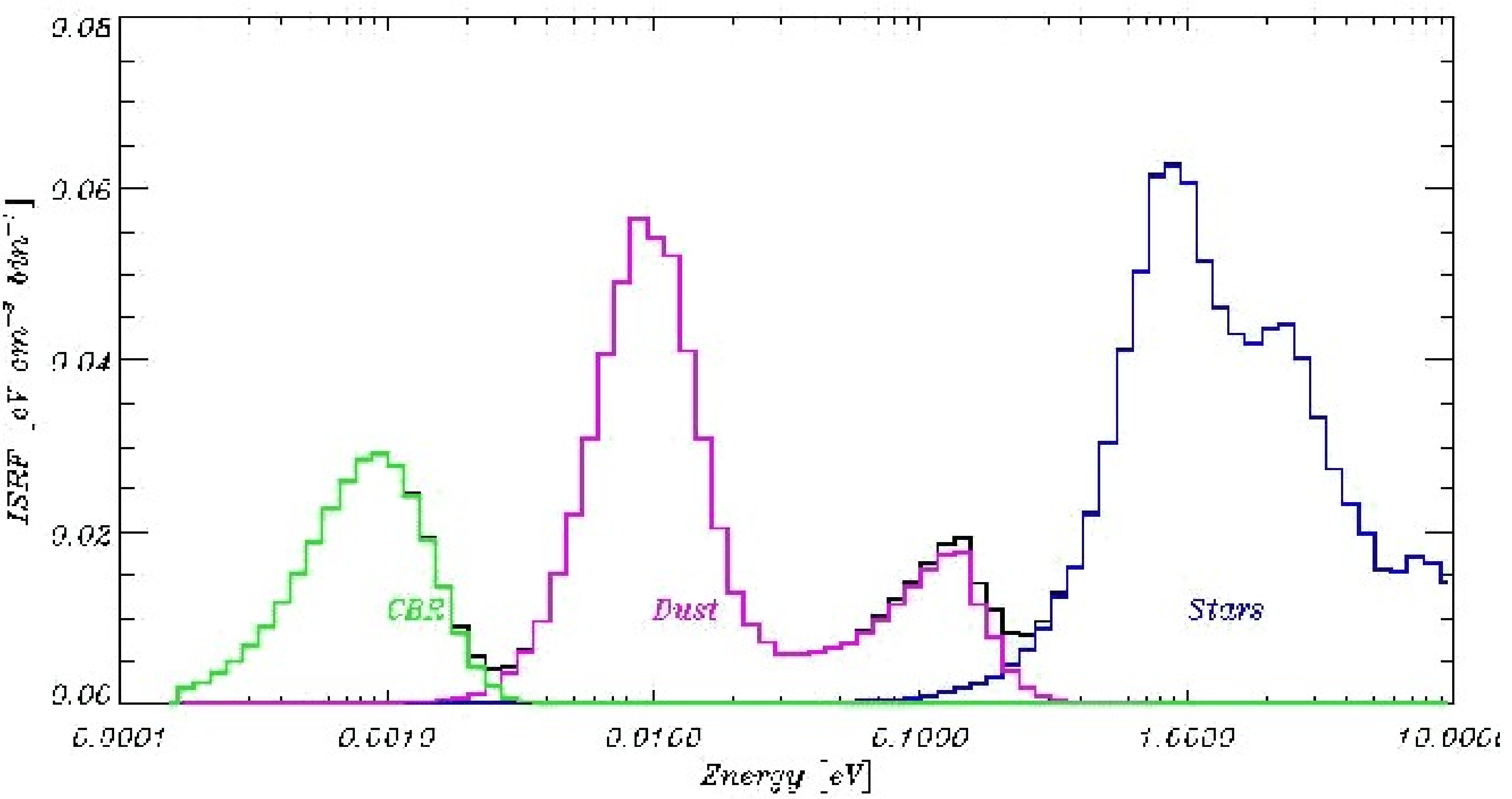
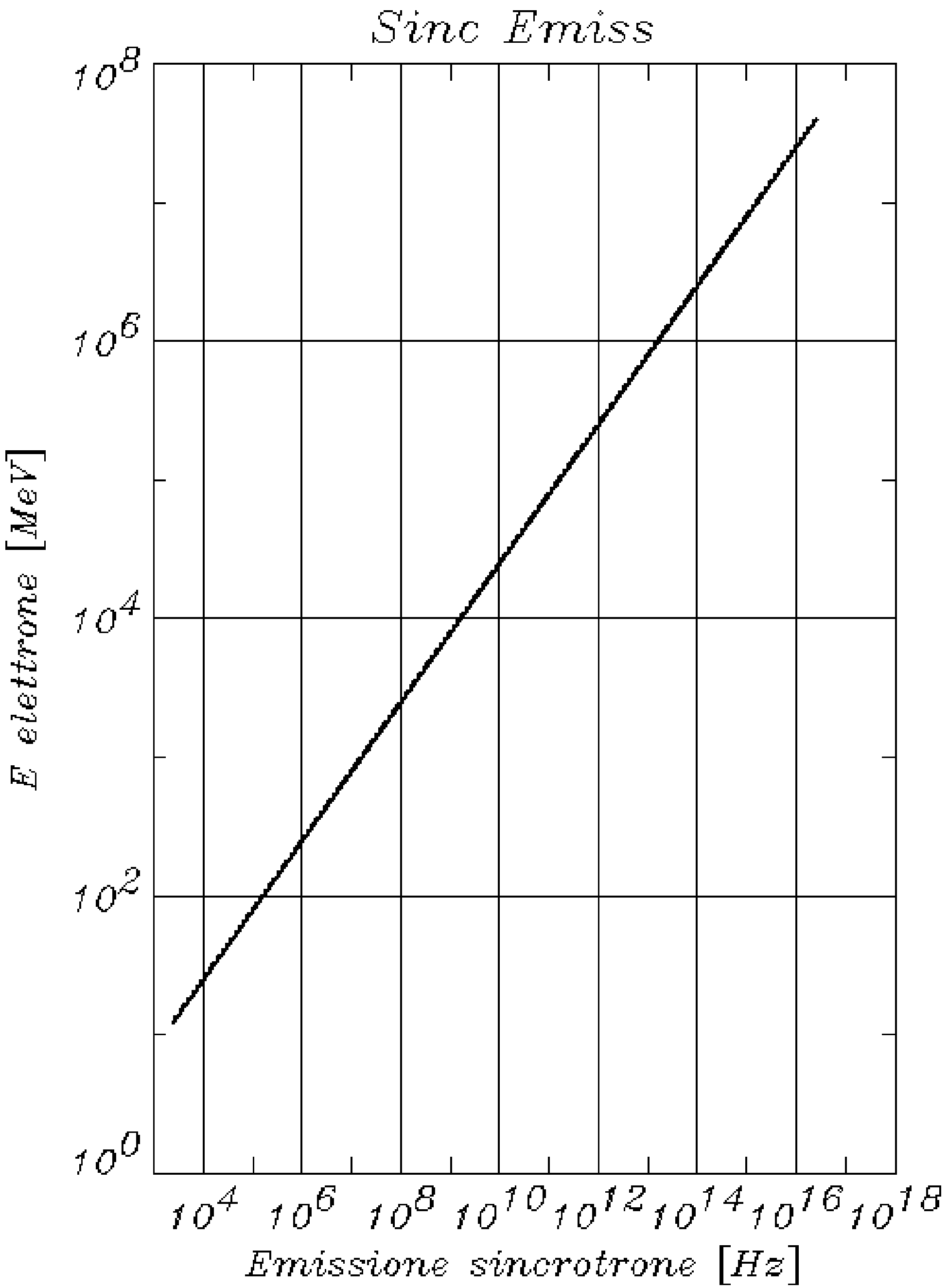
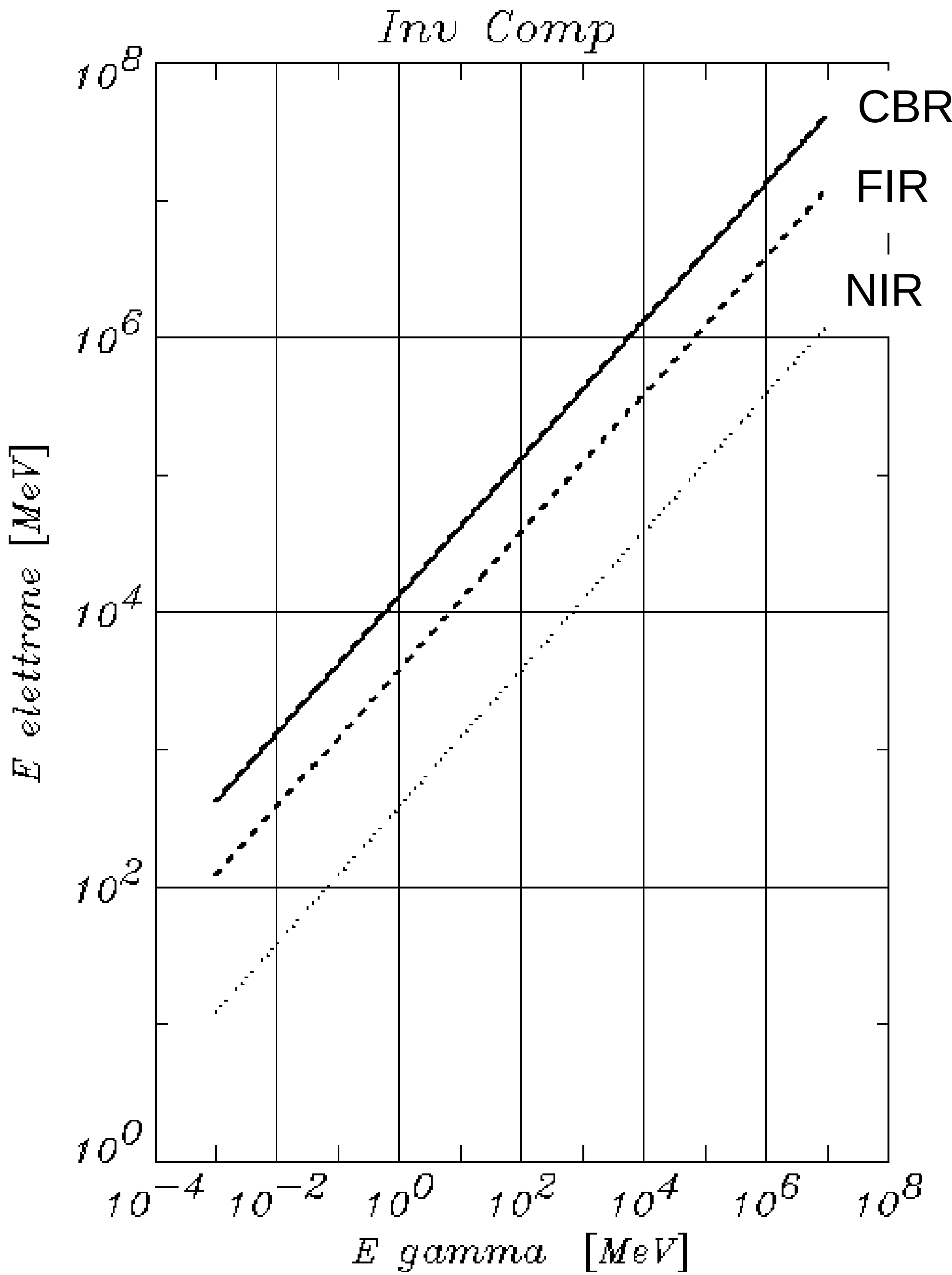
The Interstellar Radiation Field



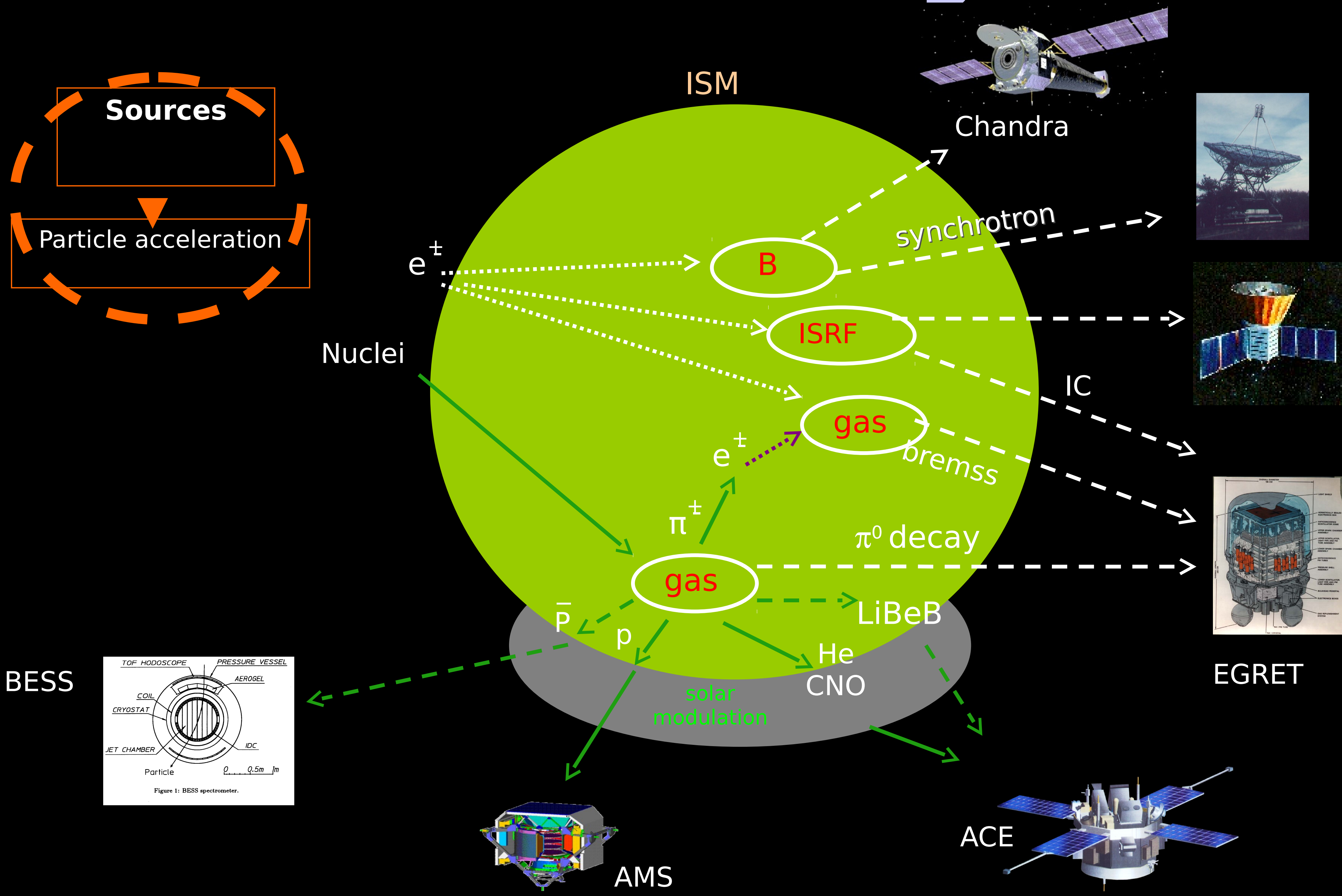
Strong, Moskalenko, & Reimer (2000)

Inverse Compton emissivity

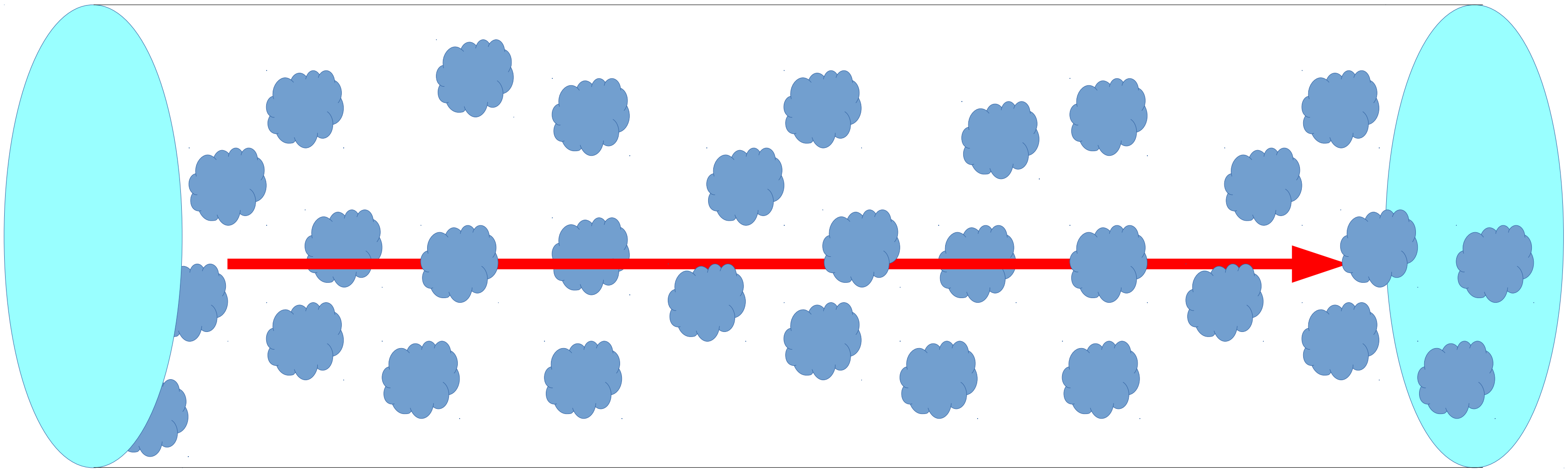




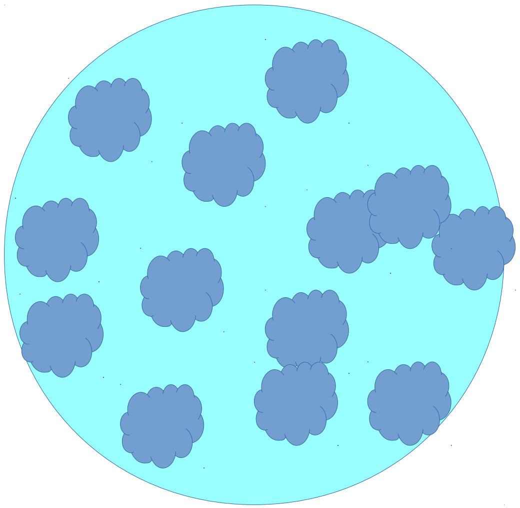
The multi-wavelenght ISM



Int. Rate



$$P = c\,\sigma\,n_t$$

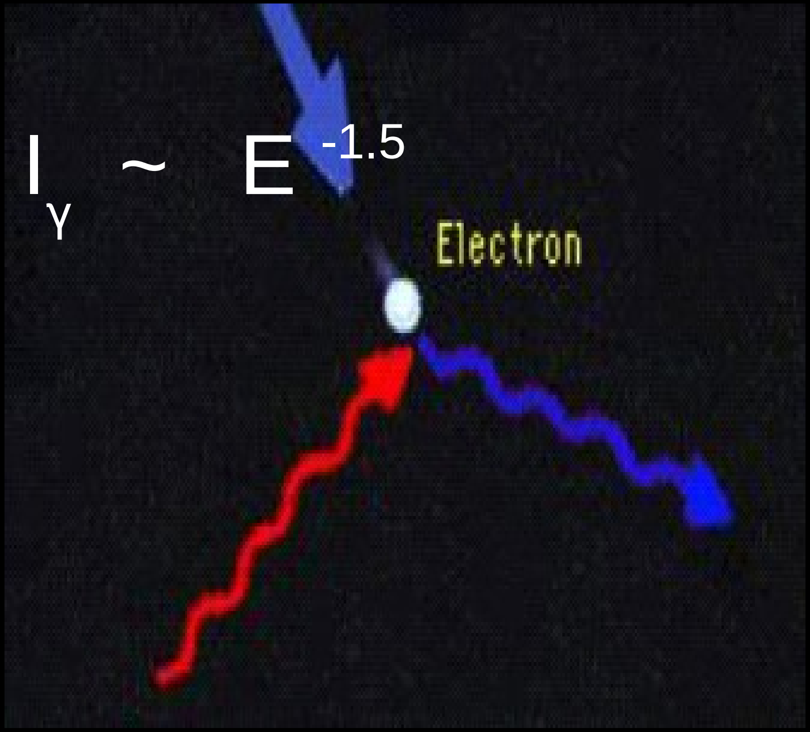


Gamma-Ray & Interstellar Medium : emission

Inverse Compton :

