High resolution X-ray detectors based on Transition Edge Sensors

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Outline

- Introduction:

  Transition Edge Sensors (TES) and their applications

- Mo-based TES for X-ray detection
- Summary

Cryogenic detectors

Low Temperature or cryogenic radiation detectors operate at temperatures T<<1K, typically ≈100-400mK

Low operation temperatures imply:

☆ Low thermal noise

☆ Decreased heat capacity

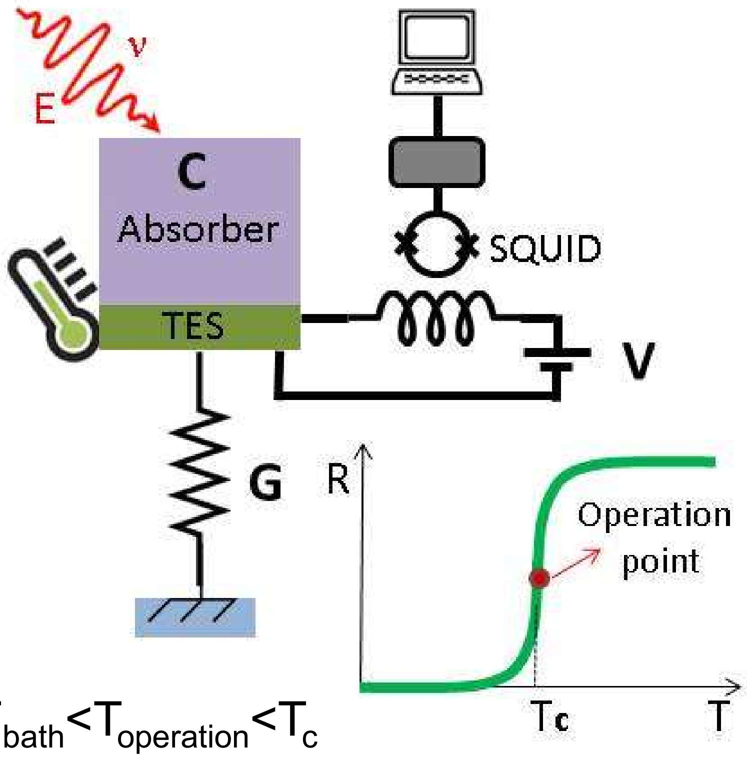
☆ Possibility of using superconductors:

Smaller detectable energy

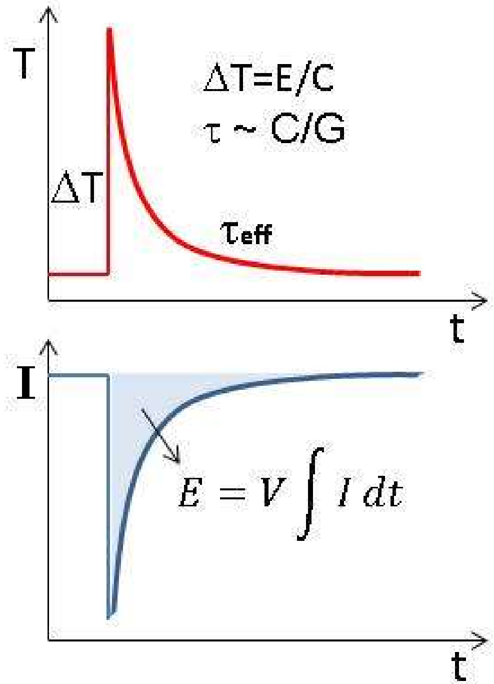
➡ • High spectral resolution ΔE
• Broadband, high detection efficiency

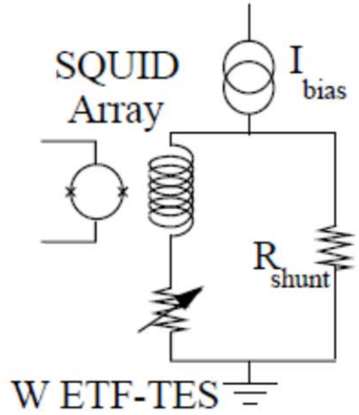
Capability of time resolved single photon spectroscopic counting

Transition Edge Sensors (TESs)



