Superconducting Single Photon Detectors

D. Prober , Yale Univ. Depts. Applied Physics and Physics

with thanks for collaborators at

Arizona, Caltech, GSFC, JPL, U Mass, Yale and their partners

Outline

- Types of sensors; motivations
- Basic concepts; applications
- TESs - x-ray; visible/NIR; THz/FIR
- STJs, KIDs - soft x-rays
- Nanowires – ‘click’; visible/NIR

Why single photon?

- Weak sources; spectroscopy
- Encode information, entangle
- Timing, coincidence
- Measure particle energy
- *S*peed is important = challenge in cold env.
- Arrays = key enabler for most future applications

- Energy scales 1 eV = 1.2 µm = 250 THz
  1 meV = 1.2 mm = 0.25 THz

Definitions

- Thermal - Bolometer – P(t)

  NEP ≈ 10^{-19} W/(Hz)$^{1/2}$ (space goal)

  - Calorimeter – E(t) $\Delta E \approx NEP\ \tau^{1/2}$

- Excitation detector – same functions; QPs ≈ meV

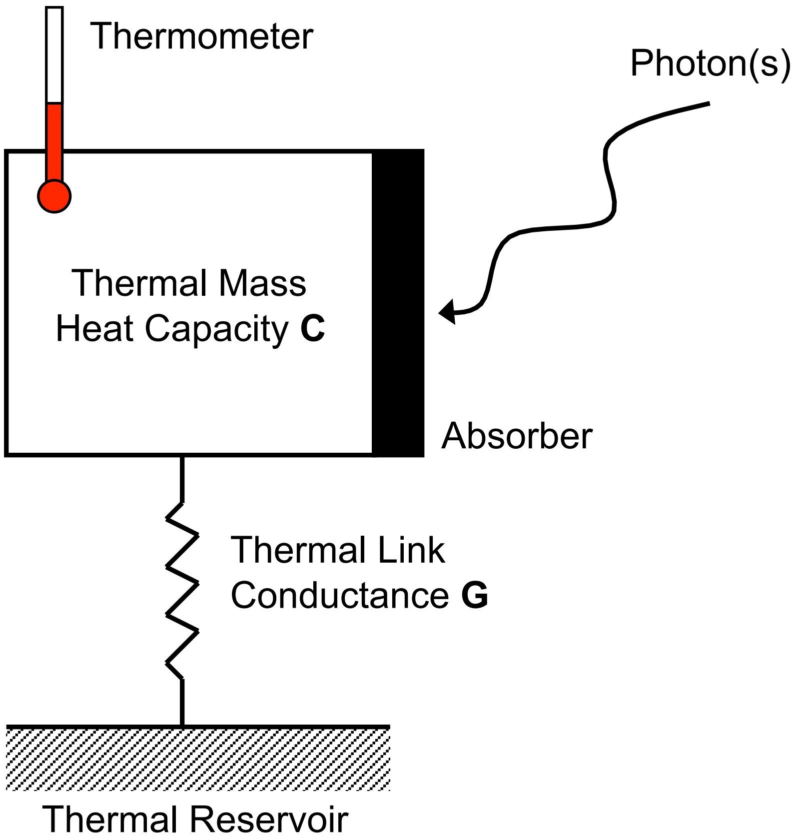
  $\Delta E/E \approx \Delta n/n \approx n^{-1/2}$ → for x-ray, $\Delta E/E = 10^{-3}$

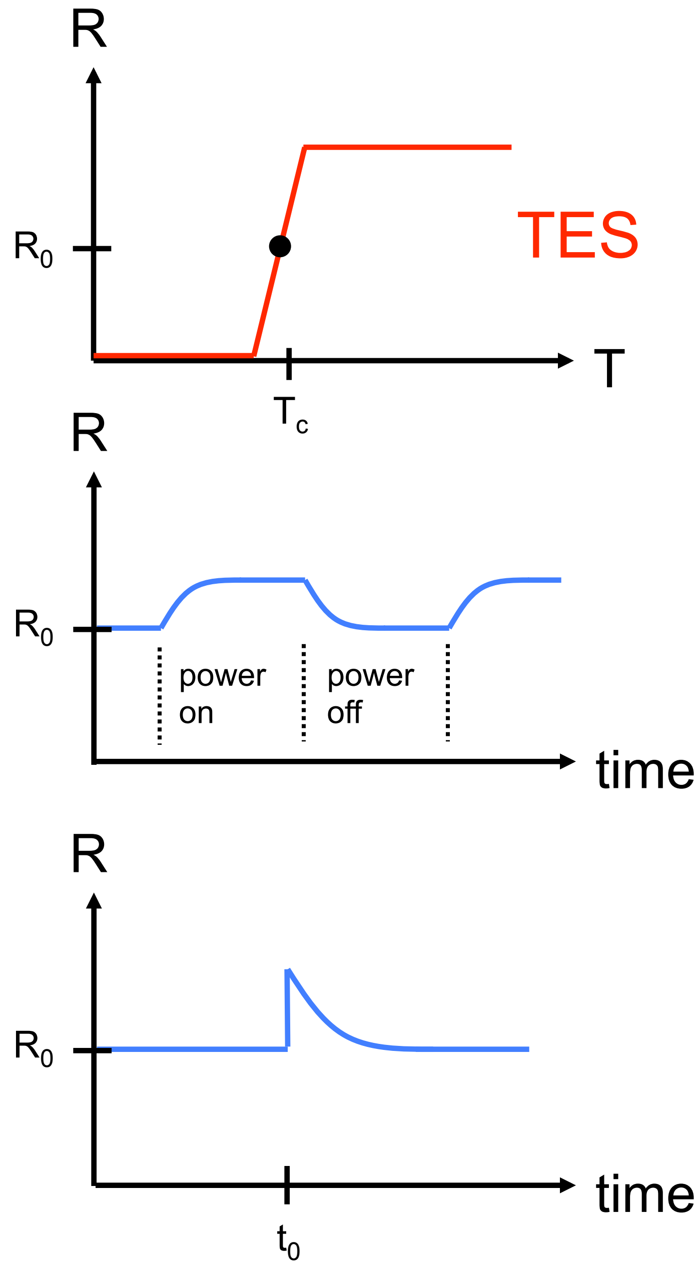
- Nanowire $I \leq I_c$; fast, sensitive, no energy res.

  ≈ PMT

- Multiplex – SQUID or μwave resonators

Bolometer Detector – Thermal → cold + small





$\Delta T = E_{ph}/C$

Single photon

$$\tau_{th} = \frac{C}{G}$$

Sensitivity Considerations

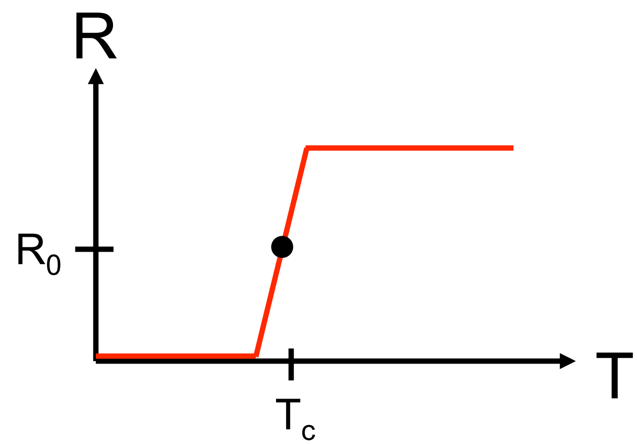
$$NEP = \Delta P/(Hz)^{1/2}$$

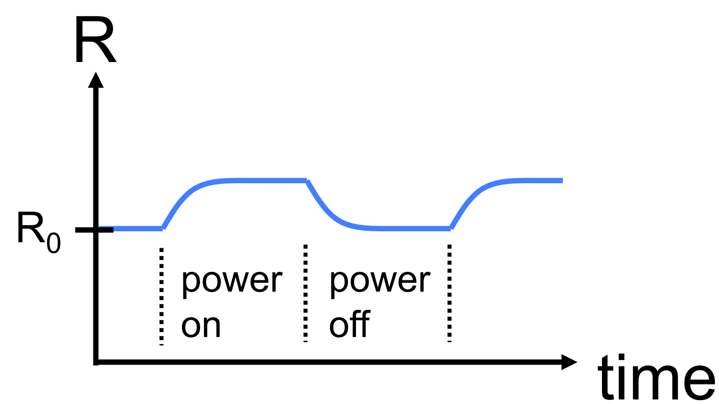
$$= (4kT^2 G)^{1/2} \ W/(Hz)^{1/2}$$

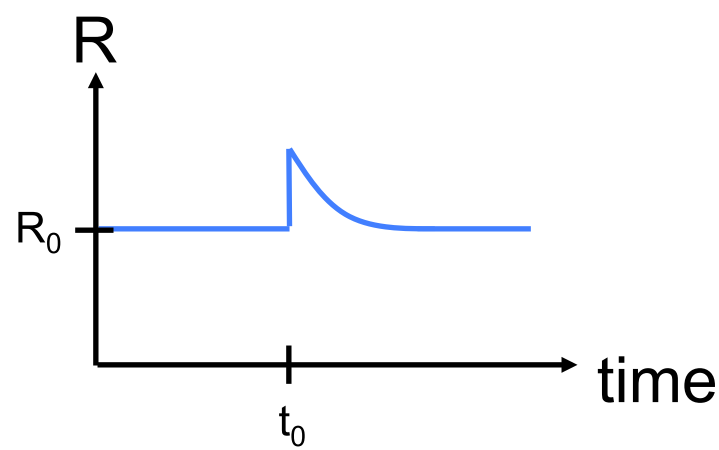
τ = C/G, want C small

'small is beautiful'; cold is essential

$$\Delta E \approx (kT^2C)^{1/2} = \text{variance}$$

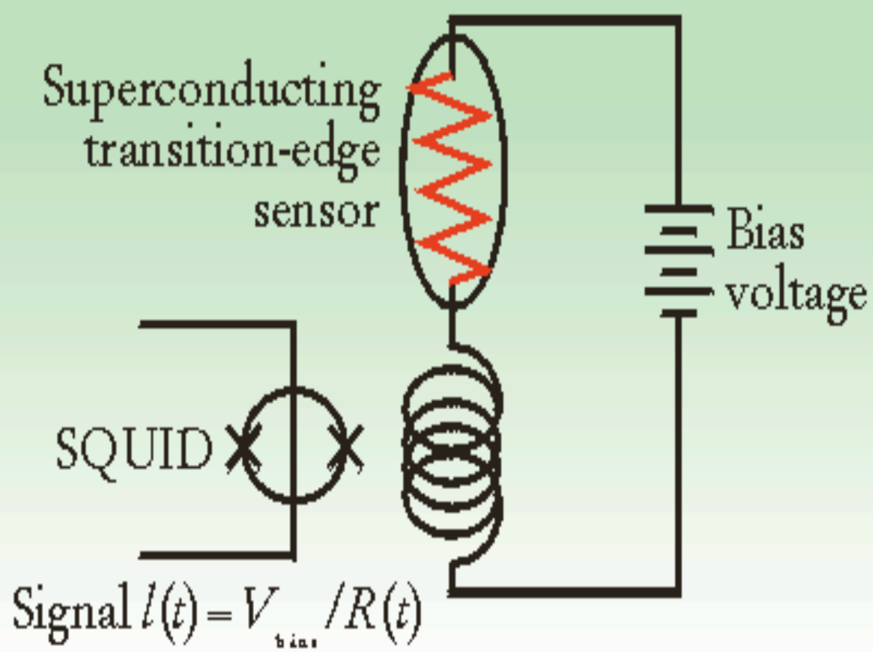






Basic Transition Edge Sensor Operation

Superconducting wire (the TES) is used as a thermometer – read out changes of resistance electrically.



Typical SC transition T_c < 1K

Voltage bias ➔ faster response, more sensitive

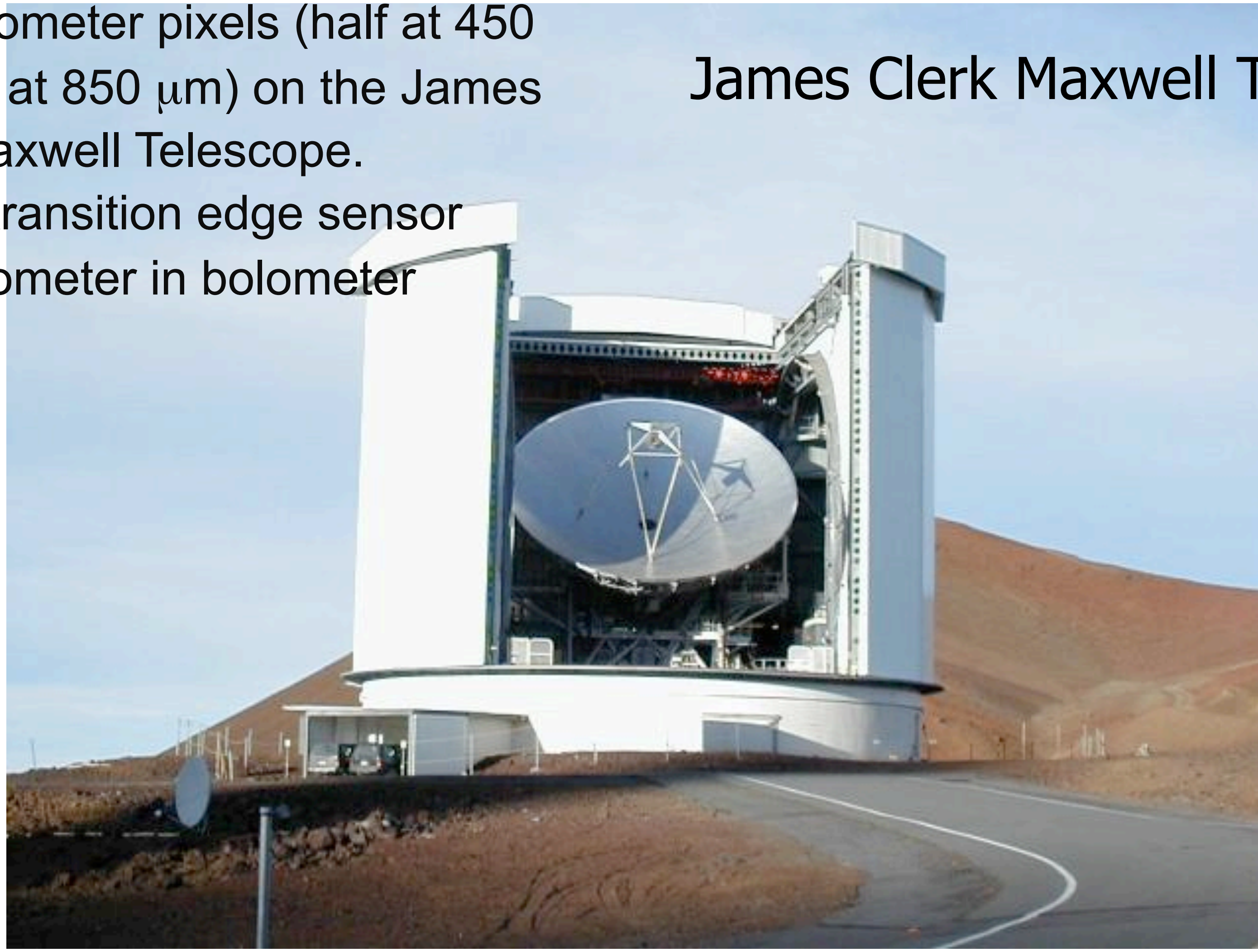
SQUIDs essential for low T multiplexing, low noise

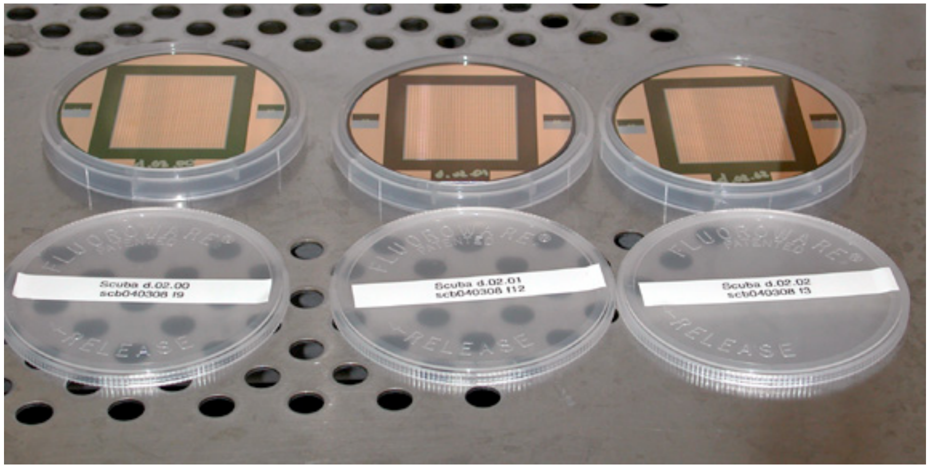
Low count rates for astro x-ray applications ≈ 100/sec

Kilbourne, TIPP09

- A collaboration of the UK, Canada, Raytheon, and NIST
- SCUBA-2 will consist of 10,240 TES bolometer pixels (half at 450 μm, half at 850 μm) on the James Clerk Maxwell Telescope.
- TES = transition edge sensor = thermometer in bolometer

