Single Photon Detectors –

from A to B (from Astronomy to Bio, and beyond)

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

with thanks for collaborators and Yale colleagues

Acknowledgements

- *Spectroscopy demo – soon*

Outline

- Types of sensors
  - Transition Edge Sensor
  - Superconducting Tunnel Junction; MKID
  - SC Nanowire, Avalanche Photodiode
- Applications
  - X-ray – astronomy, spectroscopy
  - Near IR - Quantum Key Distribution
  - Bio fluorescence

Why single photon?

- Weak sources; *spectroscopy*; $E_{ph} = hf = hc/\lambda$
- 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 $T = 10^{12}$
  1 meV = 1.2 mm = 0.25 THz
  (visible: ≈ 1.6 - 3 eV; 0.4 – 0.7 μm)

Why single photon?

- *Spectroscopy demo – dispersive spectroscopy*

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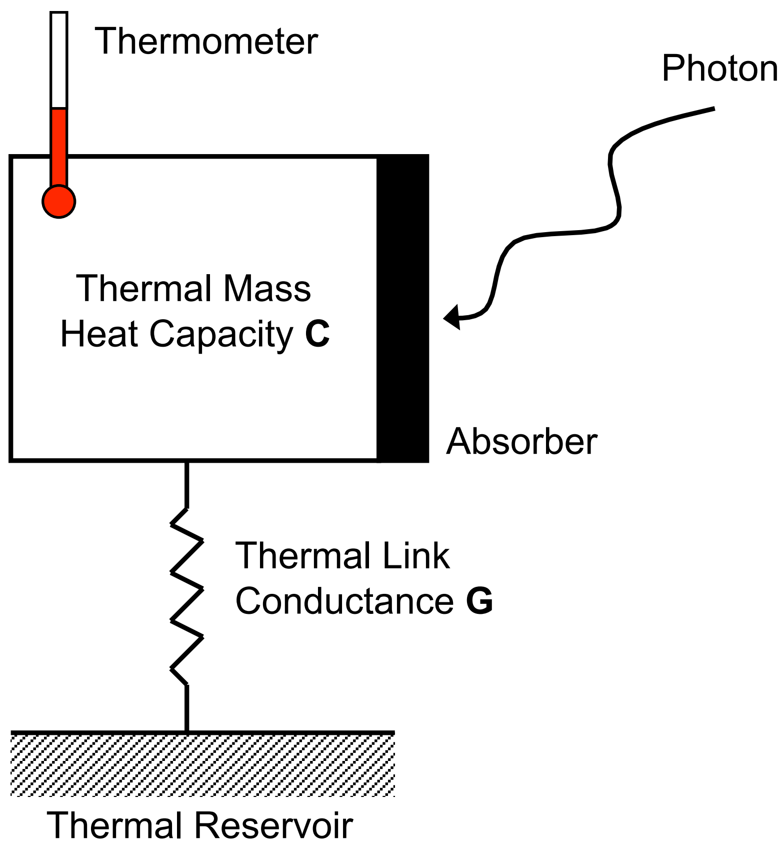
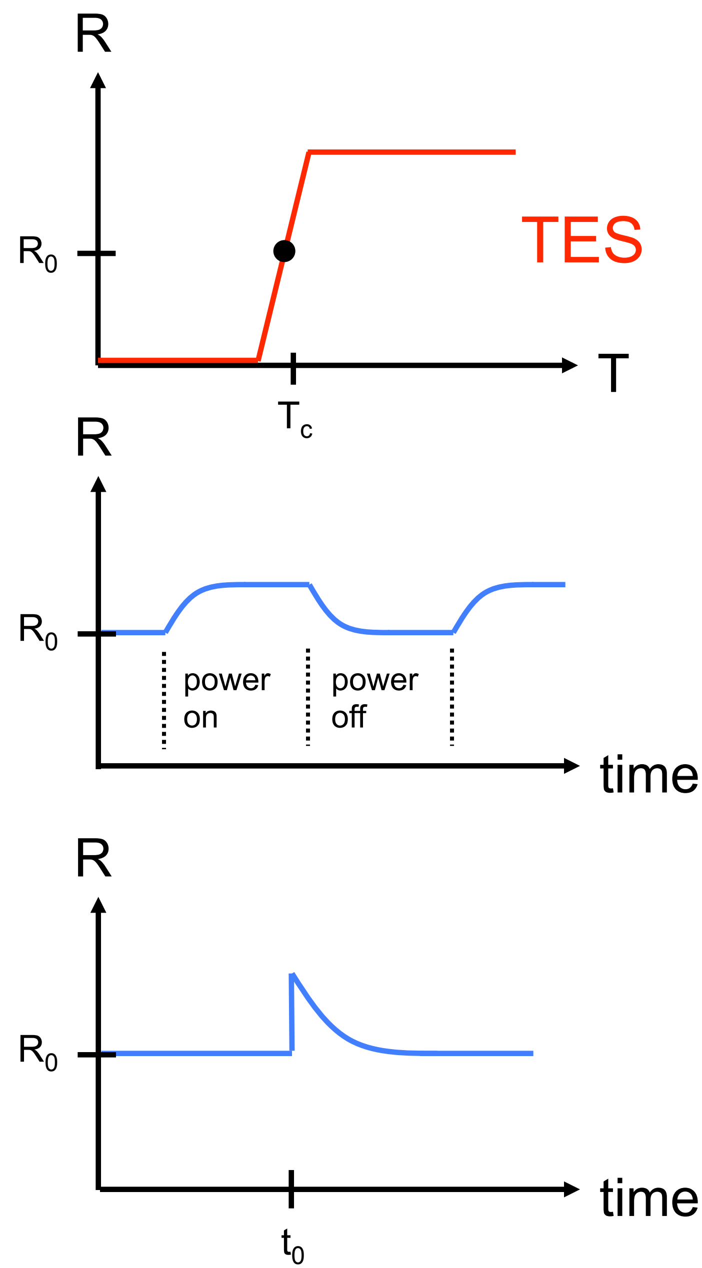
Bolometer Detector – Thermal → cold + small



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

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



Basic Transition Edge Sensor Operation

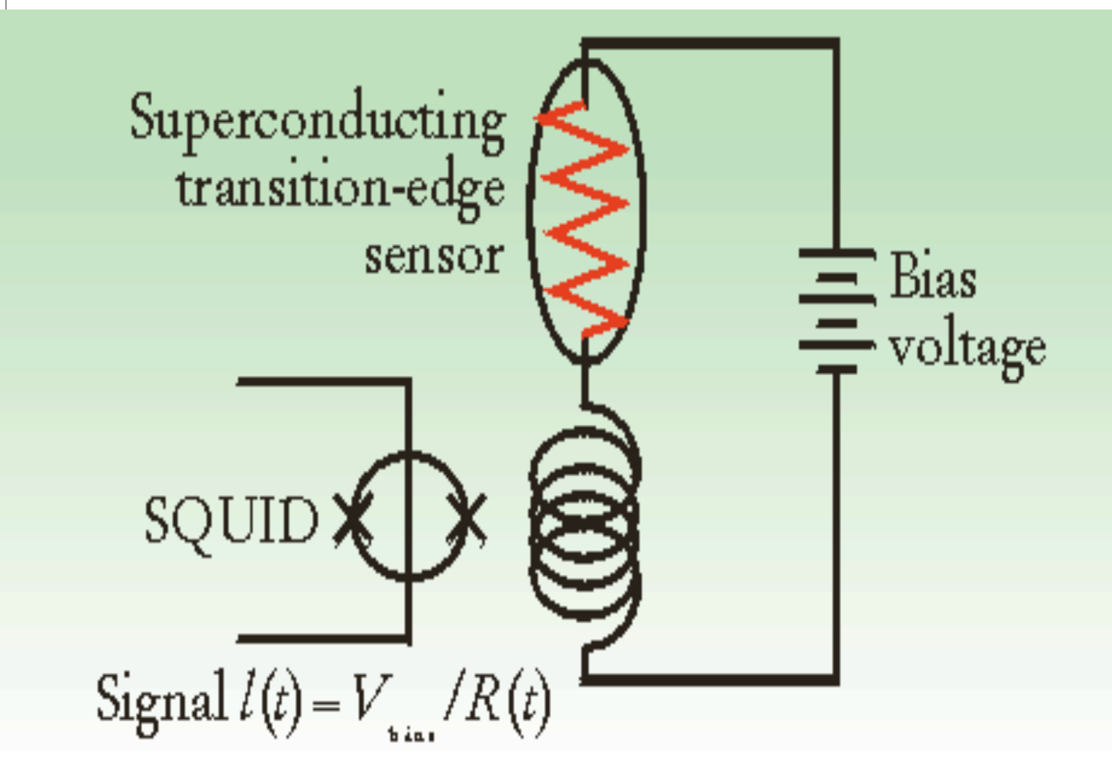
Superconducting wire (the TES) is used as a thermometer – read out changes of resistance electrically.

Typical SC transition $T_c < 1K$

Voltage bias ➔ faster response, more sensitive

SQUIDs essential for low T multiplexing, low noise

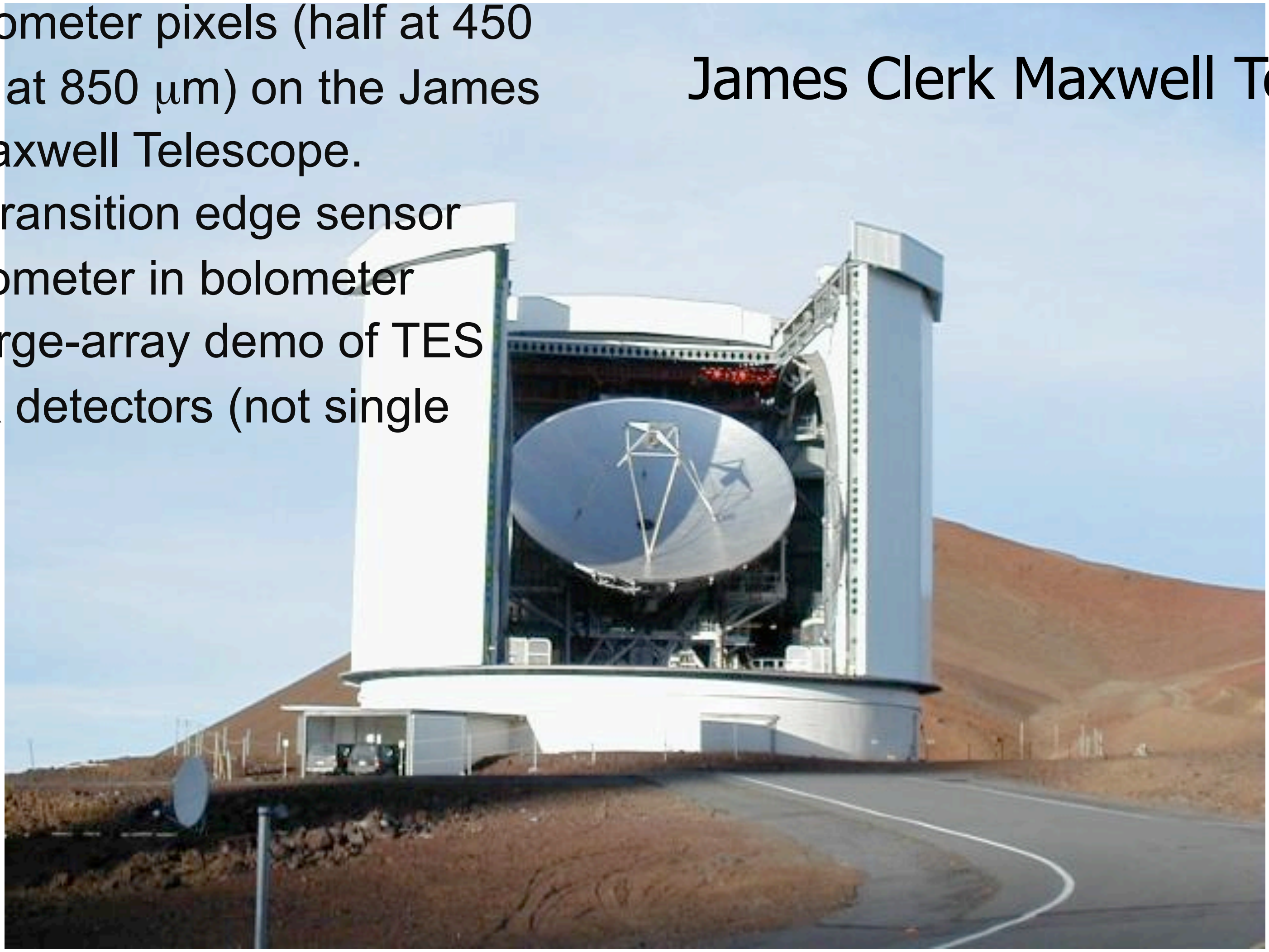
Low count rates for astro x-ray applications ≈ 100/sec; SQUID mux 'easy'



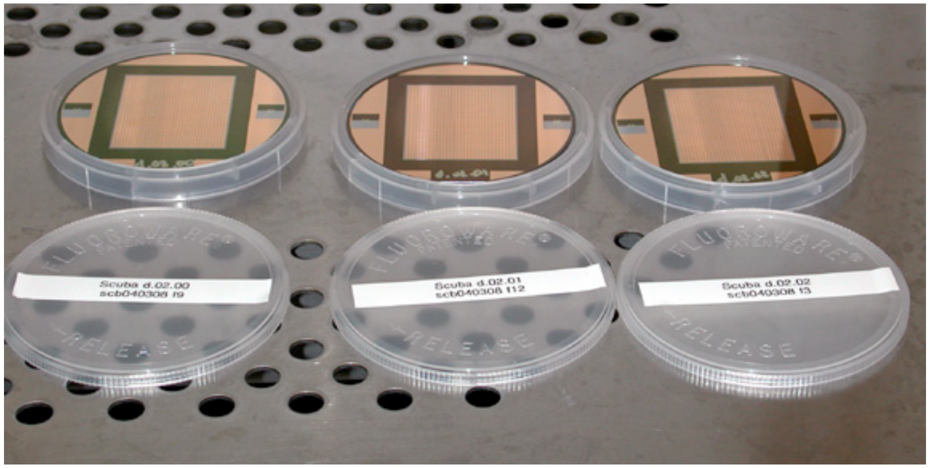
Kilbourne, TIPP09

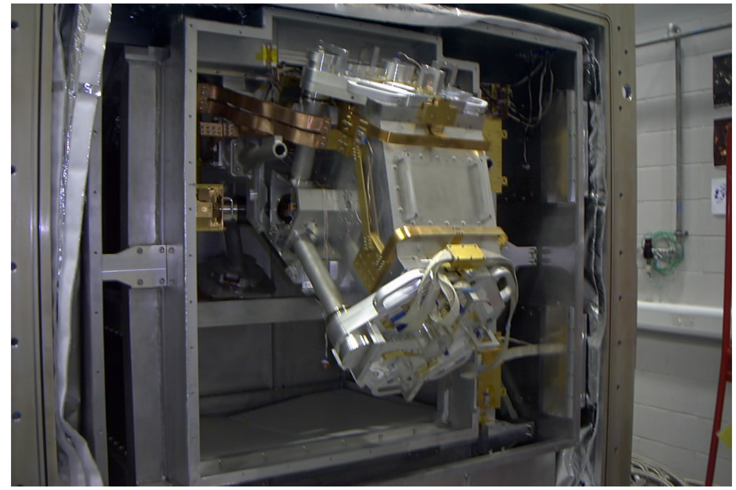
- A collaboration of the UK, Canada, Raytheon, and NIST
- SCUBA-2 will consist of 10,240 TES bolometer pixels (half at 450 μm, half at 850 μm) on the James Clerk Maxwell Telescope.
- TES = transition edge sensor = thermometer in bolometer
- First large-array demo of TES POWER detectors (not single photon)

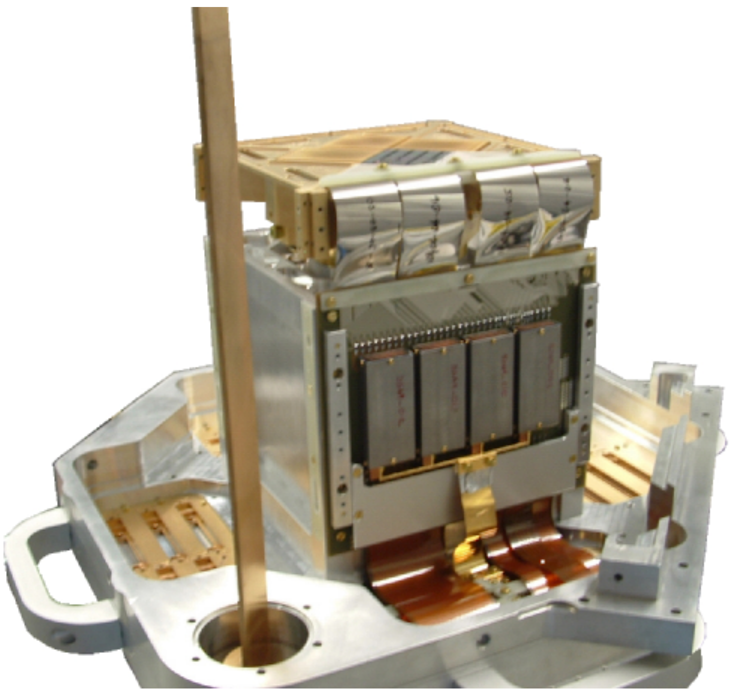
James Clerk Maxwell Telescope



Techniques of semicond. industry; special materials.

