High-Energy Astrophysics

Topics:

- X-ray and gamma-ray detection
- X-ray data analysis
- Interstellar medium
- Supernovae, neutron stars and black holes
- Accretion onto compact objects
- Cosmic rays
- Active galactic nuclei
- Gamma-ray bursts (maybe)

Grading

- Grades will be based on problem sets and the research project.
- Students may work together on problem sets, but please write up your own answers.
- We will form small groups for the projects.
- There will be both written and oral presentations of the project. During the oral presentation, questions will be asked of individual students.

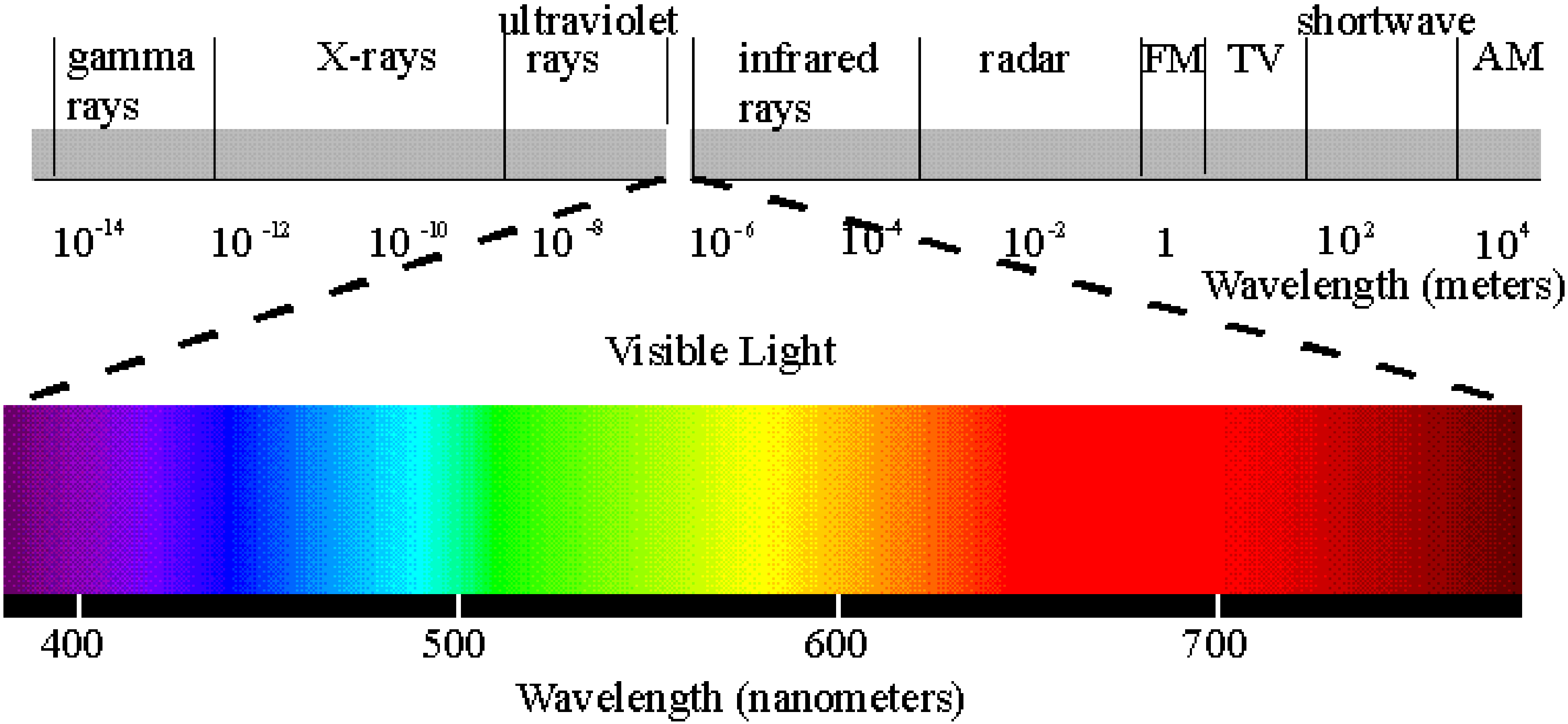
Astronomical Background

Who is comfortable with:

- Astronomical coordinates (RA and DEC)?
- Energy generation in the Sun?
- Stellar evolution on the HR diagram?
- Hubble sequence of galaxies?
- Red versus blue (galaxies)?
- Hot gas in clusters of galaxies?

These topics are covered in chapters 2-4 of Longair.

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

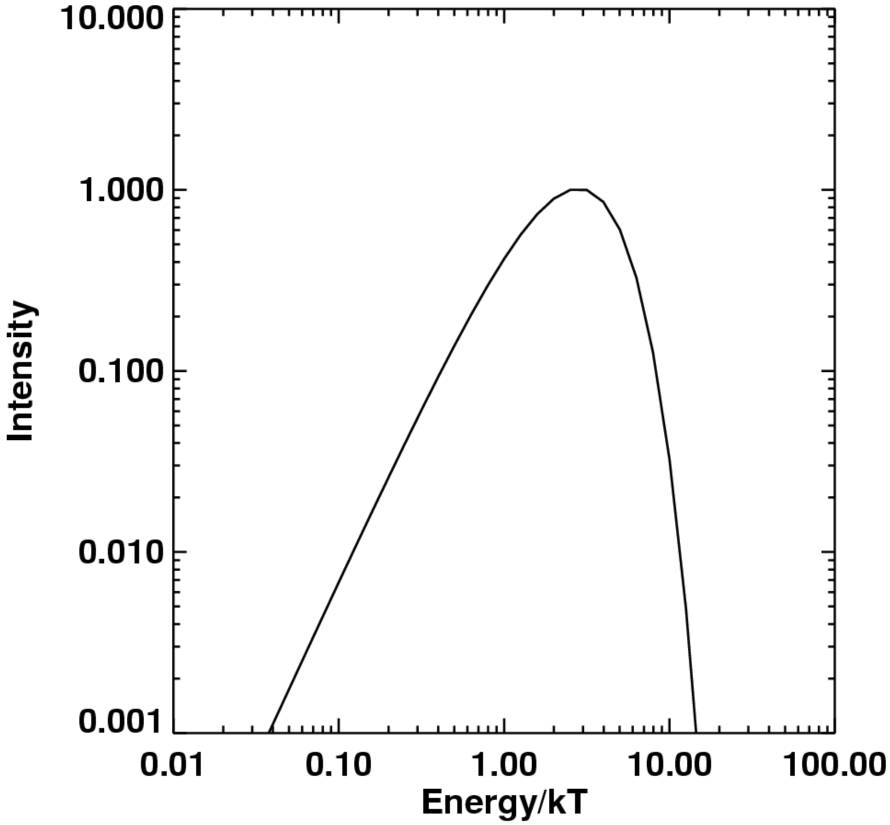
$$E(\text{keV}) = \frac{12.4}{\lambda(\text{Angstroms})}$$

