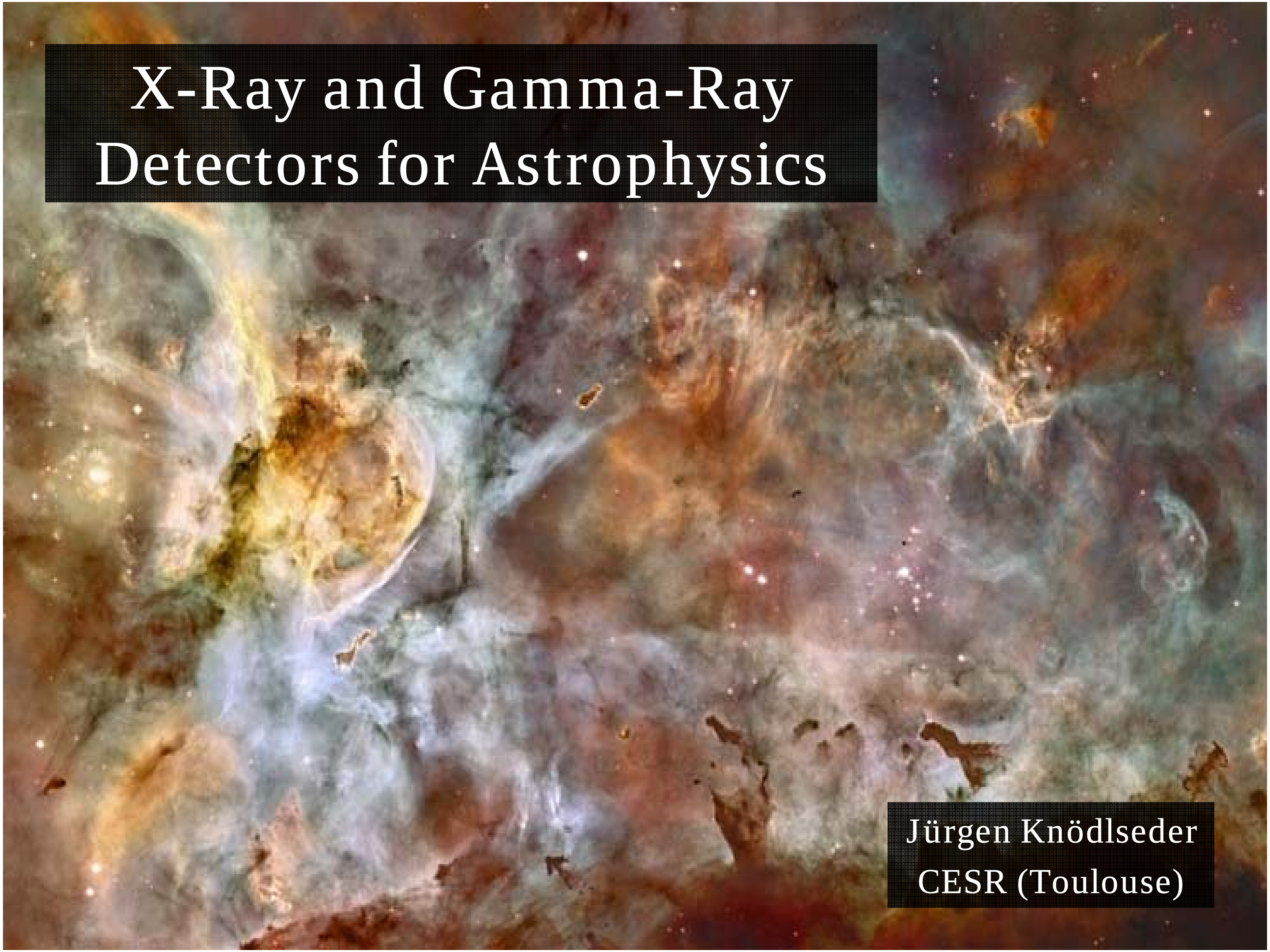
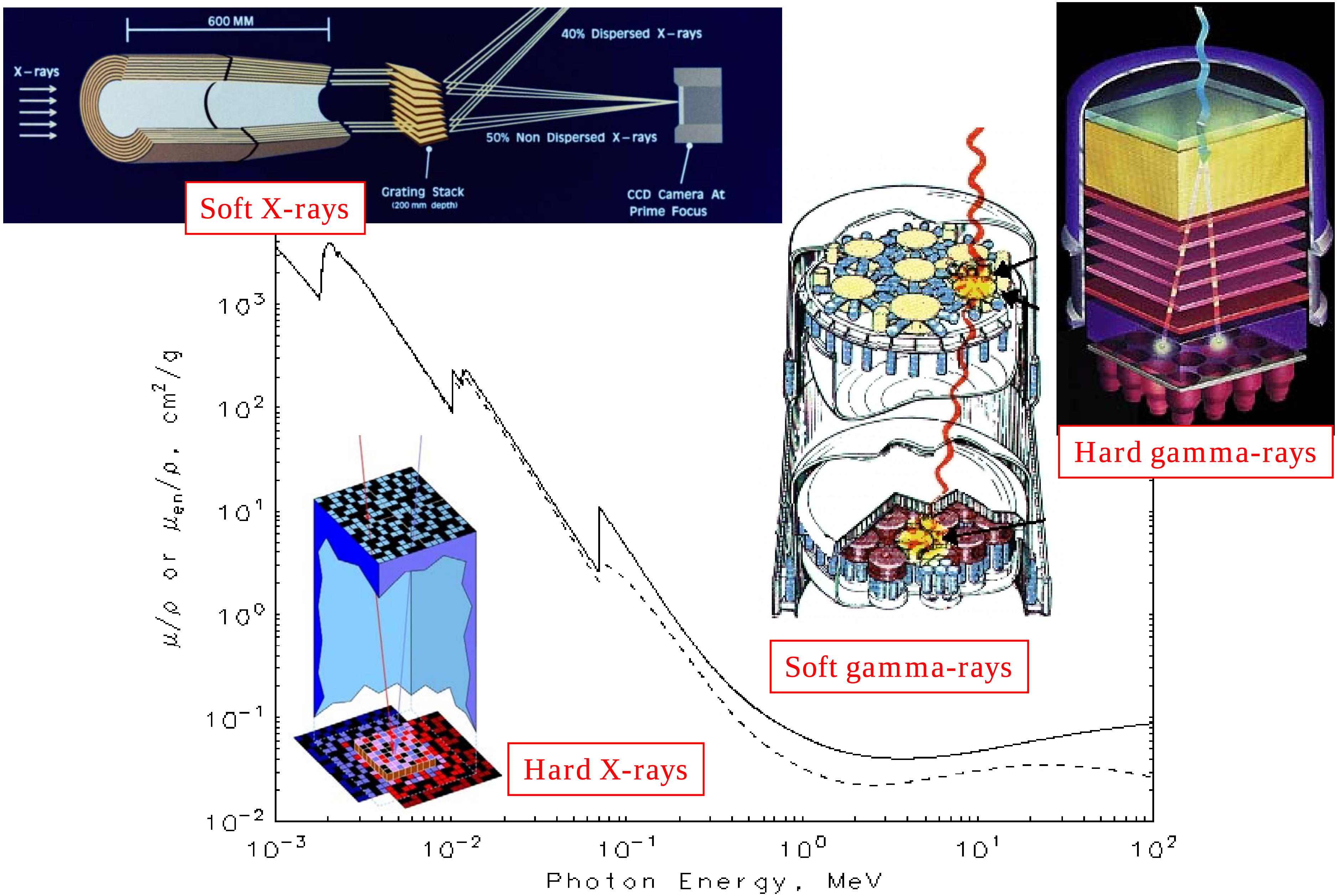


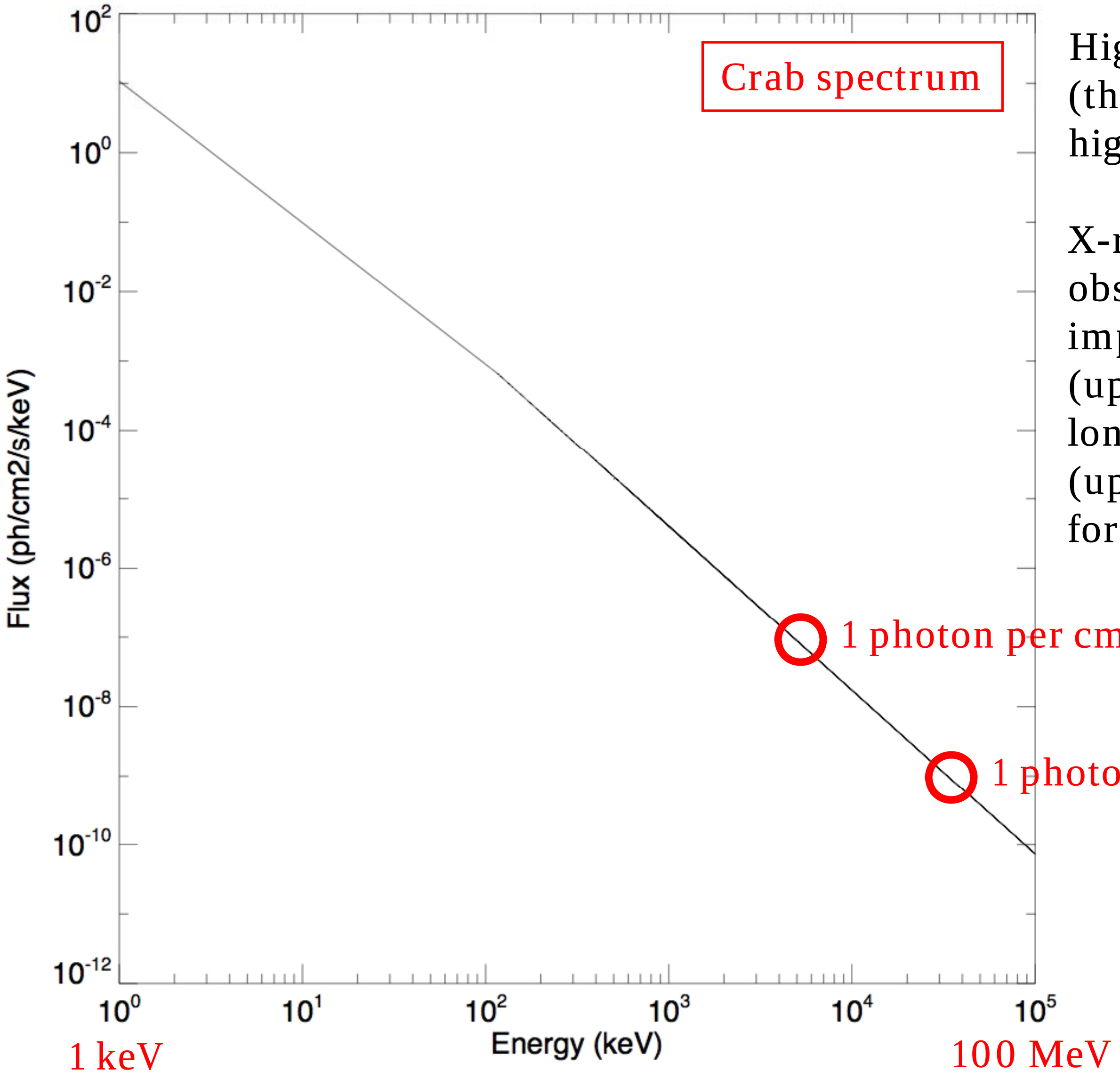
X-Ray and Gamma-Ray Detectors for Astrophysics

Jürgen Knödlseder
CESR (Toulouse)