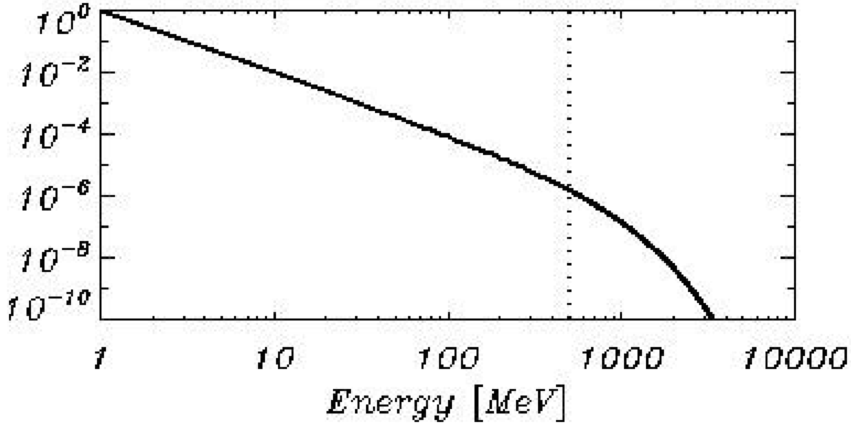
$$\nu_{ic} = \frac{4}{3}\gamma^2 \nu_{ph}$$

$$\frac{dE}{dt} = R\,\nu_{ic}\,h = \frac{4}{3}\,\sigma_T\,U_{ph}\,c\,\gamma^2$$

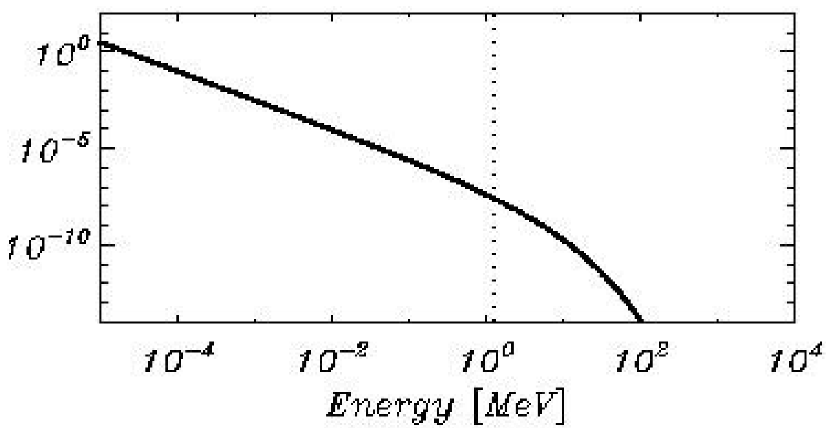


$$I_\gamma \sim E^{-1.5}$$

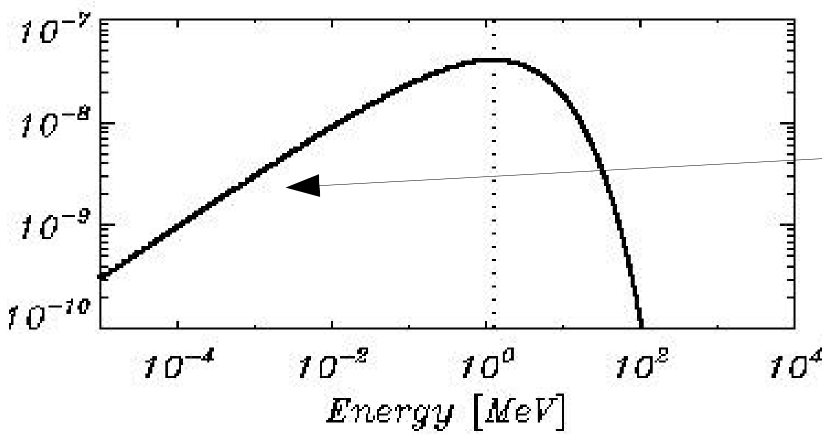
CR electrons + ISRF photons → γ rays



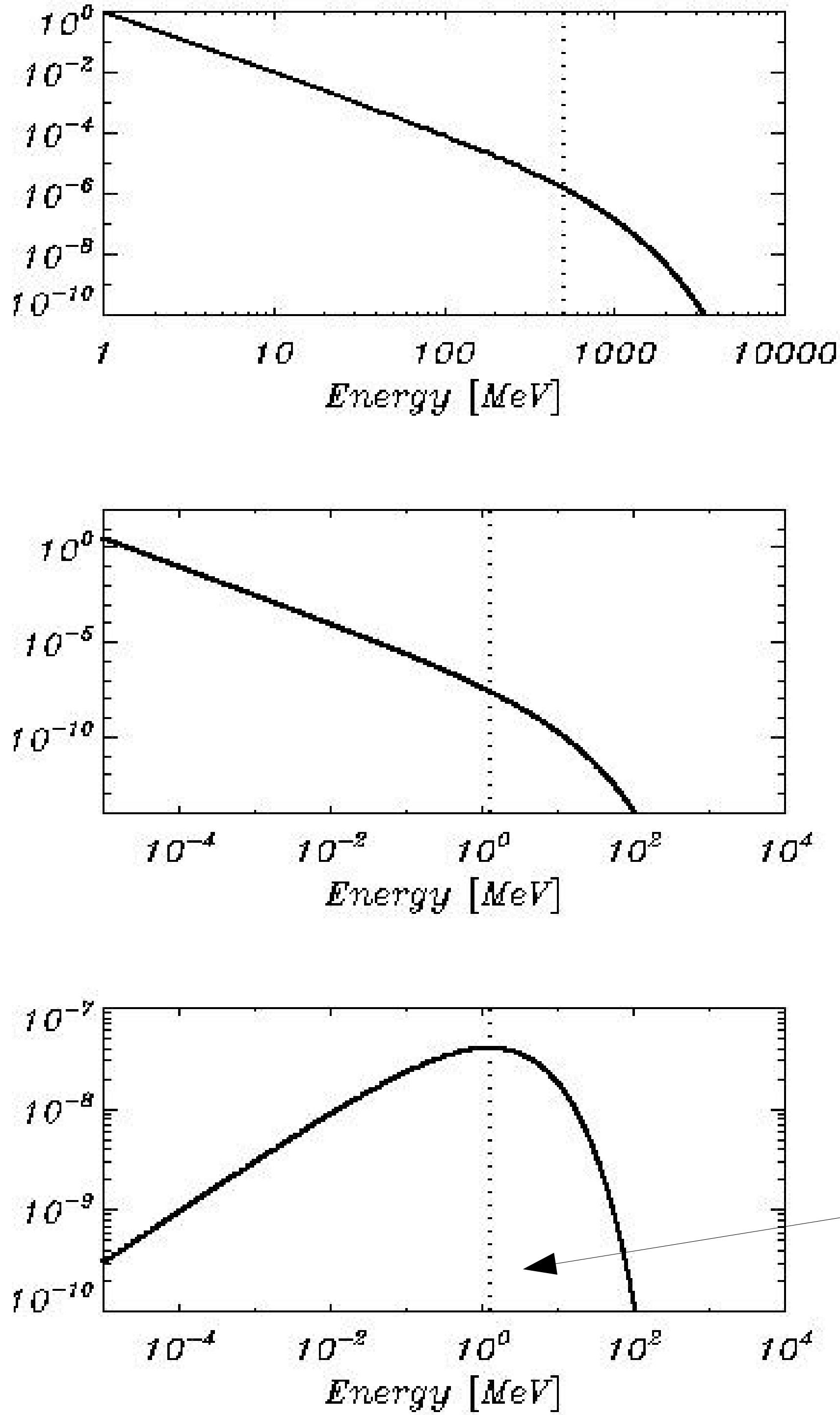
$$I_e \sim E^{-a}$$



$$I_\gamma \sim E^{-(a+1)/2}$$

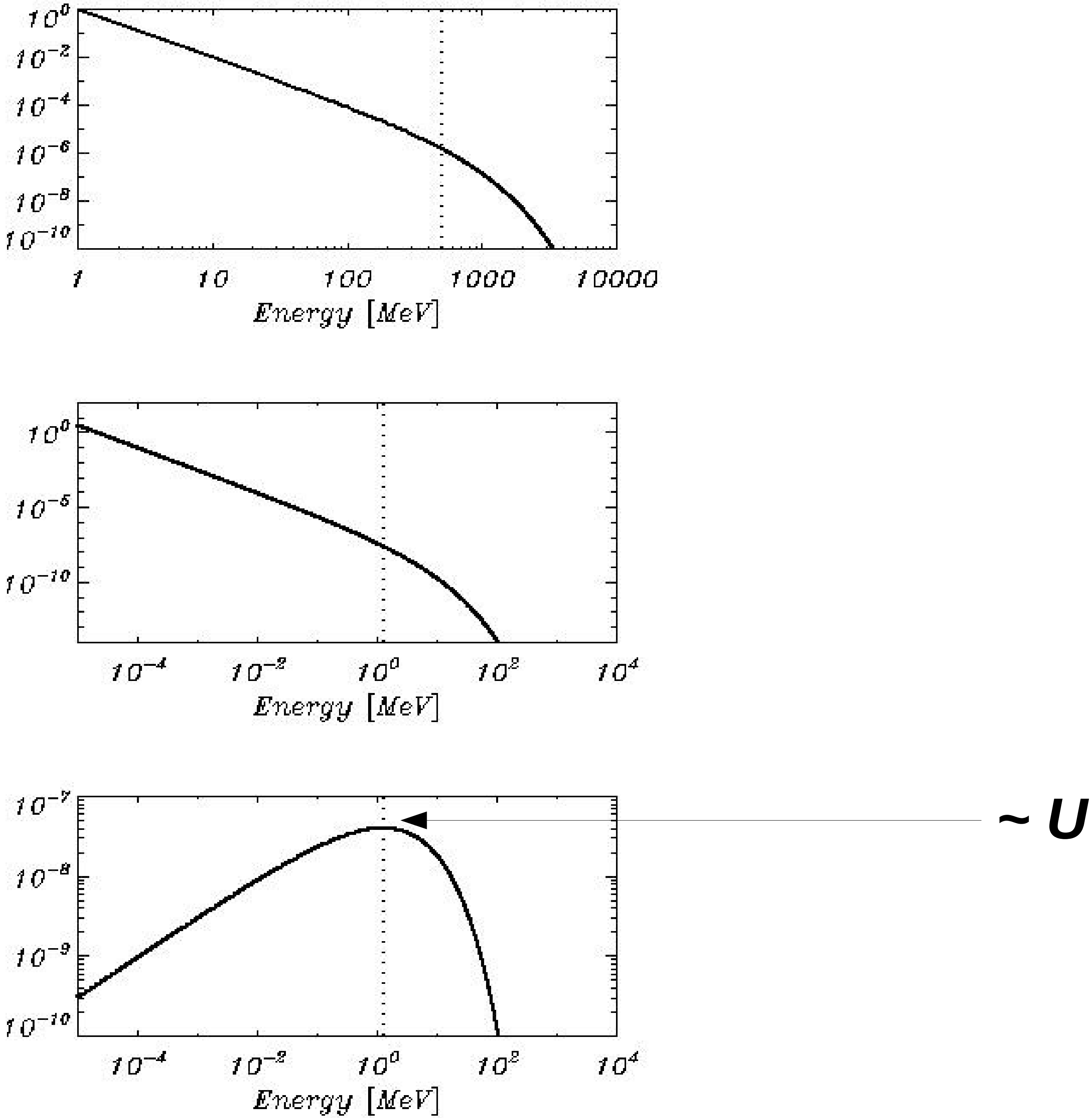


$$I_\gamma\, E^2 \sim E^{(3-a)/2}$$



Cut off !

$$\nu_{ic} = \frac{4}{3}\gamma^2 \nu_{ph}$$



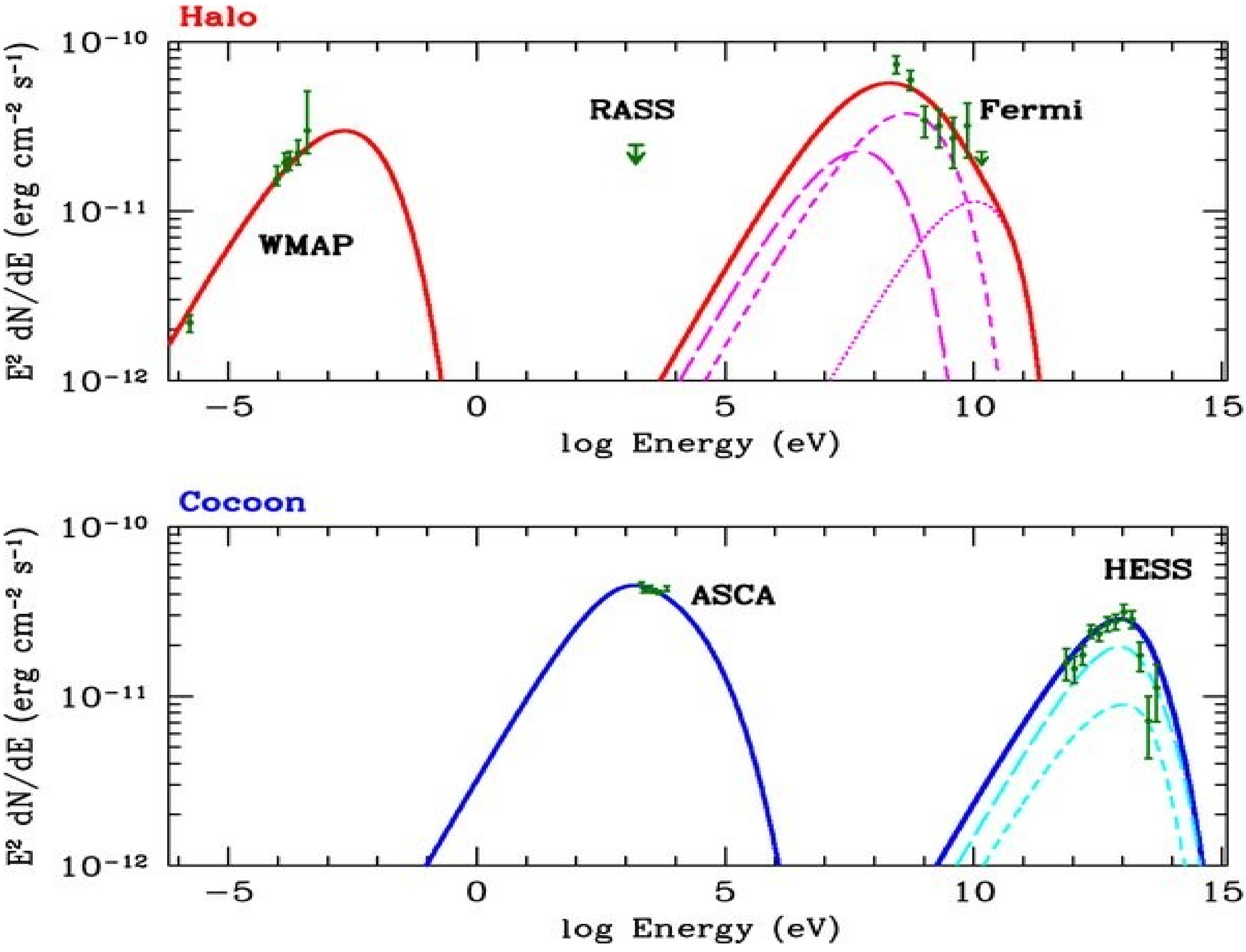
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1
10
100
1000
10000
Energy [MeV]
10^{0}
10^{-5}
10^{-10}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Energy [MeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Energy [MeV]
~ U

Synchrotron

$$\nu_{syn} = \frac{4}{3}\gamma^2 \nu_{gyr}$$

$$\nu_{gyr} = \frac{e\ B}{2\ \pi\ m_e\ c}$$

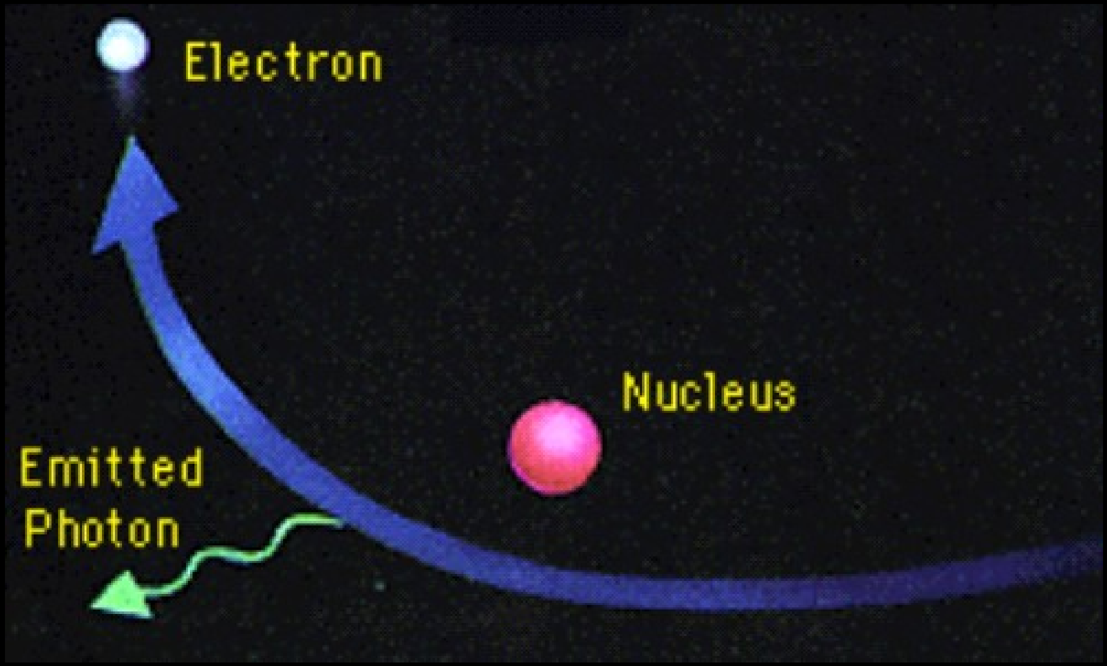
$$\frac{dE}{dt} = \frac{4}{3}\ \sigma_T\ U_B\ c\ \gamma^2$$



Halo
RASS
Fermi
WMAP
E² dN/dE (erg cm⁻² s⁻¹)
10⁻¹⁰
10⁻¹¹
10⁻¹²
−5
0
5
10
15
log Energy (eV)
Cocoon
HESS
ASCA
E² dN/dE (erg cm⁻² s⁻¹)
10⁻¹⁰
10⁻¹¹
10⁻¹²
−5
0
5
10
15
log Energy (eV)

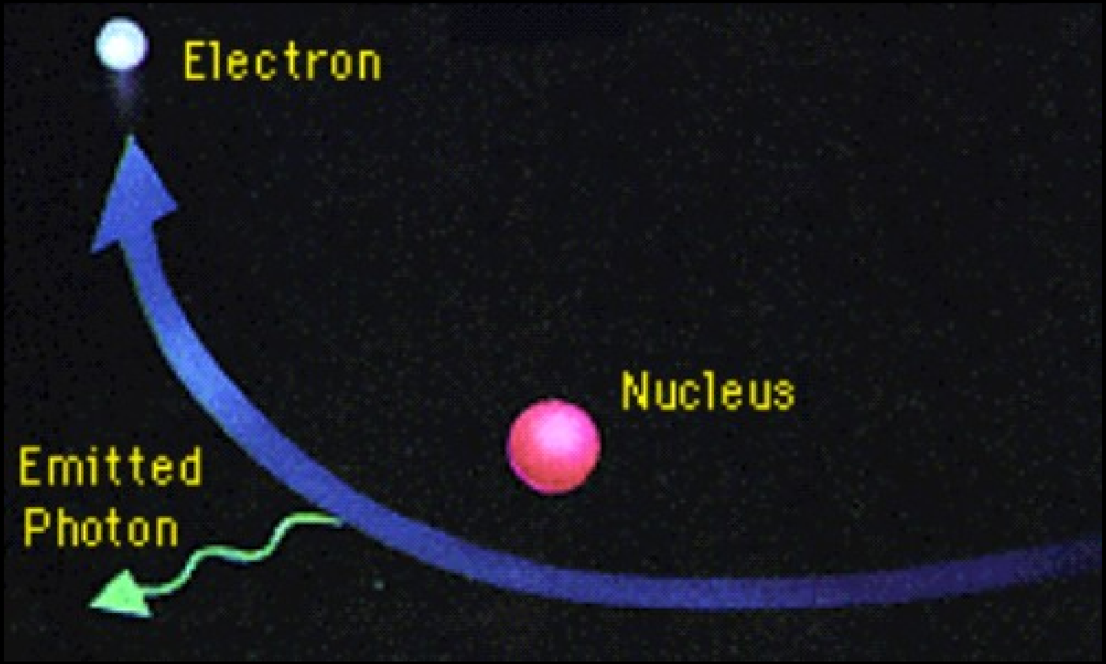
Bremsstrahlung

CR electrons + ISM nuclei → γ rays



Bremsstrahlung

CR electrons + ISM nuclei → γ rays

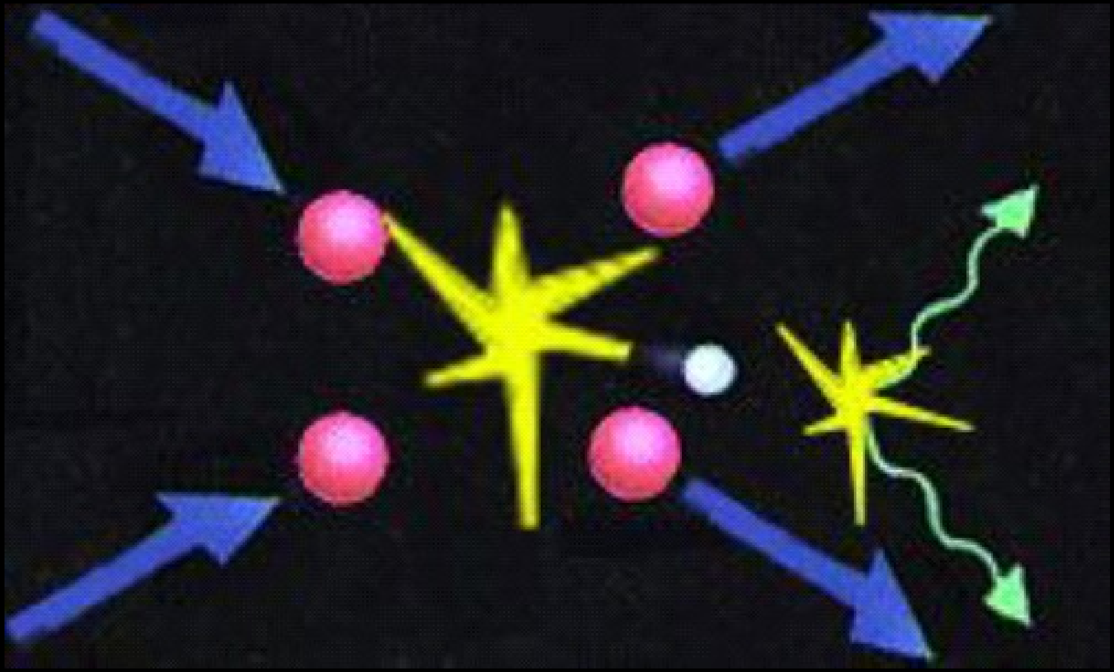


$$-\frac{dE}{dt} = 4c\alpha r_e^2 N G_a \, E$$

$$N_e(E) = kE^{-a}$$

$$I(\hbar\omega) = 4Z^2 c\alpha r_e^2 N G_a k \frac{(\hbar\omega)^{-a}}{a-1}$$

Emission processes: Neutral π decay

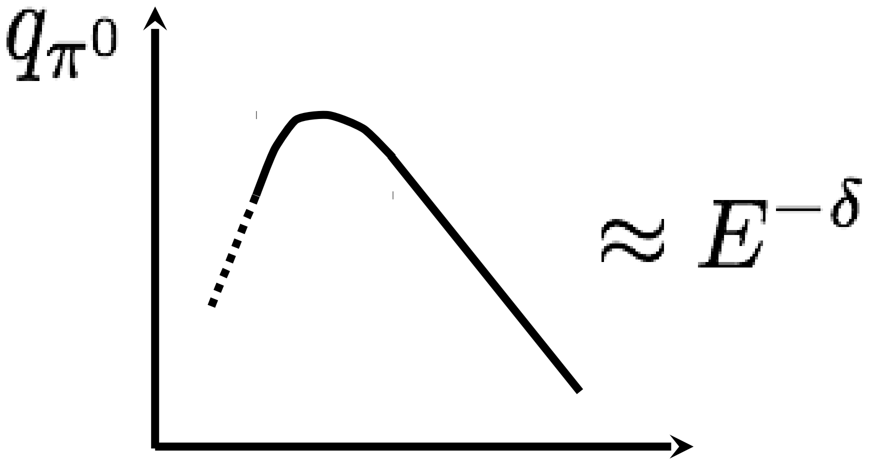


CR protons + ISM nuclei → π^0 → γ rays

p-p interactions

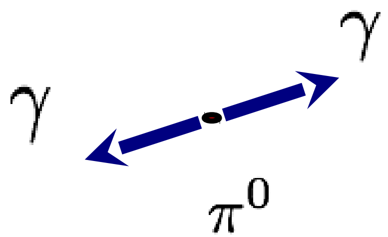
We assume a power law spectrum for CRs: $N_p(E_p) \propto E_p^{-\delta}$

