Instrument Calorimeter-II-The microcalorimeters

Flavio Gatti
University and INFN of Genoa

Few historical notes

- The first calorimetric experiment was applied to the beta decay and has been made by Ellis and Wooster in 1927
- At that time it was the problem of understanding why "β-ray" were continuous spectra instead of "α-ray" that were emitted as mono-energetic lines by nuclei, as expected within the general framework of the quantum theory of the "disintegration of the bodies"

The Average Energy of Disintegration of Radium E.

By C. D. Ellis, Ph.D., Lecturer in the University of Cambridge, and W. A. Wooster, B.A., Charles Abercrombie Smith Student of Peterhouse, Cambridge.

(Communicated by Sir Ernest Rutherford, O.M., P.R.S.—Received August 3, 1927.)

After several trials the calorimeter which was finally used consisted of two lead tubes, 13 mm. long and 3·5 mm. diameter, each with a central hole of rather more than 1 mm. diameter. Each calorimeter fitted exactly into a thin outer sheath of silver, and were supported as shown in fig. 2 (*a*) by two discs of mica A and B, which in turn were carried by the brass screw C fitting into an ebonite base DE. The thermocouples were insulated by the thinnest mica possible, a sheet of the latter being attached to the calorimeter tubes by a very small quantity of soft wax. The thermocouples were laid on this sheet of mica with a little wax at the junctions, and then another piece of mica laid on top and the whole pressed together with a hot iron.* The two lead calorimeters were made as nearly alike as possible so as to minimise the effect of external variations of temperature on the difference of temperature between them. In order still further to reduce these externally induced temperature differences, the whole calorimeter system was placed in a small cavity in a copper block, as

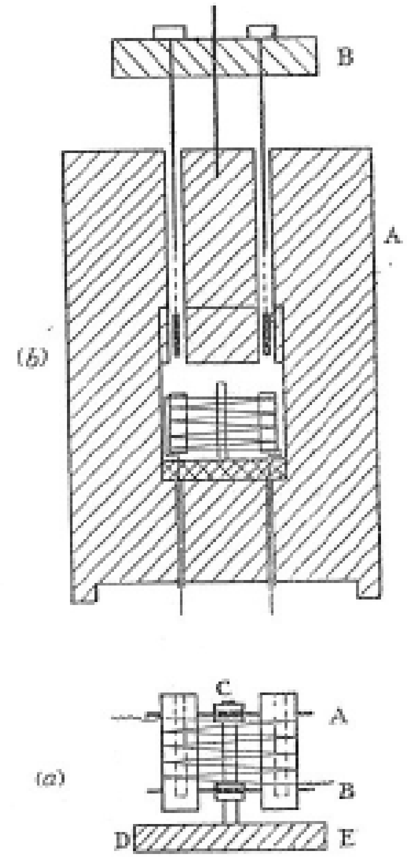


Fig. 2.

Interesting follow-up

- “ β-spectrum is continuum because of the slowing down in the material” (Lisa Meitner) or “in collision with atomic electron” (E.Rutherford)
- → ”Not conservation of energy” (N.Bohr)
- The results was $\langle E \rangle_{calorimeter} = 0.33 \pm 0.03$ MeV/atom against $E_{max} = 1.05$ MeV/atom
- → $E_{max} - \langle E \rangle$ “carried out by escaping particle”
- Pauli conjecture of the neutrino (1930)

→ First fully calorimetric detector of heat produced by particles, even if not able to detect single particle.

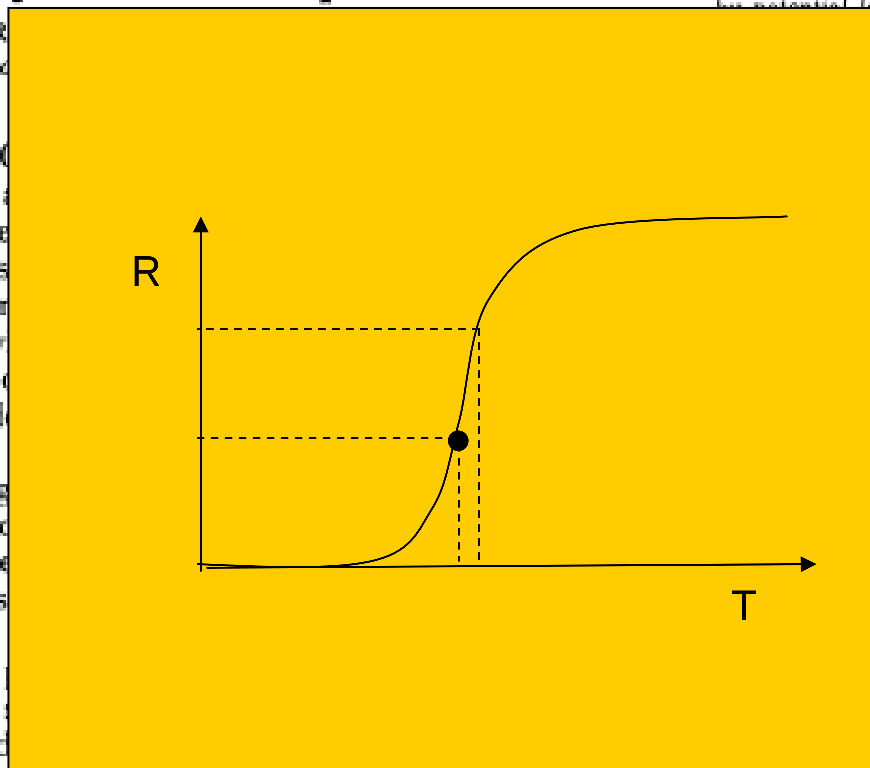
Cryogenic calorimeter

- Once the LHe and the superconductivity was discovered, several idea on thermal detection of single particle were proposed and tested.
- Big calorimeters were used at low temperature for studying fundamental properties of materials
- But in 1941, D.H. Andrews suggested first and executed in 1949 an experiment that anticipated the present most developed and advanced technology of microcalorimeters.

Single particle detection with thermal detector in1949: a technique incredibly similar to the present one

The Effect of Alpha-particles on a Superconductor*

D. H. ANDREWS, R
Chemistry Department, The Jo



SUPERCONDUCTIN
alpha-particles from a
countable electrical pulse
impact. The bolometer us
made of a strip of colur
×0.006 mm, mounted w
and maintained at the c
cryostat, as previously d
10^{-3} sec.

To provide a mounting
ca. 30 cm long and 3 cm d
facing the bolometer. The
this tube, placing it at dis
2 cm to 20 cm.

The source consisted of p
attached to the face of a s
10^{-6} cm was maintained
bolometer by a charcoal trap at liquid nitrogen temperature aided by the many contiguous surfaces at 15°K, so that the α-particles traveled from the source to the bolometer with no significant loss

TABLE I. Comparison of α-particle counts with ionization chamber and bolometer.

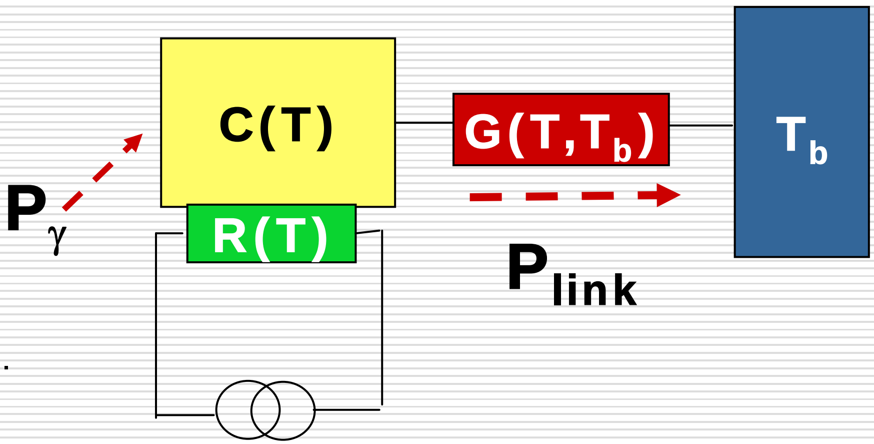
Distance from source to defining area: Average counts per second:	20 cm	2 cm
(a) Ionization chamber	40	740
(b) Bolometer	32	660

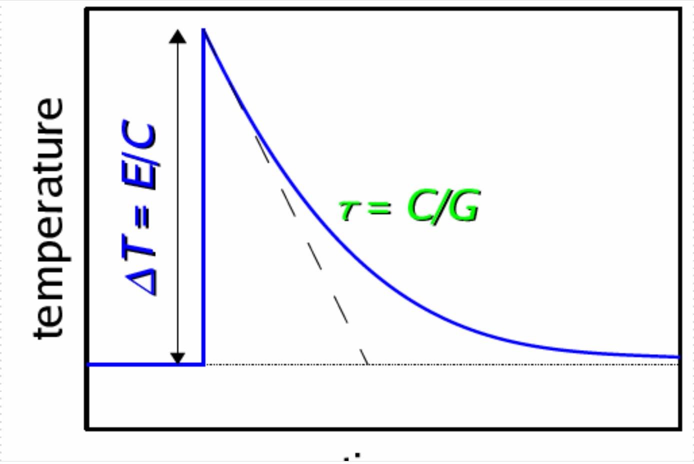
of energy. The bolometer was protected from general heat radiation by a shield held at 90°K. The α-particles passed through a hole in this shield, the opening being 7 mm diameter, in alignment with the bolometer.

The bolometer was connected to a direct current supply, and
ads to the primary of an audio transformer, the
hich led to a pulse amplifier, and thence to an
l scale-of-1000 counter.
counting was at a maximum when the CbN was
the center of the transition, half-way between
er conductivity; it was relatively constant over a
0.04° wide and fell sharply both above and below
re zone, being reduced approximately to noise
ease or decrease of 0.1°K. The electrical resistance
s 2ω in the normal state at 15°K.
of counts per second was also a function of the
lowing through the CbN, being at a maximum for
ma.
of α-particles counted with the bolometer agreed,
ble I, with the number counted with an ionization
near amplifier when the ionization chamber was
source through a slit system similar in geometry
olometer experiments. The ionization chamber slit
th a thin mica window, and the air pressure in the
t at 0.01 mm.
aphs of the peaks on the oscilloscope it is estimated
idual pulse from the bolometer is about 10^{-7} volt
second wide. The maximum signal to noise ratio
ce the pulse height may be expected to be propor-
ergy of the α-particle, experiments are being con-
ase the signal to noise ratio, in order to evaluate
th which the energy of individual particles can be
his method, and to determine the kind of pulses
produced when superconducting bolometers of this and other materials are exposed to different kinds of particle radiation. The authors wish to thank Professor Walter Koski and Mr. Carl Thomas for valuable advice and assistance.

* This work was supported in part by contract N5-ORi-166, Task IV, ONR U. S. Navy, and in part by a grant from Dr. H. A. B. Dunning.
[1] Andrews, Milton, and DeSorbo, J. Opt. Soc. Am. **36**, 518 (1946).

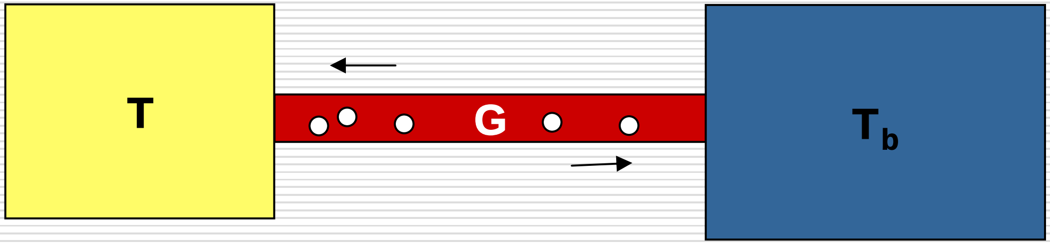
What is a Microcalorimeter for spectroscopy.





