Space-based Gamma-ray Astronomy

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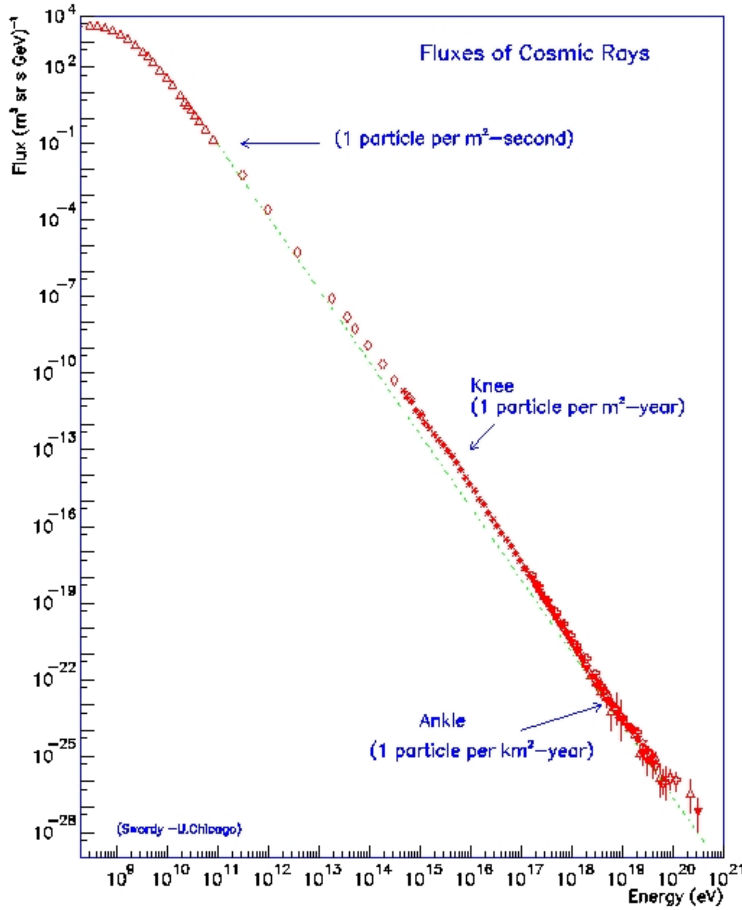
The Origin of Cosmic Rays

Victor Hess and his “Flight Ops Team”, 1912

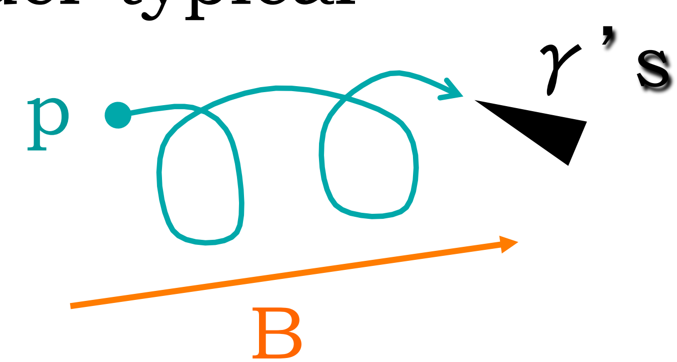


Credit S. Swordy

How to make gamma rays

From protons

- Pion decay
  - Accelerated protons (p) interact with matter
  - $p \; p \rightarrow X + \pi_0 \rightarrow \gamma \; \gamma$
- Proton Synchrotron Emission
  - Depends on magnetic field strength (not dominant under typical conditions)



How to make gamma rays

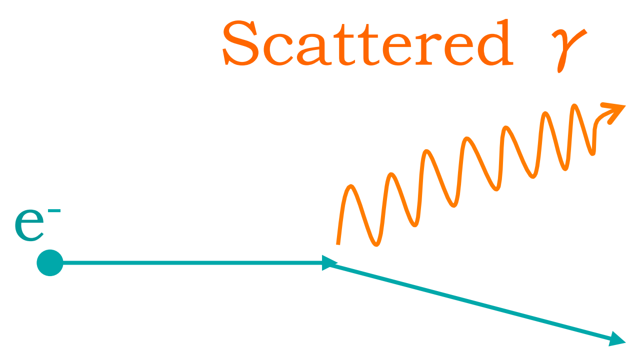
From electrons

- Inverse Compton Scattering
  - Collide highly relativistic electrons with photons from stars or the microwave background

$$e^- + \gamma_{\text{Low E}} \rightarrow e^- + \gamma$$

$$E_\gamma \propto (\gamma_{\text{Lorentz}})^2 E_{\gamma \text{ low E}}$$

$$\gamma_{\text{Lorentz}} = 1/\sqrt{(1 - v_e^2/c^2)}$$



Arthur Holly Compton

- Nobel Prize in Physics 1927
  - Scattering of photons by electrons demonstrated the particle nature of electromagnetic radiation
  - This and inverse mechanism are responsible for much of gamma ray production and detection

scattering electron in motion at an angle of less than 90° with the primary beam. But it is well known that the energy radiated by a moving body is greater in the direction of its motion. We should therefore expect, as is experimentally observed, that the intensity of the scattered radiation should be greater in the general direction of the primary X-rays than in the reverse direction.