James Clerk Maxwell Telescope

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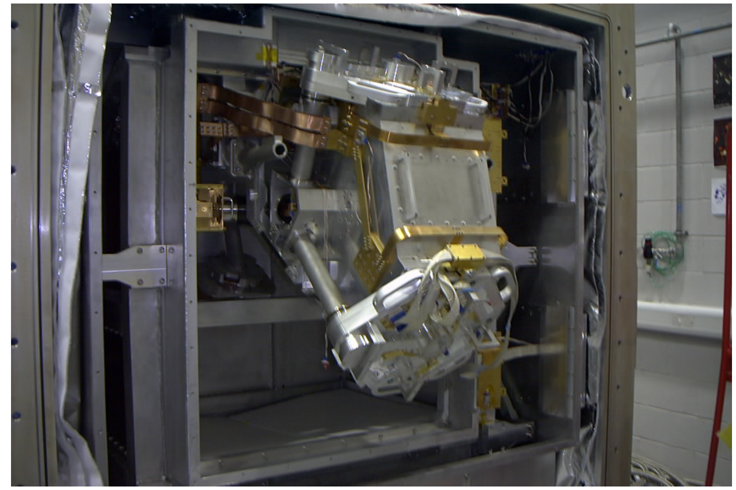
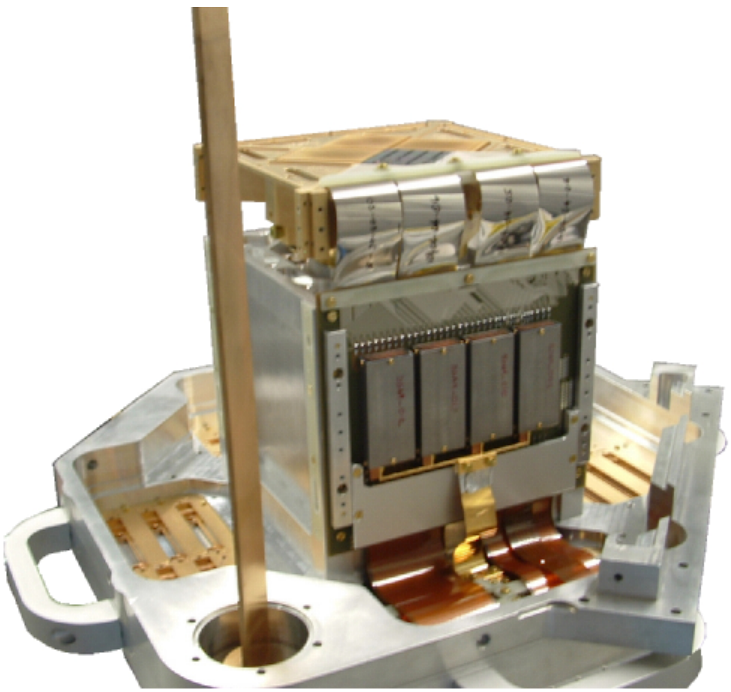
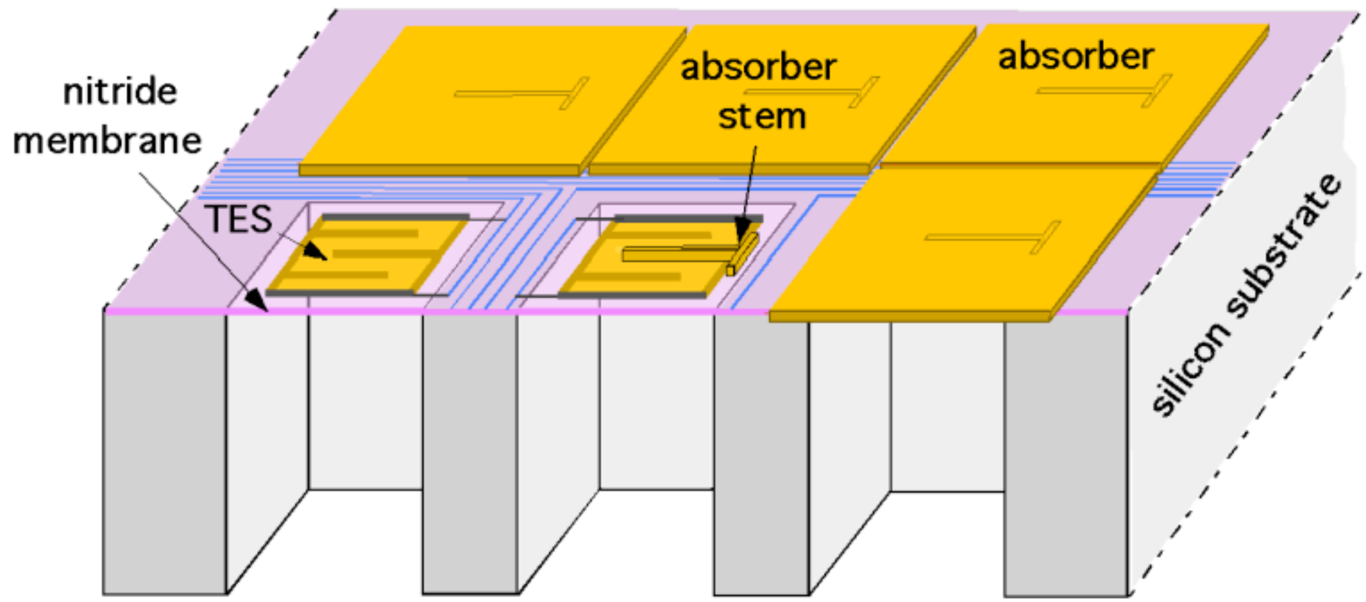


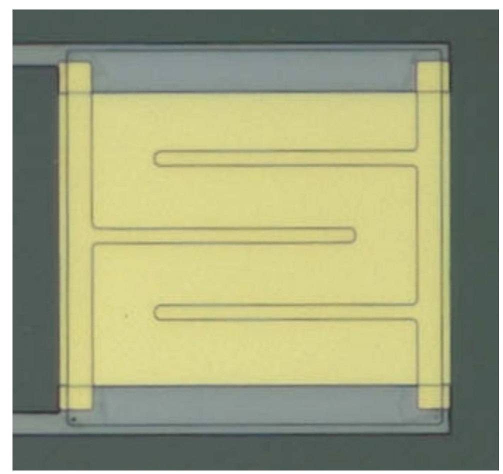


X-Ray TES structure

Robust array construction



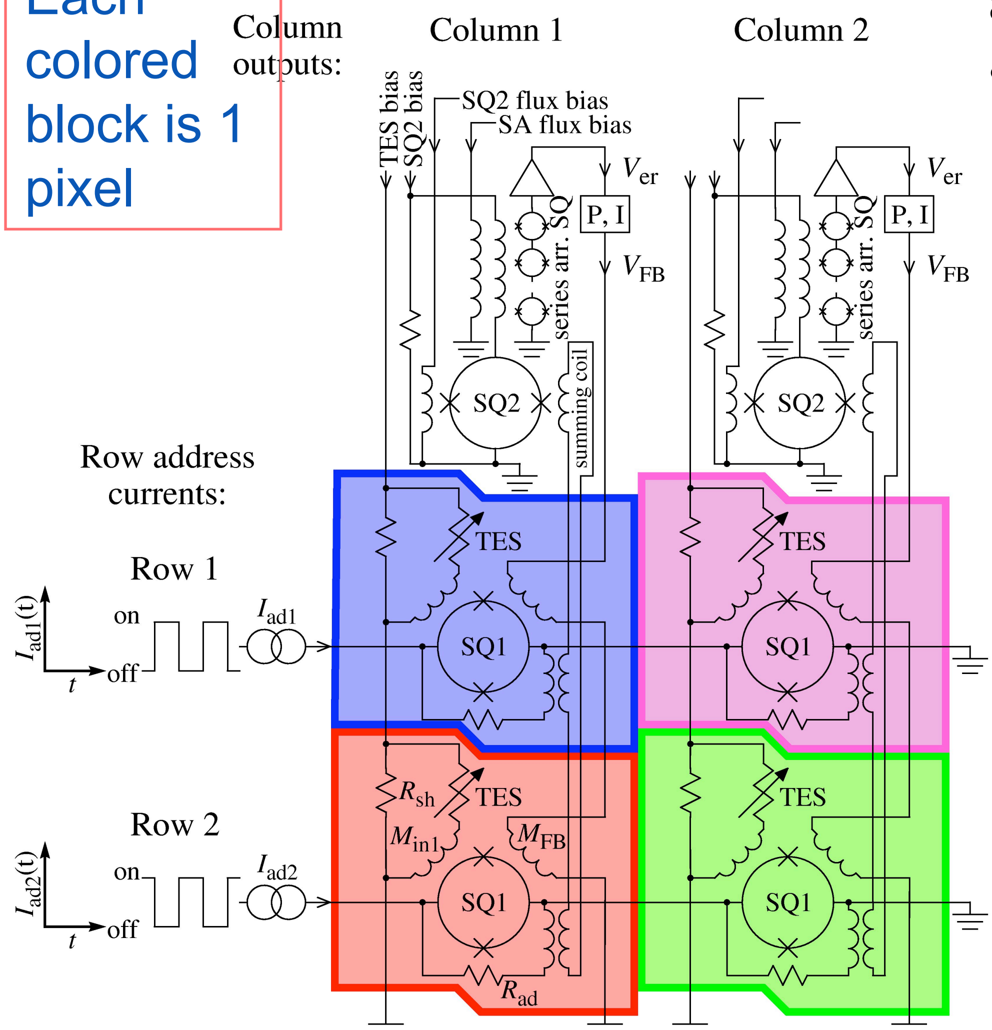
Thick Au/Bi absorber, weak attach
Mo/Au bilayer TES, non-SC stripes
reduce noise
TES is thermometer only
msec response



Kilbourne, TIPP09

Array-scale read-out using NIST time-division multiplexing *(Irwin, Doriese)*

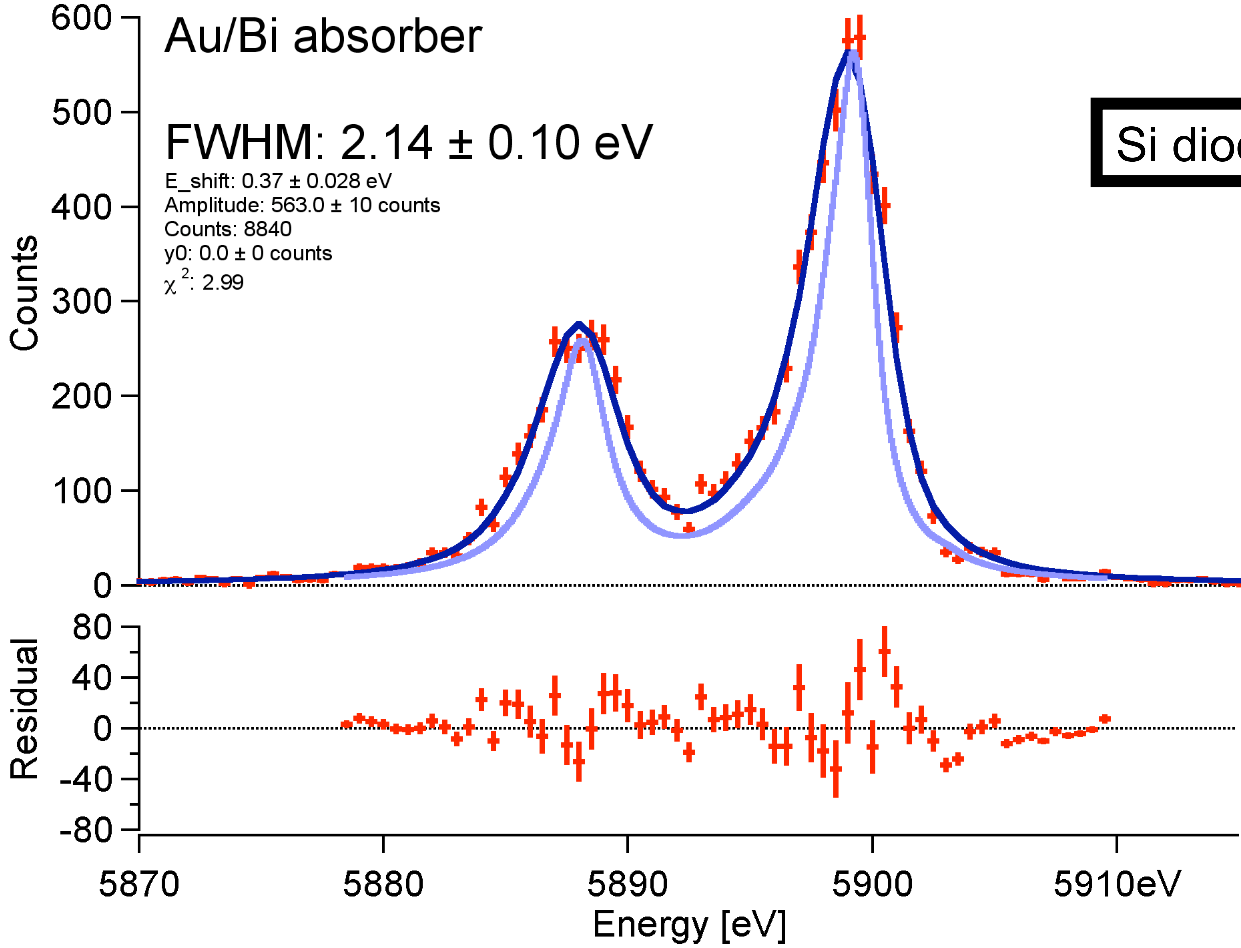
Each colored block is 1 pixel



- 2 x 2 array is shown as example of *N*-row by *M*-column array
- TDM operation:
  - each TES coupled to its own SQ1
  - TESs stay on all the time
  - rows of SQ1s turned on and off sequentially
  - wait for transients to settle, sample I_{TES}, move on
  - SQUIDs are nonlinear amplifiers, so use digital feedback
  - V_{er} sampled, V_{FB} stored for next visit to pixel
  - each column: interleaved data stream of pixels

Kilbourne, TIPP09

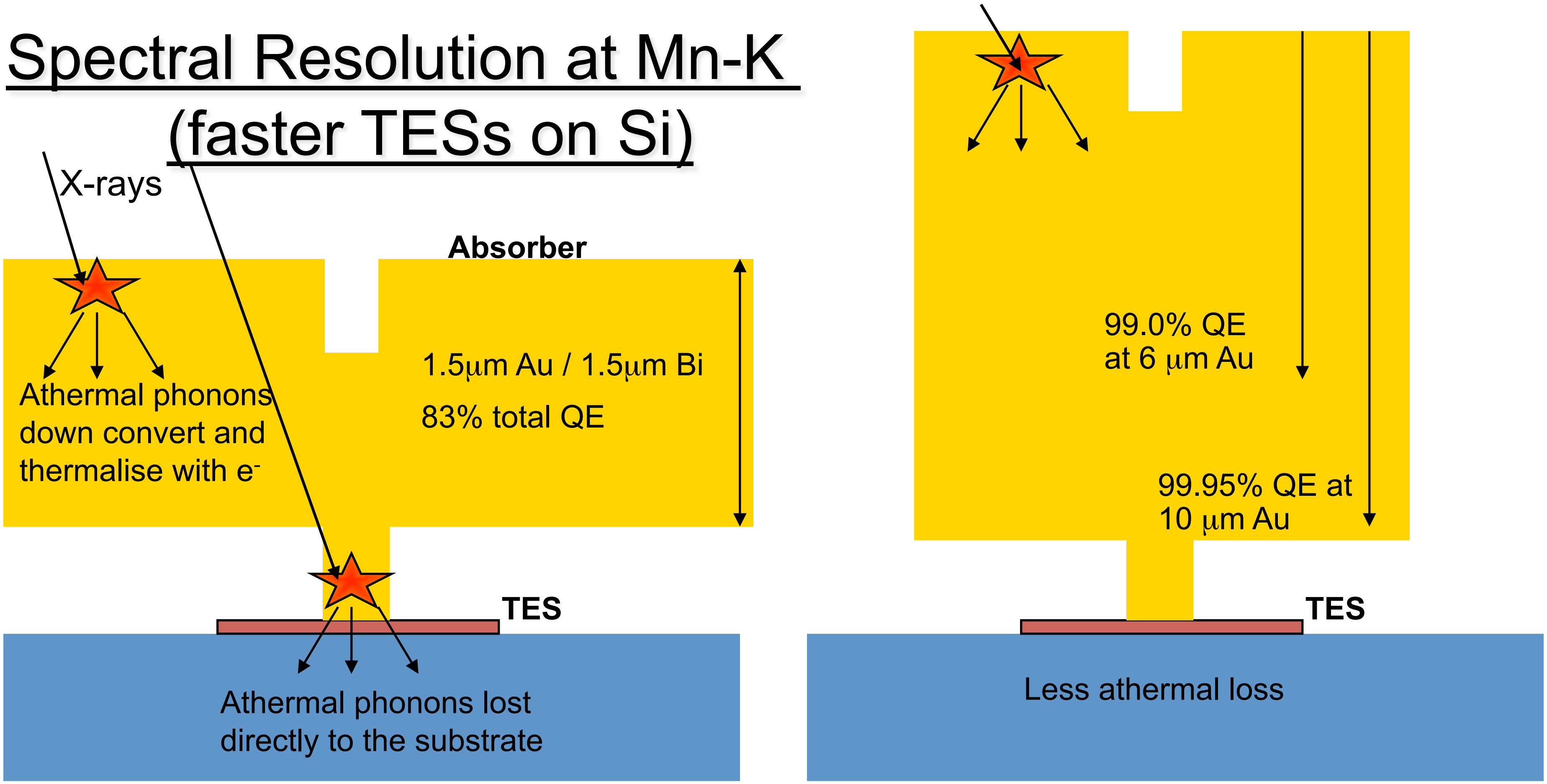
Au/Bi Absorbers (~ 1 μm Au, 4 μm Bi) on SiN membrane; msec response



Si diode – 120 eV FWHM

Kilbourne, TIPP09

Spectral Resolution at Mn-K (faster TESs on Si)



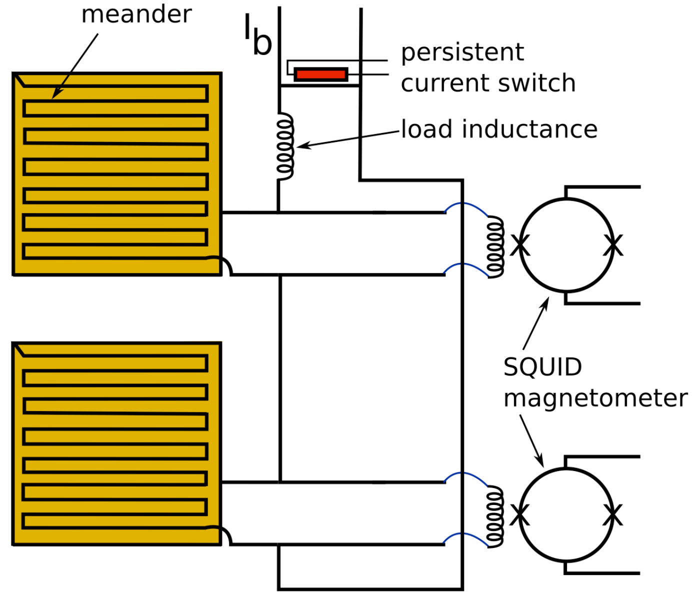
- Use thick Si, not SiN membrane; G_{th} isolation is from TES-subst. boundary resistance only not thin SiN. $\tau = C/G\,(1+L)$ L = loop gain of el-th feedback
- *BUT*, get some events with less energy = hits in the stem, ➔ loss to subst.
- Use thicker absorbers - stop more photons away from sensitive stems
  - Solar applications: 250->50 μm pitch, 10 μm thick Au (same total heat capacity)
    - ⇒ 99.95% absorption in 10 μm
    - ⇒ 99.0% absorption in 6 μm

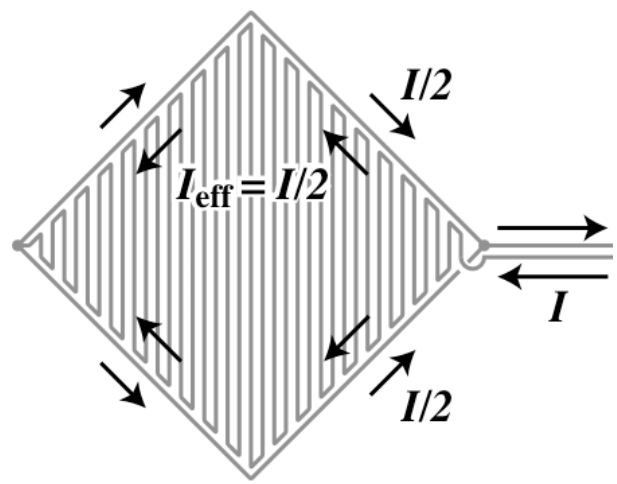
Smith et al., LTD 13

X-ray Detectors – other options may work

MMC arrays

- for close-packed arrays, meander geometries are promising
  - arrays of superconducting Nb meanders onto each of which a layer of magnetic material (Au:Er) is deposited
  - when a current passes through the meander, a magnetic field is produced in the magnetic material. No additional applied field required. Use SQUID readout.





