Transition-Edge Sensors for Visible-NIR photon detection

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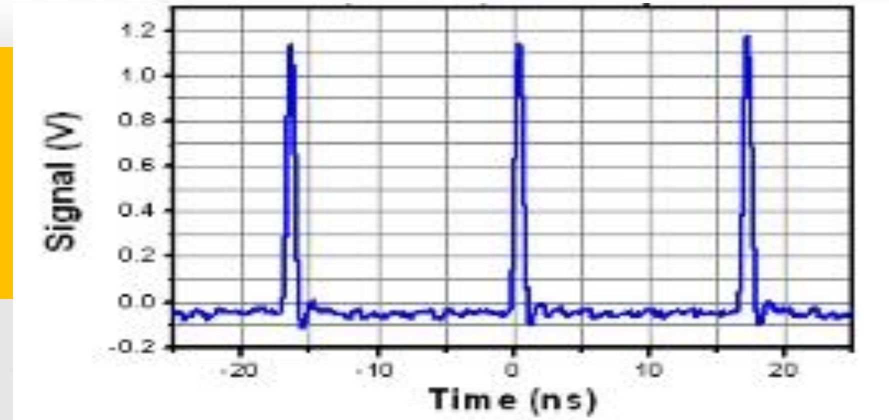
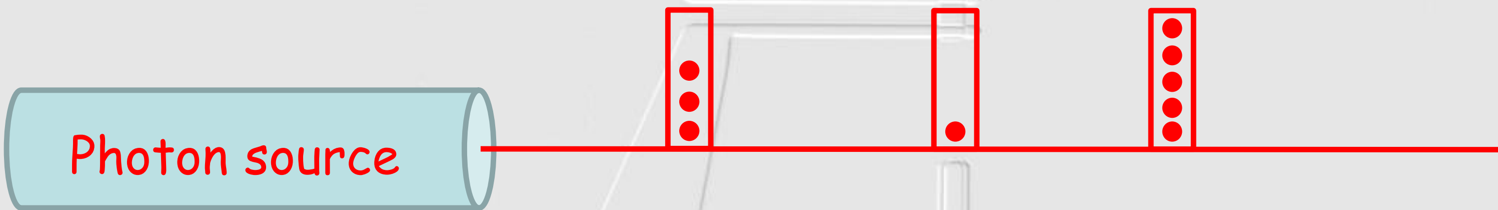
Single Photon detectors

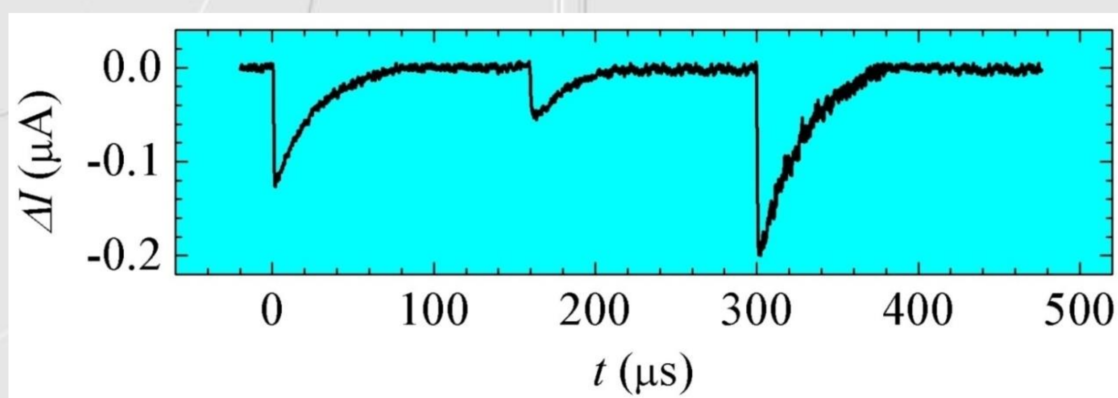
"Classical" Single photon detector
Distinguish only between zero photons and one or more photons



(Photomultiplier, APD, SPAD…)



Energy resolving or
Photon number resolving (PNR) detector



Single Photon detectors

Applications of TES as **photon number resolving detector**

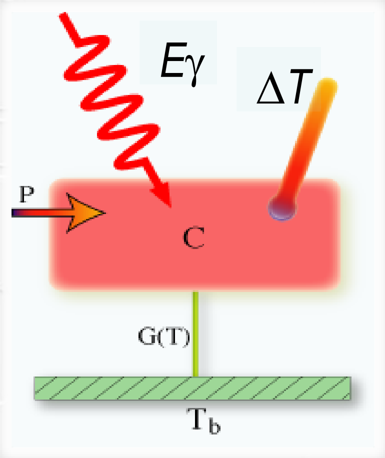
- Quantum Optics
- Quantum Information Processing (e.g. Linear Optics,Quantum Computing, Quantum Key Distribution)
- Quantum metrology

Detector requirements desired:

- High efficiency (95% at 1550 nm)
- Low dark counts / errors (Blackbody limited 1550 nm)
- **Number resolving capability (0.1 - 0.2 eV FWHM)**
- **Fast recovery time (<< 1μs), Low jitter (< 1 ns)**

Transition-Edge Sensors (TESs)

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



@1550 nm

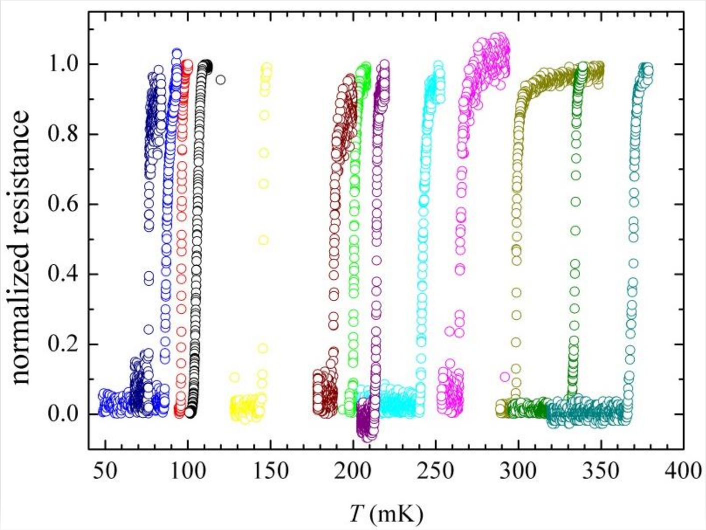
$E\gamma$ = 0.8 eV =1.26×10^{-19} J

ΔT~0.1 mK ⇦

We need TES with *C* of the order of:

$C=E\gamma/\Delta T\sim 1$ fJ/K

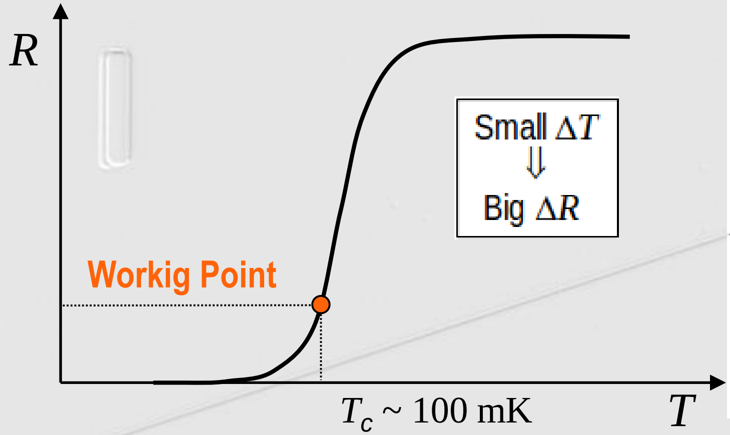
Bilayer – proximity effect

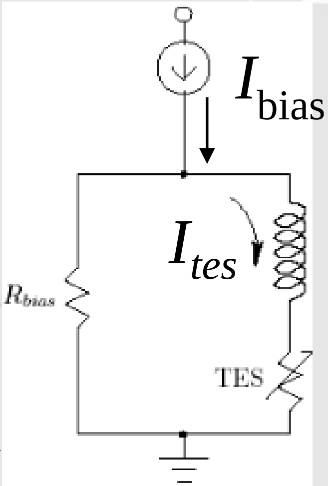


TESs bias circuit

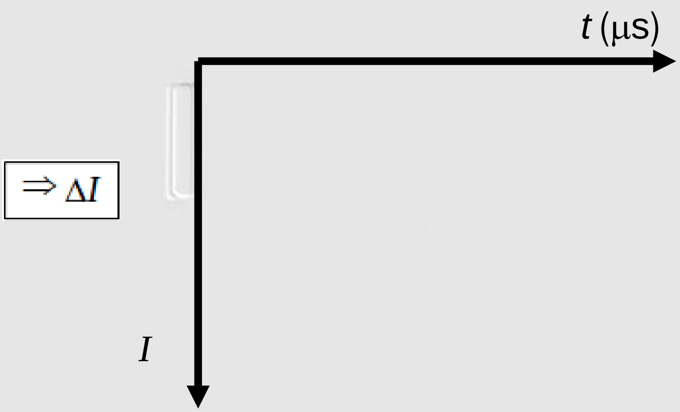
Voltage bias + dR/dT>0 $\Rightarrow$ Negative electrothermal feedback