- A simple model of a microcalorimeter as tool for spectroscopy is composed by:
  - Absorber of heat capacity C
  - Thermal link with conductance G
  - Thermistor R(T)
  - Biasing and read-out circuit
  - Thermal bath

Why cryogenic calorimeter are so attractive? → "incredible" intrinsic energy resolution in single quantum detection



Phonons random motion

- T rms fluctuations determined by phonon brownian motion between the two bodies
- Average phonons $<N> = U/kT = CT/kT$
- Internal energy fluctuation $\Delta U_{rms} = (N)^{1/2} \times kT = (kT^2C)^{1/2}$
- RMS Intrinsic Energy Noise $\approx (kT^2C)^{1/2}$
- Ex: $T=0.1$ K, $C=10^{-13}$ J/K → $\Delta U_{rms} \approx 1$eV

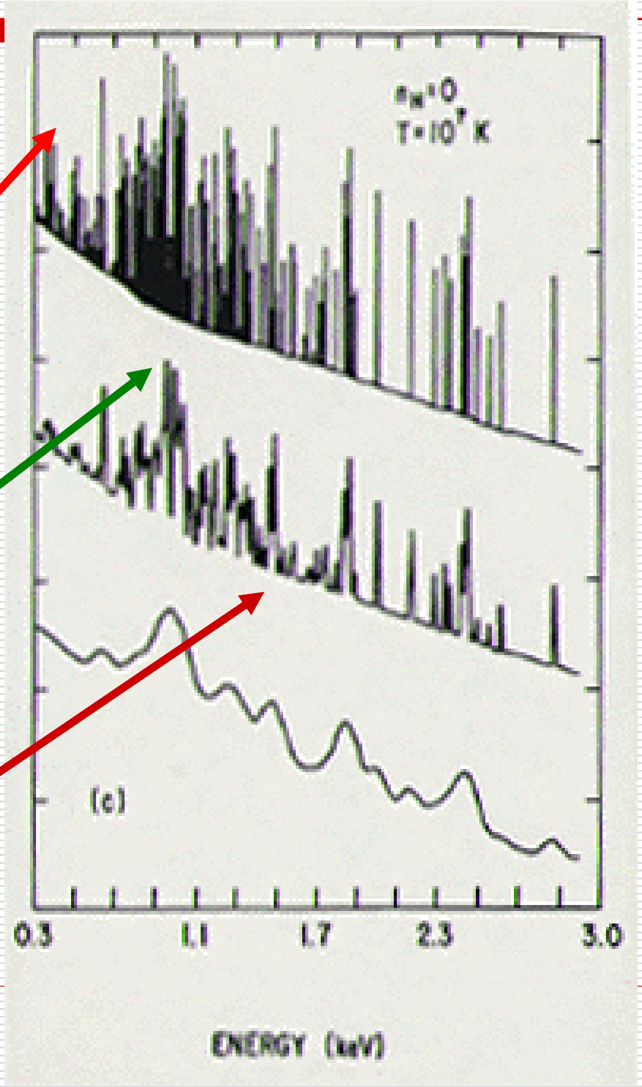
They can perform very high resolution Energy Dispersive X ray Spectroscopy (EDXRS). Ex.:hot plasma of ISM/IGM

plasma emission
(10^7K) observed with:

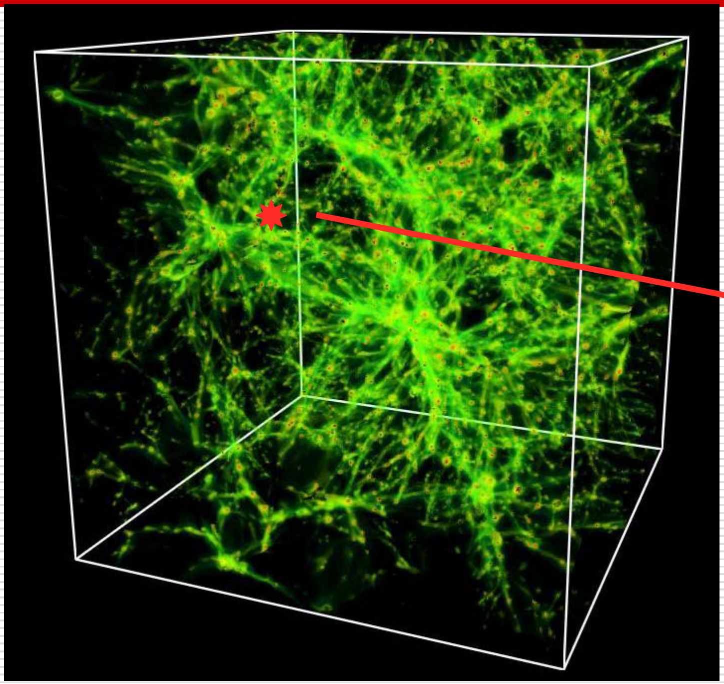
* Next generation (TES) ucal
(ΔE=2 eV: XEUS/Con-X)

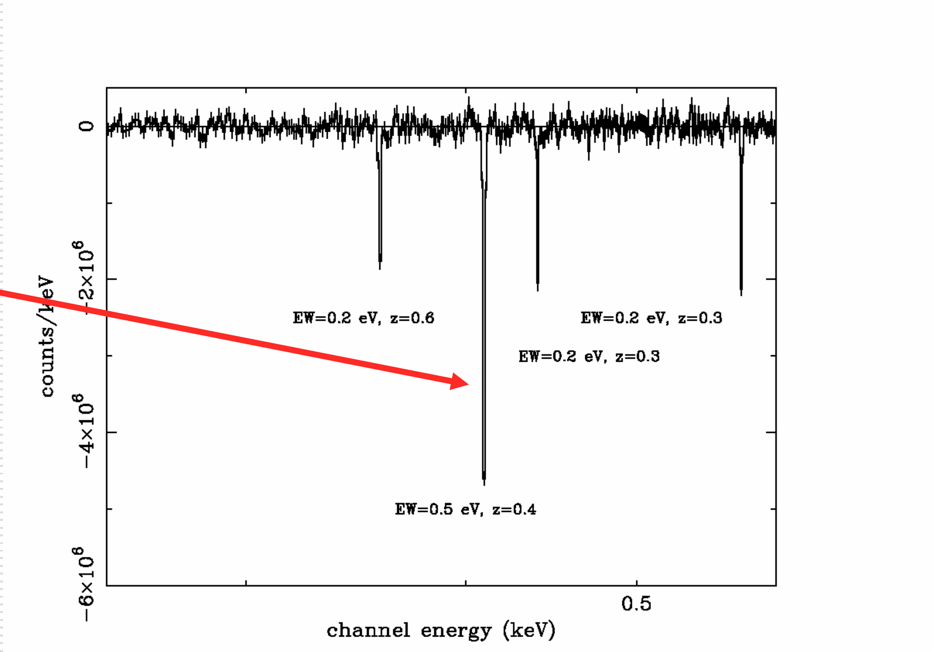
*present generation ucal
(ΔE=6-8 eV: ASTRO-E (?)

*CCD (DE=100 eV:XMM)



They can perform very high resolution Energy Dispersive X ray Spectroscopy (EDXRS). Ex: WHIM and Dark Matter

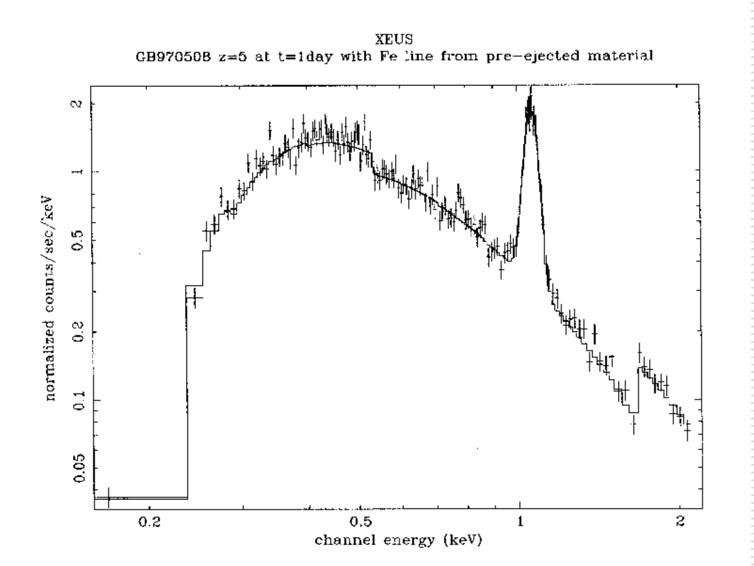


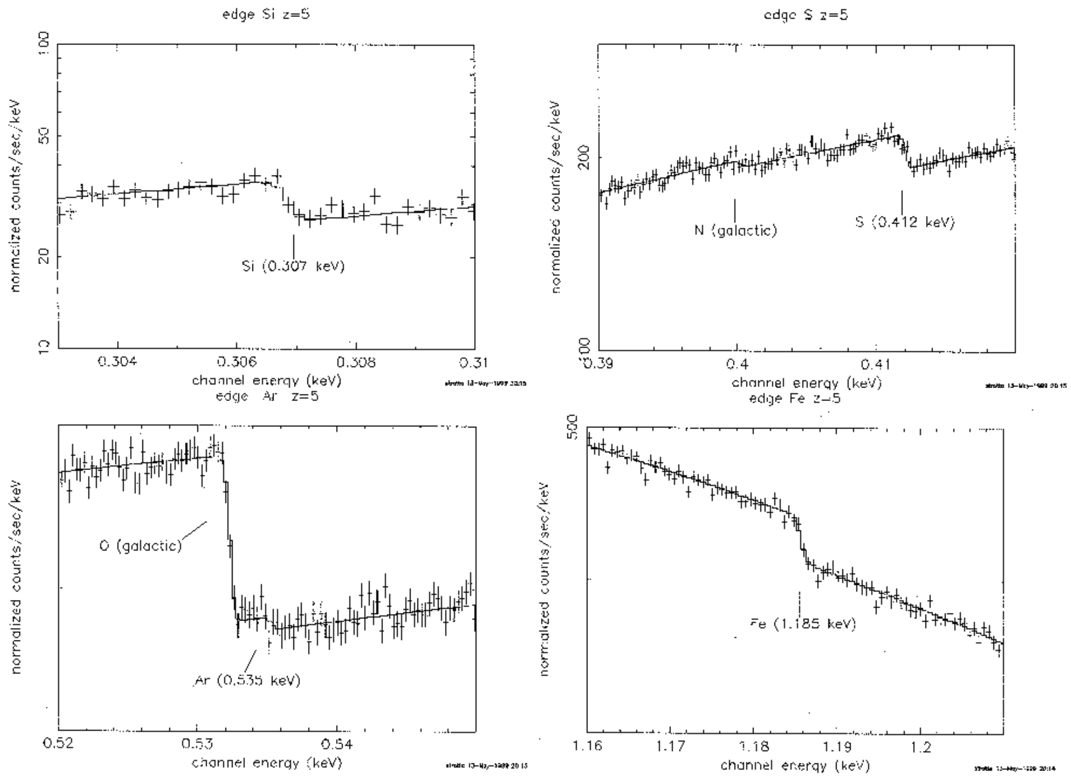


Simulations of WHIM absorption features from OVII as expected from filaments (at different z, with EW=0.2-0.5 eV) in the l.o.s. toward a GRB with Fluence=4 10^{-6} as observed with ESTREMO (in 100 ksec). About 10% of GRB (10 events per year per 3 sr) with 4 million counts in the TES focal plane detector

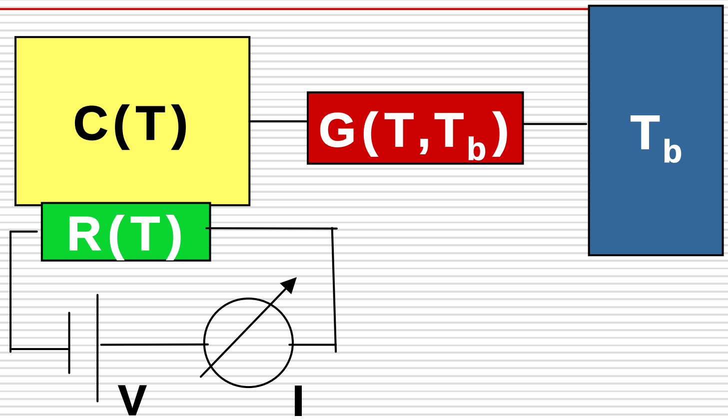
Ex: study of local and intergalactic medium in primeval galaxies with GRB with XEUS-like mission

- The Fe line in a GRB like GB970508 but at z=5
- Study of the metallicity of the ISM of a host galaxy of a GRB at z=5 through X-ray edges





Microcalorimeter model



- Steady state with only Joule power

$$W(T_0, T_b) = P_{J0}$$

- Thermal evolution at impulsive

$$C\frac{dT}{dt} + W(T, T_b) = P_J(t) + P_\gamma(t)$$

- Within the limit of small signal, the difference of the two powers, W(T,T$_b$) and W(T$_o$,T$_b$), flowing in the thermal link are approximated by the thermal conductance G x δT

$$W(T, T_b) - W(T_0, T_b) \cong \frac{dW(T, T_b)}{dT}\delta T = G\delta T$$

Microcalorimeter model

- As before, for small signals, we can approximate the differences of the two bias Joule power as follow

$$P_J(t) - P_{J0} \cong \frac{d}{dT}\left(\frac{V^2}{R}\right)\delta T = -\frac{V_0^2}{R_0}\frac{T}{R}\frac{dR}{dT}\frac{1}{T}\delta T \cong -P_{J0}\alpha\frac{1}{T_0}\delta T$$

in case of voltage biased microcalorimeter (Attention→only for voltage bias)

- Where the thermometer sensitivity: $\alpha = \frac{T}{R}\frac{dR}{dT}$

Microcalorimeter model

- Subtracting term by term the thermal equations and making the first order approx. the simplest equation of the microcalorimeter looks as follow

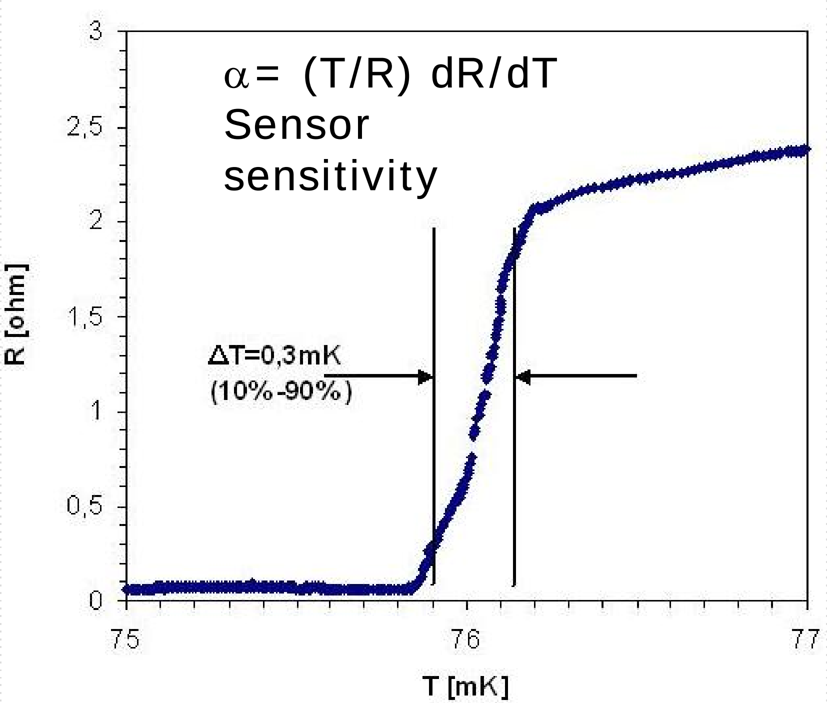
$$\frac{d\delta T}{dt} = -\frac{1}{C}\left(G + \frac{P\alpha}{T}\right)\delta T + P_\gamma = -\left(\frac{C}{G}\right)^{-1}(1+L)\delta T + P_\gamma$$

