NIST Optical Photon Detectors (UV to NIR) for Quantum Information

Mega-pixel TES camera

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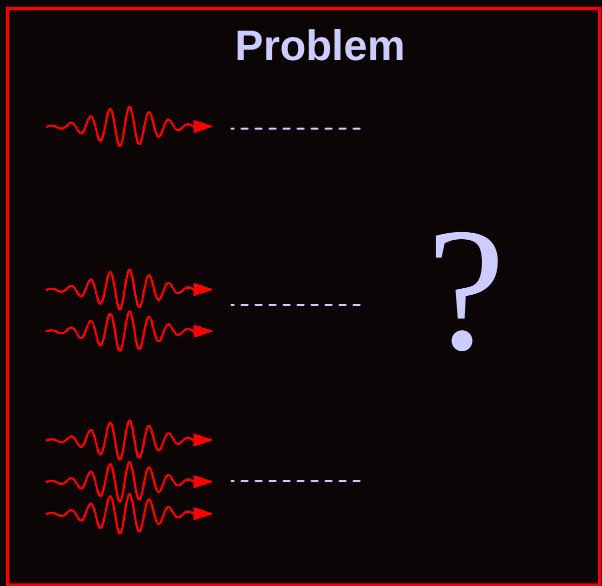
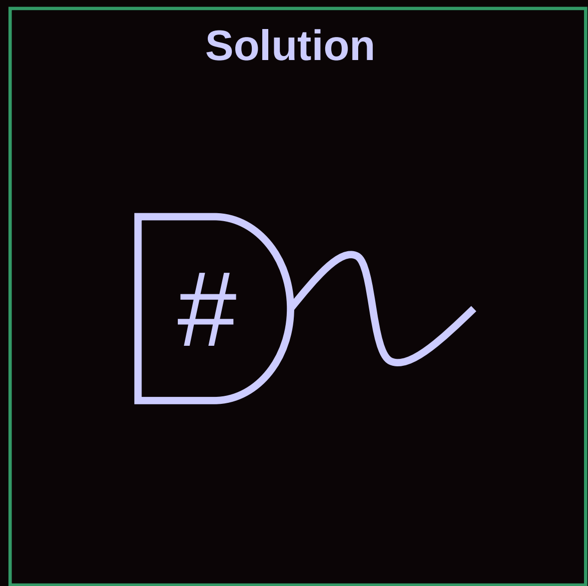
Superconducting devices for detection of single photons





NIST Colleagues

Rich Mirin (sources and detectors), Manny Knill (theory), Alan Migdall (sources and detectors), John Lehman (Optical Power Metrology)

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Recent Members:
A.J. Miller, Albion College, D. Rosenberg, MIT-LL, Robert Hadfield, Heriot-Watt Univ.

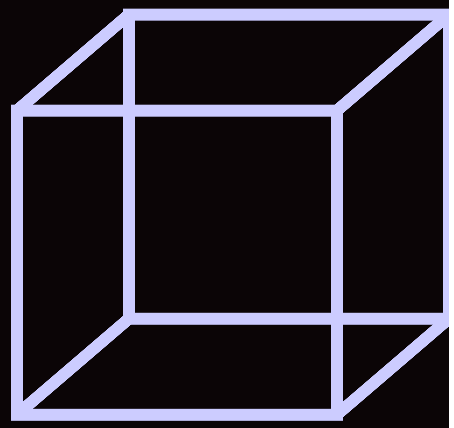
Collaborators

- Transition-edge Sensors
  - Quantum Imaging Lab at Boston Univ,
  - Quantum Cryptography Group at Los Alamos National Lab
  - University of Virginia
  - University of Queensland
  - AIST, PTB, NPL
- Nanowire Superconducting Single Photon detectors
  - Quantum Cryptography Group at Los Alamos National Lab
  - University of Rochester, Moscow State Pedagocial University, MIT/MIT-LL, JPL, TU Delft, NICT
  - BBN Technologies, Northwestern University, Heriot-Watt University, Stanford University, Toshiba - Cambridge
  - Japan: NICT, NTT, NEC

Outline

- Quantum Information and single photon metrology
  - Transition-edge Sensors
  - Superconducting nanowire single photon detectors
- Fun with photons (i.e. using detectors)
- Astronomy : past work
- Mega-pixel hyperspectral imaging
- Summary

Quantum Information …



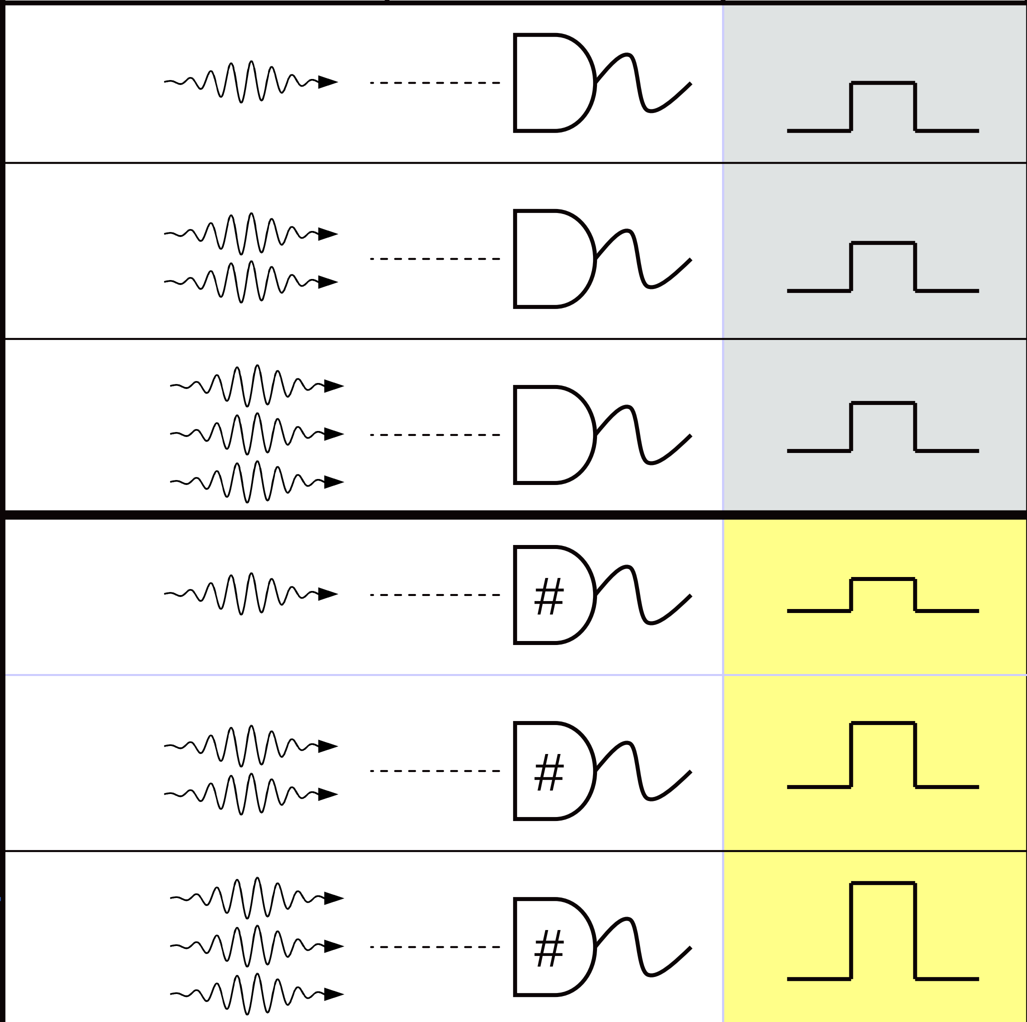
- Encodes information in quantum mechanical states
- Involves the manipulation and measurement of quantum states with high fidelity and low loss

  - Atoms, Ions, Spins, Superconductors, Cavity-QED, **Photons**
  - We need a toolbox to generate, manipulate, and measure (detect) photons.

Optical photon detector needs in Quantum Information

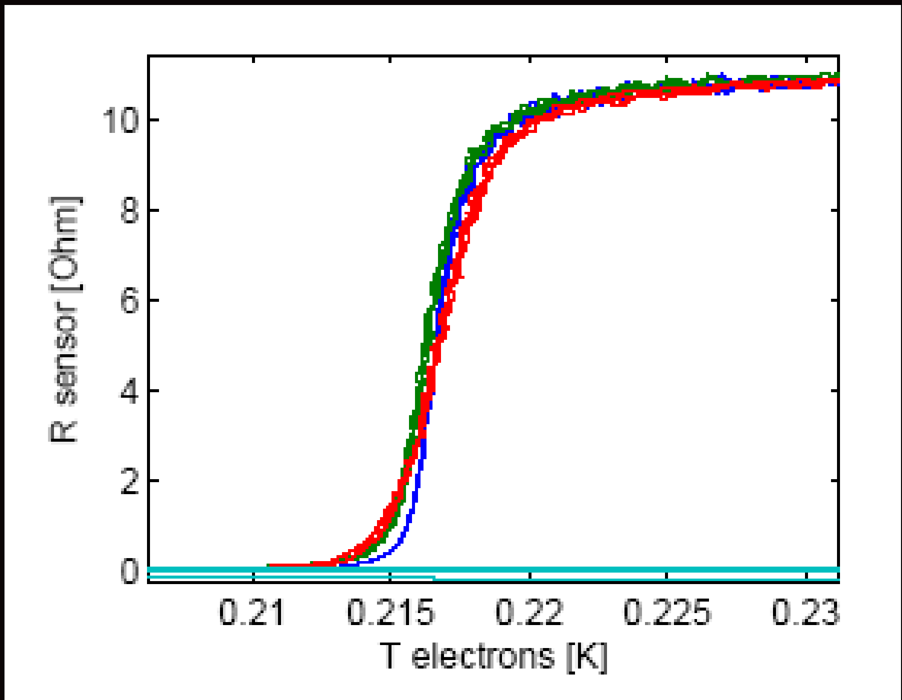
- High Quantum Efficiency
  - As high as possible
  - Broadband (100nm to 2000nm)
- Low Dark Count rate
  - No false counts
  - No afterpulsing
- Speed
  - Fast recovery
  - Fast rise / pulse pair resolution
  - Latecy
- Energy Resolving / Photon Number Resolving

Photon Counter vs. Photon Number Resolving



Optical Input	Detector	Output	Technology
			Conventional Same output signal for varying photon number input
			Photon Number Resolving Output signal proportional to photon number

Superconductivity

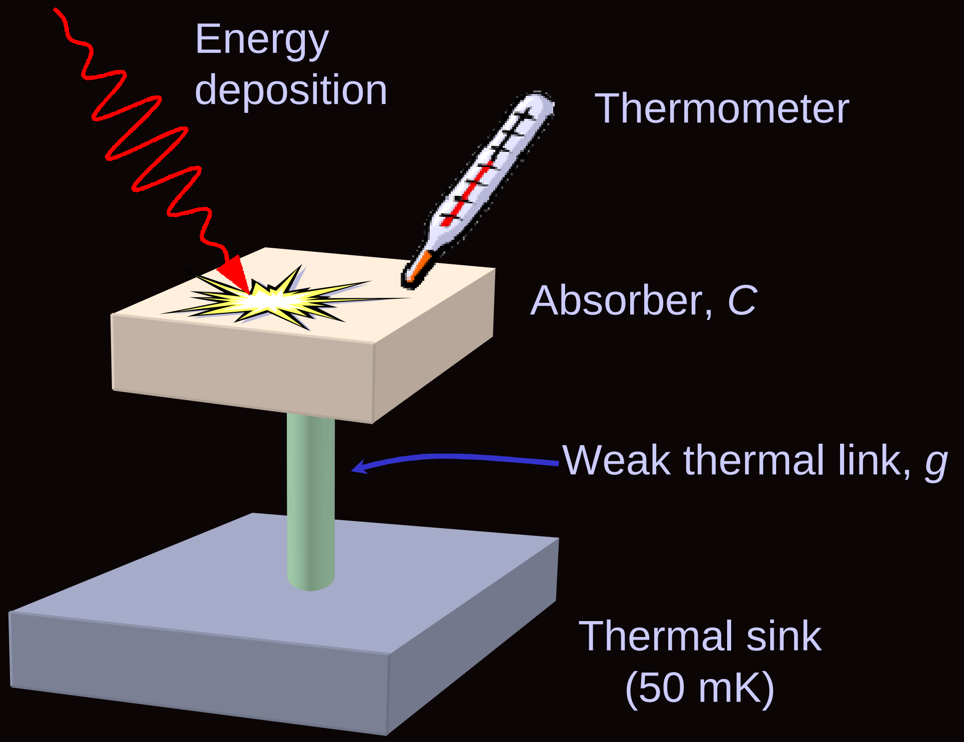


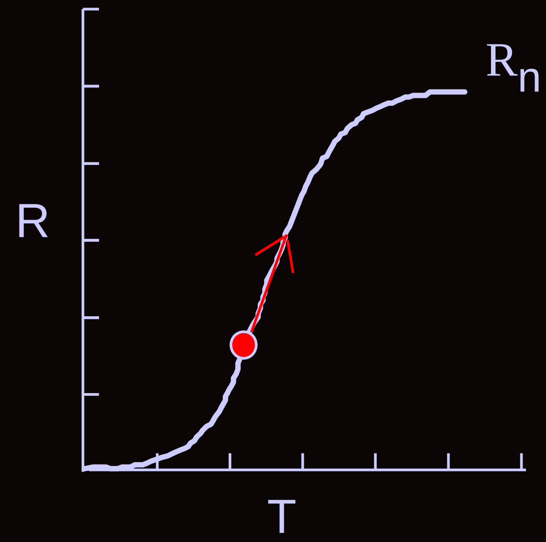
- Electrical resistance goes to zero at a critical temperature Tc
- Critical Current Ic or density Jc above which there is resistance below Tc
- Critical Field Hc
- Electrons in the superconducting ground state form Cooper pairs
- Excitations above the ground state are known as quasi-particles, energy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

Superconducting Detector Technologies

- "Photon Number Resolving"
  - Energy / Photon Number Resolving
  - Superconducting Tunnel Junction
  - Kinetic Inductance Detector
  - Transition-edge Sensor
- "Photon Counter"
  - Single photon sensitive
  - Superconducting Nanowire Single Photon Detector (SNSPD or SSPD)

Transition Edge Sensor (TES)

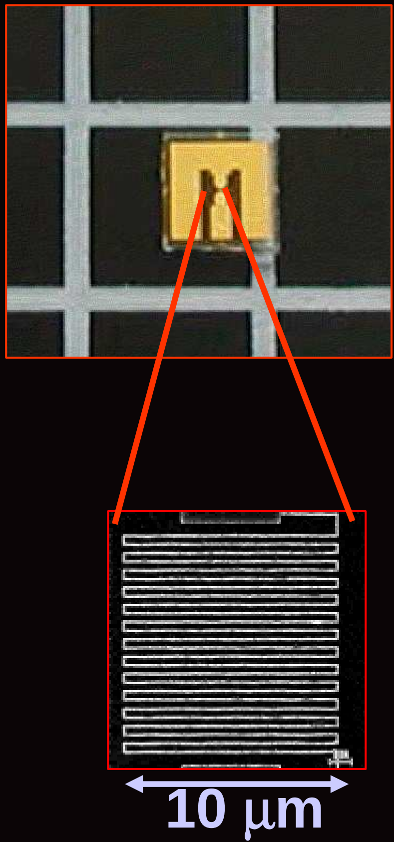




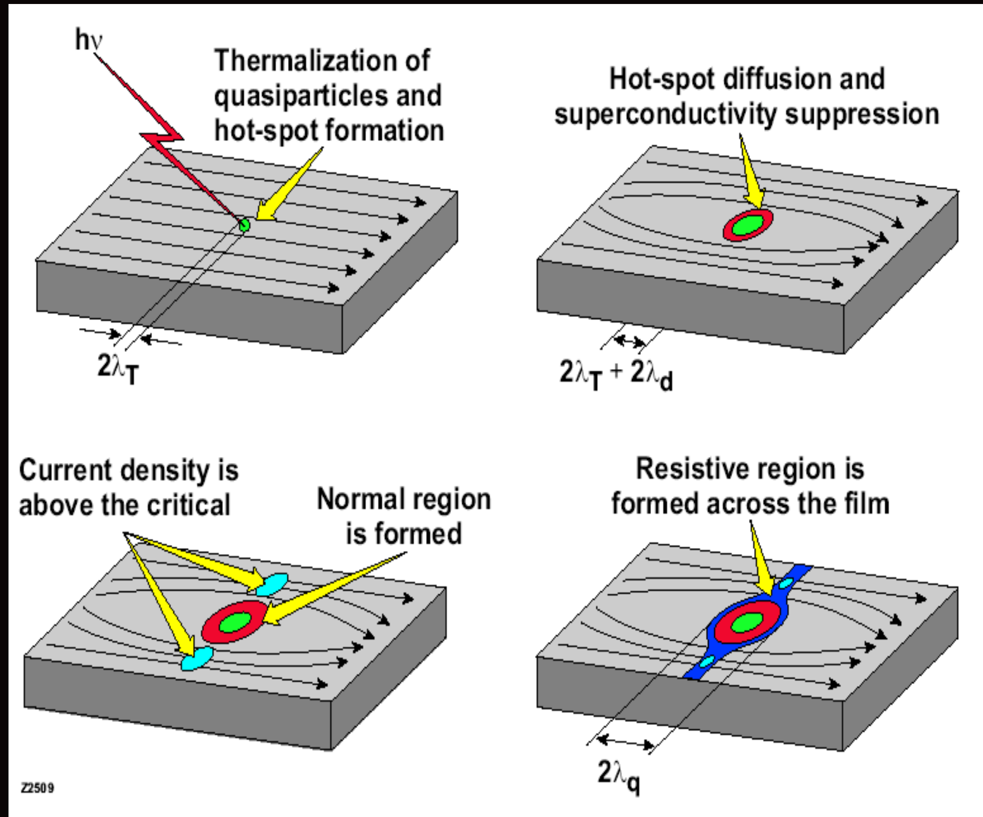
- Calorimetric detection of UV/optical/IR photons:
- Temperatures are ~100 mK to ensure low noise and high sensitivity.
- Absorber and thermometer are the same (superconducting W thin film)
- Microfabrication techniques

Superconducting nanowire Single Photon Detector (SNSPD or SSPD)

Moscow State Pedagogical University



NbN



4nm thick

<100nm wide

- Current Biased
- Very fast (10's of ps)