Fraction of proton kinetic energy transferred to pion (from data): $f_{\pi^0} \approx 0.17$



p-p interactions

Pion rest frame:



$$E_\gamma^* = \frac{m_{\pi^0}}{2}$$

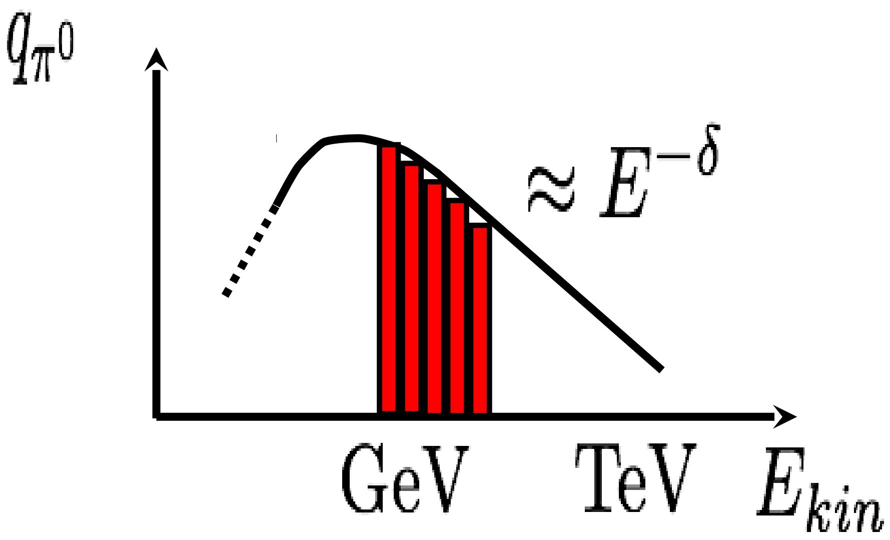
Lab frame:

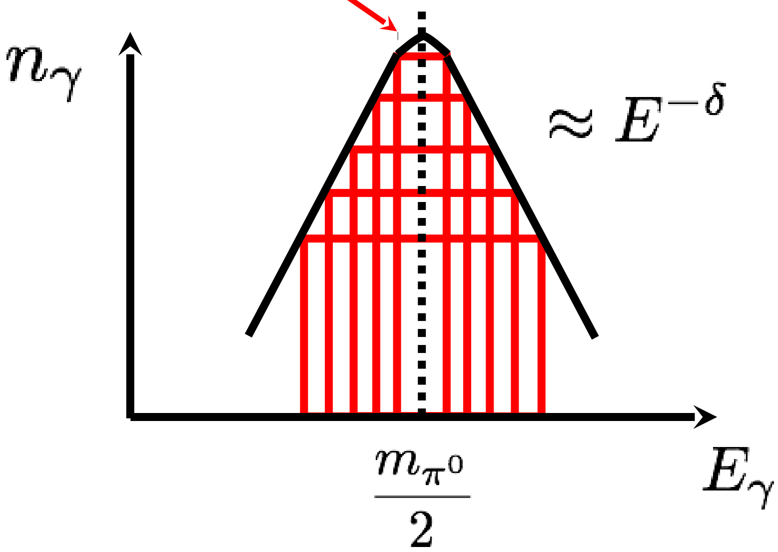
$$E_\gamma = \gamma \left(E_\gamma^* + v p_\gamma^* \cos\theta^* \right)$$

max and min energies -> $\cos\theta^* = \pm 1$

$$\frac{m_{\pi^0}}{2}\sqrt{\frac{1-\beta}{1+\beta}} \leq E_\gamma \leq \frac{m_{\pi^0}}{2}\sqrt{\frac{1+\beta}{1-\beta}}$$

p-p interactions



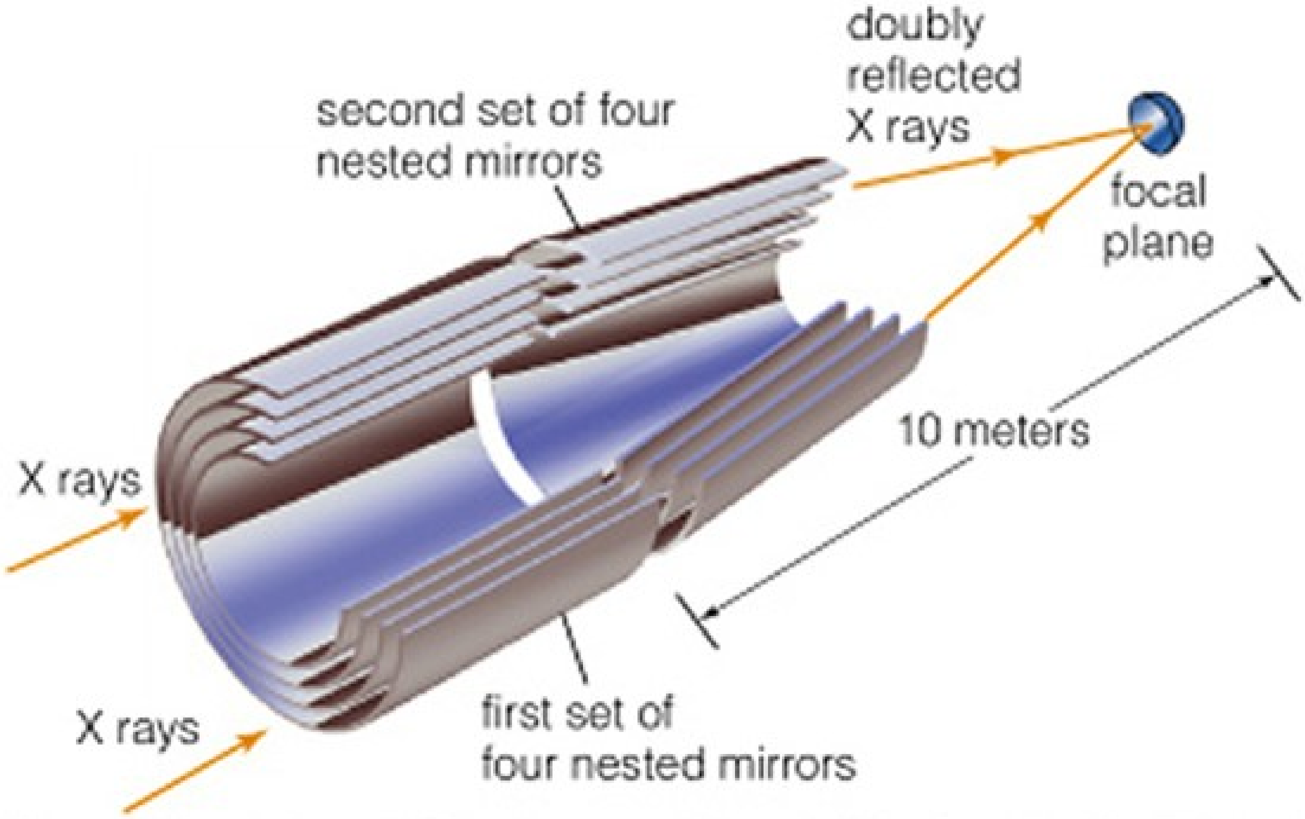


the gamma ray spectrum is symmetric (in log-log) with respect to: $\frac{m_{\pi^0}}{2} \sim 70\ \mathrm{MeV}$

at high energy the spectrum mimic the CR spectrum, with (roughly): $E_\gamma \approx \frac{E_{CR}}{10}$

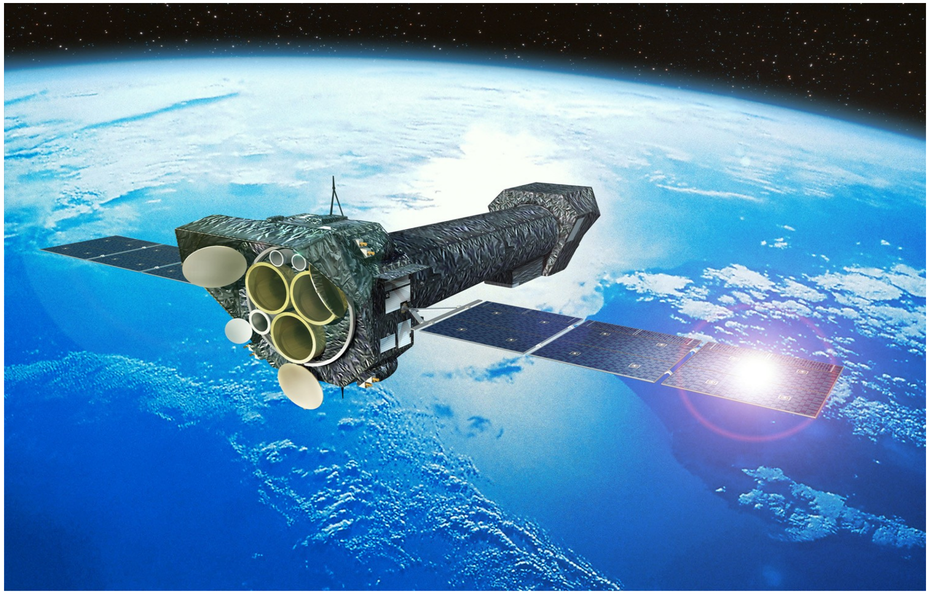
Gamma-rays telescopes

X-rays telescopes



Mirror elements are 0.8 m long and from 0.6 m to 1.2 m in diameter.

X-rays telescopes



XMM-Newton Telescope (ESA)

2000 -

Energy range : < 15 keV

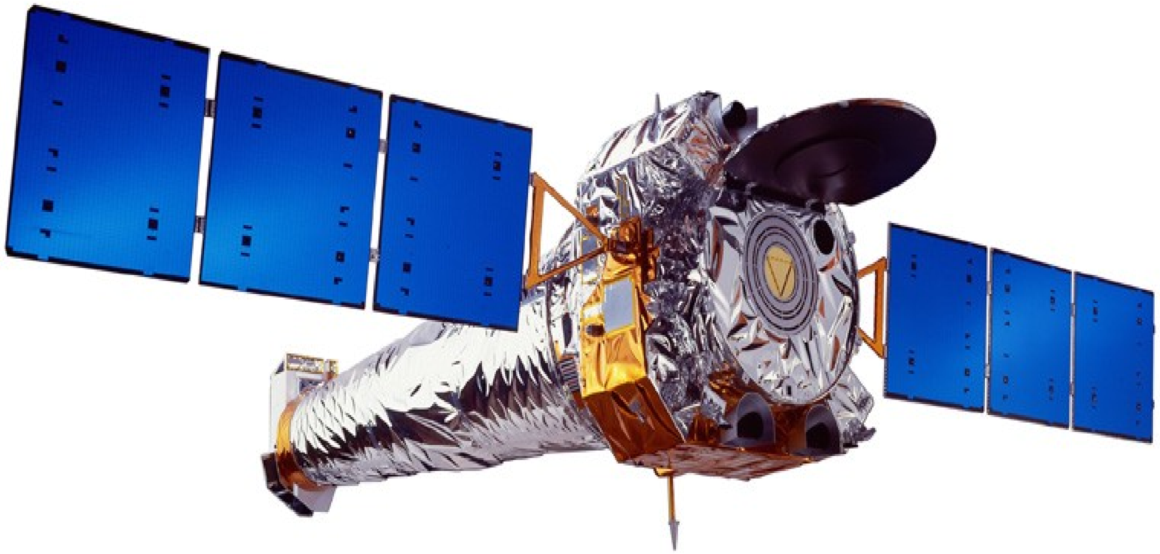
Ang. Res : 5'' – 10 ''

Chandra Xrays Observatory (NASA)

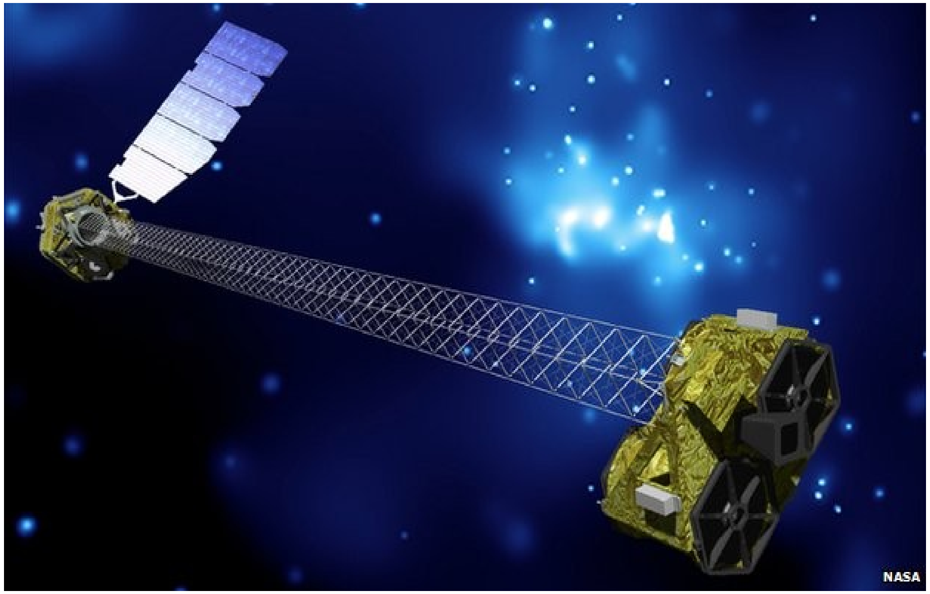
1999 -

Energy range : < 10 keV

Ang. Res : 0.5''



X-rays telescopes



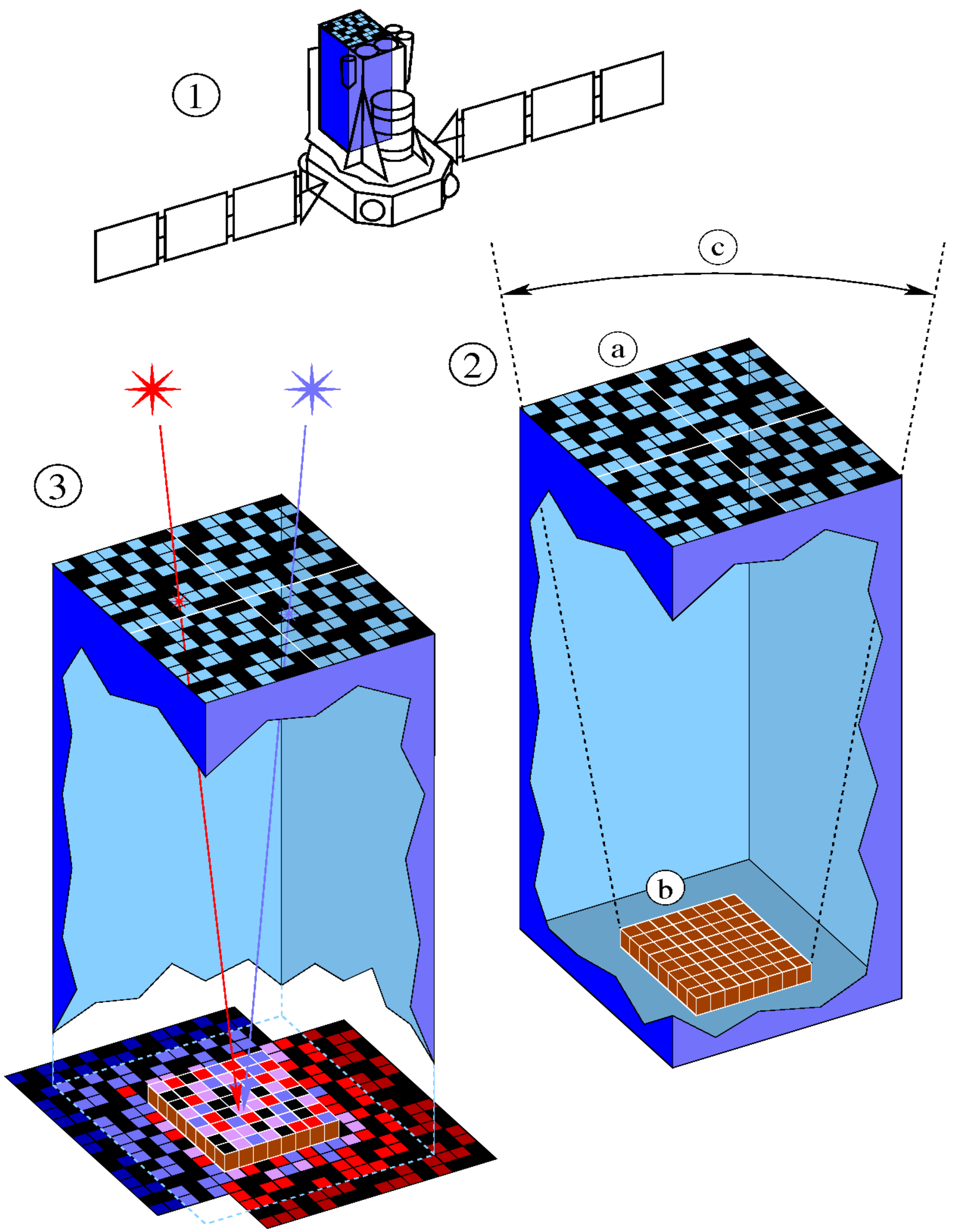
NuSTAR (NASA)

2014 -

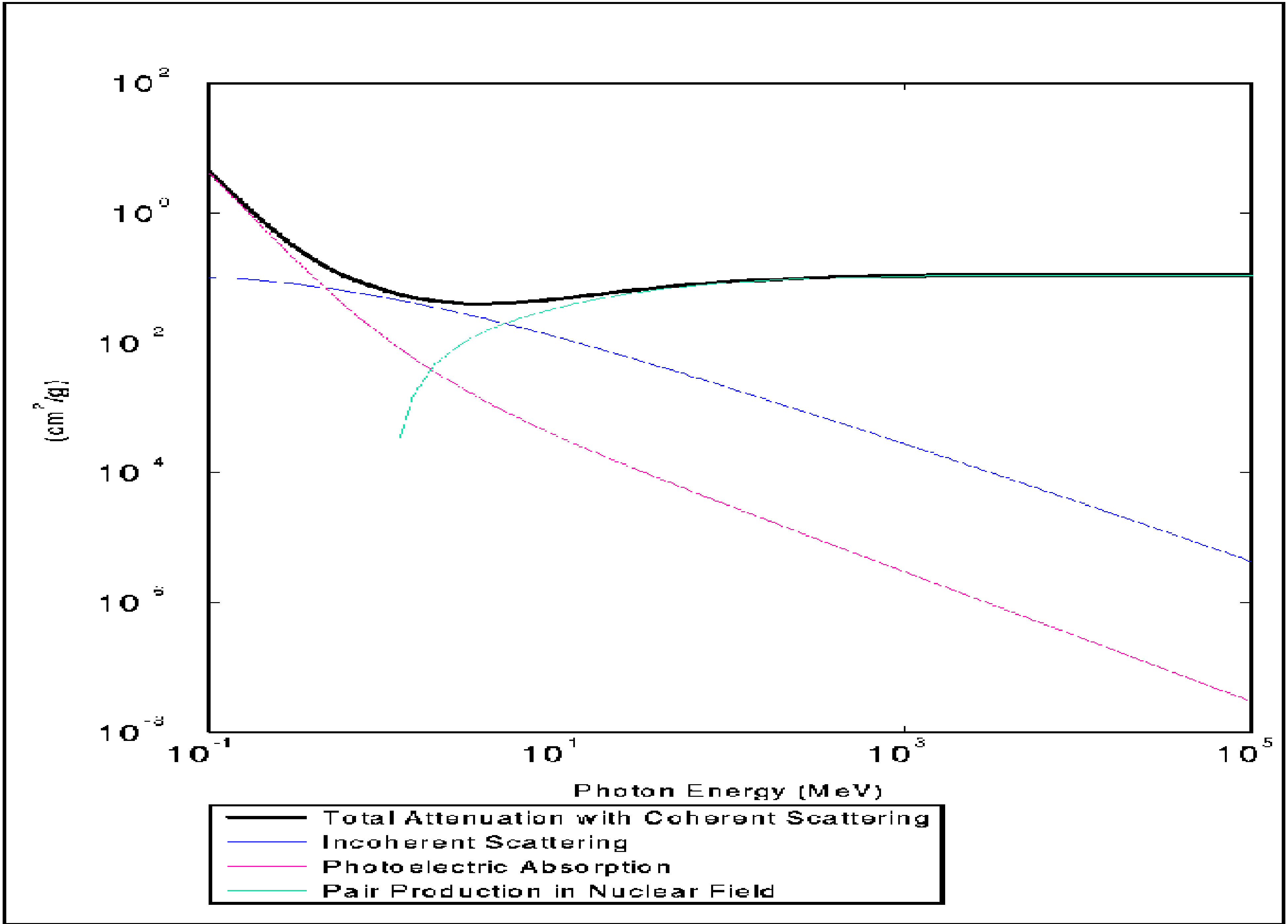
Energy range : < 80 keV

Ang. Res : 10 ''