- **Thermal time constant** $\tau = \dfrac{C}{G}$

- **Electrothermal feedback parameter** $L = \dfrac{P\alpha}{GT}$

- **ETF time constant** $\tau_{ETF} = \dfrac{\tau}{1+L}$

An example: case of superconducting Transition Edge Sensor (TES)



$$R(T) = R_0 \cdot \sqrt{R_s^2 + \left(1 - e^{\frac{T_0 - T}{\tau}}\right)^2 \cdot H\left(1 - e^{\frac{T_0 - T}{\tau}}\right)}$$

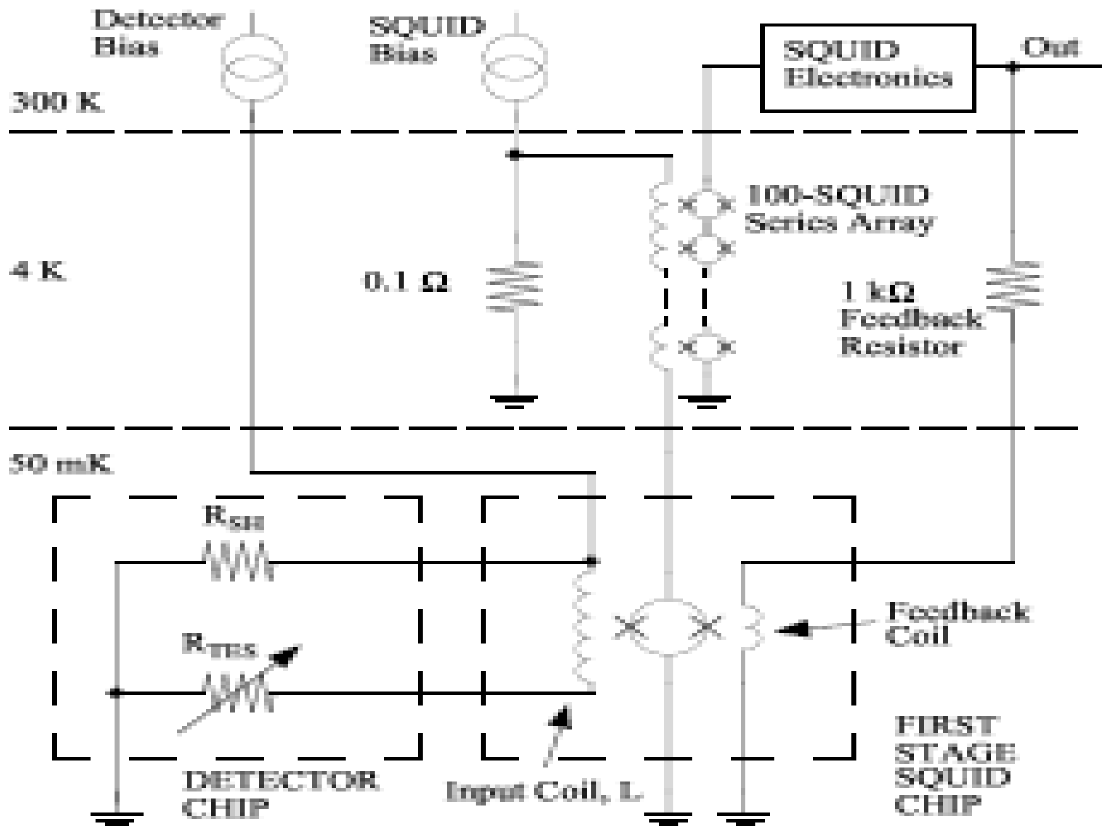
- Insert Sensor Model
- Insert bias power for sensor readout
- Make the realistic model of the detector thermal/electrical components
- Make a realistic model of all the power flow mechanism

$$P = AK\left(T_2^{\,n} - T_1^{\,n}\right)$$

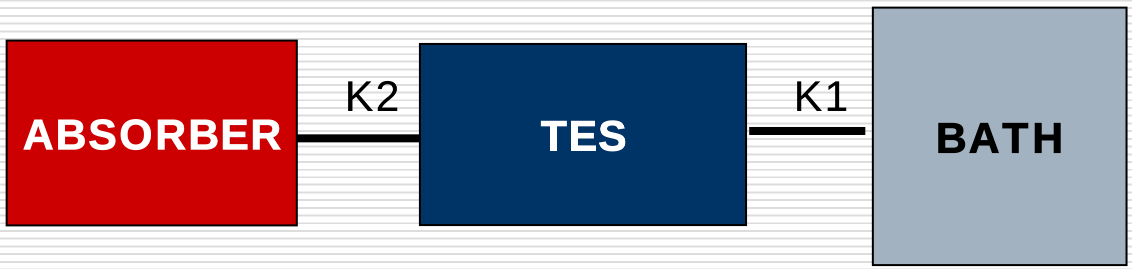
- n=2,4,5 (metal,dielectric or boundary, electron-phonon)

An example: insert the electronic parameters (case of SQUID amplifier)

- Make the electrical model of the readout circuit: example of SQUID readout of voltage biased microcalorimeter



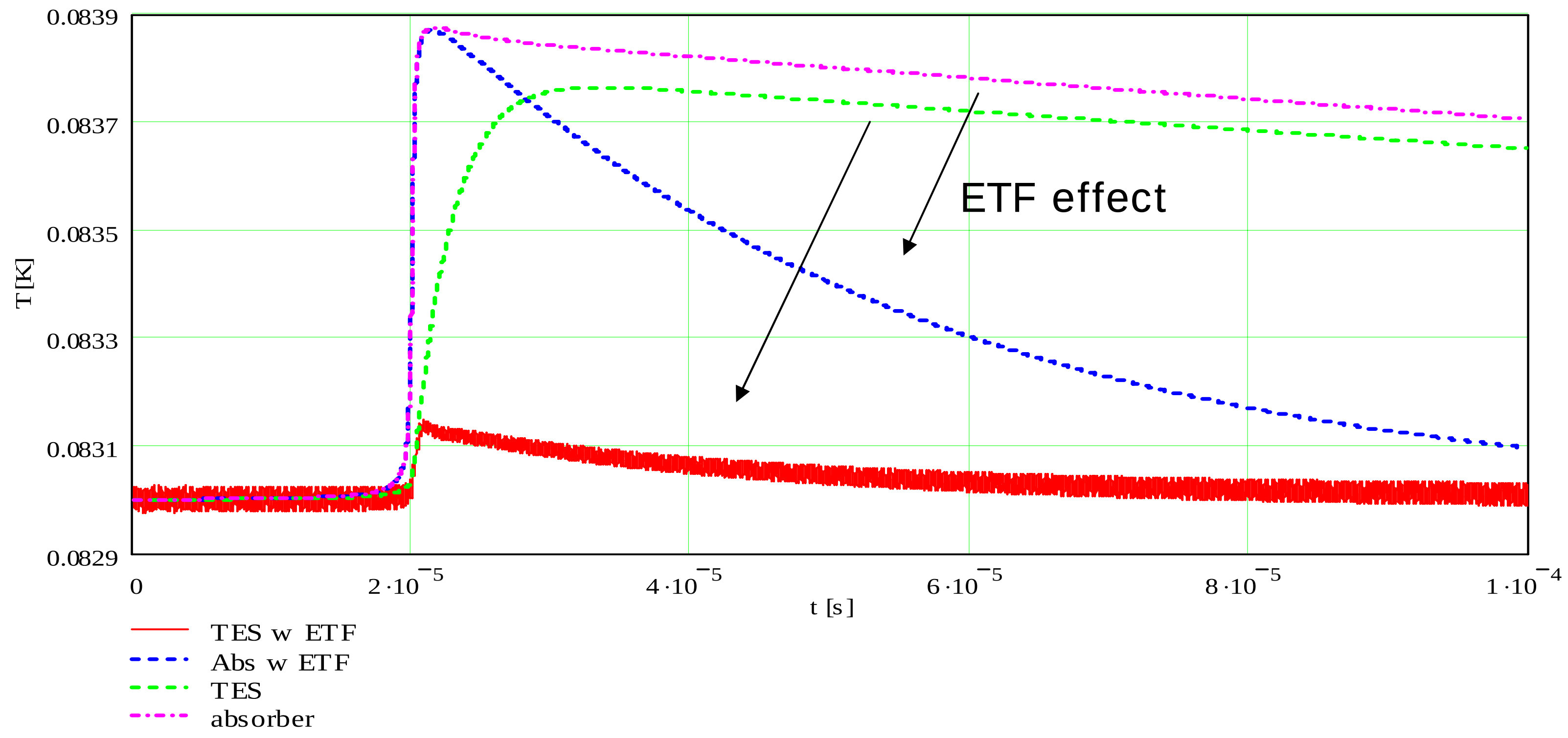
Build the minimal model: set of non linear equation→ numerical solution is required



$$\begin{cases} C_{TES}\dfrac{dT_{TES}}{dt} = K_2\left(T_{Abs}{}^n - T_{TES}{}^n\right) - K_1\left(T_{TES}{}^n - T_h{}^n\right) + R_x\left(T_{TES}\right)I_b{}^2 \\ C_{Abs}\dfrac{dT_{Abs}}{dt} = -K_2\left(T_{Abs}{}^n - T_{TES}{}^n\right) + P_\beta\left(t\right) \\ R_{st}\left(I_0\left(t\right) - I_b\right) = R_x\left(T_{TES}\right)I_b + L_p\dfrac{dI_b}{dt} + \dfrac{q}{C} \\ I_b = \dfrac{dq}{dt} \end{cases}$$

Results: ETF clearly visible

- ETF: the bias power act as negative feedback reducing thermal swing and time response.
- ETF: Linearize and sped-up the response
- ETF: becomes important if L ranges is~ $10\text{-}10^2$

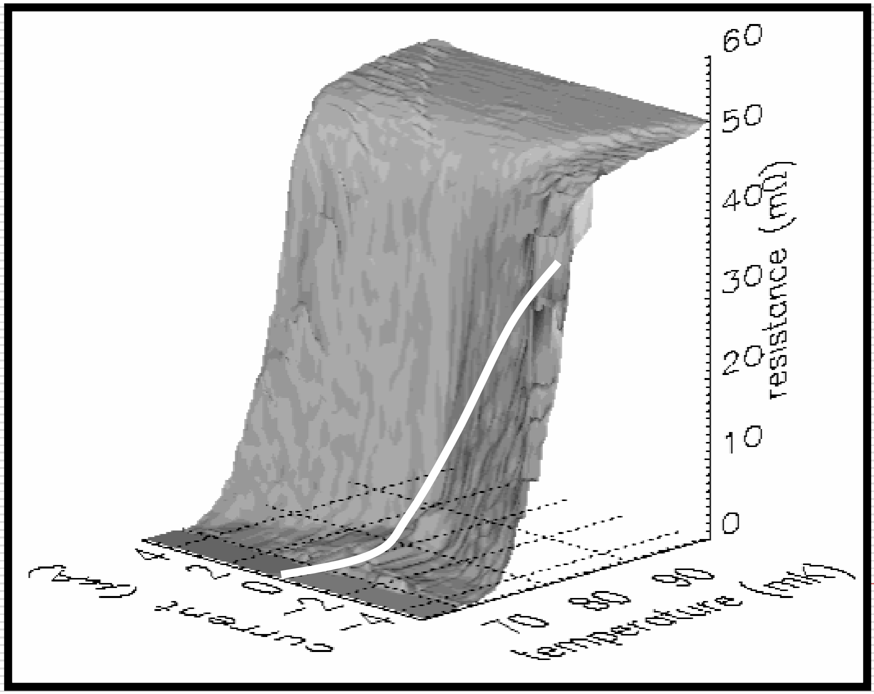


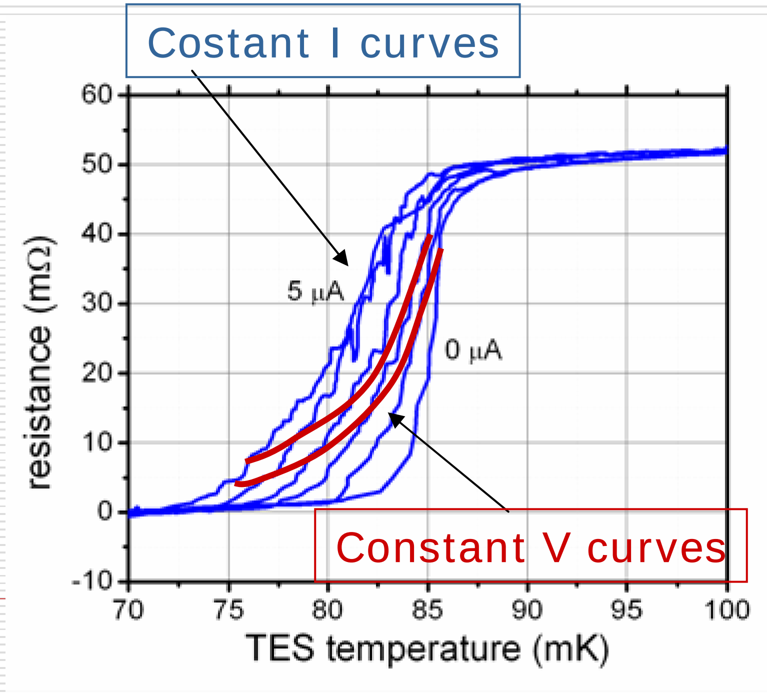
TES-Transition edge sensor

- Real TES sensor have T and I dependence

$$R(T,I) \approx R_0 + \left.\frac{dR}{dT}\right|_I \delta T + \left.\frac{dR}{dI}\right|_T \delta I \qquad R(T,I) \approx R_0 + \alpha \frac{T}{R}\delta T + \beta \frac{T}{R}\delta I$$