Exploring the X-ray and gamma-ray domain



Counting (rare) photons

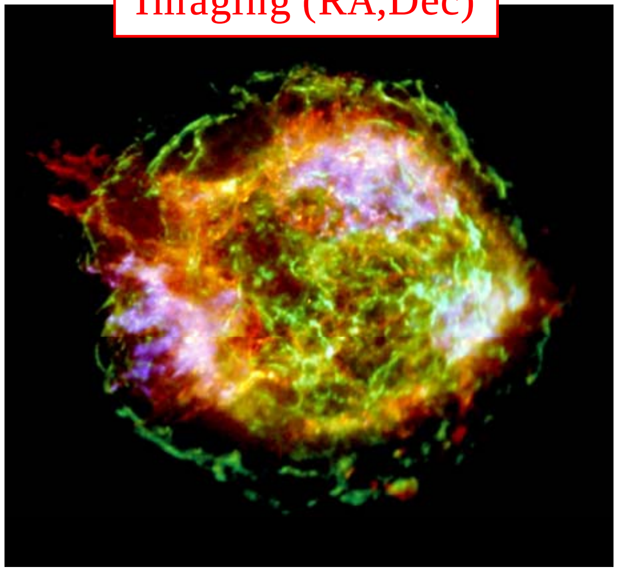


High-energy photons are rare !
(the Crab is one of the brightest high-energy sources in the sky)

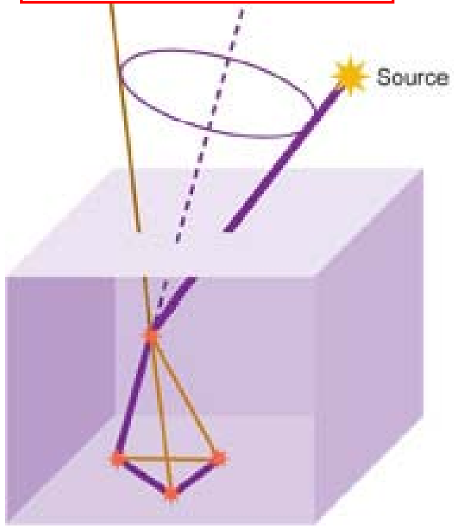
X-ray and gamma-ray observations need important collection areas (up to m^2) and long observing times (up to years for the highest energies)

The 7-dimensional photon

Imaging (RA,Dec)



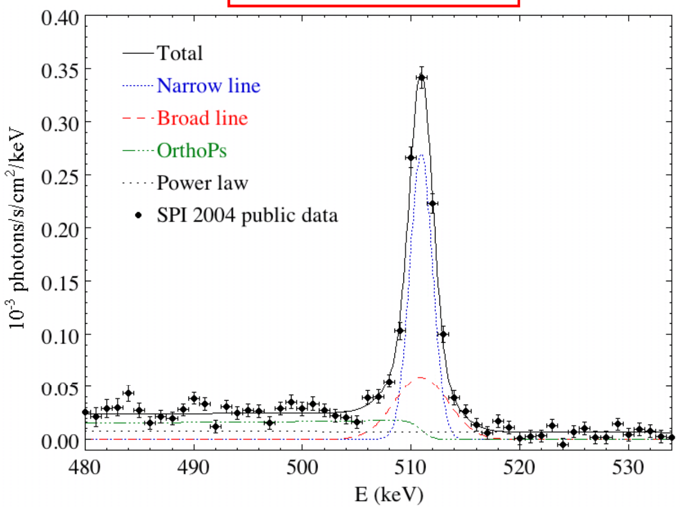
Interaction depth



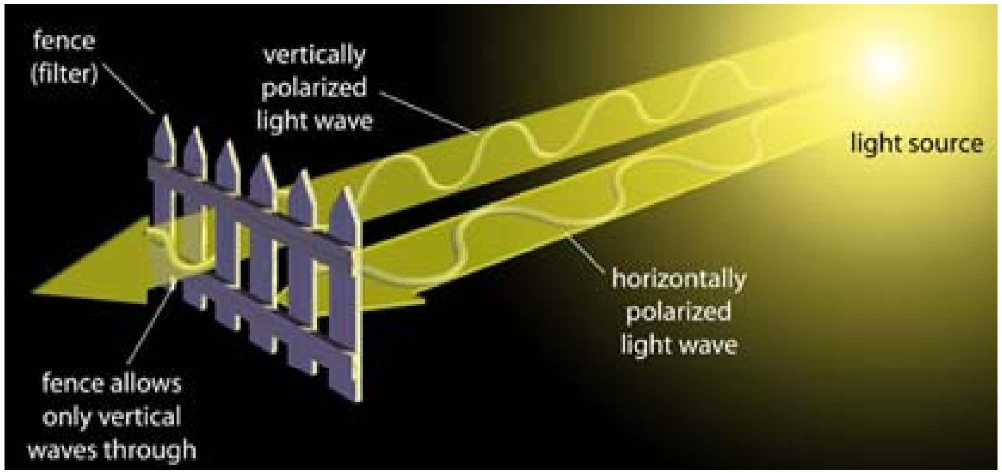
Timing (pulsars, QPO, GRB, ...)

QuickTime™ et un
décompresseur GIF
sont requis pour visionner cette image.

Spectroscopy

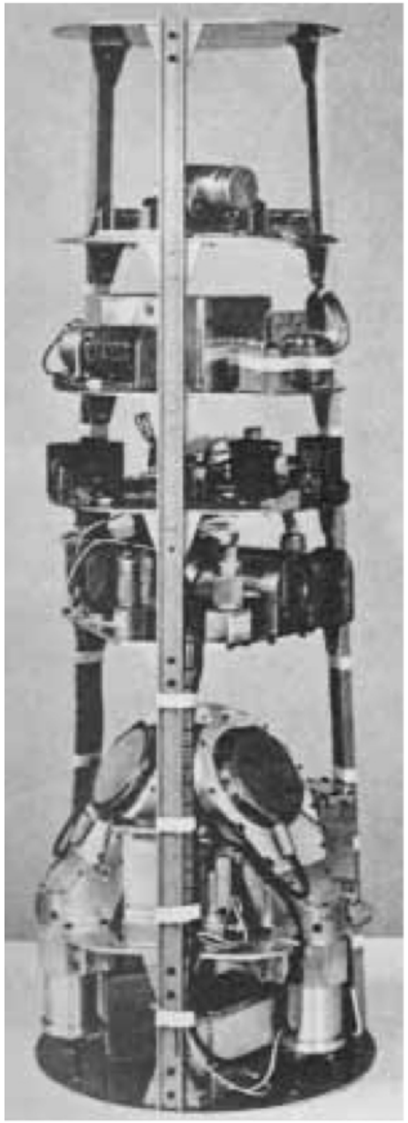


Polarization

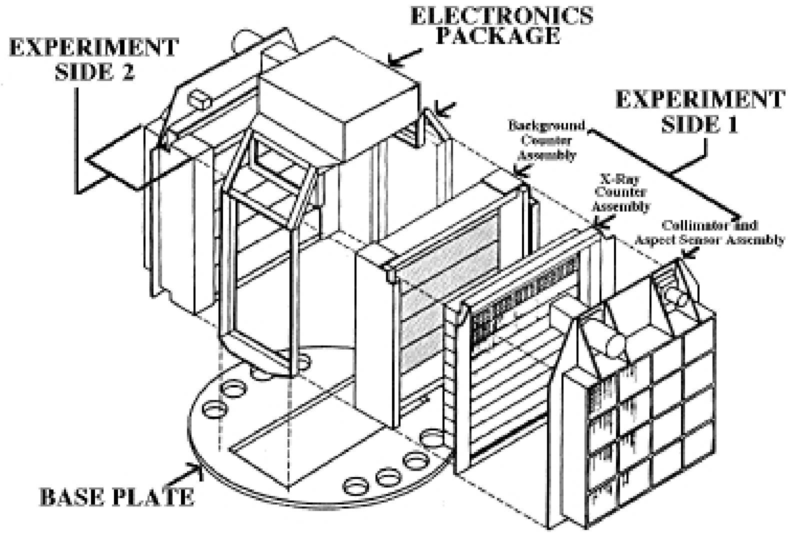


The early days of soft X-ray astronomy

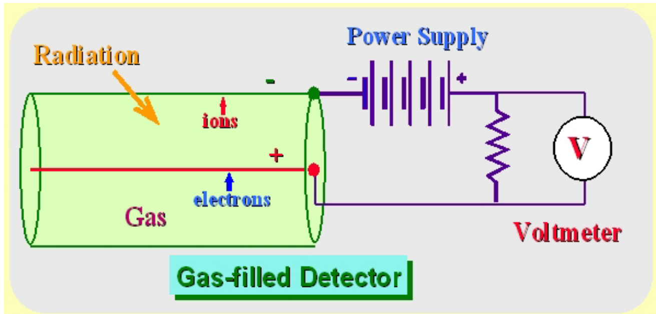
Rocket experiment (Giacconi)
(1962)



UHURU (SAS-1)
(1970-1973)

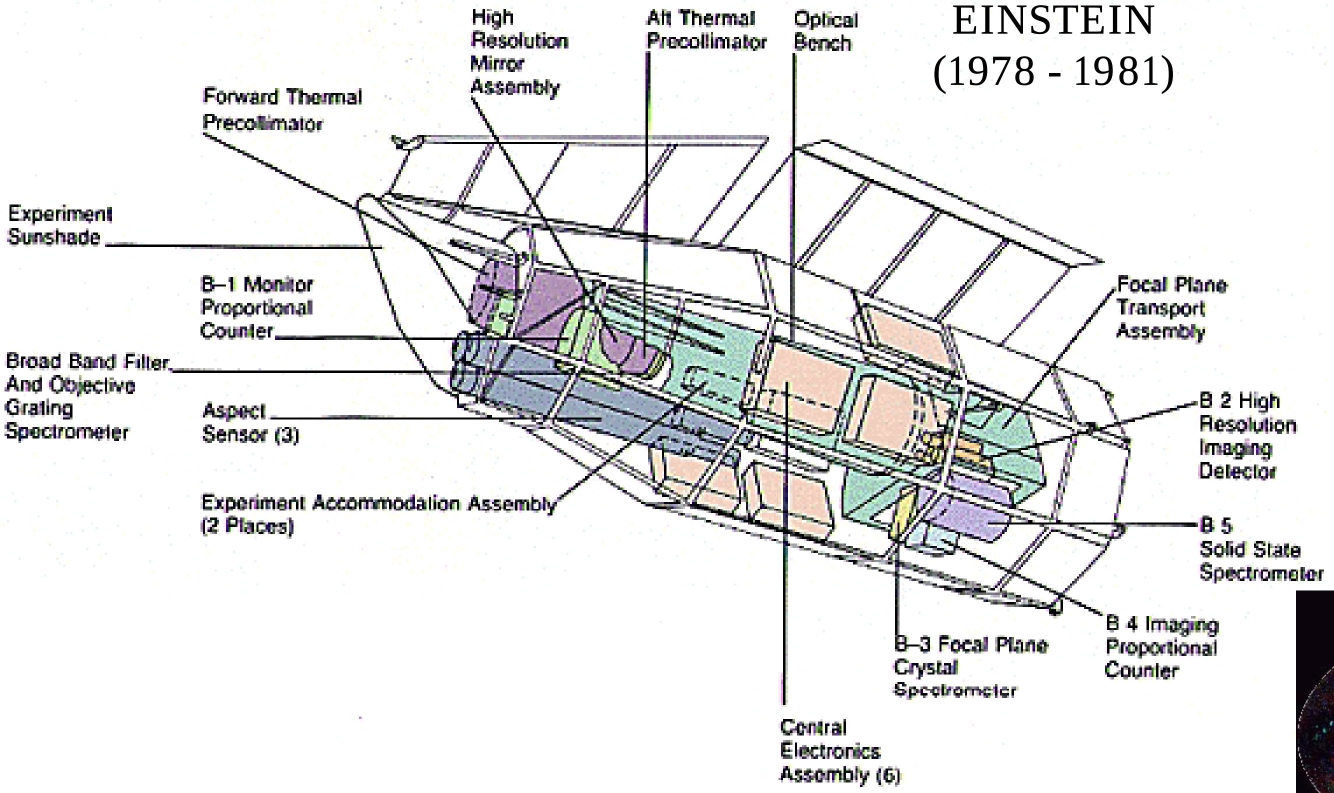


Characteristics:
- 2 collimated proportional counters pointing in opposite directions
- A_{eff} ~700 cm^2
- 2 - 20 keV



