(6) Instrumentation in high energy cosmic ray experiments

- Scientific interest
- A quick introduction to cosmic ray physics
- Nucleonic cascades and indirect observation methods
- Space-based experiments (e.g. AMS)
- Ground-based experiments (e.g. Pierre Auger Observatory)
# The electromagnetic and cosmic ray spectrum

## Energy Ranges

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<thead>
<tr>
<th>Energy</th>
<th>µeV</th>
<th>meV</th>
<th>eV</th>
<th>keV</th>
<th>MeV</th>
<th>GeV</th>
<th>TeV</th>
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<td>Solar c.r.</td>
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<td>Galactic c.r.</td>
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### Wavelength in Meters

- Radio, TV: $10^{-1}$ to $10^{-3}$ meters
- Infrared: $10^{-4}$ to $10^{-6}$ meters
- Microwaves: $10^{-7}$ to $10^{-8}$ meters
- Ultraviolet: $10^{-10}$ to $10^{-12}$ meters
- Gamma rays: $10^{-13}$ meters

### Frequencies in Hz

- Radio, TV: $10^{7}$ to $10^{9}$ Hz
- Infrared: $10^{8}$ Hz
- Microwaves: $10^{9}$ Hz
- Ultraviolet: $10^{10}$ Hz
- Gamma rays: $10^{11}$ Hz

### Wavelength in Nanometers

- Red: 650 to 700 nm
- Orange: 600 to 650 nm
- Yellow: 550 to 600 nm
- Green: 500 to 550 nm
- Blue: 450 to 500 nm
- Violet: 400 to 450 nm

### Galactic c.r. vs. Extra-galactic c.r.

- Galactic c.r.:
  - Energy: TeV
- Extra-galactic c.r. (?):
  - Energy: TeV, PeV, EeV, ZeV
Scientific Interest

Cosmic rays are next to electromagnetic radiation the messengers that allow us to probe the universe. They play a role in very different fields of research, which are concerned with very different energy ranges.

For example:

- **solar cosmic rays (solar wind):** information on solar abundances, solar activity...

- **galactic cosmic rays:** information on galactic abundances, acceleration mechanisms, interstellar medium, galactic magnetic fields; antimatter and dark matter searches...

- **extragalactic cosmic rays:** insights into unknown acceleration mechanisms in extreme environments, information on extragalactic magnetic fields, intergalactic medium, test of particle physics (standard model) at energies that are several orders of magnitude greater than those that can be generated in accelerator facilities...
Cosmic rays are everywhere

- **Muons** and **neutrinos** are constantly generated in extensive air showers from cosmic ray interactions in the atmosphere. Muons arrive at sea level with an average flux of about 1 muon per square centimeter per minute. There is also a large flux of neutrinos that reaches the ground and penetrates even through the Earth.

- Cosmic rays lead to increased **radiation exposure** for the crews of **airplanes**.

- This is a much worse problem for **space travel** (together with X-ray and \(\gamma\)-ray radiation)

- Cosmic rays are thought to provide **condensation seeds for cloud formation** in the Earth's atmosphere. Their influence on the Earth's climate is currently under discussion. They might also have an influence on the generation of **lightning**.

- **Carbon dating** uses the fraction of radioactive C14 (half-life of 5730 years) to determine the age of materials that contain carbon. C14 is generated in the atmosphere by cosmic ray interactions.
A bit of history... Discovery of cosmic rays (1)

- ~1900 it was found that electroscopes discharged even when kept in the dark and far away from natural radioactivity.

- In 1910 Theodor Wulf found that the ionization of the electroscope fell from $6 \times 10^6$ ions/m$^3$ on ground to only $3.5 \times 10^6$ ions/m$^3$ on top of the Eiffel Tower (330 m). This proved that the ionisation could not come from $\gamma$-rays from the ground, since they would have been absorbed much stronger in the air and would be negligible at 300 m.

- In 1912, 1913 Victor Hess and then Walter Kolhörster undertook several balloon flights and found that the ionization increased at altitudes above 1.5 km with respect to the level on ground. This was clear evidence that the source of ionization is located above the Earth's atmosphere. The new "radiation" was found to be at least 5 times more penetrating than $\gamma$-rays.
A bit of history ... Discovery of cosmic rays (2)

- In 1929, Skobeltsyn found very energetic particles when studying electrons in a cloud chamber. He interpreted them as secondary electrons from the cosmic "radiation". This was some first evidence for atmospheric particle showers initiated by cosmic rays.

