High-Energy Astrophysics

Topics:

- X-ray and gamma-ray detection
- X-ray data analysis
- Accreting neutron stars and black holes
- Pulsars, supernova remnants, cosmic rays
- Gamma-ray bursts

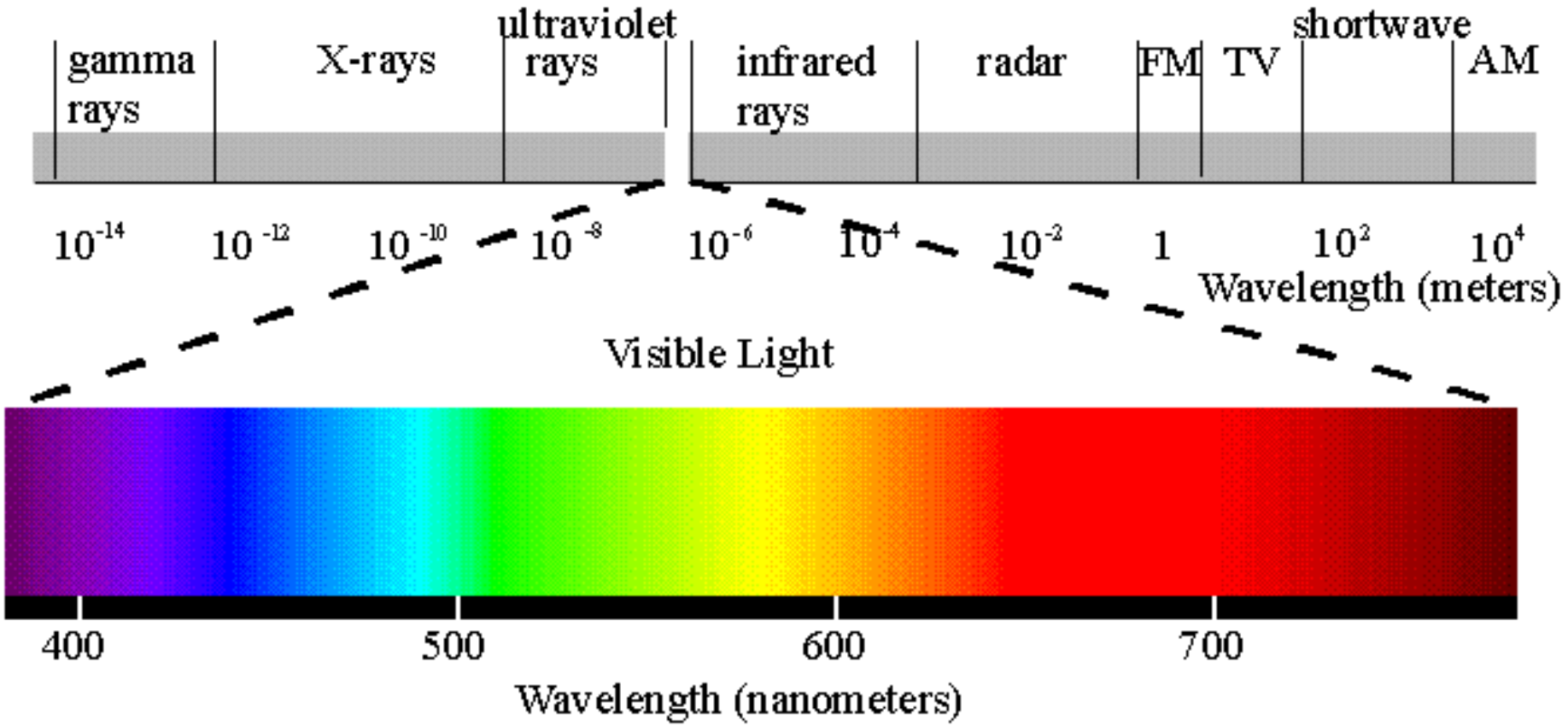
Grading

- Grades will be 50% problem sets and 50% on the data analysis project
- Students may work together on problem sets, but please write up your own answers
- Form groups of 2 for the data analysis project
- There will be both written and oral presentations of the project. During the oral presentation, questions will be asked of individual students.

Data Analysis

- Each group will get an account on orfeo
- Need to know basic unix commands
- Arrangements to set up accounts and data software will be made during the second week of classes

High Energies



By “high energy”, we mean radiation at X-ray or shorter wavelengths.

Photons

Energy of photon is set by frequency/wavelength

$$E = h\nu = \frac{hc}{\lambda}$$

Unit is electron-volt (eV, keV, MeV, GeV, TeV)

1 eV = 1.6×10^{-19} J = 1.6×10^{-12} erg

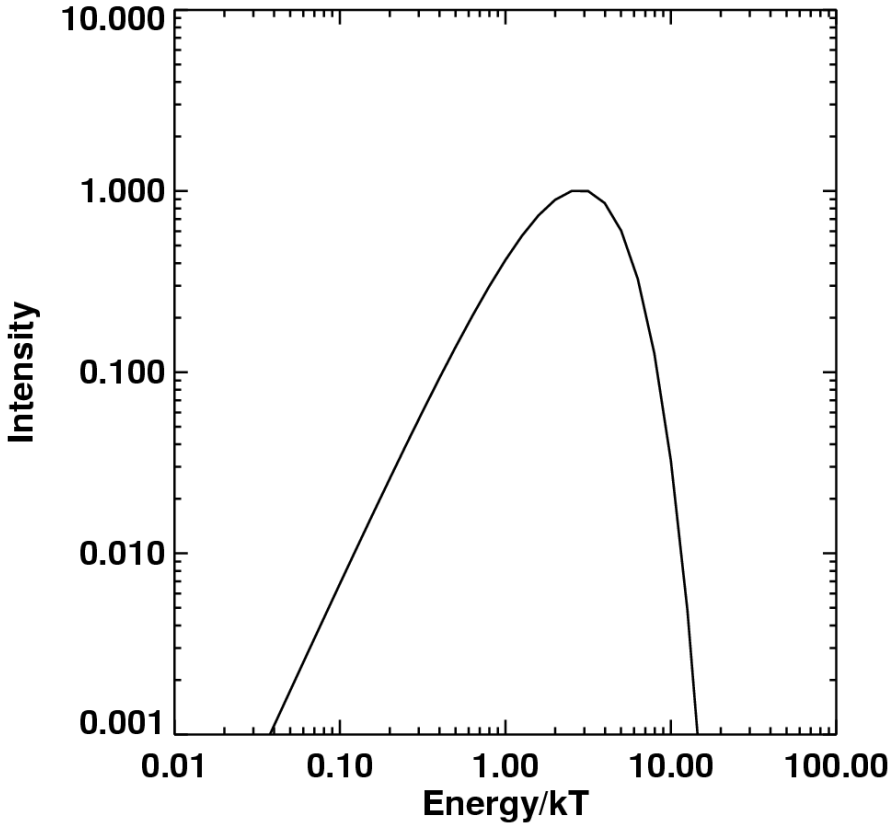
$$E(\mathrm{keV}) = \frac{12.4}{\lambda(\mathrm{Angstroms})}$$

Thermal Radiation

Average kinetic energy of particles is proportional to temperature

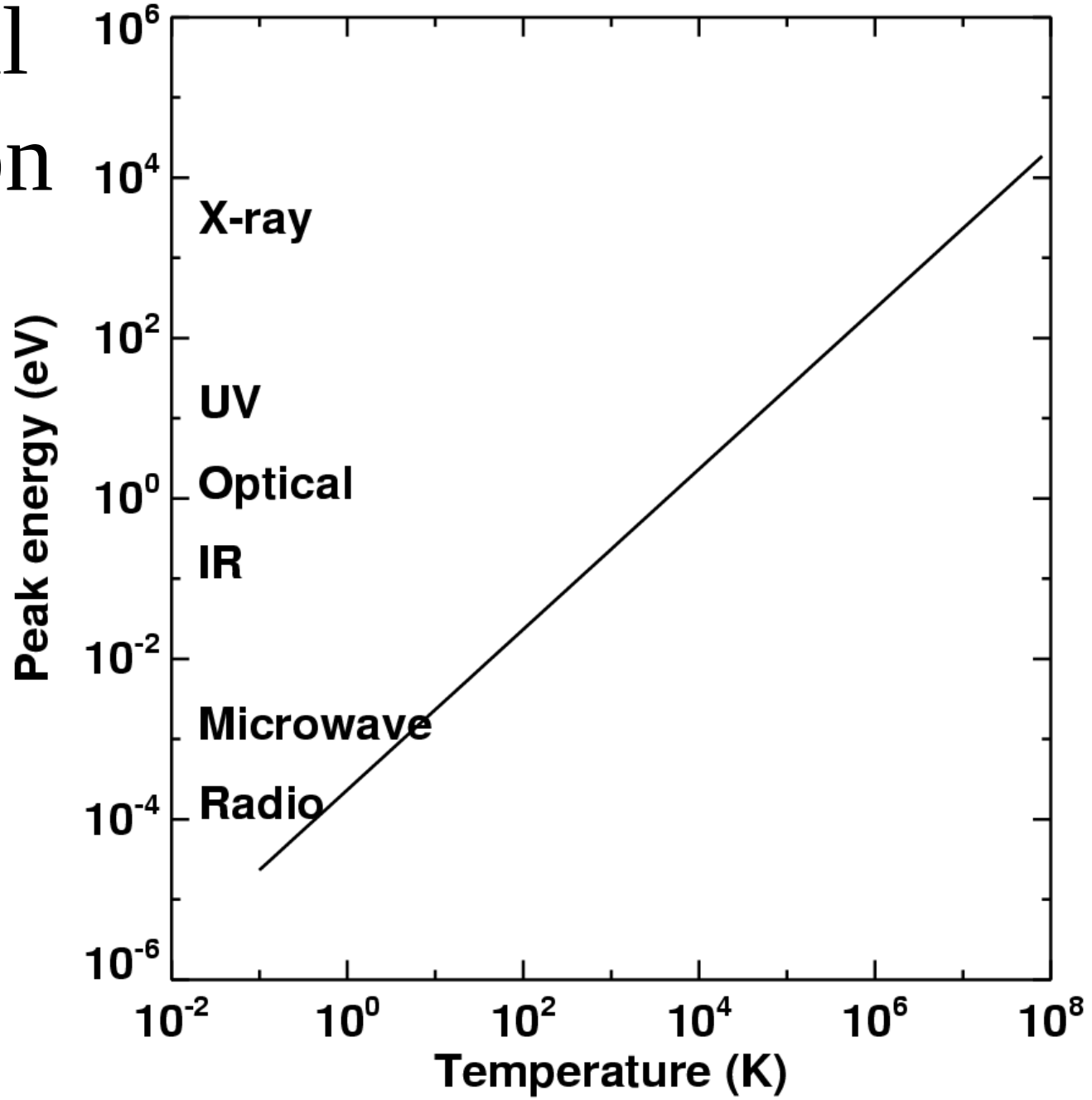
$$K = \frac{1}{2}mv^2 = \frac{3}{2}kT$$

k = Boltzmann constant = 1.38×10^{-23} J/K = 8.62×10^{-5} eV/K



Thermal spectrum peaks at 2.7 kT, falls off sharply at higher and lower energies.

Thermal Radiation



Photons above X-ray band are generally produced by non-thermal processes

X-Rays

- Measure X-ray energies in energy units (eV or keV) or wavelength units (Angstroms)
- Soft X-rays = 0.1-2 keV
- Medium (“standard”) X-rays = 2-10 keV
- Hard X-rays 20-200 keV

Gamma-rays

- Formal definition of X-ray versus gamma-ray is that X-rays come from electronic transitions while gamma-rays come from nuclear transitions.
- In practice, gamma-rays in the X-ray band are usually referred to as X-rays
- Gamma-rays typically have energies above about 100 keV

Why High Energies?

