

# X- and Gamma-ray Instruments

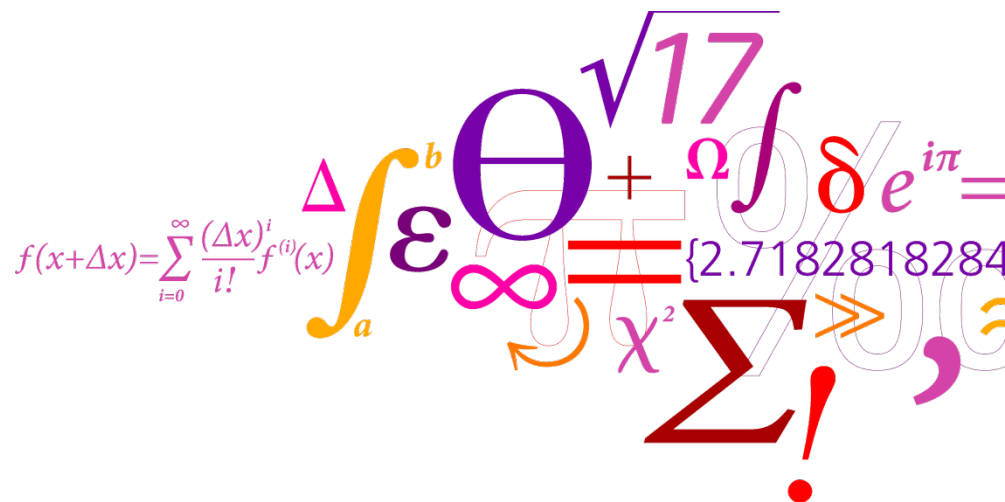
Allan Hornstrup,

Head of Astrophysics Department, DTU Space

Overview talk given at the Astronomical Instrumentation Course, NBI,  
December 8, 2009

DTU Space

Institut for Rumforskning og -teknologi



# Why other wavelengths?





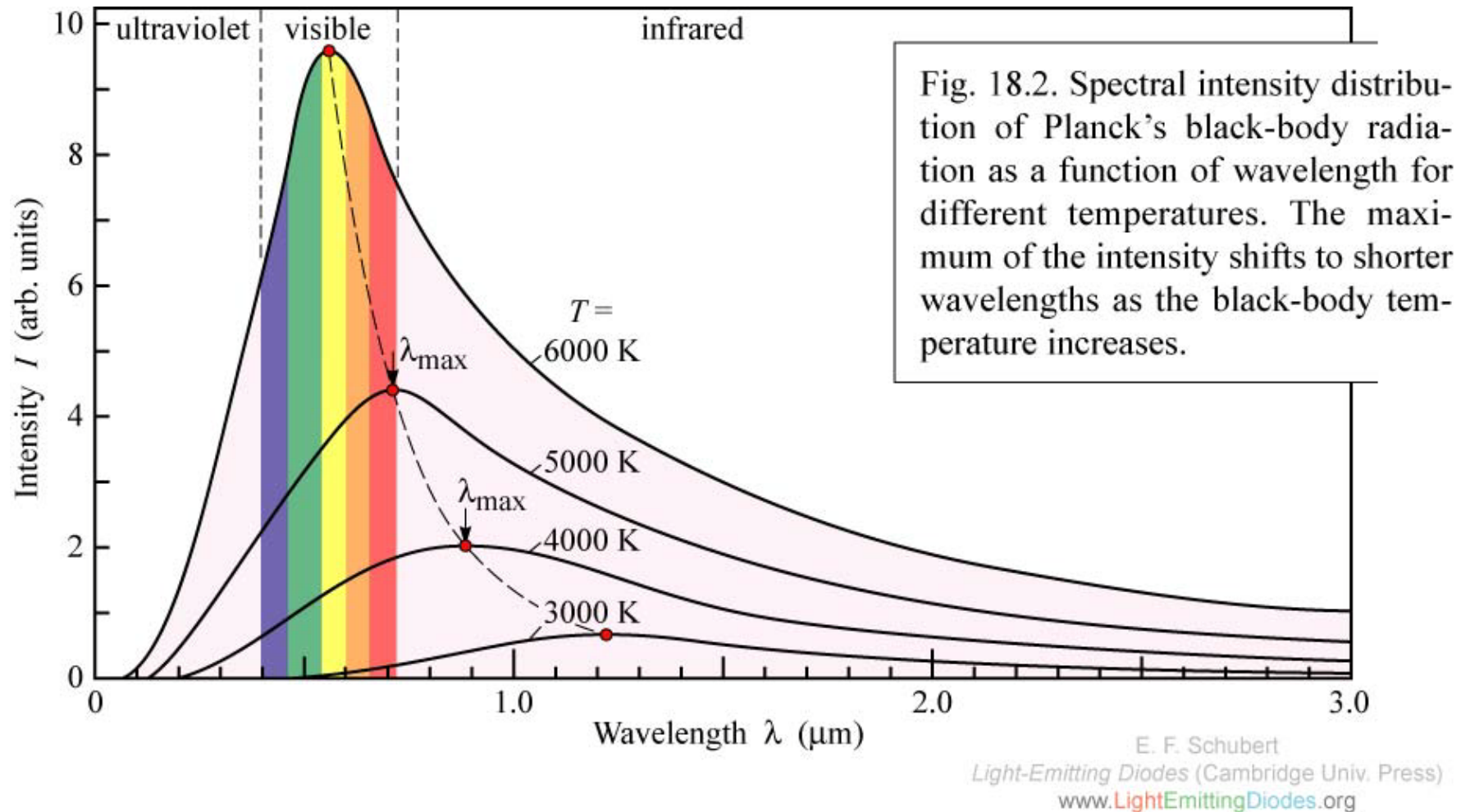
# Why from space?



# Why from space?

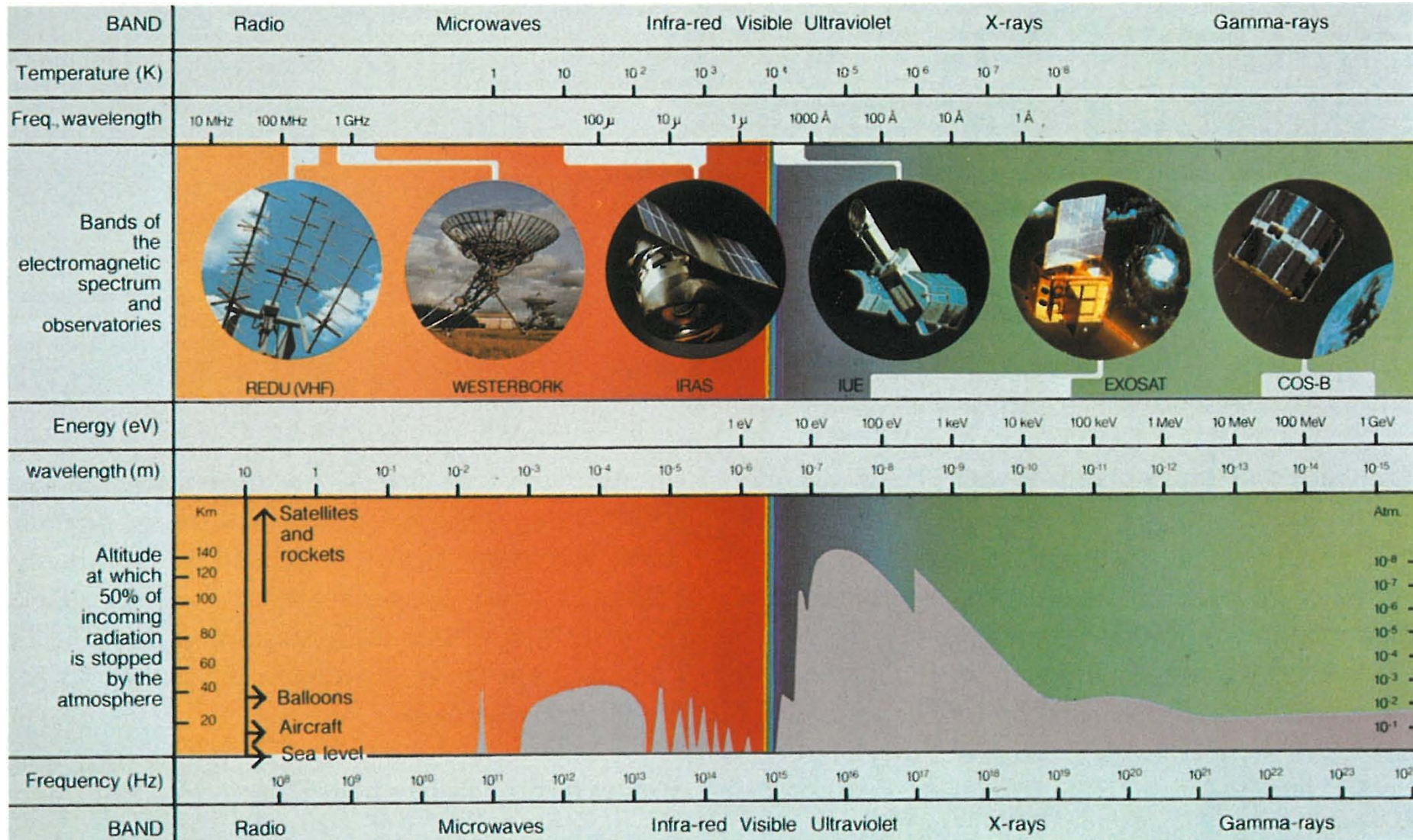


# Stars may have other colors than yellow





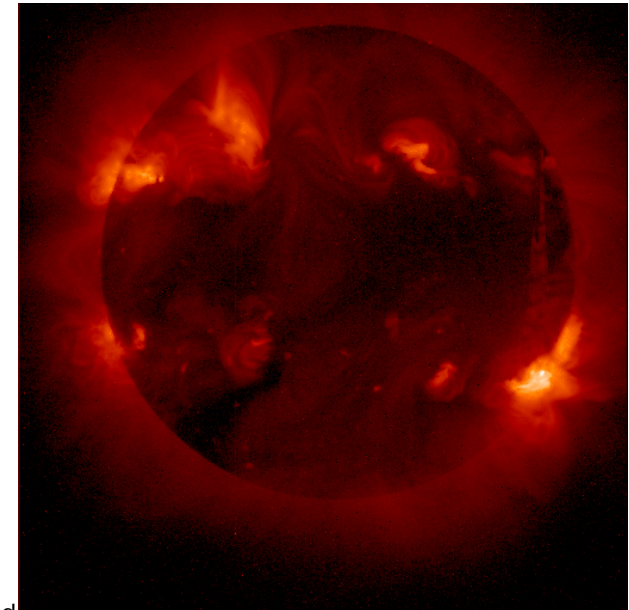
# The Electromagnetic Spectrum



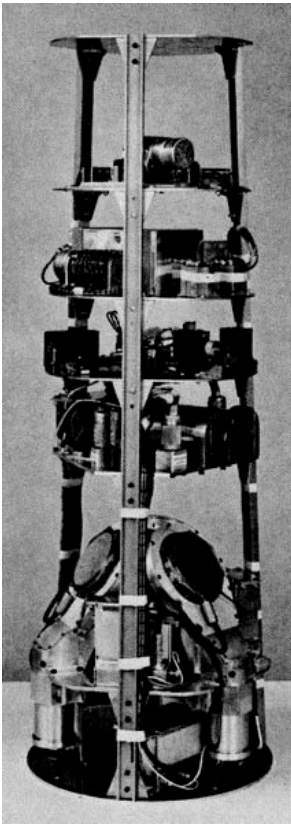




- At first, the X-ray emission from the Sun was studied
- With the emission from the Sun, not much should be visible from other stars



In the 1960's, Giacconi developed a big Geiger counter to observe X-rays from the moon. Launched on a rocket.



# Giacconi's observations of the moon in 1962

Surprising results, not only the moon was visible, but also a bright new source, and a background

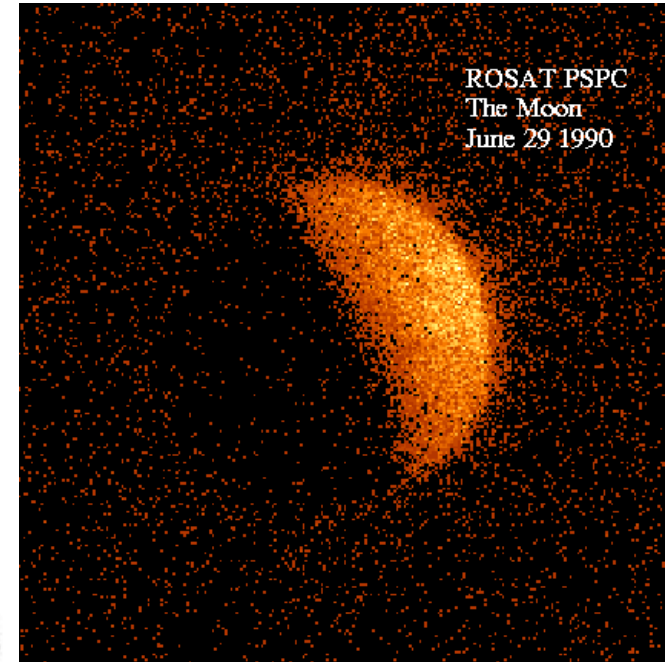
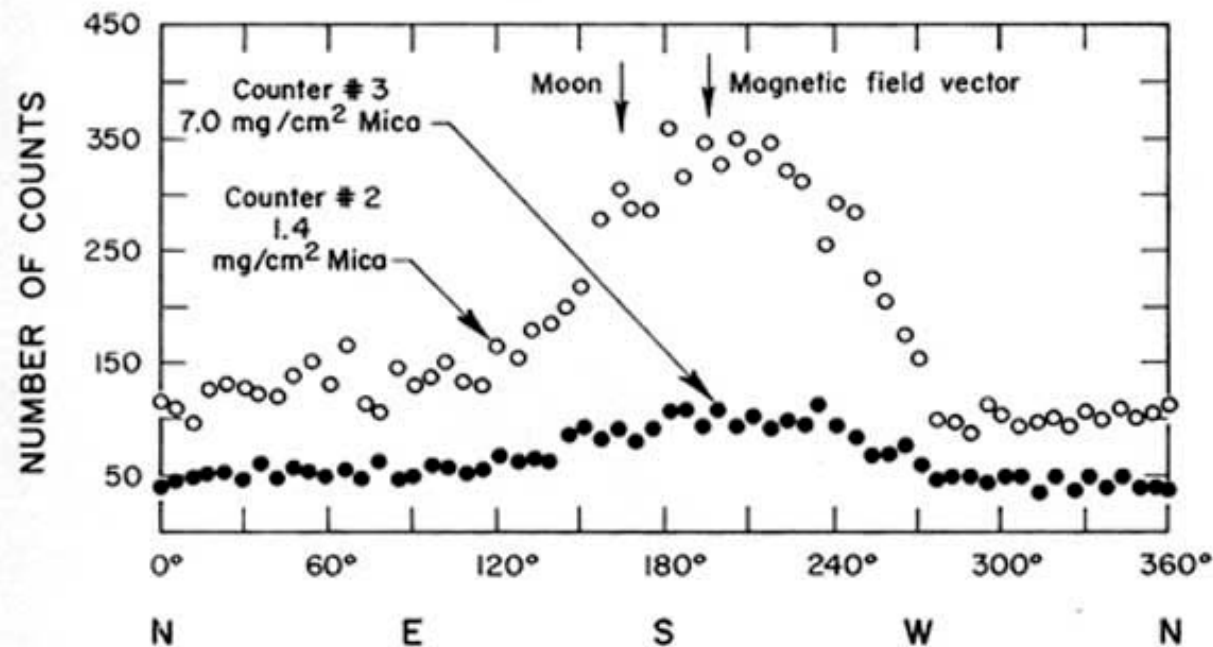
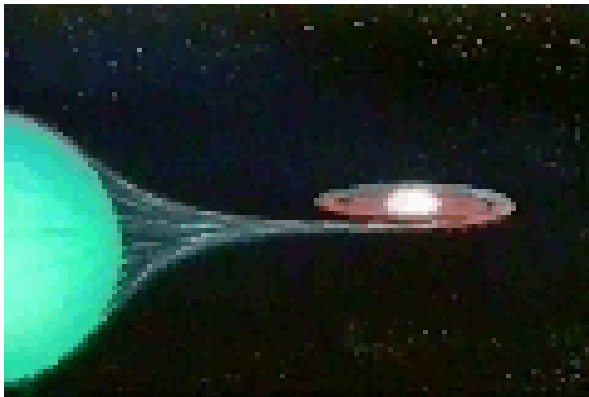
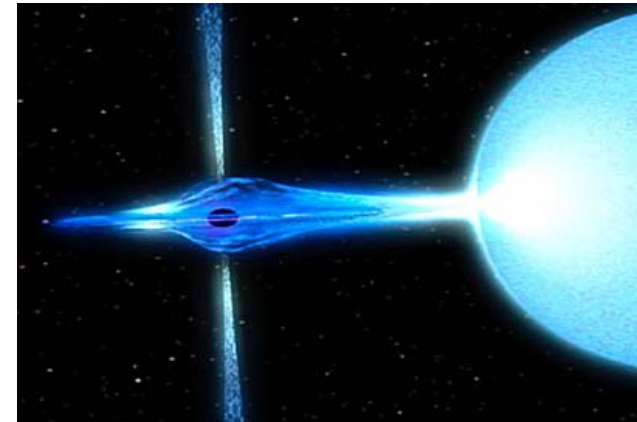


Fig. 1.2. Azimuthal distributions of recorded counts from Geiger counters flown during June 1962.



# The result: A new type of object.

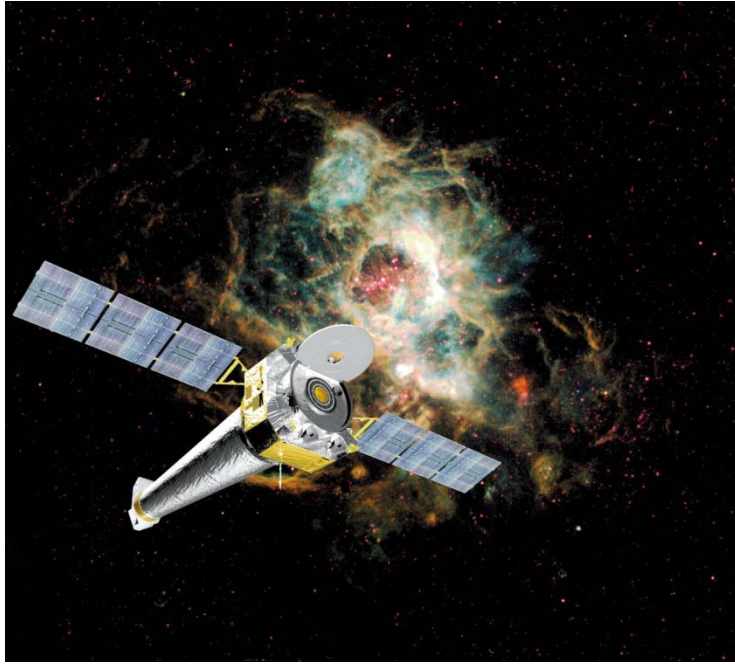
Discovered Sco-X-1 a compact binary.  
Later:  
similar systems have revealed  
Black Holes...



- In 2003, Giacconi received a (part) Nobel Prize for the discovery of the X-ray astronomy



# Typical Astrophysics Space Projects (X-rays)



- X-ray missions

Completed

# Gamma ray astronomy

- Above 10 MeV mostly non-thermal processes, related to acceleration processes for cosmic rays.
  - Electrons and nucleons are accelerated in interstellar chock-fronts or in magnetospheres
  - Collision with other particles or photons emits radiation – gamma rays
- From 100keV to 10MeV the picture is more heterogeneous, both
  - thermal and non-thermal processes occur as well as
  - Nuclear processes

# Electromagnetic radiation

- Photoelectric absorption
  - Interaction between the photon and an electron in an atom
    - Decreasing cross section with increasing photon energy
    - Increasing cross section with increasing atom-number
- Compton interaction
  - Interaction between photon and free (or bound) electron.
    - Flat max around .5 MeV
- Pair production
  - Interaction between photon and the electrical field close to an atom's nucleus.
    - Increasing cross section with increasing energy
    - Increasing cross section with atom number

# Gamma ray astronomy

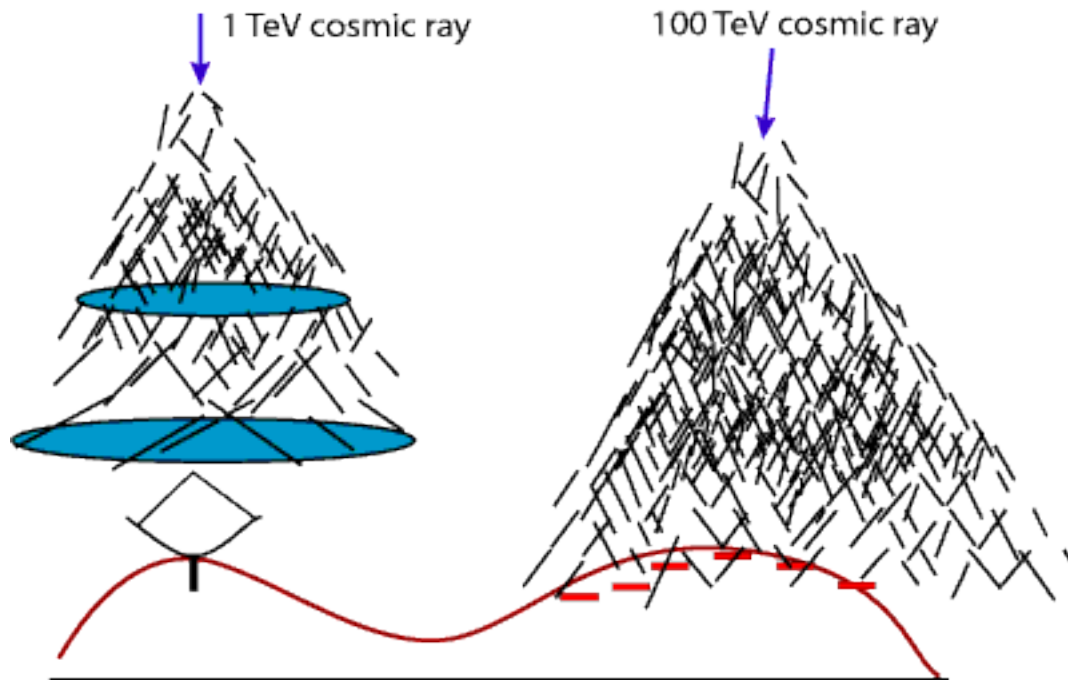
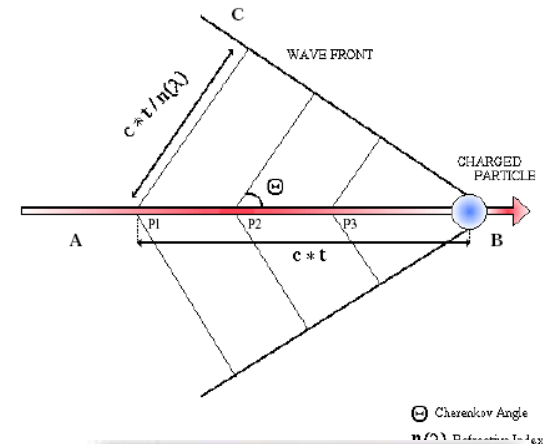
- Typical split in intervals:
  - Above 200 GeV
    - Low flux
    - Observed from ground
  - 30MeV to 200GeV
    - Still somewhat low flux
    - Photons not able to reach the ground, huge satellite instruments required
  - 1MeV to 30MeV
    - Radioactive isotopes
    - Hard to observe, poor efficiency of detectors
  - 100keV to 1MeV
    - Interesting area, many astrophysical processes.
    - Good idea to have focusing telescopes to avoid background confusion

# X-ray astronomy

- Even less well defined split (more defined by technology)
- 20-100 keV
  - Non thermal and thermal processes, emission from interesting elements from e.g. SN'e
  - Hard to focus (but wait and see ☺ )
- 0.1 – 20 keV
  - Lots of thermal sources, and also some non-thermal
  - Bremsstrahlung and power laws
  - Focusing optics – excellent in reducing background