Thermal Radiation

Average kinetic energy of particles is proportional to temperature

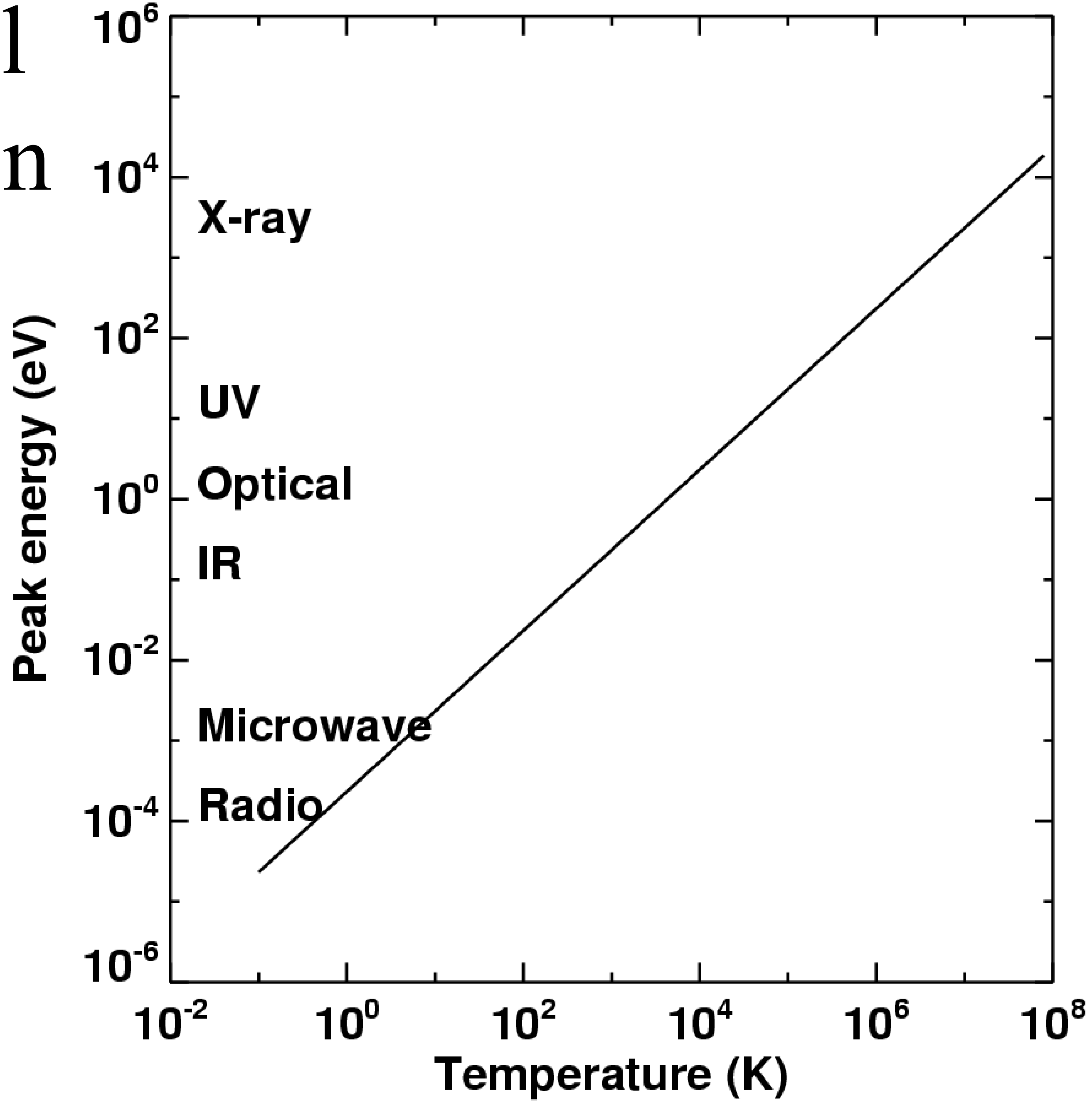
$$K = \frac{1}{2}mv^2 = \frac{3}{2}kT$$

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)
- X-rays are defined to have energies $\geq$ 100 eV.
- 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

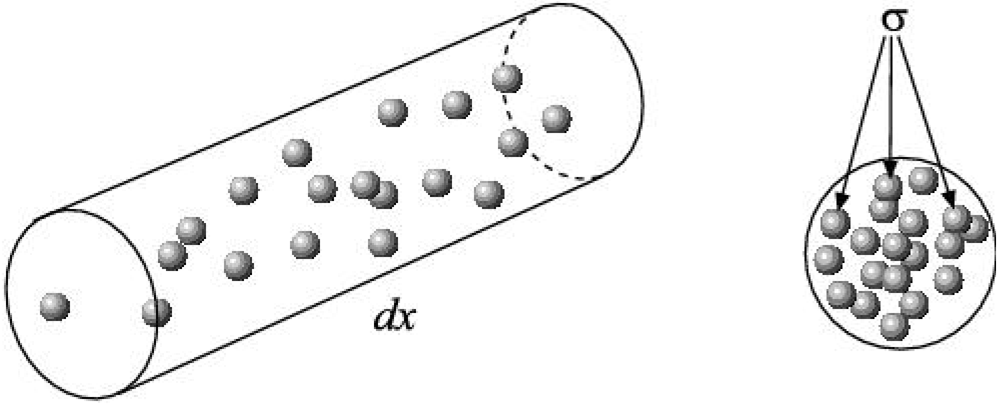
- Extreme temperatures (X-ray emitting plasma)
- Extreme densities (black holes and neutron stars)
- Extreme magnetic fields (near neutron stars)
- Extreme velocities (jets from black holes)
- Extreme explosions (gamma-ray bursts)

