Photon-number resolution with Transition-Edge Sensors

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ScuDo Scuola di Dottorato ~ Doctoral School
WHAT YOU ARE, TAKES YOU FAR

Our group at INRiM

Italy's National Metrology Institute in Turin

Innovative Cryogenic Detectors Laboratory

Mauro Rajteri

Researcher

Eugenio Monticone

Researcher

Hobey Garrone

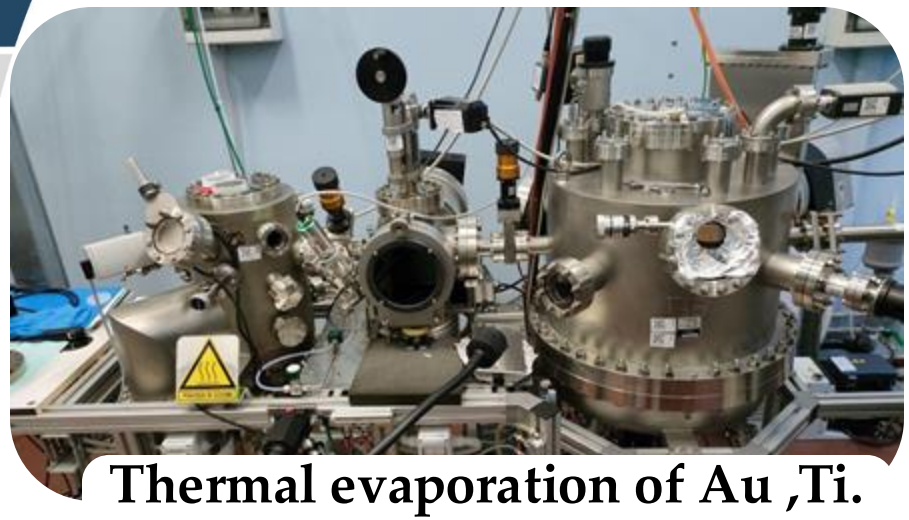
PhD student

Federico Malnati

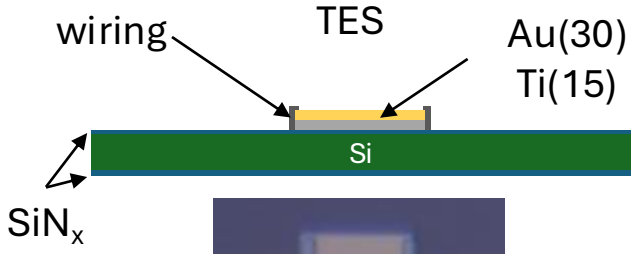
PhD student

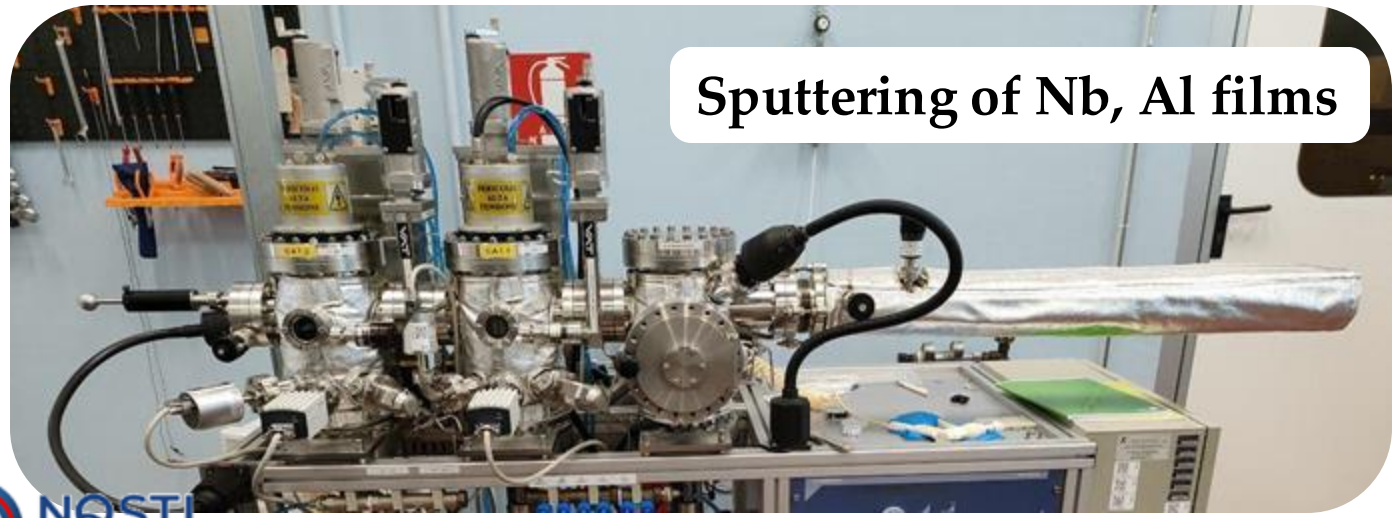
INRiM facilities for TESs

Fabrication

