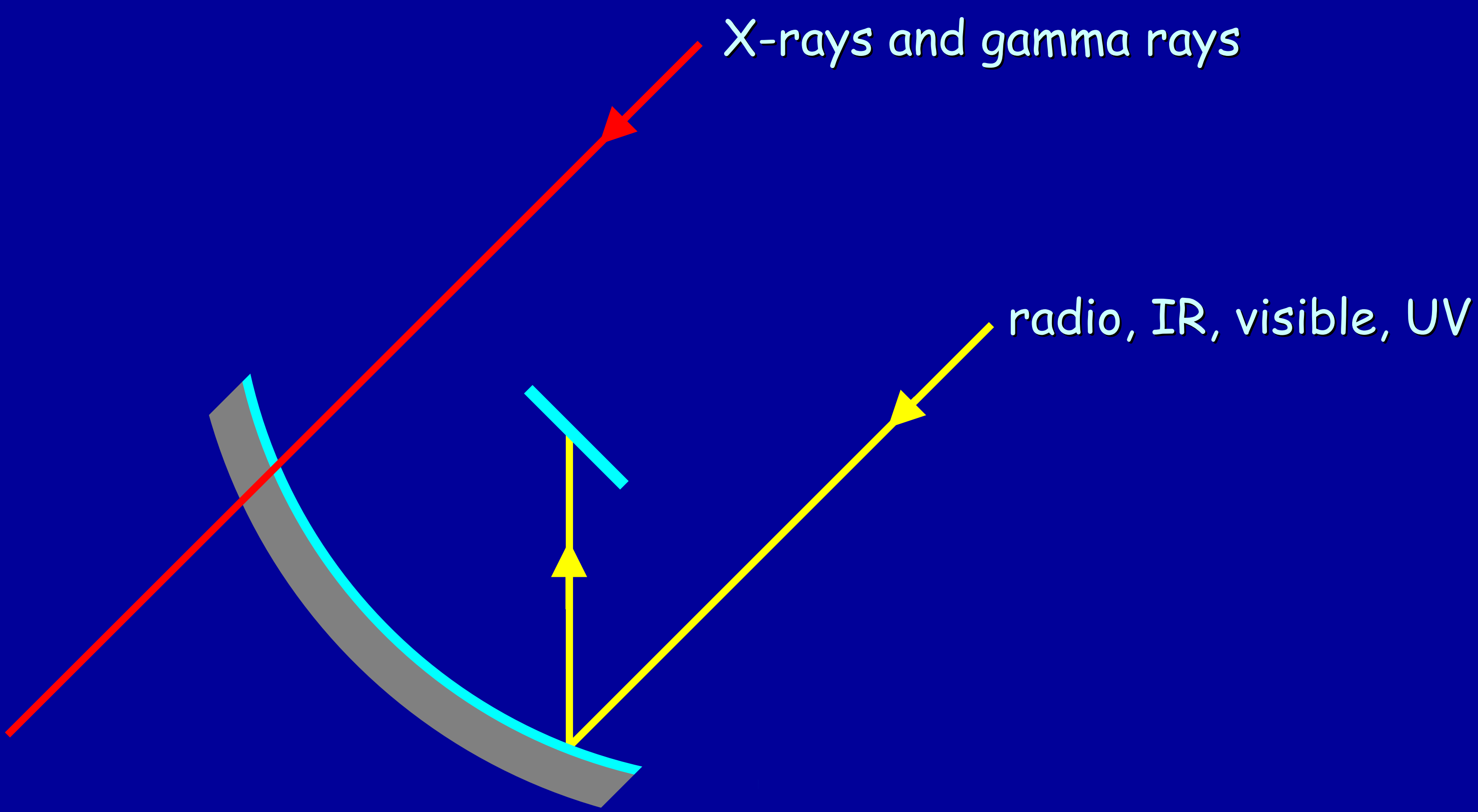
# Semi conductor detectors for soft gamma-ray astrophysics

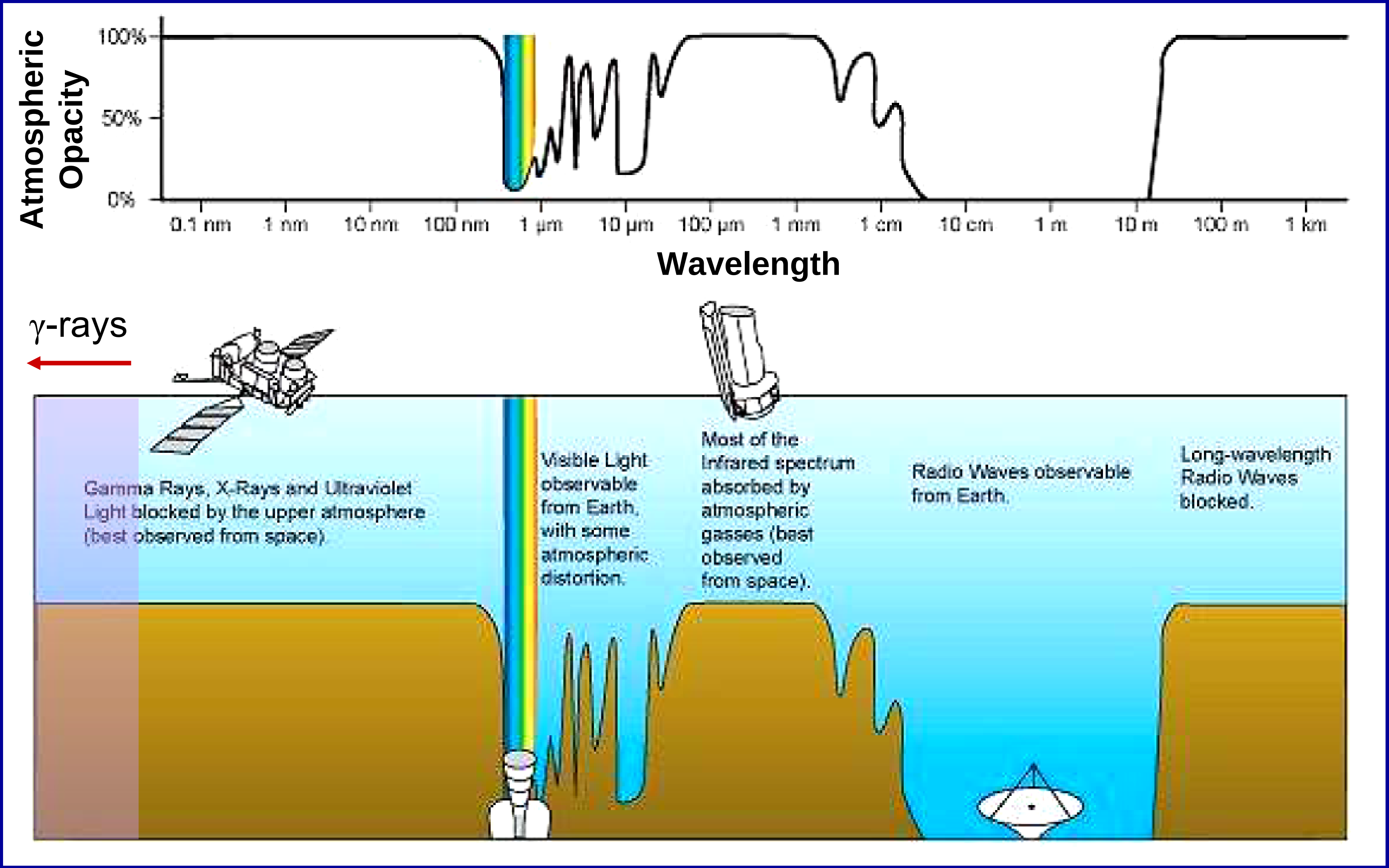
François Lebrun
APC (UMR 7164), CEA-Saclay
ISGRI PI

IWORID 2005 Grenoble

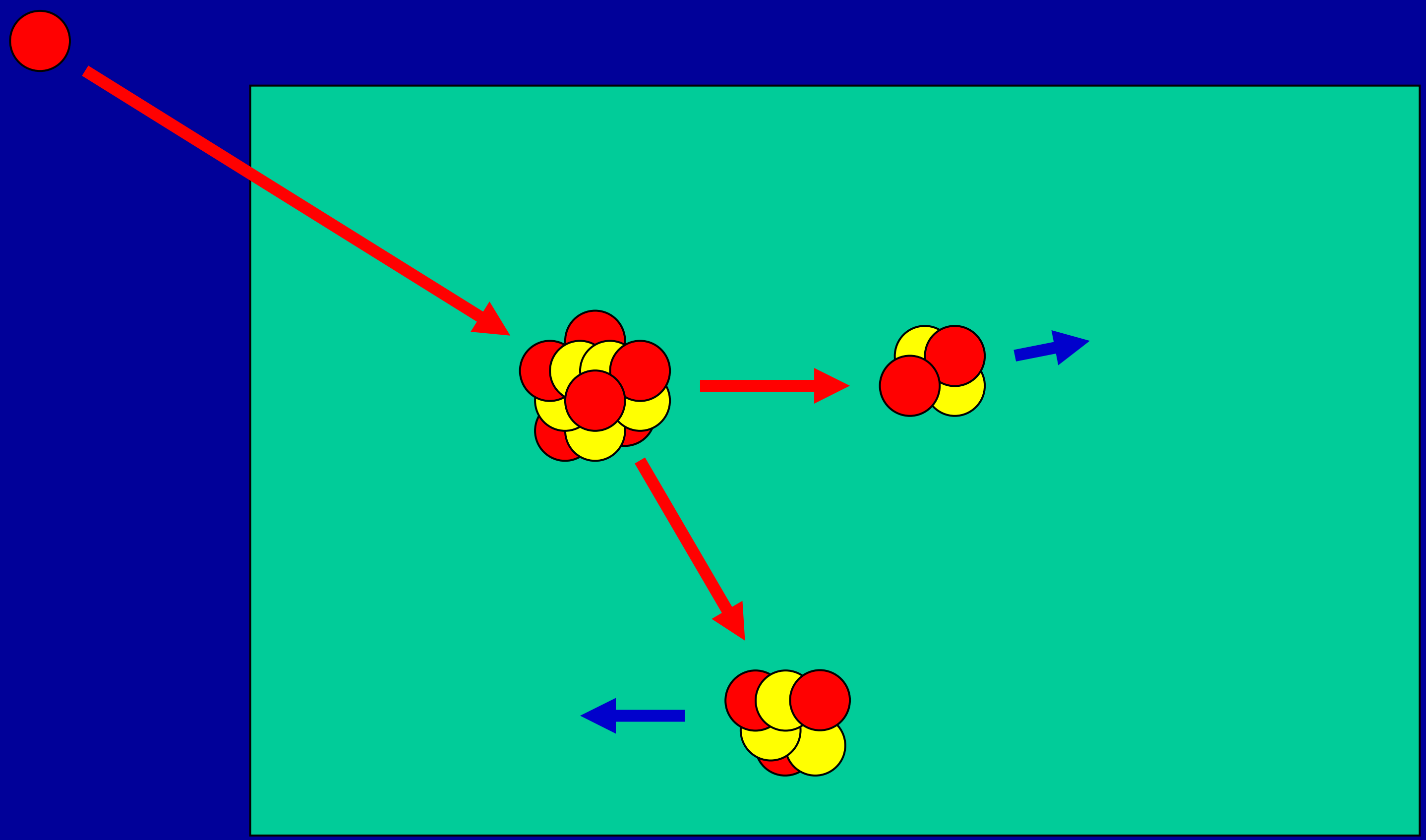
# High-energy astronomy → specific telescopes