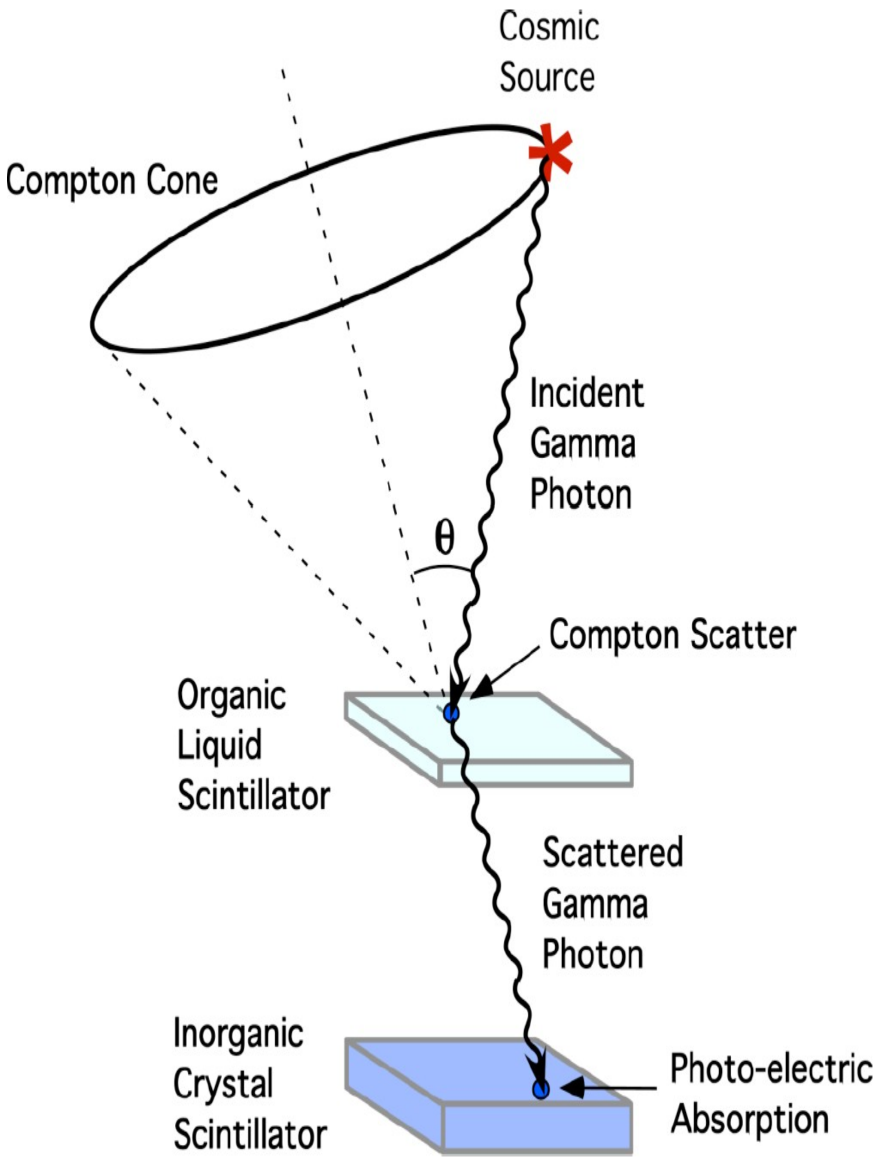
Coded Mask Telescopes

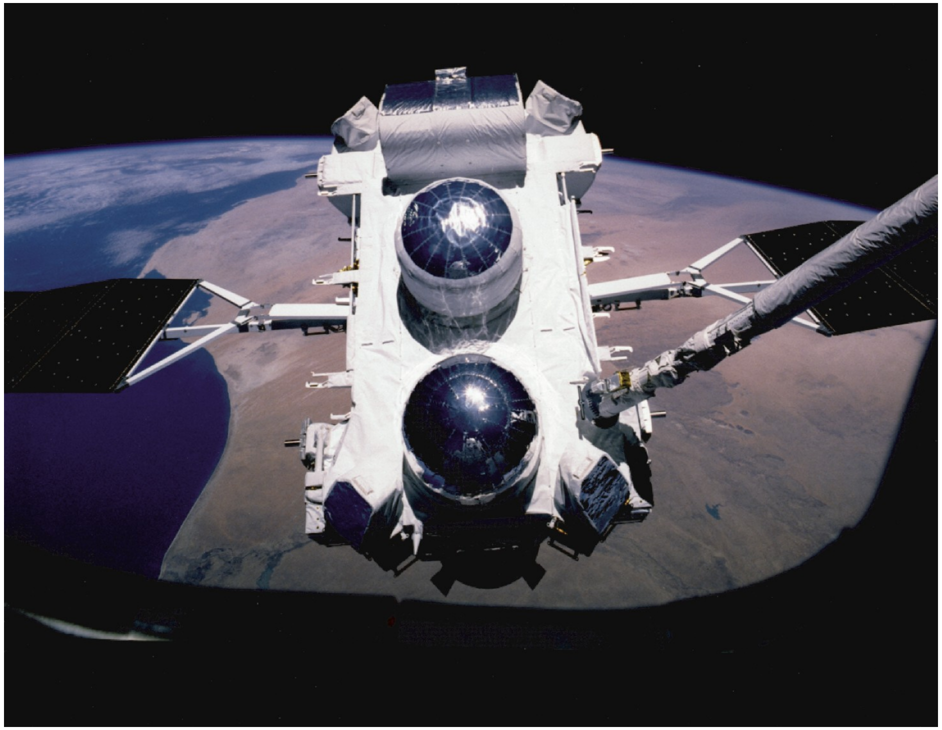


Photons detections



Compton Telescopes





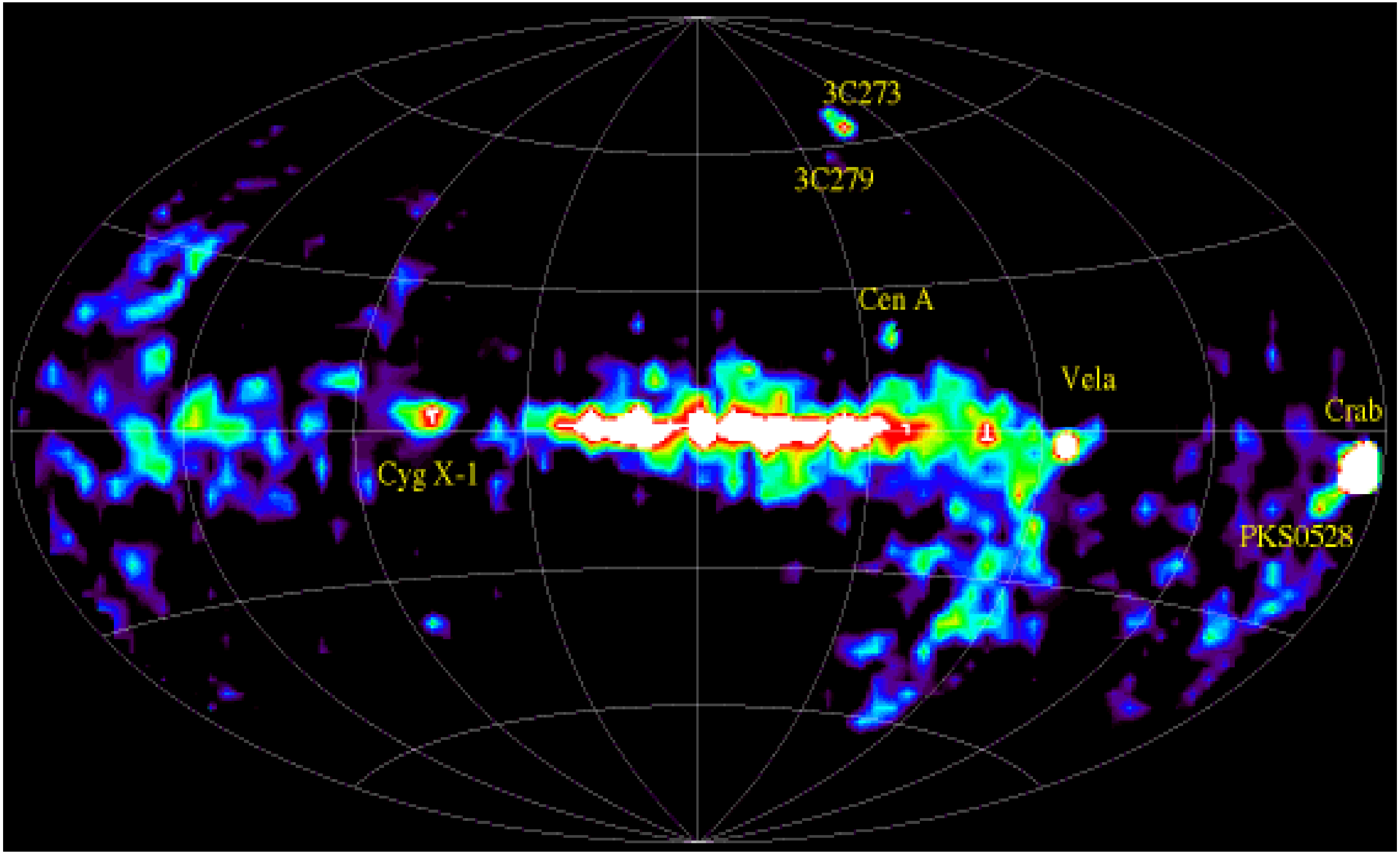
GCRO/COMPTEL (NASA)

1991 - 2000

En. range : 0.75 - 30 MeV

Ang. Res : few deg

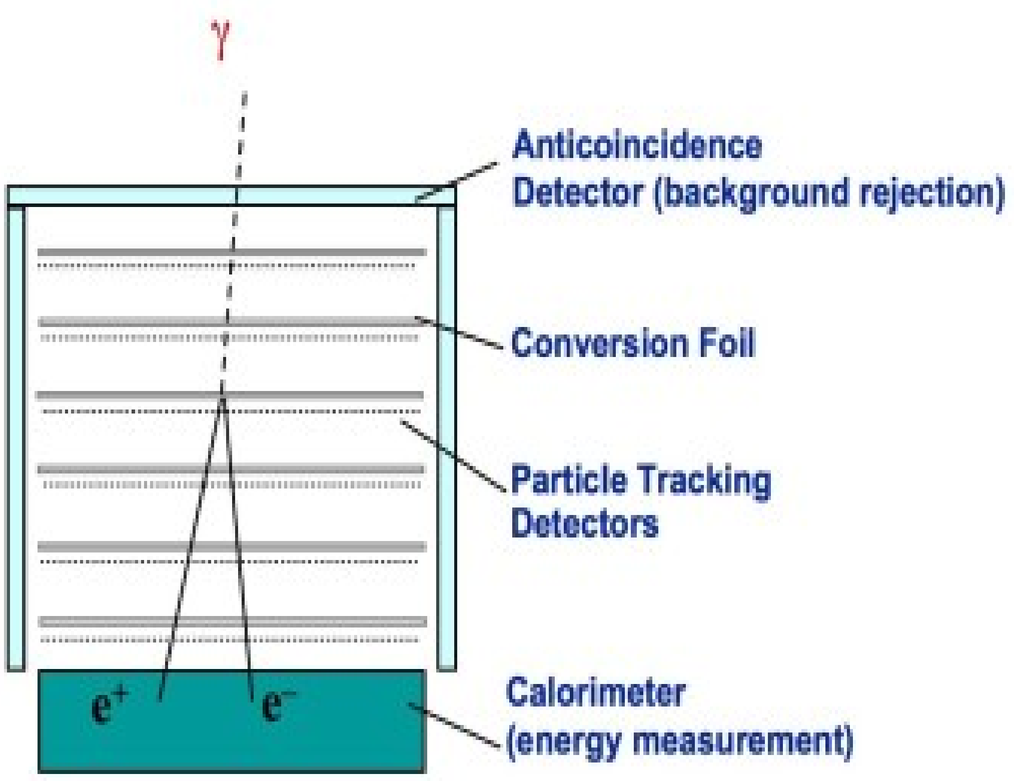
Compton Telescopes



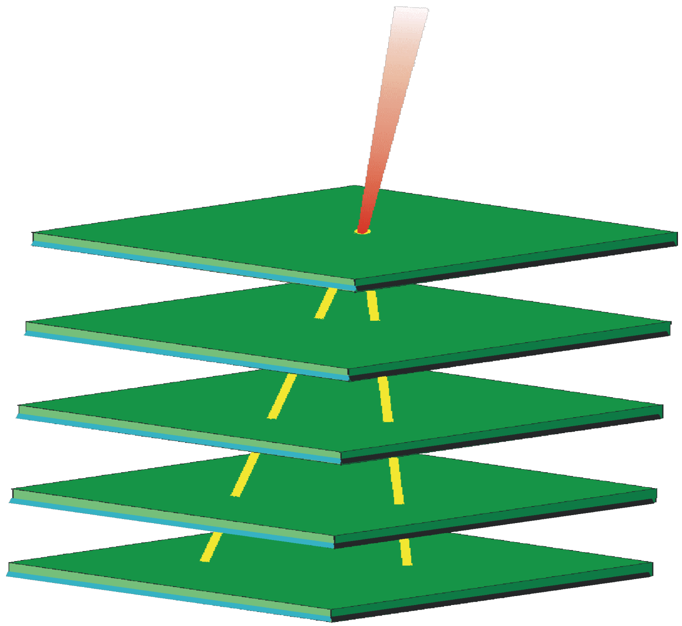
Pair Production Telescopes

En. range : > 30 MeV

Ang. Res : few deg / E



Detection in pair production telescopes

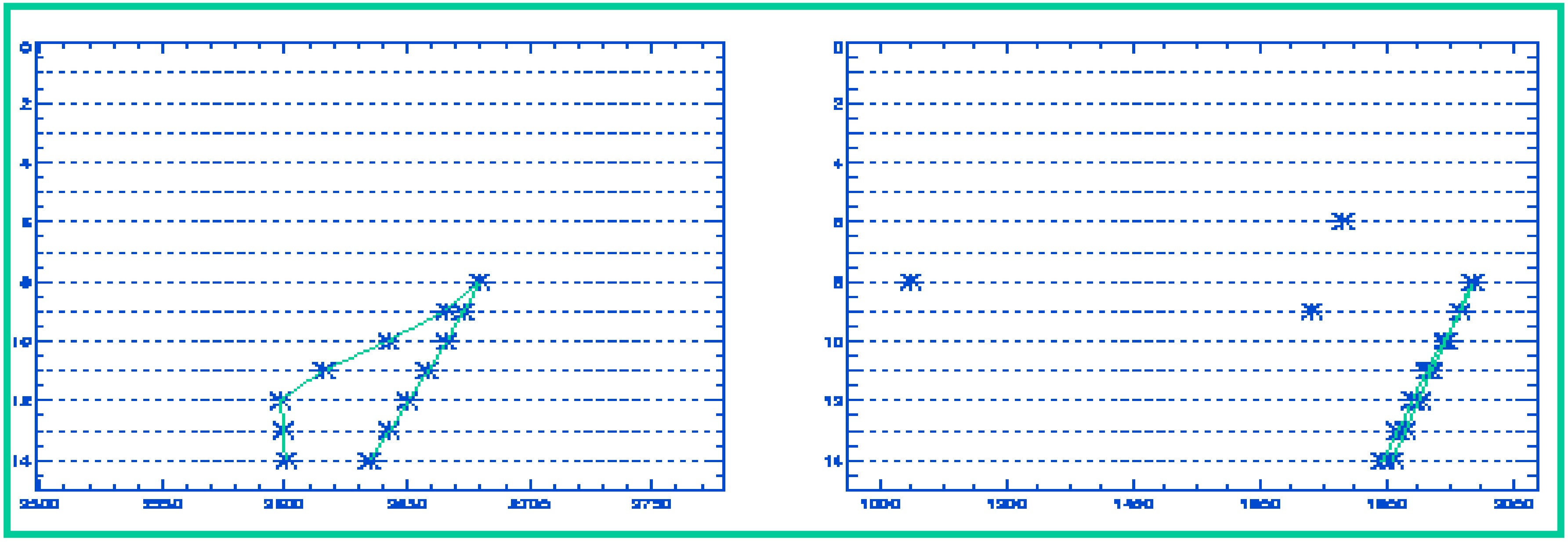


$\gamma \rightarrow e^+e^-$

conserve p and E

but:

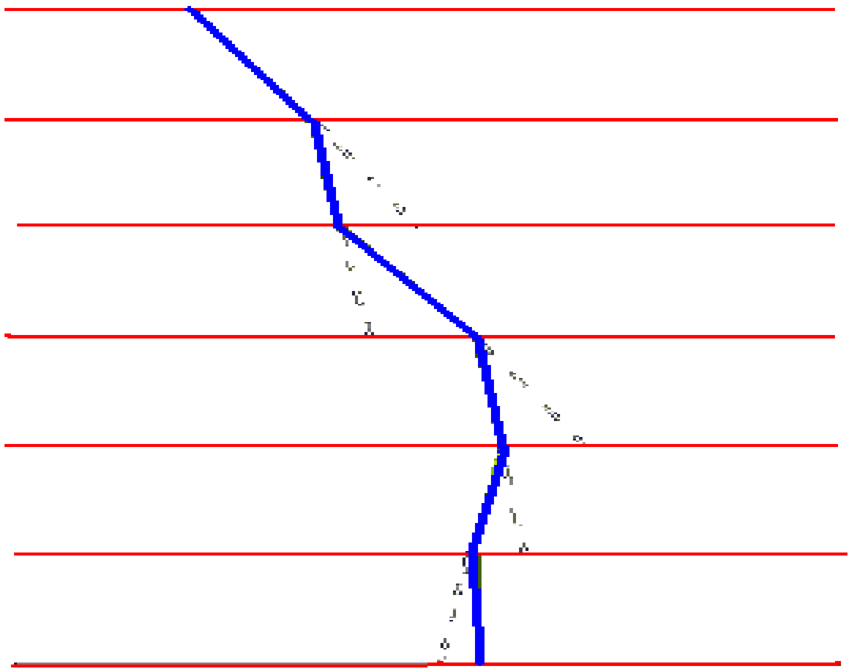
- **Only projection information**
- **Multiple Scattering**
- **Noise hits**

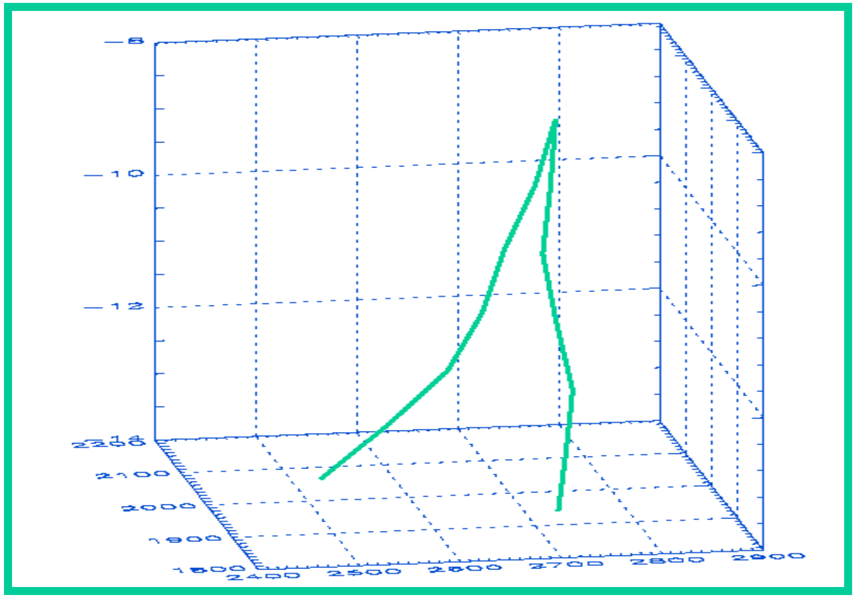


Multiple scattering

Moliere formula :

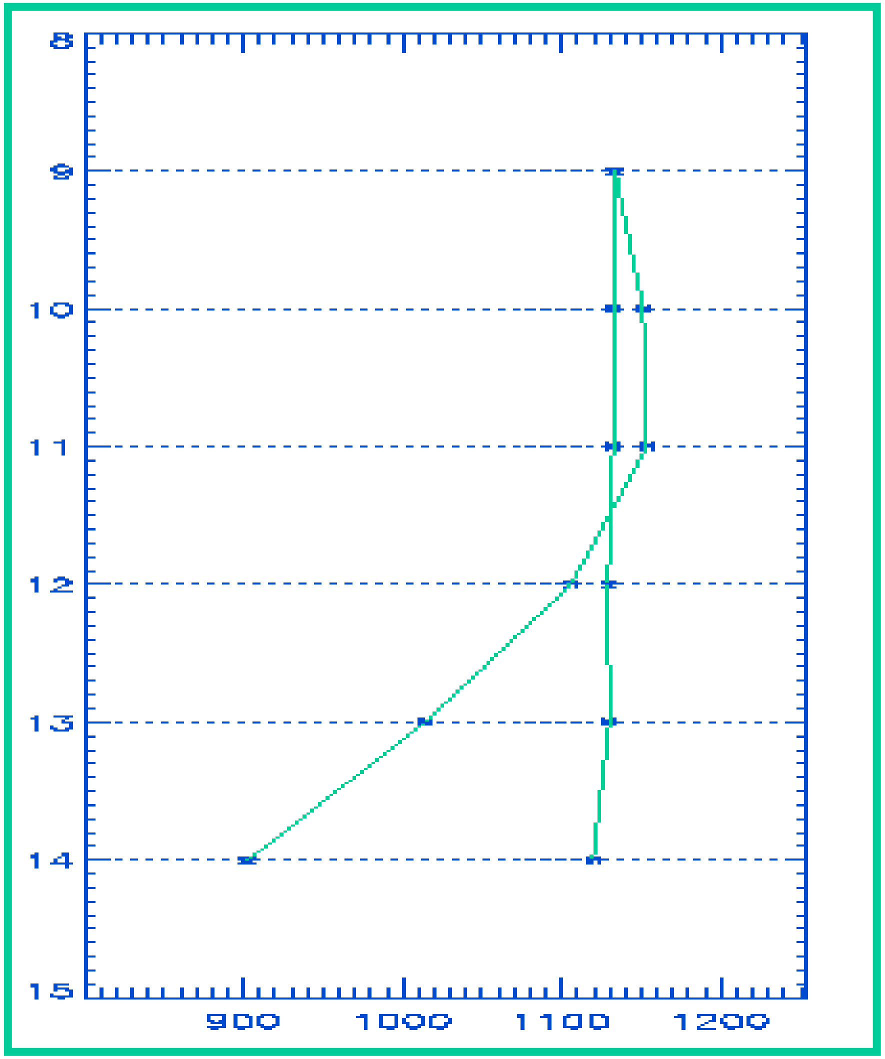
$$\theta_{rms} = \frac{13.6}{E_e[MeV]}\sqrt{\frac{z}{X_0}}\left(1+0.038\ln\frac{z}{X_0}\right)$$