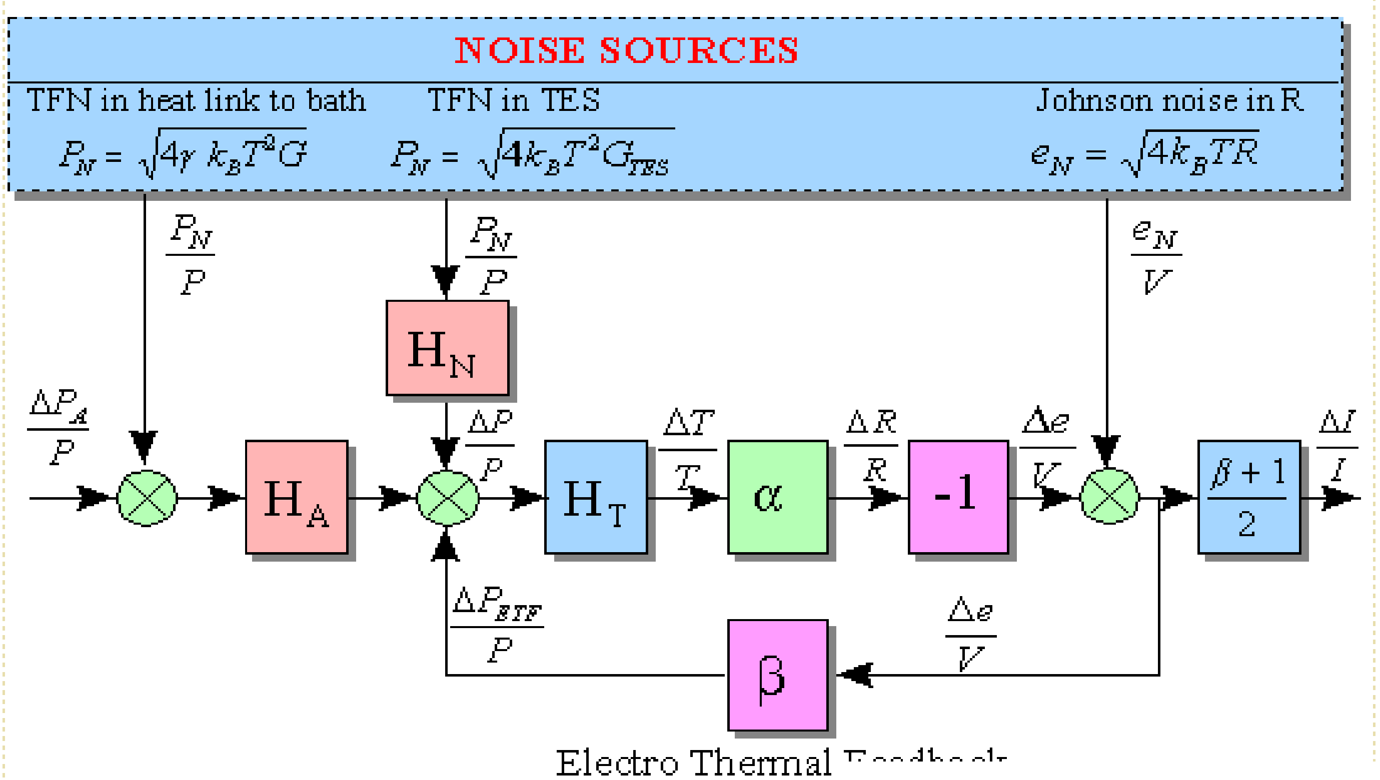
- Dynamical performance much more complex to be evaluated





Whole model for the energy resolution for TES

- Including all the noise sources (Phonon, Johnson...), the intrinsic thermal resolution contains sensor and conductance parameters: α and n ($\rightarrow G \sim T^n$)

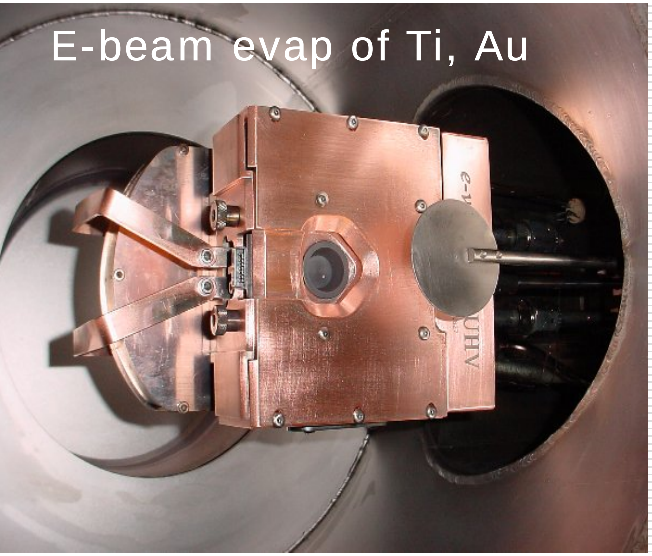


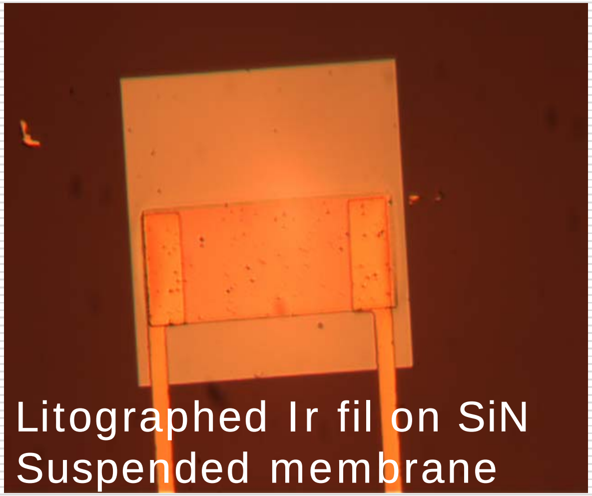
Calculated ETF
L parameter

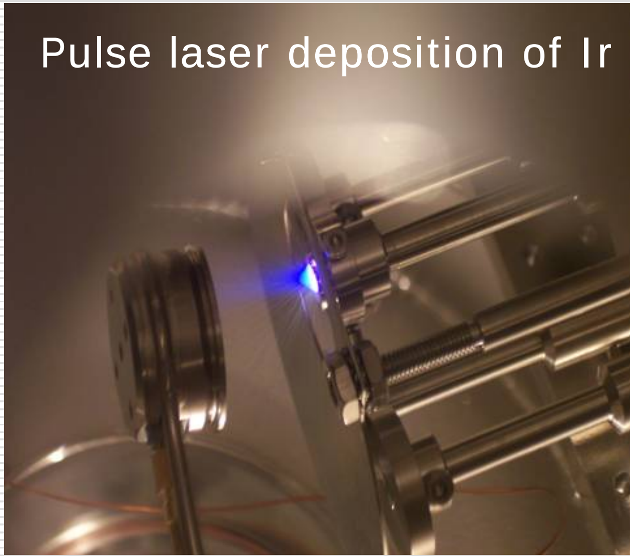
$$\delta E_{\mathrm{FWHM}} = 2\sqrt{2\ln 2}\sqrt{4 k_{\mathrm{B}} T_0^2 \frac{C}{\alpha_I}\sqrt{n/2}}\,,$$

How TES are made of?

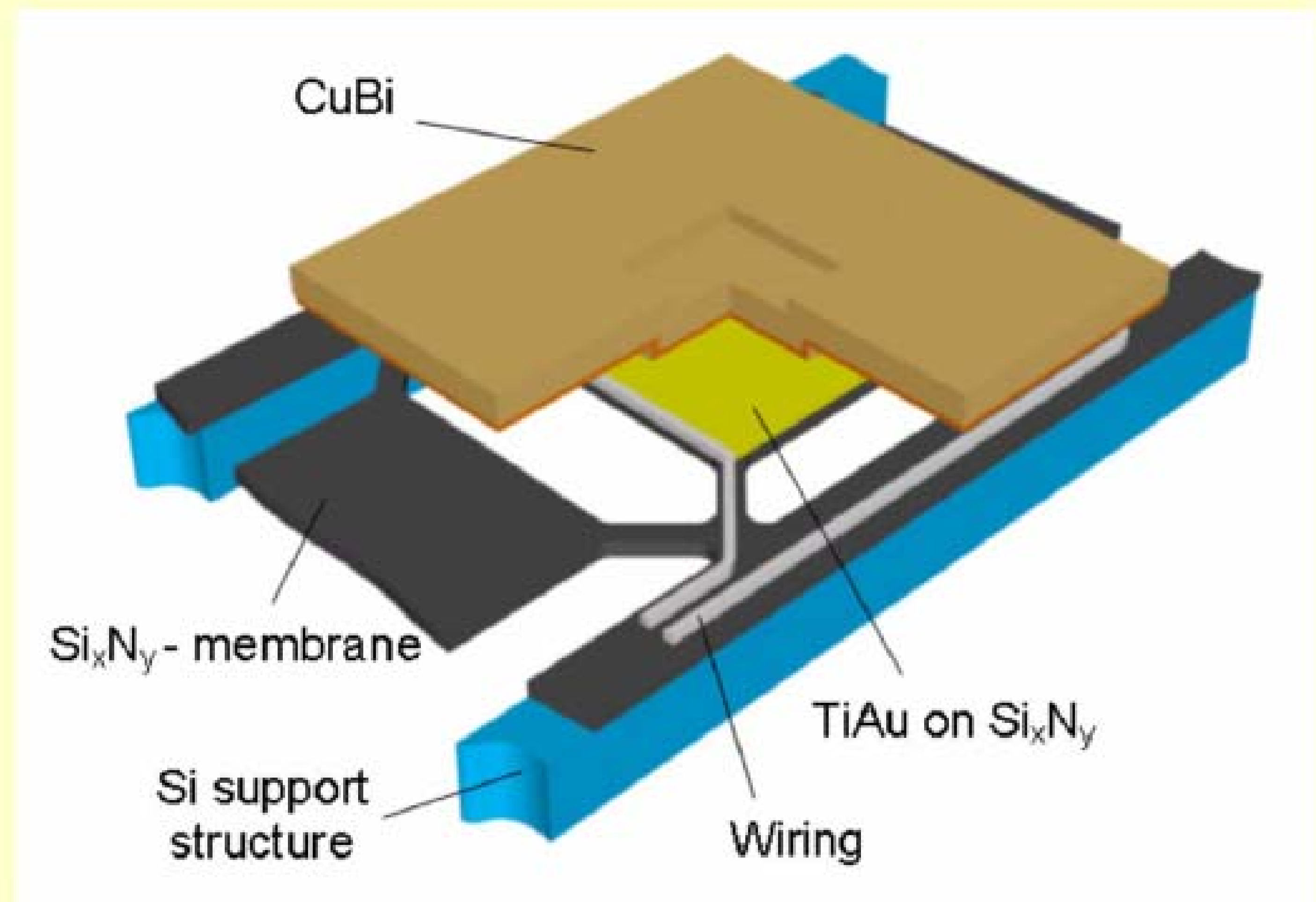
- They must have Tc in the 0.05-0.1 K range.
- Use of proximized Superconductors with metals: MoCu, TiAu, IrAu
- Film growth under high vacuum
- Lithography for all planar thin film process







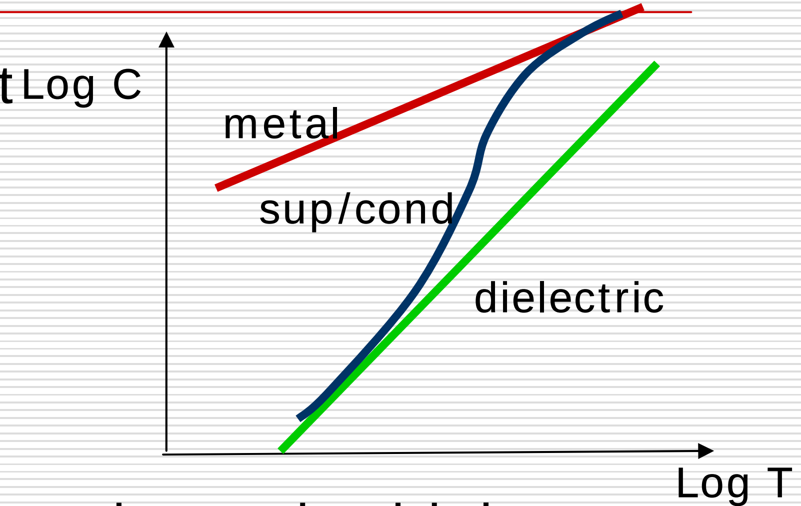
Present detector concept



Courtesy
SRON

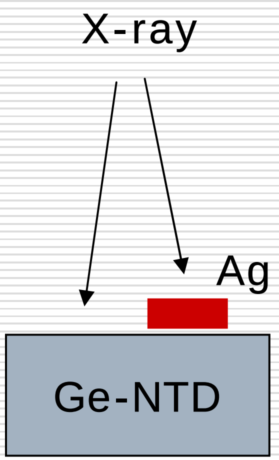
Why absorbers are made with metals?