The change in wave-length due to scattering.—Imagine, as in Fig. 1*A*,

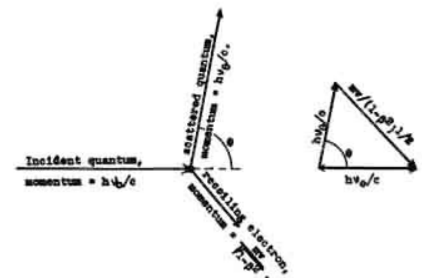


Fig. 1 A Fig. 1 B

that an X-ray quantum of frequency ν_0 is scattered by an electron of mass m. The momentum of the incident ray will be $h\nu_0/c$, where c is the velocity of light and h is Planck's constant, and that of the scattered ray is $h\nu_\theta/c$ at an angle θ with the initial momentum. The principle of the conservation of momentum accordingly demands that the momentum of recoil of the scattering electron shall equal the vector difference between the momenta of these two rays, as in Fig. 1*B*. The momentum of the electron, $m\beta c/\sqrt{1-\beta^2}$, is thus given by the relation

$$\left(\frac{m\beta c}{\sqrt{1-\beta^2}}\right)^2 = \left(\frac{h\nu_0}{c}\right)^2 + \left(\frac{h\nu_\theta}{c}\right)^2 + 2\frac{h\nu_0}{c}\cdot\frac{h\nu_\theta}{c}\cos\theta, \qquad (1)$$

where β is the ratio of the velocity of recoil of the electron to the velocity of light. But the energy $h\nu_\theta$ in the scattered quantum is equal to that of the incident quantum $h\nu_0$ less the kinetic energy of recoil of the scattering electron, *i.e.*,

$$h\nu_\theta = h\nu_0 - mc^2\left(\frac{1}{\sqrt{1-\beta^2}} - 1\right). \qquad (2)$$

We thus have two independent equations containing the two unknown quantities β and ν_θ. On solving the equations we find

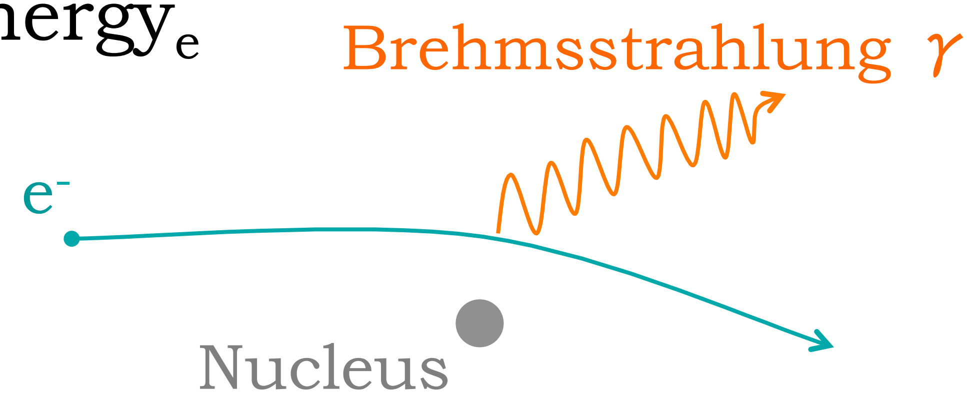
$$\nu_\theta = \nu_0/(1 + 2\alpha \sin^2 \tfrac{1}{2}\theta), \qquad (3)$$

AIP Center for History of Physics
http://www.aip.org/history/

How to make gamma rays

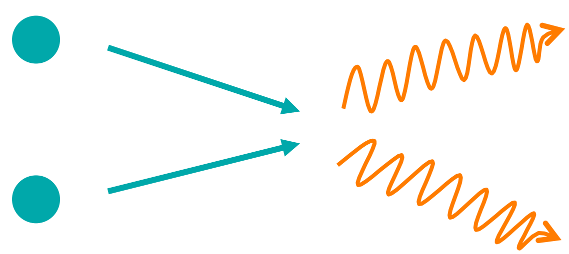
From electrons

- Brehmsstrahlung (deceleration radiation)
  - Electron deceleration by a nucleus
  - Highly relativistic electrons emit gamma rays in atomic or molecular material
  - $\text{Energy}_{\gamma} \sim \text{Energy}_{e}$



Other ways to make gamma rays?

- Topological defects left over from the Big Bang?
  - Hypothesis: Black holes formed with the early Universe decay
- By-product of dark matter interactions?
  - Hypothesis: weakly interacting massive particles (WIMPs) interact to produce gamma rays: DM + DM $\rightarrow \gamma\ \gamma$