$T_{bath} < T_{operation} < T_c$





$$\tau_{eff} \approx \frac{C}{G} \frac{1}{1+\alpha/n}$$

$$\Delta E_{FWHM} \approx 2.355 \sqrt{4 k_b T_0^2 \frac{C}{\alpha} \sqrt{nF(1+2\beta+\vartheta^2)(1+M^2)}}$$

- Typical dimensions: ~10-300 μm
- $T_{operation}$~100 mK (T_{bath}~50mK)

TESs constitute very versatile bolometers/microcalorimeters: can detect from μW to γ-rays

Transition Edge Sensors (TESs)

TESs offer single photon detection in a very broad energy range, with:

- **High spectral resolution**
- **Very high efficiency**
- **Photon-number resolving capability**
- **Low dark count rates**
- **Time constants >~1μs**

Yes, they are **slow, small** and **require cryogenics** *but*...

- **Provide revolutionary performances:**

TESs can reach ΔE~1eV@ 1-6 keV, with efficiency >98%

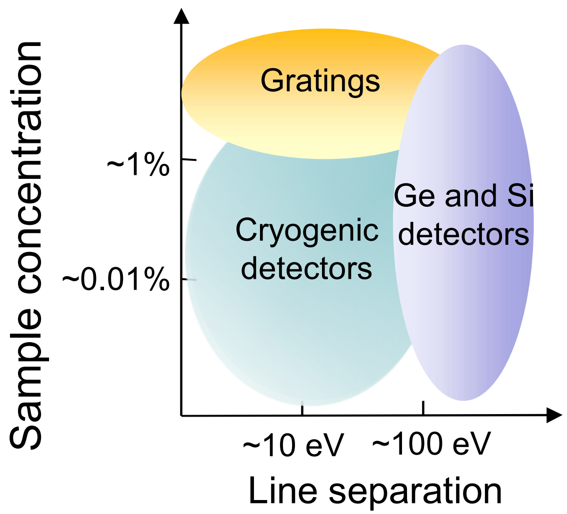
- **Arrays are mature enough**
- **Cryogen-free refrigerators are widely available**

Applications of TES detectors in science and industry

- **Particle physics**
- **Astrophysics**:
  - X-ray and γ-ray detection
  - Time-resolved spectrophotometric studies of objects (FIR-UV range)
- **Quantum Information**
- **Materials analysis**:
  - X-ray spectroscopies (synchrotrons, accelerators, electron microscopes)
    - Microelectronics, steel industry, automotion, nanotechnology, …
  - Mass spectrometers:
    - Pharmacy, medical diagnosis, polymer chemistry (quality control), forensics, agrobio industry, biology, …
  - FIR/IR spectrometers:
    - Environmental and polution control, IR molecular spectroscopy
  - Nuclear materials analysis
    - Security

TESs at synchrotron facilities

Why?



after S.Friedrich, J. Synchr. Rad. 13, 159 (2006)

Unique combination of:
- ❖ Good spectral resolution
- ❖ Large collecting efficiency
- ❖ Broadband spectral coverage

Specially valuable for:
- Photon-starved experiments
- Dilute and radiation sensitive samples

"TES can be integrated into a table-top time resolved X-ray source and a soft X-ray synchrotron beamline to perform emission spectroscopy with good chemical sensitivity over a very wide range of energies"