Stability of TES in the transition

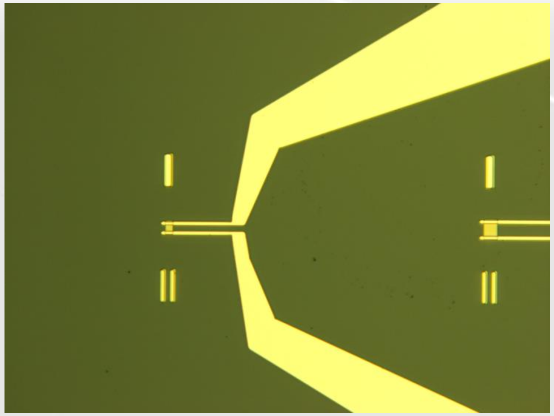


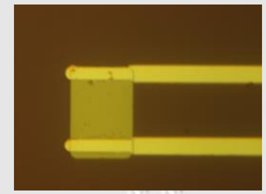


$R_{bias} << R_{tes}$

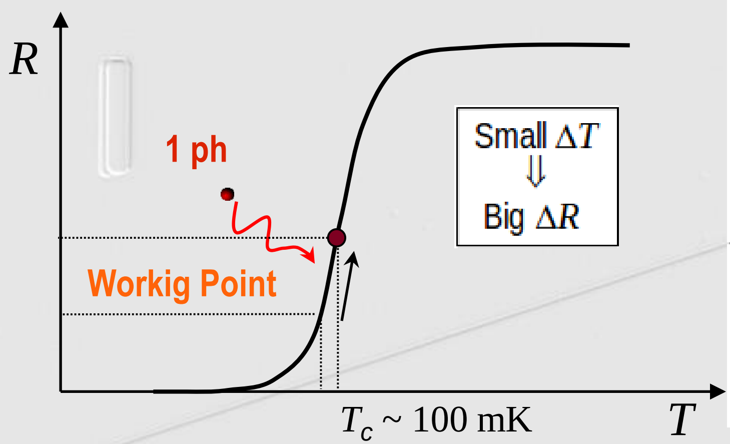


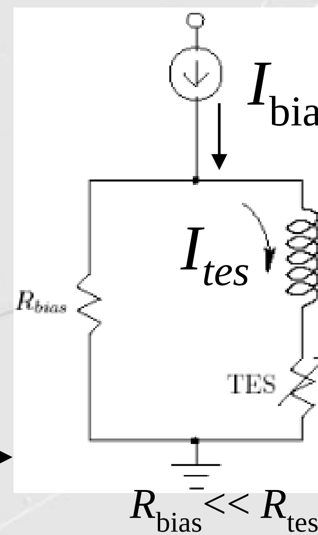
TESs as single photon detectors



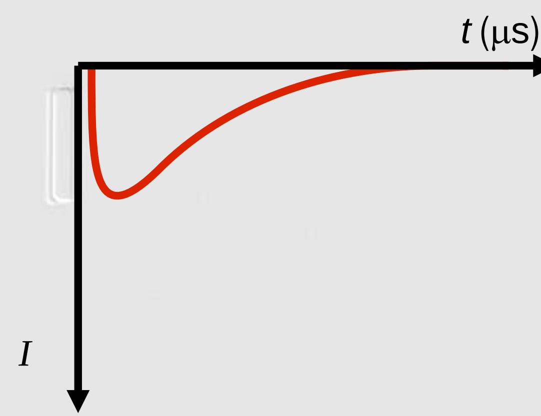


20 μm X 20 μm



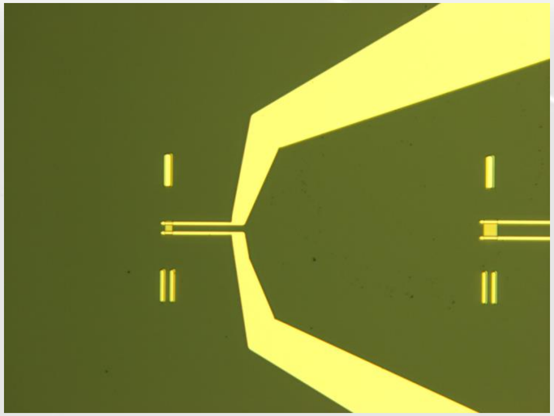


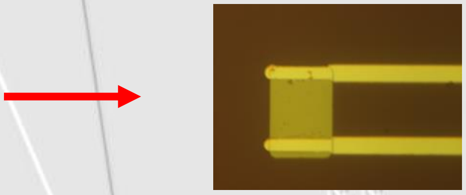
$\Rightarrow \Delta I$

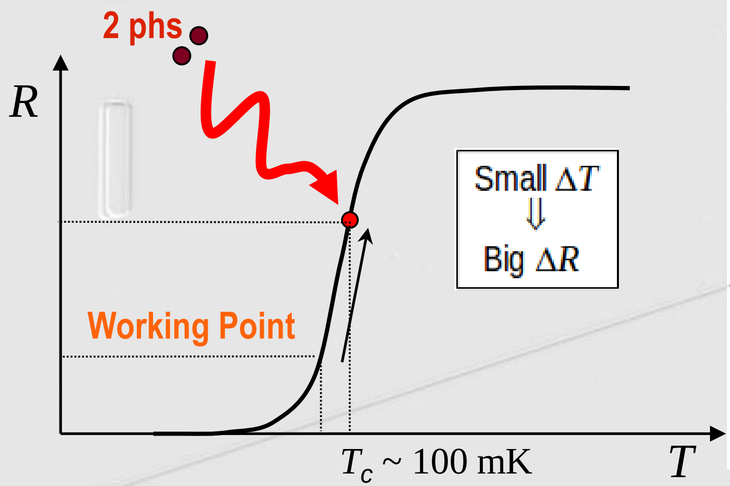


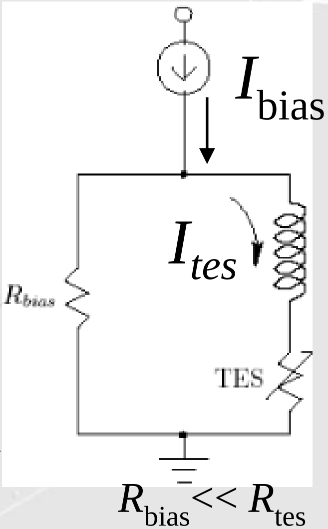
ΔT ⇨ ΔR @ Voltage bias ⇨ ΔI

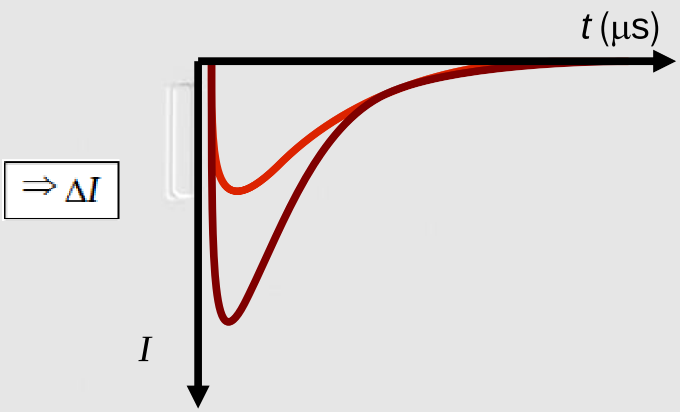
TESs as single photon detectors











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

Fabrication of TES

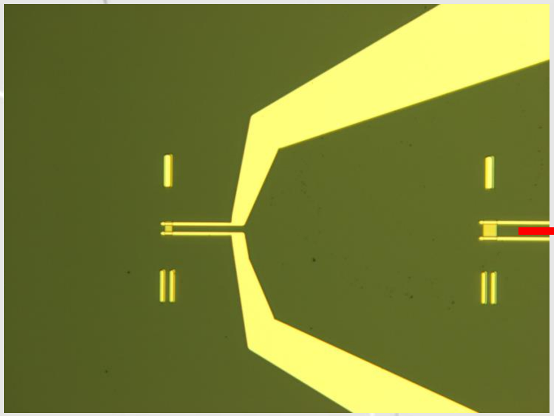
High resolution TES

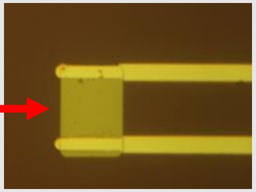
Deposition Ti/Au on Si/SiN substrate by e-gun (10^{-7} mbarr)