Detecting high energy photons

Interactions of photons with matter

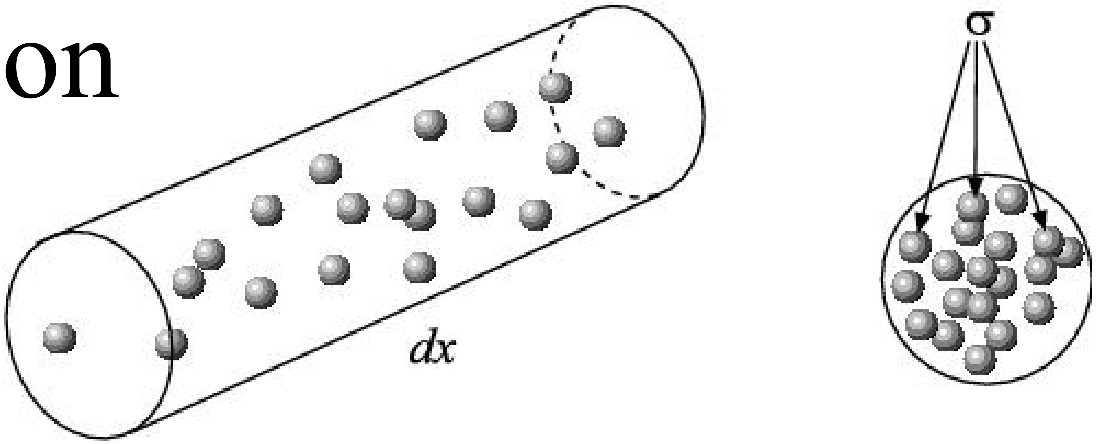
- Cross section/attenution length/optical depth
- Photoelectric absorption
- Compton scattering
- Electron-positron pair production

Cross Section



- Think about scattering of a point particle off of spherical targets.
  - Scattering is more likely for larger targets, probability $\propto$ area.
- We characterize the targets via their “cross section” = σ, units of cm^2.
- Note that cross section usually has nothing to do with the physical size of the particle, but instead with the strength of the interaction.

Cross section



- If the number density of scatters is n, then the typical number of interactions that a particle will undergo while traversing a distance dx is # interactions = $n\,\sigma\,dx$.
- Attenuation length $l = 1/n\sigma$, where n is density of atoms
- Attenuation of beam $I = I_0 \exp(-x/l)$ - *why exponential?*
- We often use the mass attenuation coefficient, μ/ρ, which is the cross second per mass (cm^2/g), where ρ is density
- Then attenuation length $l = 1/\mu = 1/[\rho(\mu/\rho)]$

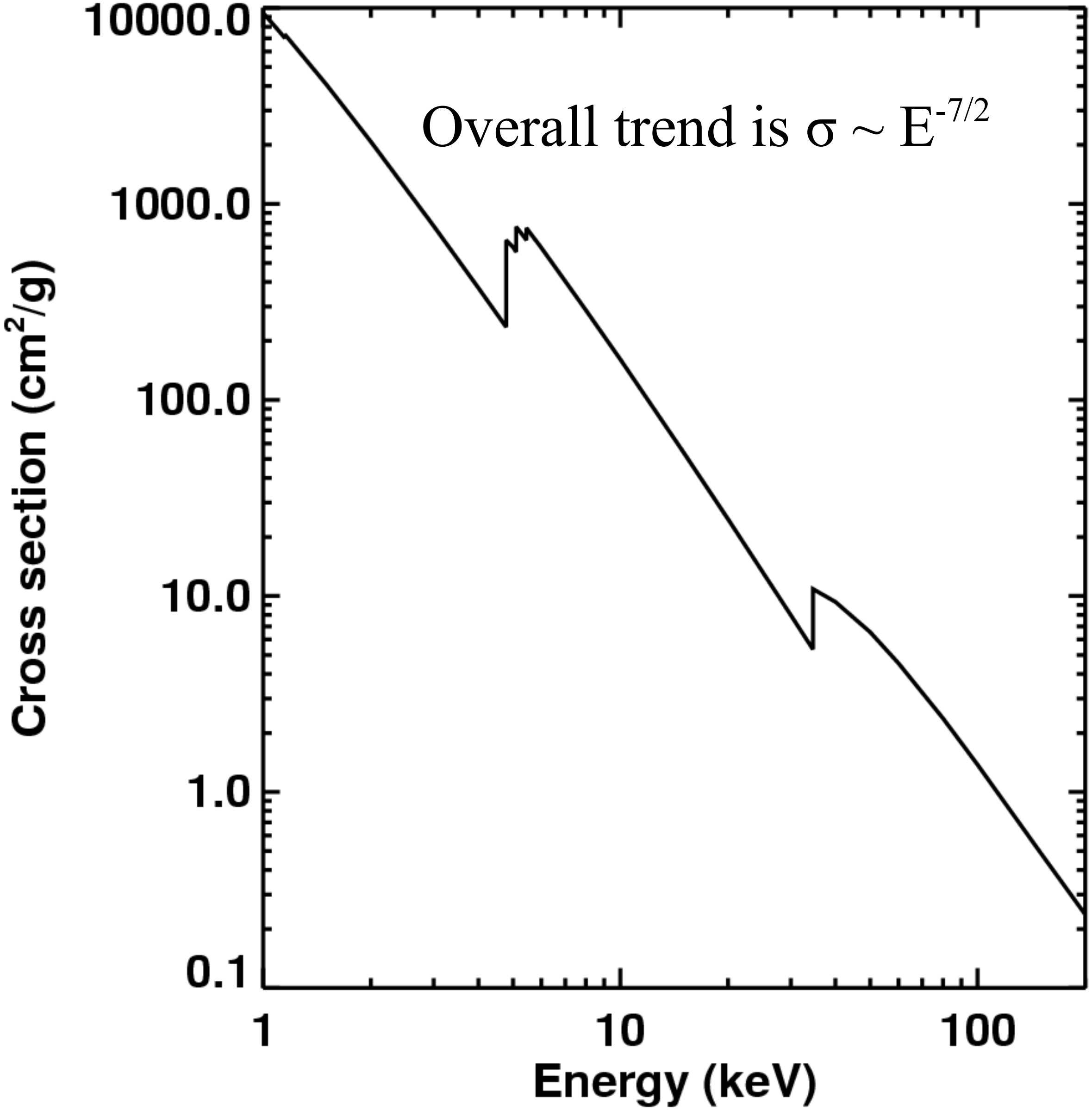
Three interactions

- Photoelectric absorption
  - Photon is absorbed by atom
  - Electron is excited or ejected
- Compton scattering
  - Photon scatters off an electron
- Pair production
  - Photon interacts in electric field of nucleus and produces an e+ e^- pair