- In 1929, with the newly invented Geiger-Müller counter, Bothe and Kolhörster found coincident events from cosmic rays in two counters separated by lead or gold at high altitude. This proved that the cosmic "rays" were in fact charged particles. The energies of the observed cosmic rays were estimated to be about $10^9 - 10^{10}\text{ eV}$.

- In 1938, Pierre Auger discovered the extensive air showers caused by very energetic cosmic rays. He measured time coincident signals in two detectors placed a few meters apart in a location high up in the Alps.

With this method, he already observed air showers with energies up to $10^{15}\text{ eV}$ and laid the foundation for the indirect observation of high energy cosmic rays.
PHYSIQUE NUCLÉAIRE.- *Les grandes gerbes cosmiques de l’atmosphère.* Note\(^1\) de MM. PIERRE AUGER et ROLAND MAZE, présentée par M. Jean Perrin.

1. Nous avons montré\(^2\) l’existence de gerbes de rayons cosmiques produites dans l’atmosphère et dont les branches peuvent être distantes de plusieurs mètres. Nous avons pu étendre cette étude jusqu’à des distances de plusieurs dizaines de mètres et mettre ainsi en évidence les effets de corpuscules de très haute énergie dans leur traversée de l’atmosphère. La mesure du pouvoir pénétrant des particules contenues

(...) 

3. On voit d’après ces résultats que les averses soudaines de rayons cosmiques décrites ici peuvent couvrir des surfaces de l’ordre de 1000 m\(^2\), et comportent donc plusieurs dizaines de milliers de corpuscules, dont une moitié environ peut traverser 5 cm de plomb. Si l’on évalue à \(5 \times 10^7\) eV la perte d’énergie de ces corpuscules (supposés être des électrons lourds) par centimètre de plomb, on voit que l’énergie totale de la gerbe, et par conséquent du corpuscule initial qui la produit peut aller de \(10^{12}\) à \(10^{13}\) eV. Les particules d’énergie aussi élevées sont certainement rares, et ce
A Quick Introduction To Cosmic Ray Physics

Since cosmic rays are mostly charged particles, they are deflected in Galactic and extragalactic magnetic fields. This makes a direct "astronomical" study of sources unfeasible. Cosmic ray experiments deal with the following main questions:

- What is the cosmic ray flux at different energies? Are there any spectral features that help us understand acceleration processes or propagation effects?
- Are there any anisotropies in the arrival directions of cosmic rays? At which energies? Large-scale anisotropies? "Clustering" of events?

The overall goal is to understand the origin of the cosmic ray flux at all energies and the underlying acceleration mechanisms.

For ultra-high energy cosmic rays (-> $10^{20}$ eV!), these mechanisms must be extremely powerful.
The Cosmic Ray Flux

- differential flux: \( dN / (dE \ A \Omega \ dt) \) in \( (m^2 \ sr \ s \ GeV)^{-1} \)

- follows roughly an \( E^{-3} \) power law \( \Rightarrow \) non-thermal sources!

- three widely observed features:
  - ‘knee’ at \( \sim 10^{15.5} \) eV (flux steepens)
  - ‘second knee’ at \( \sim 10^{17.5} \) eV (flux steepens)
  - ‘ankle’ at \( \sim 10^{18.5} \) eV (flux softens)

- most recent results (HiRes, Auger) not included here!
The cosmic ray composition at low energies

The overall cosmic ray flux consists to about 90% of protons, to about 9% of alpha particles and to about 1% of electrons. The fraction of nuclei with higher masses is very small. But this flux is completely dominated by low energy particles. The composition might change drastically at higher energies.

The composition of solar cosmic rays or solar wind (at energies of \(\sim 10-100\) keV) is similar to that of the Sun (protons, electrons, few ions).

The particles from the solar wind have enough energy to ionize the various gases in the upper atmosphere (ionosphere, \(\sim 100\) km), which then causes beautiful displays known as the Aurora. This comes mainly from oxygen and nitrogen fluorescence.

The flux of Galactic cosmic rays at low energies is attenuated by the solar wind.

photograph by Dick Hutchinson, SLAC website
The cosmic ray composition of the galactic cosmic rays arriving near Earth have relative abundances for the more common elements (including C, O, Ne, Mg, Si, Fe, Ni) that are remarkably similar to the relative abundances of these elements in the Solar System.

On the other hand, many elements that are rare in the Solar System (including Li, Be, B, F, Sc, Ti, V) have much higher abundances in the arriving cosmic rays.

