High resolution calorimetry with TES

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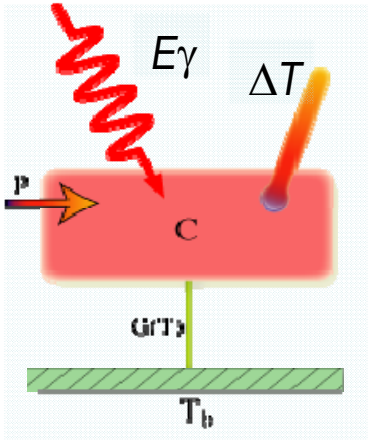
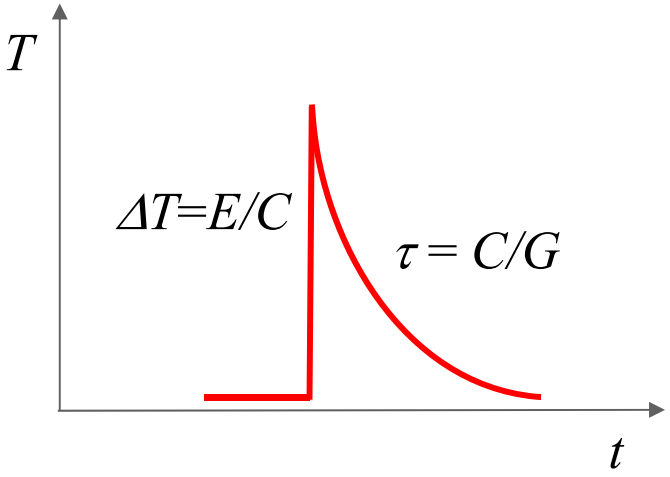
Calorimeter

Calorimeter is a device used to measure the quantity of heat transferred to or from an object.



C = heat capacity

G = Thermal conductance



NEP : thermal fluctuation noise $(4k_B T^2 G)^{1/2}$ W/Hz$^{1/2}$

$$\Delta E = NEP\ \tau\ B^{1/2} \sim (k_B T^2 C B)^{1/2} \text{ J}$$

sensors performance best at low temperatures

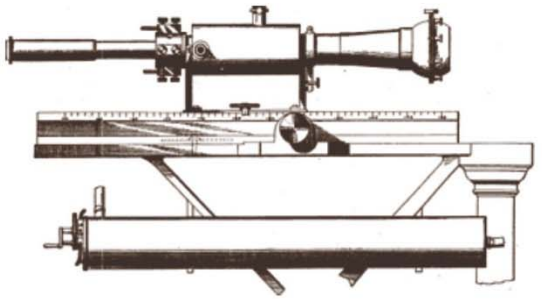
For T=0.1 K , C = 1 pJ/K , B = 1 Hz ⇨ ΔE=2 eV

Ph736_lecture thermal detectors – Un. Wisconsin

History of Cryogenic Particle Detectors

~1845	Mayer, Joule	heat is a form of energy
1876	Langley	bolometer for ir-observations of sun
1903	Curie, Laborte	calorimetric detection of integrated radioactivity
1935	Simon, Kurti	cryogenic version - 50 mK !
1939	Goetz	superconducting transition calorimeter
1949	Andrew, Fowler Williams	detection of single α particles with a superconducting calorimeter
•		
•		
•		
1984	Fiorini, Niinikoski, Moseley, Mather, McCammon	modern type cryogenic particle detectors
today		over 300 scientists are working in this field

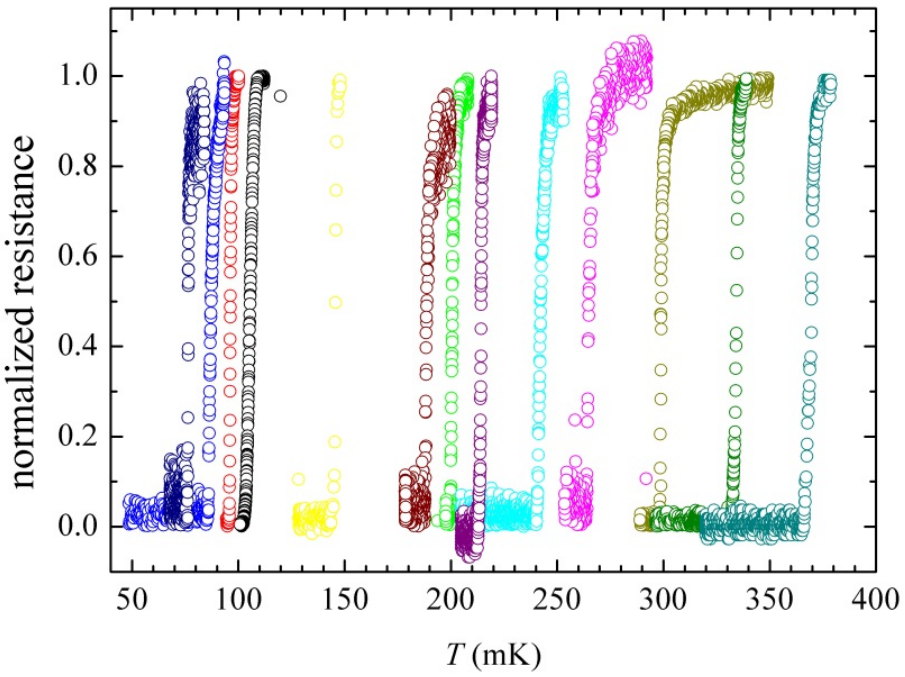

S.P. Langley (1834-1906)



Transition-Edge Sensors (TESs)

TES: a microcalorimeter made by a superconducting film operated in the temperature region between the normal and the superconducting state

Ti/Au Bilayer – proximity effect



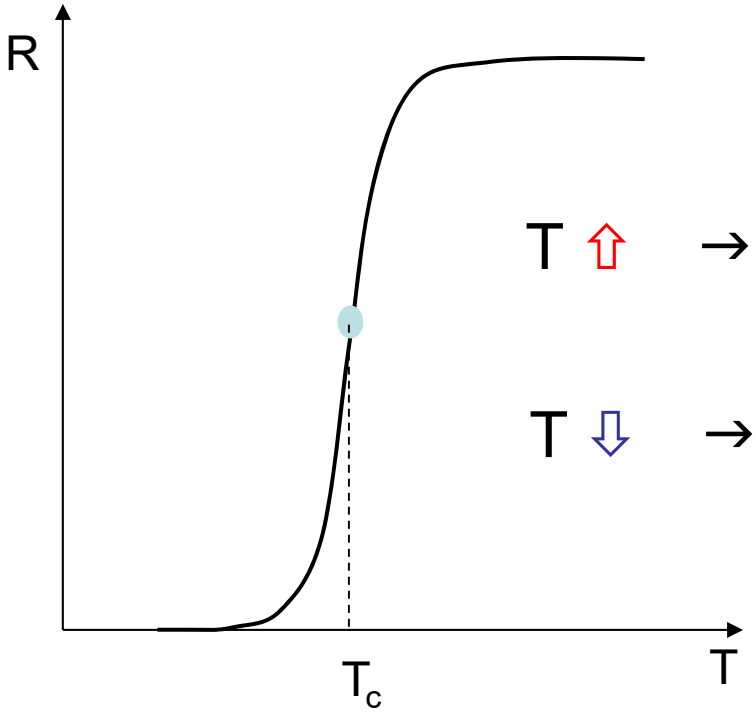
- TESs are very sensitive:
  ➥ temperature control difficult
  ⬇
  Voltage biasing and electrothermal feedback

- TESs have low resistance:
  ➥ difficult readout
  ⬇
  dc-SQUID amplifier

TES: Electro-thermal feedback

Irwin K. D. , Appl. Phys. Lett. **66** 1998 (1995)

Voltage bias and thermal bath < T_c



$T \Uparrow \rightarrow R \Uparrow \rightarrow P_e=V^2/R \Downarrow \rightarrow T \Downarrow$

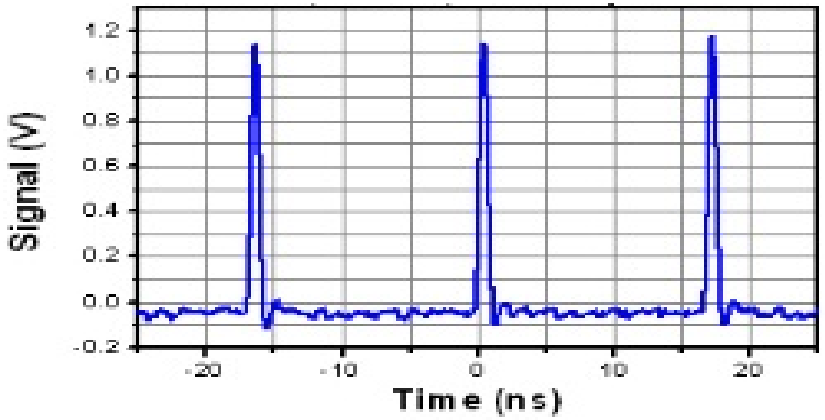
$T \Downarrow \rightarrow R \Downarrow \rightarrow P_e=V^2/R \Uparrow \rightarrow T \Uparrow$