- Photons are emitted at the characteristic energy of particles in a system.
- For a blackbody, we have Wien's Law:
  - Wavelength of peak (Ang) = 2.9×10^7 / T(K)
- In general, a system tends to produce radiation up to around the maximum energy of its particles

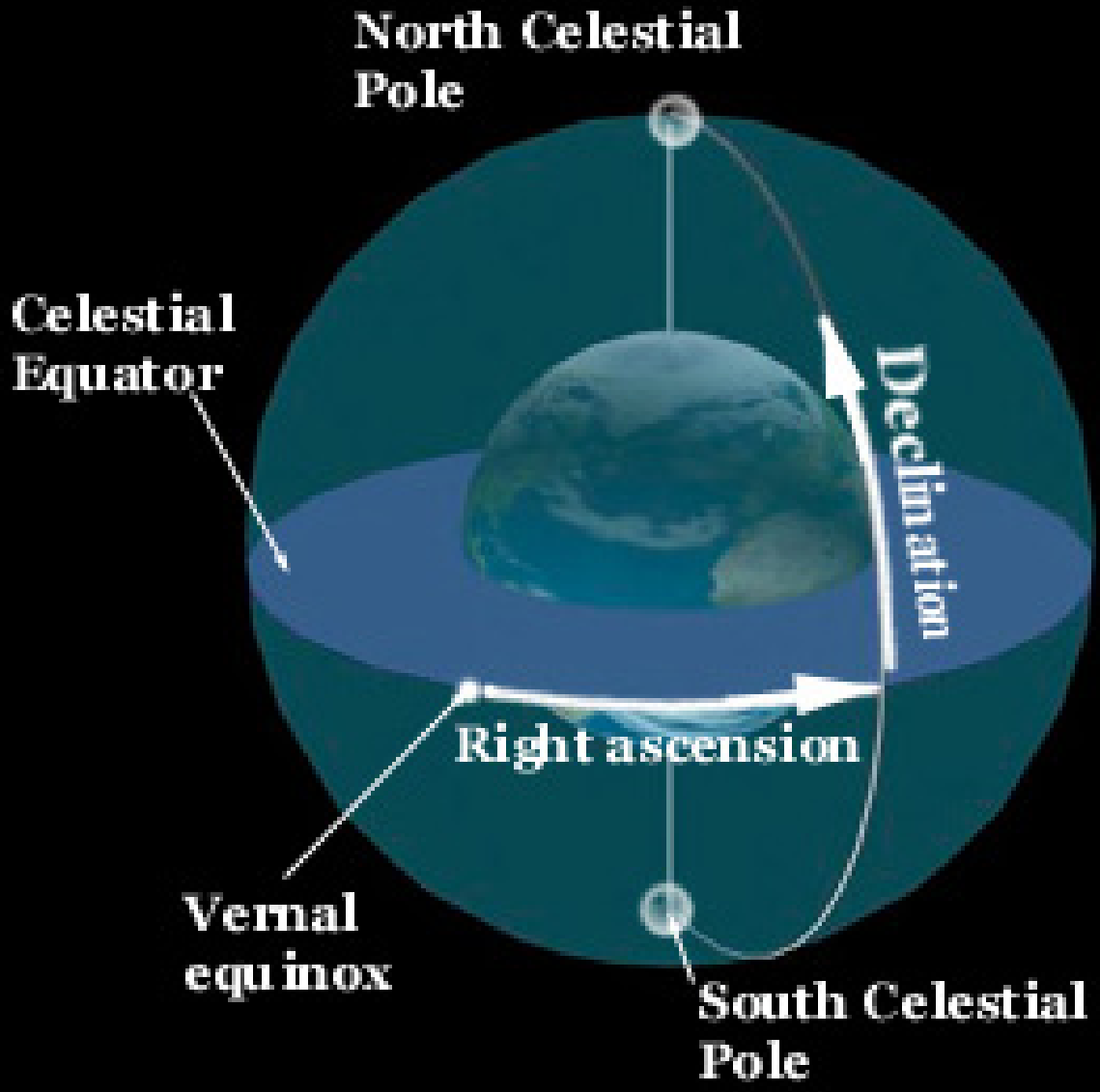
- Thus, high energy photons are probes of very energetic systems which are the most extreme environments in the Universe

Extremes in the Universe

- Extreme temperatures (X-ray emitting plasma)
- Extreme densities (black holes and neutron stars)
- Extreme magnetic fields (near neutron stars)
- Extreme velocities (jets from black holes)
- Extreme explosions (gamma-ray bursts)

Astronomical Interlude

Celestial Coordinates



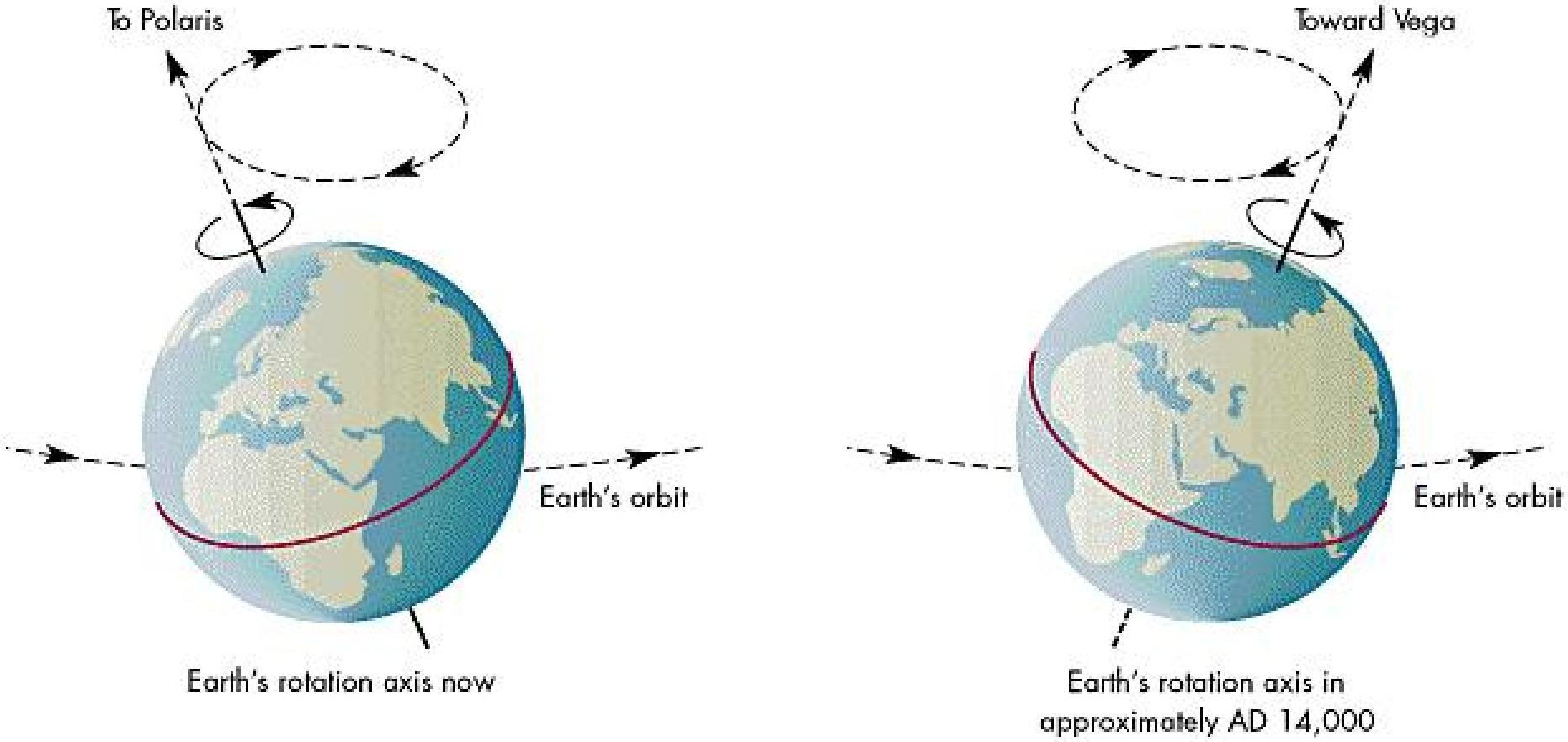
Coordinates are:

Declination = degrees North or South of the equator.

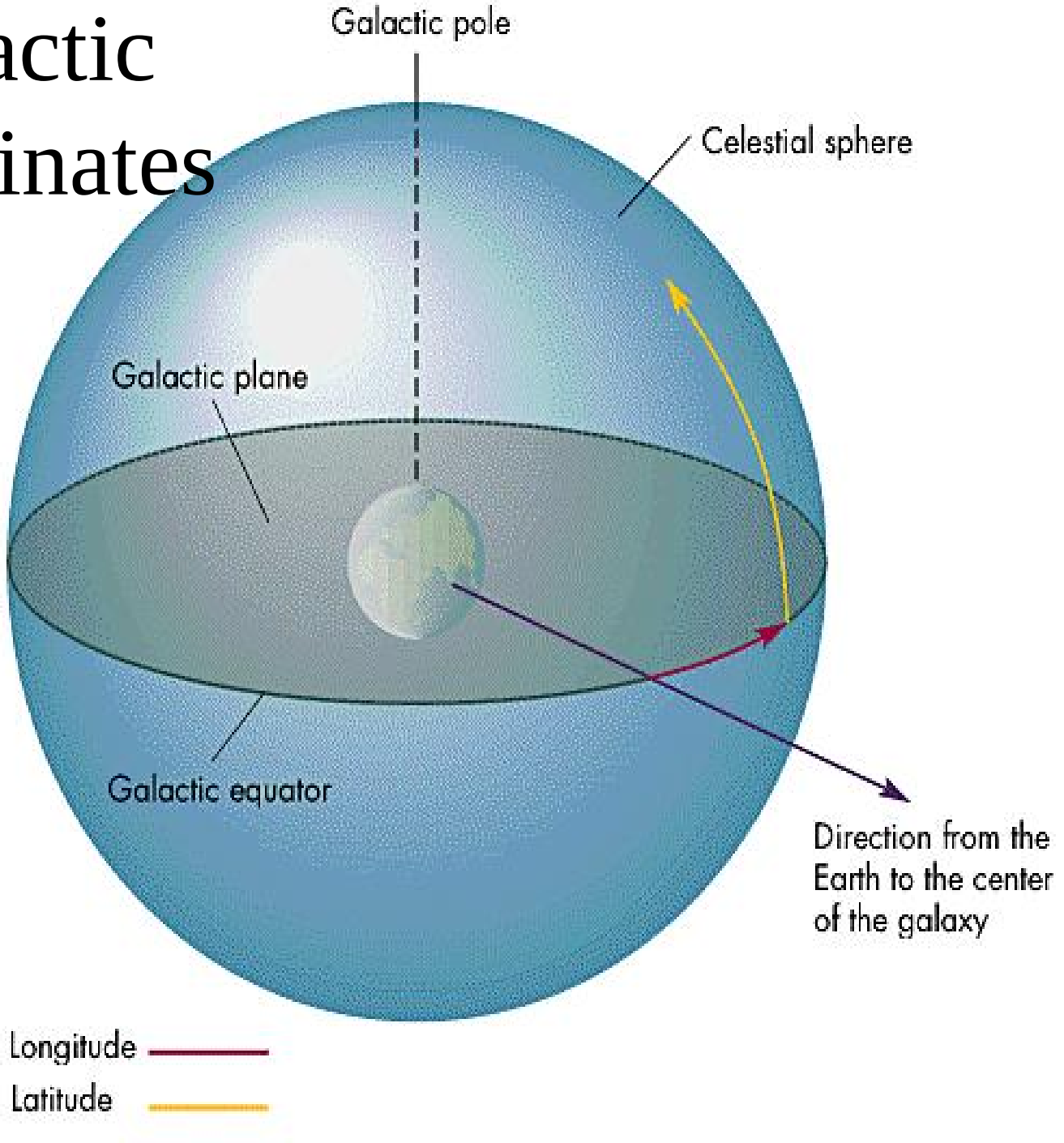
Right ascension = degrees East of the “Vernal equinox”.