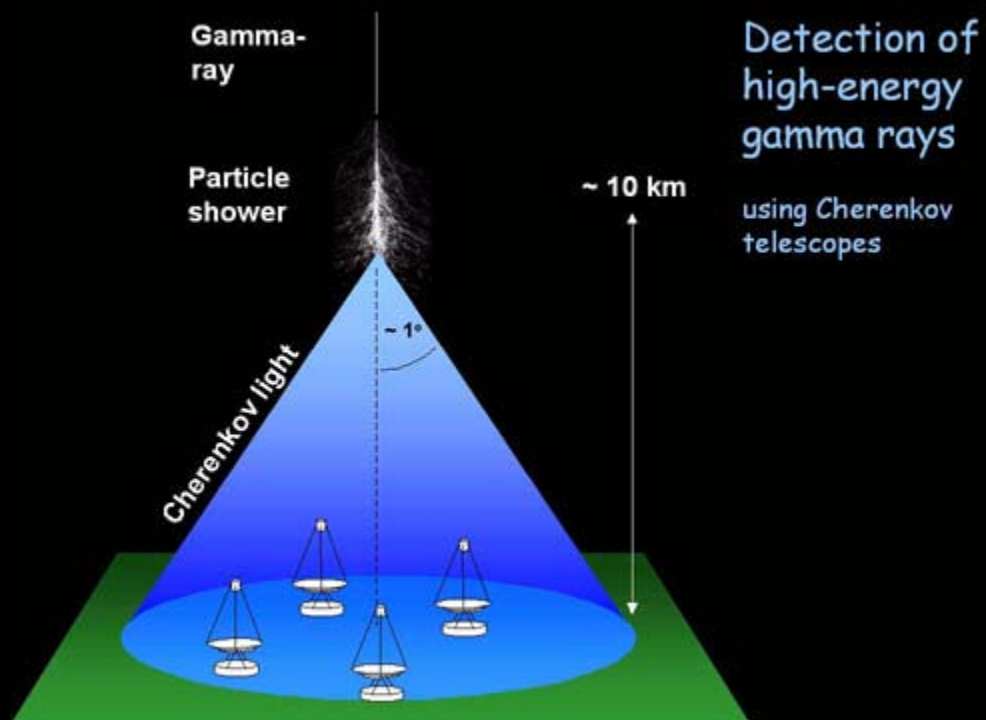
# Examples from the very high energy

- Čerenkov radiation
  - Čerenkov light is a photon equivalent to the sonic boom
  - Also observed in nuclear facilities, where there is a glow from relativistic electrons





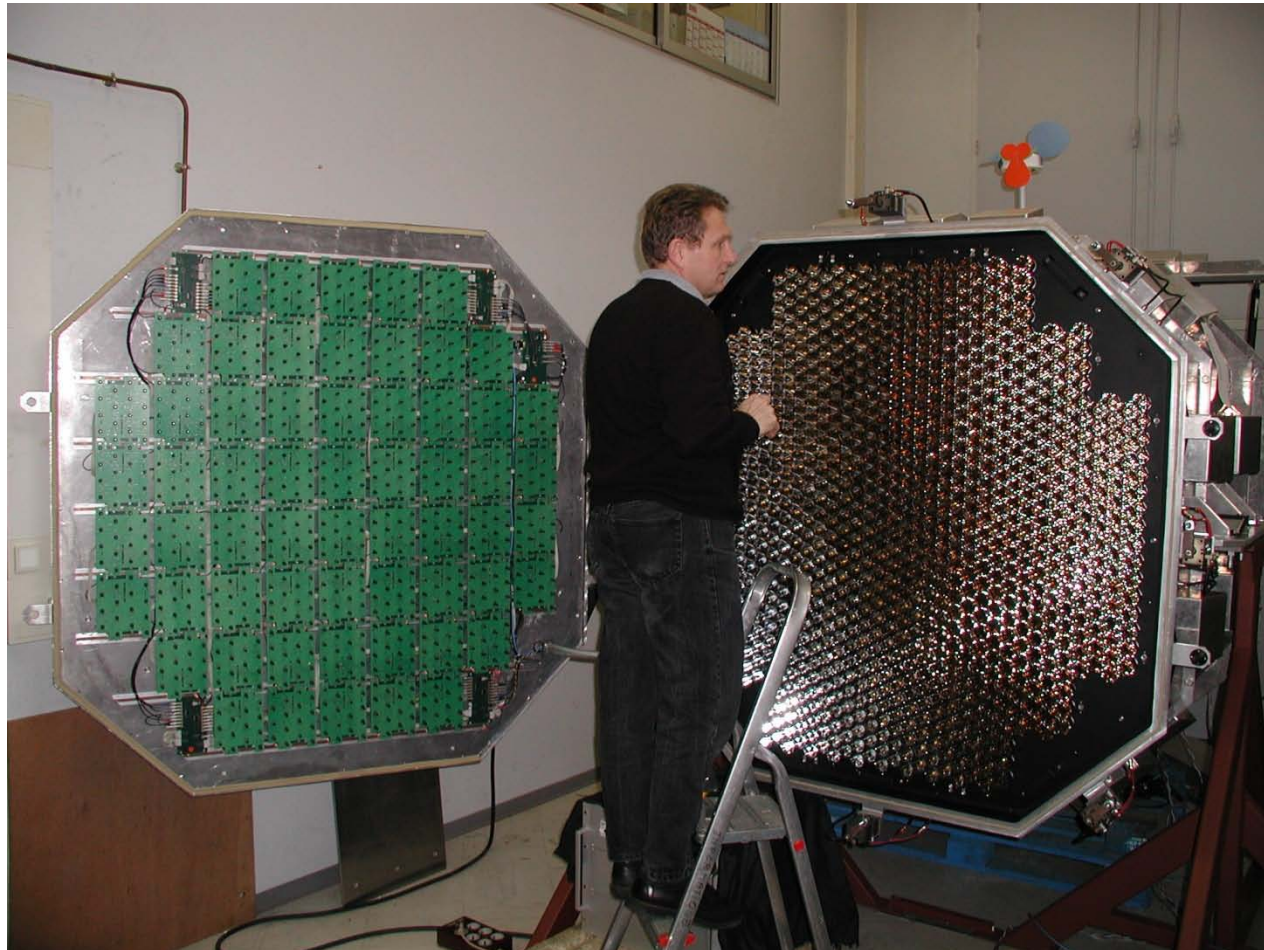
# The HESS project



# The HESS project (Namibia)



# The HESS project camera (928 phototubes)



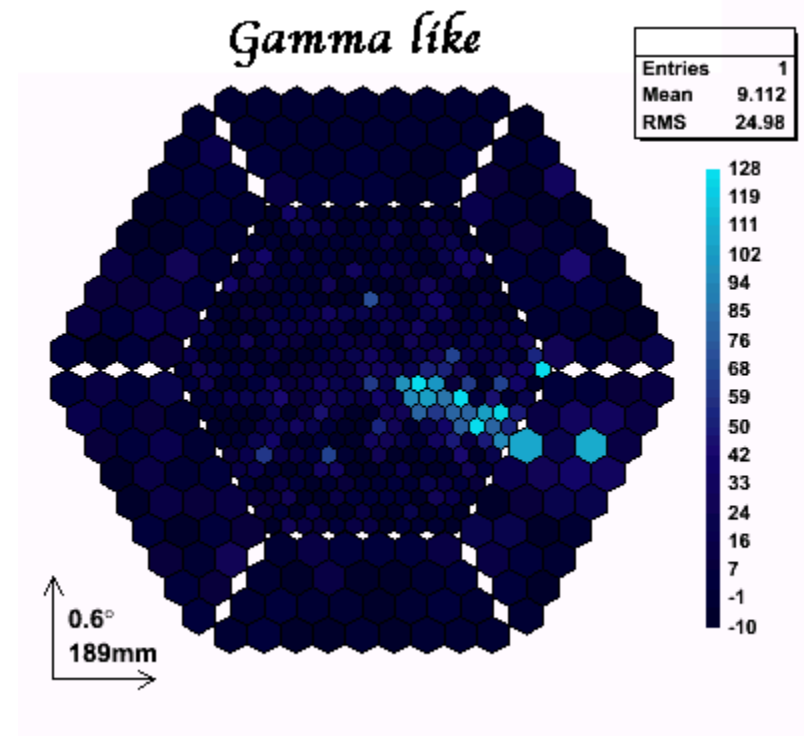
# MAGIC on La Palma



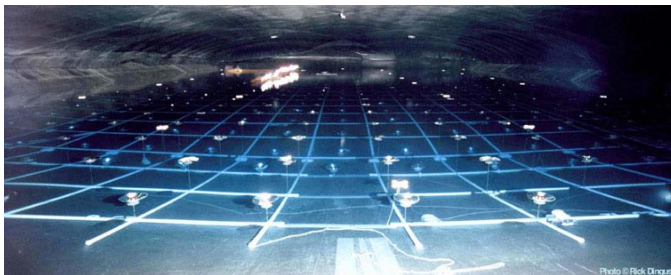


# MAGIC on La Palma

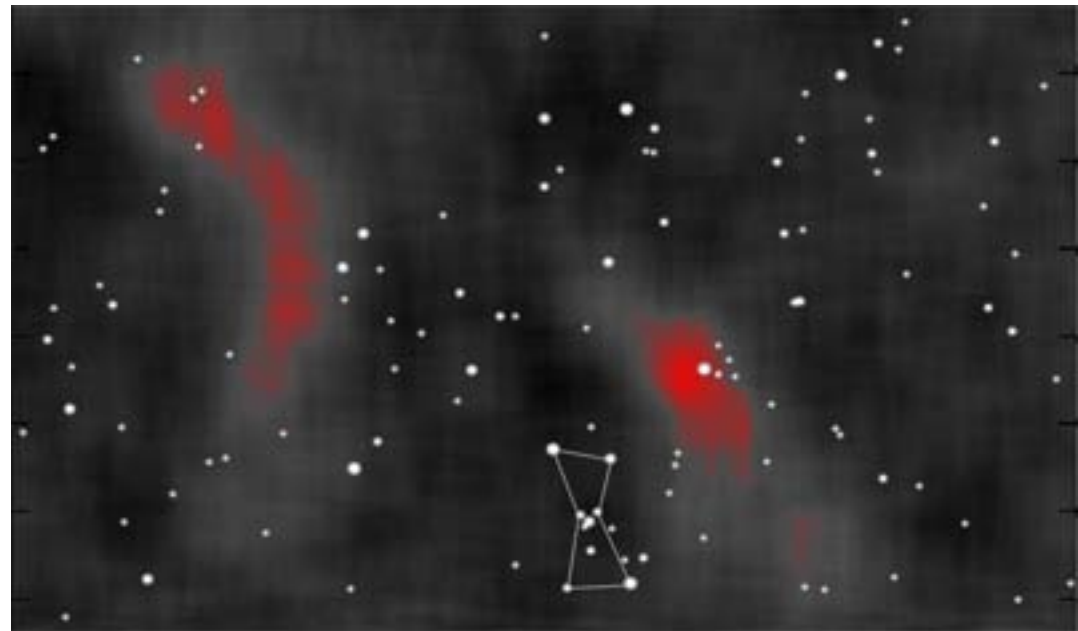
- Must separate different origins:
  - Different reactions give different signatures in the detector array



# Milagro – another Gamma Ray Observatory

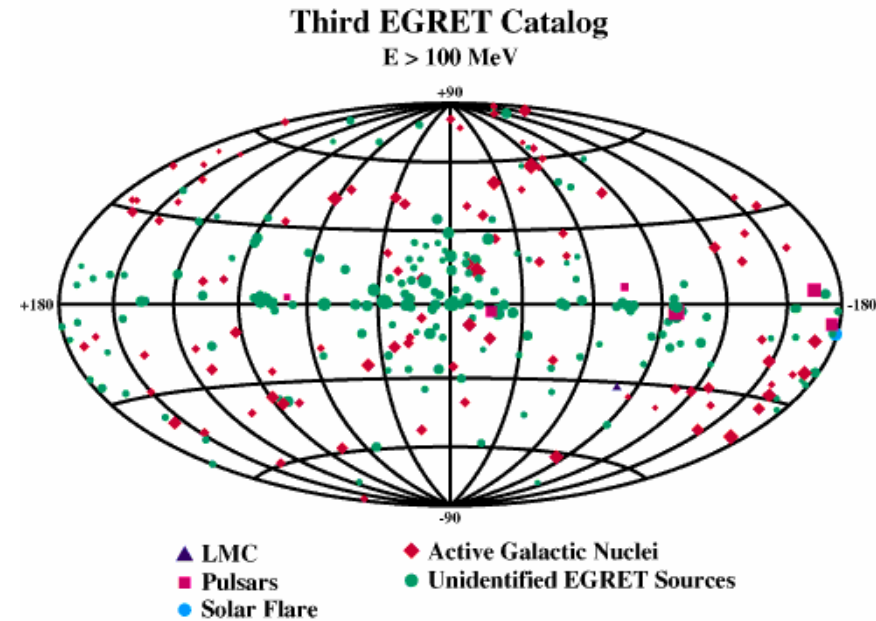


Unknown sources revealed!



# Gamma Ray Observatories in space

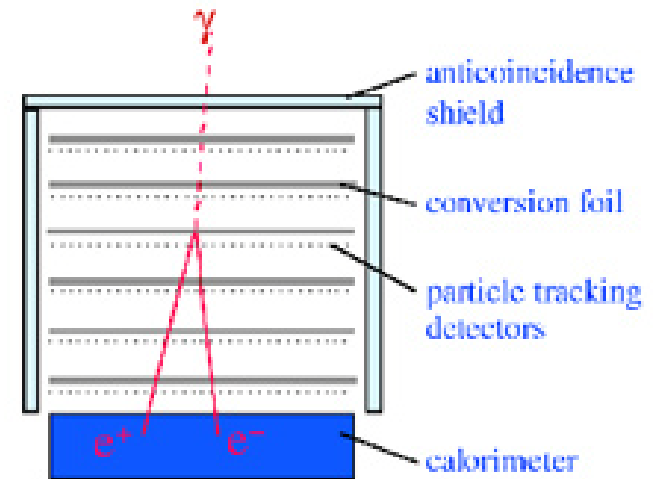
- GRO (Gamma Ray Observatory)



# Gamma Ray Observatories in space



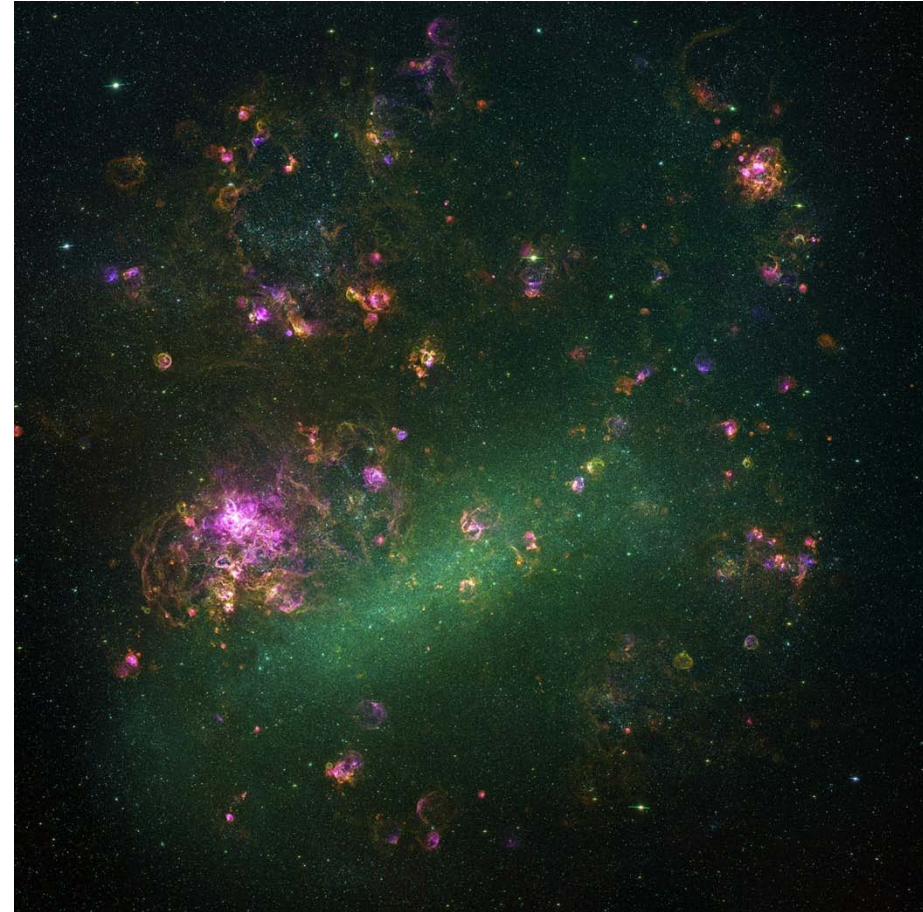
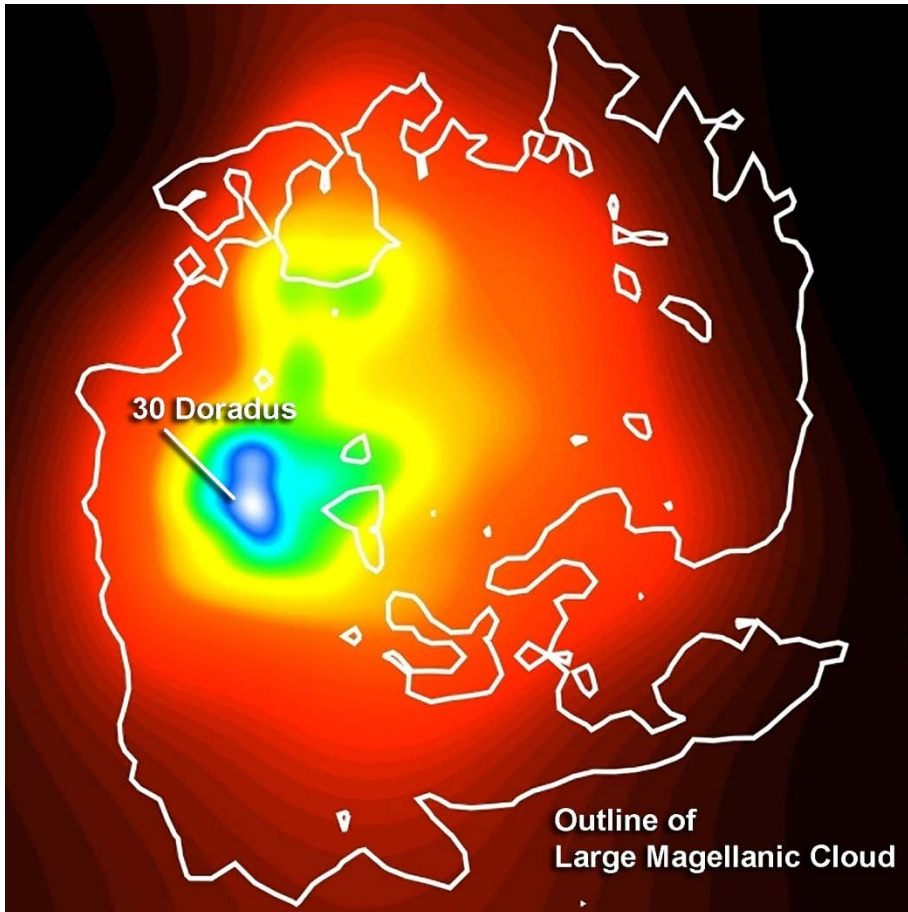
FERMI  
(previously  
known as  
GLAST)







# FERMI

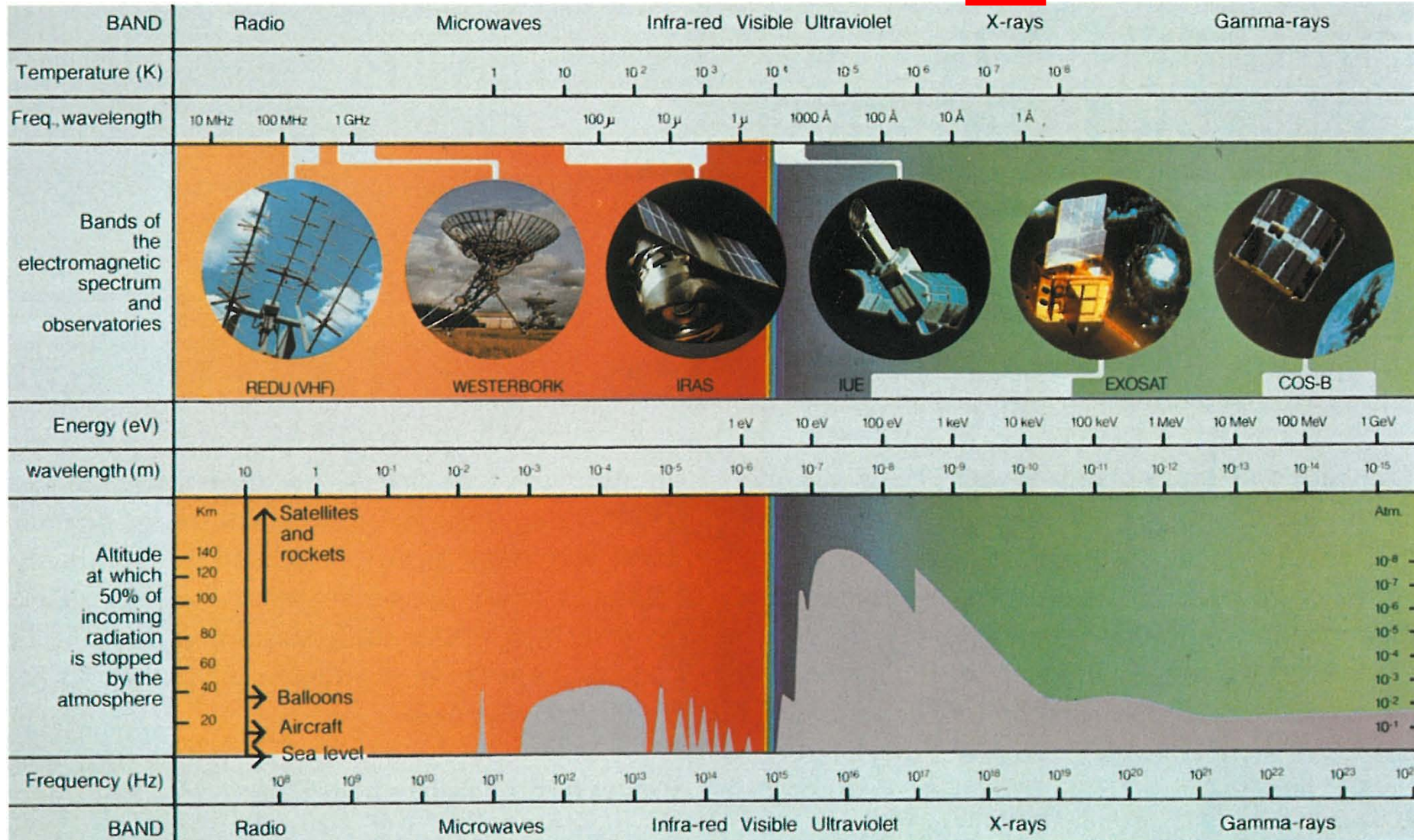


# DTU Space (astro)projects in X- and $\gamma$ -rays

- INTEGRAL – launched 2002, DTU Space PI on X-ray monitors
- NuSTAR – launch 2011, DTU Space provides special coating of mirrors
- ASIM – (NOT an astronomical project): Launch to ISS in 2014, but uses "our" X-ray detectors
- Study projects:
  - High energy focusing up to 450 keV
  - 3D detector
  - Mini gamma-ray burst detector