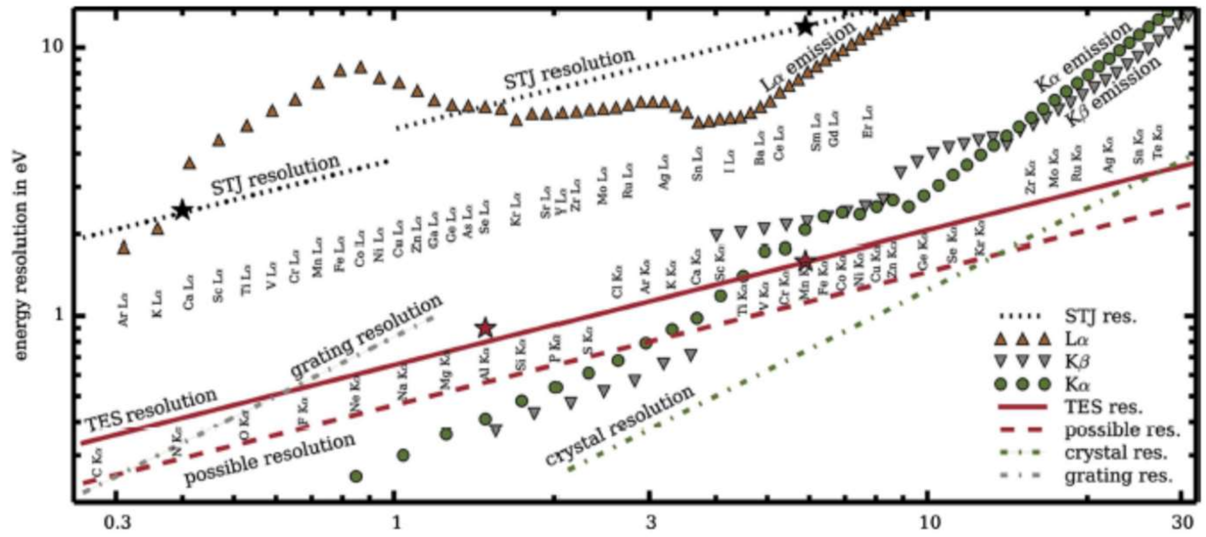


Figure 2
Present and future resolution of microcalorimeter detectors compared with natural line widths of Kα-, Kβ- and Lα-lines of a number of elements. Resolving powers of 8000 (green dash-dot) and 1200 (grey dash-dot) are shown which are realistic for a high-efficiency crystal analyzer and grating, respectively.

J. Uhlig et al. • XES with TES   J. Synchrotron Rad. (2015). 22, 766–775

TESs at synchrotron facilities

National Institute of Standards and Technology

NIST National Institute of Standards and Technology U.S. Department of Commerce

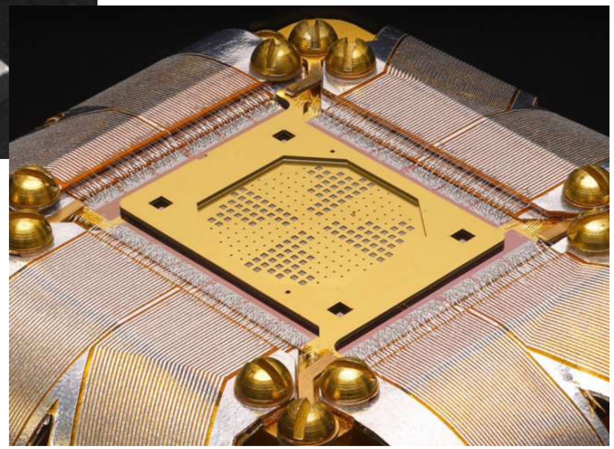
New High-Resolution X-ray Spectrometer for Beam Lines

October 24, 2014

Advanced Photon Source

Argonne NATIONAL LABORATORY

"one major problem with conventional technology is that detector efficiencies are typically in the range of 5 to 10 percent," said Daniel Swetz of the Physical Measurement Laboratory's Quantum Electronics and Photonics Division. "That is, they're throwing away about 90 percent of the photons. Moreover, they tend to have poor solid-angle coverage. The X-ray beam is spatially broad, and if you put a small detector in, you won't be using the system most efficiently."
So Swetz, along with Joel Ullom and other NIST colleagues, have been designing and fabricating a new generation of transition edge sensors (TESs) that ***detect nearly 100% of X-ray photons****, and* ***can determine energy differences between photons with a resolution of about 1 part in a few thousand*** *at a key energy range for studying materials. That capability is a factor of 50 better than current state-of-the-art detectors and provides highly detailed information about the chemical and electronic structure not easily measurable with other types of spectrometer."*



TESs spectrometers in beamlines and laboratories

Deployed (NIST)