- Dielectric have lowest specific heat
- Metals order of magnitude higher.
- Superconductor in the middle



- But, dielectrics or semiconductors produce e-h with long life, trapping the primary energy with time scale longer than the microcalorimeter time constant.
- Energy fluctuations are dominated by the well know e-h statistics: $(EFw)^{1/2} >> (kT^2C)$
- Metals and Superconductors are the best choice for the ultimate performances: metals are faster then superconductors

Trapping effect in semiconducting Ge-NTD observed since the beginnigs (D. McCammon etal, 1985) and further assessed in other works



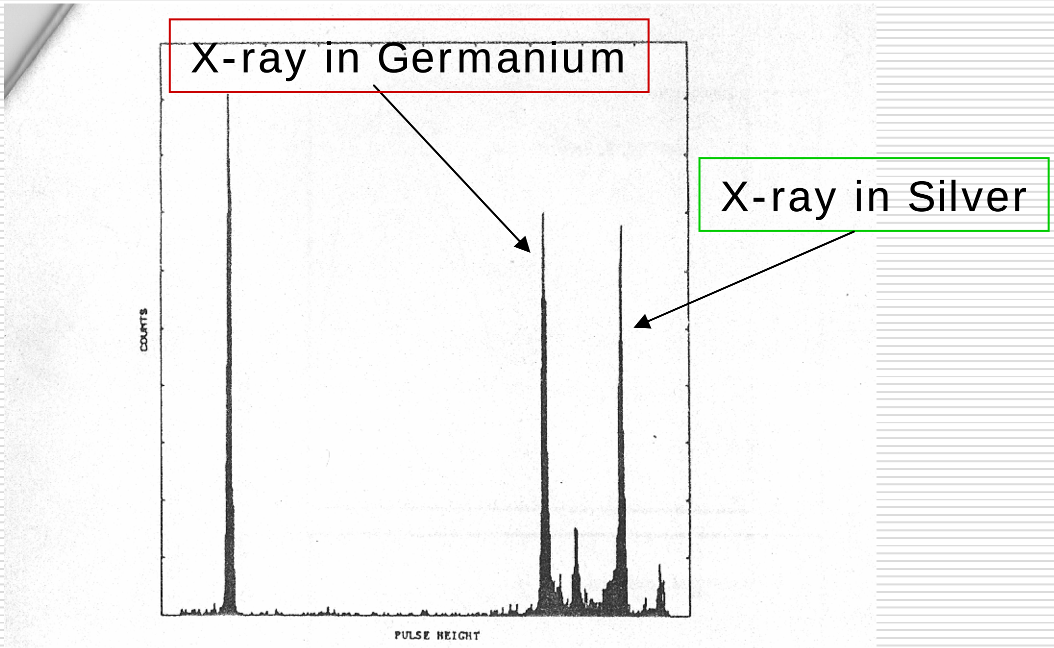
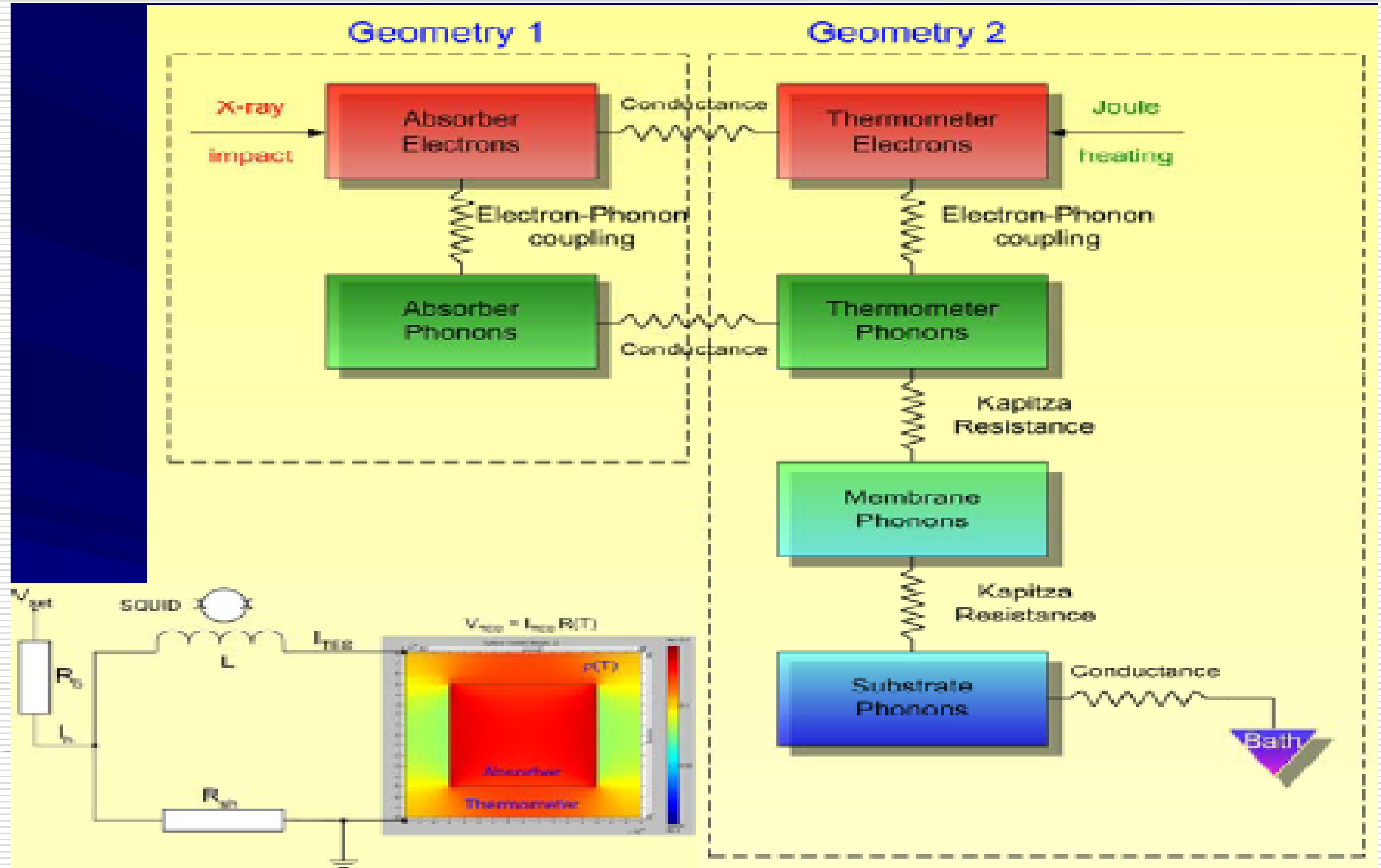


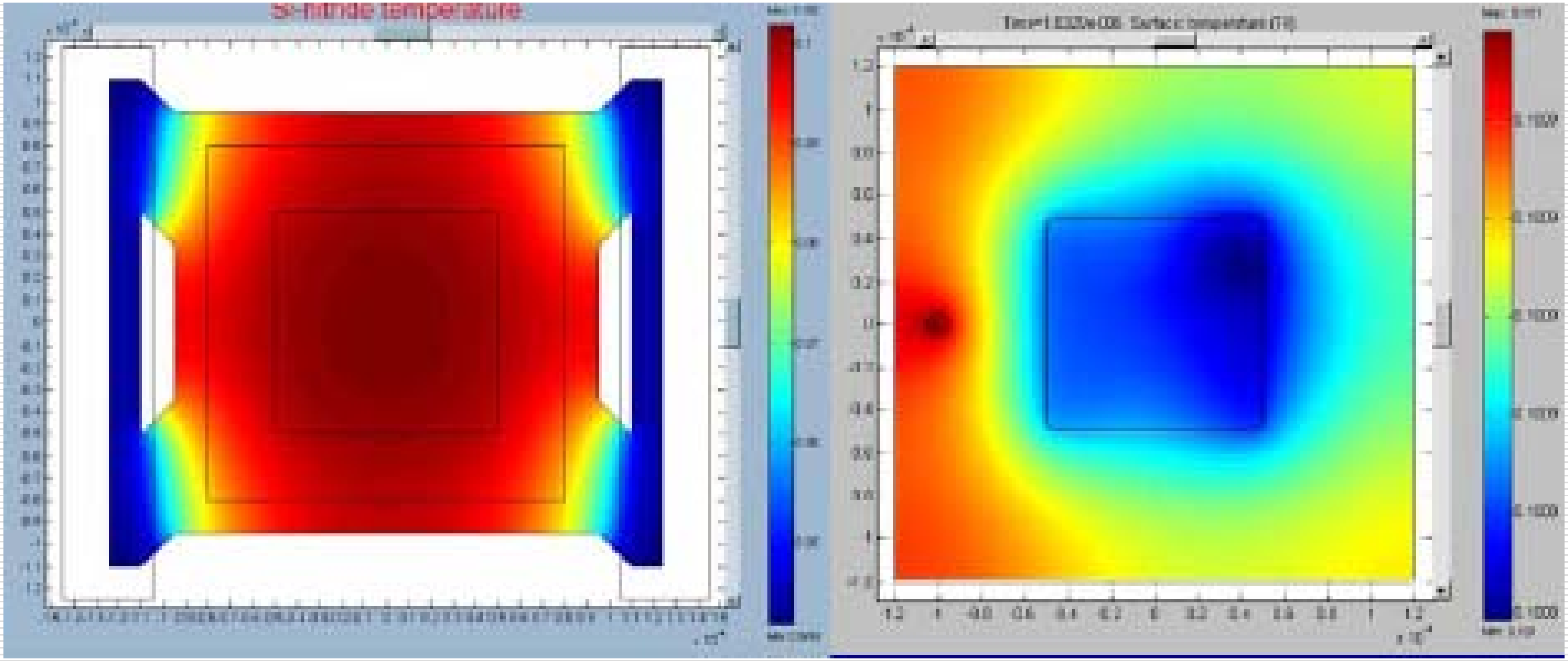
Fig. 4. Pulse height distribution of X-rays absorbed in a small dot of silver epoxy on the side of the germanium thermistor. The lower pair of peaks is due to X-rays which miss the epoxy and are absorbed directly in the germanium.

Thermal and electrical model

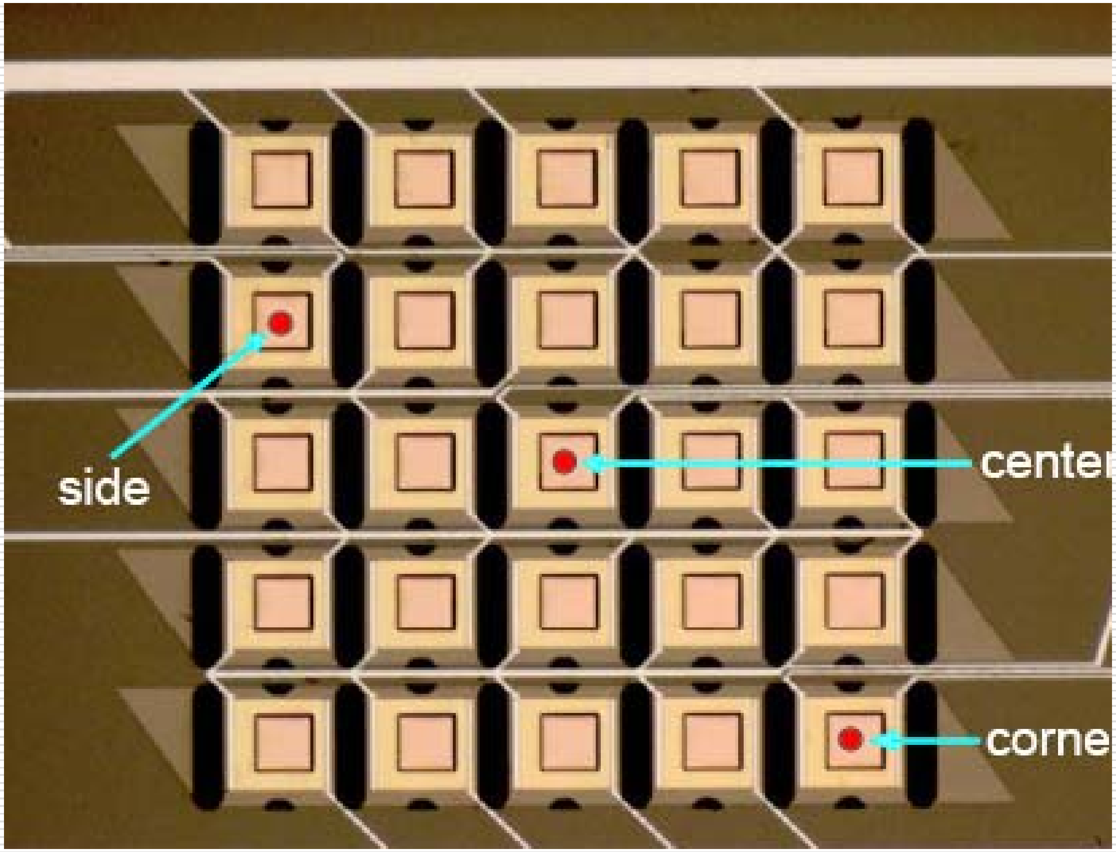


Why use of supended Membranes? →Thermal model of SiN membrane and Absorber

- G can be tailored with micromachining
- All planar processes suitable for large integration



Array development by SRON



Single Pixel Performance (SRON)

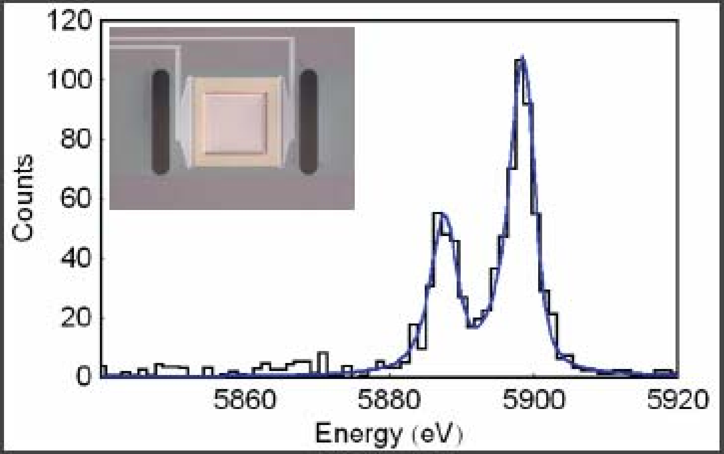
X-ray performance

Low heat capacity device

T_c = 105 mK, E_{sat} = 5.5 keV

ΔE = 1.5 eV (320 eV, BESSY)