Optical lithography and ion milling

Lift-off technique

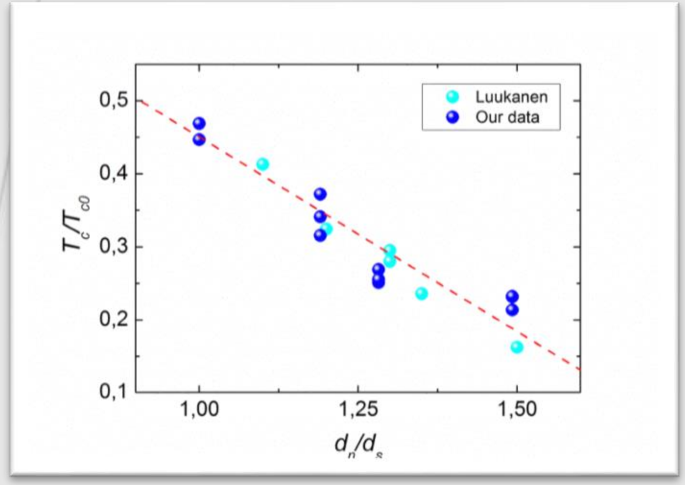
Nb or Al wiring lift-off and rf sputtering



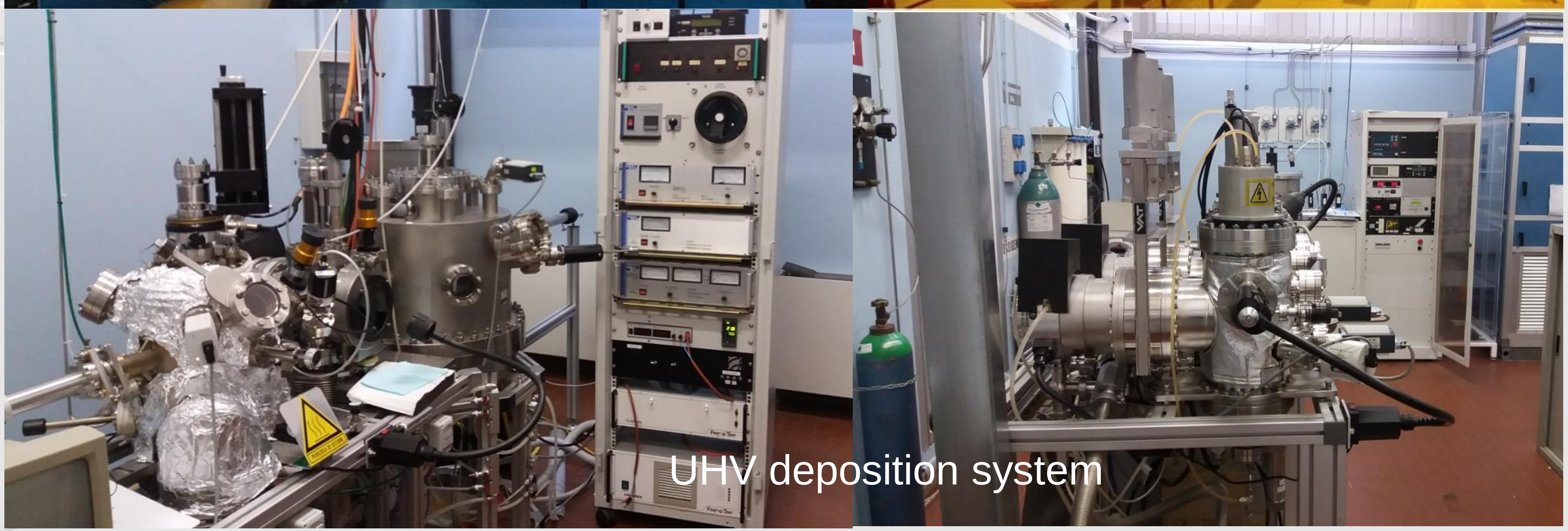


20 µm X 20 µm

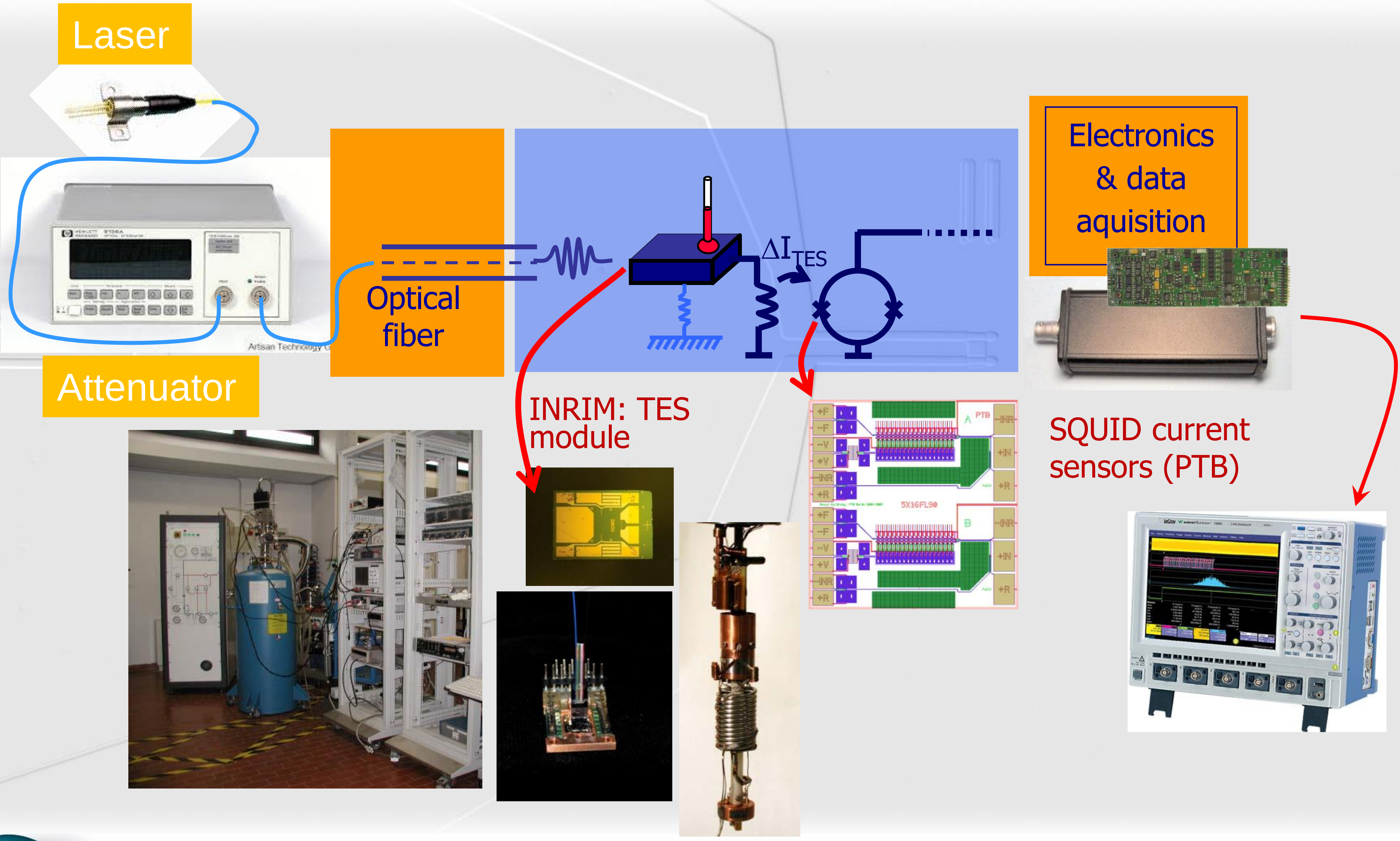
Thickness Ti = 40 nm, Au = 58 nm



Fabrication facilities at INRIM



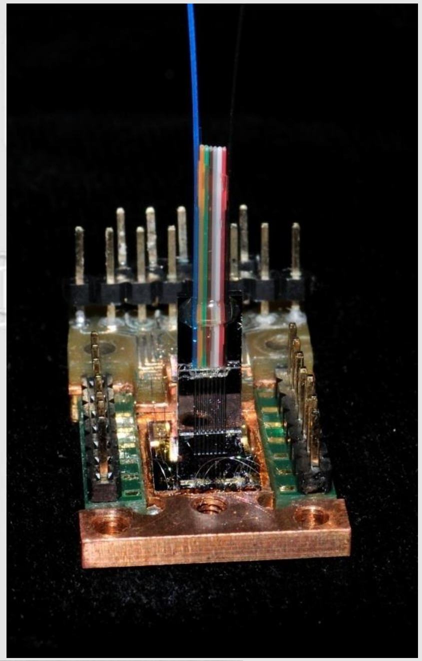
TES: photon counting

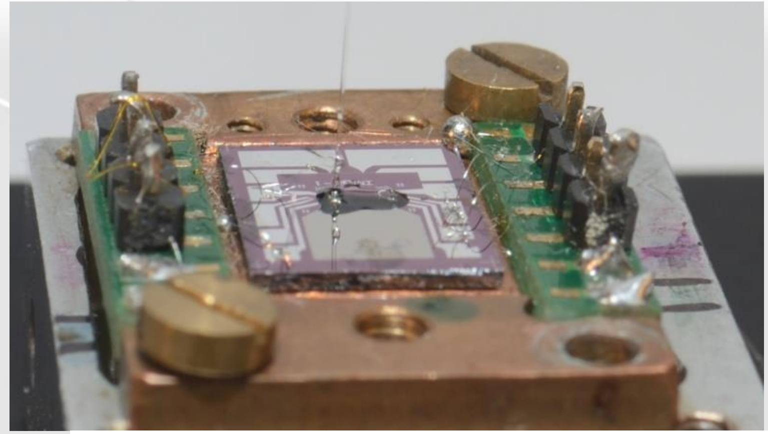


