Background ...

- The first source detection was made in the 1960s

- Important developments in the 1990s due to ...
  - ... the discovery of a large number of non-thermal $\gamma$ ray emitters: the $\gamma$ ray Universe
  - ... the results from innovative experimental techniques: the $\gamma$ ray astronomy at TeV energies

- Study of conventional physics under extreme conditions (e.g. huge gravitational or magnetic fields)

- New energy region allows sensitivity to new physics
... and definitions

<table>
<thead>
<tr>
<th>Energy range (eV)</th>
<th>Equivalent prefix</th>
<th>Nomenclature</th>
<th>Traditional detection technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^7 - 3 \times 10^7$</td>
<td>$10 - 30$ MeV</td>
<td>medium</td>
<td>satellite-based Compton telescope</td>
</tr>
<tr>
<td>$3 \times 10^7 - 3 \times 10^{10}$</td>
<td>$30$ MeV–$30$ GeV</td>
<td>high (HE)</td>
<td>satellite-based tracking detector</td>
</tr>
<tr>
<td>$3 \times 10^{10} - 3 \times 10^{13}$</td>
<td>$30$ GeV–$30$ TeV</td>
<td>very high (VHE)</td>
<td>ground-based atmospheric Čerenkov detector</td>
</tr>
<tr>
<td>$3 \times 10^{13} - 3 \times 10^{16}$</td>
<td>$30$ TeV–$30$ PeV</td>
<td>ultrahigh (UHE)</td>
<td>ground-based air-shower particle detector</td>
</tr>
<tr>
<td>$3 \times 10^{16}$ and up</td>
<td>$30$ PeV–and up</td>
<td>extremely high (EHE)</td>
<td>ground-based air-shower particle detector</td>
</tr>
</tbody>
</table>
Physical motivations

**Astronomy / Astrophysics / Cosmology**
- Multi-wavelength astronomy
- Study of exotic objects
- Photon propagation and cosmology

**Astrophysics / Particle physics**
- Cosmic ray origin and acceleration
- Probe for dark matter detection
- Microphysics at very high energy
Typical production mechanisms of low energy photons (e.g. thermal production) are not applicable when discussing $\gamma$-ray sources. $\gamma$-rays are expected to be produced via particle interactions at sites of powerful acceleration.

The energy spectrum exhibits power law behavior as a direct consequence of the acceleration mechanism.

The source power can be electromagnetic (e.g. rotating B fields near NS’s) or gravitational (e.g. accretion disk and matter infall in AGN’s).

- SN remnants
- Pulsars
- Binary systems
- Active Galactic Nuclei
- ............
Rapidly rotating neutron stars \((T \sim 10^{-3} - 1 \text{ s})\) in a huge strength magnetic field \((B \sim 10^{12} \text{ gauss})\).

Found in SNR’s.

Pulsed emission observed up to GeV.

Unpulsed TeV emission
Unified AGN Model

Supermassive BH surrounded by an accretion disk.

Particle acceleration and high energy $\gamma$-ray production in the jets

...stopping the proliferation of classes and subclasses of AGN’s quasars, Seyfert galaxies (types I and II), radio-quiet or radio-loud galaxies, Faranoff-Riley galaxies (types I and II), narrow line, broad line, no lines, highly polarized lines, flat spectrum, steep spectrum, optically violent variables, BL-Lac’s, ….
M87 jets

Chandra X-Ray

VLA Radio

HST Optical
γ-ray production mechanisms

accelerated electrons

accelerated protons

local photon fields

or

electron induced synchrotron radiation

Inverse Compton scattering

p γ → Δ → p π^0
p γ → Δ → n π^+
γ from neutral π
ν from charged π

High energy γ-rays
Absorption

High energy $\gamma$-rays are absorbed via interaction with several photon fields:

- InfraRed/Optical background
- Radio halos
- Cosmic Microwave Background

The last one put a stringent cutoff above 100 TeV
Gamma Ray Bursts

- Detected in the 1960’s by military satellites
- Very short gamma emissions ($10^{-2} - 10^2$ s)
- Isotropic distribution
- Energy ranging from keV to tens of GeV
- Several kinds of timing and spectra
- Detected ~ 1/day

The X-ray counterpart detection with better pointing accuracy instruments allowed candidate source identification at cosmological distances!

Huge emitted energy. Unknown origin. Many theoretical models.
Light from dark matter

Dark matter candidates (e.g. neutralinos) might cluster and annihilate in the galactic halo.

High energy photons could be produced:
- in the decay (a gamma line)
- by means of synchrotron losses suffered by decay generated electrons

Simulation of Dark Matter clumps
The Earth atmosphere is opaque to high energy gamma ray. It corresponds to about 28 radiation lengths.

Only experiments performed above the atmosphere, on balloons or satellites, can detect the primary gamma rays.

The gamma ray fluxes are very low and decreases rapidly with energy.

Example: $\gamma$-rays from Vela

$\Phi (E_\gamma > 100\text{MeV}) \sim 10^{-5} \text{ photons/cm}^2/\text{s}$ and $d\Phi/dE \sim K\cdot E^{-1.89}$

$A \sim 1000\text{cm}^2 \Rightarrow \text{few photons/day above } 10\text{ GeV}$

Gamma ray astronomy above $\sim 100$ GeV can be done only with ground based detectors.
Satellite-based detectors

The photon properties are measured by using its conversion into an electron-positron pair.

