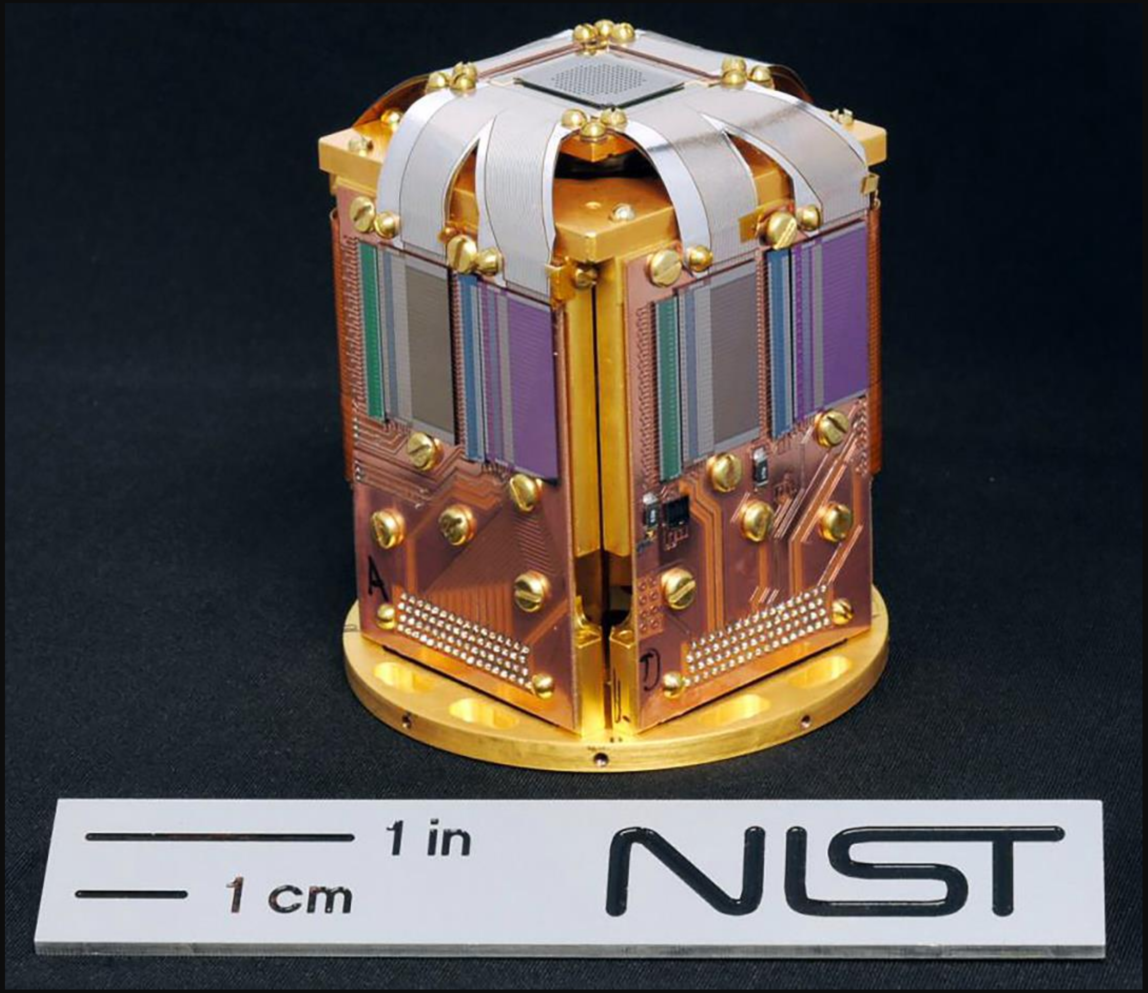
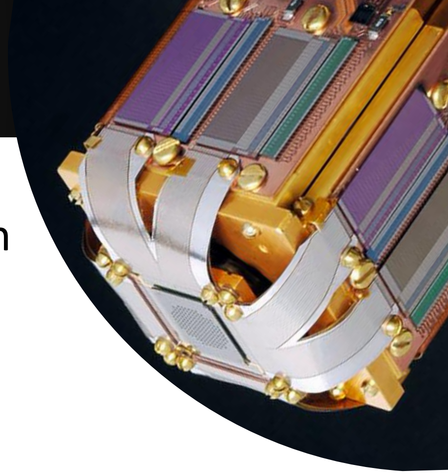
MEASURING THE TEMPERATURE OF X-RAYS

WITH SUPERCONDUCTING DETECTORS



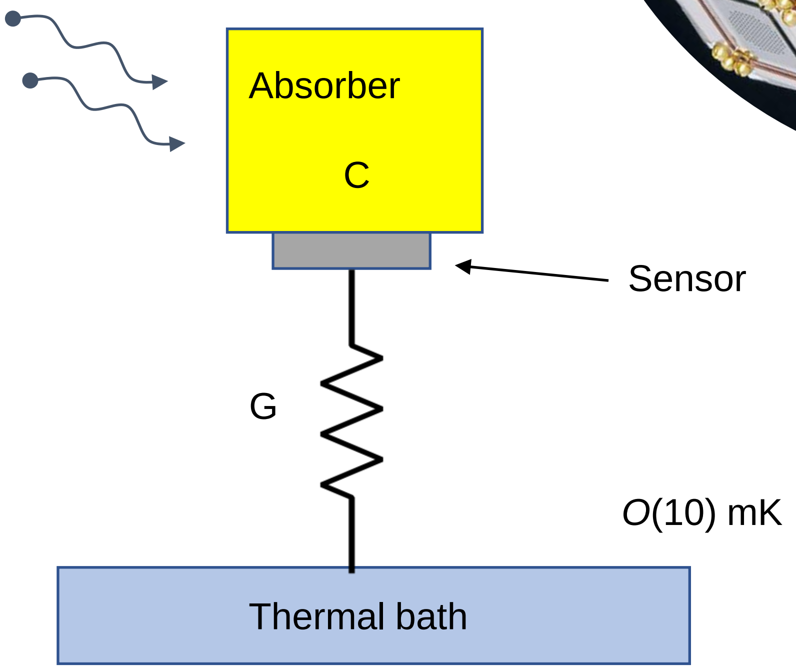
Matteo Borghesi, High Precision X-Ray Measurements 2023

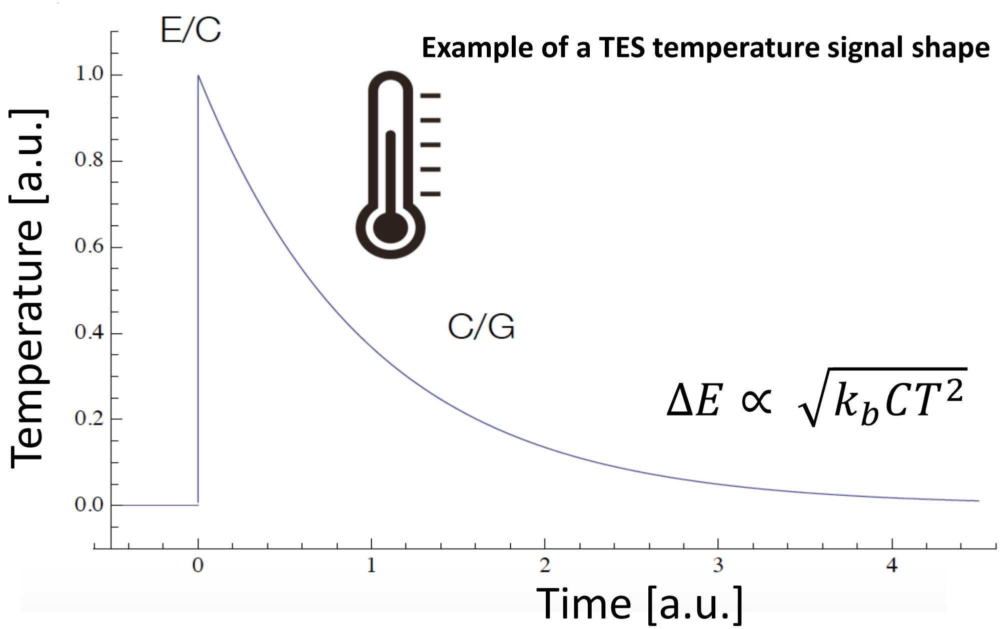
Low temperature detector working principle



- Low Temperature Detectors (**LTDs**) are **very sensitive thermometer** able to detect a temperature variation of the order of a fraction of mK

- The idea is to measure, with a temperature sensor, the energy deposited inside the detector after it has been converted into heat
  - Perfect calorimeters (in principle)
  - Phonon detectors!
  - Extremely small signals





Example of a TES temperature signal shape

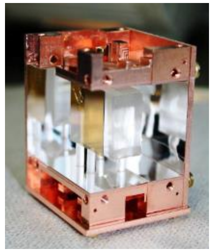
$$\Delta E \propto \sqrt{k_b C T^2}$$

A few definitions:

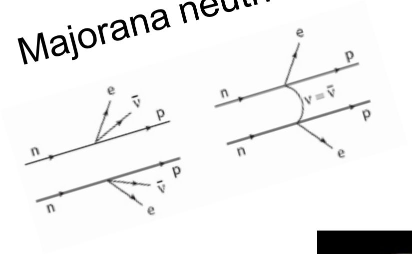
- **Calorimeter**: it measures the energy
- Bolometer: it measures the power.

- Macrocalorimeter: mass $O(100)$ g, size $O(1)$ cm
- **Microcalorimeter**: mass < $O(1)$ mg, size < $O(100)$ um

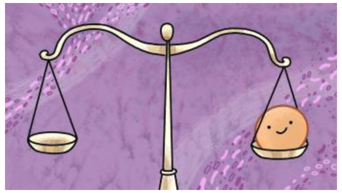
LTD application



Majorana neutrino

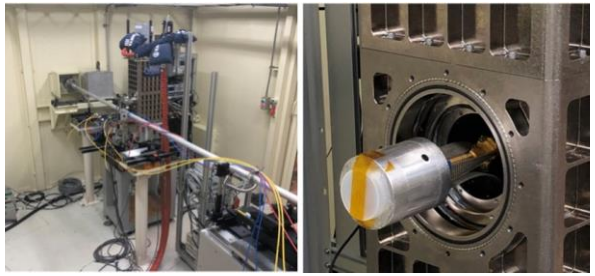


Neutrino mass



EDS spectroscopy

Beamline spectroscopy



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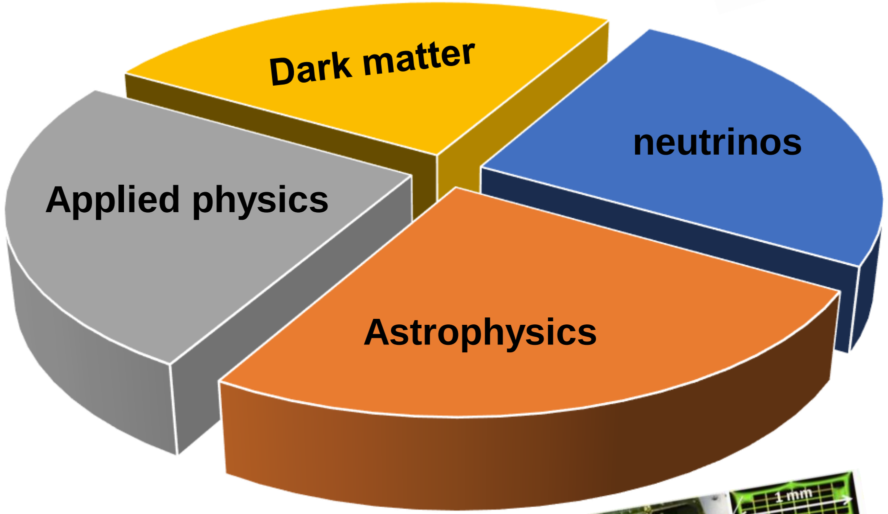
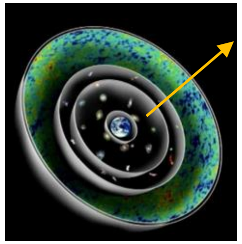
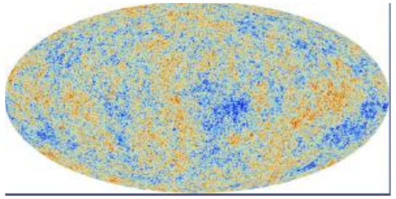
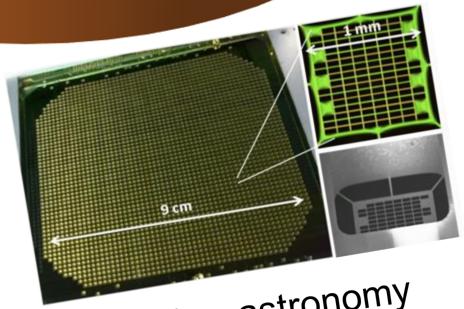


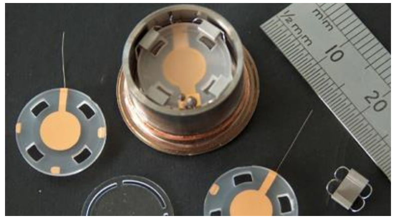


CNB





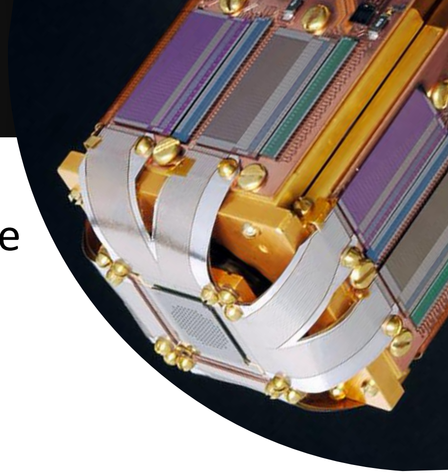
IR, X,… astronomy



Gravitational waves

CMB

Transition Edge Sensors (TES) for X-ray detection



- A Transition edge sensor is a superconductor film operated in the narrow temperature region between the resistive and the superconducting state

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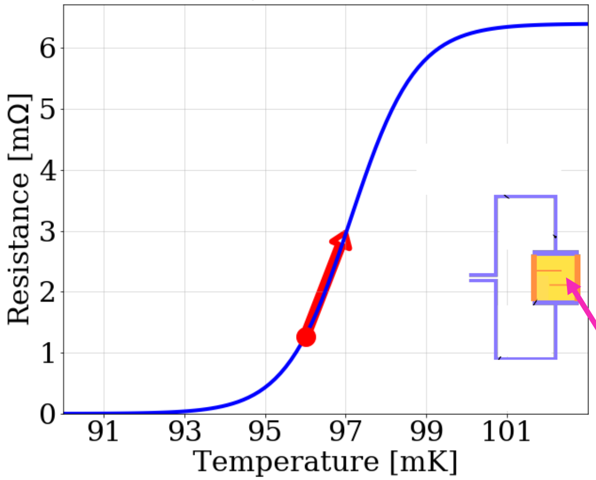
The resistance is strongly dependent on temperature