# Atmospheric absorption → space experiments



# internal background → minimization of the detector and surrounding material mass

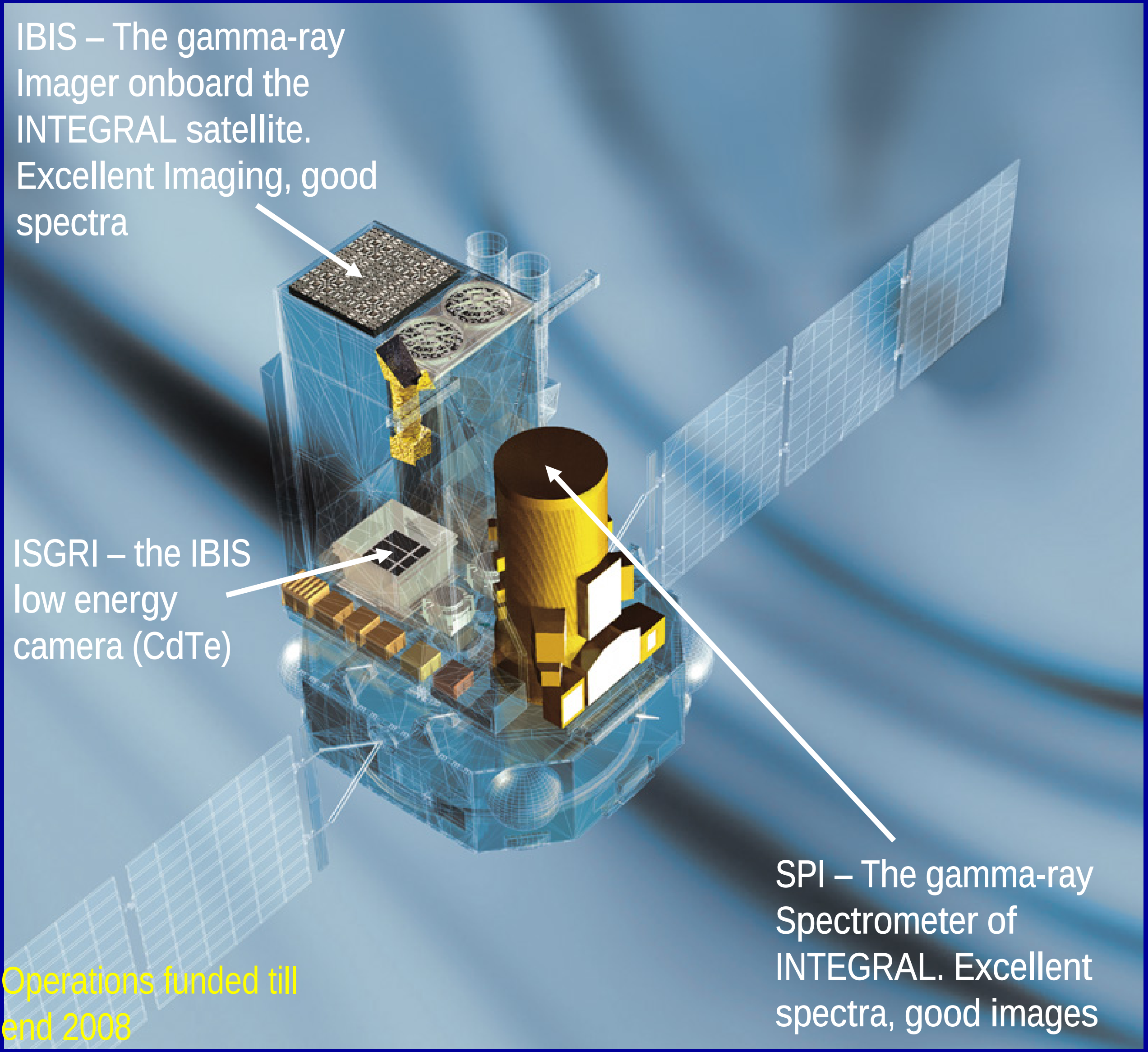


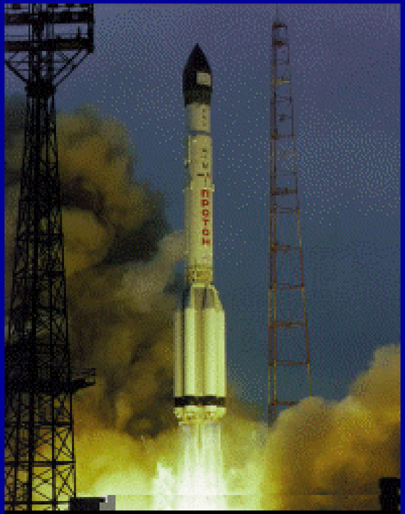
# The SIGMA gamma camera problem

- Anger camera: NaI + PMTs
- Detector: NaI 1.2 cm thick
- 1 GeV $P^+$ energy loss: ~ 10 MeV → saturation
- Area: 3200 $cm^2$ → a proton every 300 μs (eccentric orbit)
- Recovery time > 300 μs
- → Performance degradation (imaging)

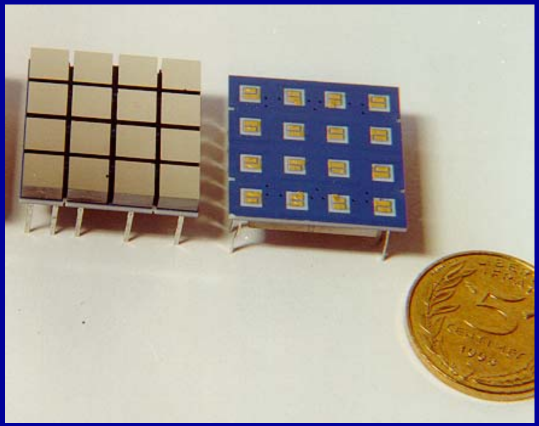
- Solutions:
  - several smaller cameras → unacceptable dead zone increase
  - Pixellated camera

# INTEGRAL: an ESA gamma-ray observatory

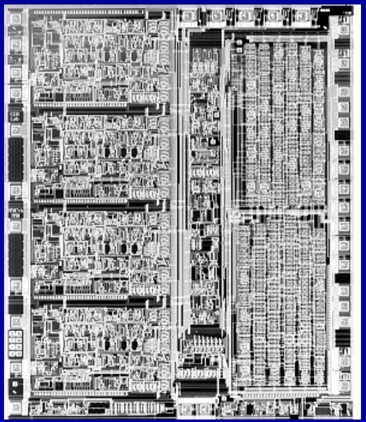


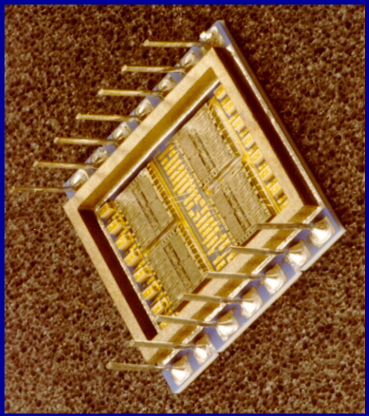
Launch: October 2002



16 CdTe
planar detectors

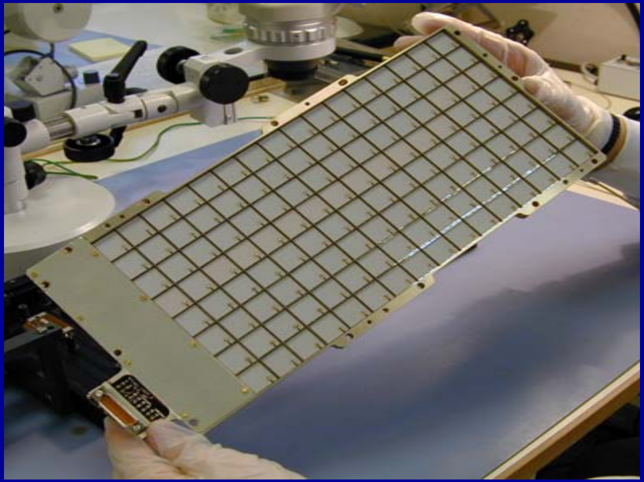


ASIC
(LETI/DSM)



FEE

Polycell



Modular Detection Unit

# From SIGMA to IBIS/ISGRI

| | SIGMA | IBIS/ISGRI |
|---|---|---|
| Energy range (keV) | 40 – 1300 | 15 - 1000 |
| Angular resolution | 18′ | 12′ |
| Spectral resolution $\Delta E/E$ (100 keV) | 13% | 8% |
| Field of view (FWHM) | 9.4° x 9.7° | 19° x 19° |
| Timing accuracy | 4 s | 64 μs |
| Broad-band sensitivity (100 keV) $\Delta E=E$, $3\sigma$, $10^6$s ($cm^{-2}$ $s^{-1}$ $keV^{-1}$) | $4\ 10^{-6}$ | $4\ 10^{-7}$ |

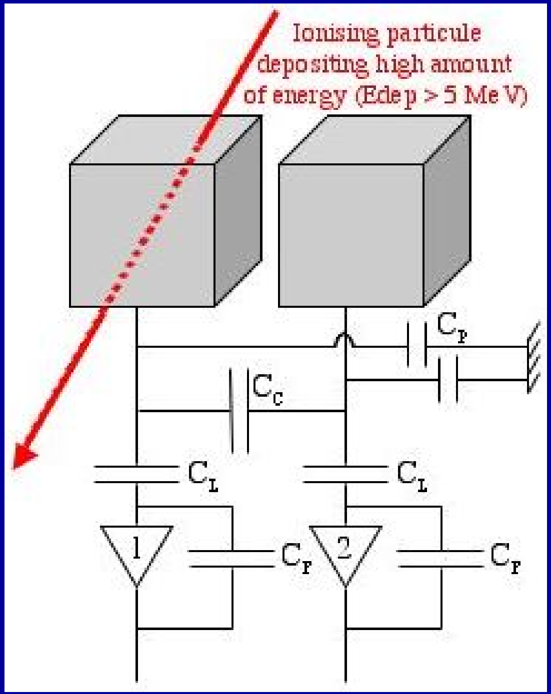
# Noisy pixels (CdTe detectors)

- Testing thousands of detectors → hundreds of them sometime noisy
- A noisy pixel can trigger continuously → blind camera !
- What can be done ?
  - Switch off the noisy pixel
  - Switch on again the off-pixel after a while
  - Raise its low threshold
- The Noisy Pixel Handling System (NPHS) implemented on board does all that

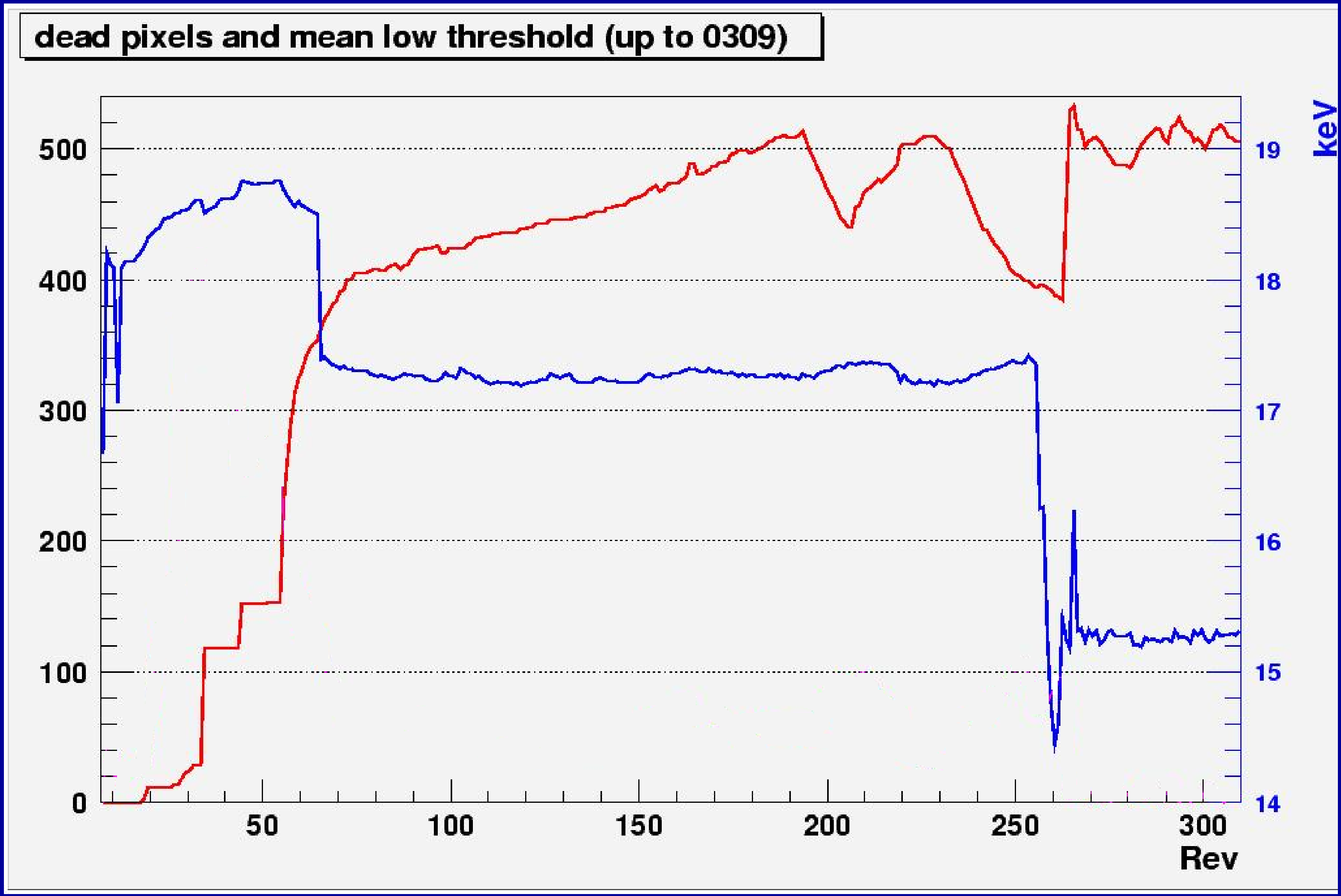
# ISGRI in flight behaviour: unexpected effects

- Many pixels automatically disabled
  - Likely origin: preamp overload → multiple triggers → detected as noisy
  - Problem solved after tuning the Noisy Pixel Handling system

