Instruments for X-ray Spectroscopy

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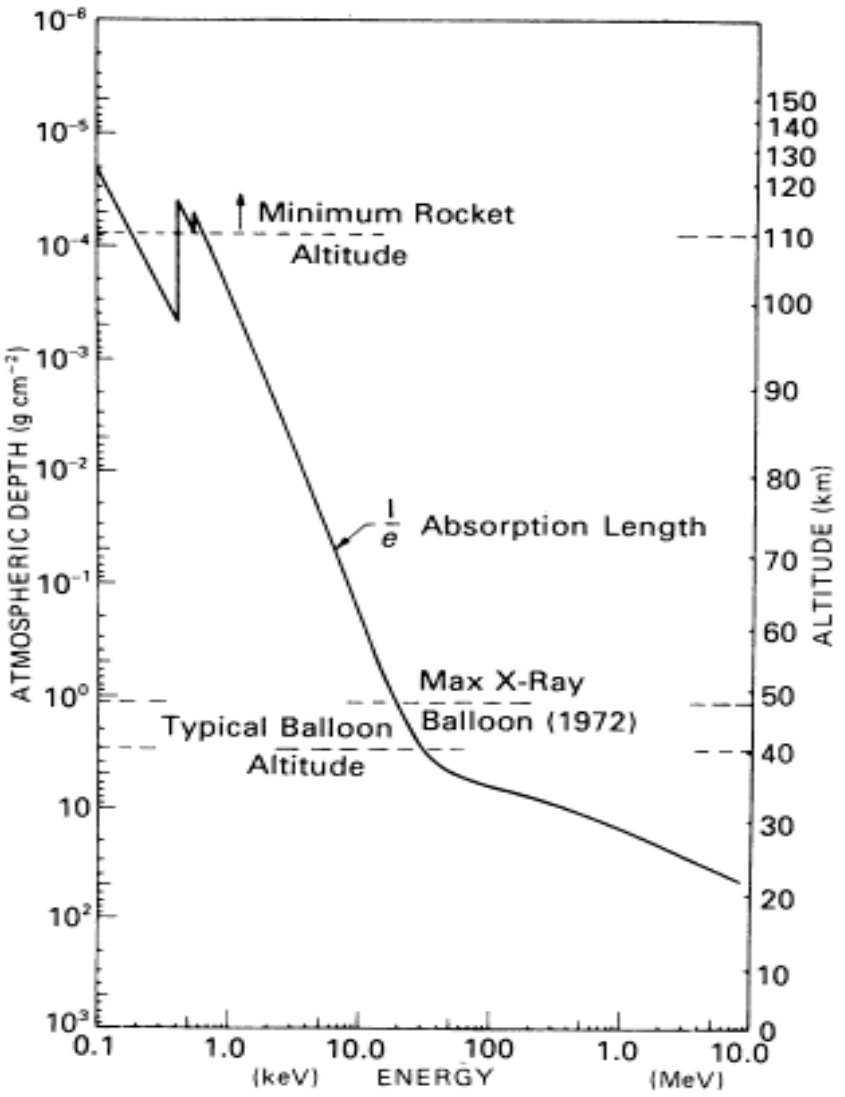
Outline

- Science goals
- Methods of X-ray detection: photon interaction with matter, Imaging techniques, bkg and sensitivity, detector typologies and spectroscopy
- X-ray spectroscopy: cryogenic microcalorimeters & techniques, grating
- ATHENA and its X-ray Integral Field Unit

Why space?

Attenuation of photons in the atmosphere

Attenuation of photons in the 1972 COSPAR International Reference Atmosphere with $1/e$ absorption length plotted as a function of energy and altitude or atmospheric depth.



X-ray spectroscopy: detector typology

- Converting photons in signal:
- Photon interaction with matter
- Ionization => electrons: ionization detectors (proportional counters, CCDs, Active Pixels,..)
- Ionization => electrons => phonons (heat): microcalorimeters
- Diffraction: Gratings

X-ray and Gamma-ray detectors

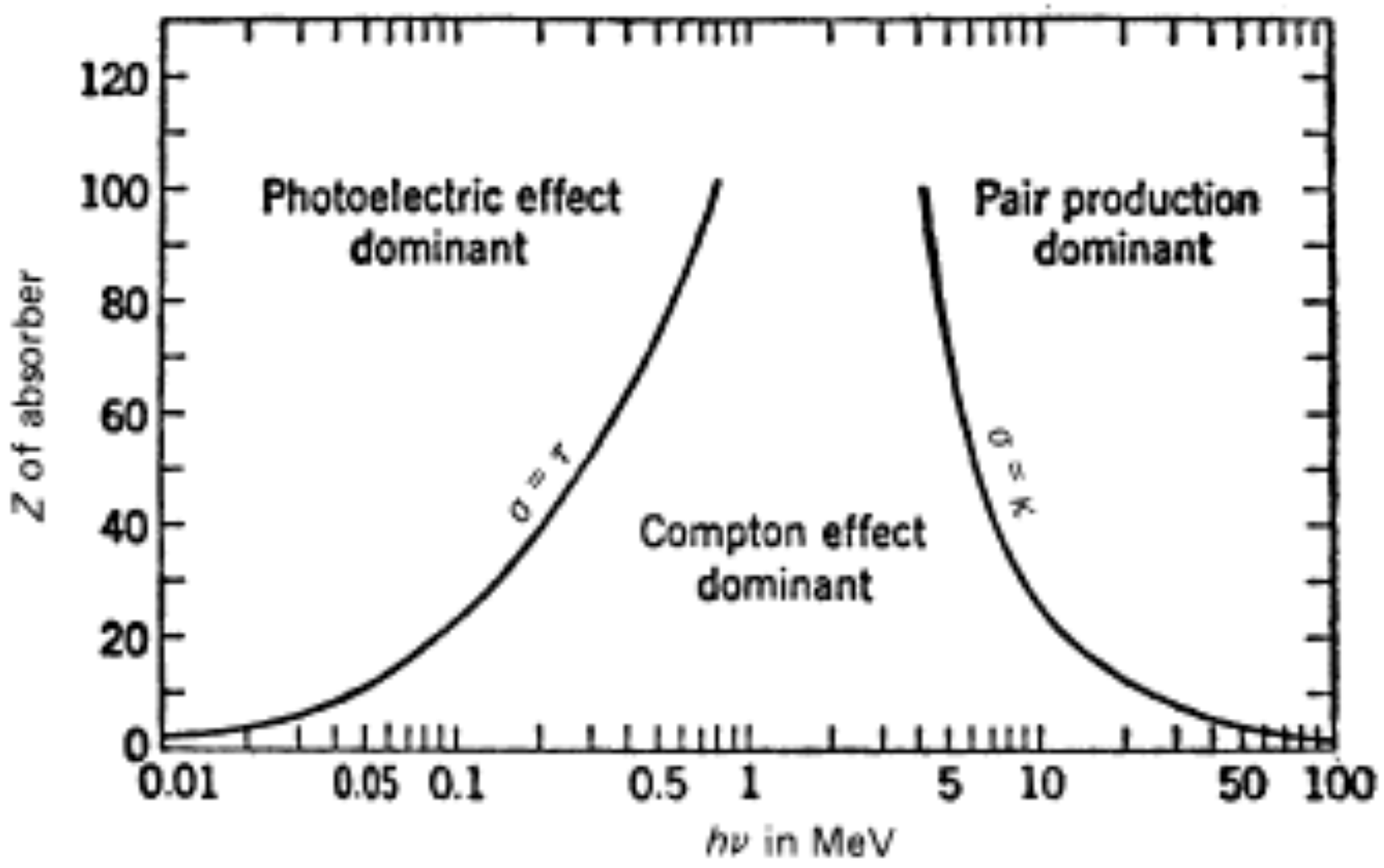
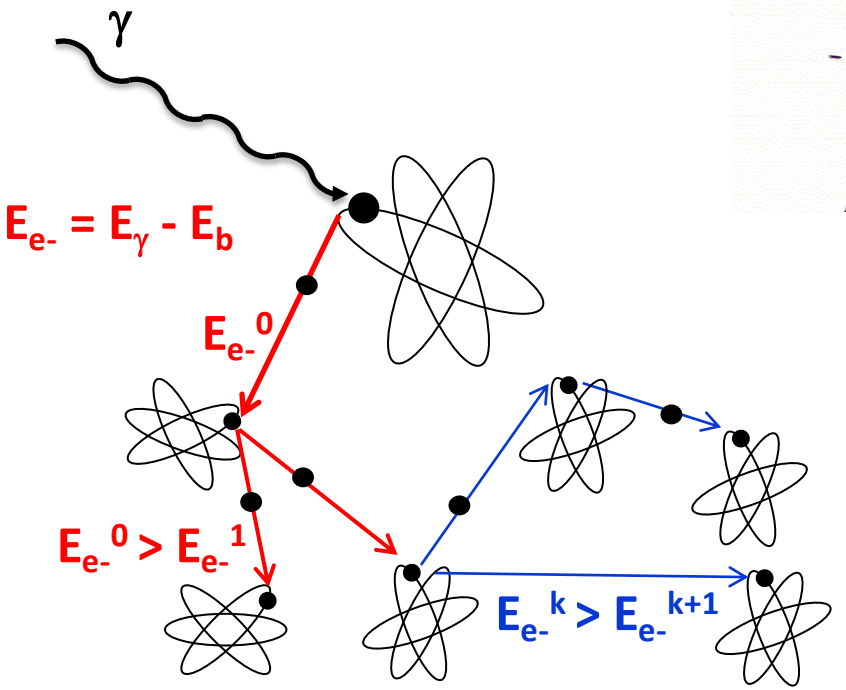