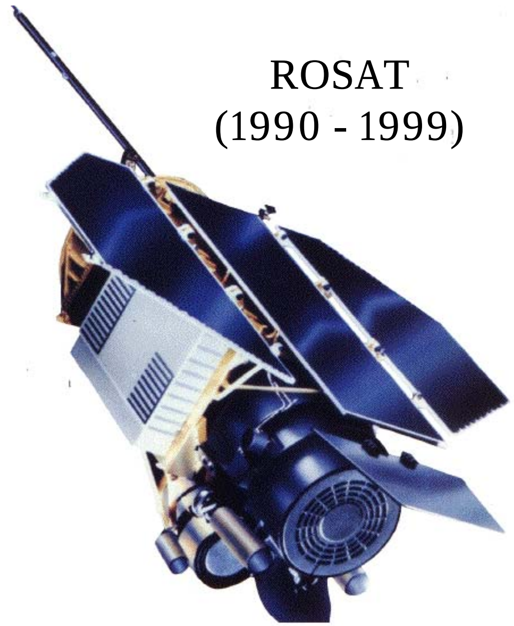
Characteristics:
- 3 Geiger counters with windows of varying thickness (-> energy)
- discovery of first extrasolar X-ray source (Sco X-1)

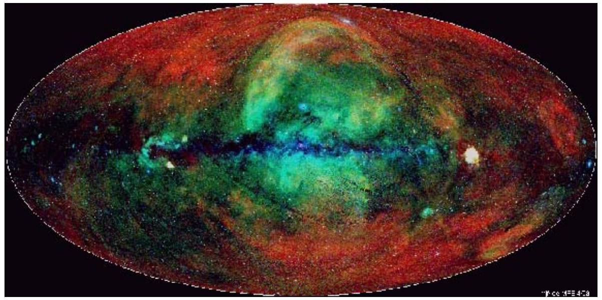
The advent of focusing X-ray telescopes



EINSTEIN
(1978 - 1981)

ROSAT
(1990 - 1999)



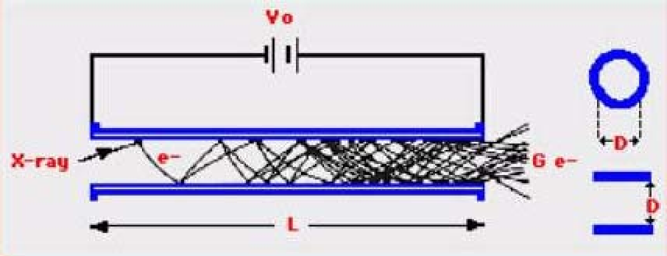


Focal plane assembly (position focus at one of 4 detectors):

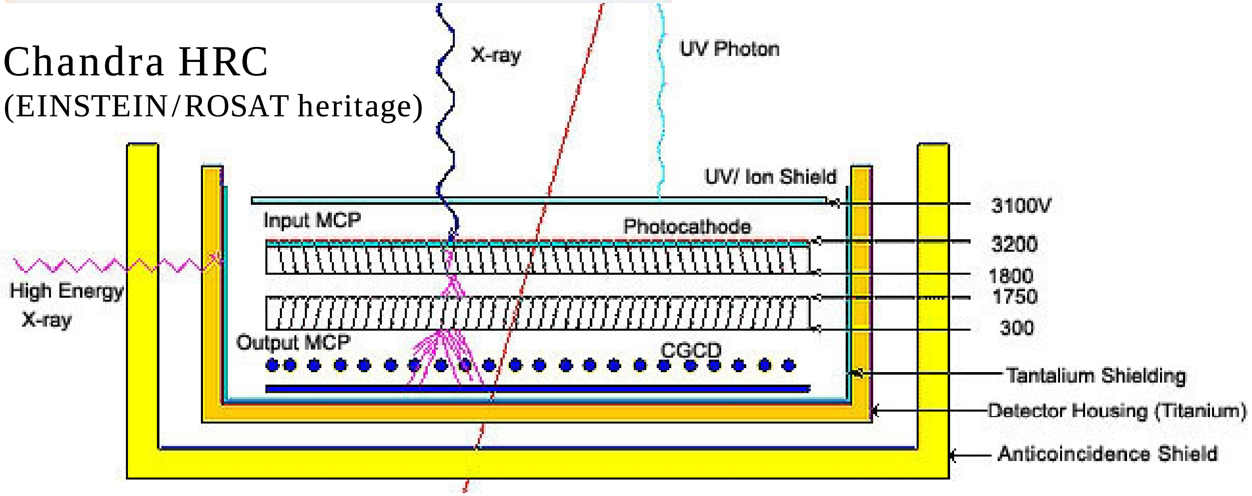
- 3 HRI: High-Resolution Imaging Detectors - micro-channel plates (5 - 20 cm^2, 2 arcsec, 8 msec, 0.1 - 3 keV)
- IPC: Imaging Proportional Counter (100 cm^2, 1 arcmin, 63 msec, 0.4 - 4 keV)
- SSS: Solid State Spectrometer - cryogenically cooled Si(Li) detector (ΔE ~ 160 eV FWHM, 0.5 - 4.5 keV)
- FPCS: Focal Place Crystal Spectrometer - proportional counter (0.1 - 1 cm^2)

Microchannel plates (MCP)

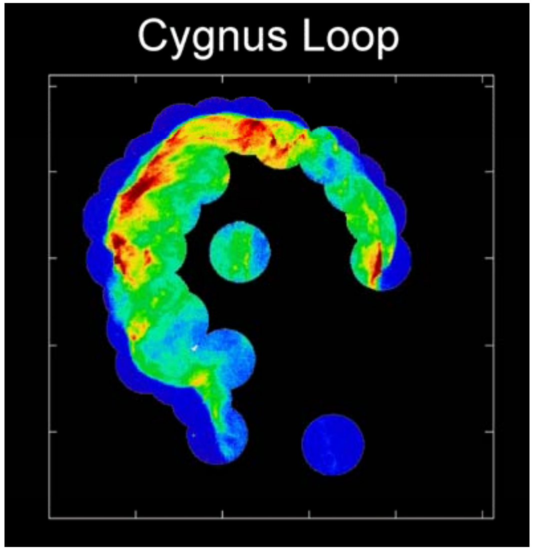
Principle



Chandra HRC
(EINSTEIN/ROSAT heritage)

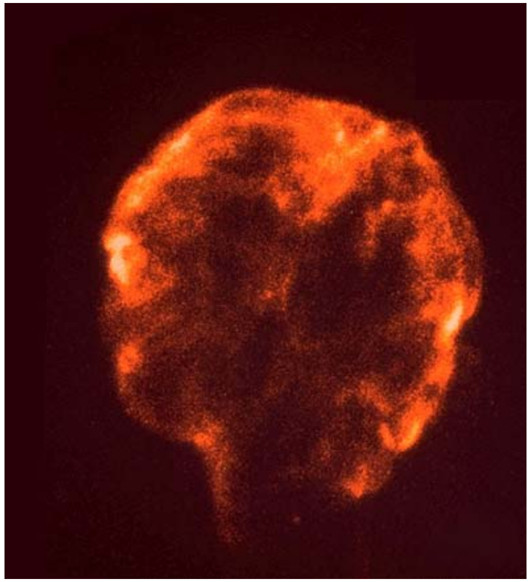


Microchannel Plate image



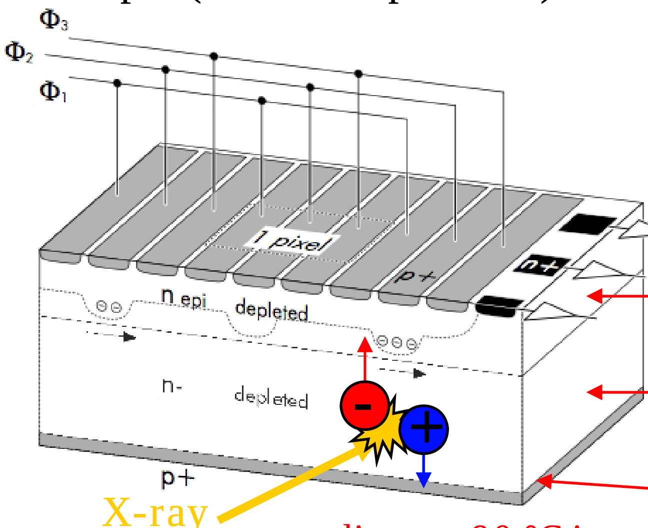
Characteristics:
- 69 million CsI-coated canted glass tubes
- detector dimension (HRC-I): 90 x 90 mm
- tube dimension: 10 μm x 1.2 mm
- 0.4 arcsec angular resolution with 30 arcmin FoV
- Readout pixel size: 6.4 μm (~ 200 Mpixel)
- 16 μs time resolution
- Poor spectral resolution of $\Delta E/E \sim 1$ (0.08 - 10 keV)

Proportional counter image



Charge Coupled Devices (CCDs)

Principle (ex. XMM pn-CCD):



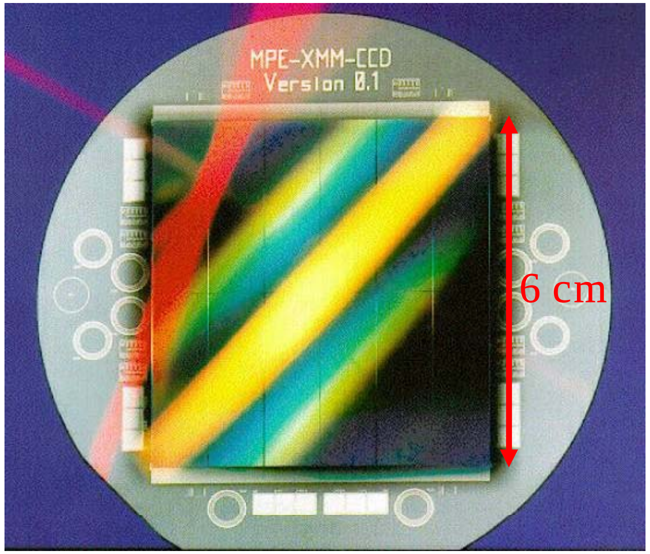
charge storage (10 µm)

radiation protection (290 µm)

minimize dead layer for low-energy response

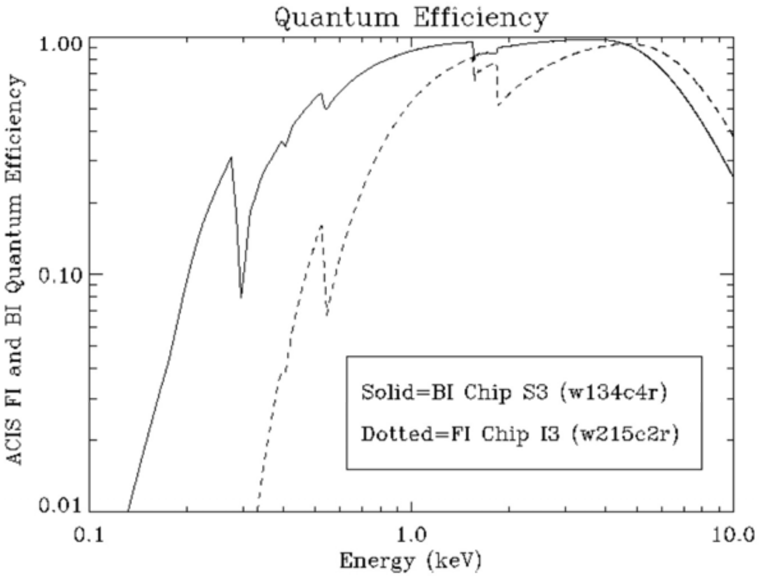
cooling to -90 °C improves energy resolution
(suppress thermally generated leakage current)

XMM-Newton backside illuminated focal plane (12 pn-CCD)