Kilbourne, TIPP09; citing GSFC team

TES for Visible and NIR

Quantum Information

- Quantum Optics
- Quantum Information Processing (e.g. Linear Optics, Quantum Computing, Quantum Key Distribution)

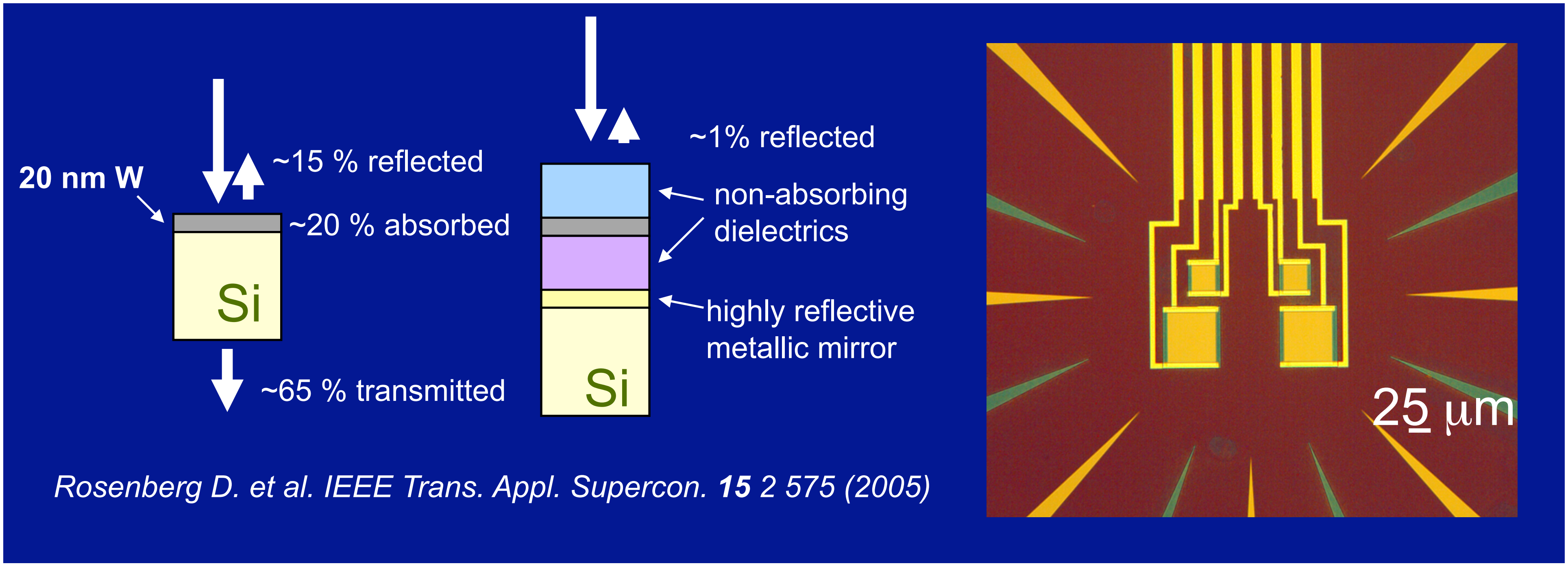
Detector requirements desired:

- High efficiency (95% at 1550 nm)
- Low dark counts / errors (Blackbody limited 1550 nm)
- Number resolving capability (0.26 eV FWHM)
- Wavelength tunability (1550nm, 850nm)
- Fast recovery time (< 1ms), Low jitter (100ns)

A. Lita LTD13

Optical Structures to Enhance Detection Efficiency *A.Lita et al. Optics Express 16, 3032-3040 (2008)*

- Optical stack increases probability of absorption in TES material
- Careful measurements of optical constants for all thin film layers
- Materials compatibility below 1 K



- 95% ± 2% system detection efficiency for 1550 nm optimized TES

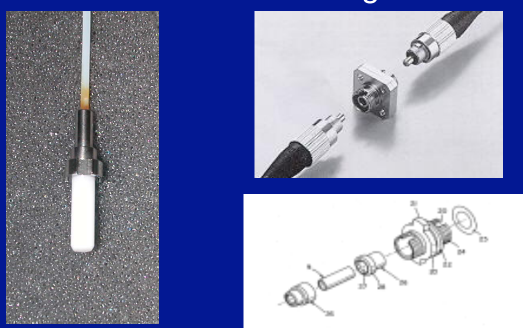
DP: T = 0.18 K; ΔE = 0.29 eV vs. 0.18 eV $\tau \approx 1\ \mu s$; *40% of en. Collected*

Room-Temp BB photons are a problem

A. Lita LTD13

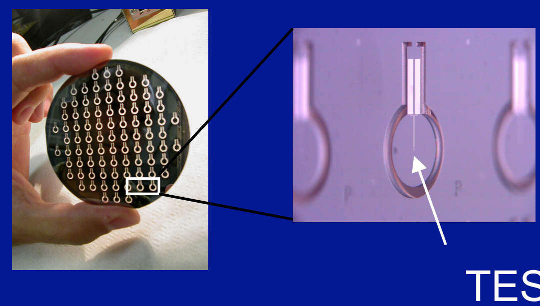
Measurement setup (Lita et al.)
Self-alignment scheme TES = 25 μm

FC/FC mating connectors



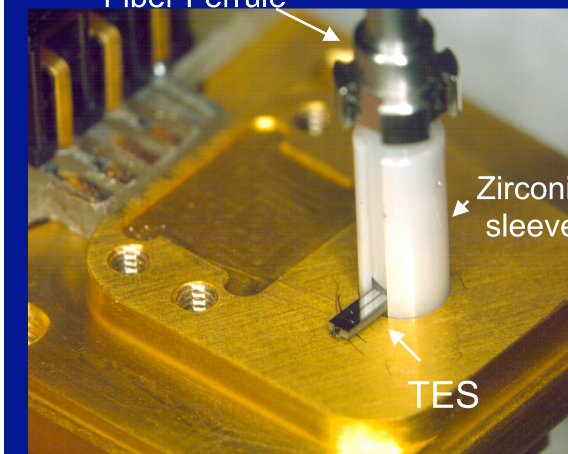
Accurately machined Fiber ferrule

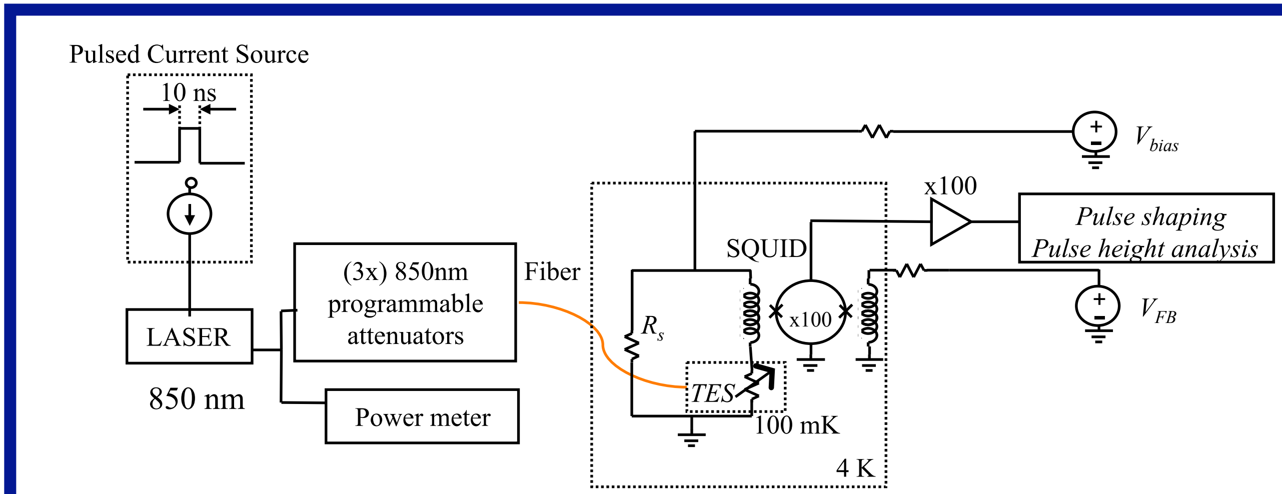
Accurately machined Zirconia sleeve



Deep RIE etch Bosch SF_6/C_4F_8 process: circular chips with precise dimensions

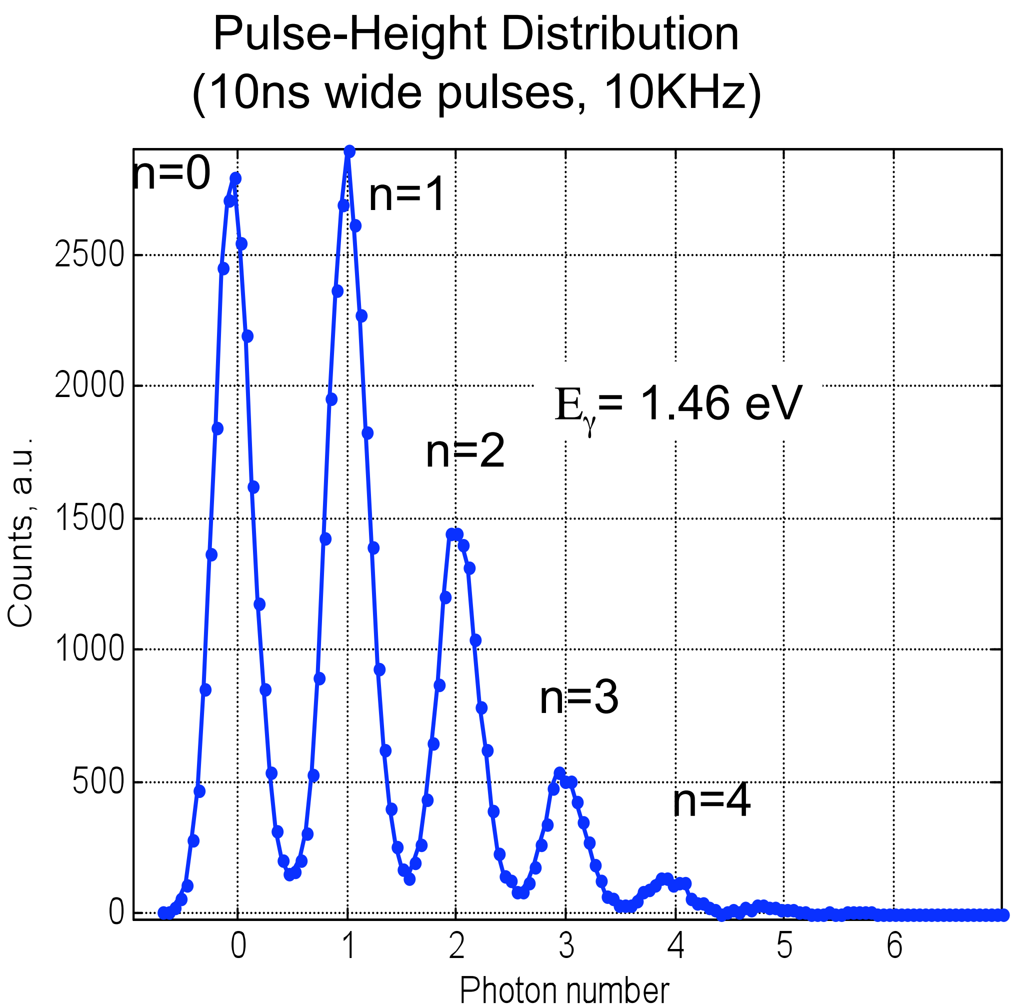
Fiber Ferrule





A. Lita LTD13

Hf TES in Optical Stack – for 850 nm -- no α-Si

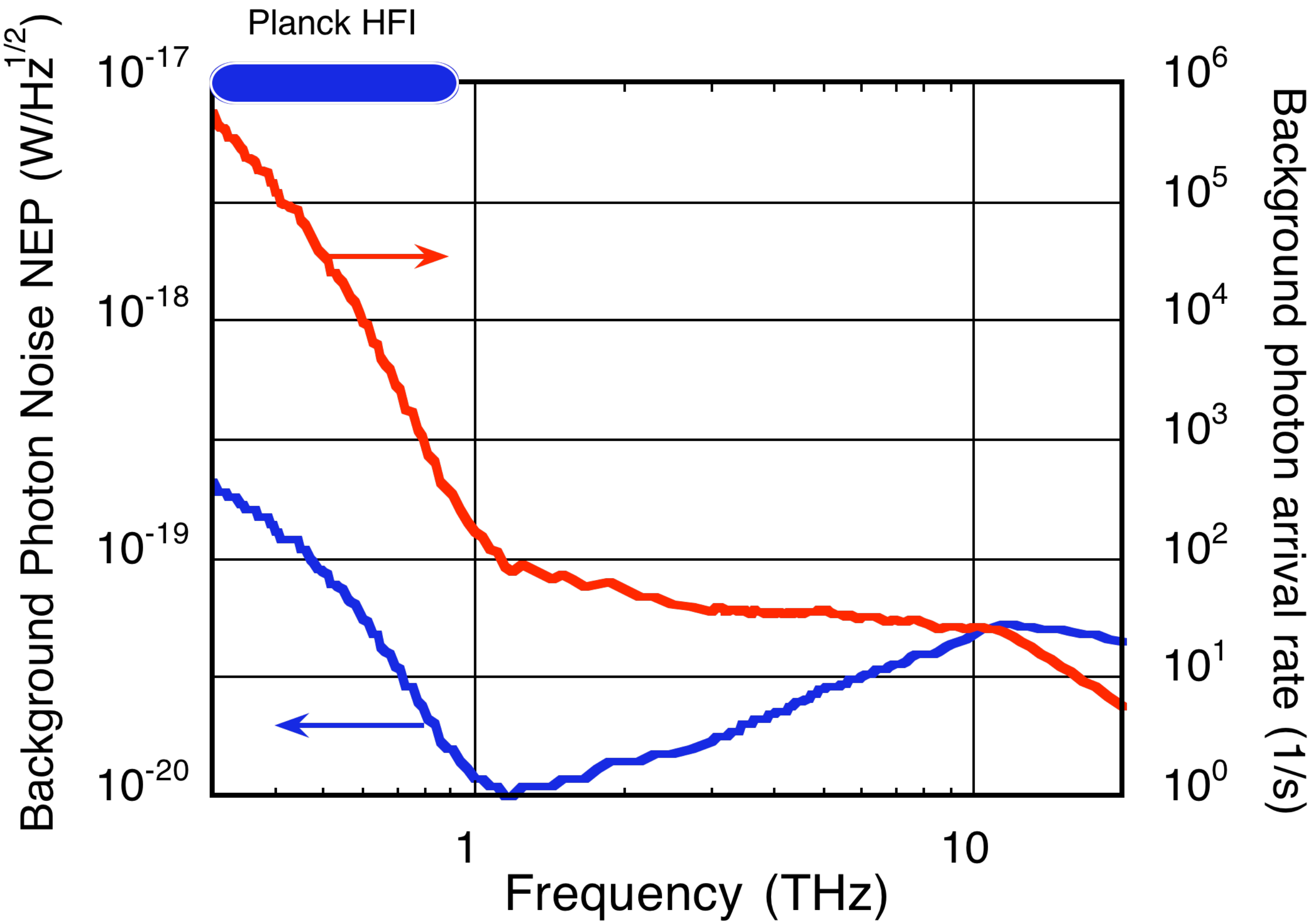


- System detection efficiency: 85% ± 2%
- $P(n) = (\mu^n / n!)\, e^{-\mu}$ $\mu = \langle n \rangle$

A. Lita LTD13

THz/FIR Single Photon Det.-

- photon counting > 1 THz (λ = 300 μm)