Photo-electrons and ionization losses



$$-\left.\frac{dE}{dx}\right|_{ion} = \frac{2\pi n Z}{m_e \beta^2 c^2}\left[\ln\left(\frac{2 m_e \gamma^2 \beta^2 c^2}{\langle I\rangle}\right) - \beta^2\right]$$

Z=atomic number

<I>=Mean Ionization potential

The energetic photoelectron (typical energy~ keV) ionizes the "absorber" → electrons/holes

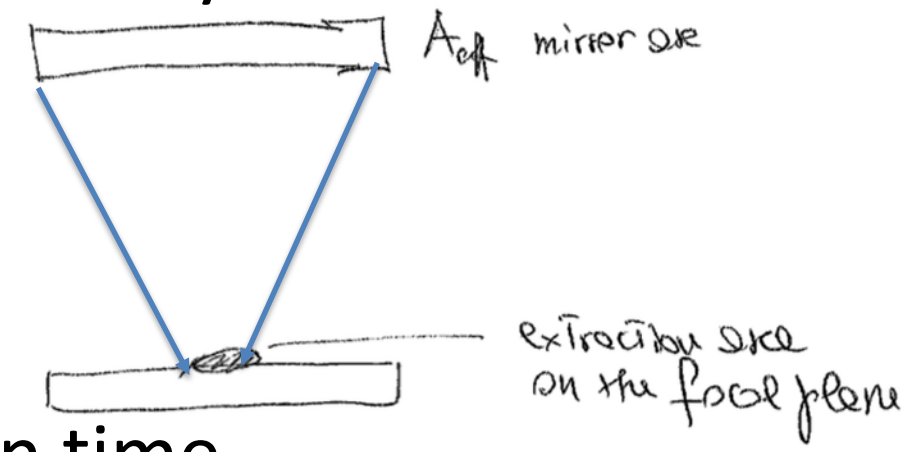
- W= average energy to create a electon-hole pair (ev/pair): larger than <I> (losses) and depend on the material

Energy resolution of ionization detectors

- W (ev/pair)
- Ar= 26.2 ev/pair (Gas proportional counters)
- Xe= 21.5 ev/pair
- Si = 3.6 eV/pair (CCD, active pixels,..)
- Ne-+=hv/W
- Example hv=1kev in Si, Ne+-=280
- Assume Poisson $\sigma_E = \mathrm{W}\sqrt{N} \cong 70\ \mathrm{eV}$

Sensitivity (minimum detectable flux)

- $\varepsilon(E)$= focal plane instrument efficiency
- B(E)= bkg cts/cm2/s/keV
- F(E)= source flux ph/cm/s/keV
- ΔE=energy range,
- Ts,Tb=source and bkg integration time
- by counting the N of source and bkg counts and applying Poisson statistics σ_F is derived
- Fmin= n_σ σ_F (e.g. n_σ=5, 5sigma detection limit)



Sensitivity (minimum detectable flux)

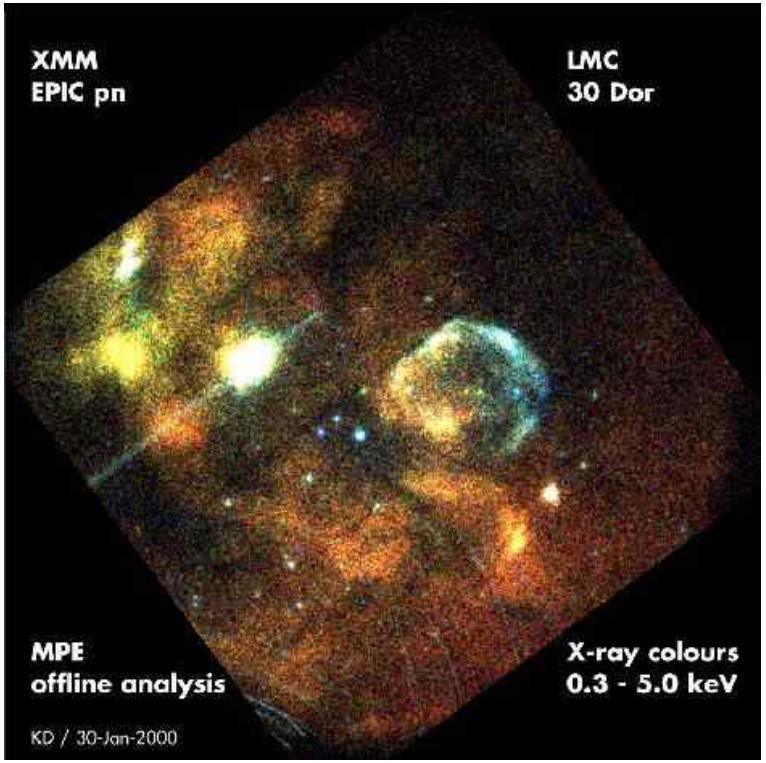
- $\sigma_F = \frac{1}{\varepsilon(E)\sqrt{\Delta E\, A_{eff}}} \sqrt{\frac{S(E)\varepsilon(E)+\frac{B}{c}}{T_s} + \frac{\frac{B}{cb}}{T_b}}$
- c=Aeff/As=concentration factor (>>1 for mirrors)
- b= Ab/As (bkg and source extraction regions, for mirro imagin b>>1)
- Bkg dominated case: $S\varepsilon << B/c$

Minimum detectable flux

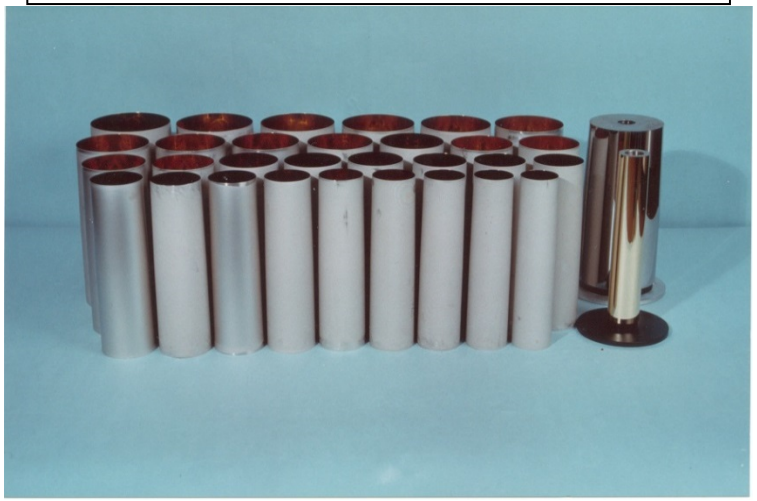
- $F_{lim} = \frac{n_\sigma}{\varepsilon(E)} \sqrt{\frac{B/c}{\Delta E \, A_{eff} T_s}}$