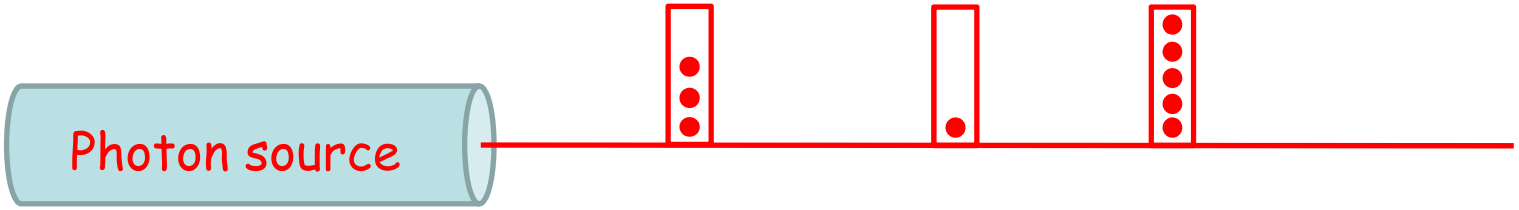
Bias: very easy & response time reduced

Single Photon detectors

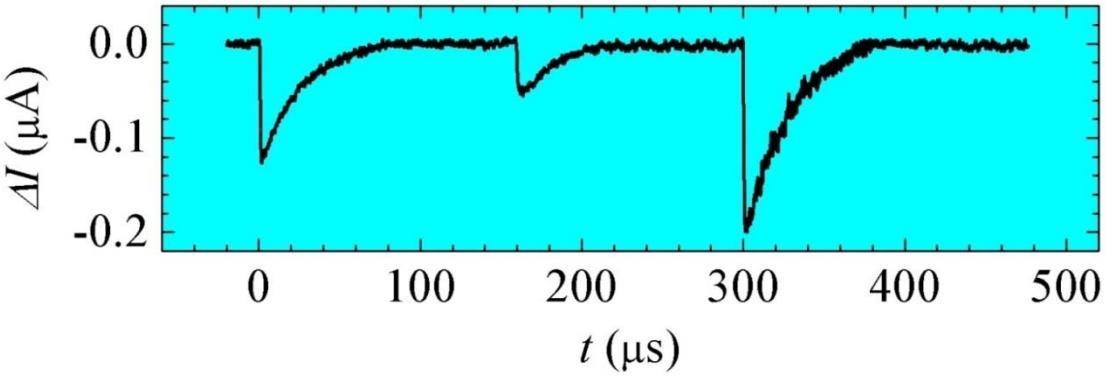
"Classical" Single photon detector

(Photomultiplier, APD, SPAD…)