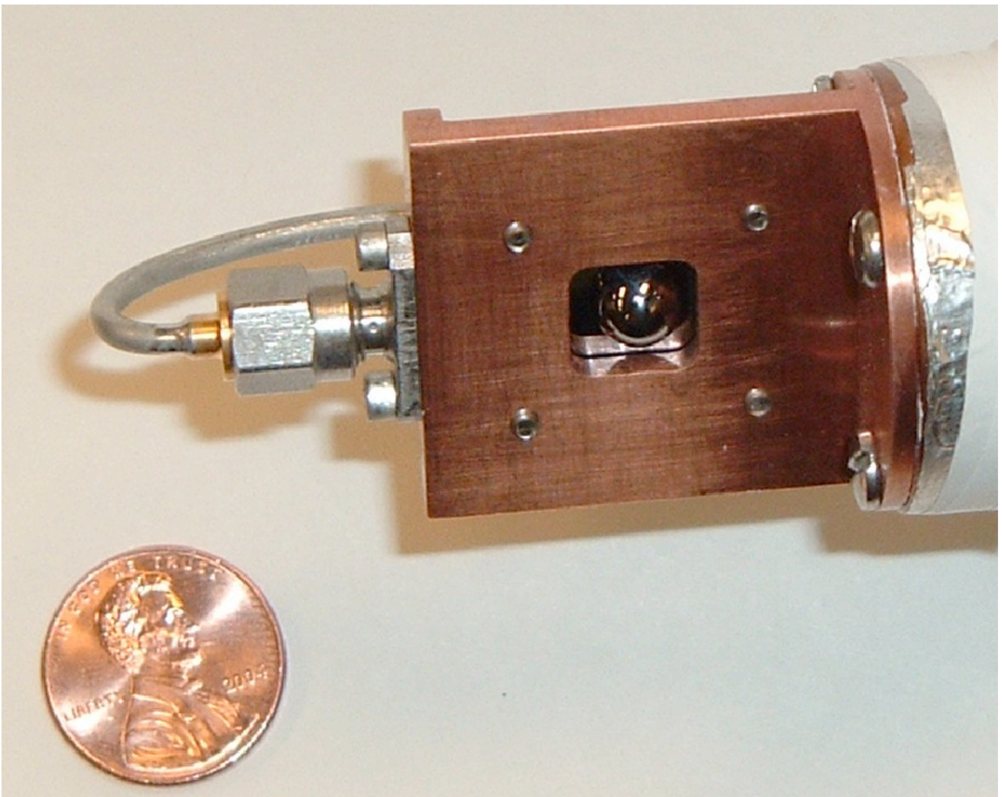


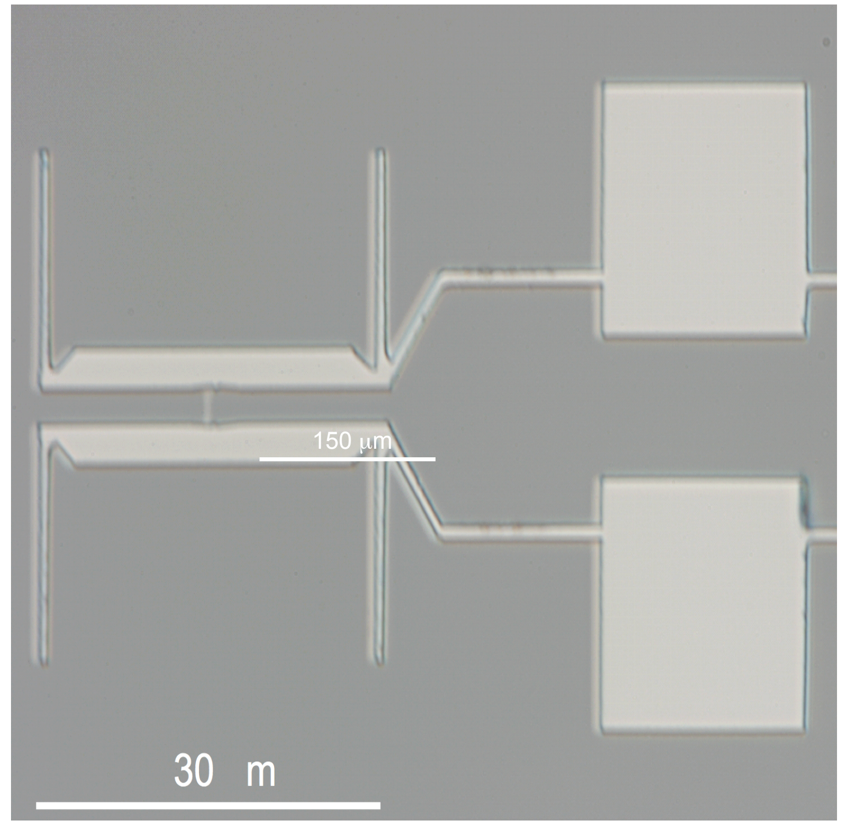
B. Karasik

Phonon Cooled HEBs at Yale (Nb; for R.T. sources)

Double Dipole Antenna, 1.2 THz Design†; 1 x 2.5 μm Bridge

Total of 22 chips fabricated and shipped: 9 for Caltech, 7 for JPL, 6 for Yale





† Double dipole antenna design made with advice from Anders Skalare at JPL

D.Santavicca, Yale

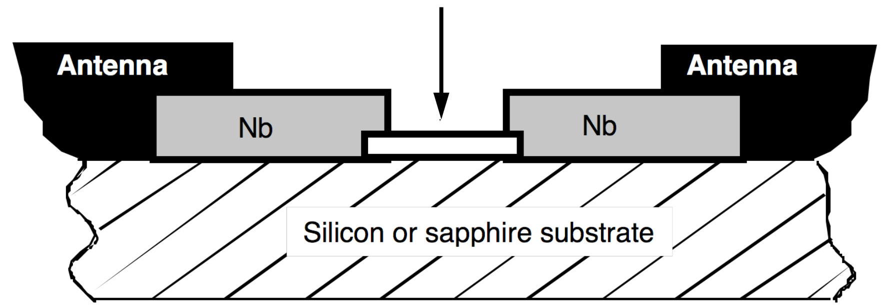
Antenna-Coupled Ti TES Nanobolometer

Small Ti volume = fast and sensitive
→ no substrate in heat capacity

Higher superconducting gap in Nb confines excitations in the Ti

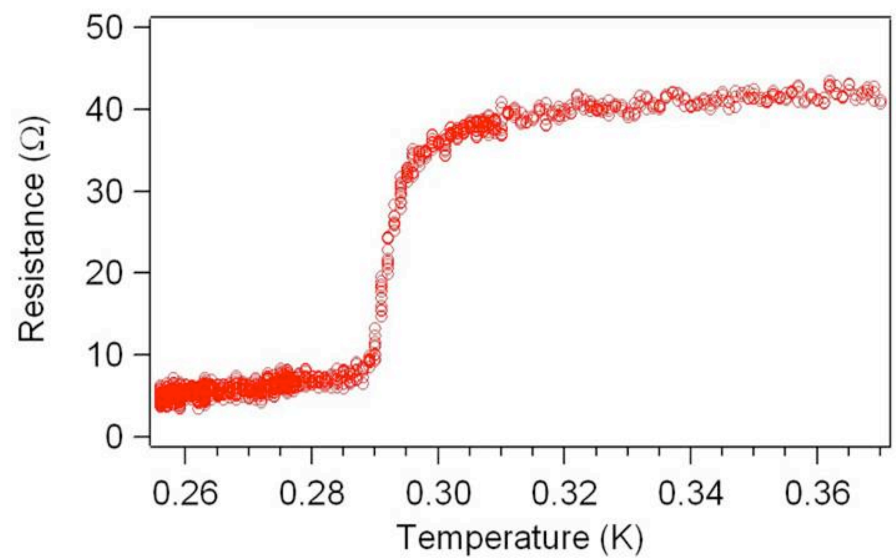
Want completely shielded environment -but- want fast interrogation (readout) which could perturb detector and let in stray photons

Challenge: $P_{sat} \sim 1$ fW
but at T = 0.3 K blackbody = 30 fW! (single-mode)



From B. Karasik, JPL

RF reflection changes on the transition

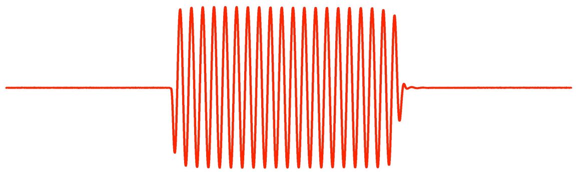


D.Santavicca, Yale

Testing with Fauxtons

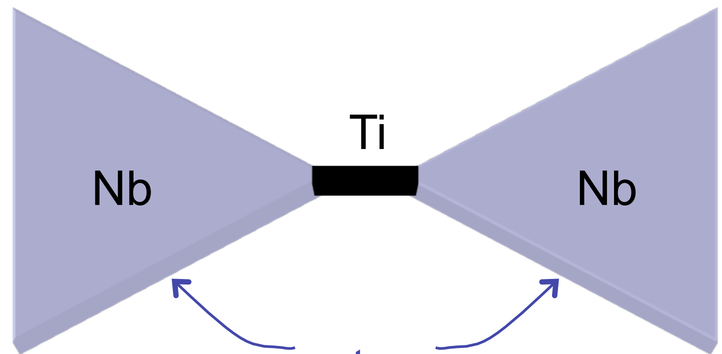
fauxton (faux photon) – a new "quanta" for single photon testing

Fast microwave (20 GHz) pulse; absorbed pulse energy (fauxton) = energy of single higher-freq. photon



Readout by measuring the reflection coefficient at 1 GHz with low noise cryogenic microwave amplifier

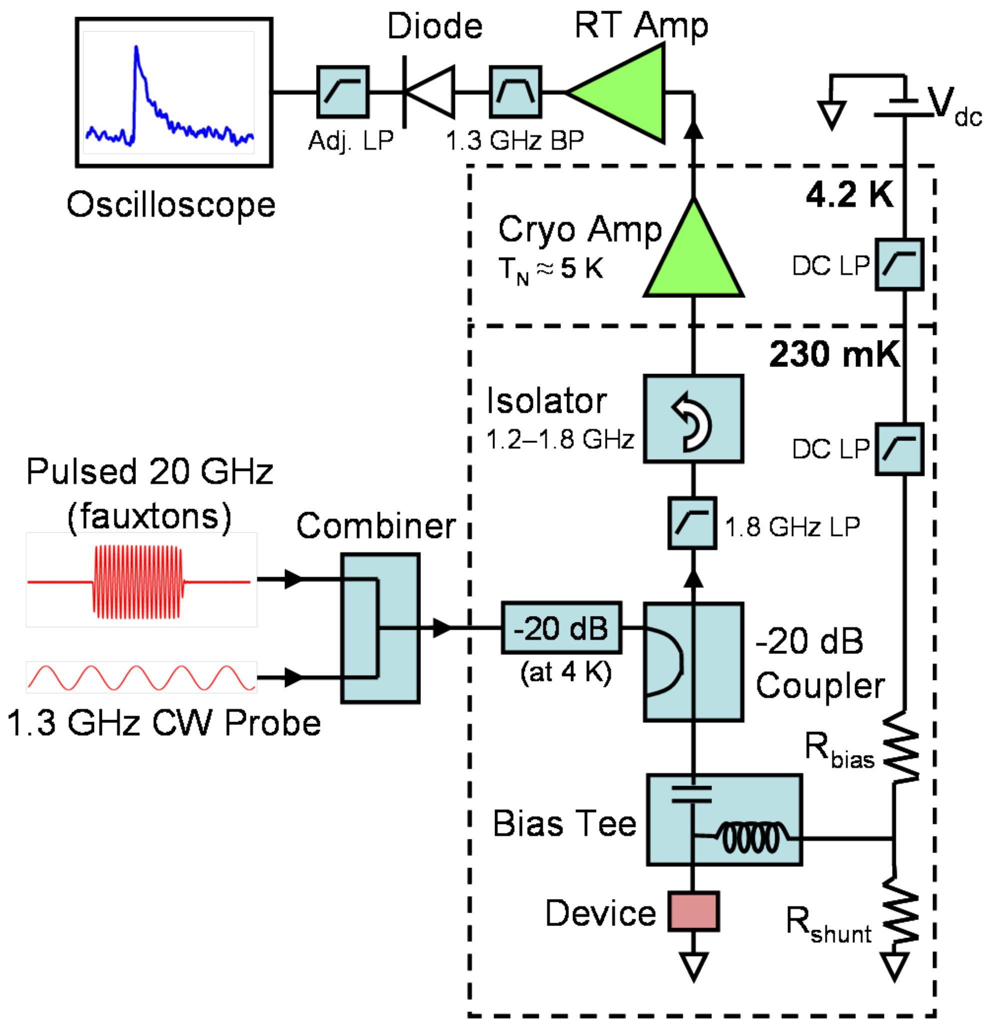
Leads (rf, dc) are not shown

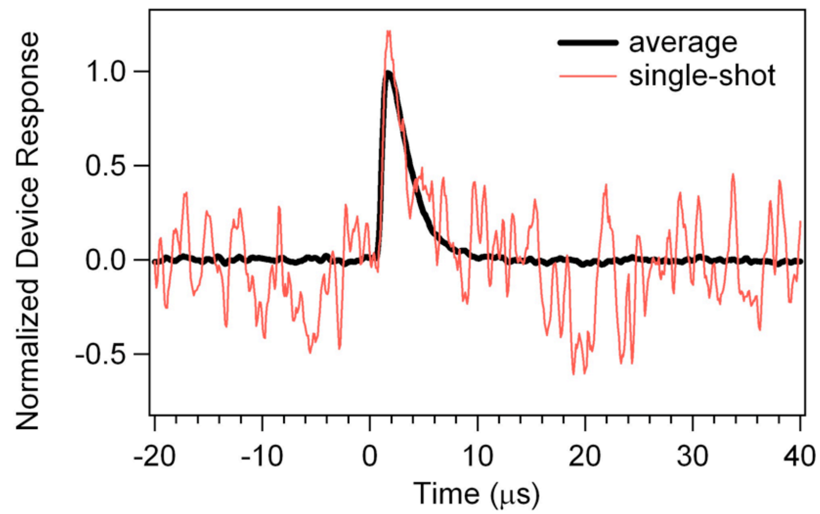


- Testing in a dark environment; no stray photons P << 1fW
- Arbitrary tunability of fauxton energy
- Can "sneak up" on hardest problems; optimize device fabrication, performance, and signal processing while a THz single-photon test system is developed

D.Santavicca, Yale

Testing with Fauxtons





R_{shunt} = 50 ohms or 3 ohms

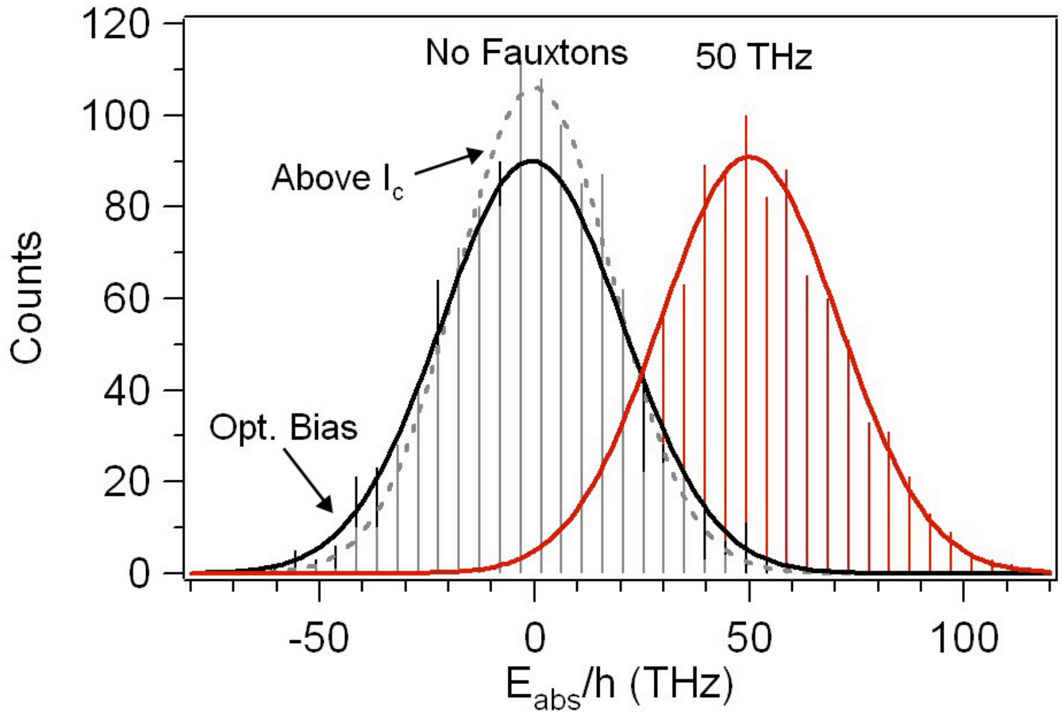
τ_o = 7 μsec vs. 2 μsec

R_{shunt} doesn't short the microwaves!

