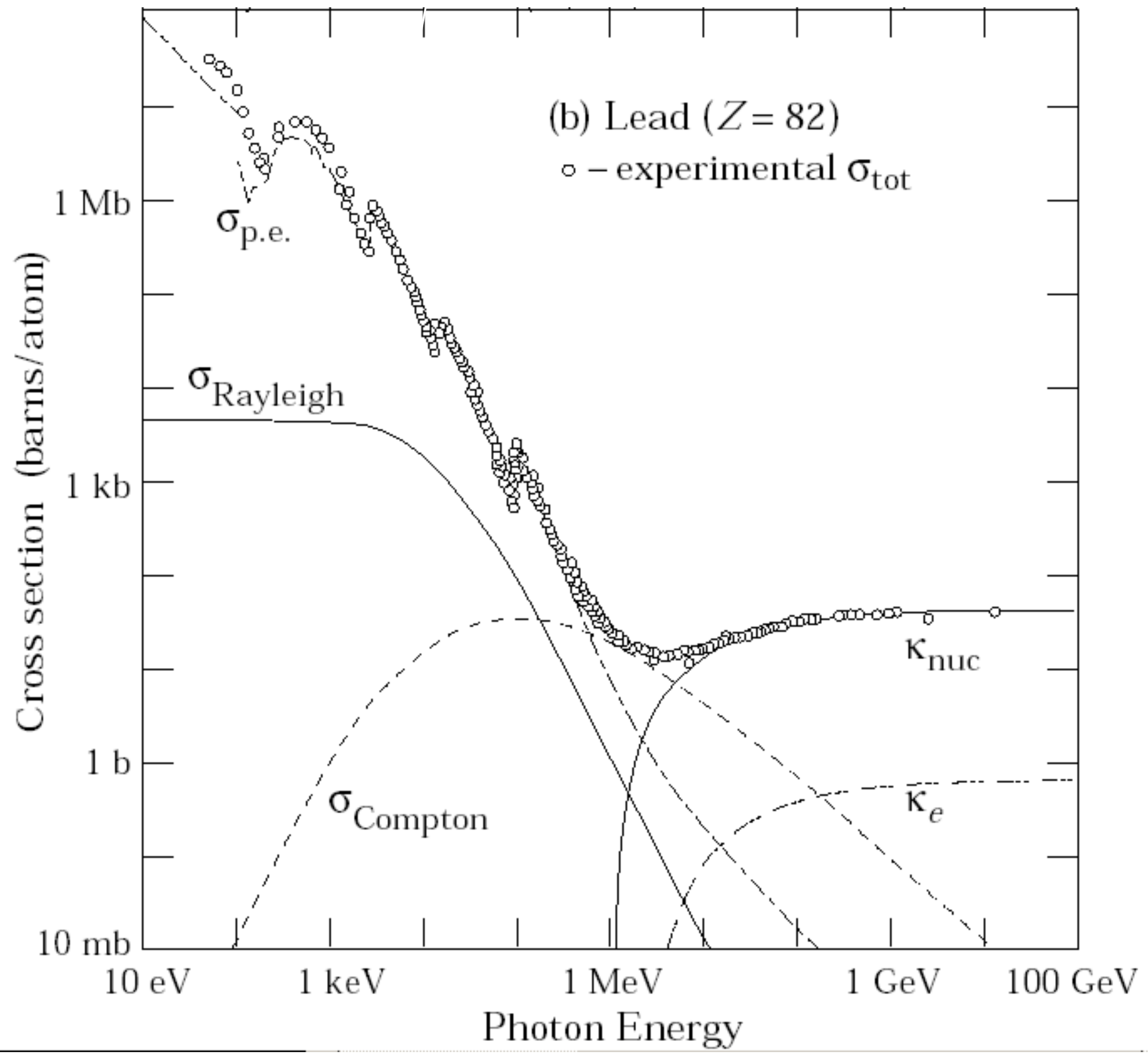
Astrofisica Nucleare e Subnucleare

GeV Astrophysics

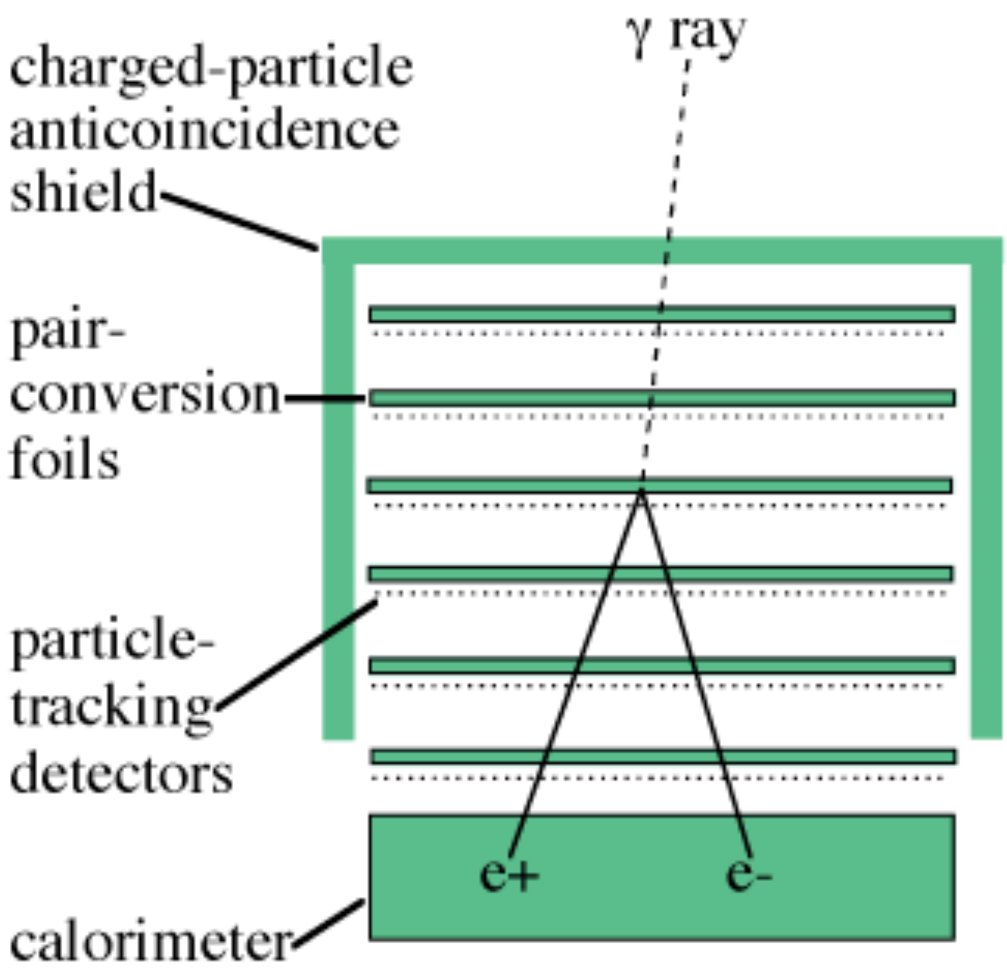
Exercise on GeV gamma-rays

- Find the web sites of AGILE and Fermi/LAT
- Check the status of “new” gamma-ray detectors (CALET, DAMPE, Gamma-400, HERD)

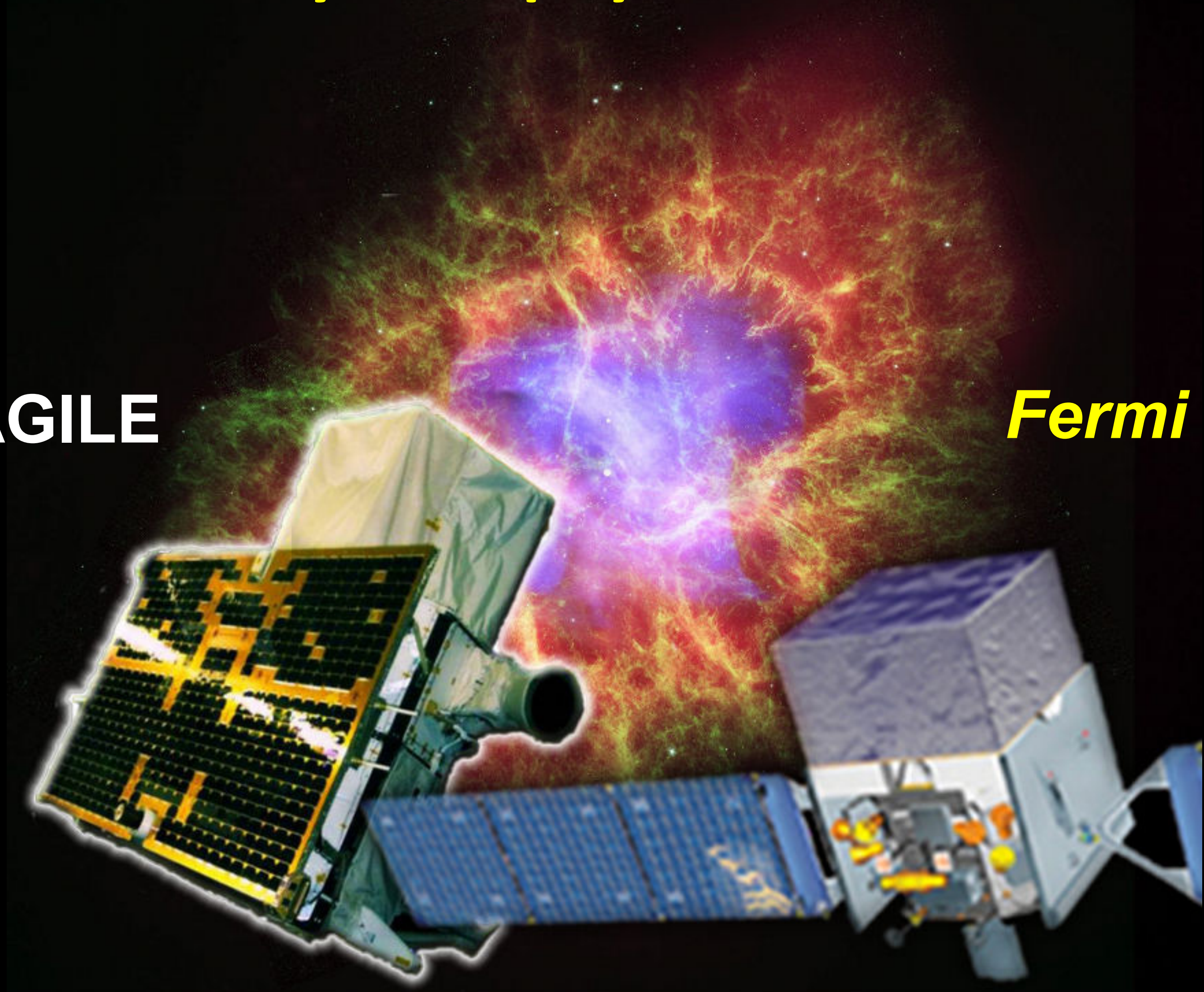
Photon Interactions



Detector Project



Gamma-ray astrophysics above 100 MeV



Picture of the day, Feb. 28, 2011, NASA-HEASARC

Astrofisica Nucleare e Subnucleare

Electromagnetic Showers

ELECTROMAGNETIC SHOWERS

SCIAMI ELETTROMAGNETICI

$$-\frac{dE}{dX} \simeq \frac{E}{X_0}$$

SIA $e^{\pm}$ CHE γ

$E = E_i e^{-\frac{X}{X_0}}$

ΔX DOPO UNA LUNGHEZZA DI RADIAZIONE $= X_0$
(AFTER ONE RADIATION LENGTH)

$$-dE = \frac{E\,dX}{X_0} \qquad \Delta E \simeq E\frac{\Delta X}{X_0} \simeq E$$

RADIAZIONE
(RADIATION) $e^{\pm} \rightarrow e^{\pm}\gamma$ BREMSSTRAHLUNG

CONVERSIONE
(CONVERSION) $\gamma \rightarrow e^{+}e^{-}$ CREAZIONE COPPIE
(PAIR CREATION)

$$1 \rightarrow 2$$

$$E_i \rightarrow 2\left(\frac{E_i}{2}\right)$$

DOPO TANTE LUNGHEZZE DI RADIAZIONE
(AFTER MANY RADIATION LENGTHS)

$$X = t X_0 \qquad t = \frac{X}{X_0}$$

$$1 \rightarrow 2^t \equiv N$$

$$E_i \rightarrow 2^t\left(\frac{E_i}{2^t}\right) = N\left(\frac{E_i}{N}\right) = N E(t)$$

$$E(t) = \frac{E_i}{N} = \frac{E_i}{2^t}$$

QUANDO $E(t)$ ARRIVA A E_c
(WHEN) (REACHES) $\left(E = \frac{E_i}{N} = E_c\right)$

DIVENTANO DOMINANTI :
(BECOME DOMINANT)