Vernal equinox is defined as the position of the Sun on the first day of spring. Note it is a point on the sky, not the earth.

Precession of the Earth

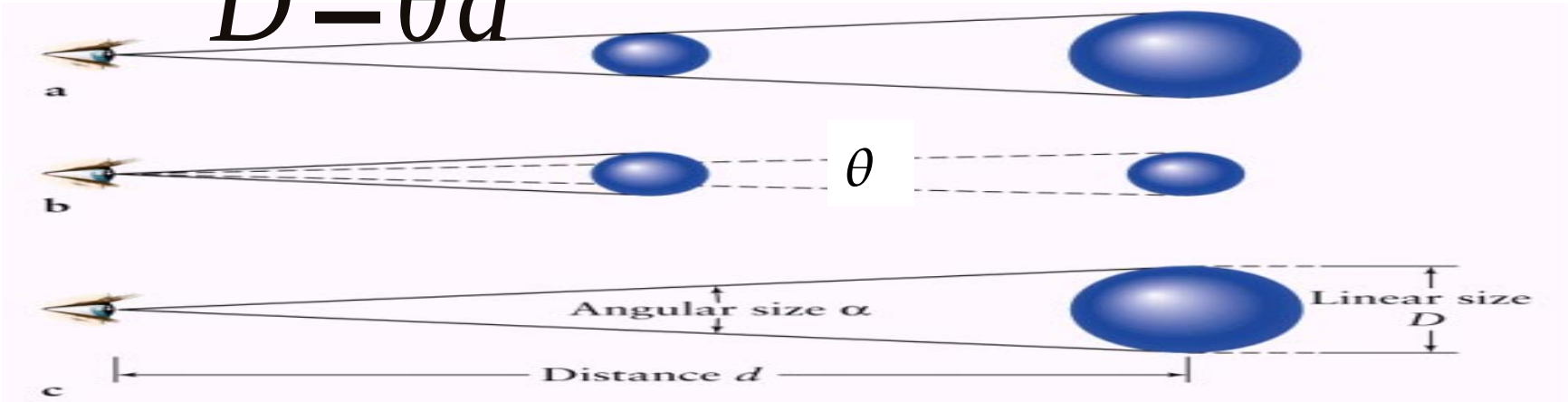


Galactic coordinates



Angular Size

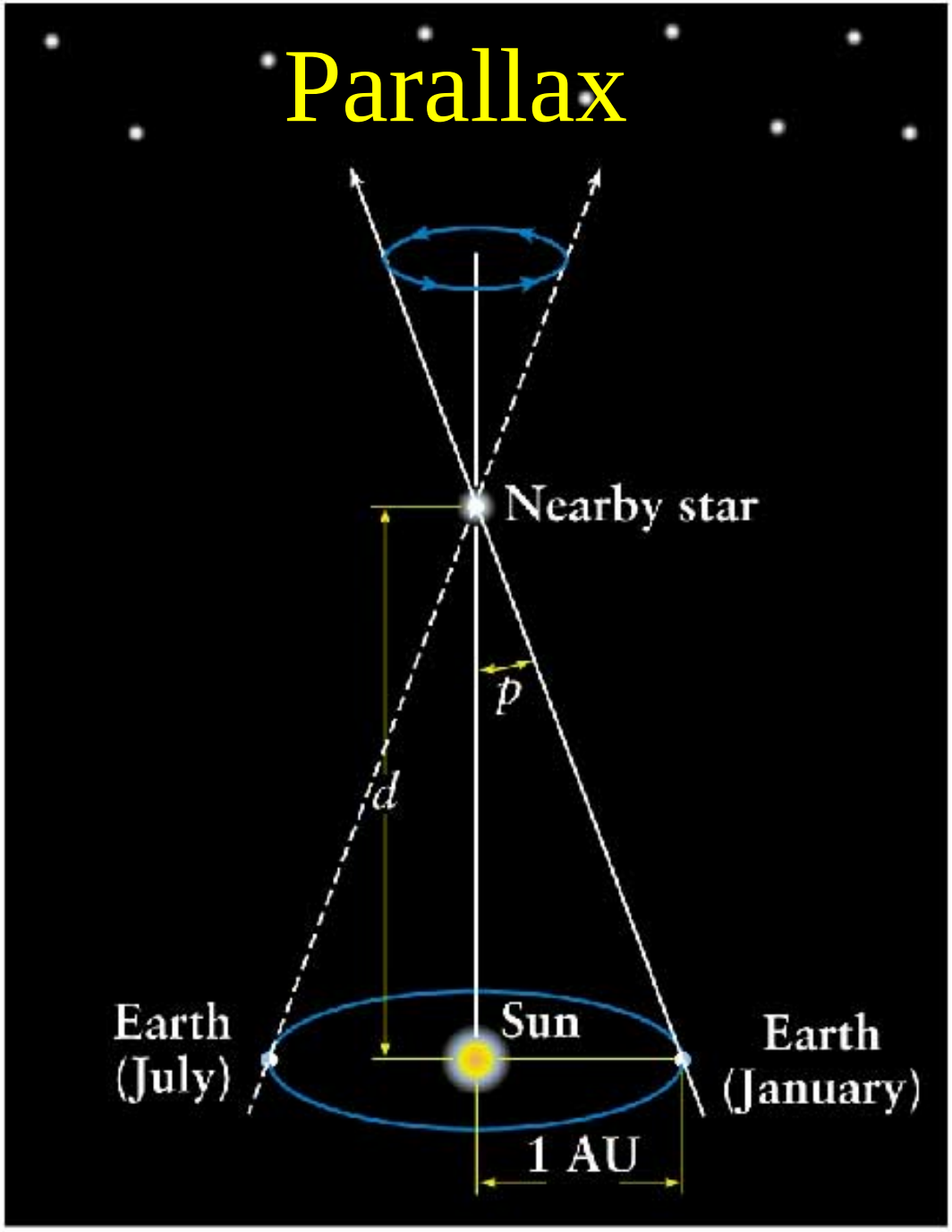
$$D = \theta d$$



1º = 60 arcminutes = 60′

1′ = 60 arcseconds = 60″

1″ = 4.85×10^{-6} radians



Parallax

As Earth moves from one side of the Sun to the other, a nearby star will seem to change its position relative to the distant background stars.