- Useful web site for photon cross sections is:

http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html

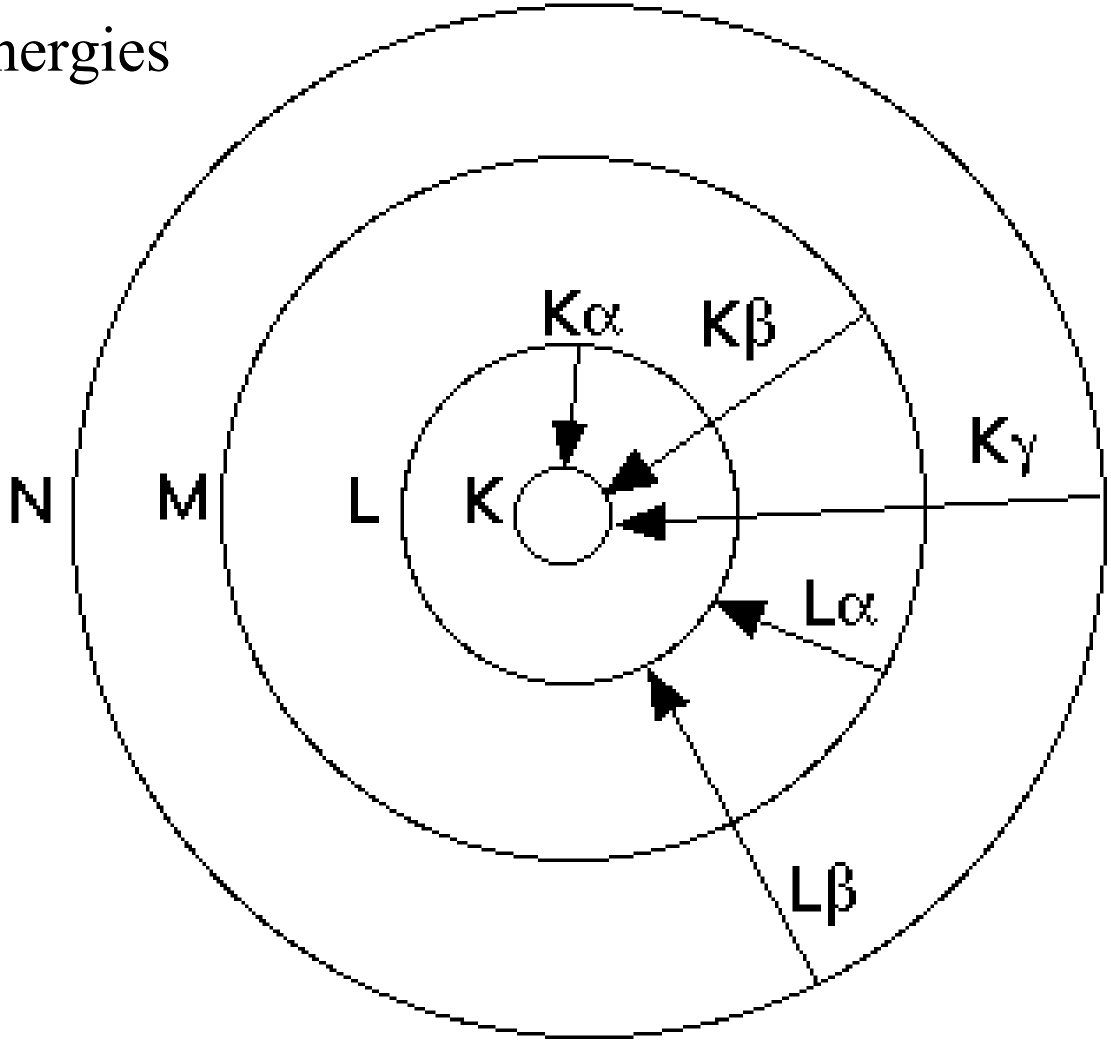
Photoelectric cross section in Xe



- Why are there edges?
- Why does cross section increase across an edge?

Photoelectric absorption

“Edges” occur at the characteristic electronic transition energies



When in emission, elements produce characteristic lines at these energies

Photoelectric absorption

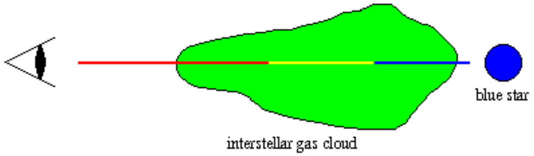
The photon electric cross-section scales with Z^5

This means that high-Z detectors are more efficient at high energies.

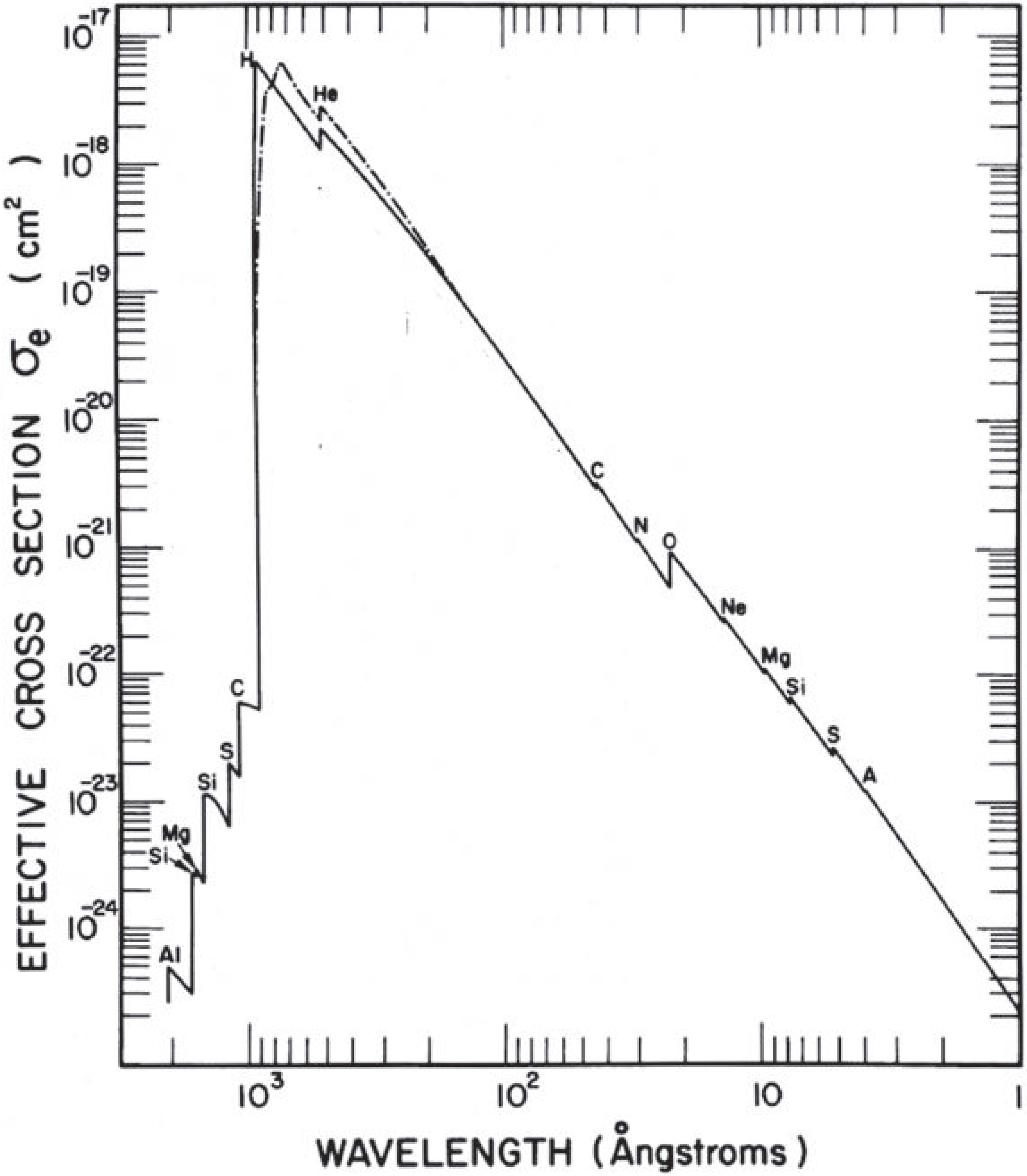
Over all shape of cross-section scales roughly as (energy)$^{-7/2}$.