System Detection Efficiency

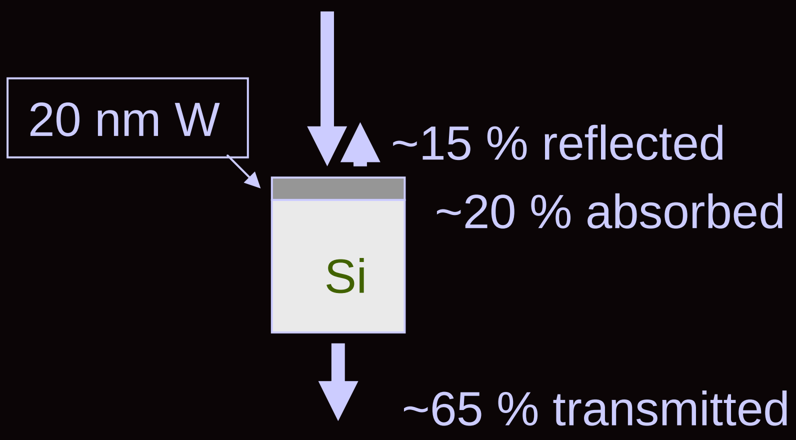
- Optical coupling efficiency
  - Single mode fiber
  - Fiber to device coupling
- Absorption efficiency into the active area/region
- Internal quantum efficiency / conversion efficiency
- Trigger efficiency (i.e. electronics and thresholds)

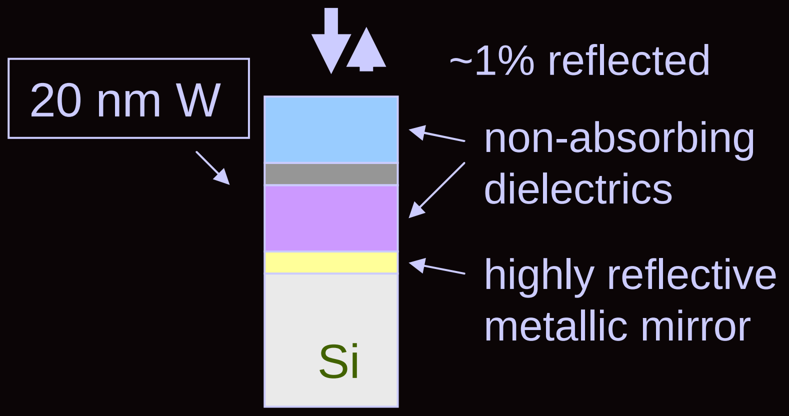
Superconducting Fabrication Facility (TES)

- 2700 sq ft class 100 space
- I-line 5x lithography
- E-beam lithography
- Reticle generation
- Sputter deposition (x2)
- ECR PECVD deposition
- LPCVD (x2)
- Thermal oxide / diffusion (x2)
- Thermal deposition (x2)
- RIE (x2)
- Plasma etching
- Ion mill etching
- 3 inch wafers

Optical Structures to Enhance Detection Efficiency

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

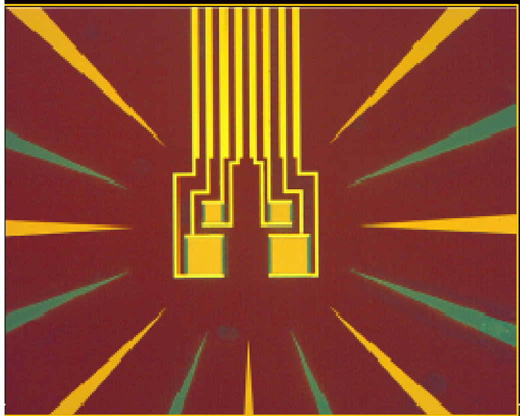


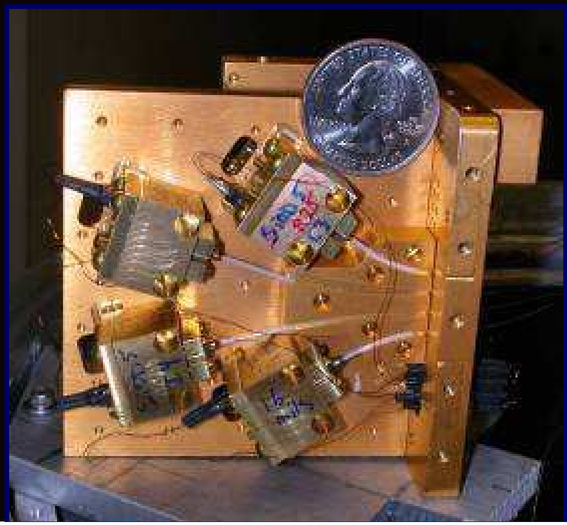


Rosenberg D. et al. IEEE Trans. Appl. Supercon. ***15*** *2 575 (2005)*

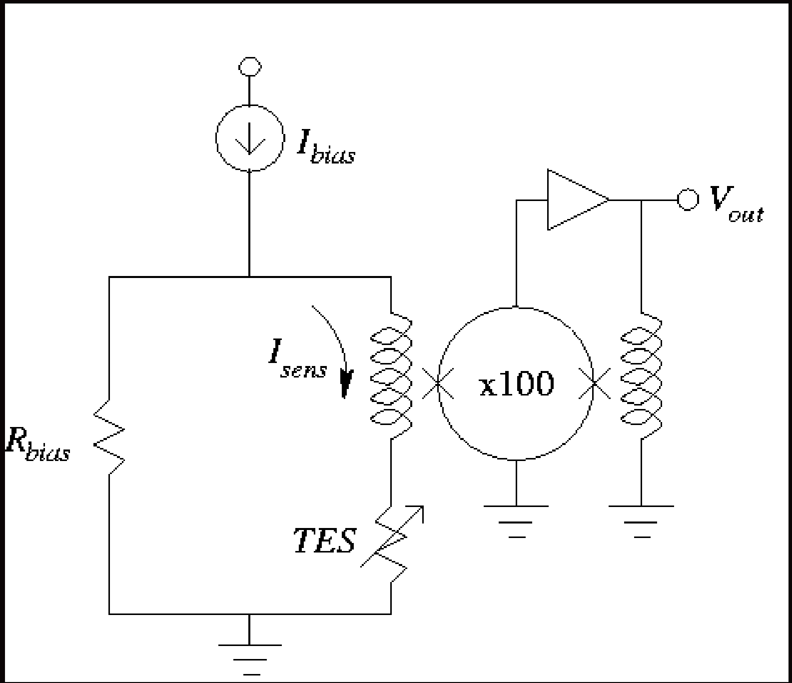
Fiber Coupling

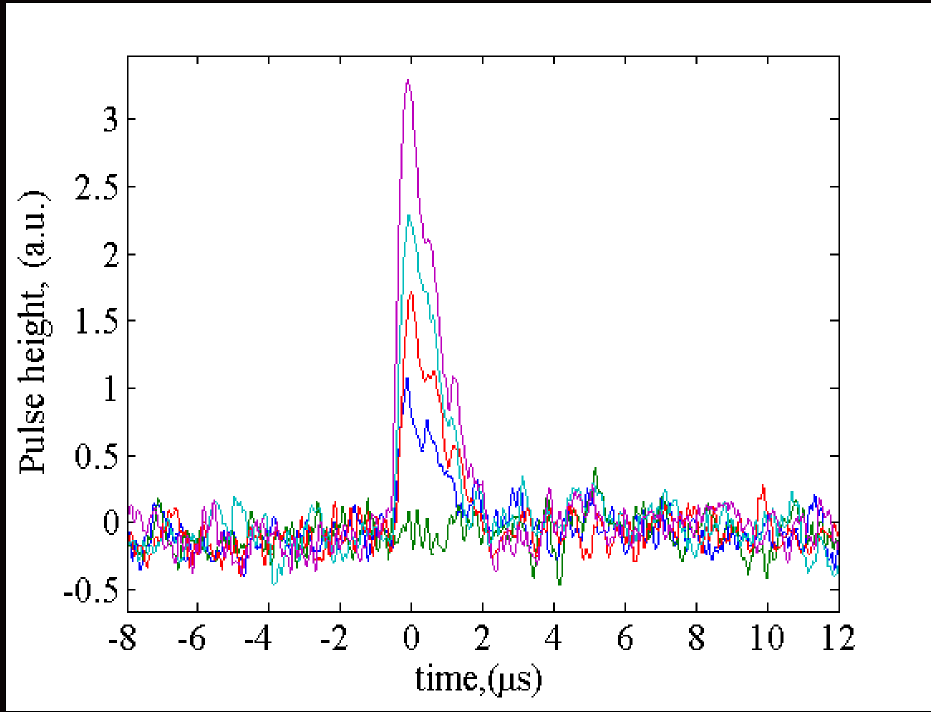
- Compatibility with large Temperature change





TES Signal





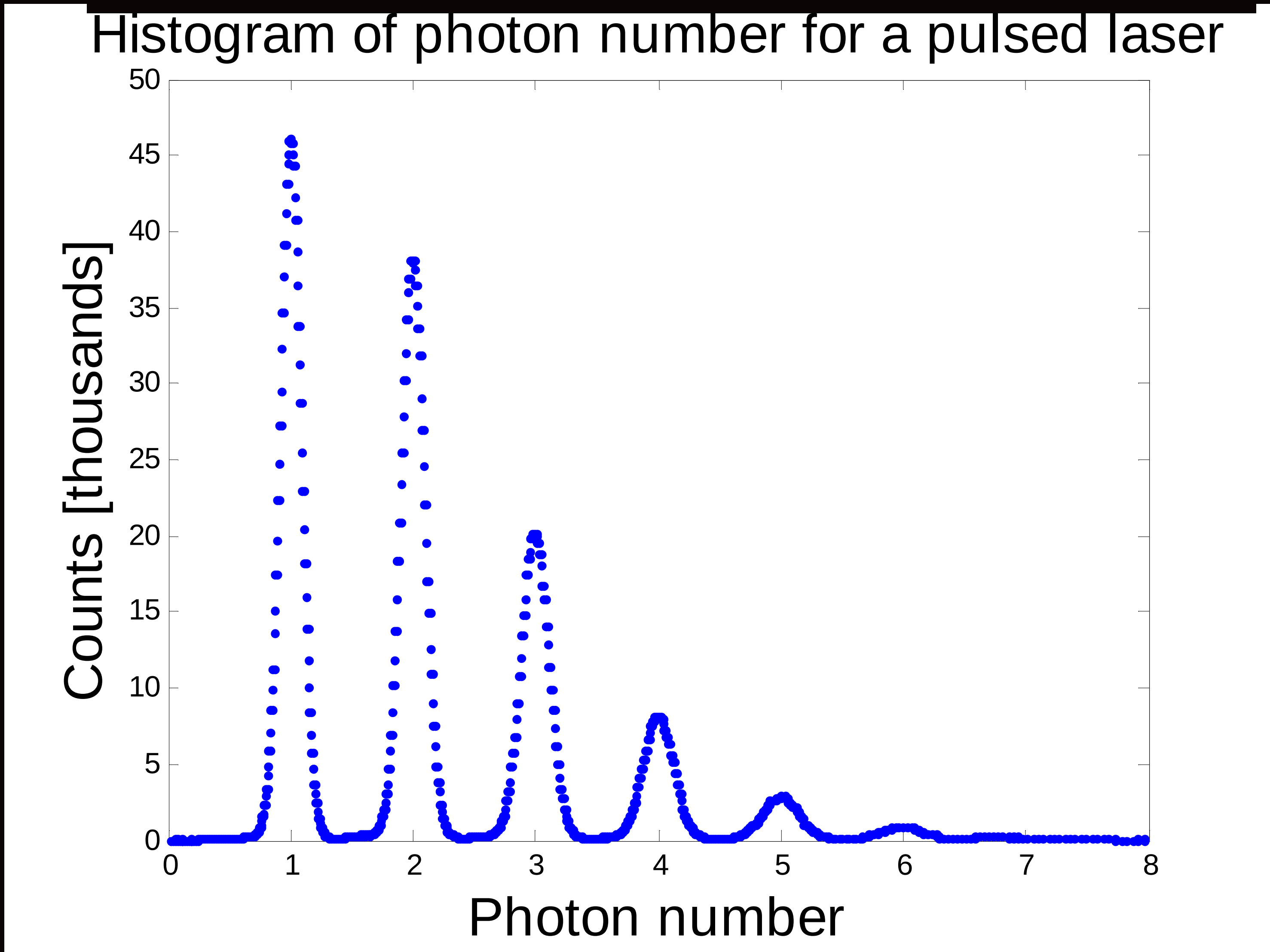
- Device is voltage biased
- Current through device is pre-amplified using a cryogenic SQUID array amplifier
- Signal can then be processed using RT electronics

Output signal is proportional to number of absorbed photons

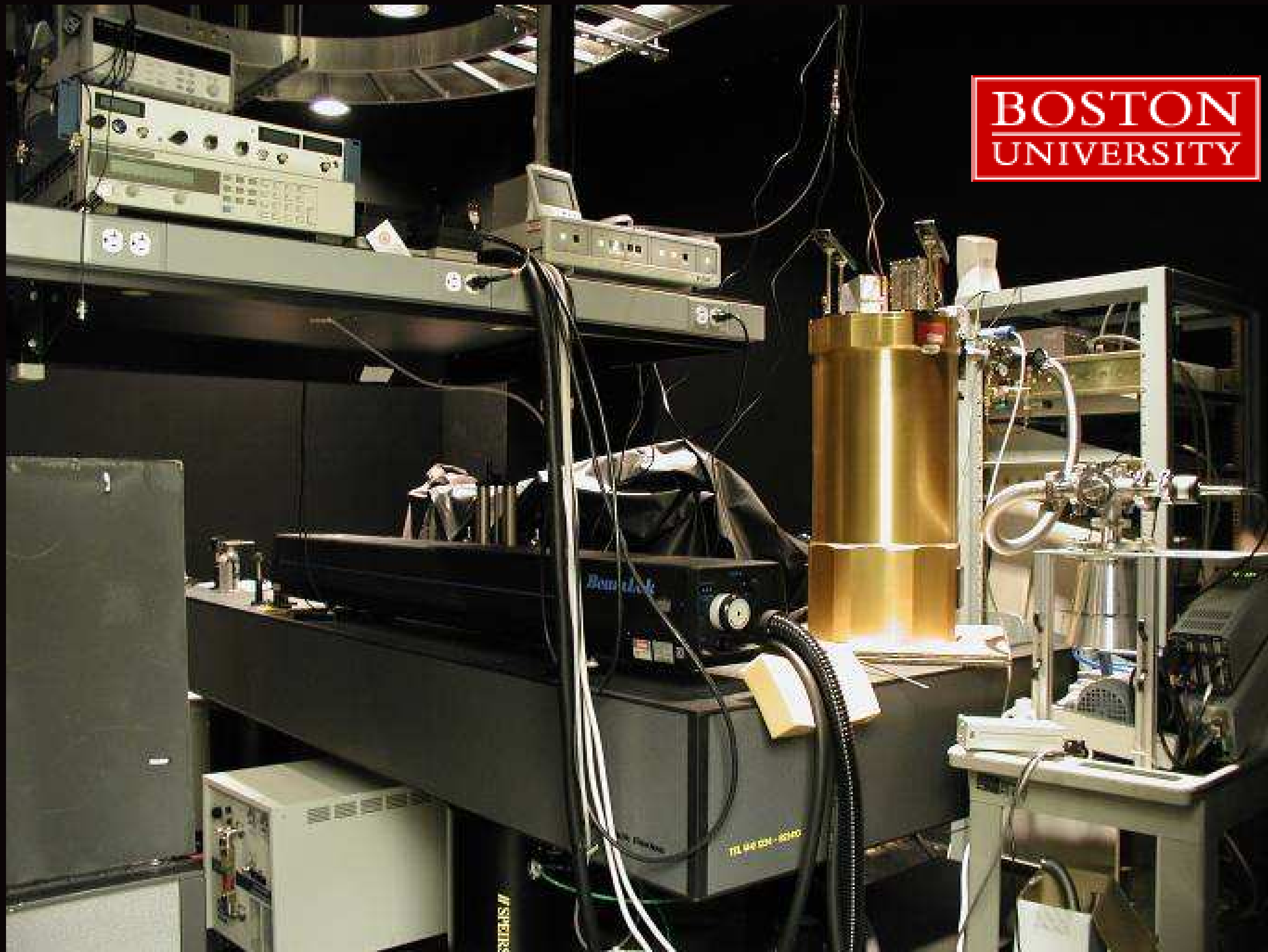
- Optimized now for photon-number resolution, not speed (τ_{rise}~100 ns, τ_{fall}~10 µs)
- Absorption events show good distinguishability
- Much slower than APDs

~95% System Detection Efficiency

Photon Number distribution – 1550 nm pulsed laser

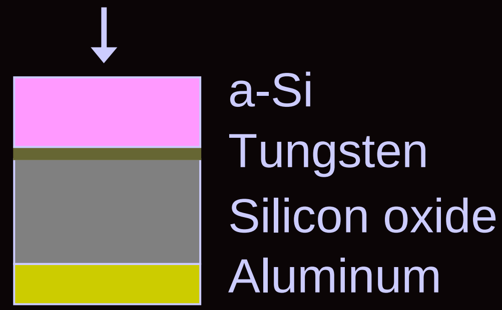


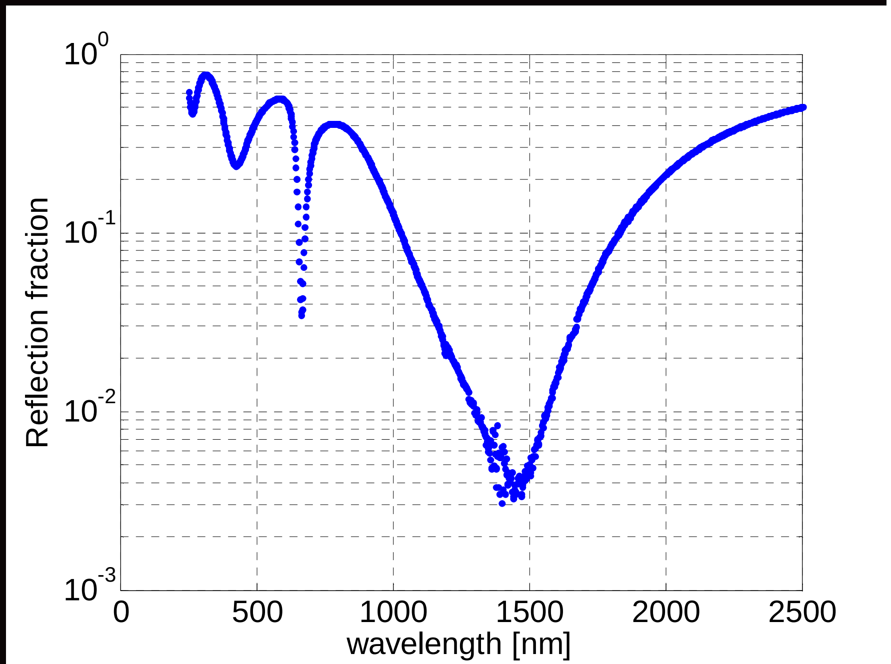
Picture of System



New Materials

- Higher speed
  - Rise time
  - Recovery time
- Tunability for different wavelengths
  - Dual band devices
  - 850nm
  - 1064nm
  - Optimal for loop-hole free test of Bell's inequality