X-ray optics

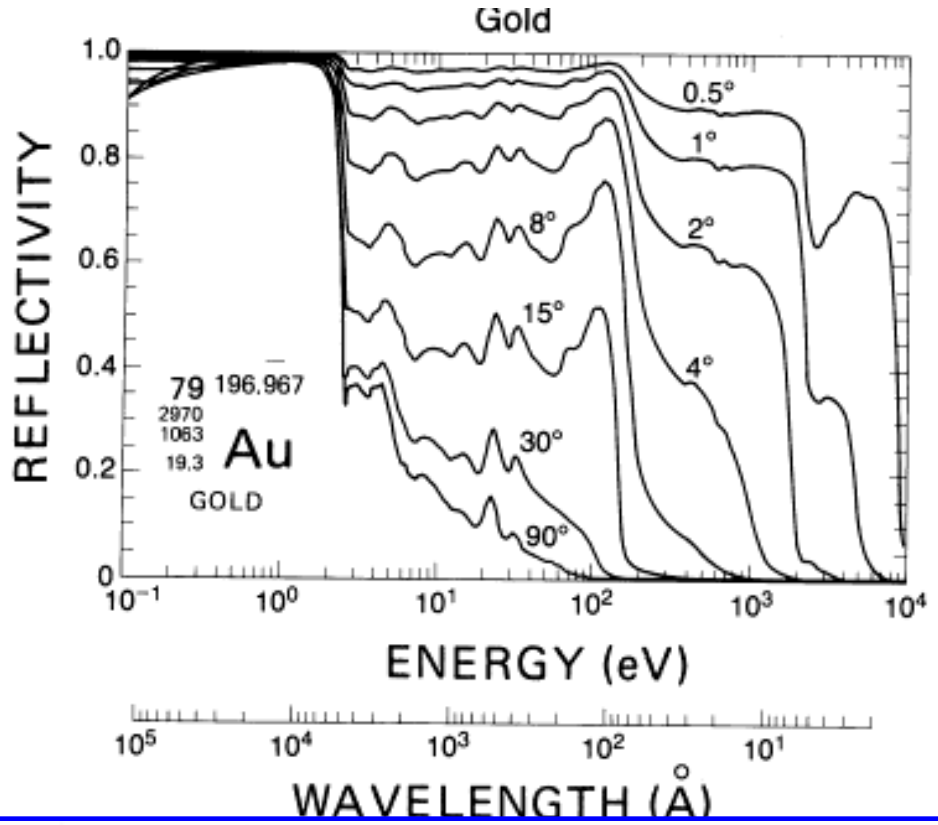
- Exploit grazing reflection of X-rays to produce real images
- Reflection of X-ray at grazing angles below a critical angle $\alpha_c = Z^{1/2}/\text{Energy}$

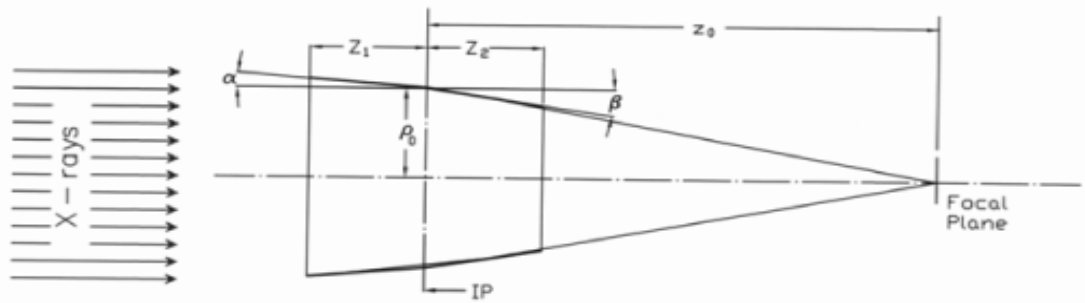


Soft X-ray (0.1 – 10 keV) optics of the Italian-Dutch Beppo-SAX satellite



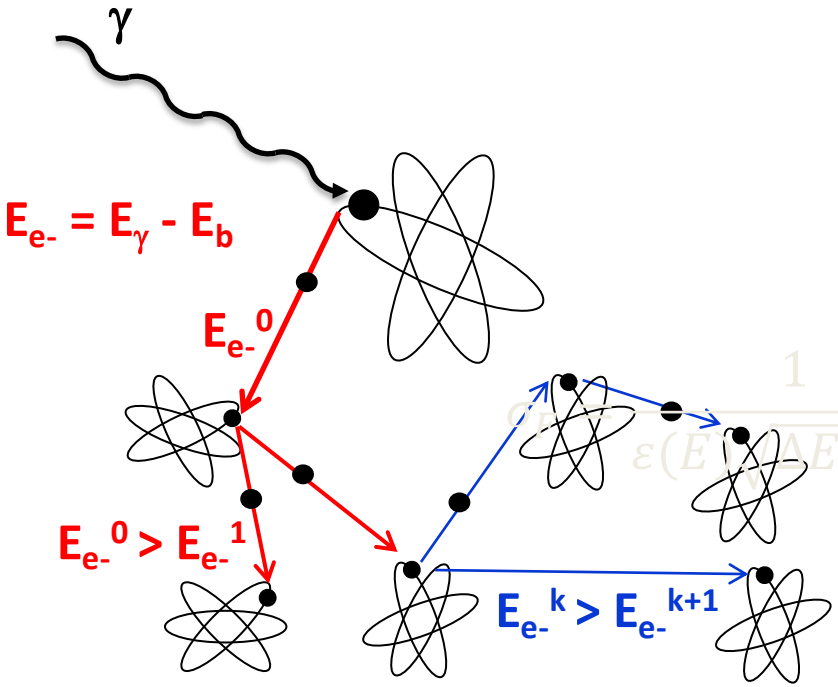


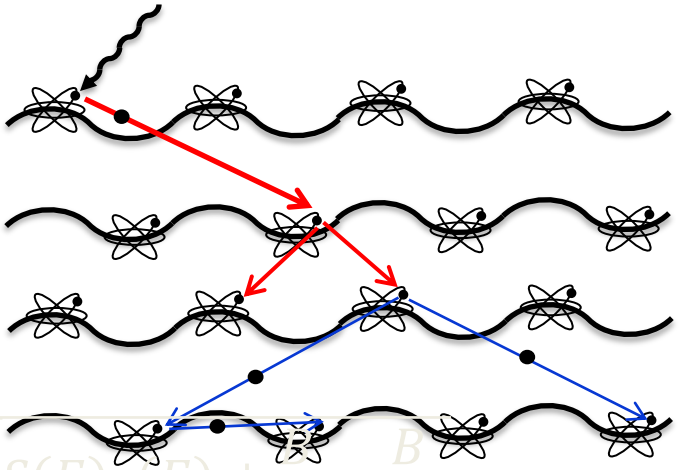




Cryogenic Microcalorimenters for X-ray spectroscopy

Microcalorimeter: heat sensitive detectors





An electron in a solid interacts with the motion of the lattice and can be scattered into a different state.