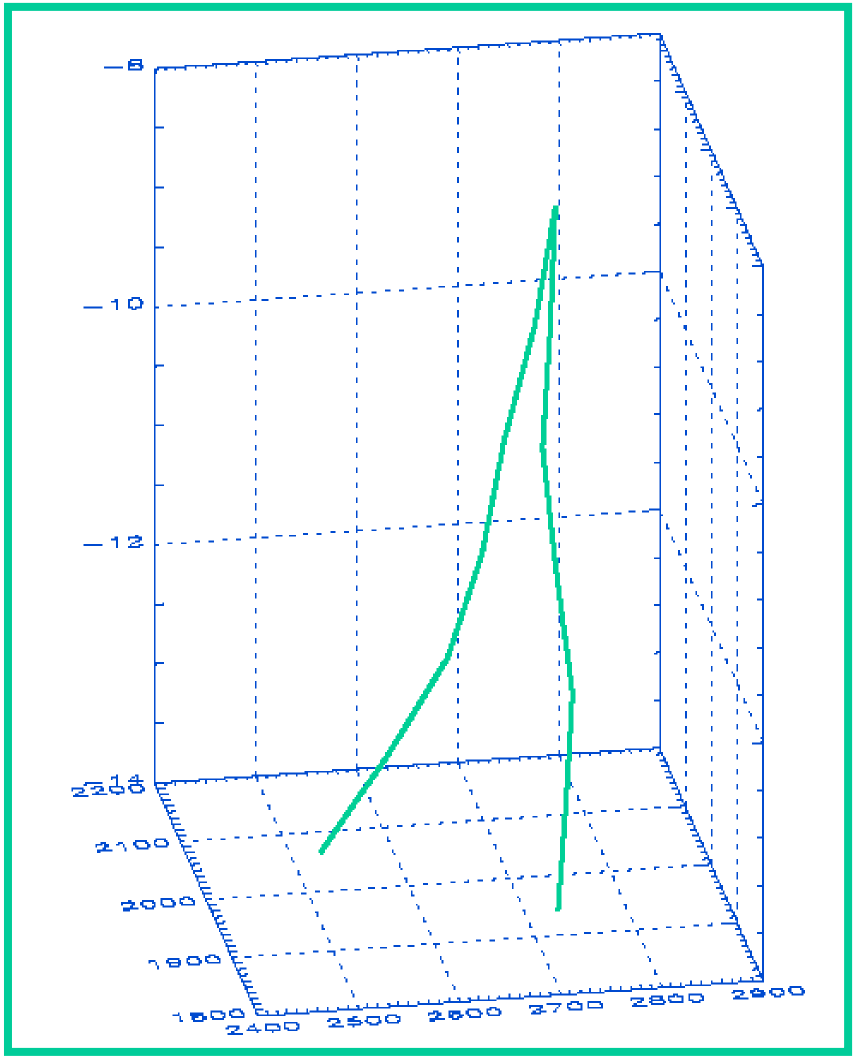




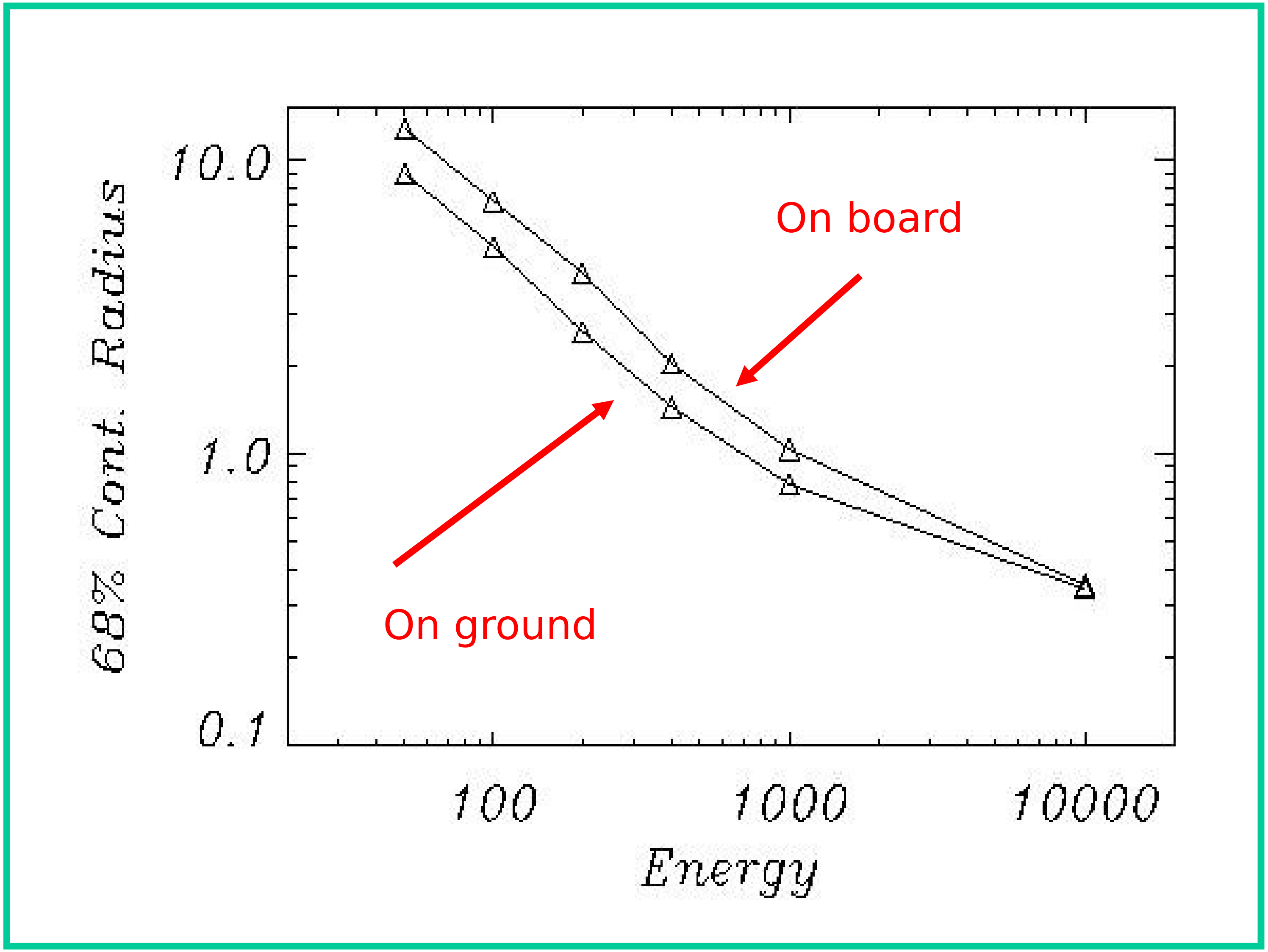
- *Measure of MS angles along the track and crossed thickness*
- *Three-dimensional track reconstruction*
- *Energy loss (bremsstrahlung and ionization)*

Track reconstruction – Kalman F.





Angular Resolution

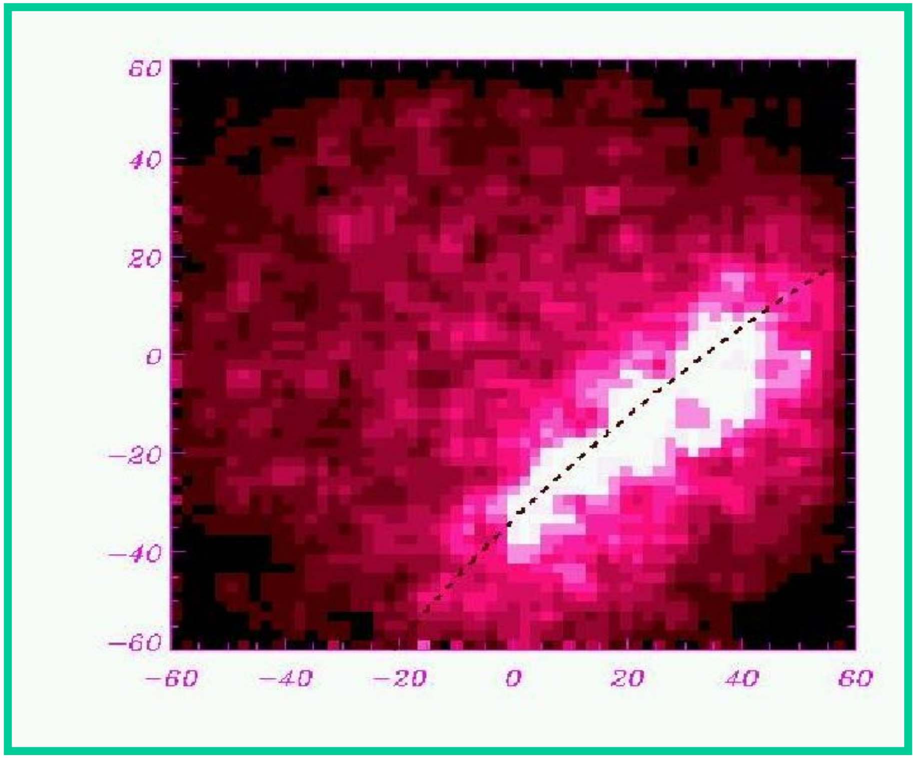


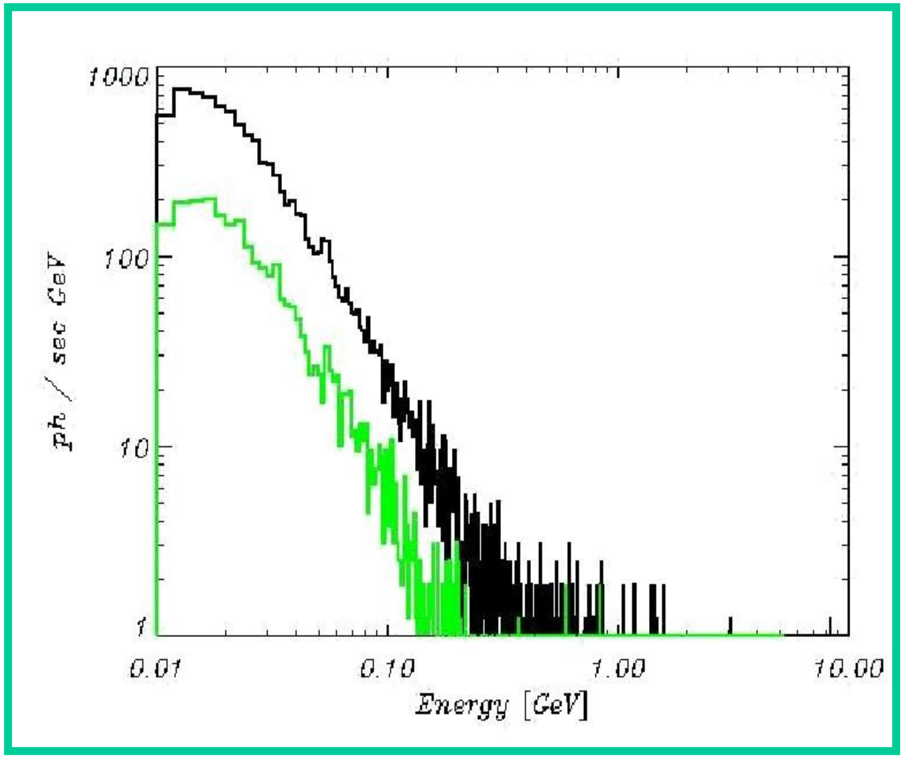
Albedo Photons Cut

The earth atmosphere is an intense source of gamma-ray photons

$$F = 5 \cdot 10^{-5} \left(\frac{E}{100\ MeV} \right)^{-2} \frac{ph}{cm^2\ s\ sr\ MeV}$$

Direction reconstruction allows to discriminate the events

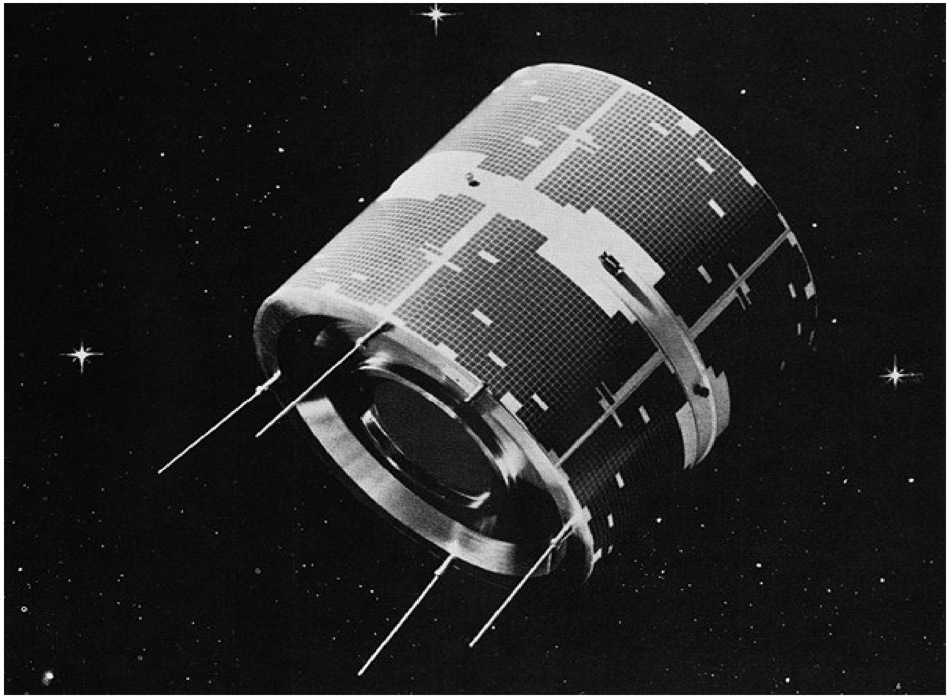




Pair Production Telescopes

SAS 2 (NASA)

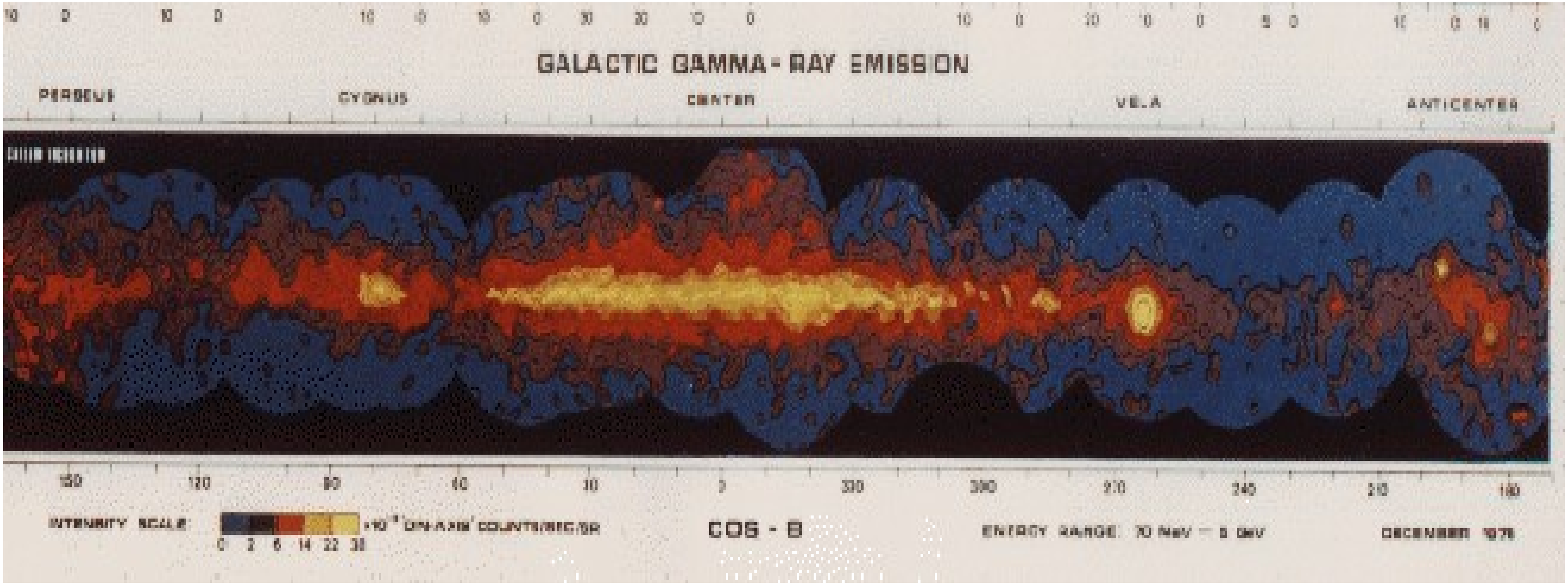
1973 - 1974



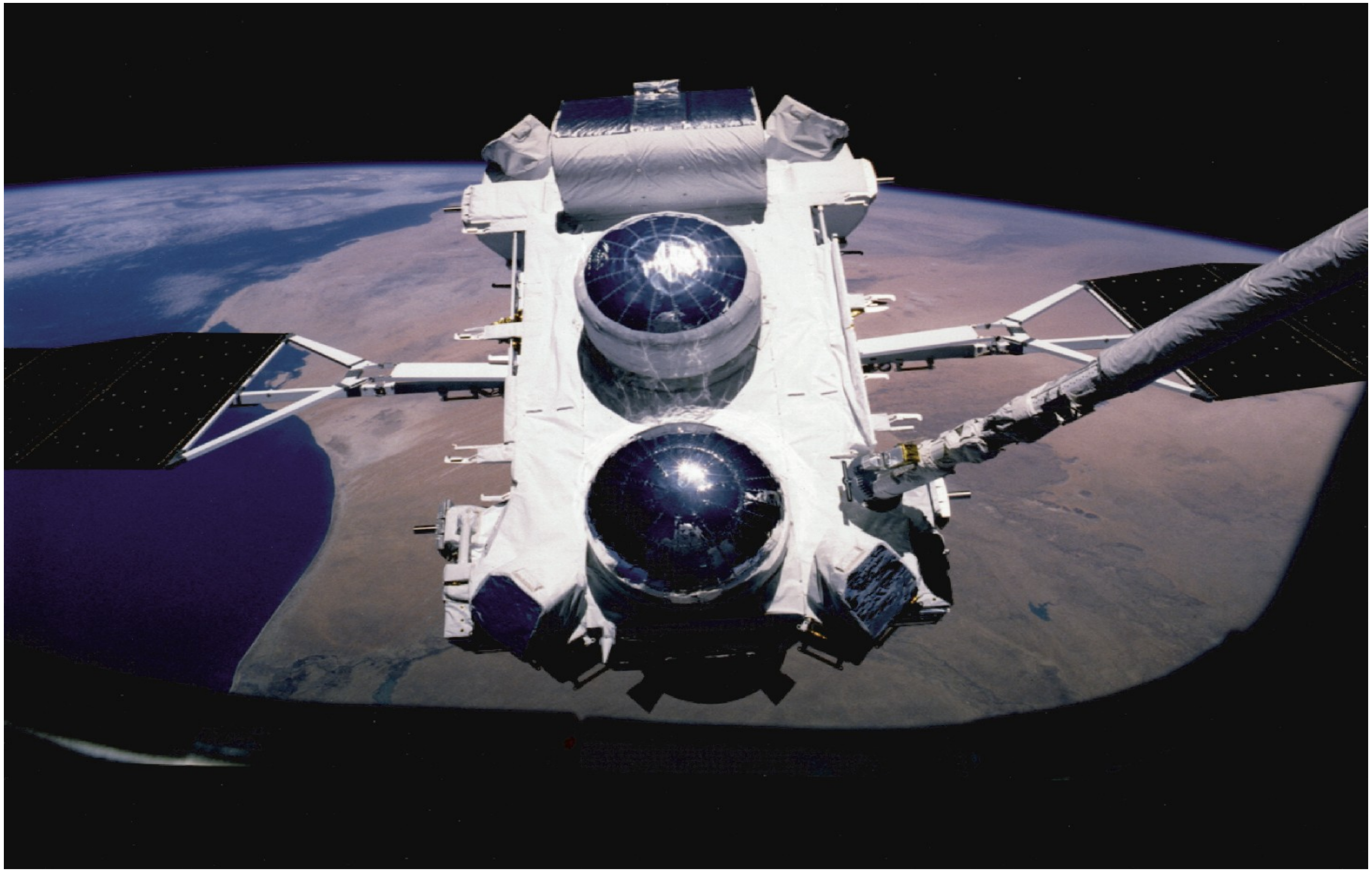
COS B (ESA)