	Spectrometer	Technique(s)	E (keV) of expts.	Date deployed	Array type
A.	Lund Kemicentrum	TR-XAS; TR-XES	2–10	October 2010 December 2013	ar13 ar13
B.	NIST TR	TR-XAS; TR-XES	2–10	January 2013 January 2015	ar13 ar14
C.	NIST metrology	XRF line metrology	2–10	November 2012	ar13
D.	NSLS beamline U7A (NIST)	PFY-NEXAFS; XES	0.25–1	October 2011 April 2014	ar13 ar14
E.	APS 29-ID	RSXS	0.25–1	Jul., 2014	ar14
F.	Jyväskylä Pelletron	PIXE	1–14	February, 2011 February 2014	ar13 ar13
G.	PSI πM1	π^--atom spectroscopy	4–15	October 2014	ar14

Planned

System	Technique(s)	E range of expts.	Array type
SSRL 10-1	PFY-NEXAFS; XES	250 eV–1 keV	ar14
J-PARC K1.8BR	K^--atom spectroscopy	5 keV–7 keV	ar14
LLNL TEMS	EBIT	50 eV–10 keV	NASA
NSLS-II 7-ID	PFY-NEXAFS; XES	250 eV–1 keV	ar14
NIST EBIT	EBIT	250 eV–10 keV	ar14

Synchrotron-based:
- Absorption and emission spectroscopy
- Energy-resolved scattering

Accelerator-based:
- Spectroscopy of hadronic atoms
- PIXE spectroscopy

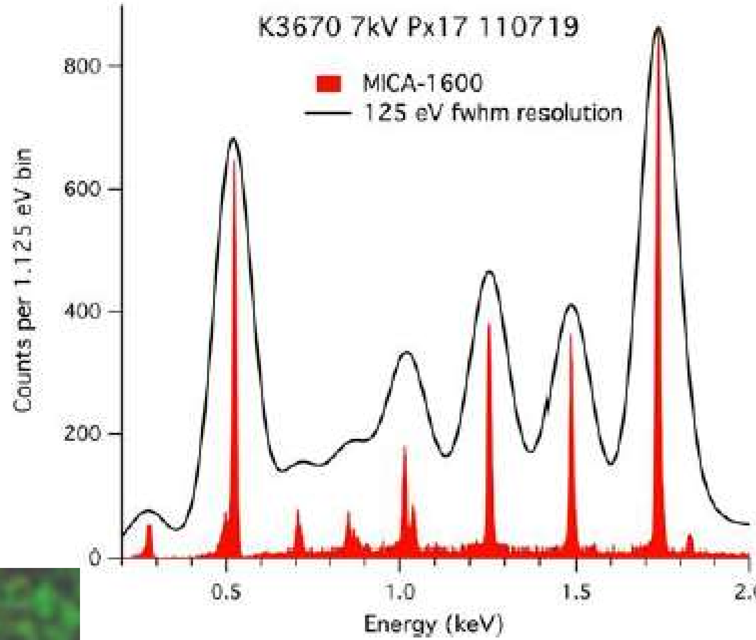
Laboratory-based:
- Time-resolved absorption and emission spectroscopy
- Metrology of X-ray emission lines

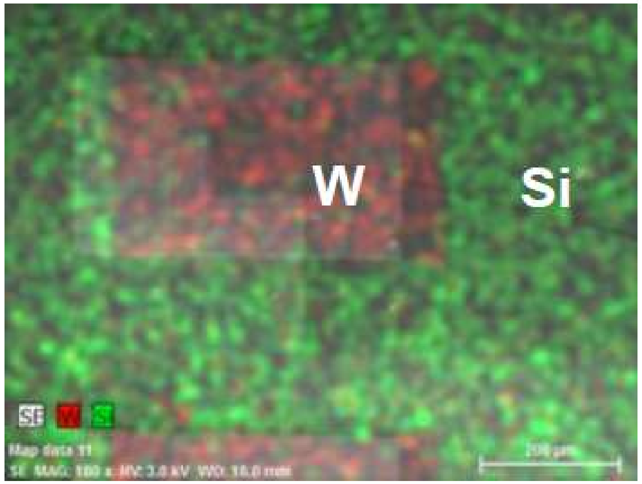
Doriese et al., Rev. Sci. Instrum. 88, 054108 (2017)