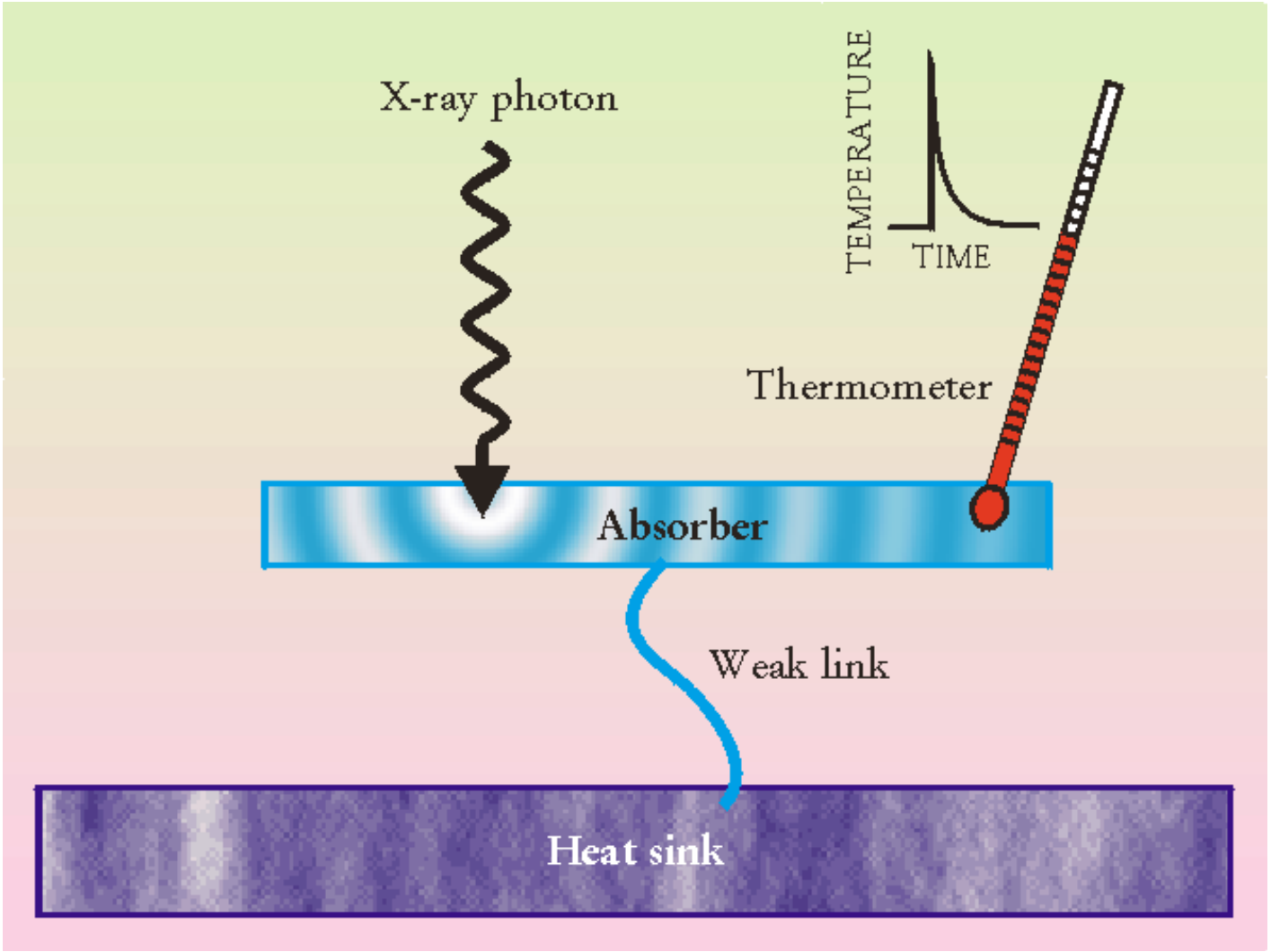
The primary energy Eγ is first absorbed by the electron system, and the temperature of the "hot" electrons carries precise information about Eγ.

About a metal absorber:

- Photoelectric absorption
- The energetic photoelectron provides energy to other shell electrons as well as to free electrons → cascade of electrons
- The number of electron increase, then decrease the energy of each electron
- When this energy is ~ < eV, the electron can only interact with the lattice: phonon emission ($G_{e\text{-}ph} \sim 1/T^3$, e-ph decoupled at T<0.1K)
- Then the electrons go at the thermal equilibrium (Maxwell-Boltzmann distribution): this is what we call "Thermalization".

….

X-ray Calorimeters



Microcalorimetry principle

Direct detection: **How is energy measured?**

Equilibrium: The energy is deposited in an isolated thermal mass and the resulting increase in temperature is measured. At the time of the measurement, all of the deposited energy has become heat and the sensor is in thermal equilibrium. The ultimate energy resolution is determined by how well one can measure this change in temperature against a background of thermodynamically unavoidable temperature fluctuations.

THIS IS CALORIMETRY.

$E_\gamma = h\nu$

C, T_0

$E_\gamma \sim \Delta Q = C \cdot \Delta T$

$\rightarrow \Delta T \sim E_\gamma / C$

From thermodynamics, at the thermal equilibrium,

the total content energy is: $E_T \sim C \cdot T_0 \sim NKT_0 \rightarrow N \sim C/K$

Energy of the bkg fluctuations $\sigma(E_T) \sim \sqrt{N \cdot KT_0} \sim (KT^2C)^{1/2}$

So, in microcalorimetry you compare $\sigma(E_T)$ with E_γ

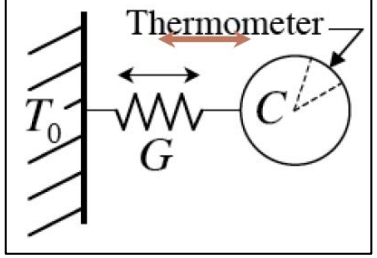
THIS IS CRYOGENIC MICRO-CALORIMETRY

To decrease $\sigma(E_T) \sim (KT^2C)^{1/2}$

Low temperature → Cryogenic detector

Low heat capacity detector → micro detector

More precisely, random transport of energy between heat sink at T_0 and detector over thermal link G produces fluctuations in the energy content of C.



"Thermodynamic Fluctuation Noise (TFN)".

Not a limit on resolution, but sets the scale!

Energy resolution limit

- So for a microcalorimeter:
- k=8.6e-5 eV/K Boltzmann constant), thus for T=0.1K, the energy required to produce a phonon is kT=W=8.6E-6 eV (compare with W=3.6 eV for Si ionization detectors)
- Note that N=hv/kΔT, with ΔT=few mK
- Example hv=1keV, N~ 10^9
- Assume Poisson $\sigma_E = \mathrm{W}\sqrt{N} \cong 0.3\ \mathrm{eV}$

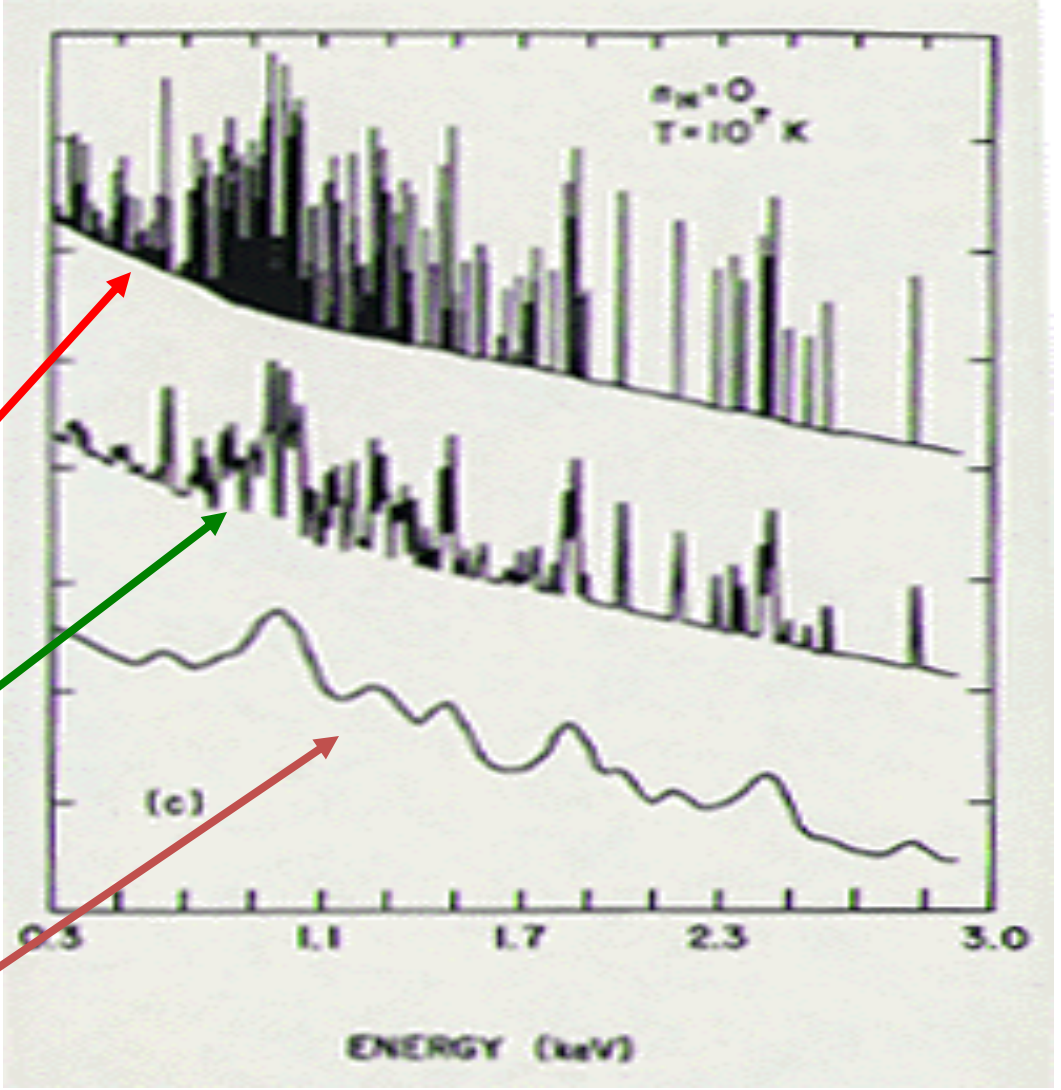
High resolution X-ray spectroscopy with ucalorimeters

plasma emission (10^7K) observed with:

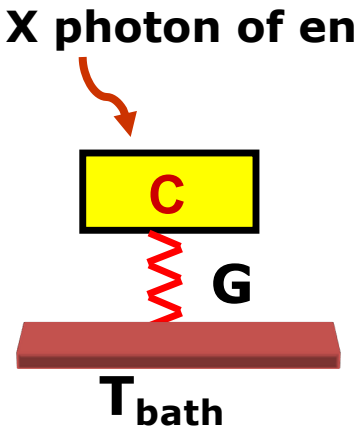
* TES ucal (ΔE=2.5 eV: Athena)

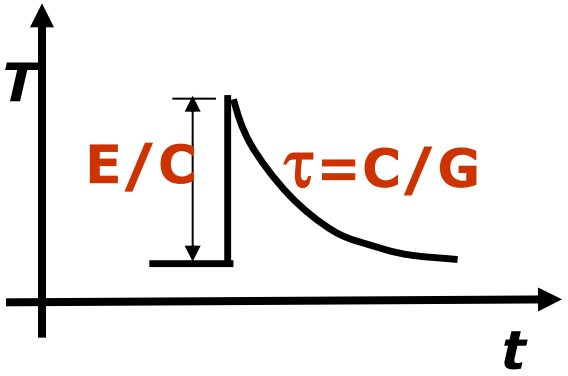
*present generation ucal (ΔE=4-6 eV: Hitomi)

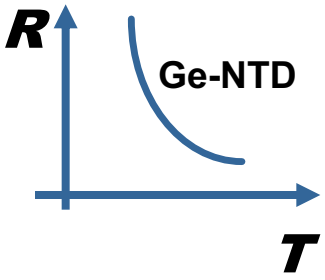
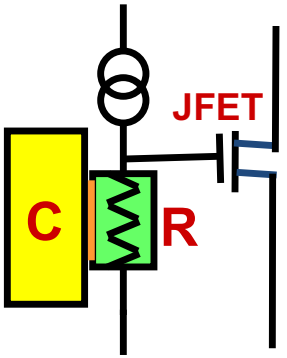
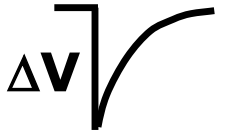
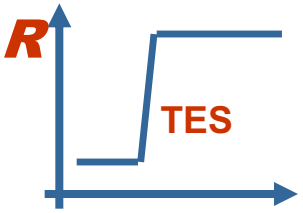
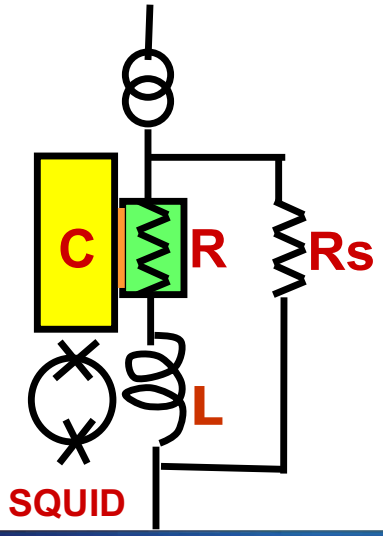
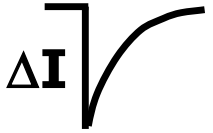
*CCD (ΔE=100 eV:XMM)



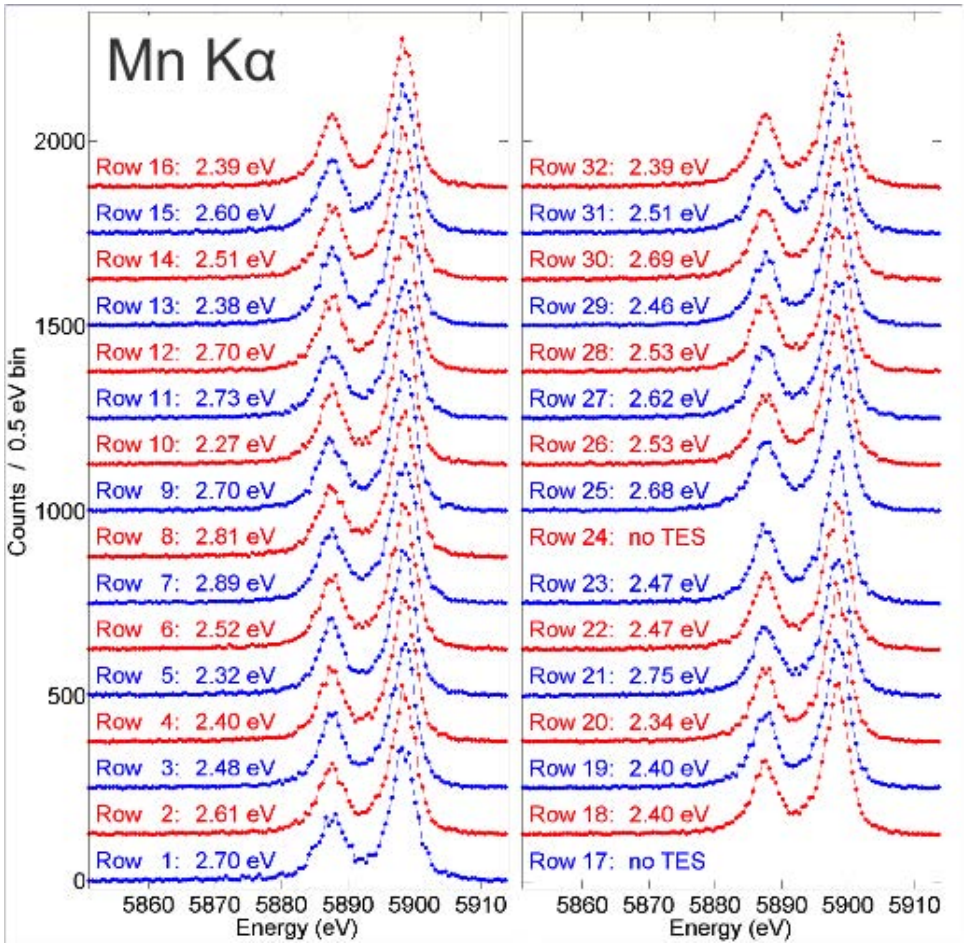
How a microcalorimeter works





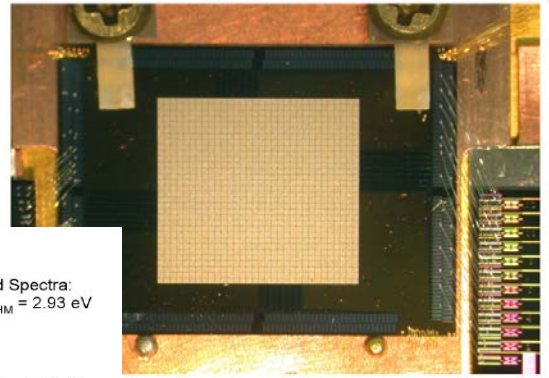
Sensor type	Electronic coupled device	Output Signal
		 =IA ΔT (R/T)
		 =IA ΔT (1/T)