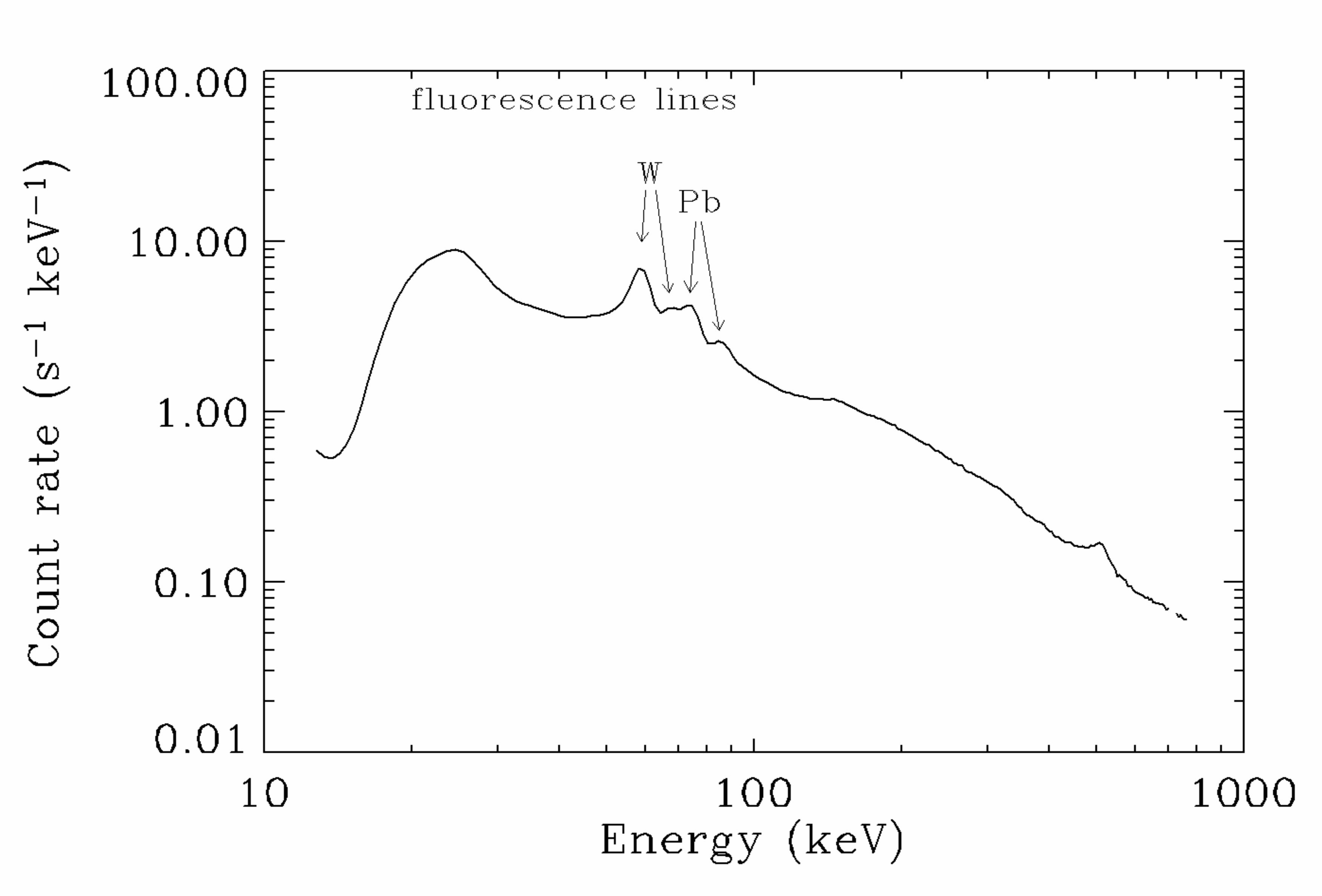
- Events with zero rise-time (10%)
  - preamp saturation (E>5 MeV)
  - Capacitive coupling → Trigger of neighbouring detectors
  - Easy correction



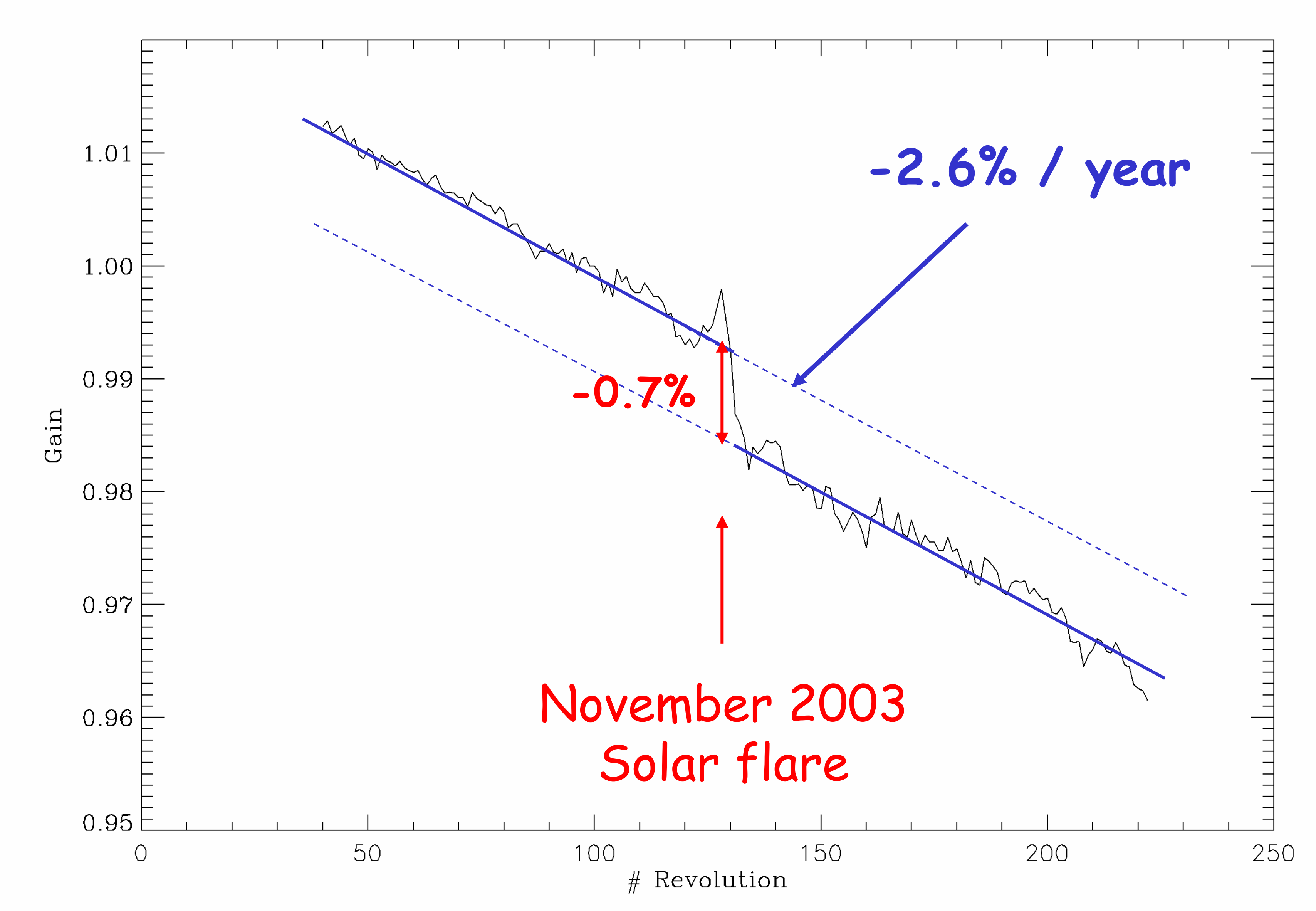
# ISGRI in flight behaviour: detector stability

