The 2016 CERN Summer Student Lectures

Astroparticle Physics (1/3)

Laura Covi

Institute for Theoretical Physics
Georg-August-University Gottingen

elusives-invisiblesPlus
neutrinos, dark matter & dark energy physics

$[q, p] = i\hbar$

MARIE CURIE ACTIONS

Outline

- Introduction:
  - The beginnings: 100+ years of cosmic rays
  - Basic concepts
- Dark Matter: a multi-particle and multi-wavelength search
- Recent Data in cosmic rays, neutrino and gravitational wave (NEW!) astronomy
- Outlook

Definition according to Wikipedia:

Astroparticle physics, the same as **particle astrophysics**, is a branch of particle physics that studies elementary particles of astronomical origin and their relation to astrophysics and cosmology. It is a *relatively new* field of research emerging at the intersection of particle physics, astronomy, astrophysics, detector physics, relativity, solid state physics, and cosmology. Partly motivated by the historic discovery of neutrino oscillations, the field has undergone remarkable development, both theoretically and experimentally, over the last decade.

Astroparticle physics was originally mostly concerned with **charged particles,** but nowadays a large part of the activities concerns also neutral particles, i.e. **neutrinos, photons** (mostly not optical range), **Dark Matter** and also **Gravity waves**...

Multiparticle and Multiwavelength Approach !

Definition according to Wikipedia:

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Multiparticle and Multiwavelength Approach !

Astroparticle.org: Looking for messengers from the Early Universe, the violent Universe and the invisible Universe !

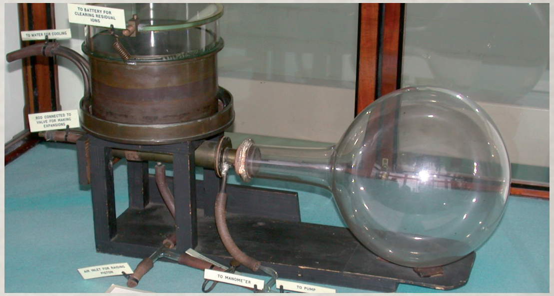
A bit of HIstory

1912 Discovery by Victor Hess

1911

CTR Wilson: Development of the cloud chamber and publication of the first pictures

In 1895 CTR Wilson started investigating cloud formation in dust-free air. He discovered that condensed bubbles appear when air molecules are ionised by X-rays. In 1911 Wilson demonstrated with a cloud chamber that alpha and beta rays could be visualised. Two of the published pictures contained straight tracks which were probably the first photographs of cosmic particles. One year before their discovery, Wilson misinterpreted these tracks as beta rays.



Original Wilson cloud chamber (Cavendish Museum)

1911—1912

VF Hess: Calibration measurements with gamma rays

VF Hess in his lab in 1915

In 1910 Hess became an assistant at the just-founded Radium Institute of the Imperial Academy of Sciences in Vienna. He performed absorption measurements in air with the strongest gamma source available at the institute and experimentally confirmed the absorption coefficient predicted by Eve.
He improved the electrometer's construction and developed a calibration method for electrometers using gauge radium sources of different strengths. For calibrated detectors from the company Günther & Tegetmeyer (Braunschweig), the accuracy when measuring the strength of unknown sources was about 5 per mil; uncalibrated instruments achieved 3% accuracy.

1911

VF Hess: First three balloon flights

In August and October of 1911, Hess performed three balloon flights reaching altitudes of 200m to 1000m and confirmed the findings of Wulf, Bergwitz and Gockel. To prepare for a new series of flights, Hess designed and ordered improved instruments, two for gamma-ray detection and one with thin detector walls to measure beta rays.

Victor F Hess in the balloon's basket sometime between 1911 and 1912

1912

VF Hess: Six balloon flights from the Prater in Vienna at lower altitudes

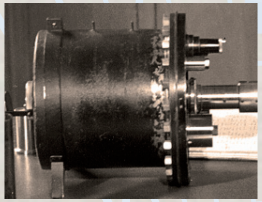
Six new flights were financed by the Imperial Academy of Sciences and supported with balloons from the Royal Imperial Austrian Aeronautical Club in Vienna. Hess measured the ionisation mainly with two or three electrometers:

1 17 April, during an eclipse of the sun at 1900m—2750m of altitude
2 26—27 April, at night for six hours at 300m—350m of altitude
3 20—21 May, at night at 150m—340m of altitude
4 3—4 June, at night at 800m—1100m of altitude
5 19 June, in the afternoon at 850m—950m of altitude
6 28 June, at night at 280m—360m of altitude