Materials composition analysis:
X-ray fluorescence in electron microscopes

TES X-ray detectors can provide ~50x better resolution than SDDs

Commercial SEM-mounted cryogen-free spectrometer (16-TES array) from STAR Cryoelectronics





Real-time X-ray map: conventional detectors do not have the energy resolution to tell apart W M-lines from Si K-lines

Development
of
Mo/Au based TES for X-ray detectors

as part of a european backup for X-IFU/Athena

Research team & contributors:

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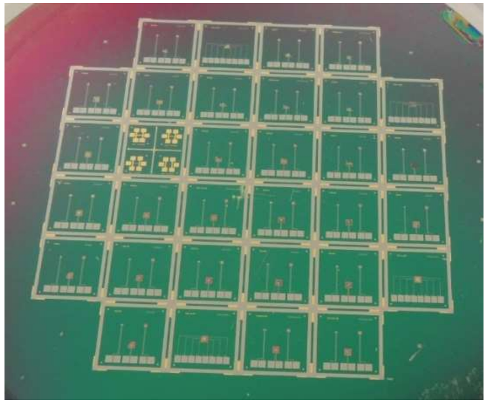
Plan Nacional del Espacio

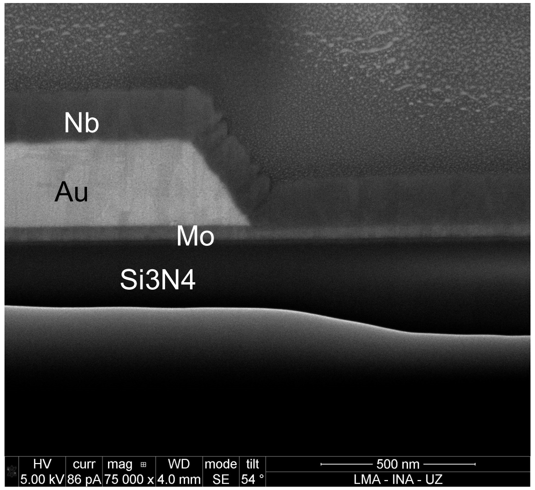
Core Technology Program Contract "Optimization of a European TES array"

H2020 projects: "Integrated **A**ctivities for the **H**igh **E**nergy **A**strophysics **D**omain" 2015-19 and new 2020-23