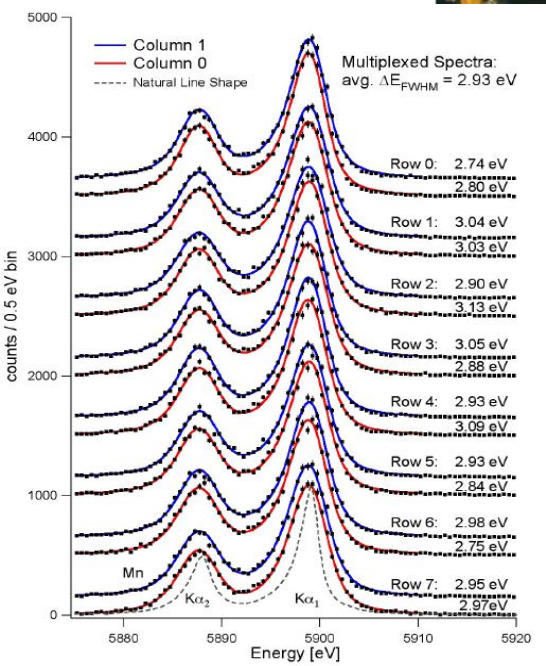
What about the Array?



http://ltd16.grenoble.cnrs.fr/IMG/UserFiles/Images/TD16Grenoble_TDMCDMreadout_DORIESE.pdf

32x32 NASA GSFC – IXO/XMS
(bond pads for 256 channels only)





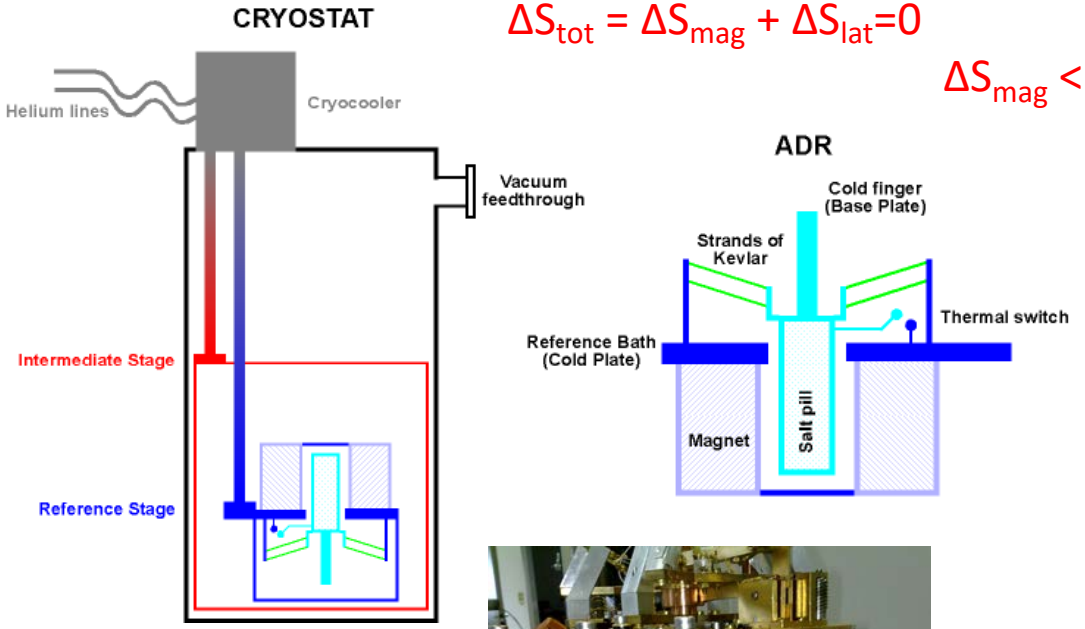
Eckart, Doriese, SPIE Newsroom , 2009

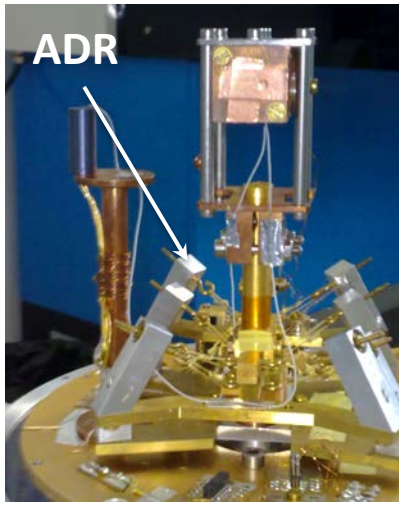
The ADR

Magnetocaloric effect

$\Delta S_{tot} = \Delta S_{mag} + \Delta S_{lat} = 0$

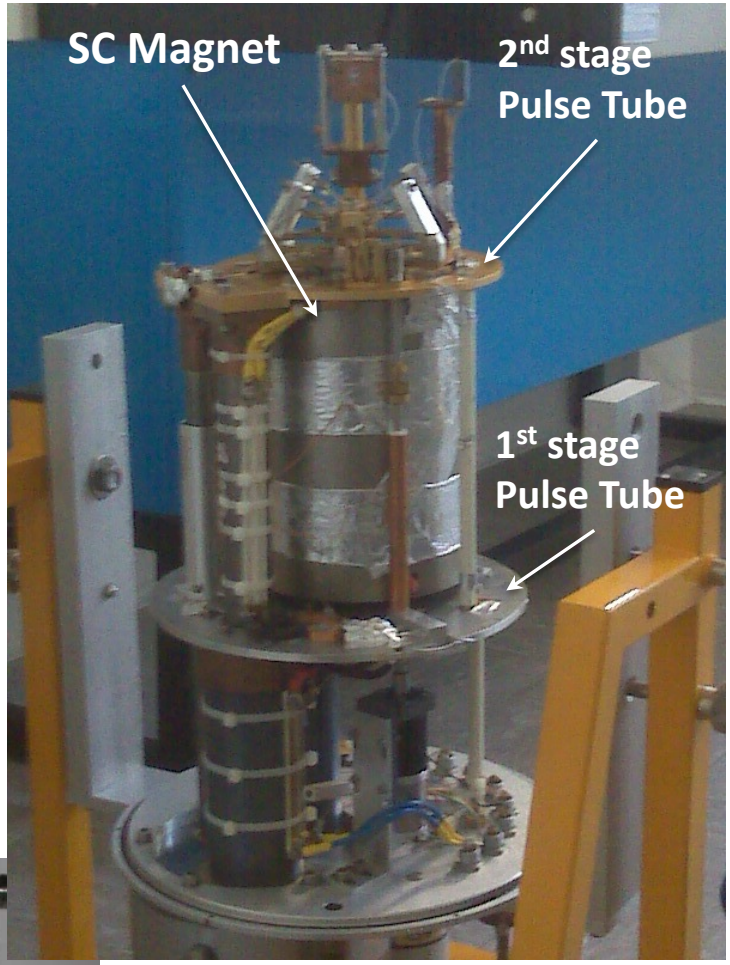
$\Delta S_{mag} < 0 \rightarrow \Delta S_{lat} > 0$