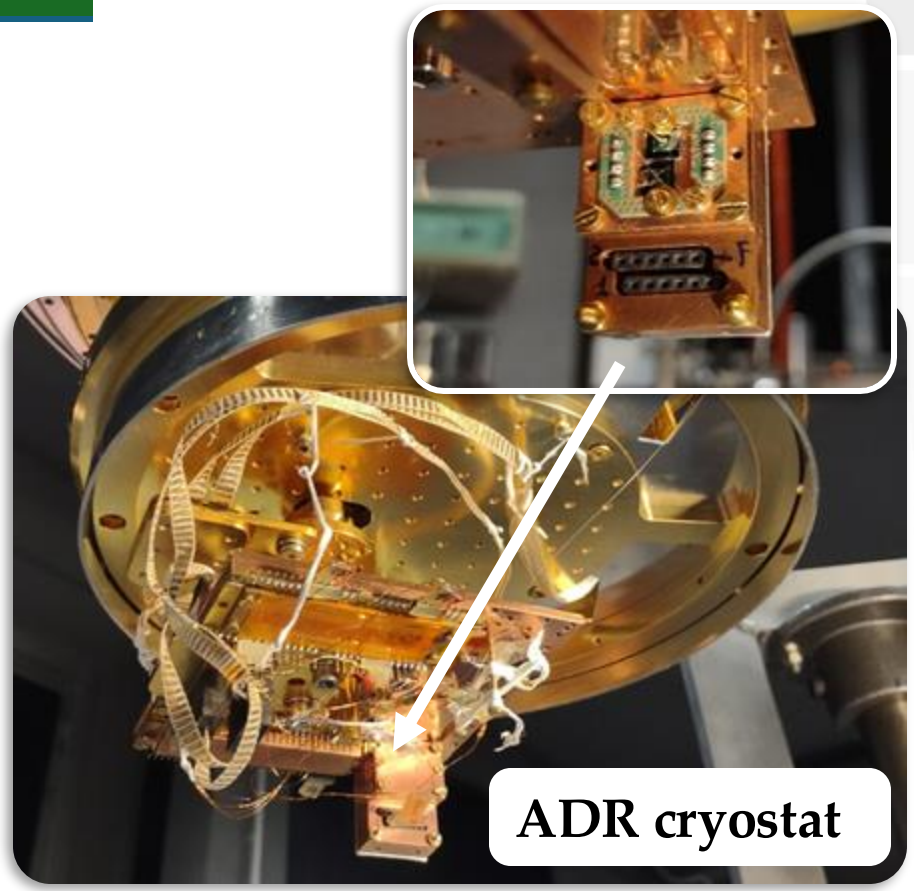


Thermal evaporation of Au ,Ti. Depositions in rapid sequence.





Characterization



STAR: project overview

Array of single photon detectors based on:

superconducting transition-edge sensors (TESs)

Requirements:

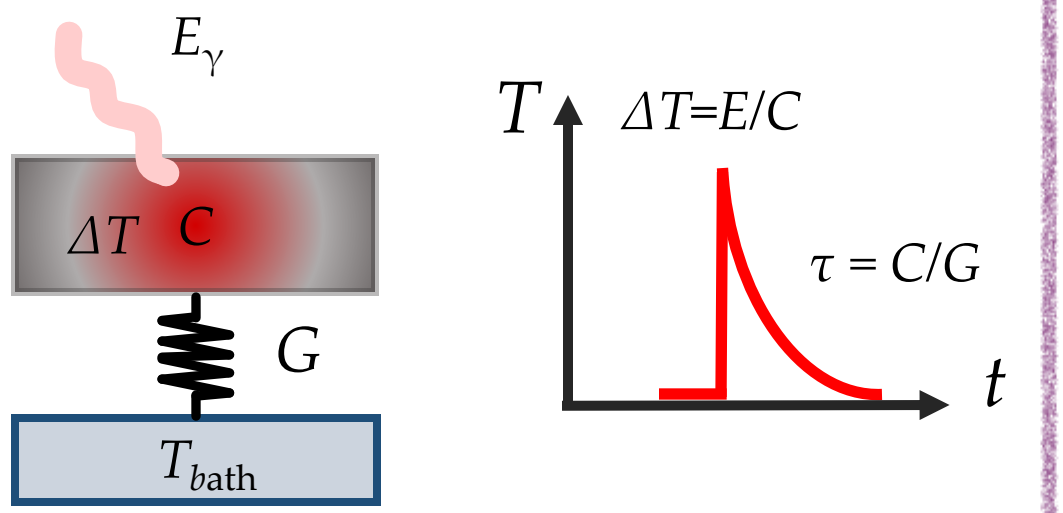
- Resolving power of 4 (for precise photon-number discrimination)
- Response time < 1 μs
- Detection quantum efficiency > 90%

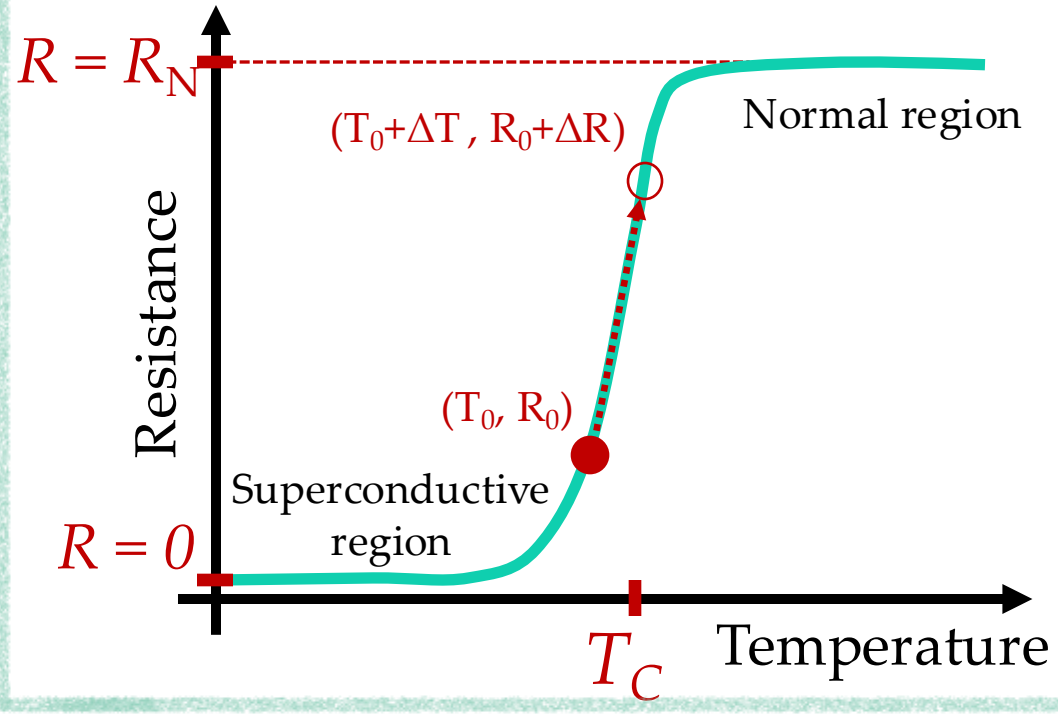
Technology:

- Tuning TESs critical temperature using proximity effect
- Antireflection coating and optical cavity for maximizing QE