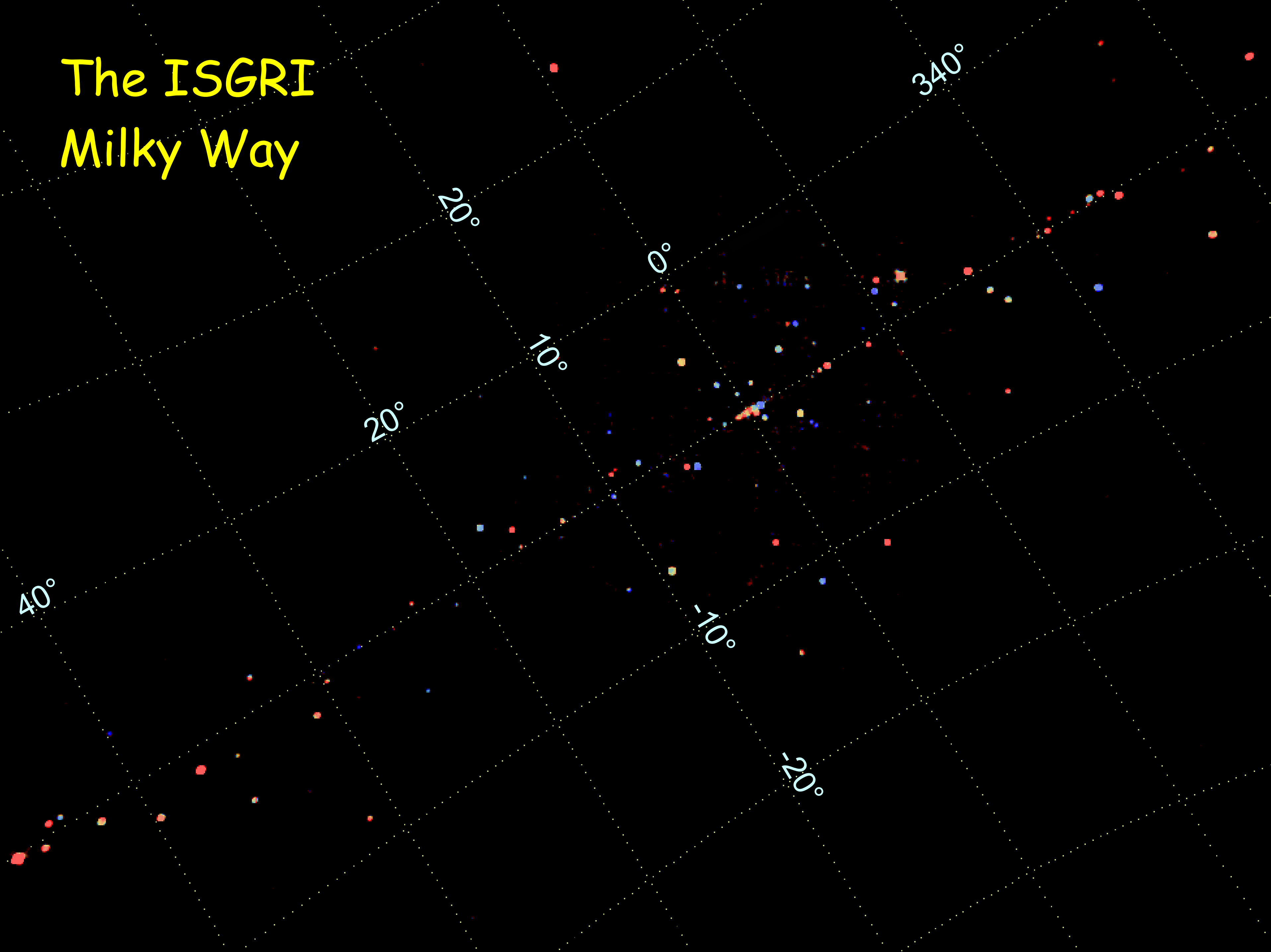


# ISGRI in flight behaviour: background

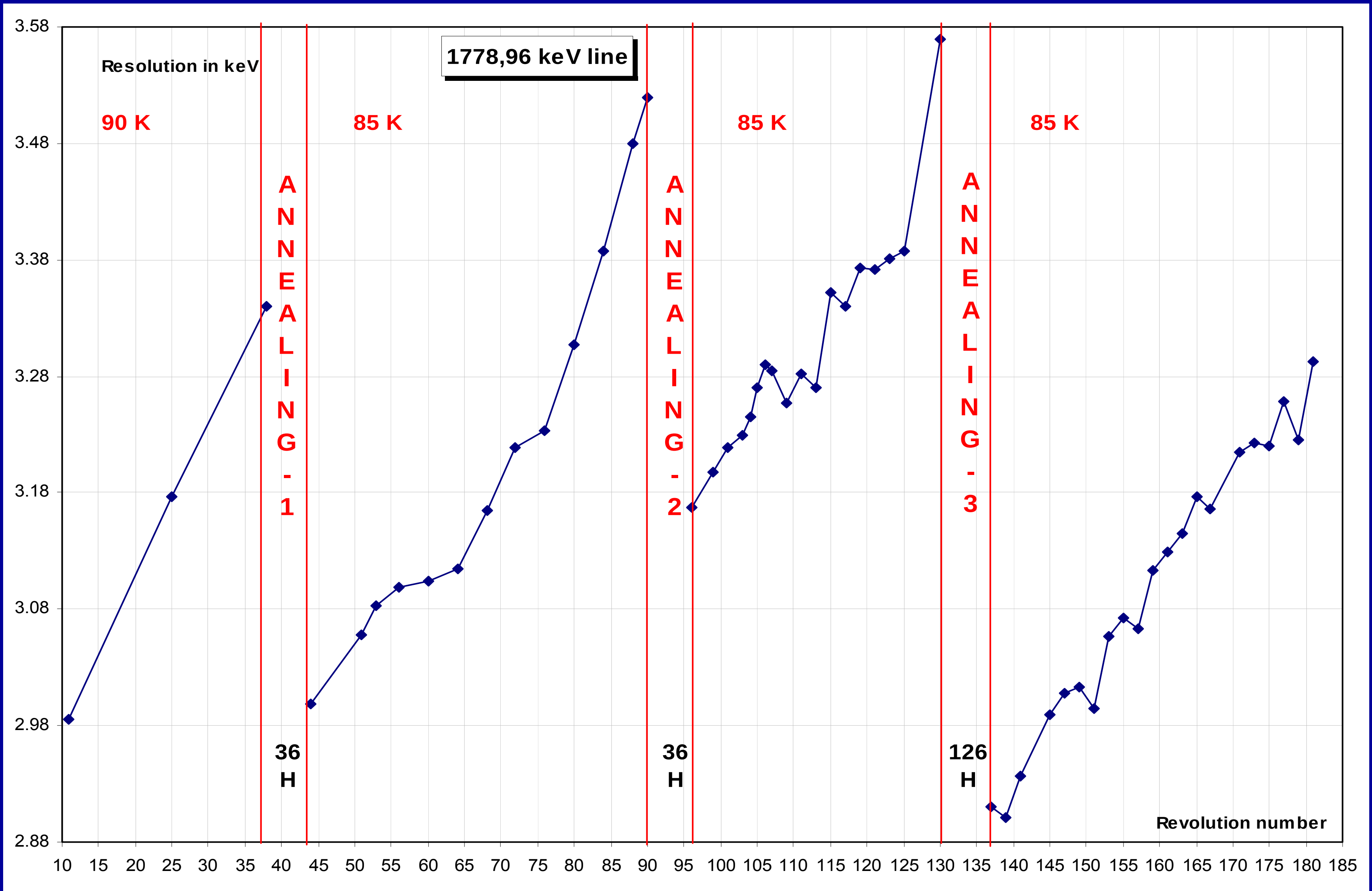


# ISGRI in flight behaviour: degradation




The ISGRI
Milky Way
340°
20°
0°
10°
20°
40°
-10°
-20°

# SPI: in-flight annealings



# Soft gamma-ray astrophysics scientific needs for the future

| | sensitivity | imaging | Energy range | Energy resolution | Field of view | Fast timing |
|---|---|---|---|---|---|---|
| X-ray binaries | X | XX | X | X | | X |
| AGNs | XX | X | | | | |
| pulsars | X | X | X | | | XX |
| Supernovae | XXX | X | XX | XX | | |
| SNRs | XX | XXX | XX | XX | | |
| GRBs | X | X | X | | XXX | XX |
| $e^+e^-$ | X | X | | XX | XX | |
| CR interactions | XX | XX | XX | | XX | |
| ISM radioactivity | XX | XX | XX | XX | XX | |

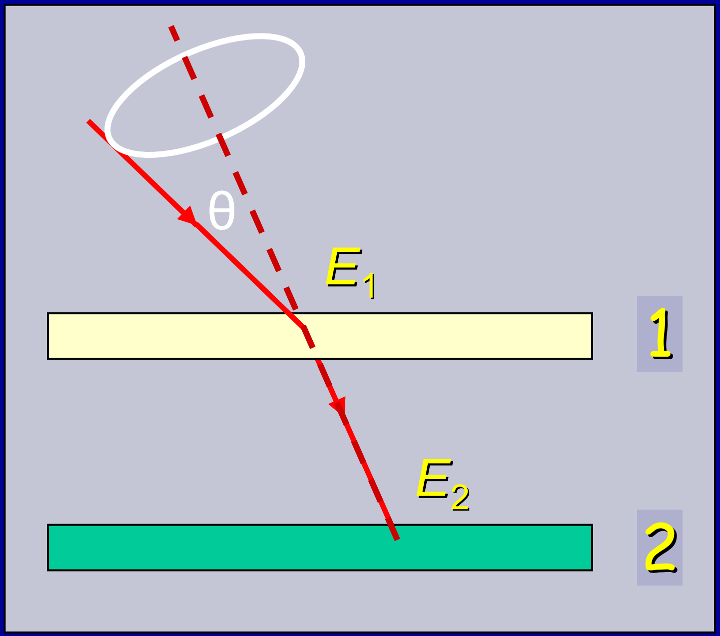
# Compton Telescopes

# Compton telescope

A basic Compton telescope features two layers of position sensitive detectors

Layer 1: made of scattering material to scatter the incident gamma ray

Layer 2: made of absorbing material to absorb the scattered photon




Both incoming photon energy $E_0$ and the scatter angle θ can be derived from the Energy deposits $E_1$ and $E_2$

$$E_0 = E_1 + E_2$$

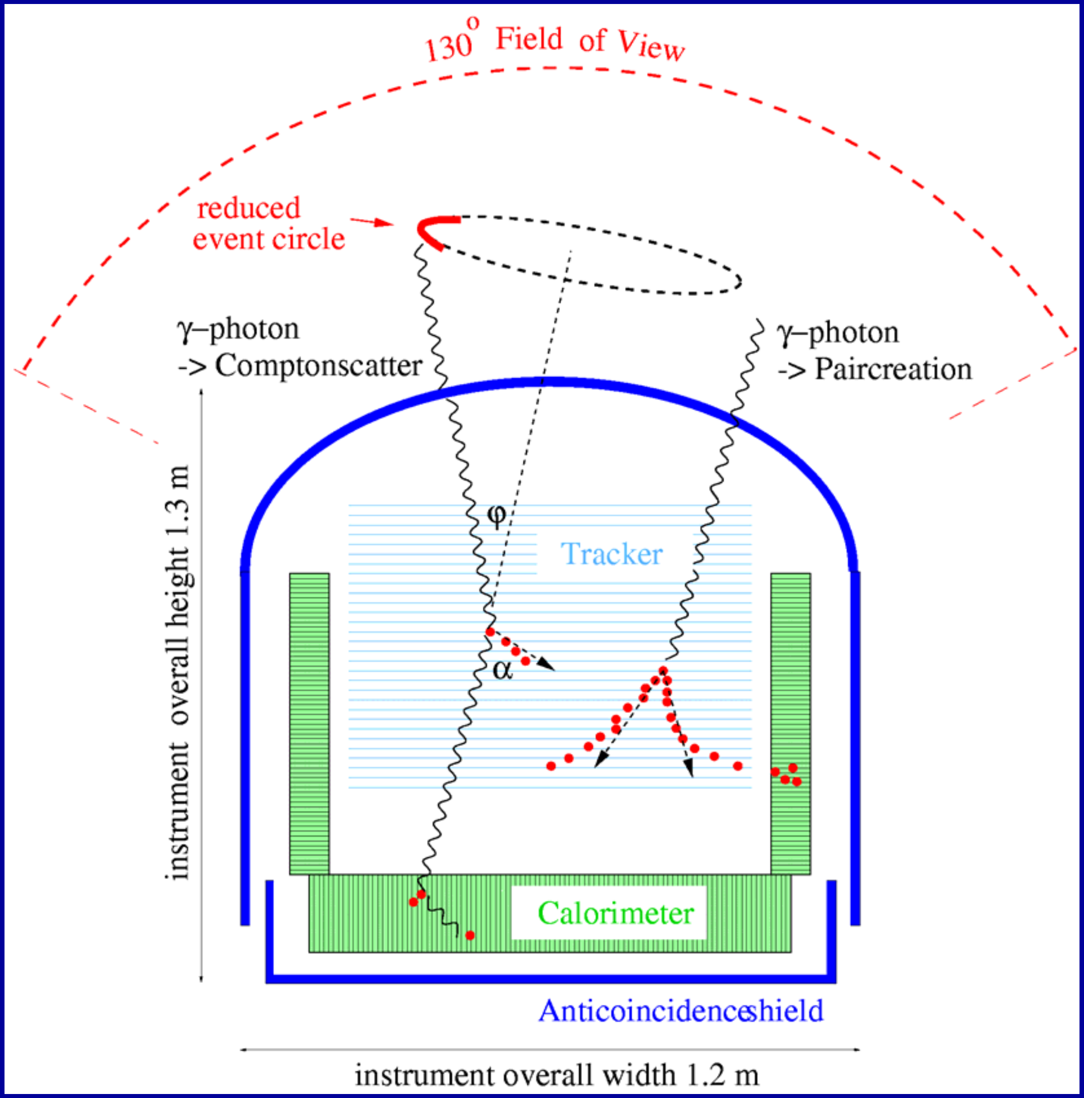
$$\cos\theta = 1 + m_e c^2 (1/E_0 - 1/E_2)$$

In addition Compton telescopes allows for polarization studies

# Detectors for Compton telescopes

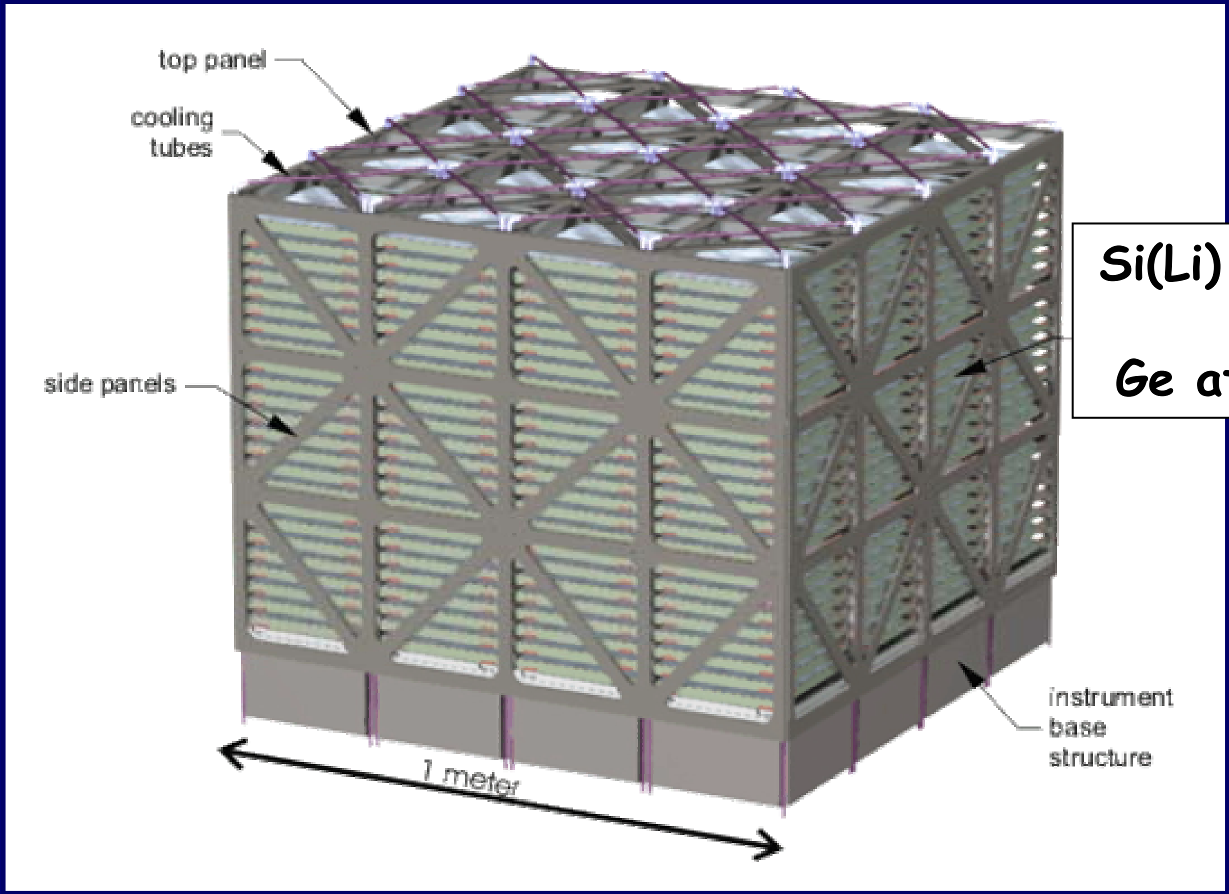
- Scattering layer: low Z material (e.g. Si)
  - Maximum scattering efficiency
  - Minimum absorbing efficiency
  - Minimum doppler broadening
  - Possibility to measure the electron recoil
- Absorbing layer: High Z material (e.g. CsI, CdTe, CdZnTe)
- For both layers, the best energy resolution is mandatory to achieve a good angular resolution (e.g. Ge)
- The sensitivity depends on the angular resolution
- In fine the energy resolution is the key parameter