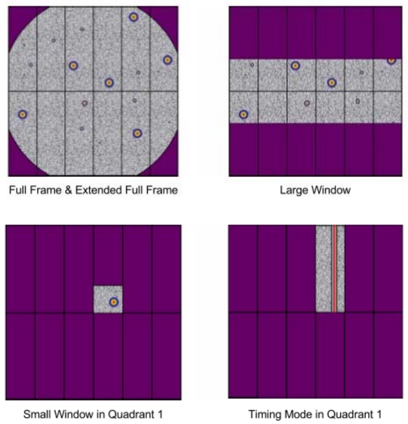


12 x (200 x 64 pixels) ~150 kpixel

Front/back illumination:



Readout modes:



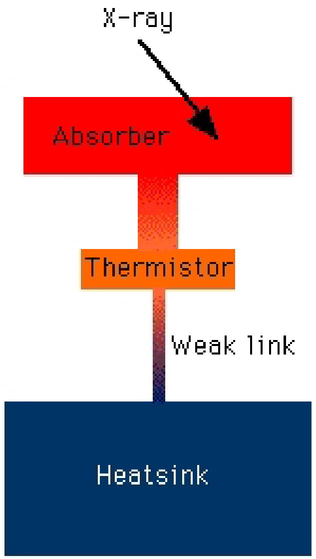
Adapt readout time to reduce pile-up:

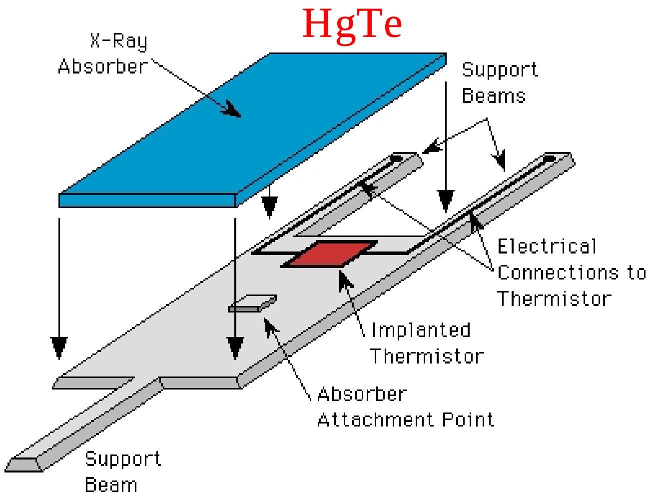
- ext. full frame: 199.2 ms
- full frame: 73.3 ms
- large window: 47.7 ms
- small window: 5.7 ms
- timing mode: 30 µs
- burst mode: 7 µs
  (allows up to 60000 cps)

CCDs have limited count rate capability !
Next generation: pixel detectors (no charge transfer)

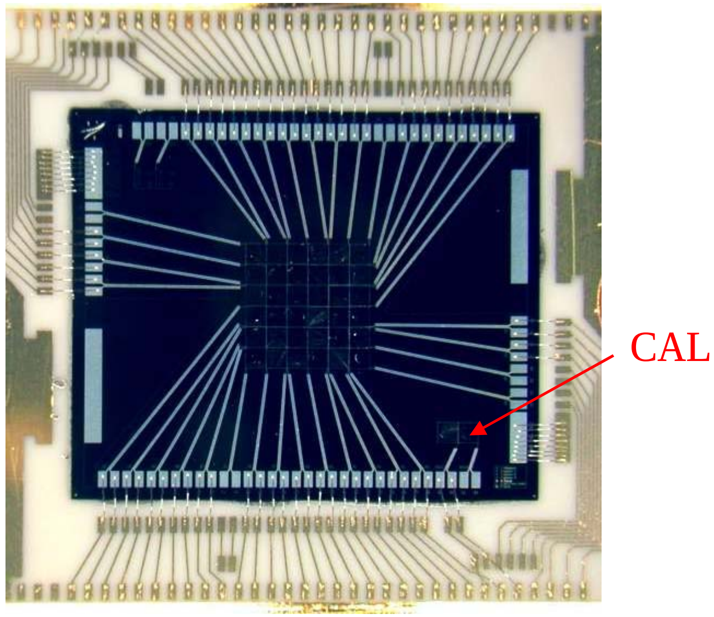
Micro-calorimeters

Principle



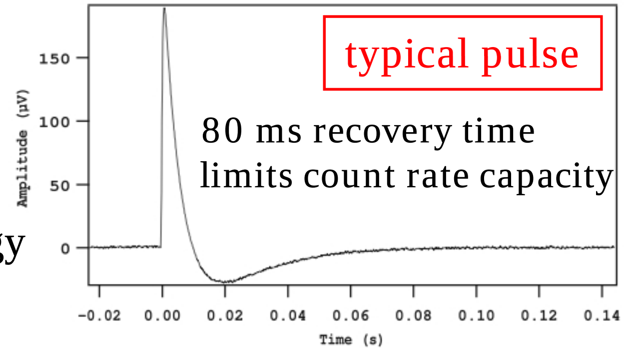


Suzaku XRS



Considerations:

- absorber with small heat capacity (-> large ΔT)
  (implies < mm pixels; array needed for reasonable FoV)
- thermistor: temperature-dependent resistance
  (doped semiconductor or superconducting transition edge - TES)
- cooling to < 0.1 K
  (note: liquid He ~4 K)
- nearly constant energy resolution over large band

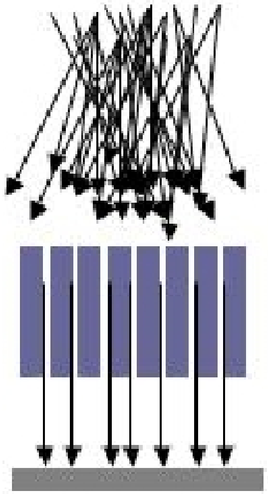


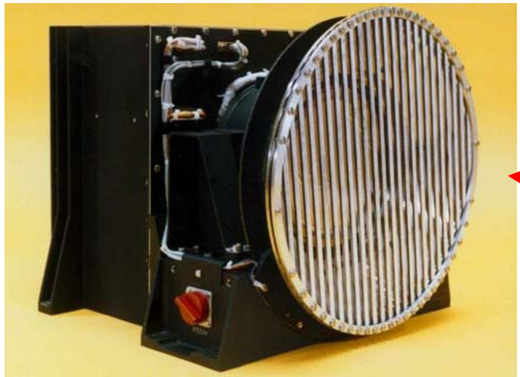
Characteristics:

- 36 pixel (0.4 mm^2) array
  (micromachined silicon)
- Si thermistors
- Energy range: 0.3 - 12 keV
- 6 keV photon -> ΔT ~ 9 mK
- ΔE ~ 6.5 eV FWHM (R ~ 1000)
- 4 stage cooling system (~60 mK)
- Liquid Helium loss compromised operations