Transition-Edge Sensors

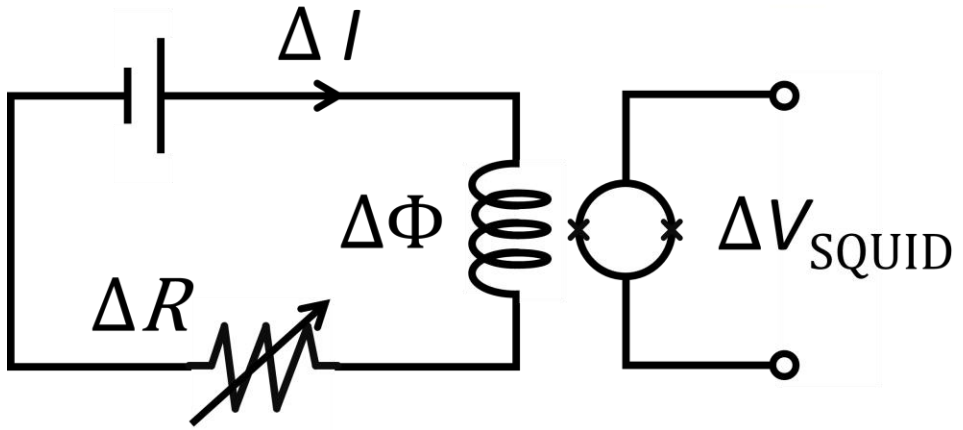
- TES: detector that exploit the strongly **temperature-dependent resistance** of the superconducting phase transition occurring at critical temperature T_c

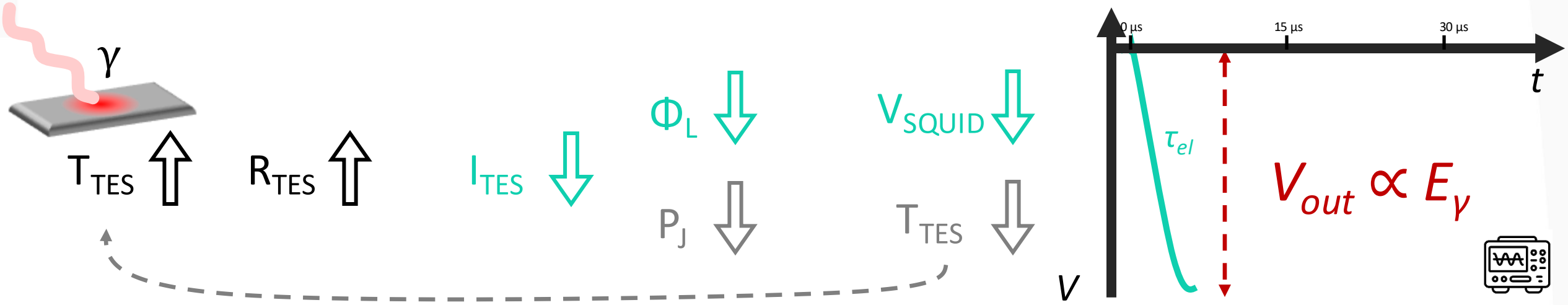




TES working principle

Electrothermal Feedback (Irwin, 1995)





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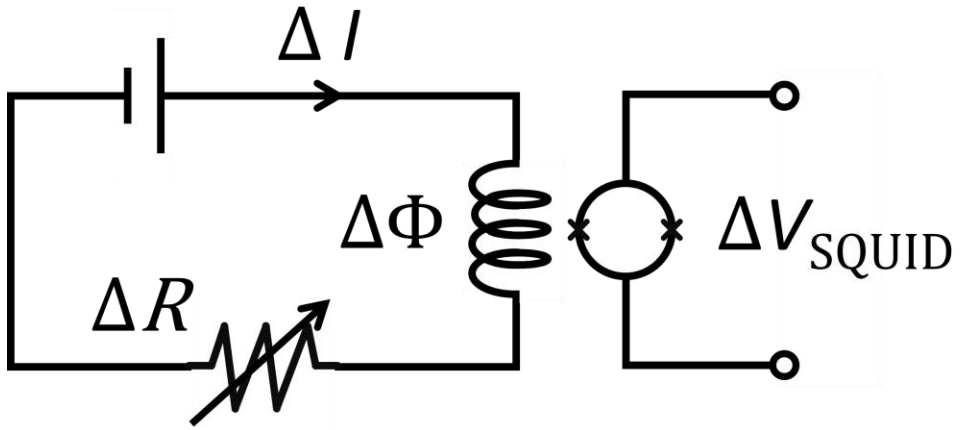
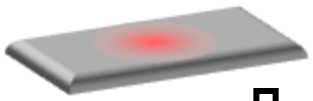
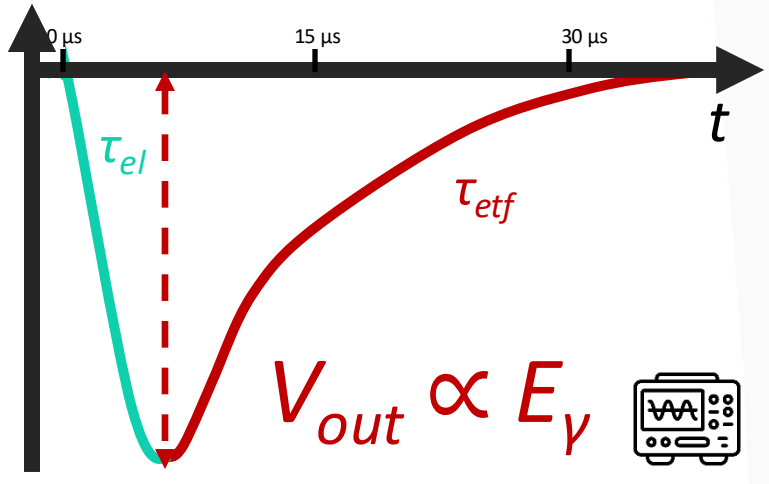
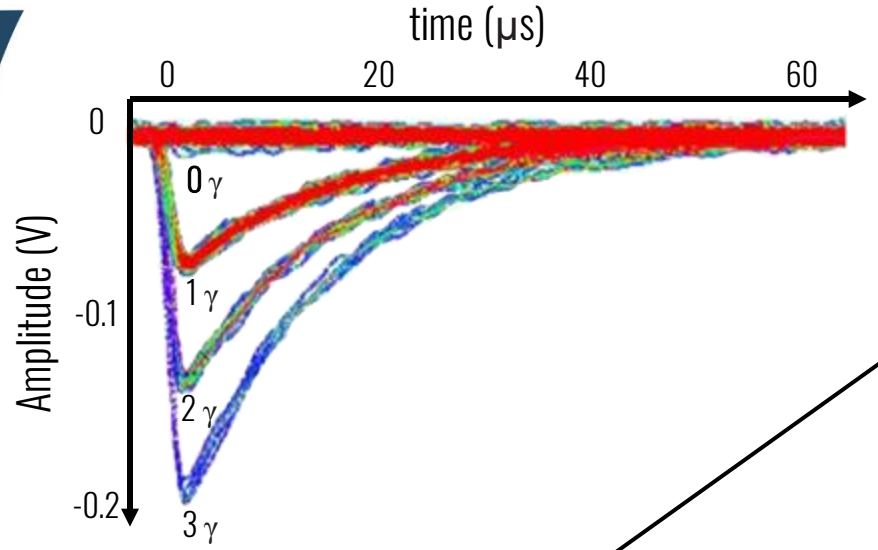