# MEGA




- Records both Compton scattering and pair creation
- Electron recoil measurement
- Tracker (scattering layer): Si
- Calorimeter (absorbing layer): CsI

# The advanced Compton telescope



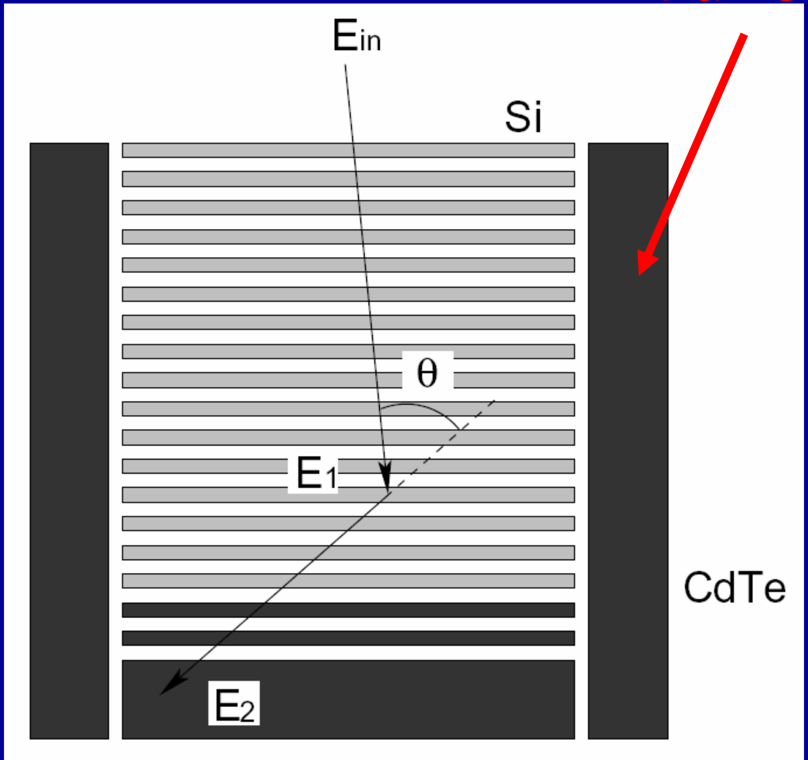

Si(Li) at -40°C
or
Ge at -180°C

Wide field Compton instrument dedicated to nuclear astrophysics

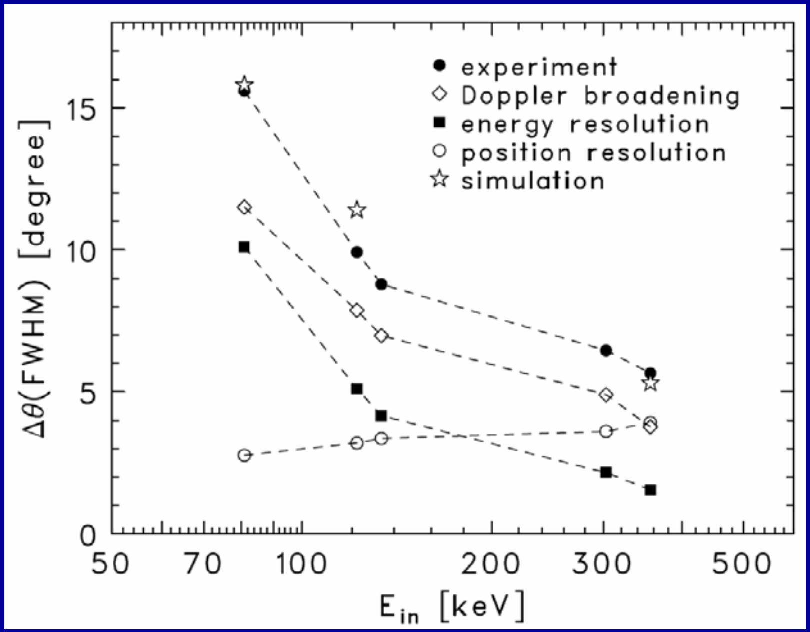
Goal: sensitivity < $10^{-7}$ cm$^{-2}$ s$^{-1}$

# Steps toward a Compton telescope for the NEXT mission

Stacks of shottky CdTe diodes




Angular resolution



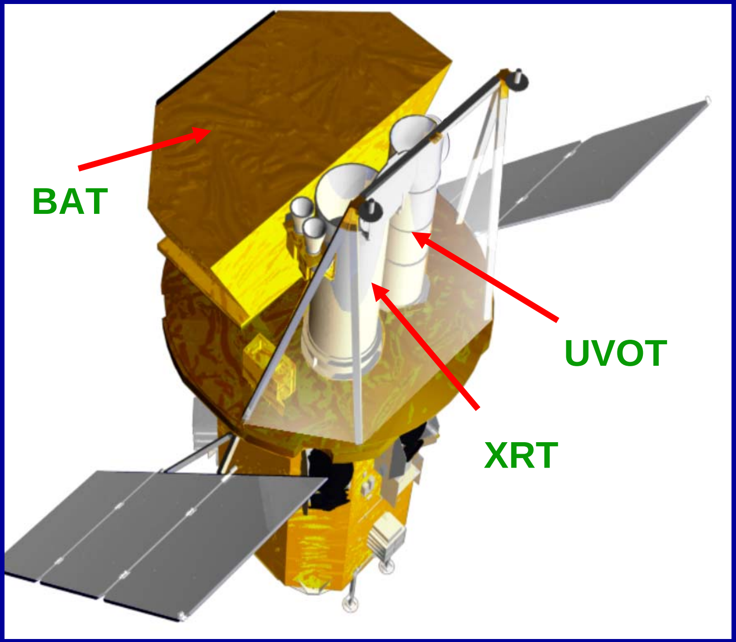

T. Tanaka et al. 2004, SPIE Glasgow

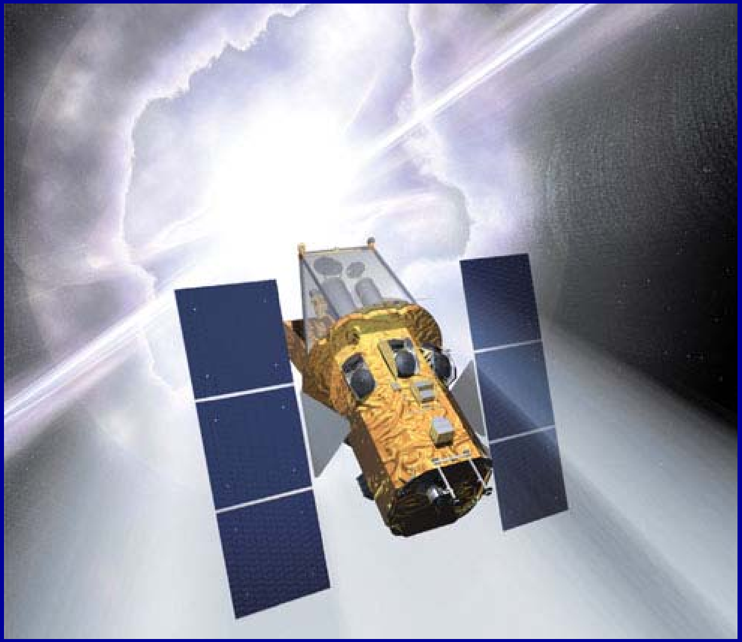
# Coded Mask Telescopes

# SWIFT
# Catching GRBs

| | |
|---|---|
| Telescope | Coded aperture |
| Telescope PSF | 17′ FWHM |
| Position accuracy | 1′ – 4′ |
| Detector | 32k CZT pixels |
| Energy resolution | 7 keV FWHM |
| Timing resolution | 100 μs |
| FOV | 2 sr |
| Energy range | 15 – 150 keV |
| Sensitive area | 5200 $cm^2$ |
| Max. trigger rate | 195 000 $s^{-1}$ |

Barthelmy et al. 2005, AAS

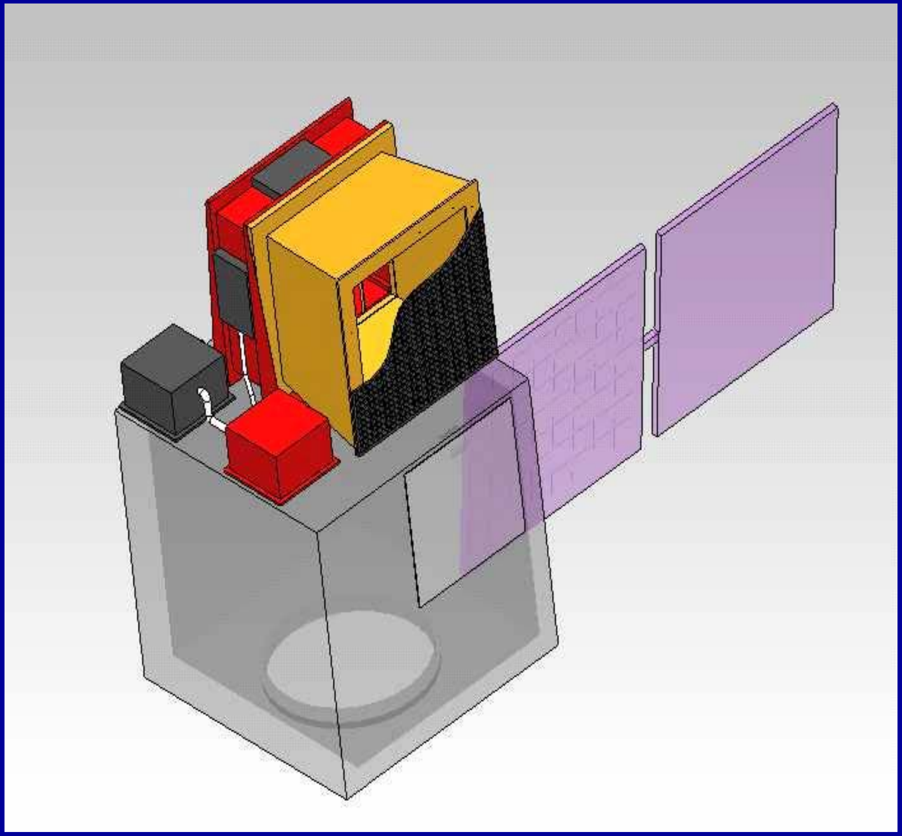


# Study of GRB prompt emission with ECLAIRs

## Space gamma-ray telescope

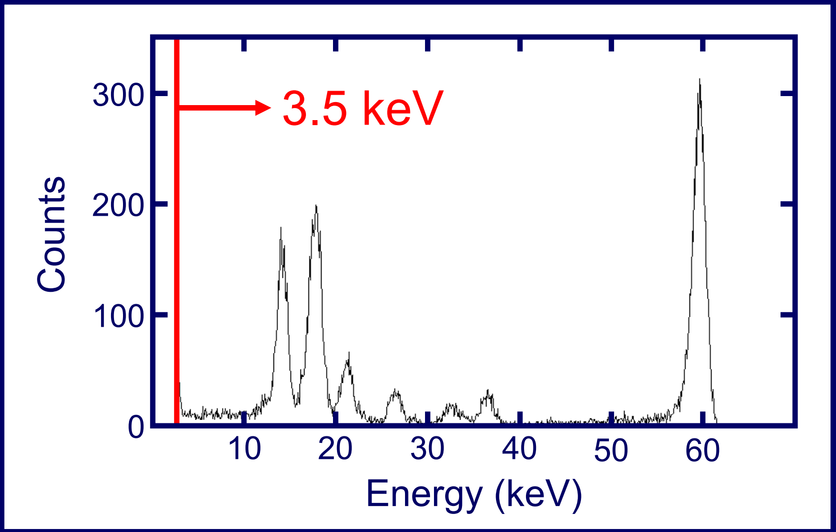
## coupled to ground based optical telescopes