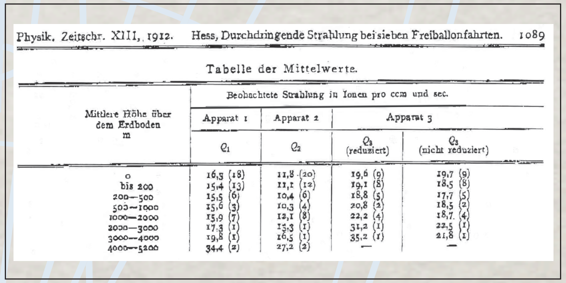
7 Aug 1912

VF Hess: Seventh balloon flight, reaching an altitude of 5350m Discovery of cosmic rays

With the hydrogen-filled balloon Bohemia, provided by the German Aero Club in Bohemia, Hess, together with W Hoffory and E Wolf, reached an altitude of 5350m and landed at noon in Bad Saarow/Pieskow in Brandenburg. All three detectors measured a strong increase in ionisation.



Electrometer used by VF Hess in 1912



Physik. Zeitschr. XIII, 1912. Hess, Durchdringende Strahlung bei sieben Freiballonfahrten. 1089

Tabelle der Mittelwerte.

Mittlere Höhe über dem Erdboden m	Beobachtete Strahlung in Ionen pro ccm und sec.			
	Apparat 1	Apparat 2	Apparat 3	
	Q_1	Q_2	Q_3 (reduziert)	Q_3 (nicht reduziert)
0	16,3 (18)	11,8 (20)	19,6 (9)	19,7 (9)
bis 200	15,4 (13)	11,1 (12)	19,1 (8)	18,5 (8)
200—500	15,5 (6)	10,4 (6)	18,8 (5)	17,7 (5)
500—1000	15,6 (3)	10,3 (4)	20,8 (2)	18,5 (2)
1000—2000	15,9 (7)	12,1 (8)	22,2 (4)	18,7 (4)
2000—3000	17,3 (1)	13,3 (1)	31,2 (1)	22,5 (1)
3000—4000	19,8 (1)	16,5 (1)	35,2 (1)	21,8 (1)
4000—5200	34,4 (2)	27,2 (2)	—	—

Mean values of all measurements during the seven flights at different altitudes (the number of ionisation values in brackets)

Seven flight routes of VF Hess in 1912

VF Hess summarised the results of these seven flights as follows:

- At altitudes of less than 1000m, the results are in general agreement with previous measurements.
- A radiation of high penetration power hits the atmosphere from above, which cannot be caused by radioactive emanations.
- This radiation contributes to the total amount of observed ionisation at lower altitudes as well.
- Assuming gamma radiation, the sun is not the source of the extraterrestrial radiation.
- There is no difference between ionisation measured during the day and at night.

DESY ASPERA Durham University

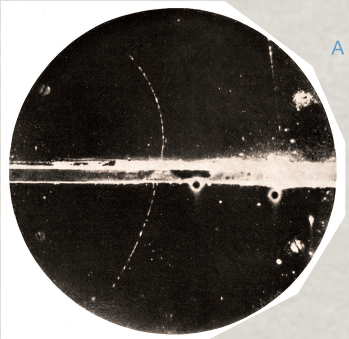
http://www.desy.de/2012vhess

1933—1947 Birth of Particle Physics

1932

CD Anderson: Discovery of the positron

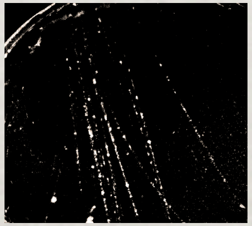
In 1931, with a cloud chamber operating in a strong magnetic field, Anderson observed cosmic ray tracks with negative and positive charges, which were interpreted as electrons and protons. Since many positive tracks had the same ionisation as the electrons, Anderson introduced a 6mm-thick lead plate into the chamber. In photographs from 1932, he found tracks with the ionisation and track length observed for electrons, but with a positive charge. This anti-electron (positron) had been predicted two years earlier by PAM Dirac.



A positron with an energy of 63MeV entering the lead plate from below and leaving the plate with an energy of 23MeV. For a proton, the track length would be ten times shorter.