PER $e^{\pm}$: IONIZZAZIONE

PER γ : COMPTON E FOTOELETTRICO

N SMETTE LA CRESCITA ESPONENZIALE

N RAGGIUNGE IL MASSIMO

$$N_{MAX} = \frac{E_i}{E_c}$$

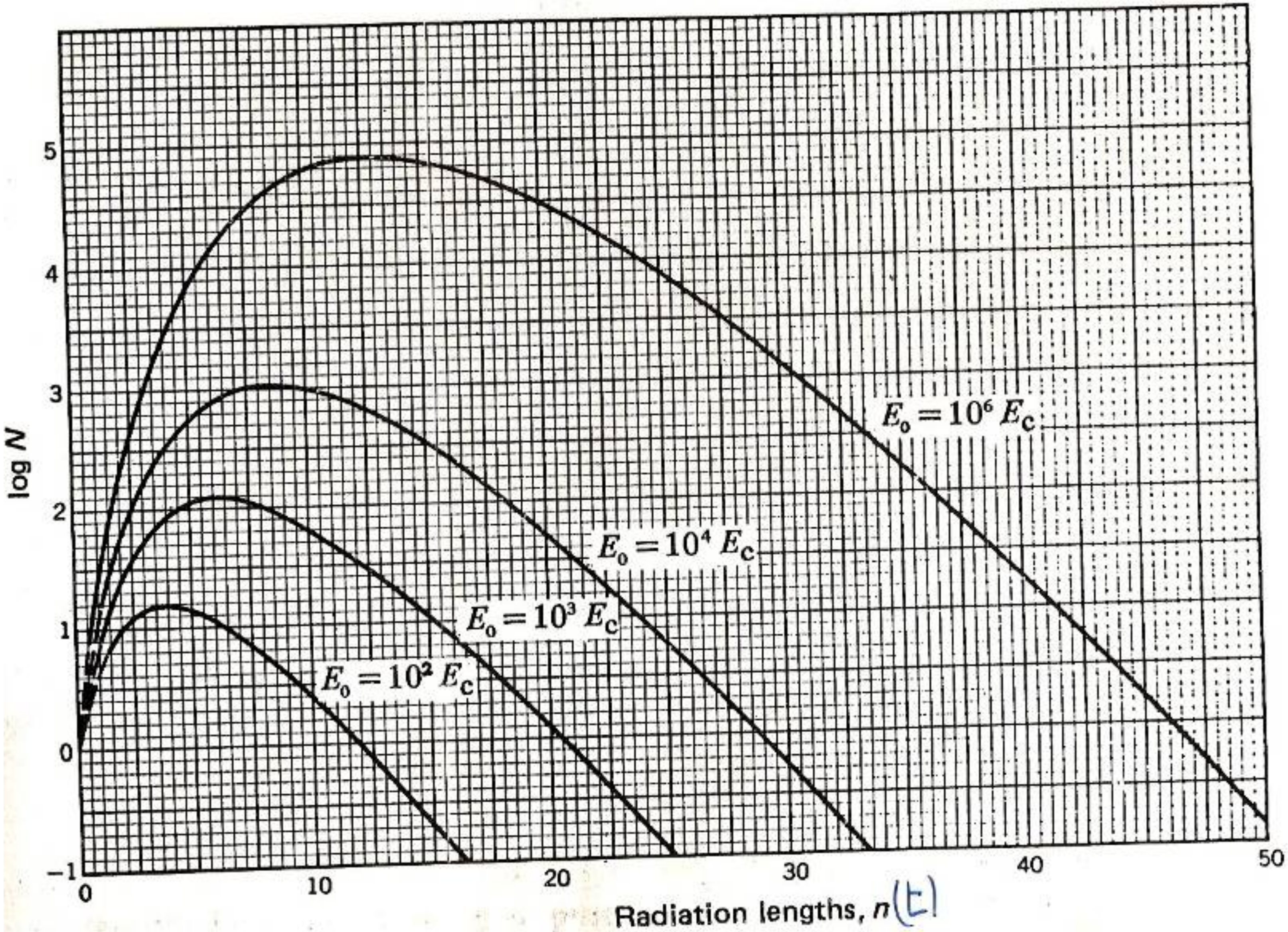
$$N_{MAX} = 2^{t_{MAX}} = \frac{E_i}{E_c}$$

$$t_{MAX} = \ln \frac{E_i}{E_c} \cdot \frac{1}{\ln 2}$$

N POI DECRESCE PER

PROGRESSIVA PERDITA DELLE ENERGIE RESIDUE

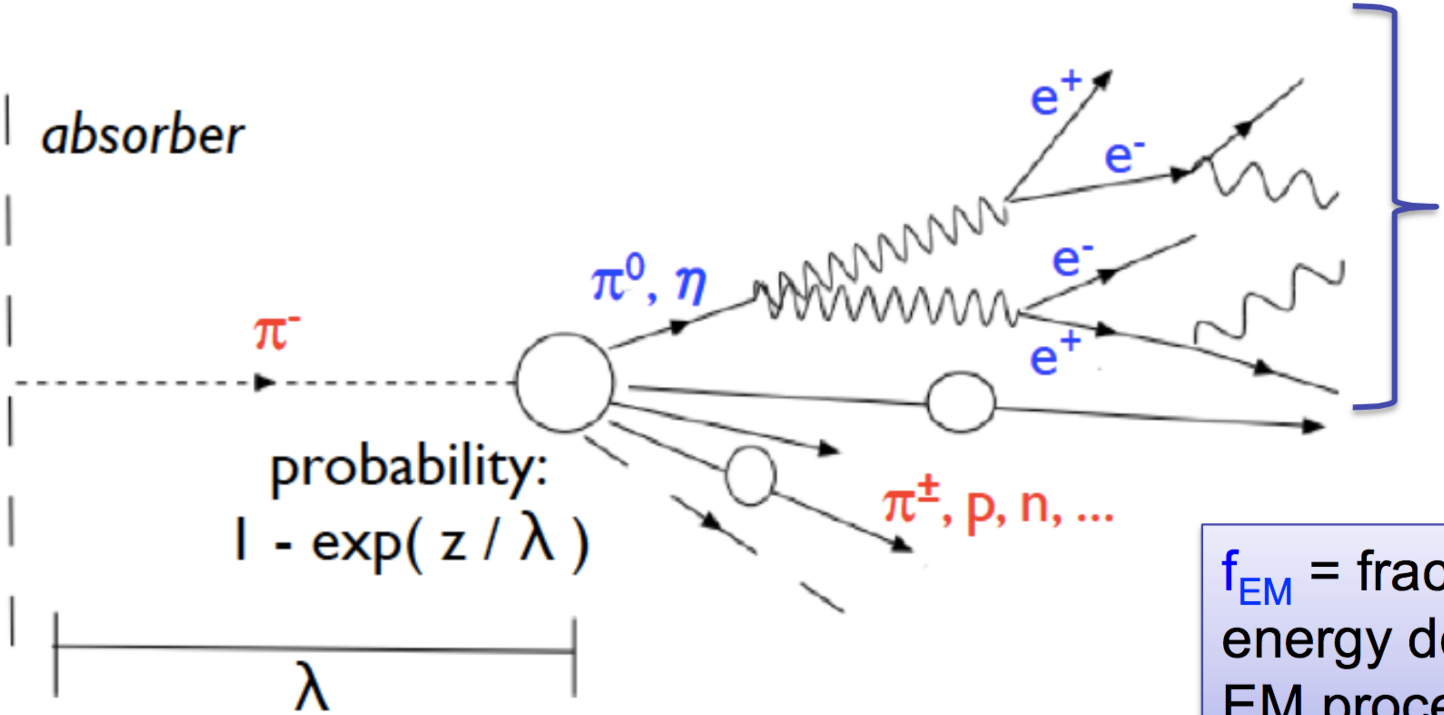
Fig. 4.6. The total number of particles N in a shower initiated by an electron of energy E_0, as a function of depth n, measured in radiation lengths; E_c is the critical energy of the material. (From Leighton, 1959, p. 693, after Rossi & Greisen, 1941.)



Astrofisica Nucleare e Subnucleare

Hadronic showers

Hadronic showers



π_0 production is a one way street: all energy deposited via EM processes

f_{EM} = fraction of hadron energy deposited via EM processes

Electromagnetic → ionization, excitation (e±)
→ photo effect, scattering (γ)

Hadronic → ionization (π±, p)
→ invisible energy (binding, recoil)

Hadronic shower

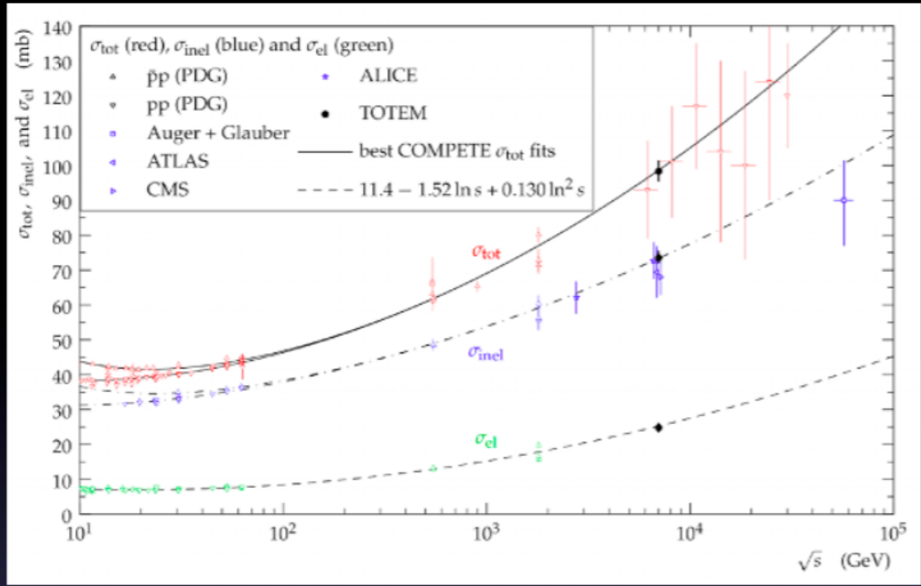
- Hadronic interaction Cross section

$$\sigma_{Tot} = \sigma_{el} + \sigma_{inel}$$

$$\sigma_{el} \approx 10mb \qquad \sigma_{inel} \approx A^{2/3}$$

$$\sigma_{Tot} = \sigma_{tot}(pp)A^{2/3}$$

where: $\sigma_{tot}(pp)$ increases with $\sqrt{s}$



- Hadronic interaction length

$$\lambda_{\text{int}} = \frac{1}{\sigma_{tot} \cdot n} = \frac{A\rho}{\sigma_{pp} A^{2/3} N_A} \approx \left(35 g/cm^2\right) A^{1/3}$$

$$N(x) = N(0)\mathrm{e}^{-x/\lambda_{\text{int}}}$$

- λ_{int} characterizes both longitudinal and transverse shower profile

Rule of thumb argument: the geometric cross section goes as the square of the size of the nucleus, a_N^2, and since the nuclear radius scales as $a_N \sim A^{1/3}$, the nuclear mean free path in gm/cm^2 units scales as $A^{1/3}$.

Hadronic shower

Hadronic interaction:

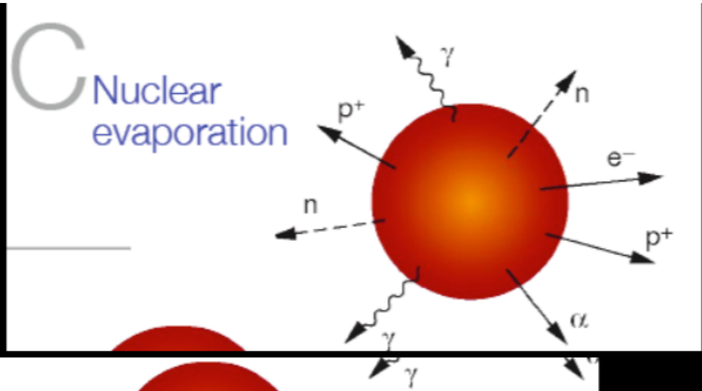
Elastic:

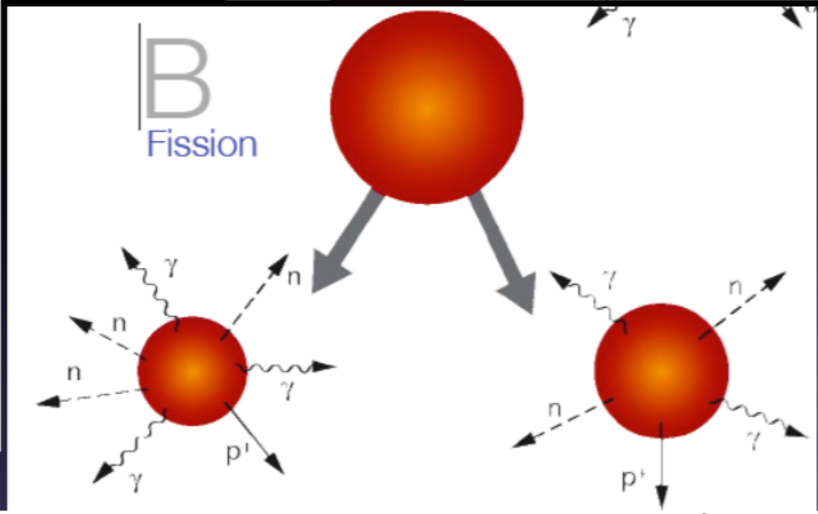
$$p + \text{Nucleus} \rightarrow p + \text{Nucleus}$$