Transition shape of an HOLMES-like TES



- The TES design can be changed to match different experimental needs

- Typical detector dimension: 10-300 µm
Signal time *O*(100-1000) µs

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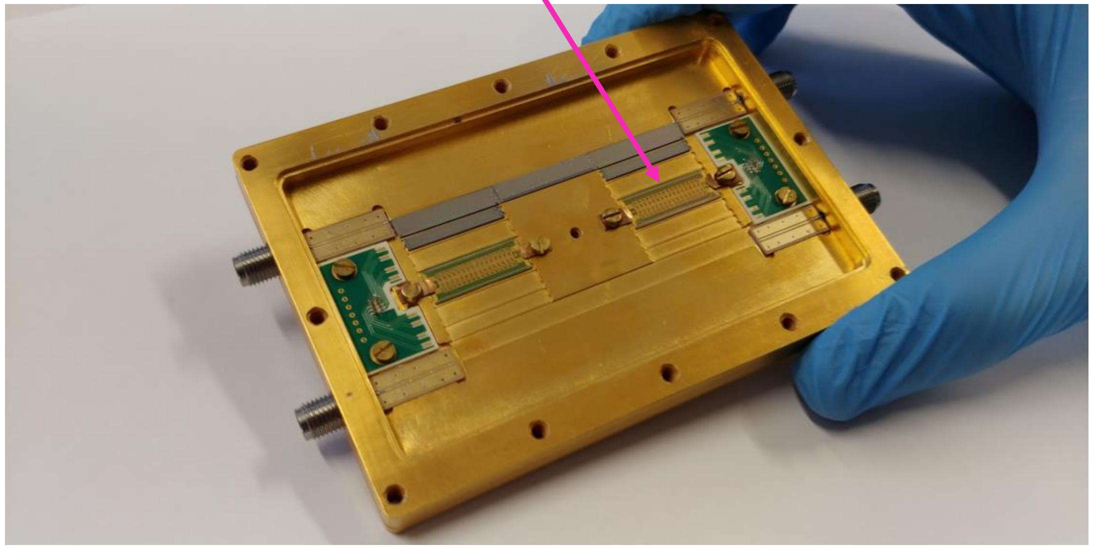
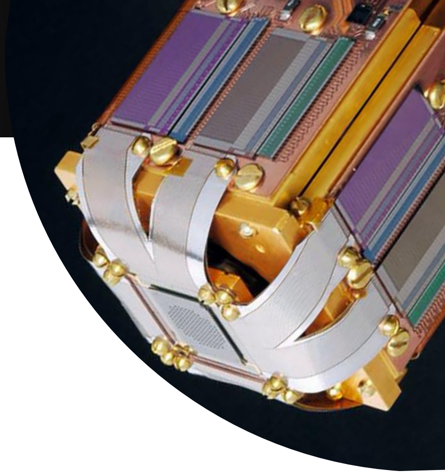
Practical collecting area and photon counting capability only when built into array of devices



- Competitive with HPGe and solid state and wavelength-dispersive spectrometers

Why use TES



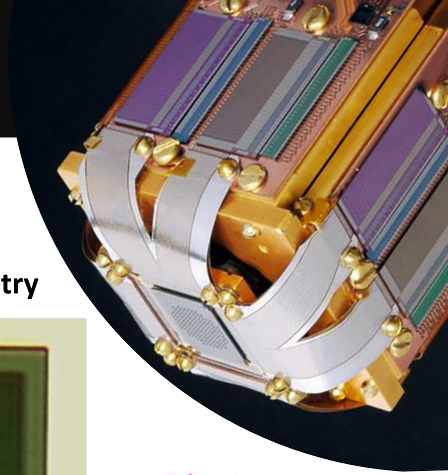
Pros

- Very high energy resolution
- Fully active (no dead layer)
- Low spurious count rate
- Single photon detector
- Wide selection of materials
- Many multiplexing techniques!

Cons

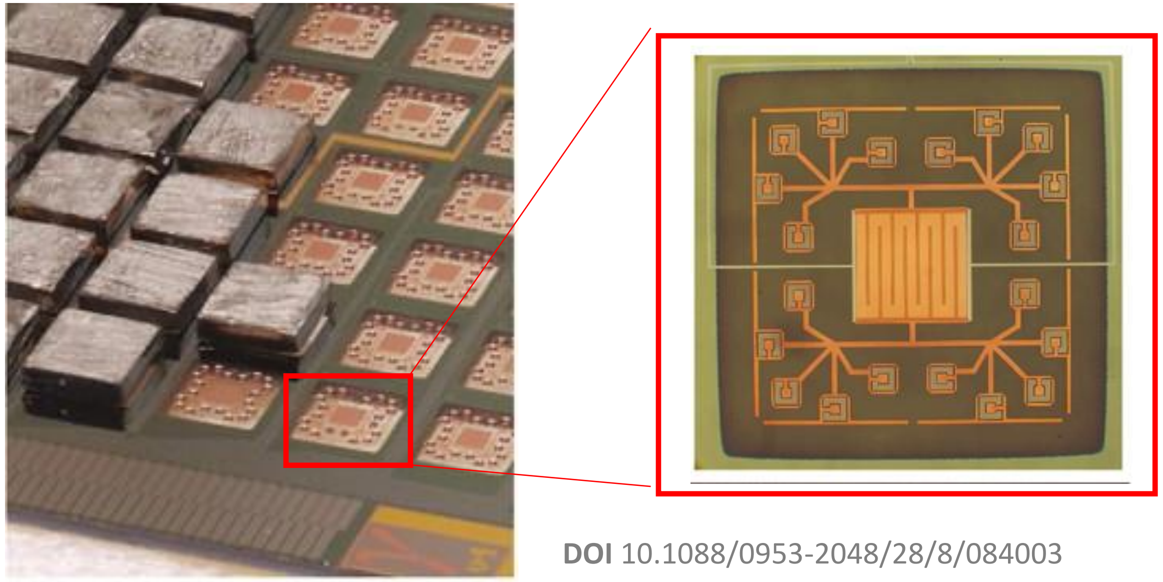
- Slow detectors
- Low temperature *O*(100) mK
- Non-trivial signal processing
- Multiplexing is mandatory

Components of a TES



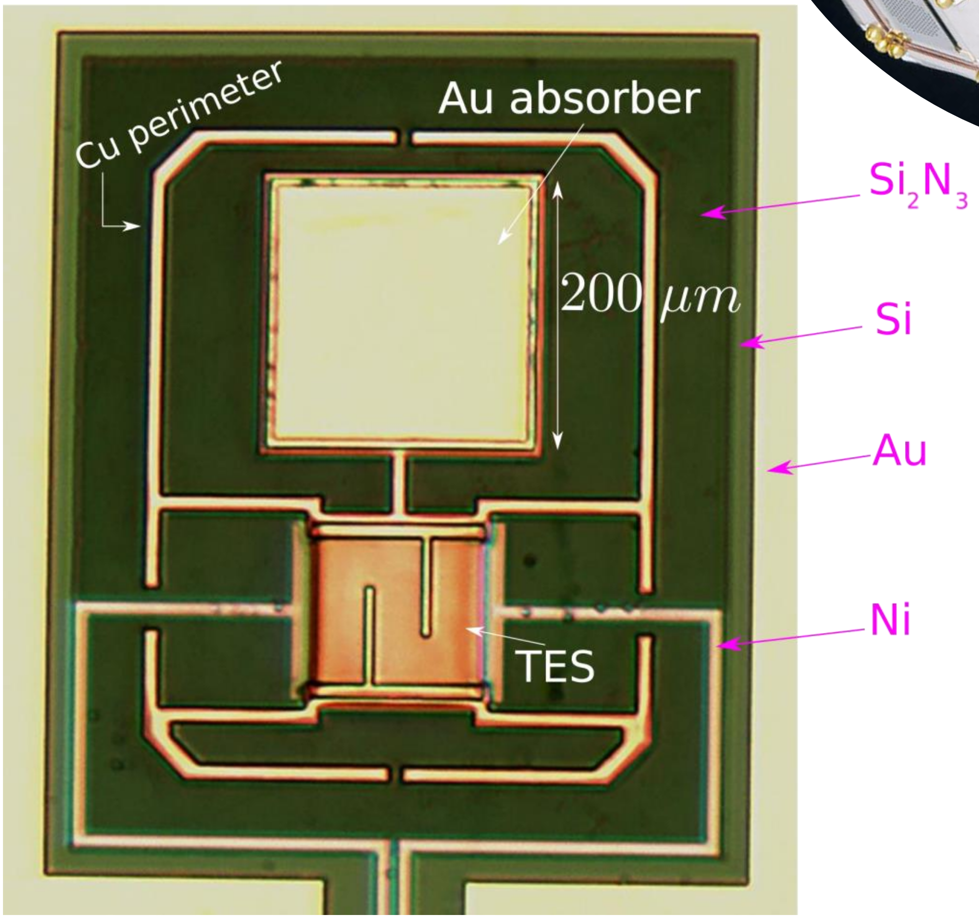
- A TES microcalorimeter is made of 3 elements:
  1. The X-ray interact in the **absorber**.
  2. The temperature variation is detected by the TES **thermometer**
  3. The detector cools down again thought the heat exchange with the **thermal bath**

Array of TES for gamma-ray spectroscopy with absorbers attached on top

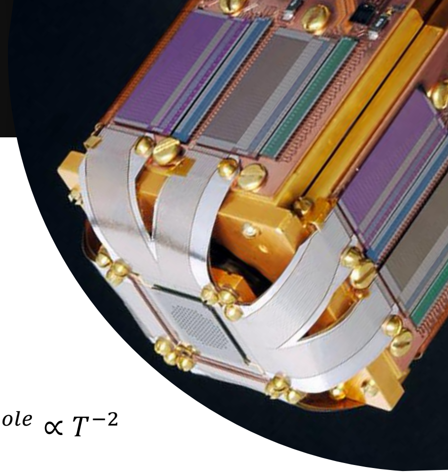


DOI 10.1088/0953-2048/28/8/084003

Topview of a detector design with sidecar geometry



Components of a TES: absorber



- In an ideal absorber, all the energy of the X-ray is partitioned between the phonon (and the electron) system of the absorber.

- An absorber can be made of **different materials**! (normal metals, semiconductors, superconductors…)

Requirements:

- Small heat capacity

$$C(T) = c_{tot}(T) \times M$$

$$c_{tot}(T) = c_r(T) + c_e(T) + c_m(T)$$

$$c_r(T) \propto \left(\frac{T}{\theta_D}\right)^3 \quad T \ll \theta_D$$

$$c_m(T)^{dipole} \propto T^{-2}$$

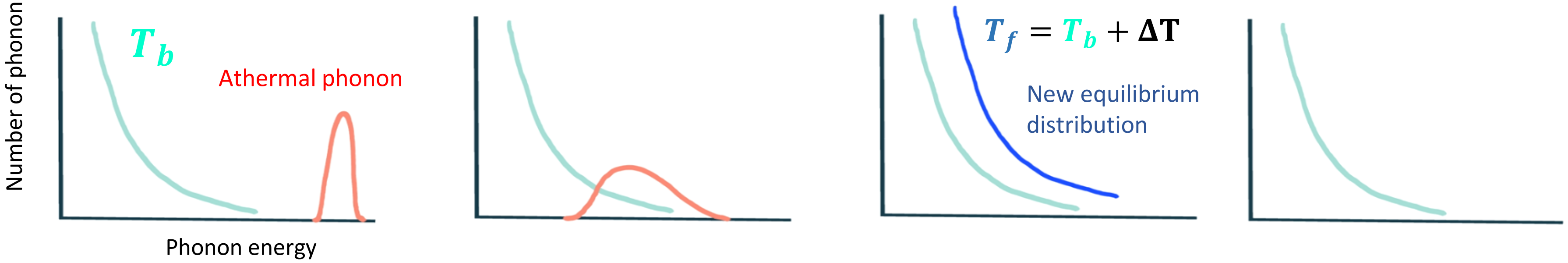
$$c_e(T)^{semicond} = 0$$

$$c_e(T)^{metal} \propto \frac{T}{\theta_F}$$

$$c_e(T)^{supercond} \propto \left(1.76\,\frac{T_c}{T}\right)^{\frac{3}{2}} e^{\frac{1.76T_c}{T}}$$

- Large collecting area

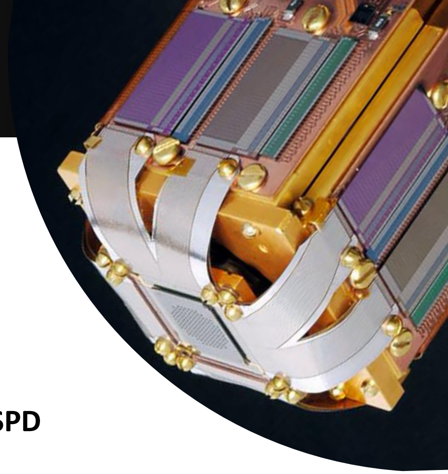
- Fast and efficient thermalization ($O(10^{-10})$ s)



- Stopping power

E < 1 keV → the sensing structure could be enough
1 < E < 10 keV → thin film (3 µm Au 96% @ 6keV)
E > 10 keV → thick films or bulk foils glued with cryogenic epoxy

Components of a TES: absorber



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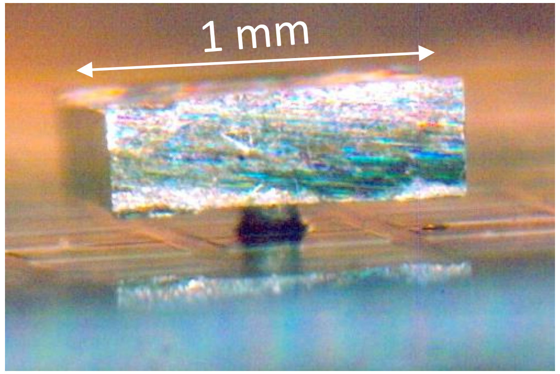
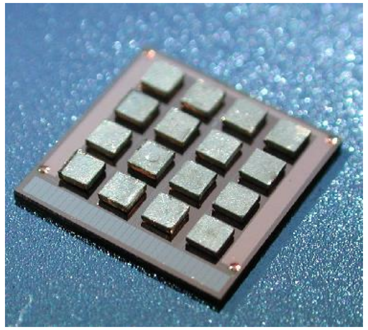
- An absorber can be made of **different materials**! (normal metals, semiconductors, superconductors…)