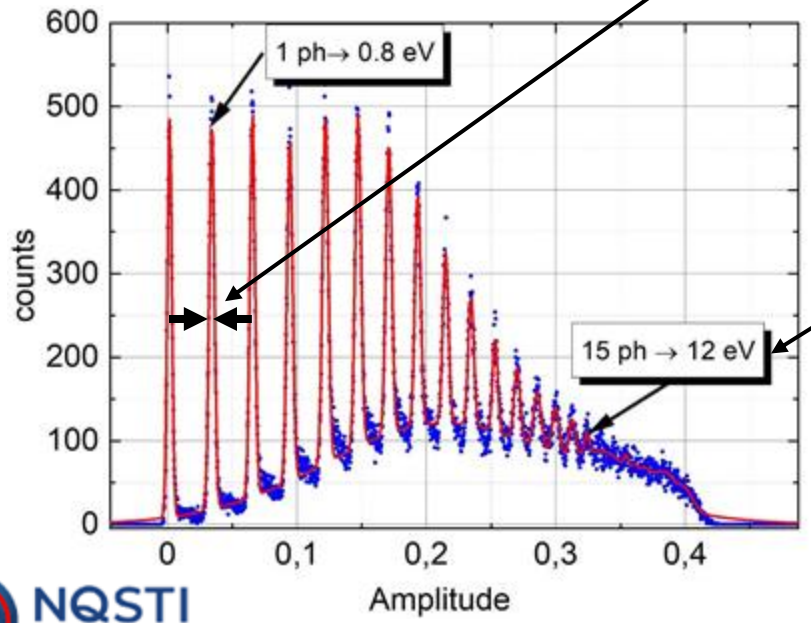


T_{TES} ⇩ R_{TES} ⇩ I_{TES} ⇧ Φ_L ⇧ P_J ⇧ V_{SQUID} ⇧ T_0



Some Figures of Merit





Energy resolution:

$$\Delta E_{FWHM} \simeq 7\sqrt{k_B E_{sat} T_C \sqrt{(1+2\beta)\underbrace{(1+M^2)}_{\simeq 10}}}$$

$$\propto \sqrt{k^{-1}\,\mathrm{A}\,T_c{}^3}$$

Saturation energy:

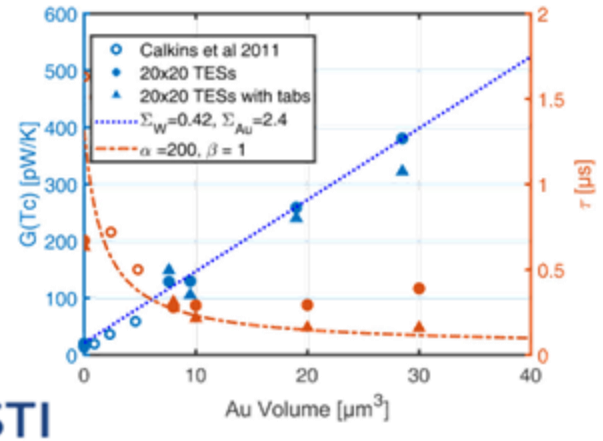
$$E_{sat} \simeq \frac{CT_c}{\alpha} \propto \mathrm{A}\,T_c{}^2$$

Best result @INRIM ⇨ ΔE = 0.11 eV @NIR
(20 x 20) μm²

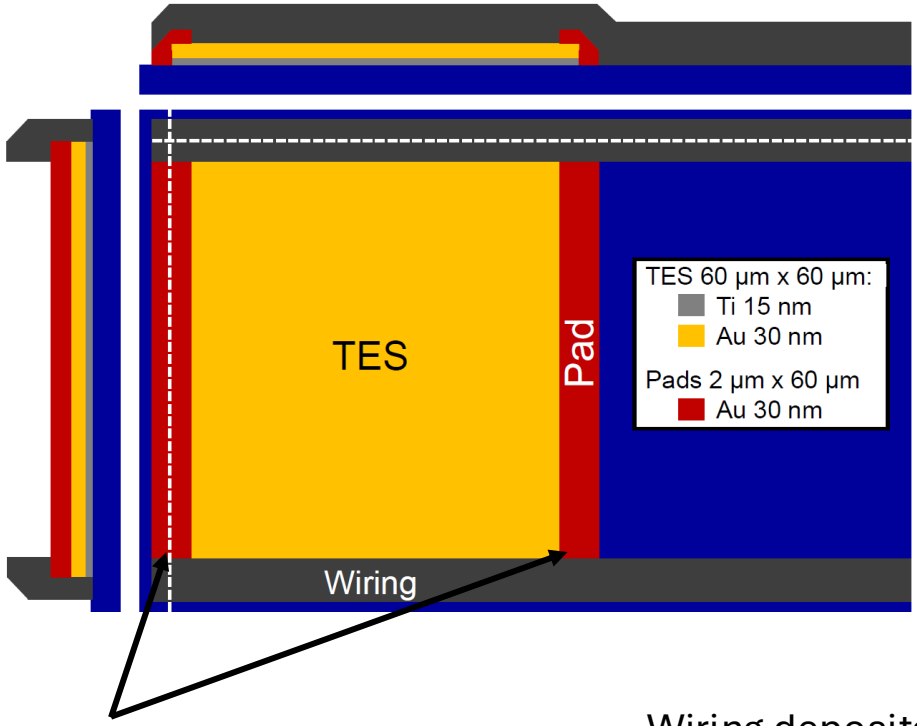
Recent developments: fast TESs

$$\textbf{Recovery time} \propto \frac{C_e}{G} \propto T_c^{-3}$$
$$(\sim 5\tau_{\text{etf}})$$

Enhance the thermal conductance by adding **Au pads** in TES design



[5] Hummatov, "*Fast transition-edge sensors suitable for photonic quantum computing*". Journal of Applied Physics (2023).