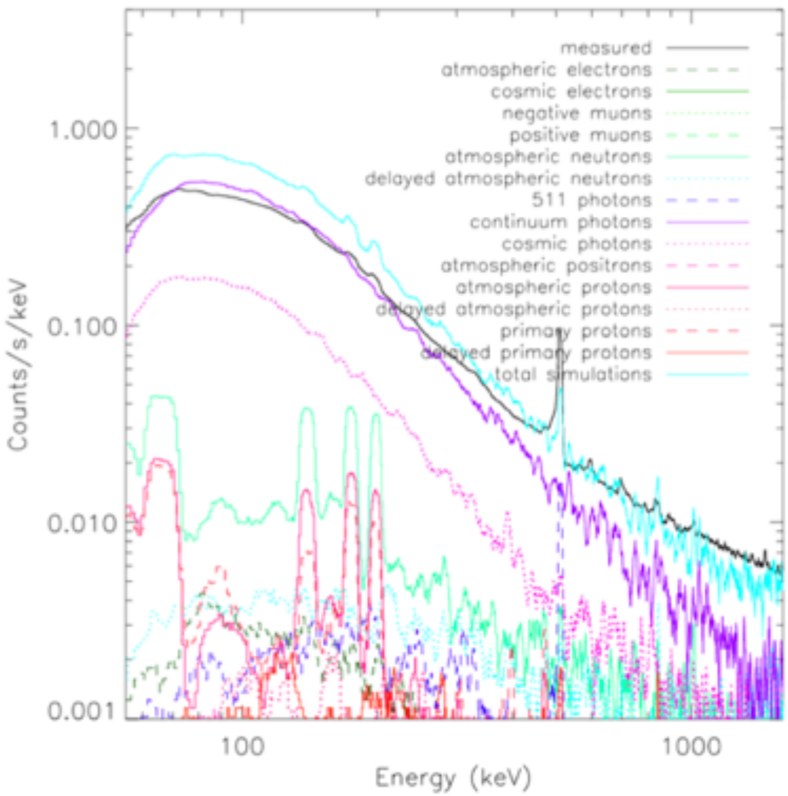


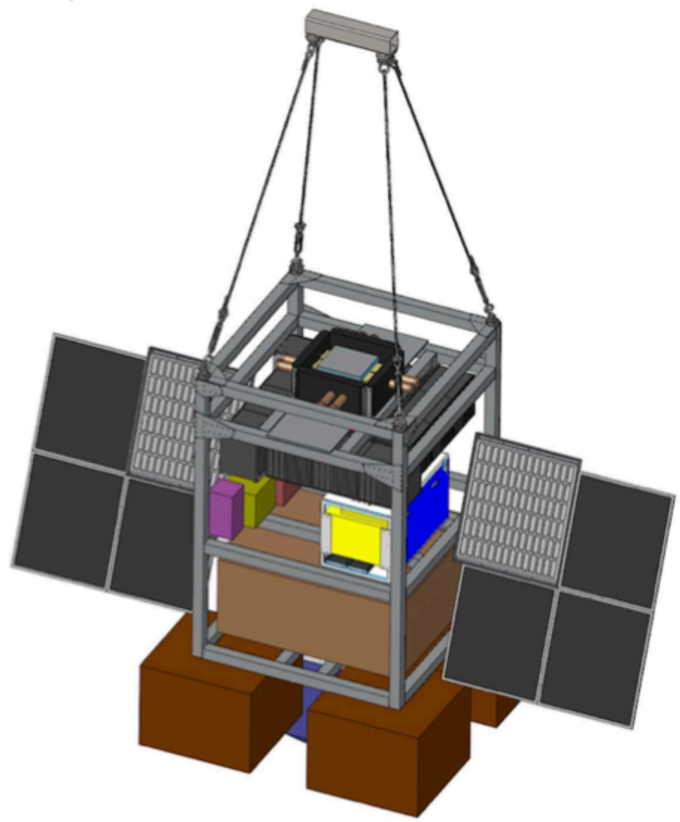
WIMP + WIMP $\rightarrow \gamma + \gamma$

Why look for cosmic gamma rays?

- Supernova explosions release radioactive isotopes
- Cosmic rays are mostly protons
- Radio and later X-ray observations
  - Synchrotron emission from populations of accelerated electrons
- Infrared, optical, and UV observations
  - Target material and low energy photon populations

NB: we still use balloons, too





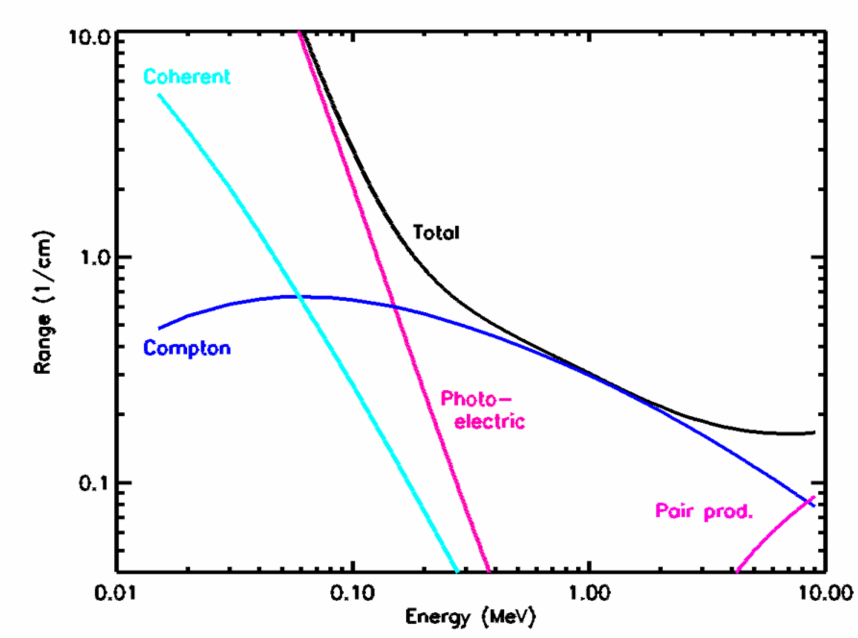
Nuclear Compton Telescope.
Credit: S. Boggs/NCT collaboration

How to “see” gamma rays

Gamma rays are scattered and absorbed in matter (troublesome for standard focusing techniques)