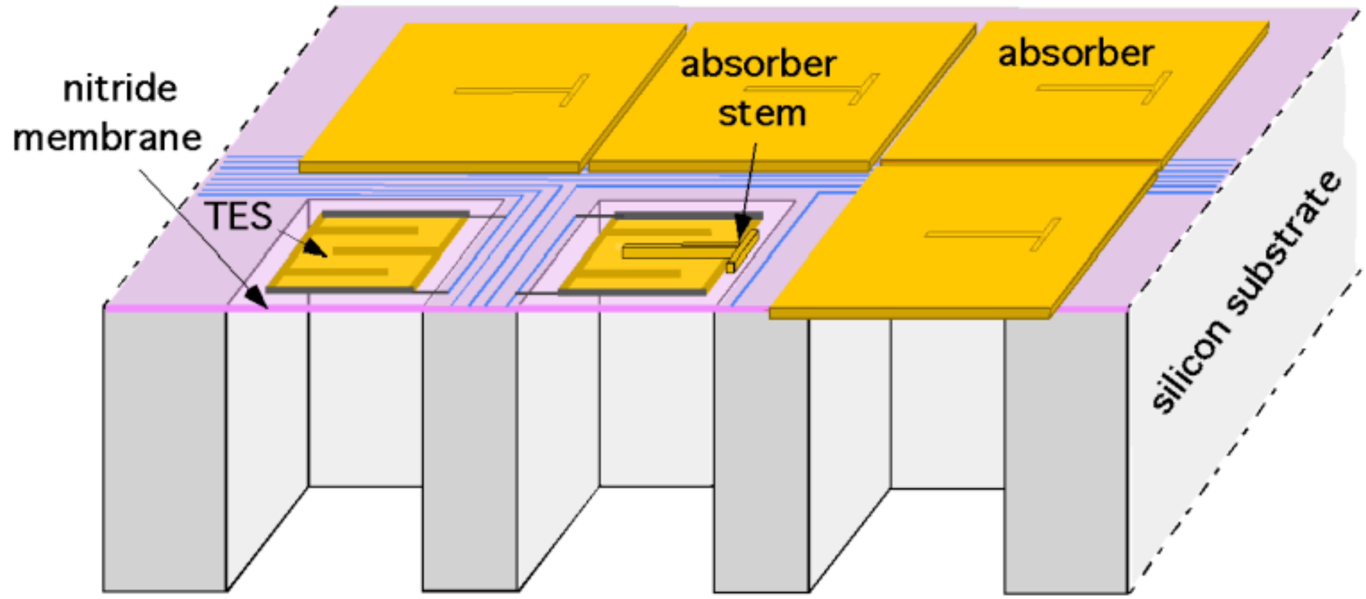






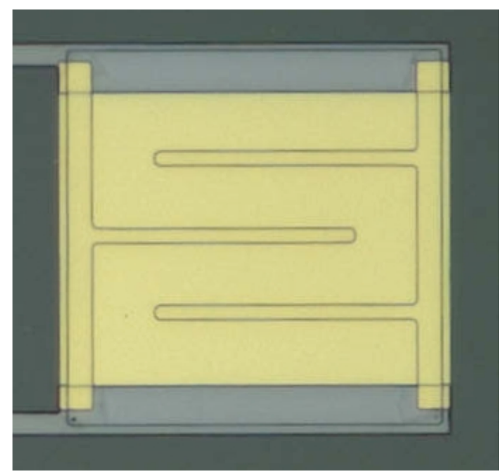
X-Ray TES structure

Robust array construction



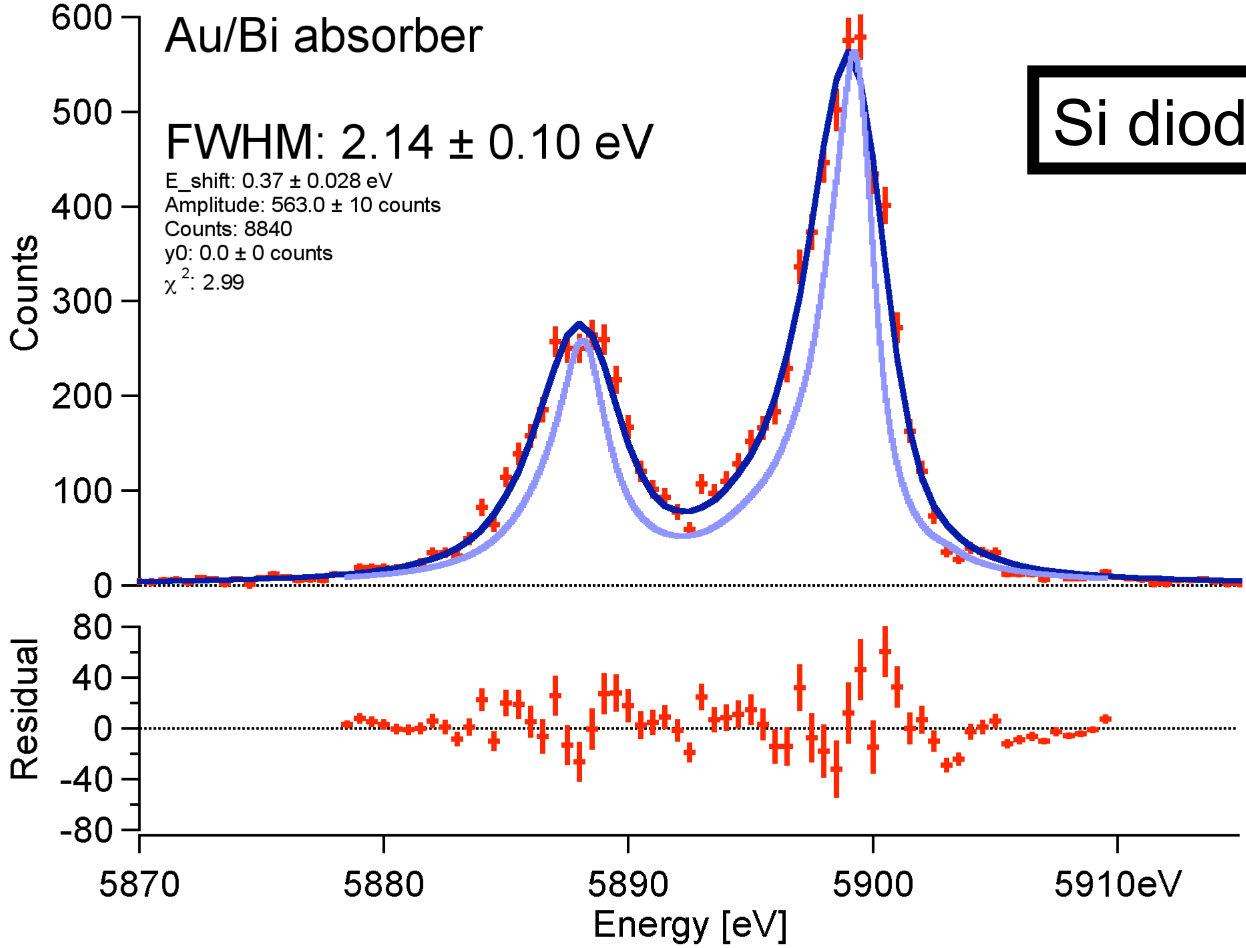
Thick Au/Bi absorber, weakly attach Mo/Au bilayer TES

TES is thermometer only



Kilbourne, TIPP09

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

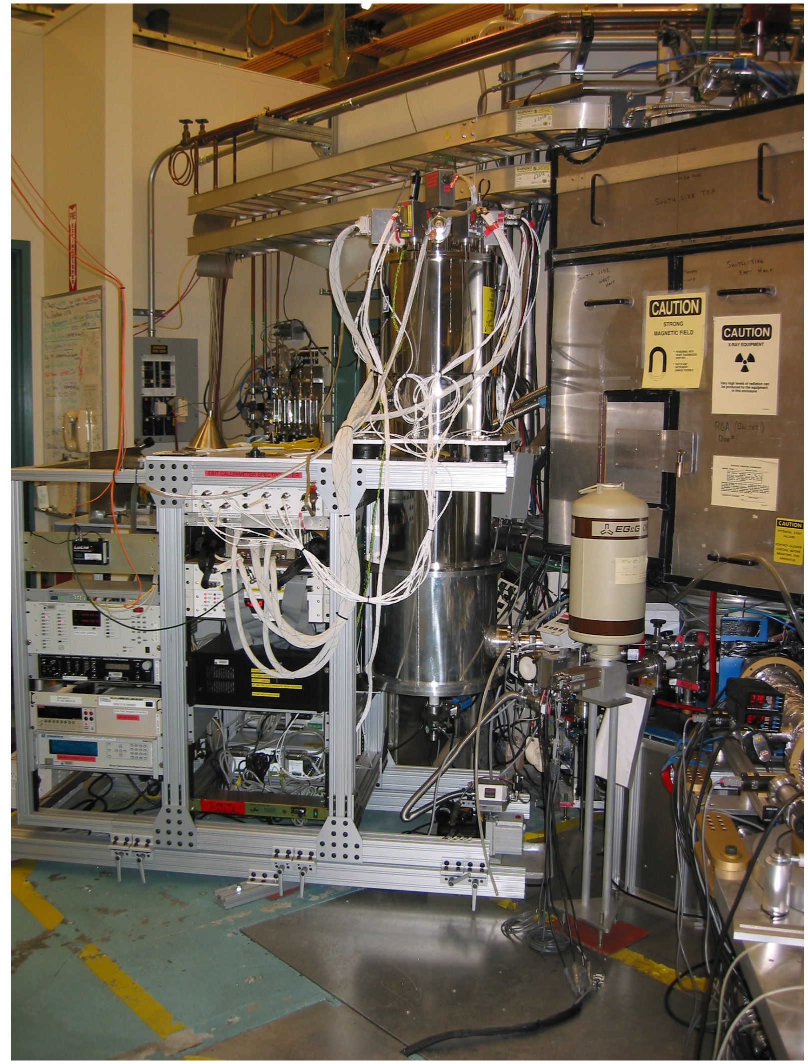


Si diode – 120 eV FWHM

Kilbourne, TIPP09

Application to Laboratory Astrophysics

- Electron-Beam Ion Trap at LLNL
  - Astrophysically relevant plasmas in the laboratory
- Currently:
  - EBIT Calorimeter Spectrometer uses silicon thermistor array for broad-band coverage
  - Dispersive spectrometers for high energy resolution below 1 keV
- Next generation: TES spectrometer
  - Match (exceed) ΔE of upcoming missions
  - Reduce the need for the dispersive spectrometer

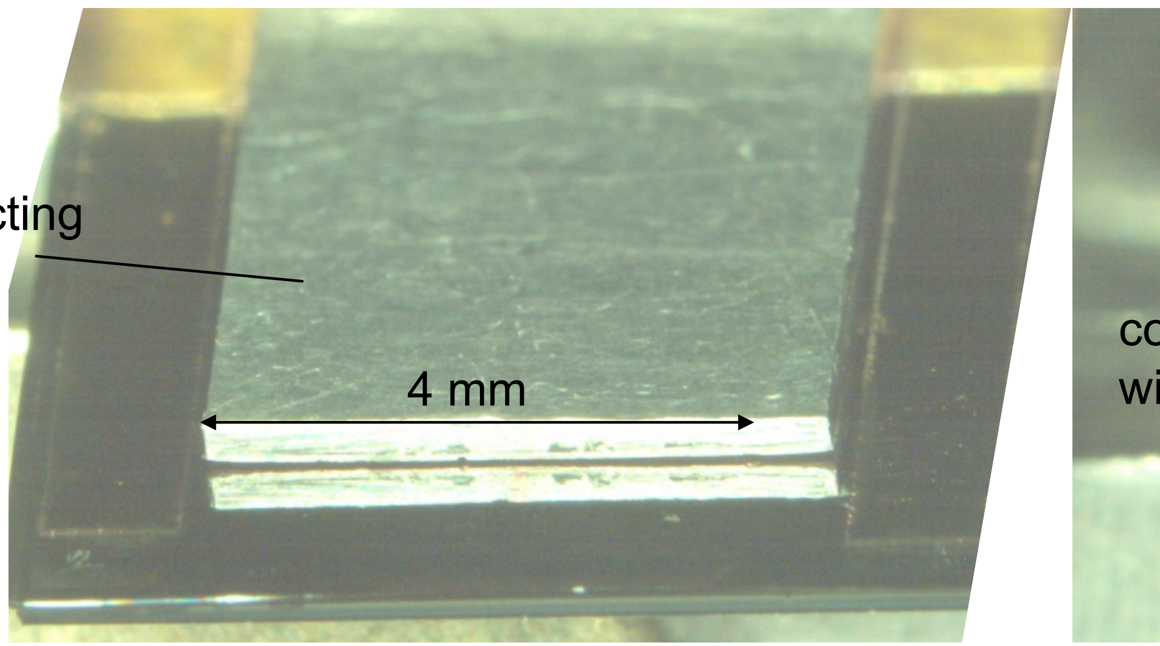


EBIT Calorimeter Spectrometer at LLNL (2008)

Microcalorimeter alpha particle detectors

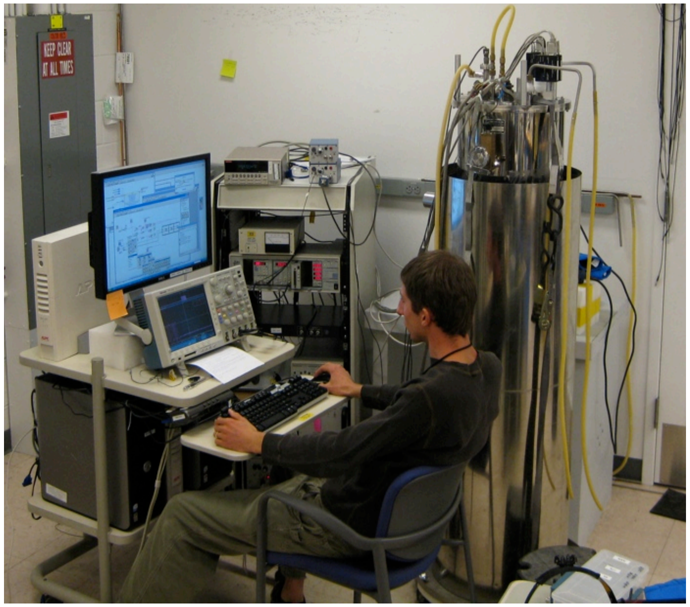
- –environmental monitoring
- –nuclear safeguards
- –medical assay

‘Scaled up x-ray TES’

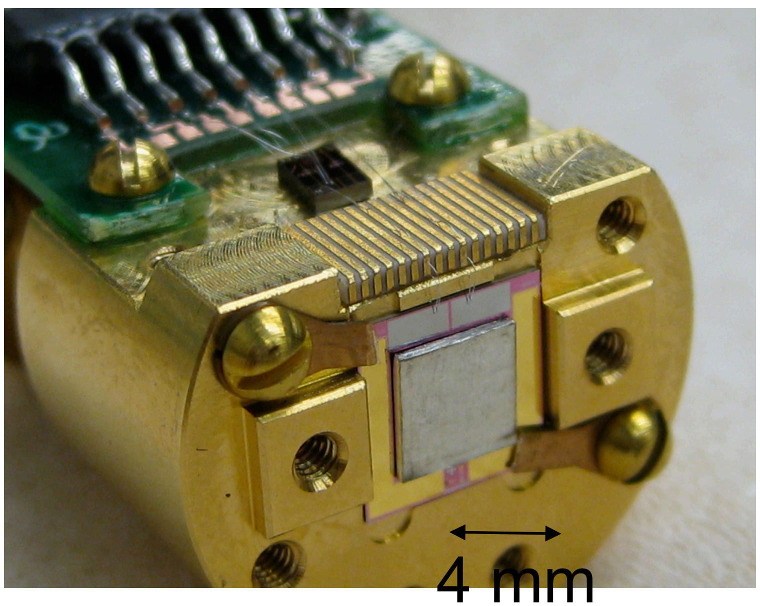


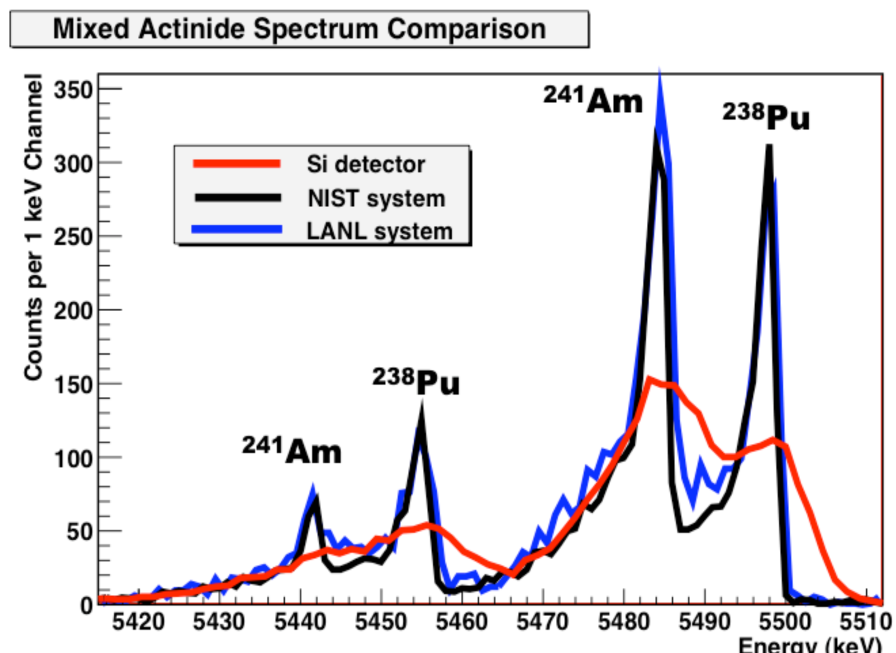
J. Ullom, LTD13

Technology dissemination



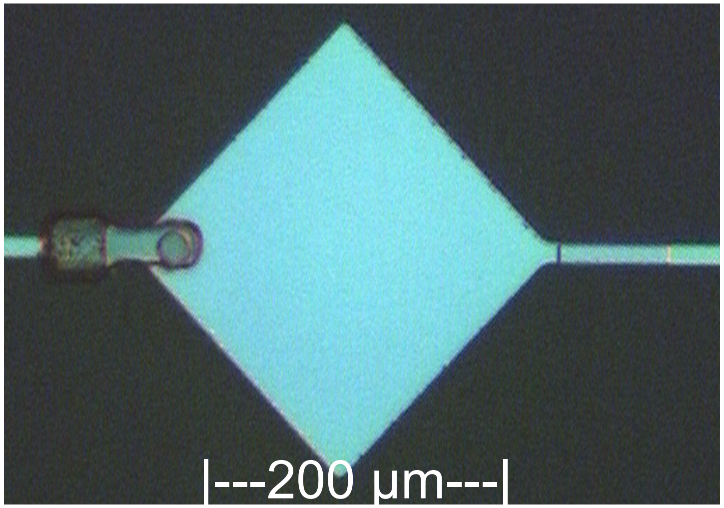
- 4 channel alpha spectrometer installed at LANL
- SQUIDs, SQUID electronics, wiring from STAR Cryoelectronics
- TESs originally from NIST, now from STAR Cryoelectronics
- High quality spectra routine
- Phase II SBIR awarded for commercial system