Experimental schematic for fauxton testing
Trigger signal used

D.Santavicca, Yale

Testing with Fauxtons: Energy Resolution



Measurement (fwhm)

ΔE_{total} = 50 THz

ΔE_{amp} = 43 THz

ΔE_{device} = 24 THz

≈ 100 meV

Theory

$\Delta E_{device,th}$ = 20 THz

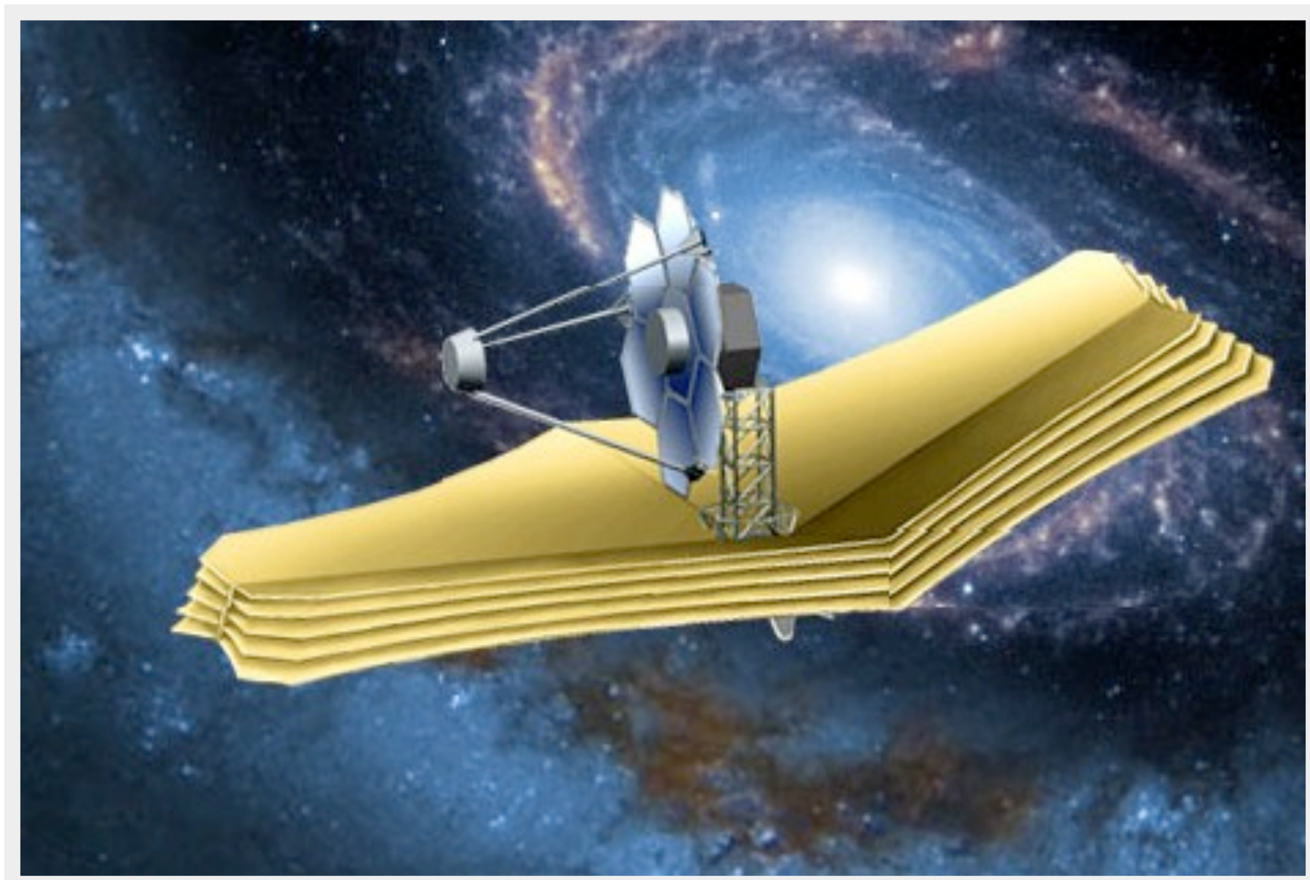
Future:

- Present device: 4 x 0.35 x 0.07 μm; T_c = 0.3 K; smaller volume and T_c = 0.2 K ➔ $\Delta E_{device,th}$ = 0.8 THz
- Lower noise amplifier – SQUID or Jos. paramp (Y)

D.Santavicca, Yale

Future sensitivity challenges in space

Future spectroscopic space missions featuring cryocooled (4-5 K) primary mirrors (e.g., SPICA, SAFIR, CALISTO, SPECS) will require a ~ 3-order of magnitude detector sensitivity improvement

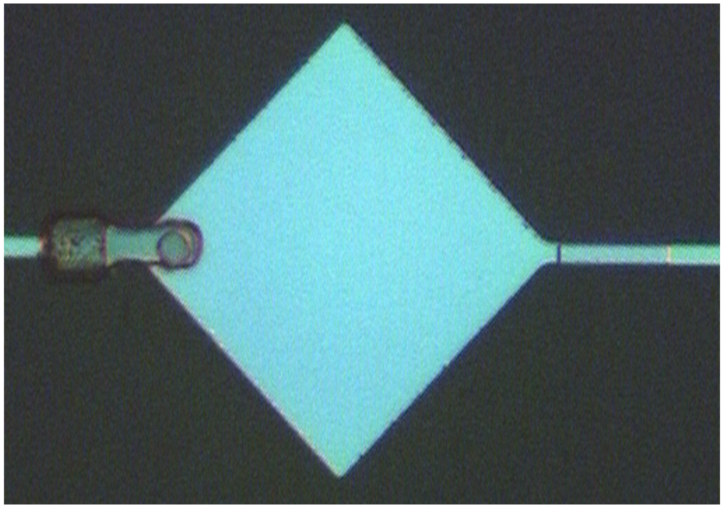


- Photon integration below 1 THz
- Photon counting above 1 THz

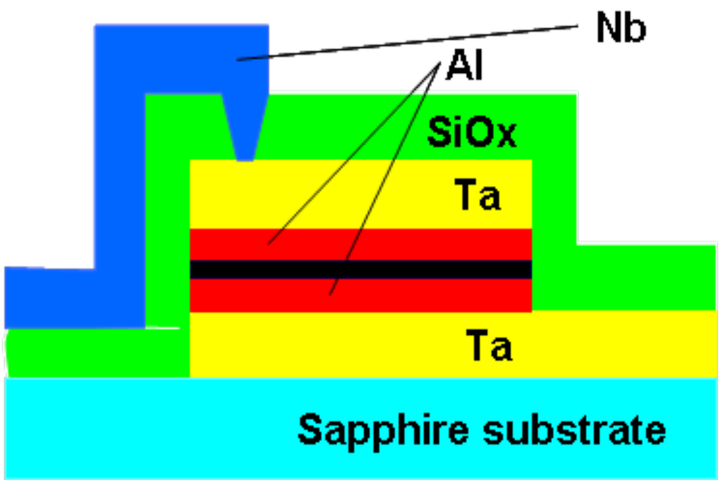
Karasik&Sergeev, *IEEE Trans. Appl. Supercond*. 2005

-- see Karasik (SQUID), Santavicca

STJ (excitation) detector



Photon breaks Cooper pairs ➔
2 quasiparticles/photon initially,
multiply by cascade to n ≈ E_{ph}/E_g,
then tunnel thru oxide barrier
δn = statistical variation in n



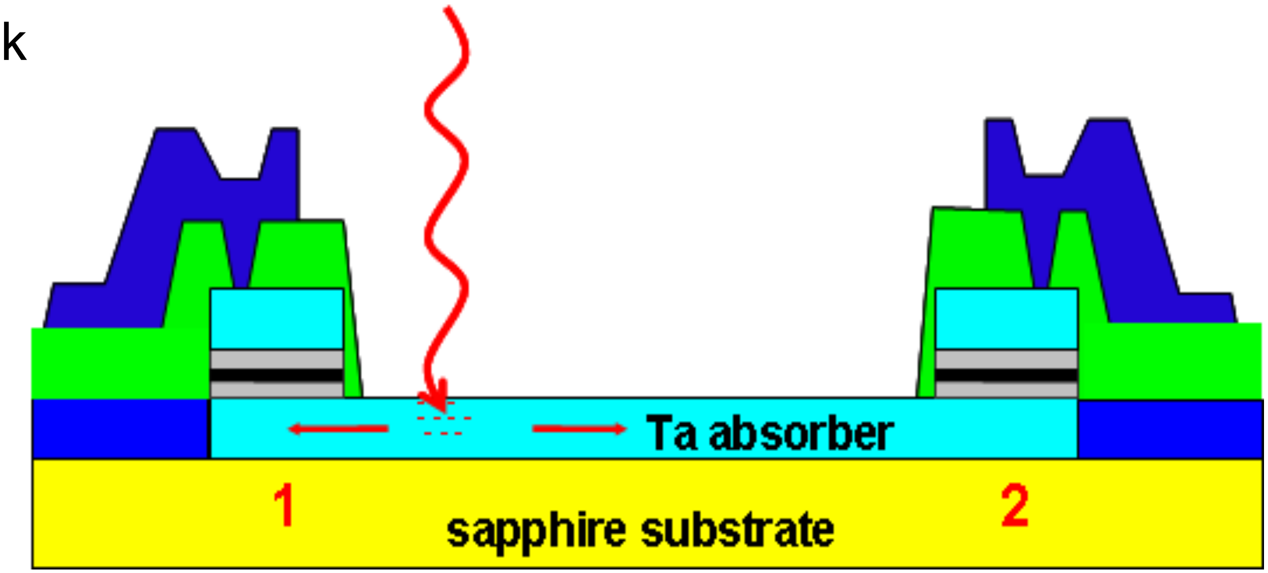
$T \ll T_c$

STJ – high impedance ➔
charge division imaging = DROID

P. Verhoeve, LTD 13

DROIDs (ESA) – faster than TES, worse resolution

- Distributed Read-Out Imaging Detectors
- Find E from the 2 pulses
- UV photons from back
- Many 'pixels'



Ta absorber
30x400 μm^2,
0.5 μm thick

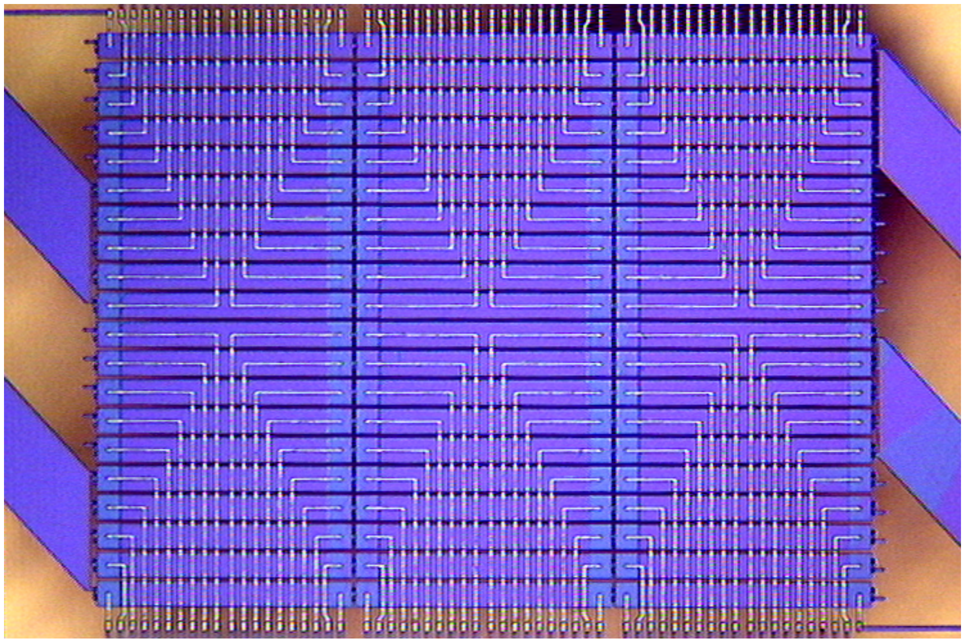
ΔE= 16.6 eV @ 5.9 keV (tunnel limit 7.0 eV)

ΔE= 12 eV @ 5.9 keV, Yale, Lin et al.

- Much stronger trapping and smaller tunnel limit if Al-Ox-Al junctions are on the side of Ta absorber = Yale approach.

P. Verhoeve, LTD 13

First Results On The Imaging Capabilities Of A DROID Array In The UV/Visible

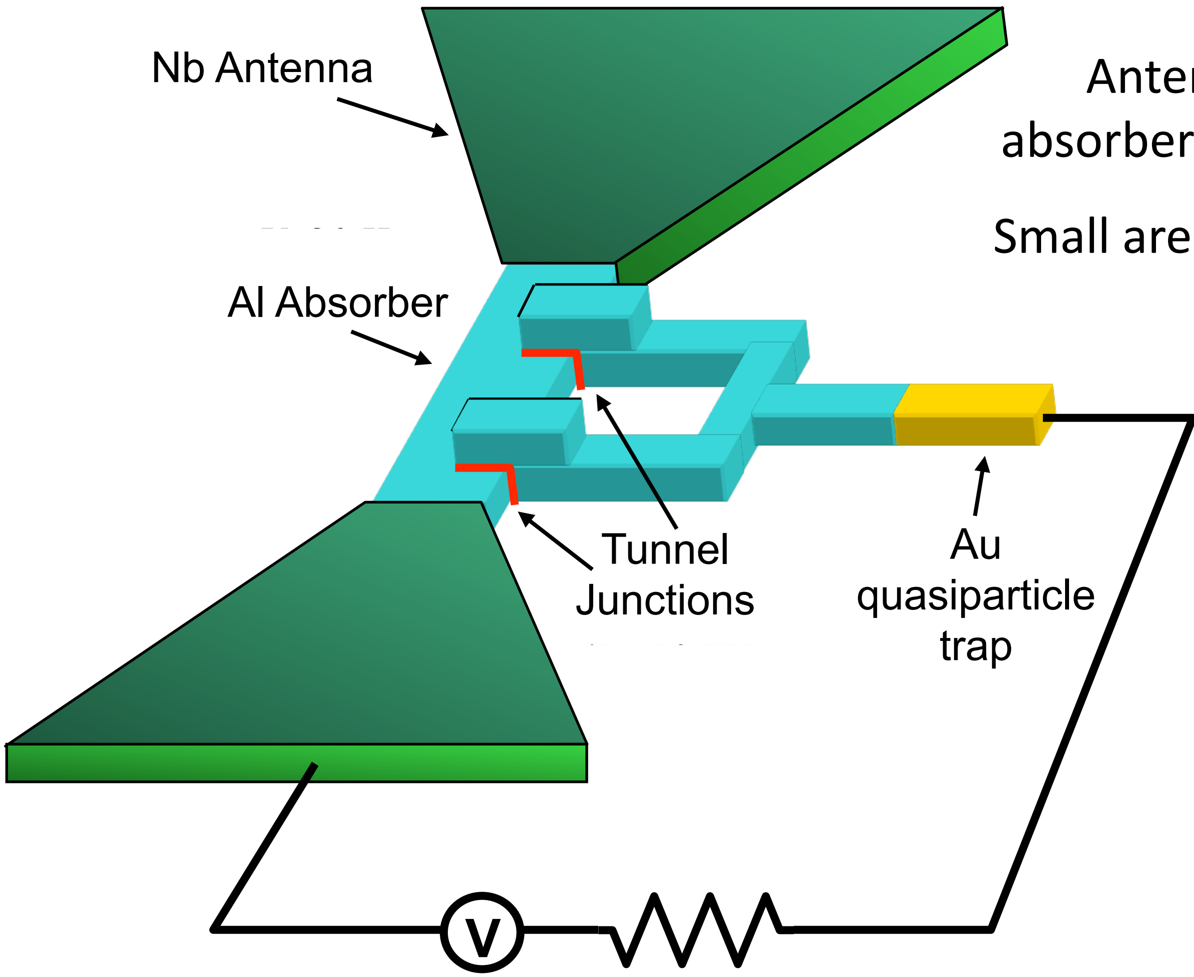


R.A. Hijmering,
et al., LTD13

Timing info

- 3x20 DROID array 33.5x 360 μ m^2
- 5.5 x S-Cam 3; photons from back side
- 11 ‘pixels’ per DROID; 660 ‘pixels’ total
- Measured in S-Cam3 system (single STJs)
- Offline coincident events determination
- Testing, development in progress

Submm STJ Detector –



Antenna impedance matched to absorber R_n → good quantum efficiency

Small area junctions → low dark current

Expect $R \geq$ (2e)/photon for photon energy ≥ Al gap

Tested w. RF-Single-Electron Transistor (Yale, 1998)
-challenging to bias

RF reflection readout w, HEMT
= fine, but not single photon

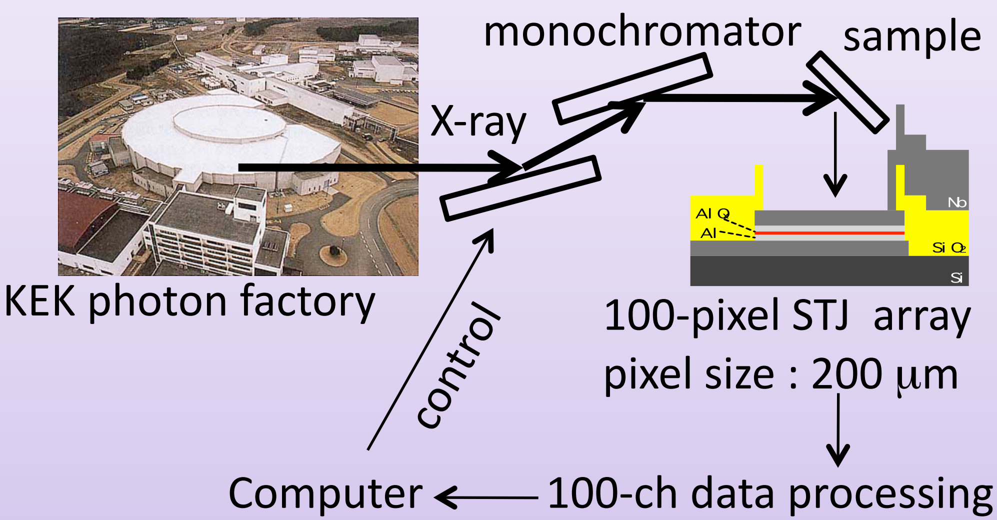
JPL – dispersive Qubit readout, promising (Echternach)

Teufel, Schoelkopf, D.P. (Yale) + GSFC fab

Soft X-Ray Spectrometer Using 100-Pixel STJ Detectors for Synchrotron Radiation – advantage is count rate; no imaging

X-ray Absorption Fine Structures

Non-destructive measurement of charge states and bond length



Advantages of STJ-XAFS

- Separation of light elements due to good energy resolution (< 30 eV)
- High sensitivity in soft X-ray (< 1 keV)
- Large solid angle coverage of 10^{-2} sr
- Fast response, >10^{6} cps @ 100-pixel
- Automated operation (Pulse tube + ^{3}He)
- Energy resolution – fine control from monochromator, not STJ