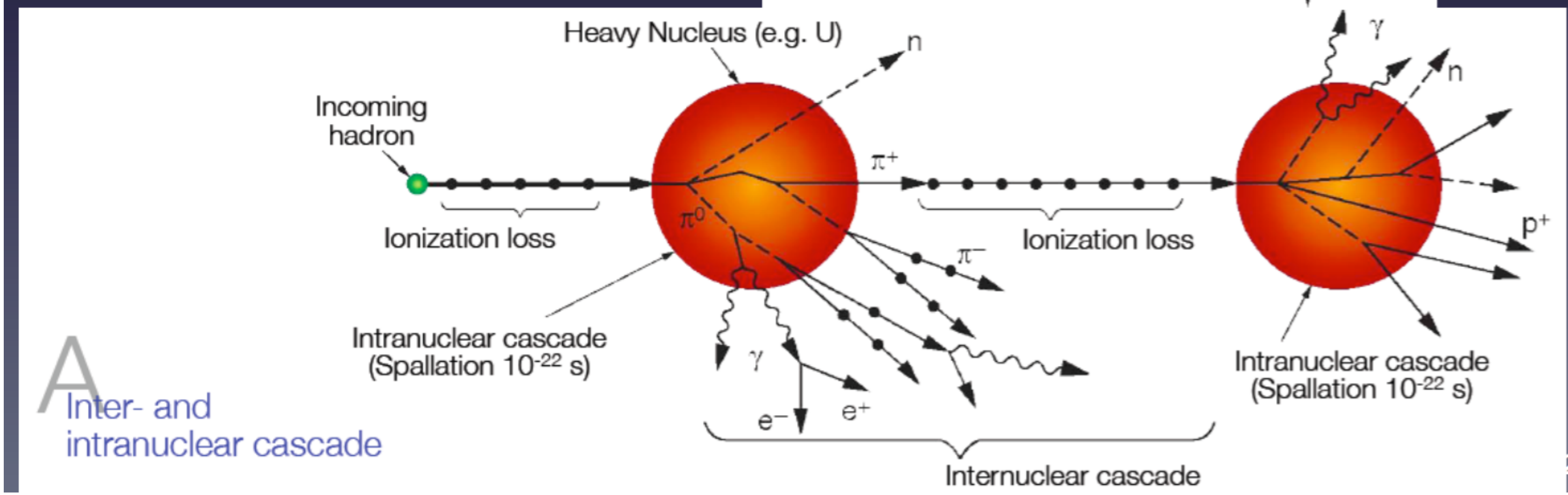
Inelastic:

$$p + \text{Nucleus} \rightarrow$$
$$\pi^+ + \pi^- + \pi^0 + \ldots + \text{Nucleus}^*$$

$$\left[\begin{array}{ll} \text{Nucleus}^* & \rightarrow \text{Nucleus A} + n, p, \alpha, \ldots \\ & \rightarrow \text{Nucleus B} + 5p, n, \pi, \ldots \\ & \rightarrow \text{Nuclear fission} \end{array}\right]$$

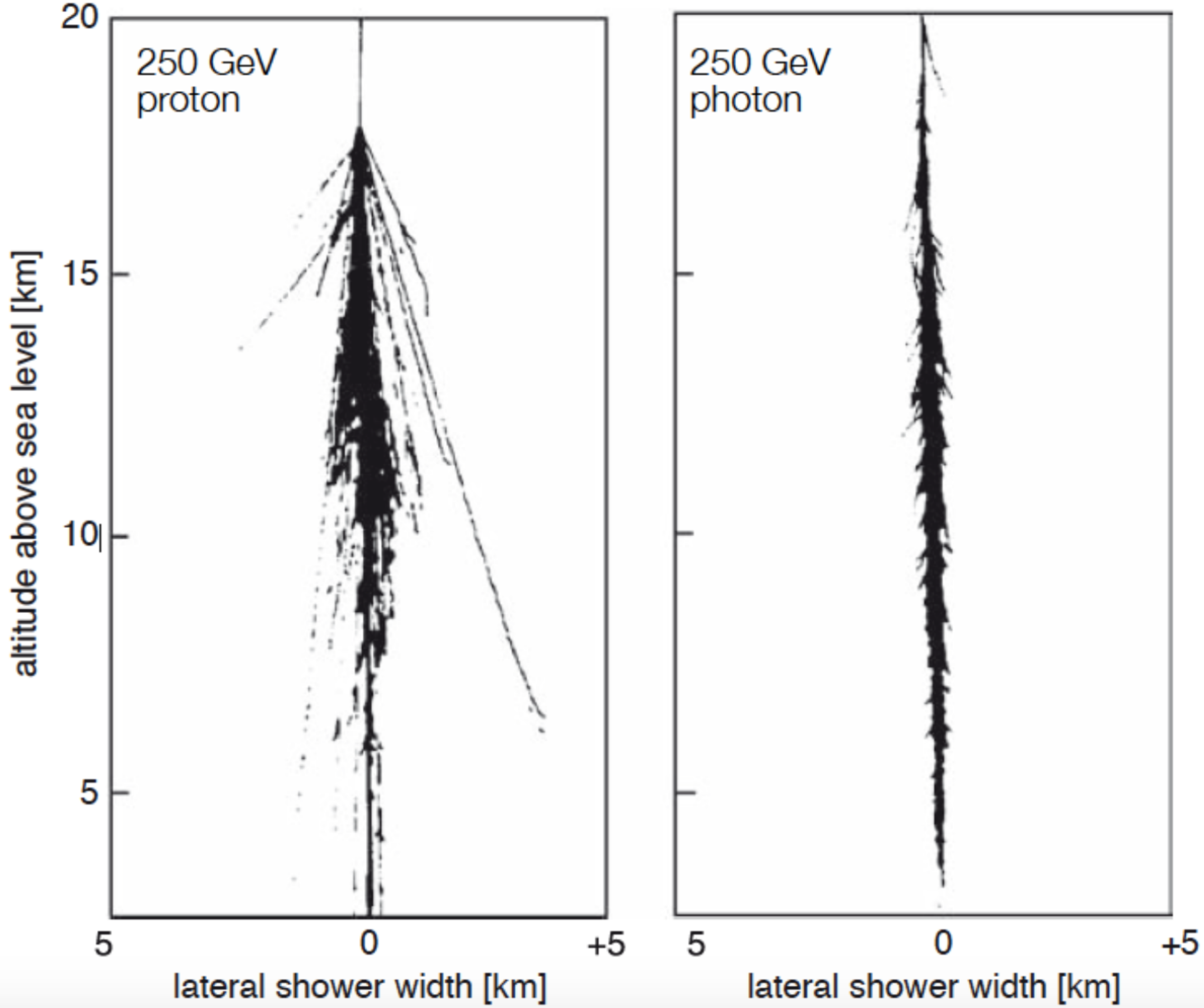






Courtesy of H. C. Schoultz Coulon

Comparison hadronic vs EM showers

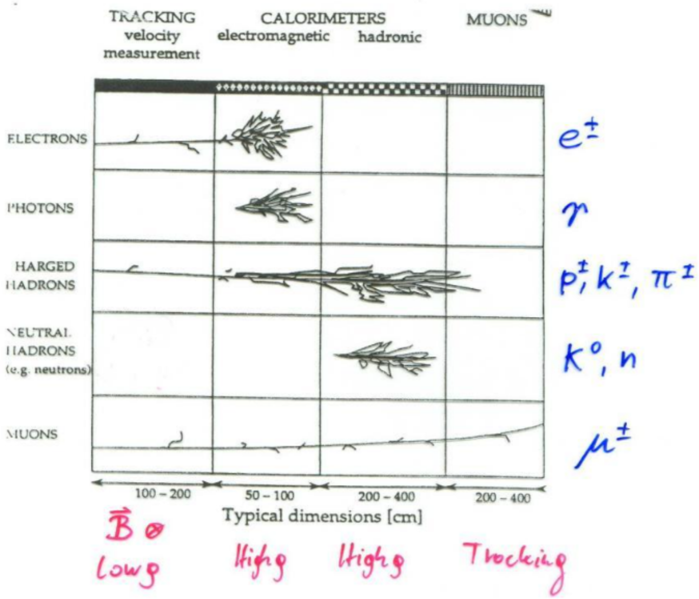


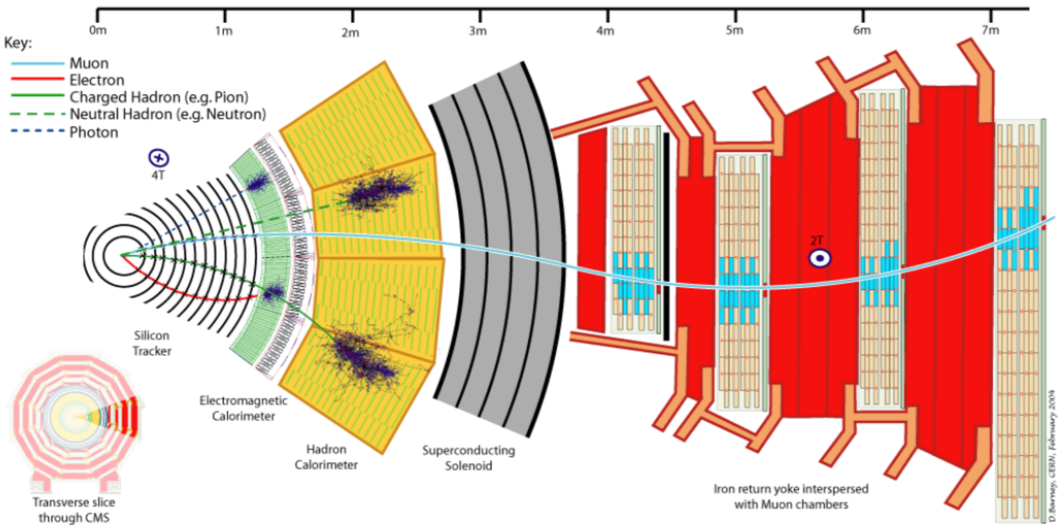
Simulated air showers

Astrofisica Nucleare e Subnucleare

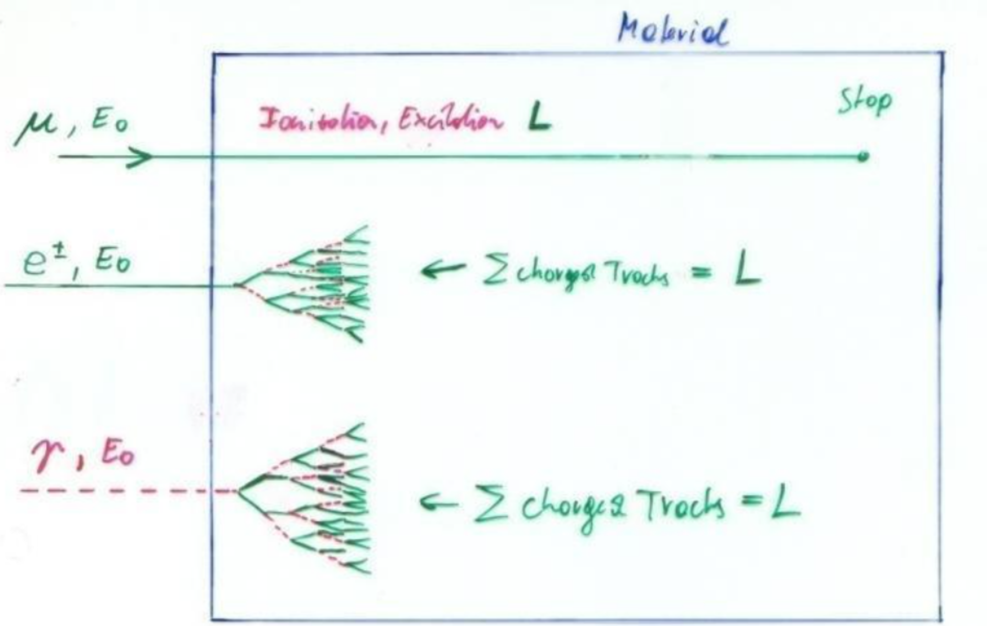
Calorimeters

Calorimetry





Calorimetry: Energy Measurement by total Absorption of Particles



The $e^{\pm}$ in the Calorimeter ionize and excite the material

Ionization: e^-, I^+ pairs in the Material

Excitation: Photons in the Material

Measuring the total Number of e^-, I^+ pairs or the total Number of Photons gives the particle Energy.