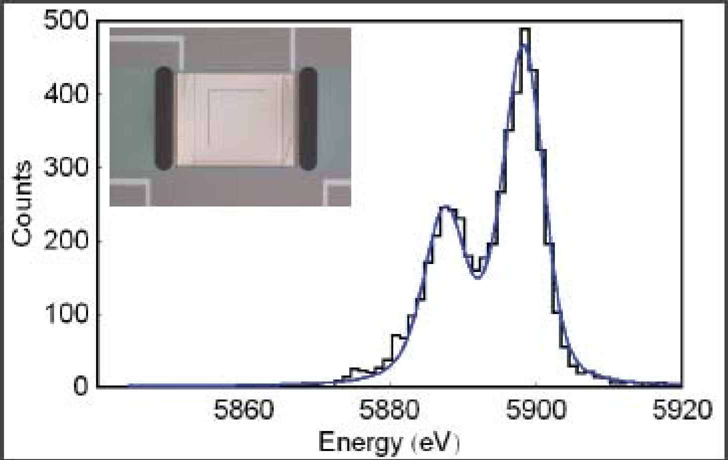
ΔE = 2.5 eV (5.9 keV)



High heat capacity devices

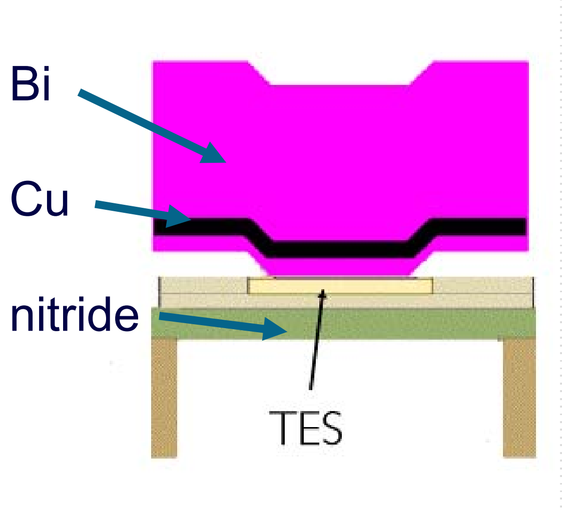
T_c = 125 mK, E_{sat} = 17.3 keV

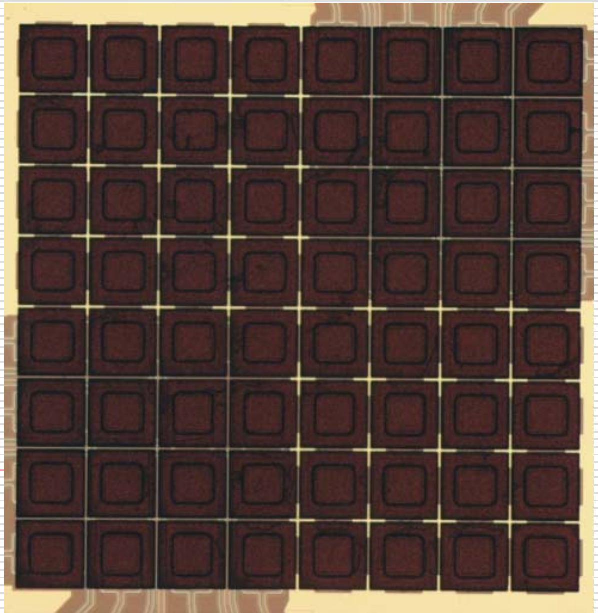
ΔE = 5.0 eV (5.9 keV)



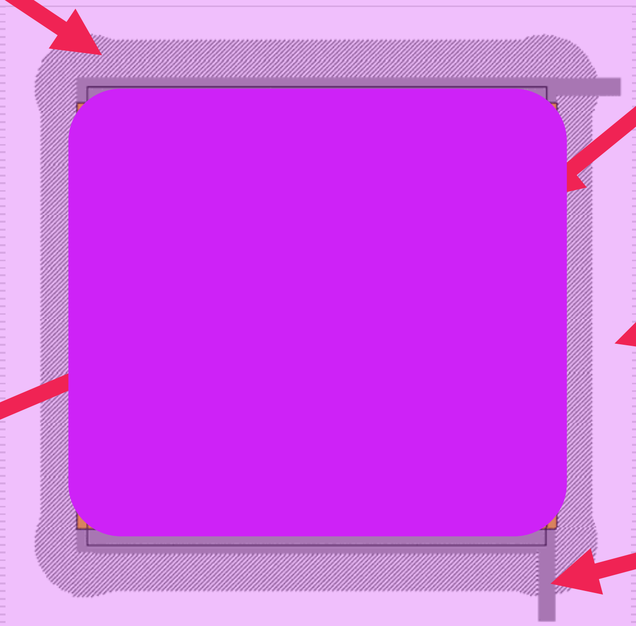
NASA-Goddard developments

- Mo/Au TES
  - Electron-beam deposited
  - Tc ~ 0.1 K
  - Noise-mitigating normal-metal stripes
- Absorbers joined to TES in micro-fabrication
  - "Mushroom" shaped to cover the gaps
- Emphasis on absorbers needed for Constellation-X reference design
  - 0.25 mm pitch (TES is 0.13 mm wide)
  - 92% fill factor
  - 95% QE at 6 keV

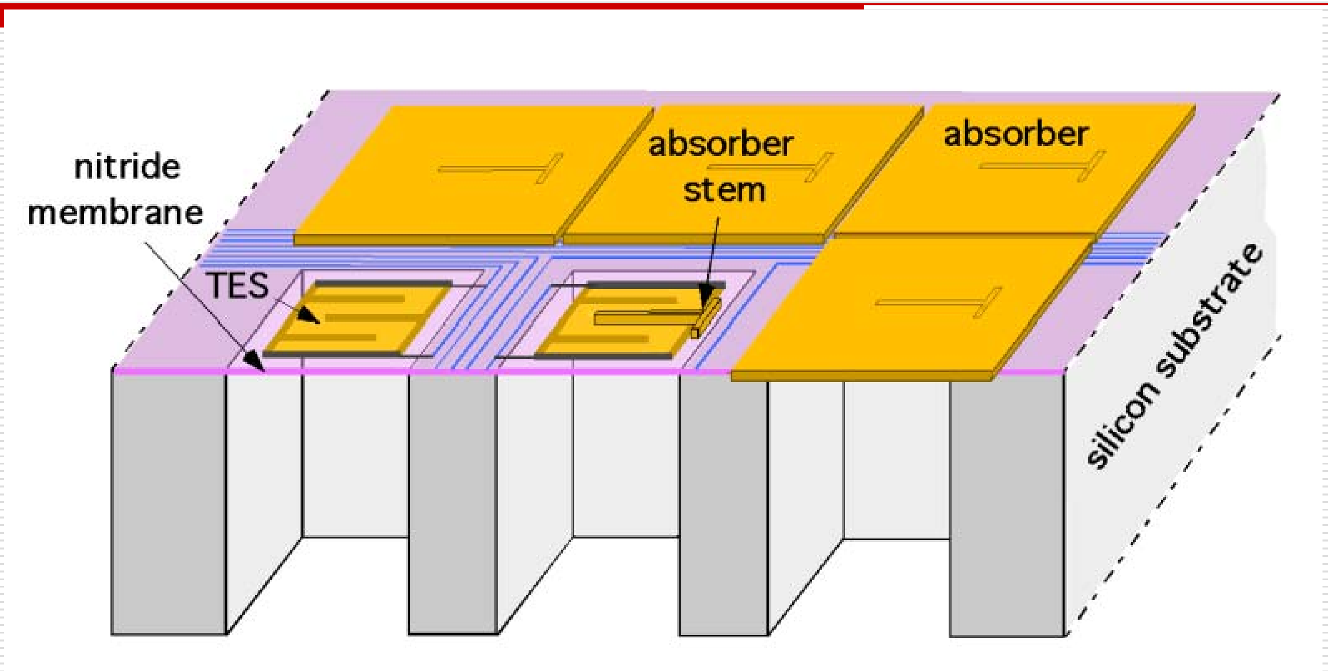




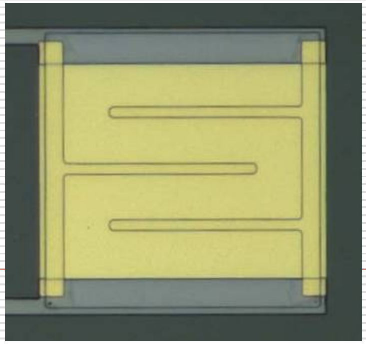
NASA-Goddard developments

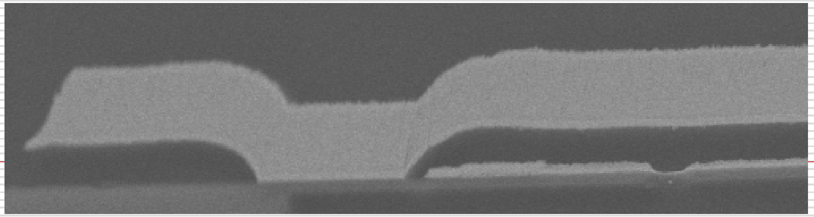


New method for absorber fabrication (Gold)