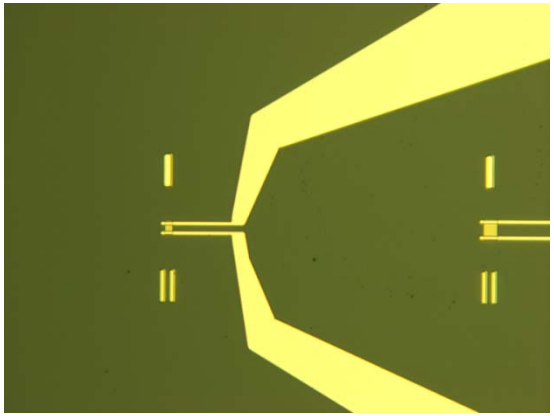


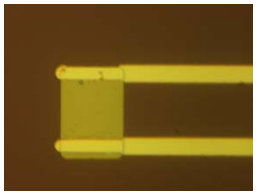


Energy resolving or
Photon number resolving (PNR) detector

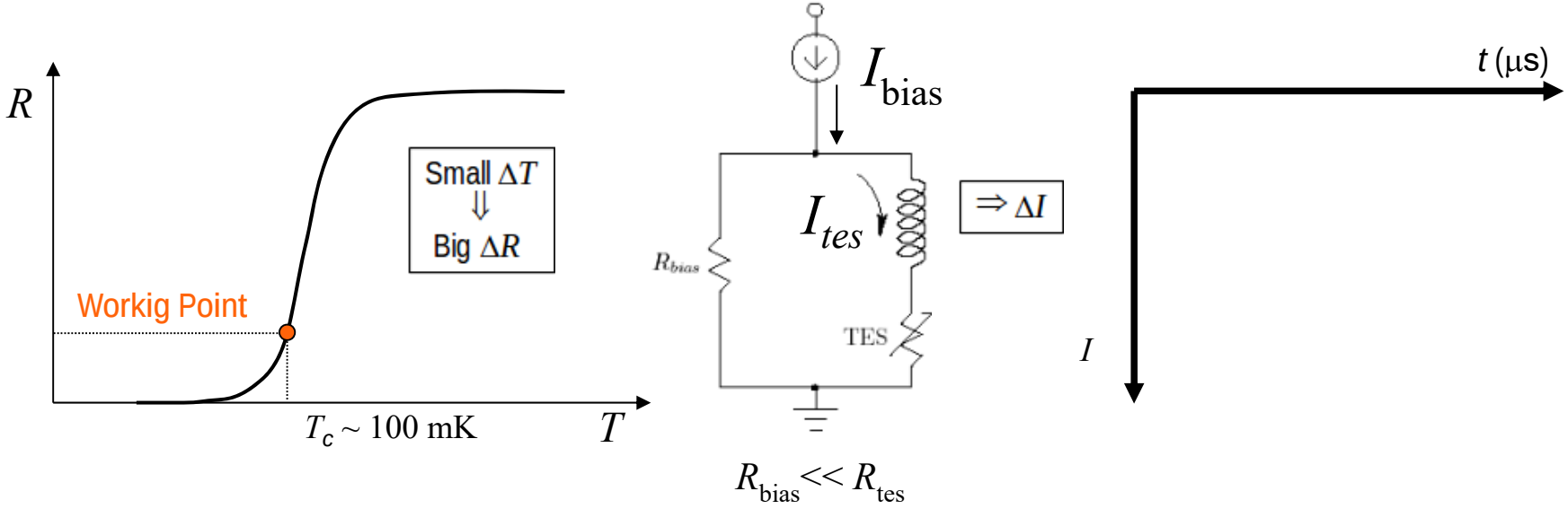


TESs as single photon detectors

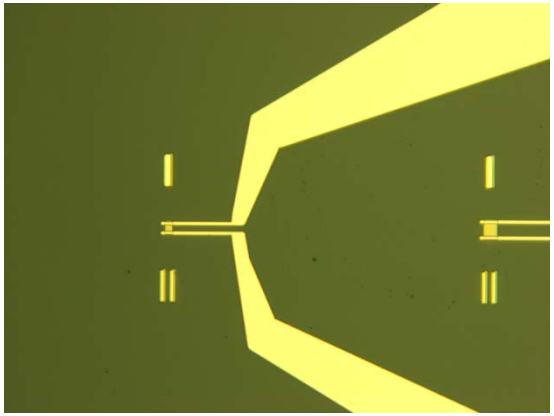


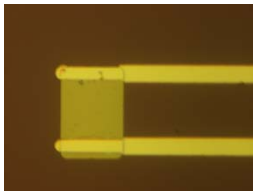


20 µm X 20 µm

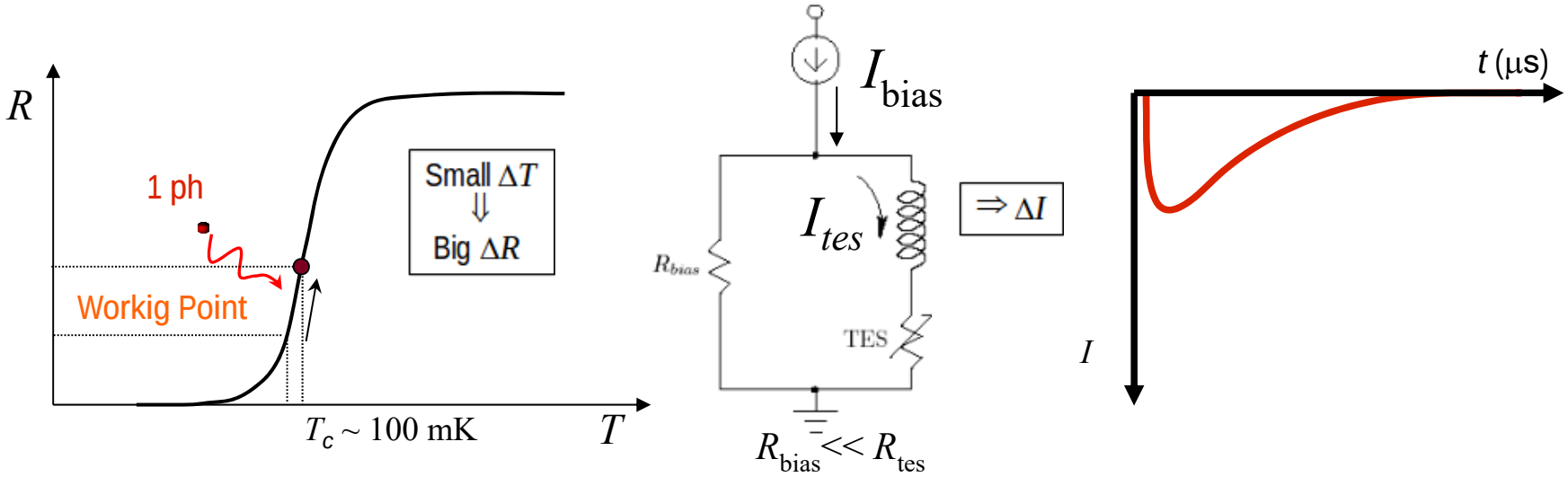


TESs as single photon detectors



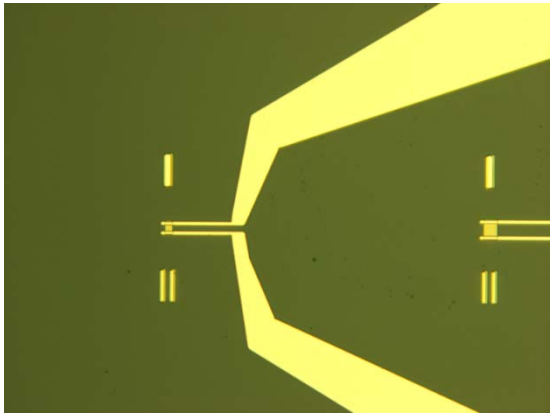


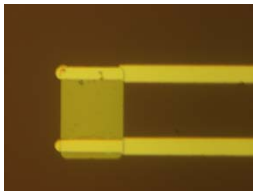
20 μm X 20 μm



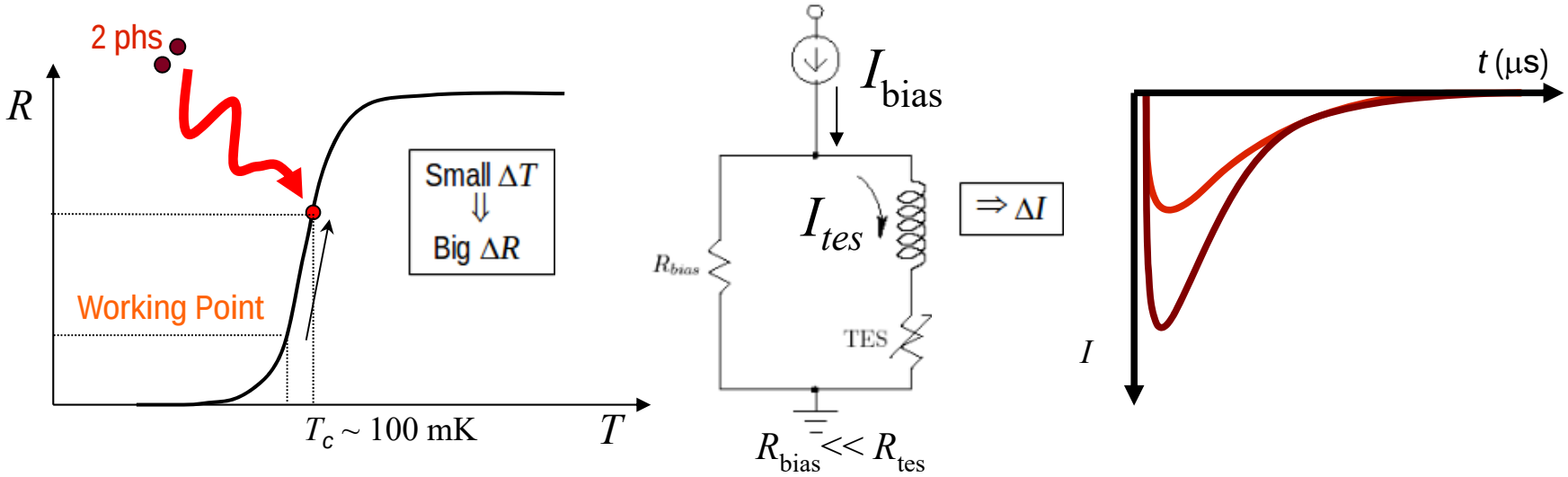
$\Delta T \Rightarrow \Delta R$ @ Voltage bias $\Rightarrow$ ΔI

TESs as single photon detectors





20 μm X 20 μm



ΔT ⇨ΔR @ Voltage bias ⇨ ΔI

Performances

Transition sharpness

$$\tau_{eff} = \tau_{th}\left\{1+\frac{\alpha}{n}\left(1-\frac{T_s^n}{T_c^n}\right)\right\}^{-1} \approx \frac{n}{\alpha}\tau_{th} \approx \frac{C}{G} \propto T_c^{-3}$$

Effective response time

↕ **Trade-off between response time and energy resolution**

$$\Delta E_{FWHM} \approx 2.36\sqrt{4kT_0^2\frac{C_e}{\alpha}\sqrt{n/2}} \propto T_c^{3/2}$$

Energy resolution

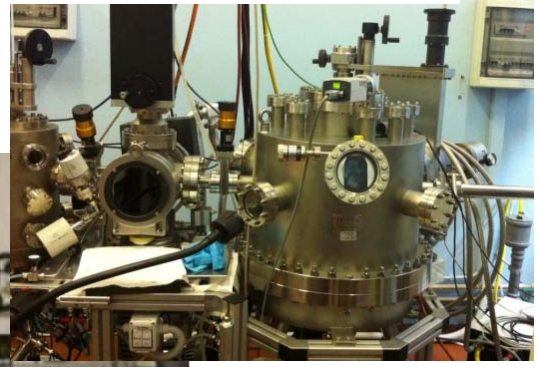
↕ **Trade-off between energy resolution and saturation energy**

$$E_{\max} \approx \frac{CT_c}{\alpha}$$

Saturation Energy

INRIM-NM fabrication facility

- Sputtering Nb/Al technology
-
- UHV system Ti, MgB_2, Nb
- E-beam evaporator Ti/Au, AuPd, SiOx, etc
- Optical litography, RIE, ion milling for thin film pattern
- Wedge Bonder system