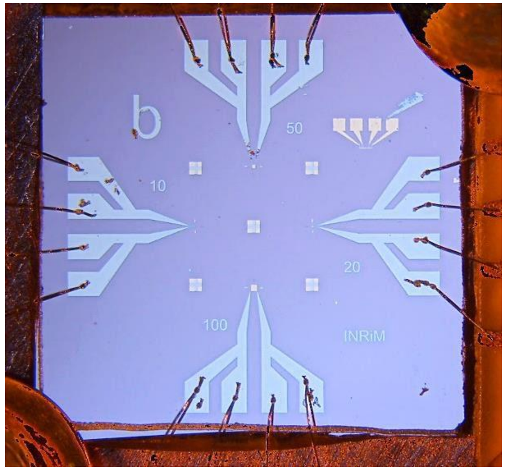
TES designed for gamma ray detection

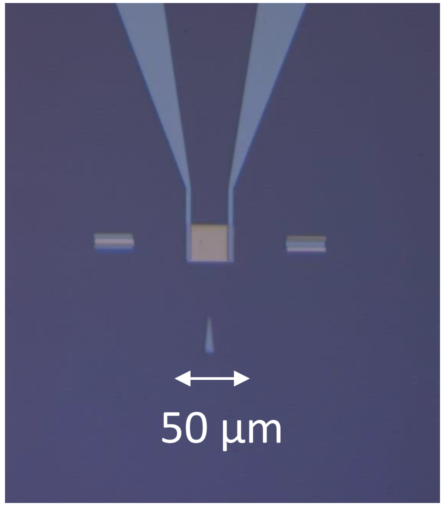




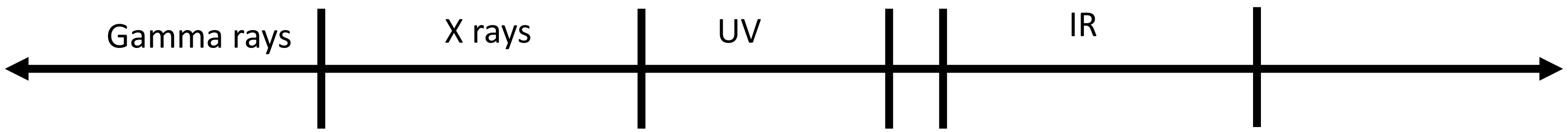
Credit: J. Ullom, NIST

TES designed for IR SPD

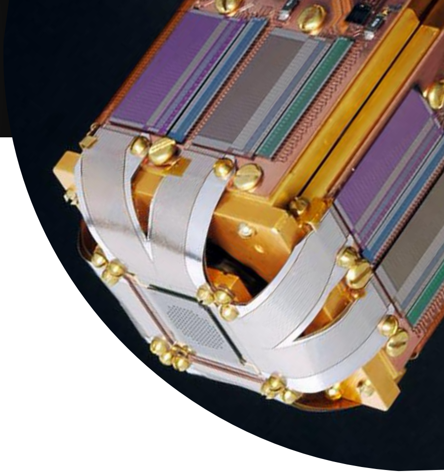




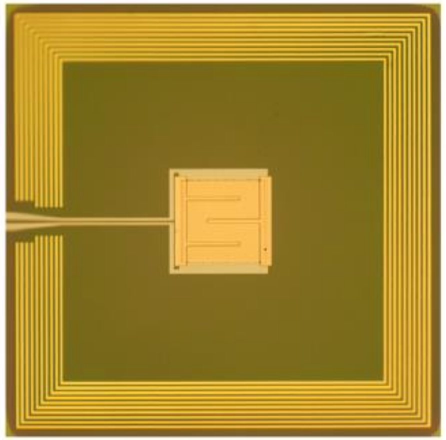
Credit: INRIM

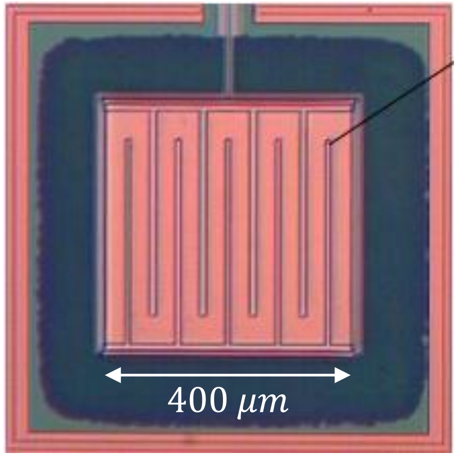


Components of a TES: sensor



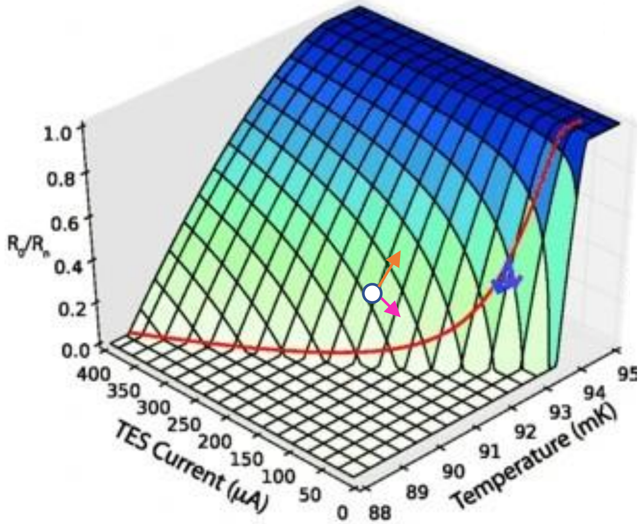
- TES thermometer: superconducting film (usually a bilayer normal metal- superconductor) biased to reach the superconducting-to-normal transition region





T_C usually chosen to be as low as can be achieved → 30-100 mK

- The shape of the film resistance is not trivial. $R_{TES}(T, I, B)$ depends on different things, such as: the material and the dimension of the film, the geometry of the TES, …

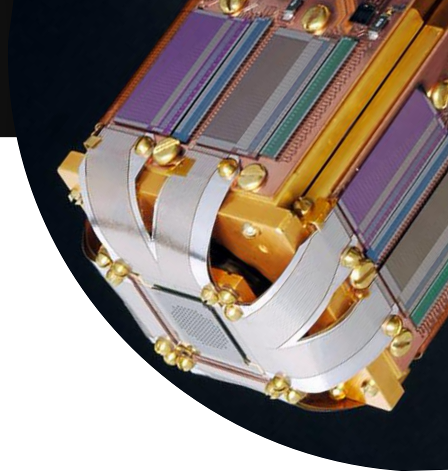


https://doi.org/10.1007/s10909-011-0431-4

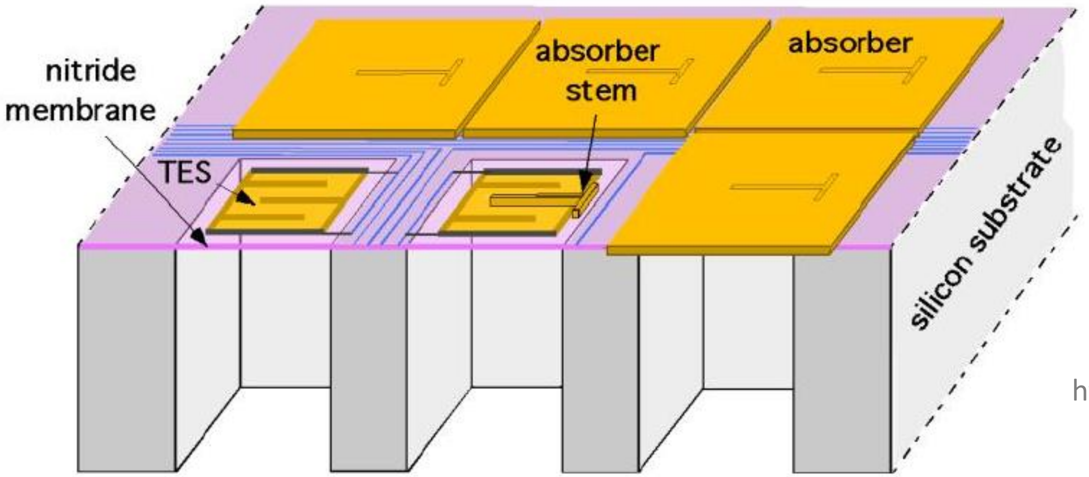
- The TES is biased to a point ○ $R_0(T_0, I_0)$ where the dynamic range and the sensitivity is highest → ~ 20% R_N
- Complexity of the curve captured by the two derivatives:

$$\alpha = \frac{T_0}{R_0}\frac{dR}{dT}\bigg|_{T_0} \qquad \beta = \frac{I_0}{R_0}\frac{dR}{dI}\bigg|_{I_0}$$

Components of a TES: thermal isolation

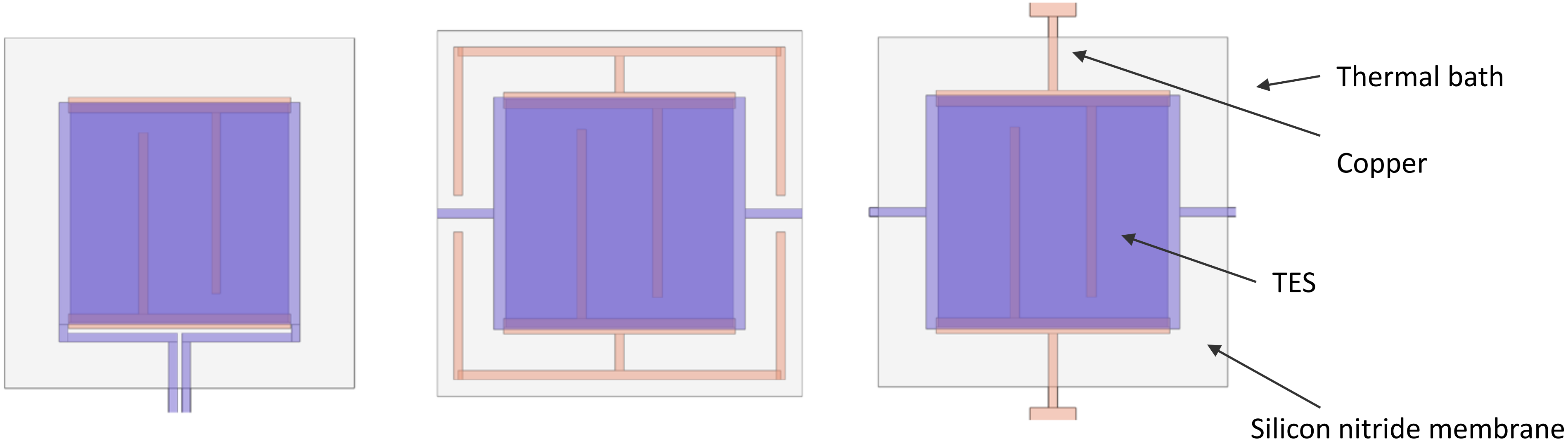


- Thermal isolation necessary to avoid escape of phonons and to match the bandwidth of the amplifiers
  - Electron-phonon decoupling
  - Limiting phonon transport
  - …



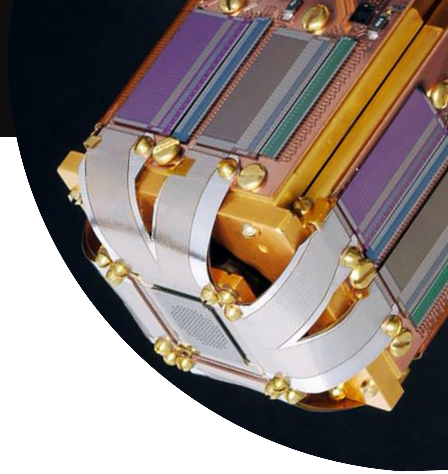
https://doi.org/10.1117/12.734830

- But high thermal conductivity is crucial to reduce the dead time



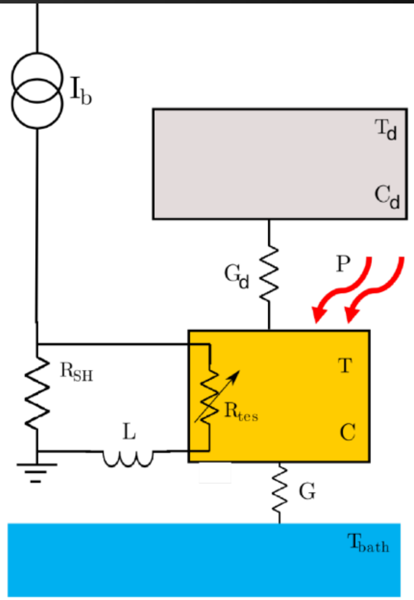
Credit: Hays-Wehle

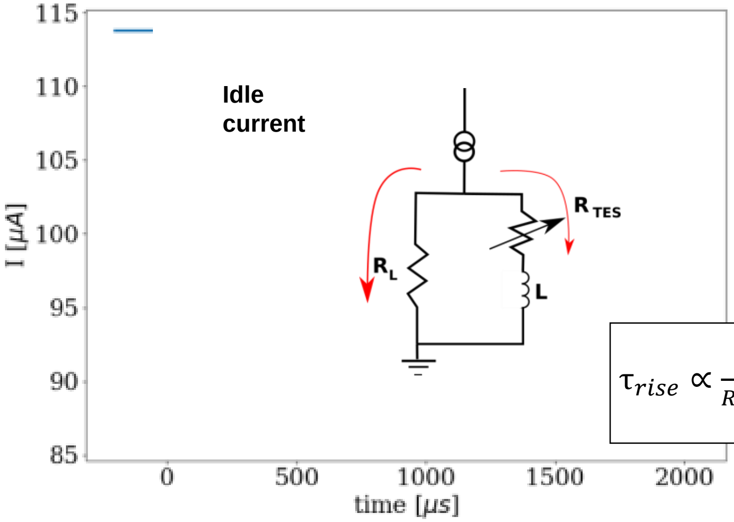
TES signal shape



- The TES behavior can be described by a set of *n* differential equations:

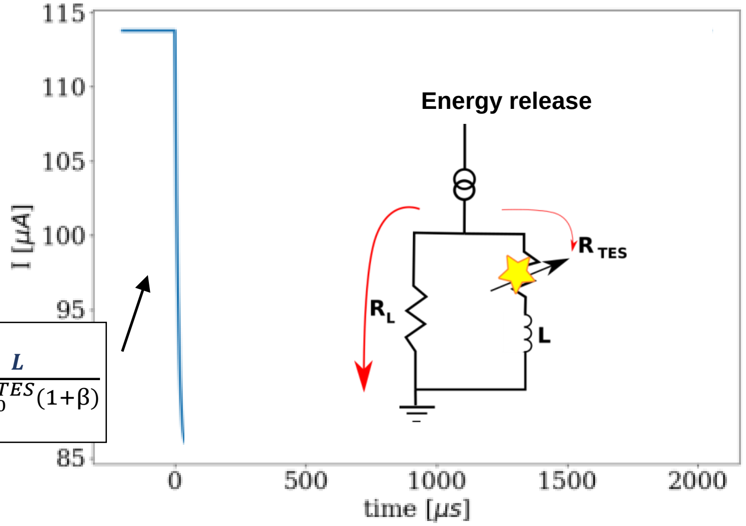
$$
\begin{cases}
L\dfrac{dI}{dt} = V - IR_{sh} - IR_{TES}(T,I) \\
C\dfrac{dT}{dt} = -K(T^n - T_b^n) - K_d(T^{n_d} - T_d^{n_d}) + P_J + P \\
C\dfrac{dT_d}{dt} = K_d(T^{n_d} - T_d^{n_d})
\end{cases}
$$