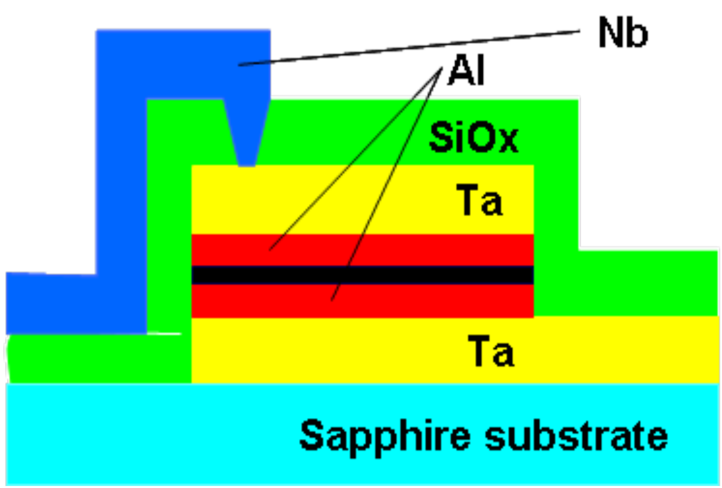




J.Ullom

STJ (excitation) detector





Photon breaks Cooper pairs ➔ 2 quasiparticles/photon initially, multiply by cascade until $n_{avg} \approx E_{ph}/E_g$; this qp charge then tunnels thru oxide barrier

➔ statistical variation $\delta n \approx n_{avg}^{1/2}$ this gives the energy resolution of the STJ detector

$T << T_c$

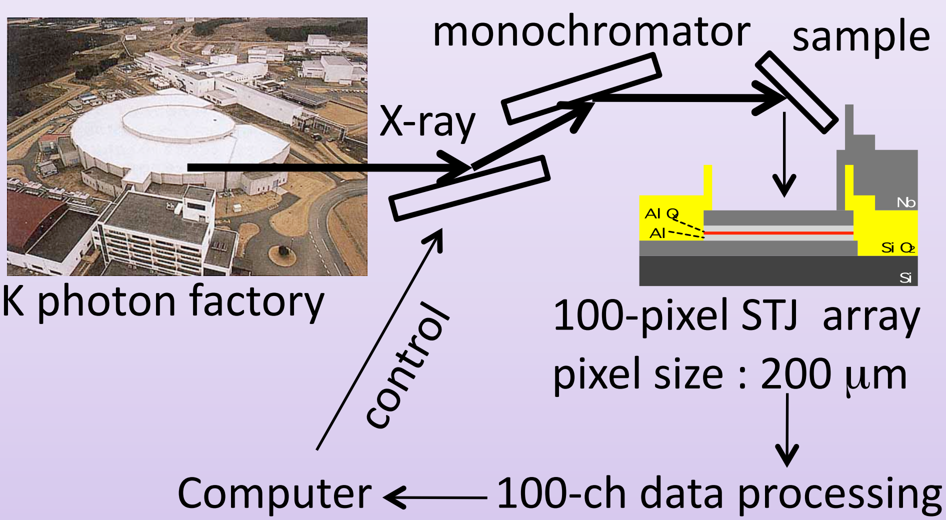
STJ – high impedance ➔ semicond. amplifier

P. Verhoeve, LTD 13

Soft X-Ray Spectrometer Using 100-Pixel STJ Detectors for Synchrotron Radiation

X-ray Absorption Fine Structures

Non-destructive measurement of charge states and bond length



Advantages of STJ-XAFS

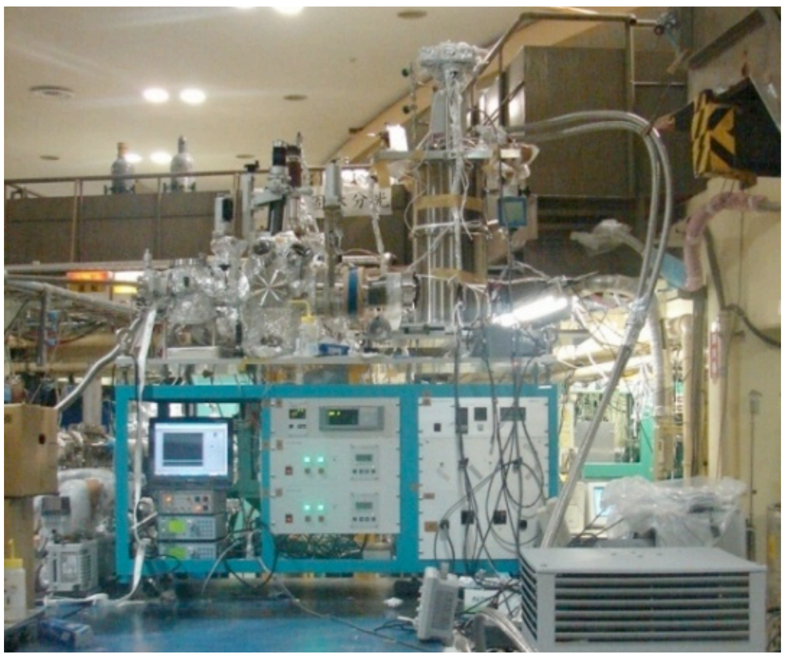
- Separation of light elements due to good energy resolution (< 30 eV)
- High sensitivity in soft X-ray (< 1 keV)
- Large solid angle coverage of 10^{-2} sr
- Fast response, $>10^6$ cps @ 100-pixel
- Automated operation (Pulse tube + ^{3}He)
- Energy resolution – fine control from monochromator, not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

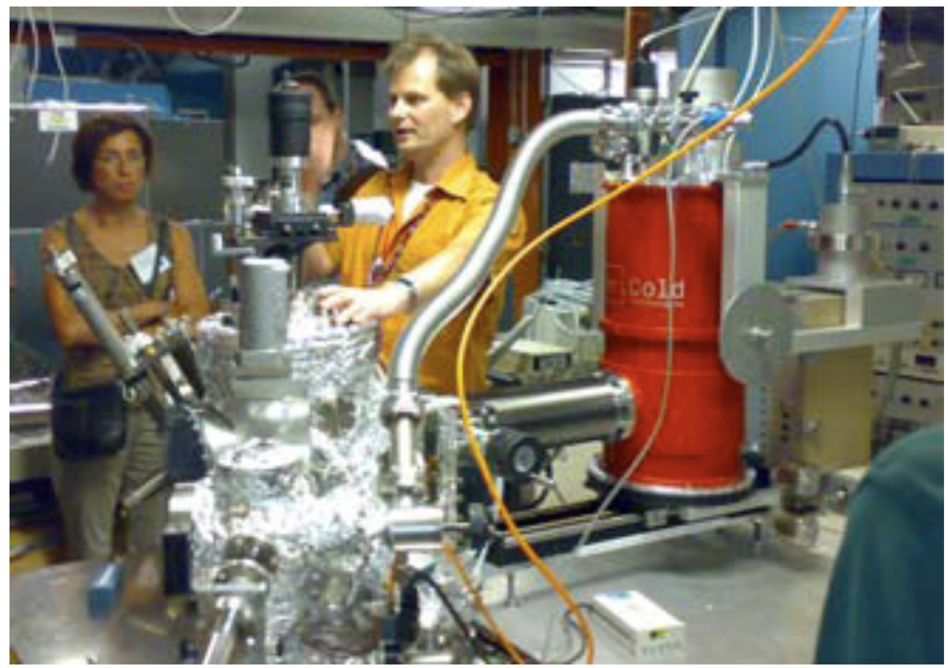
Shigetomo Shiki, (AIST)-LTD13

Beam Line use of STJs – need count rate
(does not need TES energy resolution)

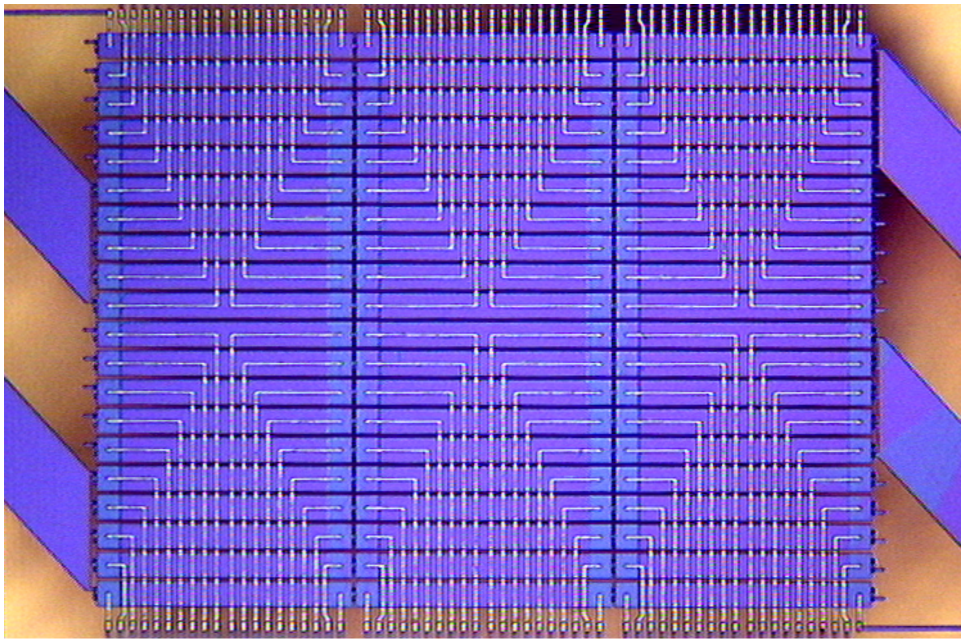
Natl. Inst. of Advanced Industrial Science and Technology (AIST), Japan
0.2 – 2 keV

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





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



R.A. Hijmering,
et al., ESA   LTD13

DROID =
Distributed ReadOut
Imaging Detector

- 3x20 DROID array 33.5x 360µm^2 ➔ 120 amplifiers
- Photons from back side
- Ta DROIDs, Ta/Al STJ; 11 'pixels' per DROID
- Measured in S-Cam3 system (single STJs)
- Offline coincident events determination
- Testing, development in progress

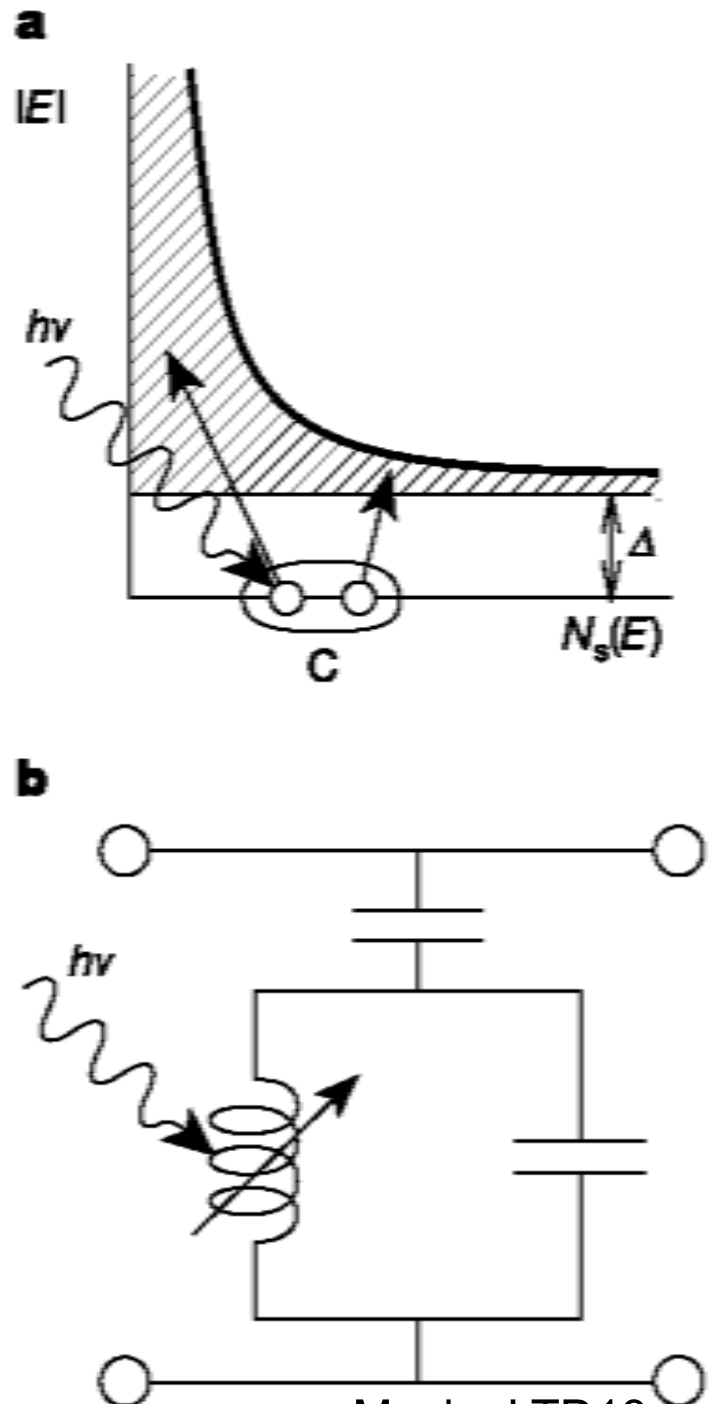
Microwave Kinetic Inductance Detector

Absorb photon in supercond. quarter-wavelength resonator.

Inductance = magnetic + kinetic

Kinetic inductance increases and resonant freq. decreases, due to reduced number of pairs

-the hometown candidate!



Mazin, LTD13

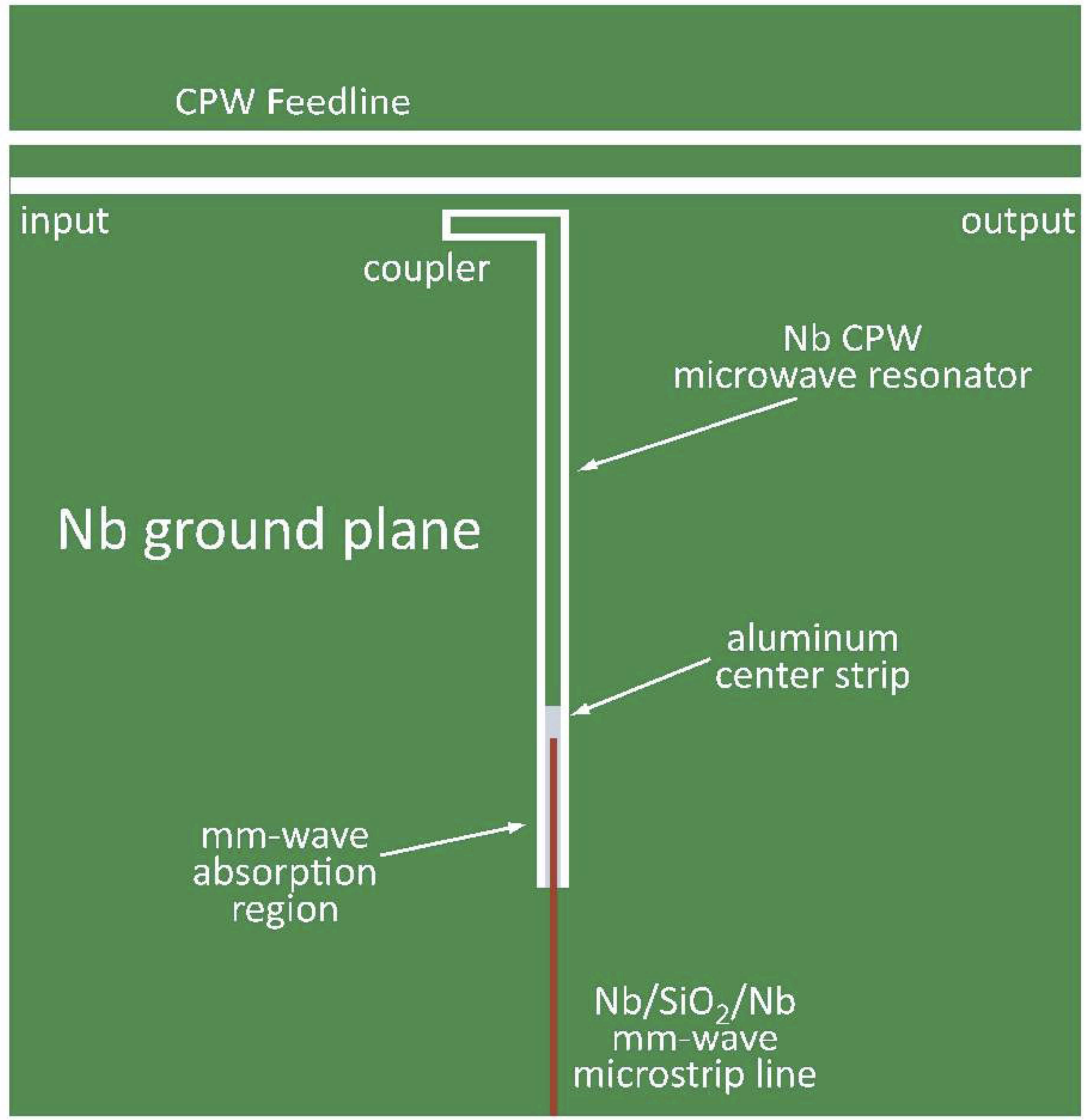
First demo – mm-wave camera at CSO

Detects power.