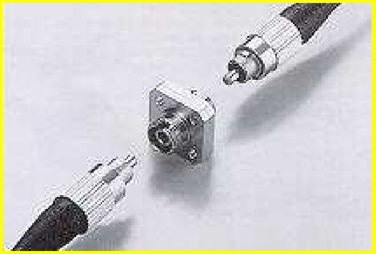


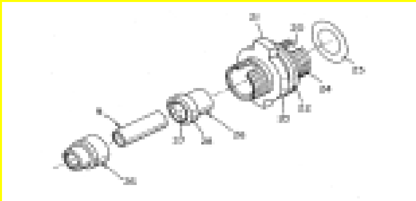


New alignment scheme

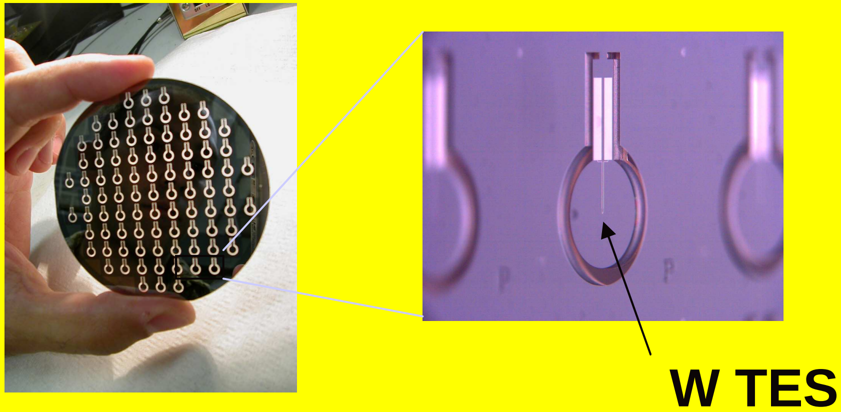
FC/FC mating connectors

Zirconia
Fiber ferrule





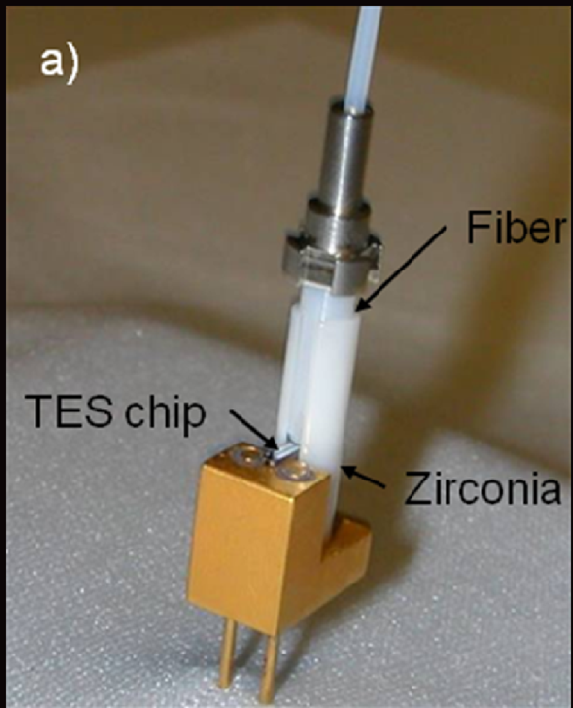
FC/FC
Zirconia sleeve

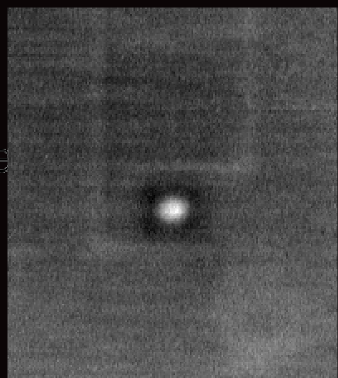


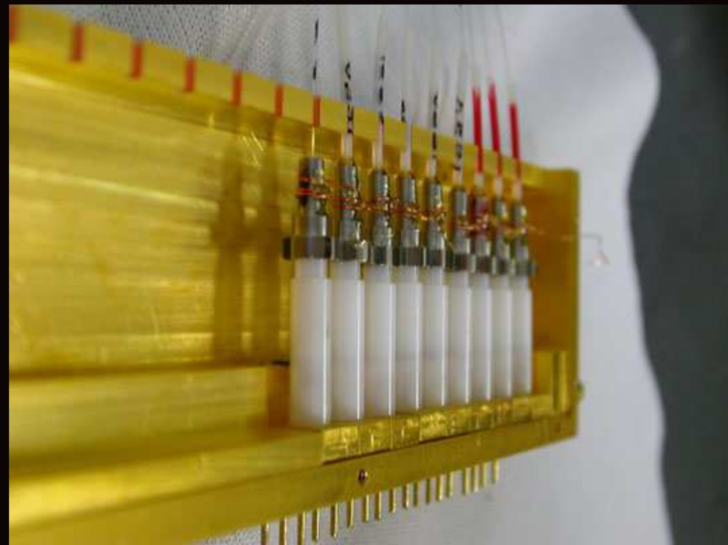
Deep RIE etch Bosch SF_6/C_4F_8 process:
circular chips with precise dimensions

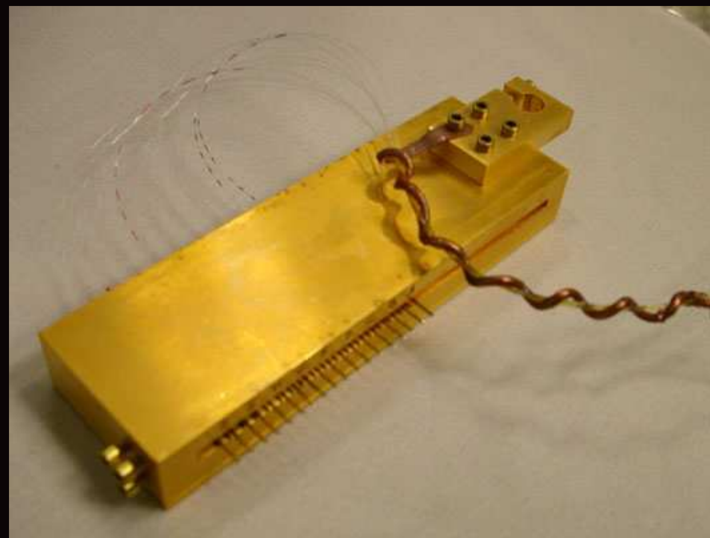
- Zirconia sleeve's inner diameter matches the fiber ferrule
- Zirconia sleeve's inner diameter matches the circular chips with the center positioned tungsten TES

Alignment continued…



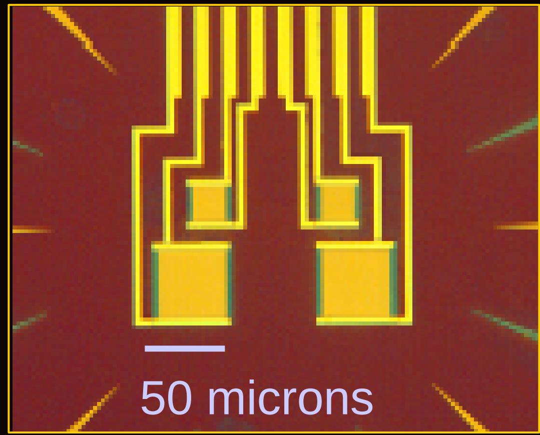


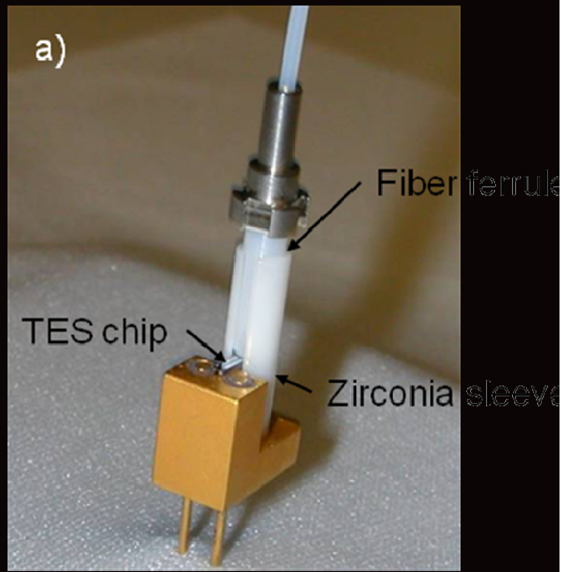




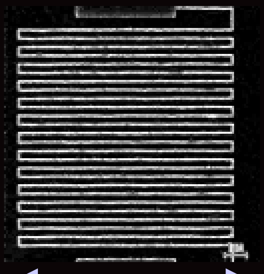
Unique Features of TES detectors

- Photon Number Resolution
- Low Noise
  - NEP < 10^{-19} W/√Hz (limited by stray light)
  - **Limited by blackbody radiationn (BLIP)**
- "High" QE at telecommunication wavelengths
  - >95% end-to-end measured at 1550nm
  - AR coatings give no limit, in principle
  - Tunable wavelength response by adjustment of coatings
- "Slow" speed
  - Decay time ~1μsec
  - 10 MHz clocked systems can be used
  - Faster speeds possible with materials research and electrical readout improvements





How do you make SNSPD's more practical?



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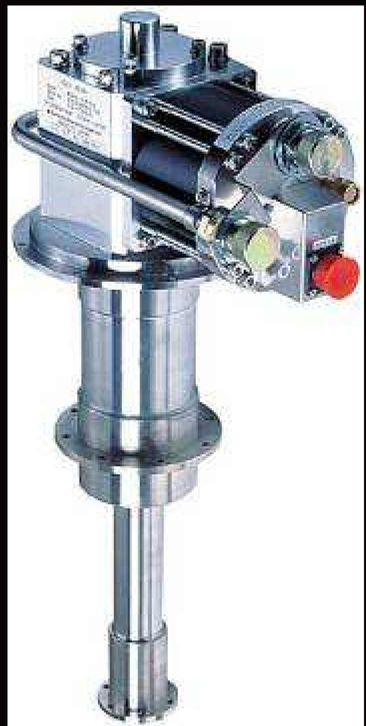

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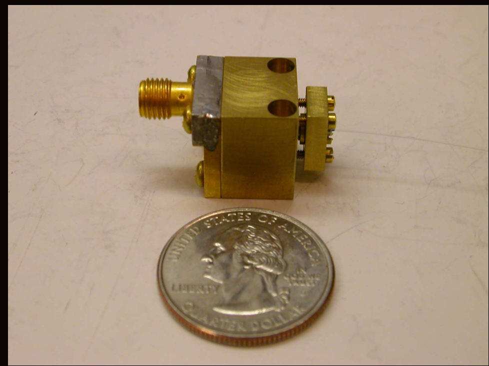
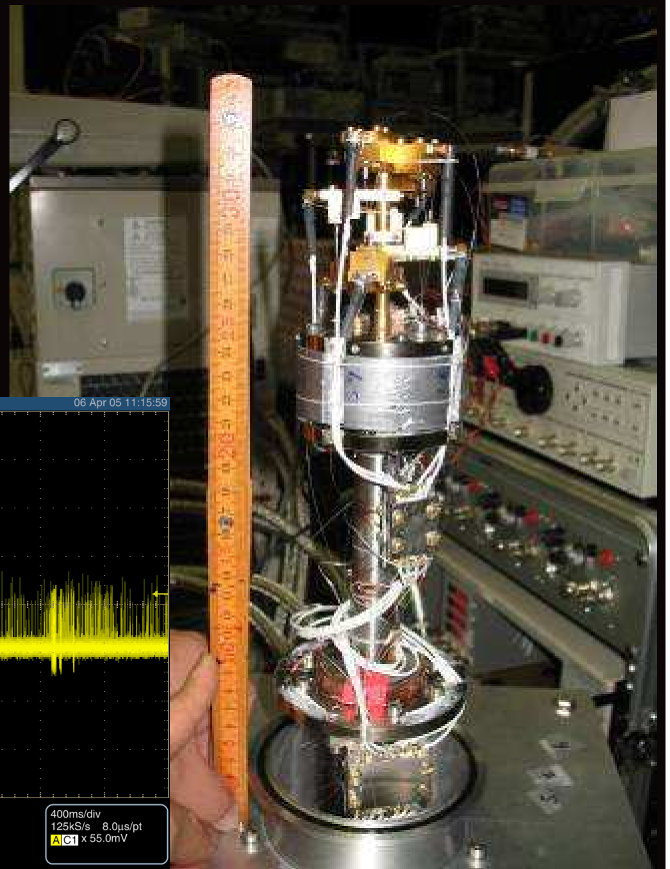
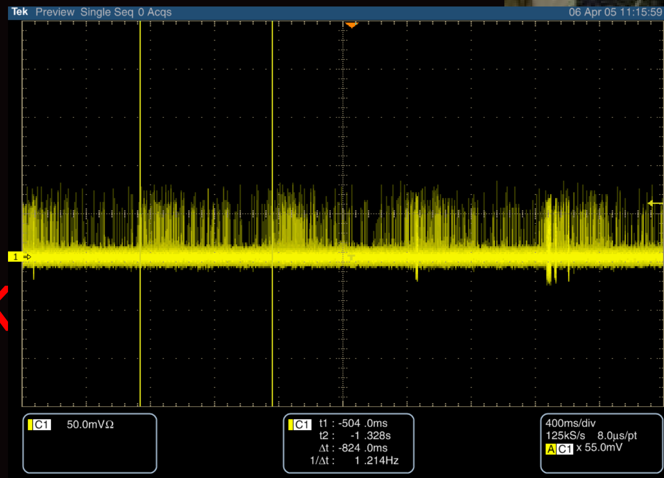
Cryogen-free operation !!!

Packaging, Optics and Temperature

- Fiber coupling can be done in ways similar to the TES.
- Temperature stability is very important for dark counts



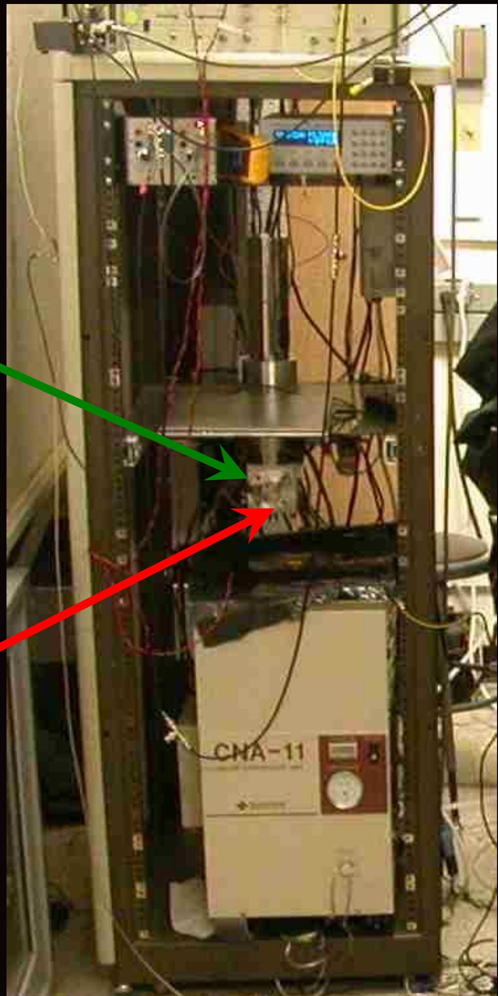




NIST Packaging + Moscow devices

Fiber inputs

Coax outputs



System details:

- Cryogen-free refrigerator (~4 K)
  4 SSPDs

- Fiber coupled

- Detection Efficiency
  1–6% (900 nm – 1800 nm)
  (Includes fiber coupling losses)

- Low Dark Counts
  100 Hz → <10 Hz

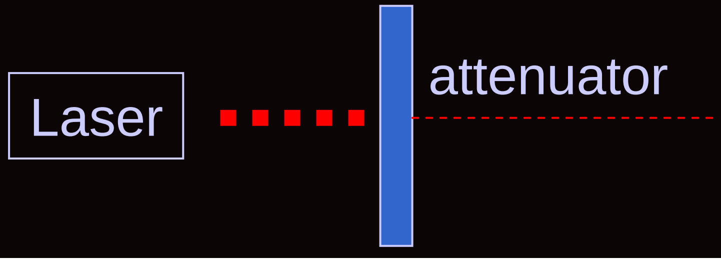
- No Afterpulsing or re-emission!