The fact that the cosmic ray abundances fill in the deep valleys in the Solar System abundances is understood quantitatively as the result of nuclear interactions of cosmic rays with interstellar gas (nuclear spallation).

The lower abundances of H and He in the cosmic ray composition could come from the fact that the lighter elements are more difficult to accelerate in the cosmic ray sources.

This composition seems to hold for energies up to the knee-region.
The Cosmic Ray Composition at High Energies

Transition from light to heavy around the “knee” (1-10 PeV), seen by KASCADE (and other experiments).

Rigidity dependent cutoffs.

Evidence for a transition from heavy to light above $\sim 10^{17}$ eV

Recent results from HiRes and Auger not included (will be discussed later).
Anisotropy Searches

left: AGASA sees excess towards G.C. at EeV energies
-> claim refused by Auger

right: indirect evidence from HESS for cosmic ray acceleration in GC and G. Plane

left: SUGAR sees excess toward G.C. at EeV energies
-> claim refused by Auger

right: AGASA sees clusters of events at > 40 EeV.
-> claim refused by HiRes

A. Zech, Instrumentation in High Energy Astrophysics
There are several possible sources for the energy needed for acceleration of the cosmic ray particle:

**kinetic energy:**
- translation (shock fronts in supernova remnants, GRB, AGN \(\Rightarrow\) Fermi acceleration)
- rotation (pulsars, black holes, neutron stars)

**gravitational energy:**
- material falling onto accretion disks (AGN, binary systems...)

**electromagnetic energy:**
- magnetars ...

**Galactic cosmic rays** supposed to be accelerated in shock waves in supernova remnants. No direct proof has been found so far.

One assumes that the cosmic rays at the highest energies (\(>\sim 10\) EeV) are of **extra-galactic** origin. Their sources must be particularly violent objects to provide their enormous energies. AGN, GRBs, pulsar wind bubbles are being explored as possible sources.

In a different approach, the so-called "TOP-DOWN" models, ultra-high energy cosmic rays are the **decay products of supermassive exotic particles.**
Fermi Acceleration (1)

Fermi Acceleration at shock waves is an important mechanism to explain the energies of Galactic and maybe extra-galactic cosmic rays. **Energy from a shock wave is transferred to single particles in repeated encounters.** The energy of the particle increases at each encounter.

We assume that an infinite plane shock wave is moving with velocity $-u_1$ through the interstellar medium. Its velocity is non-relativistic.

The shocked (downstream) plasma has a velocity $v = -u_1 + u_2$, with $|u_2| < |u_1|$. An "encounter" happens when a particle crosses the shock front from upstream into the downstream region and is then scattered back again into the upstream region.

The charged particle is scattered on irregularities in the turbulent magnetic field that is carried along with the downstream plasma. The particle gains energy in each encounter. A magnetic field alone cannot change the energy of a particle, as we know. However, here the magnetic field is moving relative to the upstream frame, which corresponds to an electric field:

$$\vec{E} = \vec{V} \times \vec{B} \quad \text{for} \quad V \ll c$$
Fermi Acceleration (2)

The acceleration process can be described as a "Lorentz boost" by changing the frame of reference through the encounter:

The energy of the particle in the upstream region is $E_1 \sim pc$, i.e. the particle is relativistic.

Its energy in the rest frame of the downstream plasma is thus:

$$E_2 = \gamma E_1 (1 - \beta \cos \theta_2)$$  \hspace{1cm} \beta = V/c$$

In this frame, the energy of the particle does not change. It interacts only with magnetic fields, which change its direction. Its energy does change with respect to the initial rest frame.

Transforming back into the upstream frame:

$$E_3 = \gamma E_2 (1 + \beta \cos \theta_1)$$

In the same way, the particle will get reflected again in the magnetic field lines of the upstream region.

The fractional energy gain per encounter is:

$$\frac{\Delta E}{E_1} = \frac{E_3 - E_1}{E_1} = \frac{1 - \beta \cos \theta_2 + \beta \cos \theta_1 - \beta^2 \cos \theta_2 \cos \theta_1}{1 - \beta^2} \cdot 1$$

A shock wave moving to the left through the interstellar medium with velocity $-u_1$. 