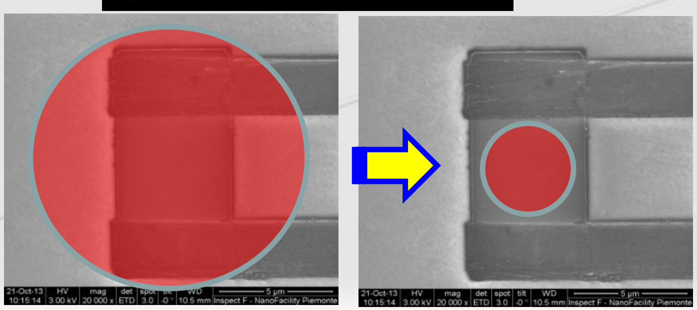
INRIM-TES: optical alignment

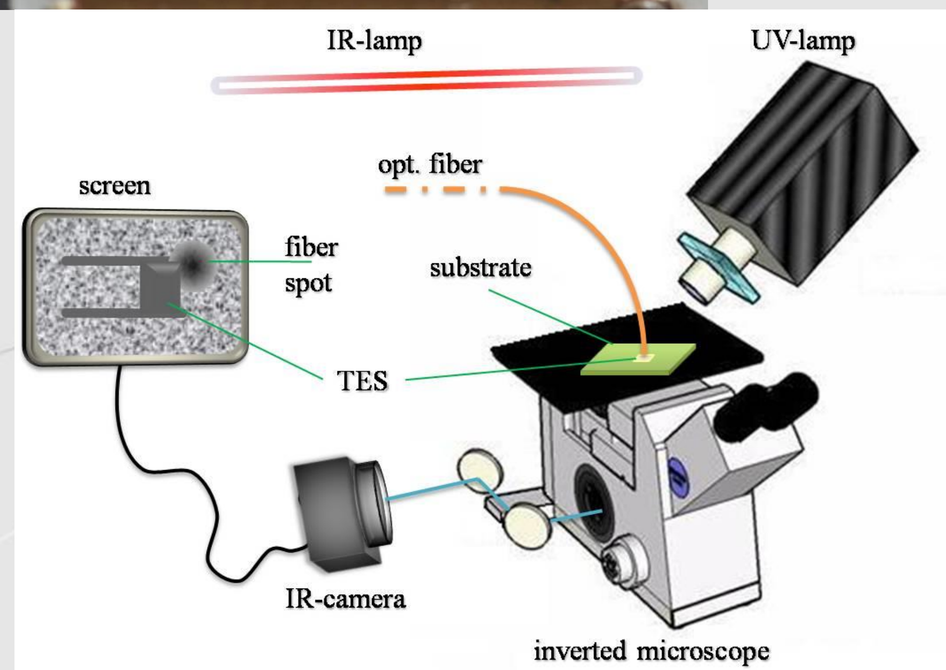
Coupling:

- alignment through the chip
- small core fibers



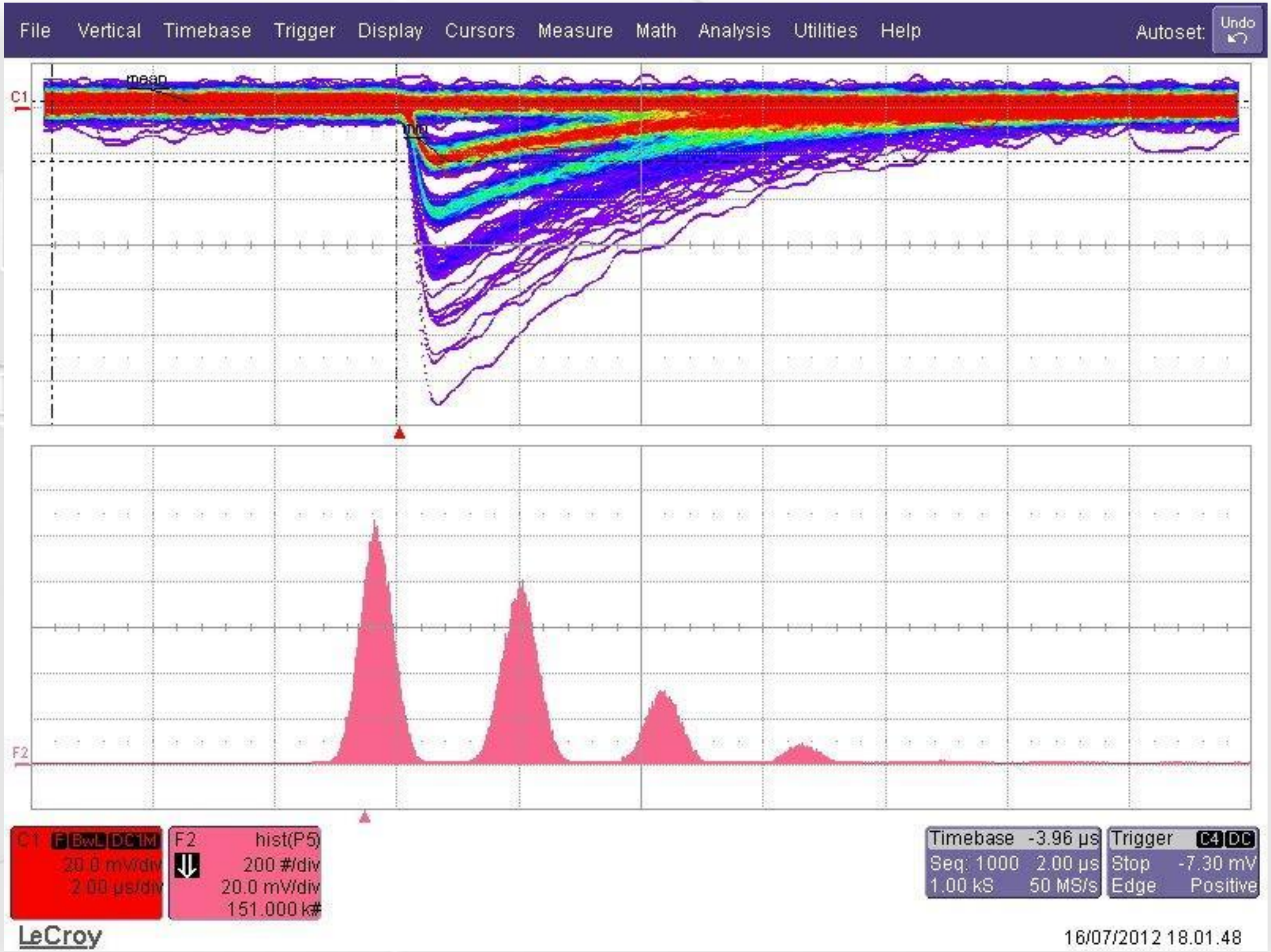






3-axis stage, controlled by DC stepper motor

TES: photon counting



TES: important parameters

$$\Delta E_{FWHM} = 2.355\sqrt{4k_B T_c^3 \frac{\gamma V}{\alpha}\sqrt{\frac{n}{2}}} \propto T_c^{3/2}$$