If N is the total Number of e^+, I^+ pairs or photons, on $N = c_1 E_0$:

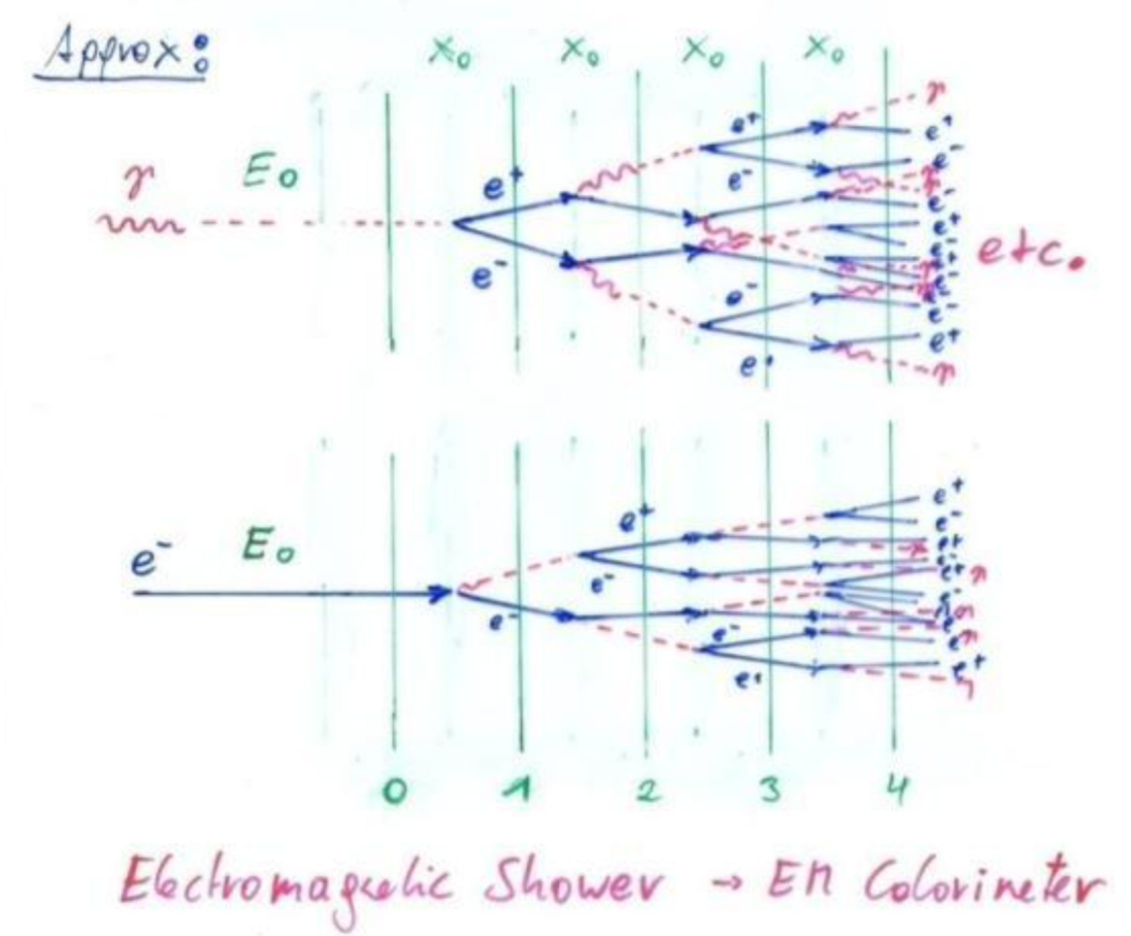
$\Delta N = \sqrt{N}$ (Poisson Statistics)

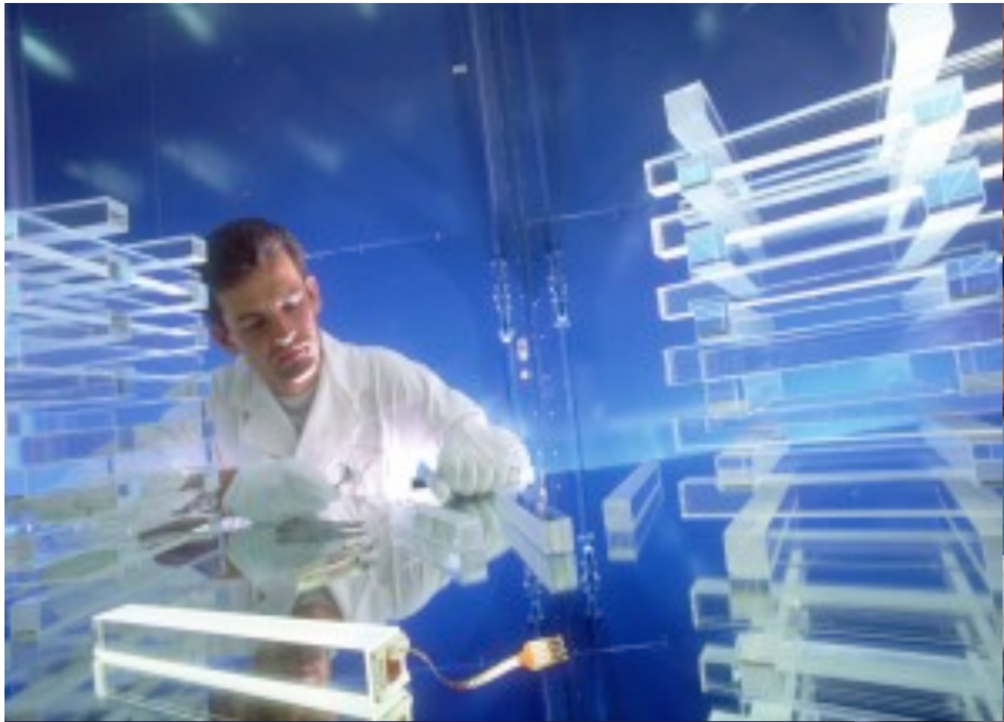
$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{a}{\sqrt{E}} \rightarrow \text{Resolution}$$

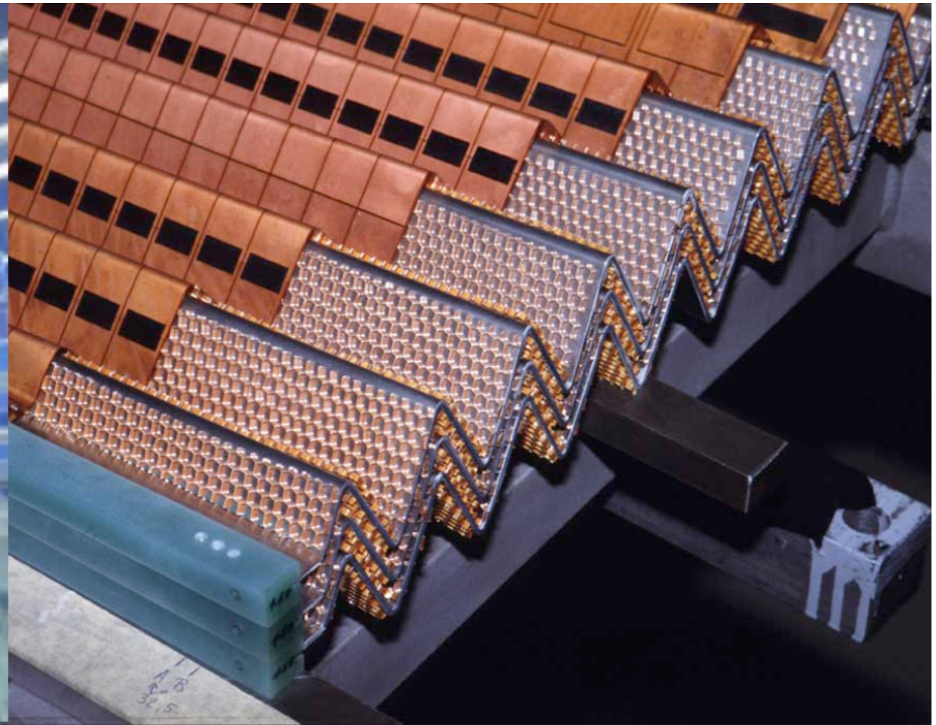
Only Electrons and High Energy Photons show EM cascades at current GeV-TeV level Energies.

Strongly interacting particles like Pions, Kaons, produce hadonic showers in a similar fashion to the EM cascade →Hadronic calorimetry

Bremsstrahlung + Pair Production → EM Shower







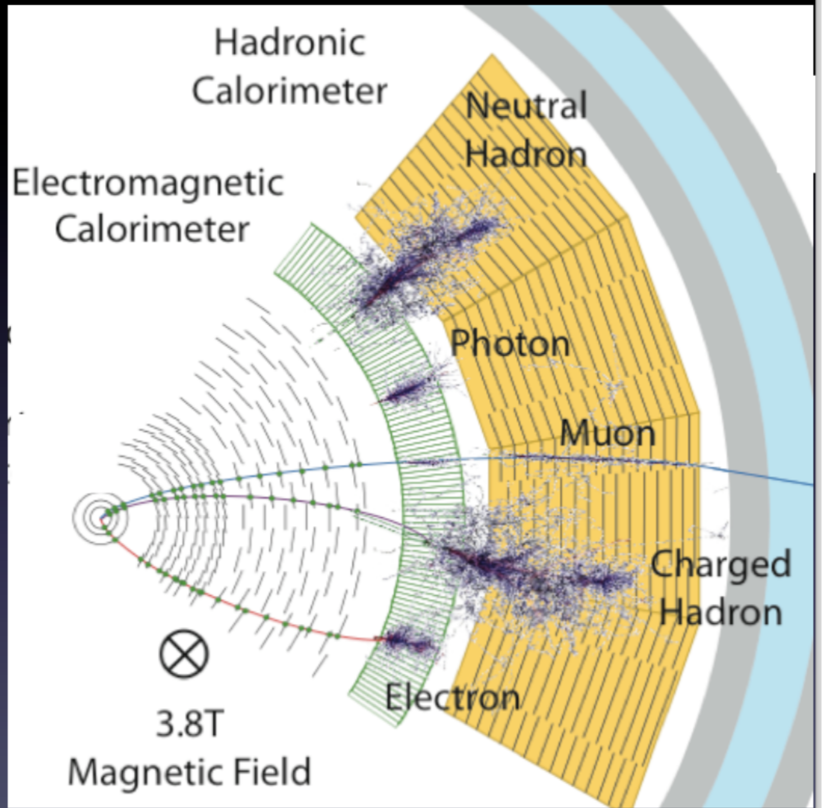
Detectors for Particle Physics

Calorimetry

D. Bortoletto

What is a calorimeter ?

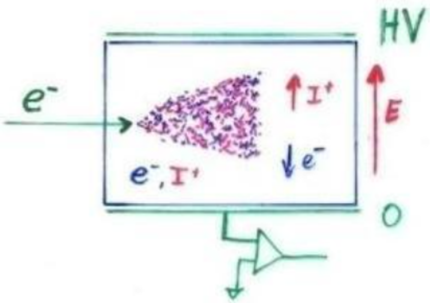
- In nuclear and particle physics calorimetry refers to the detection of particles through total absorption in a block of matter
  - The measurement process is destructive for almost all particle
  - The exception are muons (and neutrinos) → identify muons easily since they penetrate a substantial amount of matter
- In the absorption, almost all particle's energy is eventually converted to heat → calorimeter
- Calorimeters are essential to measure neutral particles



Calorimetry: Energy Measurement by total Absorption of Particles

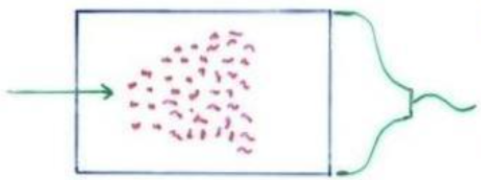
The measurement is destructive. The particle can not be subject to further study.

Energy Measurement by



Collecting the produced Charge

Liquid Nobel Gases (Nobel Liquids)



Measuring the Photons produced by the collision of the $e^\pm$ with Atom Electrons of the Material.

Scintillating Crystals, Plastic Scintillators

Total Amount of e^-, I^+ pairs or Photons is proportional to the total track length is proportional to the particle Energy.

Calorimetry

Calorimeters can be classified into:

Electromagnetic Calorimeters,
to measure electrons and photons through their EM interactions.