A. Zech, Instrumentation in High Energy Astrophysics
Fermi Acceleration – Energy Gain

For an isotropic flux, the angular distribution of particles hitting a plane is:

$$\langle \cos \theta \sin \theta \rangle = \int_0^{\pi/2} \int_0^{\pi/2} \cos \theta \cos \theta \sin \theta \ d\theta$$

If we assume an isotropic upstream flux, the mean $\cos \theta$ is given by:

$$\langle \cos \theta \rangle = \int_{\pi/2}^{3\pi/2} \cos \theta \cos \theta \sin \theta \ d\theta = -2 \int_{\pi/2}^{\pi} \cos^2 \theta \ d\cos \theta = -2 \left[ \frac{1}{3} \cos^3 \theta \right]_{\pi/2}^{\pi} = -2/3$$

In an analogous way, the mean $\cos \theta$ for the reflected particle flux is:

$$\langle \cos \theta_1 \rangle = 2/3$$

One obtains for the average fractional energy gain:

$$\langle \Delta E \rangle = \frac{1 + 4/3 \beta + 4/9 \beta^2}{1 - \beta^2} - 1$$

If the shock wave is non-relativistic, i.e. $\beta \ll 1$

$$\frac{\langle \Delta E \rangle}{E_1} \approx \frac{4}{3} \beta$$
Fermi Acceleration – Some Conclusions

This is called the "First Order Fermi Acceleration", since it is linear in $\beta$. The fractional energy gain depends only on the difference of velocities $V$ between the upstream and downstream plasma.

**How many encounters does a particle need to reach an energy $E$?**

Energy gain per encounter:  
$$\Delta E = \zeta E_0$$

Final energy after $n$ encounters:  
$$E = E_0(1 + \zeta)^n \rightarrow n = \frac{\ln(E/E_0)}{\ln(1 + \zeta)}$$

The finite lifetime of the accelerator puts thus an upper limit on the total energy gain.

**What is the energy distribution of a flux of particles after acceleration?**

$P$ is the probability that a particle escapes from the accelerating region. The proportion of particles accelerated to energies $> E$ is thus:

$$N(E \geq E) \propto \sum_{m=n}^{\infty} (1 - P)^m = \frac{(1 - P)^n}{P}$$

Substituting $n$ yields:  
$$N(E \geq E) \propto P^{-1} \left(\frac{E}{E_0}\right)^{-\gamma}, \quad \gamma = \frac{\ln(1/(1 - P))}{\ln(1 + \zeta)}$$

The Fermi Acceleration process leads to a power law spectrum of particle energies.
Fermi Acceleration and cosmic rays

- More quantitative calculations show that Fermi acceleration leads to a universal spectral index of \( \sim 2 \).

- Fermi developed an acceleration mechanism of cosmic rays first using magnetic fields carried in clouds. This leads to a "second order fermi acceleration" (energy gain is second order in \( \beta \)). Acceleration on shock waves is a more promising mechanism.

- Energy loss mechanisms (e.g. synchrotron radiation) play an important role in gradual acceleration mechanisms and can greatly lower the net energy gain.

- Estimates of the acceleration on supernova shock fronts yield an upper energy limit of \( \sim 100 \) TeV (T. Gaisser). Energies could be higher under certain conditions.

- Acceleration on relativistic shock waves could also lead to a higher energy limit. Enhancements of the magnetic fields by turbulences and instabilities seems to improve the upper energy limit for SNR to several PeV.

- Shock waves powered by supernovae are assumed to provide only sufficient energies for Galactic cosmic rays roughly up to the "knee" region. Similar (maybe relativistic) shocks in extragalactic objects (AGN, radio galaxy lobes, GRB...) might reach significantly higher energies.
Only very few sites can be considered for Fermi-like acceleration of the most energetic cosmic rays.

A potential site needs to have a long enough lifetime.

The extension and the magnetic field of the site need to permit the particle to be confined long enough. The particle's gyro-radius needs to be smaller than the accelerating region:

\[ r_G [kpc] = \frac{E [EeV]}{Z \cdot B [\mu G]} < L \]

The Hillas diagram shows sites that fulfill these basic criteria. For a given energy \( E \), the product of extension \( L \) and magnetic field \( B \) has to be larger than \( E/Z \). All the potential sites are thus above the diagonal lines for a certain \( E \) and \( Z \).
Propagation Effects

**magnetic fields** (galactic, extragalactic)

=> one expects an isotropic flux for energies below \(~1\) EeV for charged cosmic rays

=> only at the highest energies (\(>\) several 10 EeV) can charged cosmic rays point back to their sources

**adiabatic energy loss** (red-shifting)

**\(e^+e^-\)** pair production with CMB

**photo-spallation** of nuclei (\(E_{\text{threshold}} \sim \) atomic number)

**GZK effect** with CMB (photo pion-production)

=> should lead to a cut-off in the spectrum around 60 EeV

1: \(p + \text{redshift} + e^+e^-\)
2: \(1 + \text{GZK}\)
3: \(\text{Fe} + e^+e^-\)
4: \(3 + \text{photo-spallation}\)
Top-Down Models

Top-Down models present an alternative to the "bottom-up" acceleration of particles in astrophysical sources. Here, the ultra-high energy cosmic rays are suggested to be decay products of very heavy exotic particles (i.e. often unknown particles outside of the Standard Model).