1975 - 1982

Pair Production Telescopes

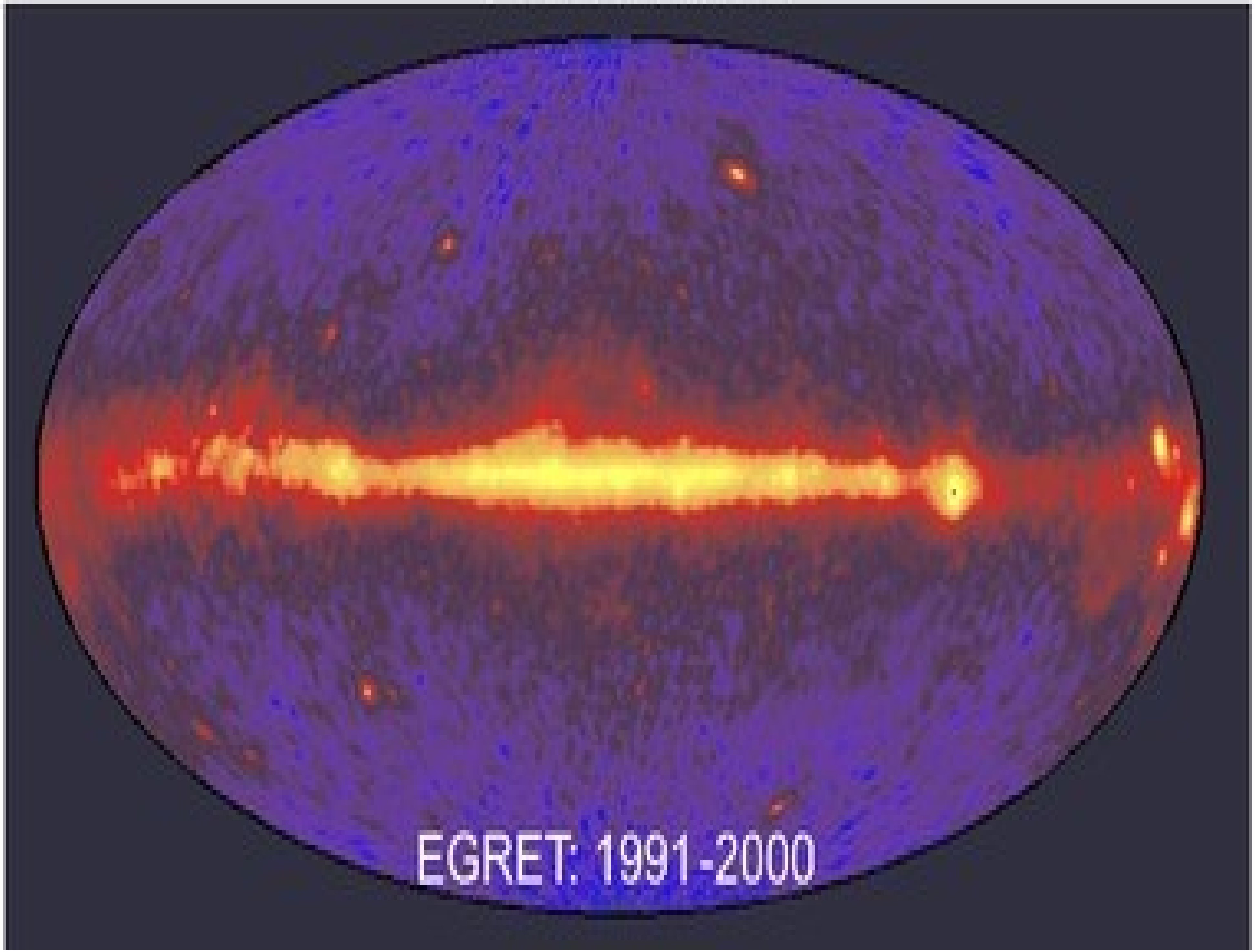


Pair Production Telescopes

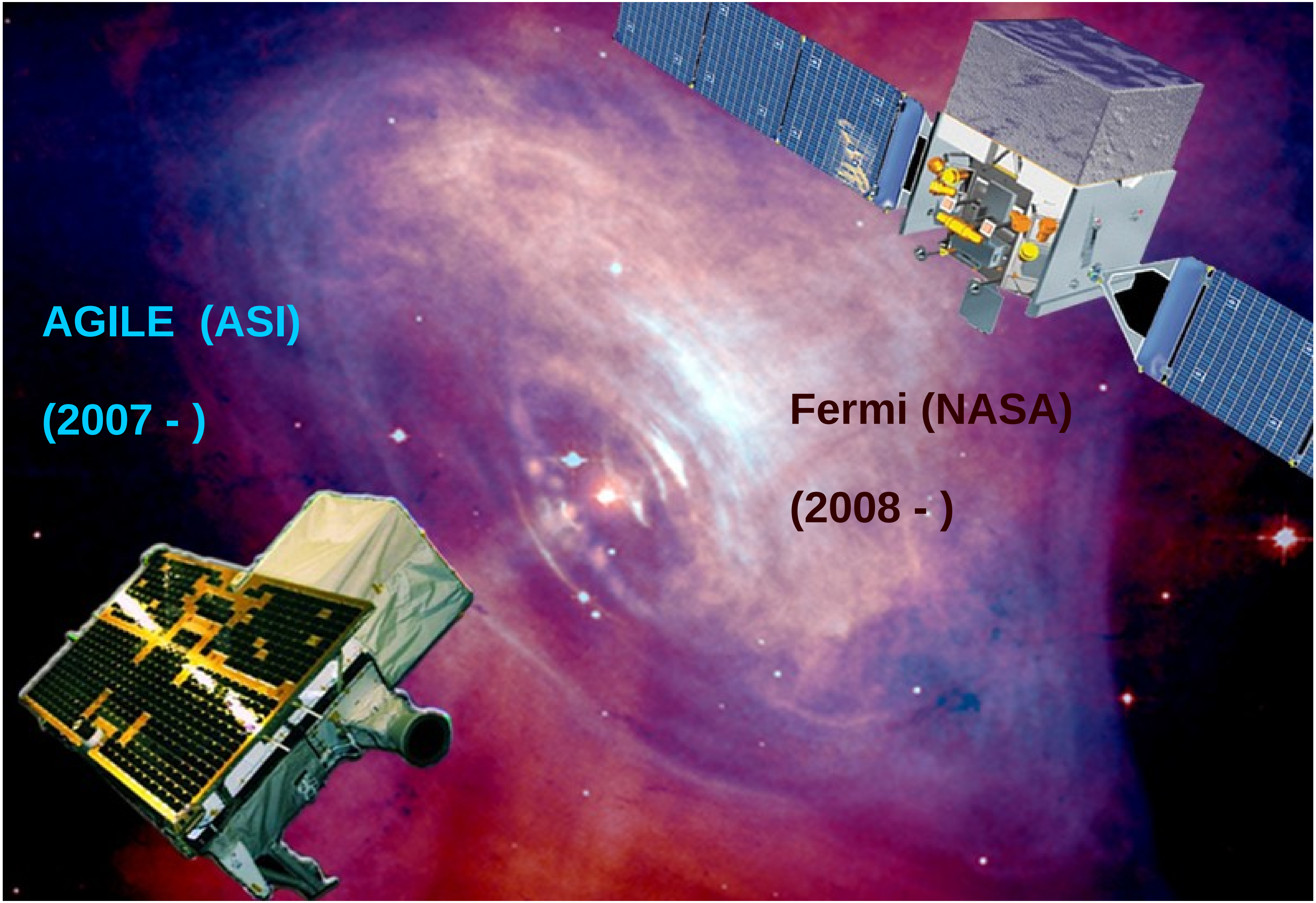


GCRO/EGRET (NASA)

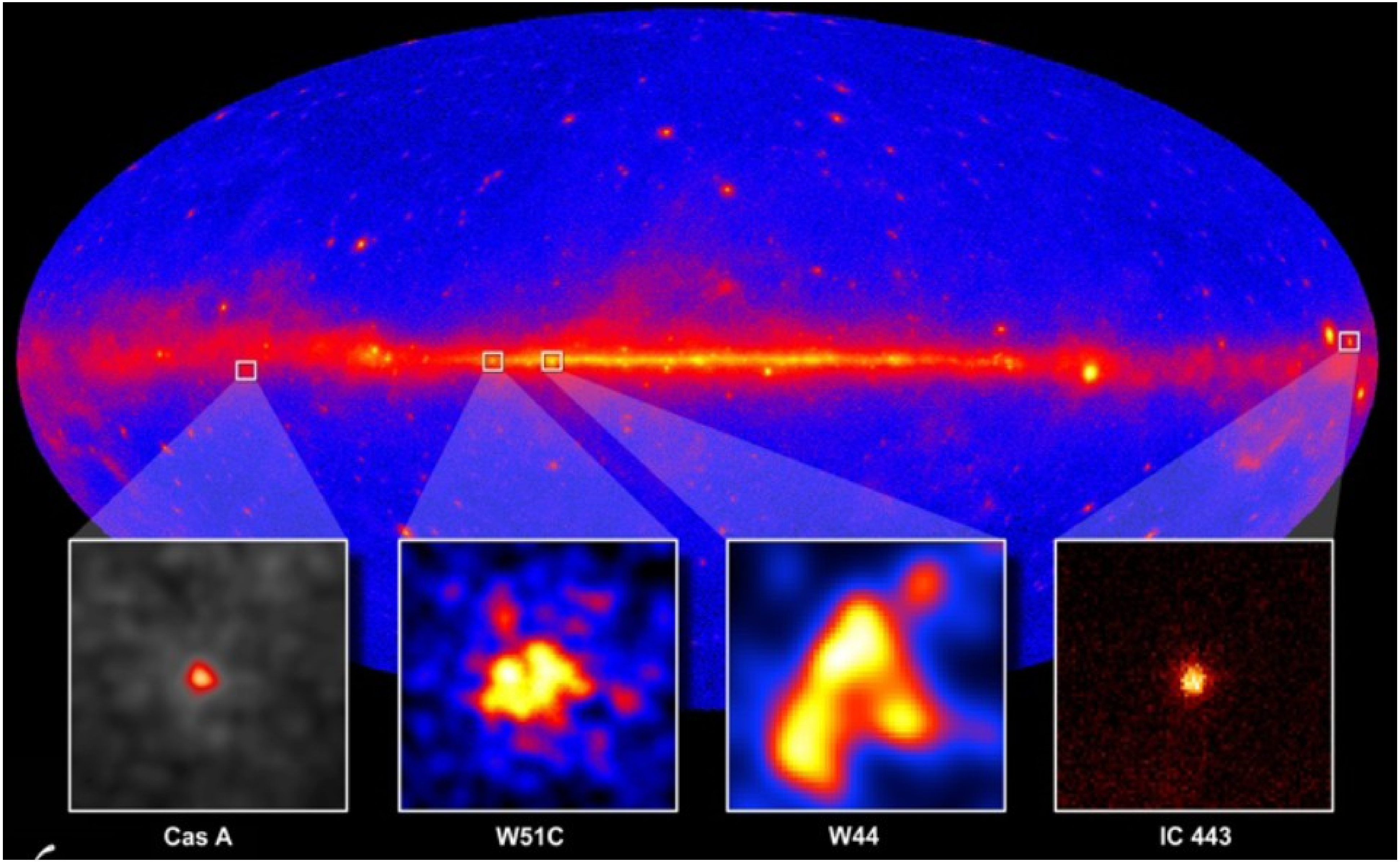
1991 - 2000


EGRET: 1991-2000

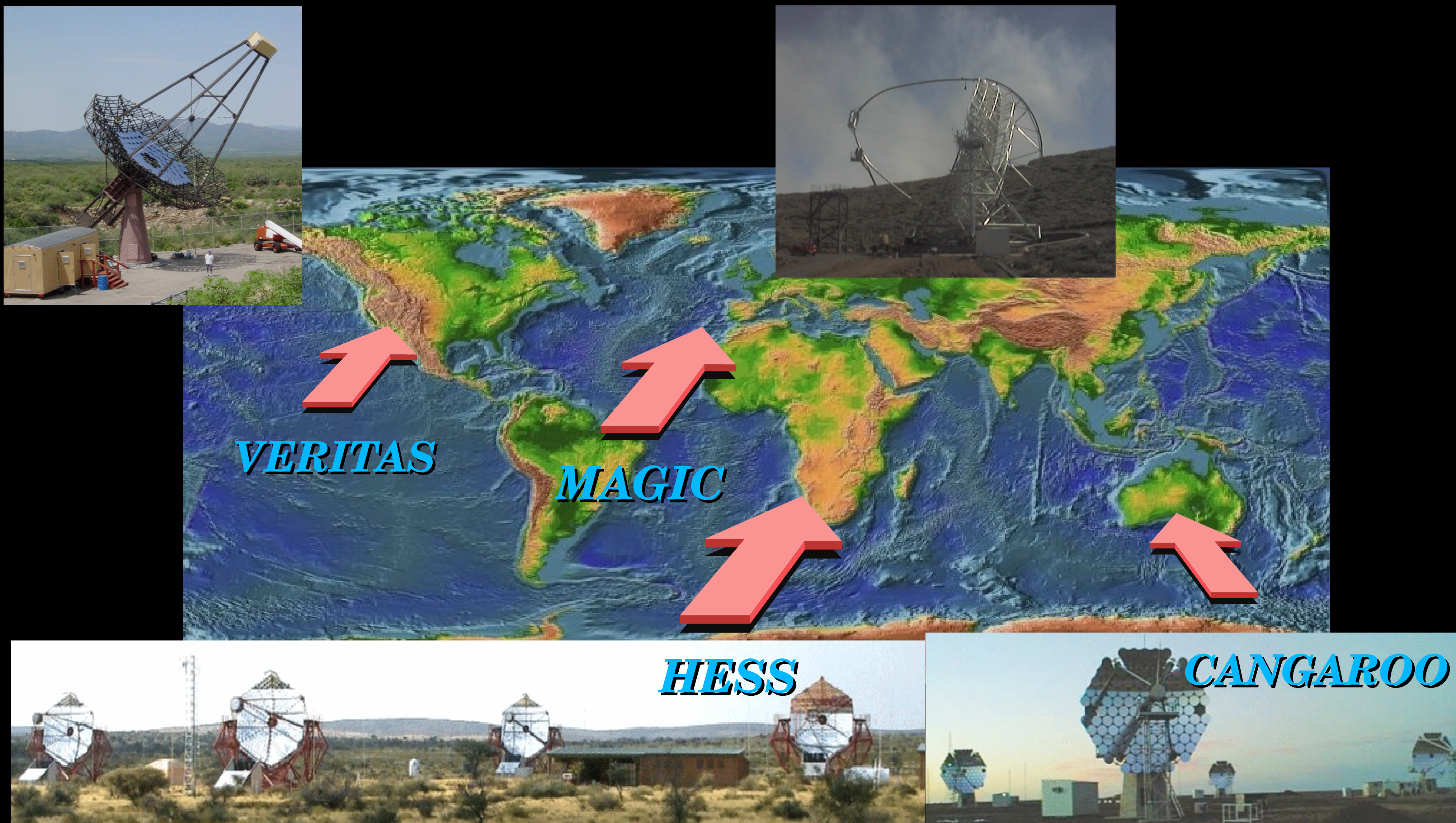
Pair Production Telescopes



Pair Production Telescopes



Overview of Existing Cherenkov Telescopes

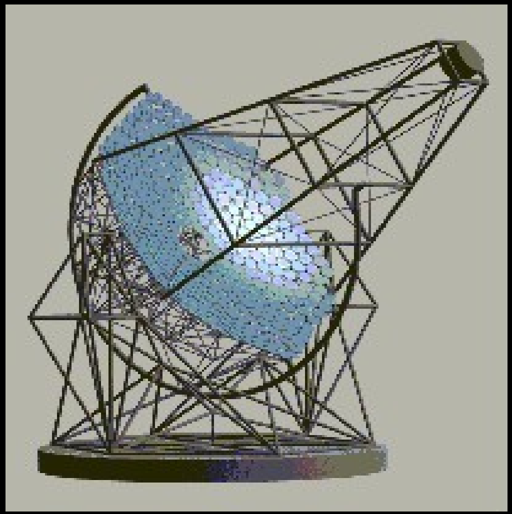


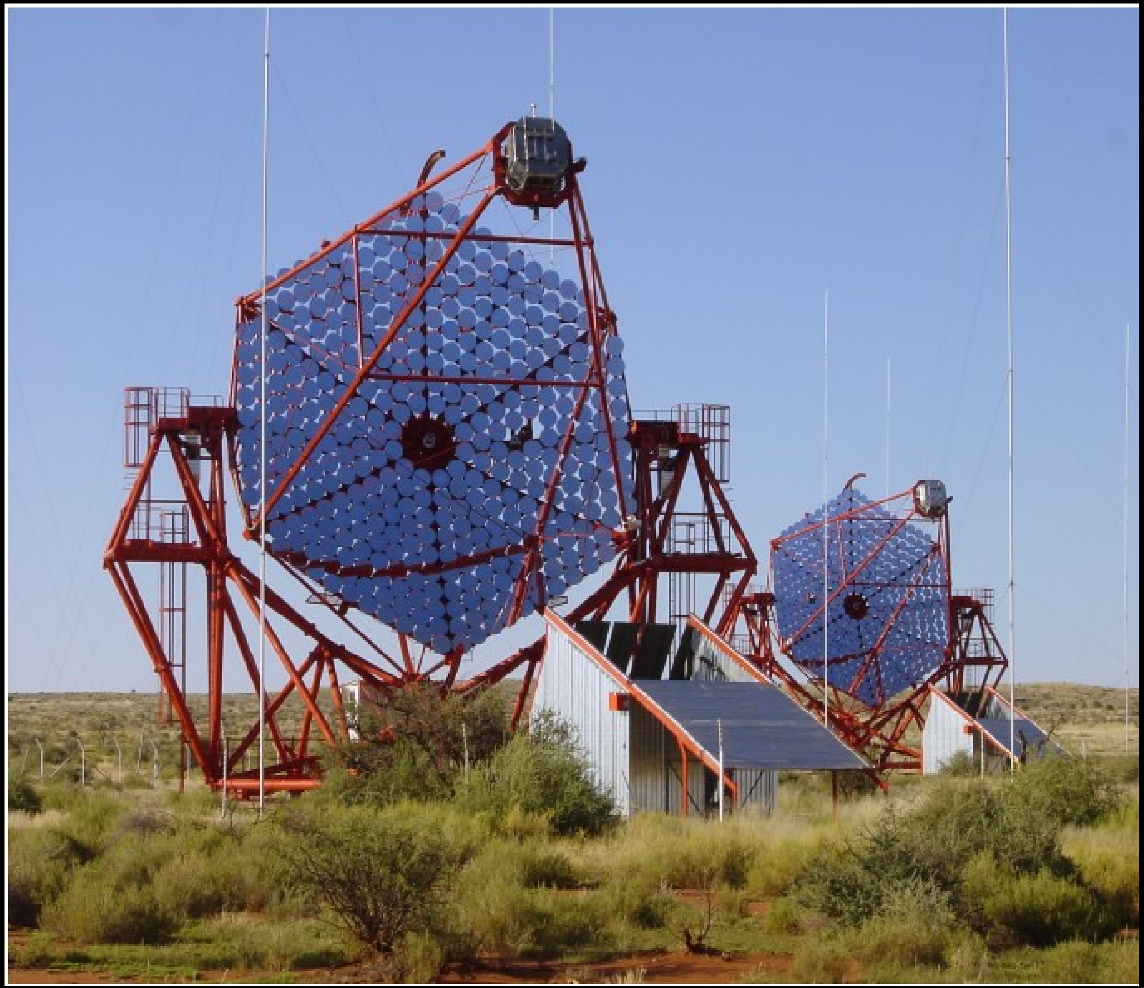
Telescopes & Mirrors

H.E.S.S consists currently of 4 telescopes.
They are arranged in a square with 120 m side length and provide multiple stereoscopic view of air showers.

Each telescope consists of a dish with an effective area of 107 m^2 and a camera. The mirrors collect Cherenkov light from air showers and focus it onto the camera.

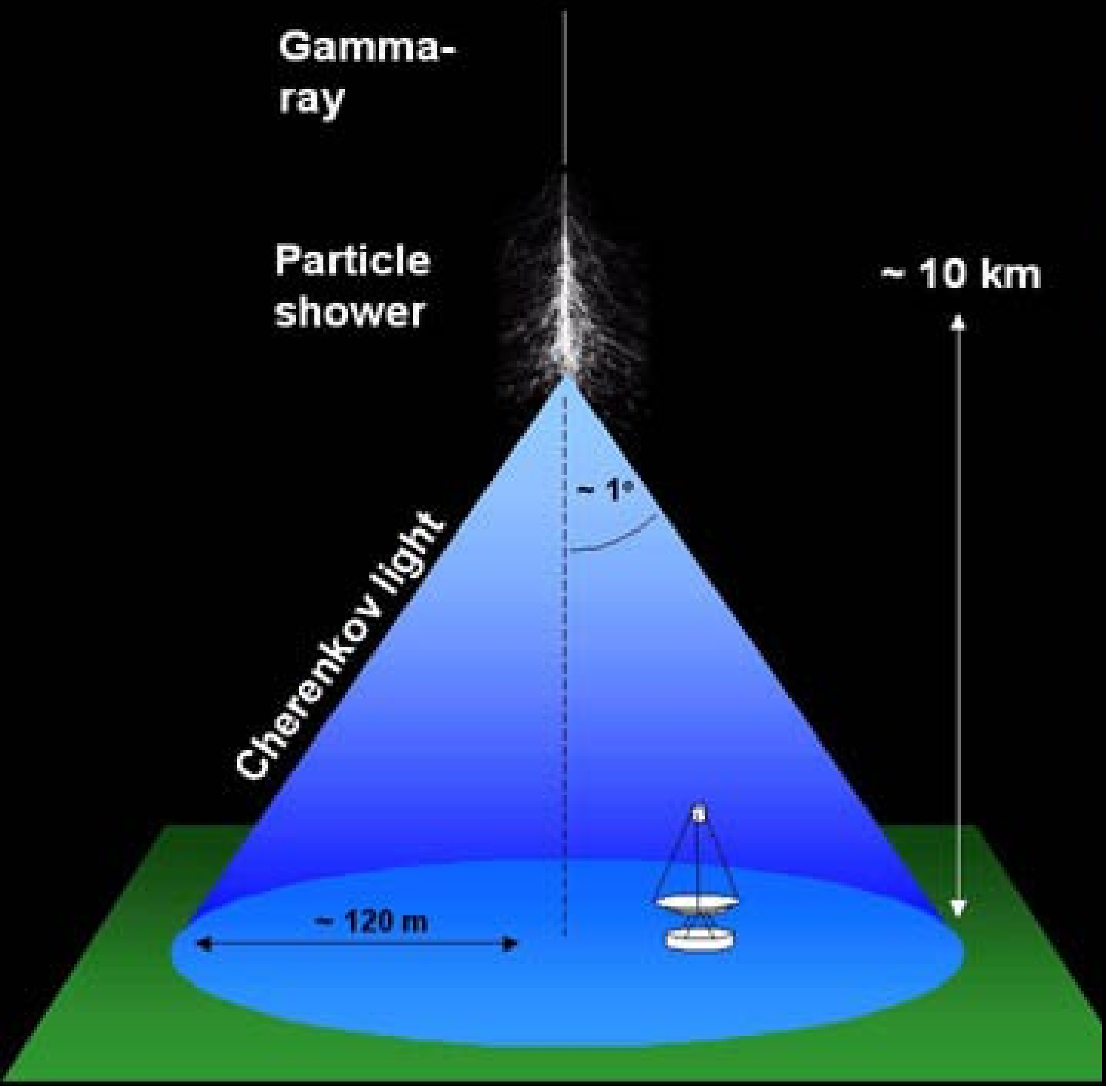
A computer controlled motor moves the telescope around a vertical axis and the dish around an elevation axis. Maximum slewing speed: 100°/ min.