This means that photo-absorption detectors rapidly become inefficient at high energies.

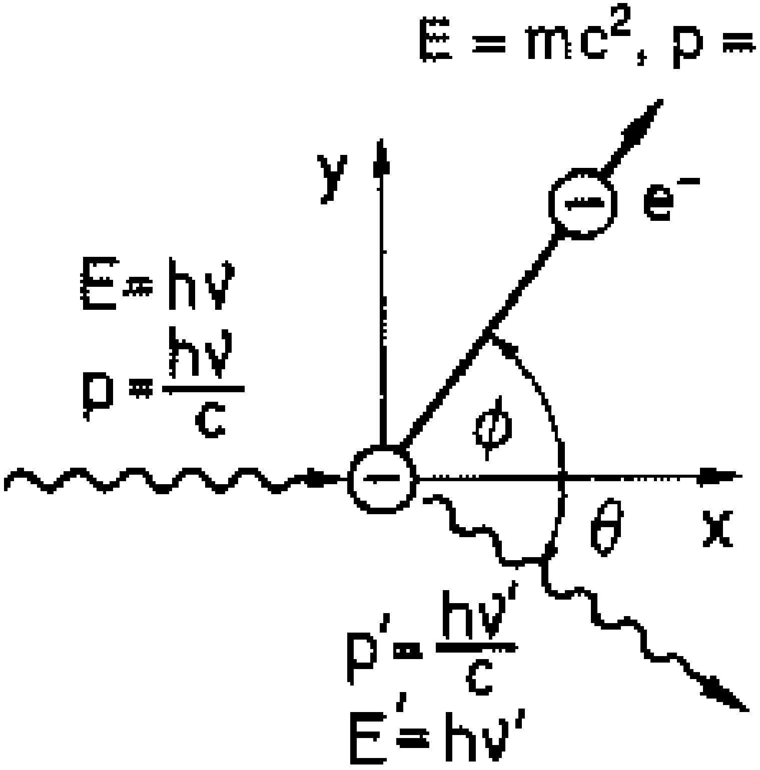
Interstellar absorption



Cross section versus wavelength for material with 'cosmic' abundances, meaning ratio of each element to H equals that in the Sun.



Compton scattering



$$E' = E\left[1 + \frac{E}{mc^2}\left(1 - \cos\theta\right)\right]^{-1}$$

Compton scattering

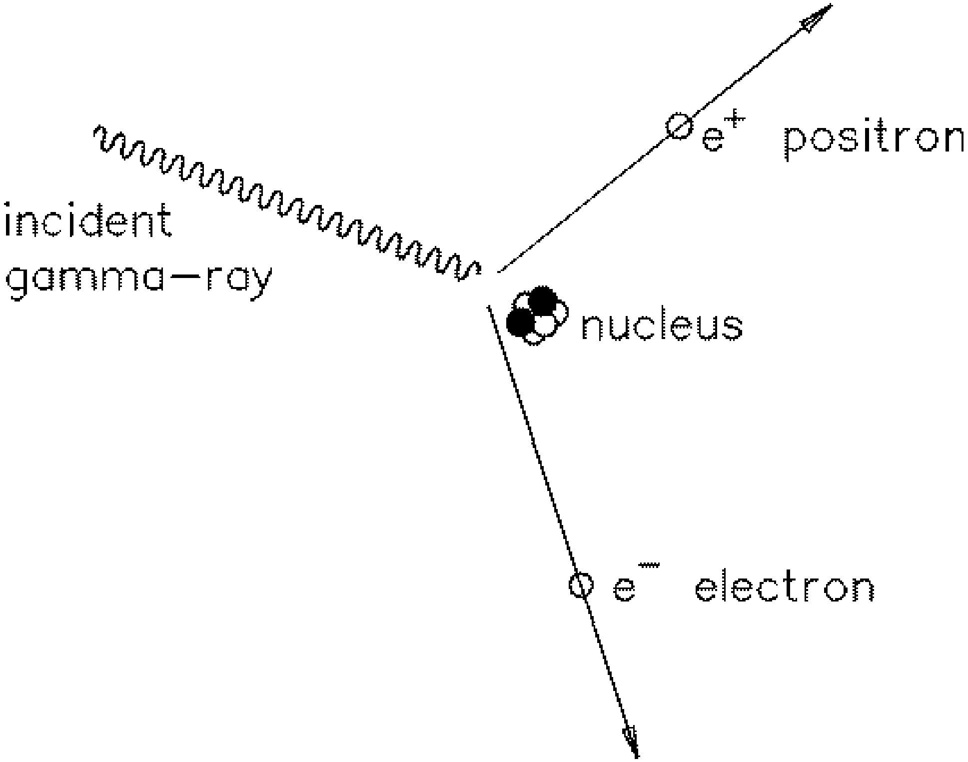
$$\mathrm{E} \ll \mathrm{mc}^2 \Rightarrow \sigma = \sigma_T = 6.653 \times 10^{-29}\, m^2$$

$$\mathrm{E} \gg \mathrm{mc}^2 \Rightarrow \sigma = \frac{3}{8}\sigma_T \frac{E}{mc^2} \ln\left(\frac{2E}{mc^2} + \frac{1}{2}\right)$$

For an electron at rest, the photon loses energy.

A moving electron can increase the photon energy. This is "inverse-Compton" scattering.