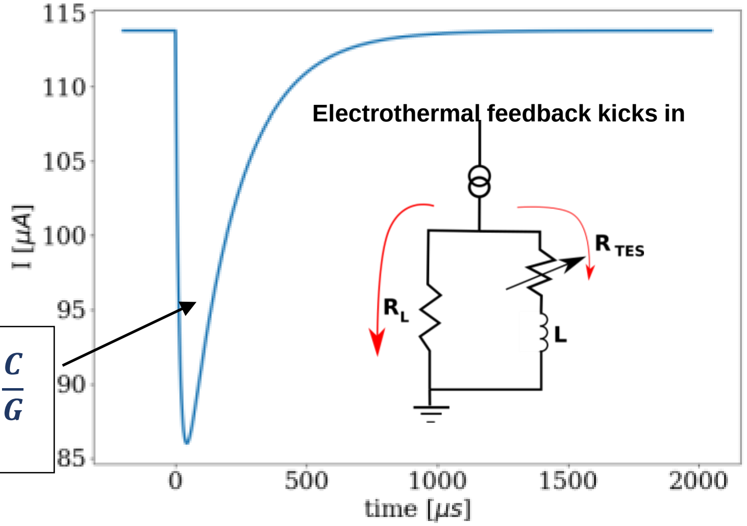
Idle current

$\tau_{rise} \propto \dfrac{L}{R_L + R_0^{TES}(1+\beta)}$

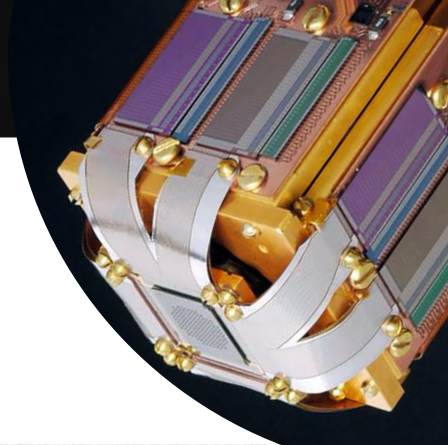


Energy release

$\tau_D \propto \dfrac{C}{G}$

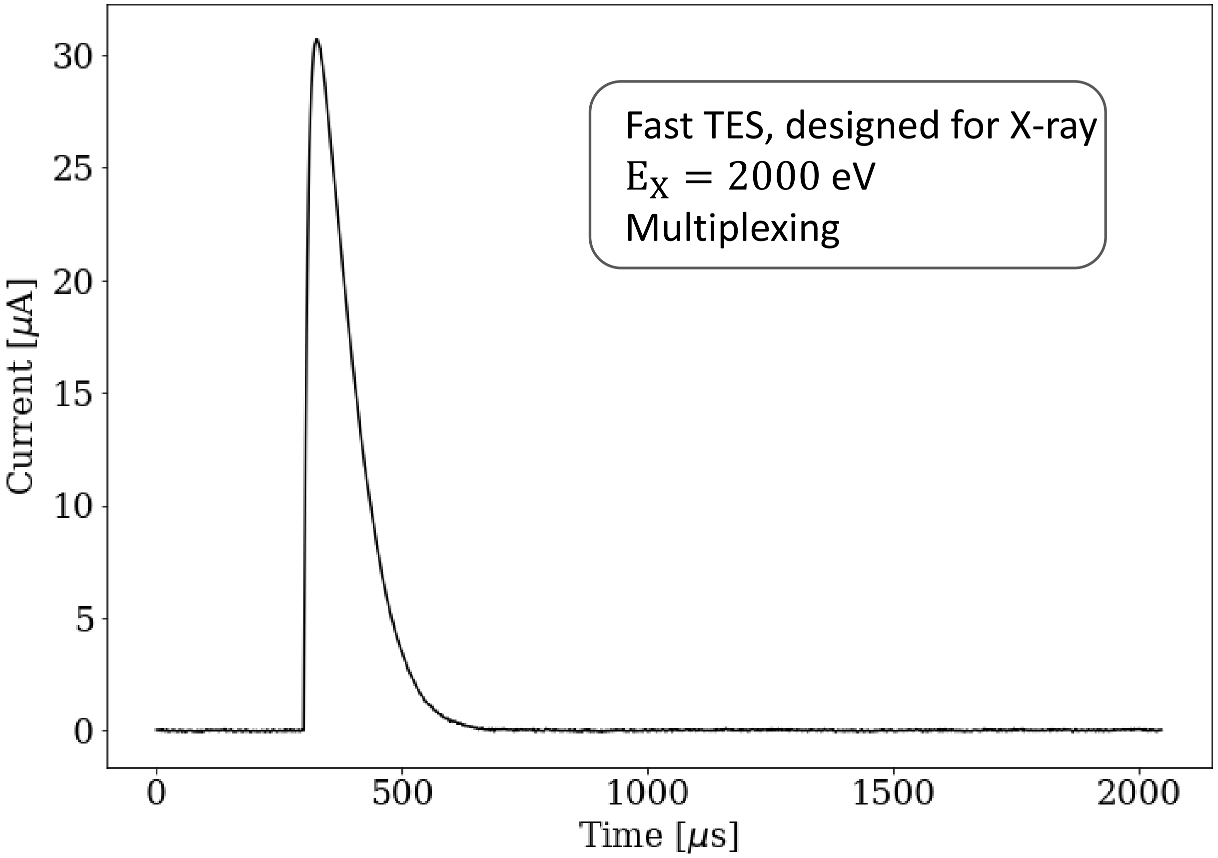


Electrothermal feedback kicks in

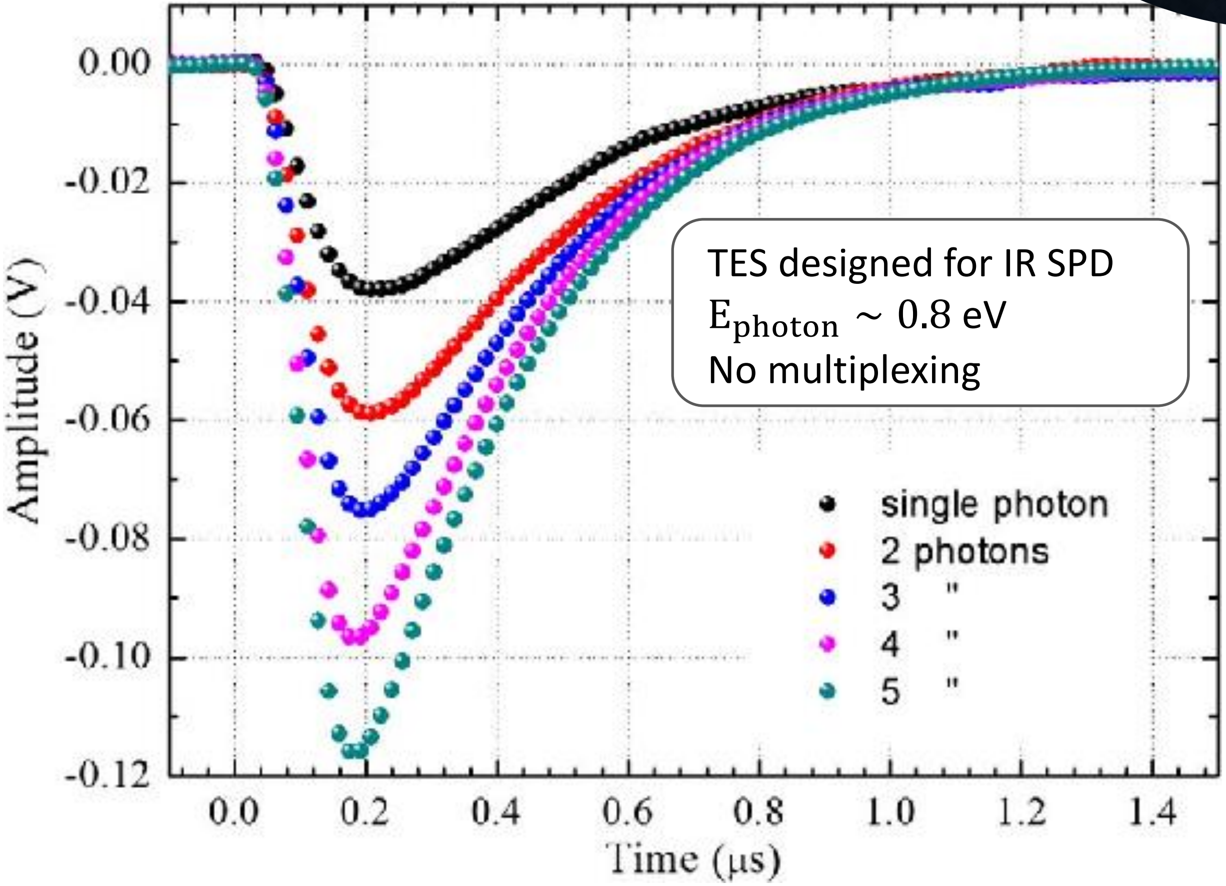


TES signal shape

- Tuning the parameter of the electrical circuit (and of the TES), the signal time can remarkably change



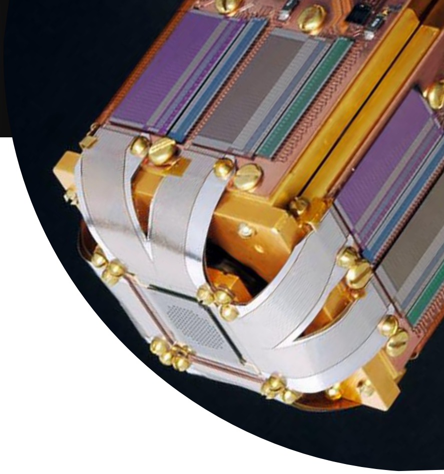
Fast TES, designed for X-ray
$E_X = 2000$ eV
Multiplexing



TES designed for IR SPD
$E_{photon} \sim 0.8$ eV
No multiplexing

DOI: 10.1109/TASC.2013.2238981

Cryogenics: from 300K to 20mK



Mechanical cryocooler from 300K to 4K

Thermodynamic cycle on sealed 4He gas

- Plug and play
- Consume “only” electricity
- Small vibration

From 4K to mK

$^{3}\mathrm{He}/\,^{4}\mathrm{He}$ diluition refrigerator

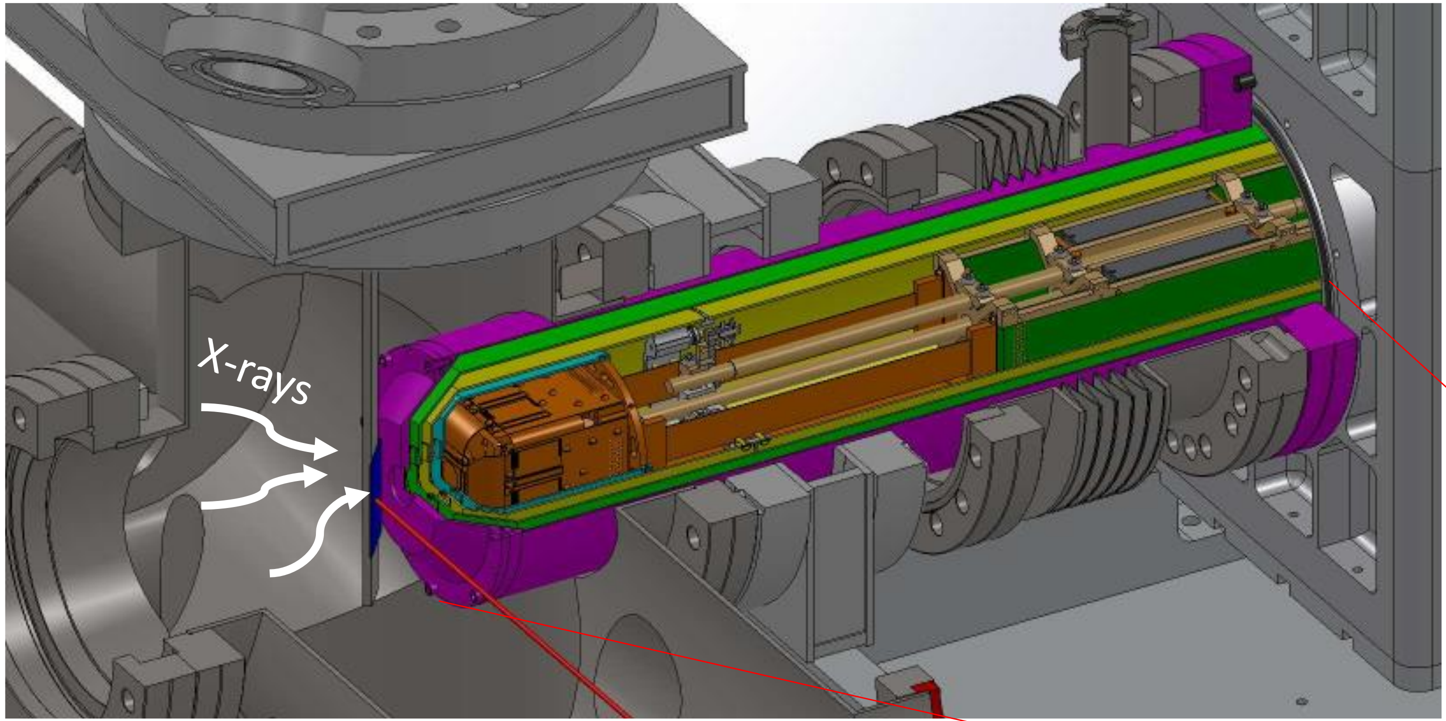
- $\mathrm{T_{min}} \sim$ 10 mK
- Infinite operation time (duty cycle 100%)
- 3He/4He mixture
- Not compact

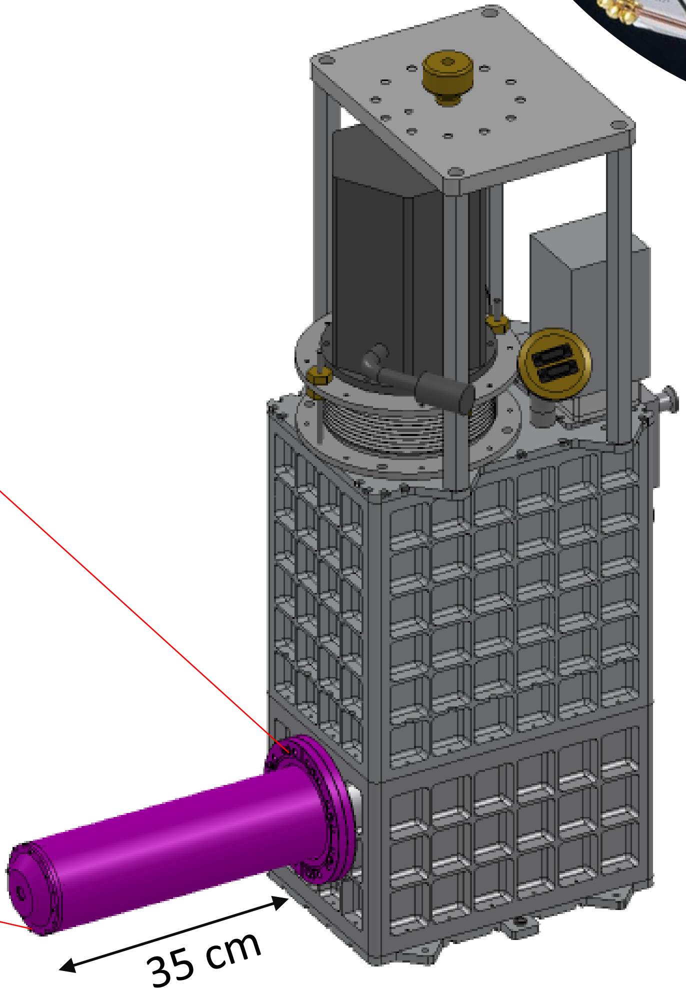
Adiabatic demagnetization refrigerator (ADR)

- $\mathrm{T_{min}} \sim$ 50 mK
- Good operation time (duty cycle $\sim$ 85%)
- No liquid cryogenic
- “Compact” !