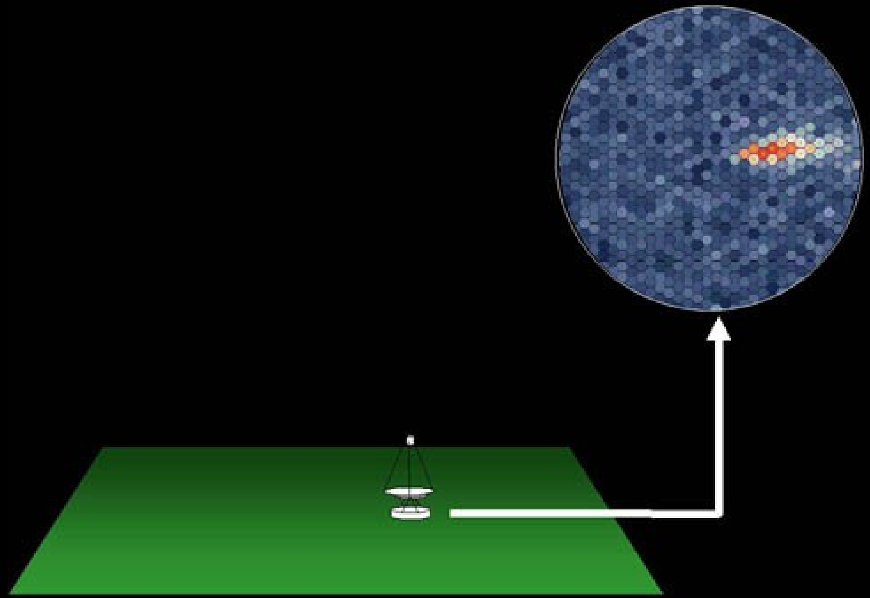




The Davies Cotton telescopes have a focal length of 15 m and a reflectivity of ~80 %.

Observing an air shower with a single telescope

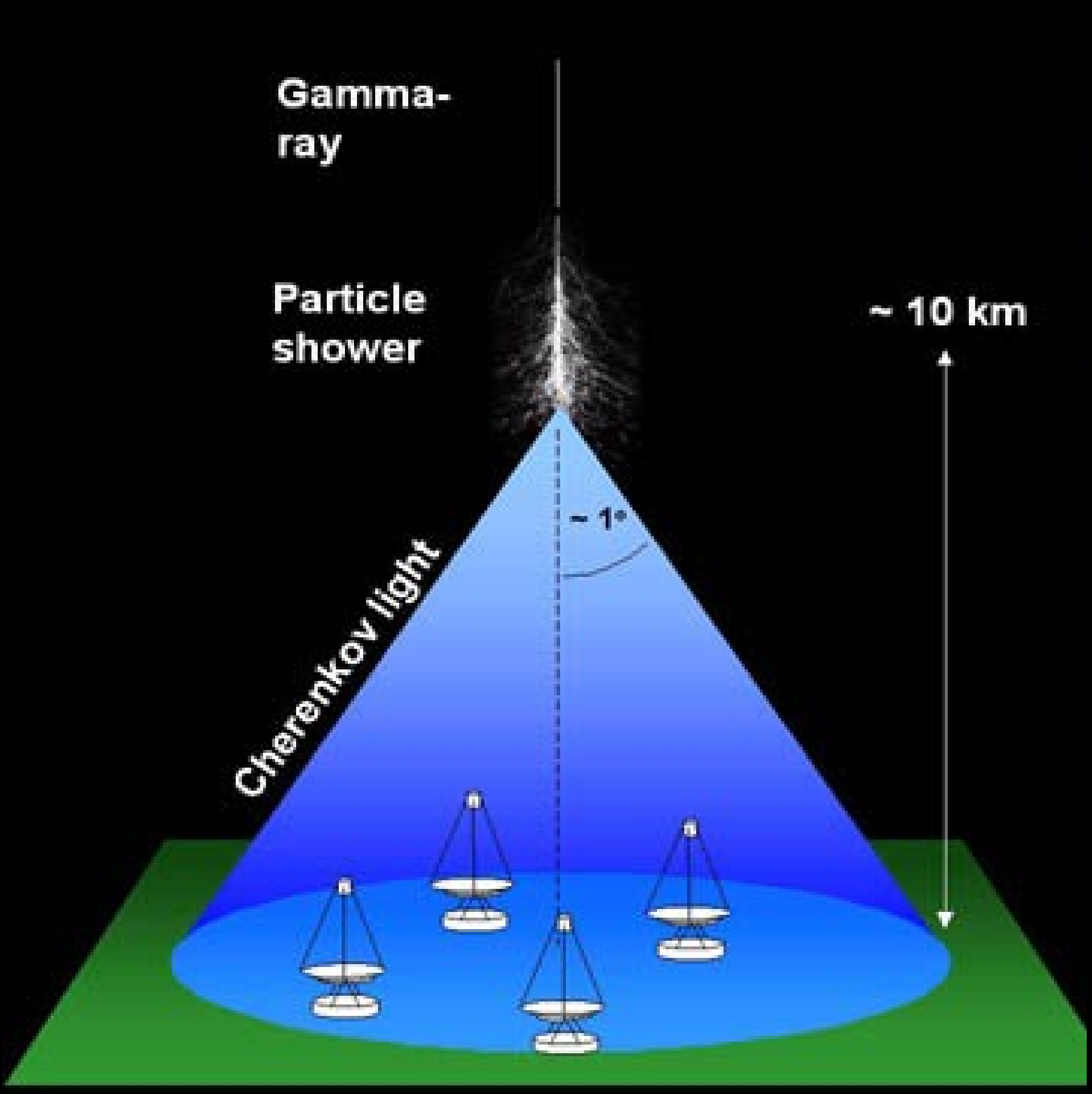


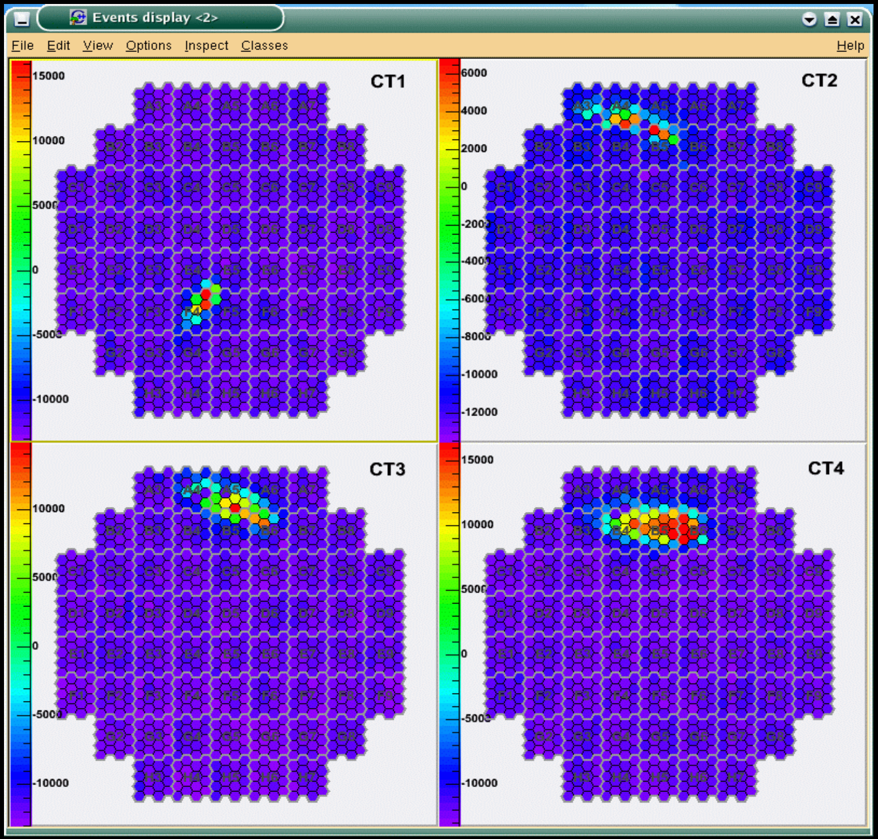


Air showers from gamma rays with E >100 GeV develop at a height of about 10 km. A pool of Cherenkov light from the shower with a radius of ~120 m reaches the ground.

The image of the shower can be seen as a single track with the camera of one telescope.

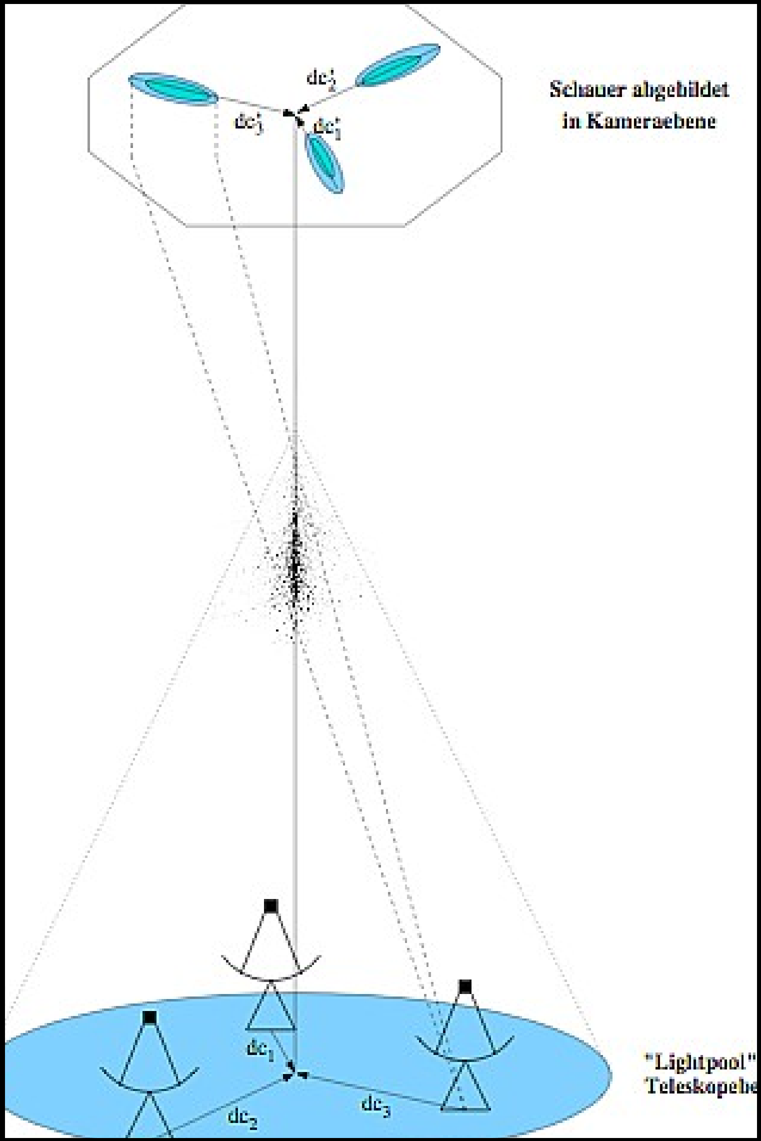
Stereoscopic Observation of an Air Shower





With several telescopes, a stereoscopic (or multiscopic) view of a single shower is possible. This allows to reconstruct the shower geometry and to reject background signals.

Air Shower Image Projection



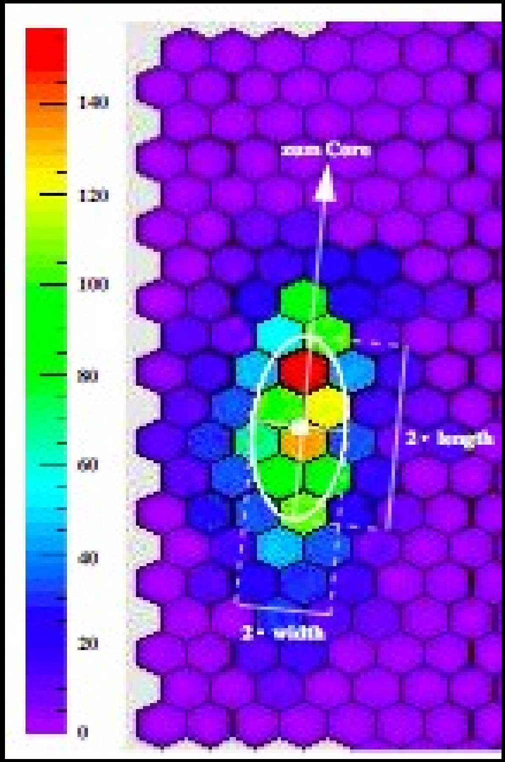
The image of the air shower that is projected onto the camera has the form of an ellipse.

In the reconstruction of the air shower, one fits an elliptical form to the image to extract the "Hillas-parameters" that characterize the air shower. Two important parameters are the width and the length of the ellipse.

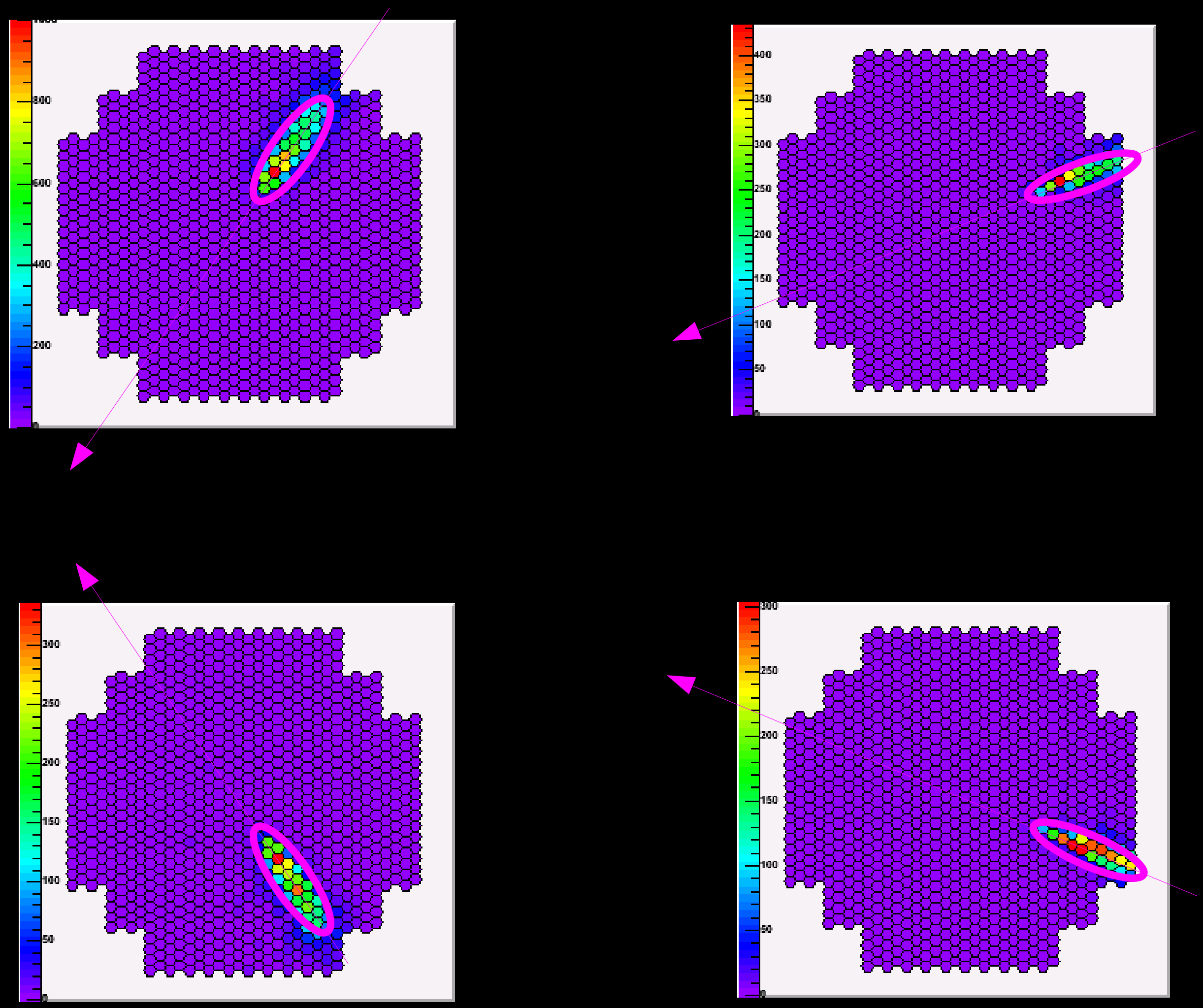
One also takes into account the distribution of intensities over the PMTs that are part of the image.

In the image shown here, the red pixel has the largest number of photoelectrons. It indicates the direction of the shower core.

(figures taken from the Ph.D. thesis by Oliver Bolz, Ludwigshafen 2004)



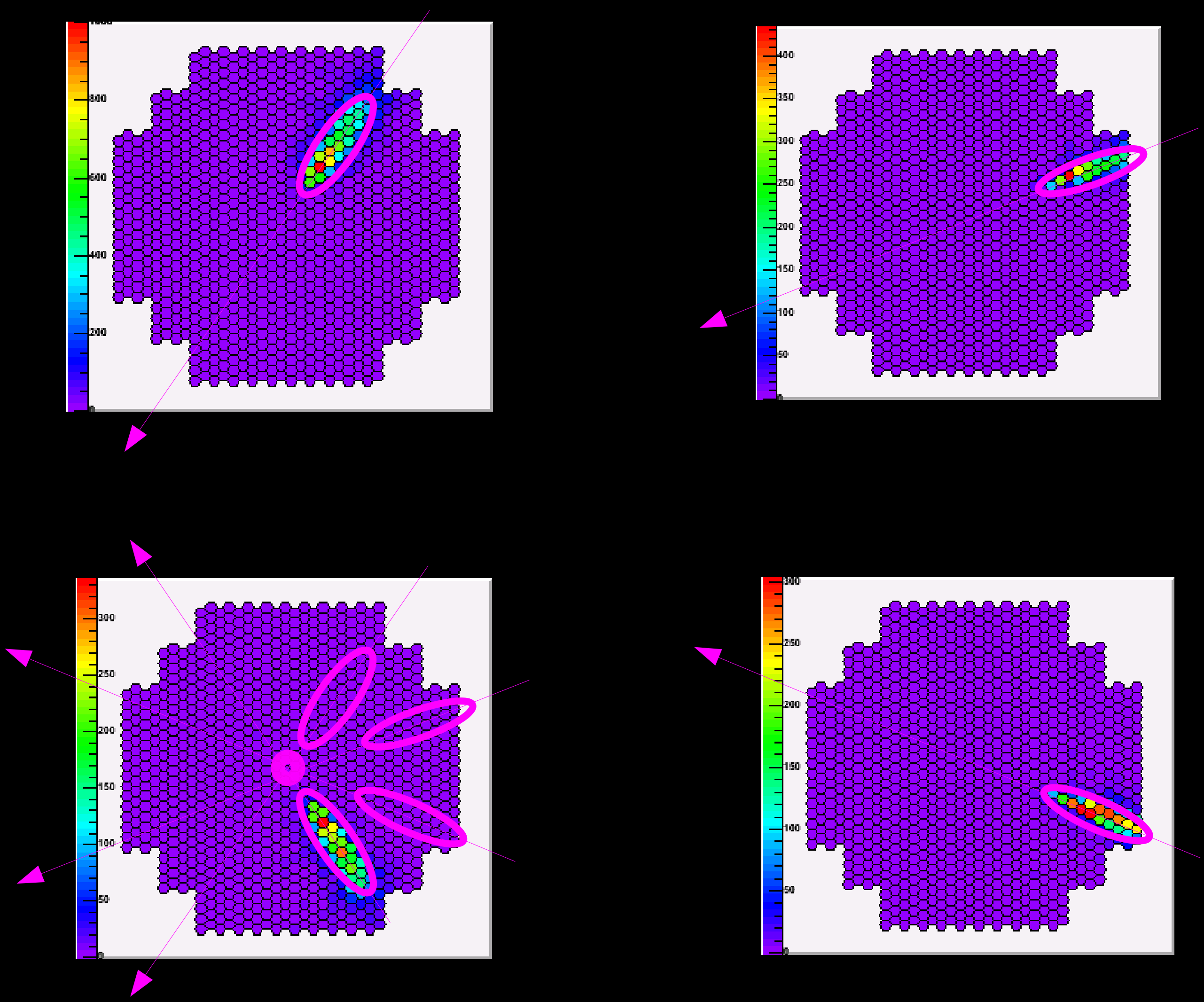
Reconstruction of the Direction of the Air Shower



The stereoscopic observation provides information on the direction of the air shower.