$$d = 1 / p$$

d = distance to nearby star in parsecs

p = parallax angle of that star in arcseconds

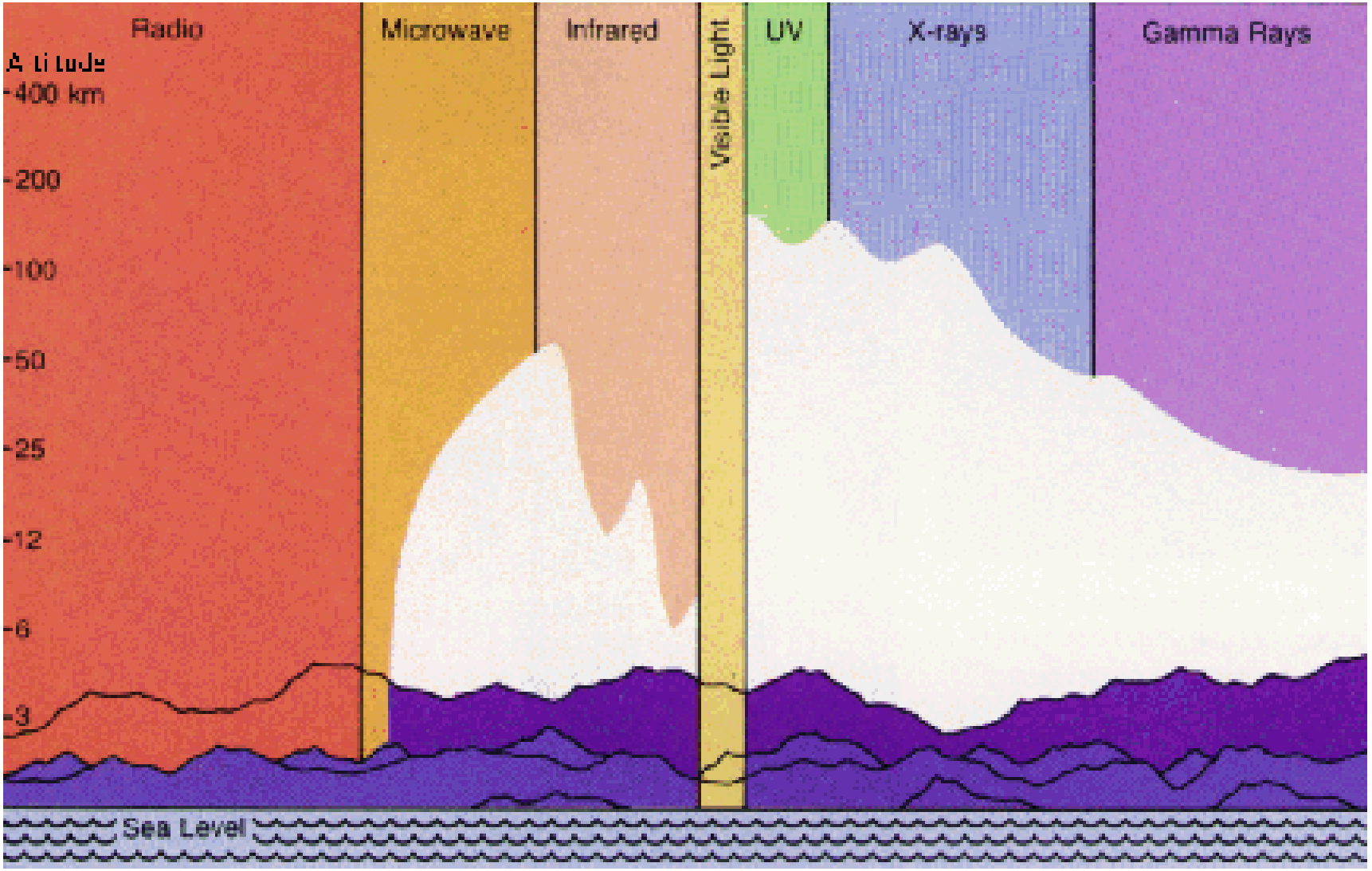
1 parsec = 3.26 light years

$= 3.086 \times 10^{18}$ cm

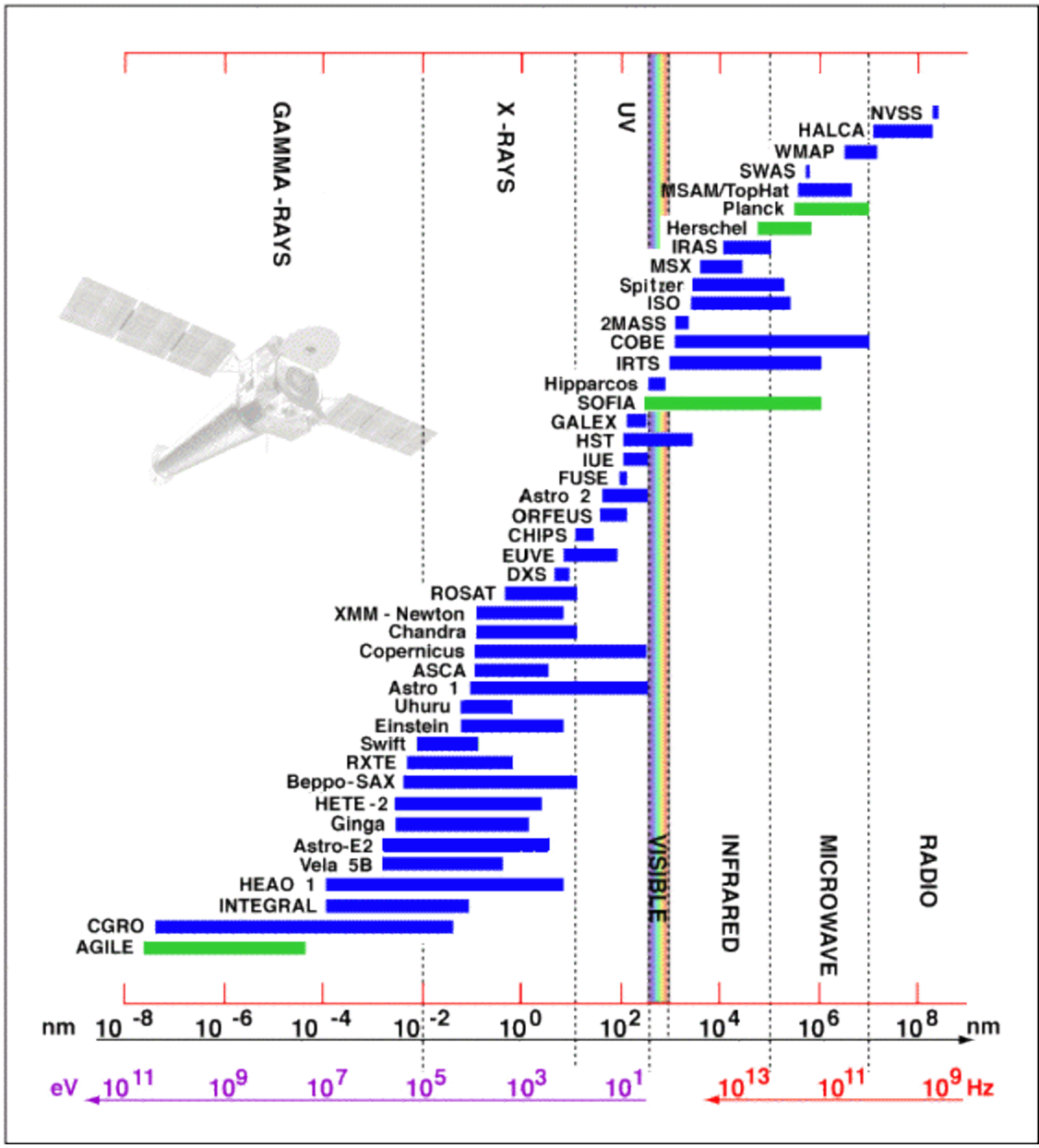
Instruments for High Energy Astronomy

- Advances in observations follow directly from advances in instrumentation
- First key advance was development of rockets to loft telescopes above the atmosphere

Atmospheric Transmission



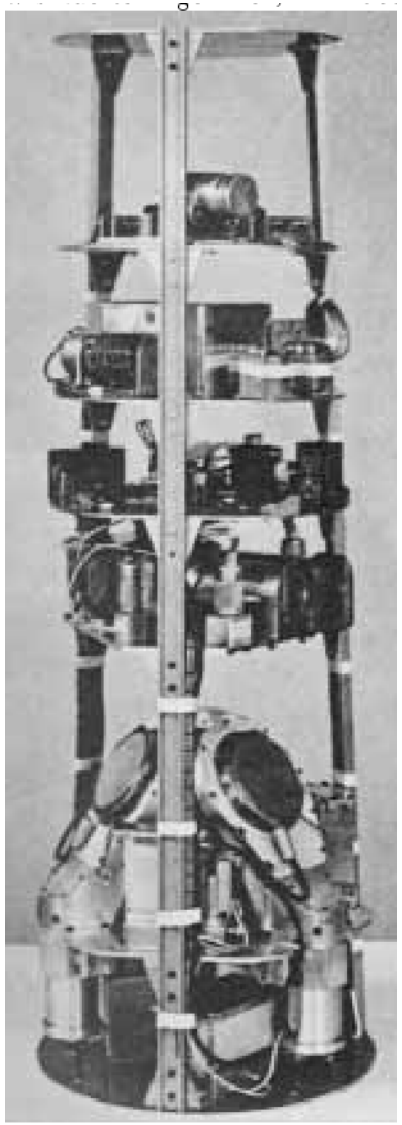
Space-Borne Observatories



X-ray instruments

- Convert X-rays to electrical signals
- Sounding rockets
- Satellites

Rocket Flight (1962)



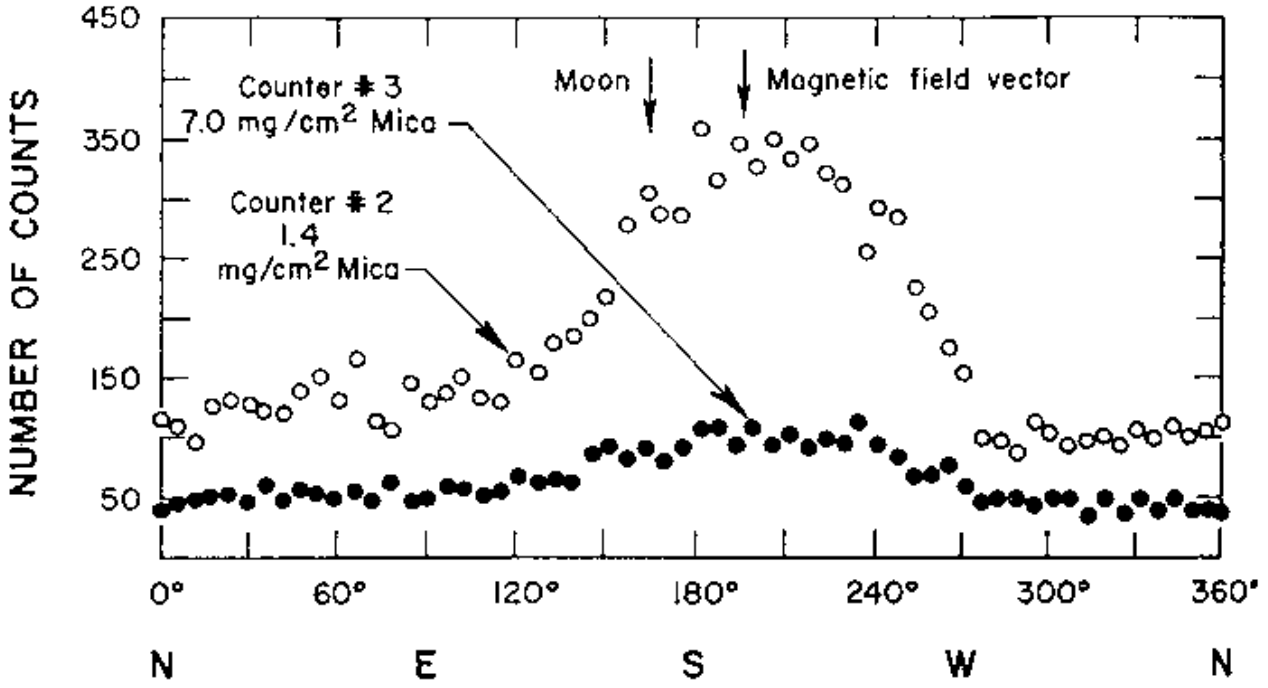
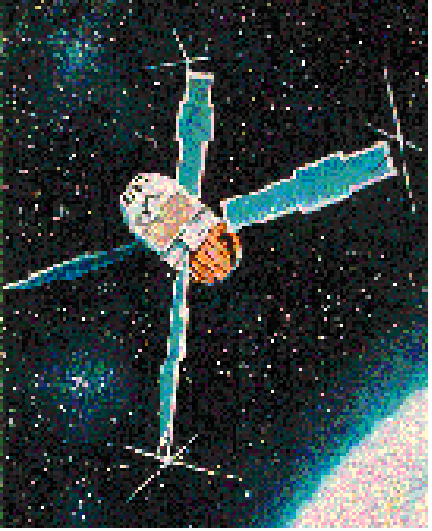
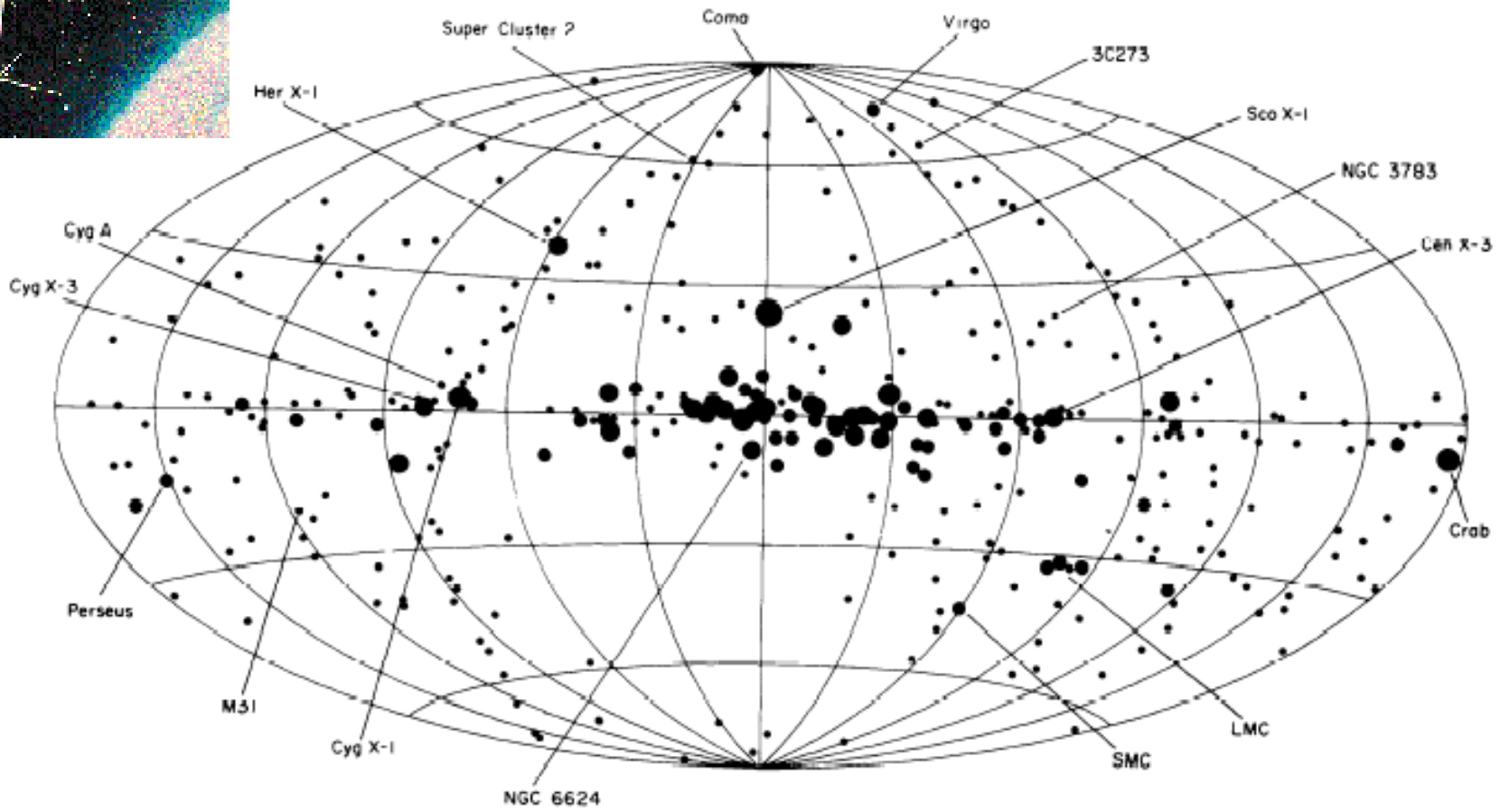


Figure 2. The first observation of Sco X–1 and of the x–ray background in the June, 12, 1962 flight. From Giacconi, *et al.*, 1962.