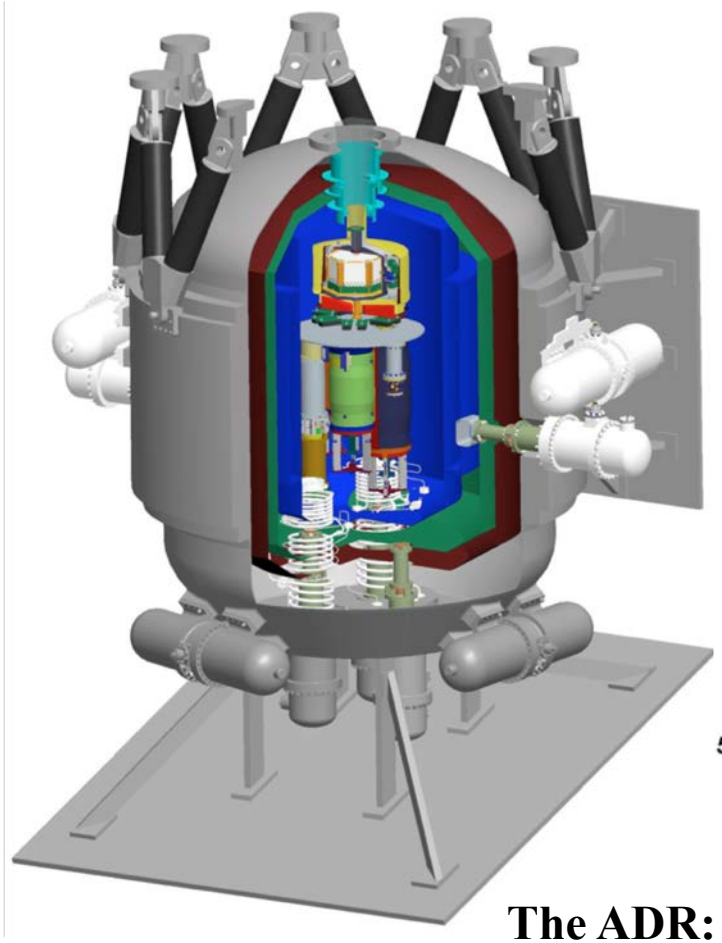






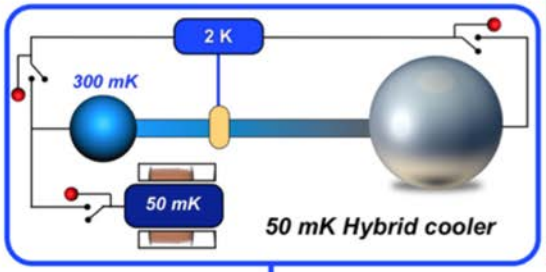


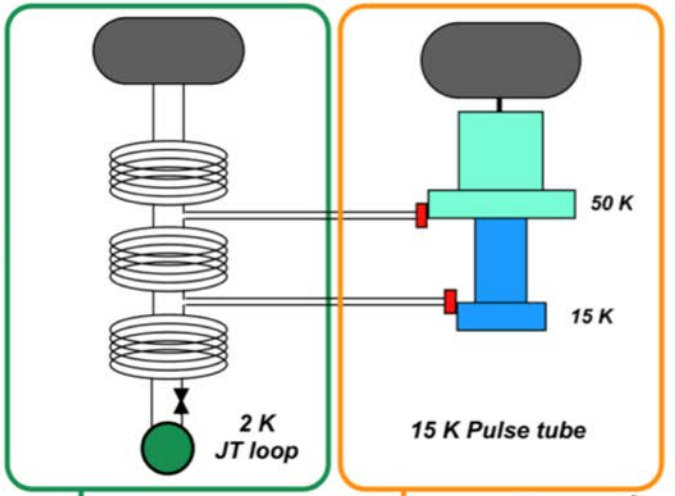
X-IFU cryostat and cooling chain

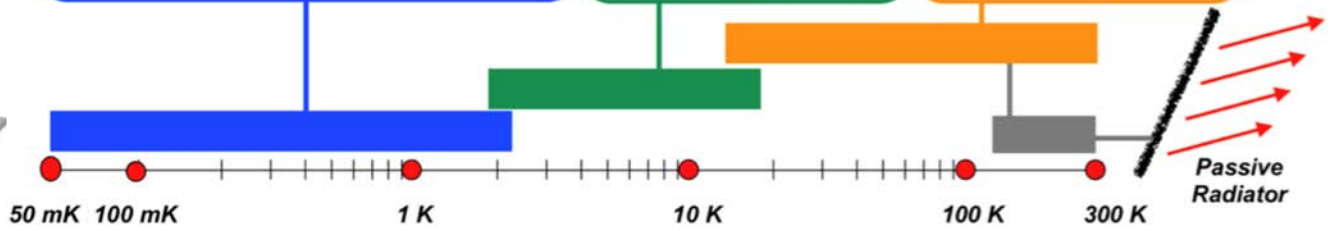




CEA/CNES



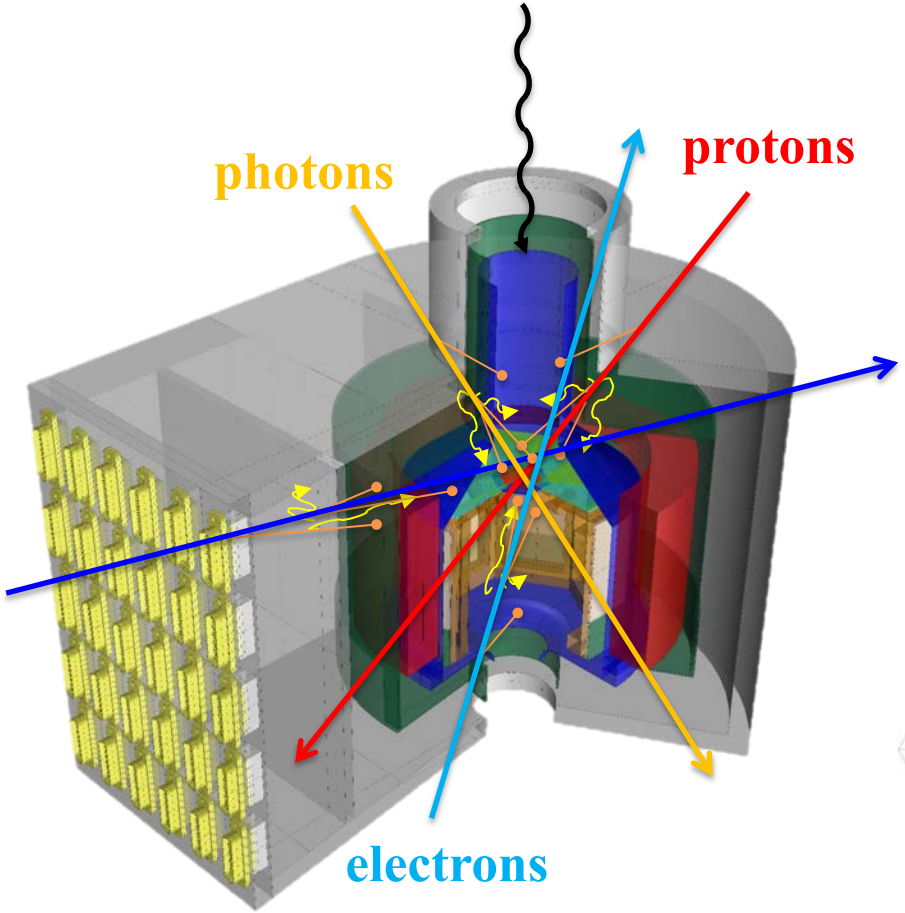




The ADR: at 50 mK we need of ~ 1 μW of cooling power for ~ 30 hr

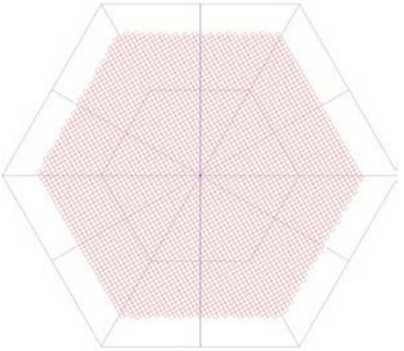
The particle background issue

The scientific signals come from the top!!

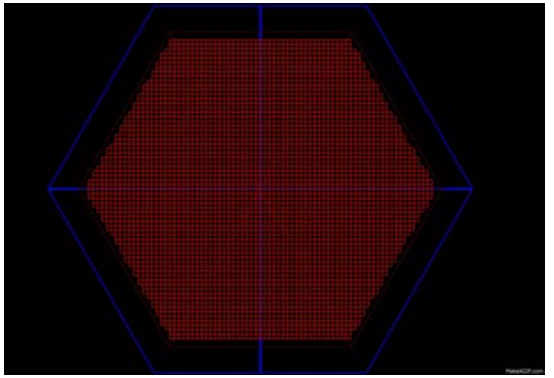


$$F_{\min} = \frac{n_\sigma}{QA_s}\sqrt{\frac{B_i A_d + B_d Q \Omega A_s}{t \Delta E}}$$