•Hadfield *et al.*, Opt. Expr. 13, 1086 (2005)

Fun with photons

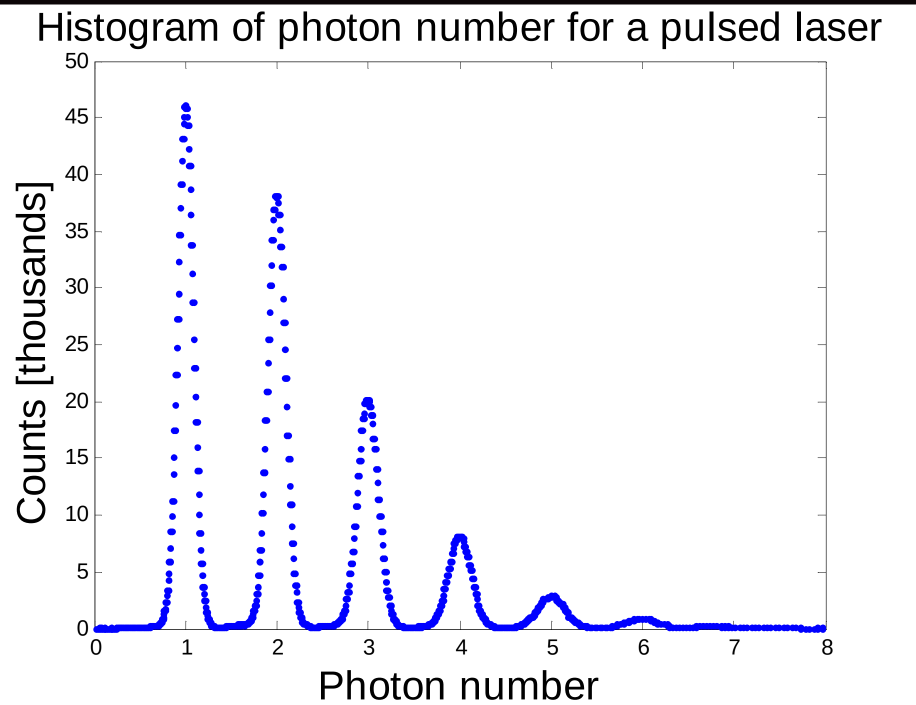
- TES
  - Photon statistics
    - Number distribution (TES) of a Poisson source
  - Quantum Optics
    - Squeezed light photon number distribution statistics
- SNSPD
  - Time correlated single photon counting, TCSPC
  - Higher order intensity correlations

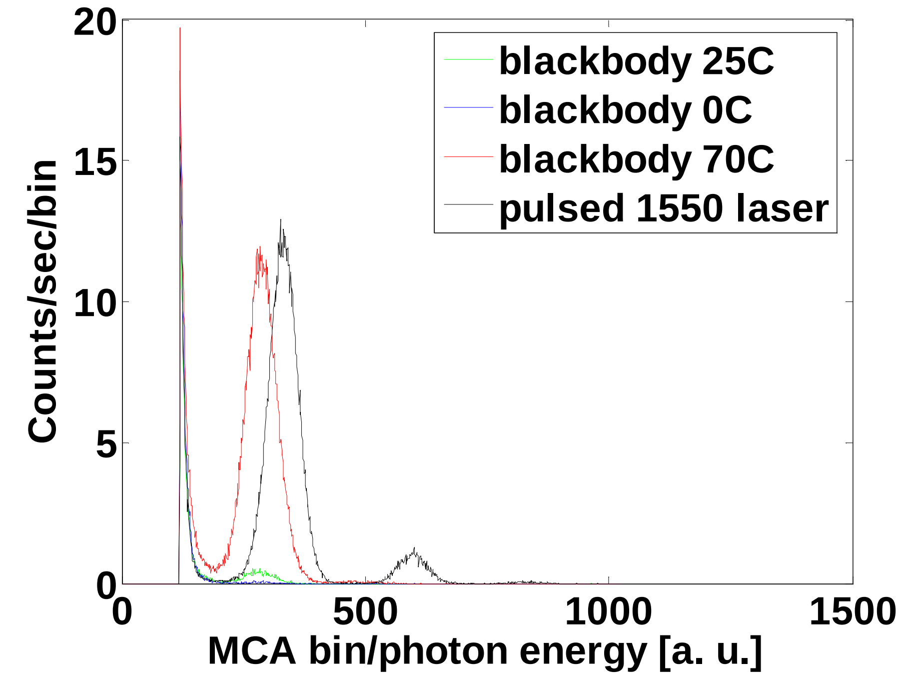
Photon Statistics



$$P(n) = \frac{\mu^n}{n!} e^{-\mu}$$

$$|\alpha\rangle$$





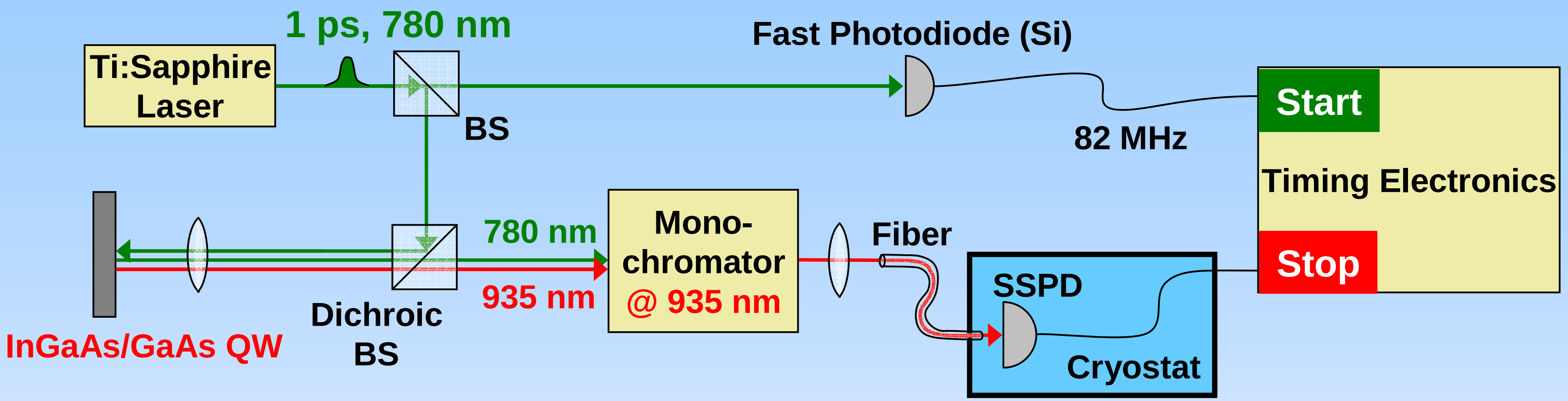
Signal to Noise ratio

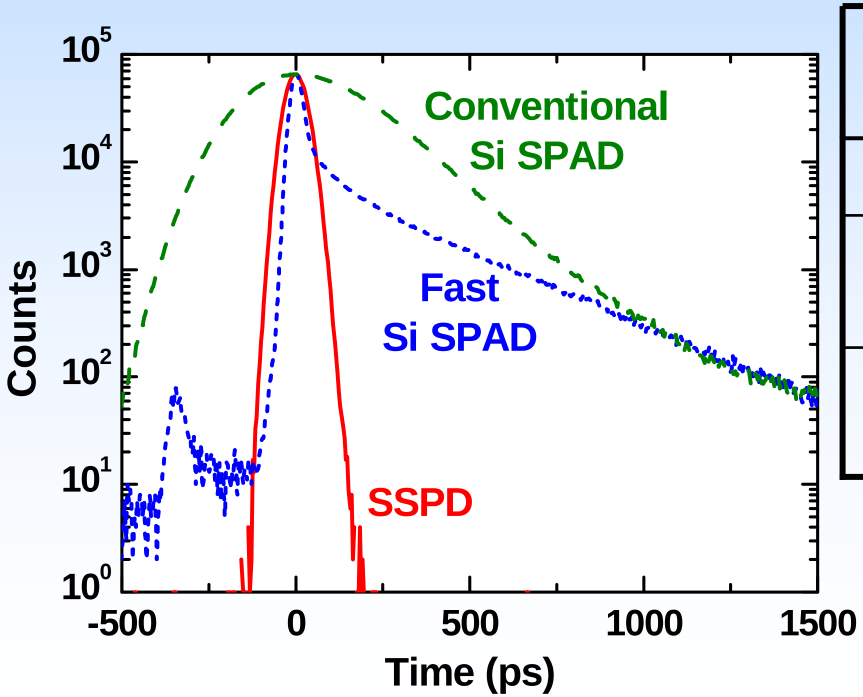
- How can you use a low efficiency detector to do anything useful?

$$Signal\ to\ Noise = \frac{\eta}{dark\_count\_rate * jitter}$$

- TES has 10 to 100x bigger DE
- SNSPD has a jitter 1000x smaller!!!
- Inversely related to error rate in a QKD system

Lifetime Measurements





Detector	IRF (FWHM)	Efficiency @ 900 nm	Dark Counts
Conv'l SPAD	350 ps	38%	~50 Hz
Fast SPAD	40 ps Long tail	5%	~50 Hz
SSPD	65 ps Gaussian	2%	<30 Hz

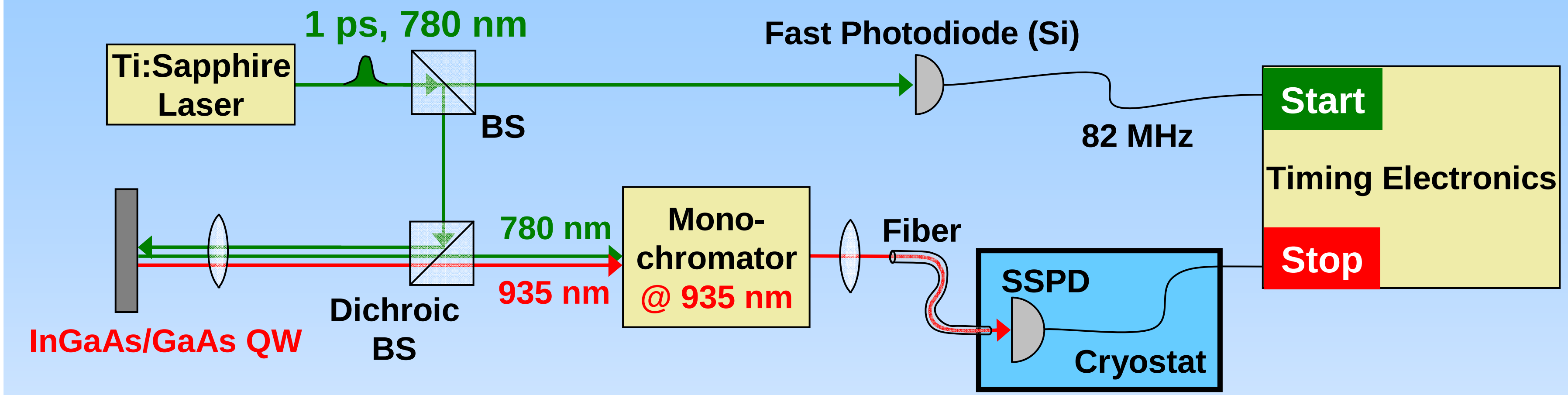
Gaussian response + Few dark counts

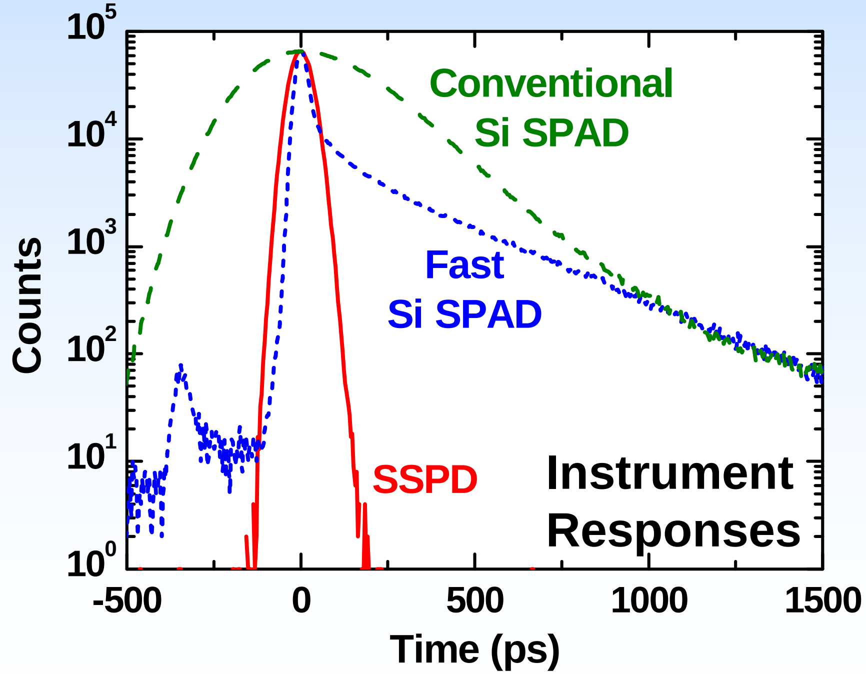
→ Tolerate low efficiency

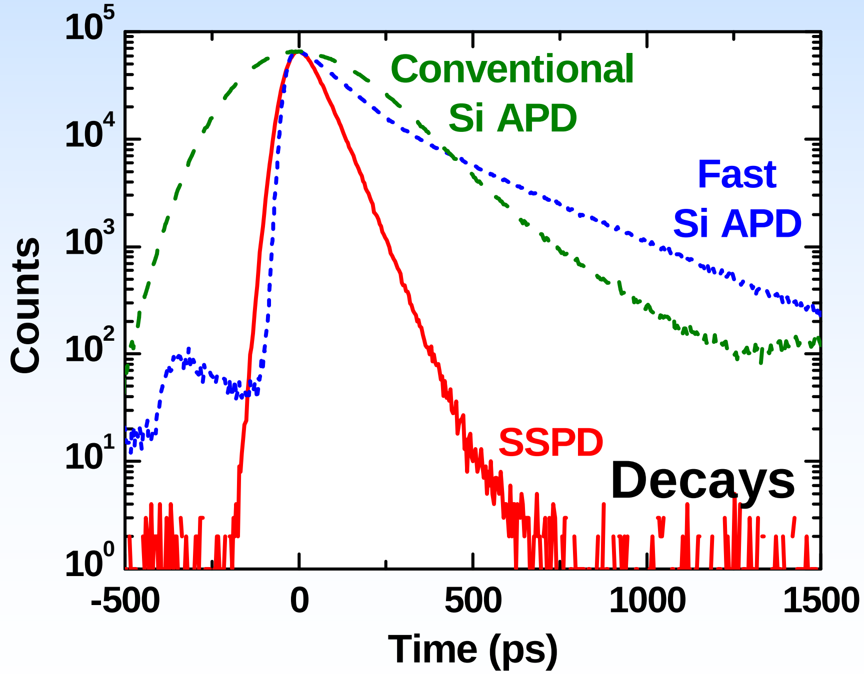
→ Identify multiexponential processes

•Stevens *et al.*, APL 89, 031109 (2006)

Lifetime Measurements



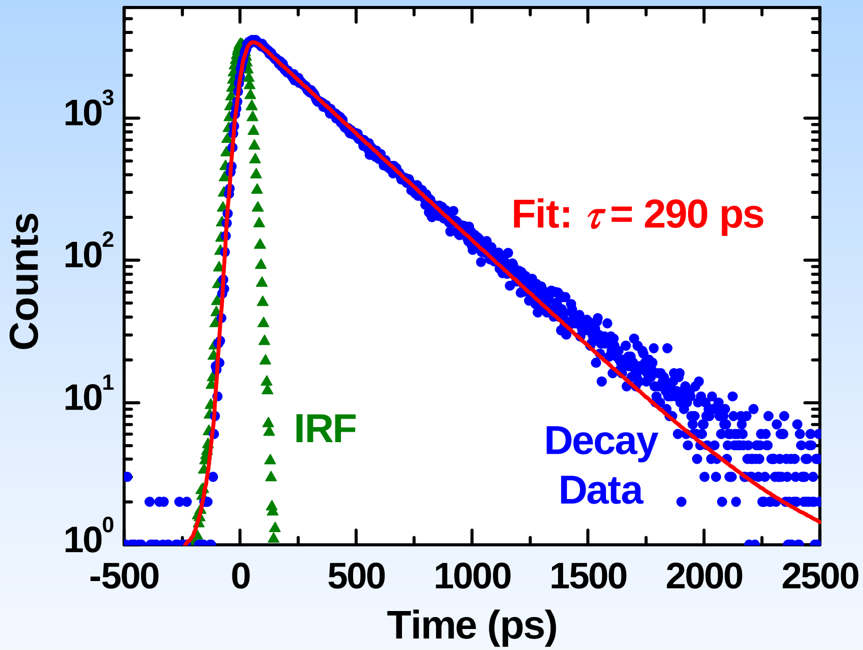




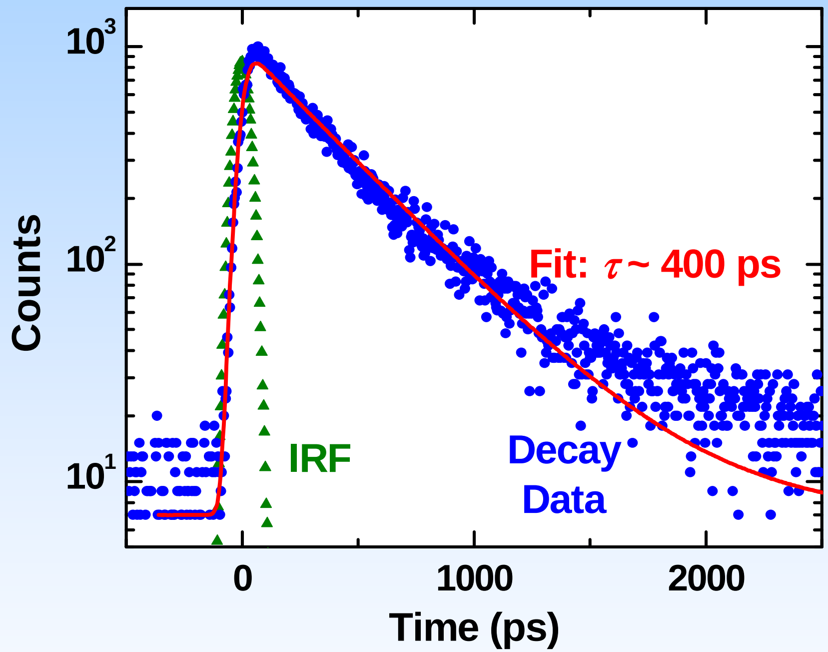
•Stevens *et al.*, APL 89, 031109 (2006)