Cross section depends on material and energy

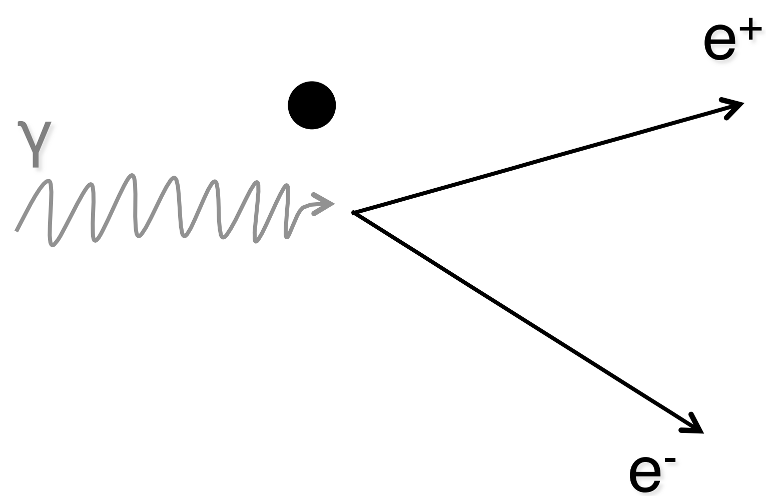
- Coherent Scattering (electron remains bound to atom)
- Photoelectric Effect
- Compton Scattering
- $e^- e^+$ Pair Production



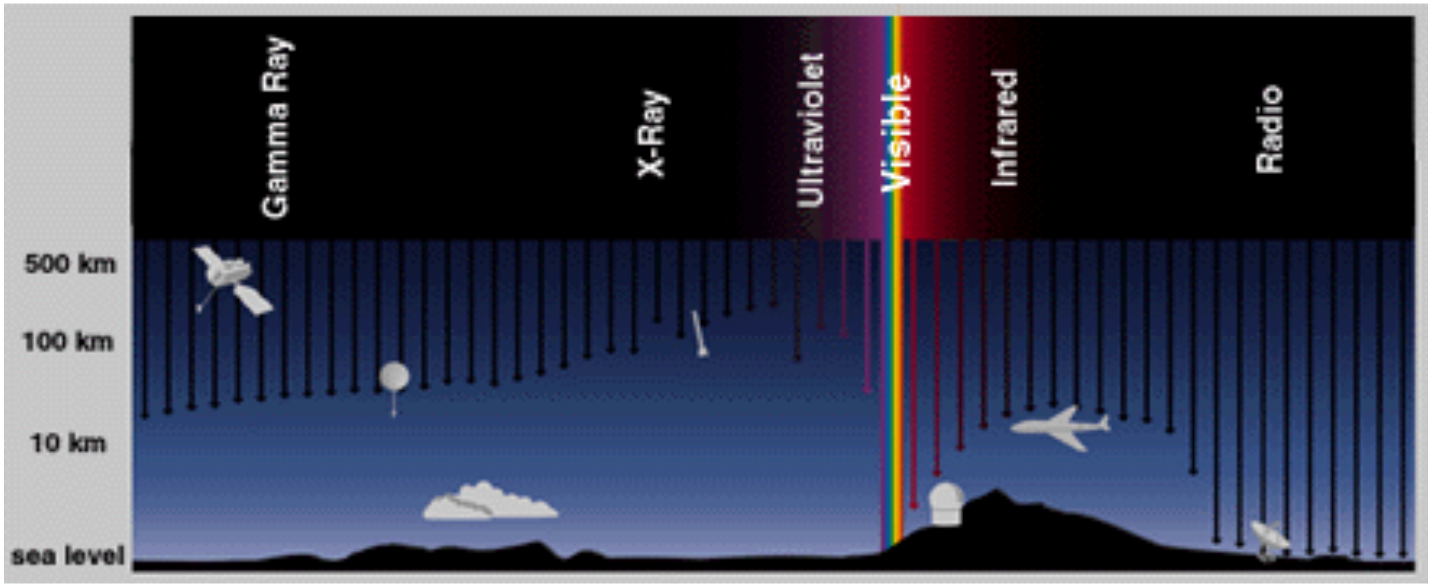
Gamma rays in Germanium
Credit: Richard Kroeger

Pair production

- Gamma ray energy is converted to an electron and positron in the presence of a nucleus



A problem for astronomy



It’s actually pretty hard to observe from the ground.

Black arrows indicate average depth for wavelengths across the electromagnetic spectrum.

Several solutions

- Solution I: put detectors in the upper atmosphere or above it
  - Balloons and rockets
  - Space probes
- Solution II: this is not a problem; it's a detector!
  - Build instruments on the ground that collect the absorption by-products

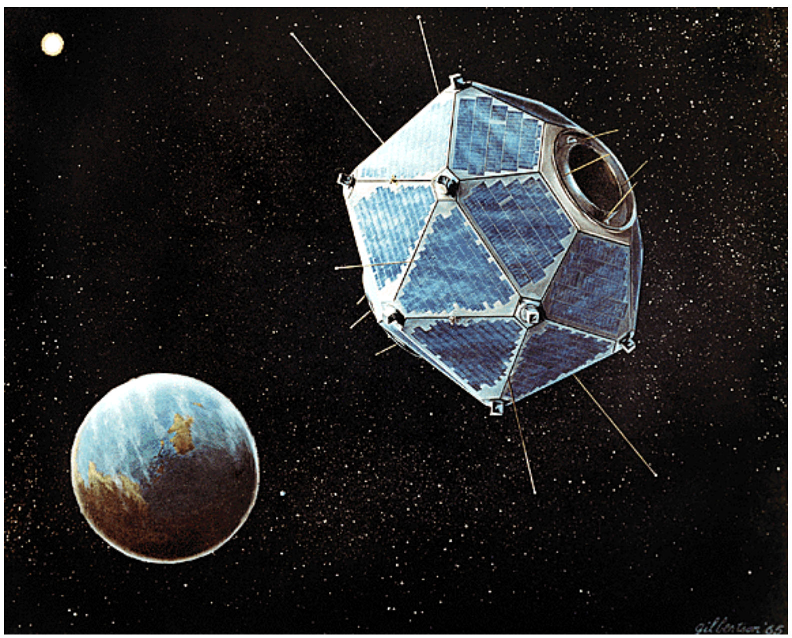
Solution I

Gamma rays with energy below ~50 are detected in space

- Using the Compton Effect: keV – MeV
  - Below a few hundred keV can used X-ray techniques, such as coded masks
- Using pair production: MeV – GeV
  - Above ~50 GeV there are so few gamma rays that satellite detectors, area ~ m^2, are too small