Uhuru (1970-1973)



339 sources

X-Ray Pulsar Cen X-3

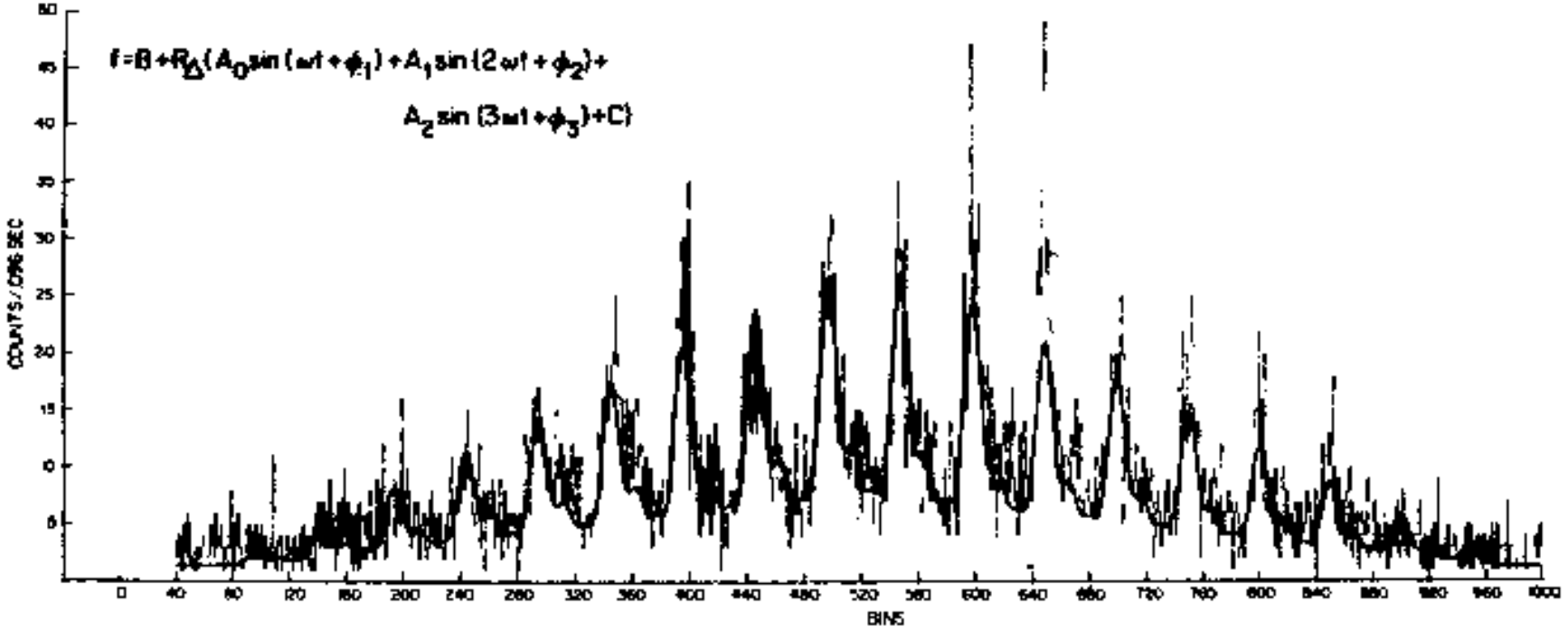
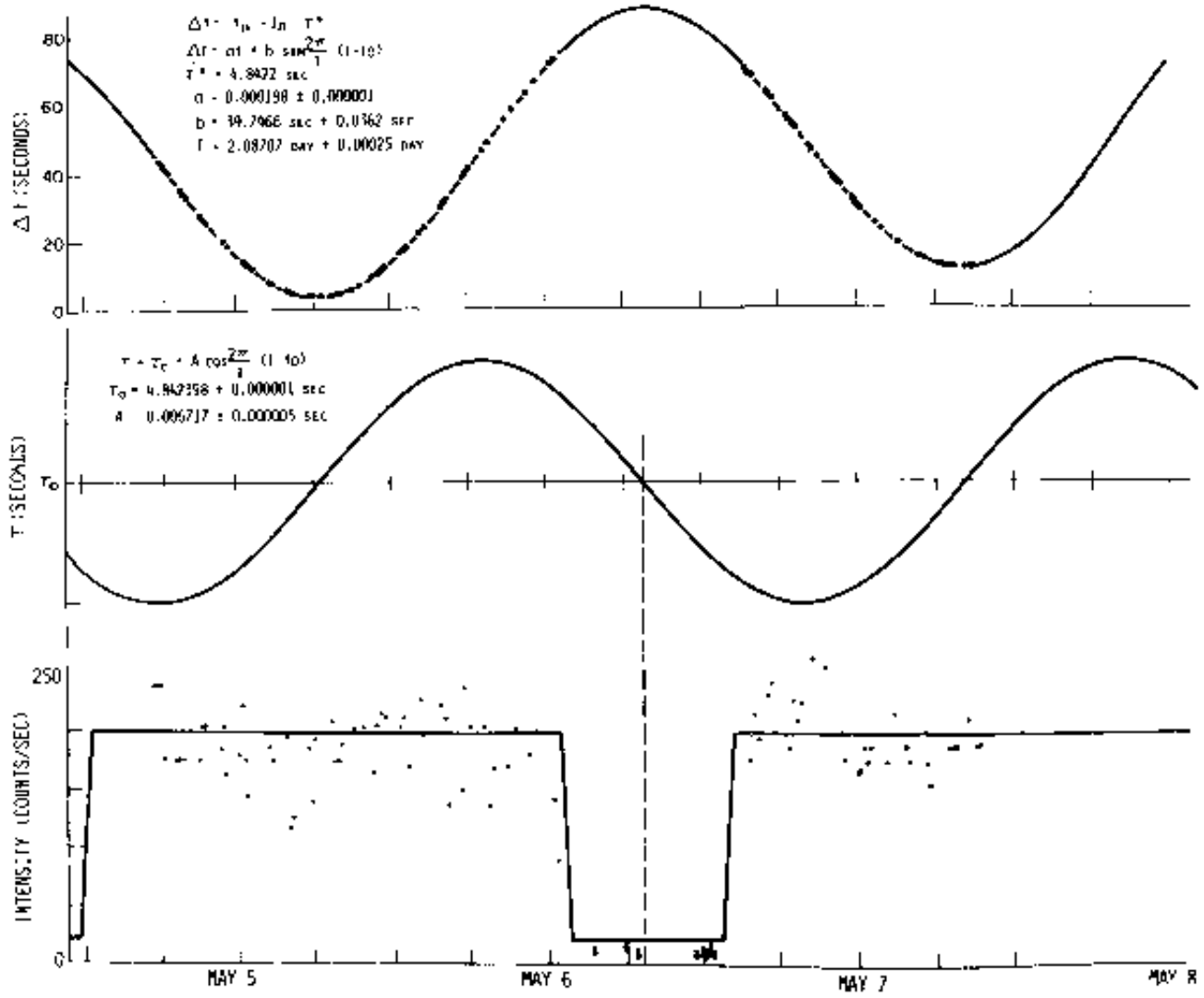


Figure 5. X–ray pulsations of Cen X–3. From Giacconi, 1974.

Pulses occur at intervals of 4.84 seconds

X-Ray Pulsar Cen X-3



Pulses are modulated at orbital period of 2.09 days

Figure 6. Period variations and occulations of Cen X–3. From Giacconi, 1974.

Einstein Observatory (1978-1981)