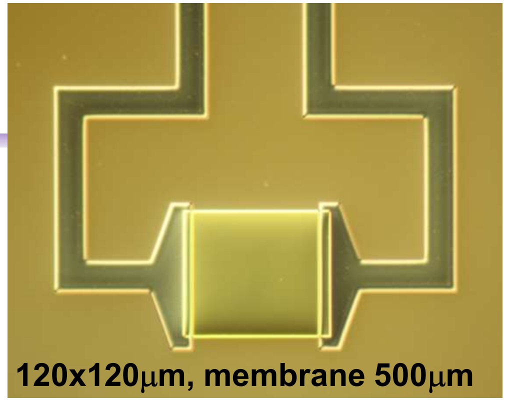
Mo/Au-based TES for X-ray detection

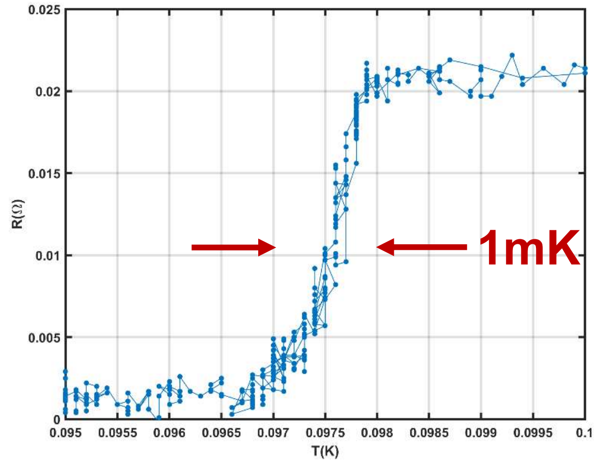


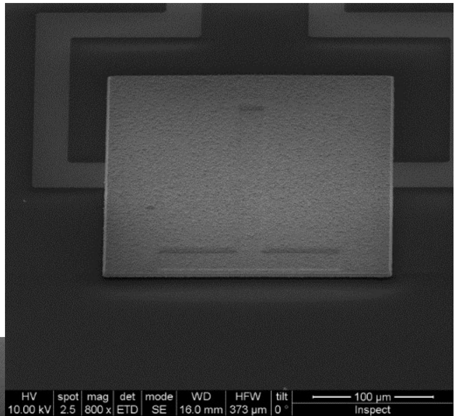
4” Wafer with TESs

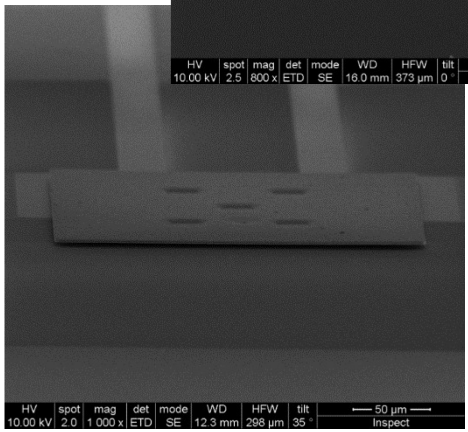


Strichovanec et al., Appl. Supercond. Conf. (2018)