Historical note: Discovery of GRBs by the Vela satellites

- Nuclear weapons test monitoring satellites
  - >70 bursts in the 1960's



Vela 5B Credit: NASA HEASARC

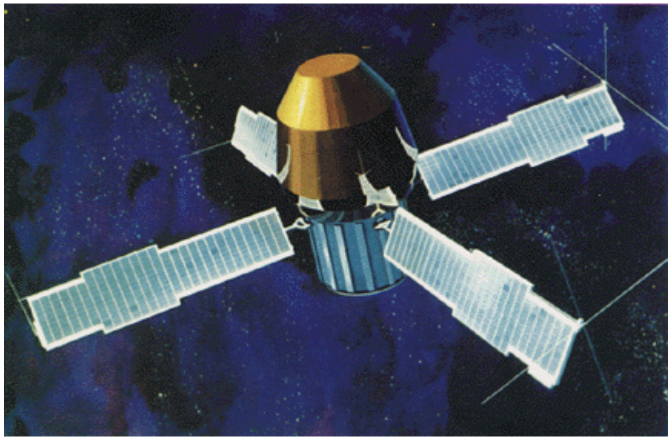
First indication of powerful, <u>very short timescale</u> cosmic explosions

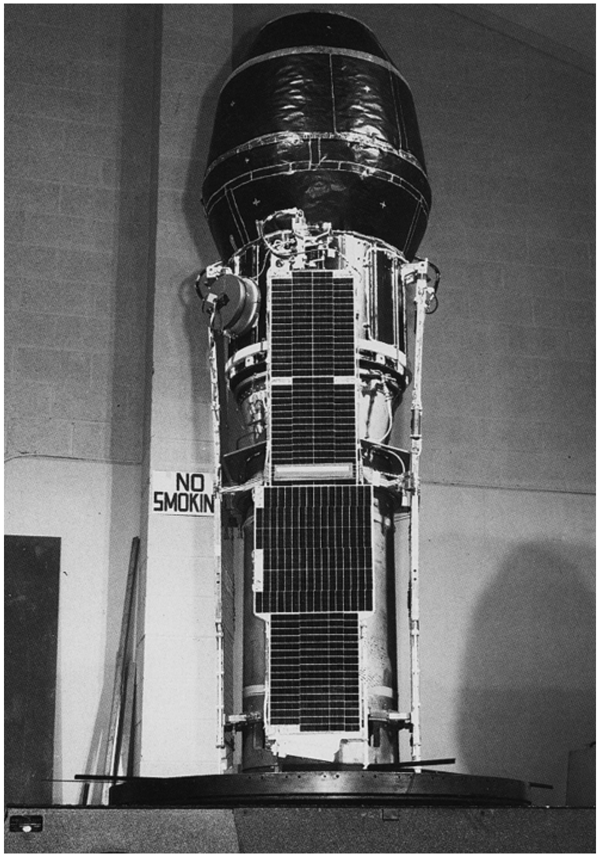
Neutron stars in our Galaxy? Not clear until later that these were extragalactic

SAS 2 mission

Small Astronomy Satellite
November 1972 - June 1973

- Mapped the high energy gamma-ray sky in detail
- Measured high energy gamma-ray background
- Confirmed that gamma rays come from dense regions of the Galaxy