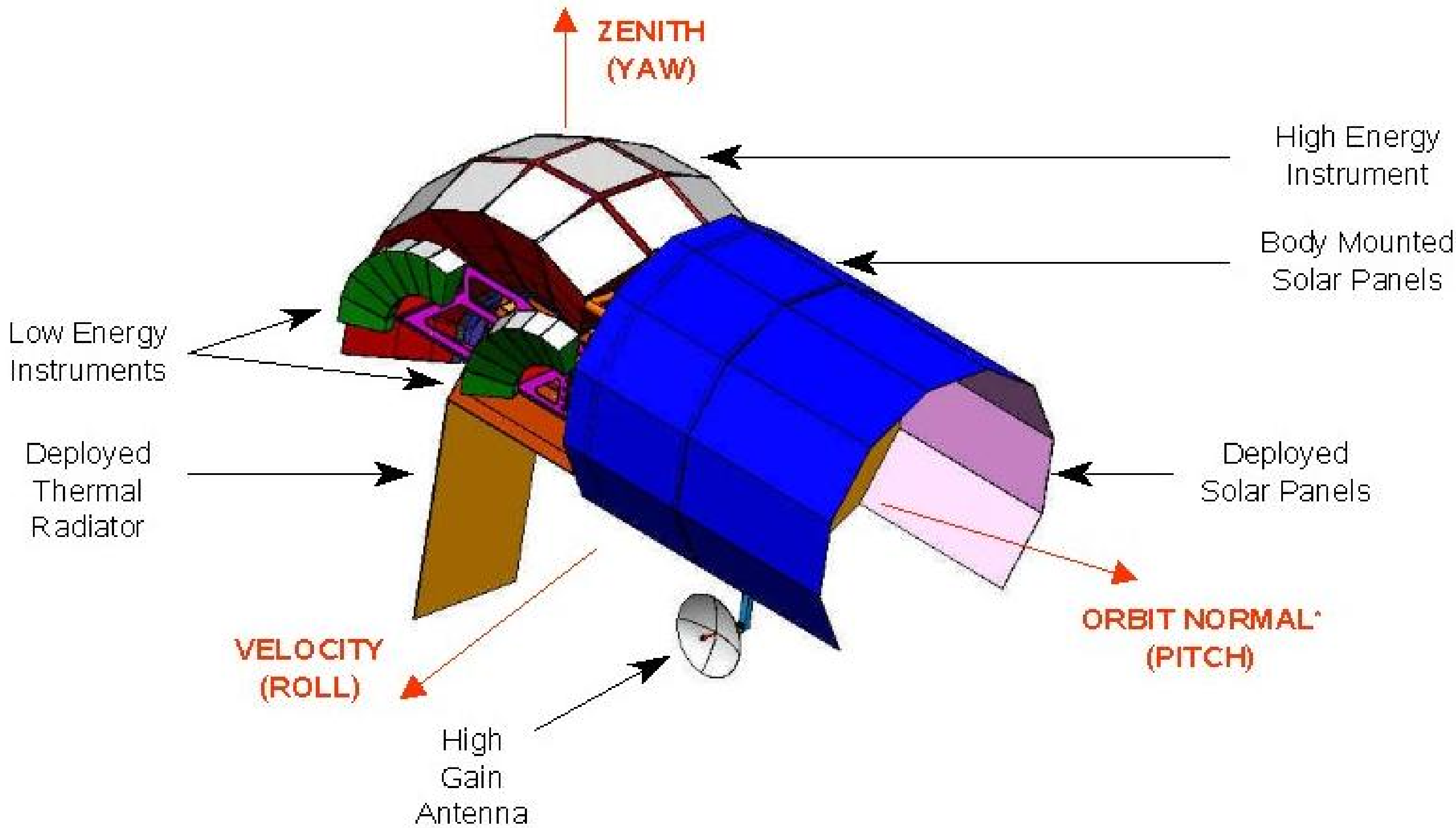
CNES microsatellite (2009)

Wide field coded mask camera

- Energy range: 3.5 - 300 keV
- Field of view: ~ 2 sr
- 1024 cm2 shottky CdTe 4x4 mm
- Advanced readout electronics



# Ultra deep X-ray survey with EXIST

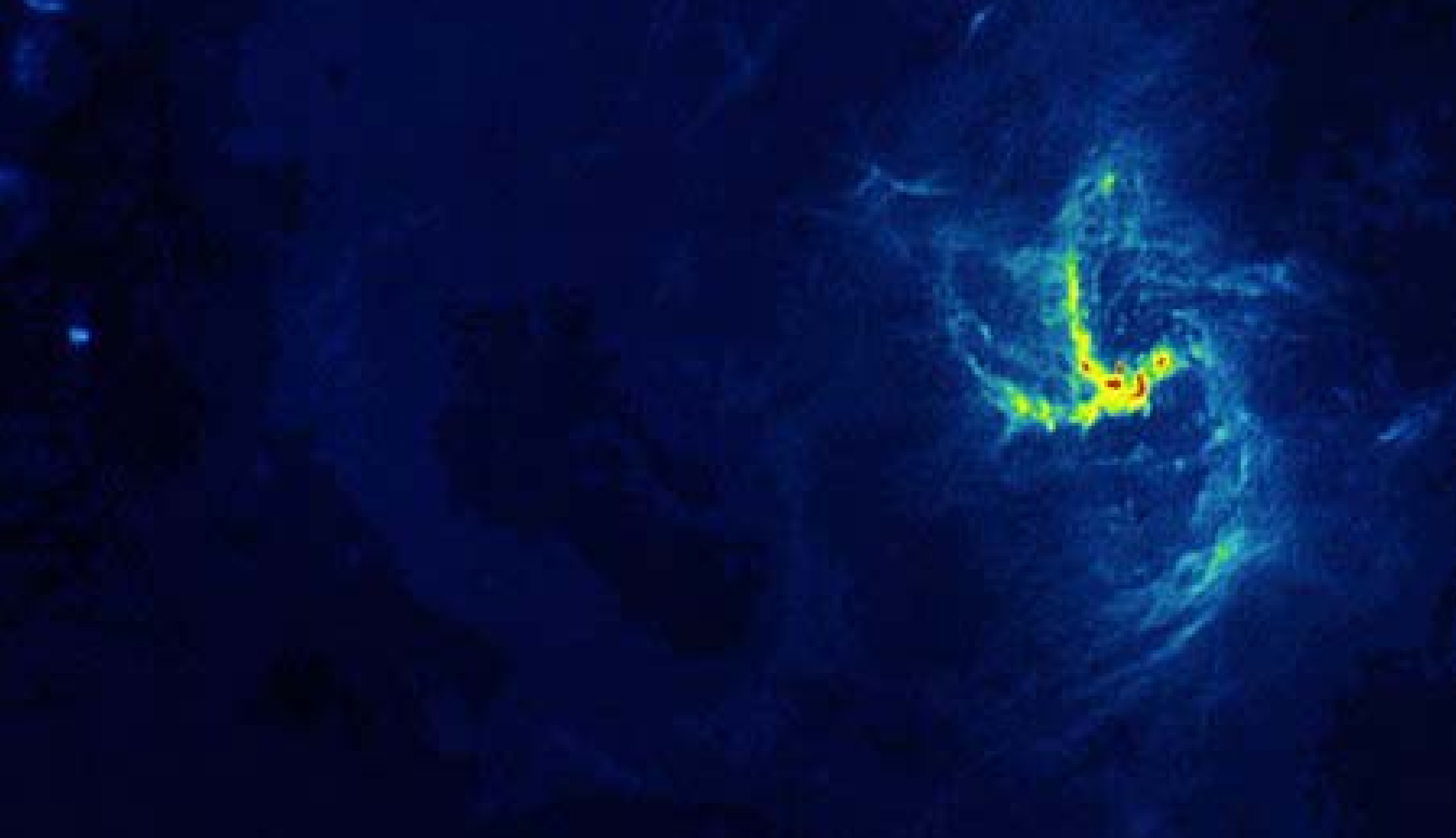



HET: 5.6 square meters of pixel CZT detectors (1.25 mm pitch)

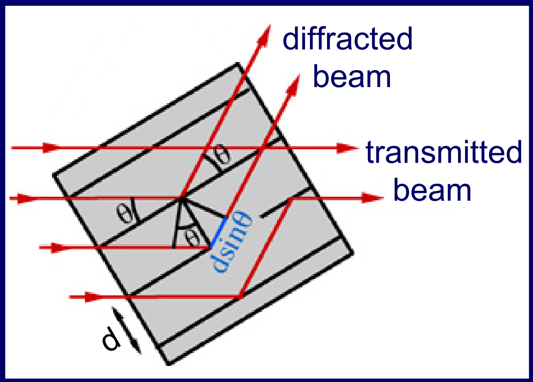
# Detectors for coded-mask soft gamma-ray telescopes

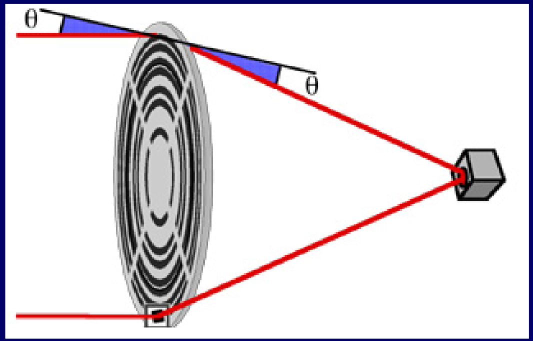
- GRANAT/SIGMA: single large NaI disk + PMTs
- INTEGRAL/ISGRI: planar CdTe
- INTEGRAL/PICsIT: CsI+PIN-diodes
- INTEGRAL/SPI: Cooled HPGe detectors
- SWIFT/BAT: planar CZT
- ECLAIRS: planar CZT
- EXIST: pixel CZT

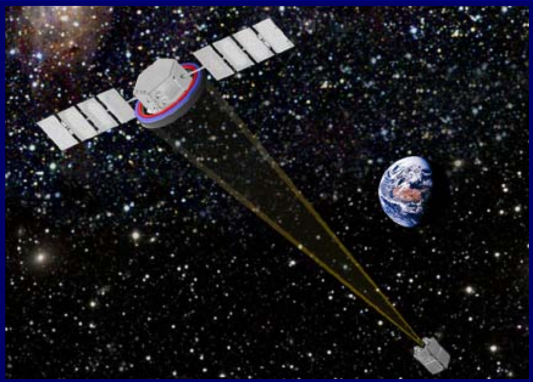
# Gamma-ray Lenses



# Towards a gamma-ray lens



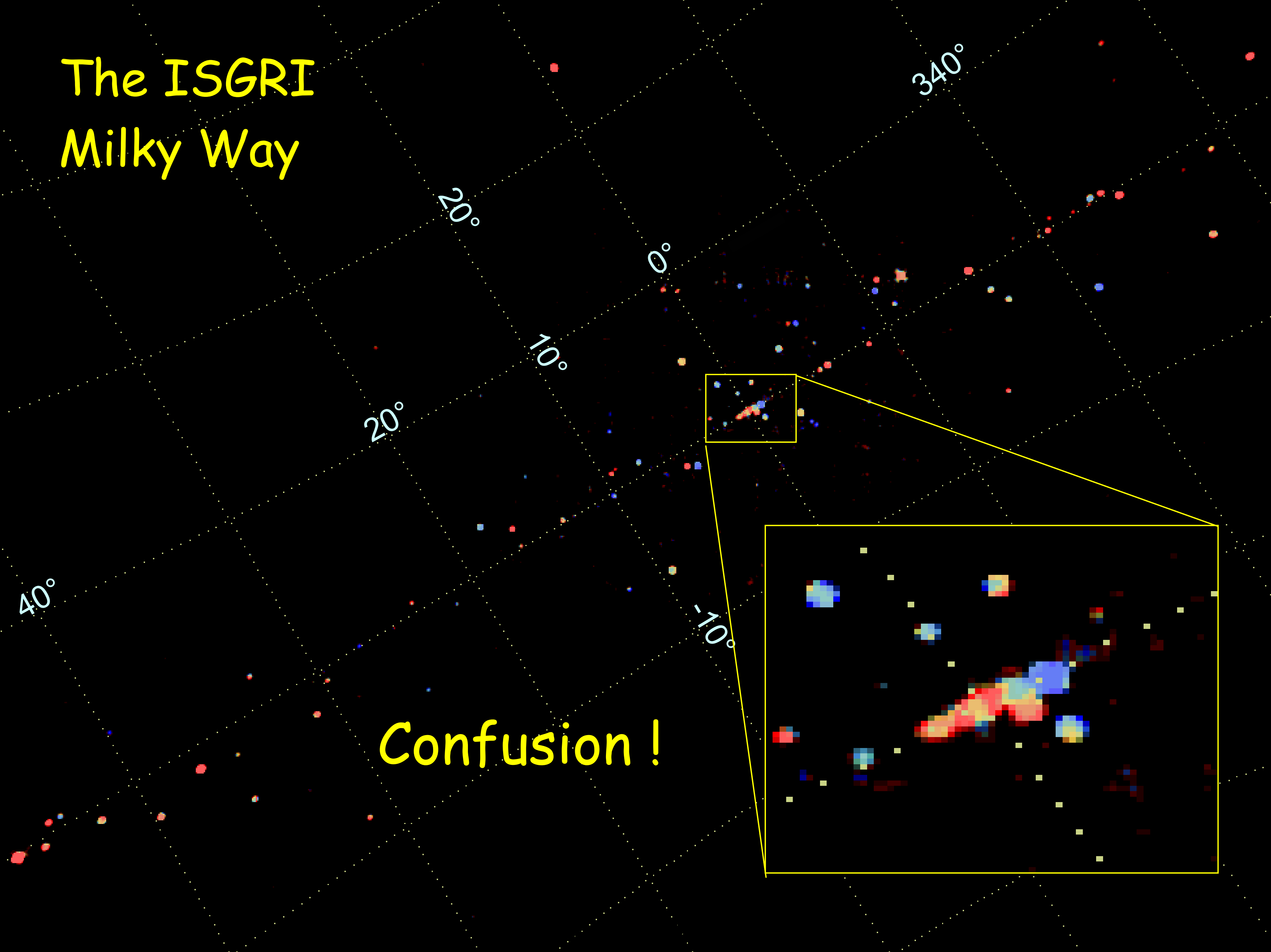



A plane parallel crystal intercepting a beam of very short wavelength radiation λ act as a 3-D Diffraction array. When entering such a crystal under an angle θ a beam of high-energy photons is therefore diffracted under the same angle θ defined by the Bragg condition: $2\, d \sin(\theta) = n\, \lambda$