Intrinsic Energy Resolution

ΔE_{FWHM} is proportional to the operating temperature T_c and is depending on the volume V of the TES and on the normal-to-superconductor transition sharpness $\alpha = T/R \cdot dR/dT$

$$\tau_{eff} = \frac{\gamma}{\Sigma T_c^{n-2}(n + \alpha/(1+\beta_I))}$$

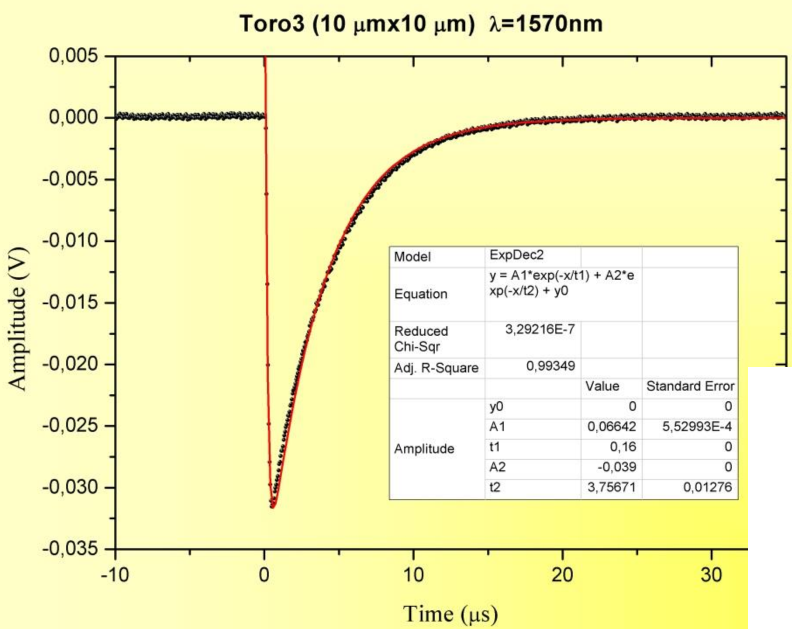
Effective TES response time

n = 3-5

By reducing the TES area and working at higher T_c, faster response times are achievable without loosing in energy resolution