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

Array concepts – strong, demonstrated; capitalizes on existing microwave digital sig. processing; open source collaboration (Ben Mazin, UCSB).

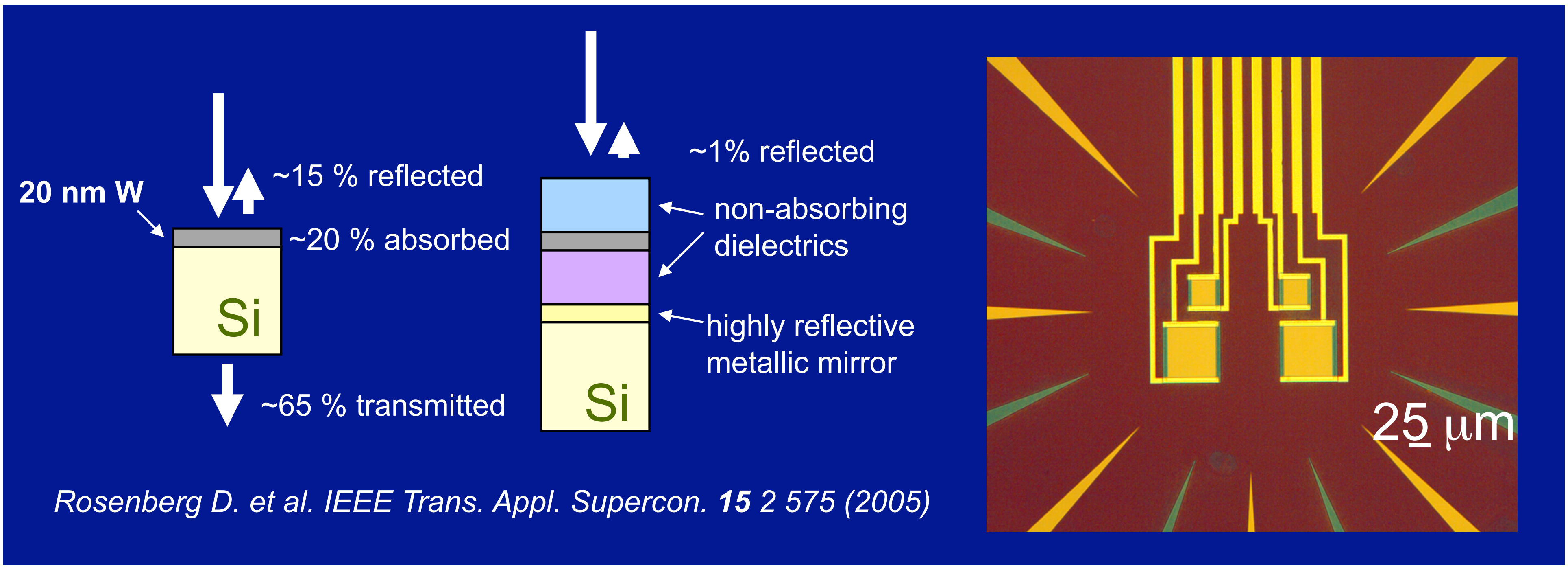
Collaboration in many areas of device development.



Maloney, LTD13

Optical TES - Structures to Enhance Detection Efficiency for Visible/IR

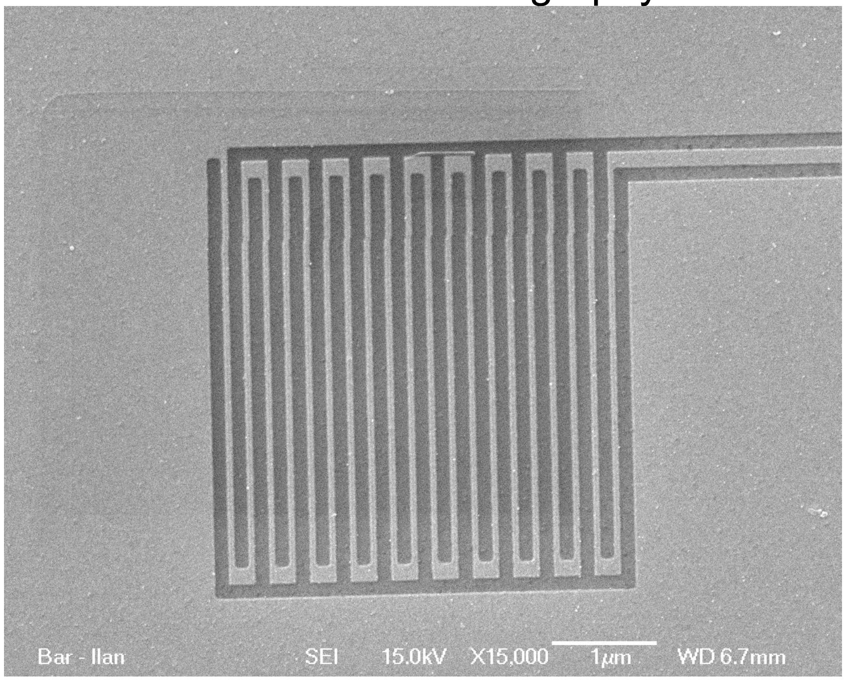
- 95% ± 2% system detection efficiency for 1550 nm
- Microsecond response



A. Lita LTD13

Superconducting Nanowire Single Photon Detectors

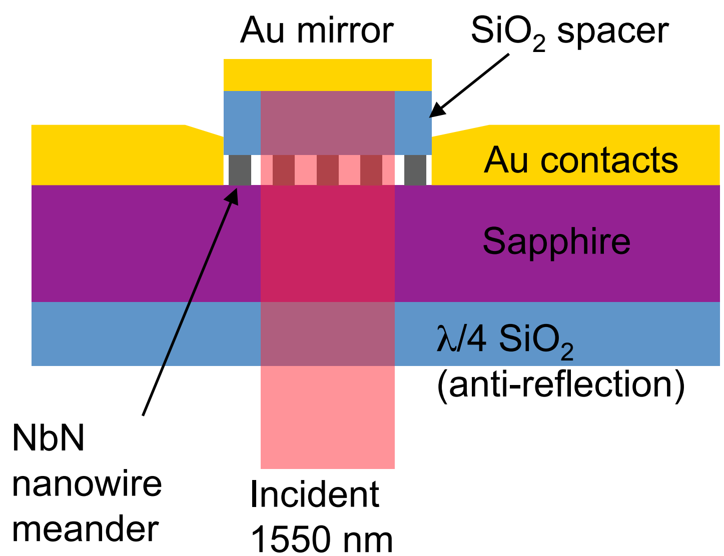
electron-beam lithography



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%

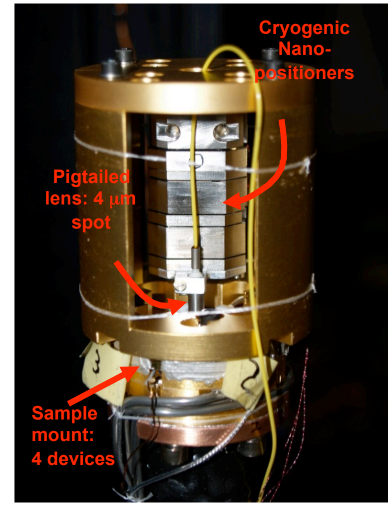
K. Rosfjord, et al., Optics Express 14, P. 527 (2006).

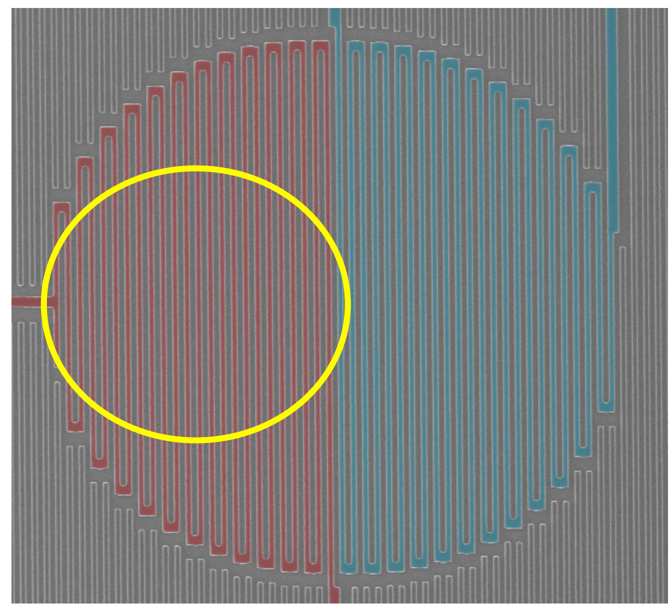
- This work is sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government

Detection System Performance

- 2 fibers coupled to detectors in a single cryocooler
  - Each fiber is integrated with a long-working-distance focuser
  - Focuser is nano-positioned over the detector
  - Light is coupled into a semicircular detector
  - < 2 dB coupling loss
- System detection efficiency = 31%
- Timing jitter < 40 ps
- Recovery time
  - < 9 ns to 50% of initial DE
  - < 20 ns to 90% of initial DE

Slides from E. Dauler, Lincoln Lab



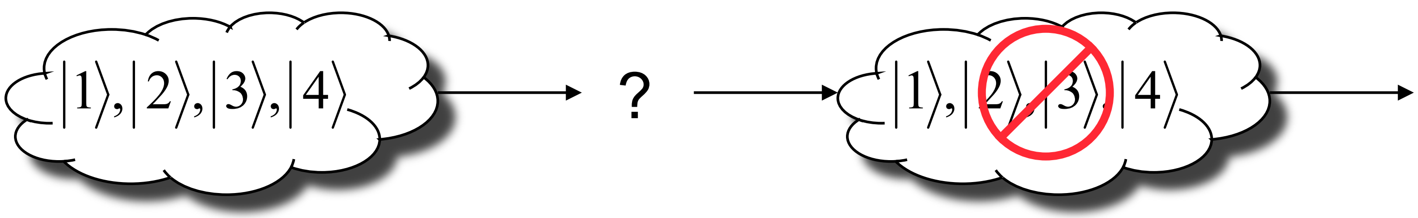


This work is sponsored by the United States Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government

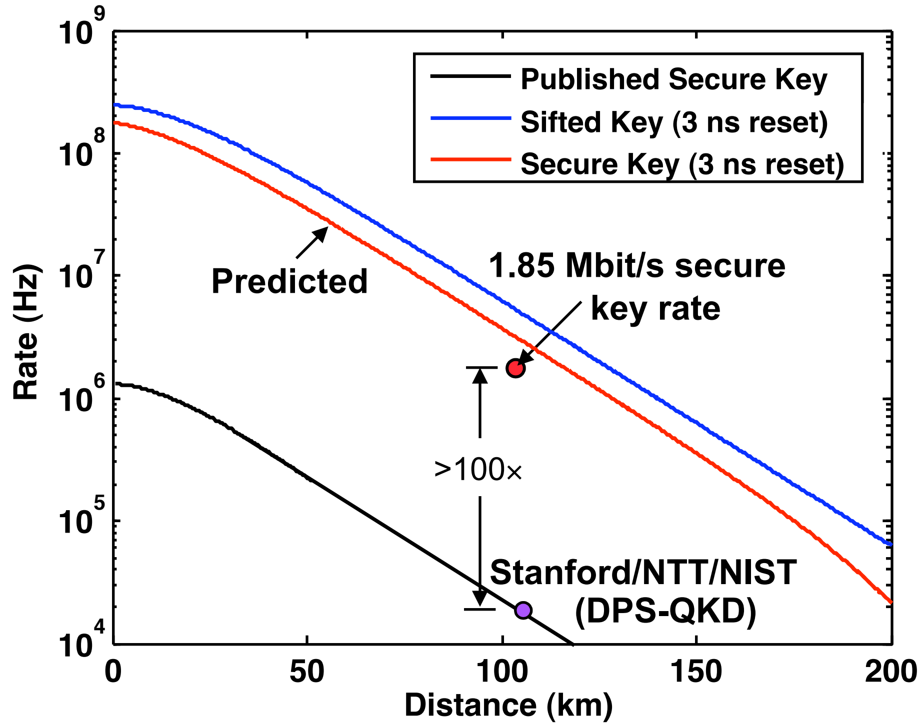
Quantum Key Distribution QKD Basics

- Key idea: send quantum states such that eavesdropping must affect the state in a measurable way

- Requirements – transmit between fiber 'terminals' that are up to 100 km apart; use conventional fiber networks, either 1550 nm or 1300 nm (to avoid 1550 traffic)



New QKD Secure Key Rate Record



- Previous record (100+km): Stanford / NTT / NIST groups demonstrated 17 kbit/s over 105 km and 10 bit/s over 200 km fiber
- New record (100+km): 1.85 Mbit/s secure key rate over 101 km of fiber
  - Utilizes higher-efficiency superconducting detectors & better DPSK technology – E. Dauler; K. Berggren talk

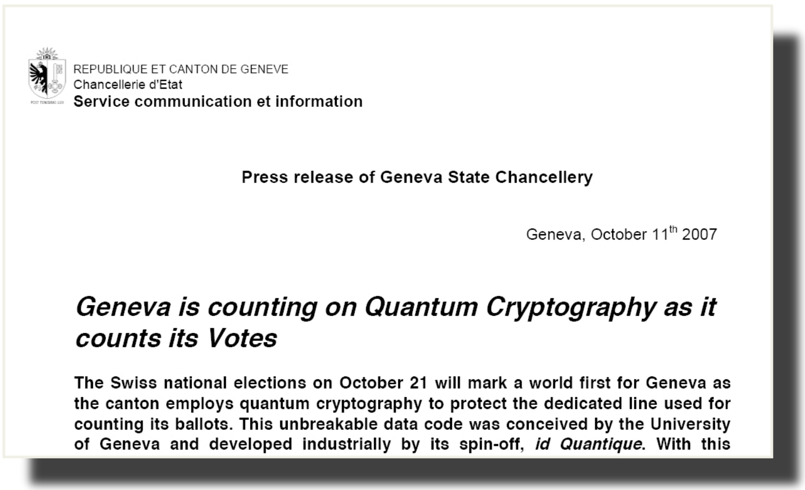
NIST Fiber QKD with LANL

Hiskett et al , New
J. Phys. 8 193 (2006)

Rosenberg et al, Phys. Rev. Lett. 98, 010503 (2007)

S. Nam, NIST Boulder

QKD secures Elections in Geneva


REPUBLIQUE ET CANTON DE GENEVE
Chancellerie d'Etat
Service communication et information

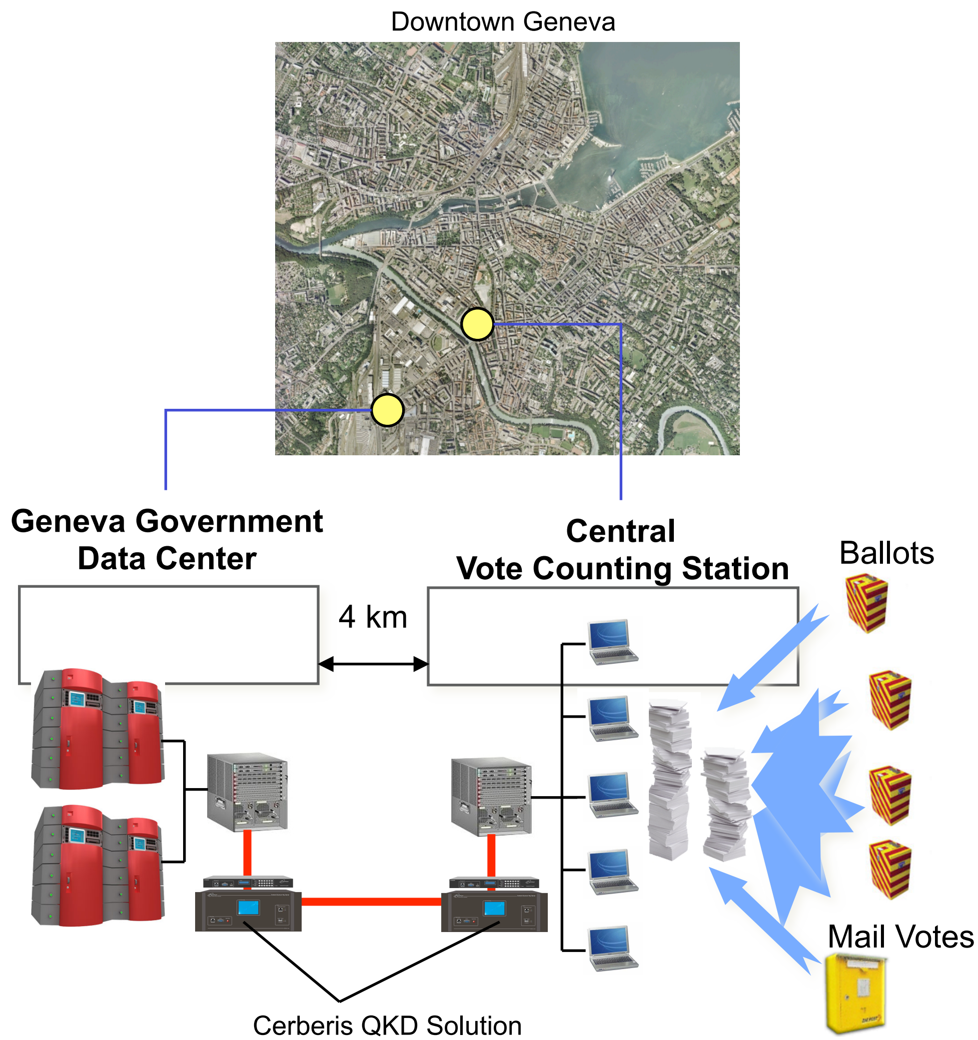
Press release of Geneva State Chancellery