Lifetime Measurements: Novel Materials

InGaAs grown on InP
λ_{Detect} = 1650 nm



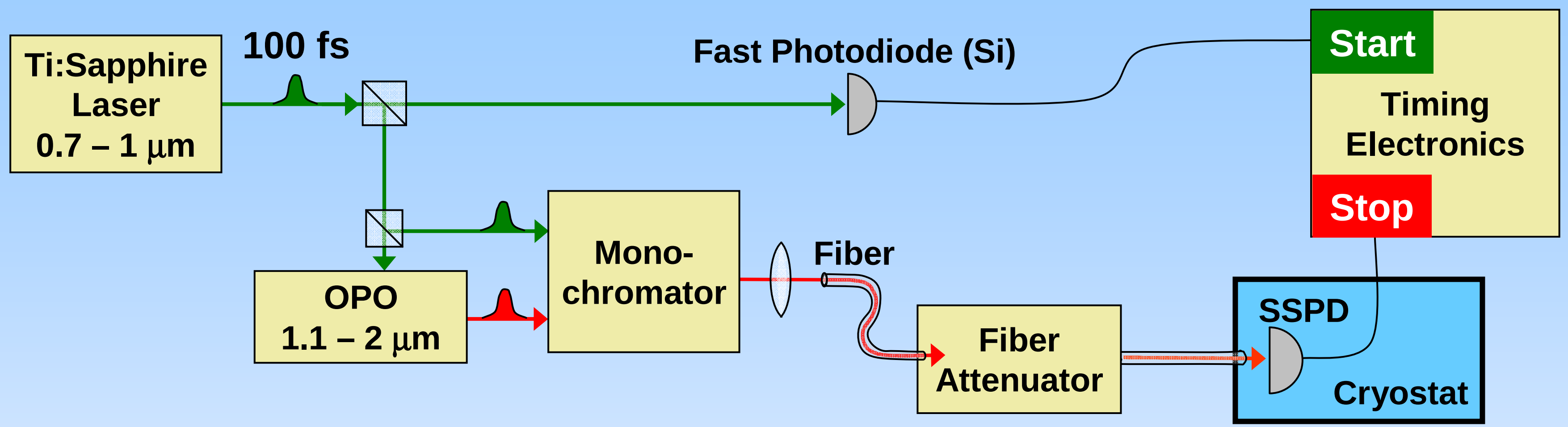
Single InGaAs Quantum Dot
λ_{Detect} = 902 nm

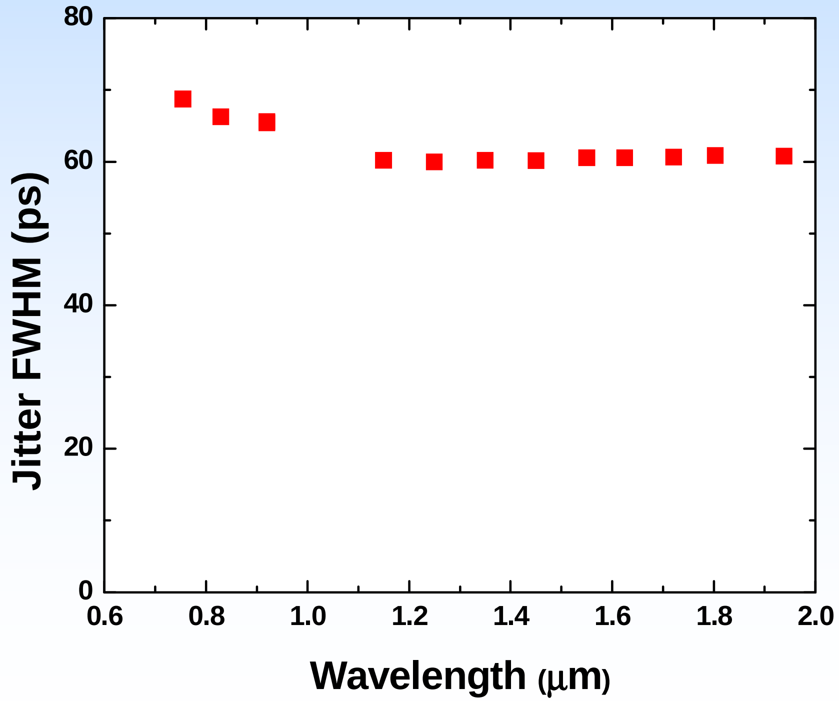


•SSPD works where Si won't (λ > 1 μm)

•Single-photon sensitivity

Jitter & Efficiency vs. Wavelength



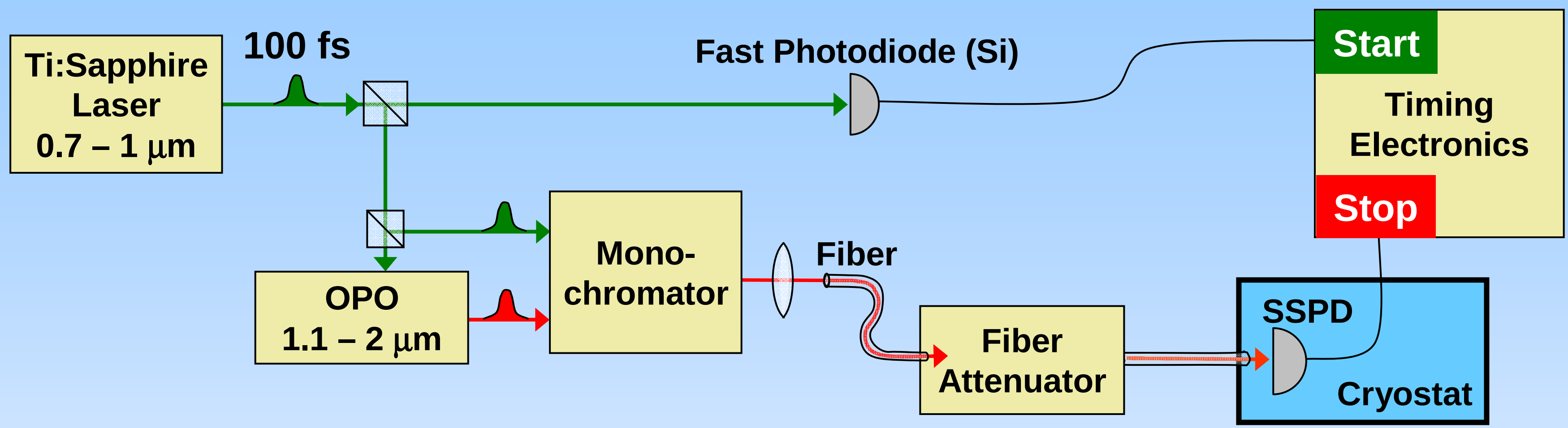


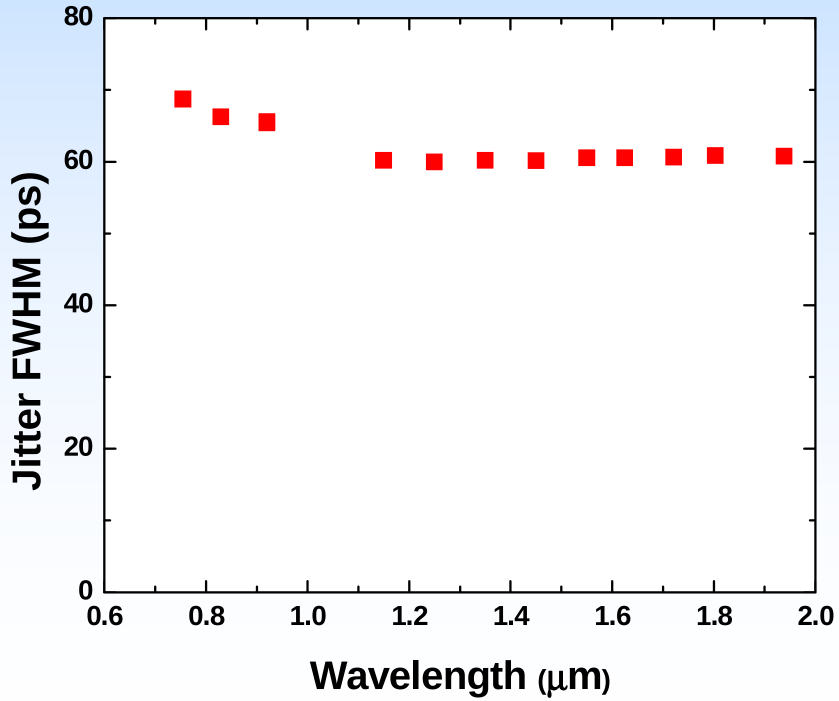
• Jitter has little or no wavelength dependence

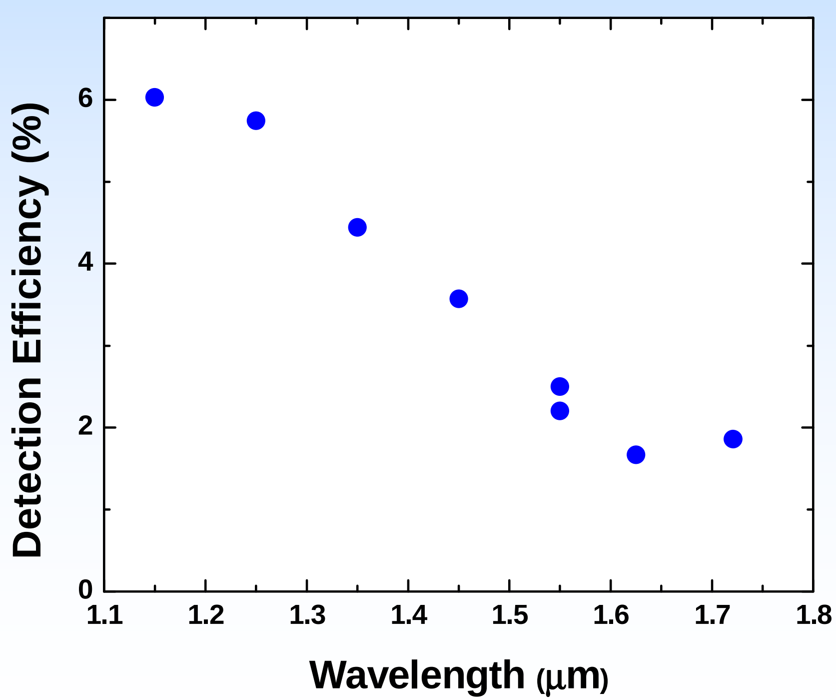
SPADs:

• λ-dependent IRF shape

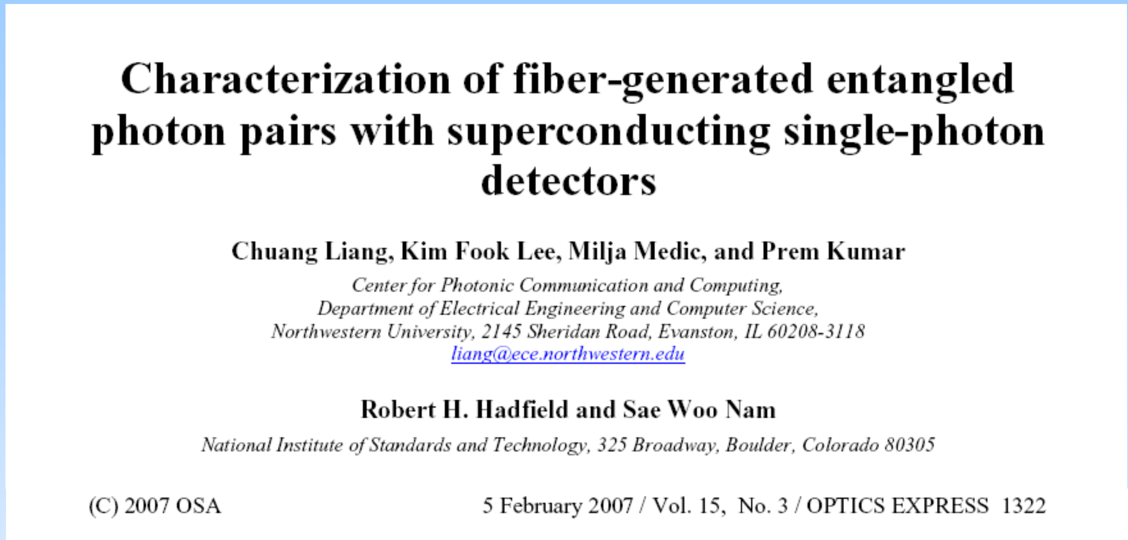
Jitter & Efficiency vs. Wavelength







Entangled Pair Generation in Fiber



Characterization of fiber-generated entangled photon pairs with superconducting single-photon detectors

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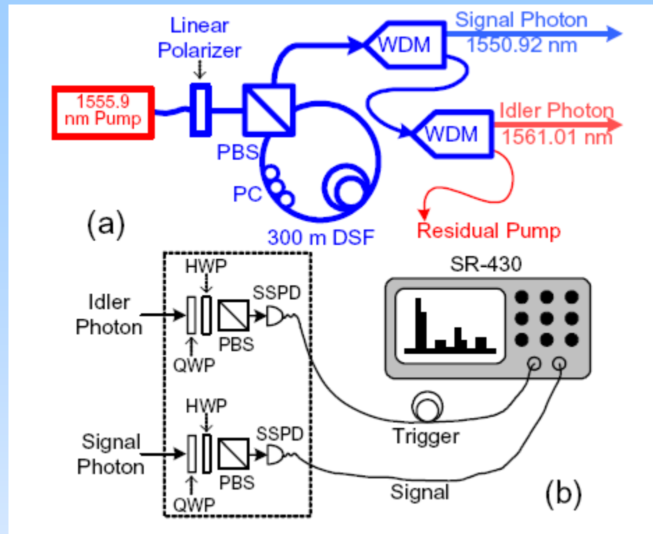

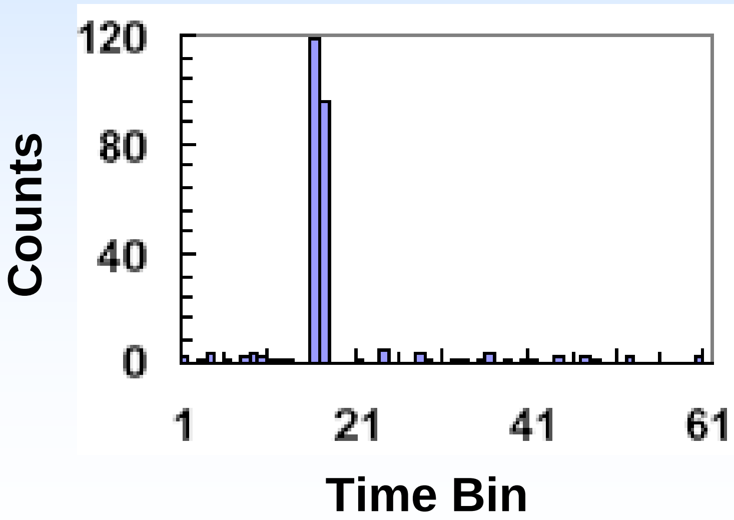

- **SSPDs ungated, free-run mode**
- **Coincidence-to-accidental ratio (CAR) > 80:1**
- **Entangled pair 2-photon visibility > 98%**
- **No background corrections!**

Correlated Pair Generation in PPLN

Correlated photon-pair generation in reverse-proton-exchange PPLN waveguides with integrated mode demultiplexer at 10 GHz clock

Qiang Zhang[1], Xiuping Xie[1], Hiroki Takesue[2], Sae Woo Nam[3], Carsten Langrock[1], M. M. Fejer[1], and Yoshihisa Yamamoto[1]

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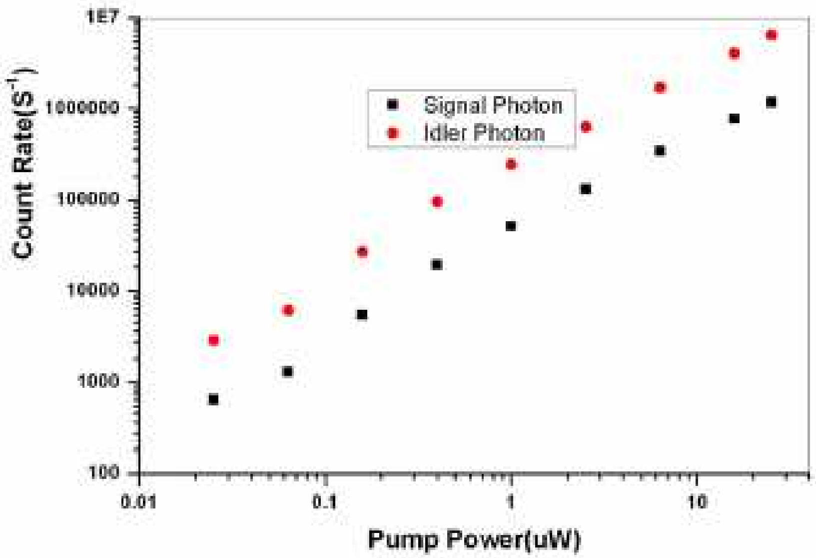
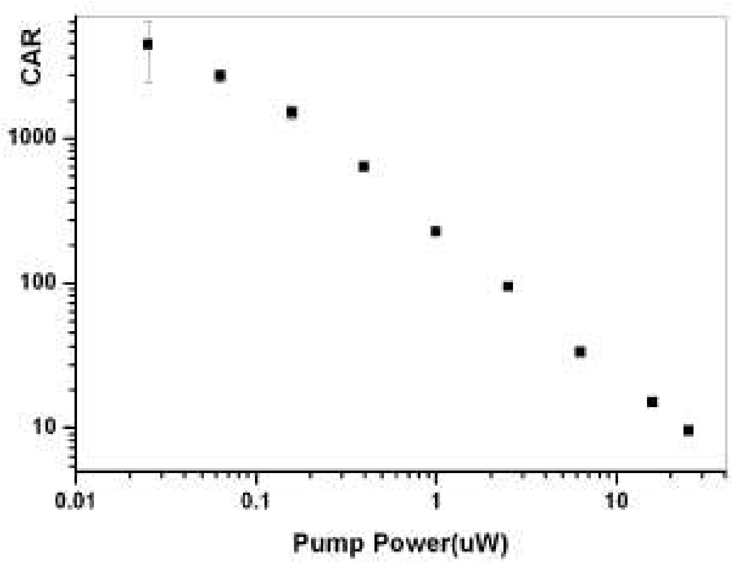
- 10 GHz clock
- Count rate 4.7 MHz +
- Coincidence-to-accidental ratio (CAR) > 4000:1
  → 50× improvement





Quantum Key Distribution at Stanford

ARTICLES

Quantum key distribution over a 40-dB channel loss using superconducting single-photon detectors

HIROKI TAKESUE[1]*, SAE WOO NAM[2], QIANG ZHANG[3], ROBERT H. HADFIELD[2†], TOSHIMORI HONJO[1], KIYOSHI TAMAKI[1] AND YOSHIHISA YAMAMOTO[3,4]