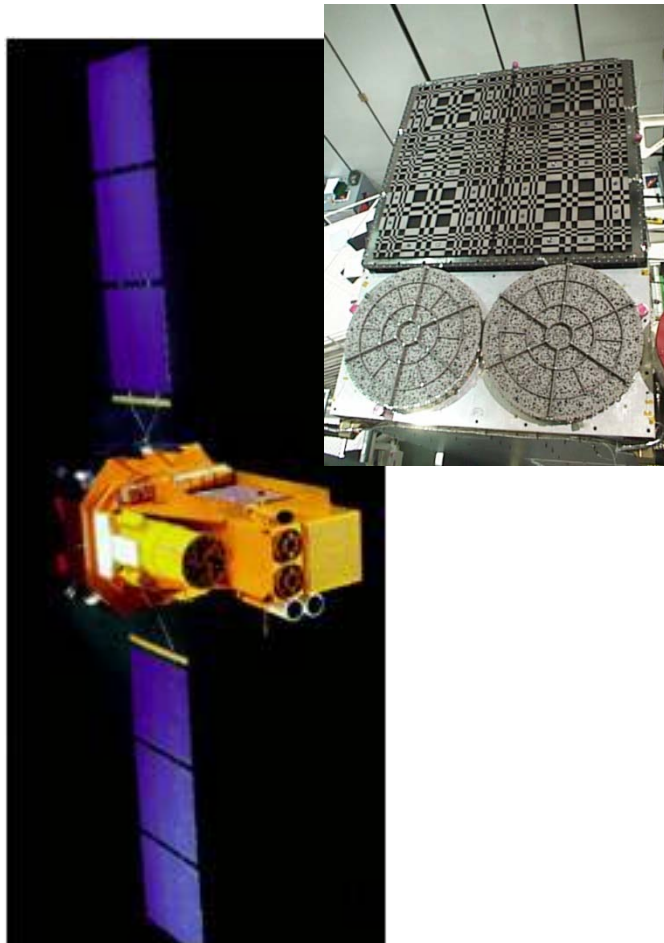
# Electromagnetic Spectrum



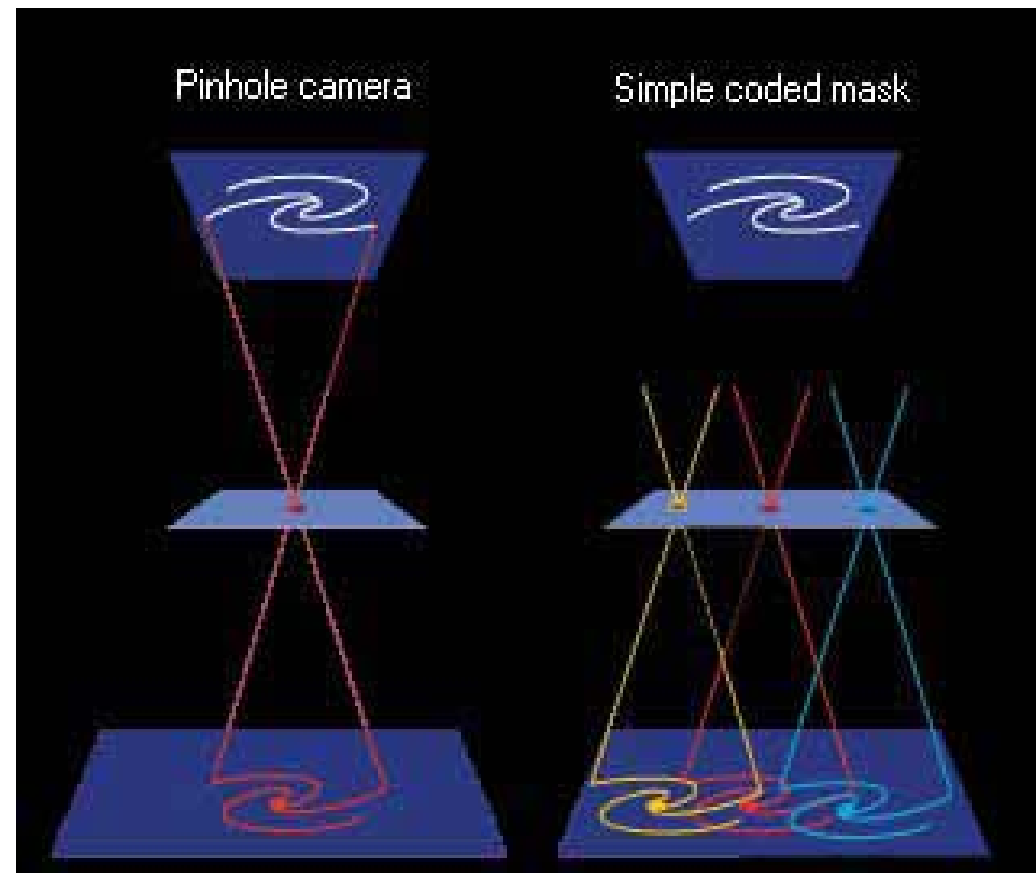
# INTEGRAL– launched 2002



# IBIS and SPI



Coded  
mask  
principle

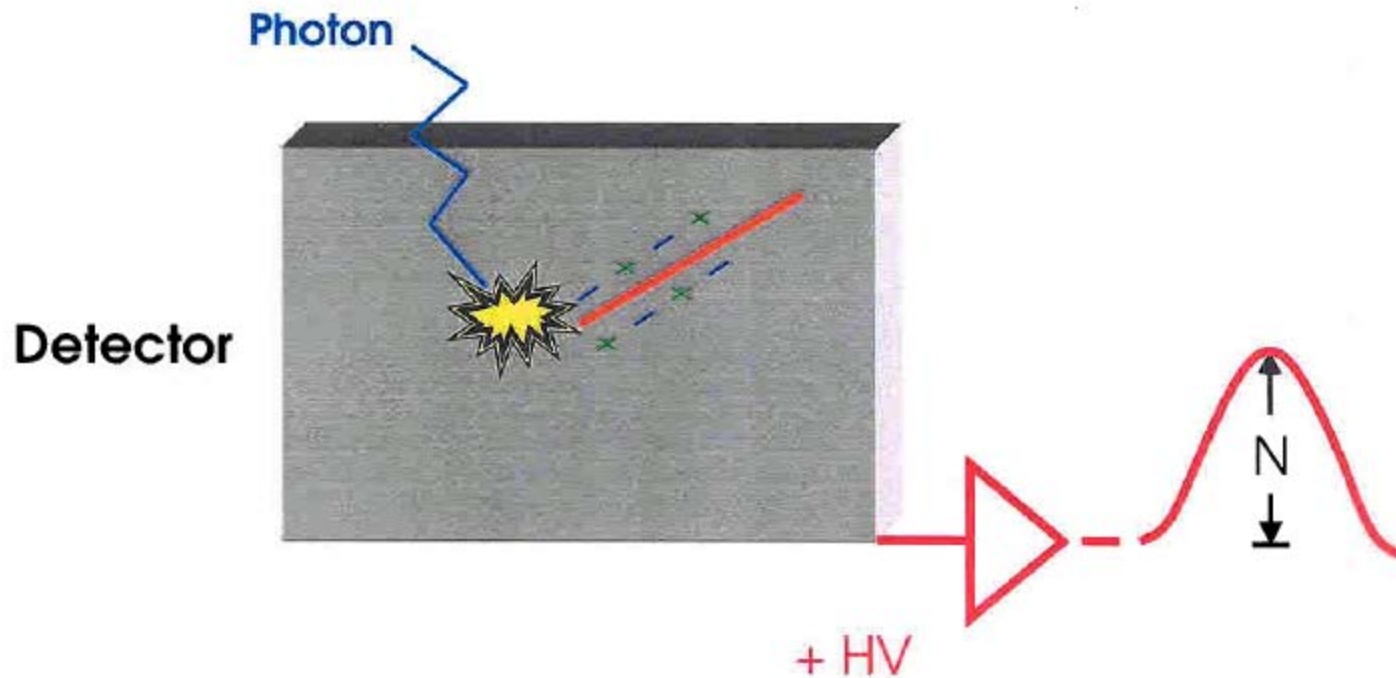




# Photon Detection

Photon Energy Conversion ( <i>Photo el., Compton, Pair Production</i> )	Detector Type	
Electric Charge	Ionization Chambers Proportional Counters Semiconductor Detectors	Charged Particles X-rays X and $\gamma$ -rays,
Light	Scintillators	$\gamma$ -rays
Phonons	Cryogenic Calorimeters	X-rays

# Photon counting detectors



$$\langle N \rangle = E / W$$

$$\sigma(N) = \sqrt{F \cdot N}$$

# Ionization Chambers and Semiconductor Detectors

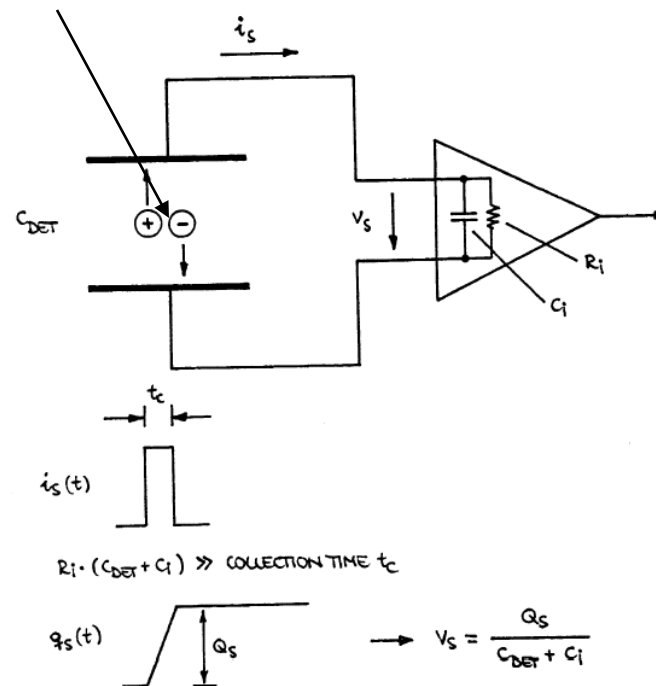
Detection volume with electric field

Energy deposited  $\rightarrow$  positive and negative charge pairs

Charges move in field  $\rightarrow$  current in external circuit  
(continuity equation)

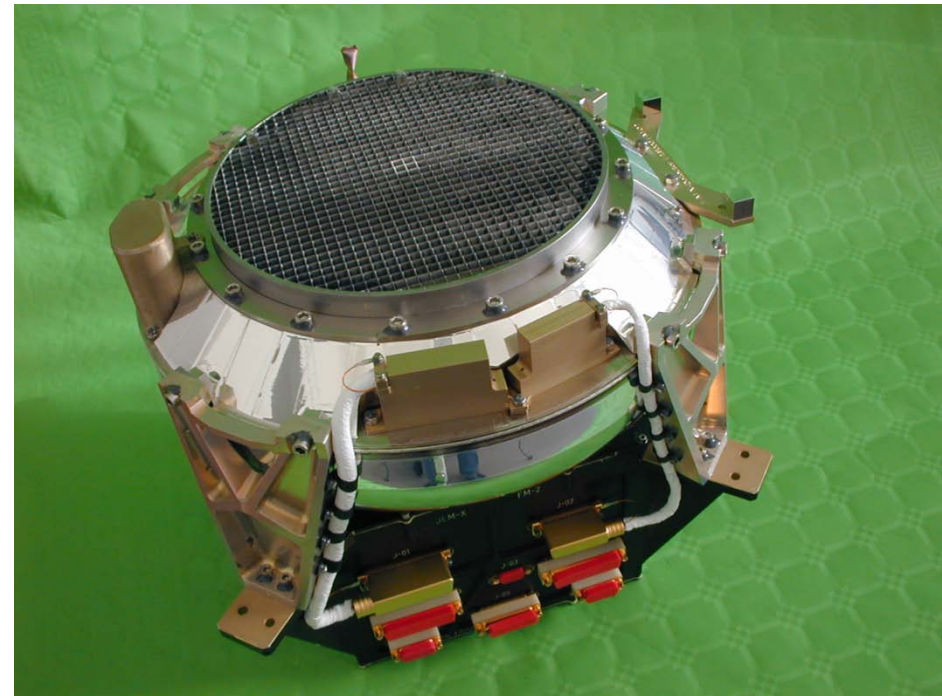
$$W_{\text{gas}} \sim 25 \text{ eV}$$

$$W_{\text{semi}} \sim 5 \text{ eV}$$

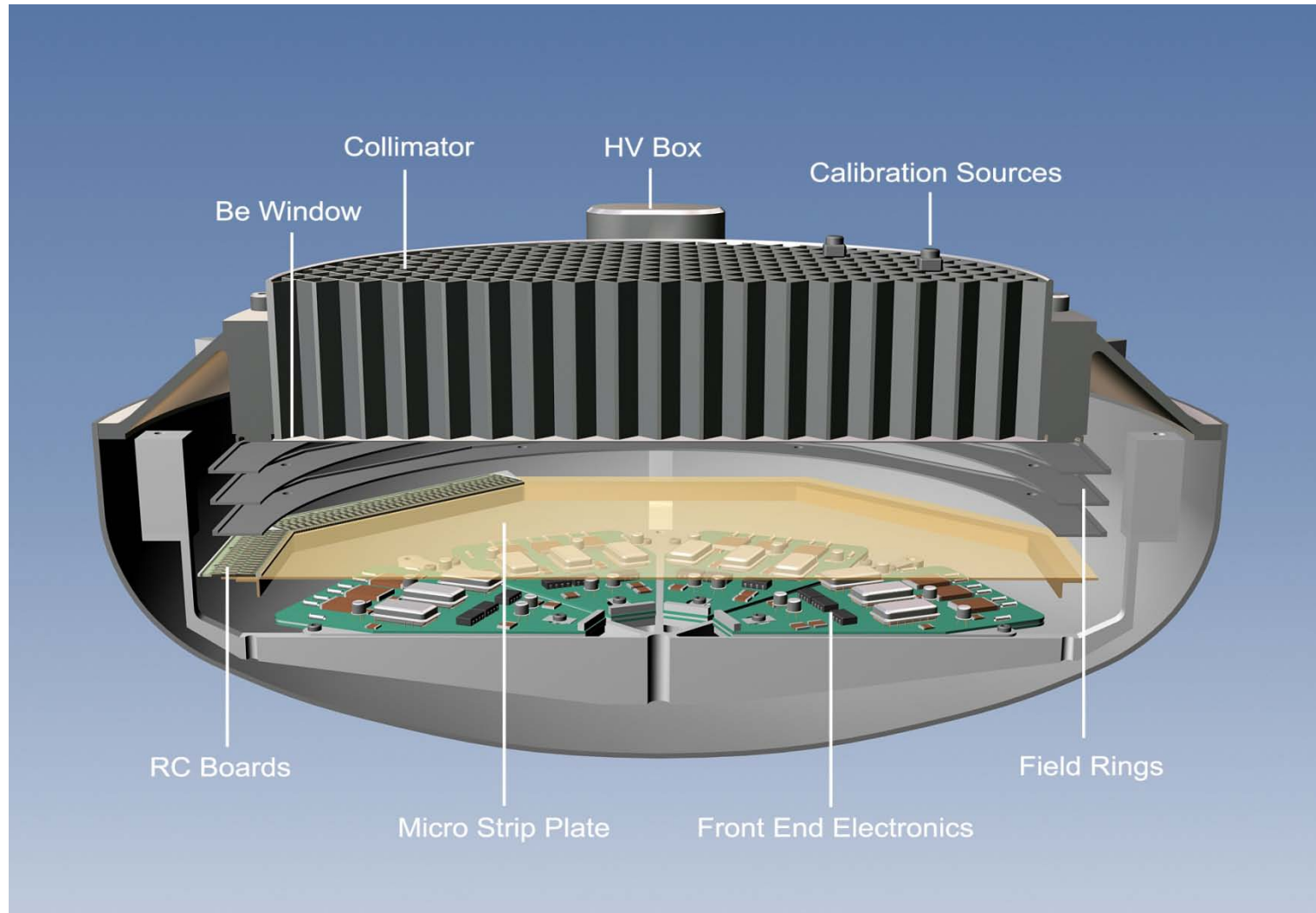




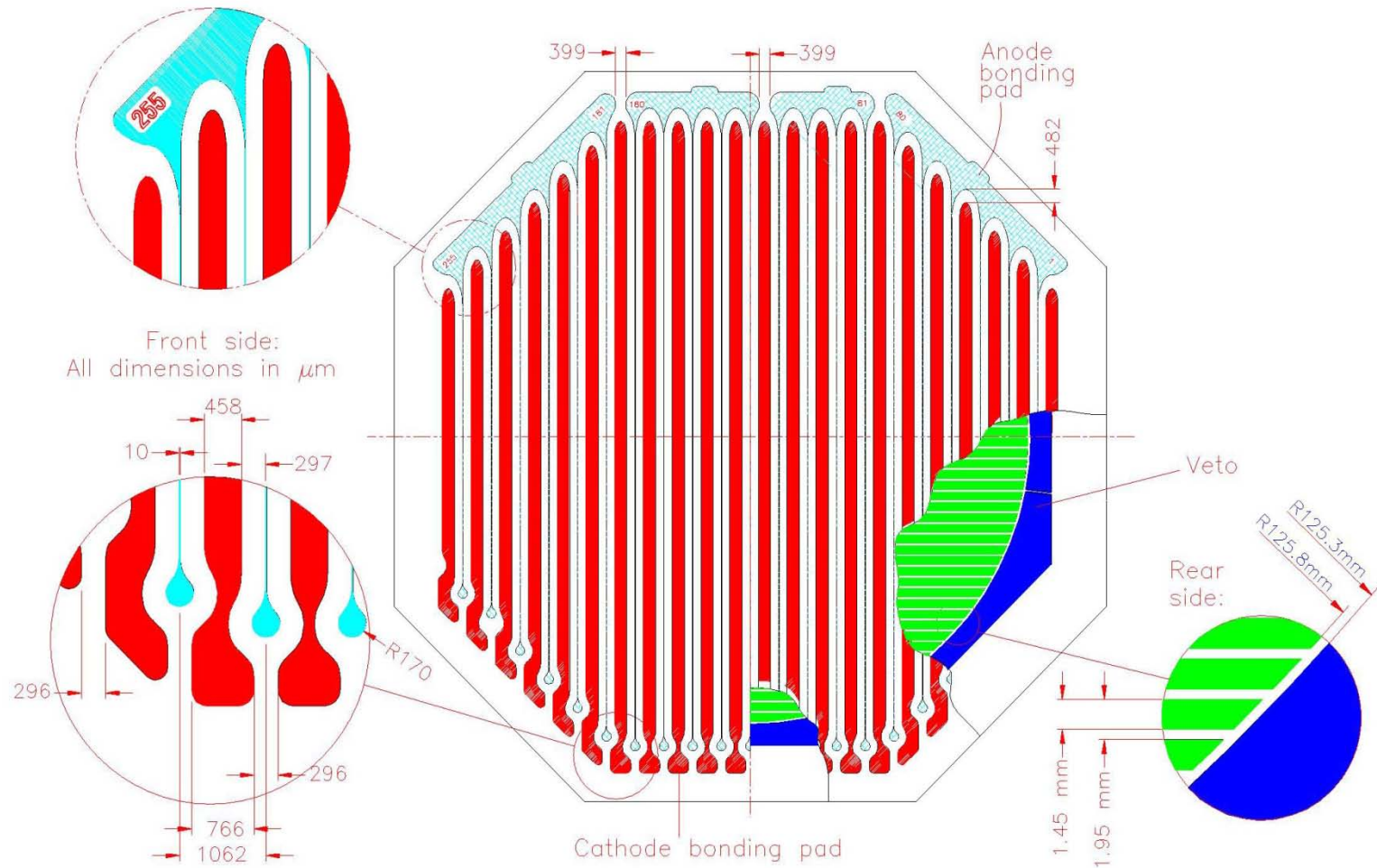
# JEM-X hardware



# The JEM-X Detector – a gas prop. counter

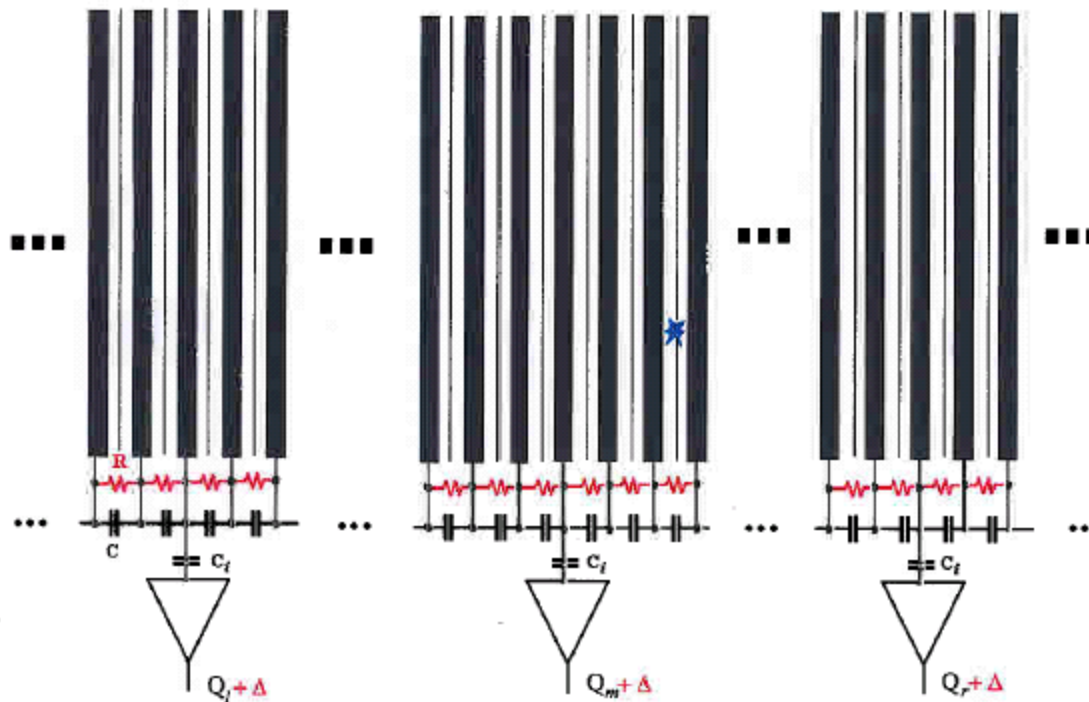


# JEM-X MS PLATE



# JEM-X Position Determination

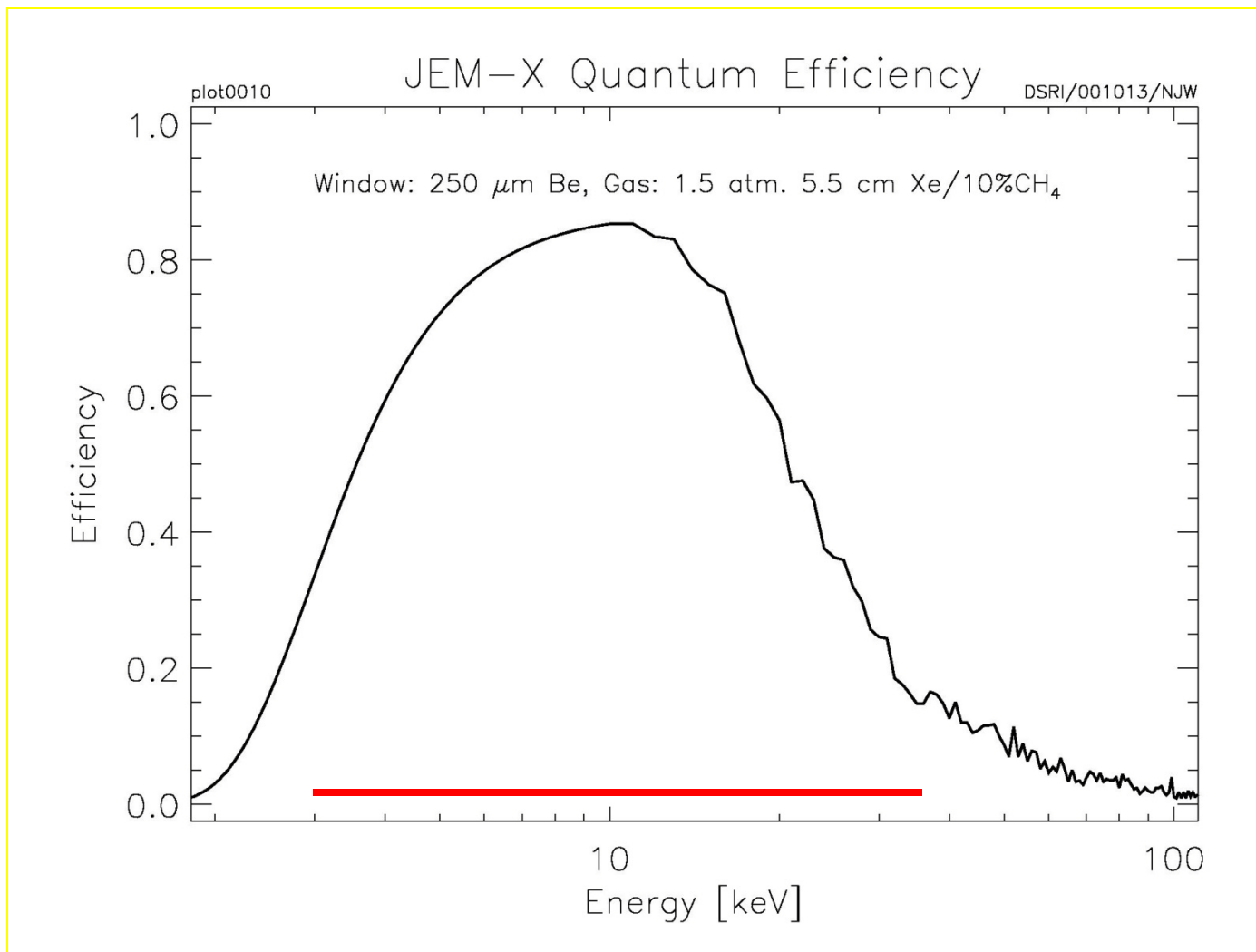
## Capacitive charge division readout



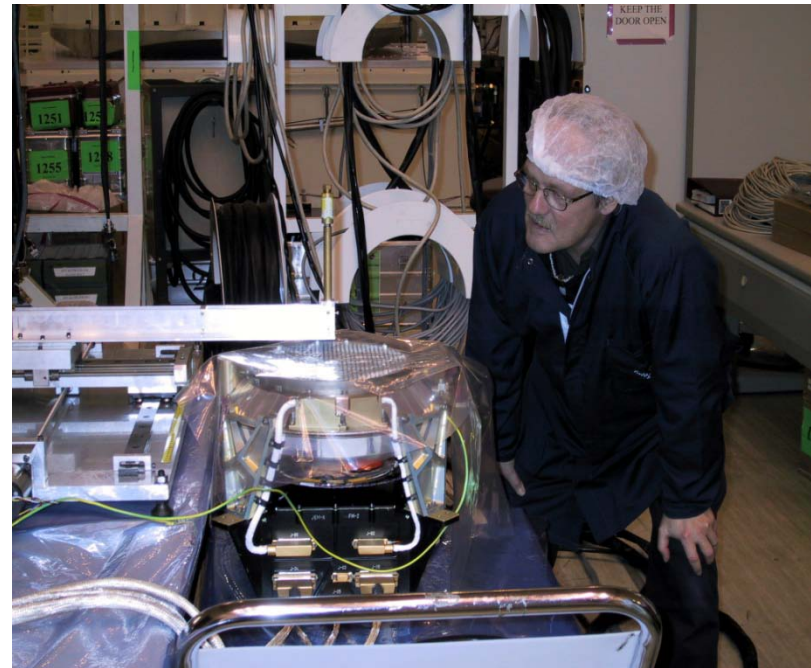
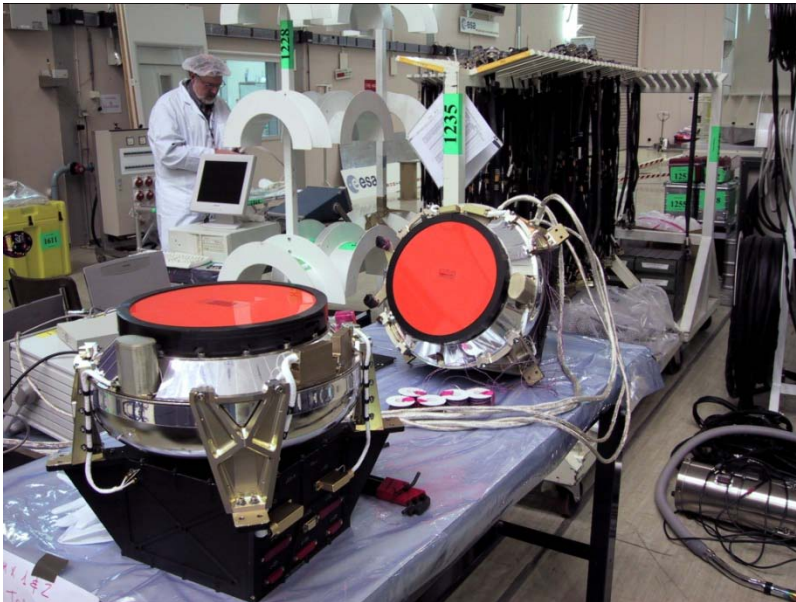
$$X_n = l_n \cdot \frac{(Q_r + \Delta) - (Q_i + \Delta)}{Q_i + Q_m + Q_r + 3 \cdot \Delta}$$