Sputtering system

Mask aligner

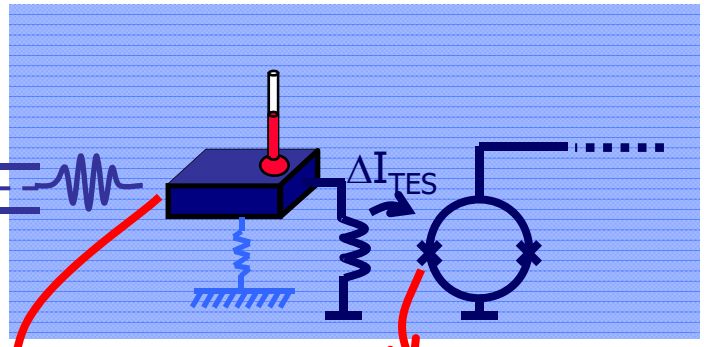
nanofacility

TES: photon counting

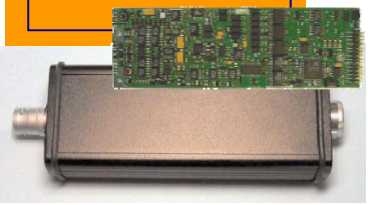
Laser

Attenuator

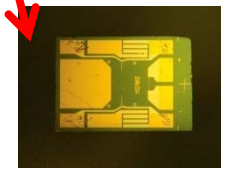
Optical fiber

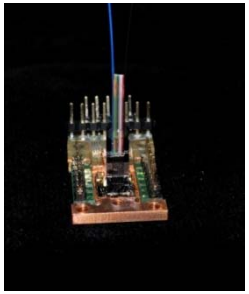


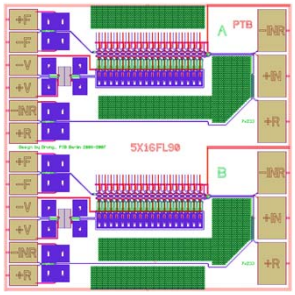
Electronics & data aquisition



INRIM: TES module





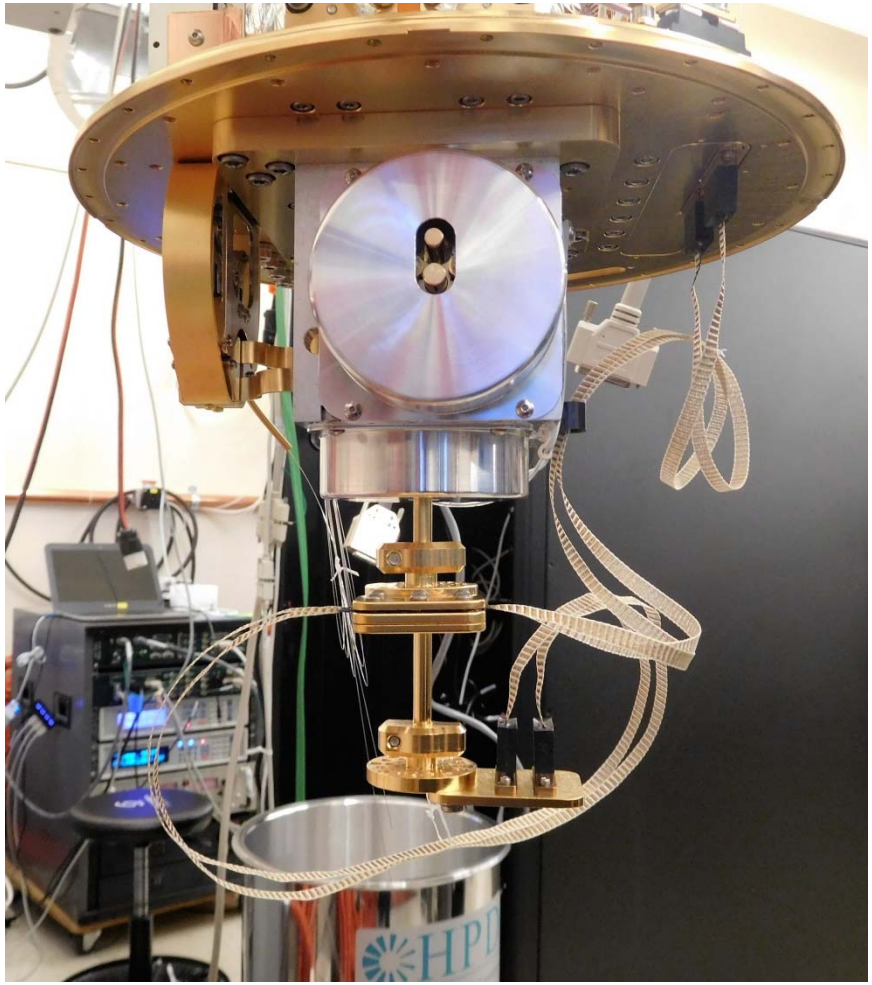


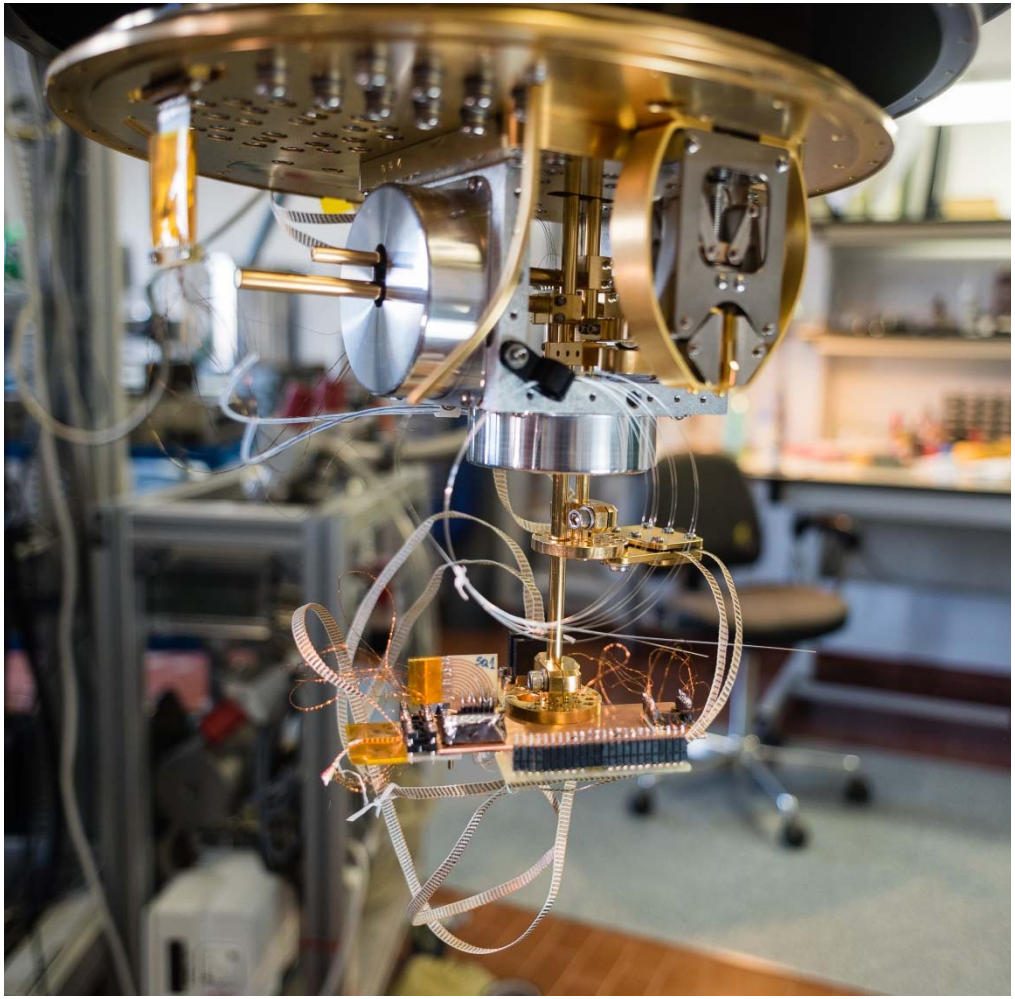
SQUID current sensors (PTB)

INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

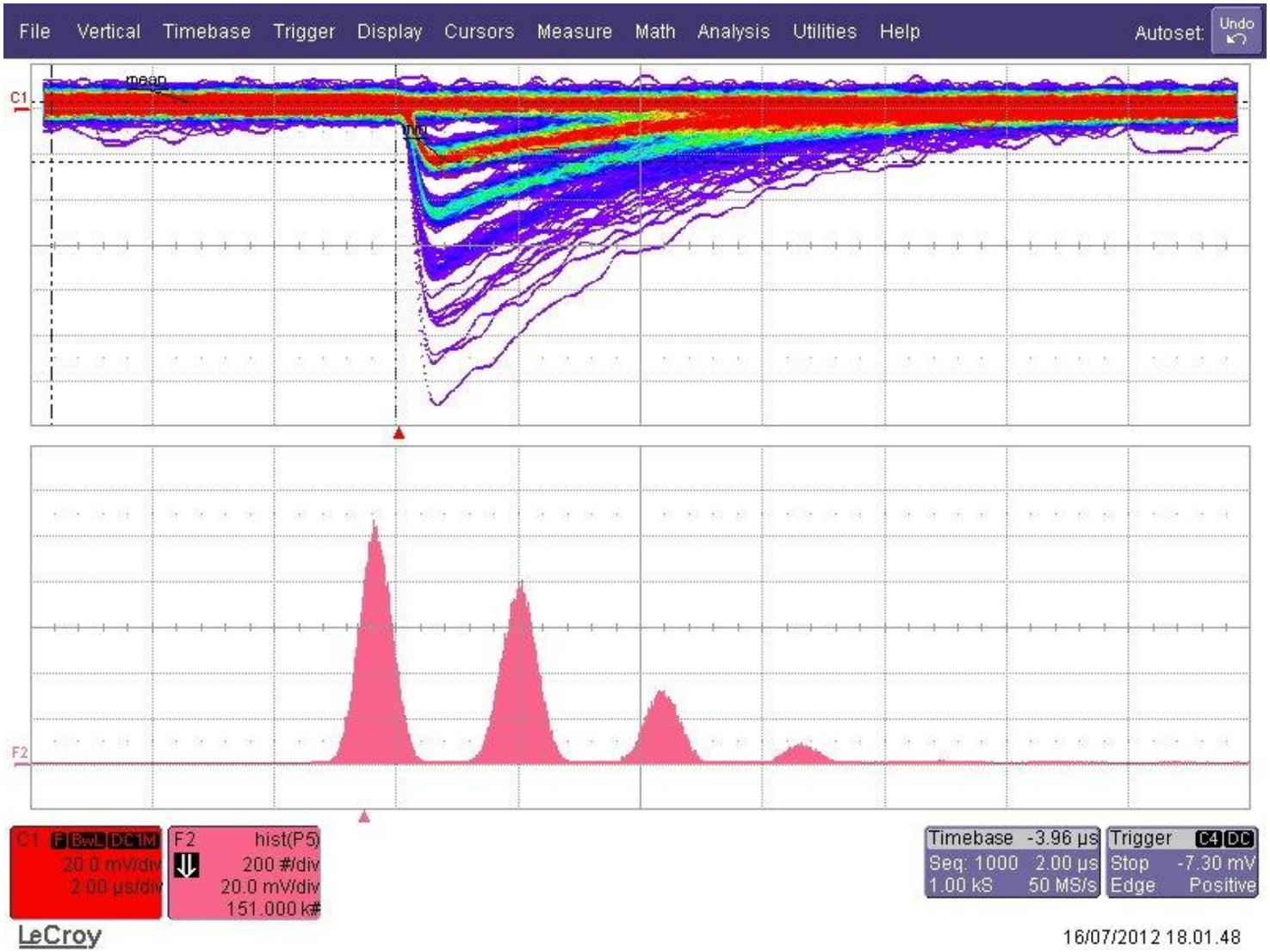
ADR

T_{min}=30 mK - Hold time @ T=50mK : 39 h - Hold time @ T=100mK : >150 h

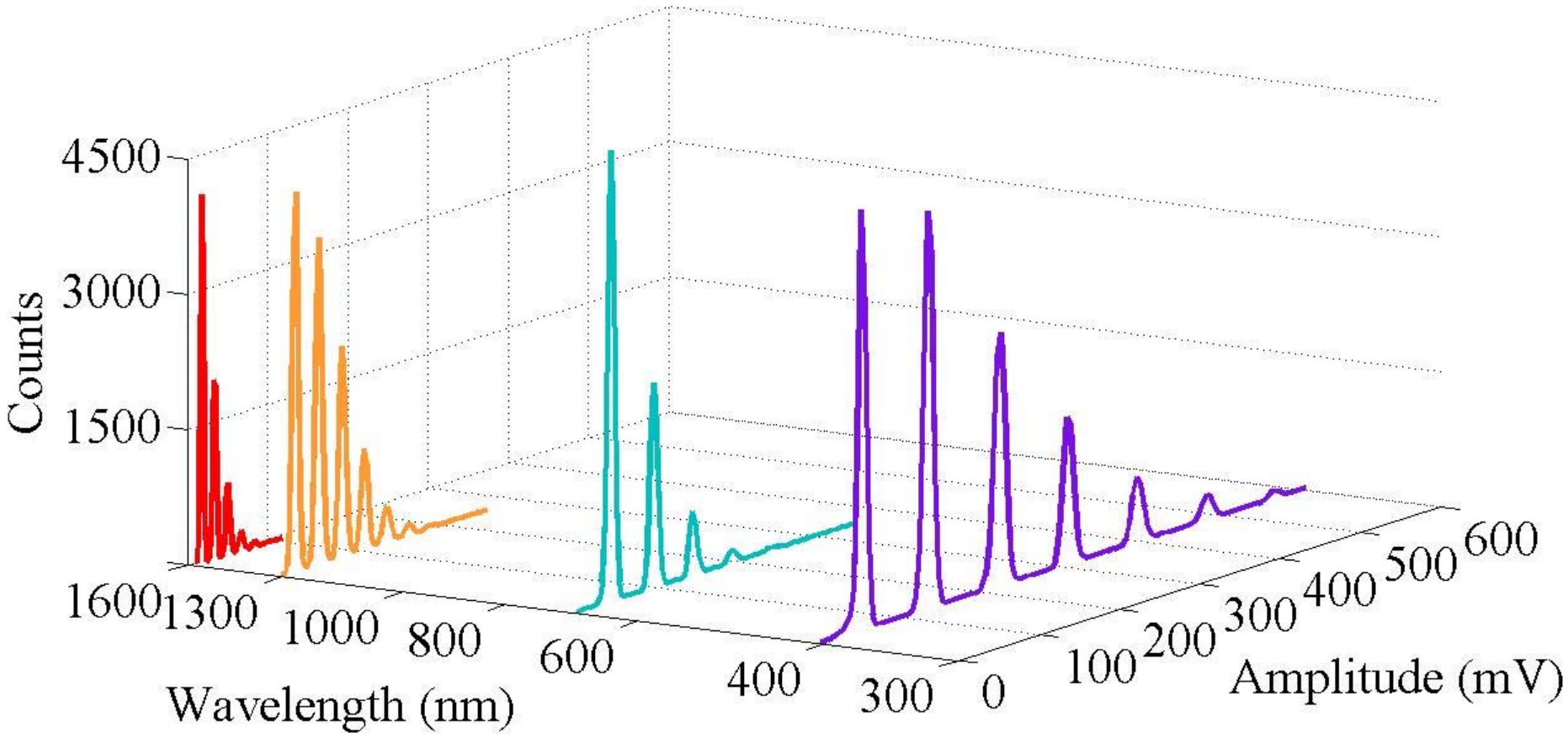




TES: photon counting

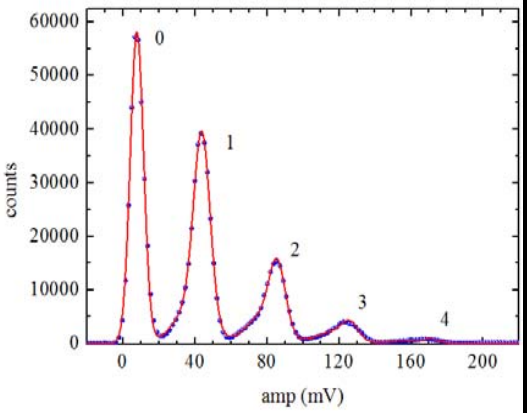


TES: photon counting

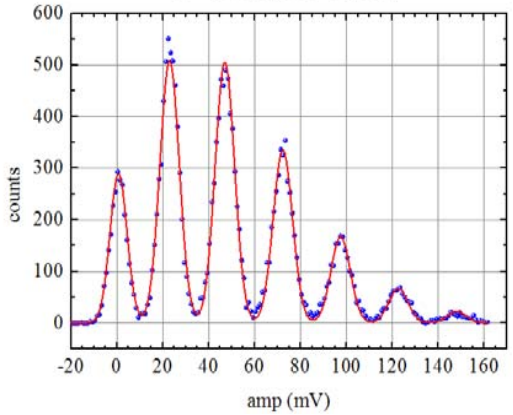


TES: photon counting

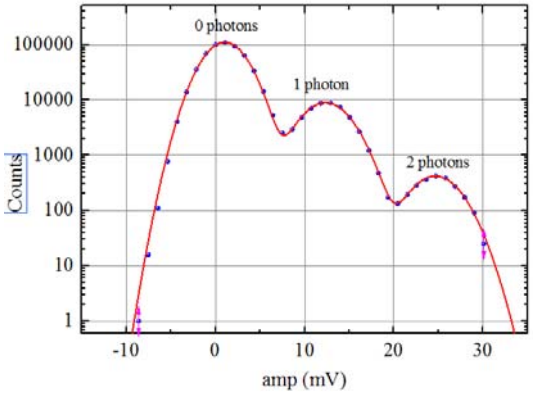
λ=690 nm, ΔE=0.41 eV



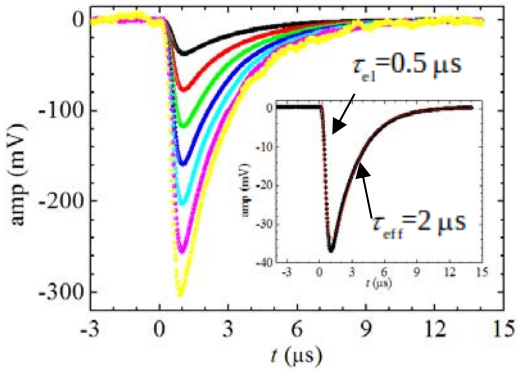
λ=1310 nm, ΔE=0.39 eV



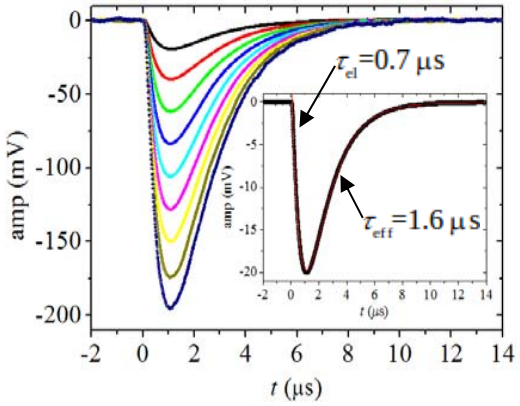
λ=1570 nm, ΔE=0.31 eV



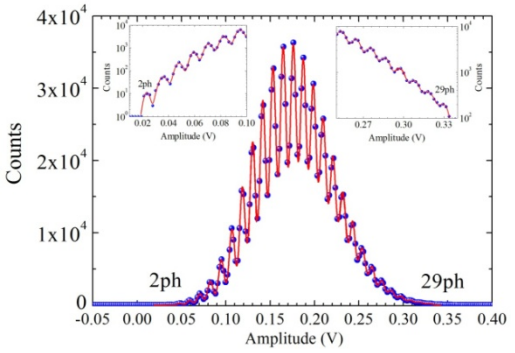
λ=690 nm
averaged single photon pulses