1933—1935

B Rossi, PMS Blackett, G Occhialini: Particle showers



Cloud chamber photograph of a particle shower with about 16 tracks. The divergence of the tracks points to an interaction in the magnet coil.

Rossi performed measurements with three Geiger-Müller counters in coincidence with and without lead shielding on top. The coincidence rate increased with the shielding, even though the opposite had been expected. The explanation was the shower production by an incoming cosmic particle.
Blackett and Occhialini demonstrated the shower production visually with cloud chamber photographs.

1934

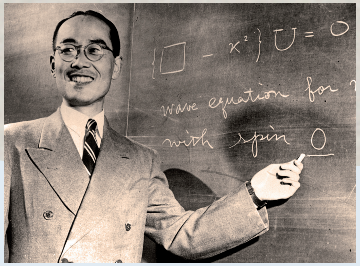
W Baade, F Zwicky: Supernovae as possible sources of cosmic rays

By investigating photographic plates taken over the past 30 years, about 13 short flaring, extremely bright objects were identified. Zwicky and Baade called them supernovae. Based on the estimated energy release, they concluded that supernovae are sources of cosmic rays. This hypothesis is still valid, but not completely confirmed.

1935

H Yukawa: Prediction of the pion

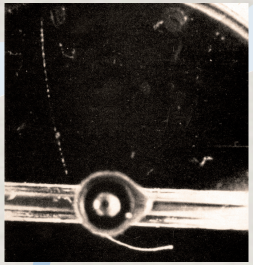
Yukawa formulated a theory to explain the dense packing of protons and neutrons in the nucleus of an atom. The short-ranged field needed a carrier with a mass inversely proportional to the range. He estimated a particle mass of about 100MeV and predicted that these particles could be produced in cosmic particle interactions.



H Yukawa, 1949

1936

SH Neddermeyer, CD Anderson: Discovery of the muon



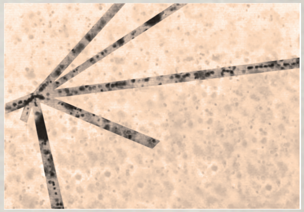
Stereographic photograph of a cloud chamber exposure. A muon enters the chamber from above and comes to rest below.

In a cloud chamber exposure with a 1cm-thick platinum plate in the centre, 6000 photographs were taken. Anderson and Neddermeyer found about 25 events where the energy loss in the platinum absorber was much smaller than measured for electrons or positrons. Since the mass should be between the electron and proton masses, they first called it the mesotron.
For several years, it was assumed that this particle was the predicted Yukawa particle.

1937

M Blau, H Wambacher: First cosmic ray nuclear interaction in a photo emulsion

The photo-emulsion technique was developed by M Blau. In 1937 a five-month exposure to cosmic particles was performed at Hess's Hafelekar cosmic ray station at an altitude of 2300m. The discovery of a so-called star was a breakthrough of this detection technique. A cosmic particle interacted with an atom of the emulsion, producing eight tracks.



A "star" produced in a photo emulsion by a cosmic particle

1938

P Auger: Extensive air showers

With two Geiger-Müller counters in coincidence, Auger and his colleagues, Maze and Robley, detected extensive air showers. They measured the rate at up to 300m of counter distance and estimated the energy of the primary cosmic particles to be about 10^{15}eV.

1942

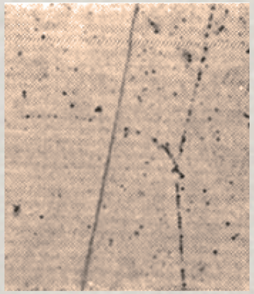
I Lange, SE Forbush: Solar cosmic particles

In February 1942, a large solar flare appeared. Lange and Forbush measured an increase in the cosmic particle rate of about 15%. They concluded that this additional fraction is caused by charged particles emitted by the solar flare.