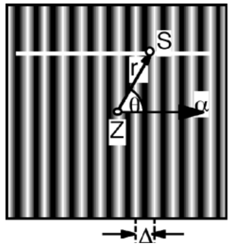
The early days of hard X-ray astronomy

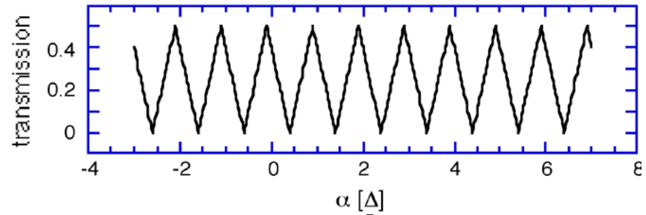
Collimators





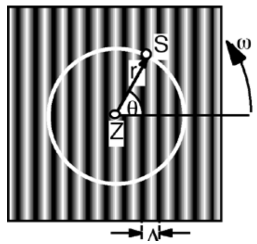
Scanning modulation collimator

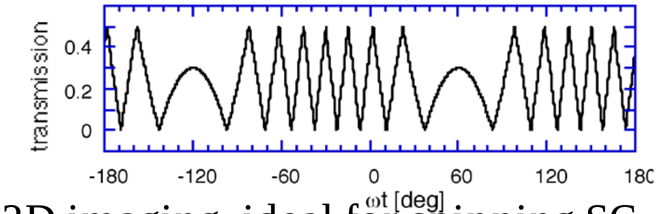




Only 1D imaging

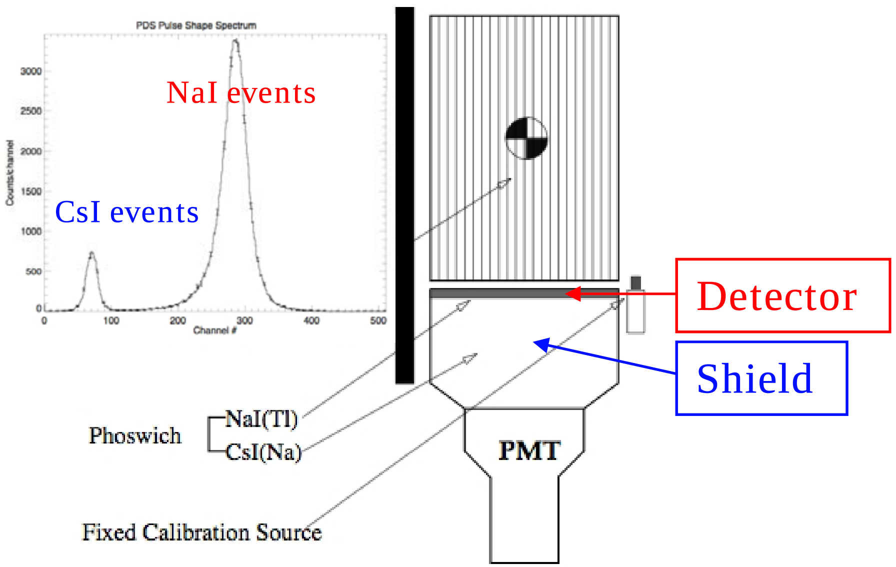
Rotation modulation collimator



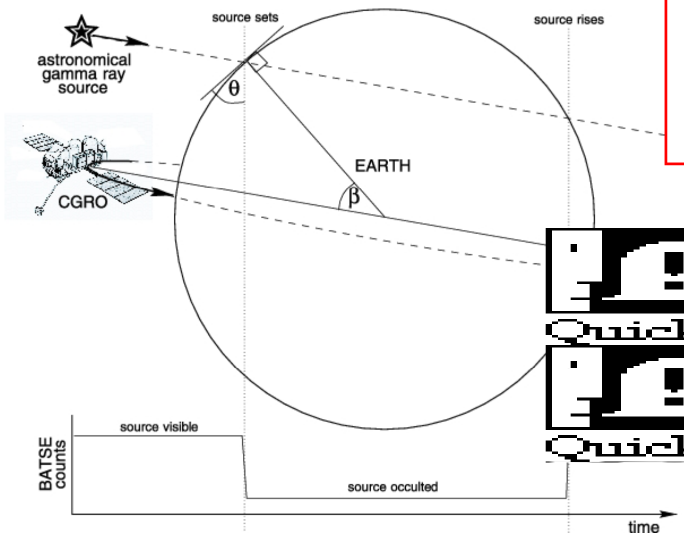


2D imaging, ideal for spinning SC

Phoswich scintillators

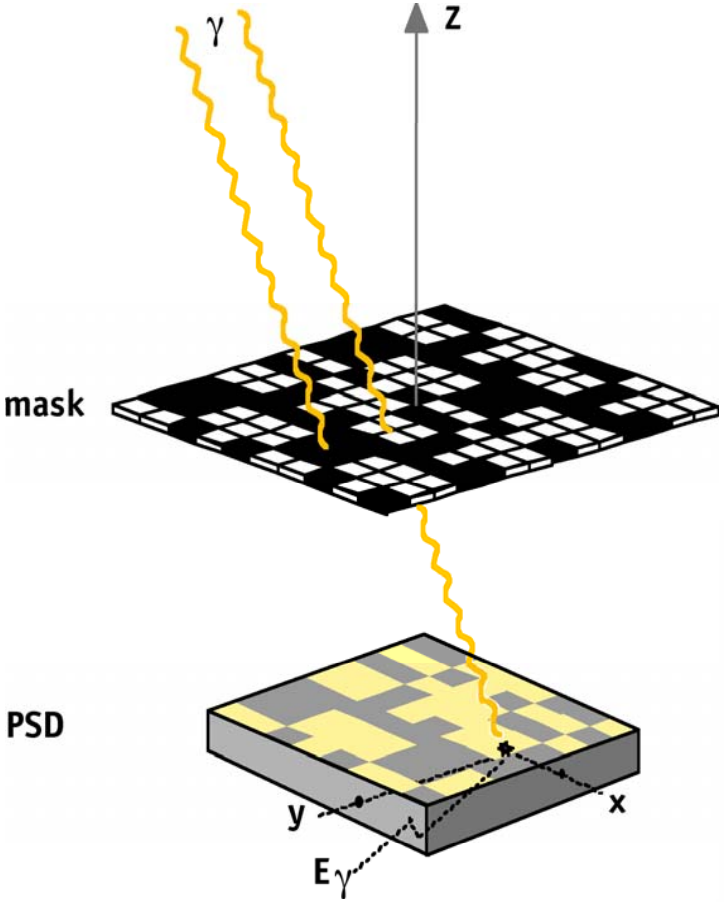


Earth occultation technique



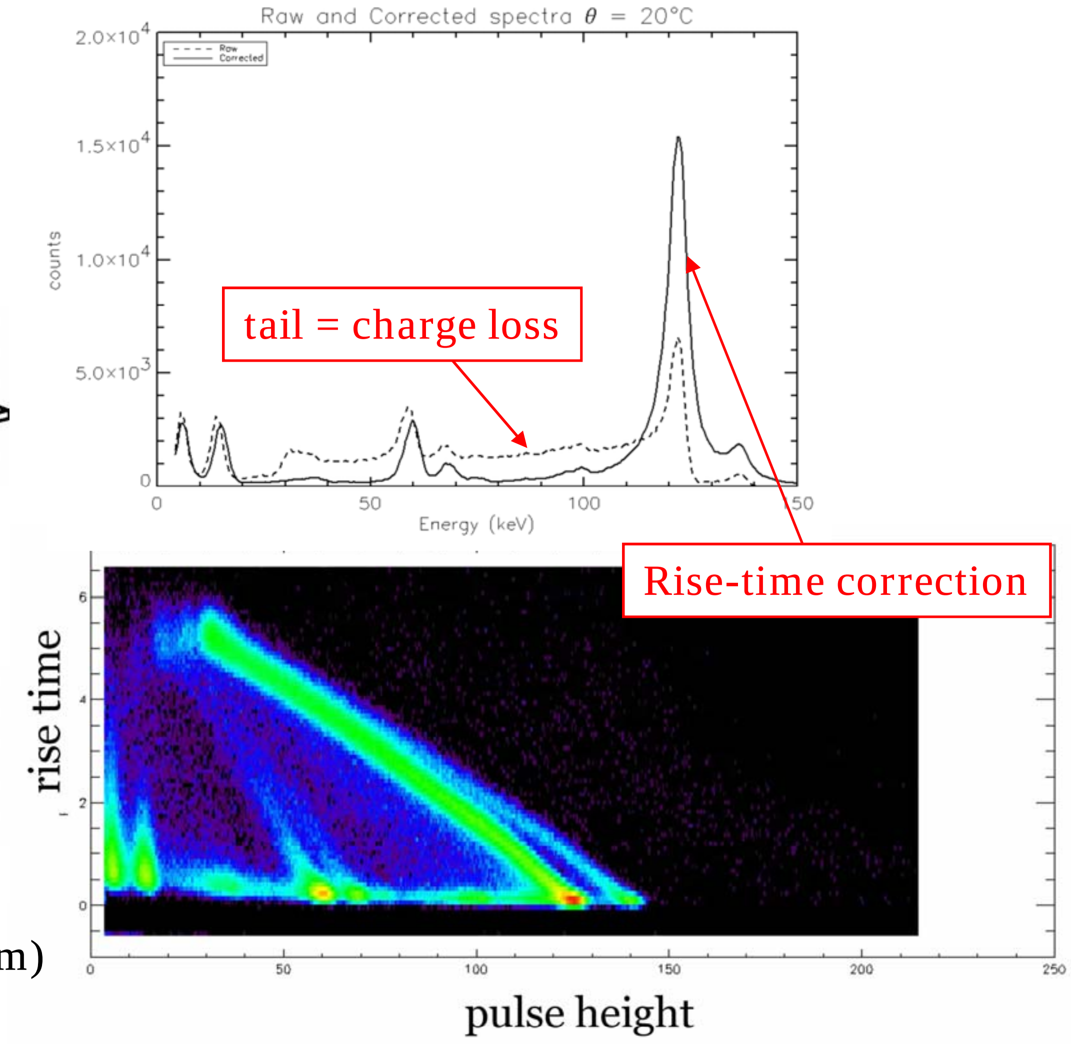
Detectors for coded masks

Coded mask system



• Pixelated detector (typically few mm)
• Thickness: few mm - tens of mm
• Material: CdTe, CTZ

Charge-loss (carrier lifetime < charge collection time)

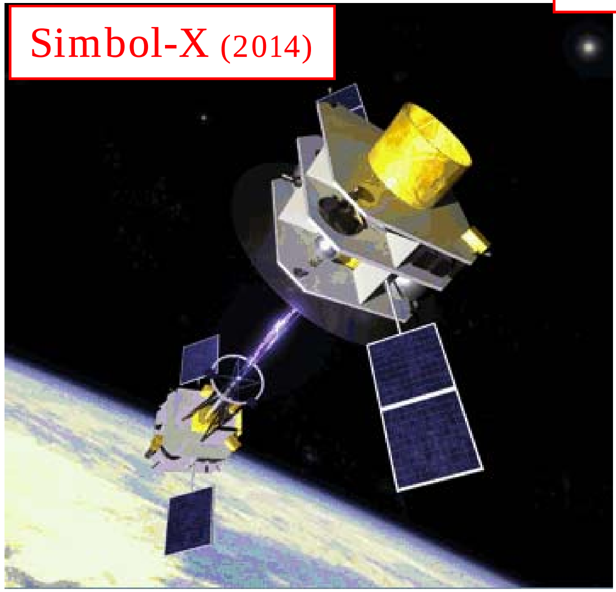


Rise-time of current pulse measures interaction depth
Empiric charge-loss correction improves energy resolution

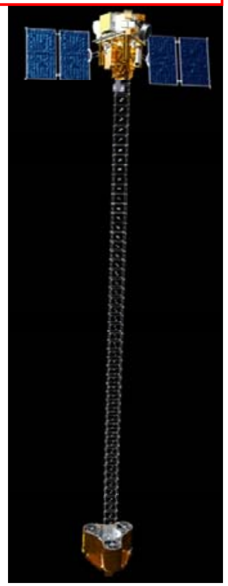
The futur of hard X-ray astronomy

Focusing at higher energies

Simbol-X (2014)

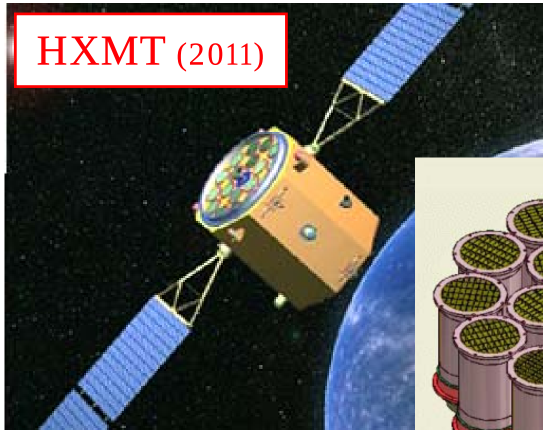


NuSTAR (2011)

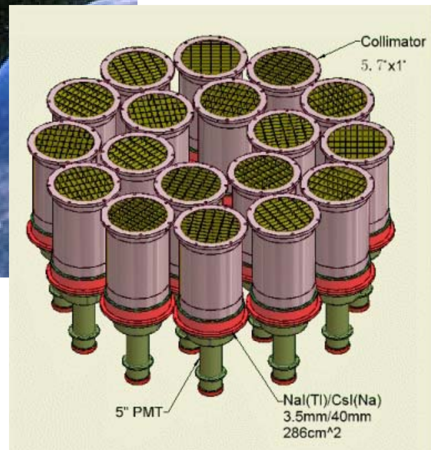


Conventional technology

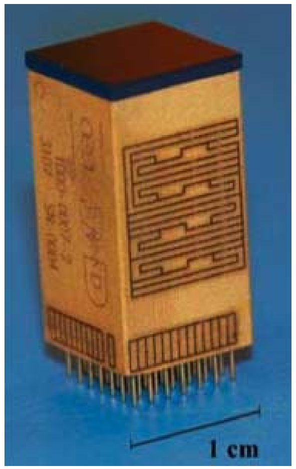
HXMT (2011)

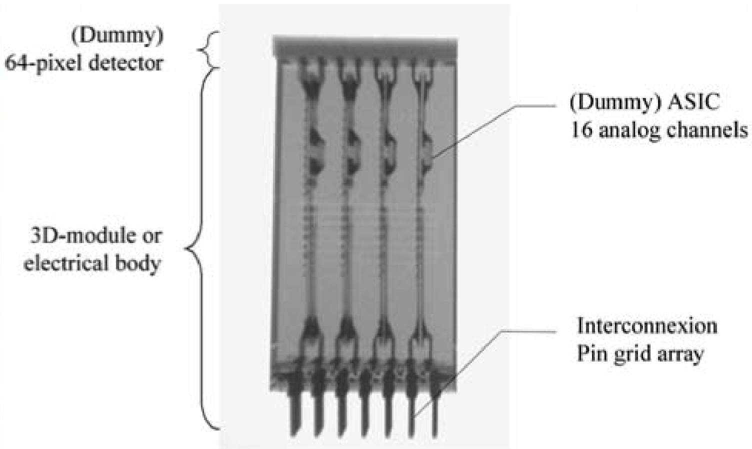


5000 cm^2



CALISTE64 hybrid prototype (CEA)



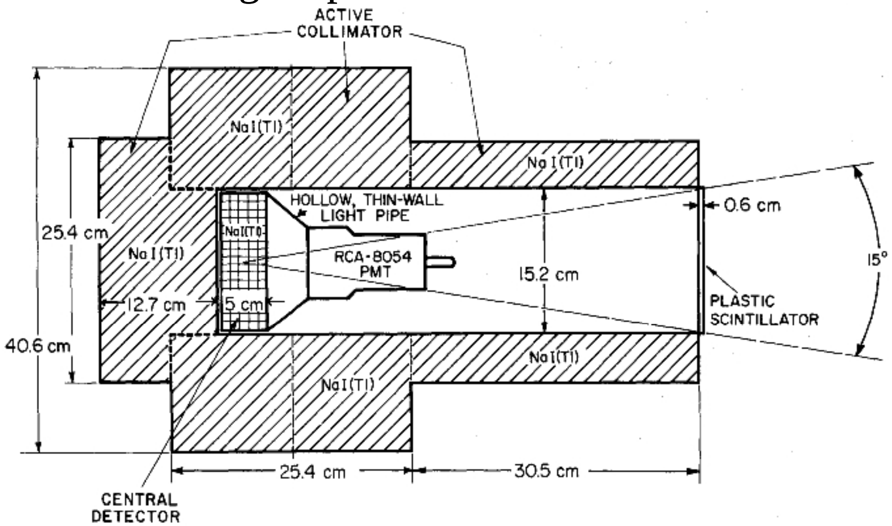


Characteristics:

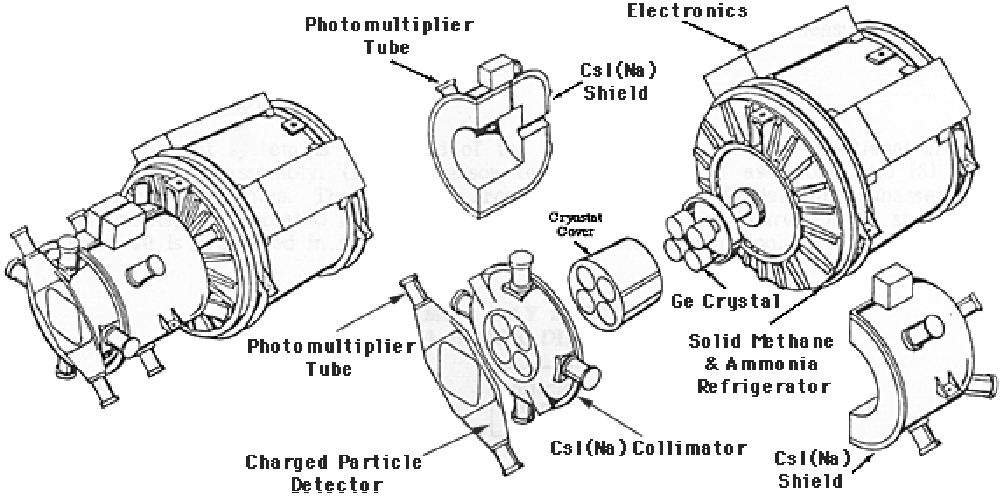
- 64 pixels of 2 mm CdTe & readout
- 4 ASICs for 64 channels (IDeF-X)
- 10 x 10 x 20 mm^3 volume
- energy range: 8 - 100 keV
- stackable
- spatial resolution: 1 mm
- time resolution: ~ 50 ns
- ΔE ~ 0.8 keV @ 60 keV (-10°C, 400 V)

The early days of soft gamma-ray astronomy

Rice group balloon detectors



HEAO-3 High-Resolution Gamma-Ray Spectrometer

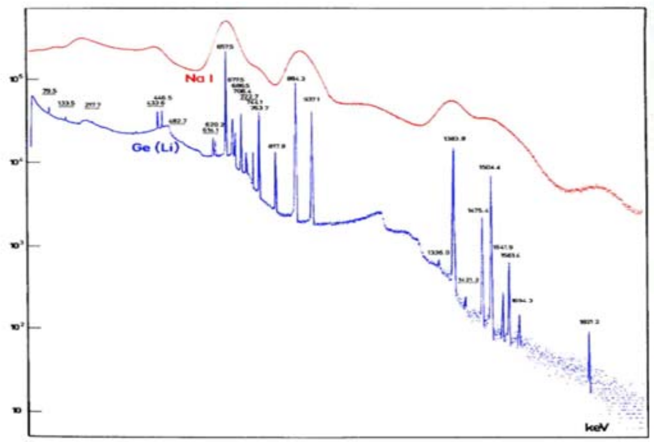


Common characteristics and features:

- collimators with large fields of view (no imaging)
- small detectors and large shields

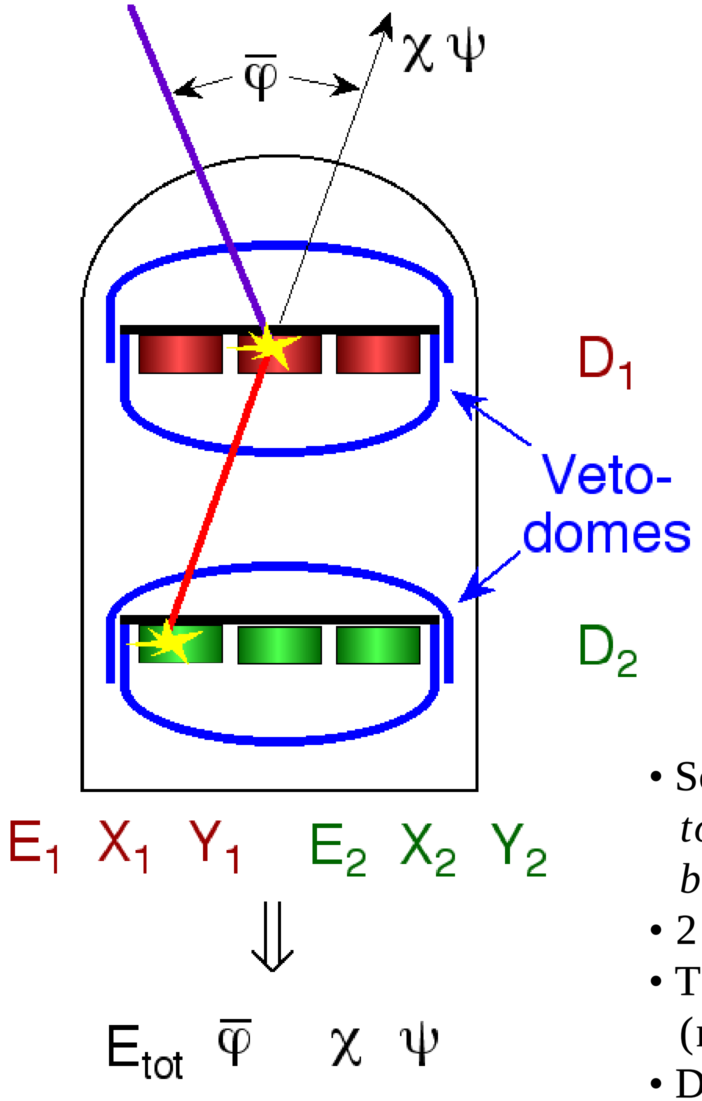
Ge spectrometers:

- excellent energy resolution
- requires cooling (80 K)
- degrades within few months in space environment (annealing to cure crystals)

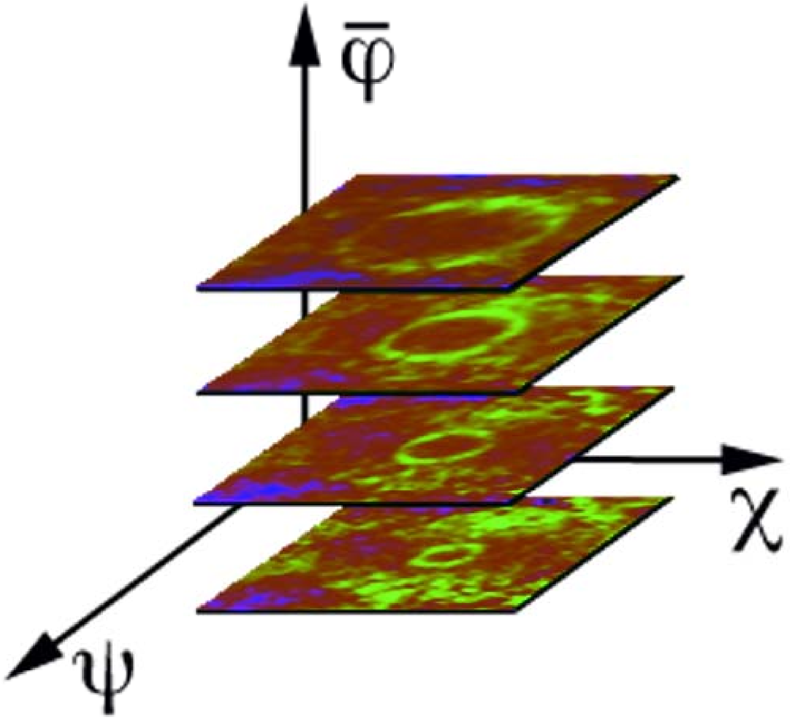


COMPTEL

Classical Compton telescope



Crab nebula in COMPTEL data-space (1-10 MeV)

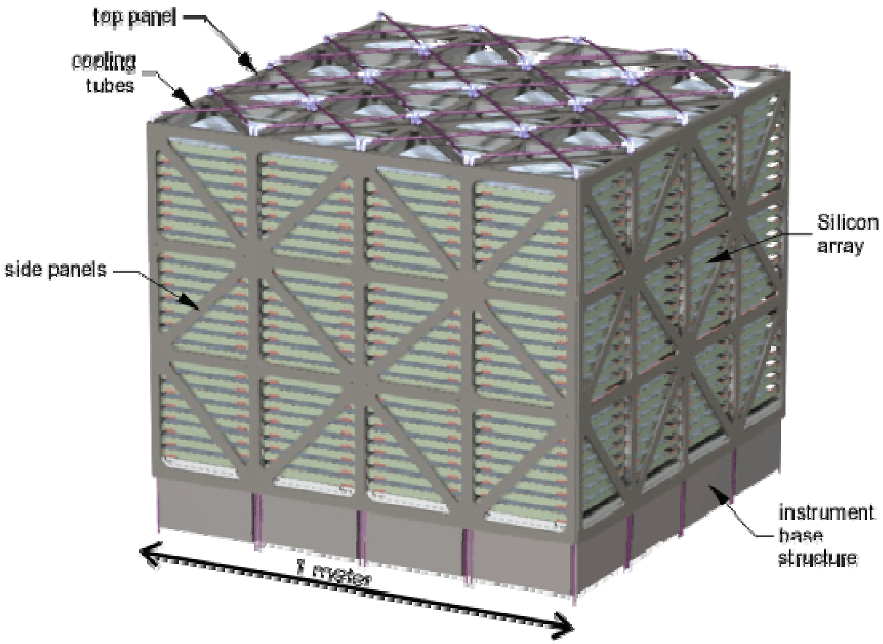


- Scintillators with 2D resolution (cm):
  top: NE213A (liquid organic, low Z), viewed by 8 PMT
  bottom: NaI (solid, high Z), viewed by 7 PMT
- 2 detector planes separated by 1.5 m
- Time of flight measurement (0.26 ns) between D1 and D2 (reduce backscattered events)
- D1 pulse shape discrimination against neutrons

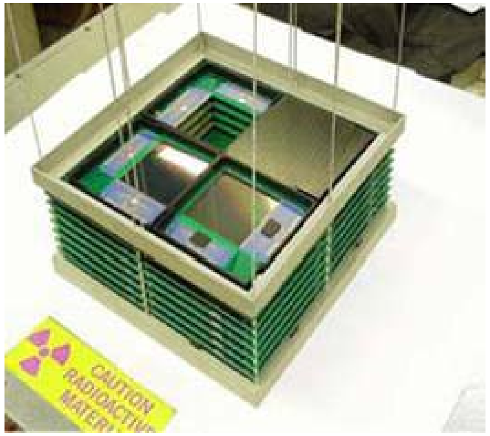
An advanced Compton telescope

Challenges

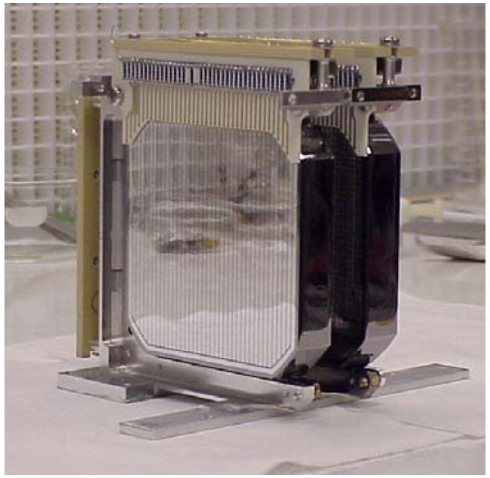
- Gain sensitivity !!!
- Improve efficiency (reduce detector spacing)
- Maintain or improve angular resolution (increase spatial / energy resolution)
- Maintain or improve energy resolution
- Measure time-of-flight
- Track scattered electron



NRL Si concept (similar to GLAST design)