Geneva, October 11th 2007

Geneva is counting on Quantum Cryptography as it counts its Votes

The Swiss national elections on October 21 will mark a world first for Geneva as the canton employs quantum cryptography to protect the dedicated line used for counting its ballots. This unbreakable data code was conceived by the University of Geneva and developed industrially by its spin-off, *id Quantique*. With this

- First Deployment: September 2006 – October 2007, with election day on October 21st
  - Installation time: 30 minutes
  - Continuous operation during more than 7 weeks
  - Encryption of a Gigabit Ethernet link
- As of 2008, used to secure all elections in the Geneva Canton
  - Used in Oct. 08, Oct. 09 and Nov. 09

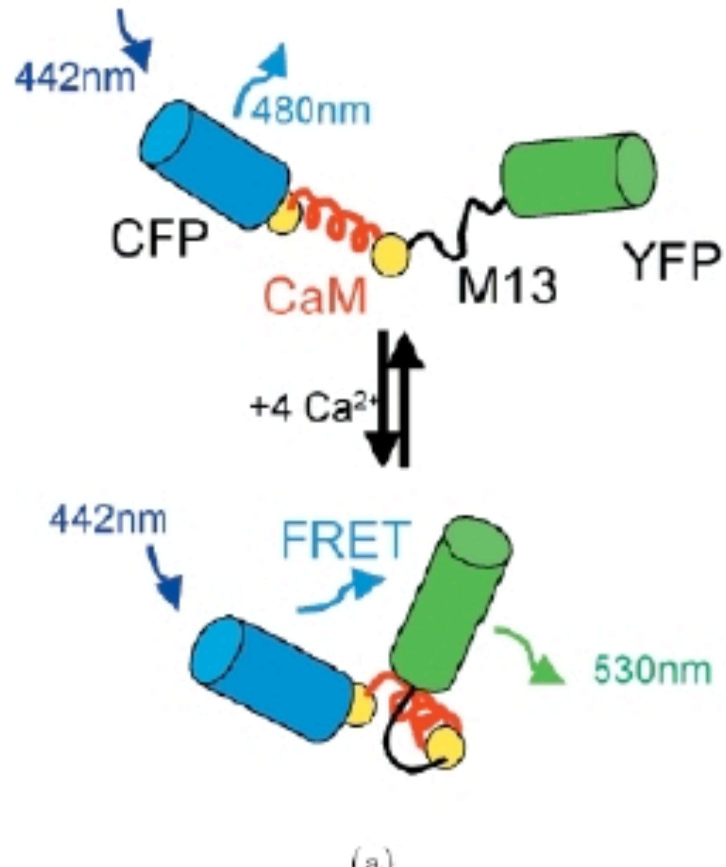


Gregoire Ribordy, id Quantique

Bio Applications – Single Molecule

- FRET – Fluorescence Resonance Energy Transfer
- Single molecules only emit 100s to 1000s of photons (typically)
- Want to know spectrum, timing, everything
- Visible, NIR; ≈ all commercial
- SPAD (like photomultipler)

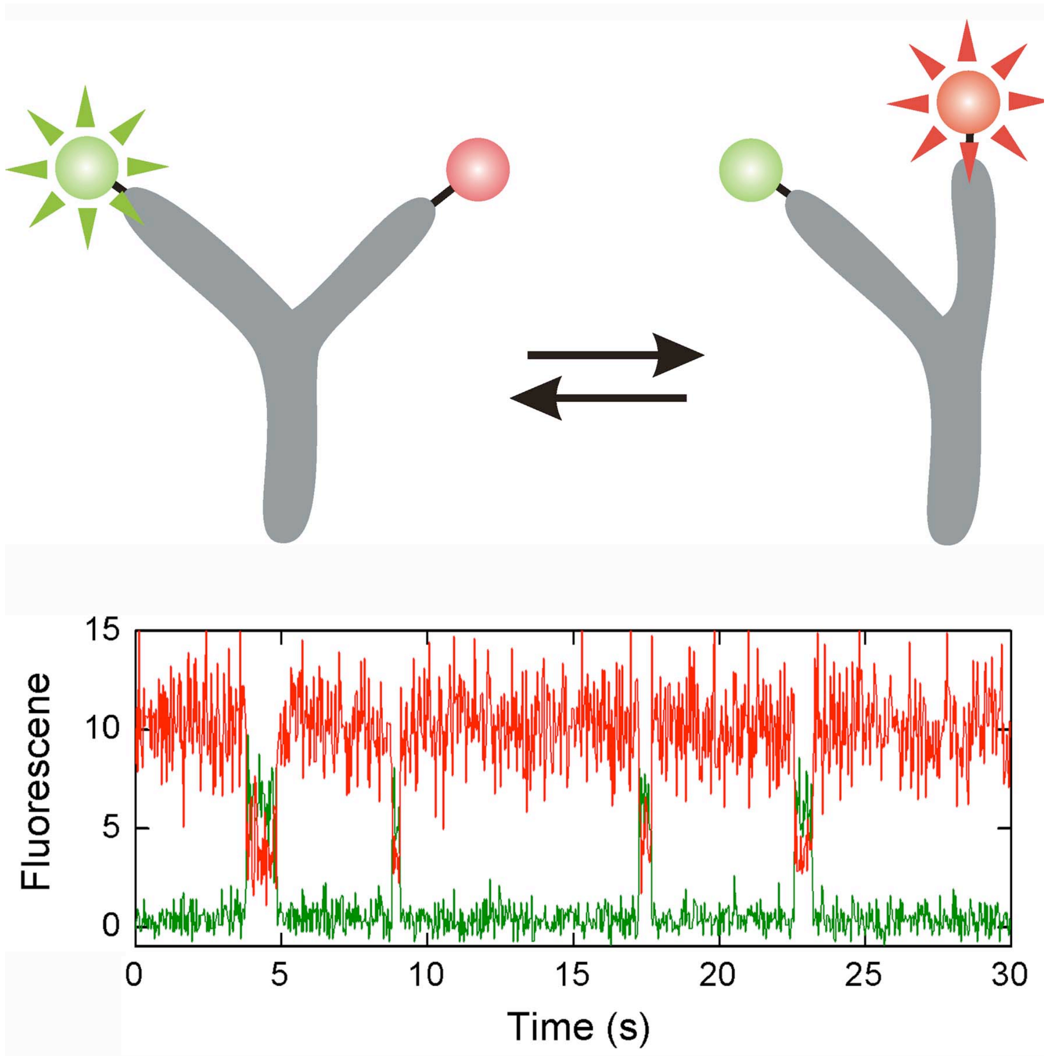
(www.labautopedia)



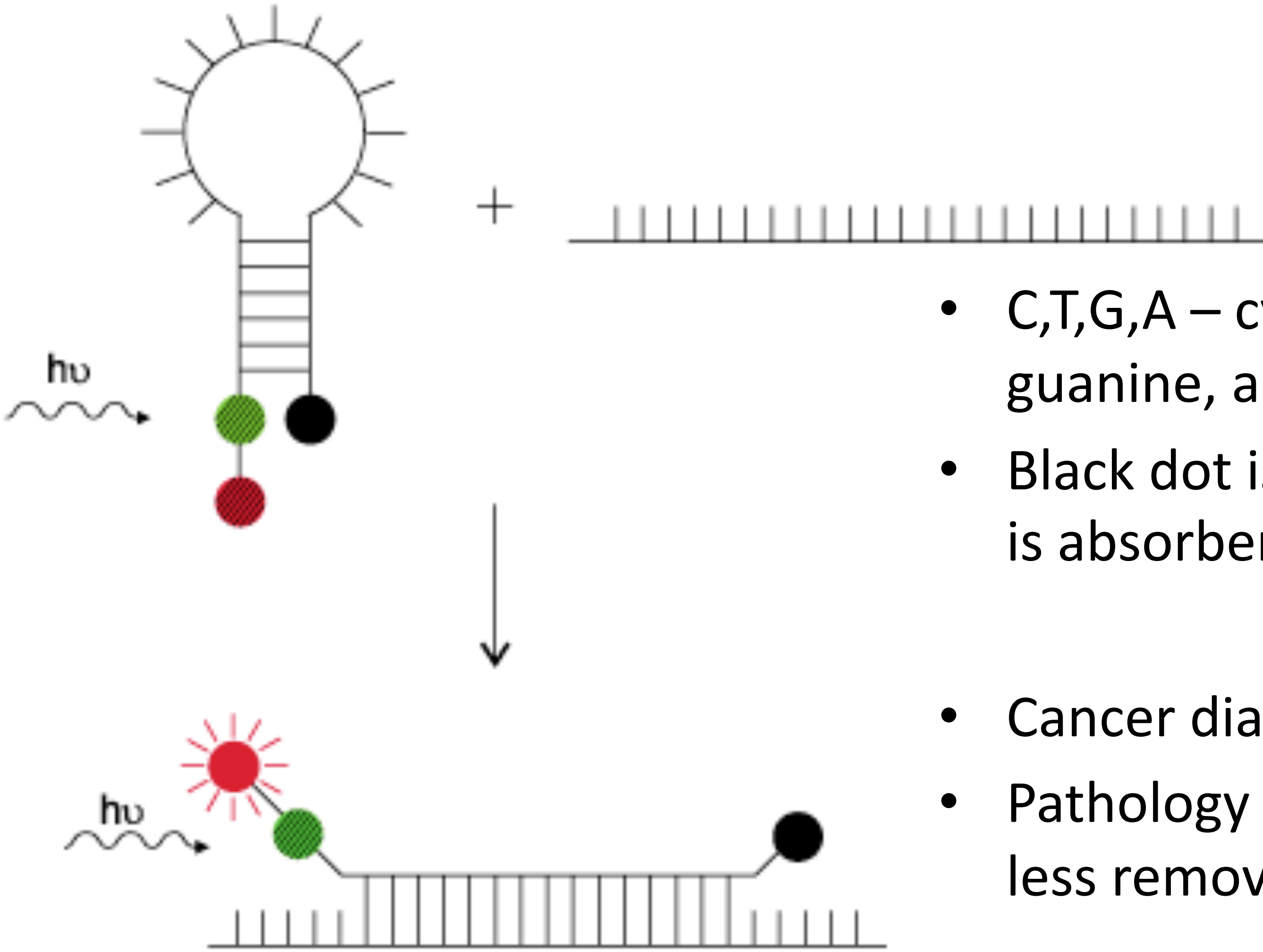
FRET = higher Ca concentration

FRET – if binding and unbinding

(measure cts/sec)



Bio Applications – Single Molecule; binding

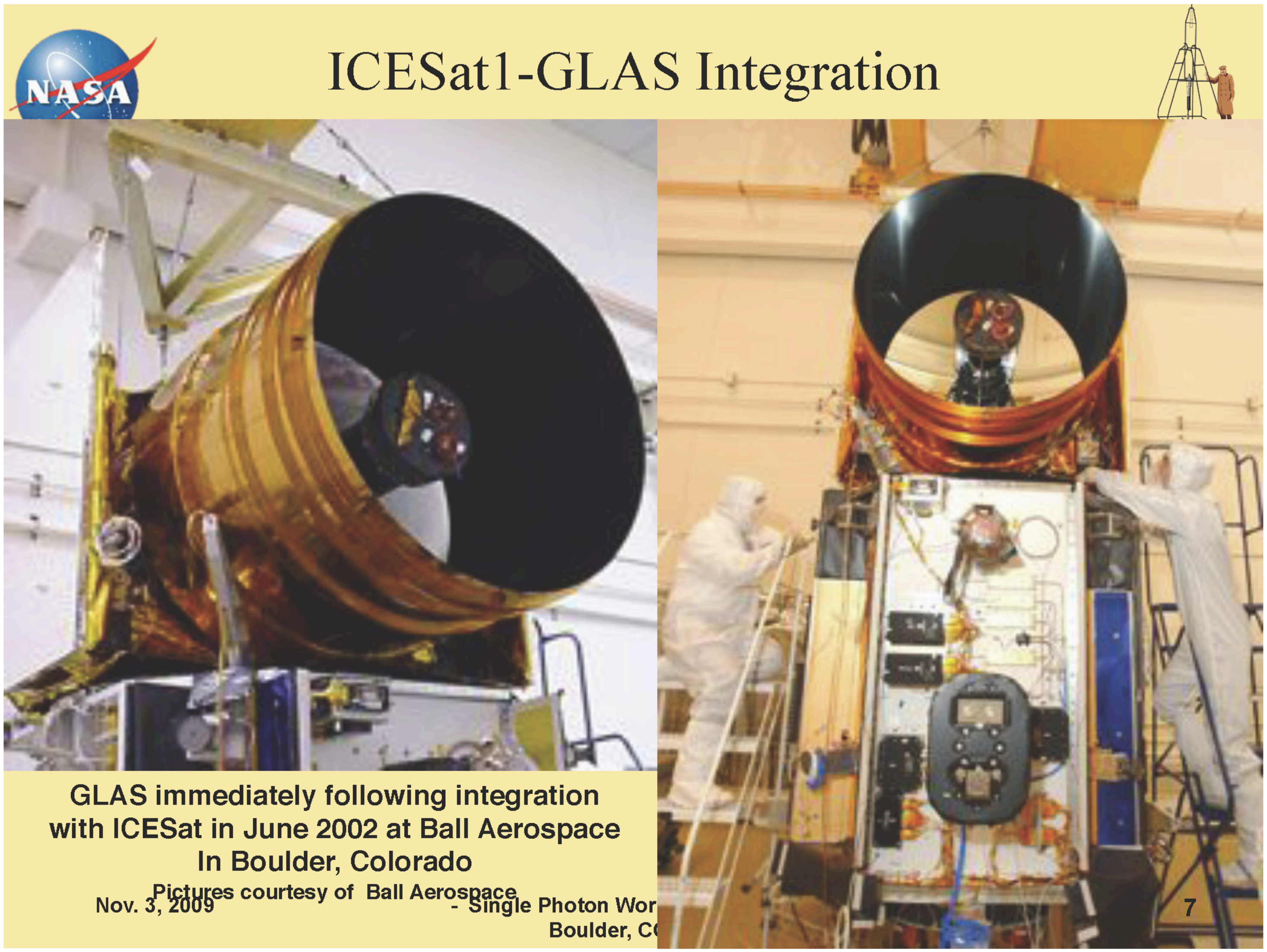


- C,T,G,A – cytosine, thymine, guanine, adenine (A--T,C--G)
- Black dot is 'quencher', green is absorber, red = fluor

- Cancer diagnostic? NIR
- Pathology during operation – less removal

- Molecules delivered by FedEx

ICESat/GLAS - Ice, Cloud and land Elevation Satellite / Geoscience Laser Altimeter System (2003)



Nd-YAG laser, 1064 nm

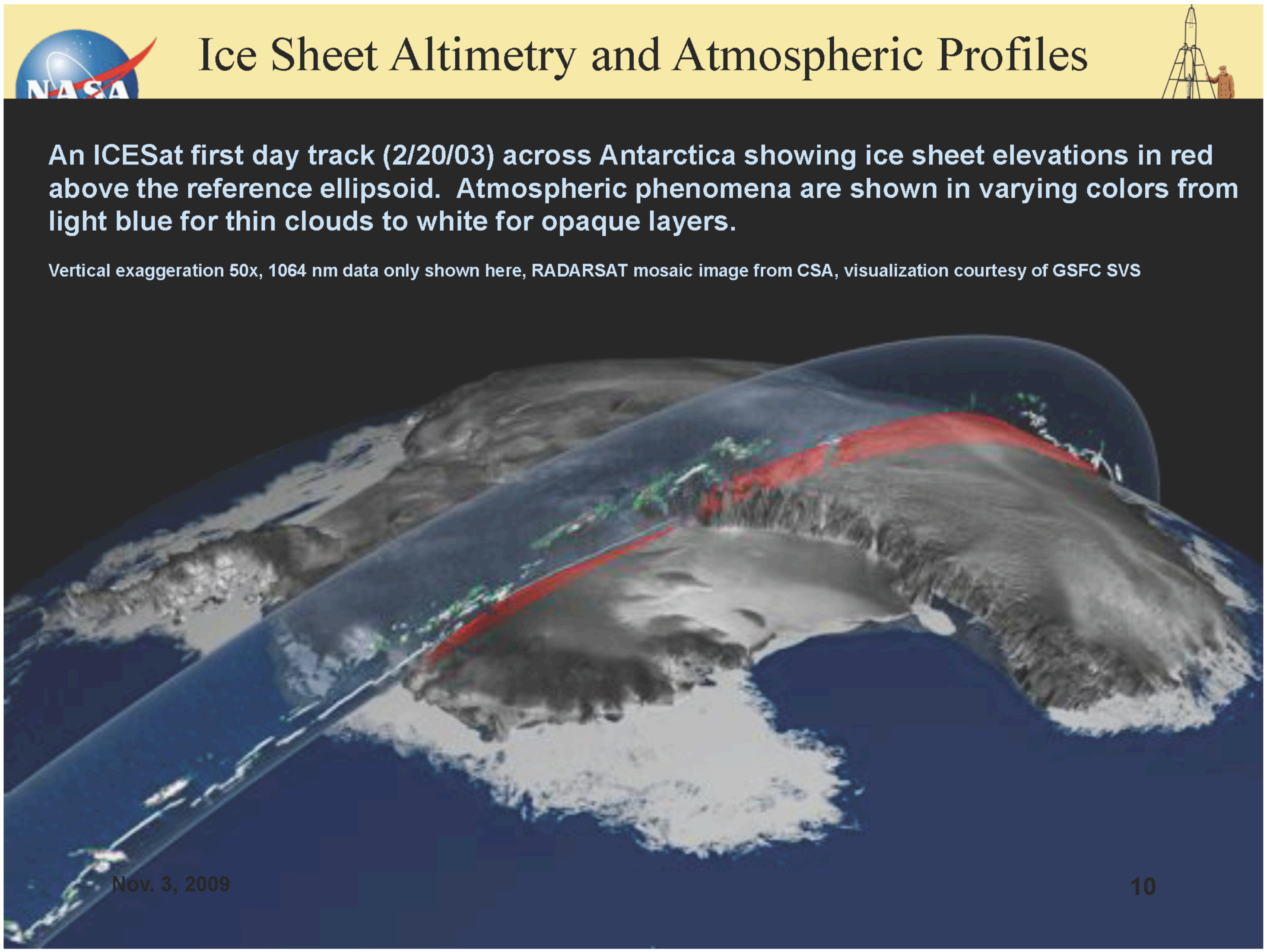
M. Kraniak, GSFC

ICESat/GLAS - Ice, Cloud and land Elevation Satellite / Geoscience Laser Altimeter System (2003)