Cryogenics: shields

- Different shields in order to: keep the vacuum, block the thermal radiation and the magnetic fields.
  X-ray transmitting windows: commercial polymer and thin Al foil.





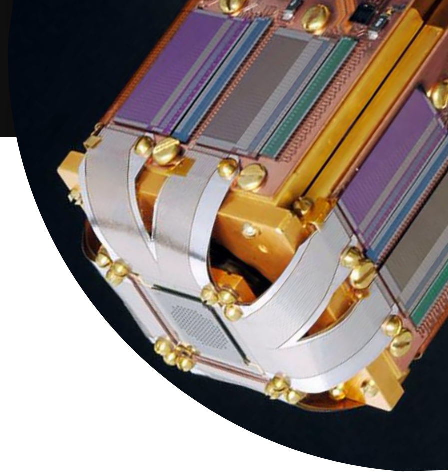
[300 K] Stainless steel vacuum shield

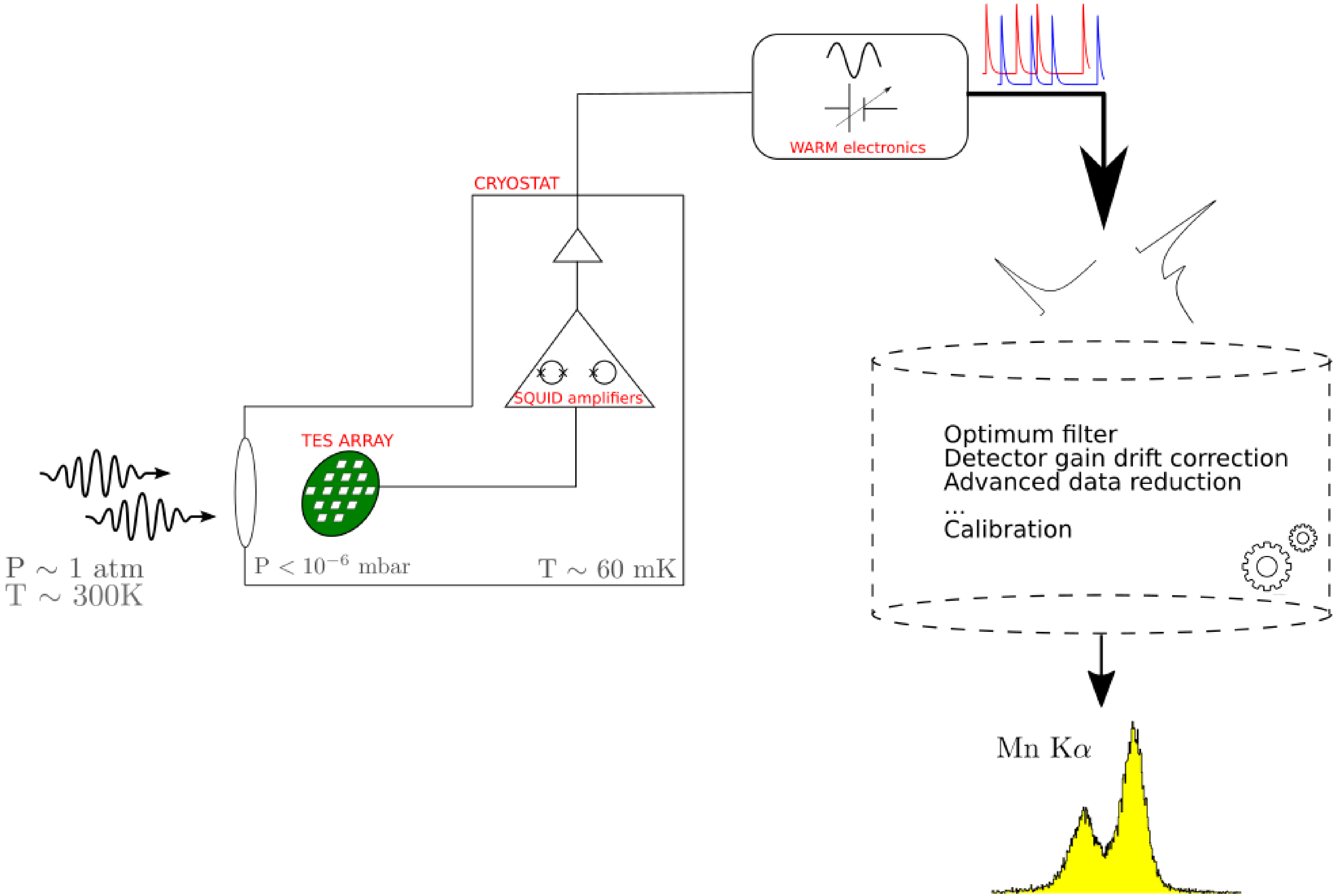
[50K/3K] Mu-metal shield with Al radiation window

[65 mK] Al shield with Al radiation window

https://doi.org/10.1063/1.4983316

Measurement workflow with an array of TES

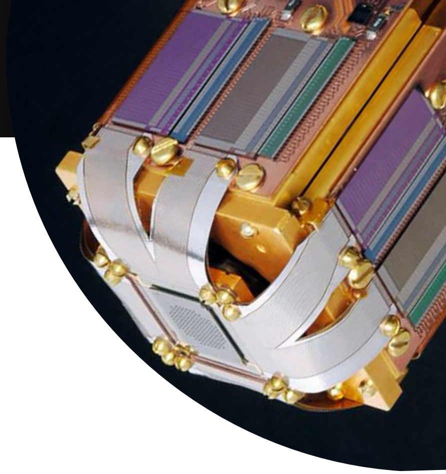




Optimum filter
Detector gain drift correction
Advanced data reduction
…
Calibration

e.g. : 100 cps x 250 det x 24h
=
O(10) Tb triggered pulse data

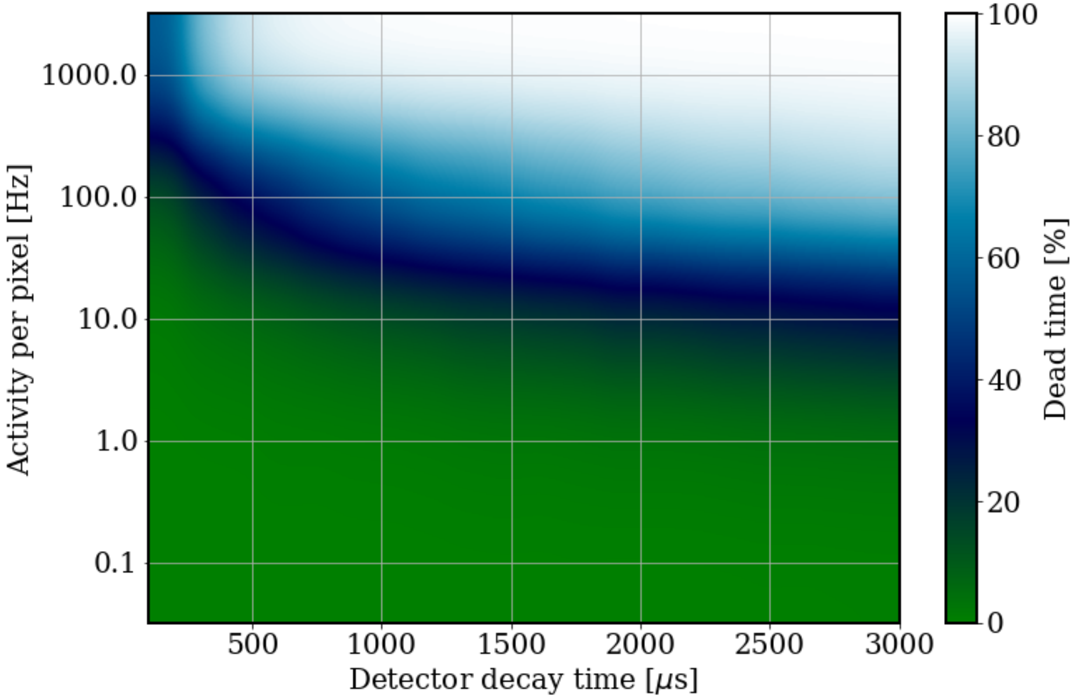
Reducing the dead time



- The analysis of microcalorimeters designed for X-rays requires grate care, because their excellent intrinsic energy resolution can hardly be achieved without an accurate analysis

- The amplitude (**energy**) of an event is **evaluated with the optimum filter technique**

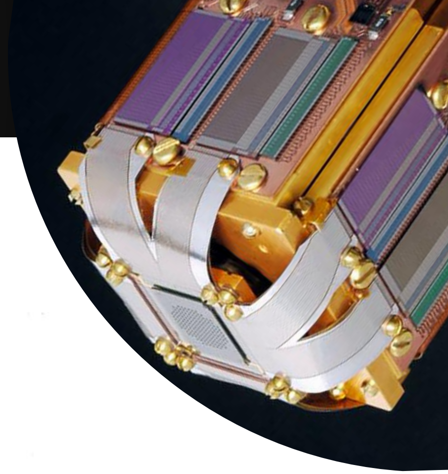
To not spoil the energy resolution, all the sample of the signals need to be recorded



- Given a source activity, faster TES and/or larger array are needed to reduce the dead time

- **Efficient multiplexing schemes to readout large array of TESs are as important as the detectors themself**

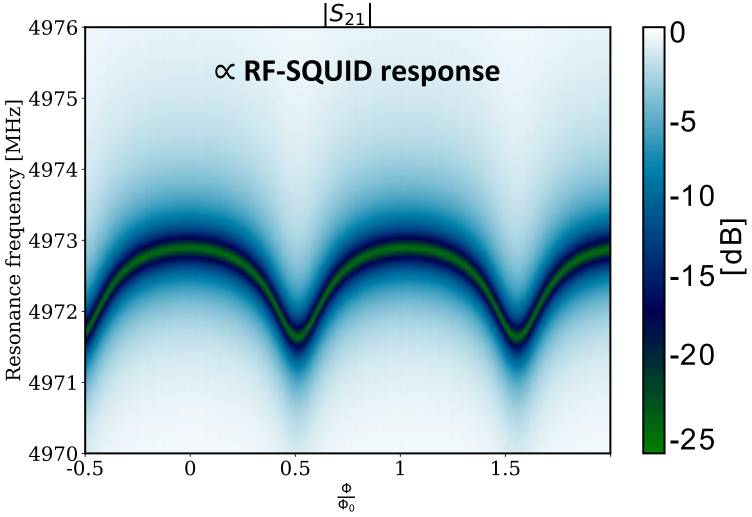
Readout: SQUID!



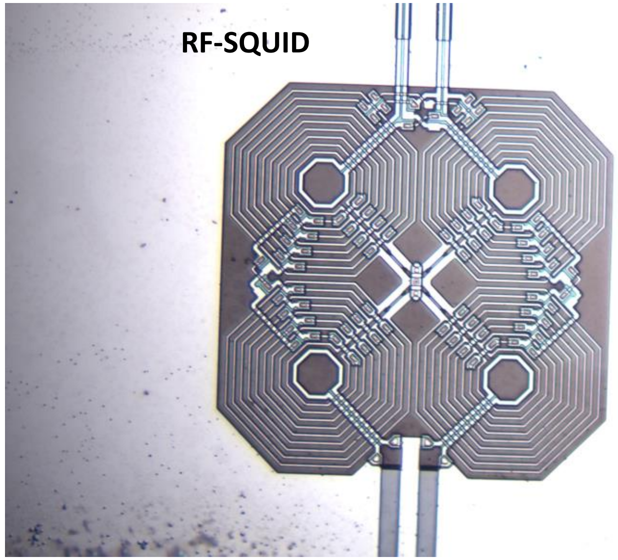
- The **TES is measured using SQUID**: Superconducting loop with two (DC-SQUID) or one (RF-SQUID) Josephson junctions
  - Most sensitive detectors of magnetic flux known

$$\text{Able to detect} \sim 2 \times 10^{-21} T \frac{m^2}{\sqrt{Hz}} = 10^{-6} \Phi_0 / \sqrt{Hz}$$

  - Very large operational bandwidth: quasistatic → > 1 GHz
  - Their response to a variation of magnetic flux is a non invertible function



- TES current seen as a variation of magnetic flux

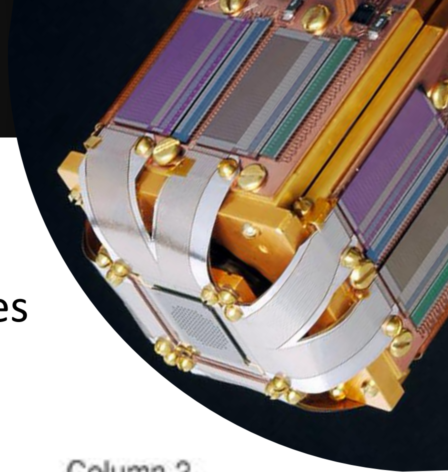


- Requirement to readout a single TES pixel with a DC SQUID
  - 5 cable from 300K to mK
  - $O(10)$ k€ for the warm electronics