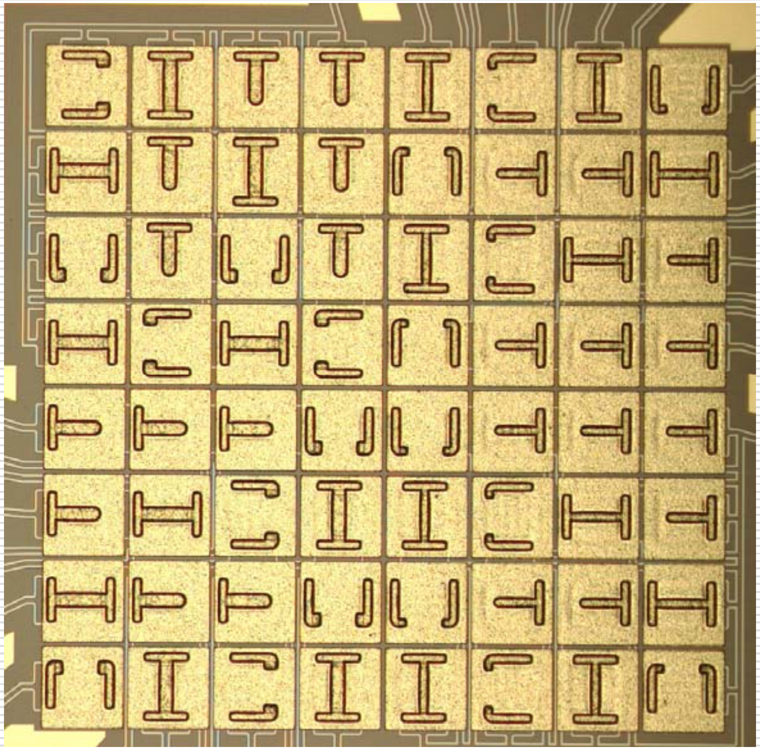


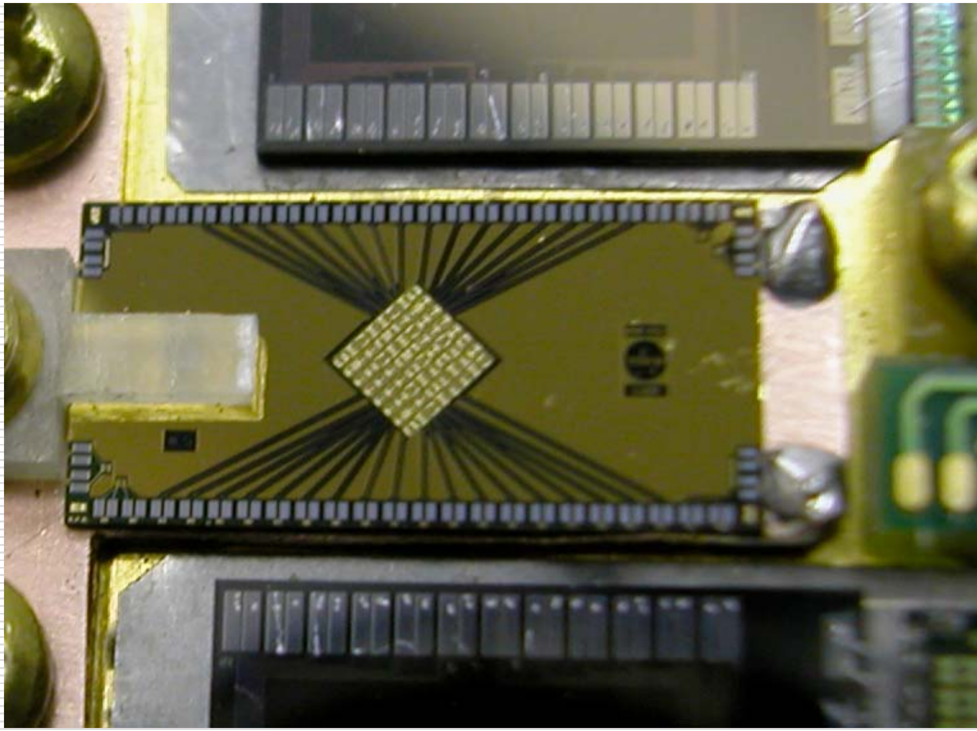
0.14 mm



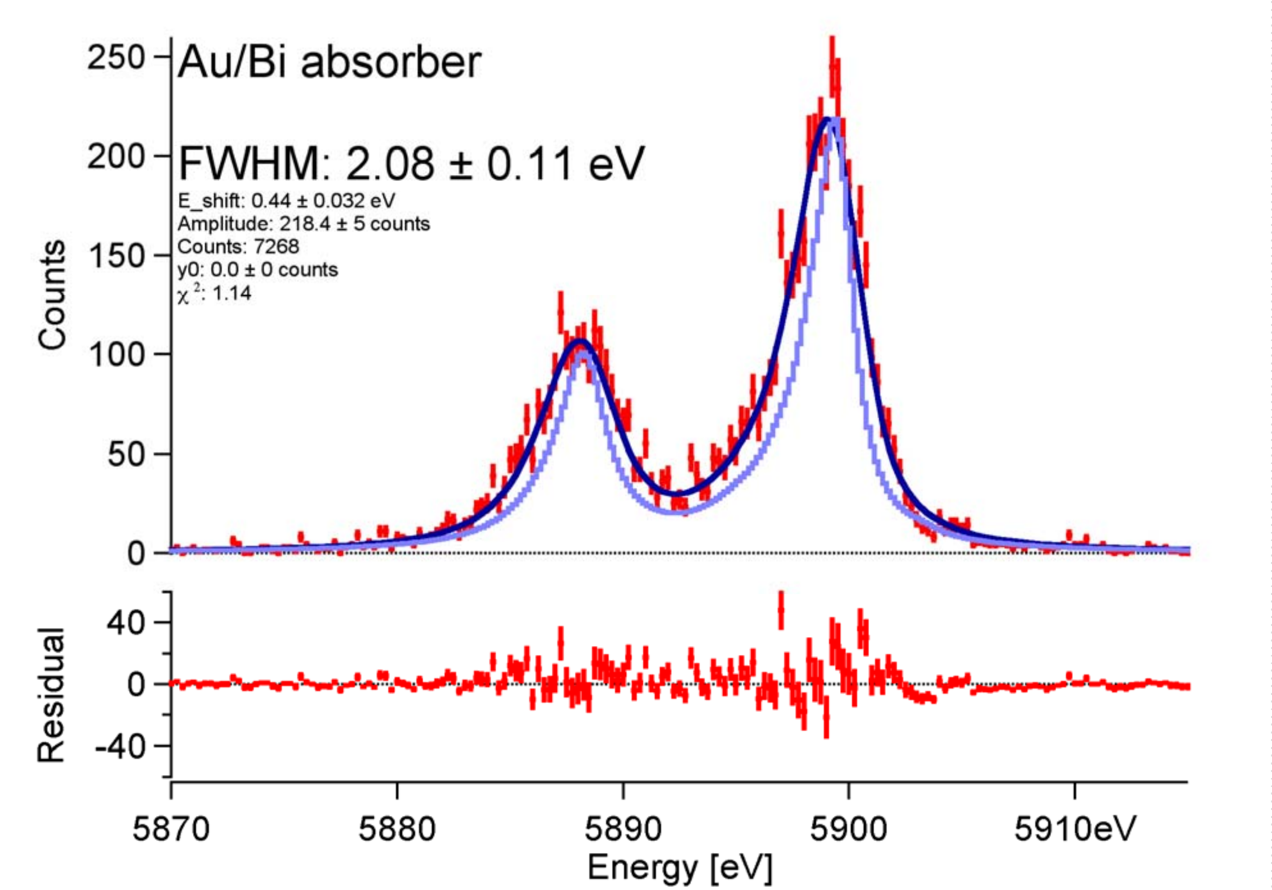


NASA-Goddard developments

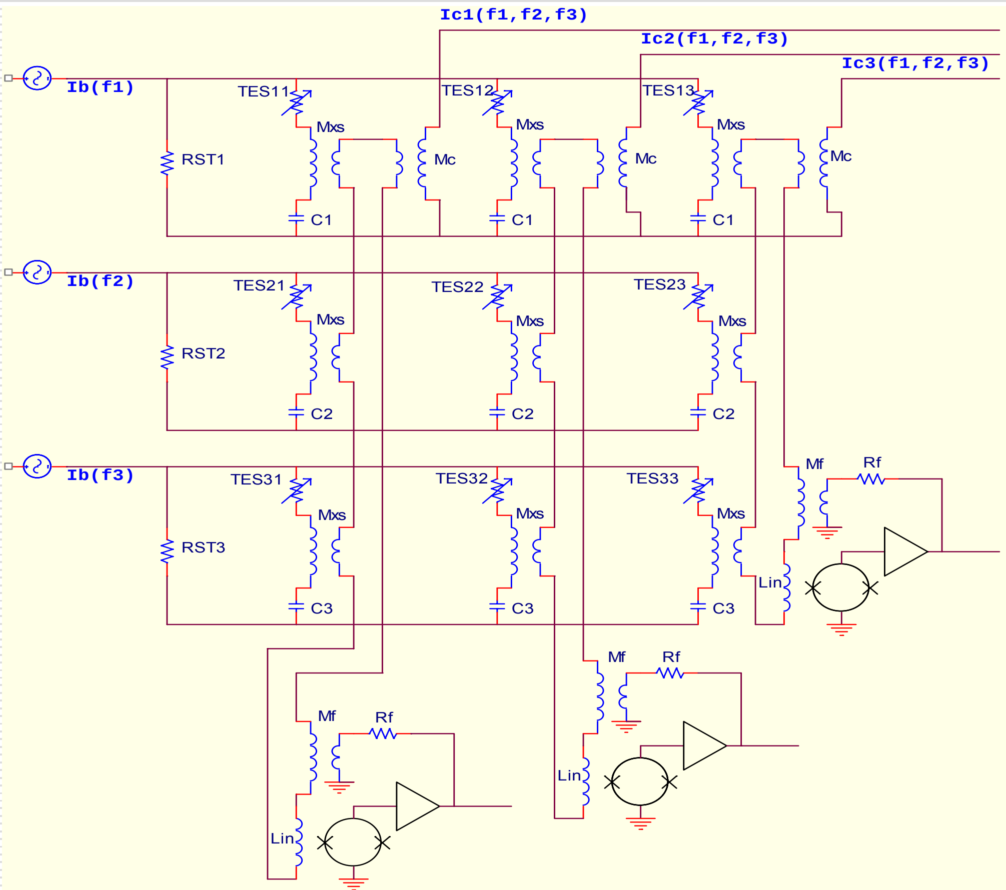


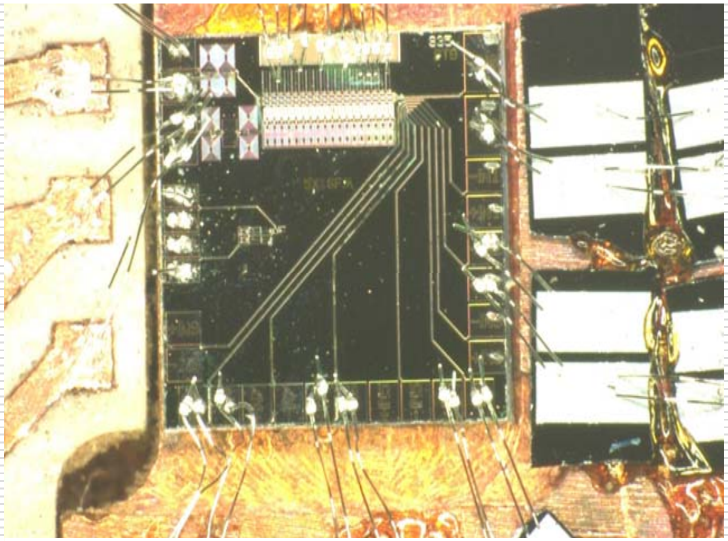


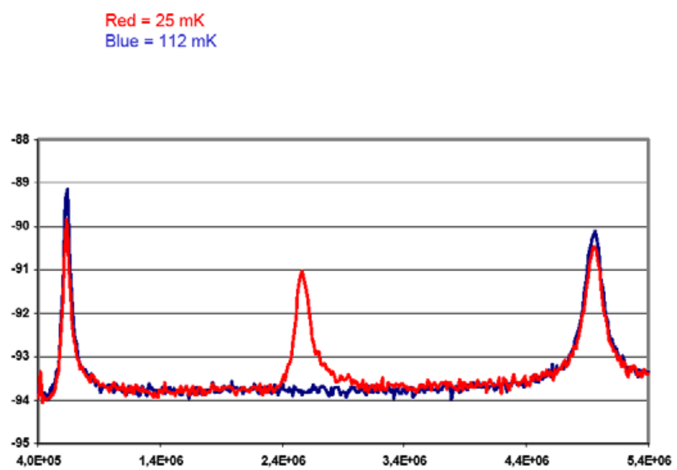
NASA-Goddard developments



Electronics: needed MUX readout. Many developments. An example: development of TDM MUX readout in Italy



