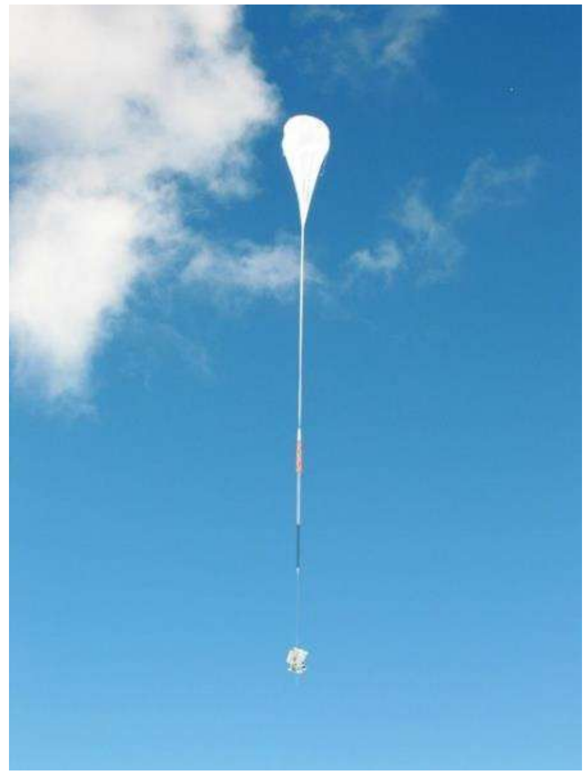
Credit: Chris Mckenney

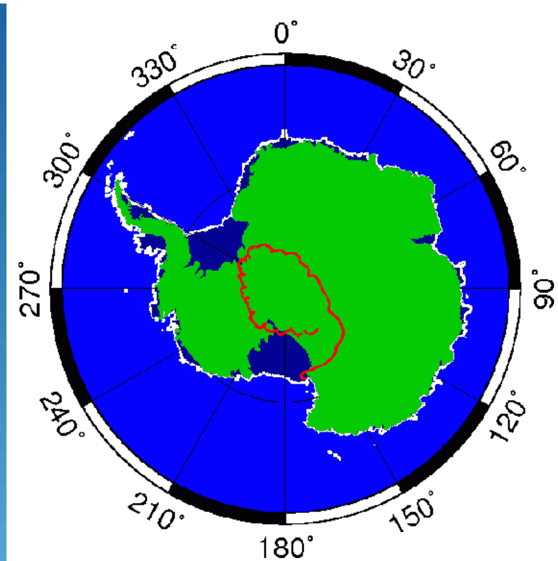


- Yield close to 100%, 20% collision (5 bandwidth exclusion)
- Qi ~ 500k@50mK, Qi ~ 40,000 under 17pW loading

MKID polarimeters for BLAST-TNG

- **BLAST**: Balloon-borne Large Aperture Submillimeter Telescope





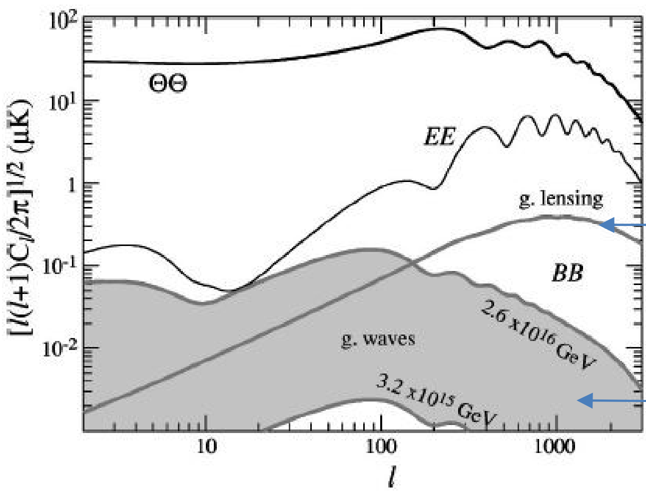
- 1.8 m mirror
- feedhorn coupled
- 3 arrays, 250, 350, and 500µm
- study star formation
- PI: Upenn + collaborators

BLAST	BLAST-Pol	**BLAST-TNG**
270 NTD detectors 2006	BLAST + Single Pol. 2010	**3000 MKID Dual –pol detector** **2017**

Research frontier

- Better performance
  - Nanowire: higher efficiency, photon number resolving, multiplexing
  - TES: faster, better NEP or energy resolution
  - MKID: better NEP or energy resolution

- Scaling to larger detector arrays: 1-1000 => 100,000 - 1M pixels



Detected by SPTPol in 2013

To detect the Primordial B-mode signal, CMB4 project proposes 500,000 detectors (multiple arrays) deployed on multiple telescopes to jointly observe for 3 years!!!

- Fabrication: 3-4 inch -> 6 inch wafer
- Readout: TDM -> microwave readout
- Refrigeration: more compact size, larger cooling power, lower cost