⬇

Unsustainable for multi-pixel array

Readout: multiplexing



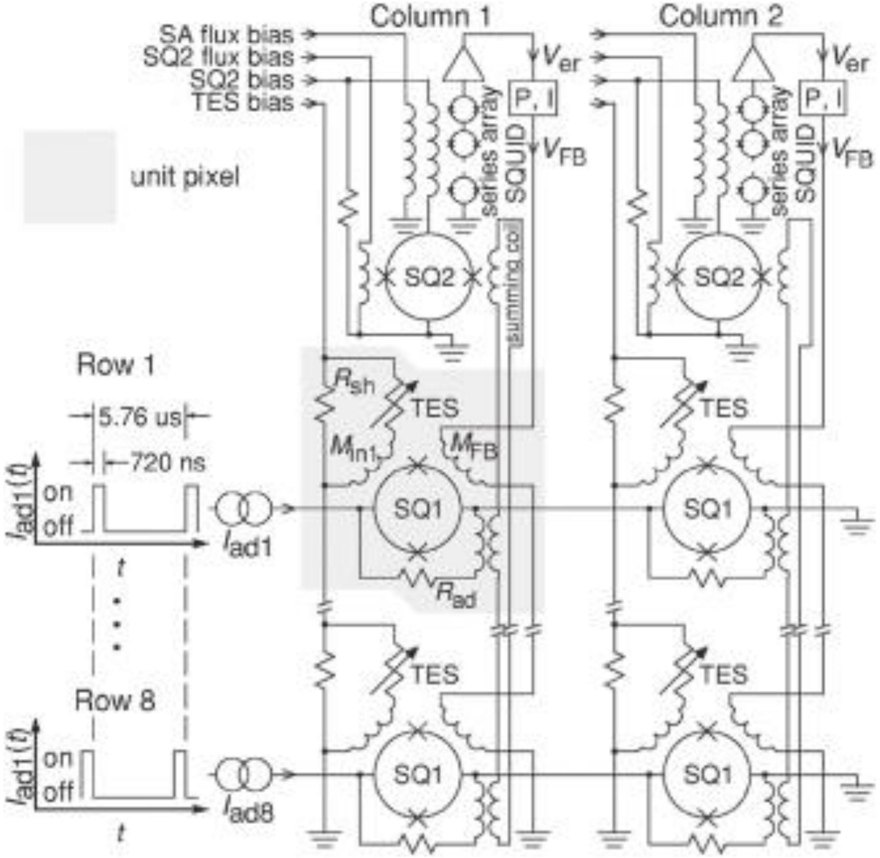
- Large TES array is needed to boost collection efficiency and count rate.
- Multiplexing (combination of different sensor signals into a smaller number of channel) is crucial it reduces the mechanical, thermal (and financial) burden of having readout circuitry for each pixel.

Time Domain Multiplexing (TDM)

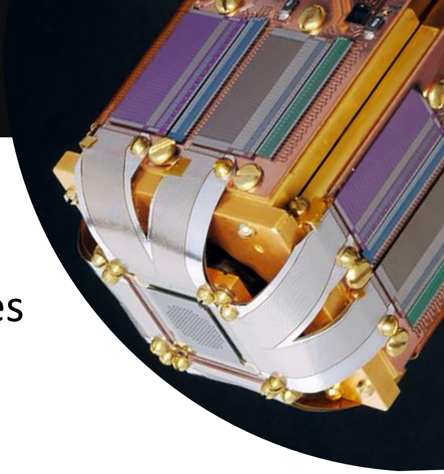
- IDEA: separating the signal in time domain
- DC-SQUIDS
- **Most mature technology**
- **Simplest operational stage**
- $\sqrt{\# \, channels}$ noise penalty
- $\mathrm{f_{samp}} \simeq \frac{1}{2 \times channels \times 160 \; ns}$
- 40:1 multiplexing readout best
- $\Delta E = 2.4$ eV with 32 multiplexed TDM TES

e.g. : 32 channel → $\mathrm{f}_{\mathrm{samp}}^{max} \simeq 100$ kHz

https://doi.org/10.1088/0953-2048/28/8/084003



Readout: multiplexing



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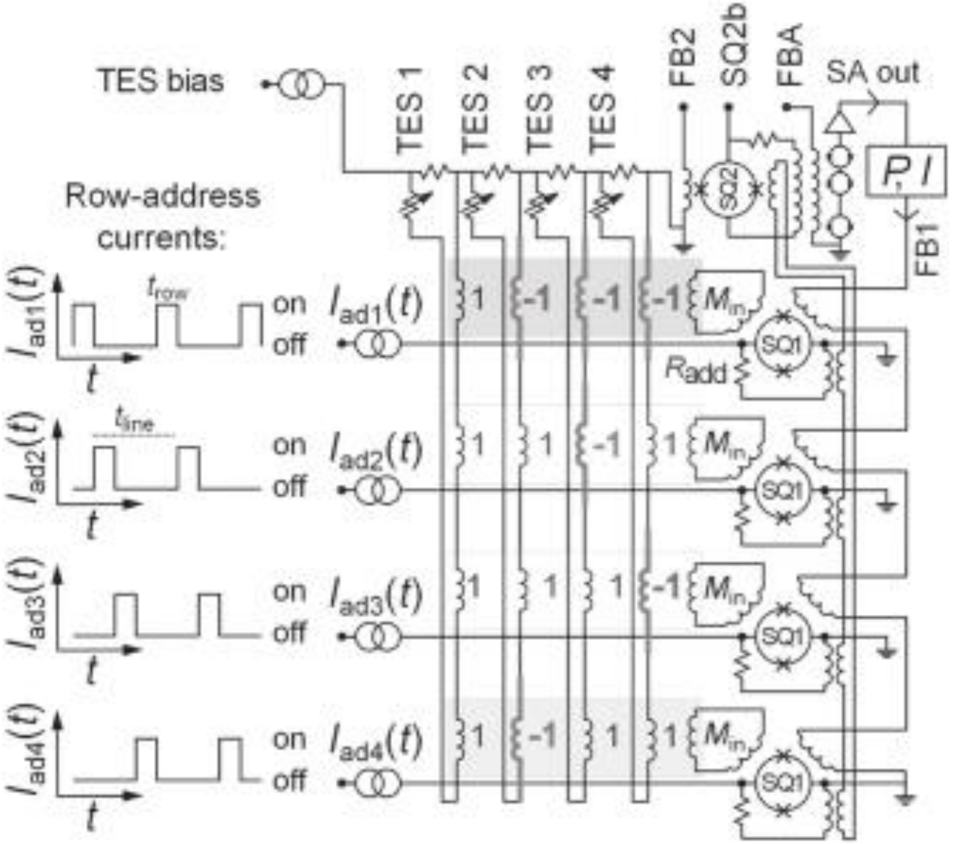
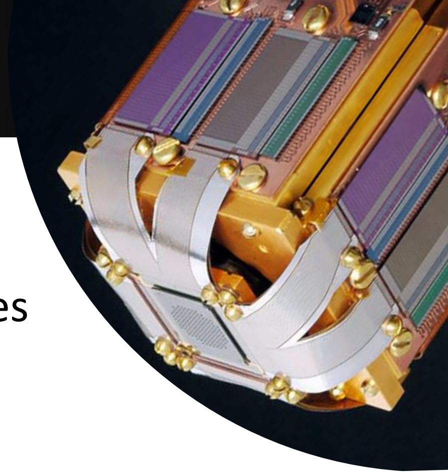
CDM

- IDEA: separating the signal in time domain, but smarter
- DC-SQUIDS
- No $\sqrt{\#\, channels}$ noise penalty
- **Capability of readout mega-pixel array** but demonstrated at small pixel counts
- Technology in development
- $\Delta E =$ 2.7 eV with 30 multiplexed CDM TES



Readout: multiplexing



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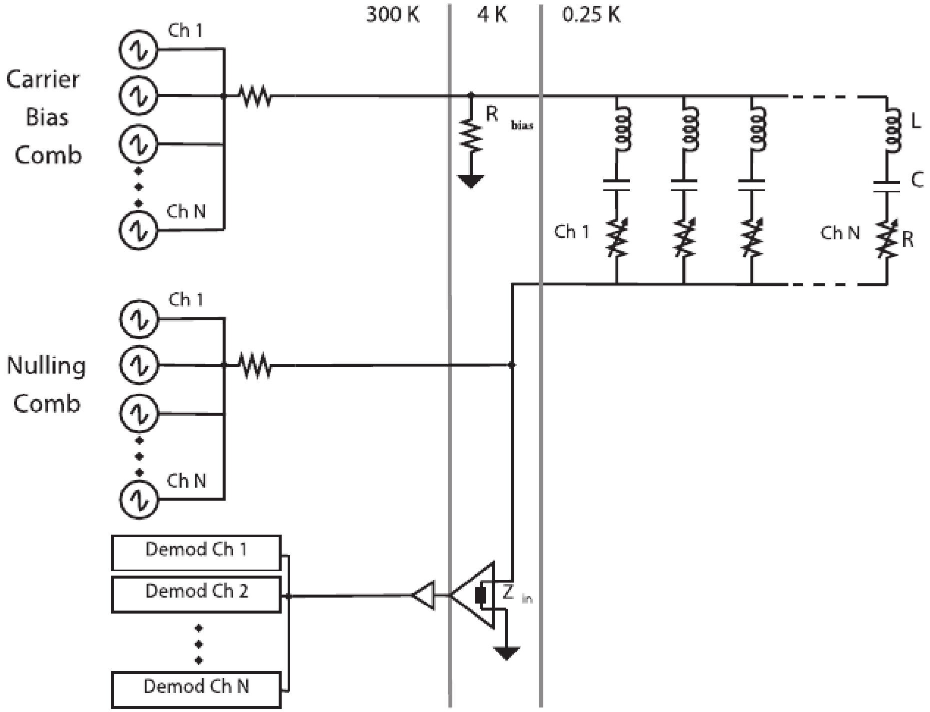
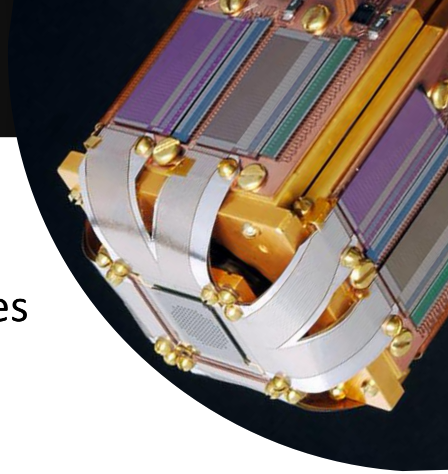
Frequency Division Multiplexing (FDM)

- IDEA: separating the signal in frequency domain
- DC-SQUIDS
- No $\sqrt{channels}$ noise penalty
- Limited dynamic range (the BW of the SQUID is dived into the different channels)
- Unwanted noise features due to non-trivial shape of the TES resistance
- **It's possible to tune the bias for each sensor**
- Amplitude modulator
- $\Delta E = 2.2$ eV with 37 multiplexed FDM TES



Readout: multiplexing



- Large TES array is needed to boost collection efficiency and count rate.
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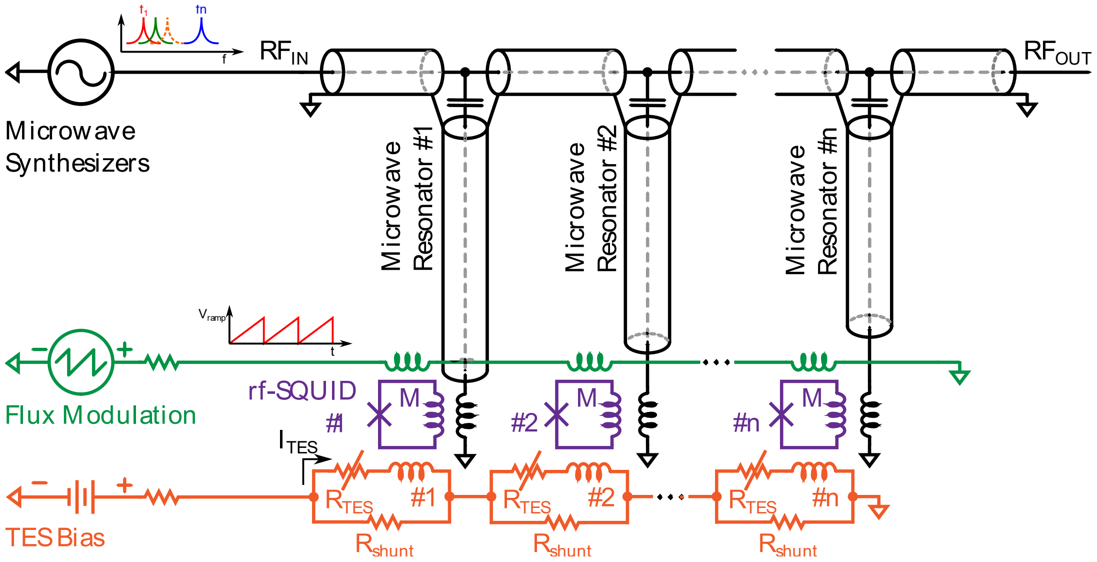
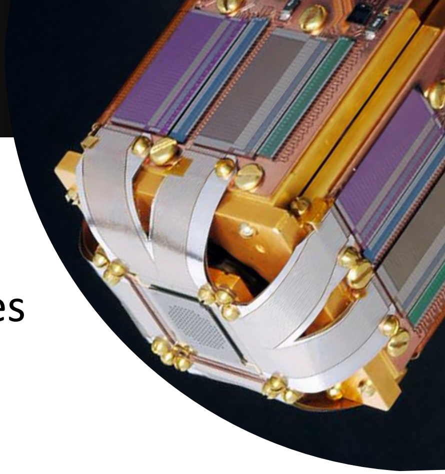
Microwave Multiplexing (μw-MUX)

- IDEA: separating the signal frequency domain
- RF-SQUIDS
- Higher noise
- High dynamic range (the BW of the HEMT id divided into the different channels
- New technology!
- **Capable of 256:1 multiplexing with a $f_{\mathrm{samp}}^{max} \simeq 500$ kHz**