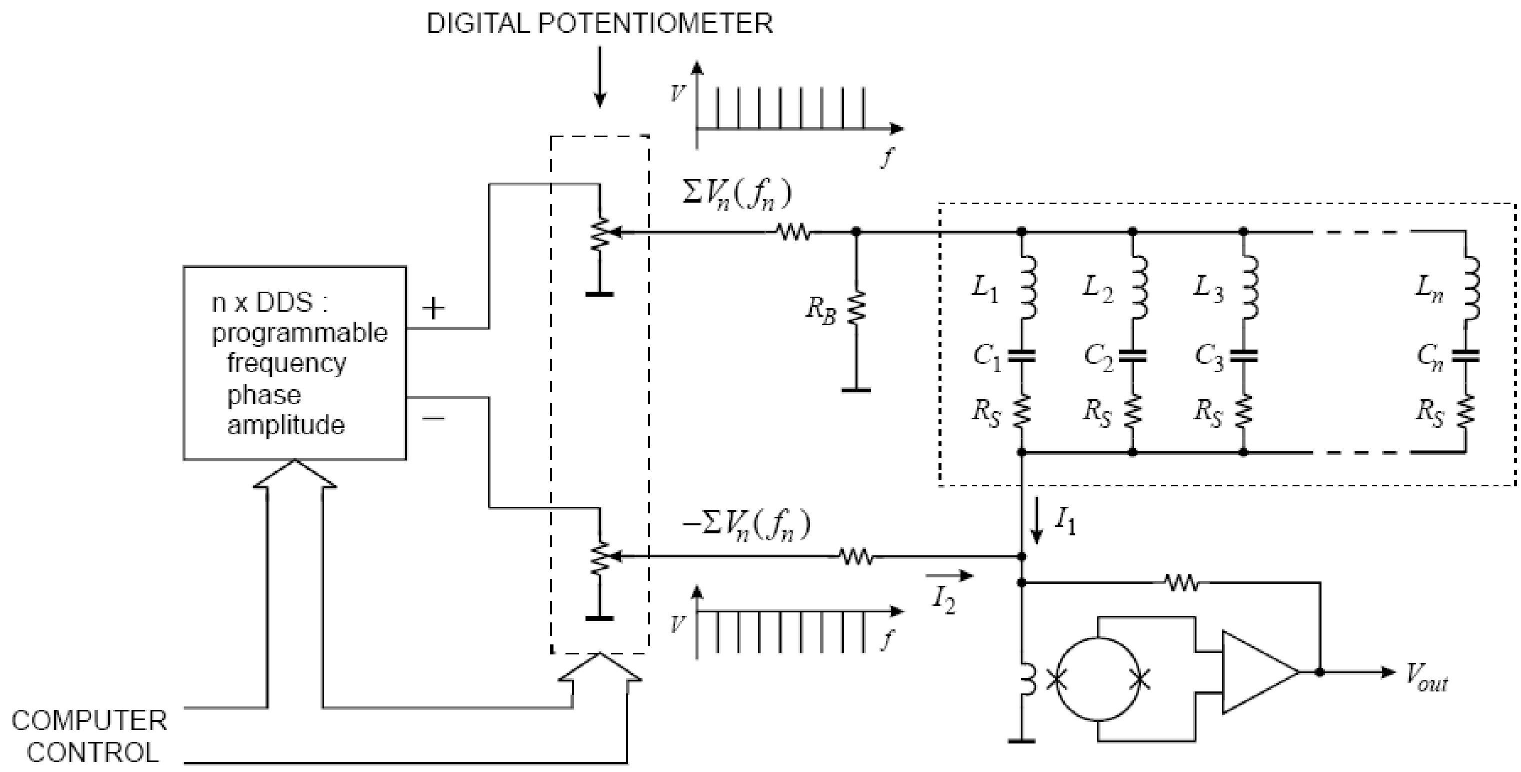




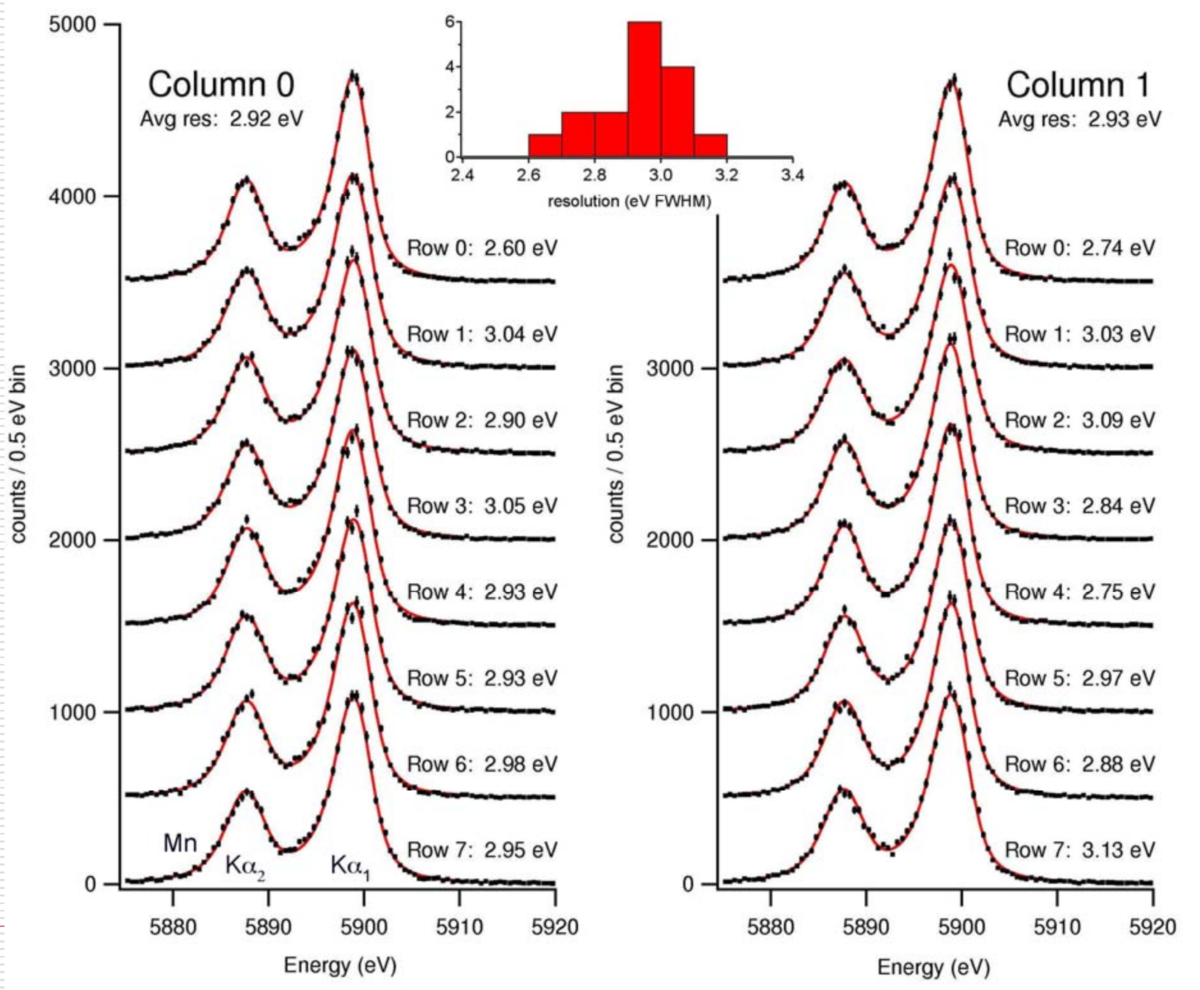
TES detectors could be a flight instrument for a next X-ray missions

- **Huge effort in US, EU, Japan**
- **US projects led mainly by GSFC → 2 eV fwhm, mux readout of 2x8 pixels (Con-X,NEXT)**
- **EU projects (+ Japan) in EURECA consortium led by SRON: 2.5 eV fwhm, mux readout in final assessment phase, 5 eV high C detector. Same performance (4.6 eV) obtained by our the Italian group with high C microcal (XEUS, EDGE).**
- **Japan: single pixel at 4.5 eV, fast development of detector/electronics (NEXT)**

Multiplexed Readout (principles)

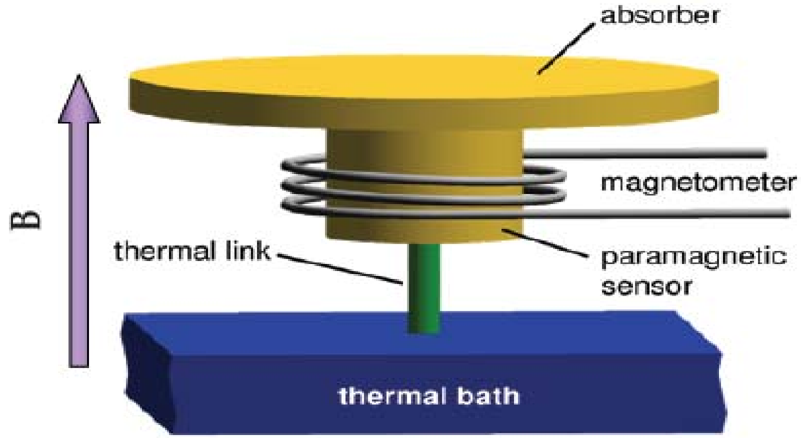


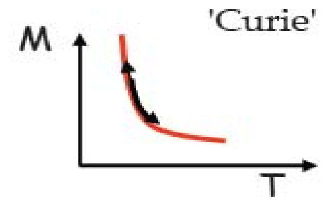
From the present 2x8 , to 32x32 pixel array as next goal of GSFC



Magnetic Microcalorimeter: a possible new promising technology (Heidelberg group)

Metallic magnetic calorimeters



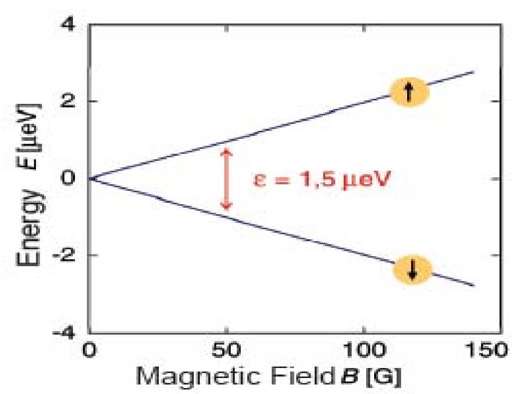


$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E}{C_{tot}}$$

<u>Very simple theory</u> :

Sensor material consists of magnetic moments only
2 level systems
Zeeman like energy splitting $\Delta E = m \cdot B$
$\varepsilon \cong 1.5\ \mu\text{eV}$

Energy deposition of 100 keV
Number of flips $\approx 10^{11}$
Change of magnetic moment $\Delta m = \frac{\Delta E}{B} \approx 10^{11}\mu_B$

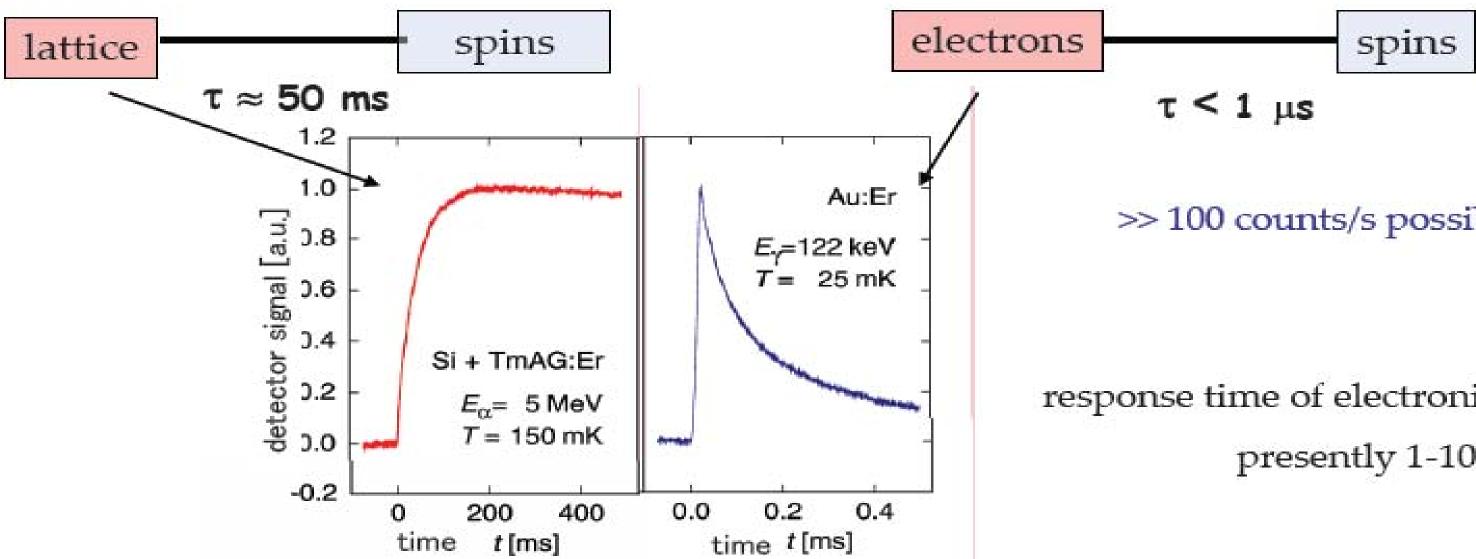


Heildeberg developments

Response times of magnetic calorimeters

Dielectric paramagnets :
(Bühler & Umlauf '93)

Paramagnetic alloys (e.g. **Au**:Er):
(Heidelberg & Brown Univ.)



>> 100 counts/s possible

response time of electronics:

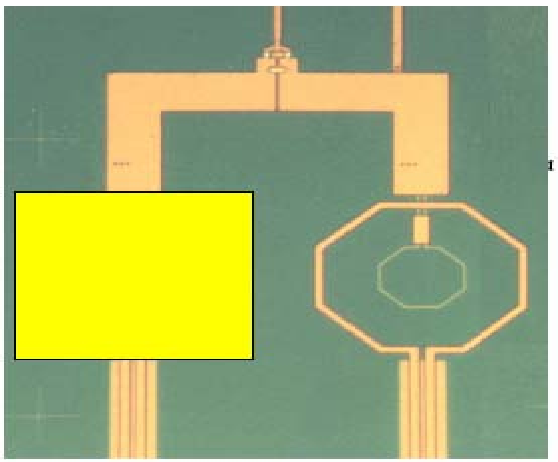
presently 1-10 µs

Sensor material presently used→
Au:Er with Erbium concentration of few hundred ppm

Heildeberg developments

Magnetic calorimeter for x-ray spectroscopy

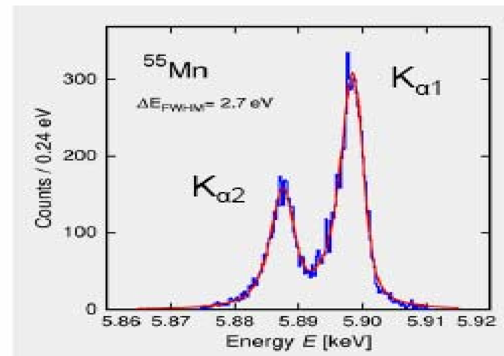
Characterization with ^{55}Fe-Source:

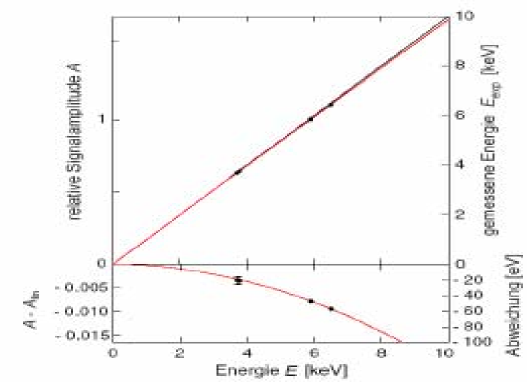


energy resolution $\Delta E_{FWHM} = 2.7$ eV

resolving power 2200

non-linearity at 6keV: < 0.8%

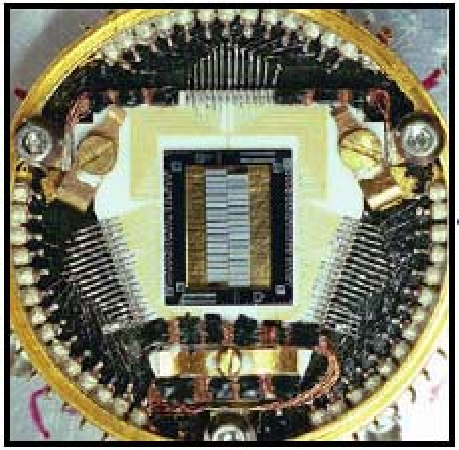




Conclusions

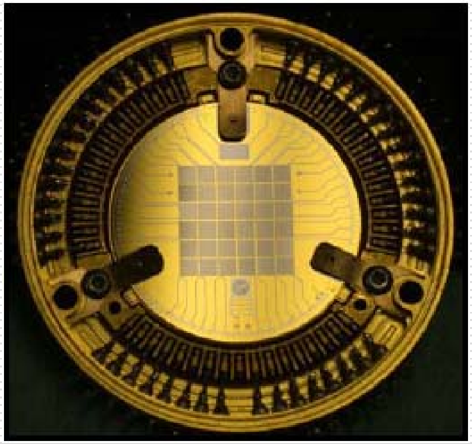
- TES microcalorimeters have achieved the goal performance in High Spectral Resolution (2 eV fwhm @ 6KeV) for application to the next missions (ConX-XEUS)
- Further improvements are under way mainly for increasing the array size.
- Other promising techniques are under study: magnetic calorimeters, KID sensors
- Advancement in readout techniques and refrigeration technology will allow fall-outs in many other fields (material science, security, pollution monitoring,...)

Don’t forget the first array with Si doped sensors for XQC and ASTRO-E that have operated in sounding rockets and in orbit

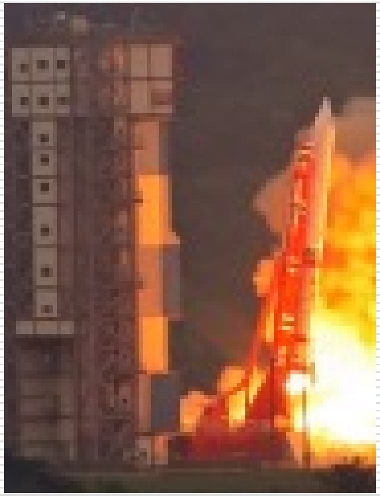


XQC for sounding rocket
Old detector

XRS on AstroE



XQC for sounding rocket
New detector



XRS operated
Few weeks before the cryo failure