Pair Production

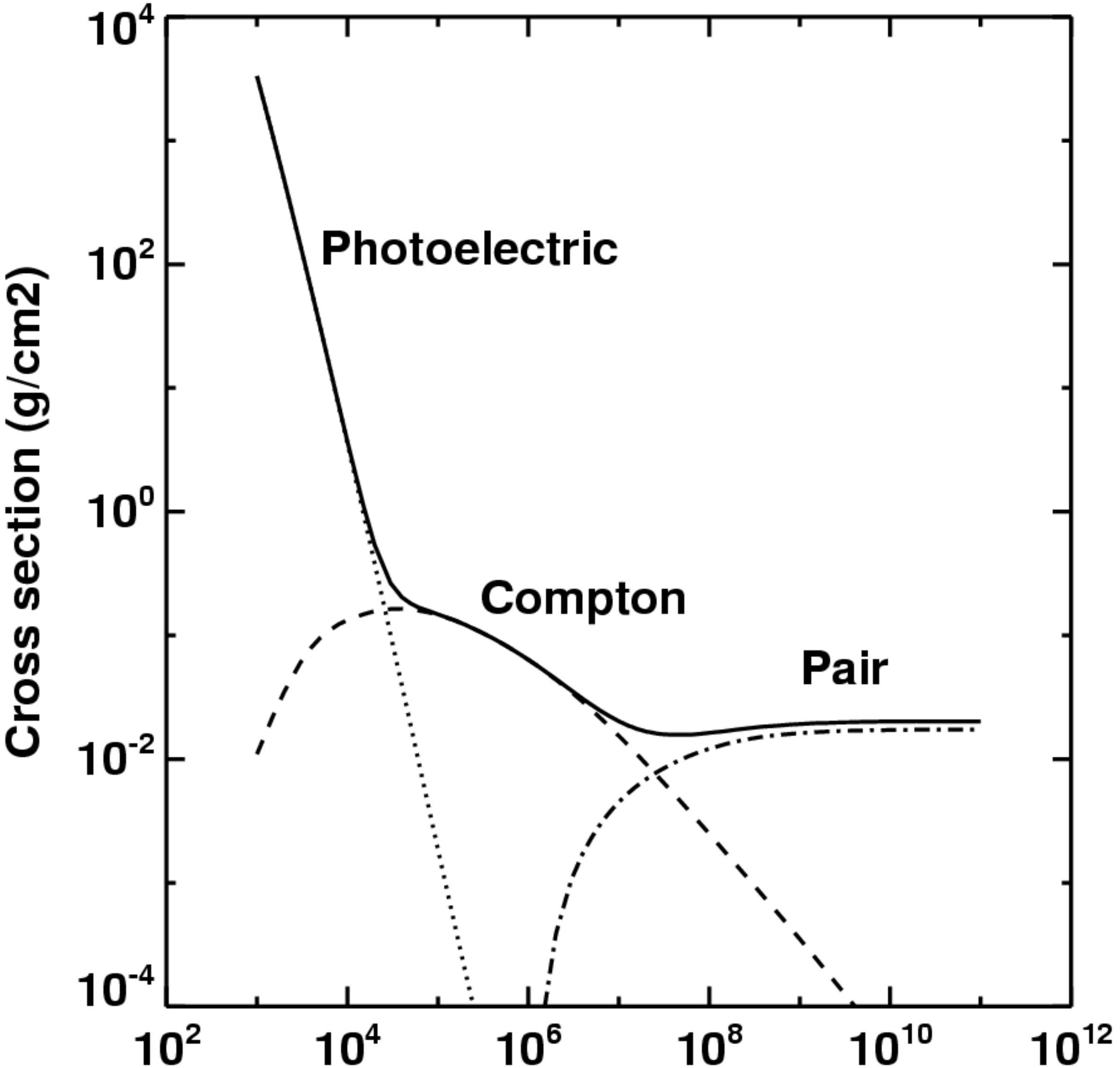


Nucleus is needed for process to converse momentum and energy

$$\sigma \propto Z^2$$

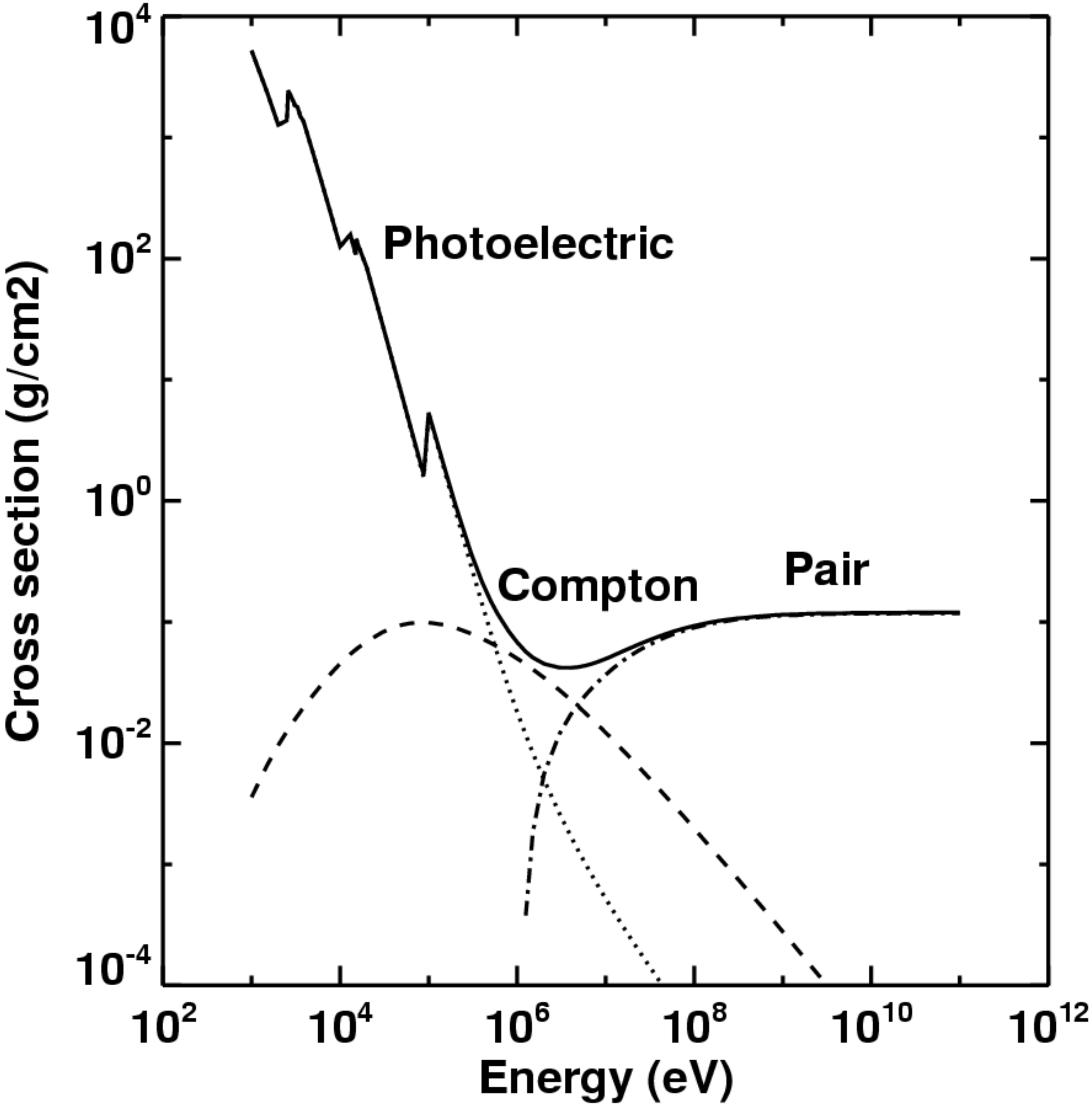
Only process with cross section which never decreases with energy, dominates at high energies