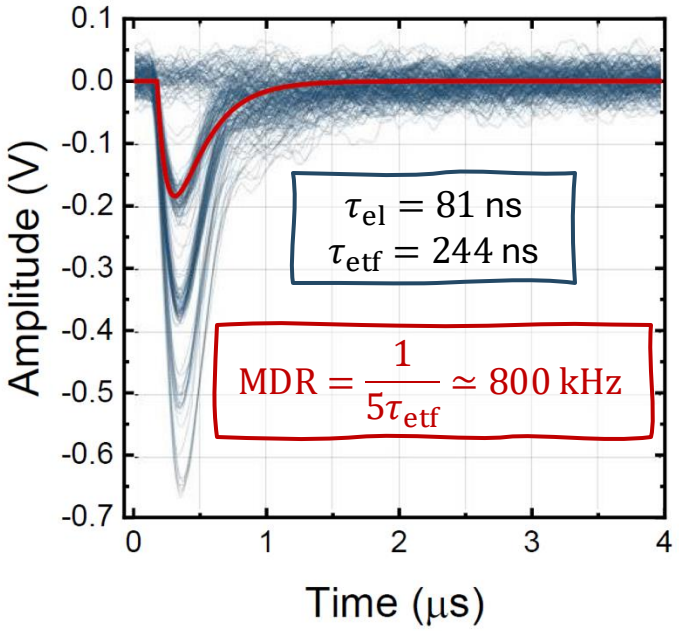
Au pads on two sides

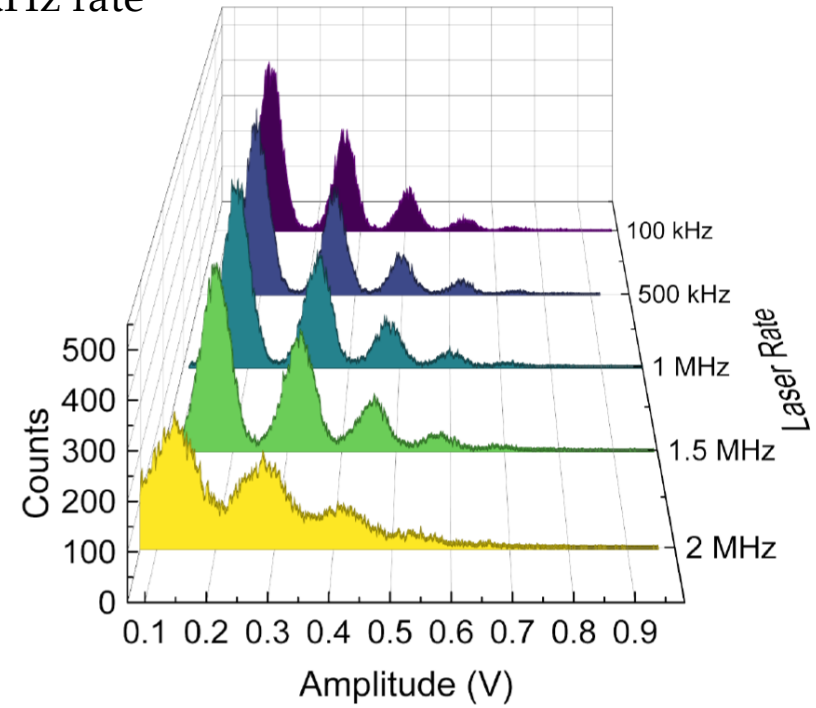
Wiring deposited on the other sides

Speeding up TESs

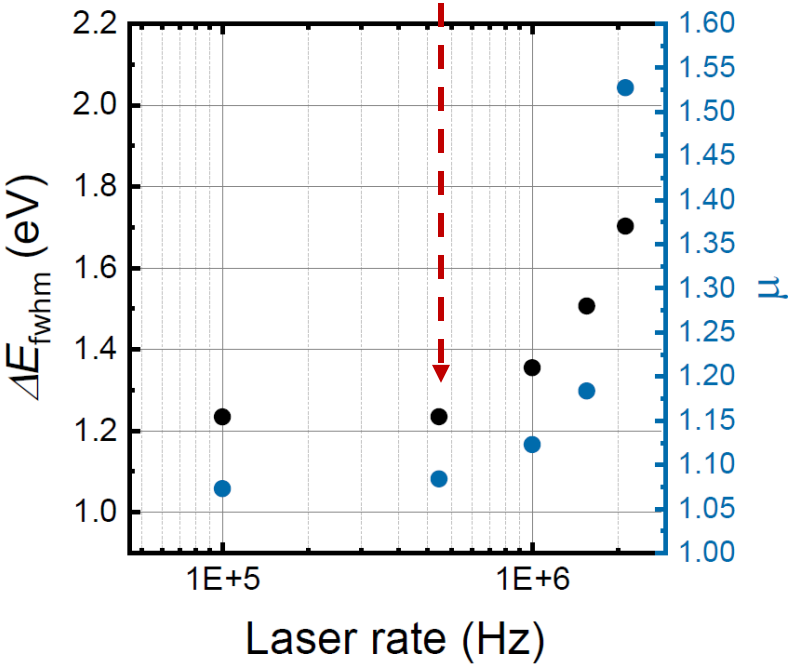
TiAu TES with a $T_C = 123$ mK and **two** gold pads $\quad G = 654 \pm 5$ pW/K