Hadron Calorimeters,
Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

Homogeneous Calorimeters,
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

Sampling Calorimeters,
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

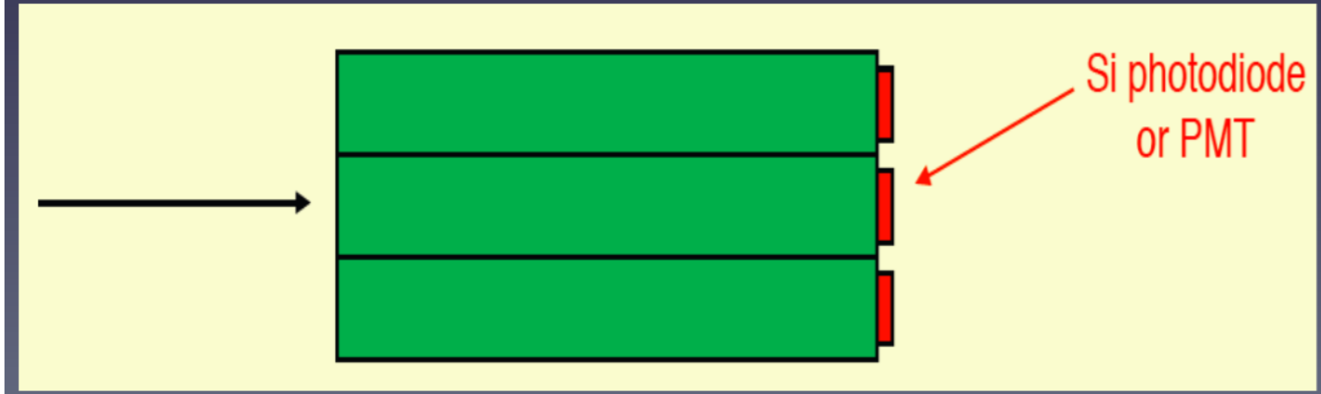
C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

EM Calorimeter configurations

- Total absorption
  - Electrons and photons stop in calorimeter
  - Scintillation proportional to energy of electron
  - Usually non-organic scintillator (BGO, $PbWO_{4,...}$) or liquid Xe
  - Advantage: Excellent energy resolution
    - see all charged particles in the shower (but for shower leakage) ➔best statistical precision
    - Uniform response ➔good linearity
  - Disadvantages:
    - cost and limited segmentation

If W is the mean energy required to produce a signal (eg an e^--ion pair in a noble liquid or a 'visible' photon in a crystal)

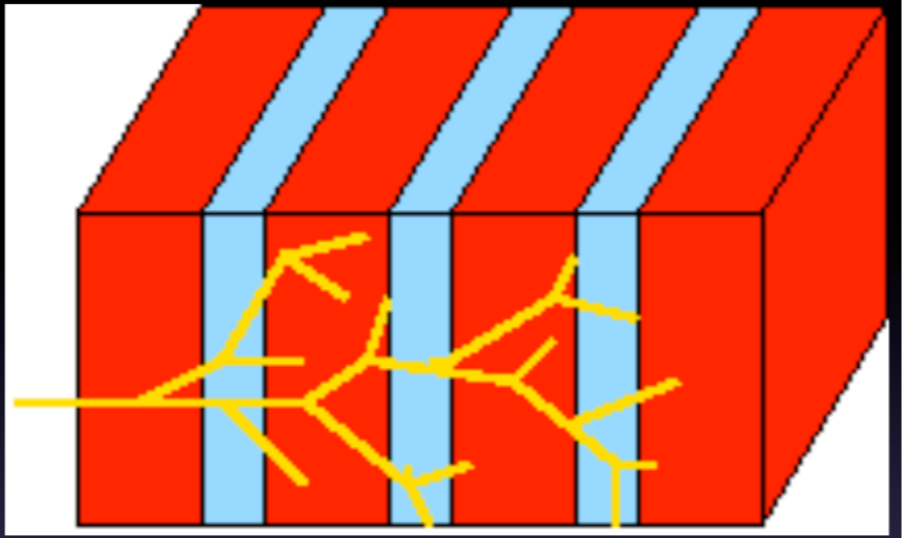
$$\frac{\sigma_E}{E} = \frac{1}{\sqrt{n}} = \frac{1}{\sqrt{E/W}}$$



- Examples:
  - B factories: small photon energies
  - CMS ECAL which was optimized for H→γγ

EM Calorimeter configurations

- Sampling Calorimeter
  - One material to induce showering (high Z)
  - Another to detect particles (typically by counting number of charged tracks)
  - Many layers sandwiched together
  - Resolution $\propto E^{-1/2}$
- Advantages
  - Depth segmentation
  - Spatial segmentation
- Disadvantages:
  - Only part of shower seen, less precise
- Examples
  - ATLAS ECAL
  - Most HCALs

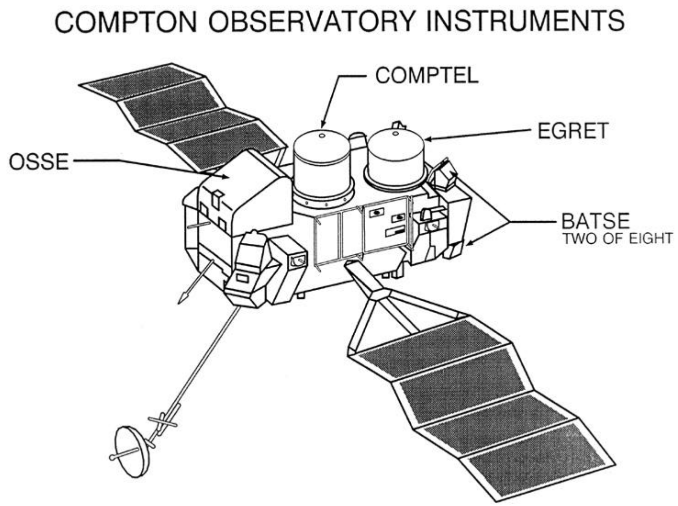


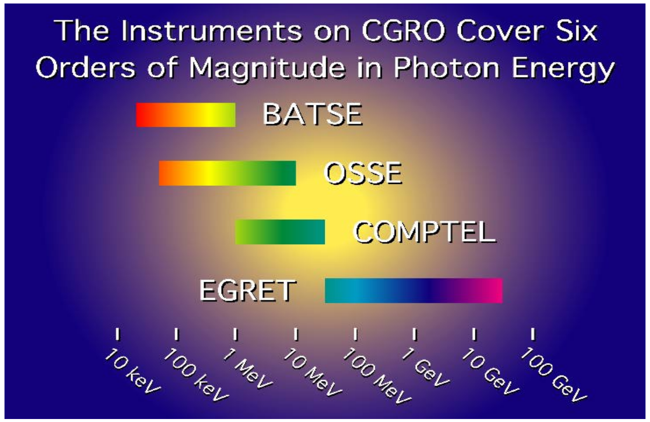
- Sampling fraction

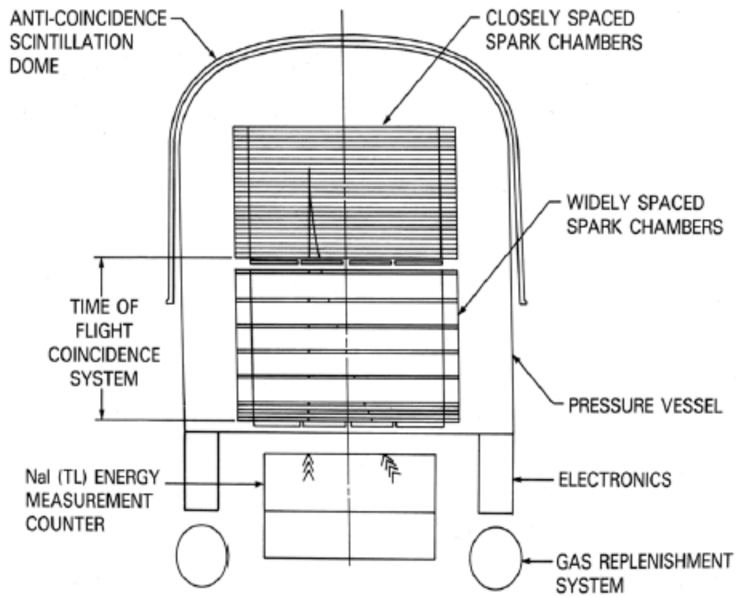
$$f_{sampling} = \frac{E_{visible}}{E_{deposited}}$$