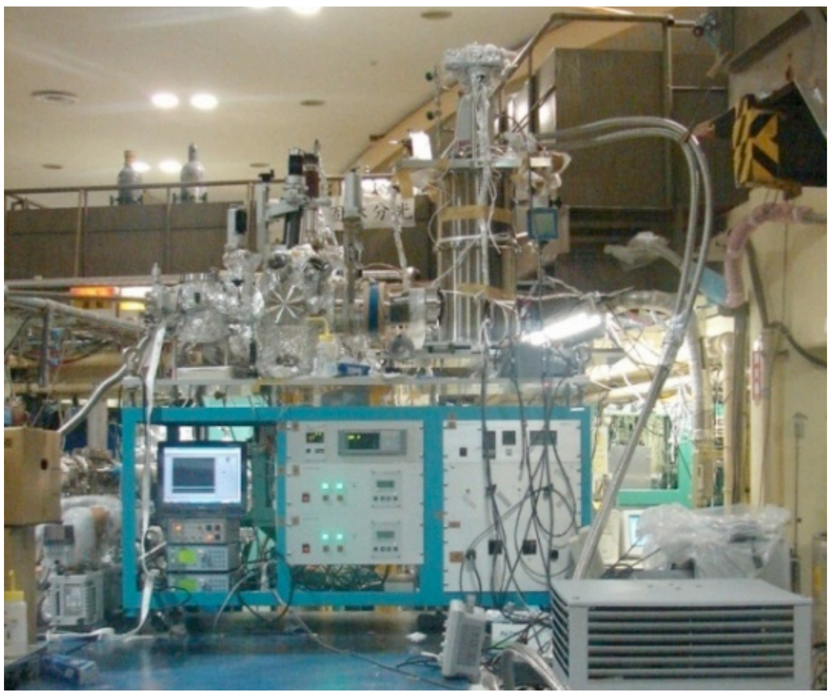
Shigetomo Shiki, (AIST)-LTD13

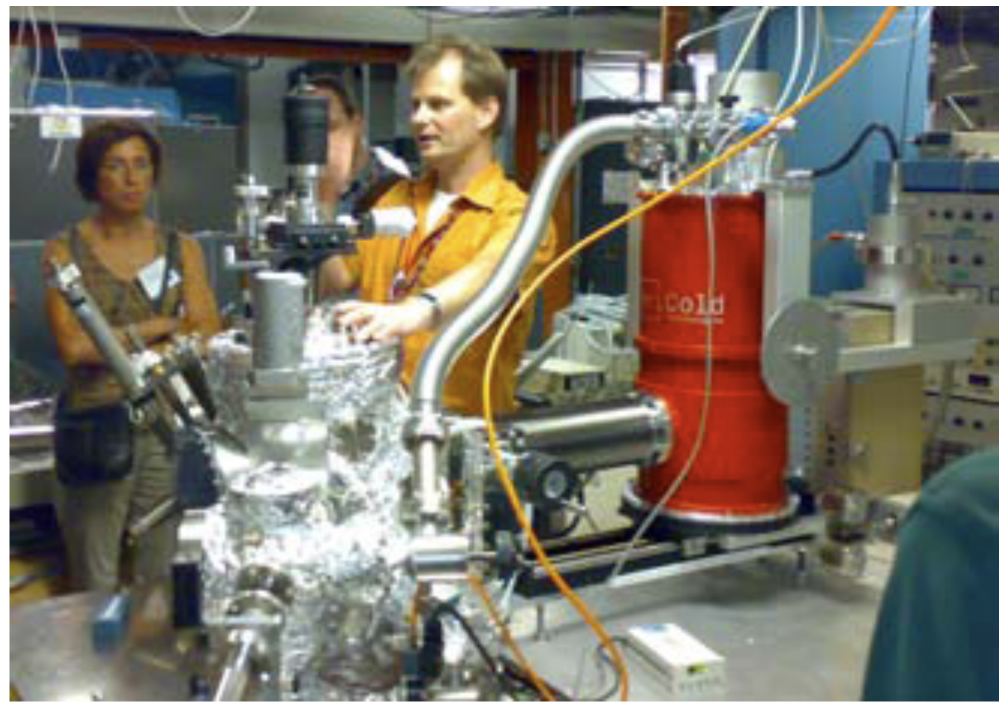
Soft X-Ray Beam Line use of STJs

– need count rate of STJ; does not need TES resolution; no imaging

Natl. Inst. of Advanced Industrial
Science and Technology (AIST)
0.2 – 2 keV

Stanford SSRL - 112 pixels
LBL-ALS - 9 pixels
– S. Friedrich, LLNL





Also, biomolecule energy + time-of-flight; using phonons to break pairs

Microwave Kinetic Inductance Detector

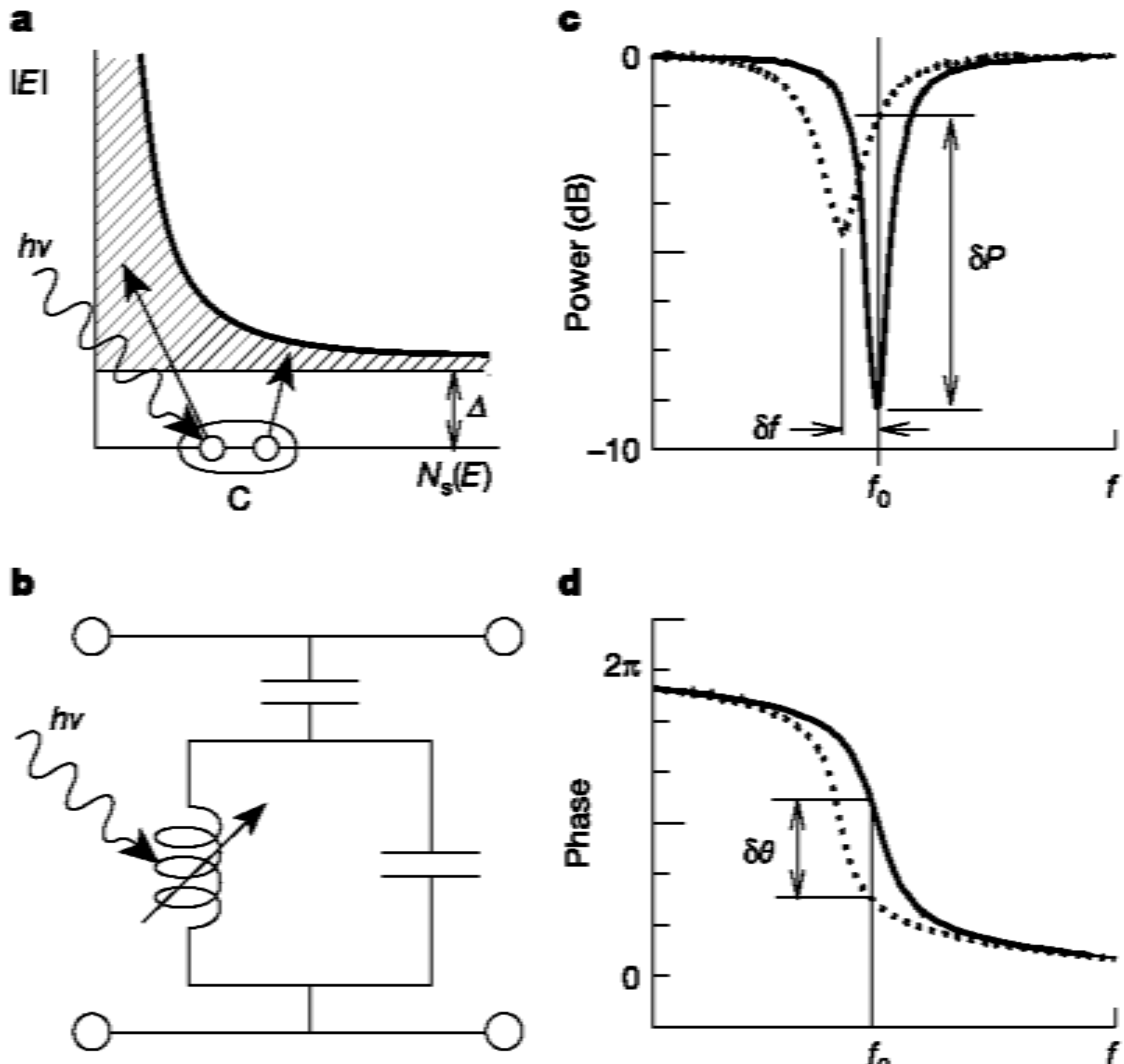
Absorb photon in SC quarter-wavelength resonator.

Inductance = magnetic + kinetic

$\frac{1}{2} L_K I^2 = \frac{1}{2} n_p m v^2$

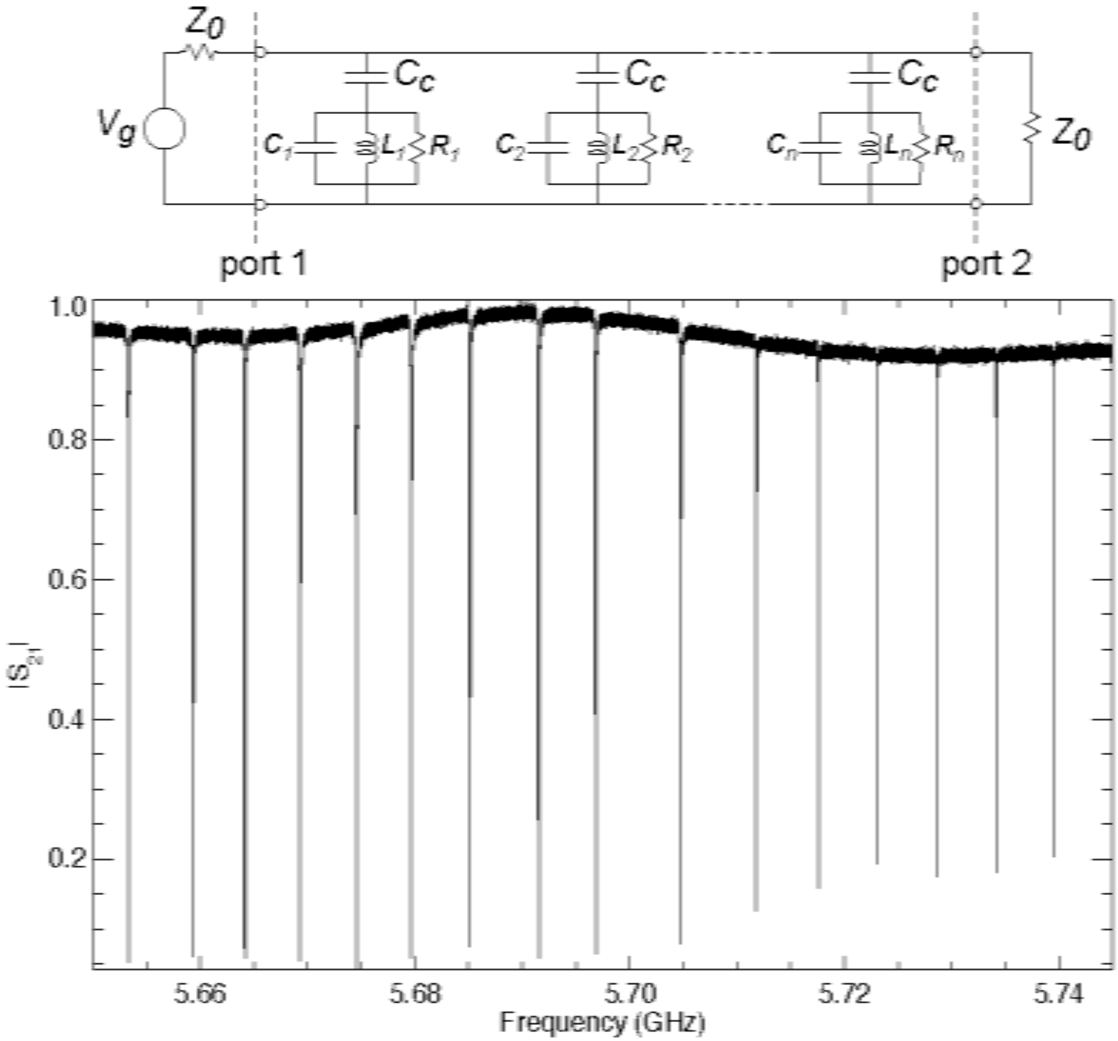
$L_K \approx 1/n_p$

$\delta n_p = - \frac{1}{2} \delta n_{qp}$



Mazin, LTD13

Microwave Kinetic Inductance Detector



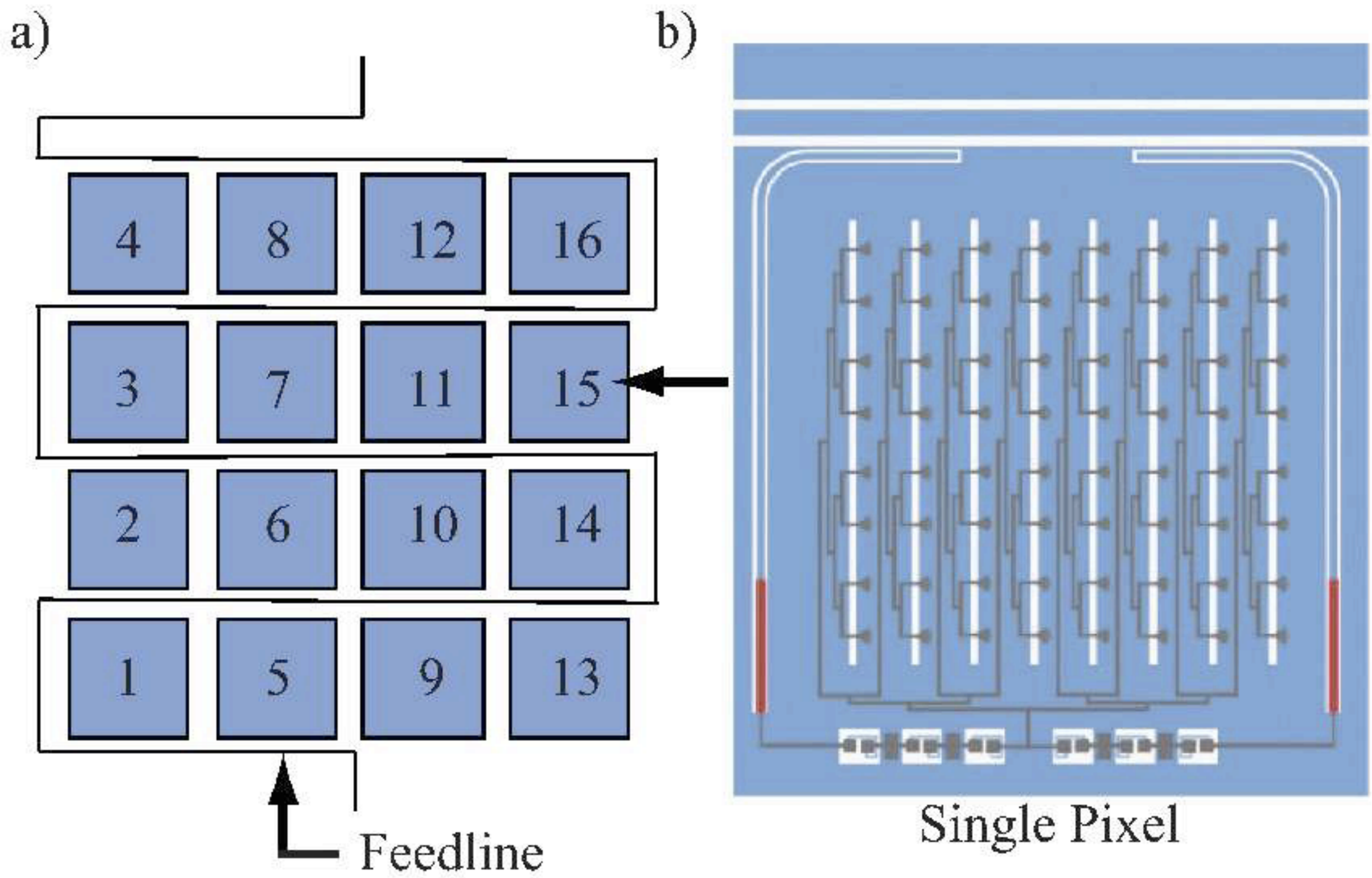
Enablers:
- low T/microwave expertise
- need for more channels
- STJ concepts
- SIS rf design
- digital signal processing

First demo: mm-wave camera

Mazin, LTD13

<u>Democam – 16 pixels, each 2 ‘colors’</u> 230, 350 GHz
– bigger, better, more colors: on the way;   pixel is >> λ

Maloney, LTD13



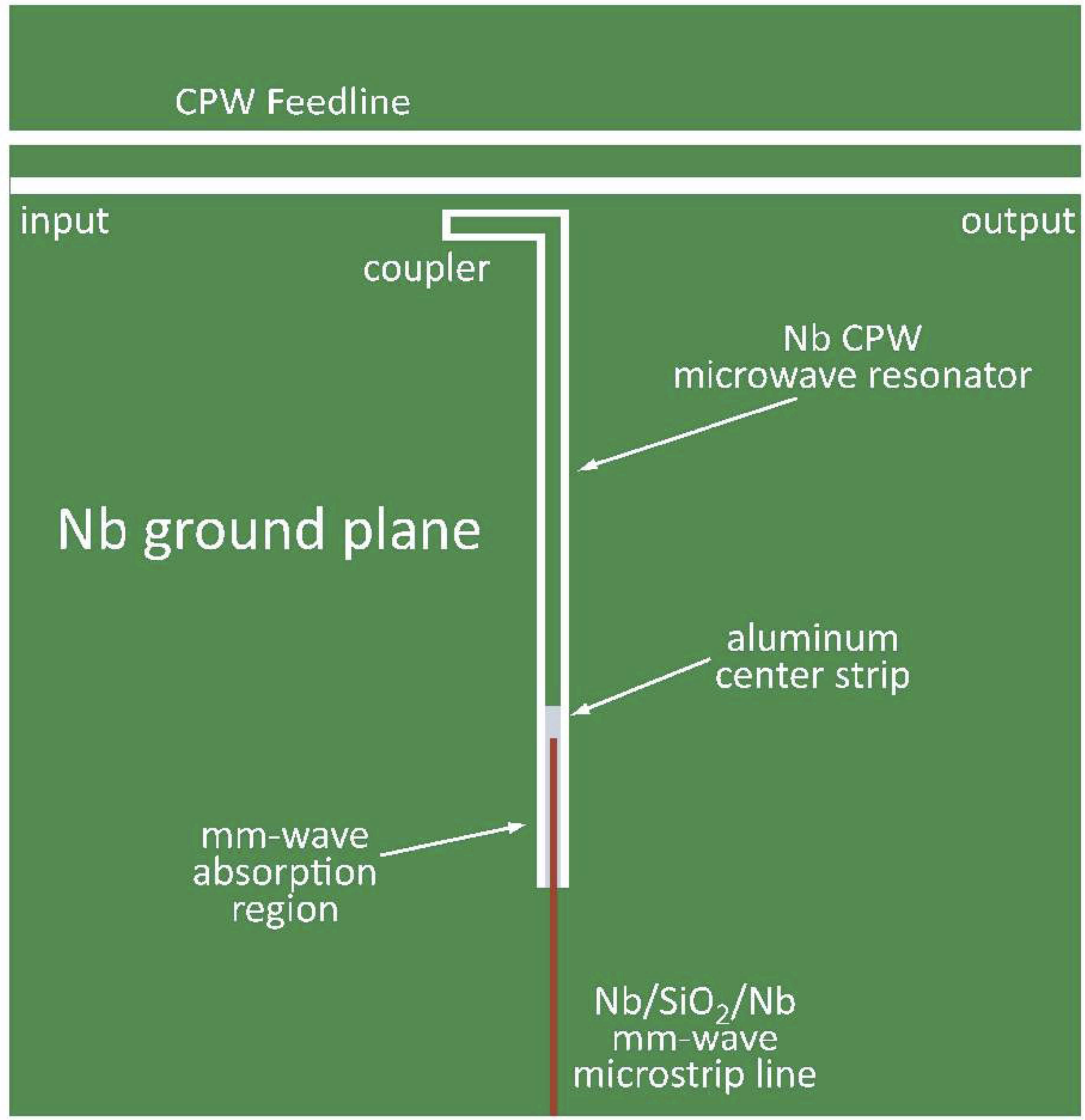
Democam – mm-wave camera

Nb microstrip to couple mm-wavelength photons from antenna to a lossy Al strip; creates qps in Al.