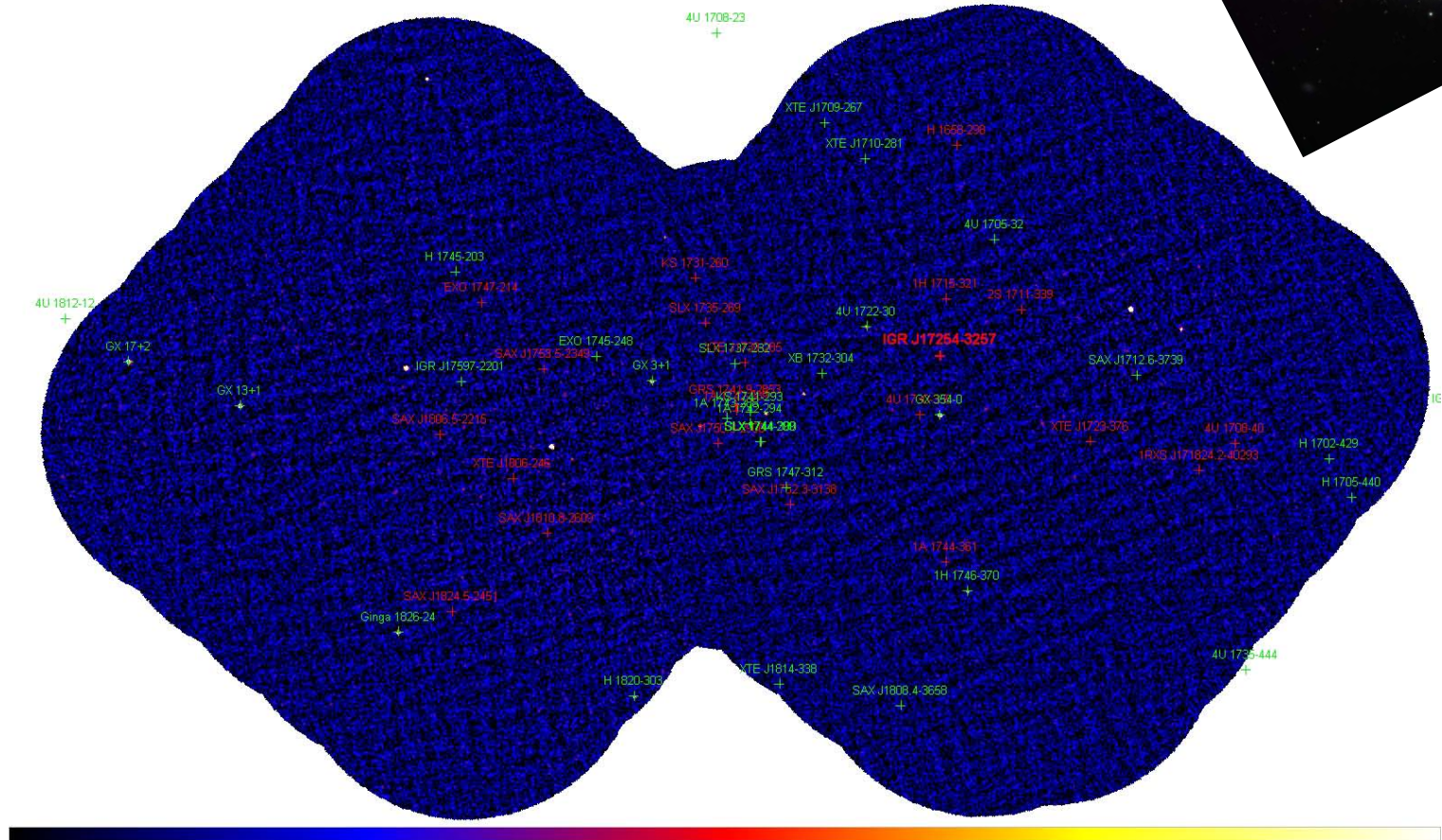
# JEM-X Quantum Efficiency



# JEM-X – The X-ray Monitor

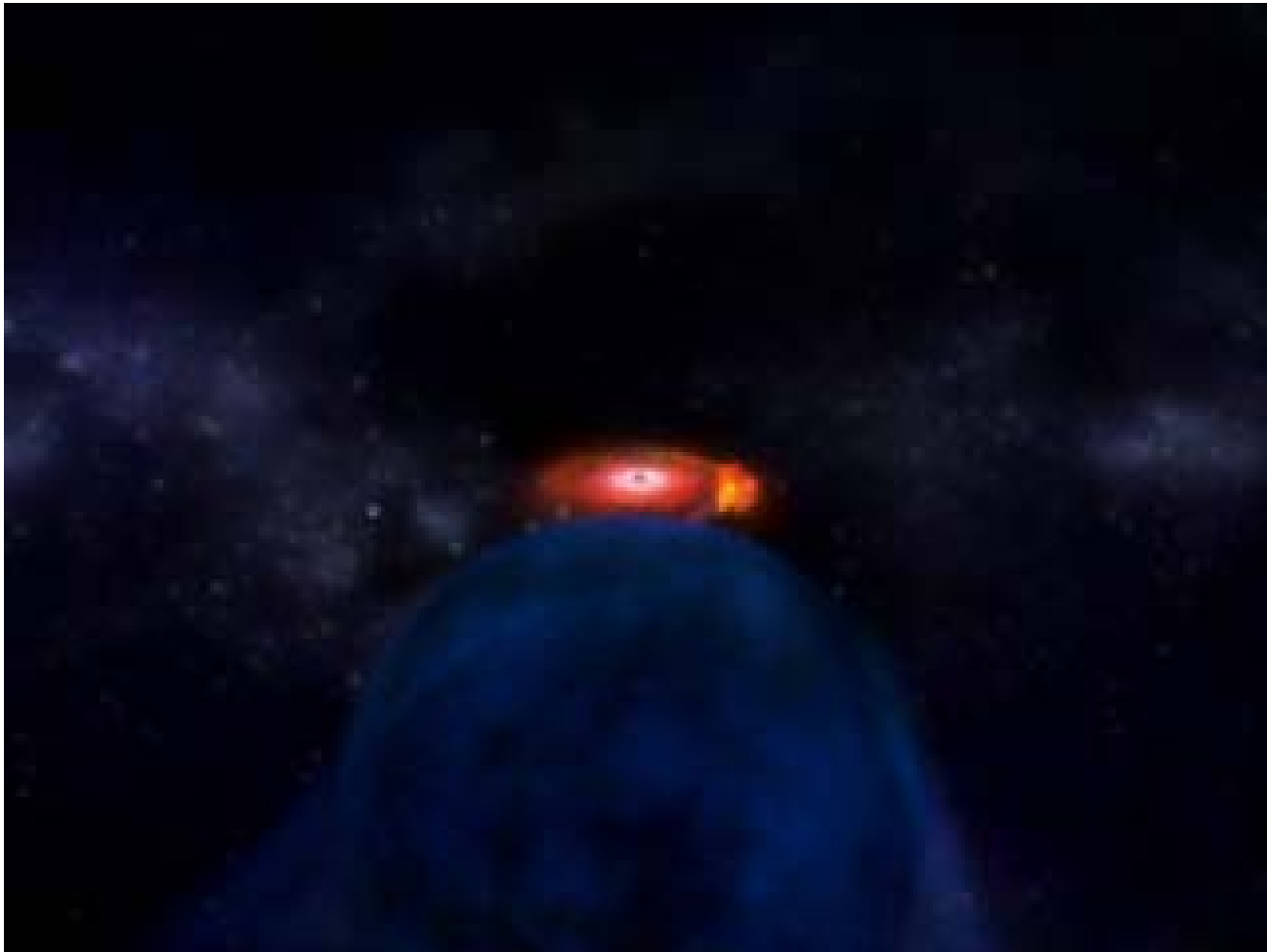


# X-ray bursters



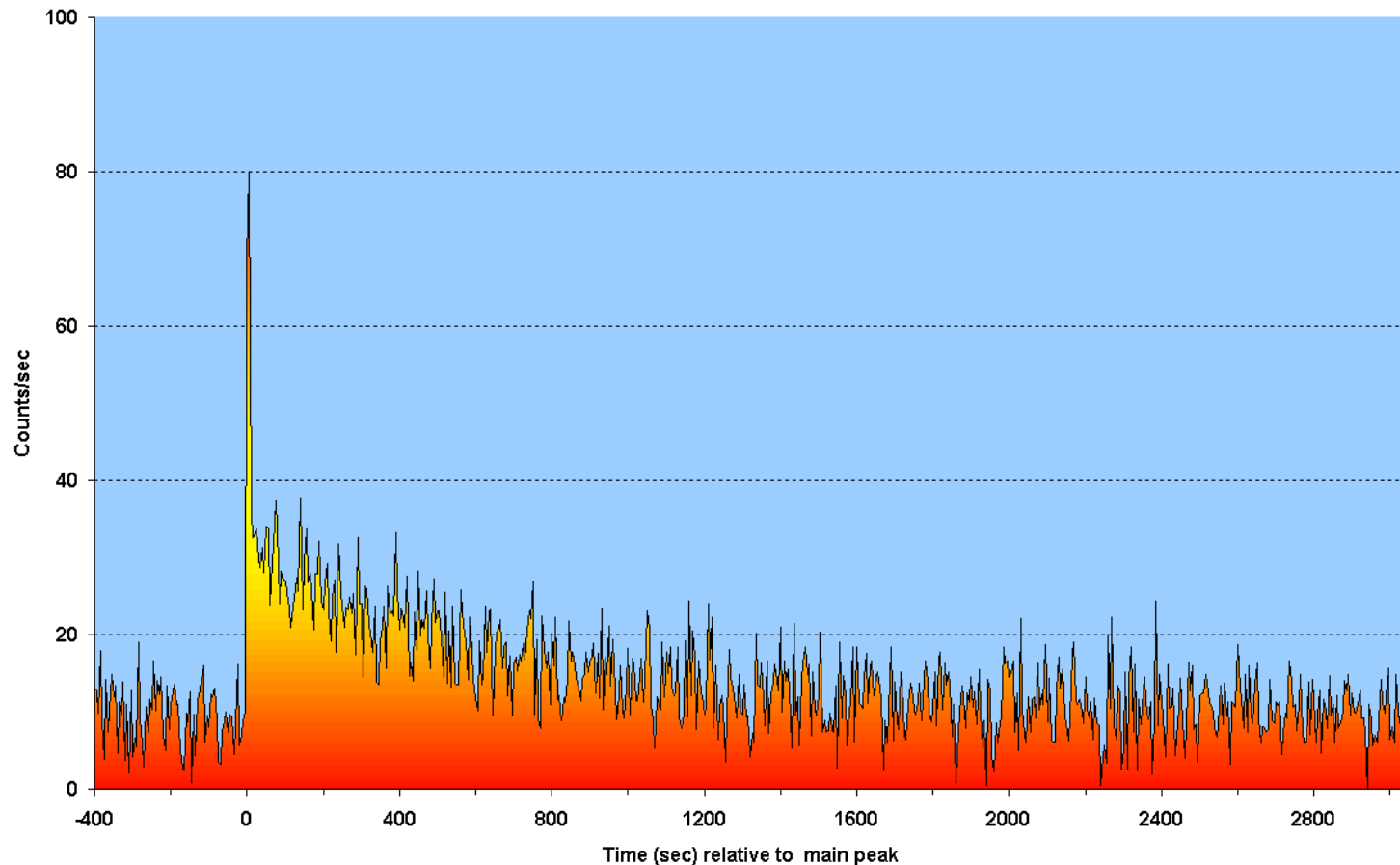
X-ray binaries in the GC region (include 48 bursters/ 86 known)

# An x-ray burster – a neutron star



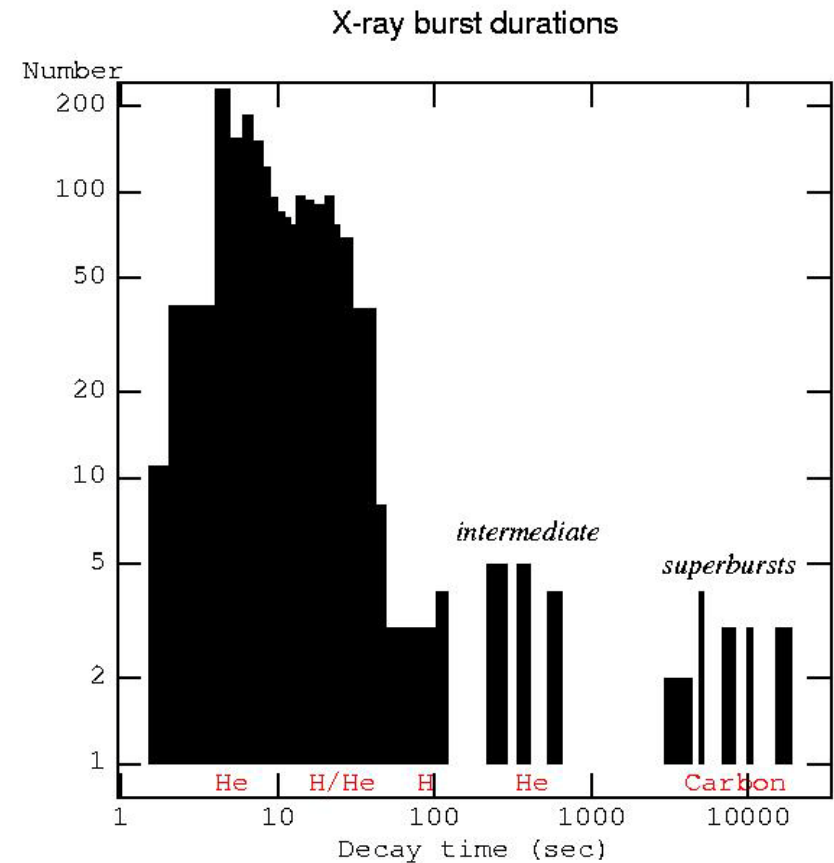
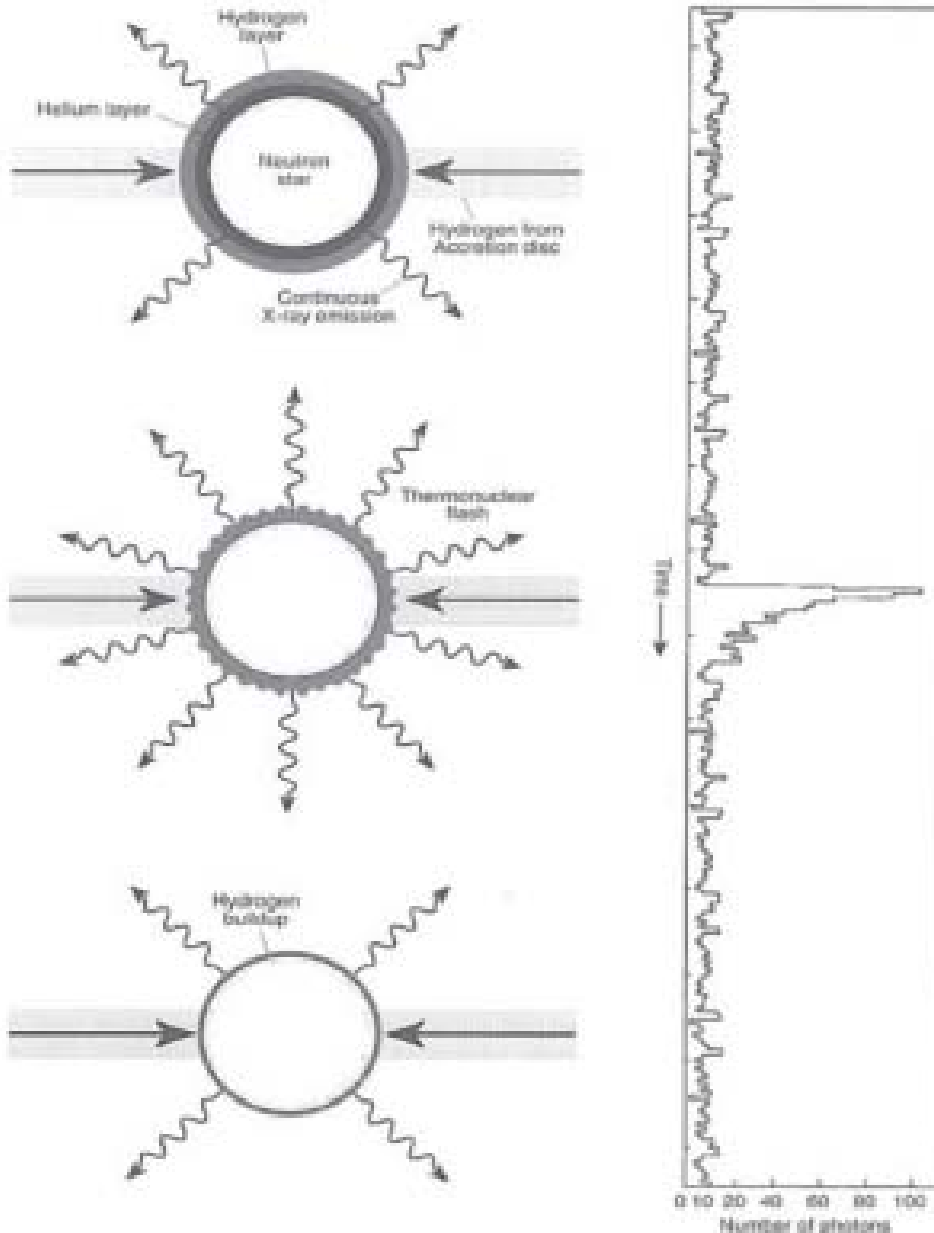


# Long X-ray burst from GX 3+1



Type I X-ray bursts are **thermonuclear explosions** in the surface layers of a neutron star accreting H and/or He from the envelope of a companion star. Their profile is characterized by a **fast rise** followed by an **exponential decay**. The emission is described by **blackbody radiation** with peak temperature  $\approx 2$  keV and X-ray softening (**cooling**) during the decay.