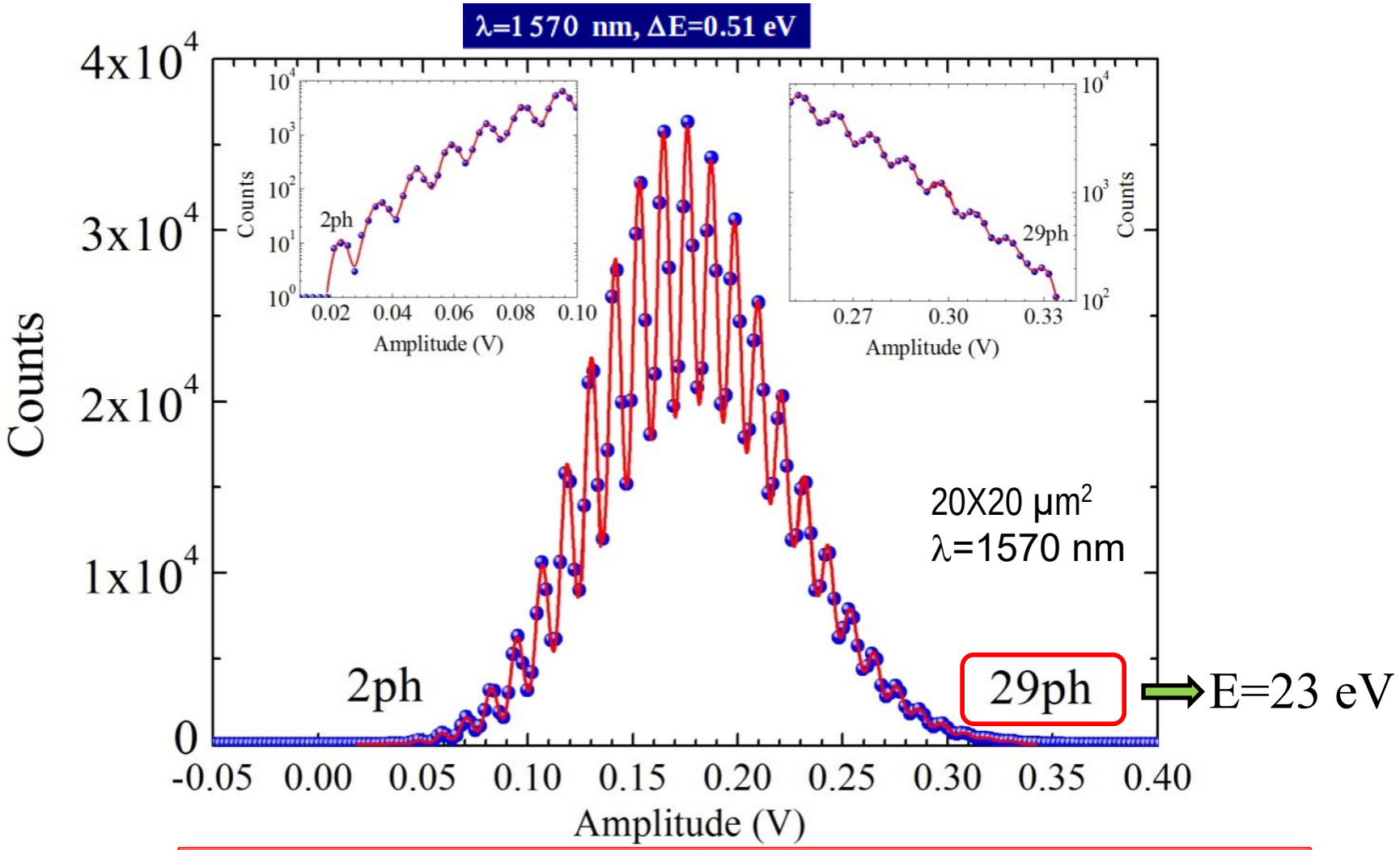
λ=1310 nm
averaged single photon pulses



λ=1570 nm, ΔE=0.51 eV

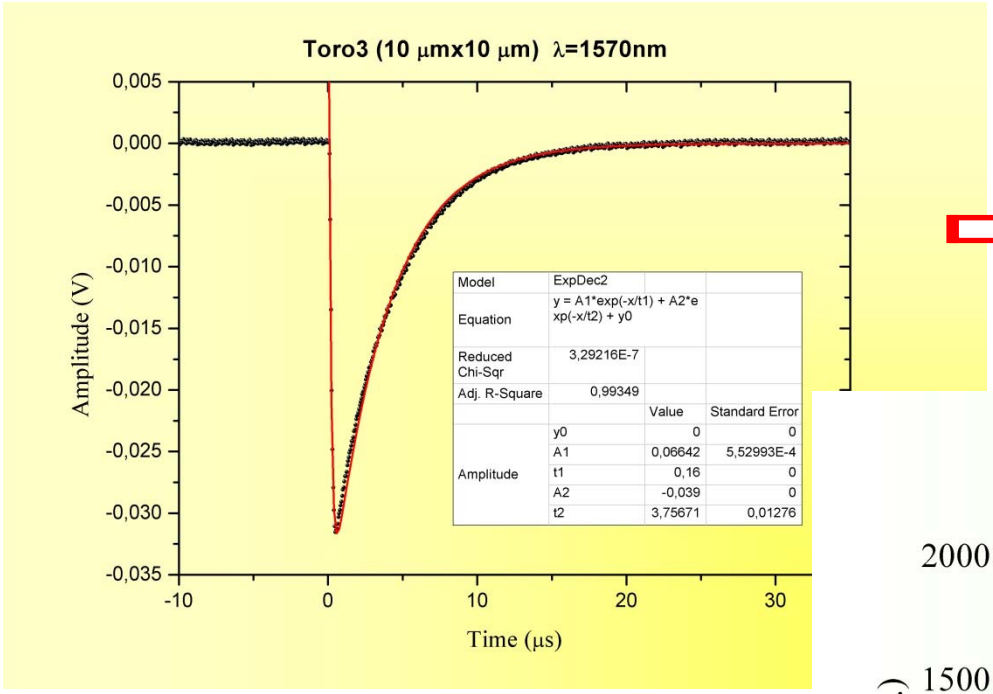


TES: photon counting

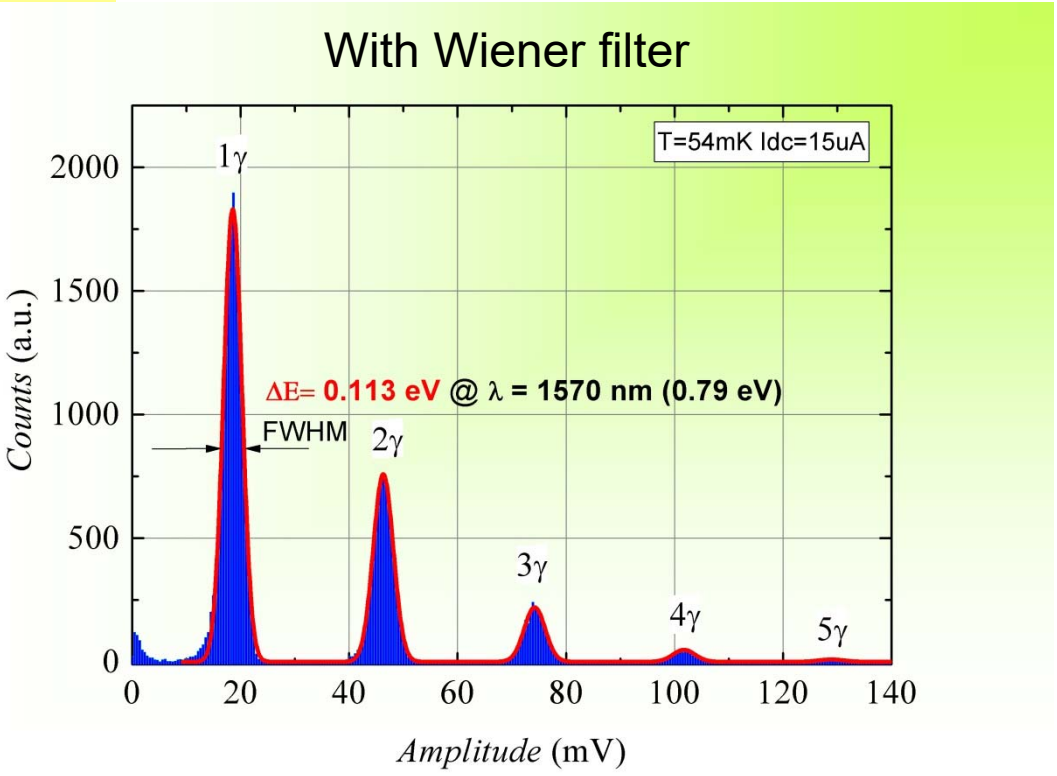


L. Lolli, et al. *J. Low Temp. Phys.*, vol. 167, pp. 803-808, 2012.

TES: High energy resolution



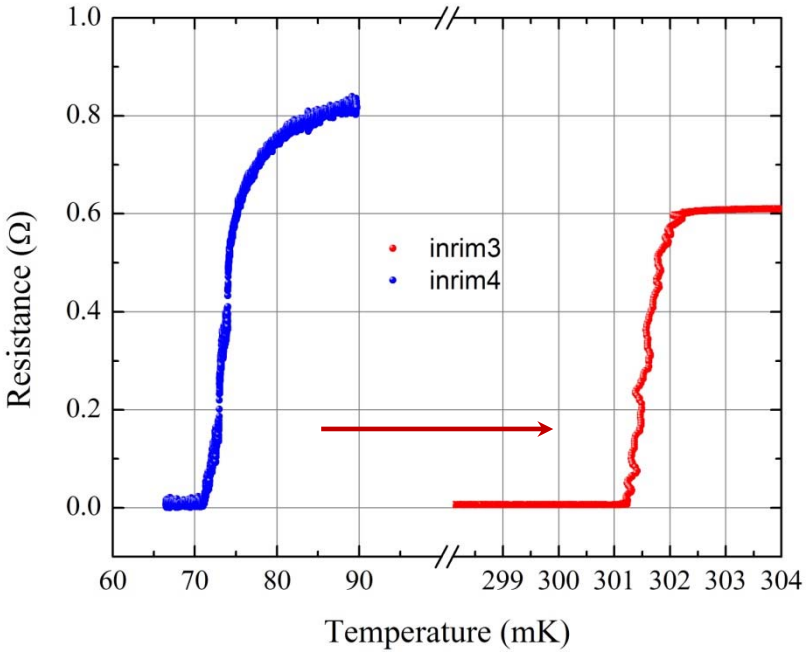
$\tau_{eff} = 3.8\ \mu s$

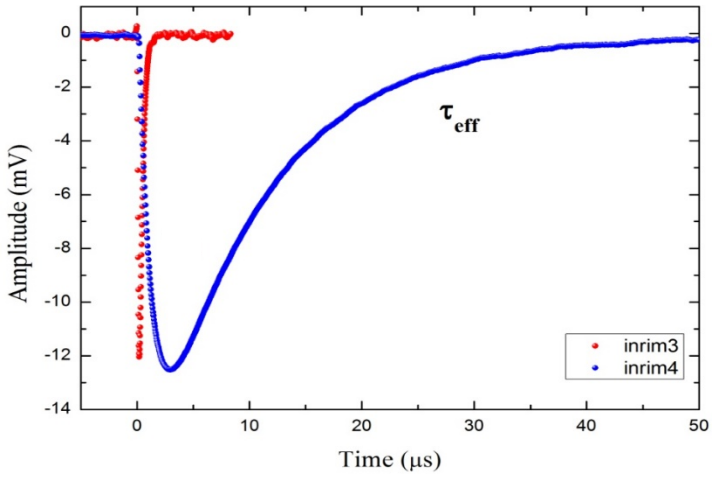


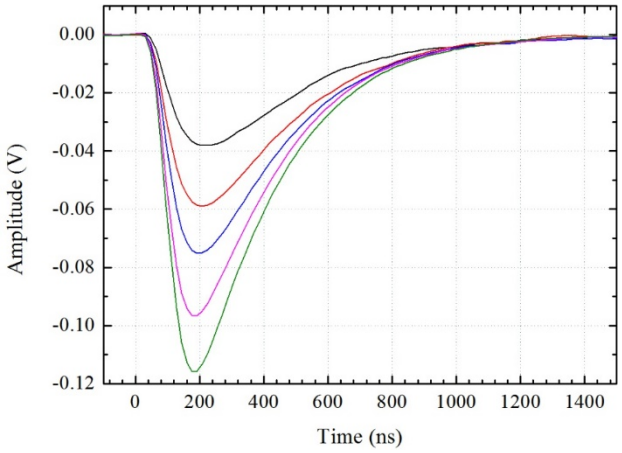
$\Delta E = (0.113 \pm 0.001)$ eV

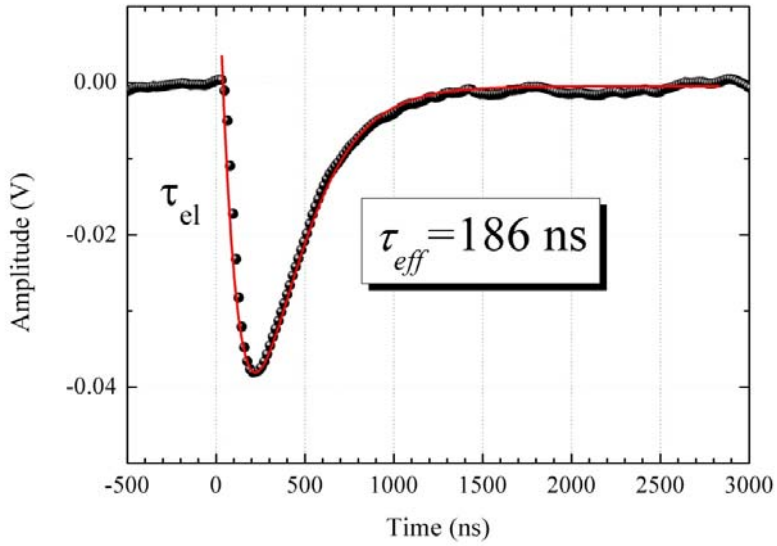
$$\Delta E = 2\sqrt{2\ln 2}\,\frac{\sigma_1 E_\gamma}{x_{2\gamma} - x_{1\gamma}}$$