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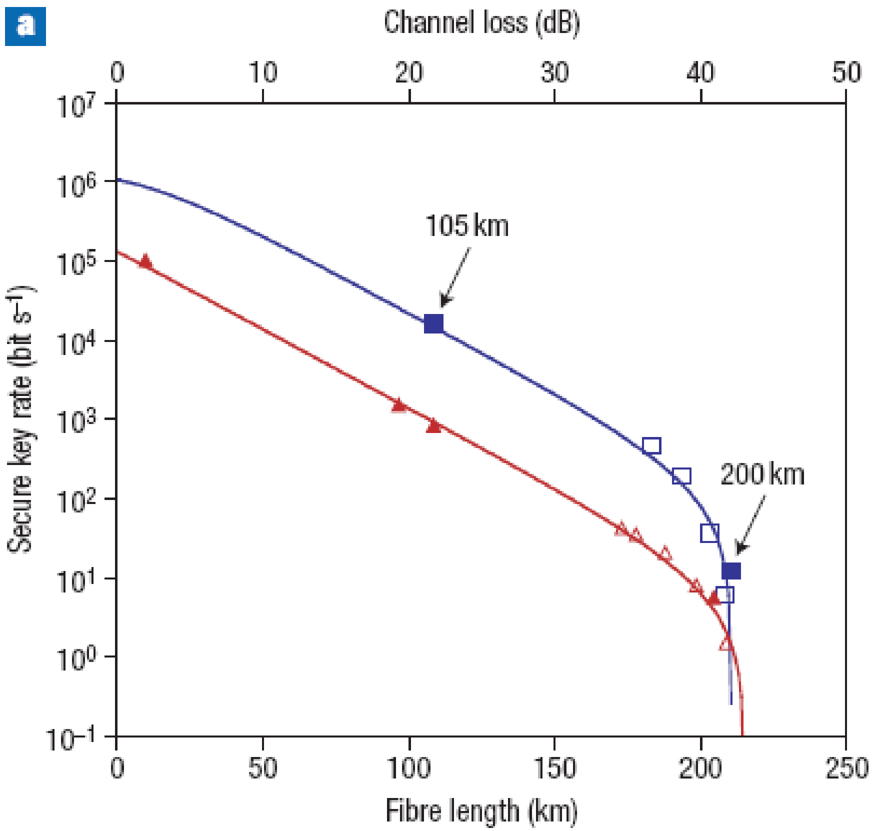
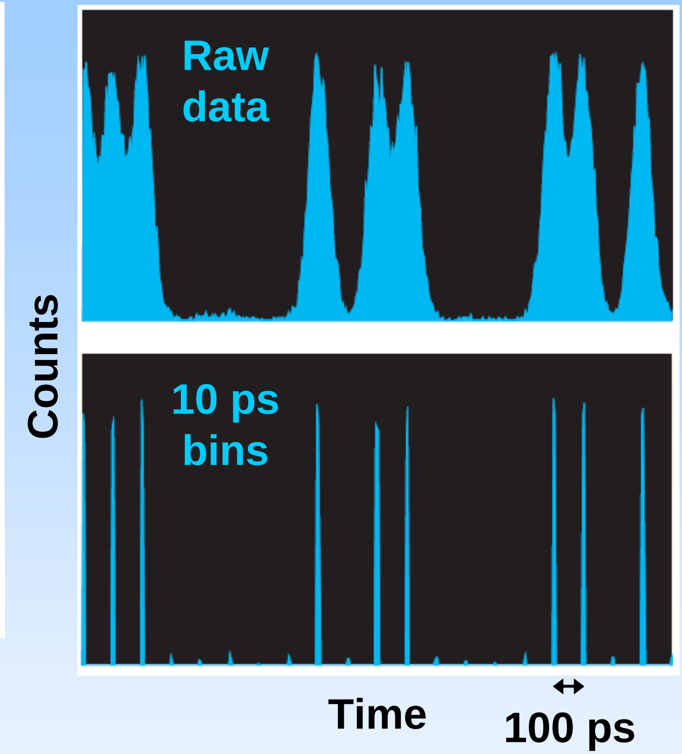


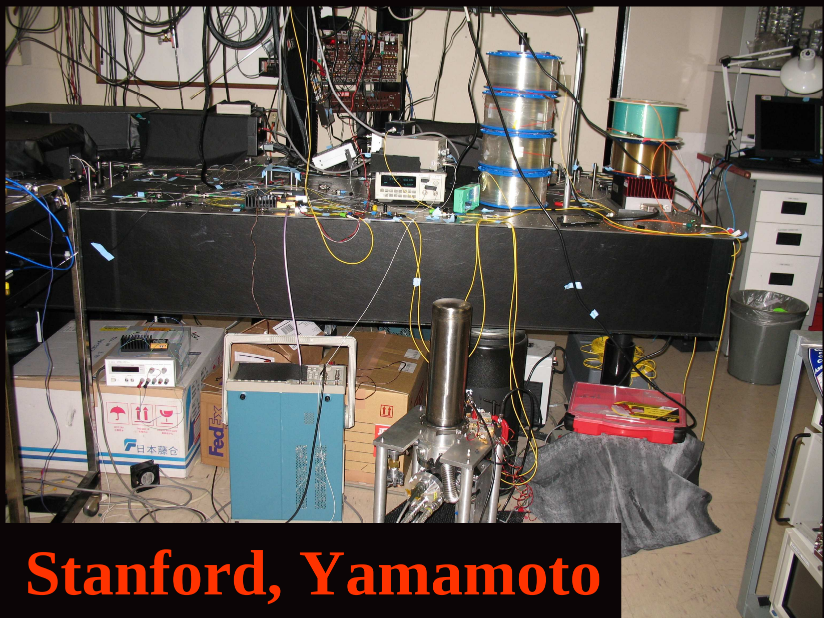


- 1st secure key at 10 GHz
- Longest fiber QKD link
  12.1 bits/s over 200 km
- 17 kbits/s over 105 km
  → 100× previous best

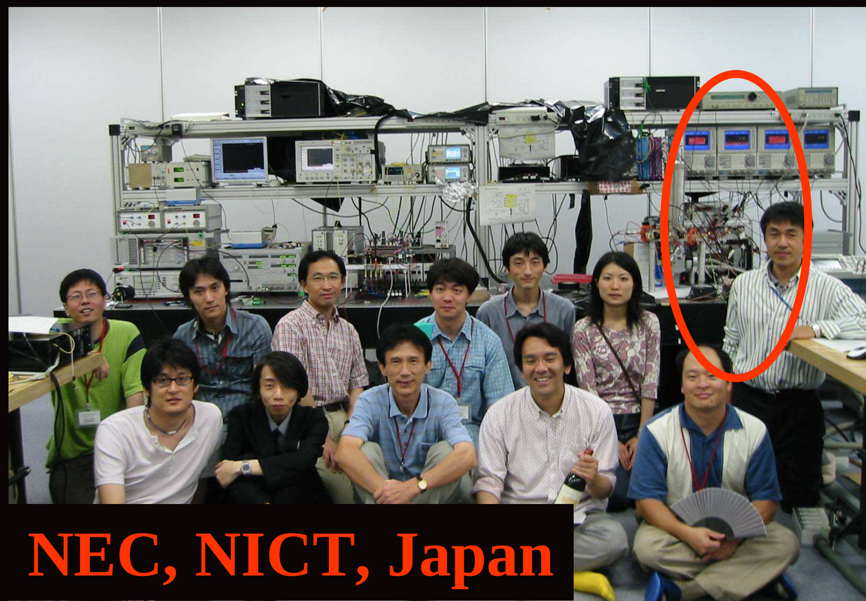
Quantum Key Distribution around the world

- Provably secure technique for key generation
- Bound the amount of information an eavesdropper could obtain
- Telecommunication band

BBN Technologies, Cambridge, MA

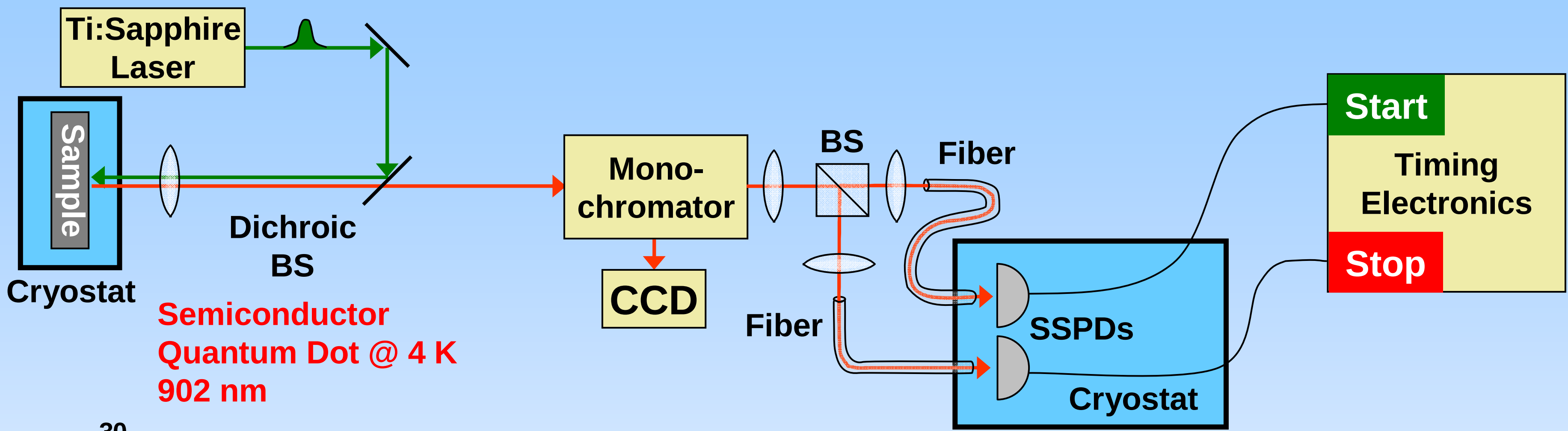


Stanford, Yamamoto



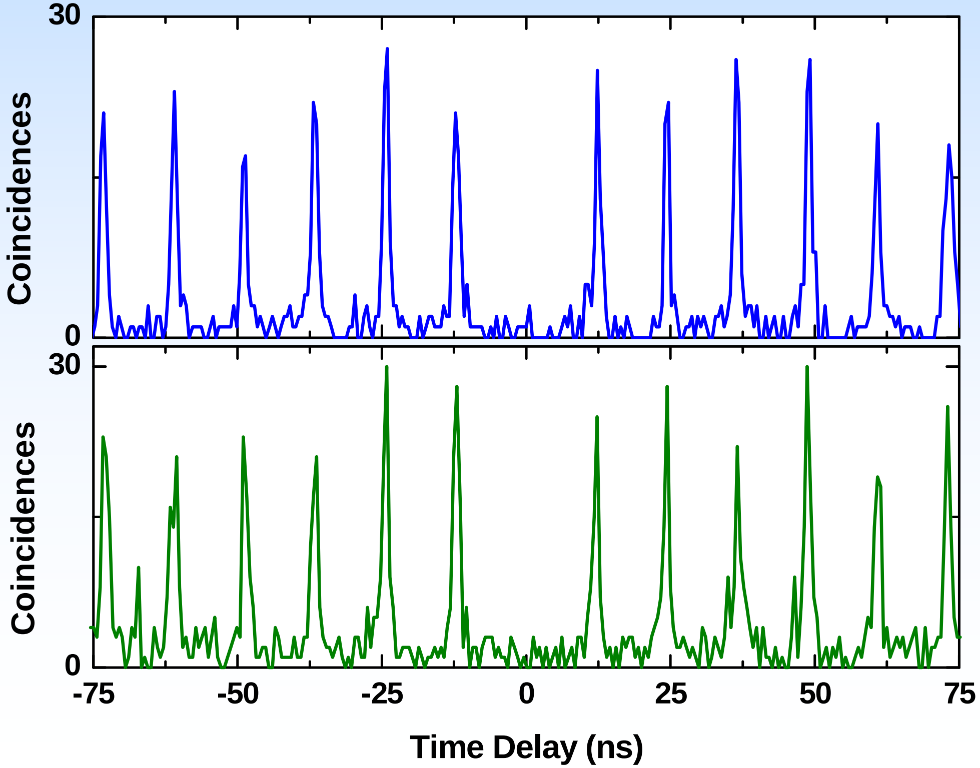
NEC, NICT, Japan

Hanbury Brown-Twiss Interferometer: SSPDs



DE ~ 2%

Dark Counts < 10 Hz



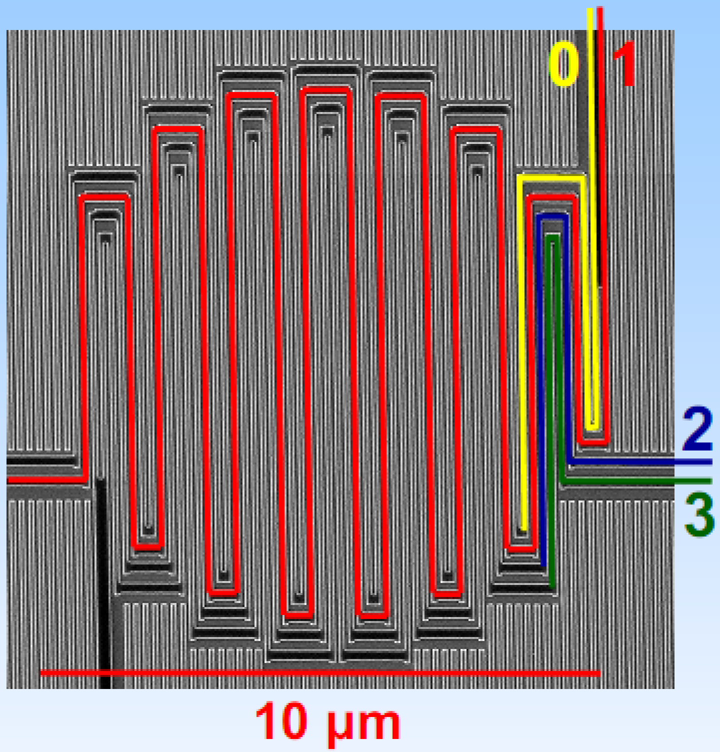
SPAD+SSPD:

$g^{(2)}(0) = 0.10$

2 SSPDs:

$g^{(2)}(0) = 0.08$

Multi-pixel SNSPD by MIT and MIT-LL

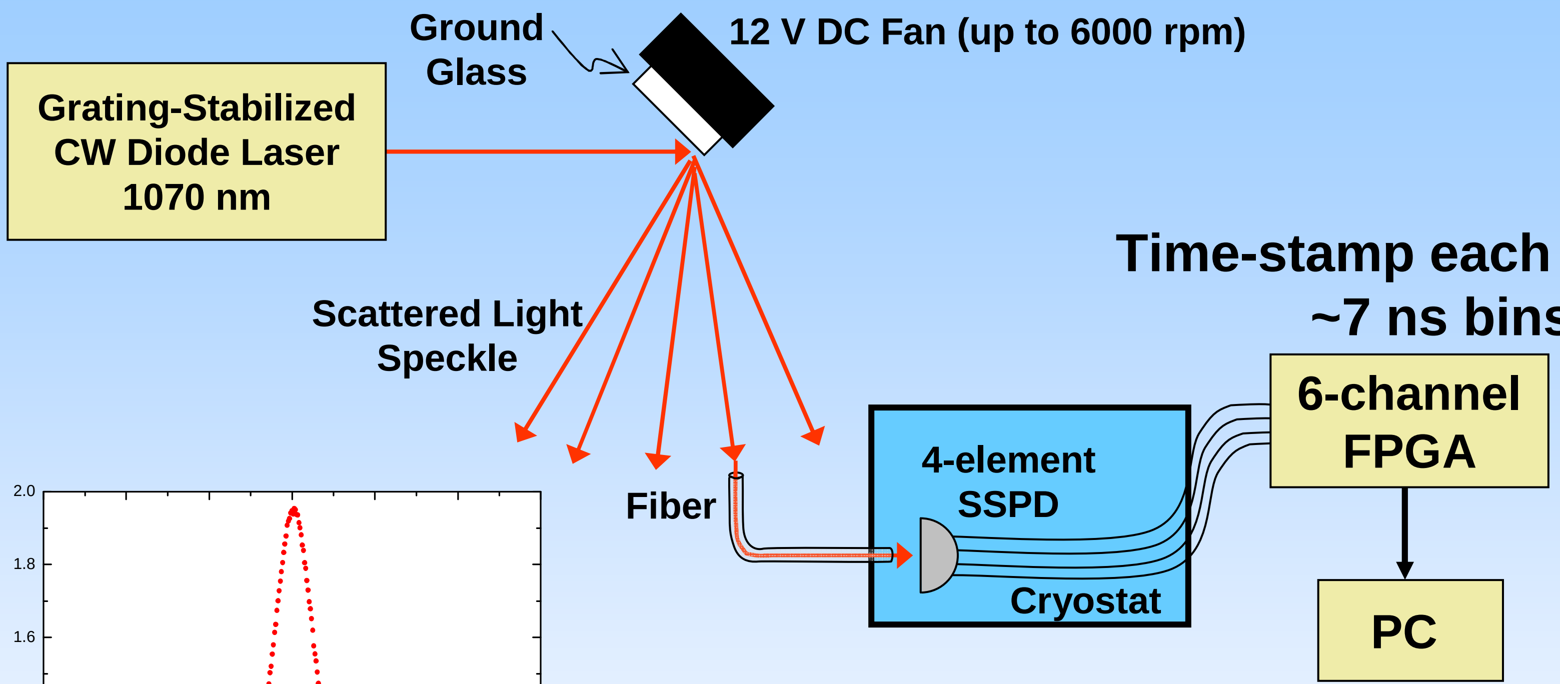


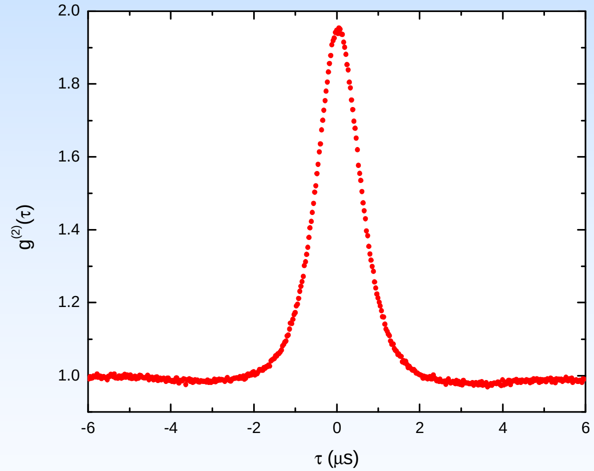
•Fabricated by Eric Dauler (Karl Berggren) at MIT

System detection efficiency up to 46% @ 1550 nm
(Sum of each of the 4 elements at 97.5% of I_C)