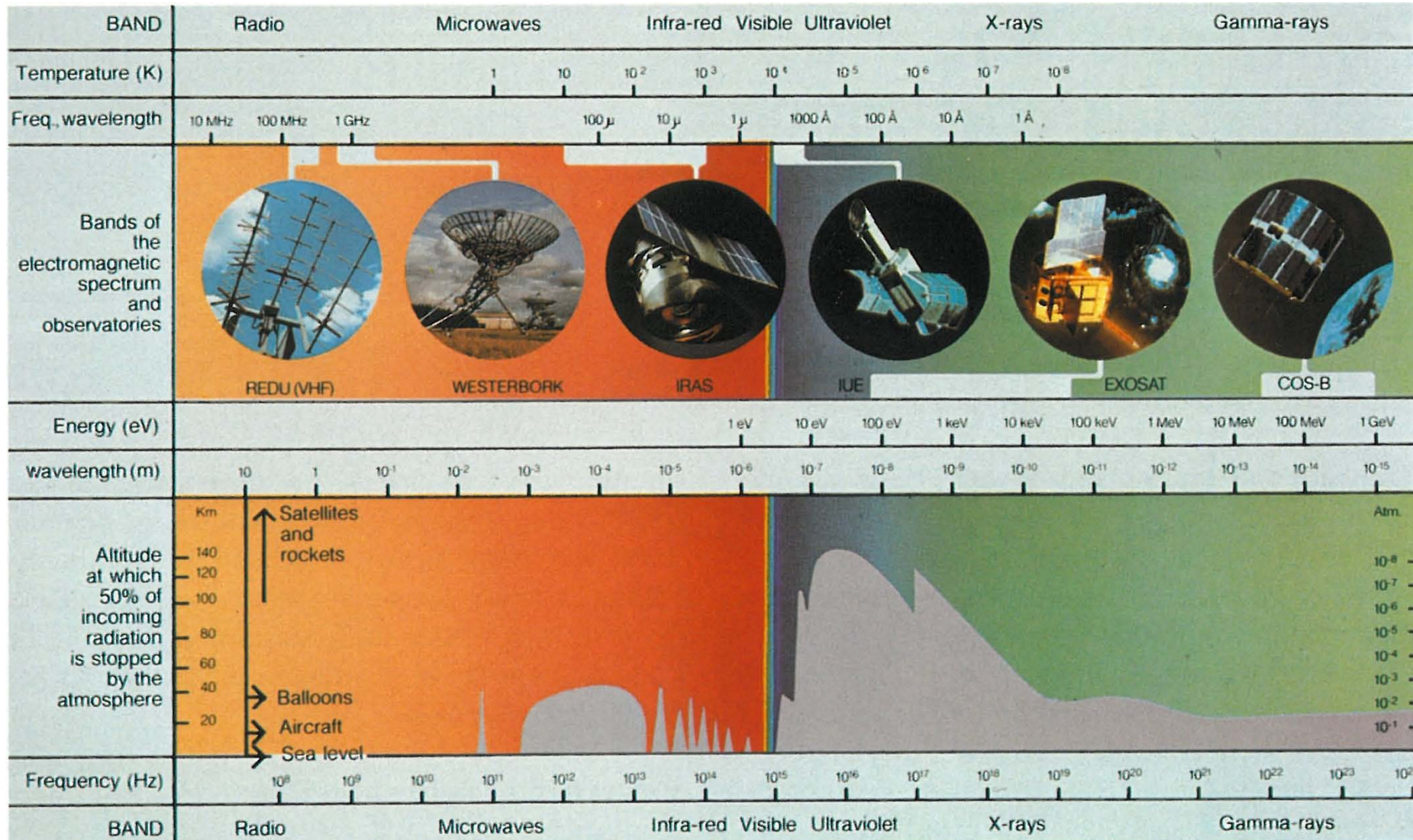
# X-ray burst mechanisms



**Break**

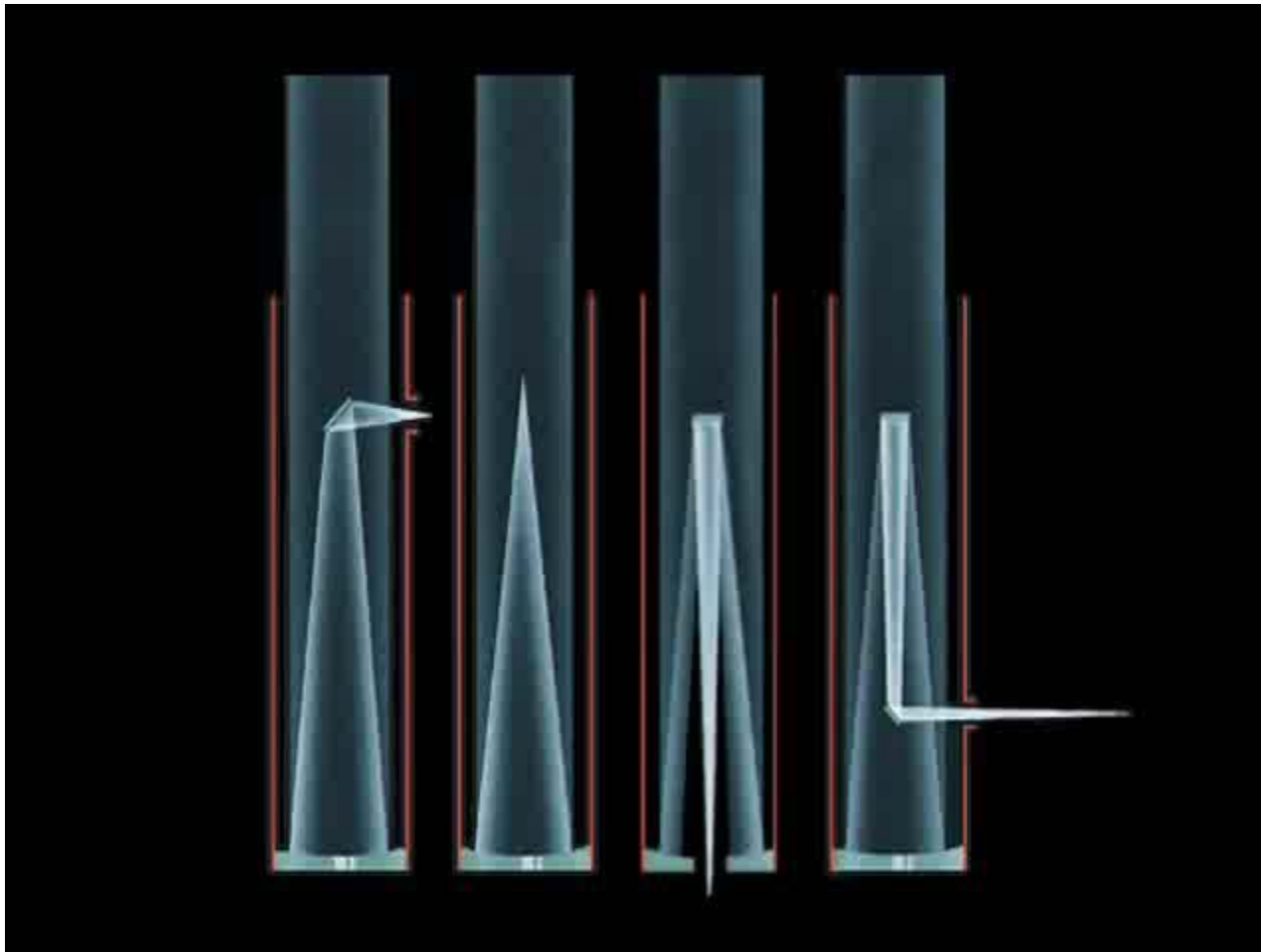


# Electromagnetic Spectrum

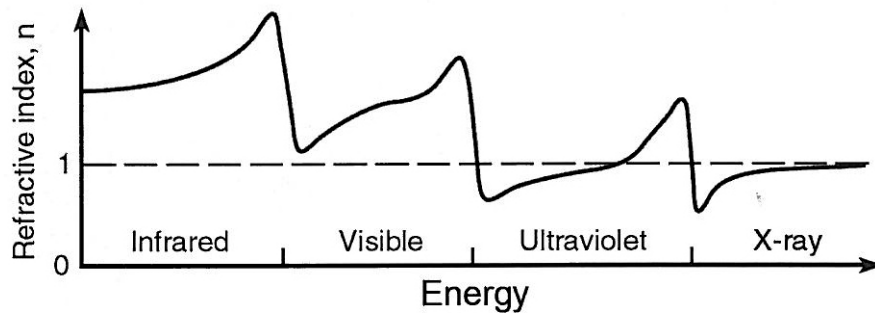




# Ordinary Telescopes – the typical version



# X-ray Telescopes – the typical version

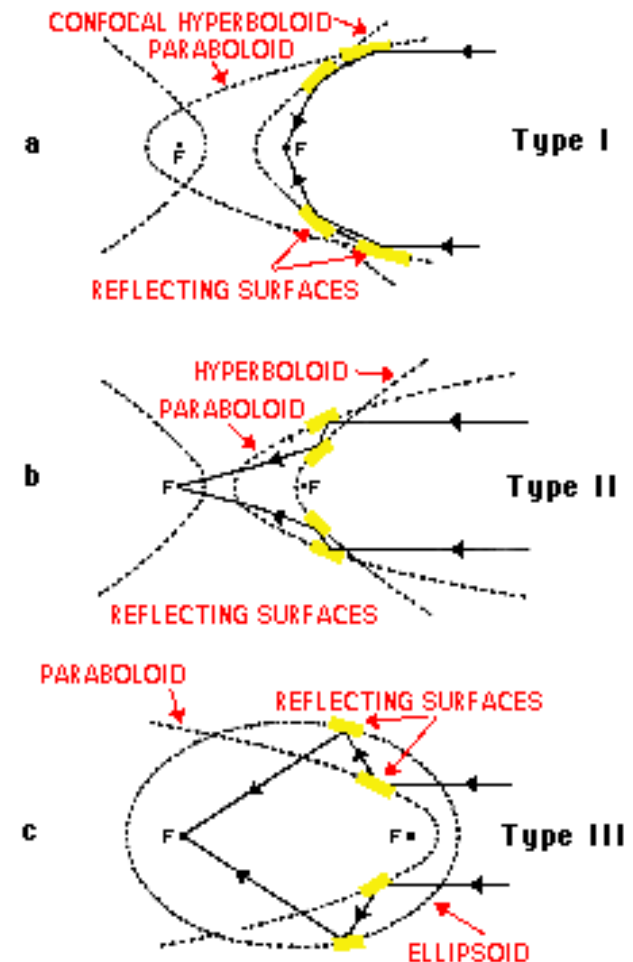


*Refractive index as function of energy*

$$V = c/n$$

But there is a difference between phase velocity and group velocity – so not a violation of relativity

*Wolter telescopes*



# X-ray Telescopes – the typical version

Definition of refractive index:

$n^2 = \varepsilon$  (is a complex number)

$n = 1 - \delta - i\beta$

$\beta = \mu \lambda / 4 \pi$

$\delta = 1/2 \pi e^2 / mc^2 N_A / A Z \rho \lambda^2$

Good constants to know:

Au – density:  $19.3 \text{ g/cm}^3$

Au – Z : 79

Au – A : 196.967

$N_A = 6.0221415 \cdot 10^{23}$

$e^2 / mc^2 = 2.8179403 \cdot 10^{-13} \text{ cm}$

$\cos(\theta_c) = 1 - \delta$

$\theta_c = \text{SQRT}(2\delta)$

Example:

Calculate the total reflection angle for a 6keV X-ray radiation hitting a Au-coated surface.

# Conversion between Å and eV:

collisions is emission of a continuum of X-rays over a wide wavelength range. This continuous radiation is called *bremsstrahlung* or *white radiation*.

When all the energy of the impinging electrons is turned into X-rays, as would occur if the electrons transferred all their energy in one collision, the wavelength of the emitted photons is the shortest attainable. This is termed the minimum  $\lambda$  or  $\lambda_{\min}$ . The radiation with the highest energy (and therefore the shortest wavelength) is deduced as follows. When all the energy of the electrons is converted to radiant energy, then the energy of the electrons equals the energy of the radiation. The energy of the radiation is given by  $E = h\nu$ , whereas the energy of the electrons is given by  $E = eV$ . When they are equal,  $h\nu = eV$ , where  $e$  is the charge of the electron;  $V$ , the applied voltage; and  $\nu$ , the frequency of the radiation. But:

$$\nu = \frac{c}{\lambda}$$

where  $c$  is the speed of light and  $\lambda$  is the wavelength of radiation. Therefore,

$$h\nu = \frac{hc}{\lambda} = eV \quad (8.3)$$

Rearranging, we get

$$\lambda = \frac{hc}{eV} \quad (8.4)$$

When all the energy of the electron is converted to x-radiation, the wavelength of the radiation is a minimum and we achieve minimum  $\lambda$  conditions:

$$\lambda_{\min} = \frac{hc}{eV} \quad (8.5)$$

Inserting the values for  $h$ ,  $c$ , and  $e$ , which are constants, we have the **Duane–Hunt Law**,

$$\lambda_{\min} = \frac{(6.626 \times 10^{-34} \text{ J s})(3.00 \times 10^8 \text{ m/s})(10^{10} \text{ Å/m})}{(1.60 \times 10^{-19} \text{ C}) \times V} = \frac{12,400}{V} \quad (8.6)$$

where  $h$  is Planck's constant;  $c$ , the speed of light;  $e$ , the charge of an electron;  $V$ , the applied voltage (in volts); and  $\lambda_{\min}$ , the shortest wavelength of X-rays radiated (in angstroms). The continuum radiation spectrum from a solid metal therefore has a well-defined short wavelength limit. This limit is a function of the accelerating voltage, but not of the solid metal. The same  $\lambda_{\min}$  would be obtained by bombardment of lead or tungsten or rhodium at the same accelerating voltage.

The Duane–Hunt Law gives the conversion factor between energy and wavelength. Most X-ray systems express wavelength in angstroms and energy in keV. To convert between these units, Eq. (8.6) gives:

$$\text{Energy (keV)} = \frac{12.4}{\lambda (\text{Å})} \quad (8.7)$$

An X-ray emission spectrum is similar for all elements, in that  $K_{\alpha}$ ,  $K_{\beta}$ ,  $L_{\alpha}$ , and  $L_{\beta}$  lines may be seen, if the element possesses enough electrons to populate the appropriate levels. However, the actual wavelengths of these lines vary from one element to



# X-ray Telescopes – the typical version

Definition of refractive index:

$n^2 = \varepsilon$  (is a complex number)

$n = 1 - \delta - i\beta$

$\beta = \mu \lambda / 4\pi$

$\delta = 1/2\pi \frac{e^2}{mc^2} \frac{N_A}{A} Z\rho\lambda^2$

Good constants to know:

Au – density:  $19.3 \text{ g/cm}^3$

Au – Z : 79

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$N_A = 6.0221415 \cdot 10^{23}$

$e^2/mc^2 = 2.8179403 \cdot 10^{-13} \text{ cm}$

Energy(keV) =  $12.398 / \lambda(\text{\AA})$

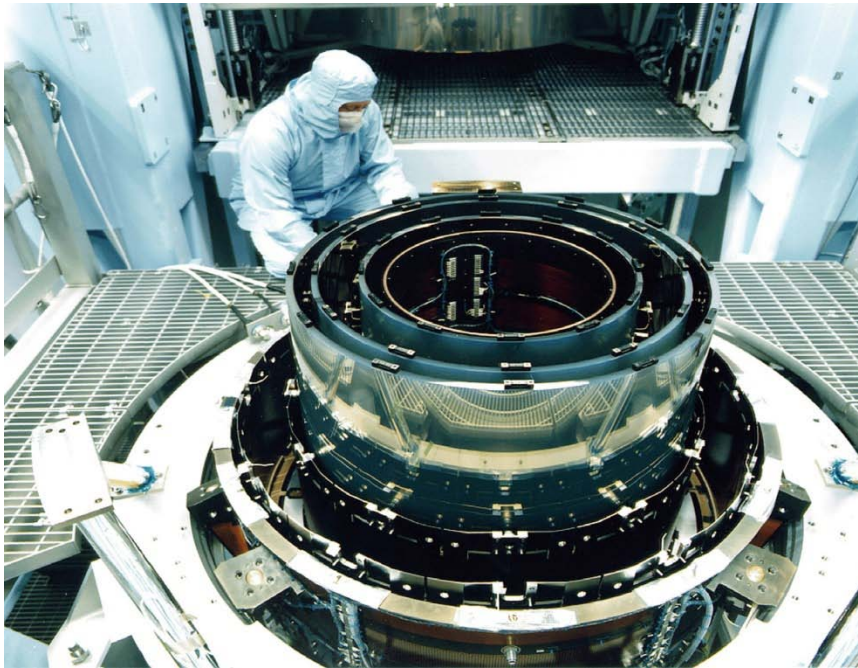
$\cos(\theta_c) = 1 - \delta$

$\theta_c = \text{SQRT}(2\delta)$

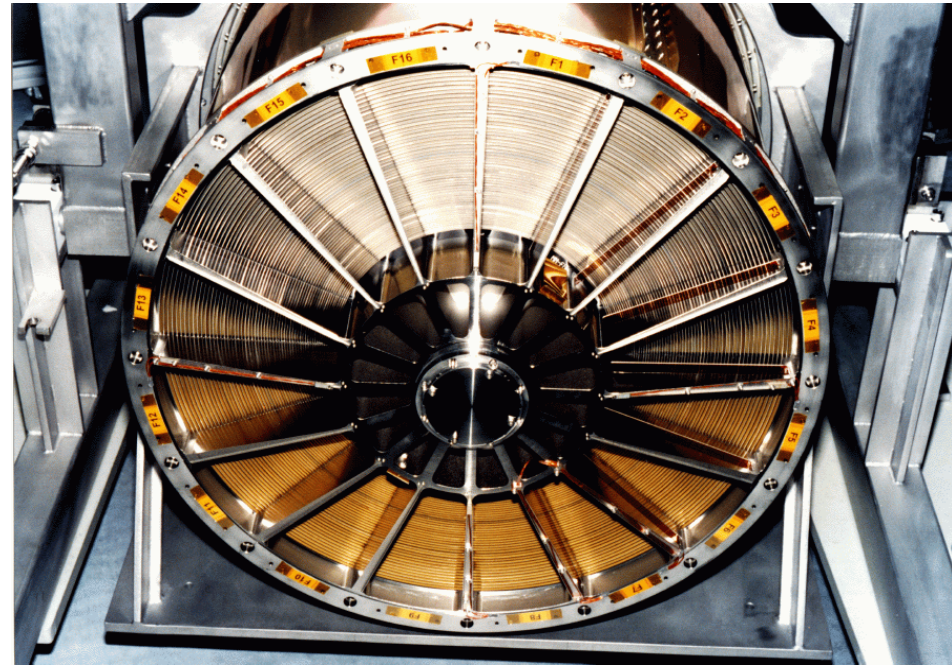
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# X-ray Telescopes – the typical version



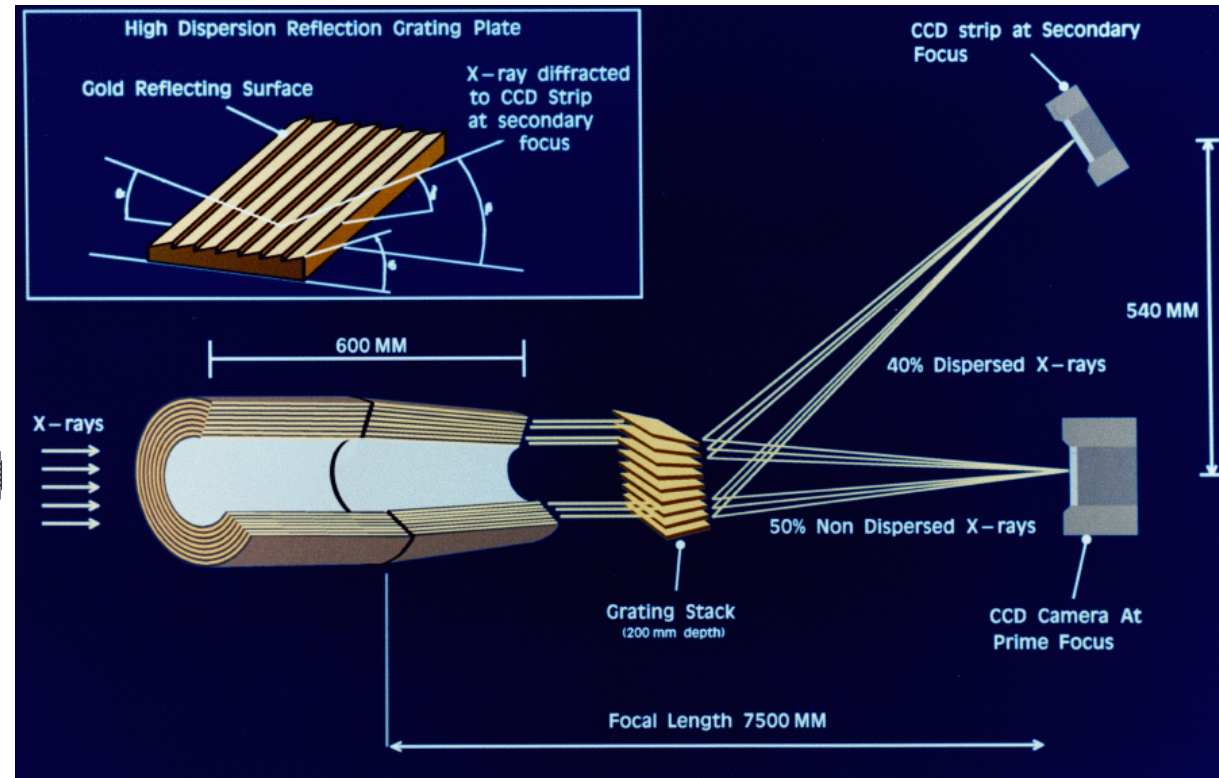
CHANDRA



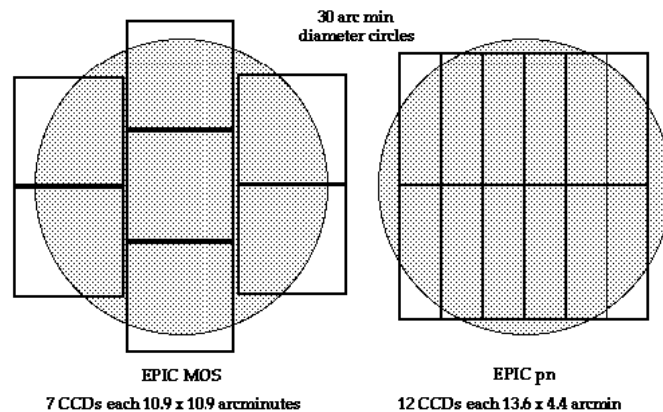
XMM

# X-ray Telescopes – the typical version

## XMM-Newton



Comparison of focal plane organisation of EPIC MOS and pn cameras

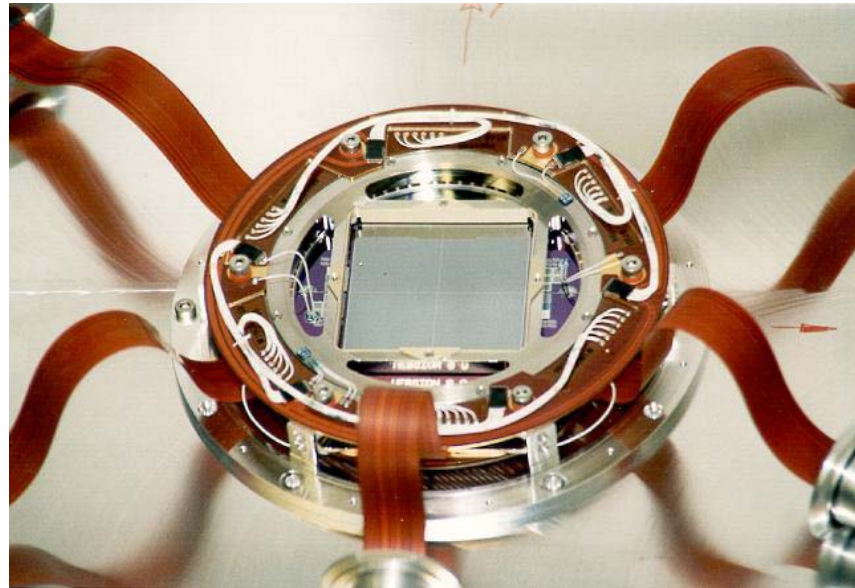




# Si based CCD in Space: XMM- NEWTON and CHANDRA



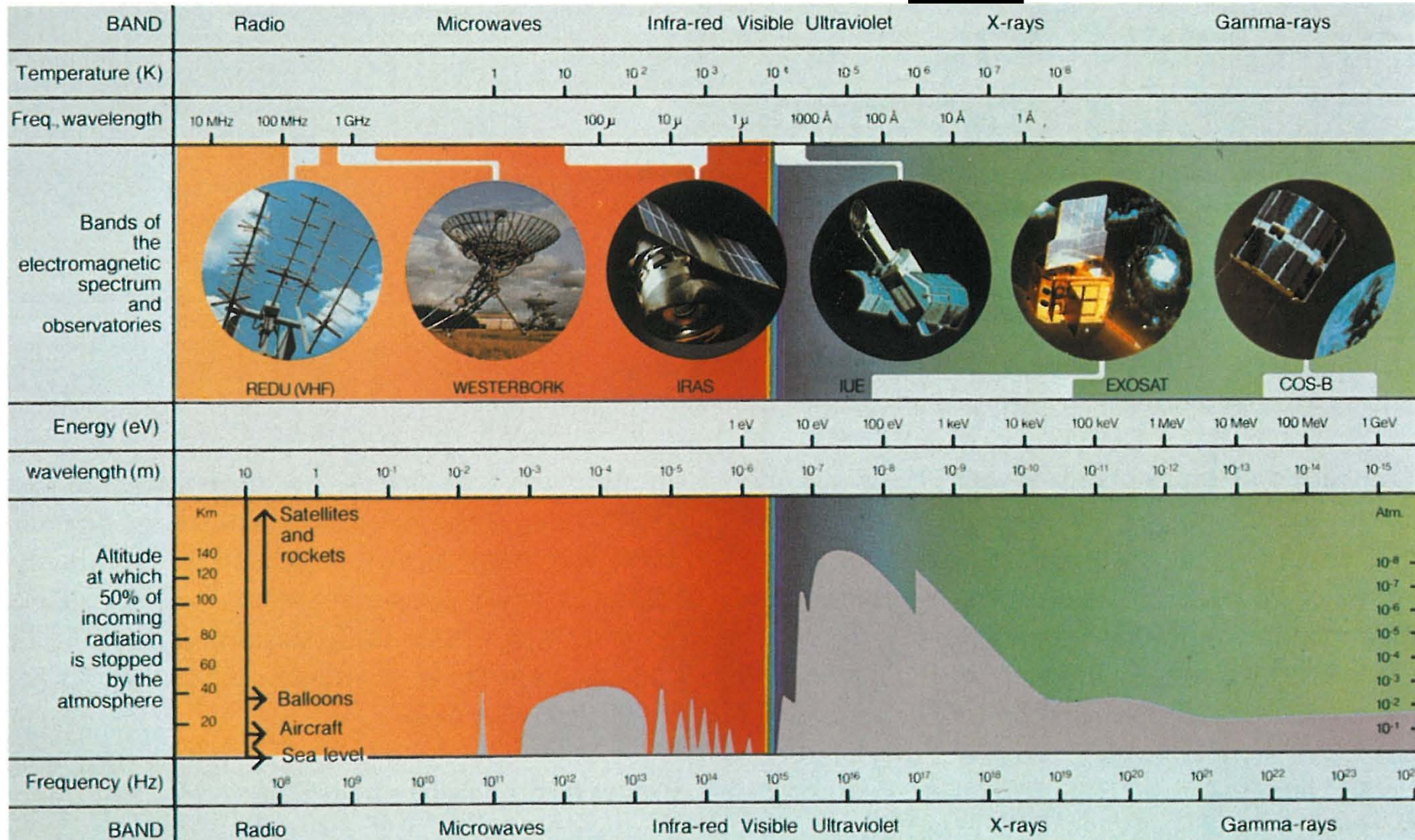
XMM-NEWTON



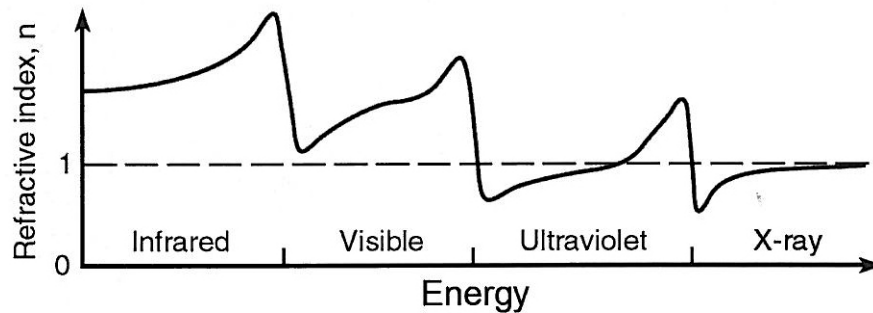
EPIC Focal Detector



# Electromagnetic Spectrum



# Focusing high energies



$$n = \sqrt{1 - \delta}$$

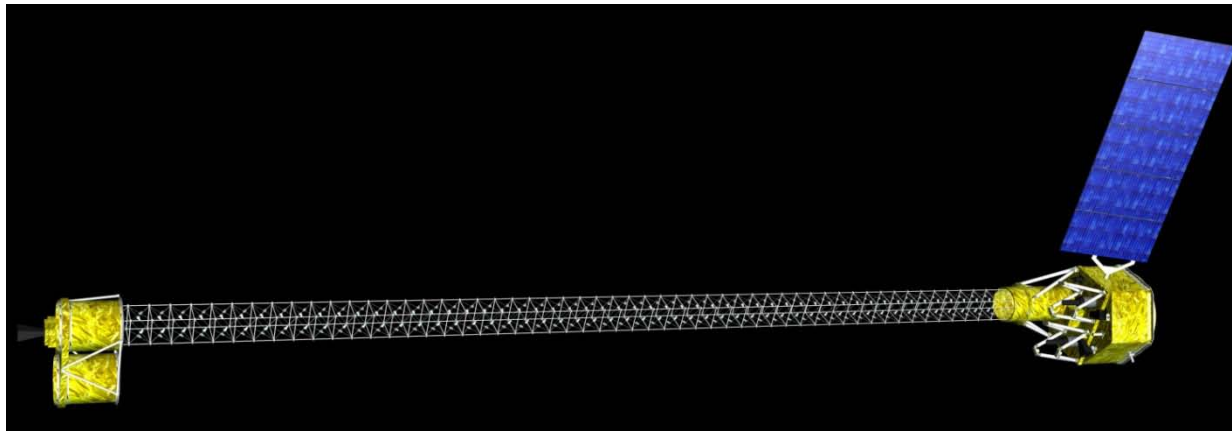
$$\delta = \frac{1}{2} \pi \frac{e^2}{mc^2} \frac{N_A}{A} Z \rho \lambda^2$$

$$\lambda(\text{\AA}) = 12.398/E(\text{keV})$$

i.e.