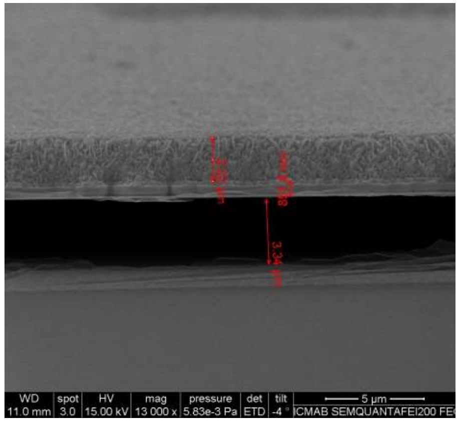


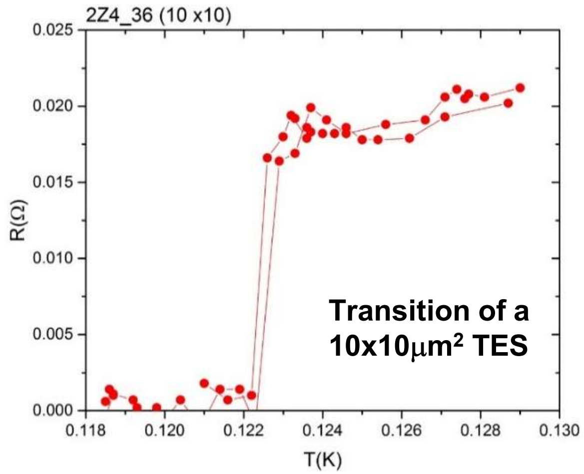




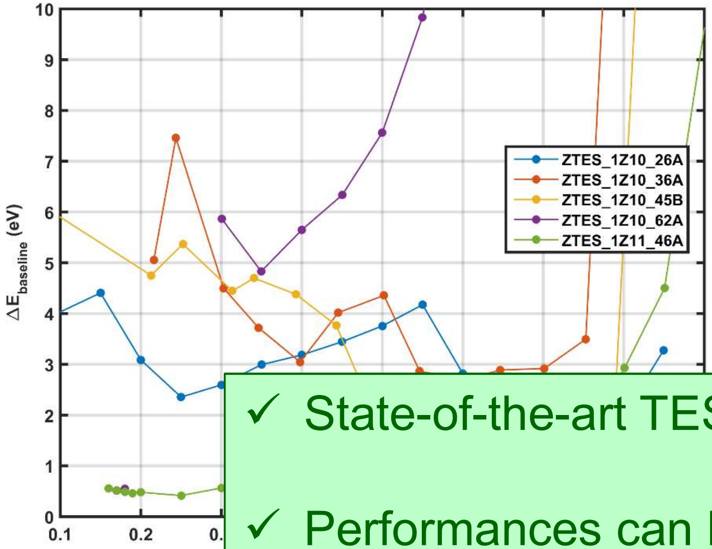


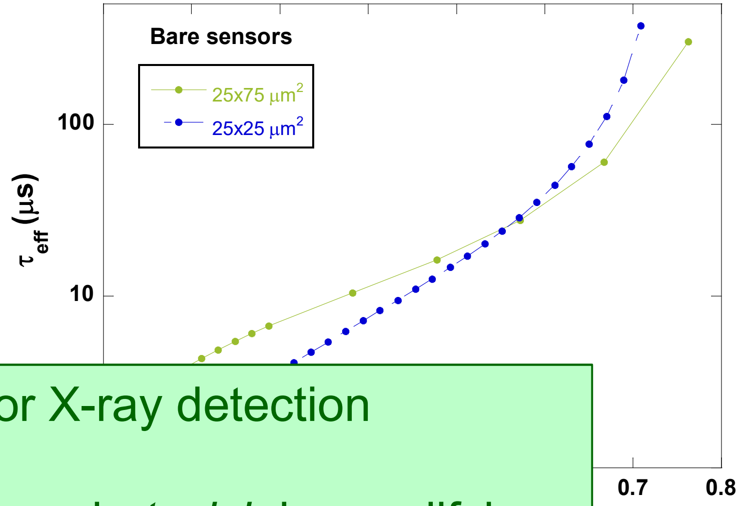
Cantilevered Bi/Au Absorbers





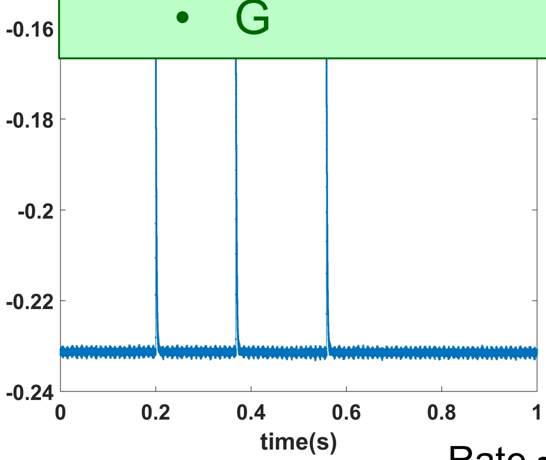
Mo/Au-based TES performances



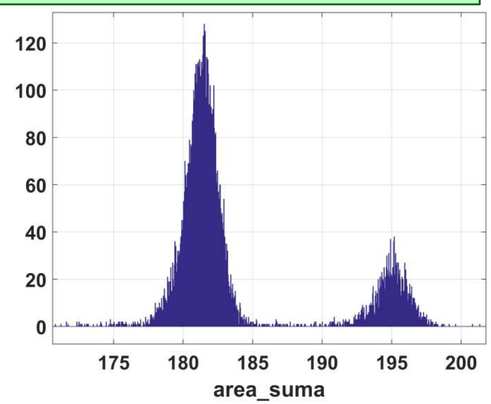


- ✓ State-of-the-art TESs for X-ray detection
- ✓ Performances can be tuned *at wish* by modifying:
  - Sensor size, shape, R and T_c
  - Absorber design
  - G

Detection of sing



Rate ~2 Hz



To summarize…

- ✧ **Cryogenic radiation detectors** are becoming essential for scientific and technological applications requiring **high sensitivity** (energy, composition) and **single photon** detection.
  - ➢ Initial drawbacks (lack of maturity, requirement of cryogenics, large arrays) are being overcome.
- ✧ Among them, superconducting **TES** are most mature and very versatile; revolutionary new instruments, in astrophysics and materials science include them

Development of TES in Spain (ICMAB-ICMA)

✧ Able to **fabricate** and **fully characterize** TES-based X-ray detectors, with:

- sizes between $10 \times 10 \mu m^2$ and $\sim 250 \times 250 \mu m^2$
- tunable operation temperature (50-400mK)
- tunable performances (QE, τ, …)

✧ **Working on**:

- TES arrays
- TES physics

✧ **Identifying specific applications** (to develop specific TES for):

- Space
- Particle physics (axion search, …)
- Quantum Information
- Synchrotron, materials science

*Need to know the **set of requirements** (QE, τ, ΔE, noise threshold, size) that might make these detectors interesting/essential **for specific applications***