Candidates are:

- **Topological Defects**: defects in the early space-time topology after the Big Bang, which decay into exotic heavy particles and then into UHECRs.

- **Superheavy Dark Matter**: very heavy exotic particles that are gravitationally bound in the galactic halo or inside heavy objects and decay into UHECRs.

- **Z-bursts**: neutrinos interact with the cosmological neutrino background to generate Z bosons. Those decay into UHECRs.

Top-Down models explain UHECRs through decays. Part of the decay products contain always pions, which decay further, producing photons and neutrinos. A considerable photon and neutrino flux are thus distinct signatures of Top-Down models, which distinguish them from the "bottom-up" models. By measuring upper limits on the photon or neutrino flux, one can test the Top-Down hypothesis.
A more fancyful approach to cosmic rays:

http://www.geocities.com/SunsetStrip/1483/
Direct and Indirect Observation of Cosmic Rays

Below 0.1 PeV:

Cosmic rays can be observed directly. The first experiments used detectors in balloons. Nowadays, detectors are also transported by aircraft, satellites and on space stations.

A direct measurement of the cosmic ray particle allows its identification. We can thus measure the energy spectra of different nuclei and even different isotopes of the same nucleus.

Above ~ 0.1 PeV:

The flux becomes so small that indirect detection methods are used to measure the air showers initiated by cosmic rays.

Ground arrays
Cherenkov detectors
Air fluorescence detectors
Radio antennae
Hadronic air showers (1)

Air showers initiated by hadrons (protons, neutrons, nuclei...) have at their center a hadronic cascade that produces pions in nuclear interactions.

The pions will then decay, mainly in the following way:

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \; ; \; \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]
\[ \pi^0 \rightarrow 2\gamma \]

The charged pions generate muons, which can decay into electrons (positrons) or reach the ground.

The neutral pions feed electromagnetic cascades, which produce electrons, positrons and photons, as we saw. A part of the electrons, positrons and photons will reach the ground.

Hadronic showers develop earlier in the atmosphere than electromagnetic showers because of the additional nuclear interactions. They also have a large muon fraction and are wider than e.m. showers.
Hadronic air showers (2)

Development of cosmic-ray air showers

Primary particle (e.g. iron nucleus)
First interaction
Pion decays
Second interaction

(C) 1999 K. Bernloehr
The superposition principle

The relations we found with the Heitler model for a simple electromagnetic air shower are still a good approximation for hadronic showers initiated by a single proton or neutron:

\[ N_{\text{max}} \propto E_0 \quad ; \quad X_{\text{max}} \propto \log(E_0) \]

If the primary particle is a nucleus with mass number \( A \) and energy \( E_0 \), we can treat it approximately as a superposition of \( A \) nucleons with energy \( E_0 / A \). We then assume that the \( A \) nucleons interact independently with the atmosphere and generate a superposition of \( A \) sub-showers. The \( N_{\text{max}} \) of the sum of these sub-showers will still be the same:

\[ N_{\text{max}} \propto E_0 \]

This \( N_{\text{max}} \) is now the sum of the \( N_{\text{max}} \) of the \( A \) sub-showers:

\[ N_{\text{max}} = A \cdot 2^{X_{\text{max}}/\lambda} \]

\[ \rightarrow X_{\text{max}} \propto \log\left(\frac{E_0}{A}\right) \]

This means that an air shower that comes from a nucleus will reach its maximum size higher up in the atmosphere than an air shower coming from a single proton! \( X_{\text{max}} \) will thus help us distinguish between different primary particles for different showers with the same \( N_{\text{max}} \) (same energy \( E_0 \)).