Trade-off between response time and energy resolution

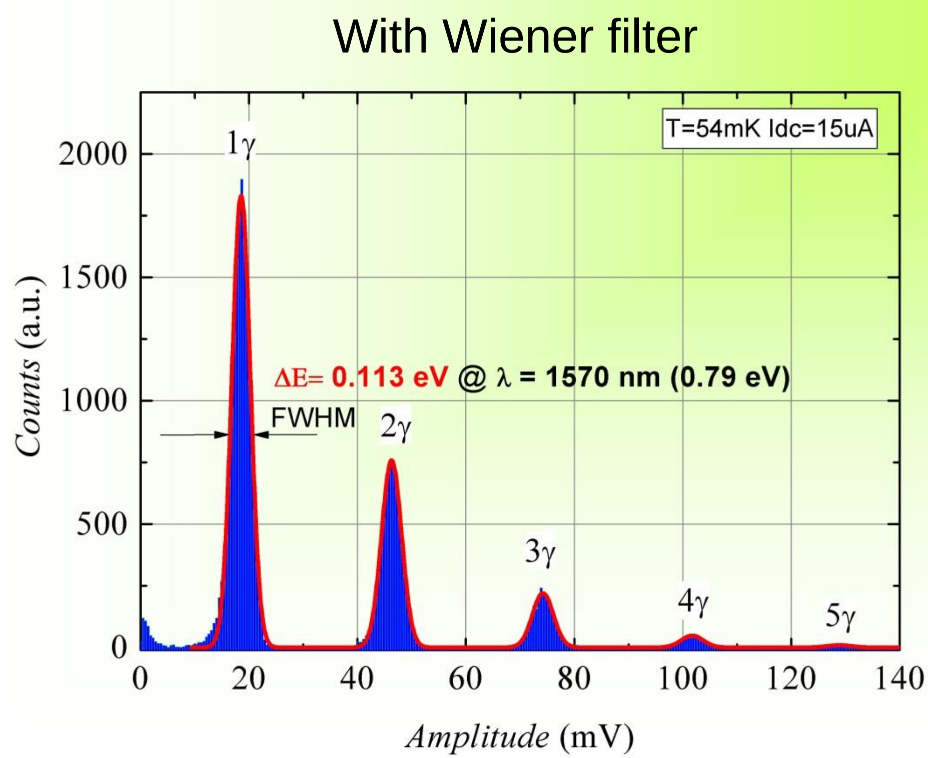
TES: High energy resolution



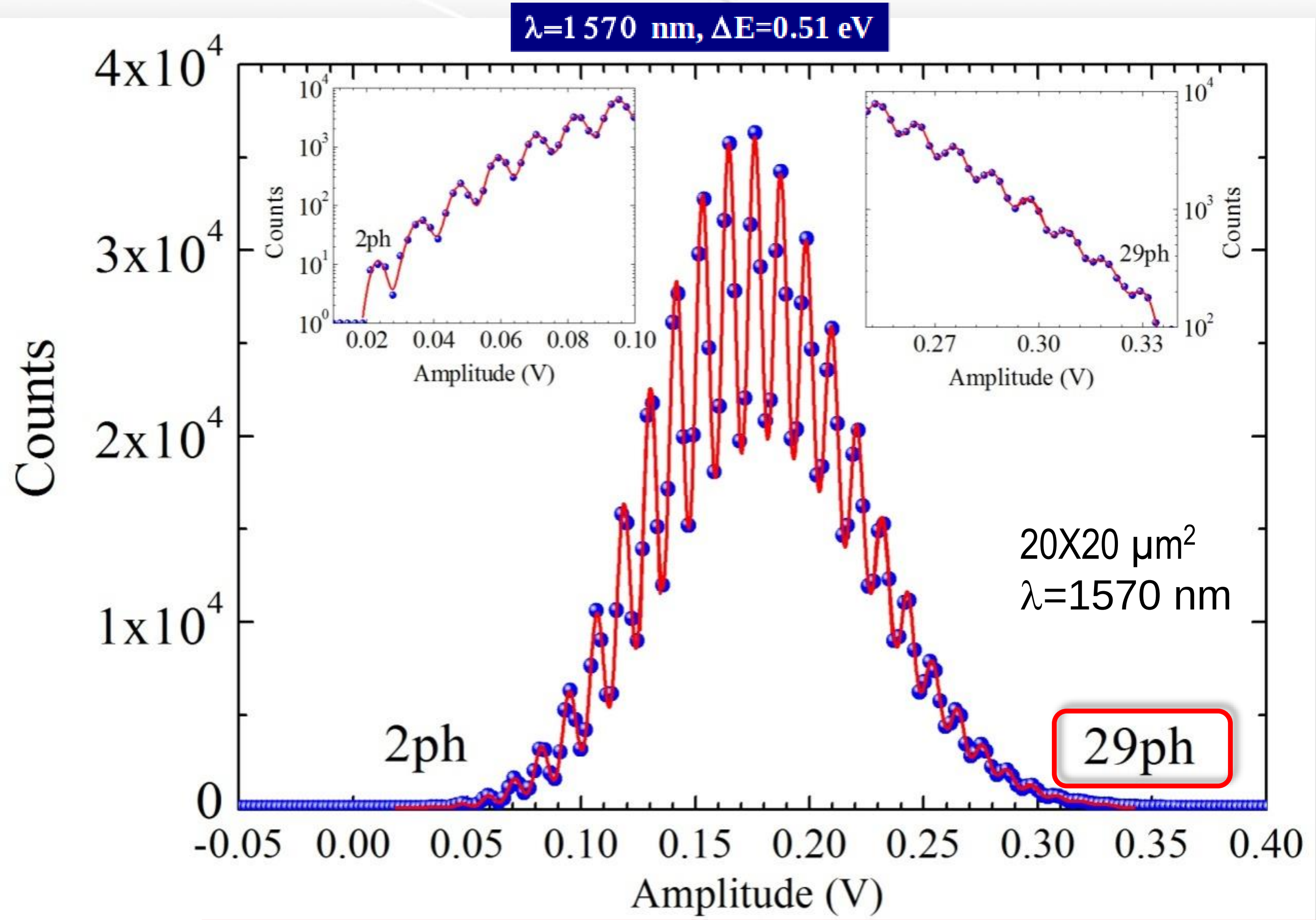
$\tau_{eff} = 3.8\ \mu s$

$\Delta E = (0.113 \pm 0.001)\ \mathrm{eV}$

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

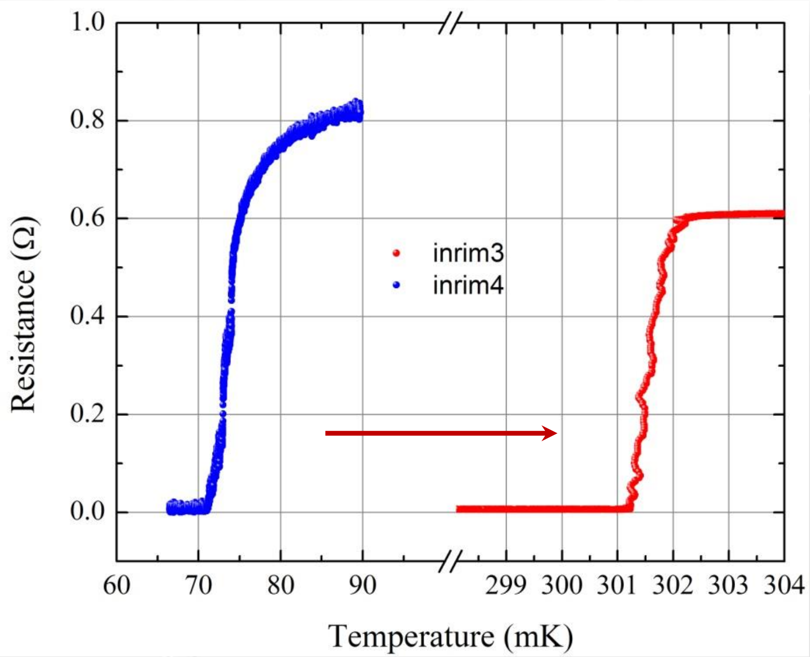


TES: photon counting

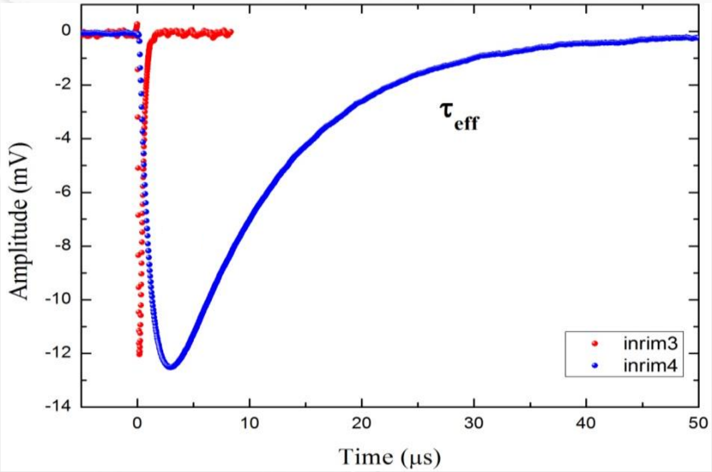


L. Lolli, et al. *J. Low Temp. Phys.*, vol. 167, pp. 803-808, 2012.

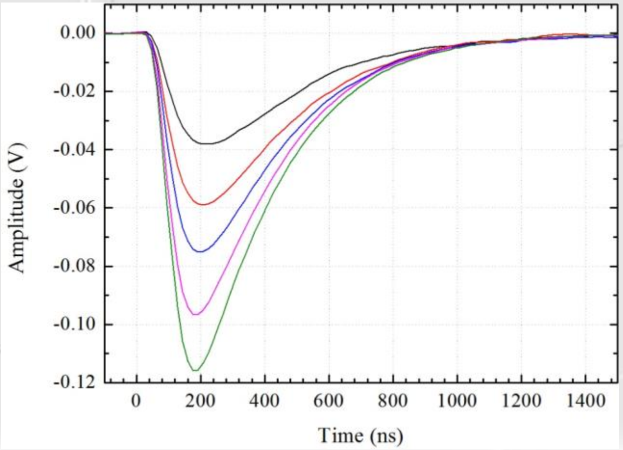
Fast TES



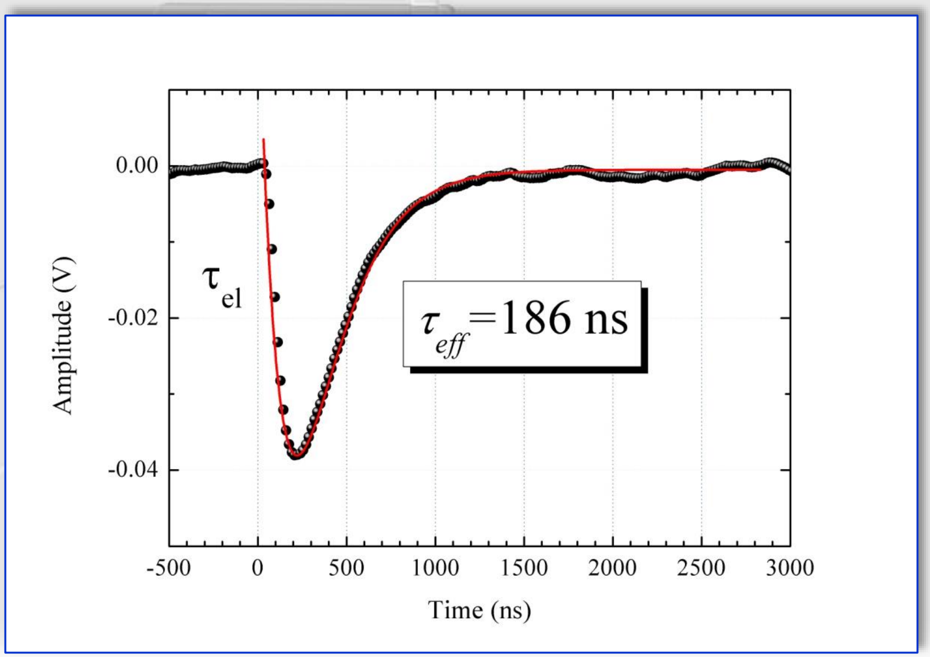
Resistance (Ω)
1.0
0.8
0.6
0.4
0.2
0.0
inrim3
inrim4
60
70
80
90
299
300
301
302
303
304
Temperature (mK)



Amplitude (mV)
0
-2
-4
-6
-8
-10
-12
-14
τ_eff
inrim3
inrim4
0
10
20
30
40
50
Time (μs)



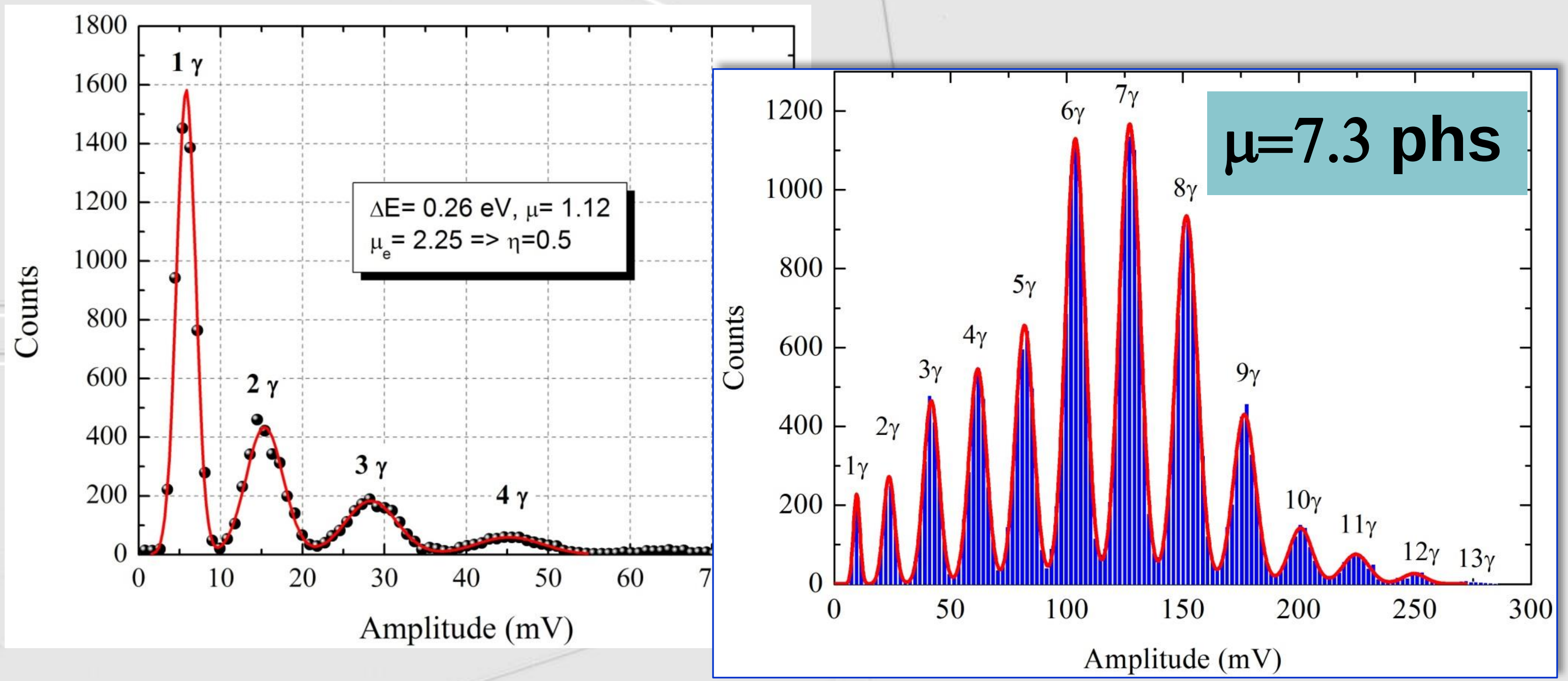
Amplitude (V)
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
0
200
400
600
800
1000
1200
1400
Time (ns)