Readout: multiplexing



- Large TES array is needed to boost collection efficiency and count rate.
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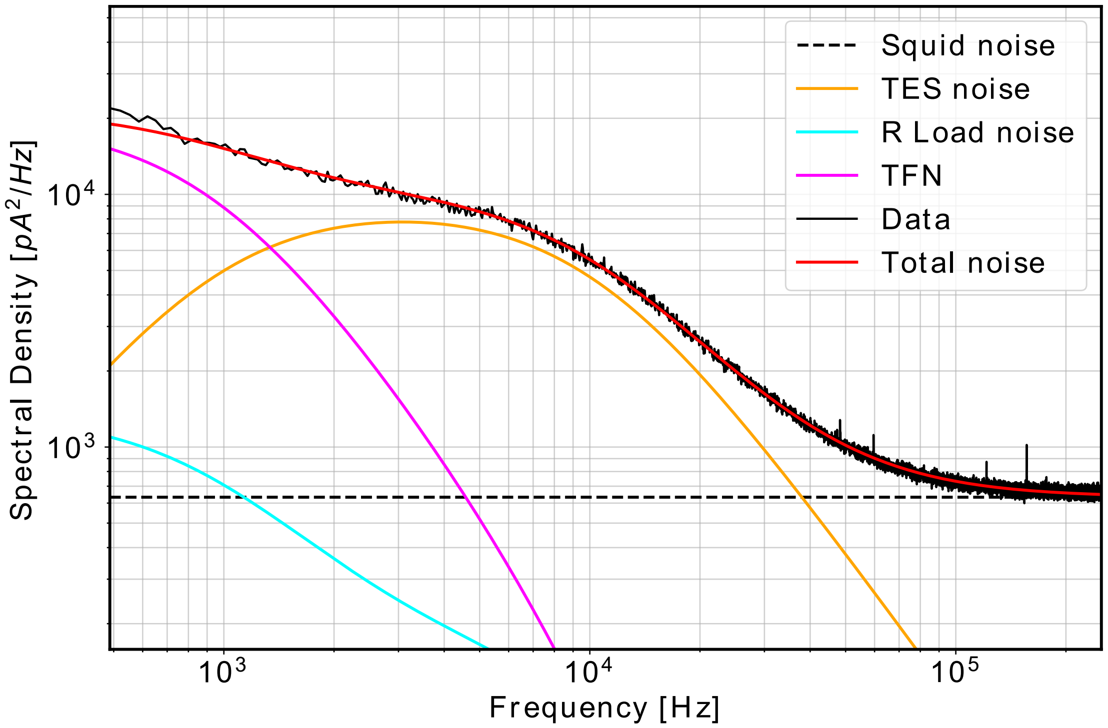
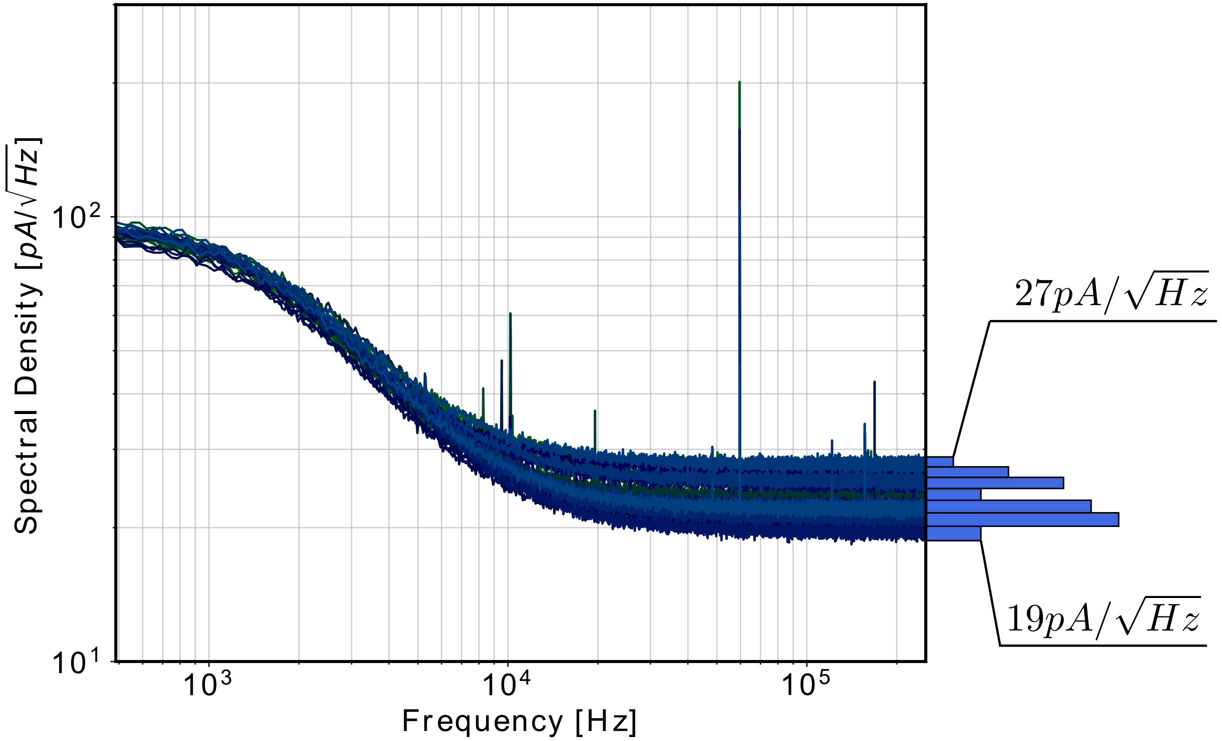
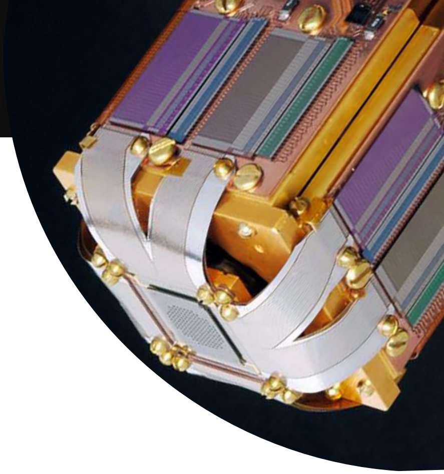
Noise of a single TES readout with uw-MUX



Noise of a 32 TES detectors readout with uw-MUX



TES application: energy dispersive X-ray spectroscopy

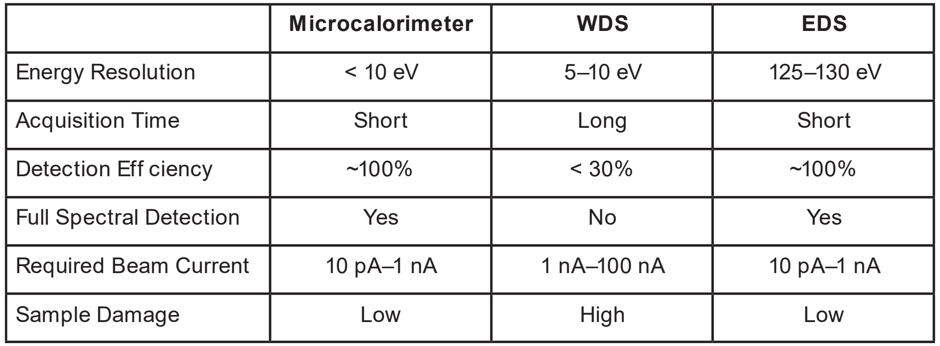


Semiconductors detectors:
- Poor energy resolution
- High count rate

TES

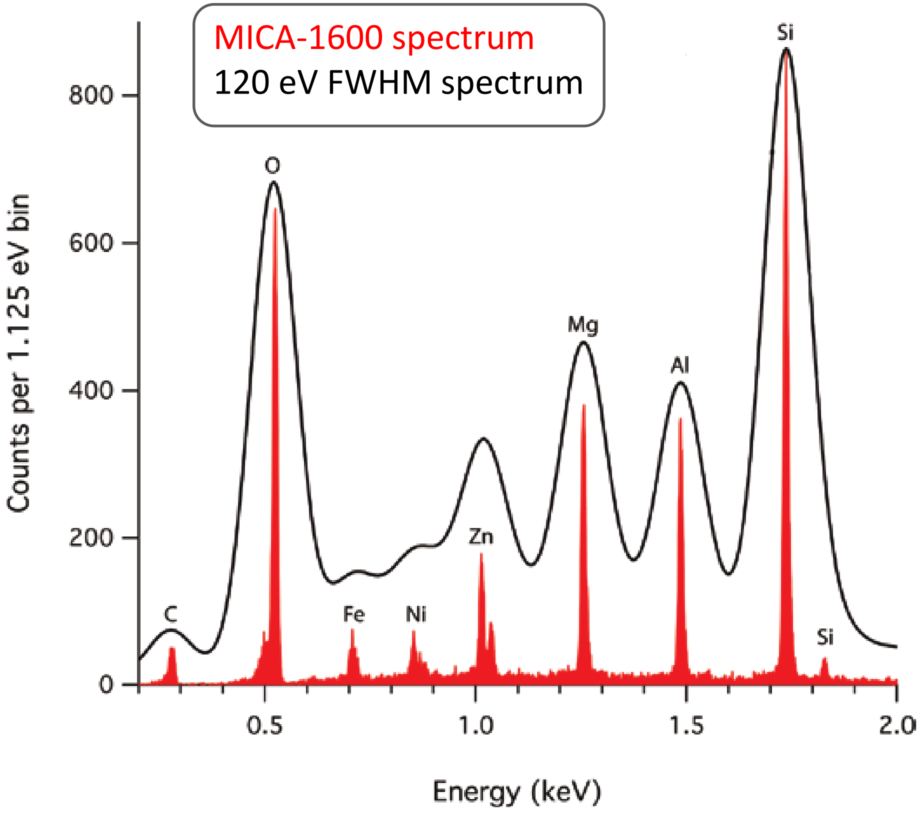
Wavelength dispersive spectrometers
- High energy resolution
- Slow, hard to operate

- **MICA-1600 commercial TES spectrometer** by Star Cryoelectronics
  - ADR refrigerator
  - Array of 16 TES
  - TDM multiplexing ?
  - Maximum count rate 10 kcps

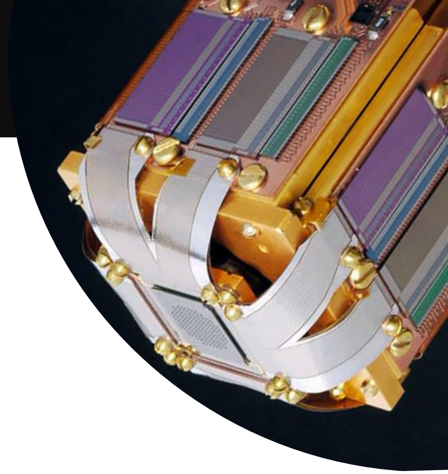


	Microcalorimeter	WDS	EDS
Energy Resolution	< 10 eV	5–10 eV	125–130 eV
Acquisition Time	Short	Long	Short
Detection Efficiency	~100%	< 30%	~100%
Full Spectral Detection	Yes	No	Yes
Required Beam Current	10 pA–1 nA	1 nA–100 nA	10 pA–1 nA
Sample Damage	Low	High	Low

https://doi.org/10.1017/S1551929512000429



TES application: X-ray spectrometer for beamline

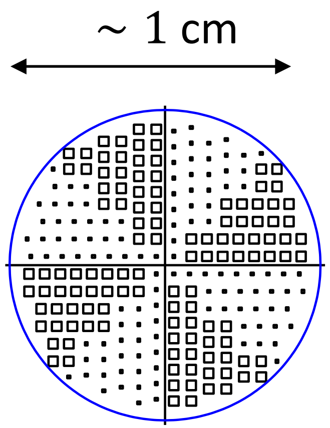


65 mK compact detector package

TDM multiplexing chip

- f_{samp} ~100 kHz

Bias resistor and inductors



Chip of 240 detectors
Two tipes of Mo/Cu TES:

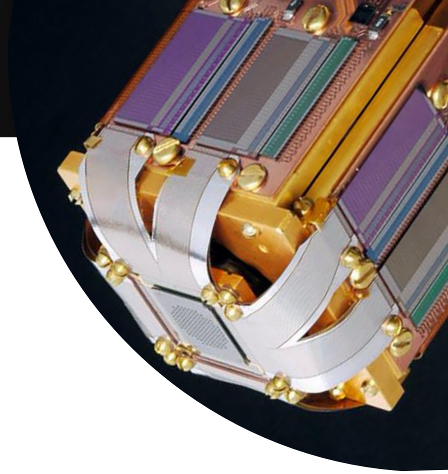
124 um with Bi absorber (2.5 um thick)

- soft X-rays
- E_{max} = 2.1 keV
- ΔE = 1.1 eV (@500 eV)

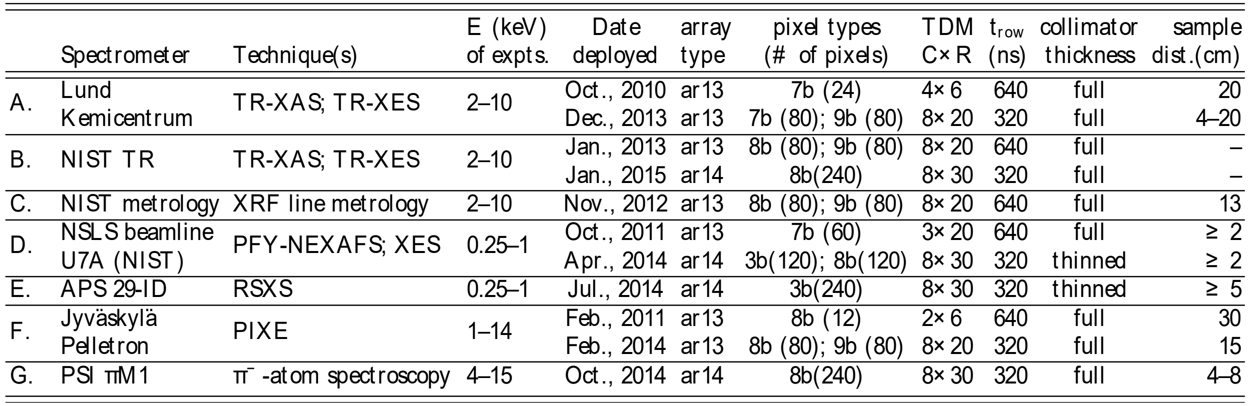
350 um with Bi absorber (4.1 um thick)

- hard X-rays
- E_{max} = 16.7 keV
- ΔE = 3.3 eV (@6keV)