E. J. Dauler *et al.*, arXiv:0805.2397

Higher Order Correlation Functions – Psuedothermal light





$$g^{(3)}(\tau_1,\tau_2)=\frac{<:I(t)I(t+\tau_1)I(t+\tau_2):>}{<I(t)>^3}$$

$$=\frac{<\hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau_1)\hat{a}^\dagger(t+\tau_2)\hat{a}(t+\tau_2)\hat{a}(t+\tau_1)\hat{a}(t)>}{<\hat{a}^\dagger(t)\hat{a}(t)>^3}$$

$$g^{(4)}(\tau_1,\tau_2)=\frac{<:I(t)I(t+\tau_1)I(t+\tau_2)I(t+\tau_3):>}{<I(t)>^4}$$

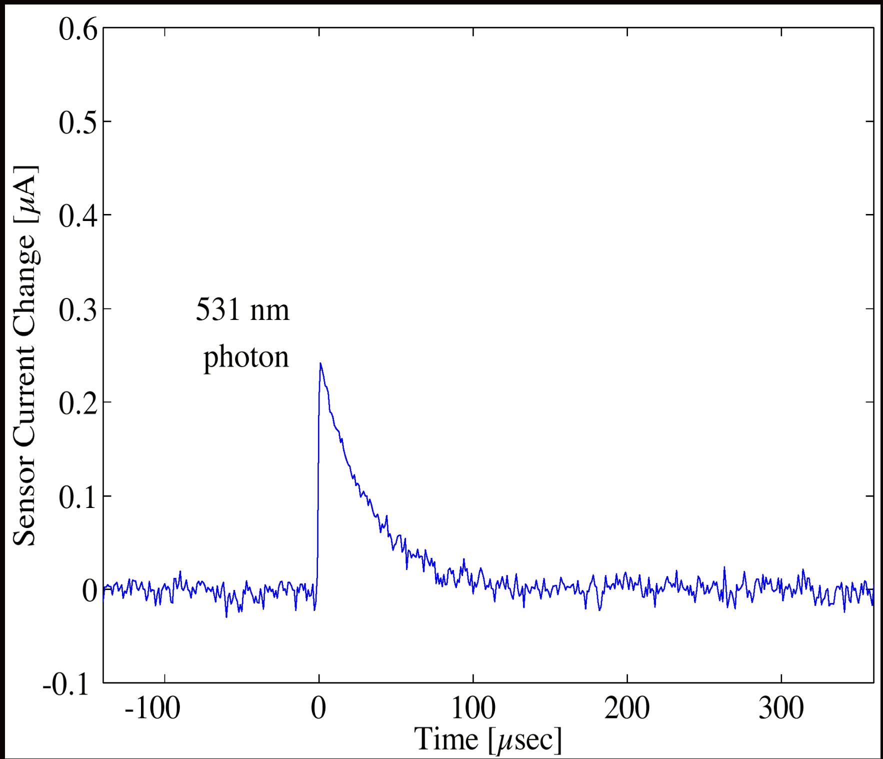
$$=\frac{<\hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau_1)\hat{a}^\dagger(t+\tau_2)\hat{a}^\dagger(t+\tau_3)\hat{a}(t+\tau_3)\hat{a}(t+\tau_2)\hat{a}(t+\tau_1)\hat{a}(t)>}{<\hat{a}^\dagger(t)\hat{a}(t)>^4}$$

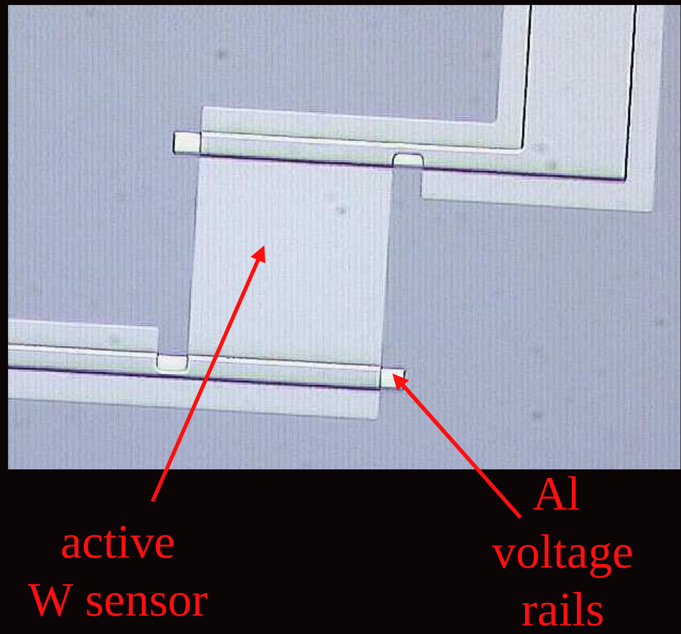
Summary of Detector Experiments to date

- TES with SPDC in a HOM interferometer
- TES in a QKD link
- TES to herald optical CAT states
- SNSPDs in a QKD link
- SNSPDs to herald photons from an SPDC source at 1550nm
- SNSPDs to perform time-correlated single photon counting (TCSPC)
- SNSPDs to perform free-space LIDAR
- SNSPDs to measure single photon sources
- SNSPD to characterize entanglement sources
- SNSPD to characterize CNOT gates
- SNSPD to measure higher order intensity correlations

Optical Photons

Collaboration with Blas Cabrera's group at Stanford University

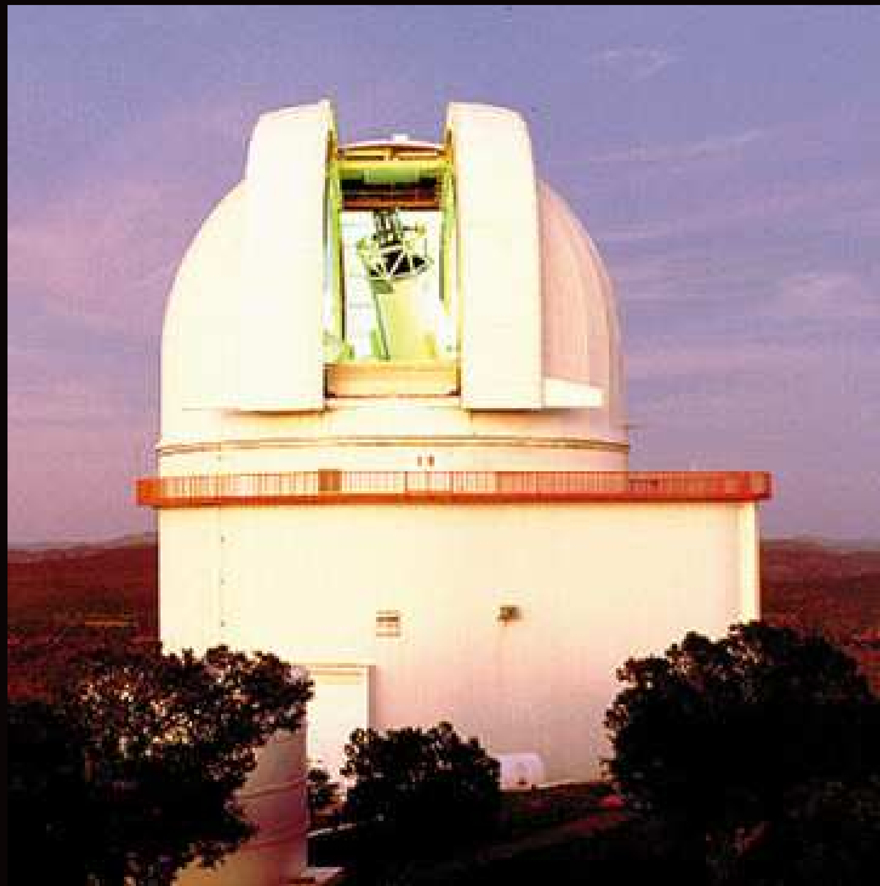


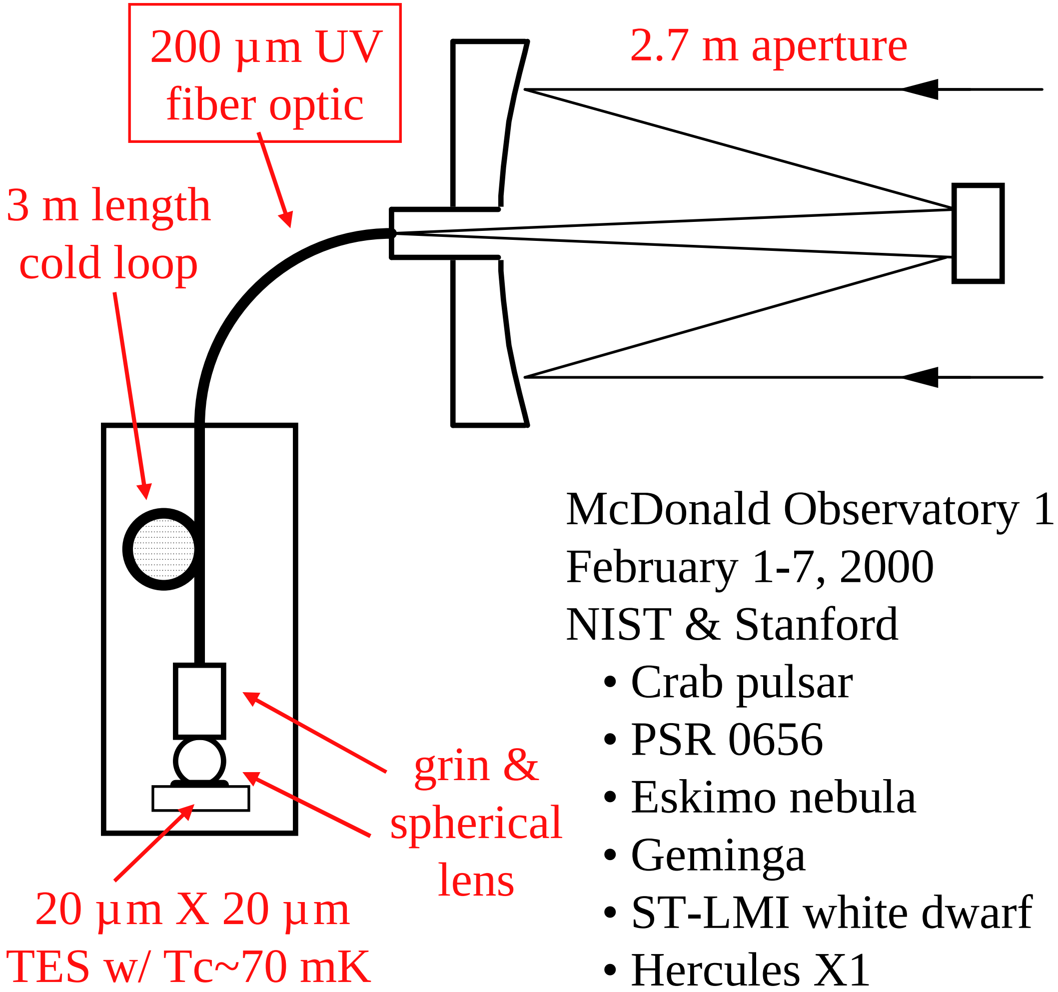


McDonald Observatory

Stanford - NIST collaboration

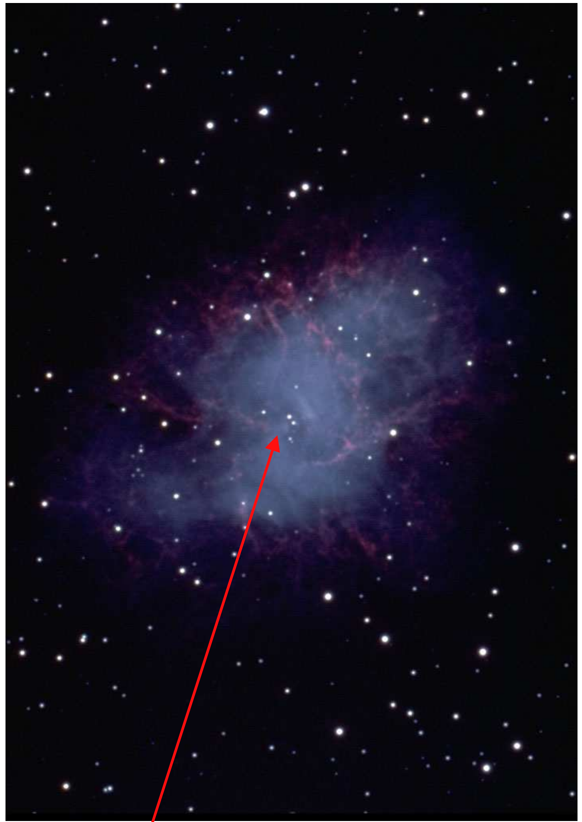
- February 2000
- 4-pixel TES optical bolometer array
- Kelvinox dilution refrigerator
- Used digital feedback electronics
- Each photon time-stamped to a fraction of a microsecond with GPS
- Data from faint periodic and quasi-periodic objects



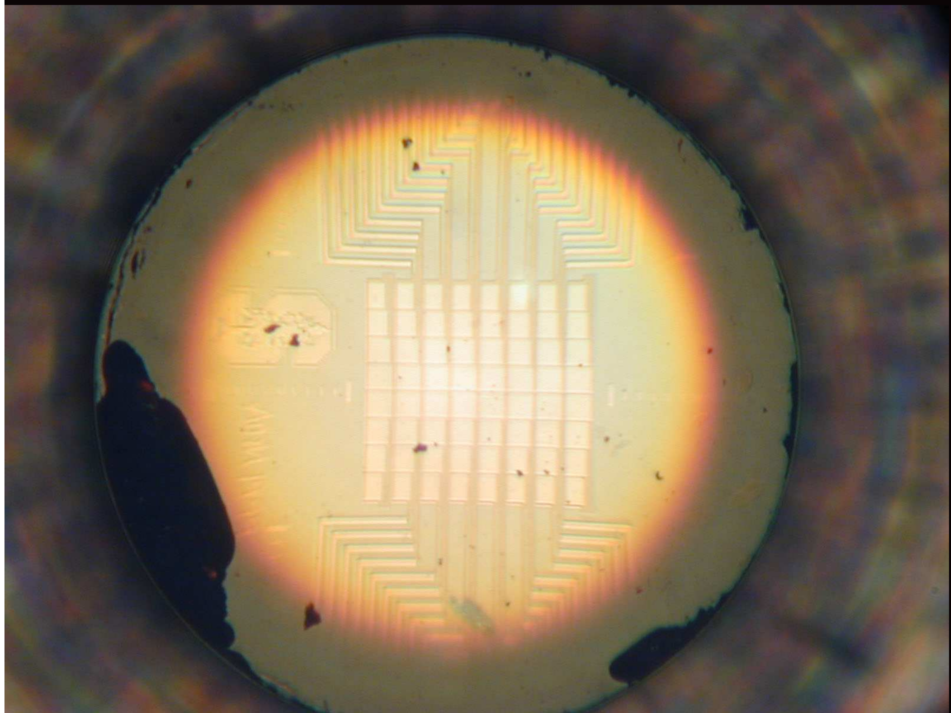


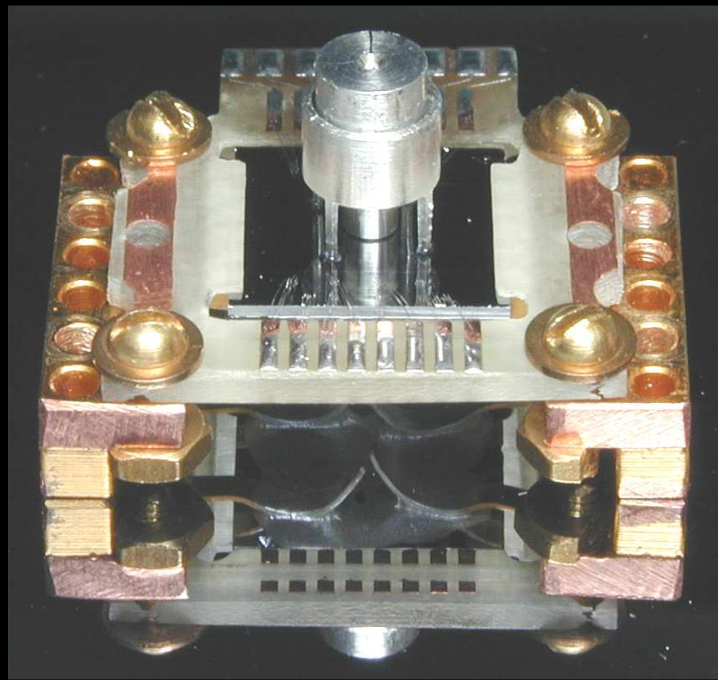
McDonald Observatory 107”
February 1-7, 2000
NIST & Stanford

- Crab pulsar
- PSR 0656
- Eskimo nebula
- Geminga
- ST-LMI white dwarf
- Hercules X1
- calibration stars