CAD

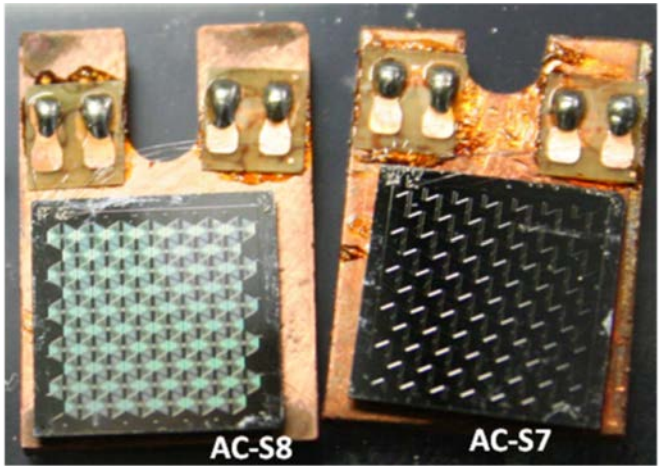


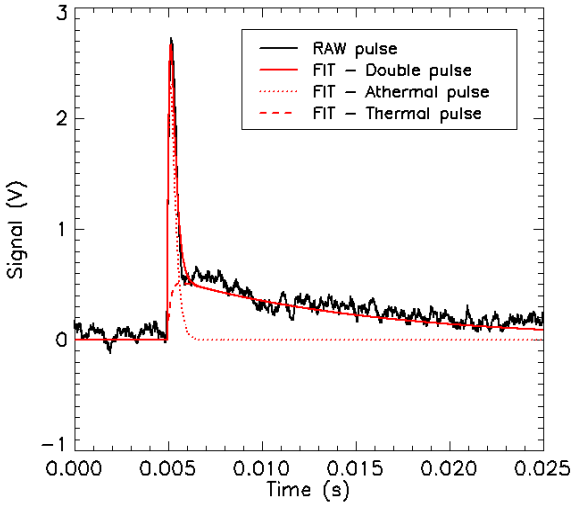
Geant4 mass model

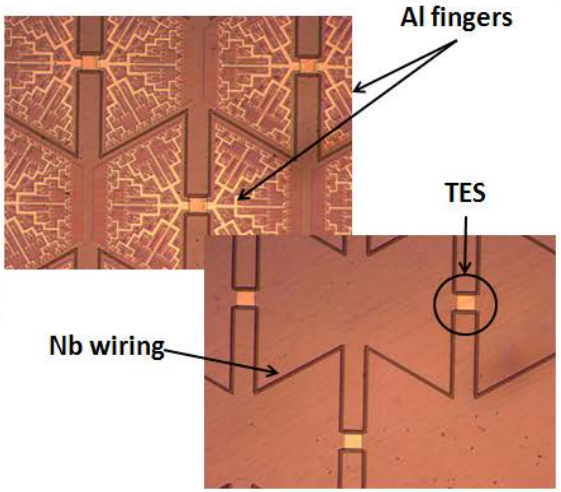


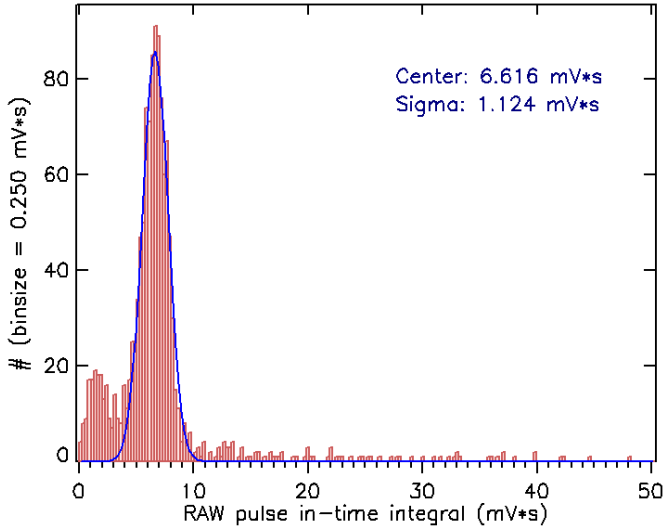
Follow S. Lotti lecture

CryoAC: a TES based anticoincidence detector





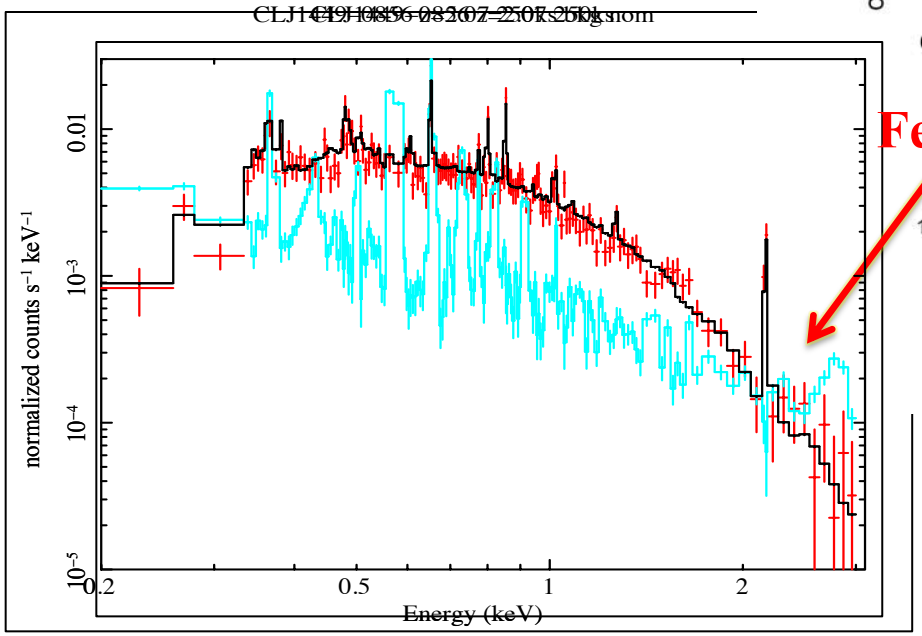




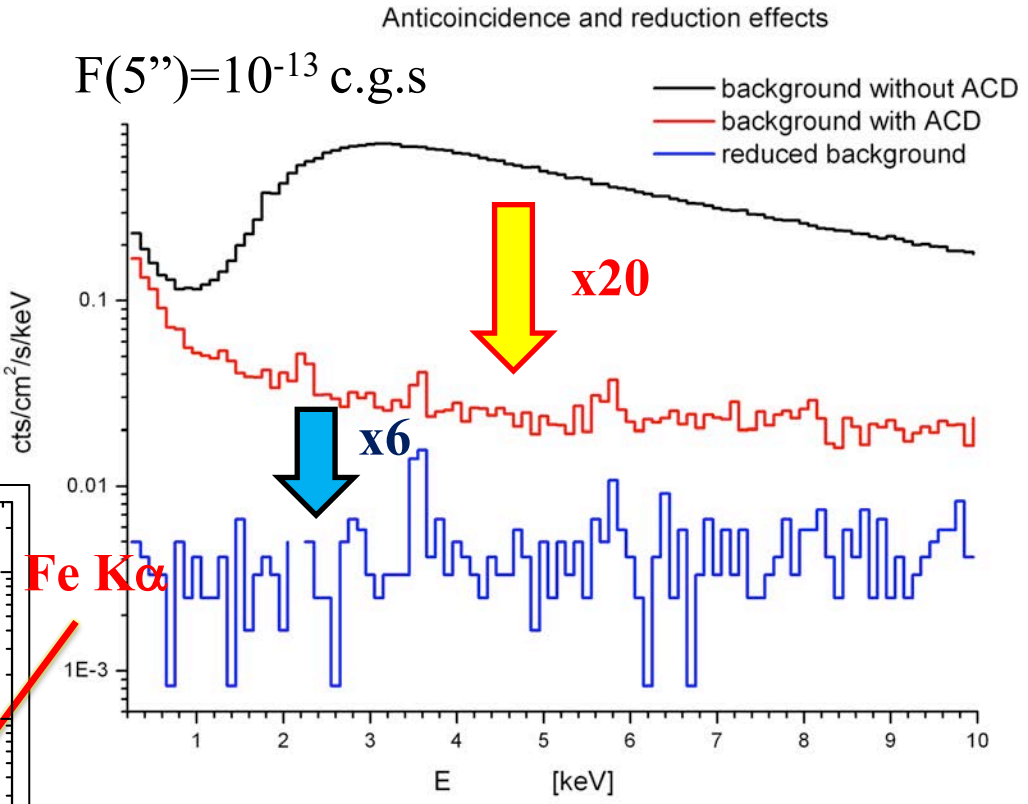
C. Macculi et al., JLowTempPhys, DOI 10.1007/s10909-015-1439-y, (2016).

Background Reduction in XIFU

$$S/N \approx \sqrt{\frac{A \cdot T_{exp}}{\Delta E \cdot B}}$$



Fe Kα



Abundance 0.3, area=1m2,f/l=12m

25