GeV Gamma-ray Astrophysics
The EGRET legacy

EGRET



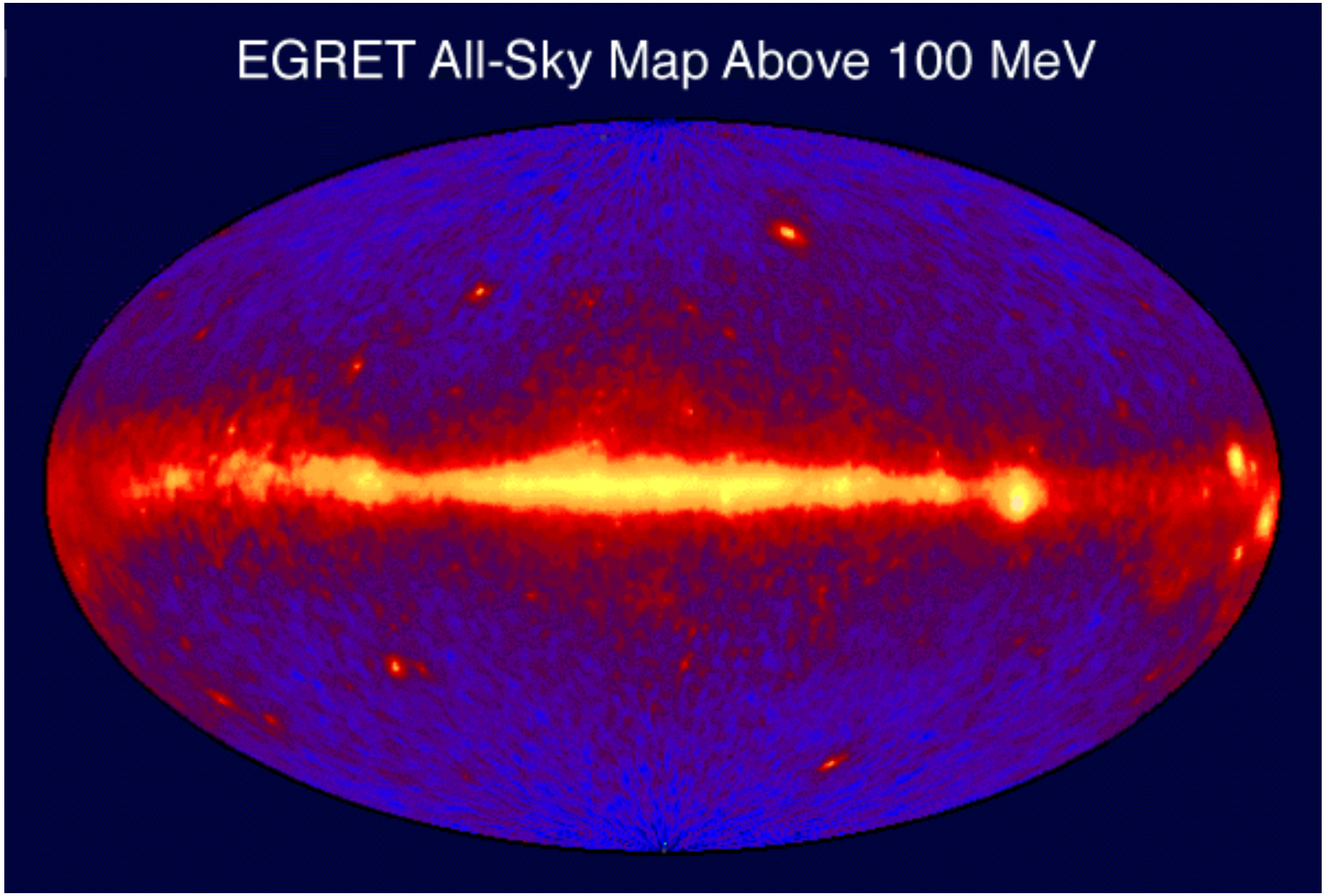




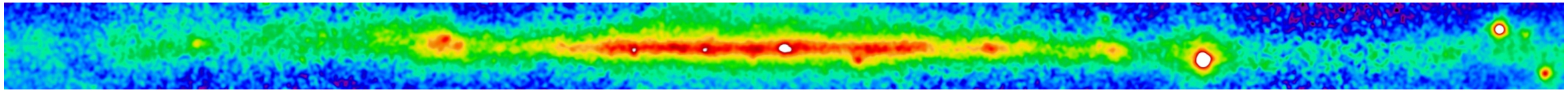
EGRET

- 1991-2000
- 30 MeV - 30 GeV
- AGN, GRB, Unidentified Sources, Diffuse Bkg

The HE sky from EGRET



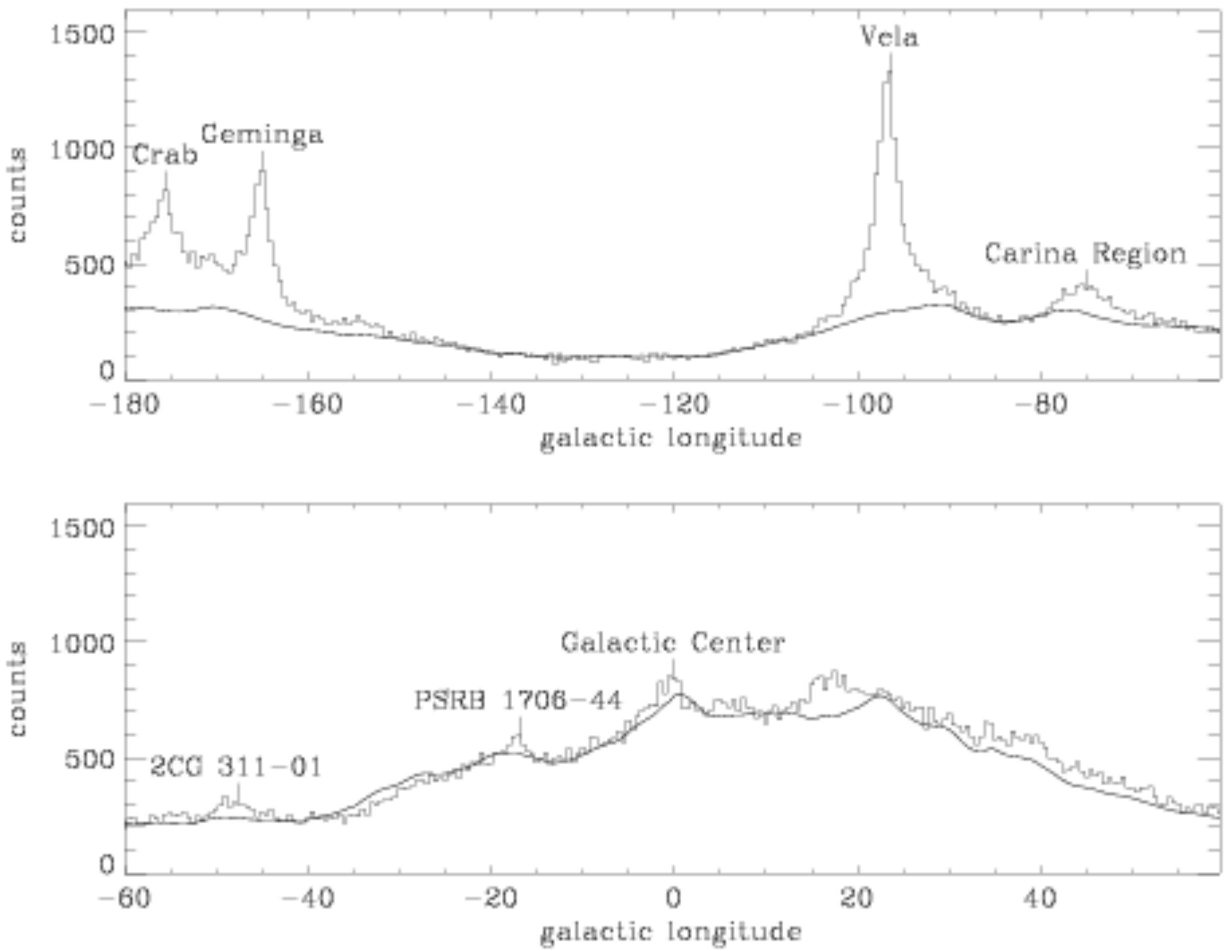
Analysis Topics



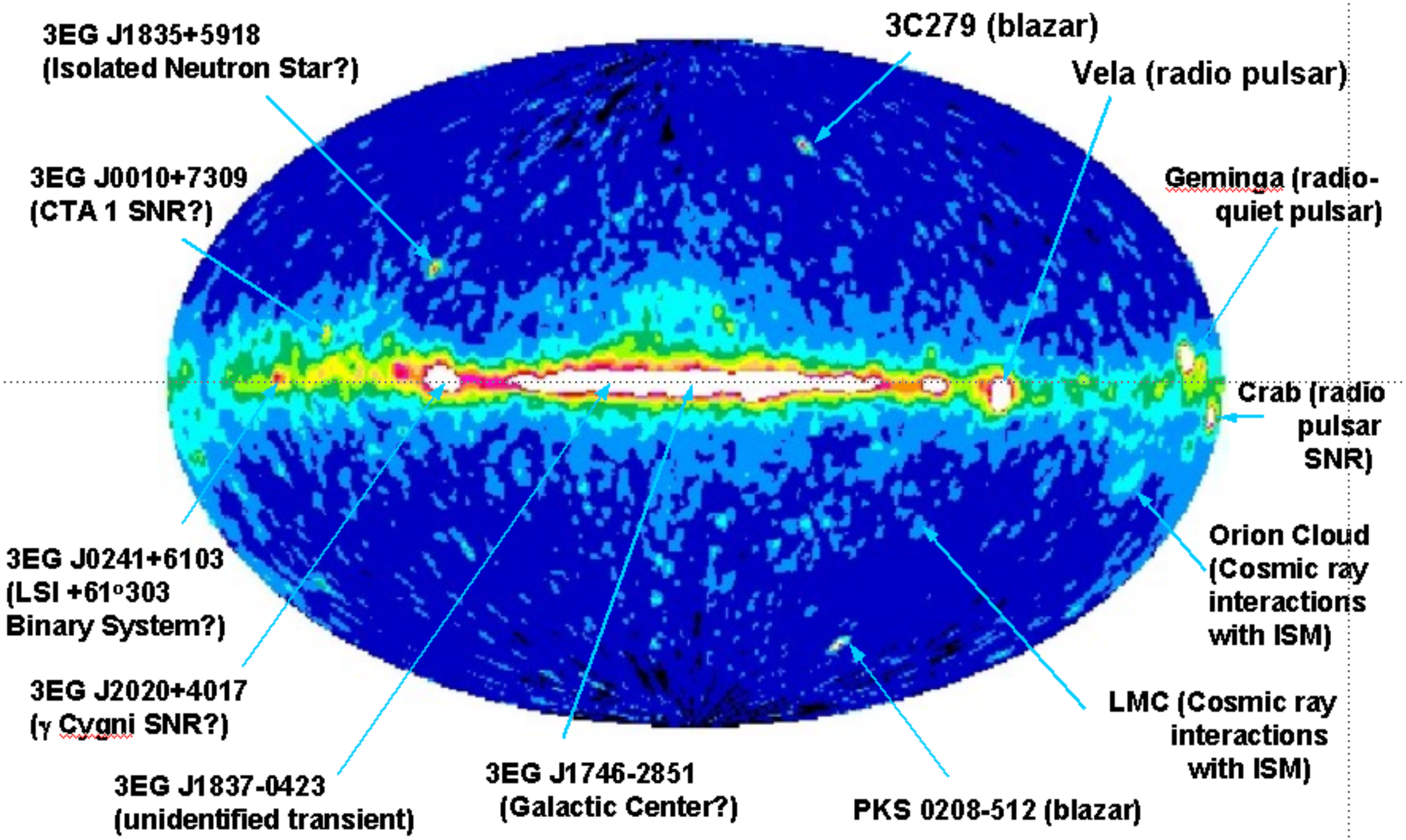
EGRET >300 MeV

- First a word about interstellar gamma-ray emission:
- Brightest at low latitudes, but detectable over the whole sky
- >60% of EGRET celestial gamma rays
- It fundamentally affects the approach to the analysis