It should be noted that the superposition principle is a stark simplification of the real process, which can only be described with the proper nuclear processes. It can thus only be used for a qualitative statement.
Photon, Proton and Iron Induced Air Showers

Vertical (z-) axis range is 30 km. First interaction at a height of 30 km. The shower is projected onto the x-z plane. Horizontal (x-) axis range is +/- 5 km around the shower core. Energy: 100 TeV. Vertical injection of the cosmic ray particle. Colors: e+, e-, photons (red) / muons (green) / hadrons (blue) (red+green -> yellow)

(www.ast.leeds.ac.uk/~fs/showerimages.html)
The Ground Array Technique

- Detection of lateral particle profile (muons, electrons/positrons, photons) on ground.
- A large array of detectors, usually scintillators or water Cherenkov tanks, is used.
- Reconstruction of the shower geometry from signal strengths and timing information from the different detectors.
- Reconstruction of the cosmic ray energy by comparison of the lateral density profile with simulations.
- Reconstruction of the cosmic ray composition from analysis of the recorded pulse shape and the curvature of the shower front.

=> 100% duty cycle (detectors can run 24 hours a day).
=> fluctuations of the lateral profile can be important
=> energy reconstruction is very model dependent
Fluorescence and Cherenkov light from air showers

- The charged particles of an air shower (>90% electrons and positrons) excite air molecules, which emit UV "fluorescence" light. The fluorescence light emission is isotropic.

- Since the charged particles have velocities close to the vacuum speed of light, they also emit Cherenkov radiation in the atmosphere (in the UV range). The Cherenkov radiation is emitted in cones along the direction of the particles. This leads to an emission in the forward direction of the shower axis (non-isotropically). Scattering of Cherenkov photons in the atmosphere distributes a part of the "Cherenkov cone" also at larger angles.
"Fluorescence" Light from Air Showers

- Usually, the term "fluorescence" refers to the process by which atoms absorb photons of one wavelength and emits photons at a longer wavelength.

- The passage of charged particles in an extensive air shower through the atmosphere results in the ionisation and excitation of the gas molecules (mostly nitrogen). Some of this excitation energy is emitted in the form of visible and UV radiation.

- Strictly speaking, this is a "luminescence" or "scintillation" process. Much to the horror of the optical physicists, the name "Air Fluorescence" has been adopted by the astrophysics community to describe the scintillation light from extensive air showers. On the positive side, this usage makes it easy to distinguish between a fluorescence detector from a scintillation detector.
The Air Fluorescence Technique

- Detection of the **longitudinal shower profile in the atmosphere** via UV fluorescence light.

- Optical detectors (mirrors and cameras with PMTs)

- Reconstruction of **shower geometry** from the observed track and the trigger times of the PTMs. Best reconstruction in stereo mode.

- Reconstruction of the **cosmic ray energy** from an integral over the observed light flux. The cosmic ray deposits ~90% of its energy into the electromagnetic cascade. The atmosphere is thus used like a huge **calorimeter**. Light flux is proportional to the energy deposit.

- Reconstruction of **composition** from $X_{\text{max}}$ measurements.

=> 10% - 15% duty cycle (Observation only possible on clear, moonless nights)

=> atmosphere needs to be well understood

=> energy dependent aperture
Cherenkov Technique

**Imaging Atmospheric Cherenkov Telescopes (IACTs):**

Telescopes like HESS, MAGIC and VERITAS observe the Cherenkov signal from γ-ray induced showers. Hadronic showers are background for these experiments, but they can also be observed as signals. The irregular shape of the shower image on the camera makes it difficult to reconstruct their geometry.

A flux measurement at the highest energies is not possible, since the Cherenkov light is non-isotropic and the portion of the showers that hit the detectors is too small.

**Non-Imaging Atmospheric Cherenkov Telescopes:**

These are ground arrays of PMTs that register all the photons from the air shower. This technique is used in combination with other surface detectors to provide an additional estimate of the energy of the shower (i.e. Haverah Park, Yakutsk, Blanca...).
The Radio Detection Technique

Technique discovered in the 1960s and tested in several experiments.

The radio signal of an air shower comes from coherent synchrotron emission from $e^+e^-$ pairs that gyrate in the earth's magnetic field.

An additional effect comes from the fact that there is a certain surplus of electrons in the air shower, which means that the shower front carries a net charge.

The radio signals can be picked up with arrays of antennae at energies $>\sim 1$ PeV. Reconstruction of geometry and energy seem very promising.

Several prototype experiments are currently testing this technique: Lopes/Lofar in combination with the ground array Kascade, Codalema... Radio antennae have also been added to the Auger Observatory.

The CODALEMA experiment in Nançay.