Amplitude (V)
0.00
-0.02
-0.04
τ_el
τ_eff =186 ns
-500
0
500
1000
1500
2000
2500
3000
Time (ns)

Fast TES

TiAu TES T_c=301 mK



λ=1535 nm

QE ~ 50 %

@ 500 kHz means
3.65×10^6 photons/s (473 fW)

Fabrication of smaller TES

Fast TES

Deposition Ti on Si/SiN substrate by e-gun (10^{-9} mbarr)

EBL

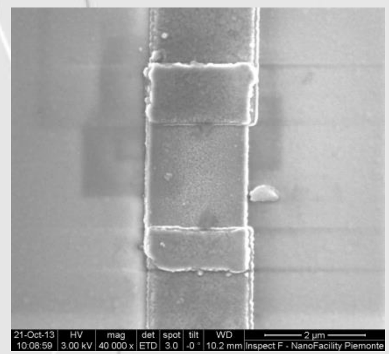
Reactive ion etching

Dimension 1 µm - 5 µm square

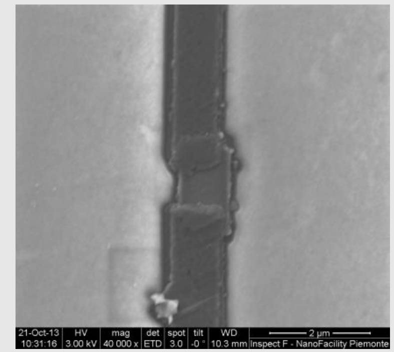
Nb wiring by lift-off and rf sputtering

Thickness Ti = 20 nm-30 nm

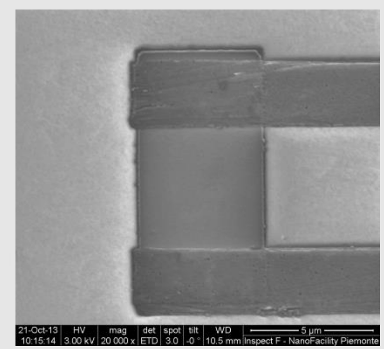
2µm × 2 µm



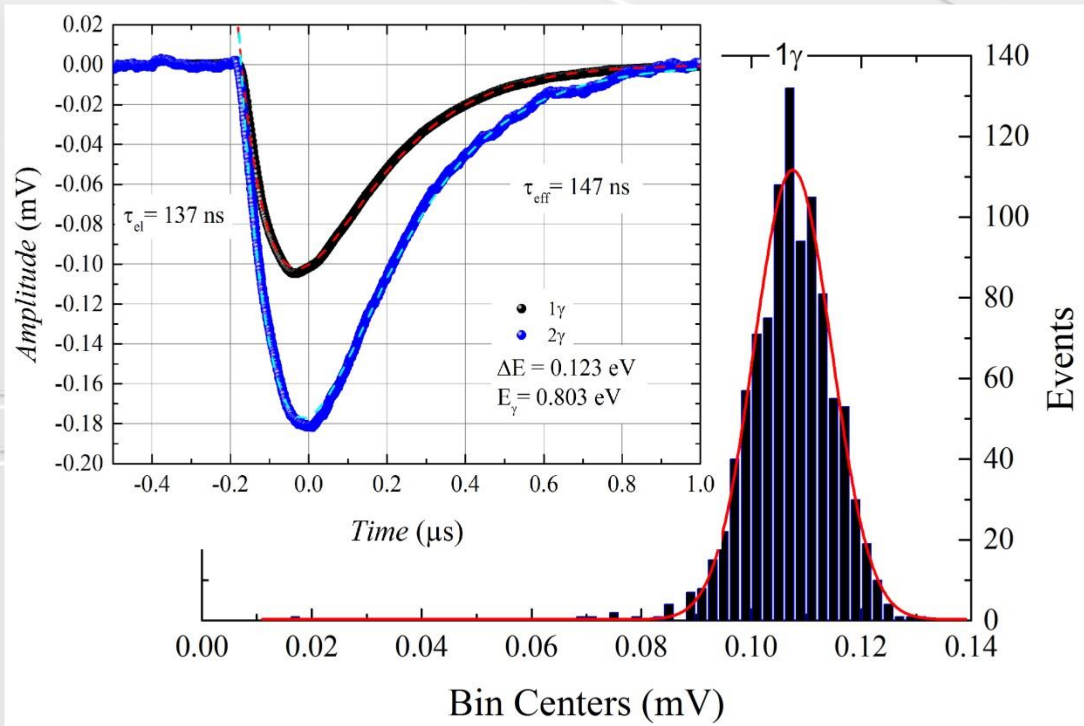
1µm × 1 µm



5 µm × 5 µm



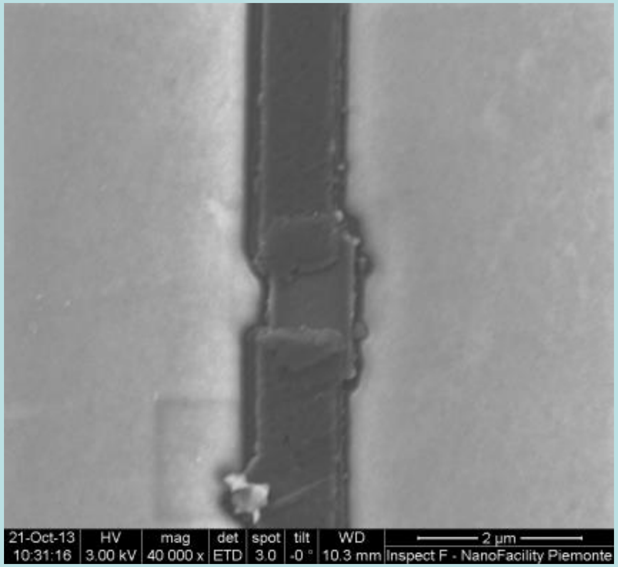
1 μm × 1 μm TES photon counting



τ_{etf} = 147ns

ΔE_{FWHM} = 0.12 eV
@ 1545nm

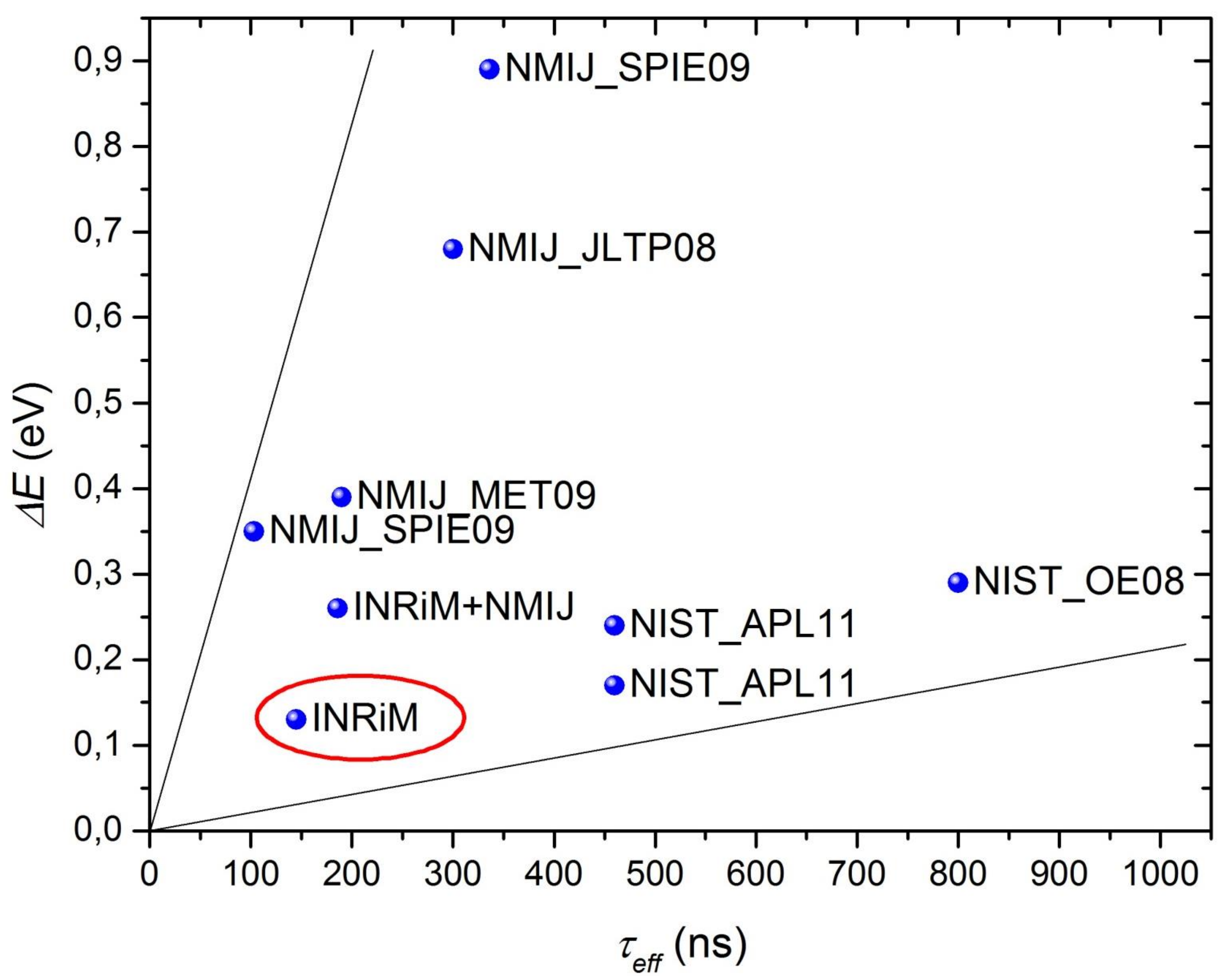
1 μm × 1 μm



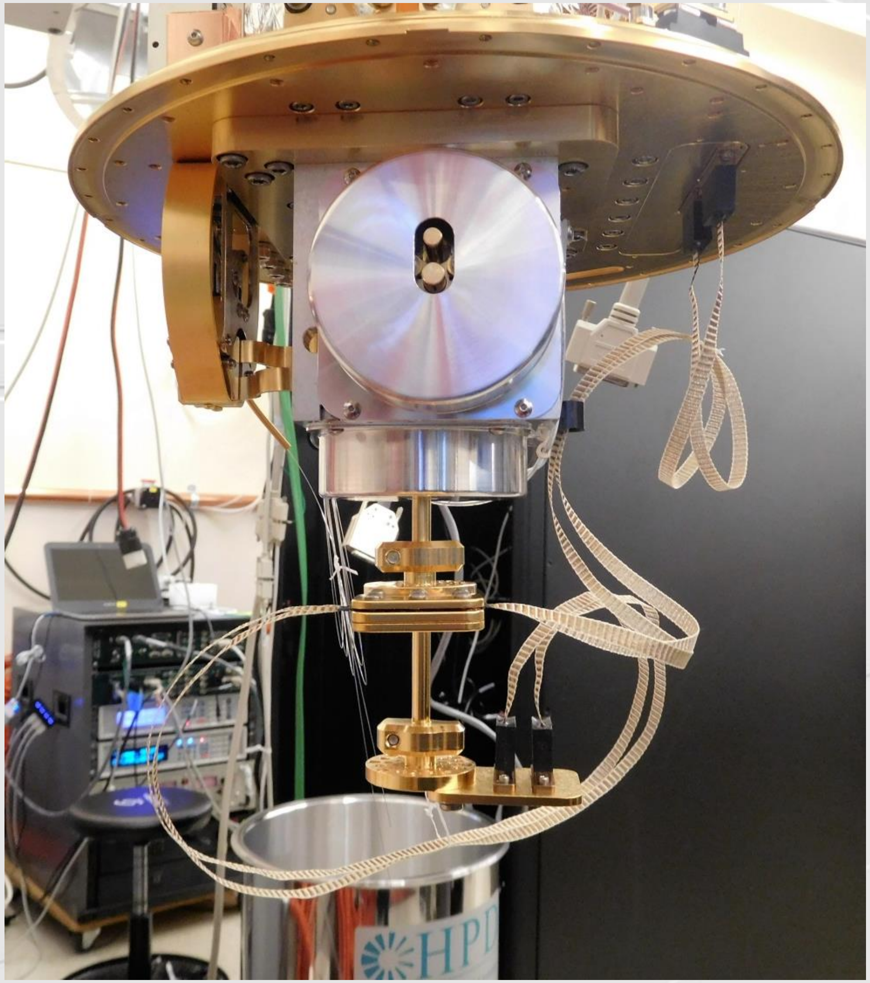
C. Portesi *et al*, IEEE Trans App Supercond, 25, 3, (2015)

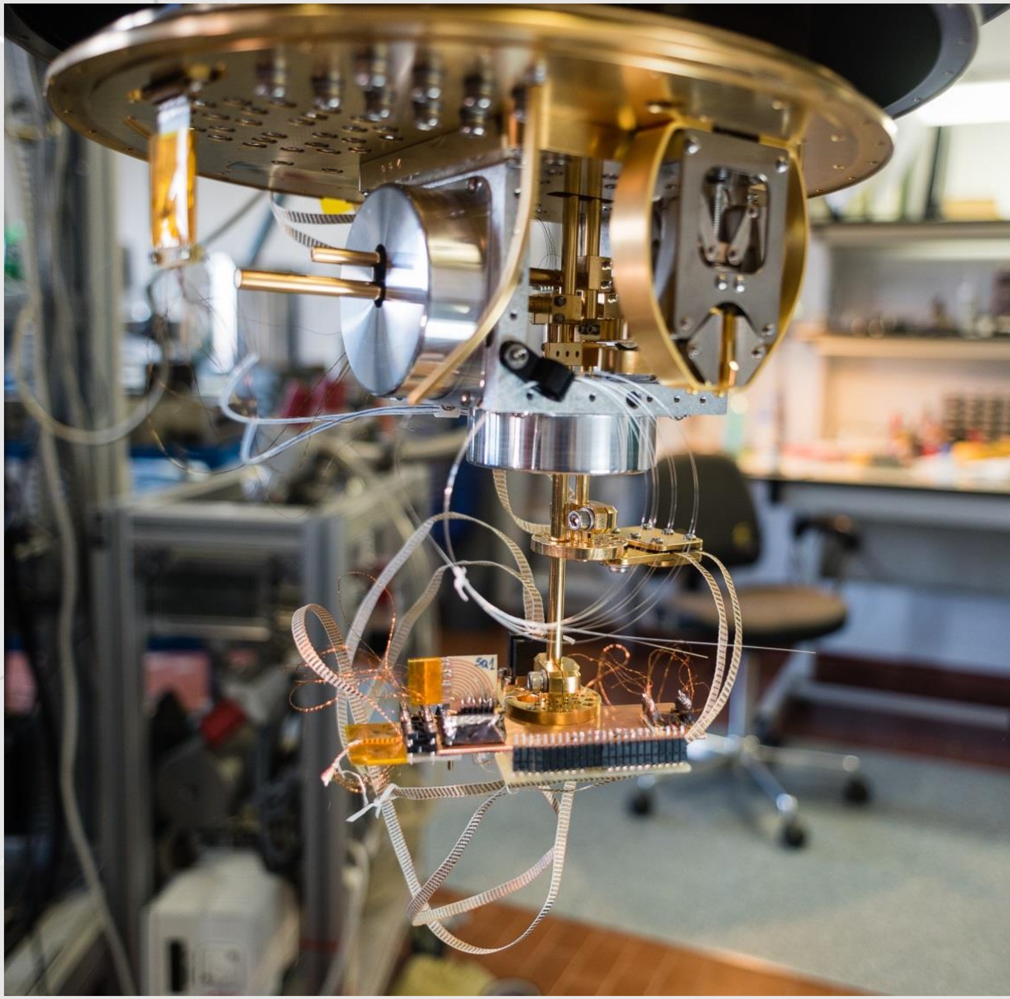
TES results in literature

…more and more closer to the origin…



ADR





Conclusions and future

TES ⇨ Photon number resolving detectors ☺

- 10-20 μm square TES:
  QE~50%, many photons resolution, slow (~10 μs)
  ↪ Cavities or Antireflection coating

- 1-2 μm square TES : QE<15% but faster (<1 μs)
  ↪ plasmonic antennas ?

Finanziamenti

2001-2004
-Fotorivelatori superconduttivi ad elettroni caldi per il VIS-IR
-Realizzazione di STJ come rivelatori in regime di conteggio di fotoni per applicazioni astrofisiche

E45 (2006-2010)
Rivelatori superconduttivi a transizione di fase per conteggio di singoli fotoni

Quantum Candela (2008-2011)

INRIM e NMIJ-AIST (2010-2011)
Evaluation of photon statistics with photon number resolving detectors and correlated photon pair sources

Progetto premiale P5 (2012-2013)
Oltre I limiti classici della misura

NEW08 MetNEMS (2012-2015)
Metrology with/for NEMS

People

Emanuele Taralli

Lapo Lolli

Chiara Portesi

Eugenio Monticone

Mauro Rajteri

Thank you for your attention!