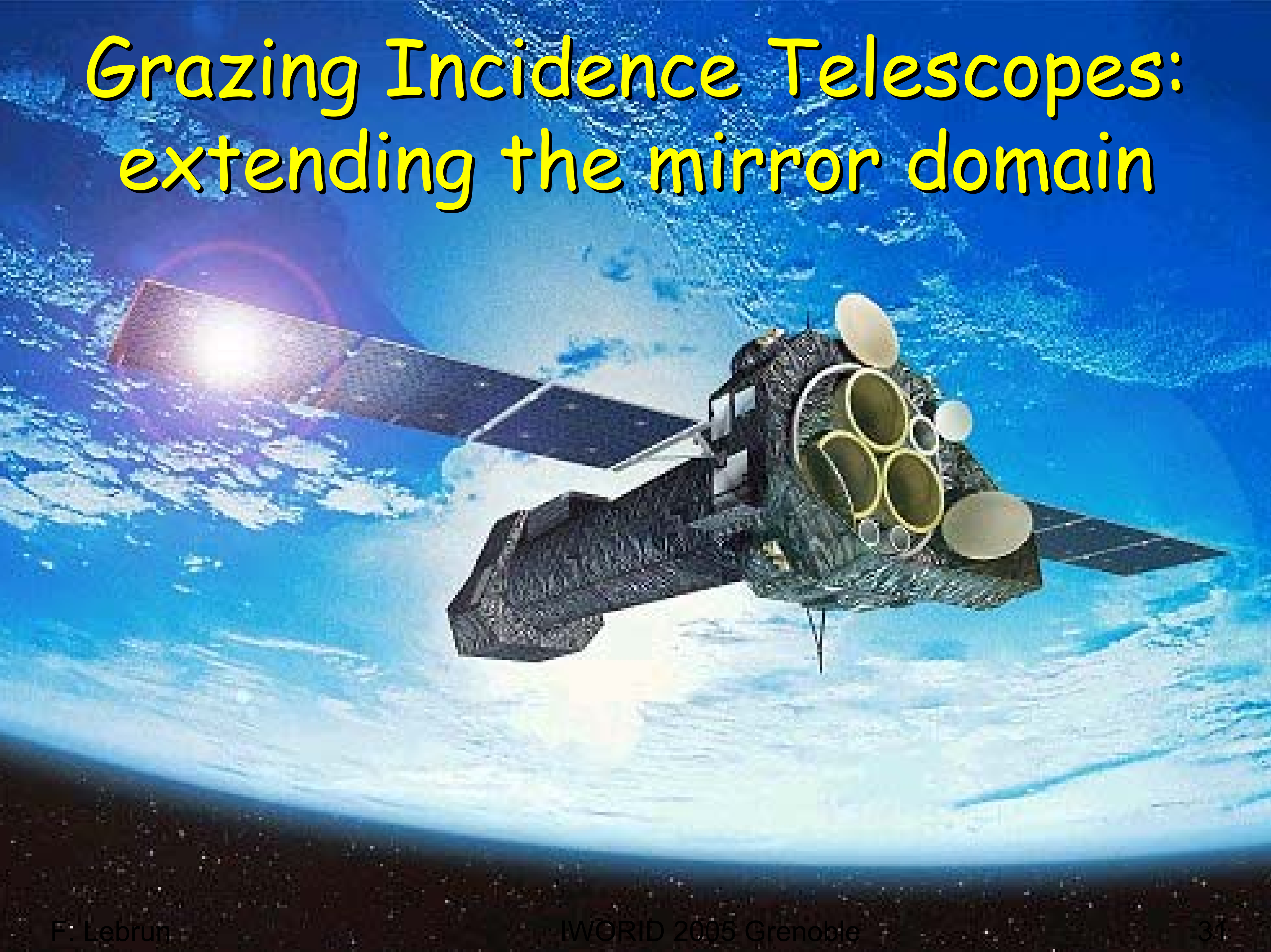
A gamma-ray concentrator (gamma-ray "lens") could then be build in mounting hundreds of such crystals onto concentric rings

Detectors at the focus could be Ge, CdTe or CZT

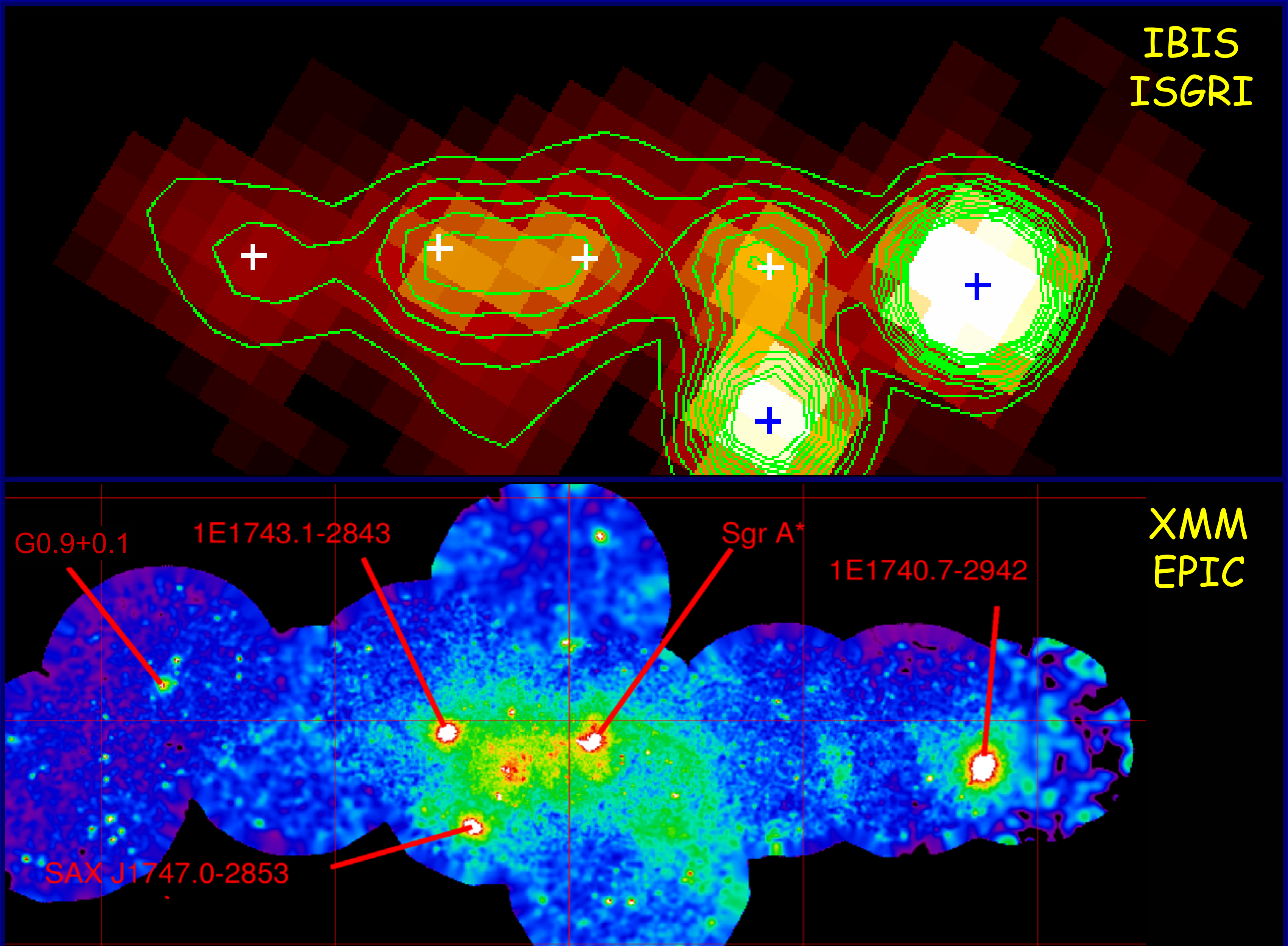
Because of their long focal distance (> 10 m) gamma-ray concentrators would require two satellites in close formation as in the MAX mission under investigation in France


The ISGRI
Milky Way
340°
20°
0°
10°
20°
40°
-10°
Confusion !

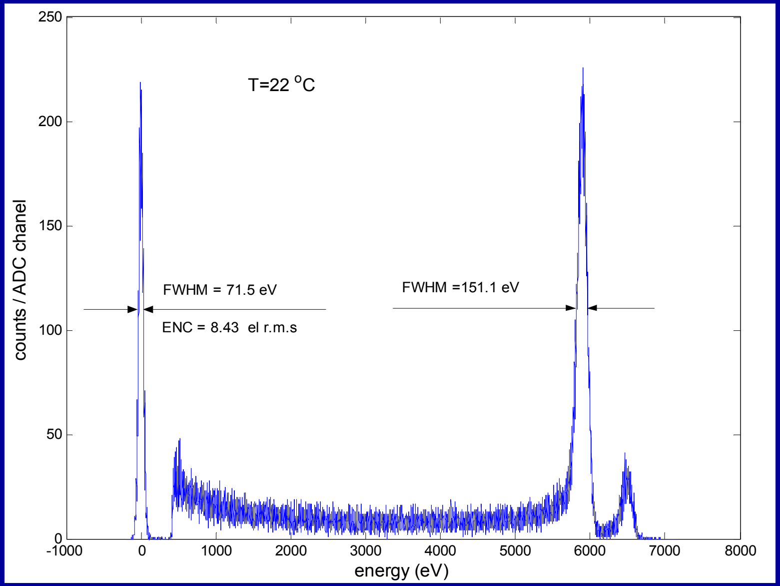
# Grazing Incidence Telescopes: extending the mirror domain