SPCMs for aerosols

M. Kraniak, GSFC

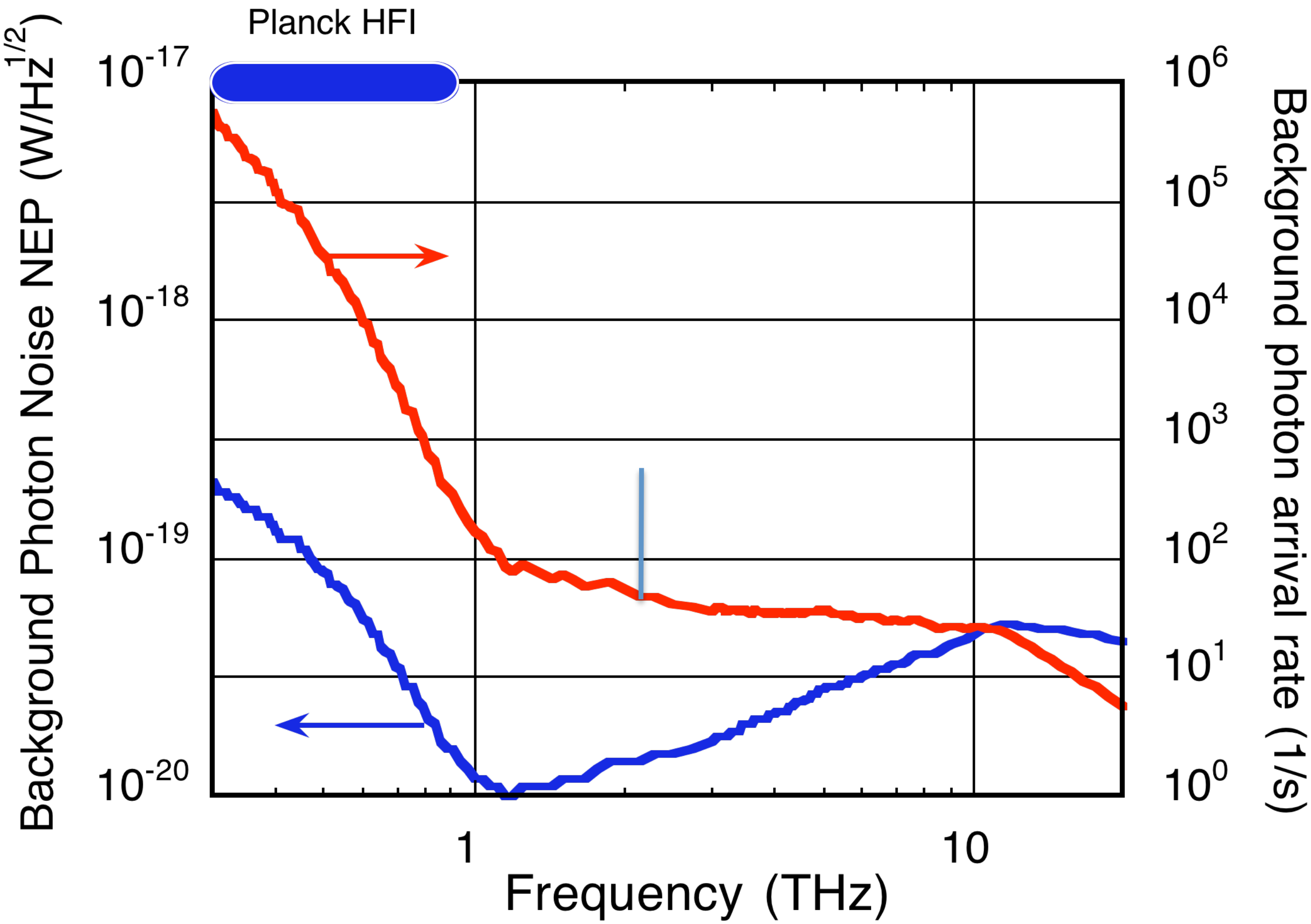
ICESat/GLAS - Ice, Cloud and land Elevation Satellite / Geoscience Laser Altimeter System (2003)



M. Kraniak, GSFC

FIR Single Photon Det.- Astro Motivation

- photon counting > 1 THz (λ = 300 μm); Quantum-dot detector demonstrated; but only 1% detection efficiency, narrow range of E_{ph}

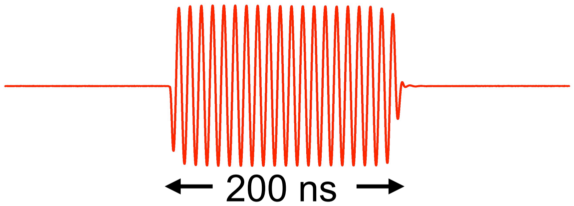


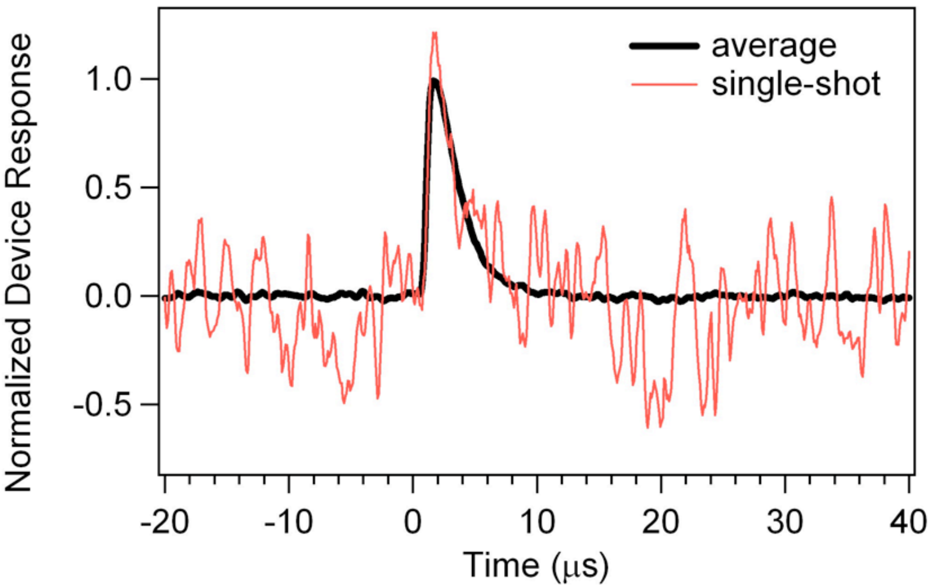
B. Karasik

Antenna-coupled nano-TES- testing with fauxtons

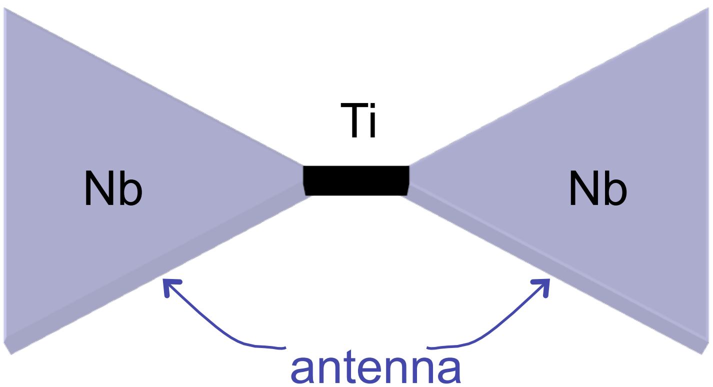
(faux photon) – a new "quanta" for single photon testing; real photons = very hard
- see Karasik – has just seen real photons; Santavicca

Fast microwave (20 GHz) pulse; absorbed pulse energy (fauxton) = energy of single higher-freq. photon. Measure the reflection coefficient (due to change of R) at 1 GHz.





Leads (rf, dc) are not shown

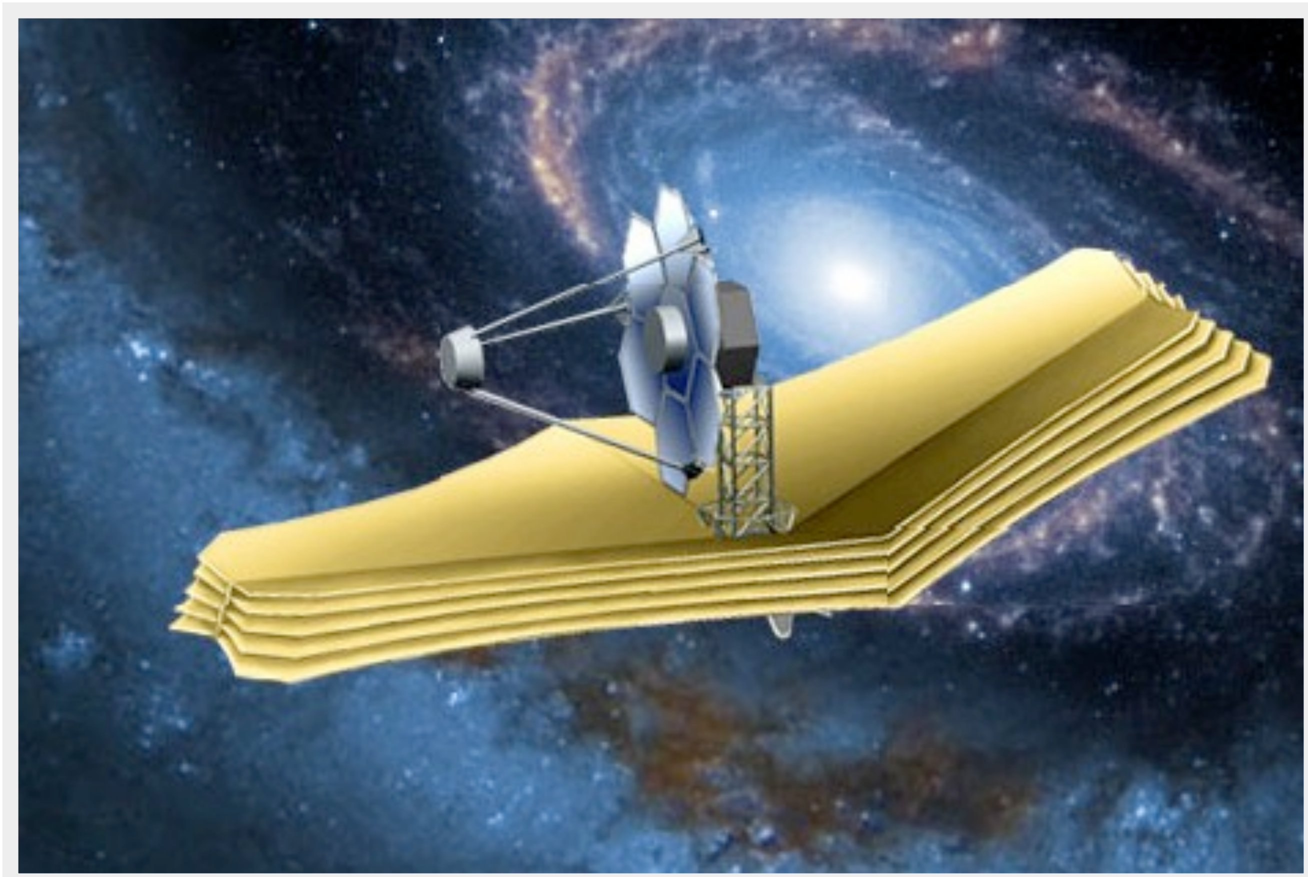


Based on measured performance, predict for smaller TES - single 1 THz (4 meV) photons can be counted!

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

END

From the following article

Single-photon detectors for optical quantum information applications

Robert H. Hadfield

Nature Photonics 3, 696 - 705 (2009)

doi:10.1038/nphoton.2009.230

Table 1. Comparison of single-photon detectors.

Detector type	Operation temperature (K)	Detection efficiency, η	Jitter time, Δt (FWHM)	Dark count rate, D (ungated)	Figure of merit	Max. count rate	Resolves photon number?	Class of report
PMT (visible–near-infrared)[31]	300	40% @500 nm	300 ps	100 Hz	1.33×10^7	10 MHz	Yes	†
PMT (infrared)[32]	200	2% @1,550 nm	300 ps	200 kHz	3.33×10^2	10 MHz	Yes	†
Si SPAD (thick junction)[38]	250	65% @650 nm	400 ps	25 Hz	6.5×10^7	10 MHz	No	†
Si SPAD (shallow junction)[41]	250	49% @550 nm	35 ps	25 Hz	5.6×10^8	10 MHz	No	†

The class of report indicates the conditions under which the detector characteristics were measured;

† represents a commercial product specification,

‡ represents the use of the detector in a practical experiment and

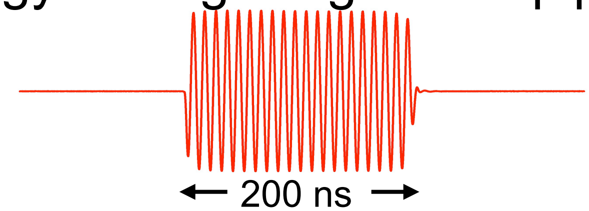
Detector type	Operation temperature (K)	Detection efficiency, η	Jitter time, Δ*t* (FWHM)	Dark count rate, *D* (ungated)	Figure of merit	Max. count rate	Resolves photon number?	Class of report
InGaAs SPAD (gated)[55]	200	10% @1,550 nm	370 ps	91 Hz	2.97×10^5	10 kHz	No	‡
InGaAs SPAD (self-differencing)[57]	240	10% @1,550 nm	55 ps	16 kHz	1.14×10^5	100 MHz	Yes	‡
Frequency up-conversion[65]	300	9% @1,550 nm	400 ps	13 kHz	1.7×10^4	10 MHz	No	‡
Frequency up-conversion[65]	300	2% @1,550 nm	40 ps	20 kHz	2.5×10^4	10 MHz	No	‡
VLPC[69]	6	88% @694 nm	—	20 kHz	—	—	Yes	§
VLPC[*]	6	34% @633 nm	270 ps	7 kHz	1.83×10^5	—	Yes	§
TES[76]	0.1	50% @1,550 nm	100 ns	3 Hz	1.67×10^6	100 kHz	Yes	‡
TES[20]	0.1	95% @1,550 nm	100 ns	—	—	100 kHz	Yes	§
SNSPD (meander)[90]	3	0.7% @1,550 nm	60 ps	10 Hz	1.16×10^7	100 MHz	No	‡
SNSPD (new)[87]	1.5	57% @1,550 nm	30 ps	—	—	1 GHz	No	§
QD (resonant tunnel diode)[96]	4	12% @550 nm	150 ns	2×10^{-3} Hz	4×10^9	250 kHz	No	§
QD (field-effect transistor)[93]	4	68% @805 nm	—	—	—	1 Hz	Yes	§

The class of report indicates the conditions under which the detector characteristics were measured;

Antenna-coupled nano-TES
- testing with Fauxtons

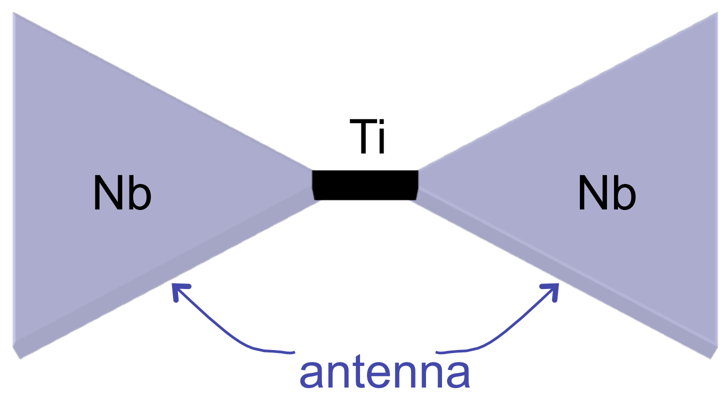
fauxton (faux photon) – a new “quanta” for single photon testing