It gets more and more difficult to reflect the X-rays using total reflection, the more energetic they are...

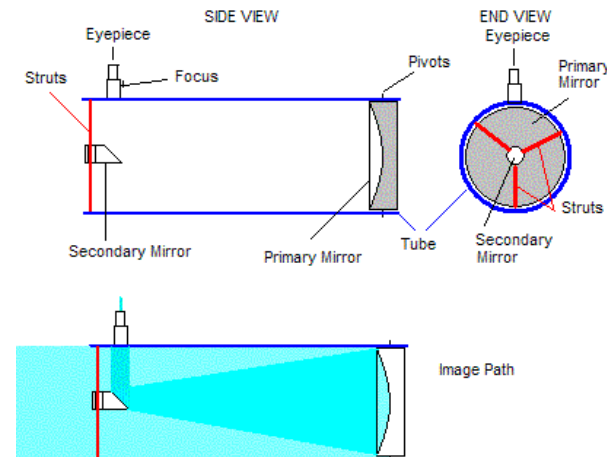
# NuSTAR – launch in 2011



Special coating of the mirrors allow for focusing of high energy radiation

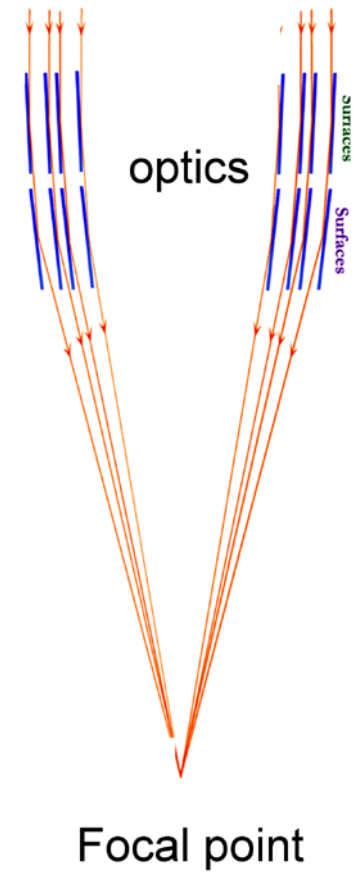
May be used to

- close-up studies of e.g. black holes
- Examination of galaxies and – clusters outside of the traditional energy ranges

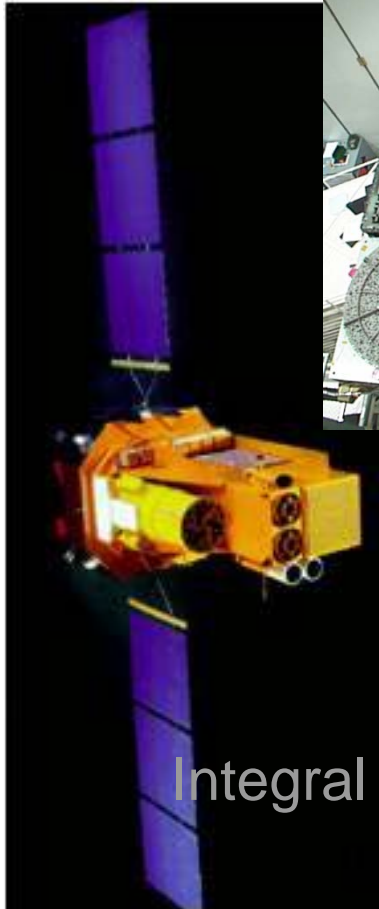


*Optical telescope*

*X-ray telescope*

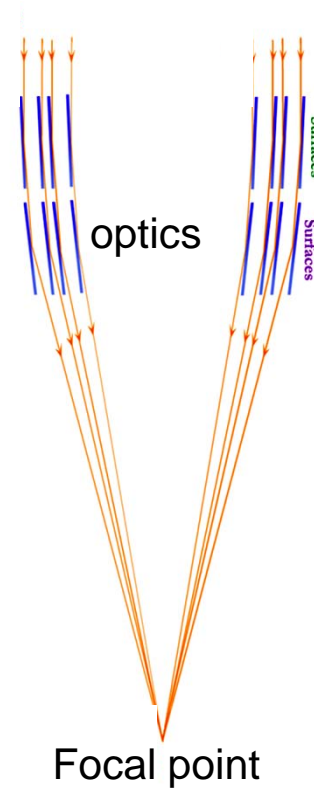


# NuSTAR's breakthrough is due to first use of focusing in the hard X-ray band

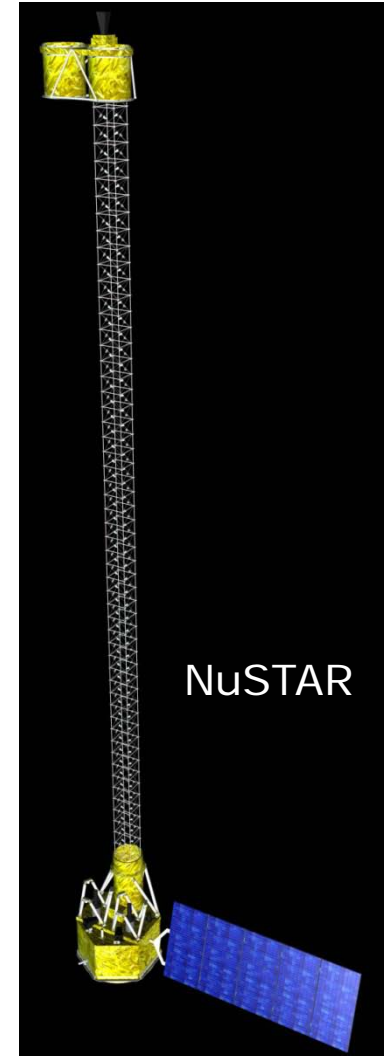


Integral

Pinhole camera



Focusing telescope

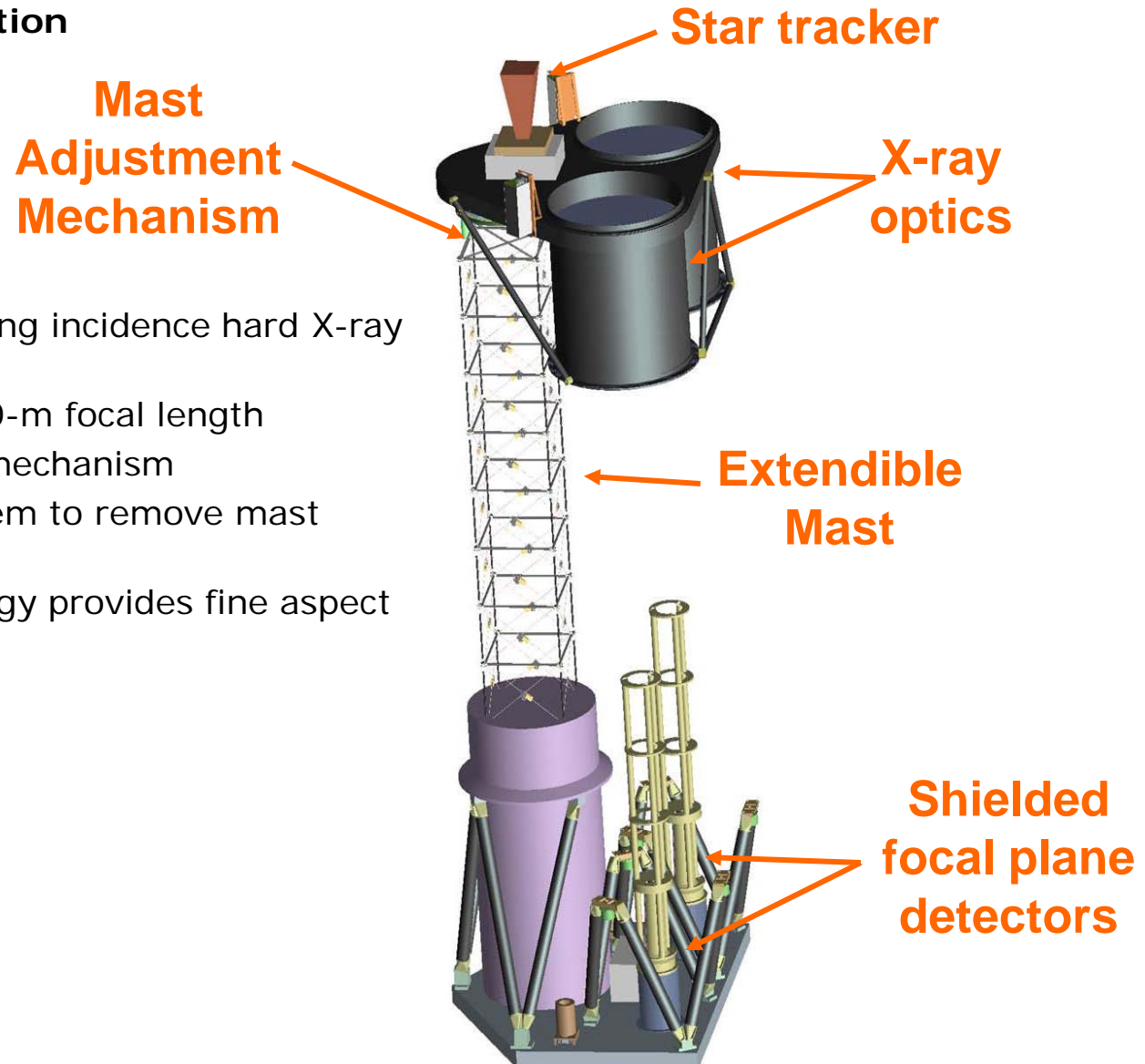


NuSTAR

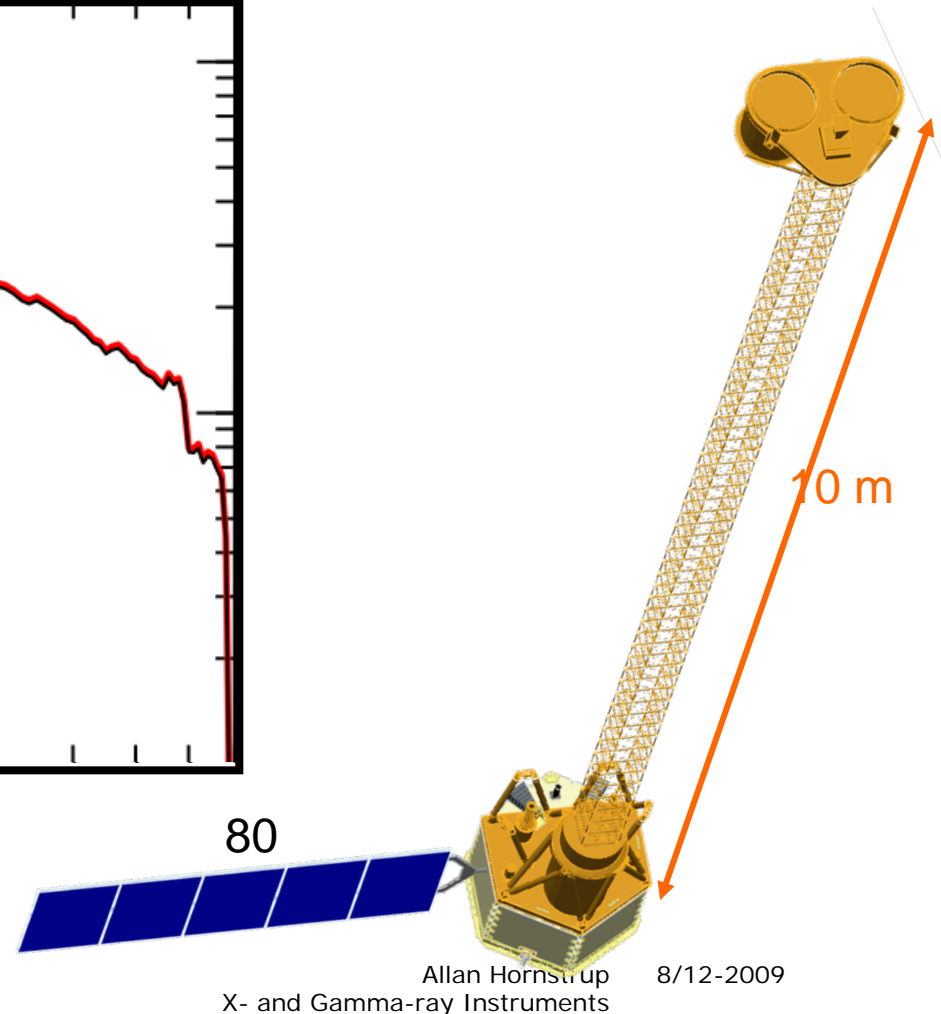
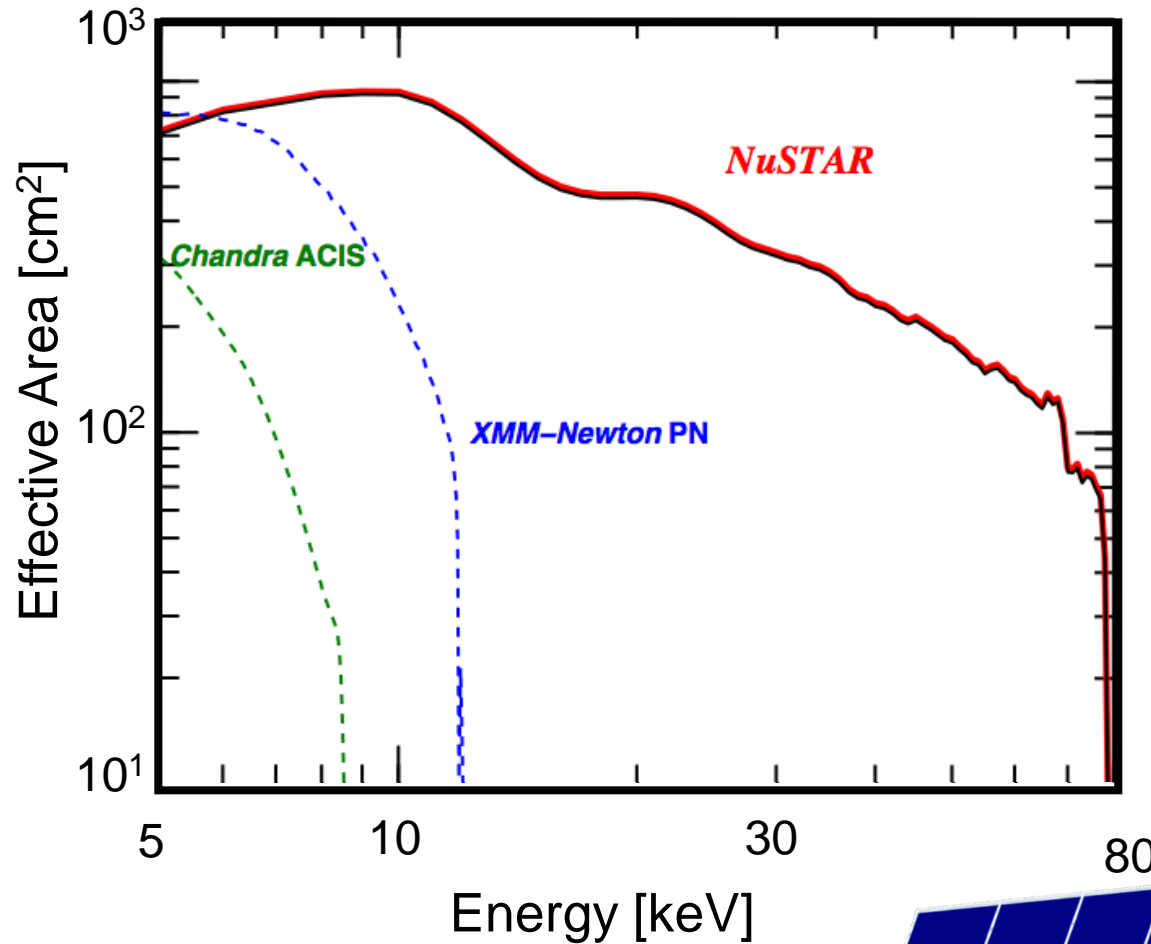


## NuSTAR Payload Description

- Two identical coaligned grazing incidence hard X-ray telescopes
- Extendable mast provides 10-m focal length
  - Single-use adjustment mechanism
- Simple laser metrology system to remove mast flexure
- Star camera head + metrology provides fine aspect

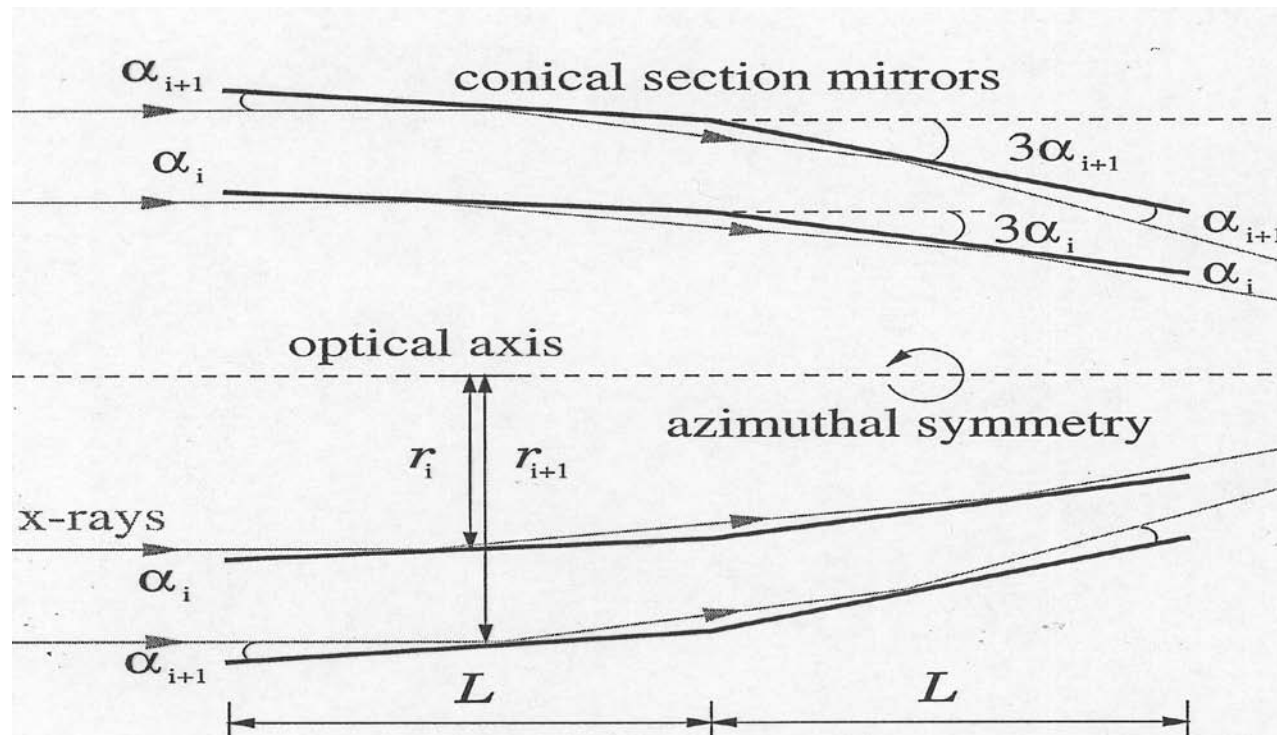


# NuSTAR extends focusing to high X-ray energies beyond Chandra & XMM



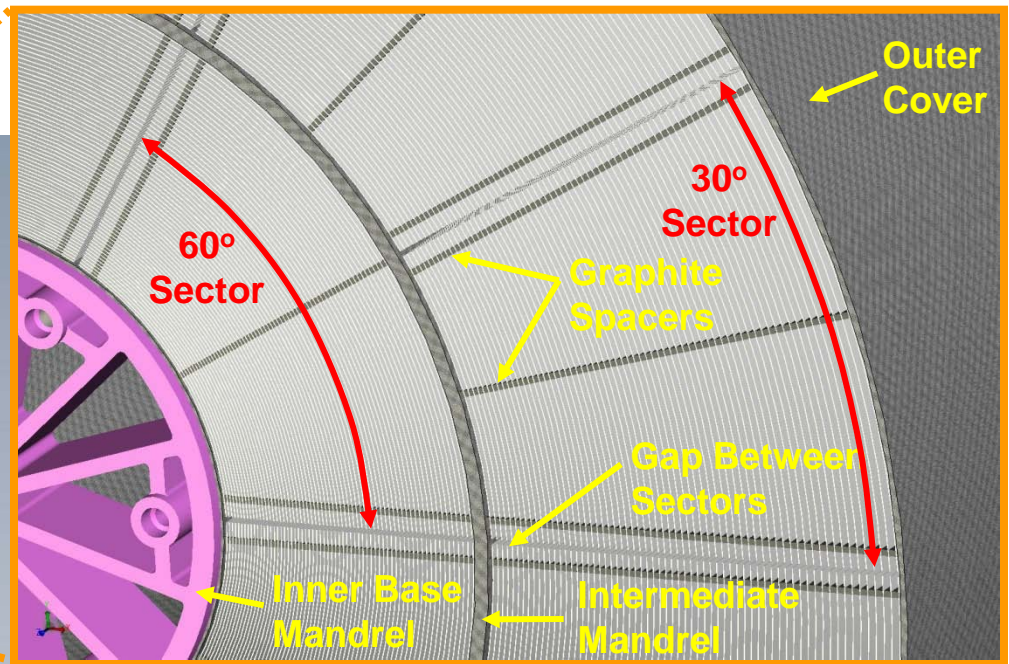
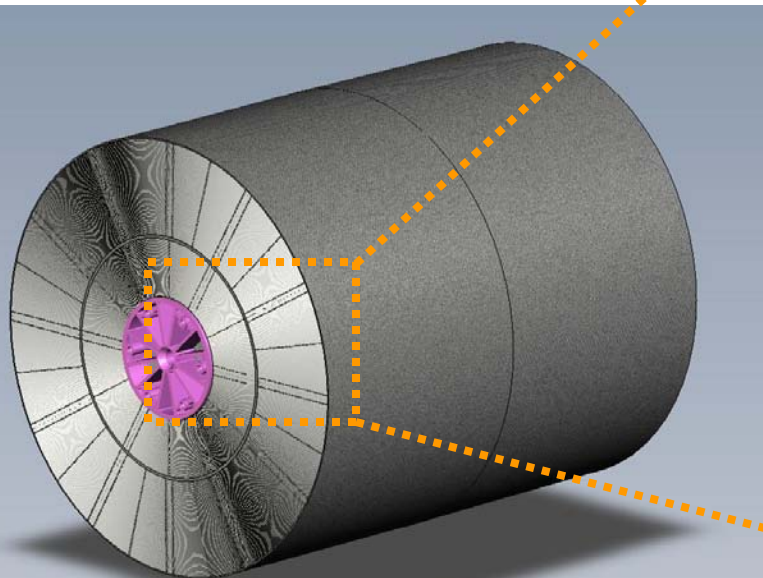
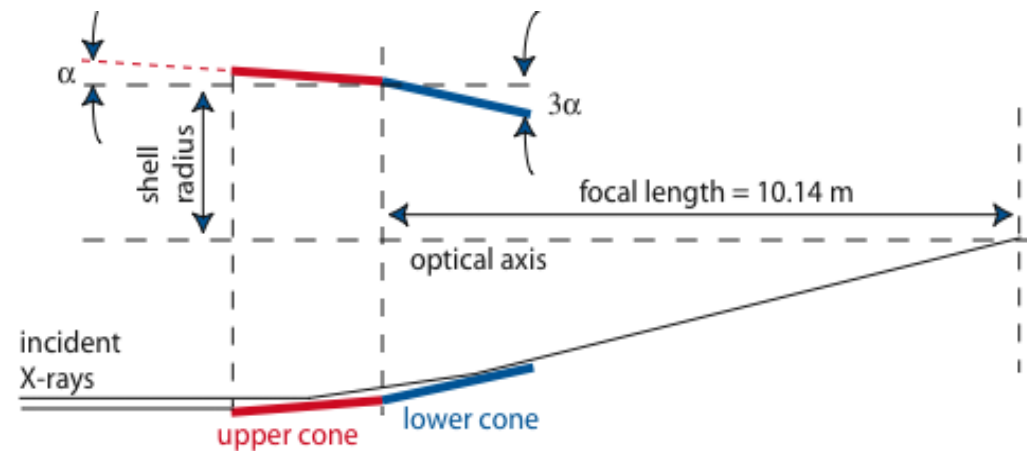
# X-Ray Telescope