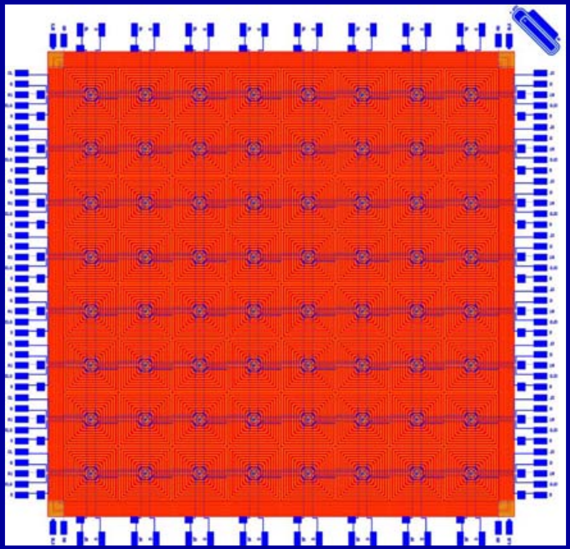
# The Galactic Nucleus

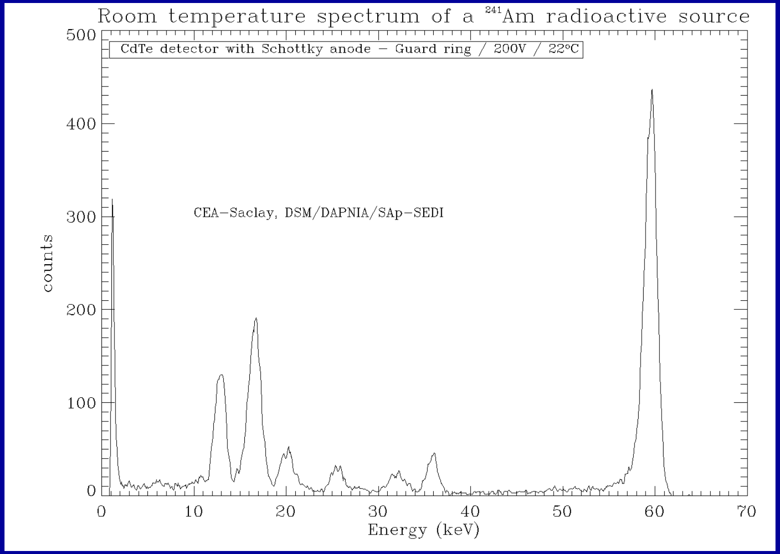


# SIMBOL-X (CNES-ASI 1-60 keV)




DEPFET : 8x8
« macro pixel »
1mm² matrix

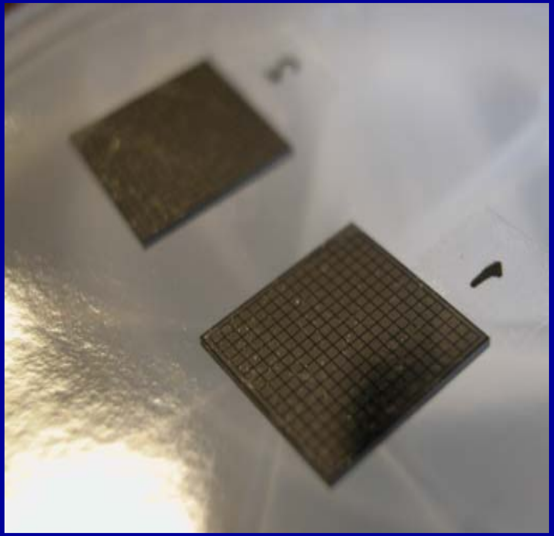




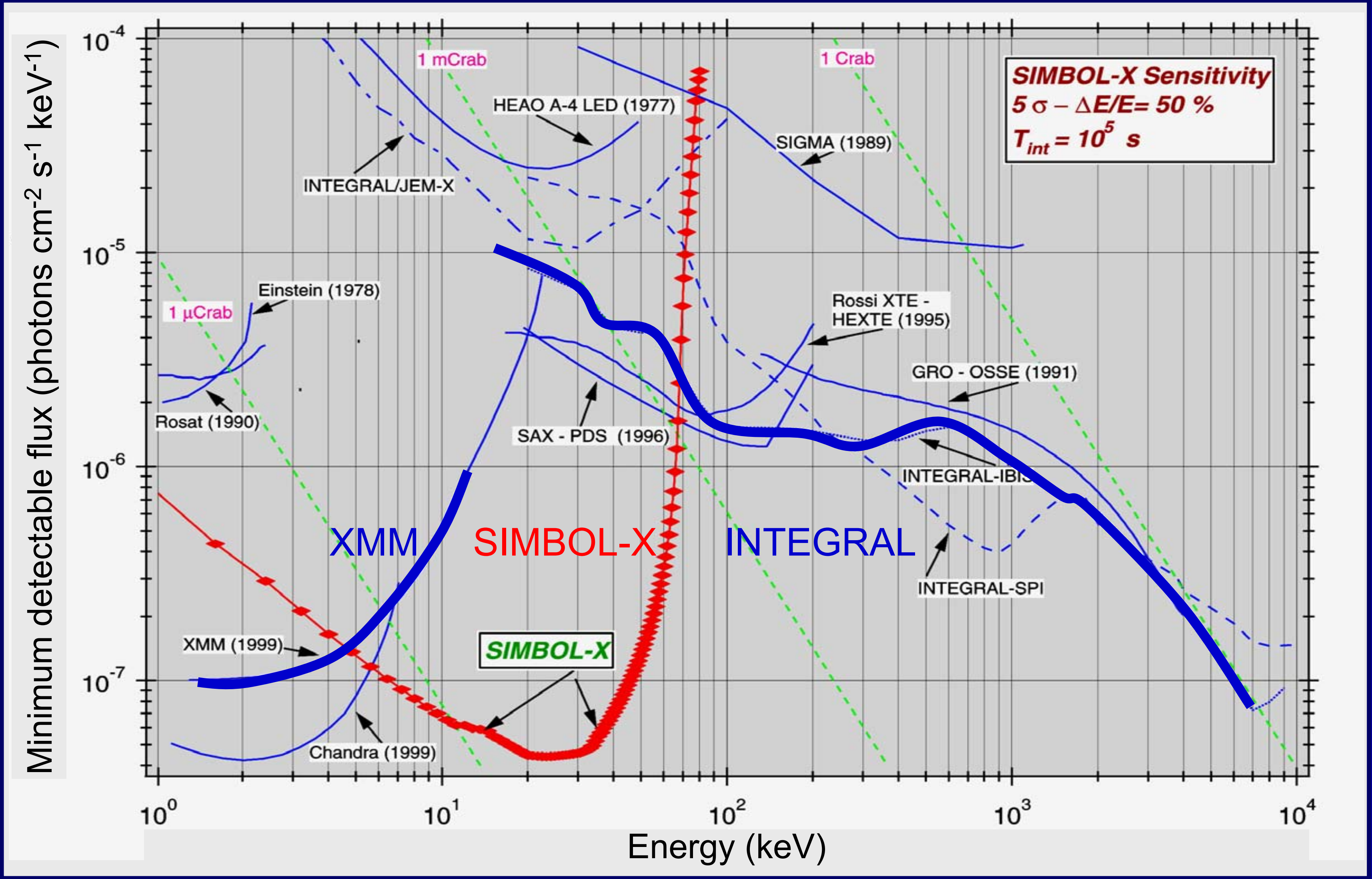

256 pixels
CdTe
Schottky
arrays,

0.5 mm thick
(ACRORAD)

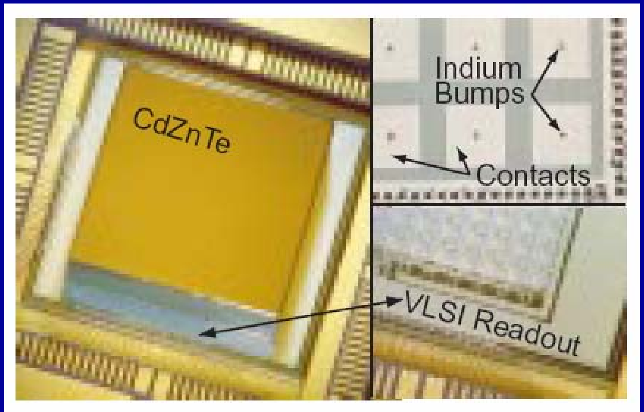
Spectrum with
IDeF-X V0
ASIC



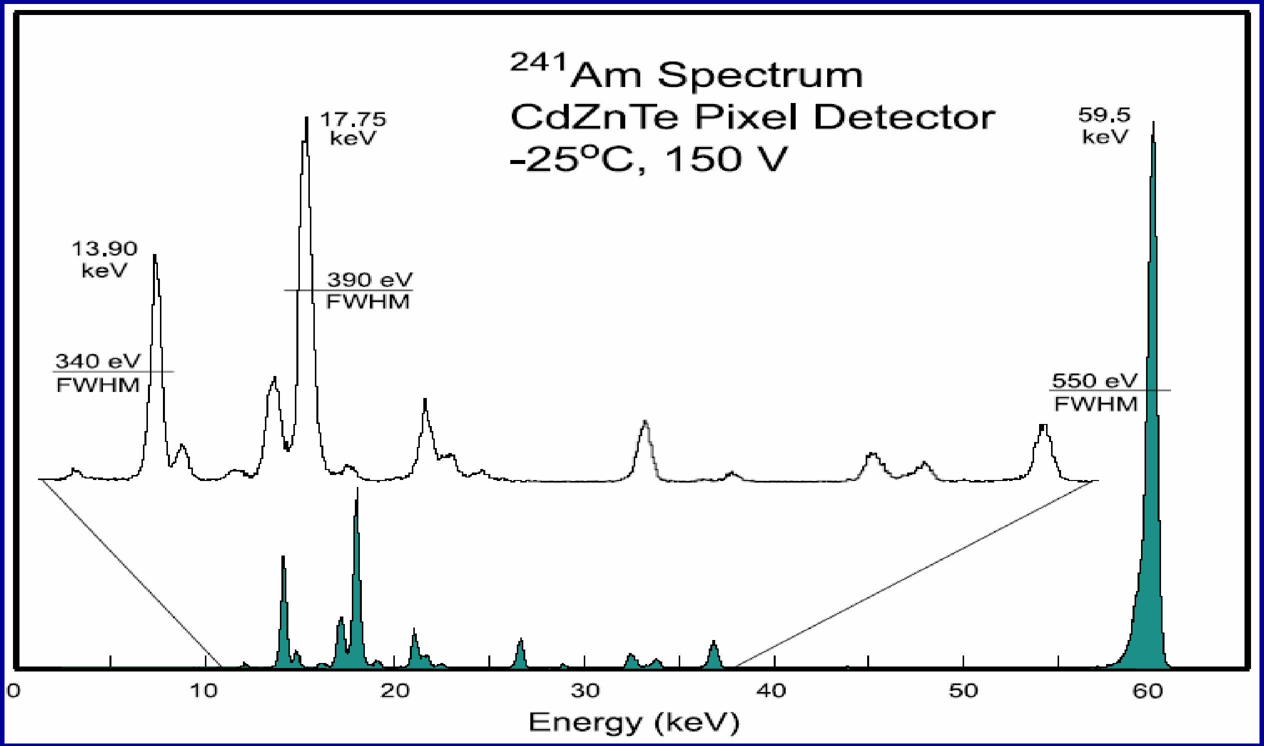
# SIMBOL-X Sensitivity



# HEFT (balloon) - NuSTAR (SMEX 6-80 keV)

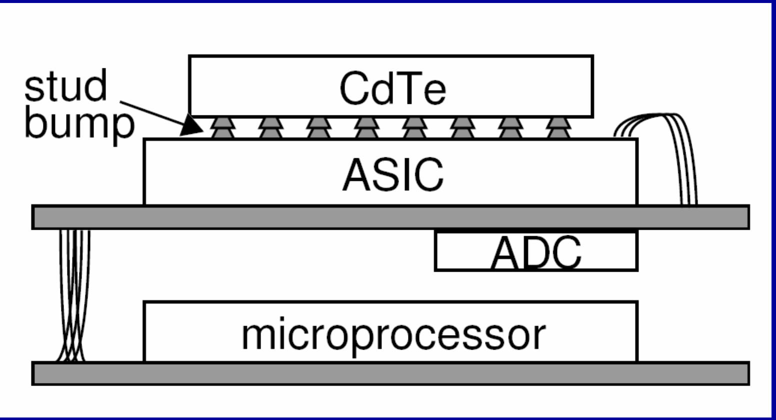


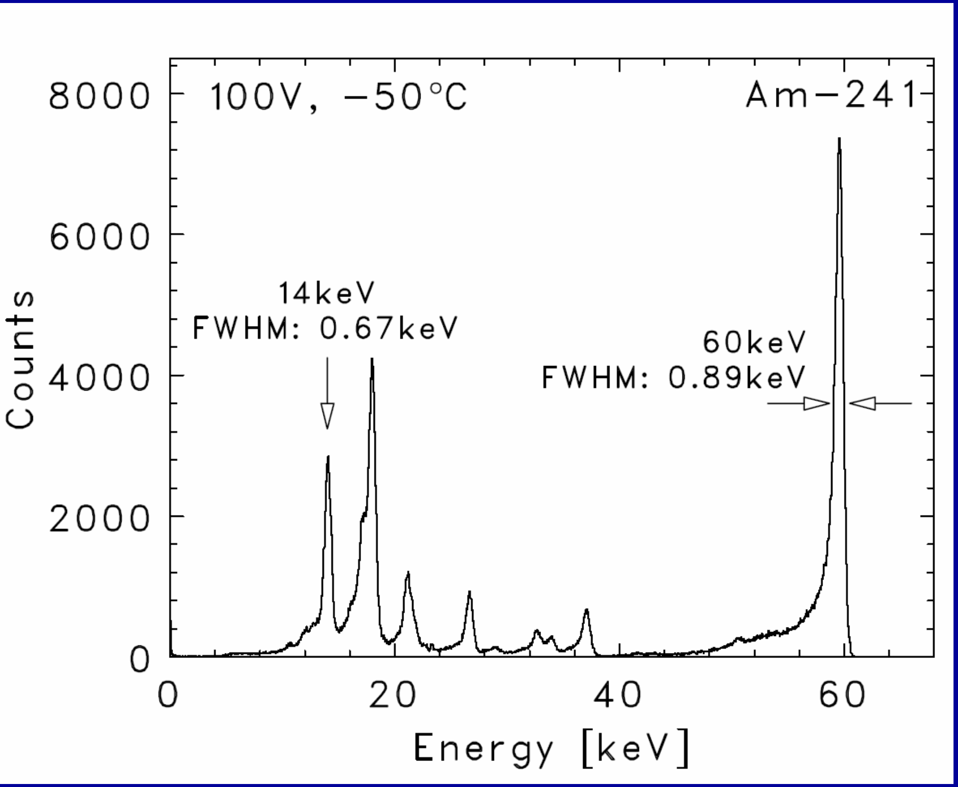

Detector: pixel CZT
Pixel size: 500m
Thickness: 2 mm
Unit dimension: 1.3 x 1.3 cm
Units/focal plane: 4
$\Delta E/E$ = 1.4% (FWHM, 70 keV)
Elect. noise (rms, leakage incl.) 40 $e^-$



# Focusing telescope for the NEXT mission (1-80 keV)

Caltech – ISAS collaboration




Detector: pixel CdTe
Pixel size: 500µm
Thickness: 0.5 mm
Unit dimension: 2.4 x 1.3 cm

# Conclusions

- Planar Semiconductor detectors such as CdTe, CZT, Ge are currently observing the soft gamma-ray sky from space
- Thanks to their satisfactory in-orbit behaviour (stability, background, degradation) it is now established that they can be safely operated and that they can maintain their performance over long periods of time in space
- More and more projects plan to use semiconductor detectors
- Both focusing and Compton telescope will take advantage of pixel detectors (CdTe, CZT) with their
  - Fine imaging capability
  - Enhanced spectral performance