Fast TES

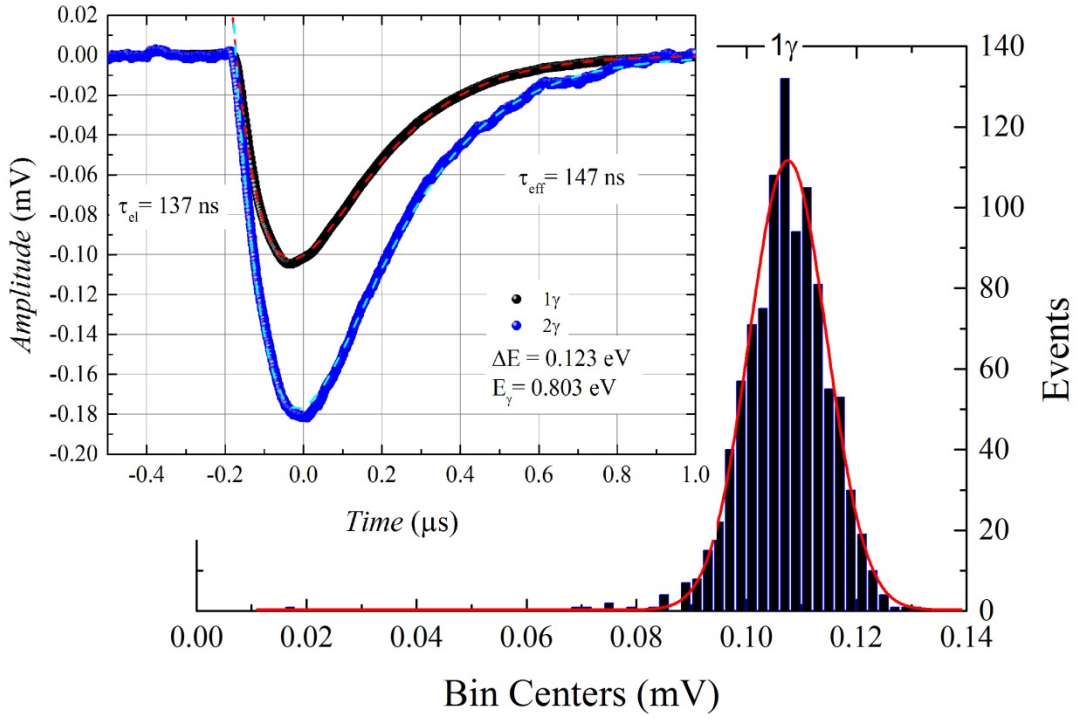

Resistance (Ω)
Temperature (mK)
inrim3
inrim4


Amplitude (mV)
Time (μs)
τeff
inrim3
inrim4


Amplitude (V)
Time (ns)


Amplitude (V)
Time (ns)
τel
τeff=186 ns

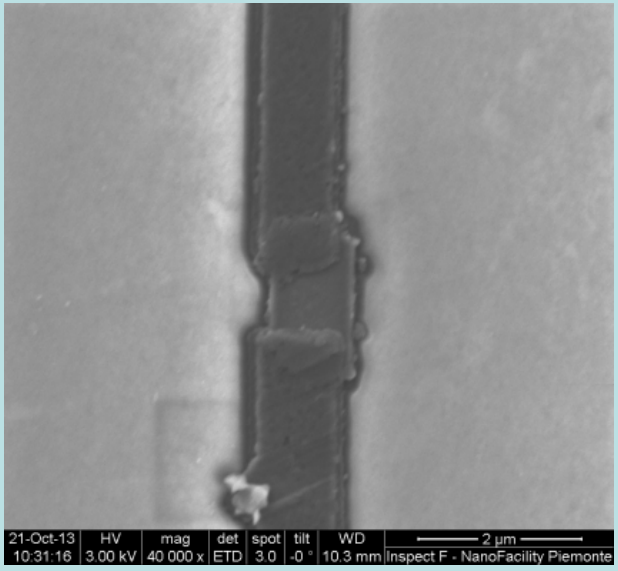
1 μm x 1 μm TES photon counting



τ_{etf} = 147ns

ΔE_{FWHM} = 0.12 eV @ 1545nm

1 μm × 1 μm



C. Portesi *et al*, IEEE Trans App Supercond, 25, 3, (2015)

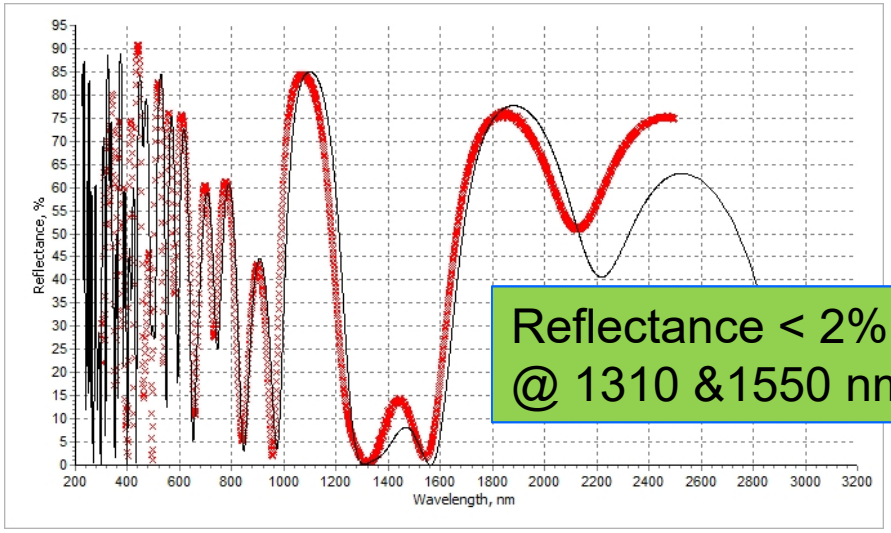
Quantum efficiency

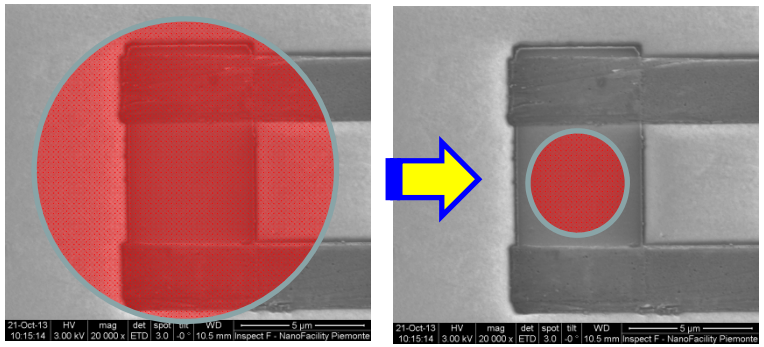
QE is limited by

Film reflectance (~50 %)

optical coupling

Antireflection coating
(2.7 μm of multilayers (Ta_2O_5/SiO_2)
(in collaboration with Thin Film Laboratory, ENEA)

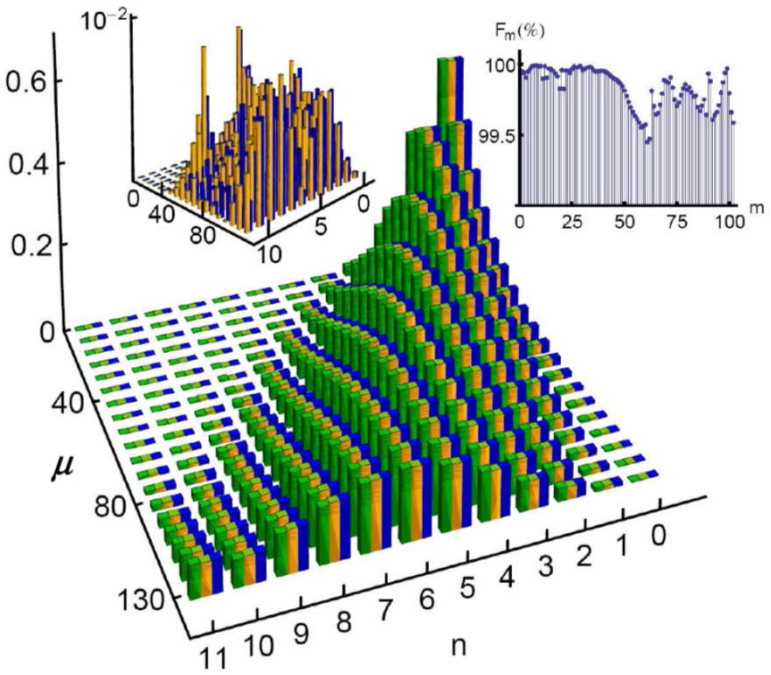




- For TESs ≥ 5 μm x 5 μm QE>90% demonstrated (NIST, AIST)
- For TESs < 1 μm x 1 μm expected QE_{max}~10% with small core fibers