Nb CPW resonator keeps qps in Al; qps last long

Nb CPW has high Q;

Nb microstrip is more lossy, but is low impedance so losses ≈ ok.

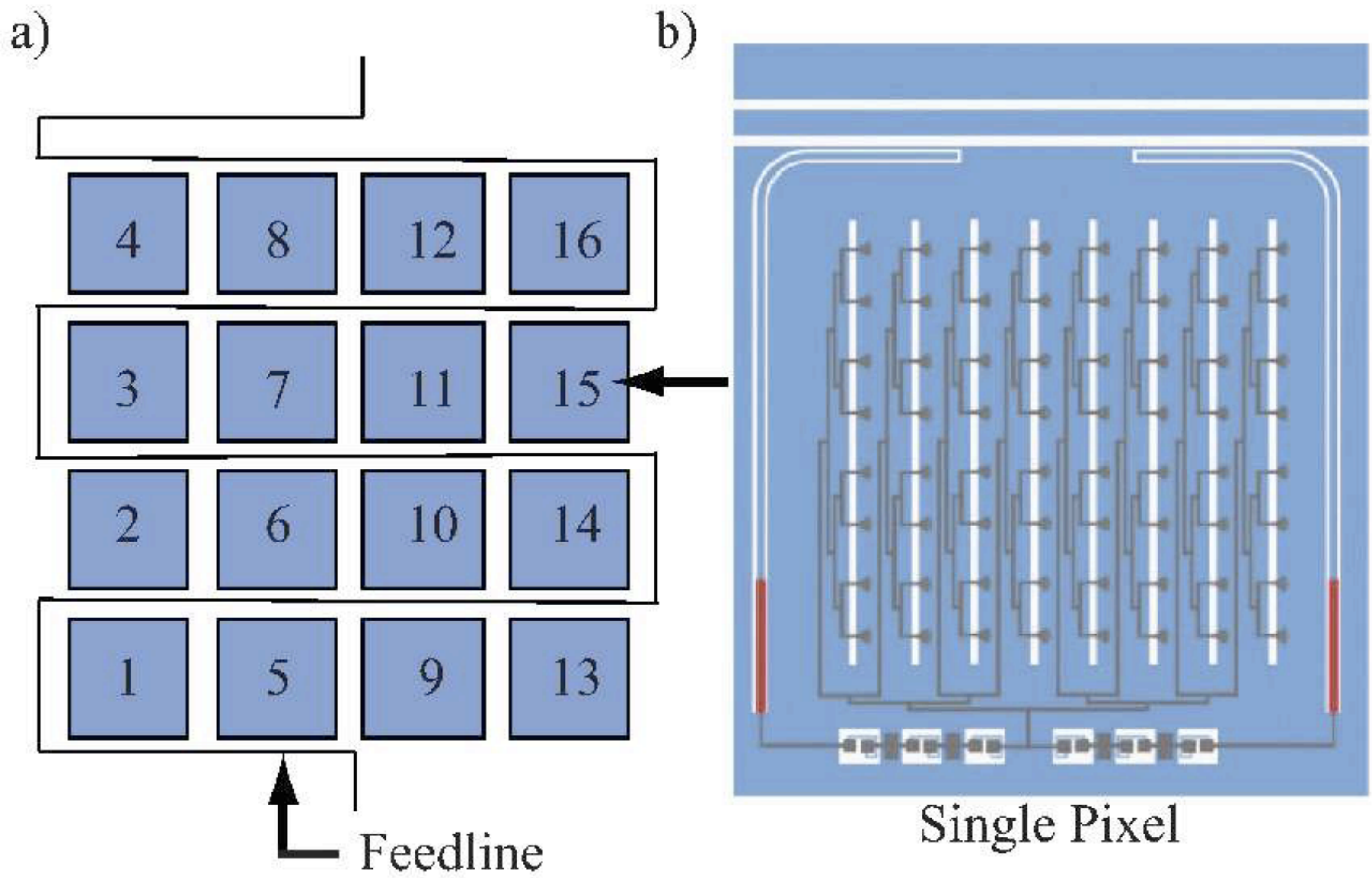


Maloney, LTD13

Democam – 16 pixels, each 2 'colors' 230, 350 GHz

– bigger, better, more colors: on the way; pixel is >> λ

Maloney, LTD13



MKID Challenges

- Two level systems (in insulator) – phase noise

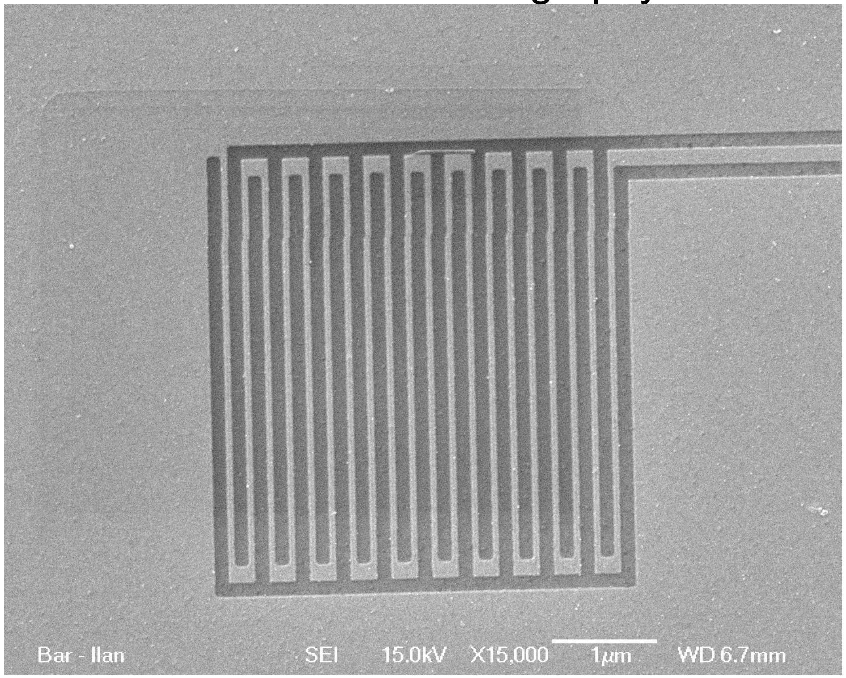
  Solutions: T ; materials development; interdigitated C; rf power (may also affect n_{qp})
- Lifetimes of qps – film quality – Barends; Wilson (Yale, 2001) τ_{rec} > ms in Al; rel to Q?
- KID concept, room T array electronics – hard, novel, and successful – first app. in submm

  "The detector fabrication is simple, requiring only ≈6 levels of lithography" Maloney, LTD 13, 2009

Nanowire Optical Coupling

- slides: E. Dauler and A.J. Kerman

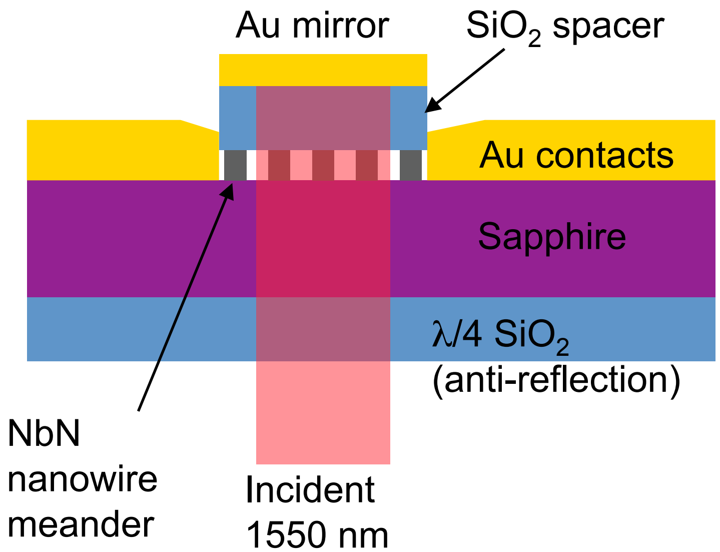
electron-beam lithography



Meander pattern - Yale Nb device

Performance shown below for MIT/LL devices made from NbN films

electron-beam and optical lithography



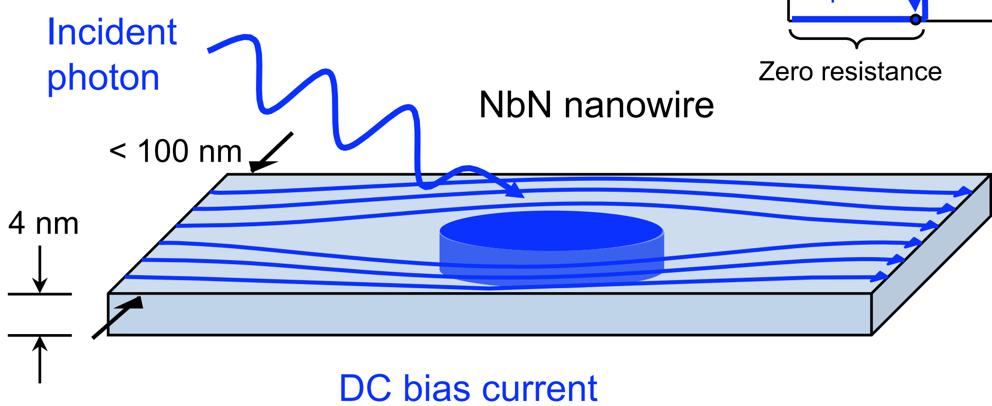
Cavity structure + AR coating improves coupling to ~ 85%

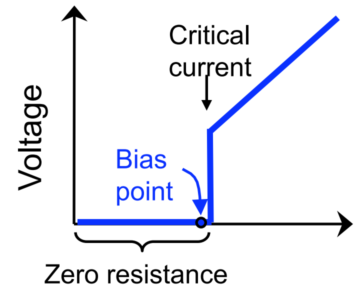
K. Rosfjord, J.K.W. Yang, E.A. Dauler, A.J. Kerman, V. Anant, G. Gol'tsman, B. Voronov, and K.K. Berggren, Optics Express 14, P. 527 (2006)

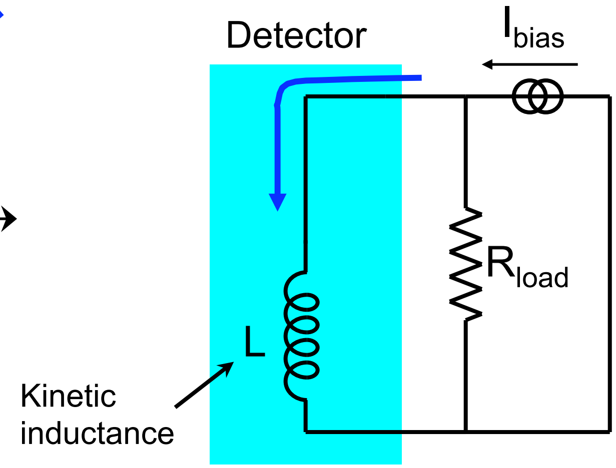
This work is sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government

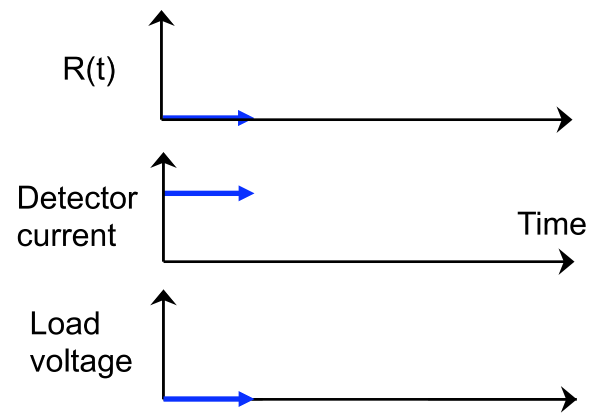
Photon Detection Mechanism

Bias NbN nanowire with DC current just below critical:







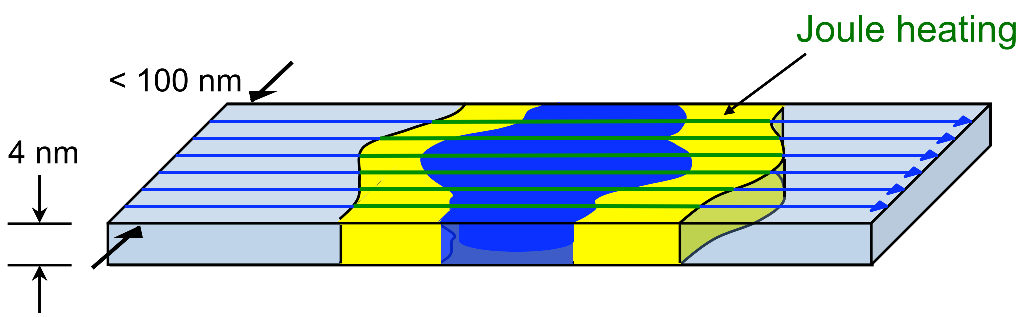


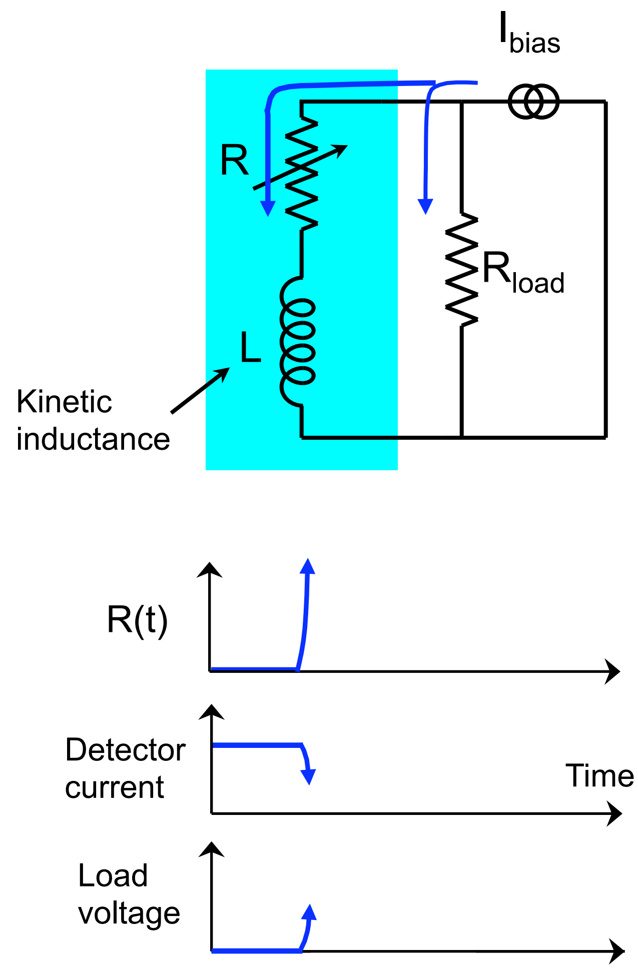
photon absorption disrupts superconductivity locally