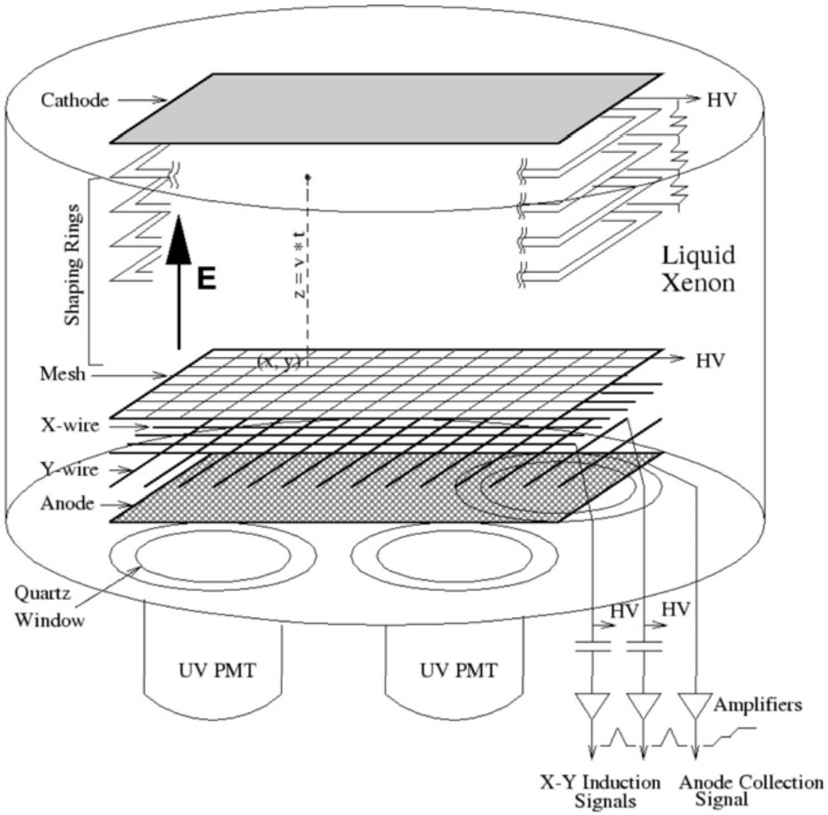
Si tracker prototype (MEGA)

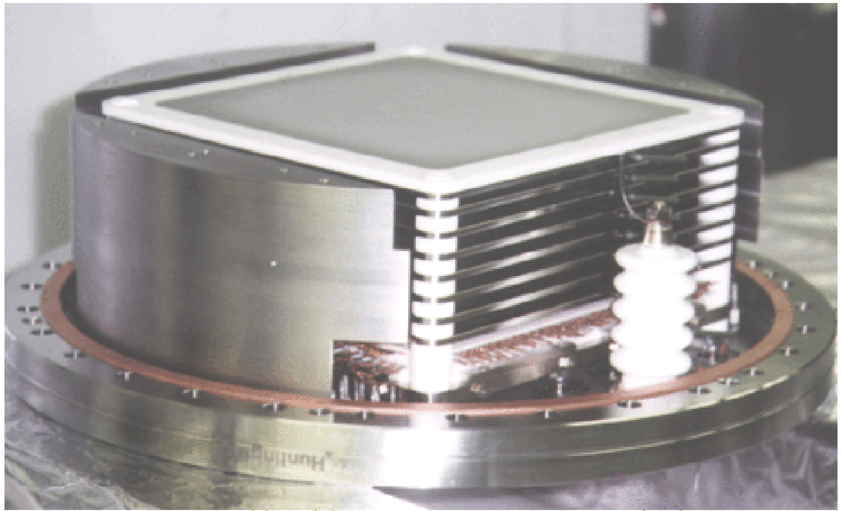


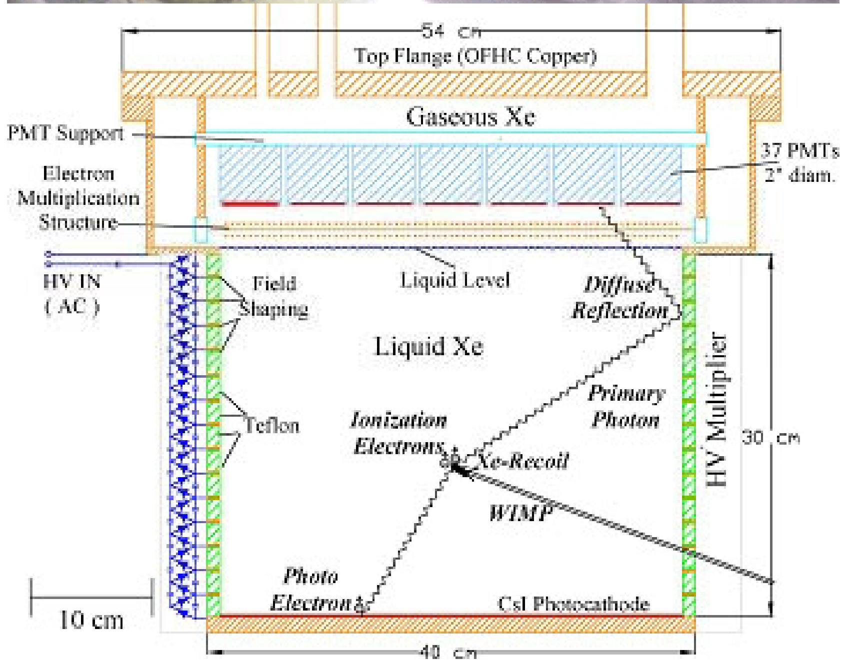
Ge strip detector (NCT)

Time projection chambers

Liquid XENON TPC



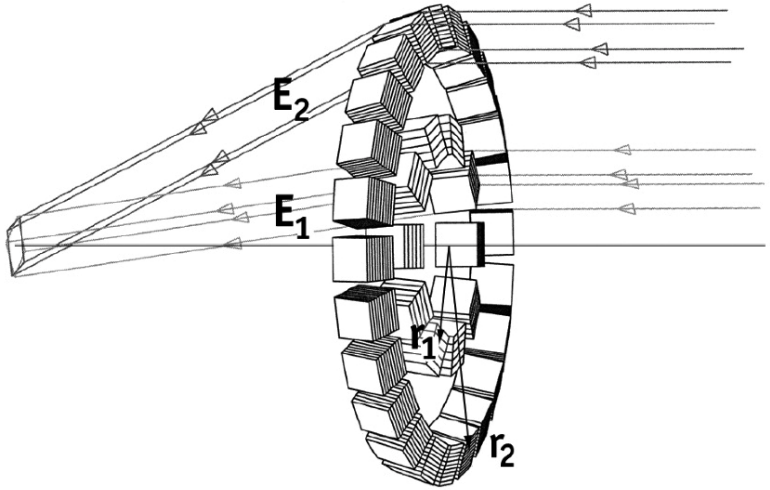




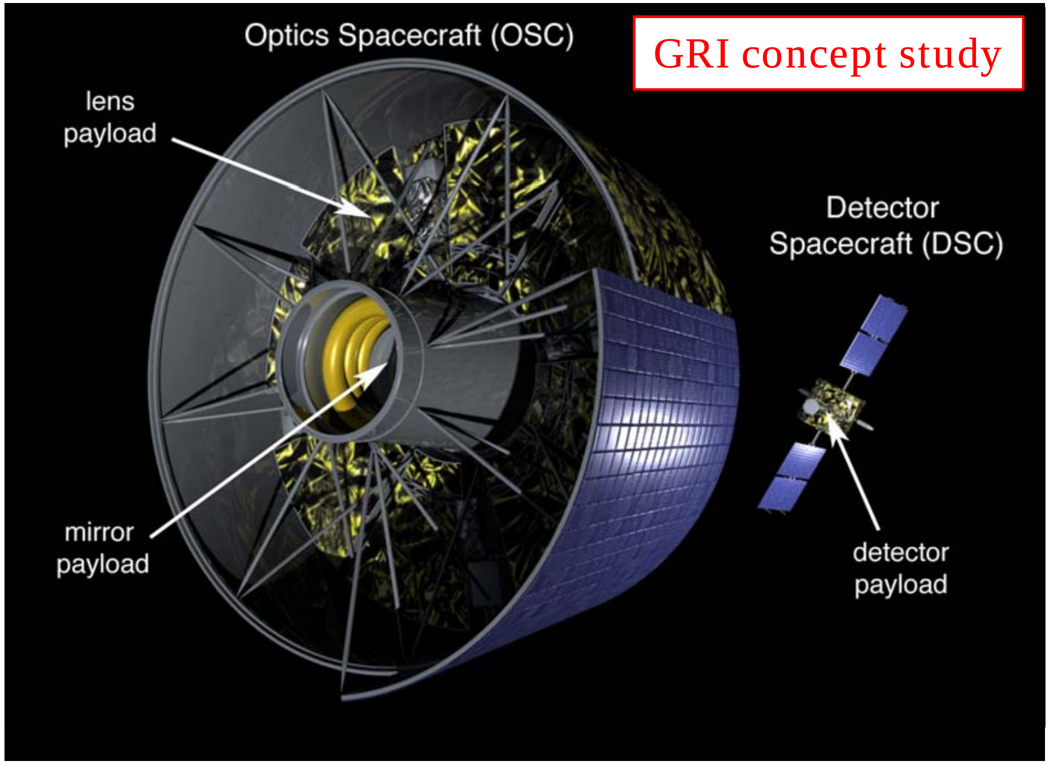
- combines drift chamber with scintillator
- scintillator: fast signal, time-tags event for drift time measurement (t,z)
- wires: x,y position
- anode: energy measurement

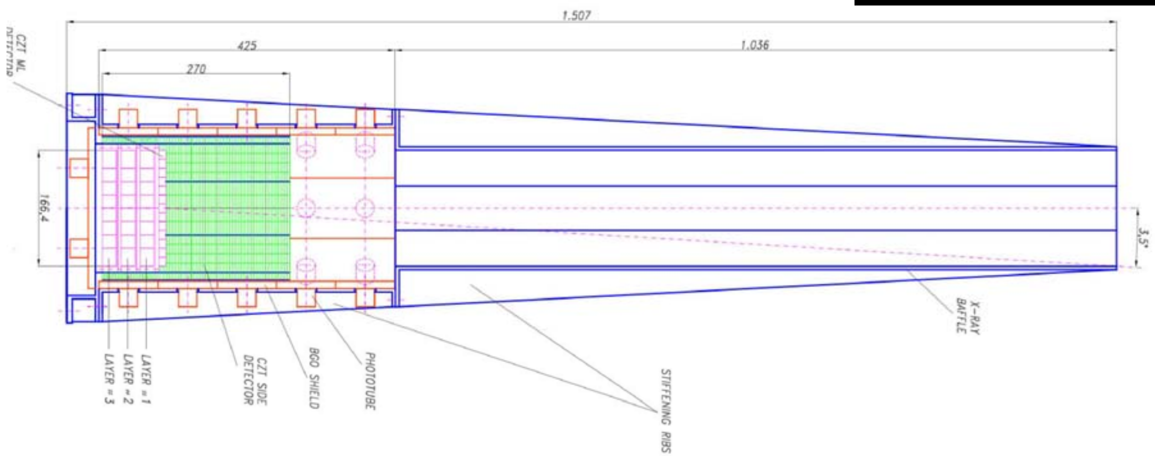
Detectors for gamma-ray lenses

$$2d_{hkl} \sin\theta = n\lambda$$



Small angle Bragg reflection allows concentration of parallel gamma-ray beam onto a small (cm) focal spot.