Photon Cross Sections in Nitrogen



Use different interactions to build detectors for different energy ranges.

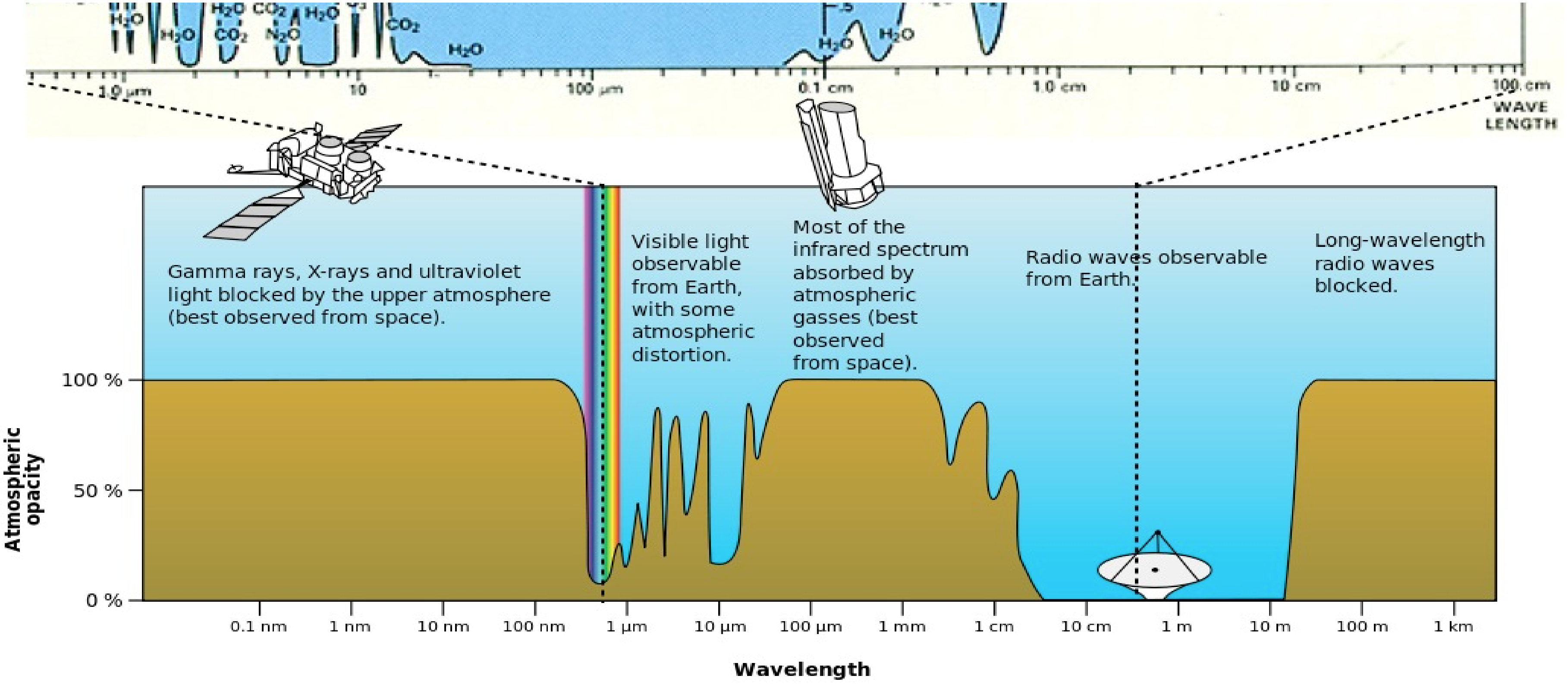
Photon Cross Sections in Lead



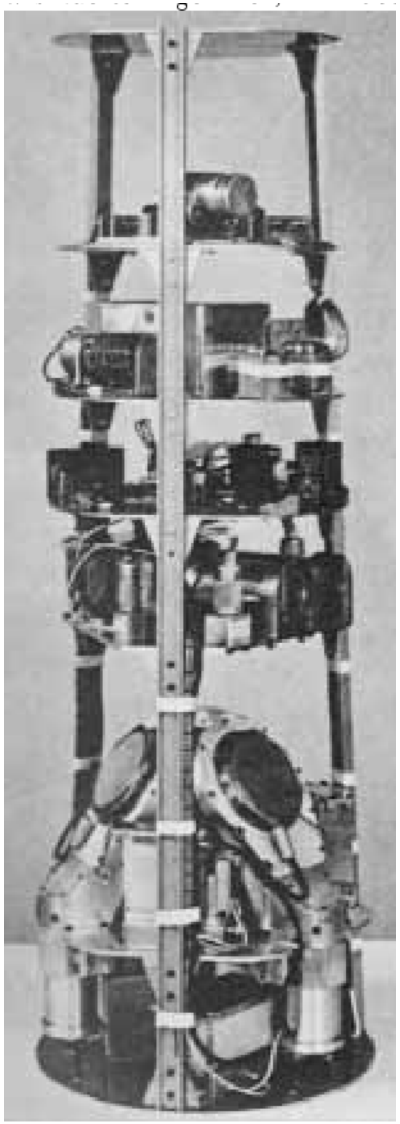
Can also use different materials.