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

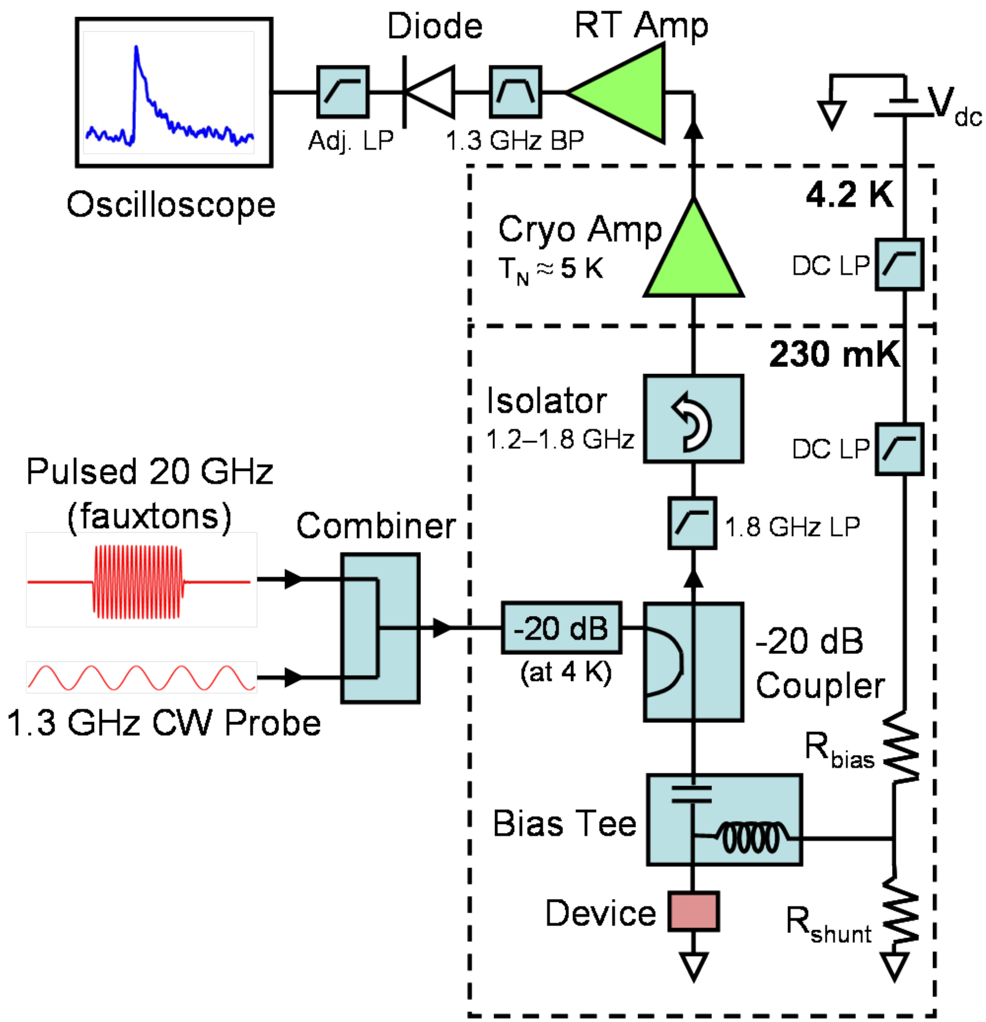
Leads (rf, dc) are not shown

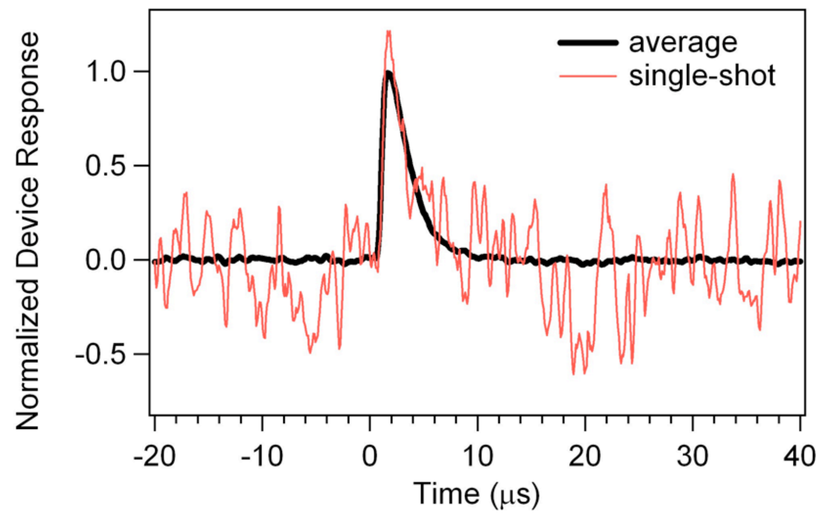


- Testing in a dark environment; no stray photons $P \ll 1fW$
- Arbitrary tunability of fauxton energy
- Can “sneak up” on hardest problems; optimize device fabrication, performance, and signal processing while a THz single-photon test system is developed

D.Santavicca, Yale

Testing with Fauxtons



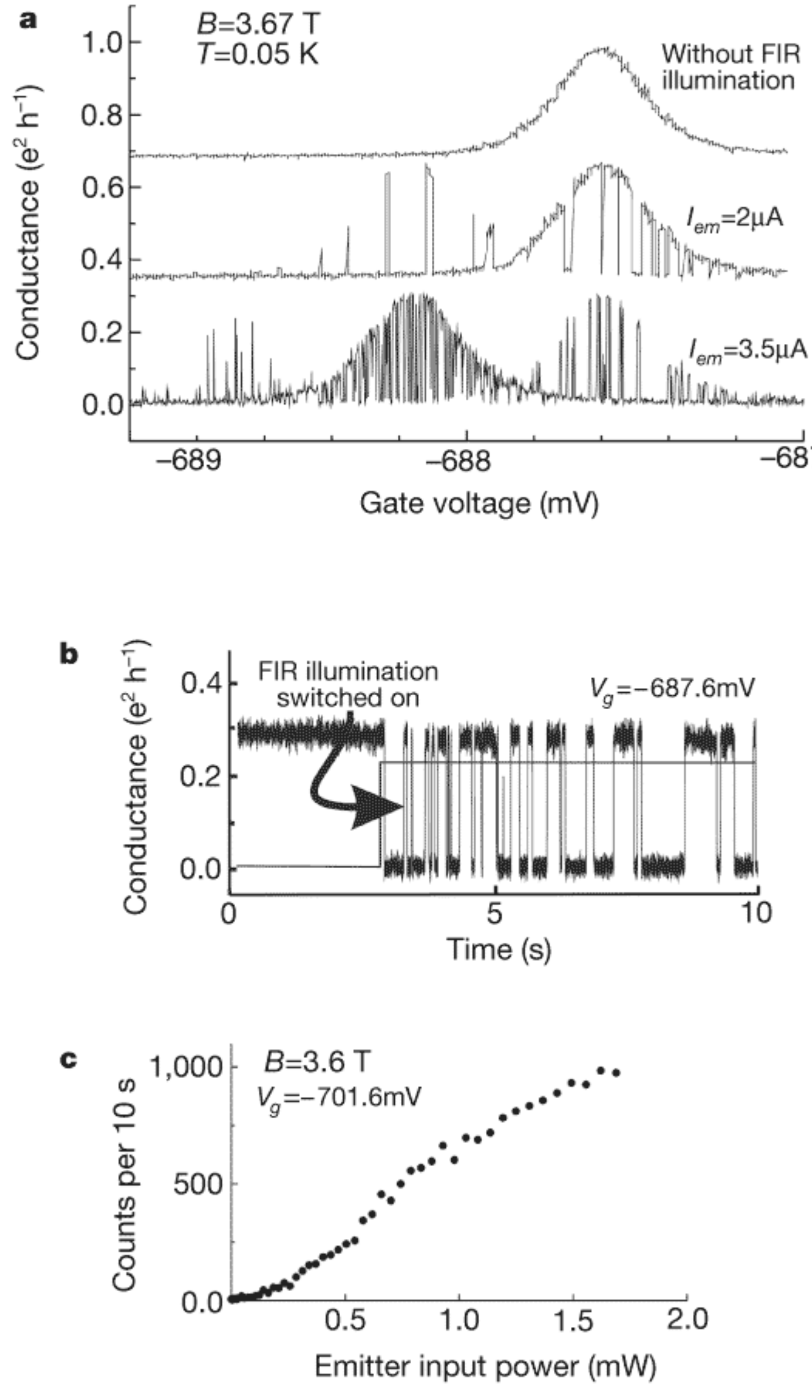


Experimental schematic for fauxton testing
Trigger signal used

D.Santavicca, Yale

Quantum Dot Detector

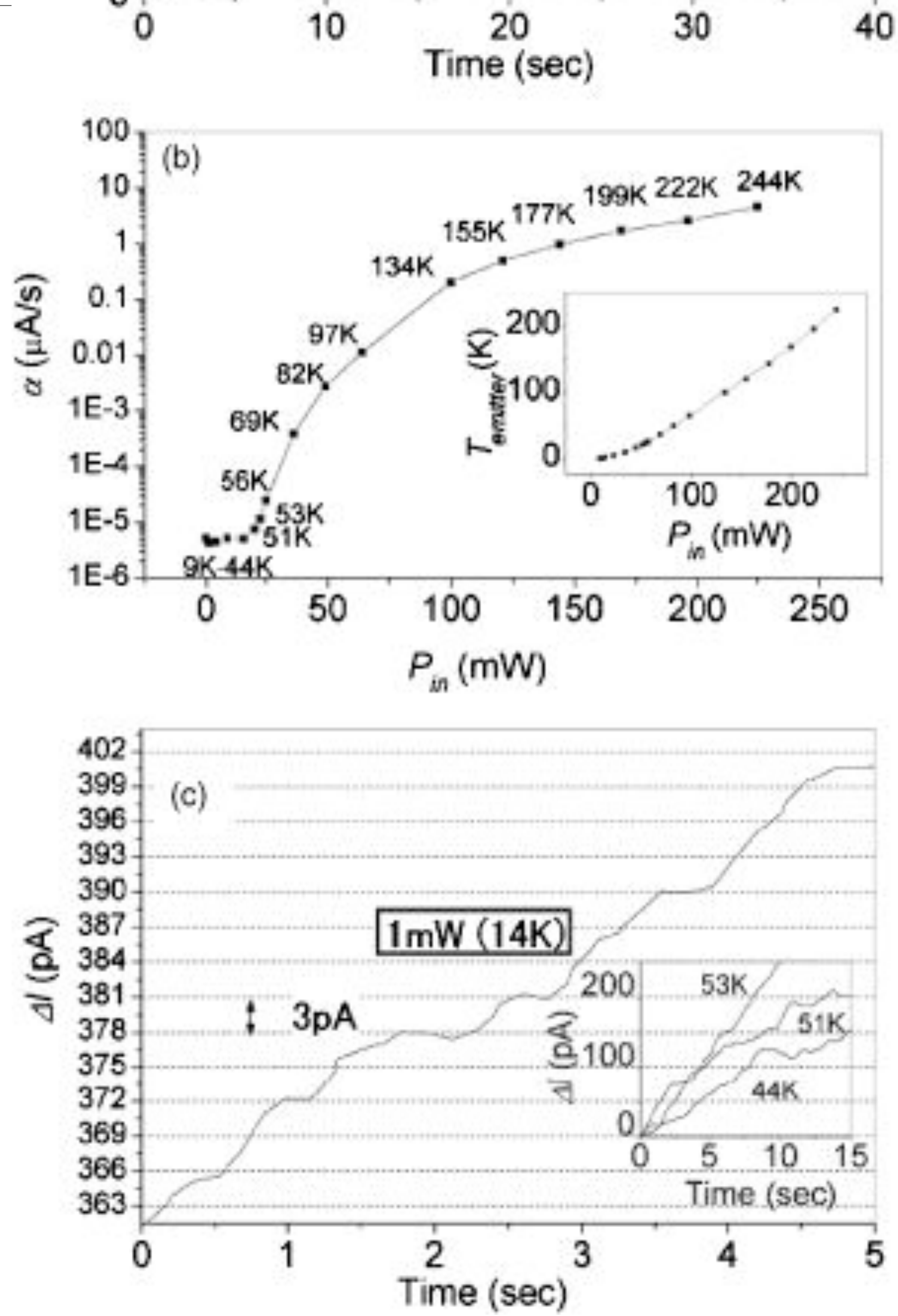
Transistor stays ‘on’ for a short time =counted photo eff. 2%

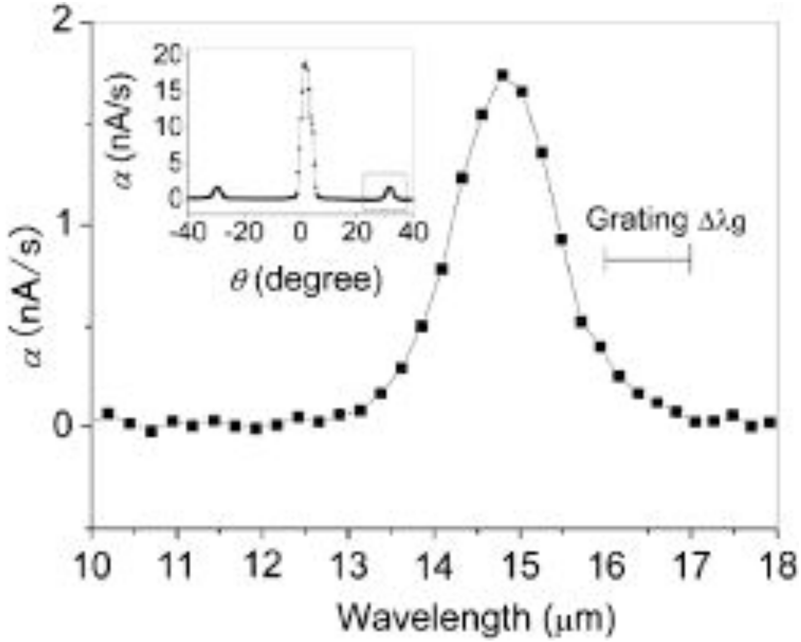


S. Komiyama et al. , Nature 403, 405 (2000)

FIR: FET Results

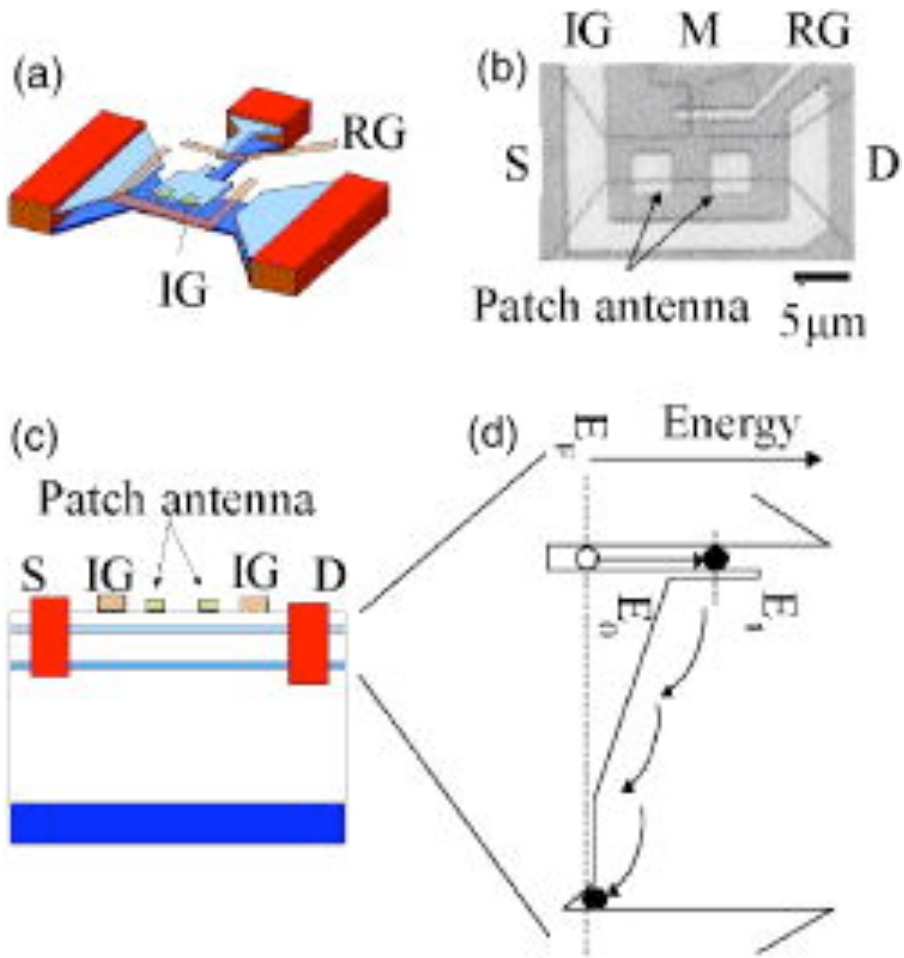
Current due to 15 μm photons increases during illumination, in steps of 3 pA (if you are charitable); note 360 μA initial current. *This is a VERY challenging detection goal!*