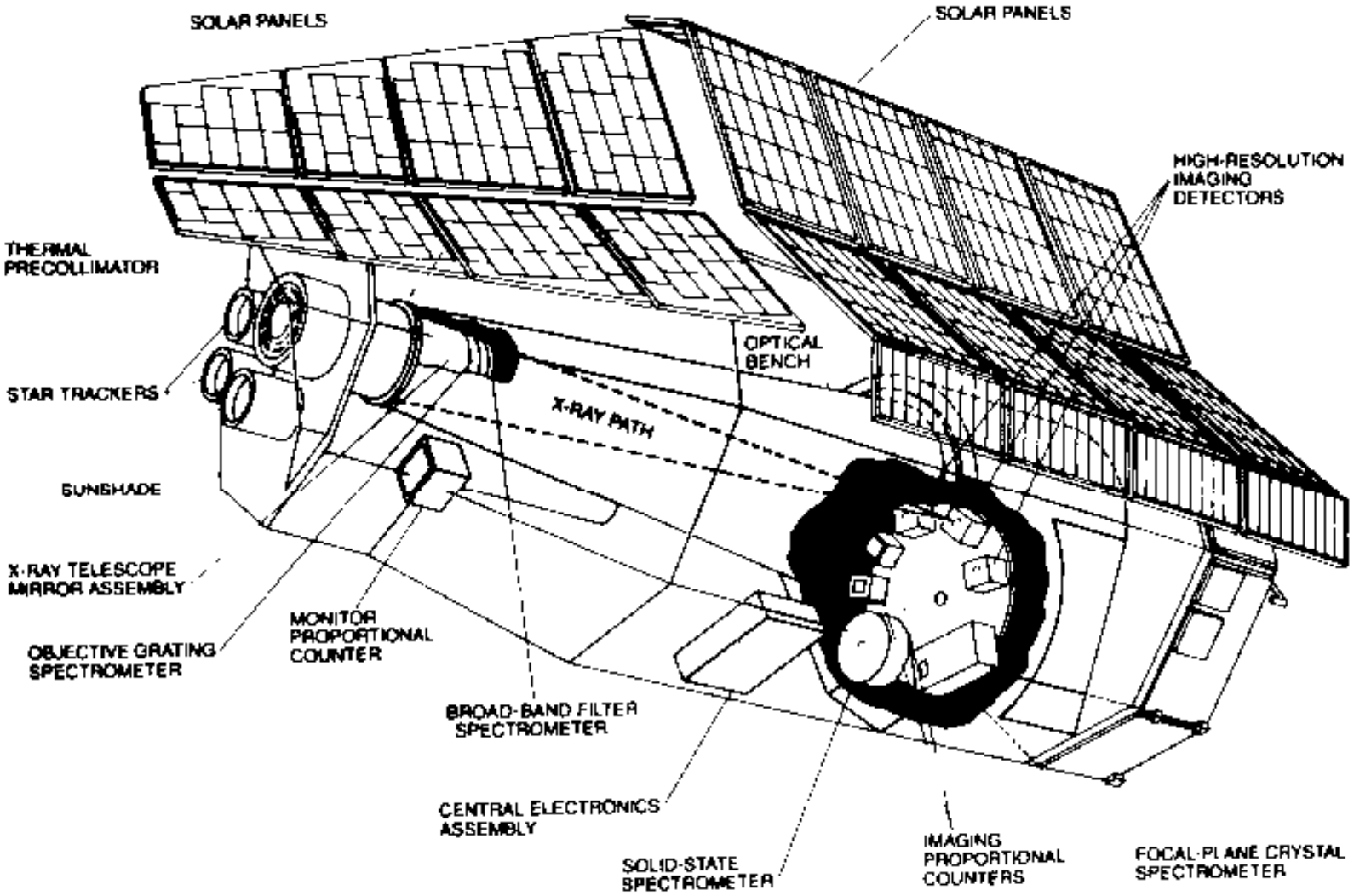
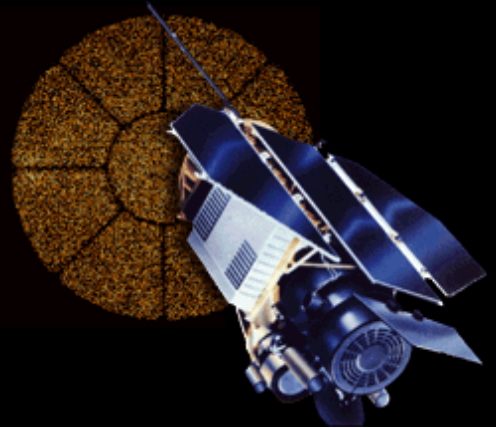
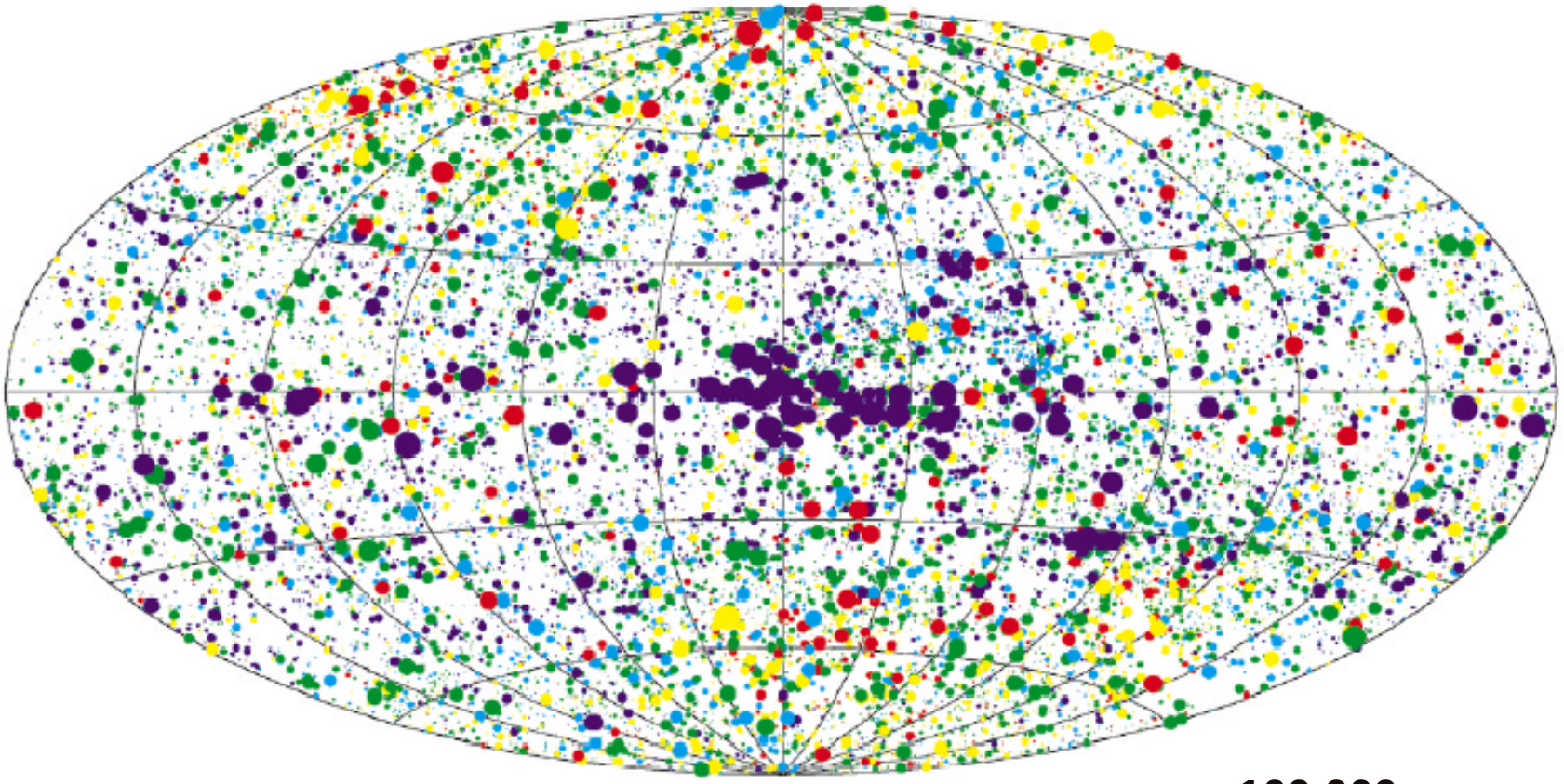


Figure 16. The Observatory Einstein schematic representation. From Giacconi *et al.*, 1979.

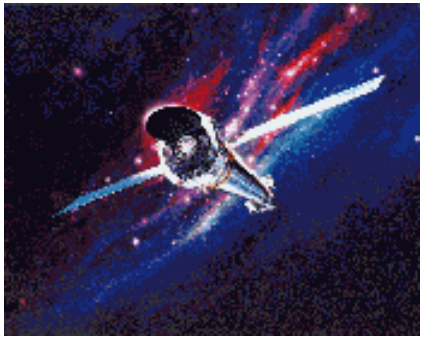


Rosat (1990-1999)

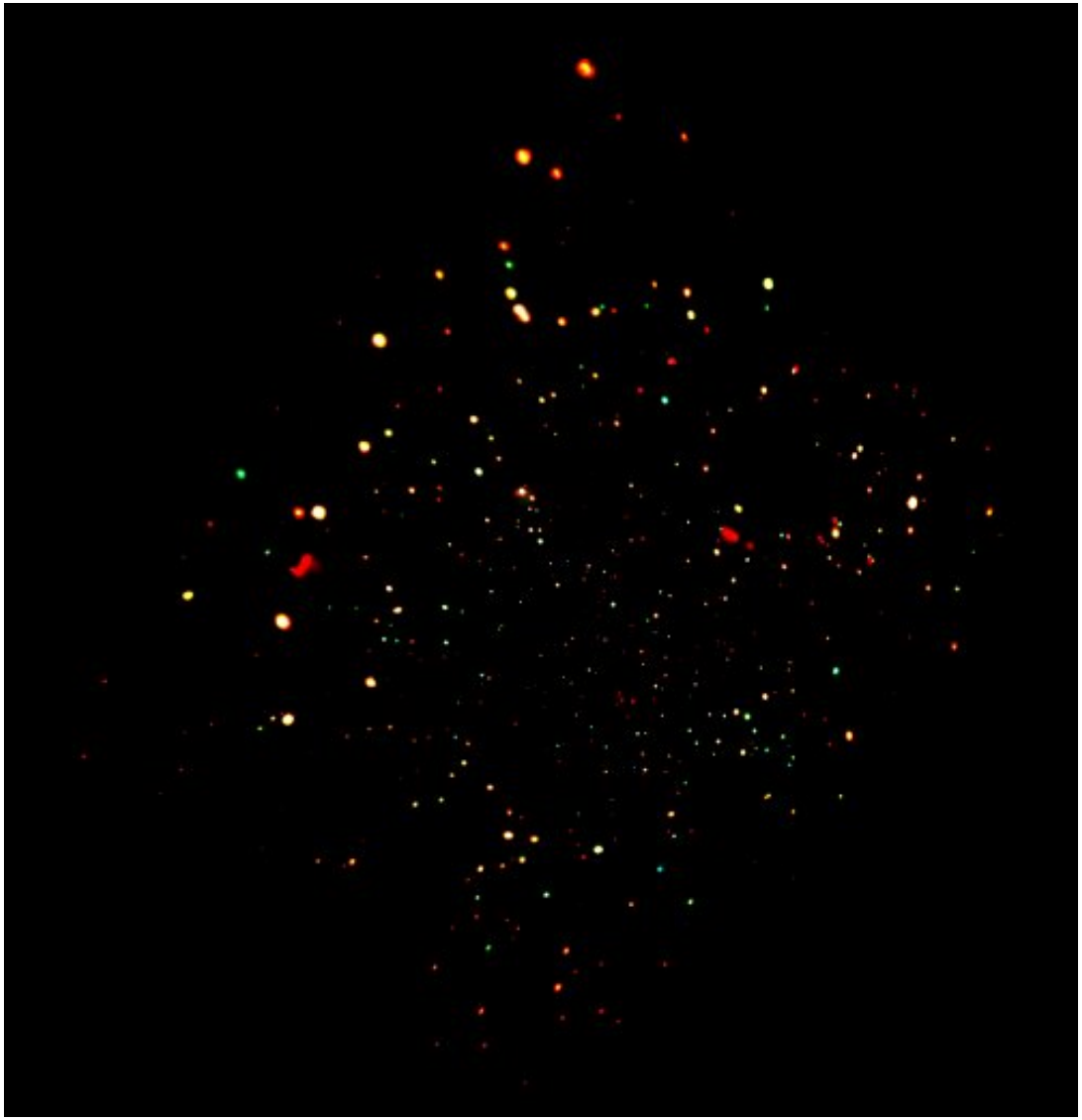


> 100,000 sources

Chandra (1999 -)



Deep exposures with Chandra finally resolved the X-ray background discovered in 1962 into individual sources, mainly AGN