G. N. Gol'tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams and R. Sobolewski, Appl. Phys. Lett. 79, 705 (2001)

Photon Detection Mechanism

Large sheet resistance allows R to grow very quickly

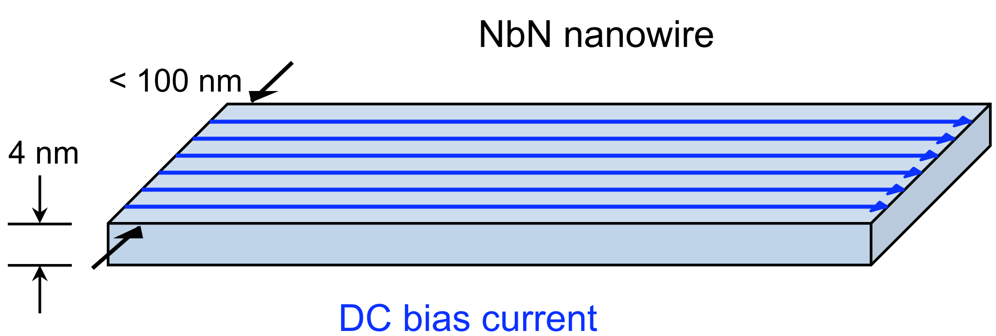


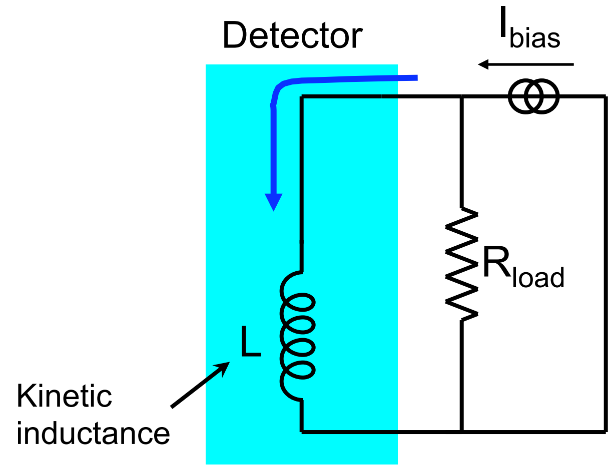


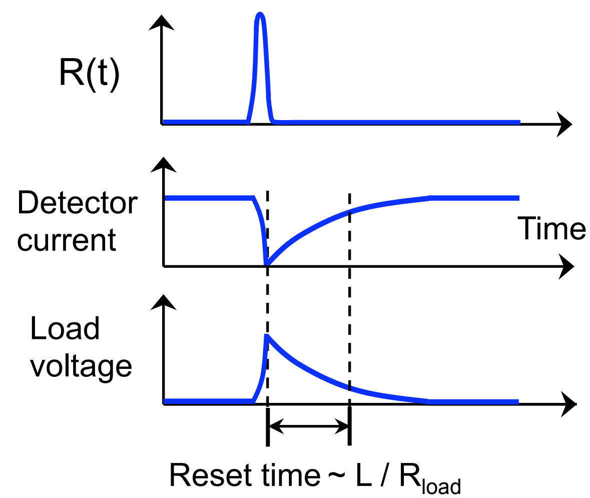
If L/R is long enough, Joule heating "runs away" ($R \gg R_{load}$) before current diverted into load

Photon Detection Mechanism

Current recovers with inductive time constant







Ouput pulse amplitude:
~ I_{bias}*R_{load} ~ 1 mV

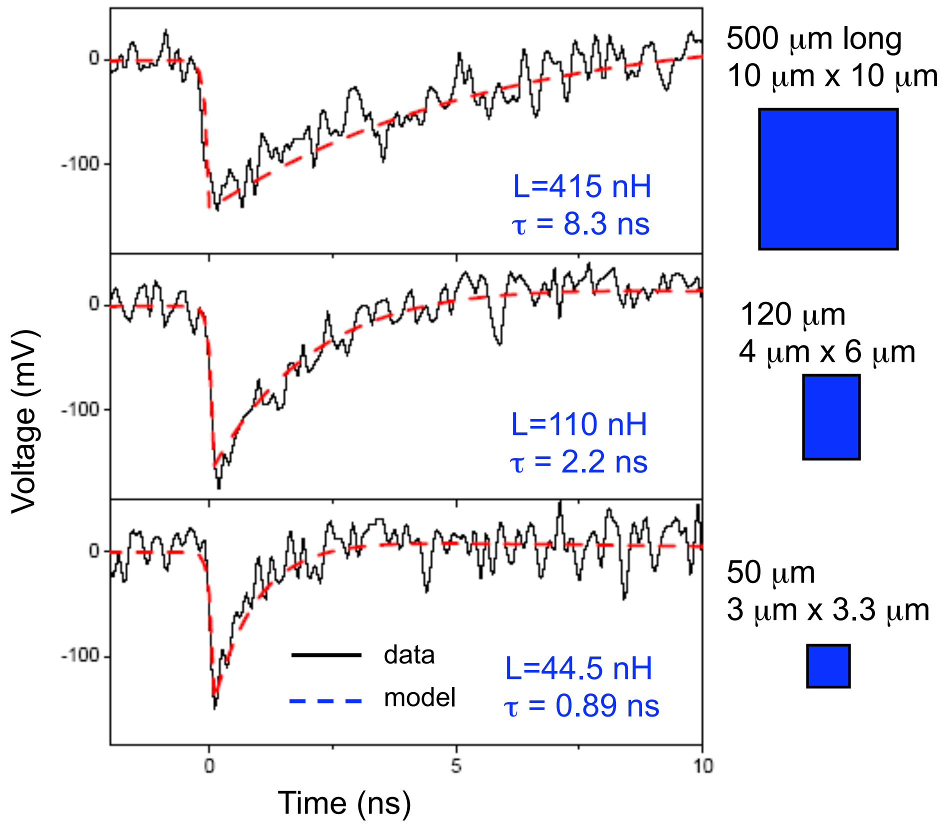
Reset time:
~ L/R_{load} ~ 3 ns

Reset time ≈ 10 ns, 10 x 10 μm^2

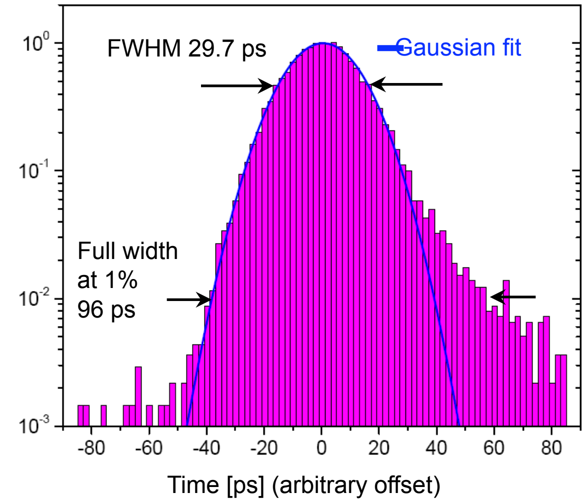
'Click' like PMT - dissipated energy
>> photon energy;
➔ does not resolve photon number

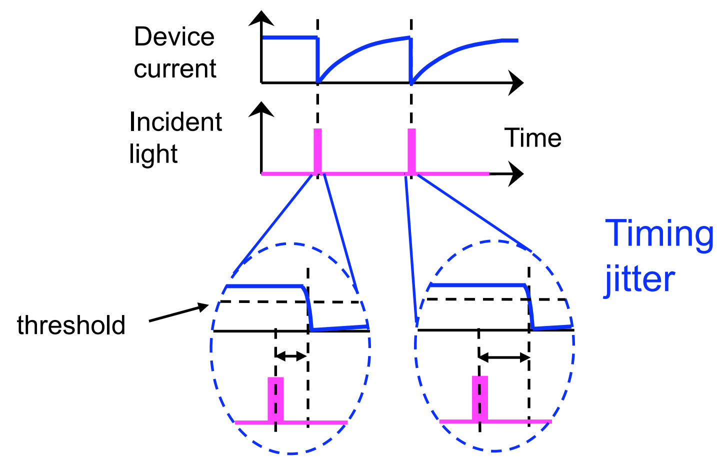
Device Characteristics

Single-photon output pulses



Measured timing jitter of device at T=1.8K
~1 photon/pulse

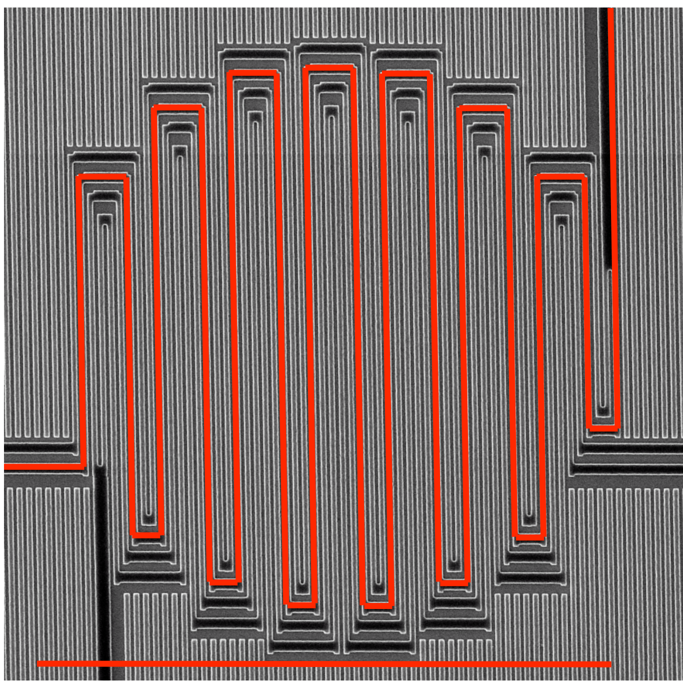


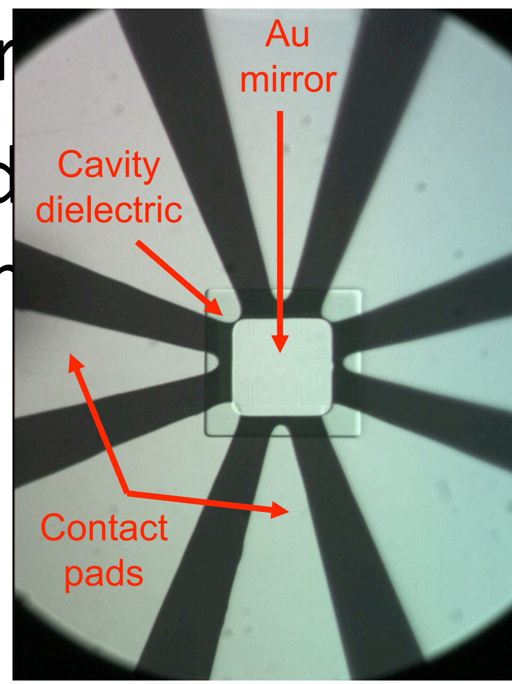


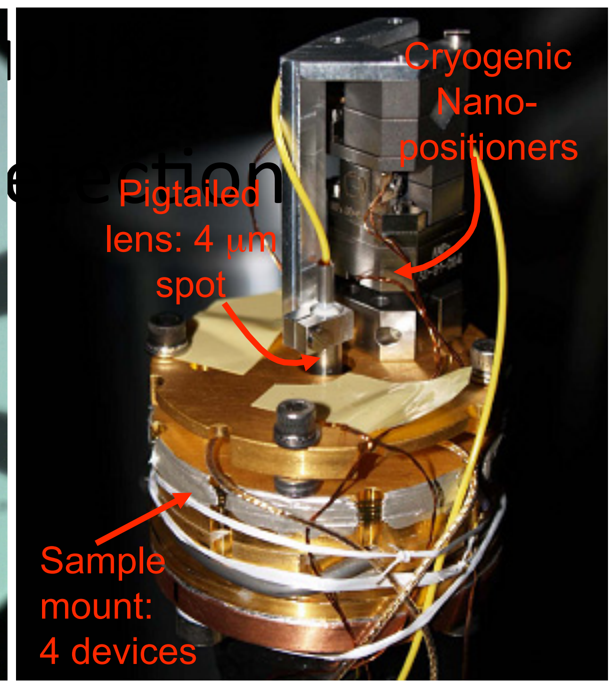
Typical detection efficiency:
40-60% at 1550 nm

Detector Design and Packaging

- Interleaved pattern
- Circular active area
- Cavity structure

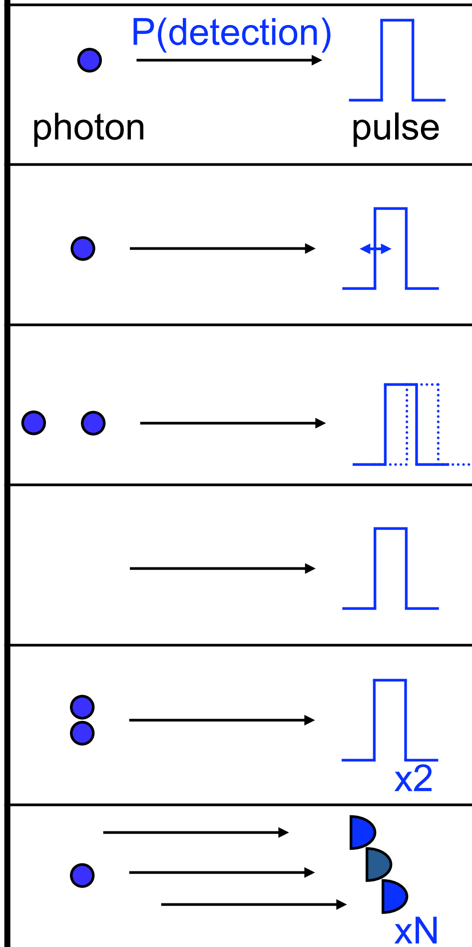






[Kerman, A., unpublished]

Multi-element SNSPD Achievements



Metric	Achieved
System Detection Efficiency	**~50% at 1550 nm wavelength**
Timing Jitter	**30 ps timing jitter per element**
Reset Time	**~9 ns reset time per element → ~400 MC/s at ~full efficiency**
Dark Counts	**< 1 kHz dark counts per channel at full efficiency**
Photon Number Resolution (PNR)	**PNR with independent 30 ps photon timing**
Arrays	**4 elements operated simultaneously**

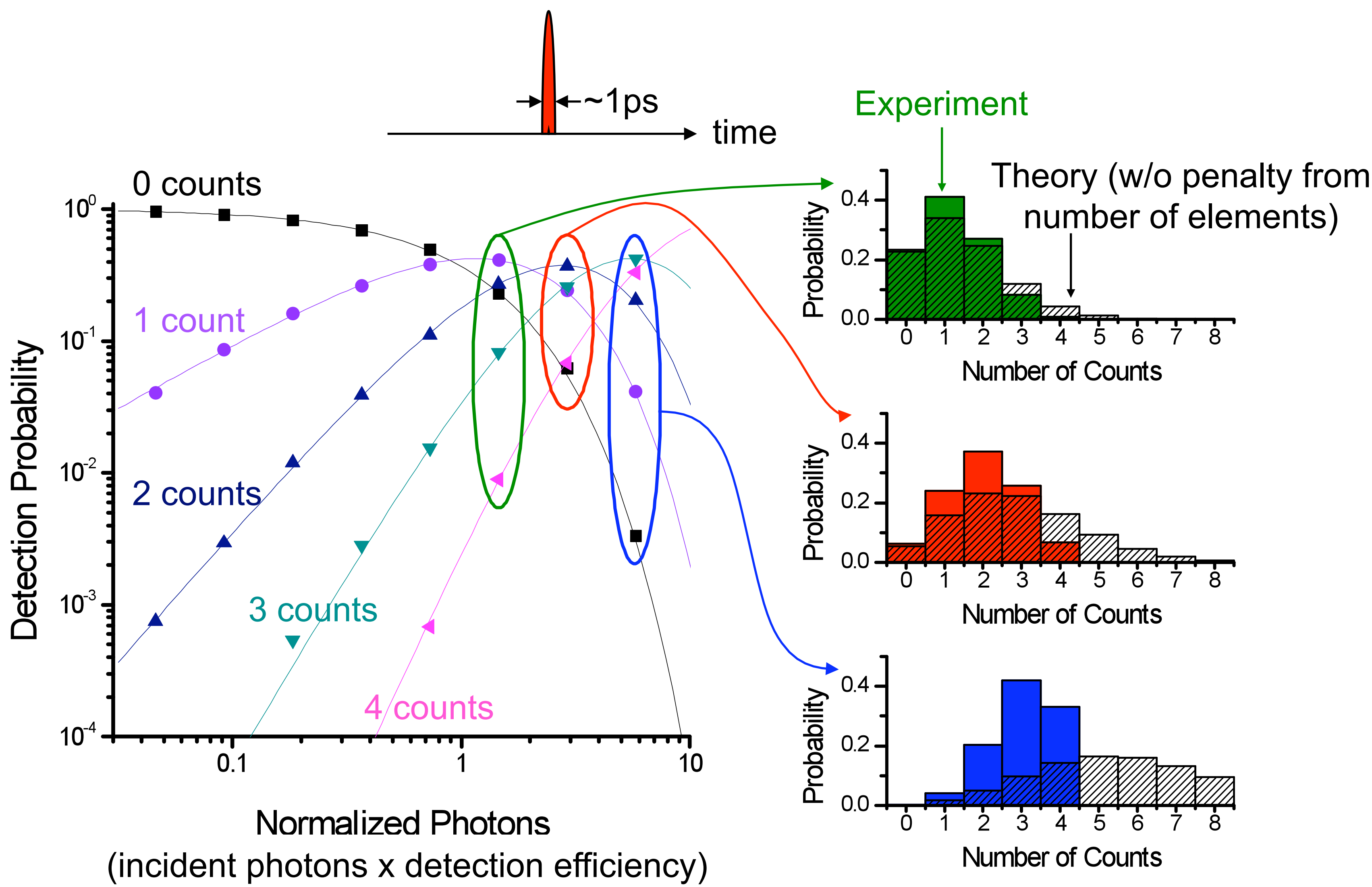
A.J. Kerman

Conclusions

- TES – mature for x-ray arrays,
  - visible/NIR pixels, excellent det. efficiency;
  - THz -- future work
- STJ – fast, on x-ray beam lines
- KID – rapid development; single-photon – more research needed
- Nanowire – v. fast, good det. efficiency - QKD
- Development of arrays – VERY promising

Thanks to colleagues who shared 'slides'.

Counting Simultaneous Photons



E.A. Dauler, A. J. Kerman, B. S. Robinson, J. K. W. Yang, B. Voronov, G. Gol'tsman, S.A. Hamilton, and K.K. Berggren, *Journal of Modern Optics,* 56, 364-373 (2008).