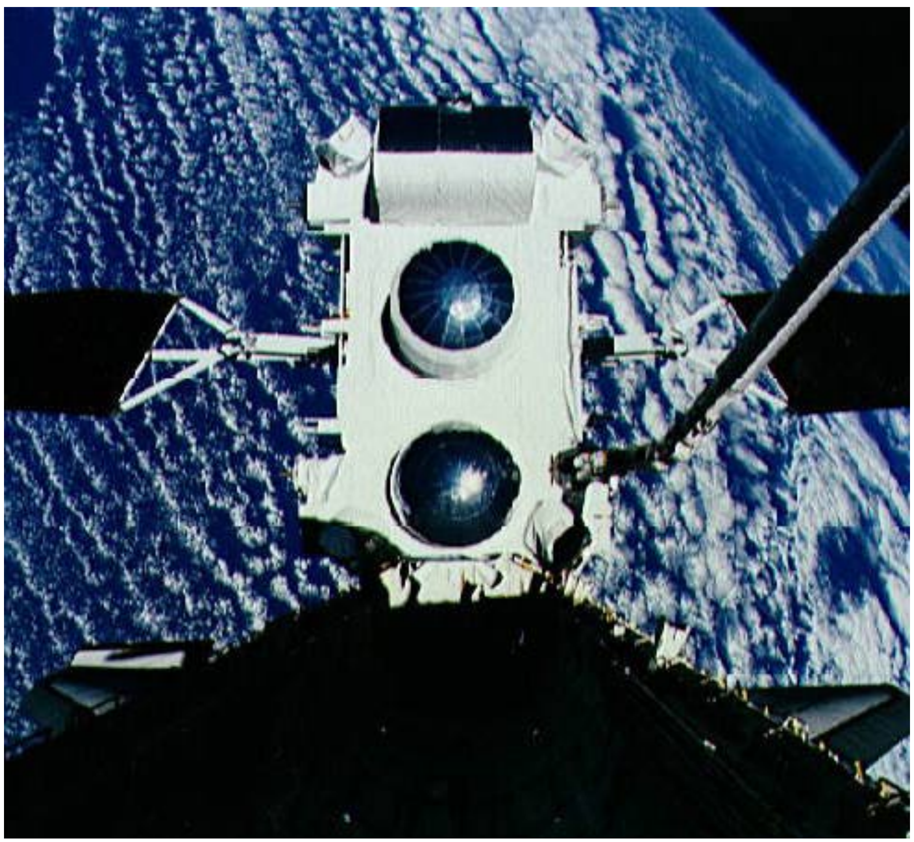
Credit: NASA HEASARC

The Compton Gamma Ray Observatory

1991-2000

4 instruments span 30 keV - 30 GeV

Deployed by the space shuttle

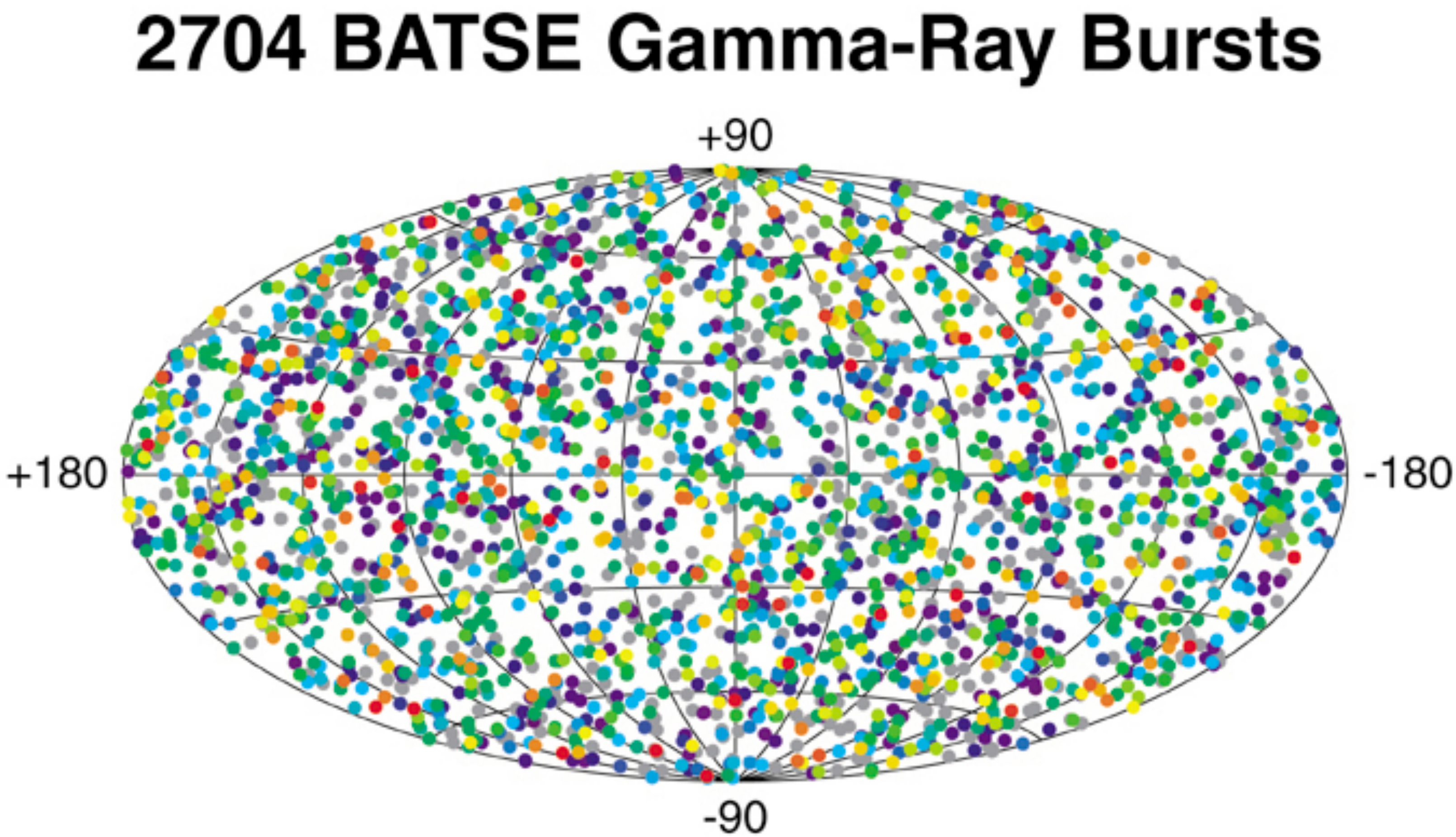


Credit: NASA

- High energy detector, EGRET
  - Pair conversion
  - >270 sources (many unidentified)
- Medium energy, COMPTEL
  - Compton technique
- Gamma-ray burst detectors, BATSE