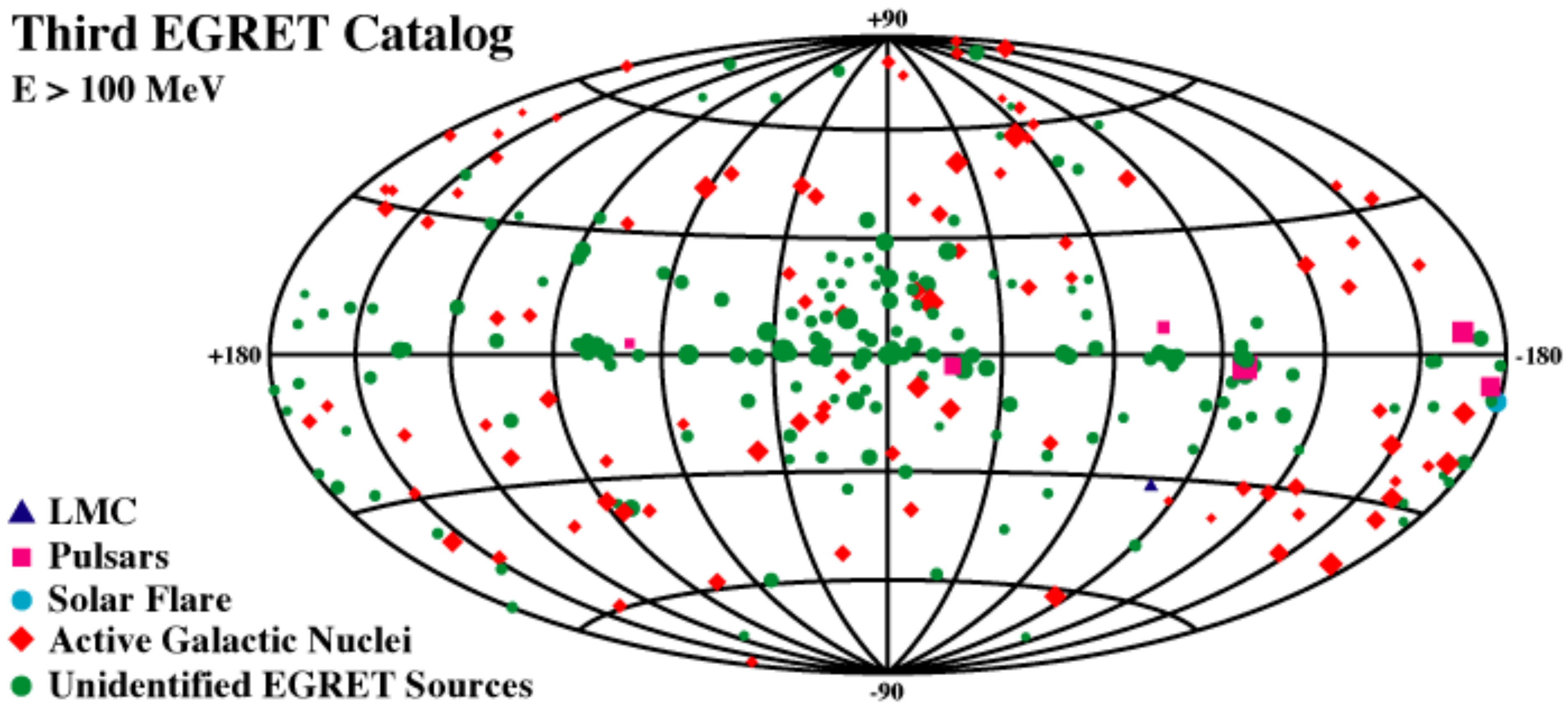
Data Analysis



EGRET All Sky Map

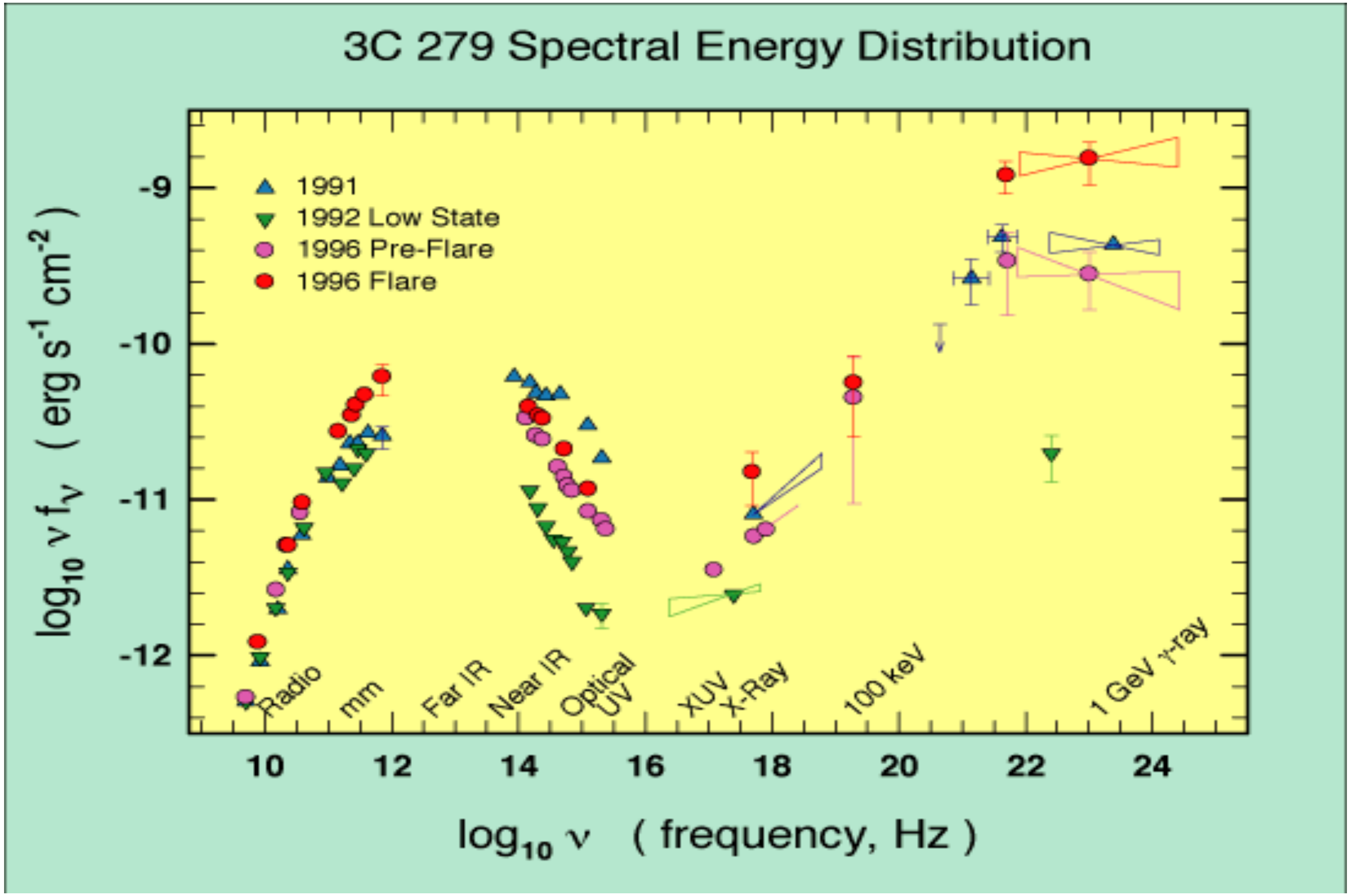


EGRET Gamma-ray Sources

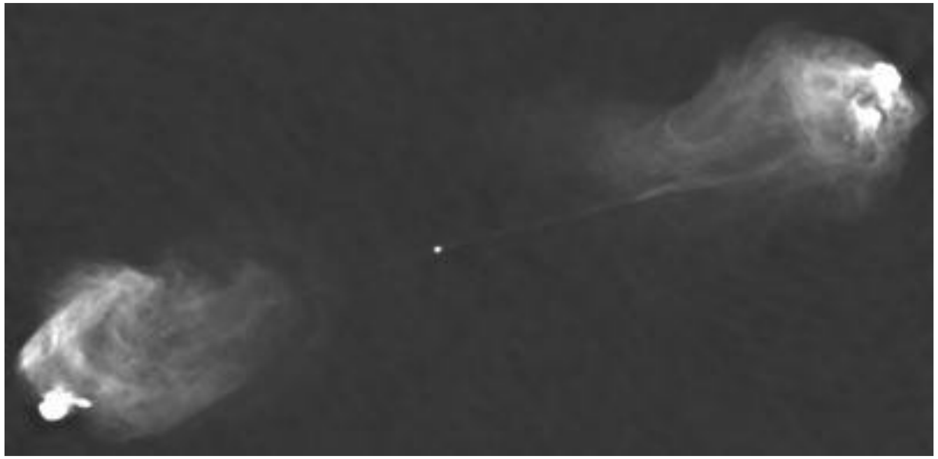


Challenge # 1

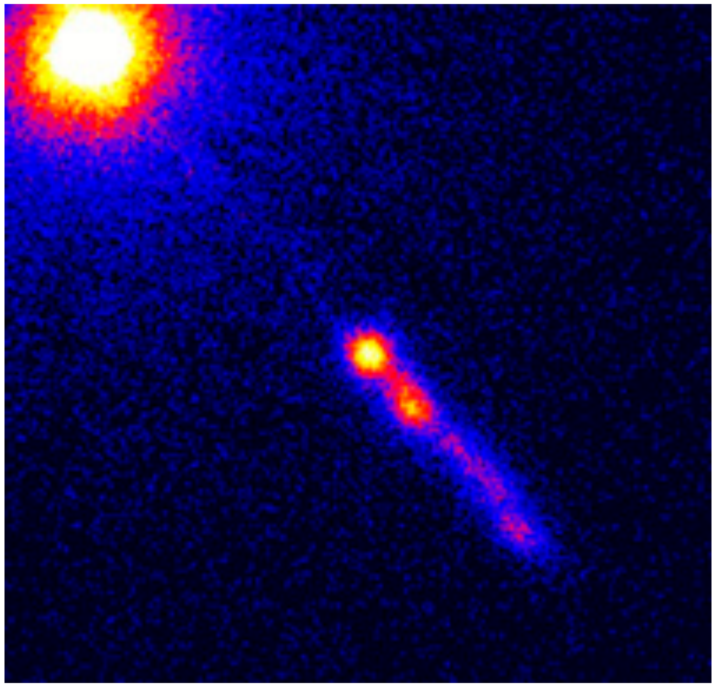
- Need simultaneous multiwavelength data to study variability and emission processes