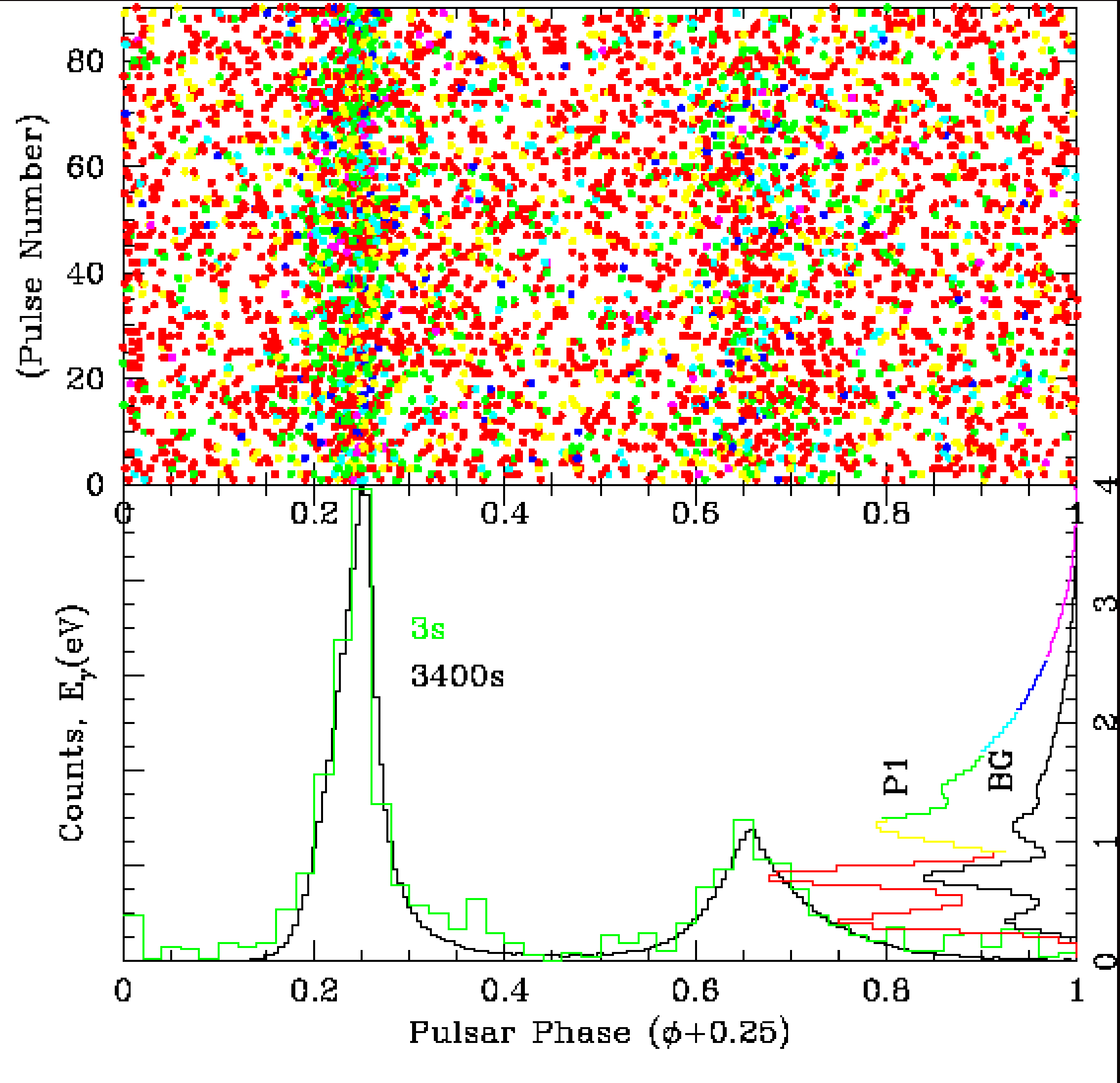


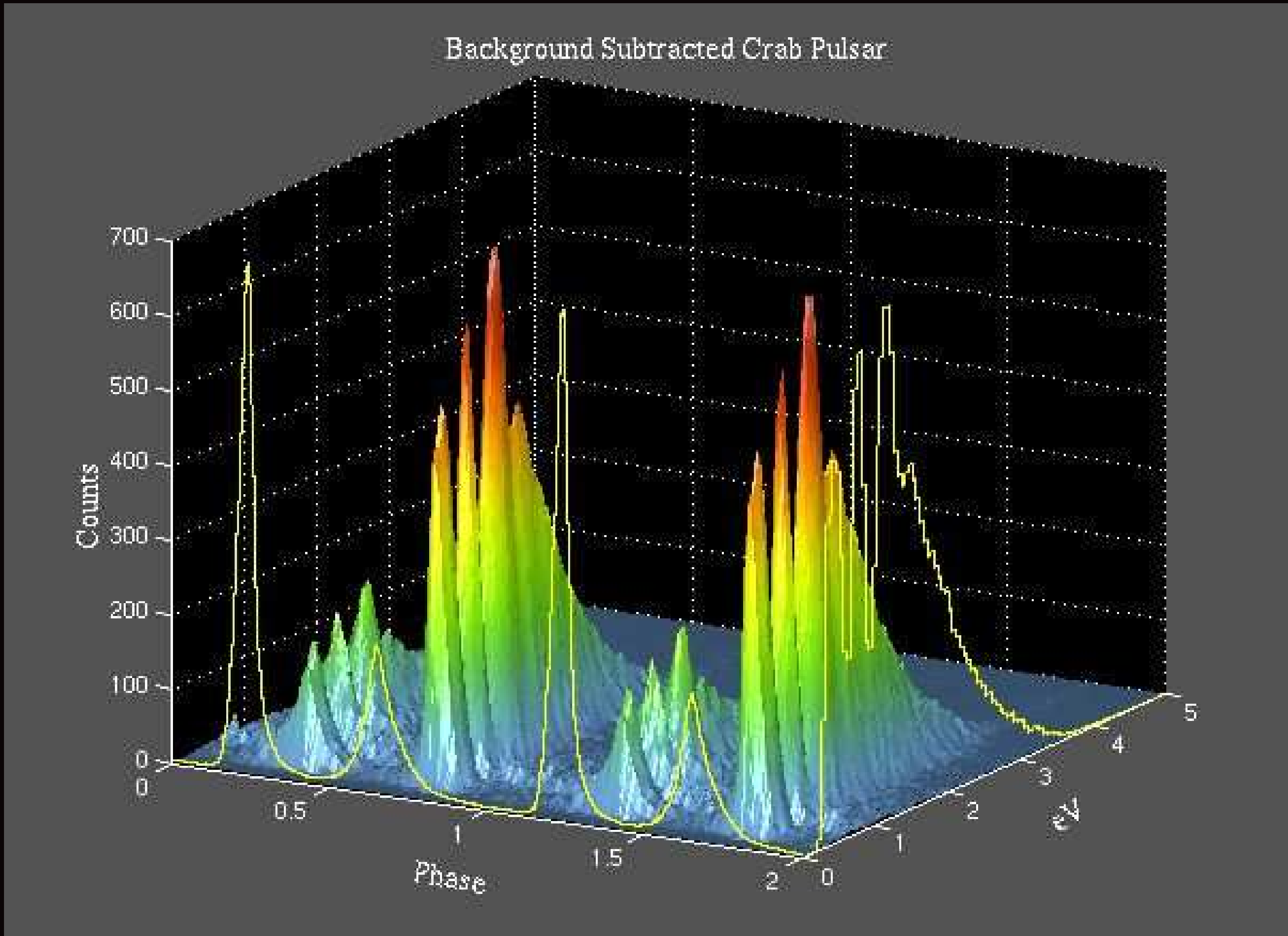
Device Packaging

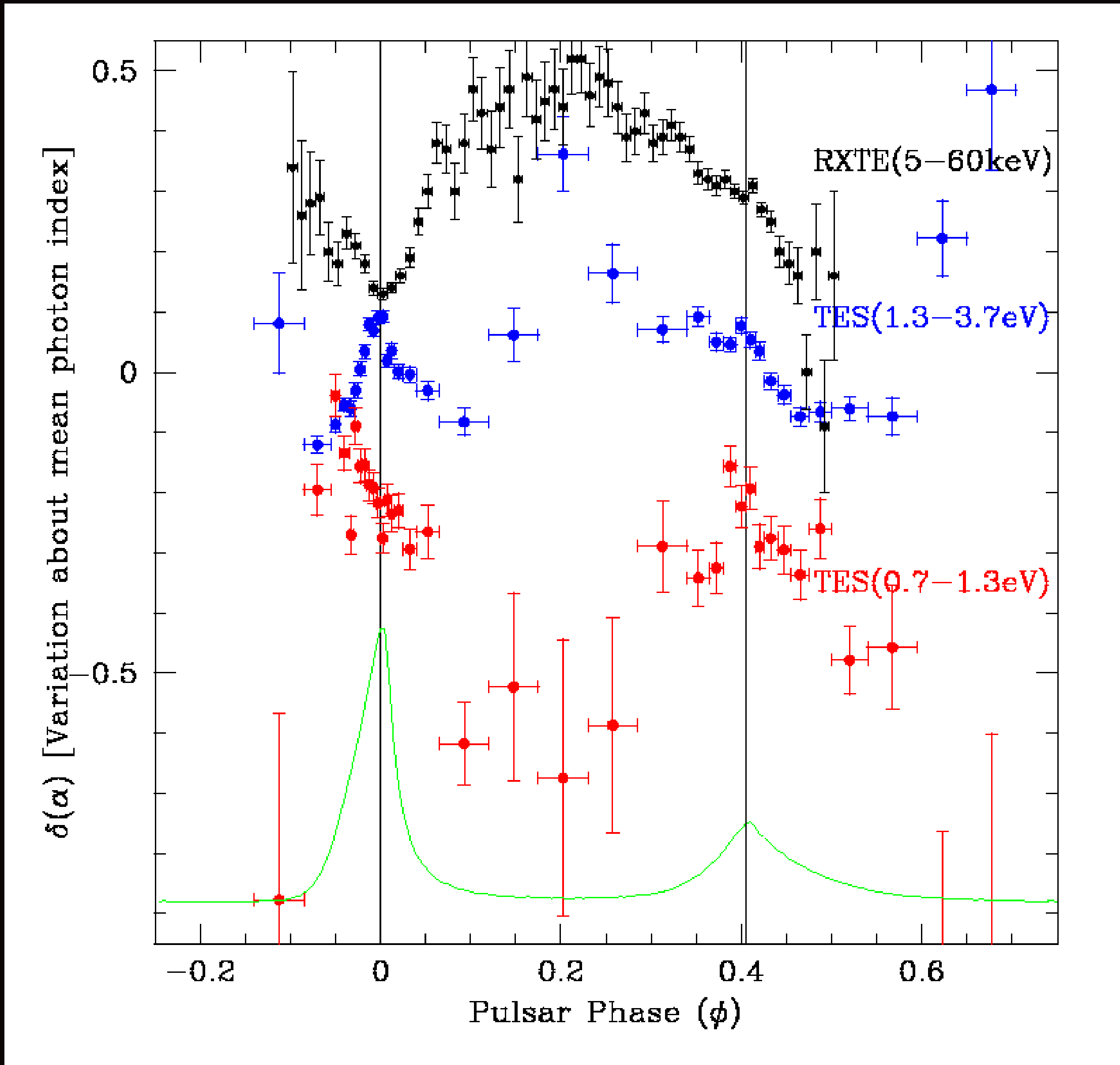




Crab Pulsar Data

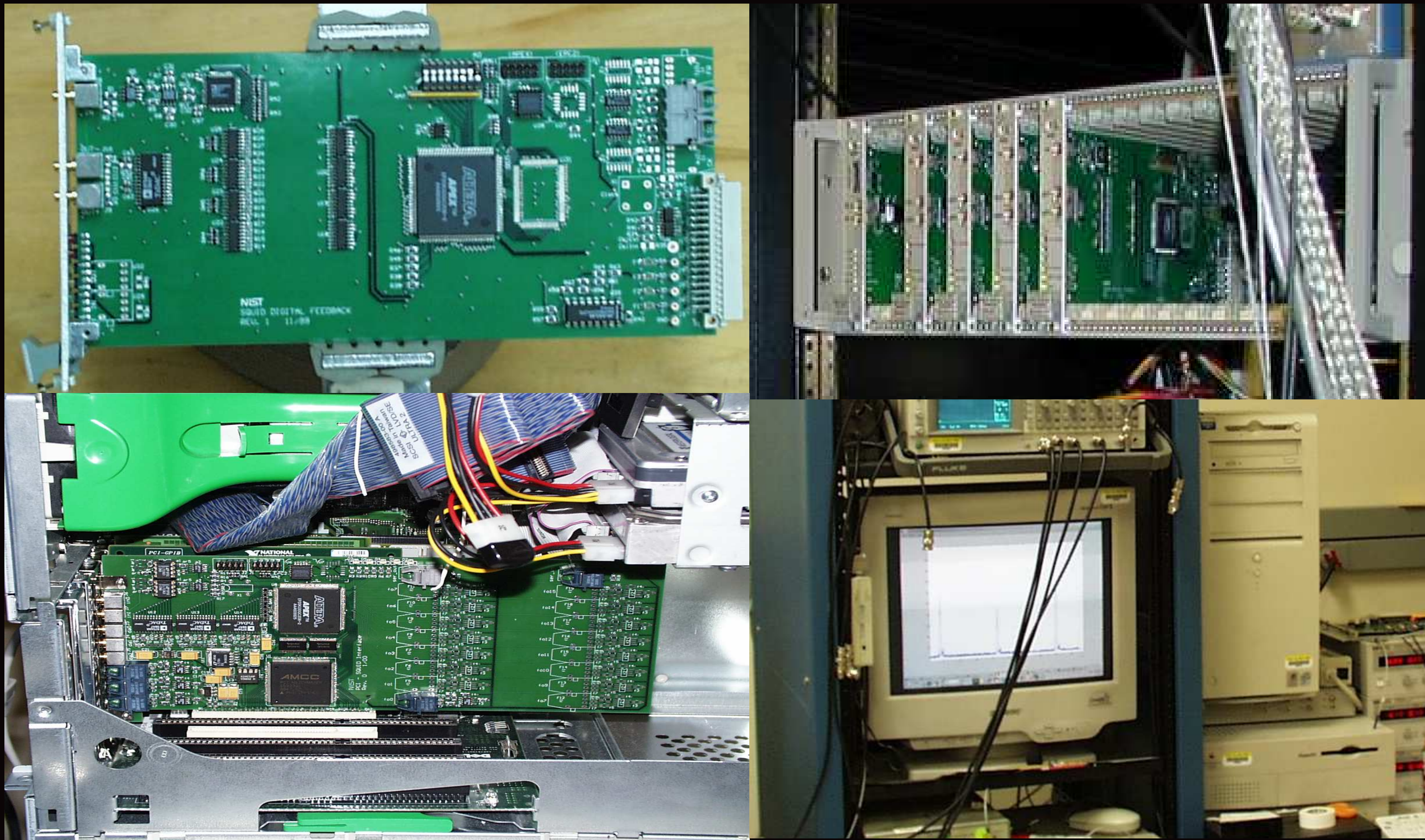



Background Subtracted Crab Pulsar
Counts
700
600
500
400
300
200
100
0
0
0.5
1
1.5
2
Phase
0
1
2
3
4
5
eV



RXTE(5−60keV)
TES(1.3−3.7eV)
TES(0.7−1.3eV)
0.5
0
−0.5
−0.2
0
0.2
0.4
0.6
Pulsar Phase (ϕ)
δ(α) [Variation about mean photon index]

Digital Electronics for SQUID readout

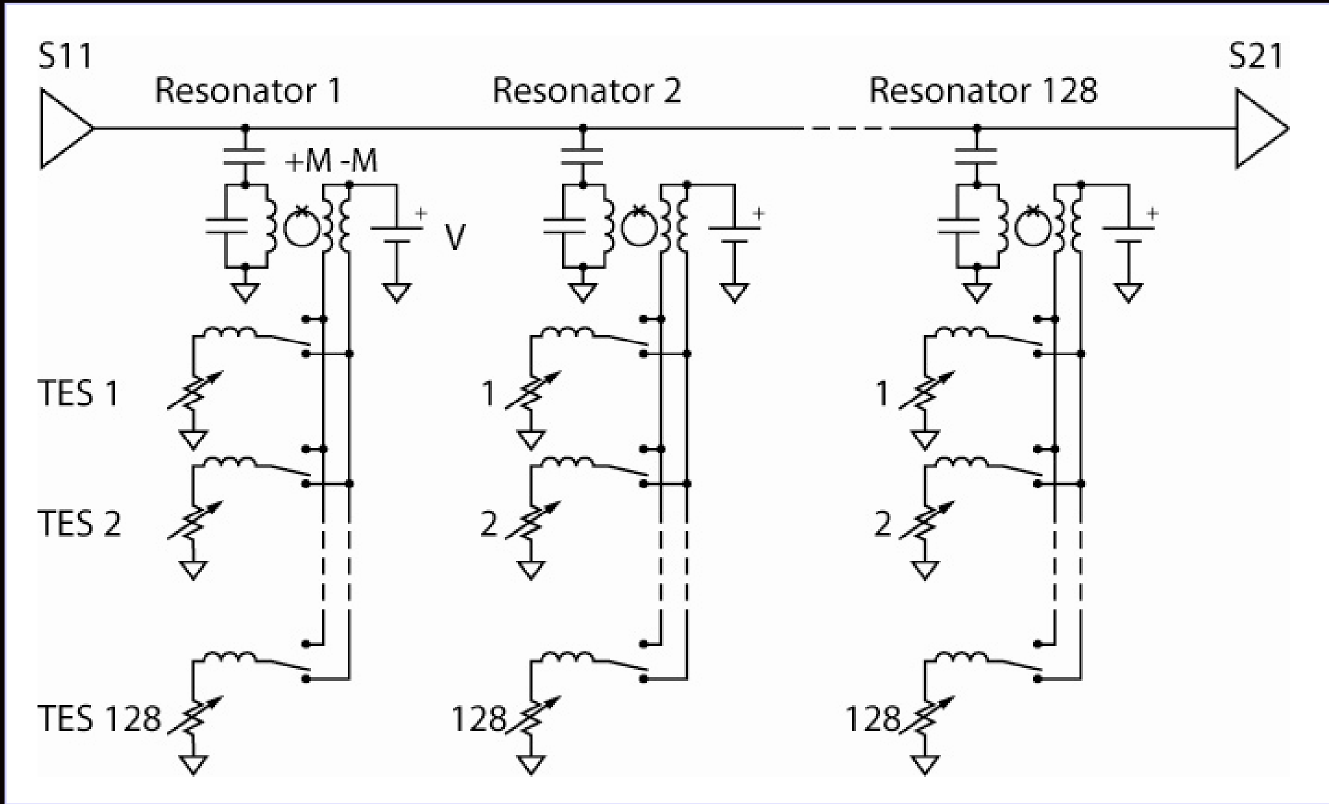


Pixel Performance and Multiplexing

- Operating resistance is ~1 ohm
- Power dissipation <100 fW per pixel
- Bias current is small (~ 100 nA)
- Modest energy resolution
- Slow count rates
- Pixels are small (25 microns x 25 microns)

- Small current steering switches at each pixel
- Inductors for Nyquist filtering

Schematic



- One coax can be used to FDM 128 channels which use CDM to mux 128 TES
  - 16k per coax
  - 5 MHz BW per carrier
- 64 coax = Mega Pixel
- 40 µs time constants
- 1 kcps
- Lenslet array

Conclusions

- Superconductivity offers another technique for achieving high performance optical detectors
- Much more work is needed to make the detectors usable in real experiments and systems
- Basic research and development into device performance is still needed.
  - What are the fundamental limits to QE, recovery time, jitter, dark counts?
  - What are the practical limits?
- Optical TES can be multiplexed reasonably with CDM
- Mega-pixel with count rates 1 kcps / active element (switch) at each pixel