  2704 γ-ray bursts

CGRO Gamma-ray Bursts



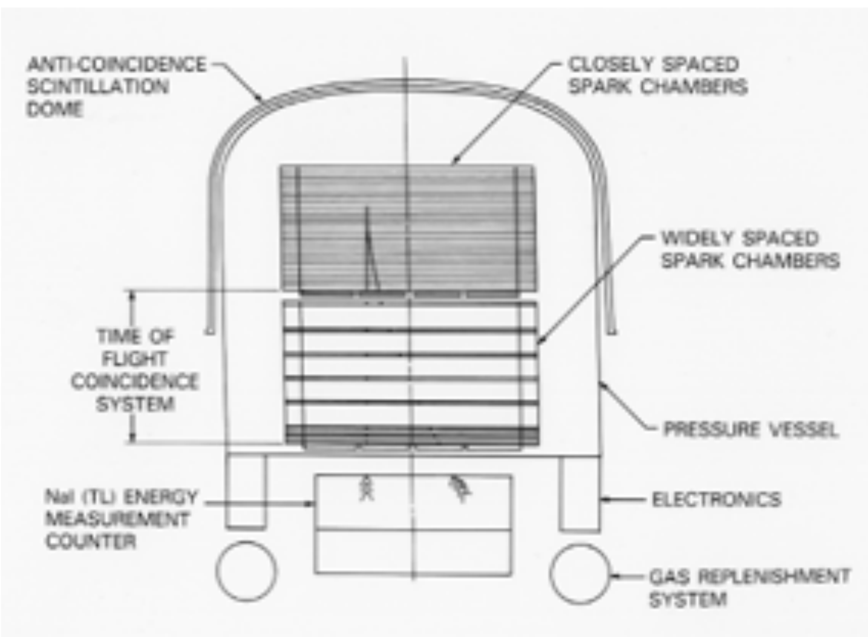
Color indicates fluence (energy flux integrated over duration of burst). Red are for long/bright bursts, purple are for weak/short. Gray do not have a calculated fluence.