1947

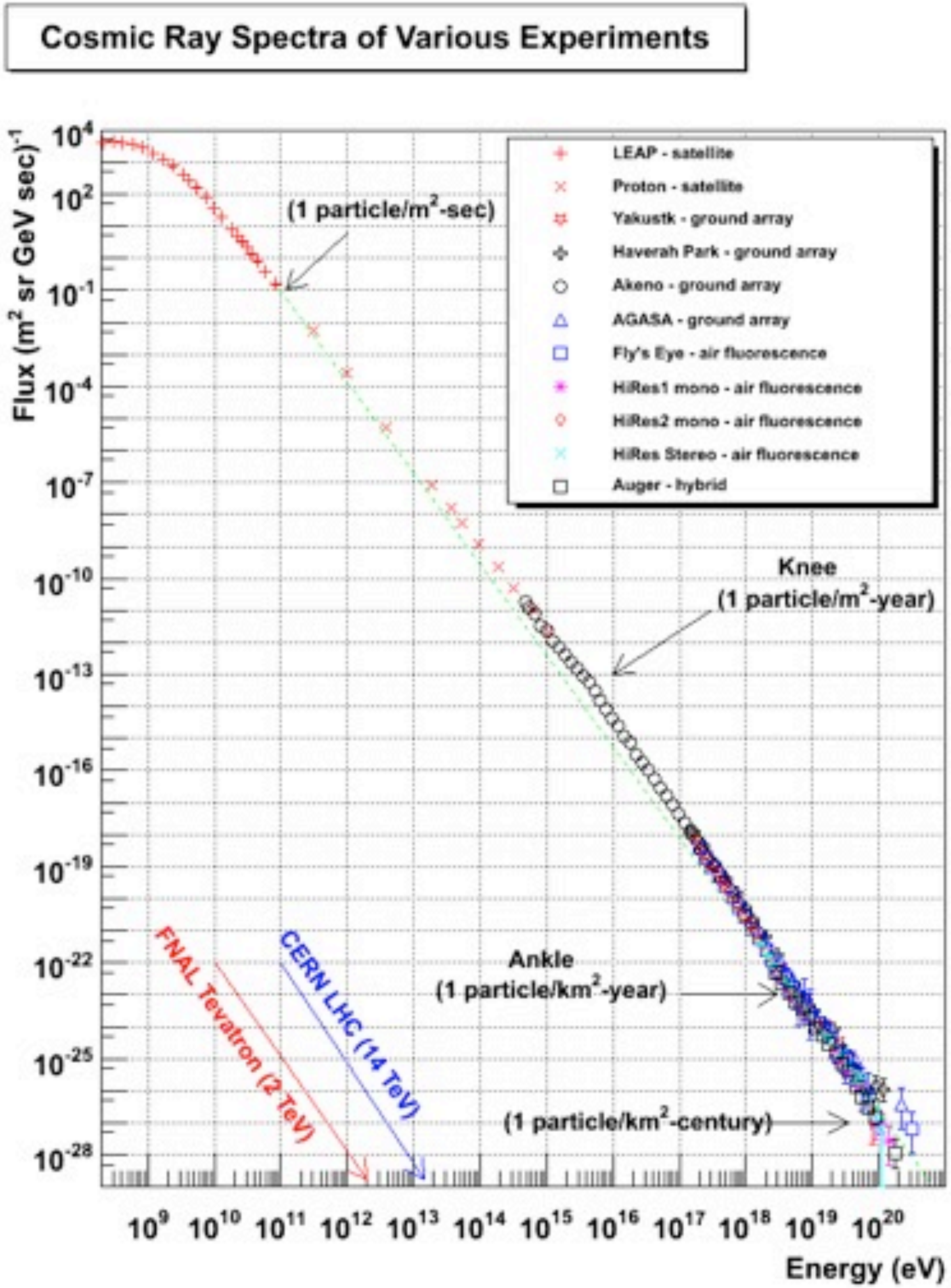
DH Perkins, GPS Occhialini, CF Powell: Discovery of the pion