A tracking detector is used to measure the photon direction, while its energy is measured by using a calorimeter. An external veto system is generally used to discriminate against the large charged-particle background.

The angular resolution is important for source identification and diffuse background rejection. It is essentially determined by multiple Coulomb scattering in the converter and by the tracker resolution.

The energy resolution is needed for the determination of the spectral shape and is then important for issues like the acceleration mechanism.
Satellite based experiments

1990 present
The OSO-3 mission

- Orbiting Solar Observatory – 3
- Launched on March 8 1967
- The gamma ray detector operated up to June 1968
- Observations of solar flares and of the diffuse X-rays
- Descended into the atmosphere on April 4 1982

621 gamma ray events above 50 MeV
The SAS-2 mission

- Small Astronomy Satellite – 2
- Launched on November 15 1972
- Operated up to June 1973 (low voltage power failure)
- Energy range 20 MeV – 1 GeV. Effective area 540 cm$^2$
- Correlated $\gamma$-ray flux with galactic structural features
The COS-B mission

- Launched on August 9, 1975 - Operated up to April 1982
- Gamma Ray Telescope + X-ray sensitive proportional counter
- Energy range 2 keV – 5 GeV. Effective area 50 cm² at 400 MeV
- Observations of γ-ray pulsars and binary systems
- Detailed γ-ray map of the galaxy
More on COS-B

- Thin (0.042 $\Lambda_R$) tungsten plates within the spark chambers were used as converters
- The energy was measured by means of CsI crystals with 4.7$\Lambda_R$ thickness

<table>
<thead>
<tr>
<th>Photon energy</th>
<th>Energy resolution (FWHM)</th>
<th>Angular resolution (FWHM)</th>
<th>Effective area</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 MeV</td>
<td>50%</td>
<td>7.2°</td>
<td>12 cm²</td>
</tr>
<tr>
<td>150 MeV</td>
<td>45%</td>
<td>4.5°</td>
<td>37 cm²</td>
</tr>
<tr>
<td>300 MeV</td>
<td>50%</td>
<td>3.2°</td>
<td>52 cm²</td>
</tr>
<tr>
<td>1 GeV</td>
<td>67%</td>
<td>2.4°</td>
<td>48 cm²</td>
</tr>
</tbody>
</table>

COS-B achieved typical source sensitivity around $10^{-6}$ photons/cm²/s
The CGRO mission

- Compton Gamma Ray Observatory
- Launched on April 5, 1991 - Deorbited on June 2000
- BATSE – OSSE – COMPTEL - EGRET
- Energy range 30 keV – 30 GeV
- Observations of $\gamma$-ray pulsars and binary systems
- Detailed $\gamma$-ray map of the galaxy
EGRET

Large improvement with respect to COS-B in effective area and flux sensitivity

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<th>Angular resolution (FWHM)</th>
<th>Effective area</th>
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<tr>
<td>100 MeV</td>
<td>26%</td>
<td>5.5°</td>
<td>930 cm²</td>
</tr>
<tr>
<td>500 MeV</td>
<td>20%</td>
<td>2.0°</td>
<td>1570 cm²</td>
</tr>
<tr>
<td>1 GeV</td>
<td>19%</td>
<td>1.2°</td>
<td>1300 cm²</td>
</tr>
<tr>
<td>10 GeV</td>
<td>26%</td>
<td>0.4°</td>
<td>690 cm²</td>
</tr>
</tbody>
</table>
EGRET All-Sky Gamma-Ray Survey Above 100 MeV
Ground-based detectors

Measuring cosmic-ray and gamma-ray air showers

- First interaction (usually several 10 km high)
- Air shower evolves (particles are created and most of them later stop or decay)
- Some of the particles reach the ground
- Measurement of Cherenkov light with telescopes
- Measurement with scintillation counters
- Measurement of low-energy muons with scintillation or tracking detectors
- Measurement of high-energy muons deep underground
- Measurement of fluorescence light (Fly’s Eye)

(C. 1989 K. Berkely)
Ground-based detectors

- Large effective areas are required due to the very small fluxes
- Knowledge of the interaction model and of the shower development in the atmosphere
- Charged cosmic ray background usually determines the low energy threshold of the experiment. Rejection improved with angular resolution, high altitude sites, muon content measurement, topological patterns, ...
- High energy threshold determined by the effective areas

- EAS detectors have too high threshold (~ 10 TeV) unless....(see below)
- IACT (Imaging Atmospheric Cerenkov Telescope) very useful in the VHE
EAS detectors

The shower front has a thickness of \( \sim 10\text{ns} \)

The shower maximum is related to the primary energy

The lateral distribution is well described by the Nishimura-Kamata-Greisen NKG formula

\[
\rho_N(r,t) = \frac{N_e(t)}{r_1^2} \cdot \left( \frac{r}{r_1} \right)^{s-2} \cdot \left( 1 + \frac{r}{r_1} \right)^{s-4.5}
\]

\[
r_1 = \frac{E_s}{E_C} X_o \approx 9.3 \text{ g/cm}^2
\]
EAS detectors

The angular resolution mainly depends on the detector timing performances, but also on the number of counters and their spacing.

$$\sigma_\theta = \frac{K \sigma_t}{N \Delta}, \quad K \approx 1,$$