Credit: NASA/BATSE

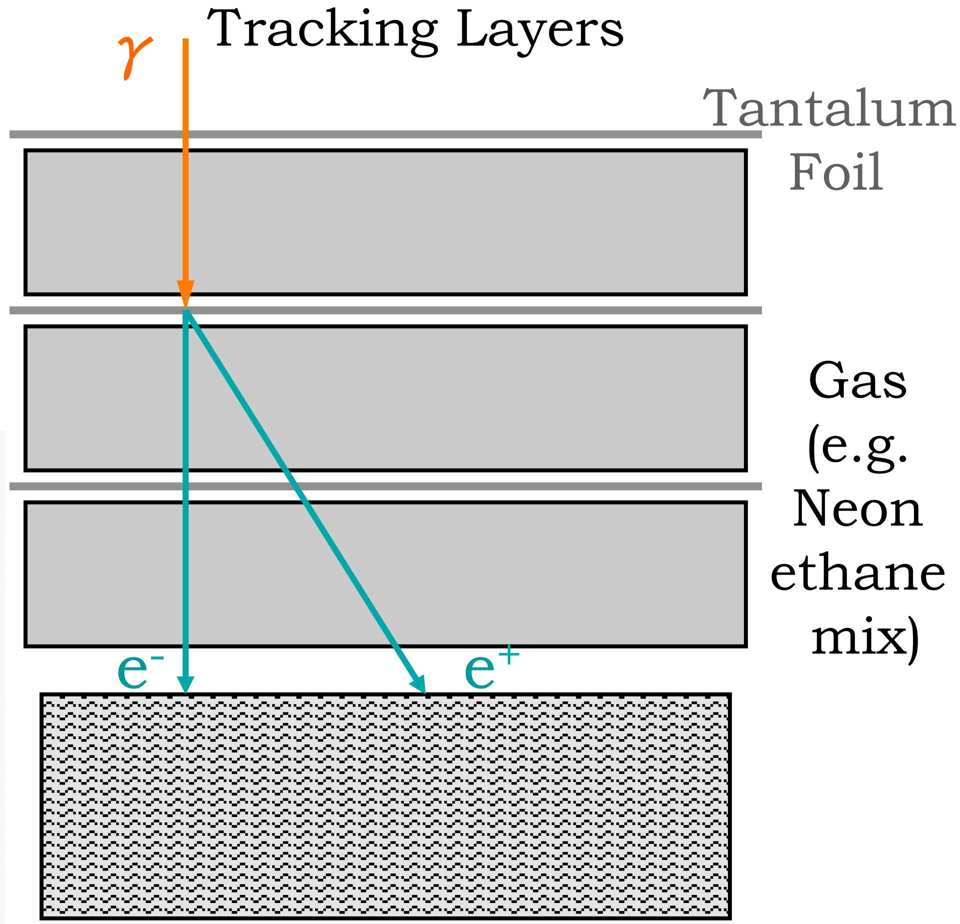
A close-up of EGRET

Detecting a gamma ray

- Direction
- Energy
- Time

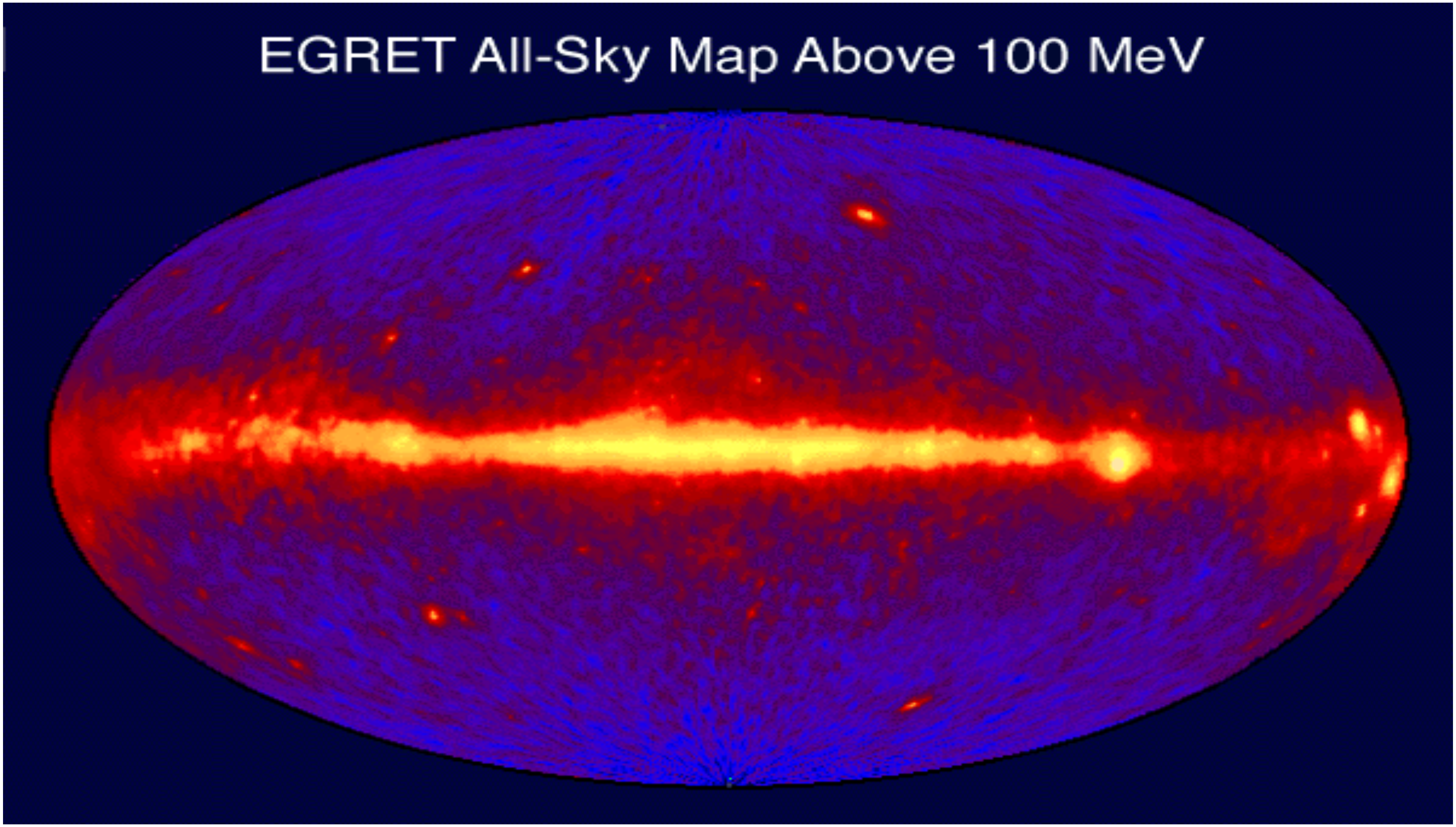


From CGRO Science Support Center



Calorimeter: 8 radiation lengths of NaI(Tl)

The High Energy Sky circa 2000

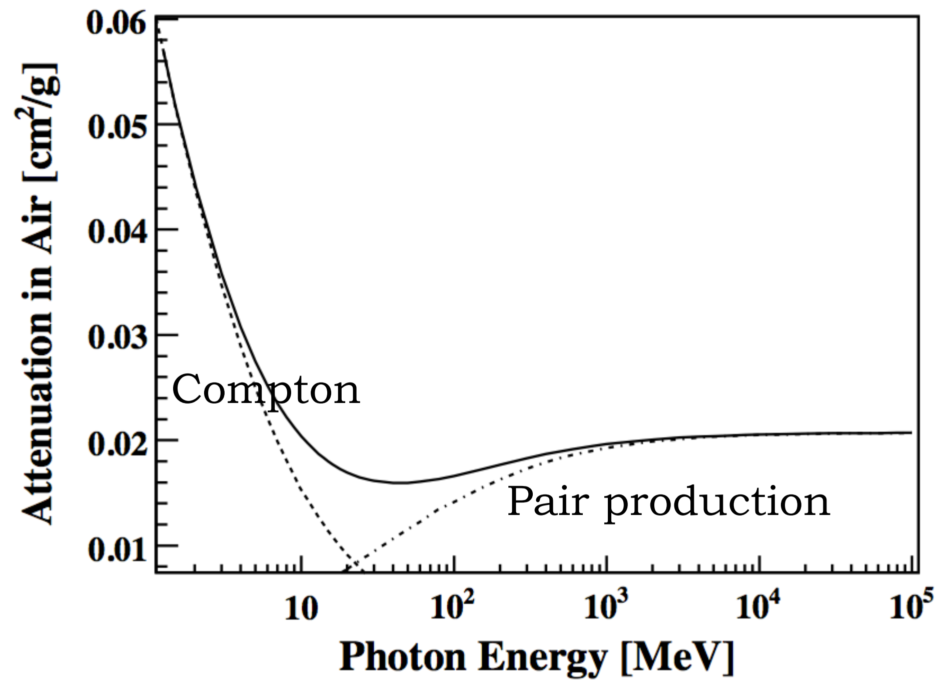


Summery

- Gamma rays below ~50 GeV must be detected in space
- Gamma ray interactions are better suited to tracking detectors than conventional optics
- Increasing detector area and resolution provide increasingly detailed maps of the sky and catalogs of sources

Gamma-ray cross sections

In Air



NIST database of photon cross sections: M.J. Berger,1 J.H. Hubbell, S.M. Seltzer, J. Chang,3 J.S. Coursey, R. Sukumar, D.S. Zucker, and K. Olsen