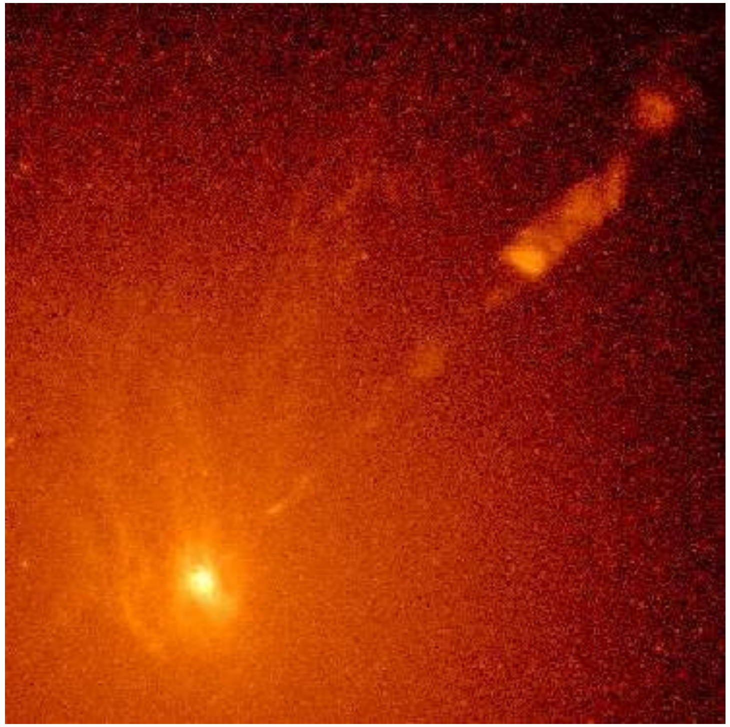
Active Galactic Nuclei



Radio

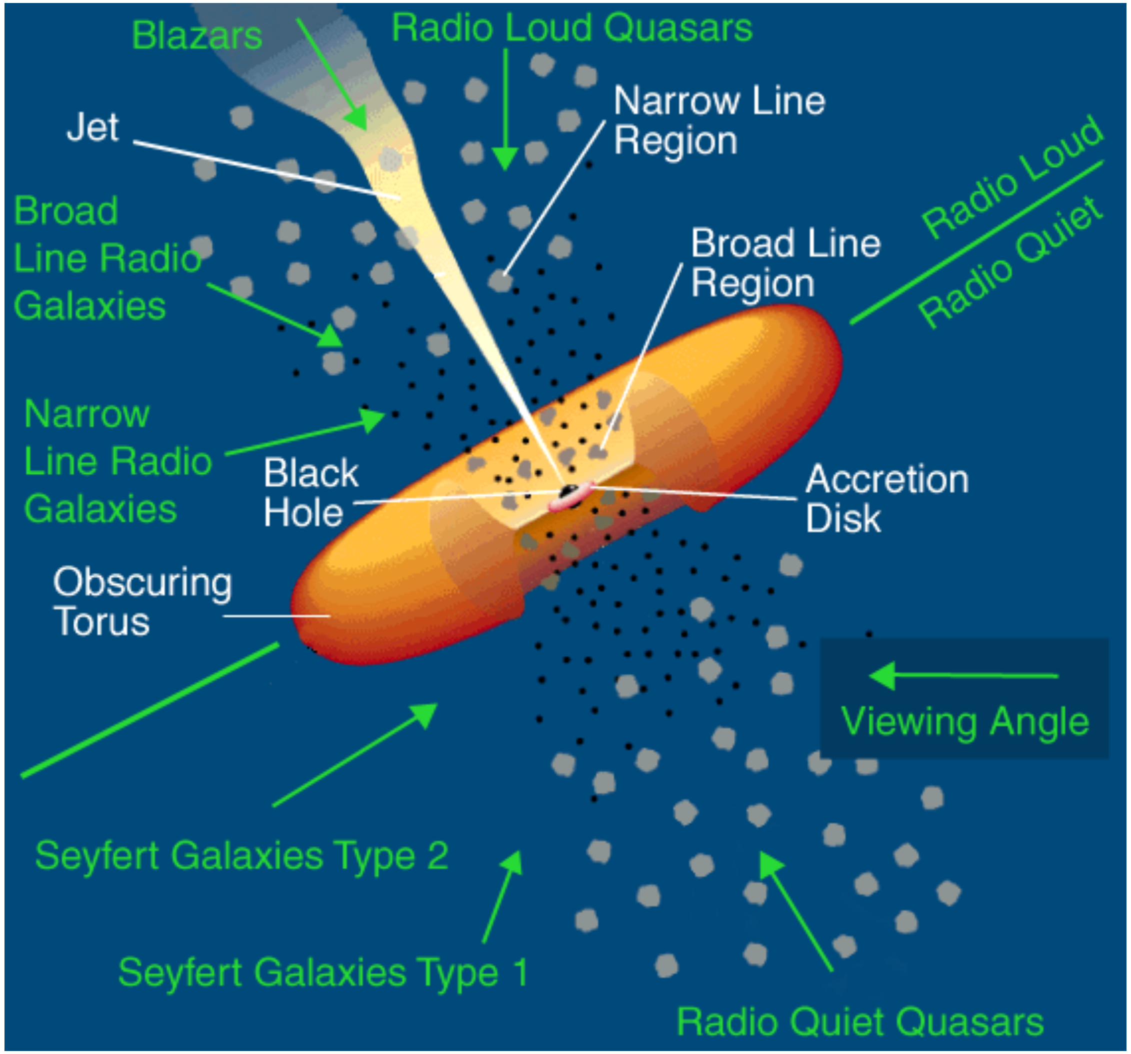


X-ray

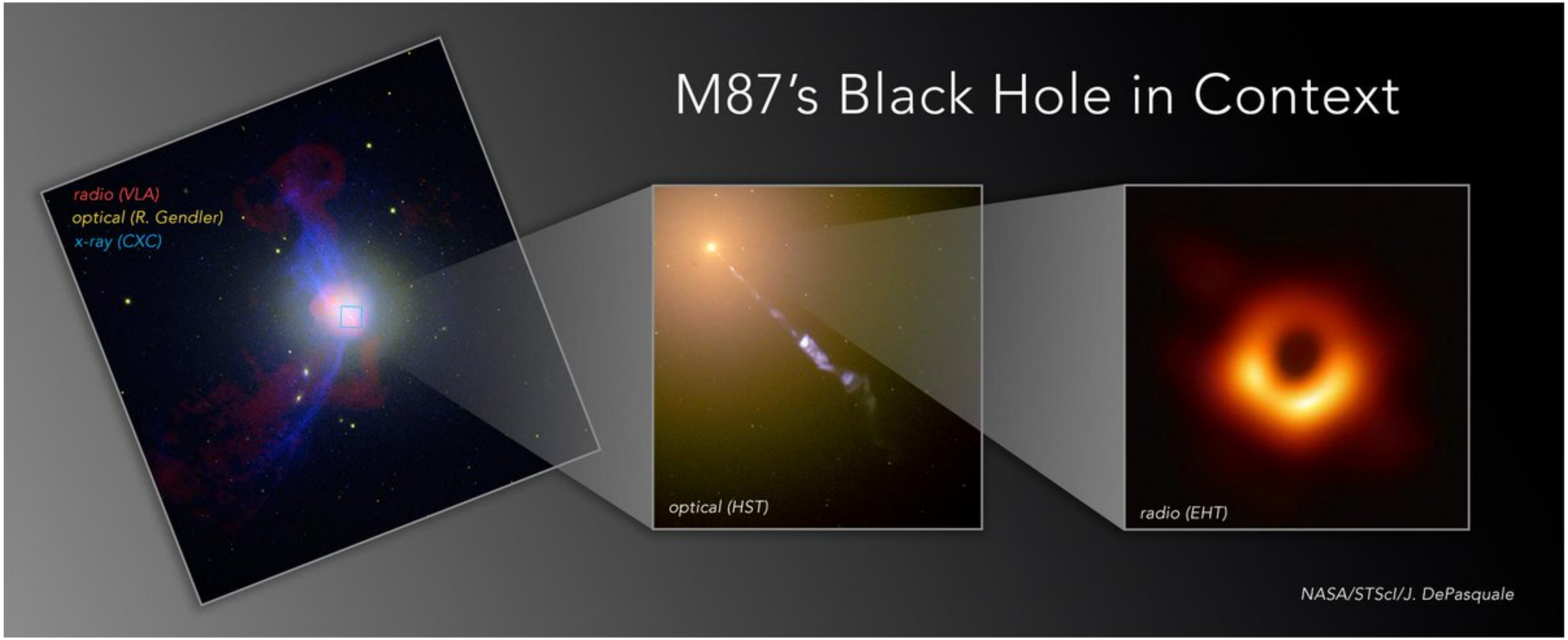


Optical

Active Galactic Nuclei



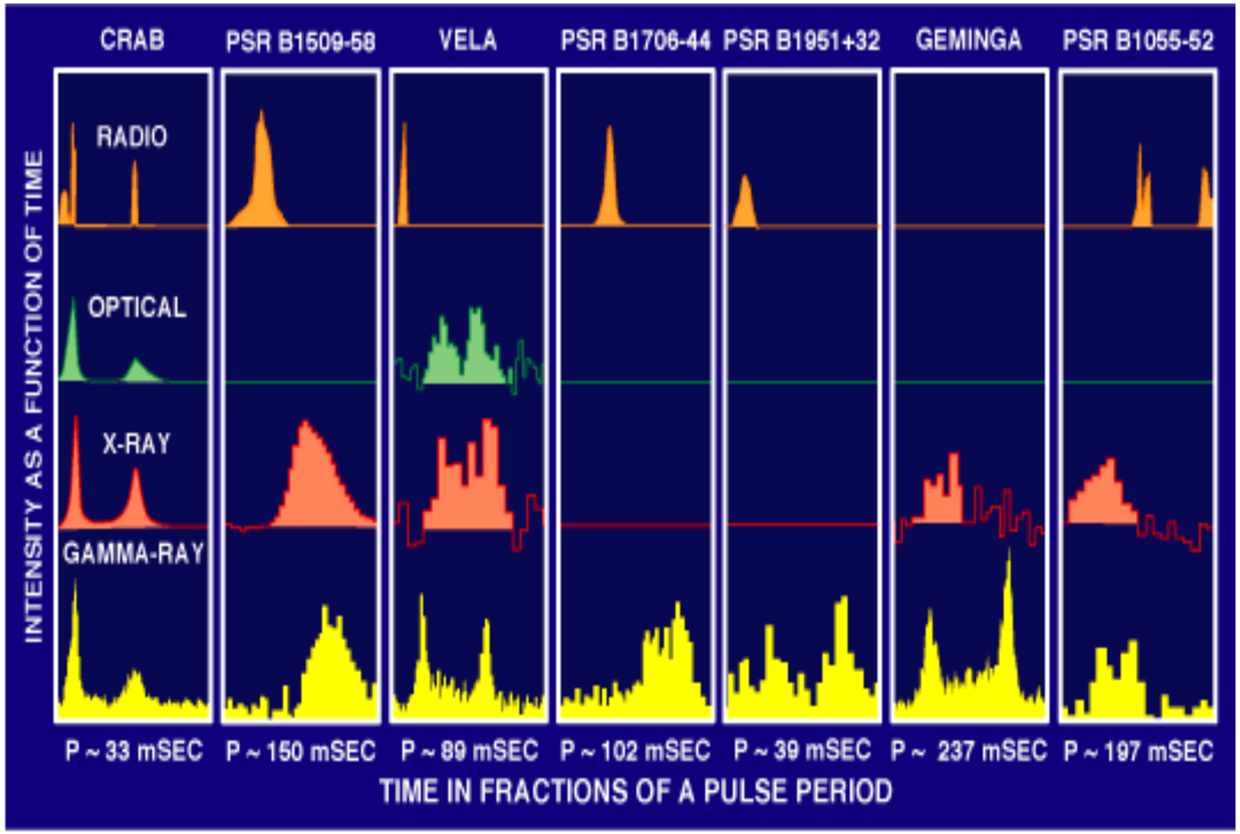
M87 scales…



M87's Black Hole in Context
radio (VLA)
optical (R. Gendler)
x-ray (CXC)
optical (HST)
radio (EHT)
NASA/STScI/J. DePasquale

Challenge # 2

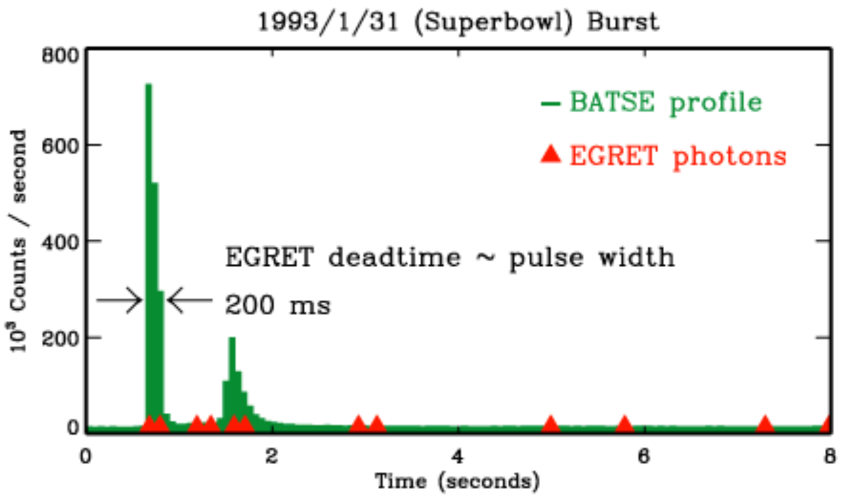
- Need more exposure and optimal timing (and radio monitoring) to discover more gamma-ray PSRs.



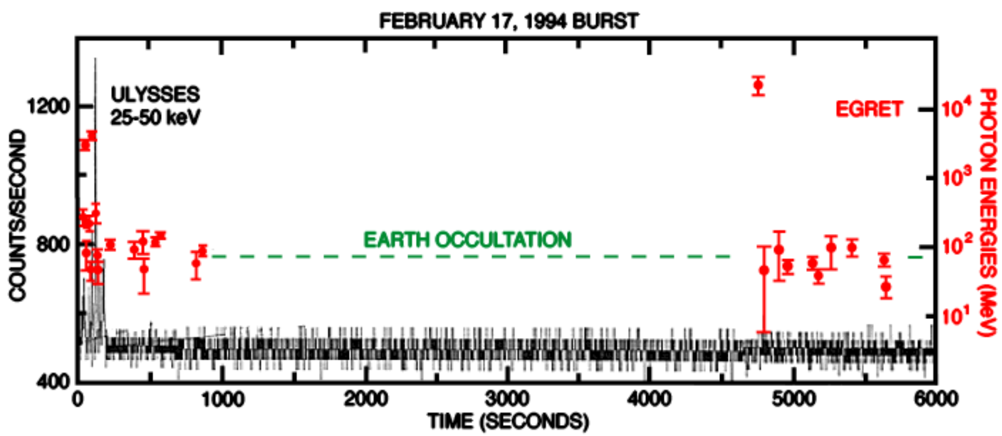
Challenge # 3

- Need fast timing for gamma-ray detection (improving EGRET deadtime, 100 msec → 100 microsec or less).

Prompt Emission (GRB 930131)

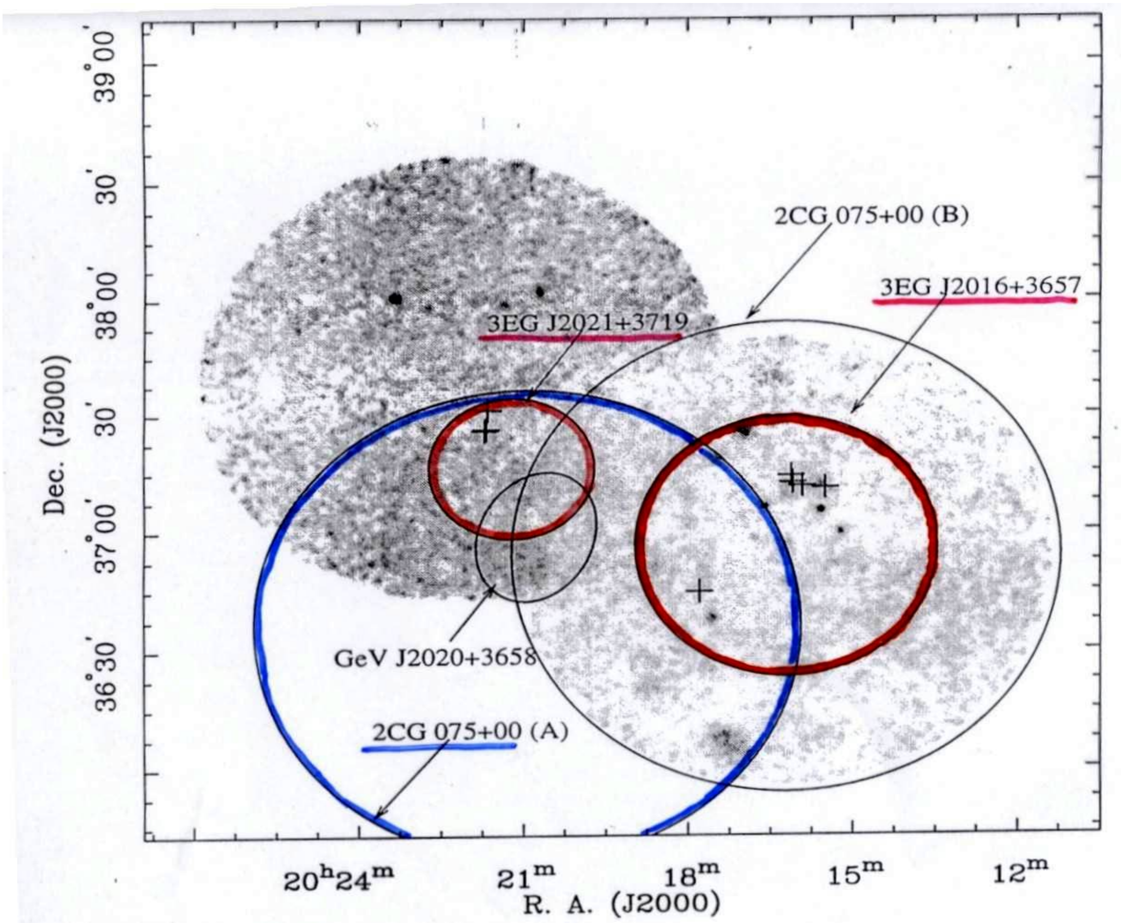


Delayed Emission (GRB 940217)



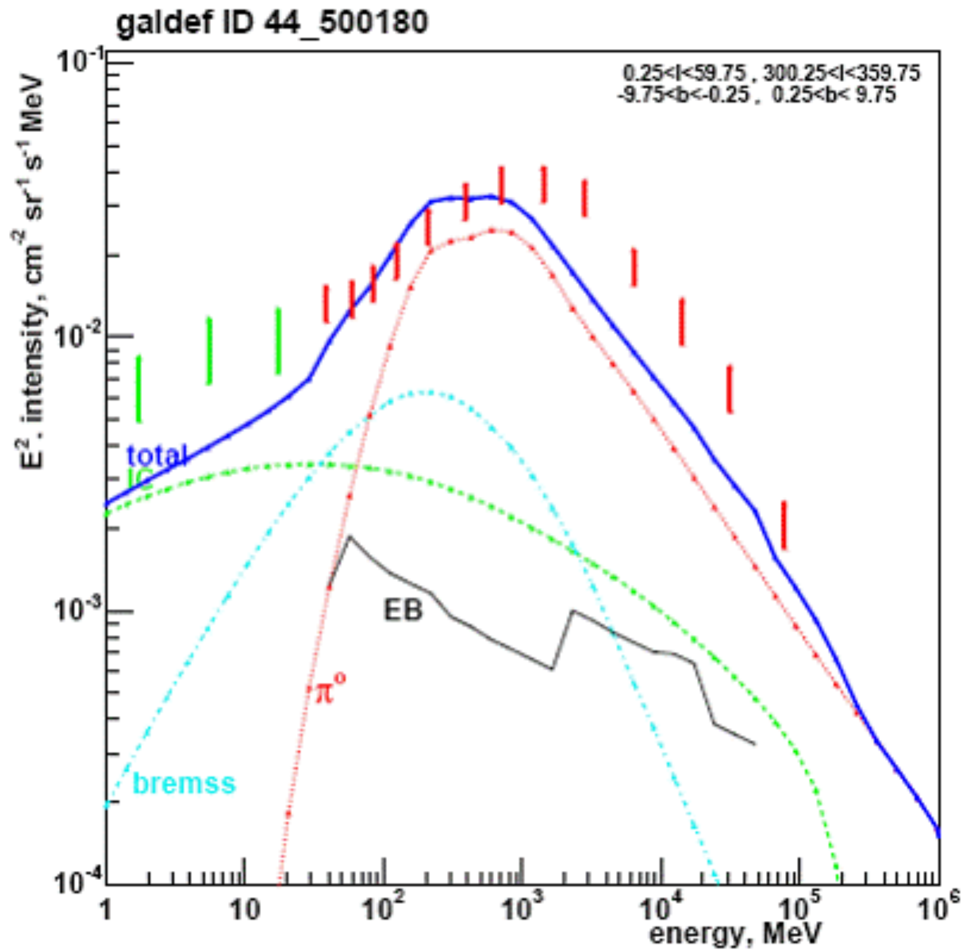
Challenge # 4

- Need arcminute positioning of gamma-ray sources (improving EGRET error box radii by a factor of 2-10).



Challenge # 5

- Need improvements in Spectral Resolution fo check for DM signals



After a long story ...