All telescopes point at the same direction in the sky, so we can superpose the images from the air shower seen in different cameras.

Reconstruction of the Direction of the Air Shower

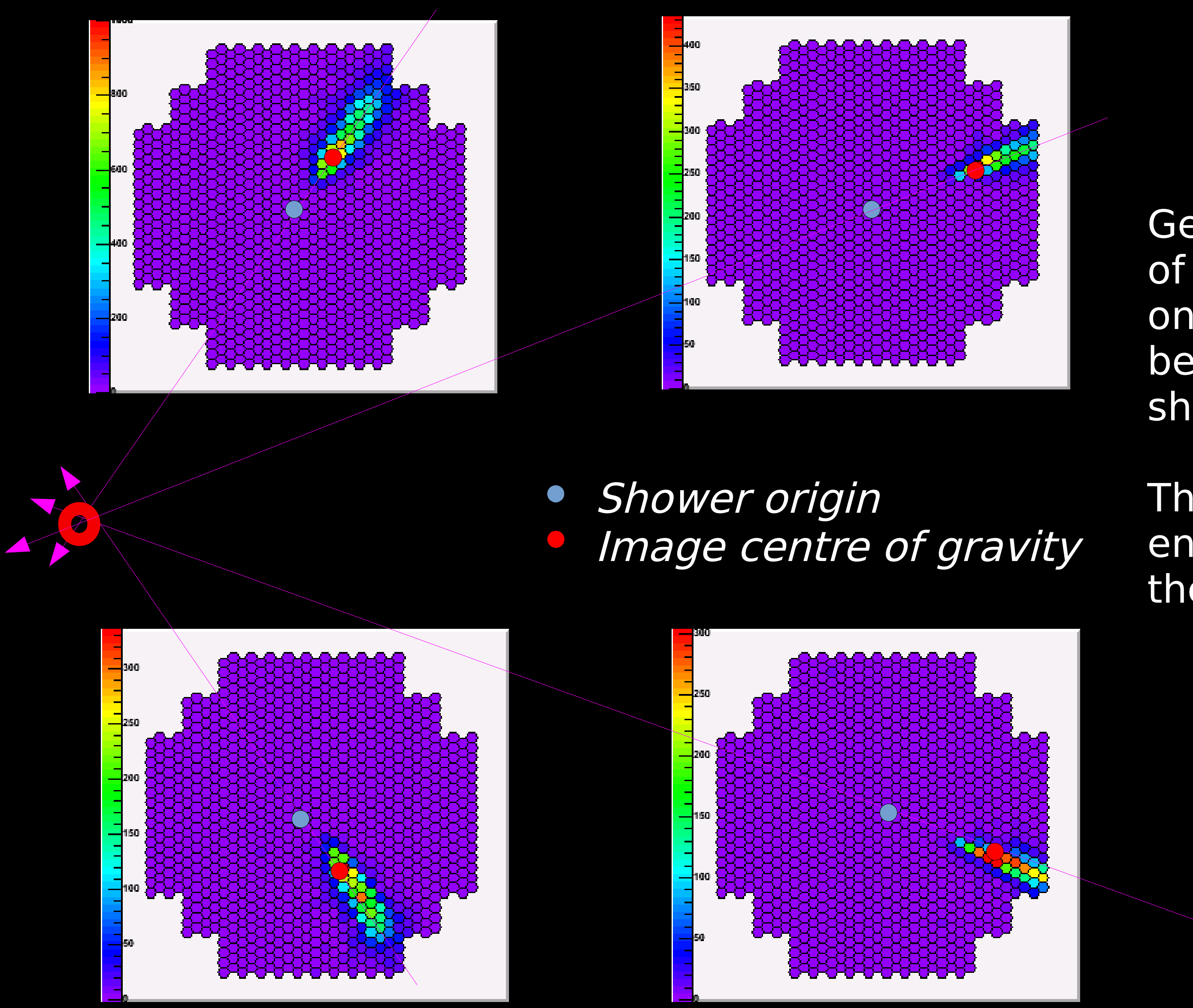


In this case, the air shower came directly from the direction the telescopes are pointing at.

If they are pointing at a known source, one would identify the shower with a photon from that source.

The angular resolution of H.E.S.S. is a few arc minutes.

Reconstruction of the Shower Impact Point



Geometrical determination of the shower impact point on the ground provides a better understanding of the shower geometry.

This is very useful for the energy reconstruction of the event.

Reconstruction of the Shower Energy

The energy of the primary particle, i.e. the γ-ray, is determined from the total recorded signal size, which can be converted into a flux of Cherenkov photons.

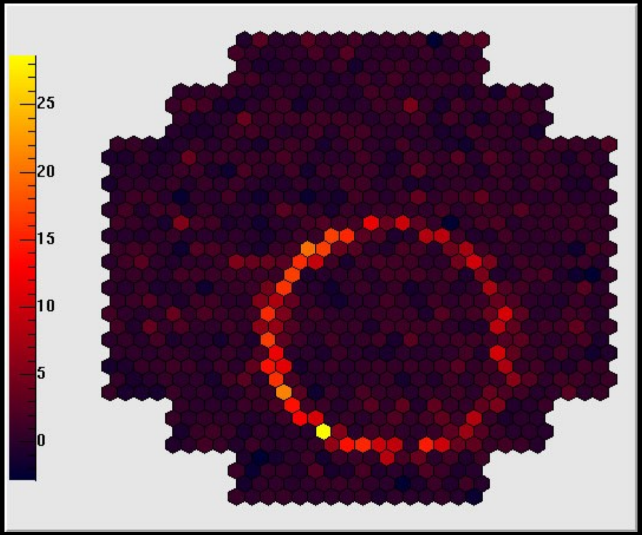
Once the geometry of the air shower – i.e. the inclination of the shower axis and the impact point – has been determined, one compares the recorded signal to lookup tables.

These lookup tables are generated with Monte Carlo simulations of γ-ray induced air showers at different energies and geometries. They contain lateral distributions of Cherenkov photon densities for each simulated shower.

A comparison of the recorded signal size and the simulated photon fluxes provides the energy of the observed shower.

The energy resolution of H.E.S.S. is on the order of 15 %.

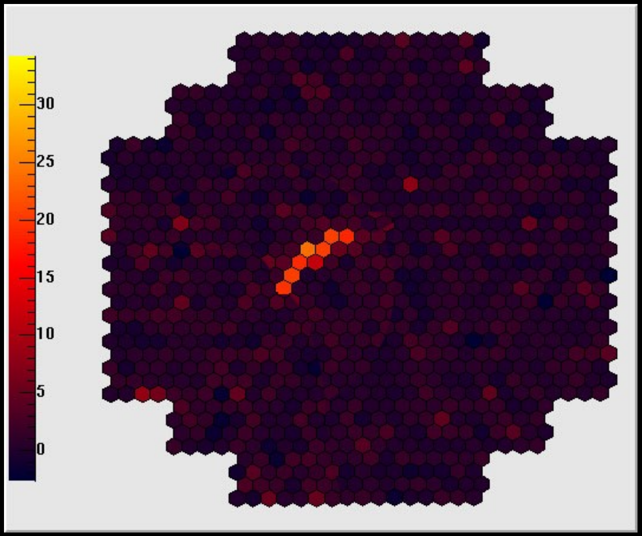
Background - Muons

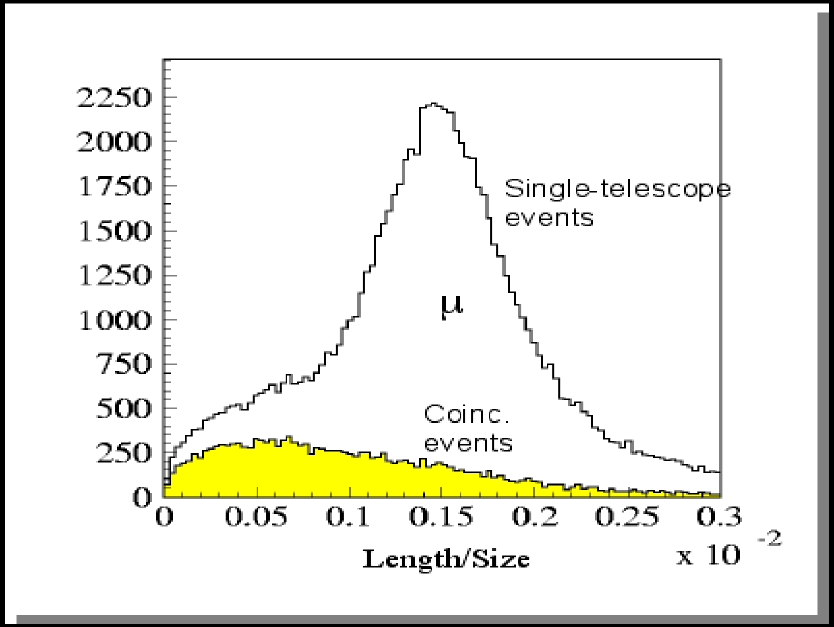


Muons that hit the telescope leave a ring-shaped Cherenkov light signal and are easily identifiable.

Muons that pass the telescope at some (not too large) distance can leave a signature that is not easy to distinguish from the image of an air shower. Due to the large muon flux in the atmosphere, this is a considerable source of background.

Muons can however be rejected by requiring at least two telescopes to be triggered simultaneously.





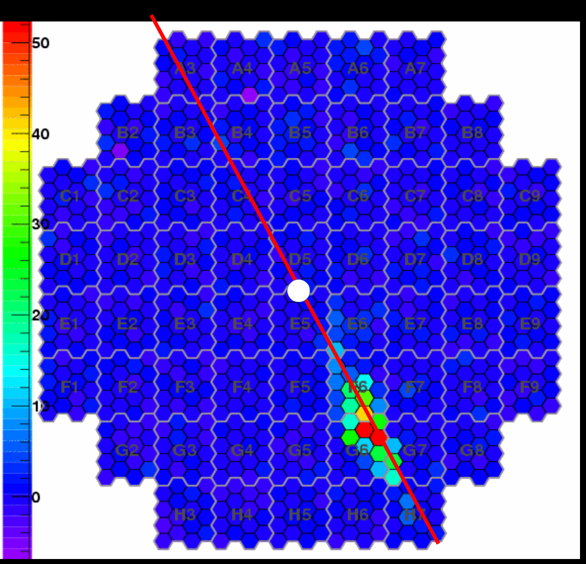
More Background – Hadronic Showers

Air showers from cosmic rays (hadrons) constitute an important background in the search for γ-ray events. Images of hadronic showers can be distinguished from γ-ray showers in two ways:

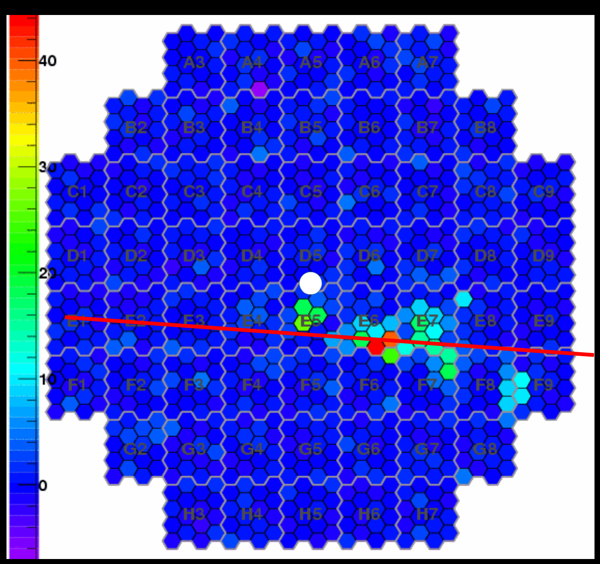
Hadronic showers do not leave a clear track. They look more like a "blob". When fitting an ellipse to the image, the width of the ellipse is usually larger than in the case of a γ-ray shower. One rejects hadronic showers by applying a cut on the observed width.

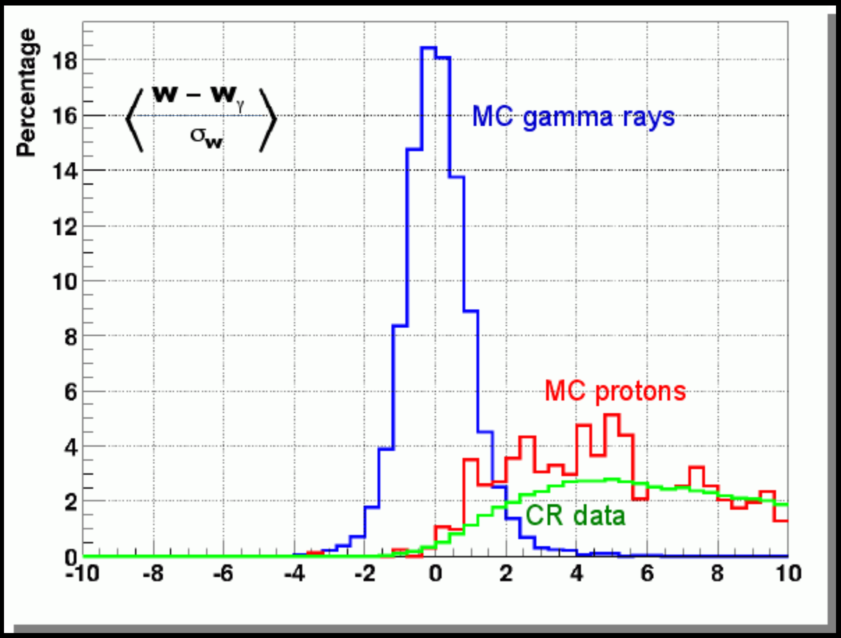
When observing a source, showers initiated by γ-rays from that source should point back to it. If the telescope points at the source, the γ-ray showers should point to the center of the telescope. Hadronic showers point in deliberate directions.

a γ-ray shower

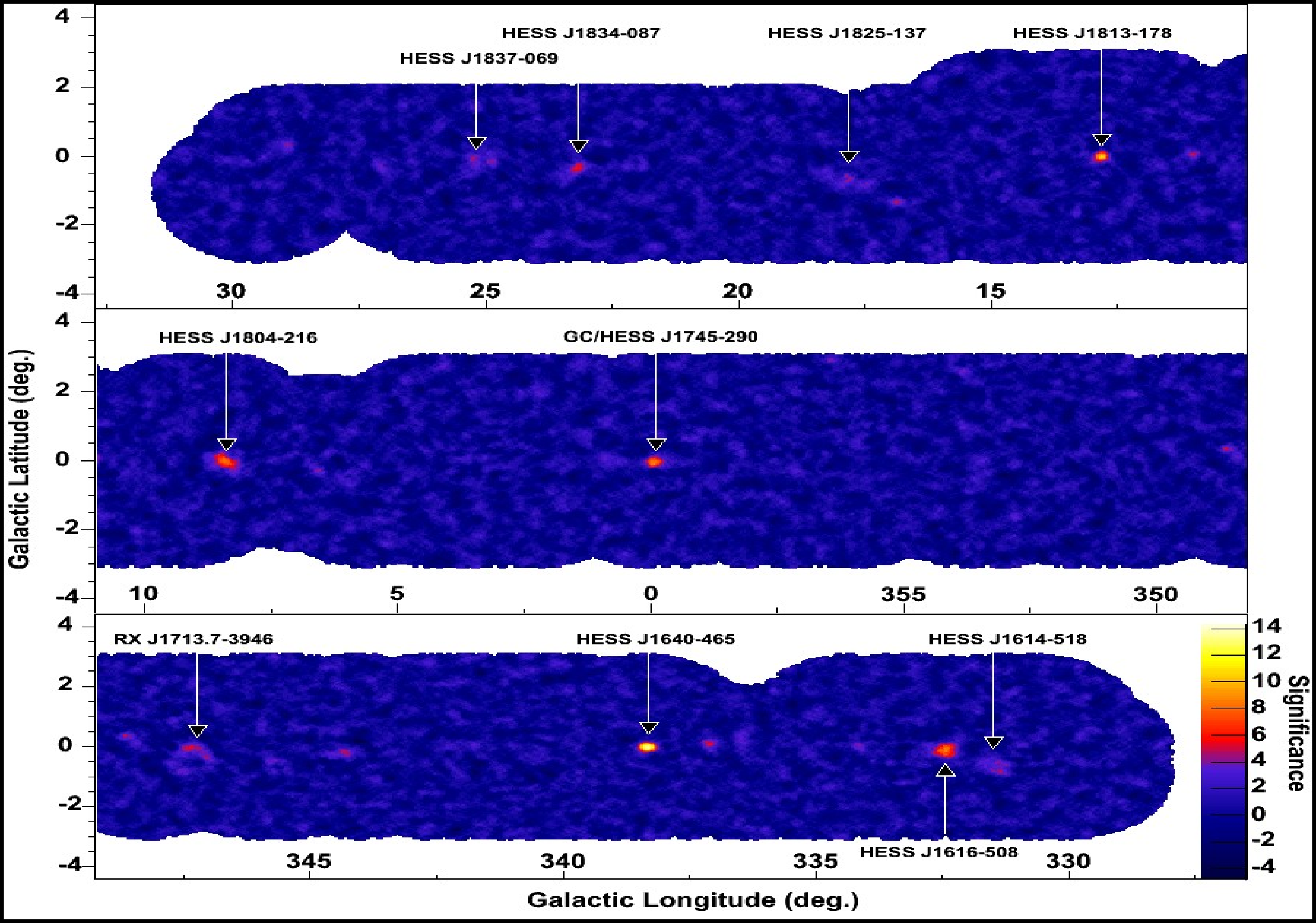


a hadronic shower





Galactic Plane Survey



All sky telescopes – Milagro

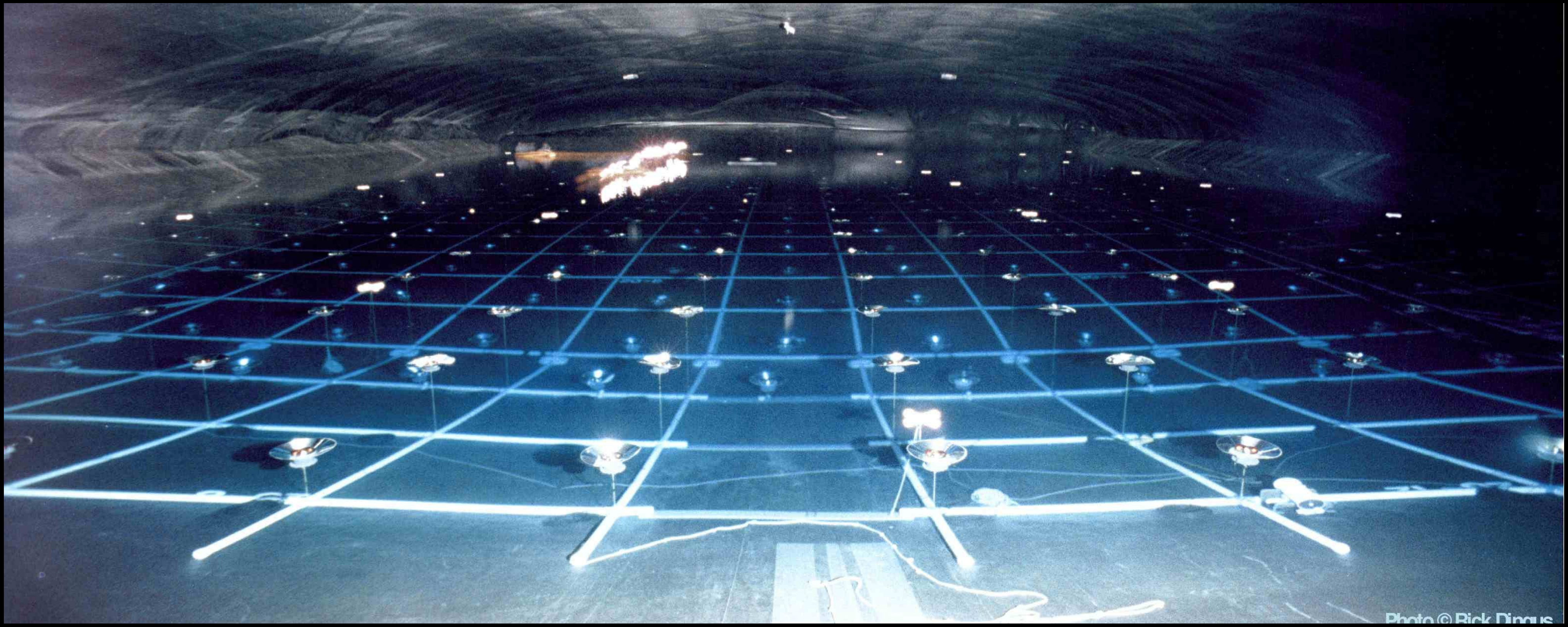
- located near Los Alamos, NM, USA; altitude 2650 m
- a pond of size 80m x 60m x 8 m filled with pure water
- 175 tanks in a larger array
- 2 layers of PMTs (723 in total) observe Cherenkov light from air shower particles
- upper layer: electrons, positrons
  lower layer: muons

All sky telescopes: Milagro

100% duty cycle, very large field of view (~ 1 sr), good sensitivity at TeV energies
=> ideal for all (northern) sky survey of gamma-ray sources

Only 0.8 degree angular resolution, higher energy threshold than IACTs

=> complementary method to IACTs and satellites; similar method used by ARGO (Tibet)



Future Projects on the Ground

H.E.S.S. II: A 5th telescope is currently being added to H.E.S.S.

mirror area: 600 m^2 — # of pixels: 2048
field of view: 3.2° — lower energy threshold: ~50 GeV

The lower energy threshold will allow a study of AGN at greater redshifts, since at lower energies gamma-rays are less absorbed in the extragalactic background light. The large mirror area will yield a better sensitivity to faint sources.

Cherenkov Telescope Array (CTA):

A joint project of the gamma-ray groups (HESS, MAGIC, etc.).
The idea is to have a large array with many telescopes to increase sensitivity.

High Altitude Water Cherenkov array (HAWC):

next generation of the Milagro style detectors, larger effective area, higher altitude (lower E threshold)