TES application: X-ray spectrometer for beamline



- Seven working spectrometer systems deployed in different facilities

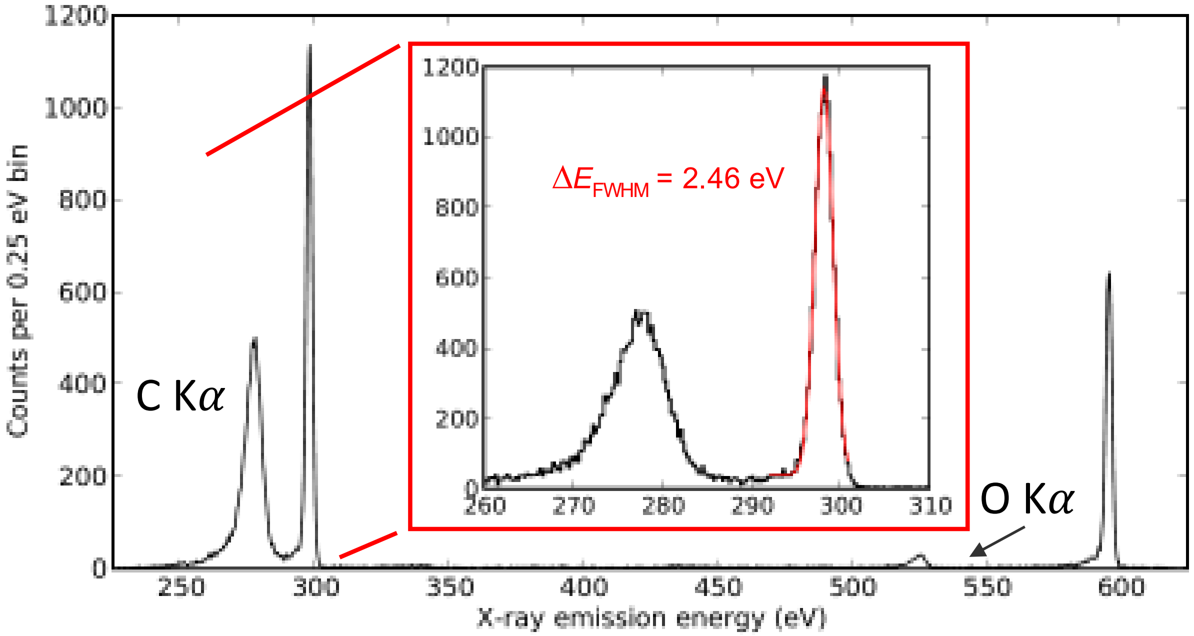


	Spectrometer	Technique(s)	E (keV) of expts.	Date deployed	array type	pixel types (# of pixels)	TDM C× R	t_{row} (ns)	collimator thickness	sample dist.(cm)
A.	Lund Kemicentrum	TR-XAS; TR-XES	2–10	Oct., 2010	ar13	7b (24)	4× 6	640	full	20
				Dec., 2013	ar13	7b (80); 9b (80)	8× 20	320	full	4–20
B.	NIST TR	TR-XAS; TR-XES	2–10	Jan., 2013	ar13	8b (80); 9b (80)	8× 20	640	full	–
				Jan., 2015	ar14	8b(240)	8× 30	320	full	–
C.	NIST metrology	XRF line metrology	2–10	Nov., 2012	ar13	8b (80); 9b (80)	8× 20	640	full	13
D.	NSLS beamline U7A (NIST)	PFY-NEXAFS; XES	0.25–1	Oct., 2011	ar13	7b (60)	3× 20	640	full	≥ 2
				Apr., 2014	ar14	3b(120); 8b(120)	8× 30	320	thinned	≥ 2
E.	APS 29-ID	RSXS	0.25–1	Jul., 2014	ar14	3b(240)	8× 30	320	thinned	≥ 5
F.	Jyväskylä Pelletron	PIXE	1–14	Feb., 2011	ar13	8b (12)	2× 6	640	full	30
				Feb., 2014	ar13	8b (80); 9b (80)	8× 20	320	full	15
G.	PSI πM1	π^- -atom spectroscopy	4–15	Oct., 2014	ar14	8b(240)	8× 30	320	full	4–8

Five more planned!

https://doi.org/10.1063/1.4983316

Example of a combined spectra of 60 detectors



TES application: X-ray astrophysics (ATHENA X-IFU)

- Instrument for X-ray imaging, timing and high-resolution spectroscopy on satellite

  Observation of hot gas and accretion around black holes

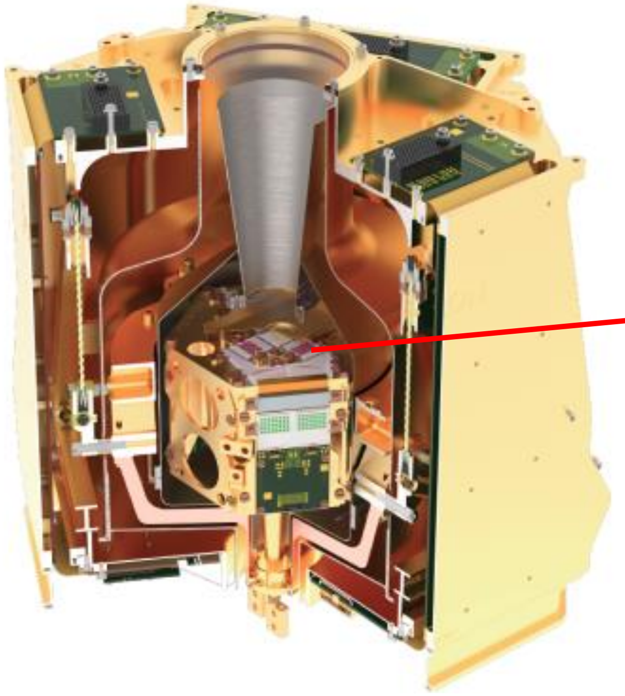
- Target: 3000 TES pixels ($T_c \sim 90$ mK, energy range 0.2-12 keV, $\Delta E = 2.5$ eV @7keV)

→

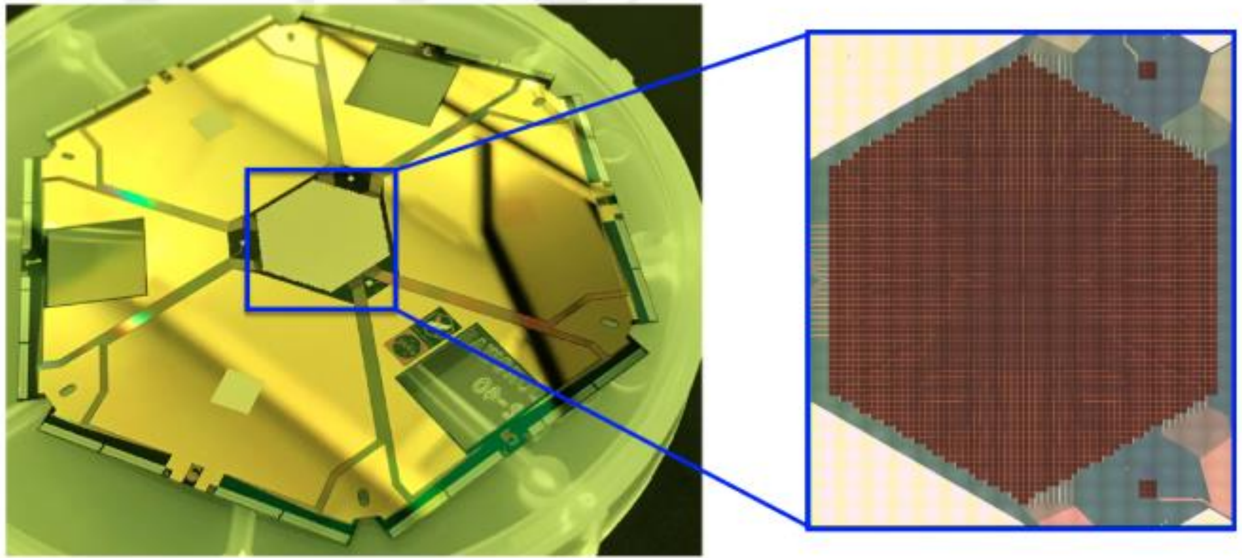
- Single pixel ΔE better than 2 eV
- Pixel filling factor better than 0.97

- Initially FDM, now TDM multiplexing?

X-IFU focal plane assembly model

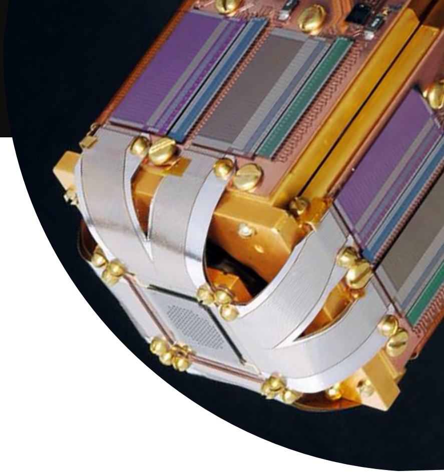


Prototype array from NASA-GSFC (3000 pixels)



https://doi.org/10.3390/app11093793

TES application: X-ray astrophysics (Lynx)

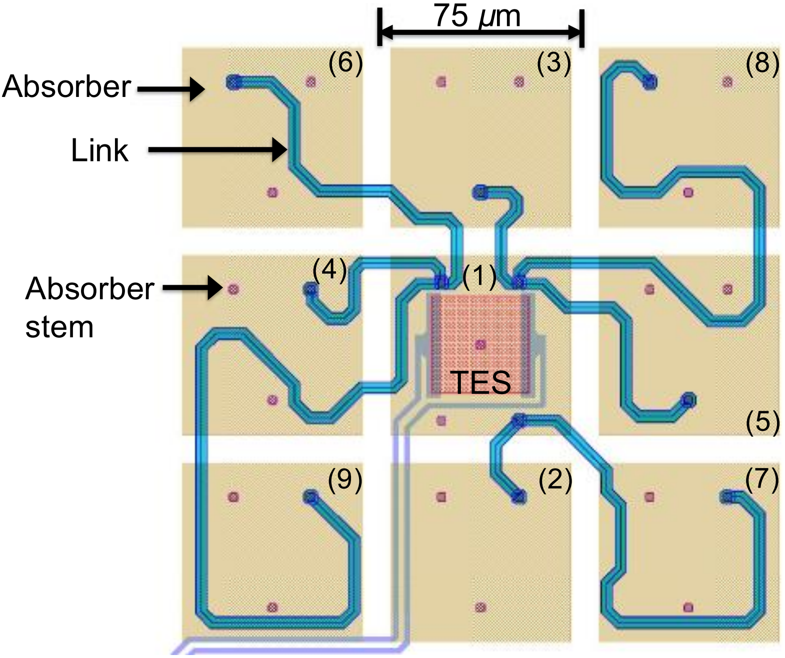


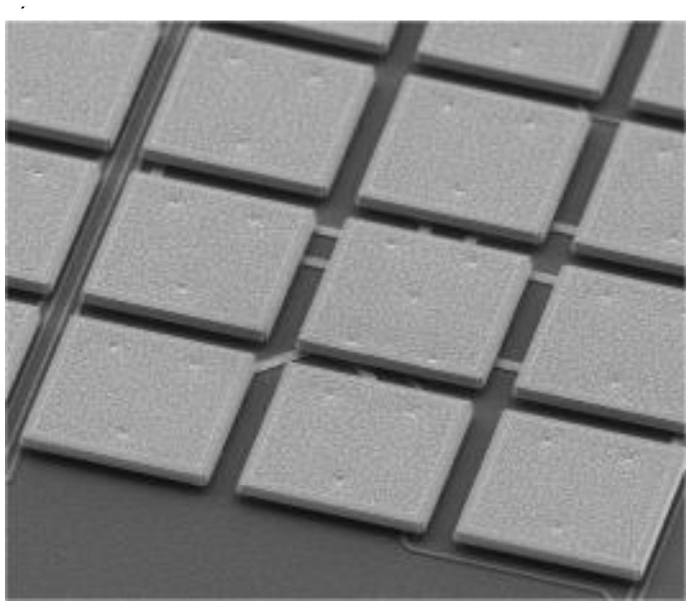
- Next generation X-ray observatory on satellite
- Ambitious goal: 100000 pixels!

Challenging requirements for the sensors and the readout

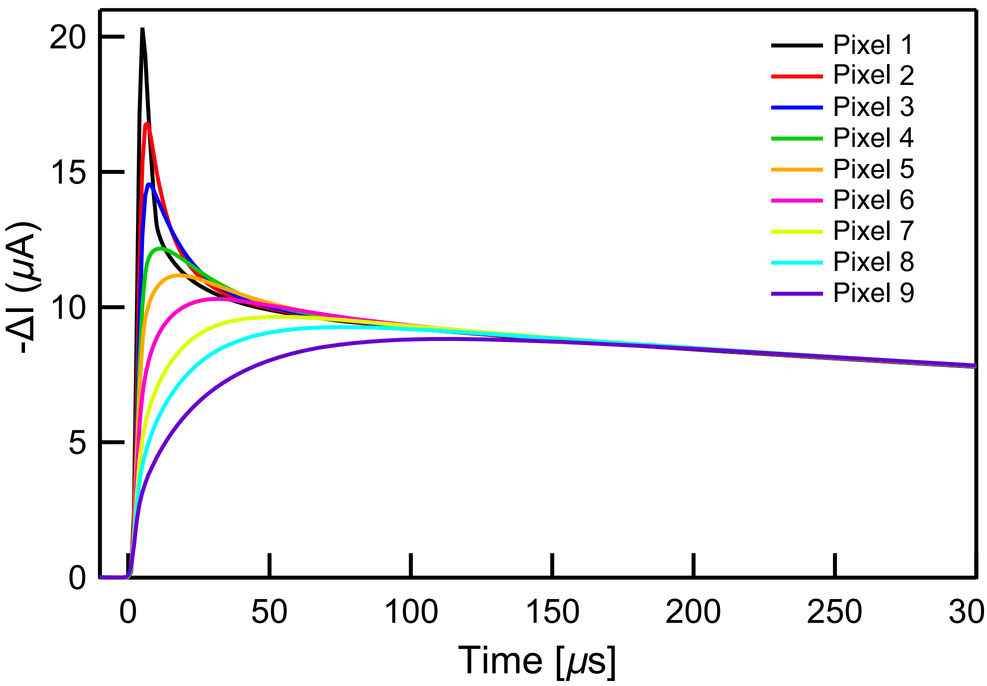
- Possible solution: hydra TES design and µw-MUX multiplexing

9-pixel hydra



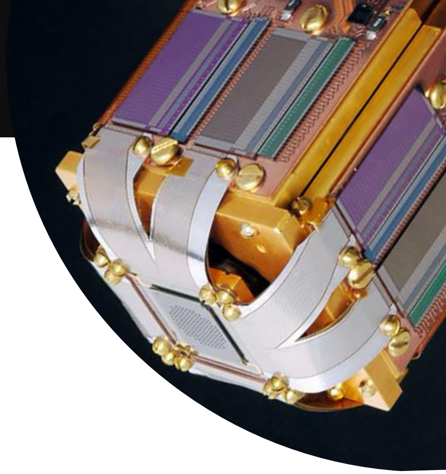


Pulses @6keV x-rays interacting in the different absorbers



https://doi.org/10.1117/1.JATIS.5.2.021008

Conclusions



- Superconducting Transition Edge Sensors are very high-resolution detectors for X-rays

- An array of Transition Edge Sensors is essential for practical applications. ➡ Multiplexing is important!

- Active field of research, multiple improvements expected in the next years!