Conical Approximation to Wolter I geometry  
Hyperboloid and paraboloid



Each NuSTAR optic will be made of 130 conic approximation Wolter-I shells

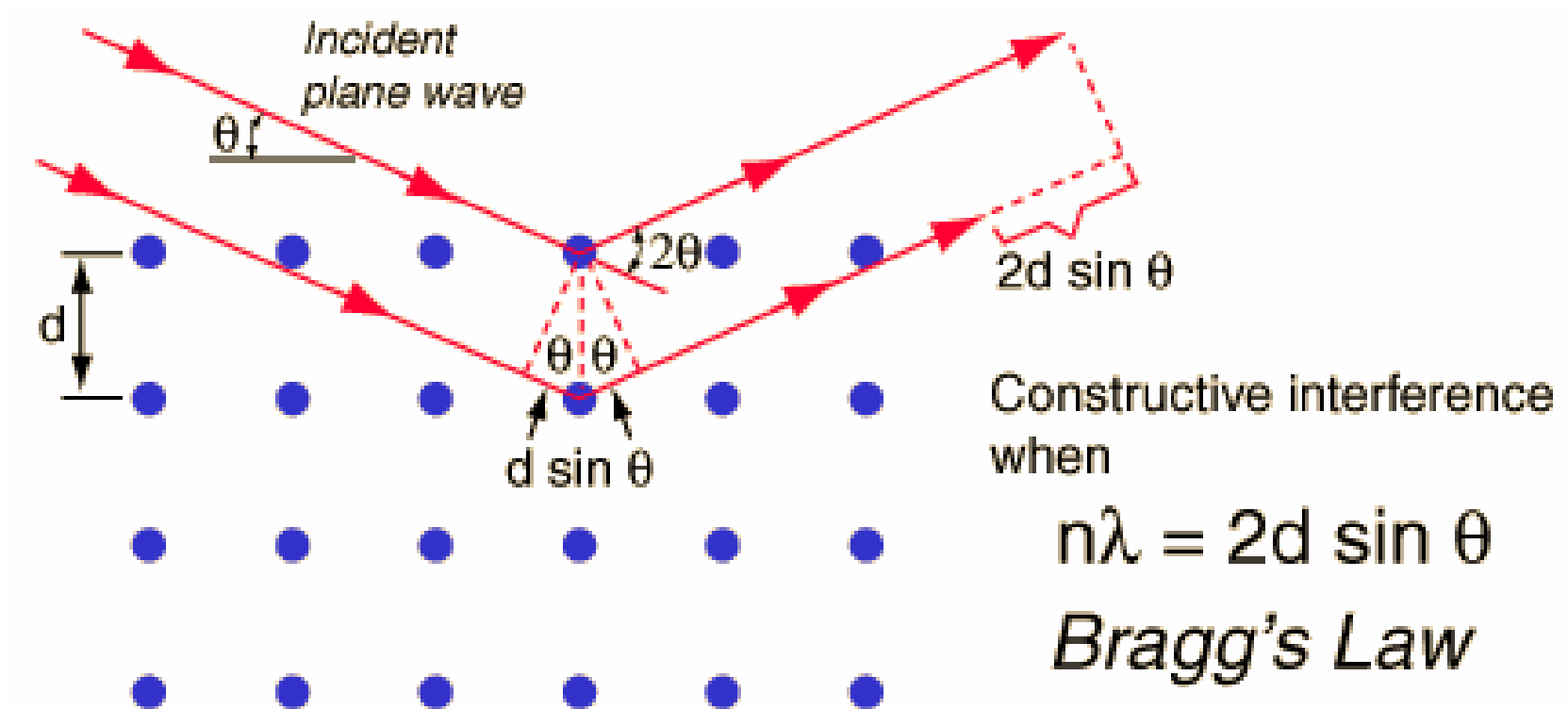
Parameter	Value
FocalLength	10.14 m
Shell Radii	54-191 mm
Graze Angles	1.3-4.7 mrad
Shell Length	225 mm
Mirror Thickness	0.2 mm
HPD Performance	40"
Total Shells Per Module	130
Total Mirror Segments	4680



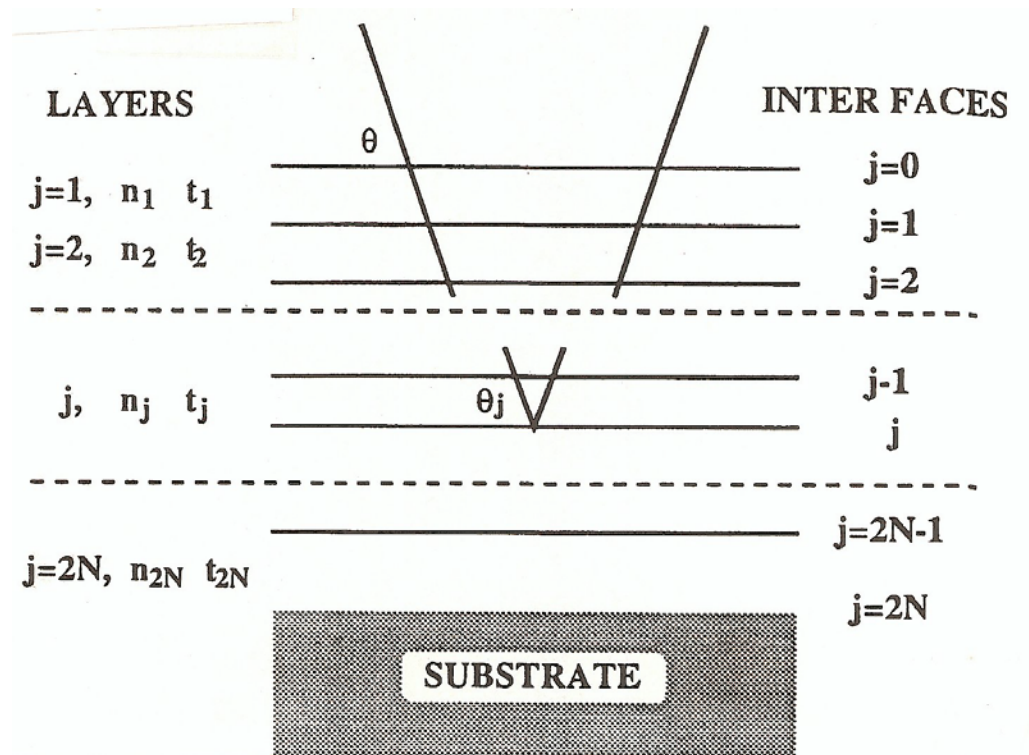


# Focusing High Energy Using Bragg's law

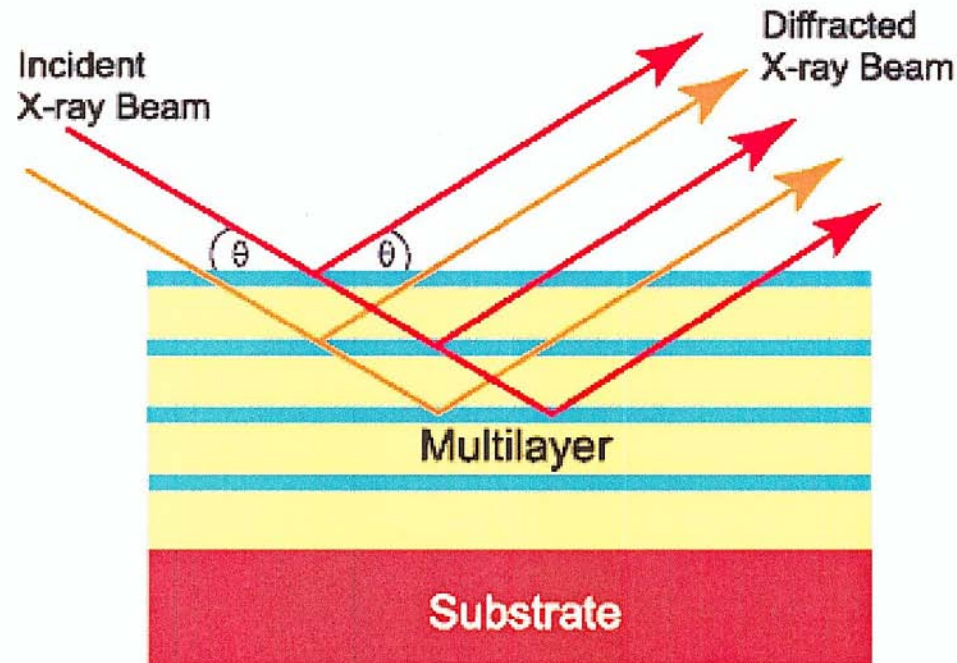
- First, look at a crystal with incident "white" X-rays



# Using Bragg's law on artificial crystals



# Multilayer structure - Artificial Bragg reflector

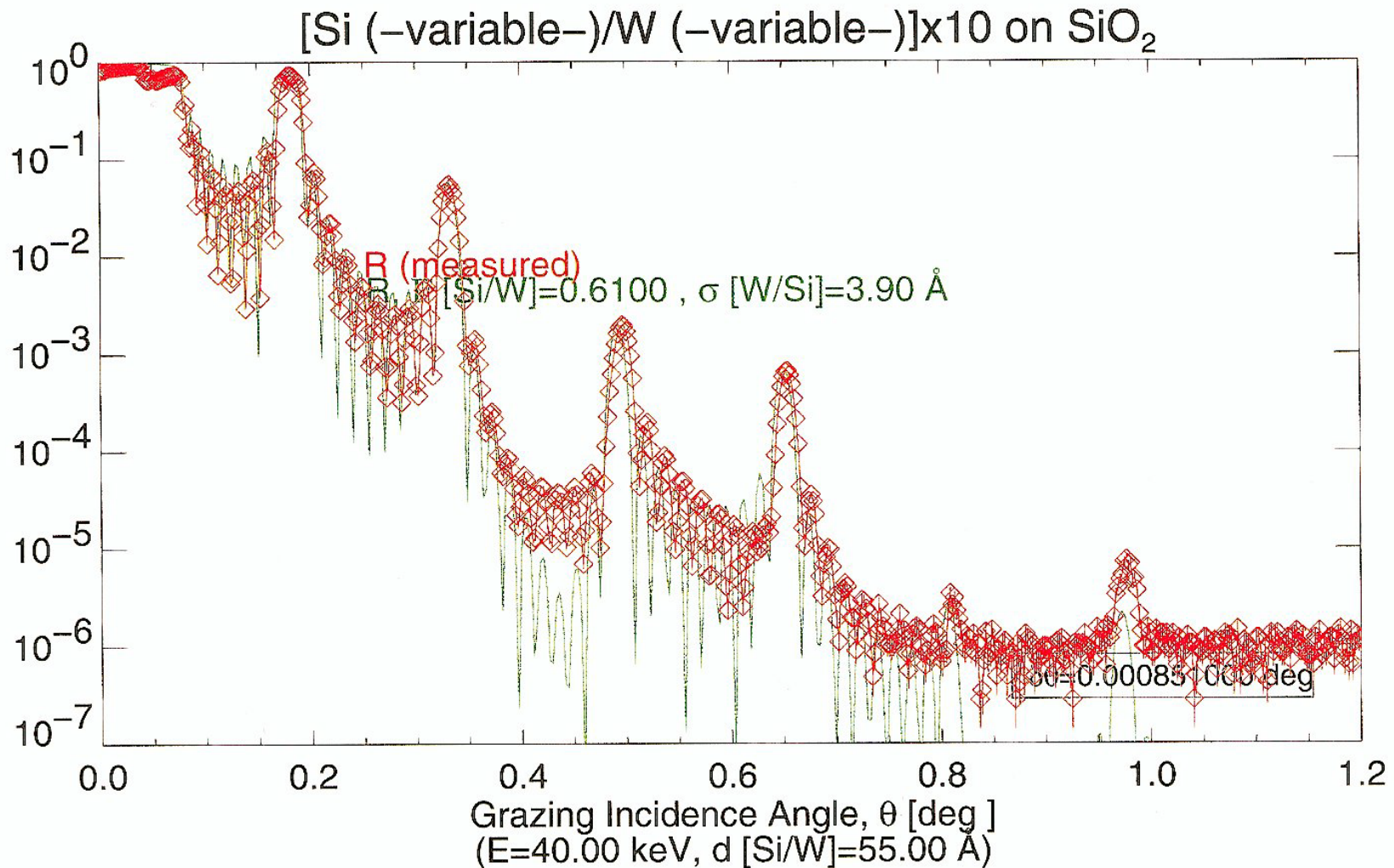


$$2 \cdot d \cdot \sin(\theta) = \lambda$$

Heavy materials : Typically W or Ni

Light materials : Typically Si, SiC, B<sub>4</sub>C or C

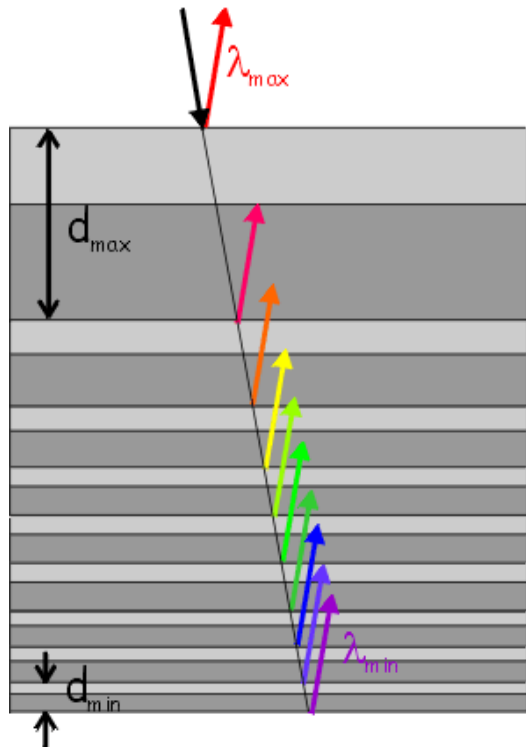
# Constant d-spacing ML



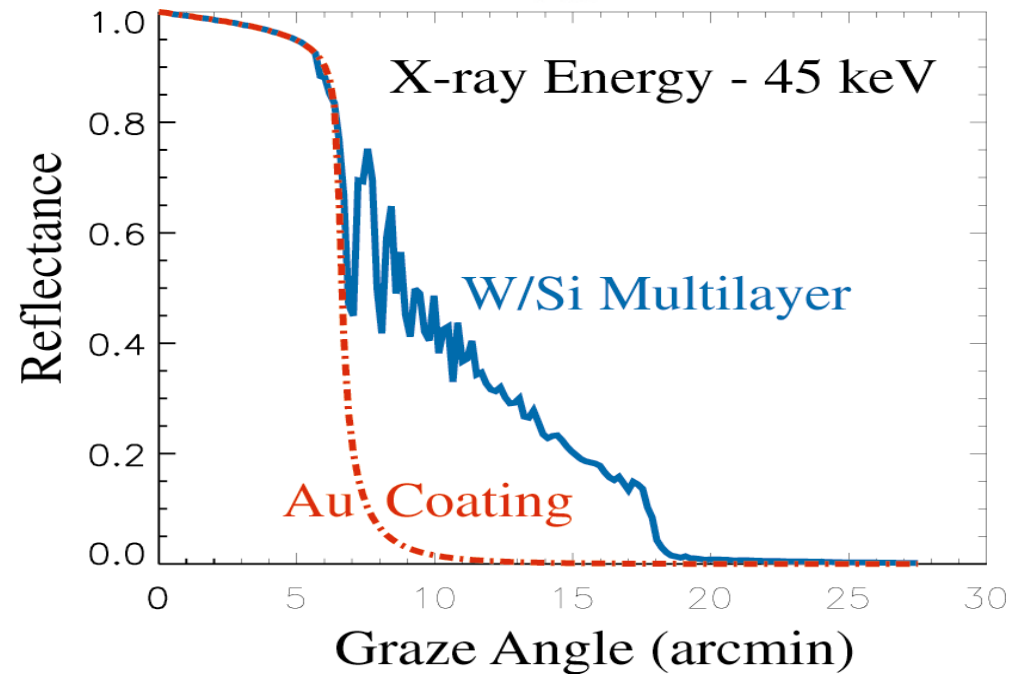
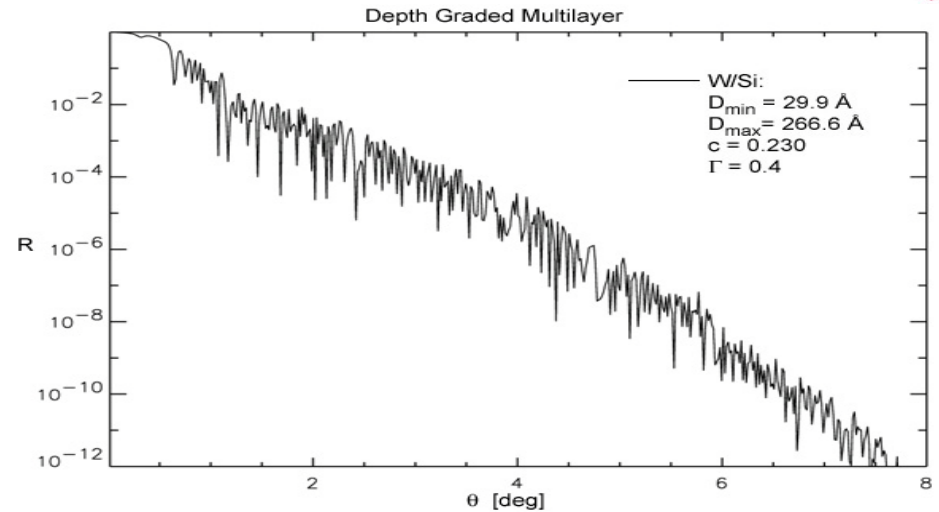


# Multilayer design

## Graded d-spacing coatings



## X-Ray energy 8 keV



# Assistance with calculations

Calculate Bragg's law here:

<http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/bragg.html>

Or

Download IDL routines from David Windt

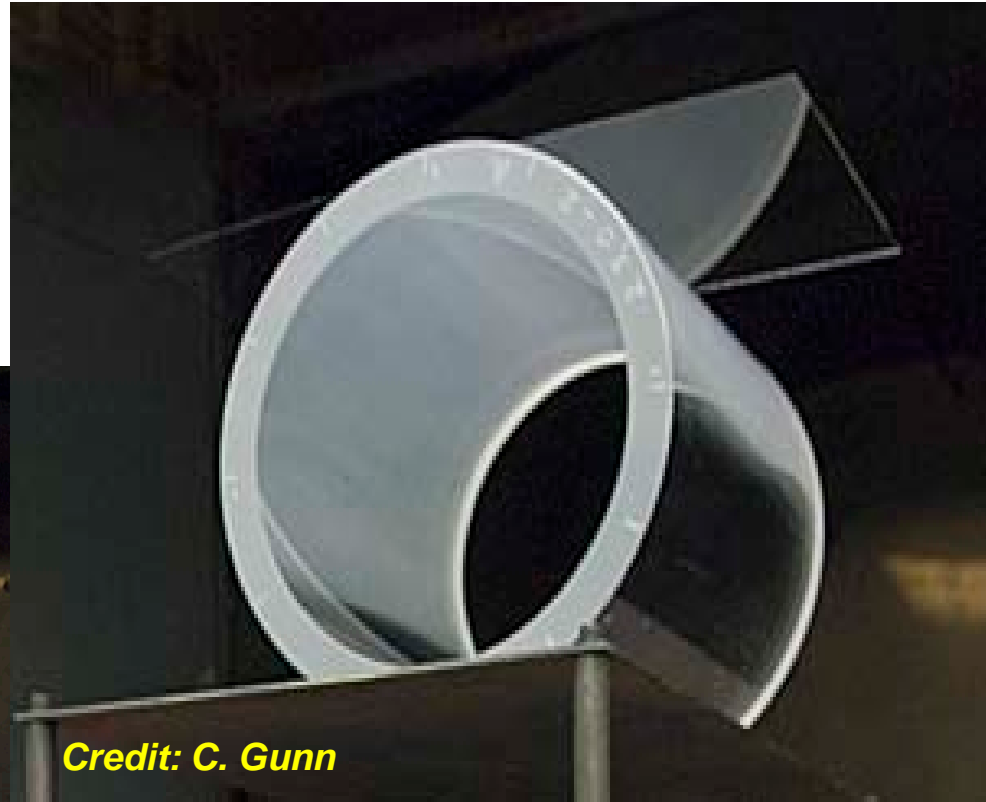
<http://www.rxollc.com/idl/>

# Mirror substrates are thermally formed from 0.21mm thin glass microsheets

- GSFC approach slumps glass directly onto highly polished mandrels
- Excellent figure (10 - 20" HPD) has been demonstrated



*Credit: C. Gunn*



*Credit: C. Gunn*

***Substrate forming in oven***

## Error-compensating Monolithic Assembly & Alignment (EMAAL)

- Each spacer is machined to the precise radius and angle with respect to the optic axis.

➤ No stack-up errors are propagated throughout optic build.

- Multilayer mirror segments are constrained to spacers with epoxy.

➤ Only near net shaped shells required to obtain high performance.

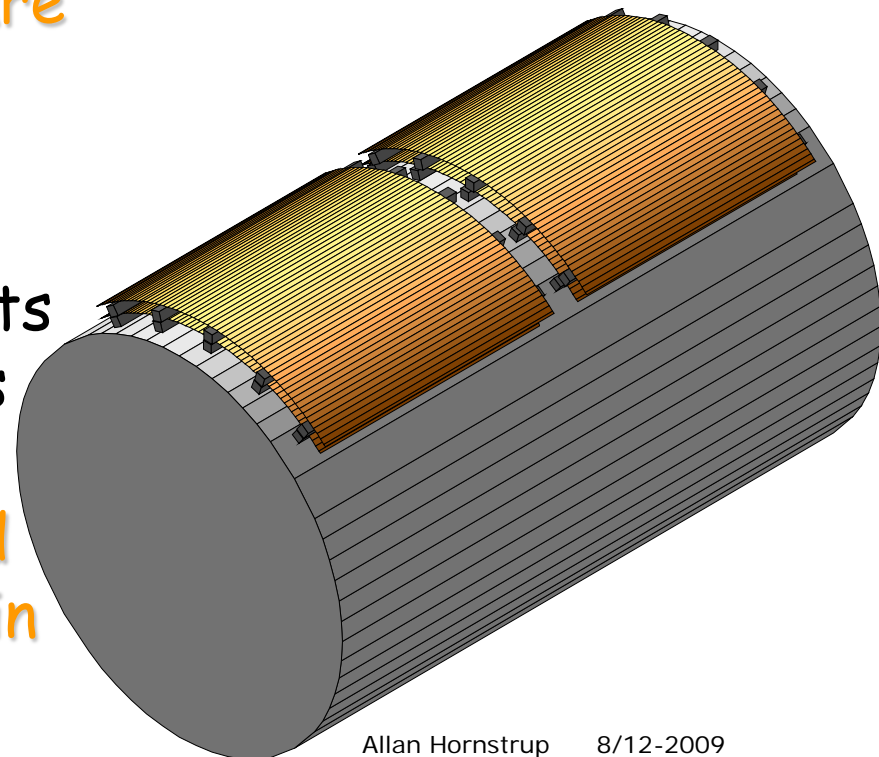
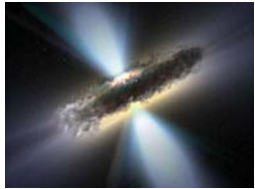




Figure error	Mid spatial frequency range	High spatial frequency range
few mm and up	few micron to few mm	nm to microns
Image degradation	Scatter - contrast	Reduction of efficiency

Half Power Diameter(HPD) : Angular range within which half of the photons at a given energy is focused.

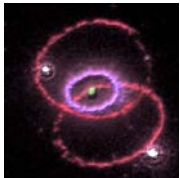
# NuSTAR Baseline Science Plan (2 yr)



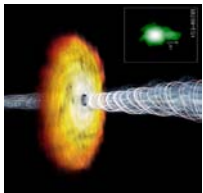
**Objective #1:** How are black holes distributed through the cosmos, and how do they affect the formation of galaxies?