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



Rocket Flight (1962)



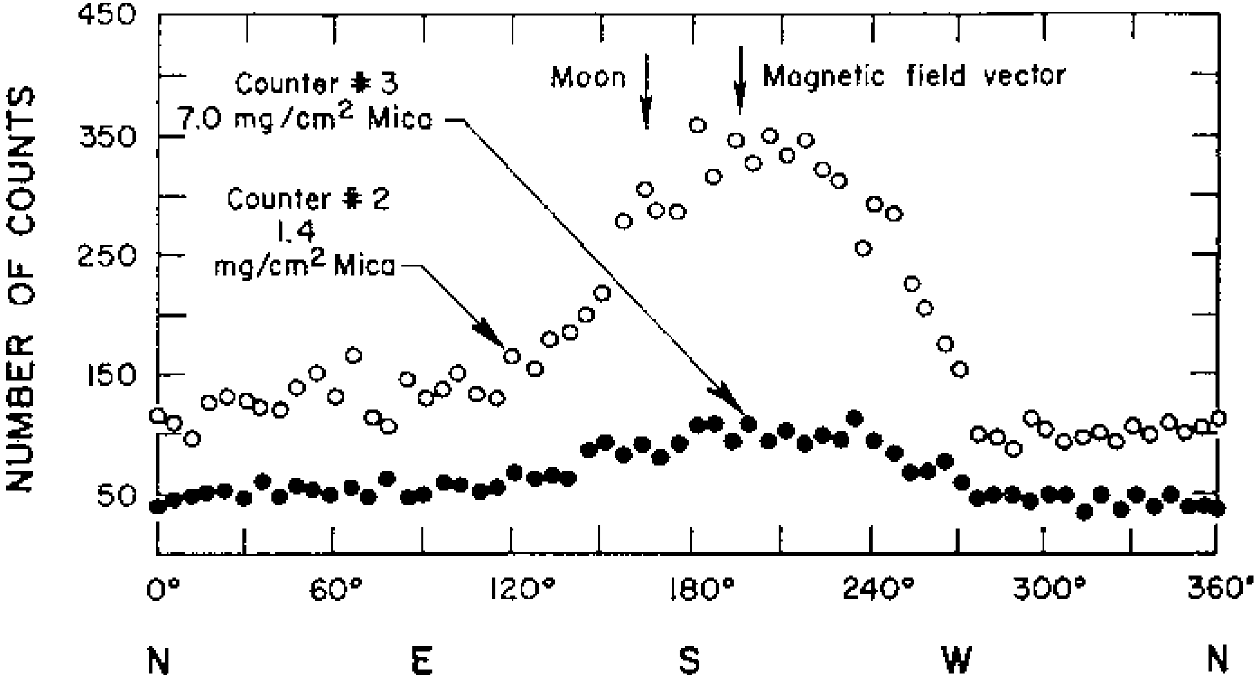
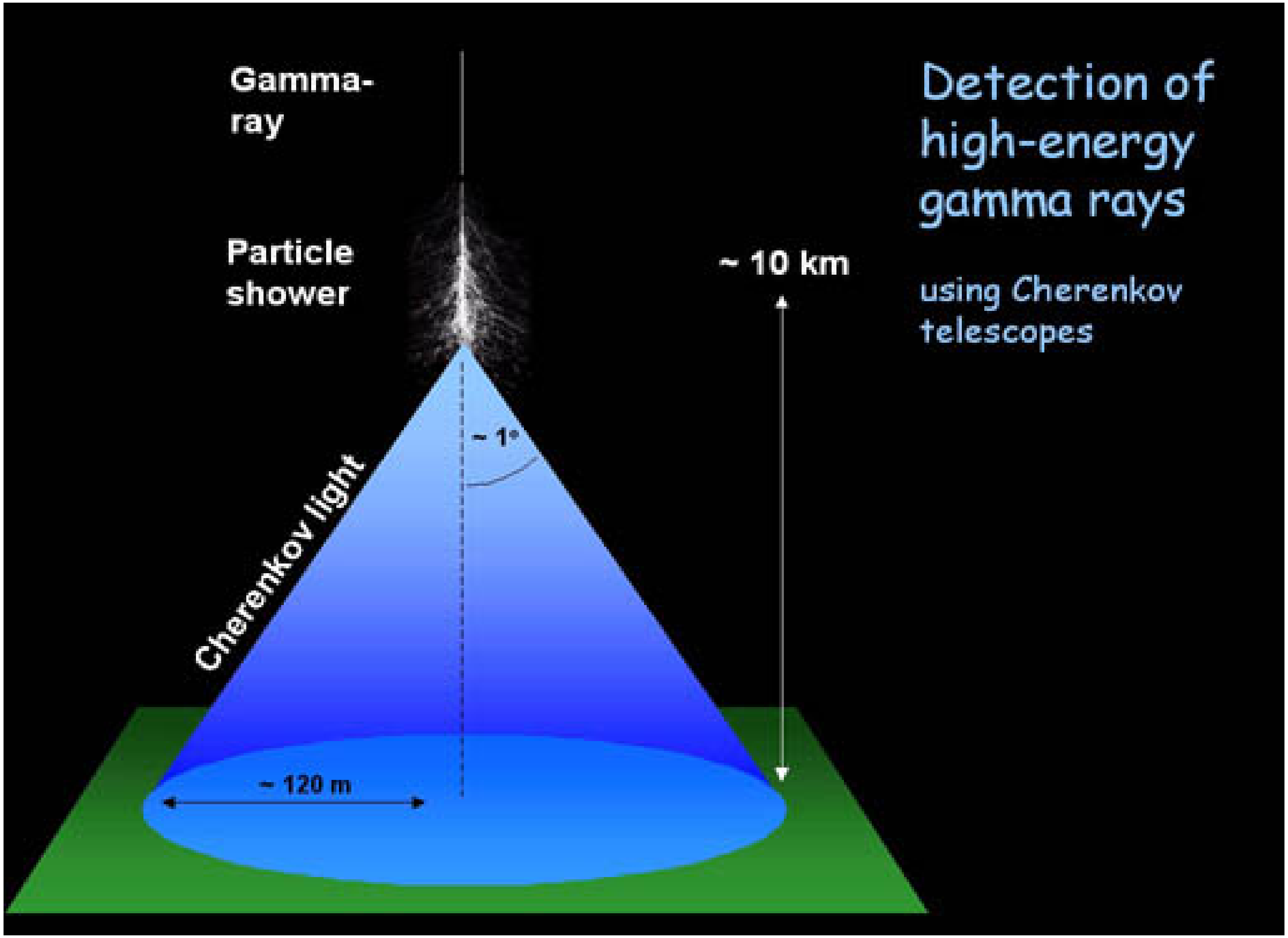


Figure 2. The first observation of Sco X–1 and of the x–ray background in the June, 12, 1962 flight. From Giacconi, *et al.*, 1962.

Air Cherenkov Telescope



VERITAS

Started operation in 2007

Still making discoveries...