TES response to 406 nm photons @50 kHz rate





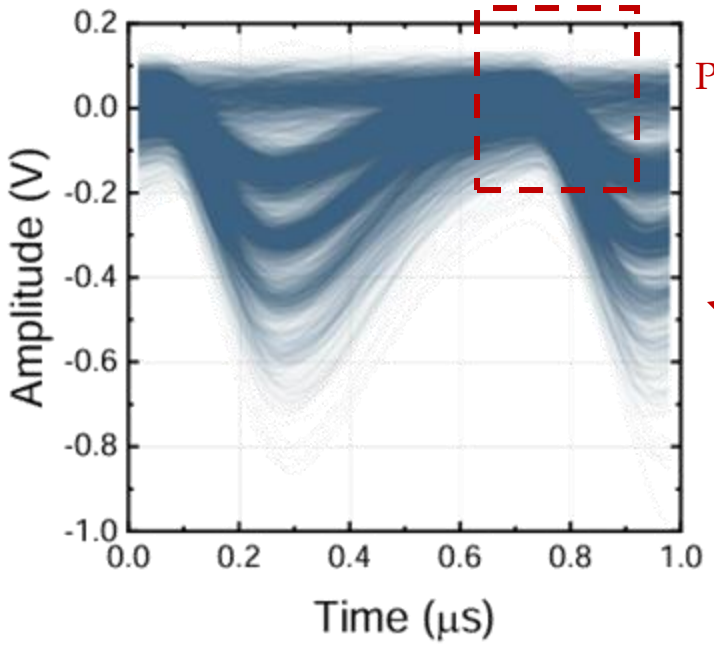
Up to 800 kHz
ΔE is preserved



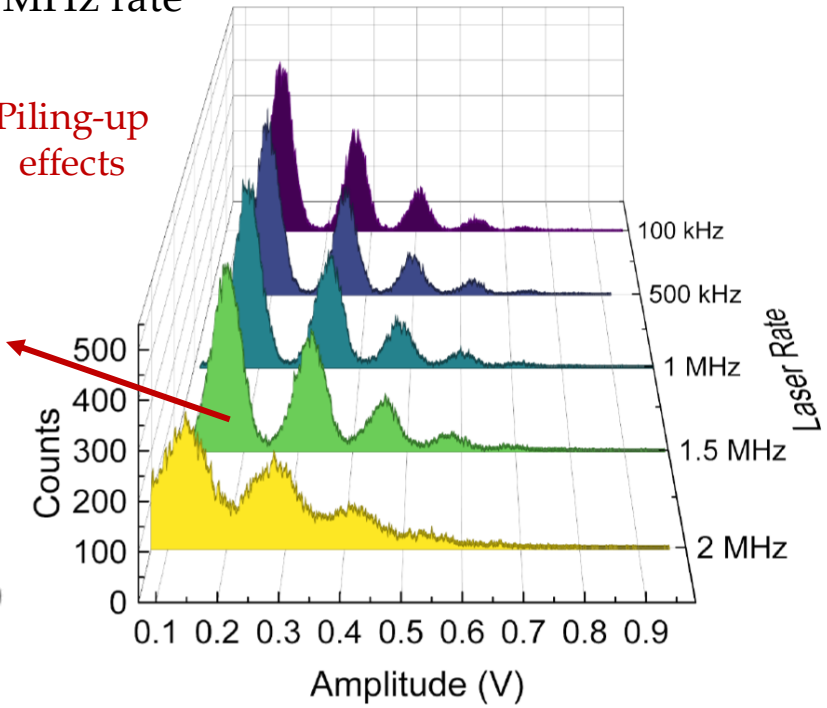
Speeding up TESs

TiAu TES with a T_C=123 mK and **two** gold pads $\quad G = 654 \pm 5$ pW/K

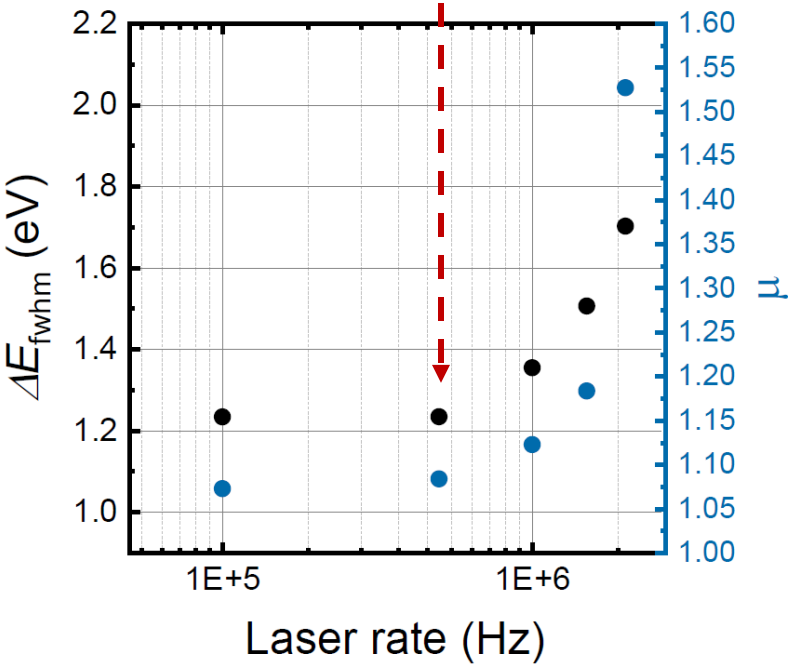
TES response to 406 nm photons @1.5 MHz rate