X-Ray Source Counts

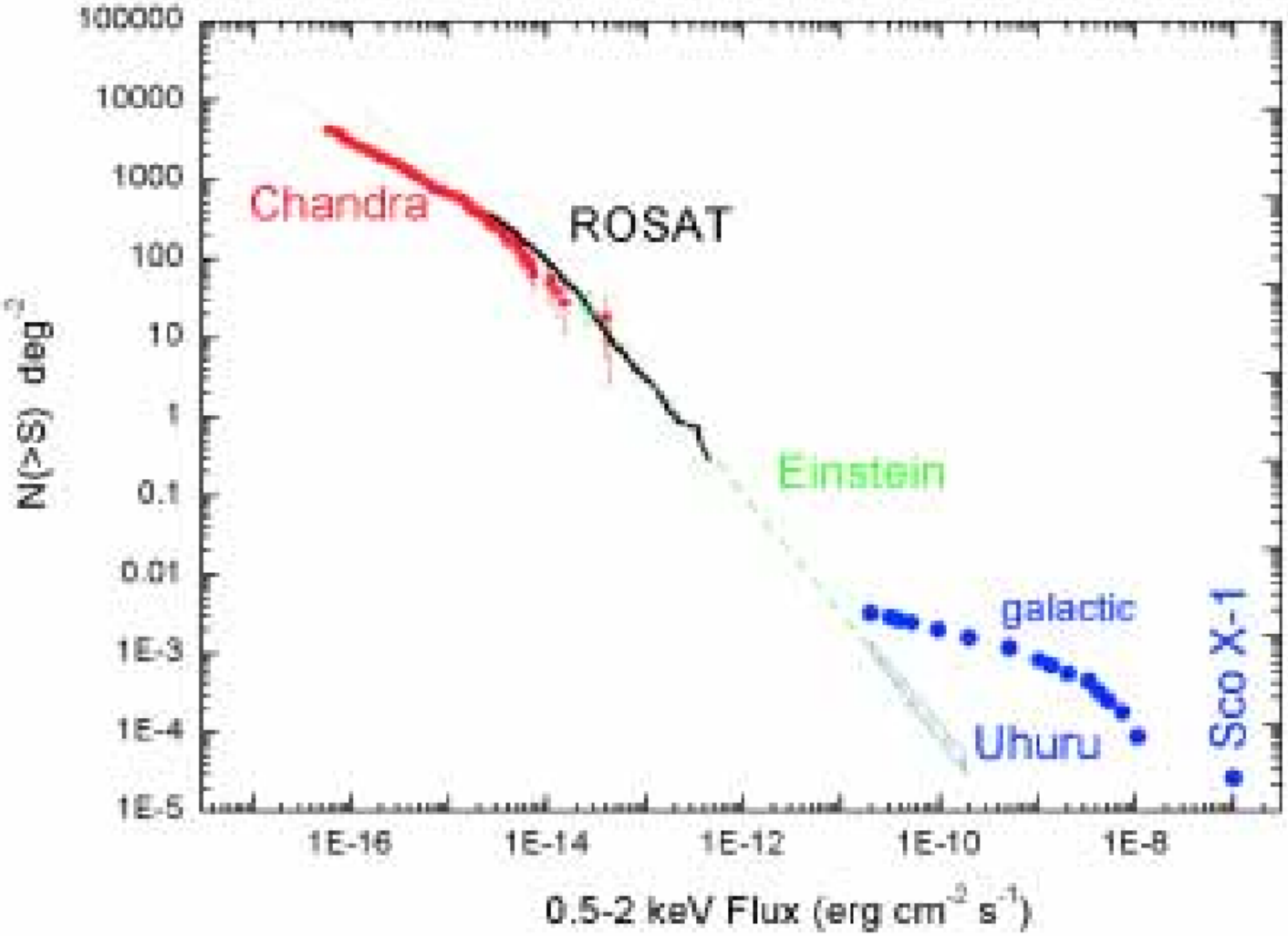
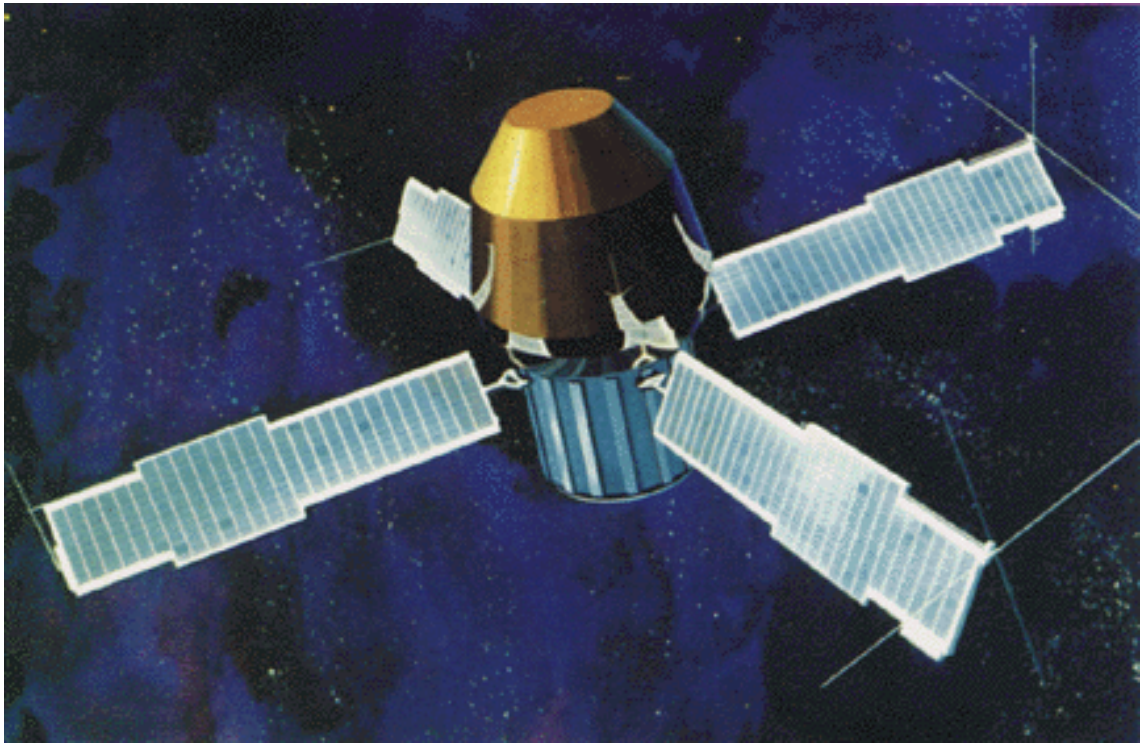


Figure 20. The sensitivity change from 1962 to 2000 (Sco X–1 to Chandra). Courtesy of G. Hasinger.

Gamma-ray instruments

- Space-based
- Ground-based

SAS-2 (1972-1973)

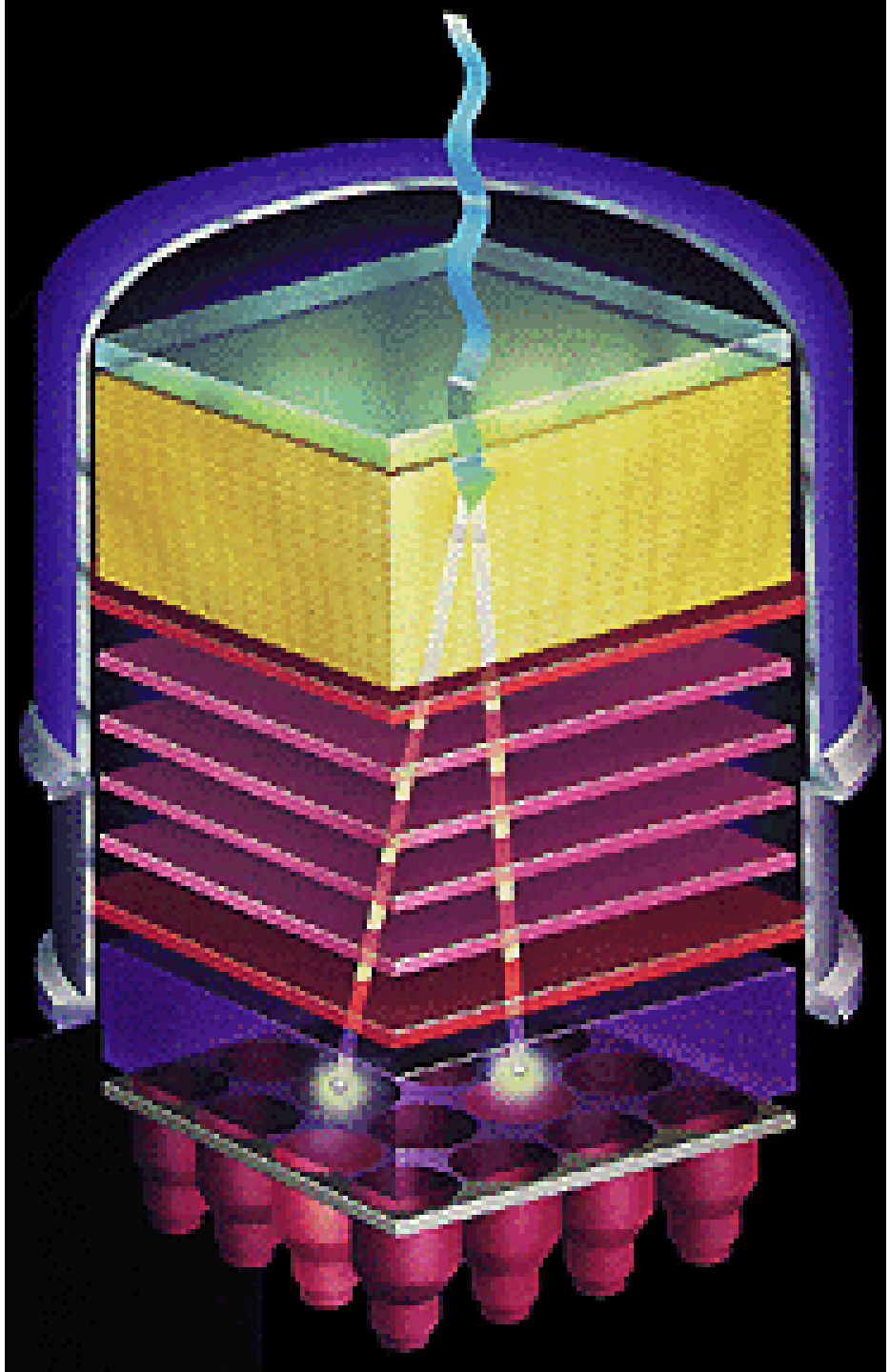


First dedicated gamma-ray satellite

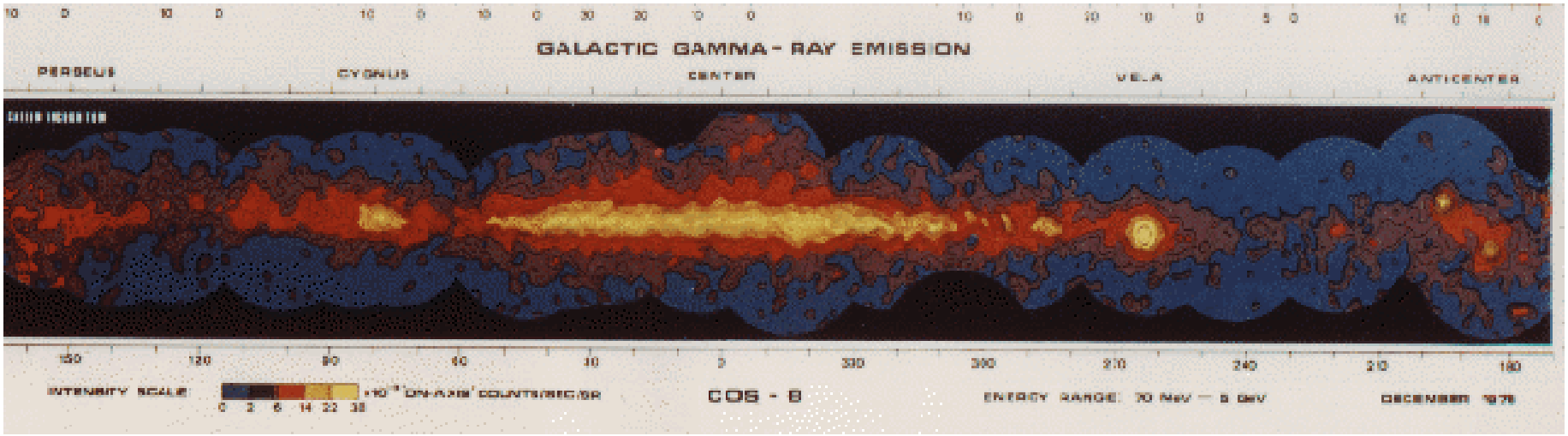
Discovered gamma-ray background

Gamma-ray spark chamber

Gamma-ray converts into electron-positron pair



COS-B (1975-1982)