TES at work

Linear Detection Model



$$\Pi_n = \sum_{m=n}^{\infty} B_{nm} |m\rangle\langle m|$$

$$B_{nm} = \binom{m}{n} \eta^n (1-\eta)^{m-n}$$

G. Brida *et al*, New Journal of Physics 14 (2012) 085001

Source Emission Statistics

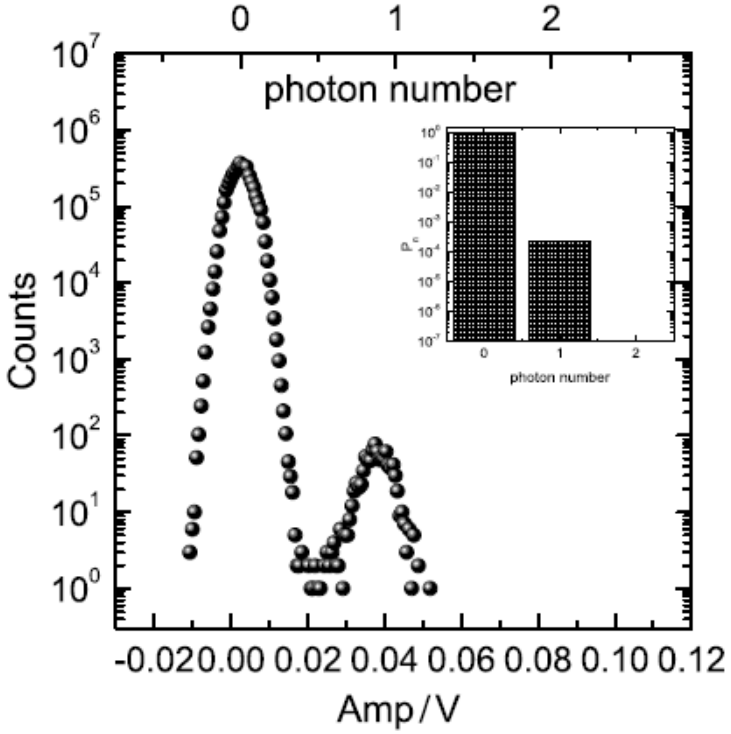
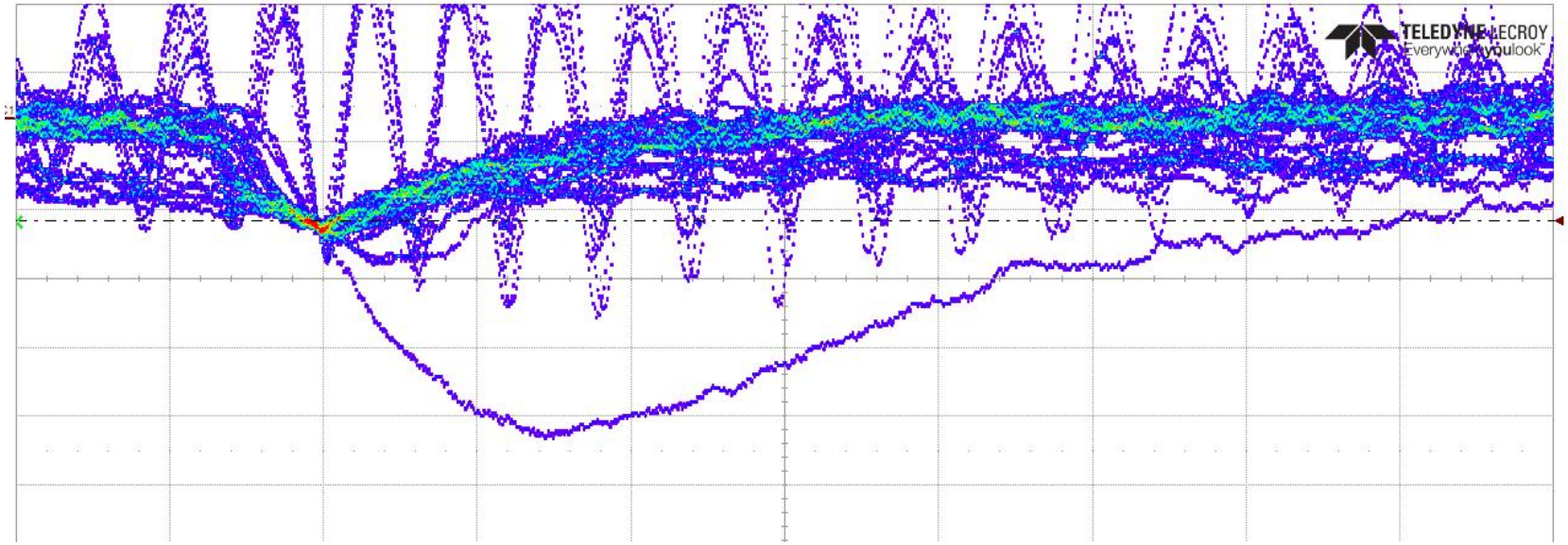


Figure 3. TES histogram of a single NV centre (centre 1).

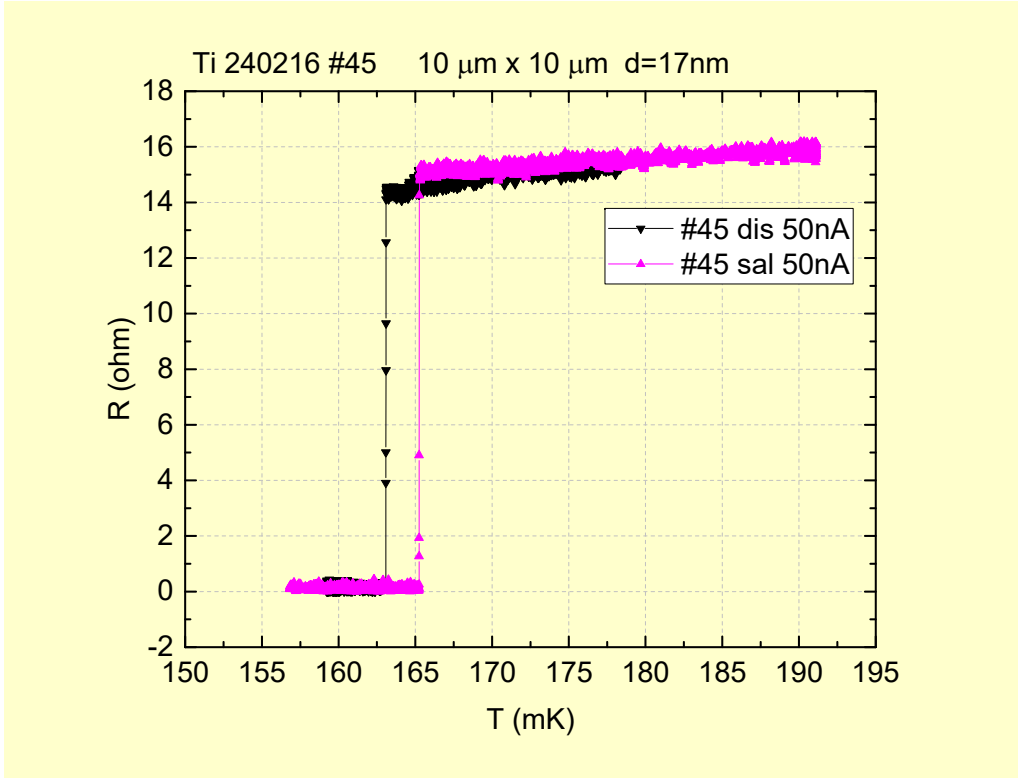
W. Schmunk *et al*, Metrologia 49 (2012) S156-S160

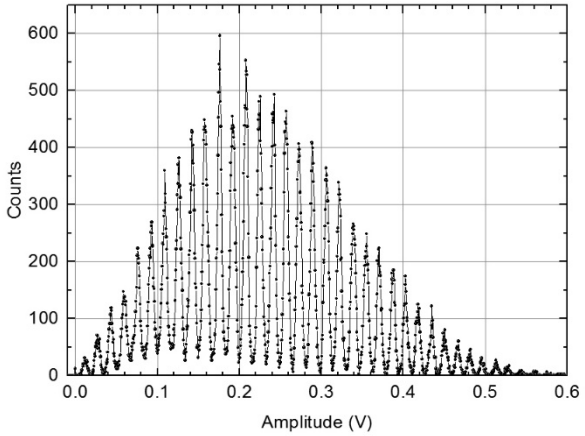
Dark counts rate

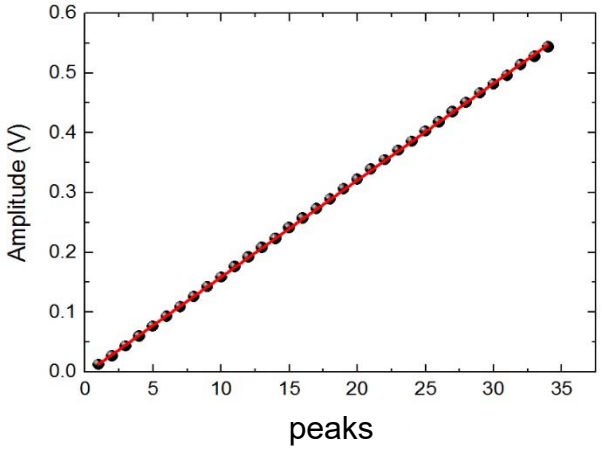


1X1μm Ti TES: 39 counts/13h ~ $8X10^{-4}$ Hz

Many-Photons detection







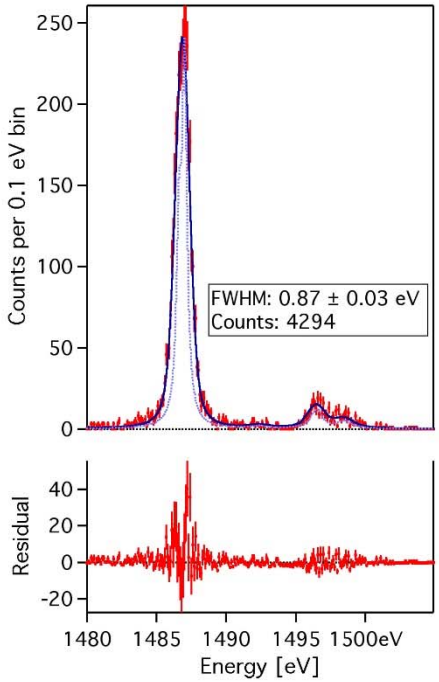
TES: X-ray

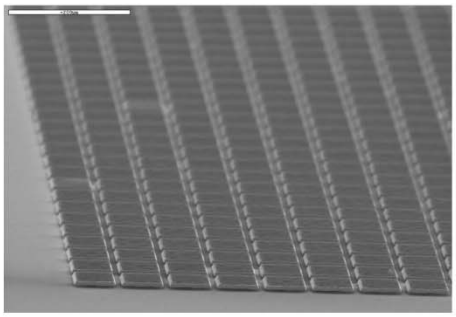
From S.R. Bandler NASA

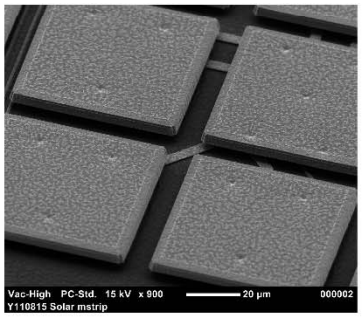
TES 36 μm x 33 μm

Conclusions:

- Excellent energy resolution achieved in small, low heat capacity x-ray microcalorimeters with low Tc
  - ✧ FWHM = 0.9 eV at 1.5 keV
  - ✧ FWHM = 1.6 eV at 6 keV
- Excellent energy resolution demonstrated in 2x2 & 3x3 Hydras
  - ✧ FWHM = 2.1 eV @ 6 keV in 3x3 Hydra
- More uniform arrays being produced
- Suitable for solar physics & astrophysics applications







Conclusions and future

TES ⇨ one of the best calorimeter from NIR to X-ray ☺

- NIR-UV ΔE=0.1-0.2 eV
- X-ray ΔE=0.8 eV @ 1.5 KeV
  ΔE=1.6 eV @ 5.9 KeV

- Imaging ⇨ array (next talk)
- Possibility to improve performances:
  ➥yes (but remember trade-offs)

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Thank you for your attention!