Piling-up effects



ΔE deteriorates
μ increases

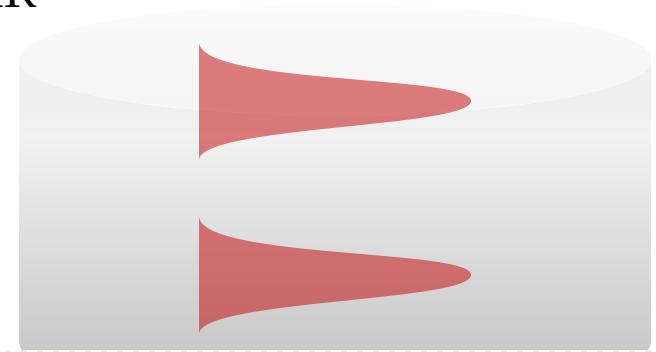


TiAu TES with **one** gold pad → $G = 413 \pm 5$ pW/K (-37%) and MDR ≃ 470 kHz

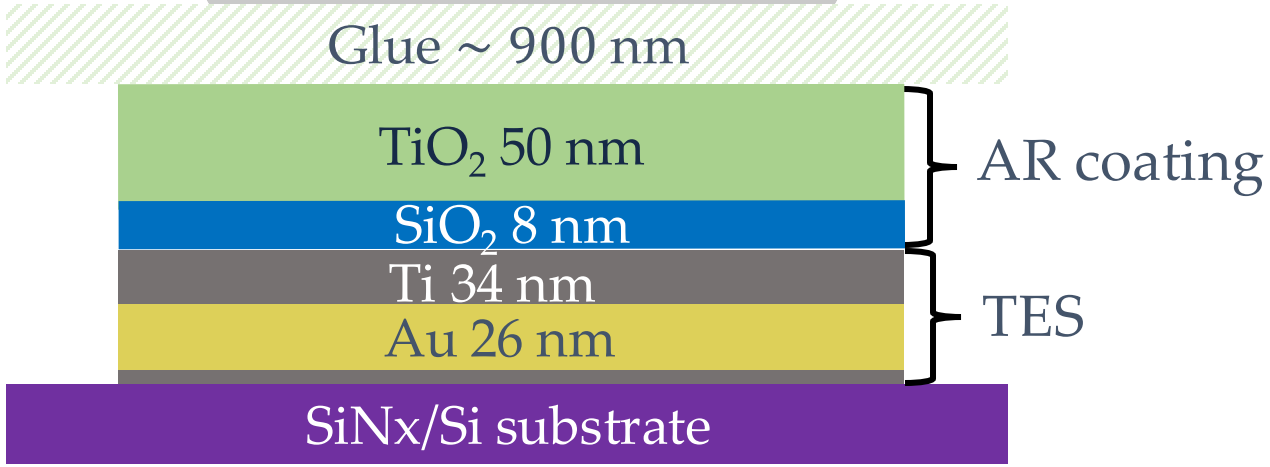
High efficiency TES layout

- **Enhancing TES detection efficiency**

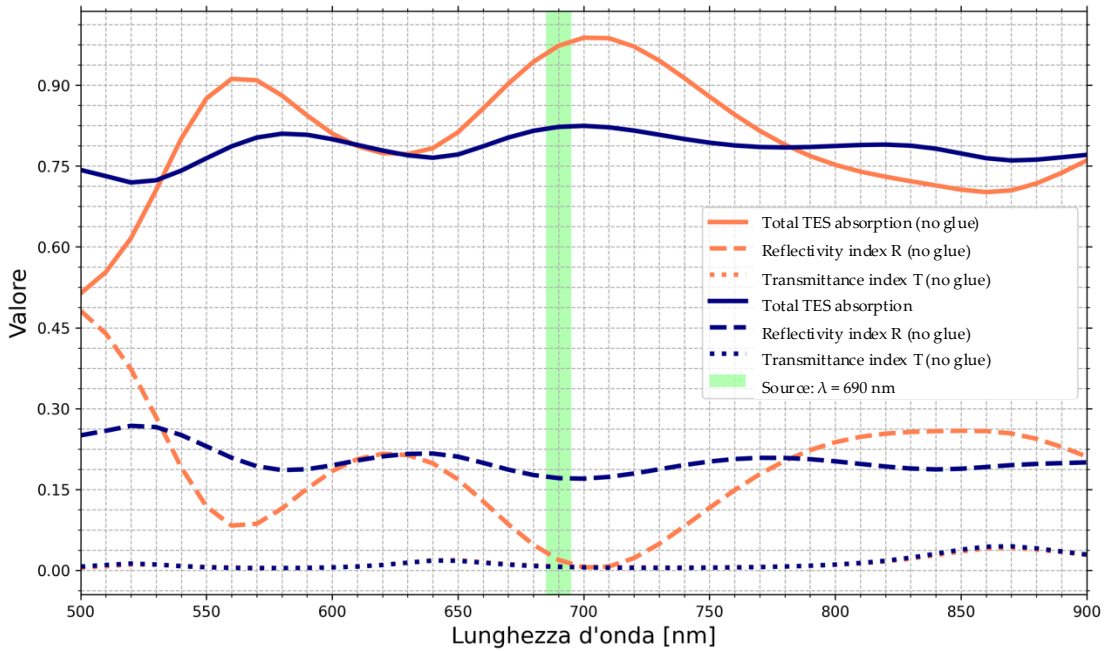
  $12 \times 12\ \mu m^2$ and $60 \times 60\ \mu m^2$ TiAuTi TESs + AR



Optical fibre



Maximum of absorption around $\lambda = 700$ nm



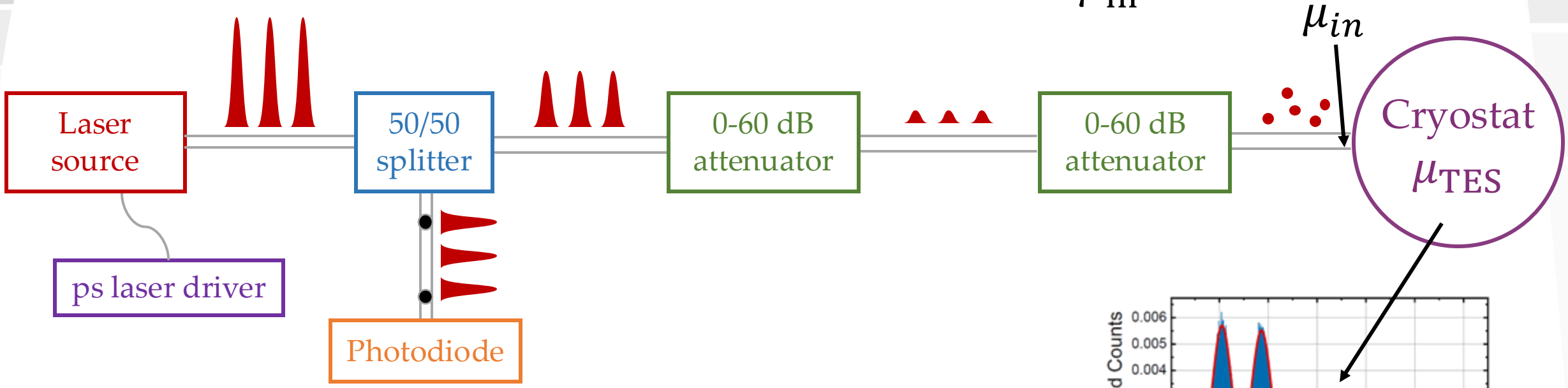
Laser source $\lambda = 690$ nm

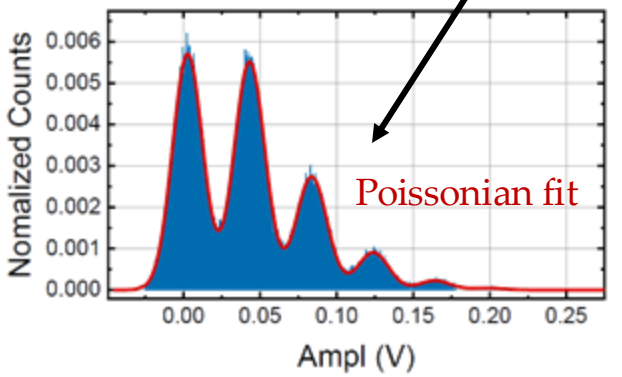
		Glue
Absorption coefficient:	0.97	0.83