**Objective #2:** How are stellar remnants distributed within the Galaxy and near the Galactic center?



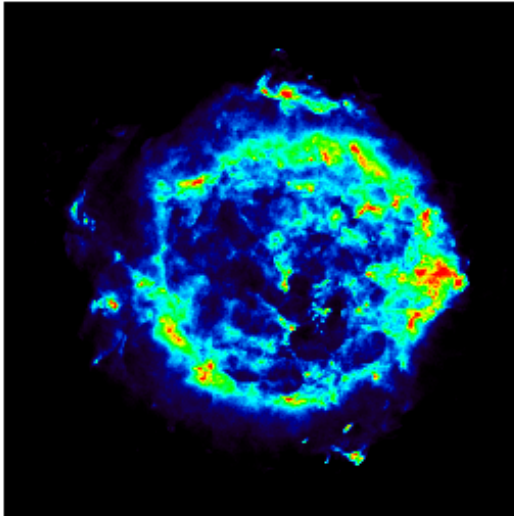
**Objective #3:** How do stars explode and forge the elements that compose the Earth?



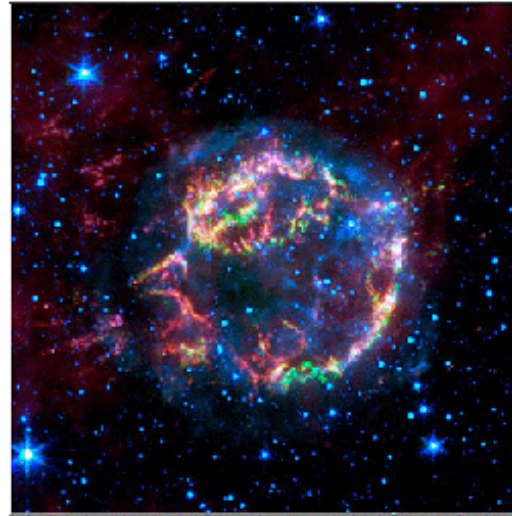
**Objective #4:** What powers the most extreme active galactic nuclei?

*~6 months of unallocated science observing time in first 2 years:  
for ToO's, additional programs, and/or to respond to primary program*

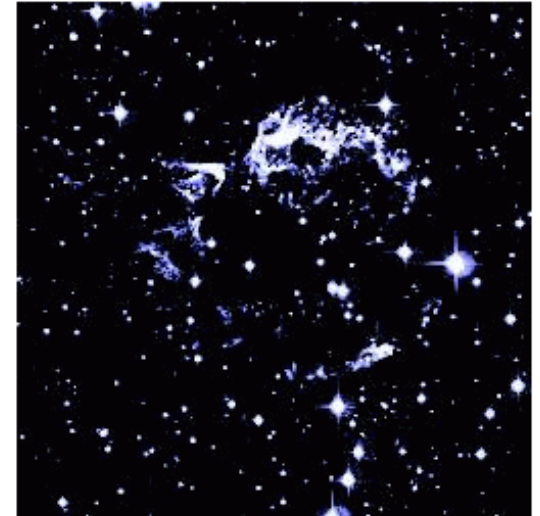
# Cassiopeia A



Radio wave (VLBI)



Infrared radiation (Spitzer)



Visible light (Hubble)

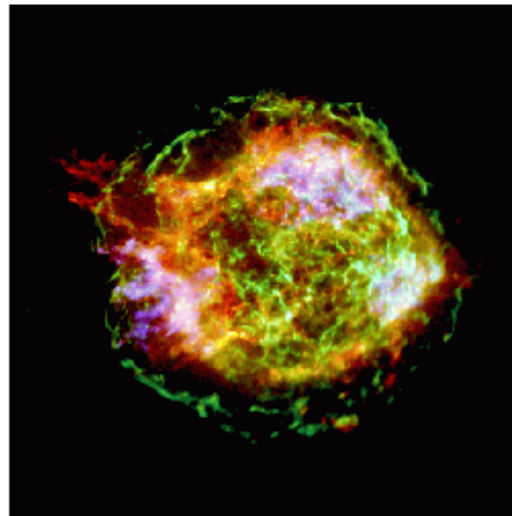
*Massive star uses up its fuel.*



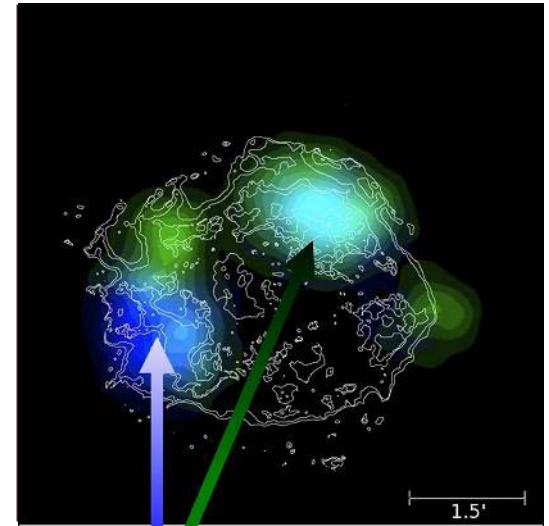
*Explosion: A supernova.*



*Expanding shell slams into  
surrounding medium at  
supersonic speed.  
Heats up and glows.*

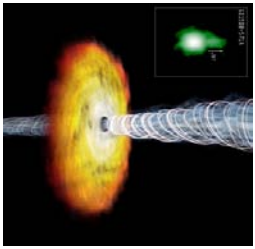


Low-energy X-ray (Chandra)

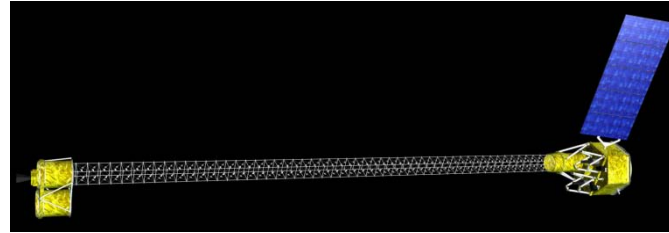


NuSTAR

## Objective #4: Blazar Monitoring



NuSTAR will conduct coordinated surveys with the Fermi Gamma-Ray Telescope and ground-based TeV telescopes to provide temporal tomography of nature's most powerful particle accelerators



NuSTAR  
X-ray (keV)

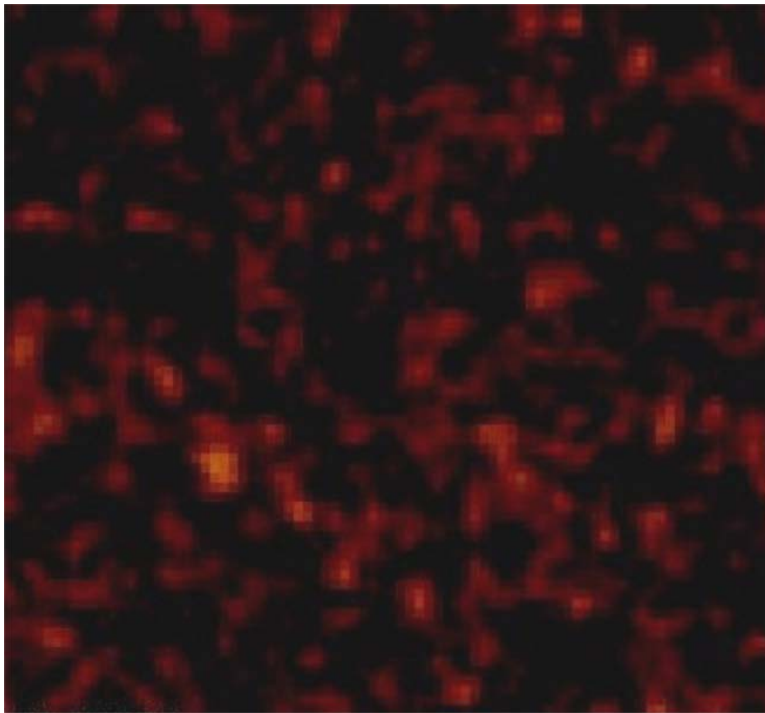
Fermi  
 $\gamma$ -ray (MeV-GeV)



HESS, Veritas  
 $\gamma$ -ray (TeV)

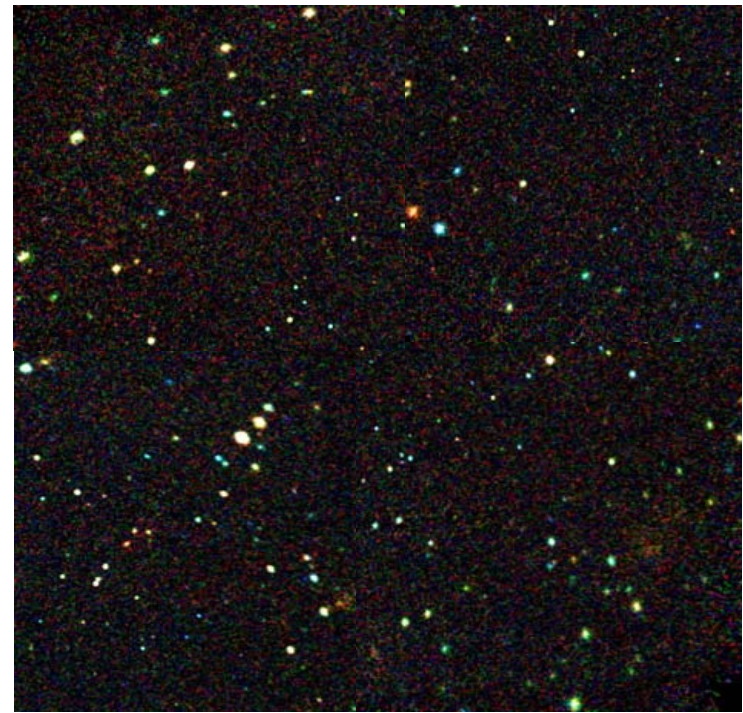


# INTEGRAL

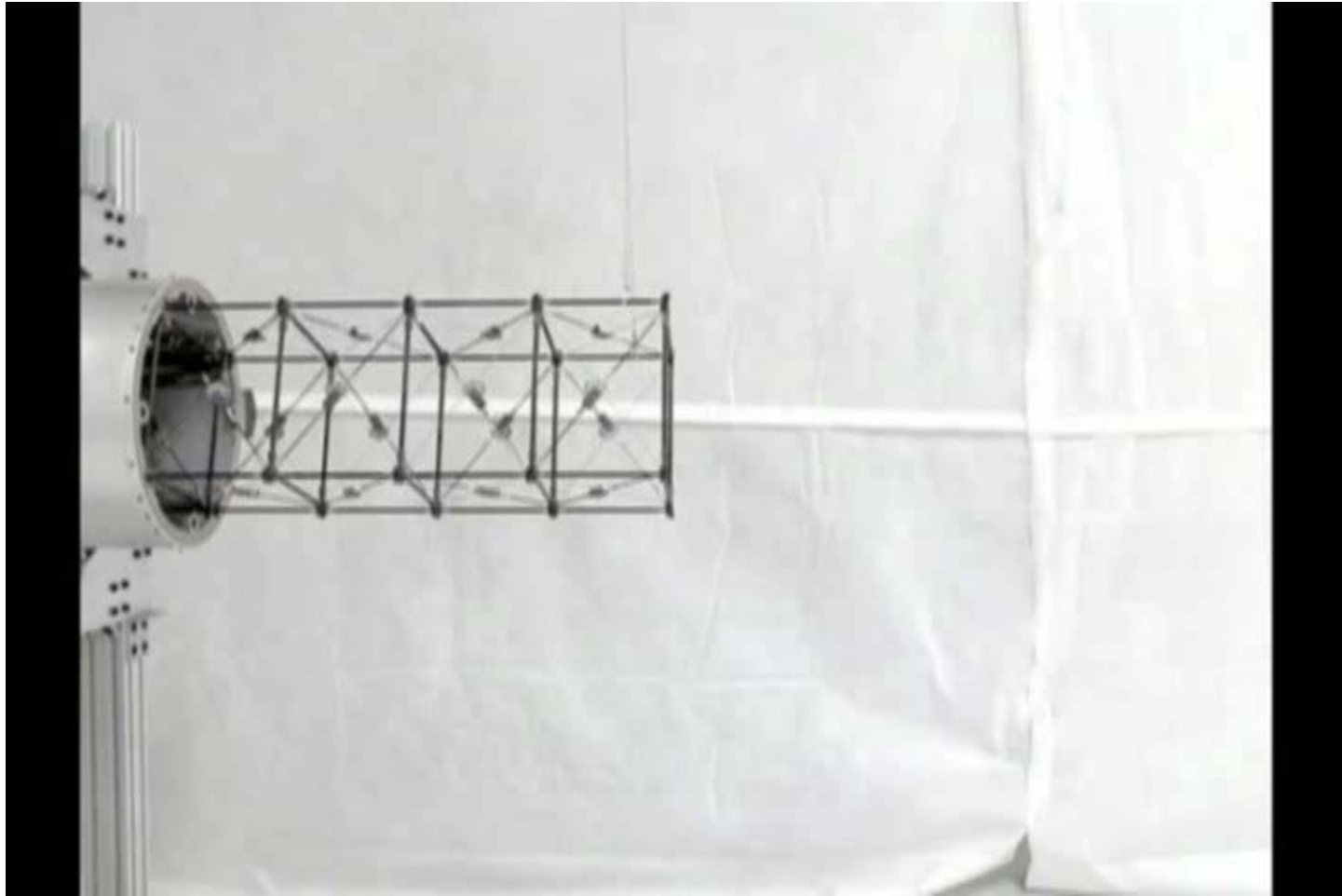
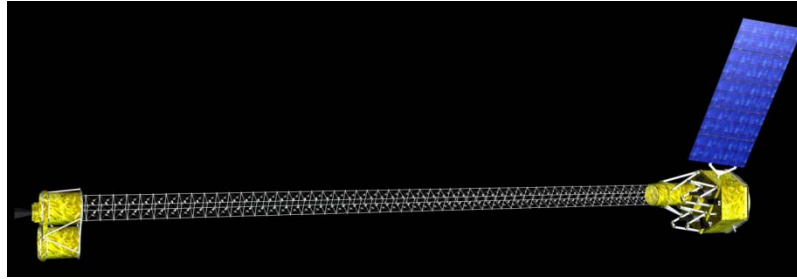


2x2 degrees, 20-40 keV  
1.5 month w/ IBIS

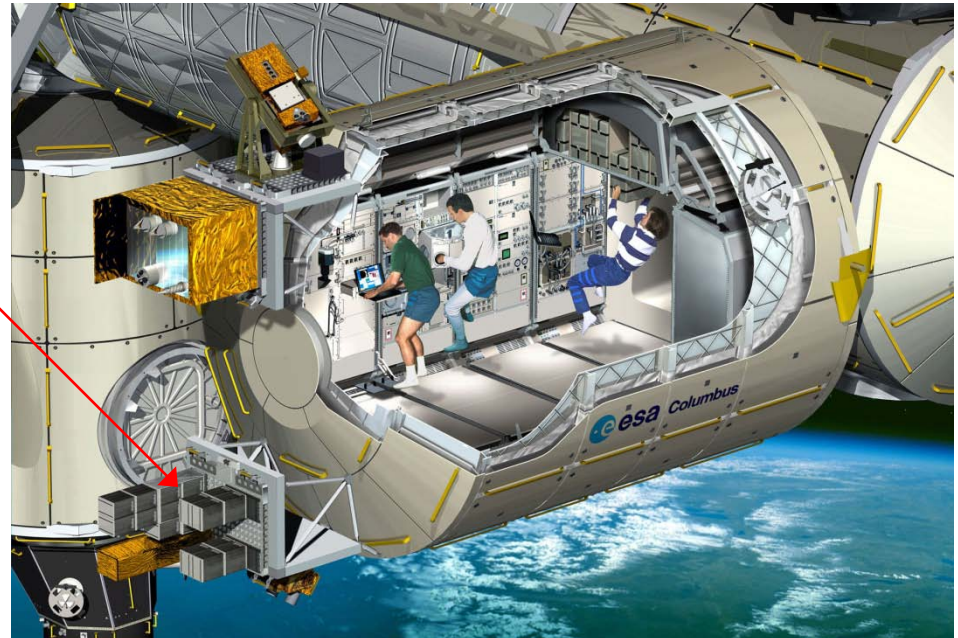
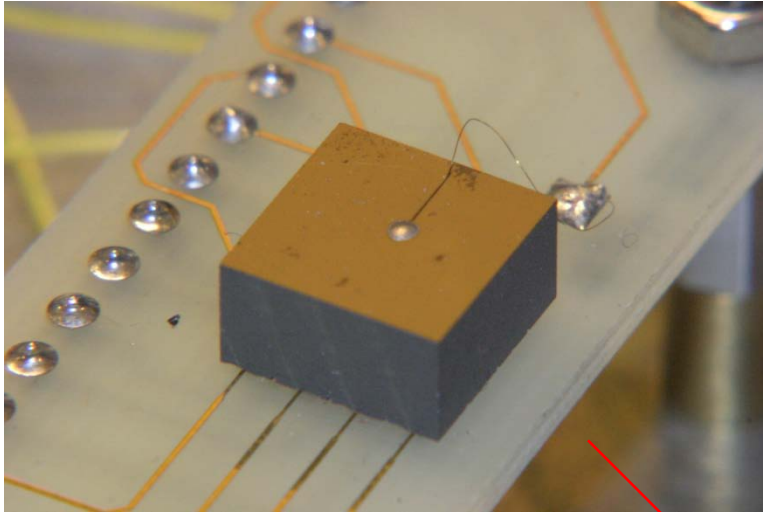
# NuSTAR



2x2 degrees  
simulated NuSTAR image



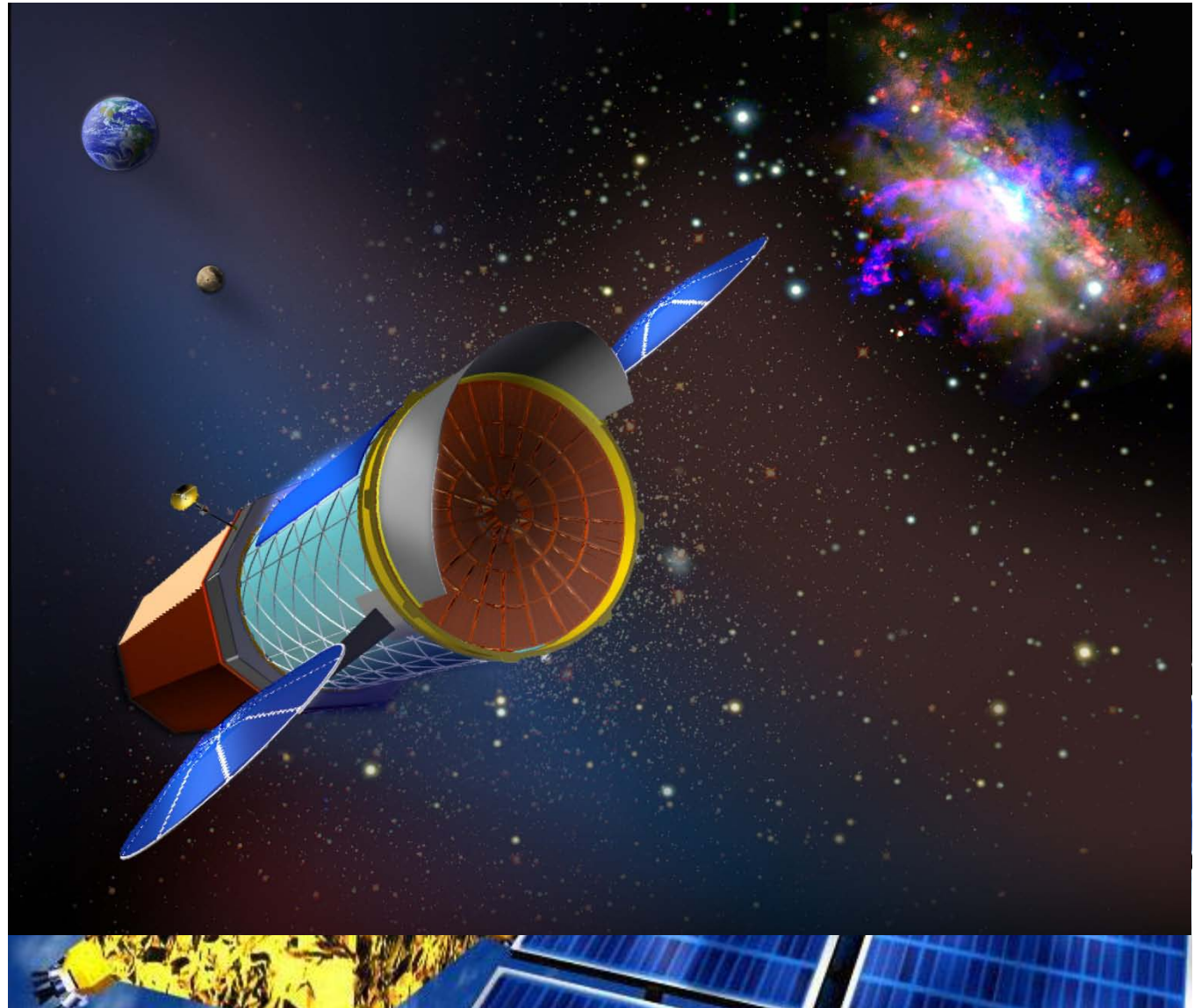
# High energy detector development





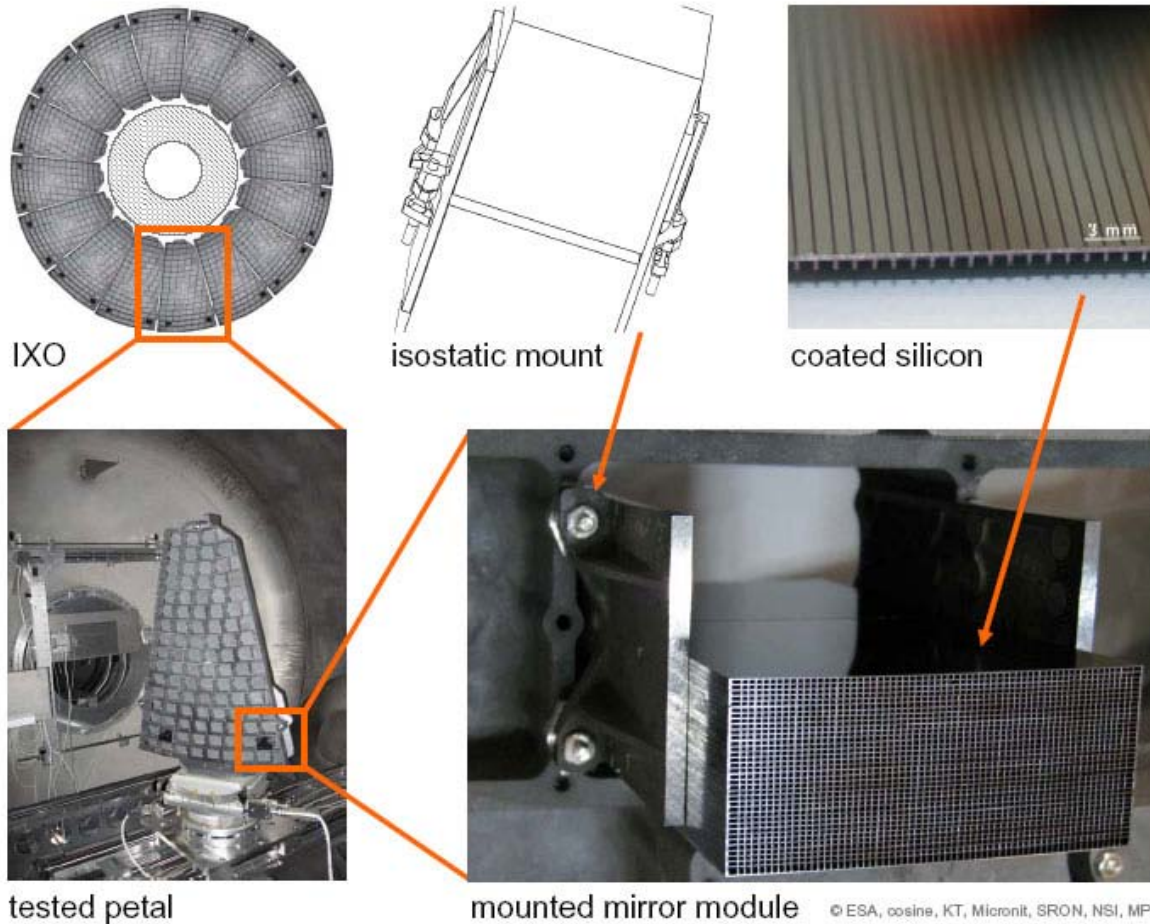
# Future X-ray mission(s)

XEUS/IXO/  
Constellation-X





# X-Ray Telescope Developments



# GRB to be found