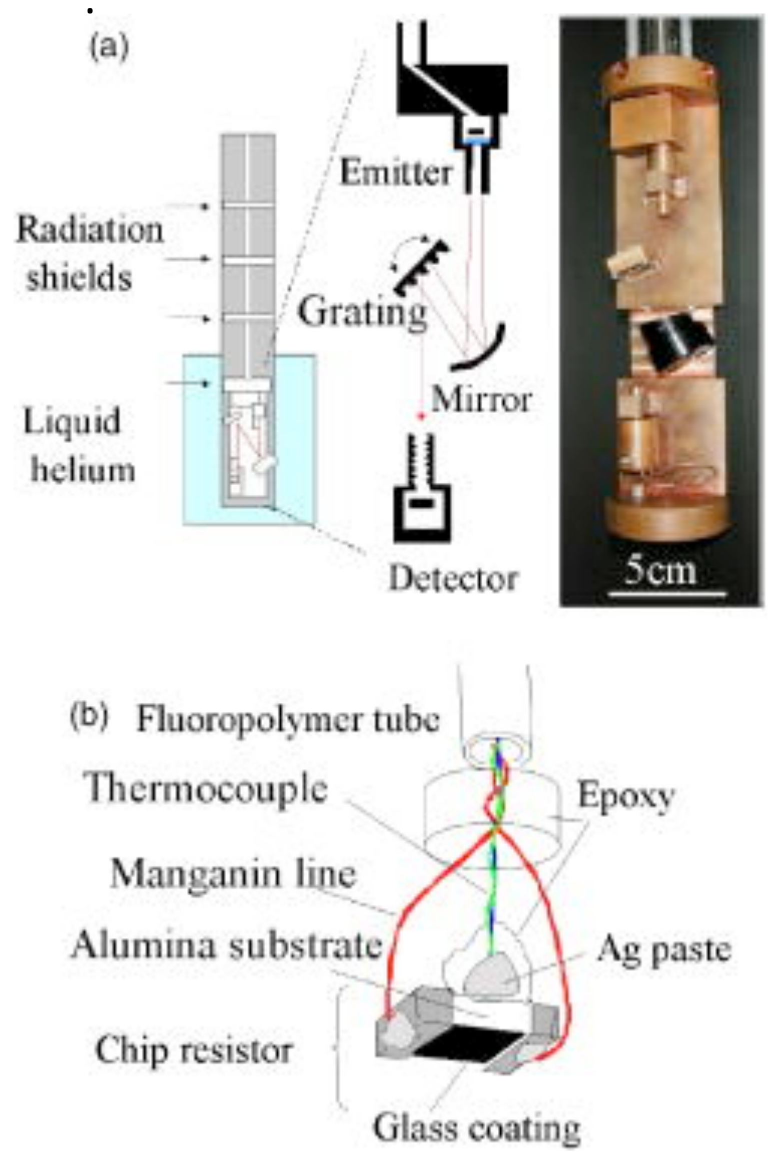


Ueda et al. J. Appl. Phys. 103, 093109 (2008)

FIR excitation – n_{photon} controls current of FET



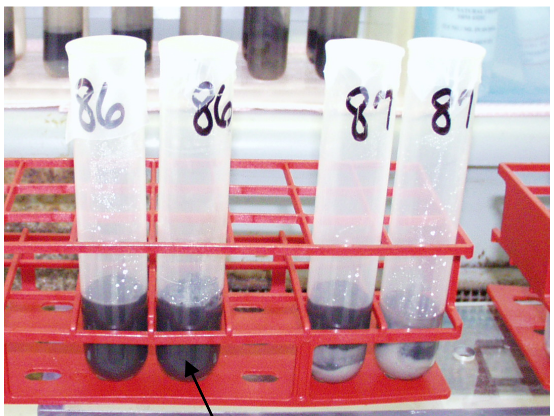
Ueda et al. J. Appl. Phys. 103, 093109 (2008)

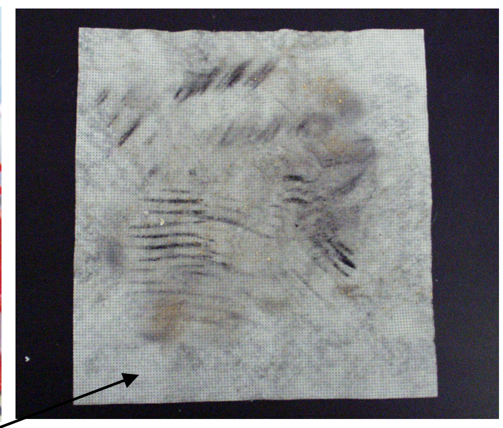


TES α particle sensors: nuclear materials analysis

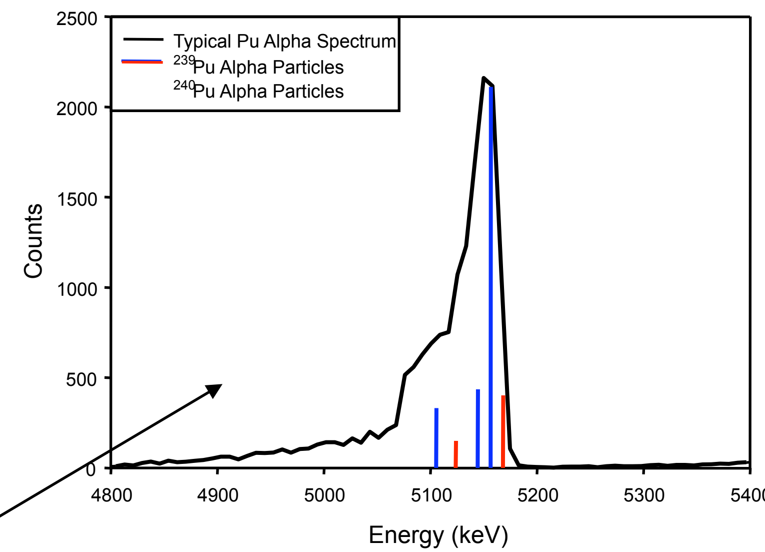
- J. Ullom, LTD13

- alpha spectroscopy is a powerful tool for trace actinide measurements
  - environmental monitoring
  - nuclear safeguards
  - medical assay
- alpha branching ratios higher than γ ➡ used for smaller samples (ug-pg)
- ~ 8 keV resolution limit of Si detectors has consequences:
  - elemental overlaps ➡ slow and expensive wet chemistry to separate elements
  - can't split ^{239}Pu/^{240}Pu ➡ slow and expensive mass spectrometry





typical alpha samples

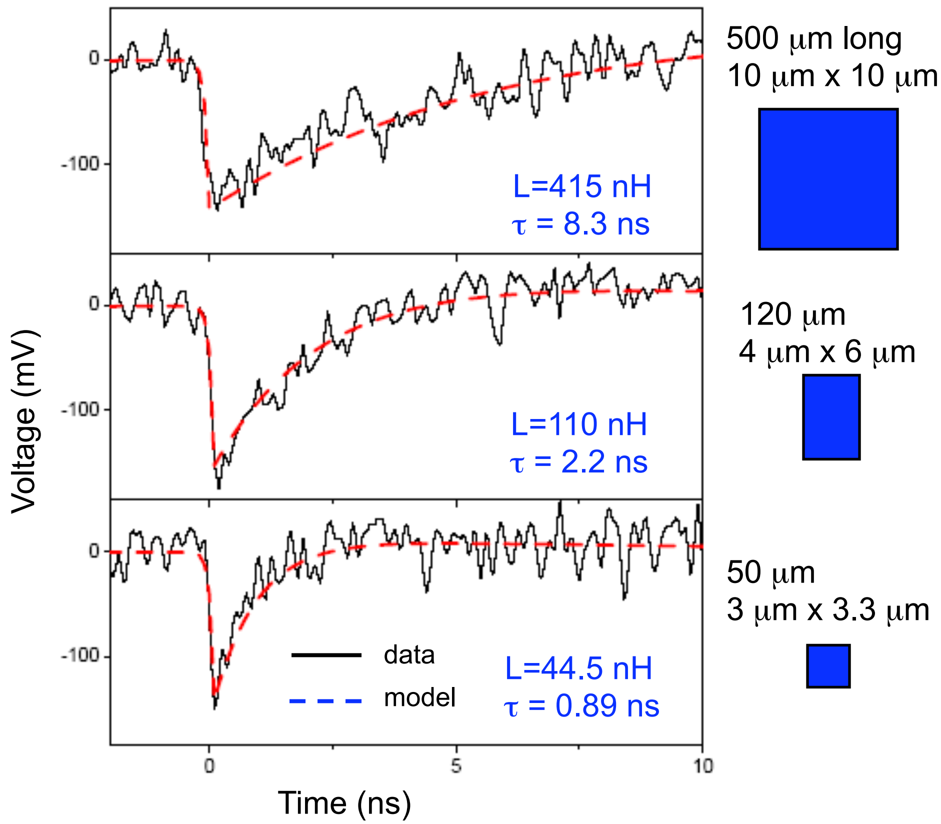


typical alpha spectrum

J. Ullom, LTD13

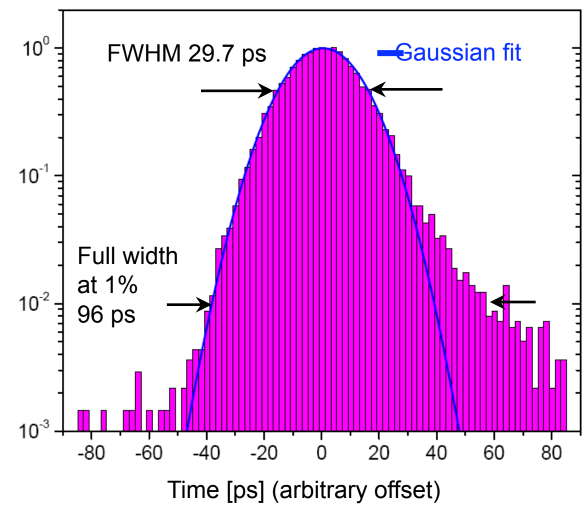
Device Characteristics

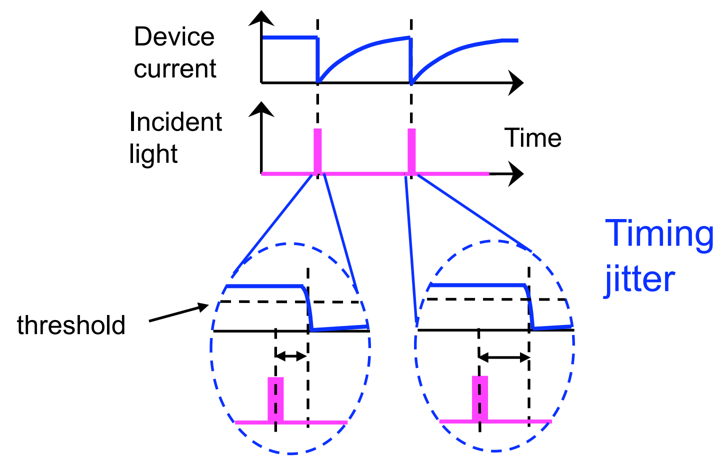
Single-photon output pulses



Typical detection efficiency:
40-60% at 1550 nm; T – 2-4 K

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





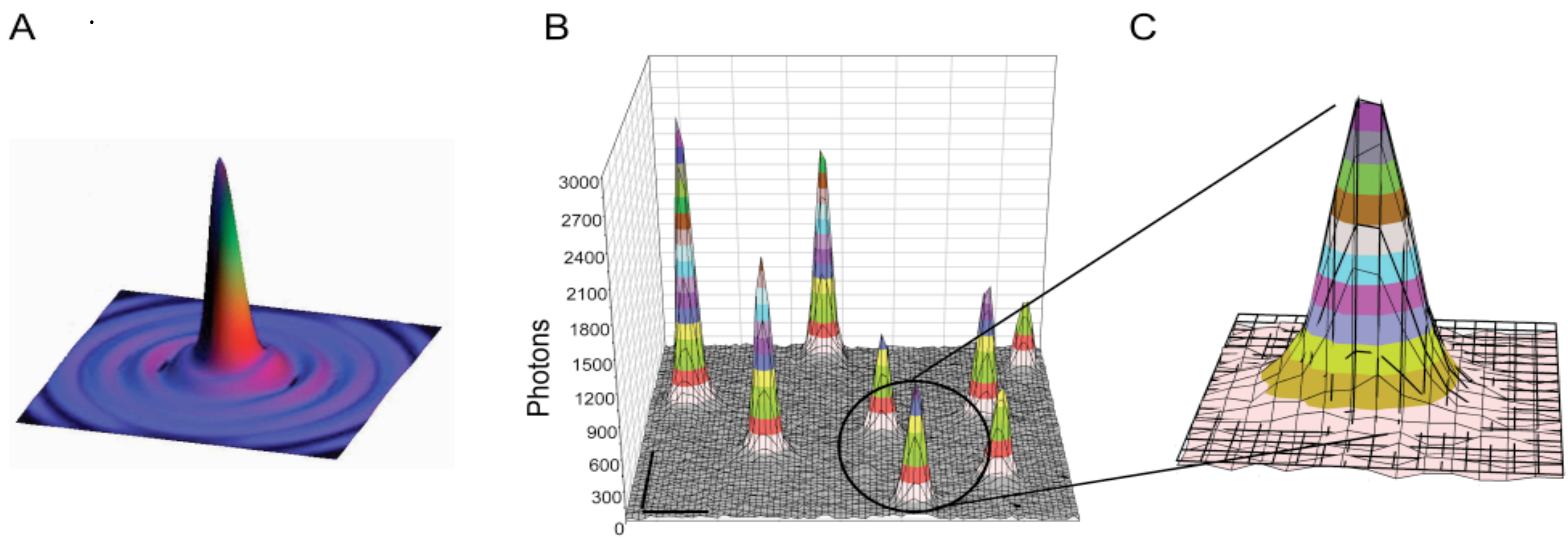
MIT LL data

QKD – Quantum Key Distribution

- Presently use InGaAs detectors over standard fiber = demo
- Tested in Swiss network *(id Quantique)* – also used single photon random number generator in voting authentication for Geneva
- Goal of QKD is to create a shared secret key that is then used to encrypt data.
- Transmission rates limited by detection efficiency, fiber losses over L ≈ 100 km, and (for fastest NbN nanowire detectors) standard electronics (electronics might not utilize the very small timing jitter of NbN detector)
- Nanowire – fast, good detection efficiency; good for QKD
- TES – higher DE, but too slow for QKD; good for other QI apps.

Ref - J.Kerman, E. Dauler

Bio Applications – Single Molecule



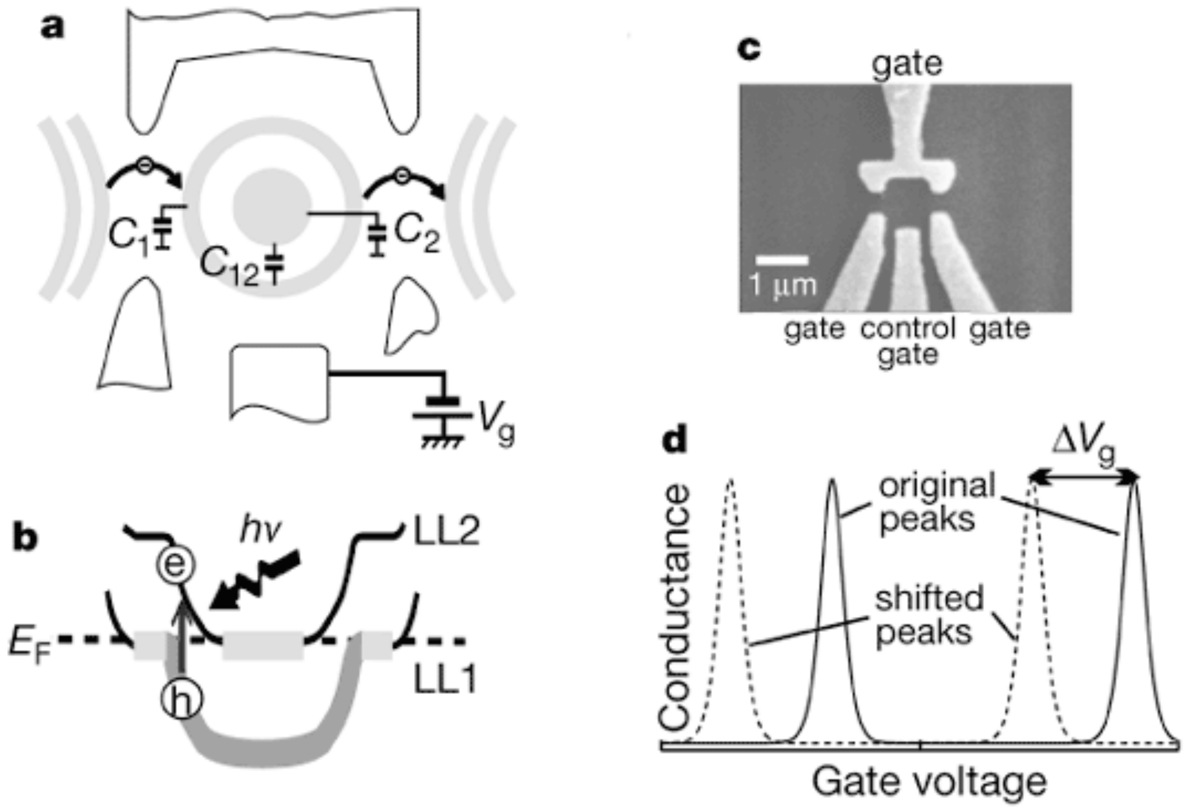
Yildiz Lab, UCB

ICESat/GLAS - Ice, Cloud and land Elevation Satellite / Geoscience Laser Altimeter System (2003)

- Uses 5 ns pulses from a diode pumped Q-switched Nd:YAG laser operating in the near infrared (1064 nanometers), used for the measurement of surface topography.
- Backscattered light in the green (532 nanometers) for aerosols and other atmospheric characteristics.
- Return photons collected in a 1 meter diameter telescope and the laser transmits 40 pulses/s to the surface.
- The spots produced on the Earth's surface will have a 70 meter diameter and the spacing between spots will be 175 meters, caused by the orbital motion of the spacecraft.
- ➔ Low power single-photon communication, distant.

M. Kraniak,
GSFC

FIR Single-photon Detectors
energies in solids, molecules. 1.Quantum Dot



SET – Quantum dot in center, use Landau levels to define hf

Needs large B field, 50 mK; small range of E_{ph}

Very cold, and small

Low Det. Eff. 2%

Recent work - FIR excitation ➔ n_{photon} controls current of FET

S. Komiyama et al. , Nature 403, 405 (2000)