Recent developments

- **Measuring detection efficiency:**

$$\mathrm{SDE} = \frac{\mu_{\mathrm{TES}}}{\mu_{\mathrm{in}}}$$





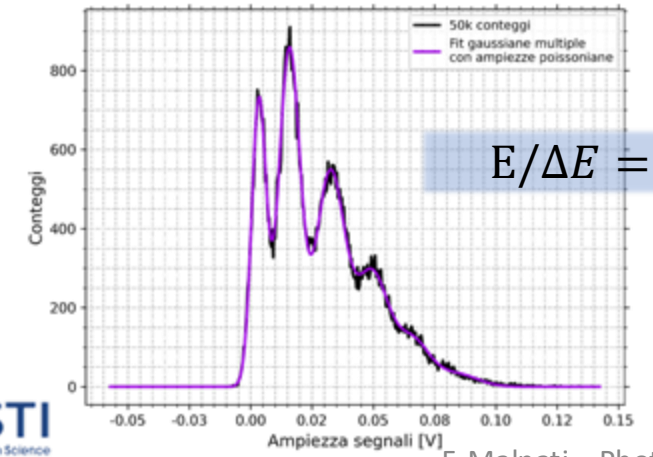
Γ = optical path attenuation
ρ = BS ratio
η = free air-fiber reflectivity
ν = laser repetition rate
λ = laser wavelenght
hc = Plank constant × speed of light

$$\mu_{in} = \frac{\mathrm{P_{diode}} \cdot \rho \cdot \Gamma}{(1-\eta) \cdot \nu} \cdot \frac{\lambda}{hc}$$

Preliminary results

$60 \times 60\ \mu m^2$ TiAuTi TES + AR

Variable [unit]	Value	Uncertainty	Contribution
Wavelength λ [m]	6.90e-07	5e-09	0.006145
Repetition rate ν [Hz]	3.125e+04	-	-
Free air/fibre interface η	3.7e-02	-	-
BS ratio λ	2.30e-03	1e-05	0.004667
Optical path attenuation Γ	3.70e-04	5e-06	0.012120
Photodiode power P [W]	1.98e-08	5e-10	0.022935
μ_{TES} [from Poissonian fit]	1.65e+00	1e-02	0.005670



$E/\Delta E = 2.25$

$\mathrm{SDE}\ (690\ \mathrm{nm}) = 85 \pm 3\ \%$

Future steps

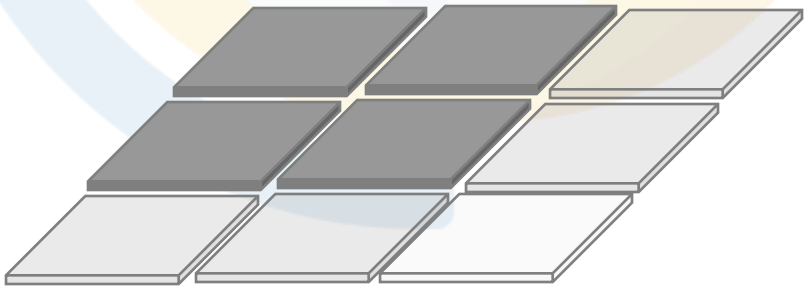
- Reduce TES response time of about 20%

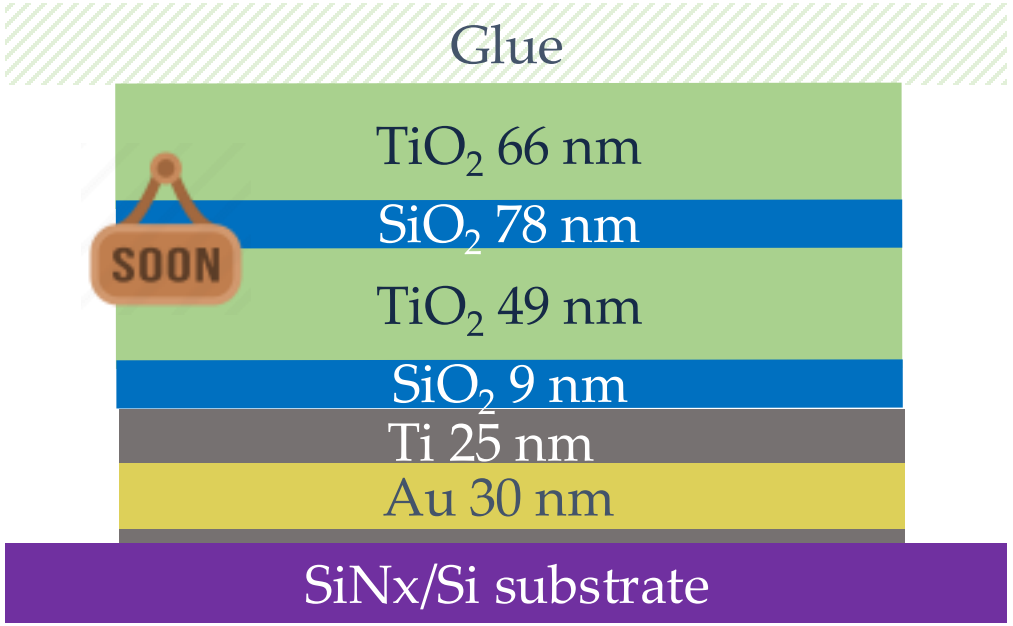
- Enhance detection efficiency to reach 90%

New 4-oxide AR coating

Simulations show SDE > 90%

- Fabricate a prototype array of TESs





Conclusions

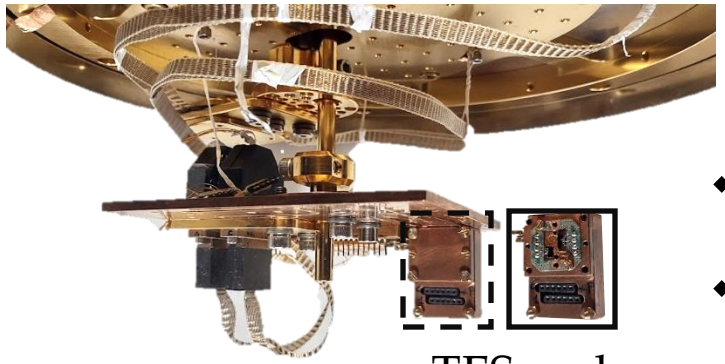
Thanks for your attention

Cryogenic setup

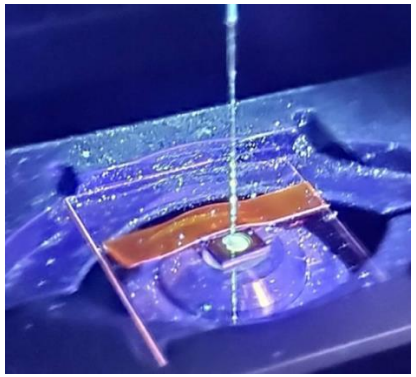
- Low-temperature setup: pulse-tube cryocooler + ADR

  3 K < 100 mK

- Stages at different temperatures (60 K, 3 K, 500 mK, 30 mK)



TES and SQUID box



- ❖ 4-wire measurements: *R vs T*
- ❖ Single-photon counting with SQUID
- ❖ An optical fibre is aligned to the TES active area and glued

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