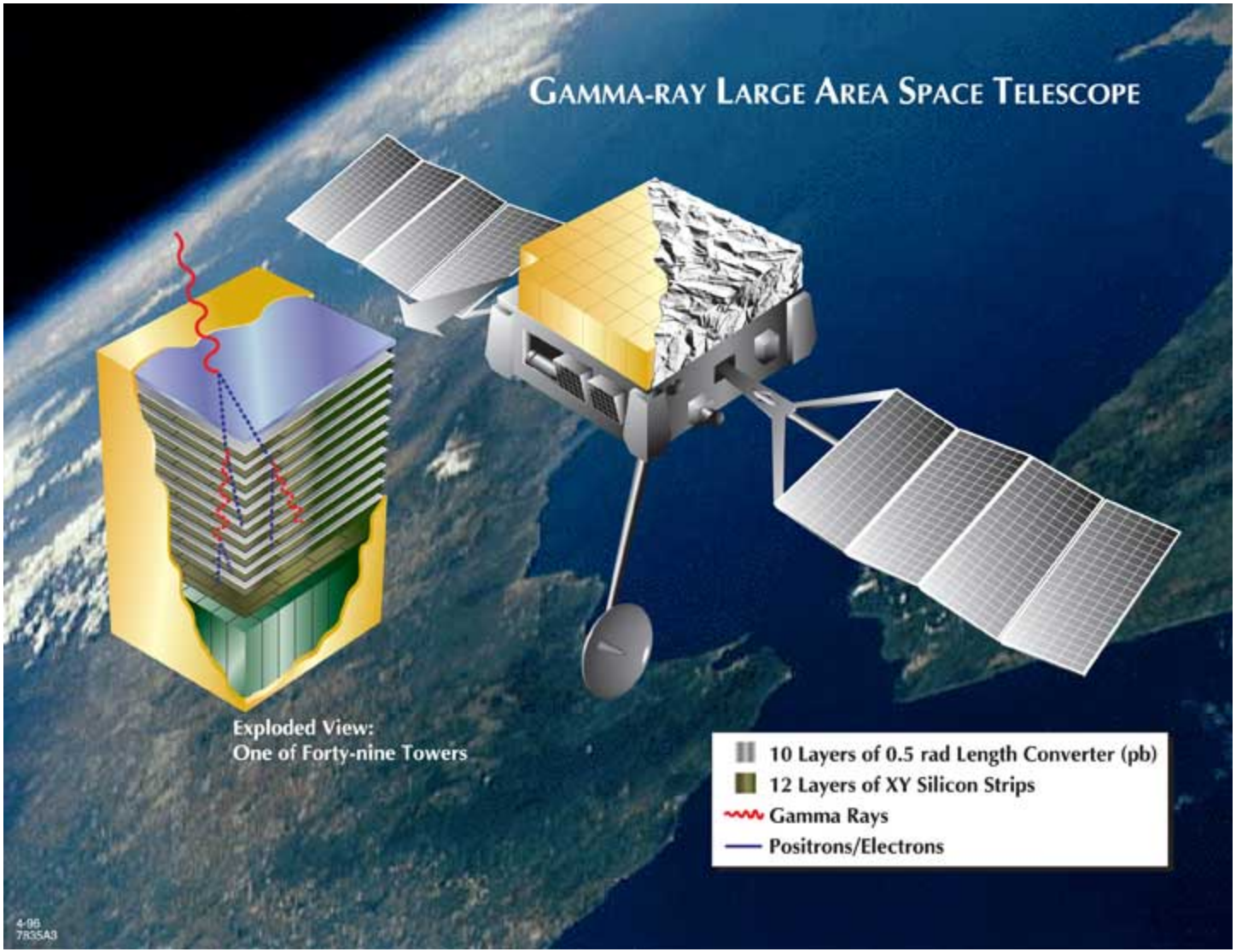


Discovered diffuse emission from Galactic plane and a population of unidentified gamma-ray point sources along the plane

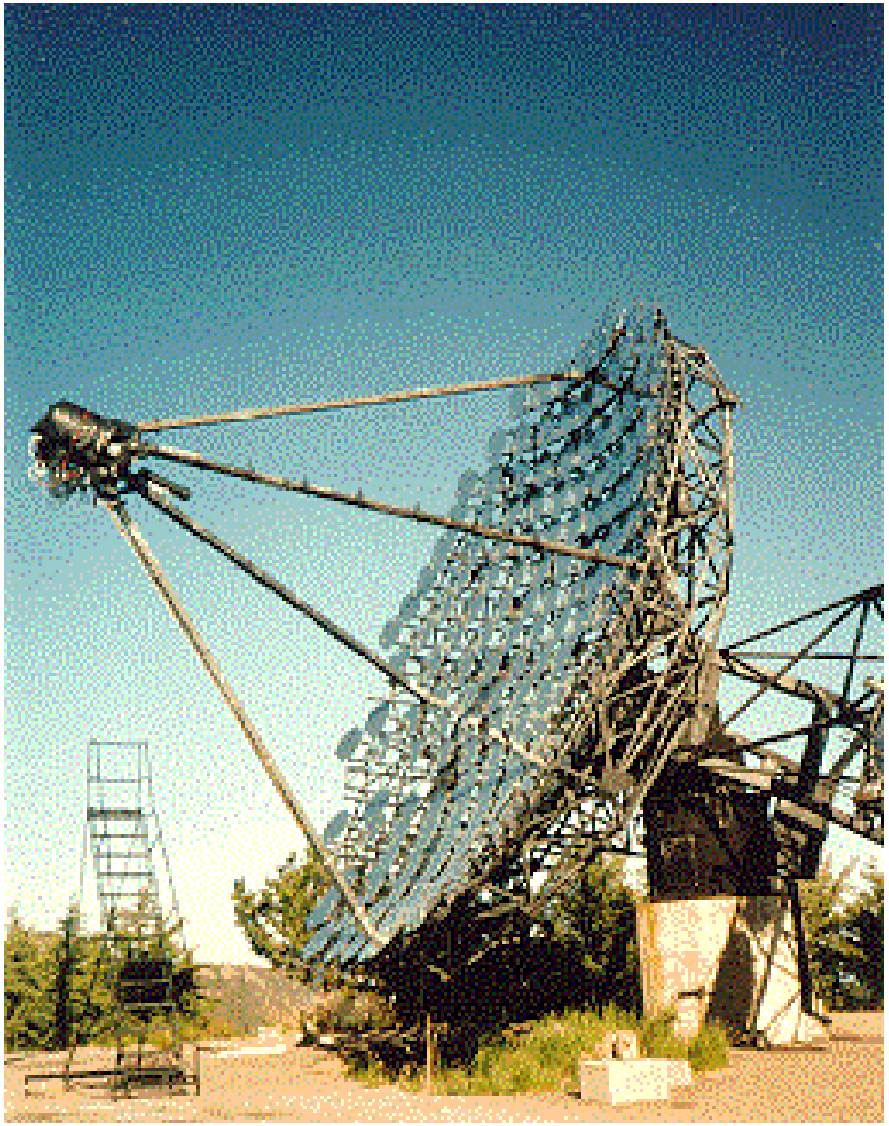
CGRO (1990-2001)

Four instruments covered energy range from 20 keV to 10 GeV. Established AGN as gamma-ray sources, gamma-ray bursts as cosmological.

Fermi (2008-)


GAMMA-RAY LARGE AREA SPACE TELESCOPE
Exploded View:
One of Forty-nine Towers
10 Layers of 0.5 rad Length Converter (pb)
12 Layers of XY Silicon Strips
Gamma Rays
Positrons/Electrons
4-98
7835A3

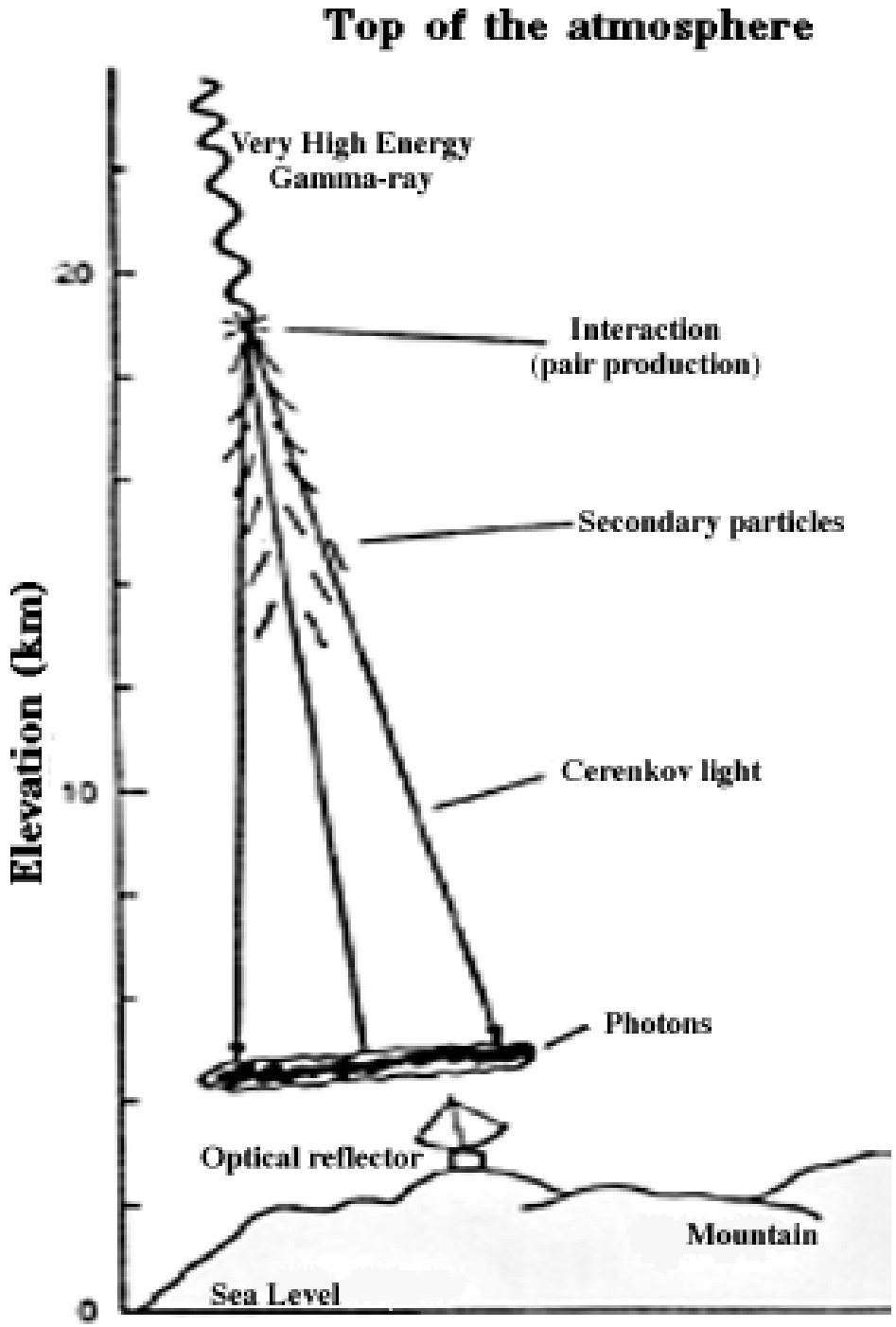
Whipple Air Cherenkov Telescope



10 meter diameter optical reflector

Very fast (nanosecond) camera

Air Cherenkov Telescope



HESS

Started operation in 2004

Major increase in sensitivity relative to Whipple

Discovered dozens of sources along the Galactic plane

VERITAS

Started operation in 2007

Now most sensitive ACT

Currently making discoveries...