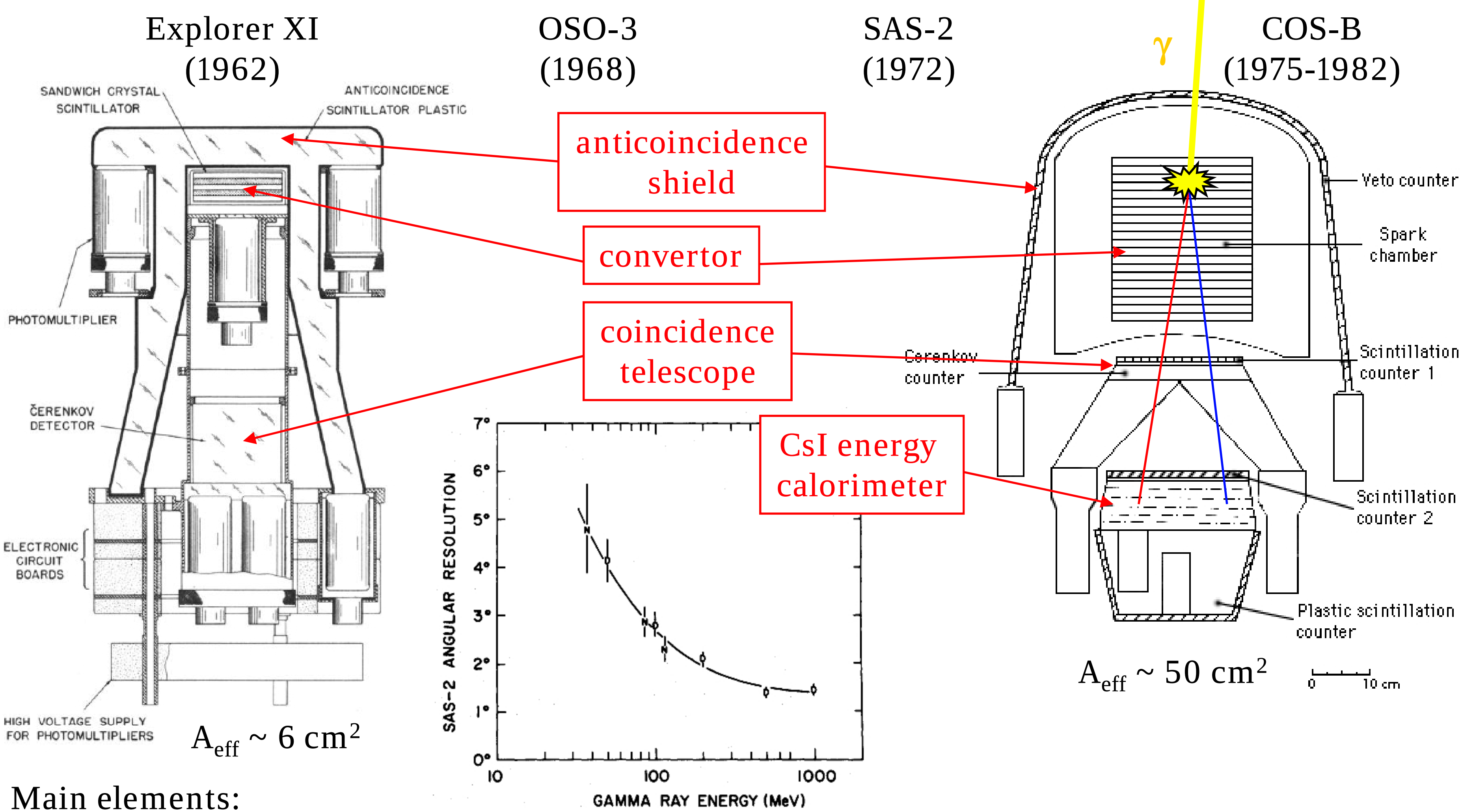




Detector requirements:

- Pixelised (few mm) detector needed
- Detector stack for MeV stopping power
- Compton reconstruction for background reduction
- Larger detector -> larger FOV

The early-days of hard gamma-ray astronomy



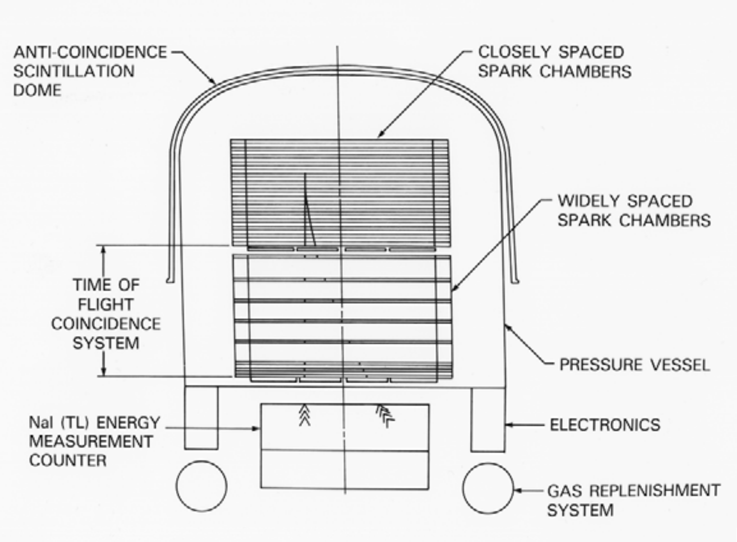
$A_{eff} \sim 6\ cm^2$

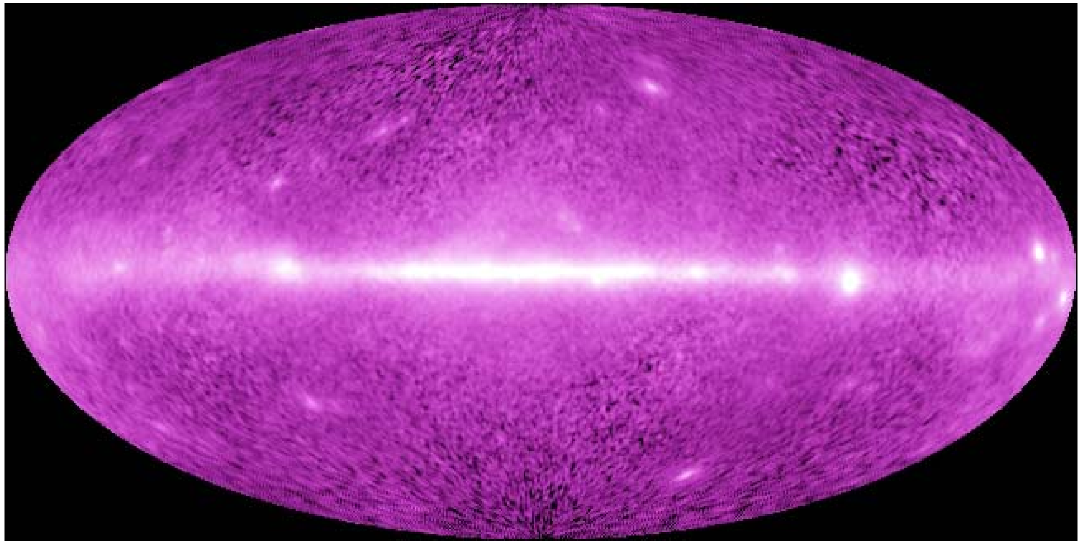
$A_{eff} \sim 50\ cm^2$

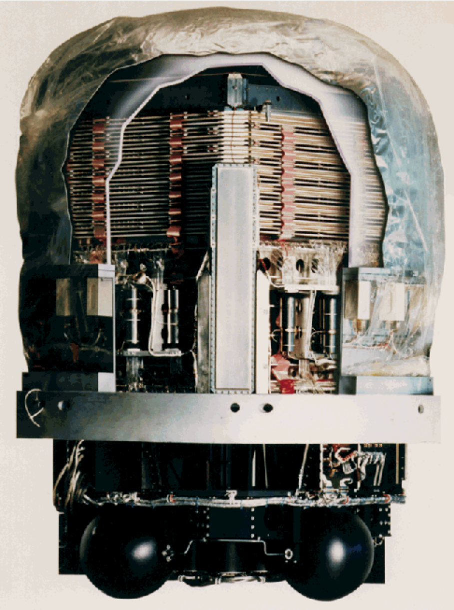
Main elements:

- gamma-pair convertor (scintillator or spark chamber with tungsten plates)
- coincidence Cherenkov telescope (triggers on e^- and/or e^+)
- energy calorimeter for pair absorption (only COS-B)
- anticoincidence shield for charged particle background rejection

EGRET







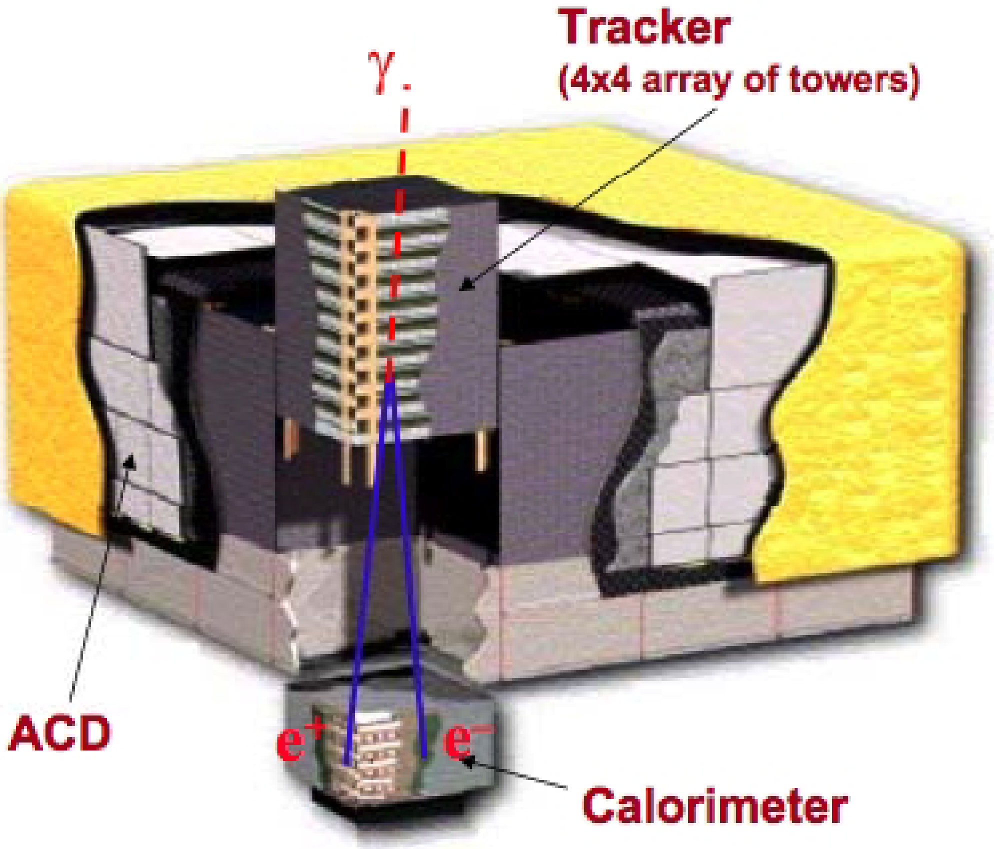
Energy: 20 MeV - 30 GeV	FOV ~ 40° (FWHM)	Weight ~ 1,8 tons
$\Delta E/E$ ~ 20%	ang.res. > 0.5°	Power ~ 190 W
A_{eff} ~ 1500 cm^2	Δt ~ 0.1 ms	

Characteristics:

- large effective area (COS-B ~ 50 cm^2)
- modest angular resolution (most sources remain unidentified)
- long deadtime ~ 200 ms
- expendables (spark chamber requires gas replenishment)
- backsplash at high energies (50% efficiency degradation at 10 GeV)

GLAST

- **Precision Si-strip Tracker (TKR)**
  18 XY tracking planes with tungsten foil converters. Single-sided silicon strip detectors (228 µm pitch, 900k strips) Measures the photon direction; gamma ID.
- **Hodoscopic CsI Calorimeter(CAL)**
  Array of 1536 CsI(Tl) crystals in 8 layers. Measures the photon energy; image the shower.
- **Segmented Anticoincidence Detector (ACD)** 89 plastic scintillator tiles. Rejects background of charged cosmic rays; segmentation mitigates self-veto effects at high energy.
- **Electronics System**
  Includes flexible, robust hardware trigger and software filters.



The systems work together to identify and measure the flux of celestial gamma rays with energy between ~20 MeV and ~300 GeV.

Conclusions

- X-ray and Gamma-ray detectors for astrophysics are based on a broad variety of technologies related to the detection physics and the science requirements
- Most detectors are today position sensitive with increasing minaturisation and an increasing number of pixels
- Most detectors are today semi-conductor devices that eventually are cooled
- Soft X-ray astronomy still awaits the advent of space-based micro-calorimeters for fine spectroscopy over a broad energy band
- Hard X-ray astronomy moves from collimators / coded masks towards focusing instruments, implying the need for small pixelised detector matrices
- Soft gamma-ray astronomy needs a major improvement in sensitivity that could be either reached by focusing or large area Compton telescopes (both need 3D pixelised detectors)
- Hard gamma-ray astronomy is in a golden age (also on ground) - what comes next ?