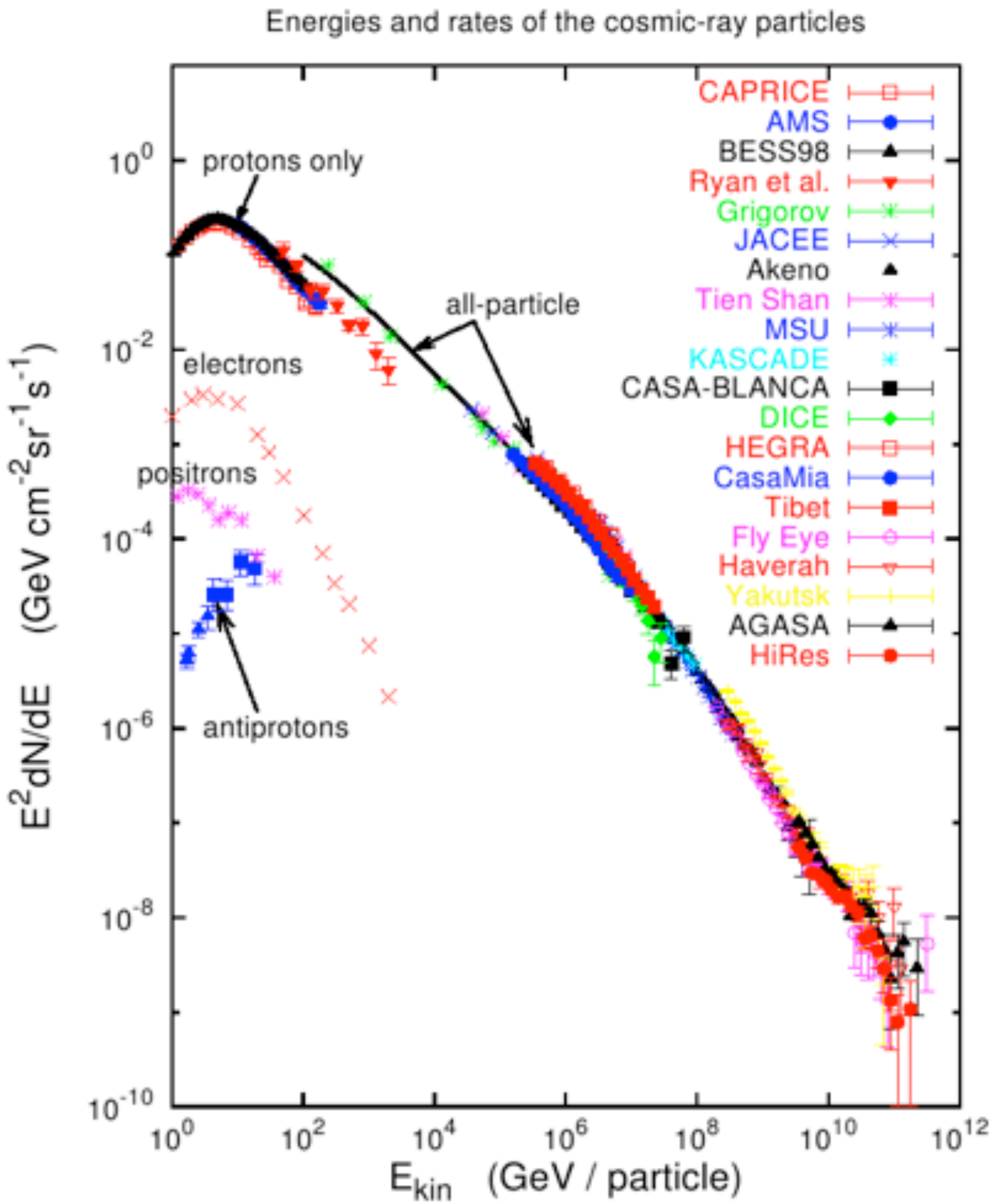
The pion event identified by Perkins. Tracks B and C are protons; D is a tritium nucleus. The short track E is a recoil nucleus. The grain density and scattering of track A correspond to a particle with a mass of about 100MeV.



In 1938 Yukawa and Sakata predicted the lifetime of the Yukawa particle to be about 10^{-8} seconds, which was 100 times shorter than the measured lifetime of the muon.
The problem was solved with the discovery of the pion in photographic emulsions in 1947. Perkins found one event, and two months later Occhialini and Powell identified 25 pion interactions.
In Britain, the emulsion technique was improved by Powell, Perkins and others, in cooperation with the Ilford company.

Cosmic Rays spectrum



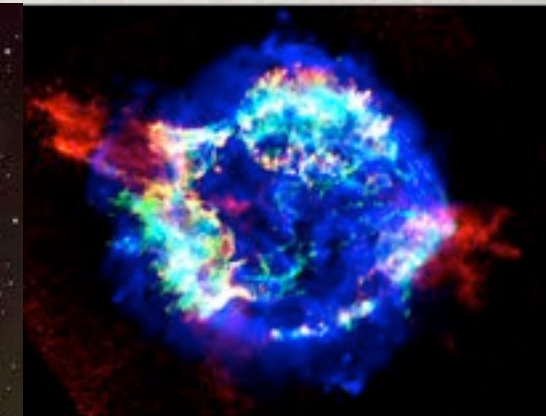


Basics: sources and acceleration

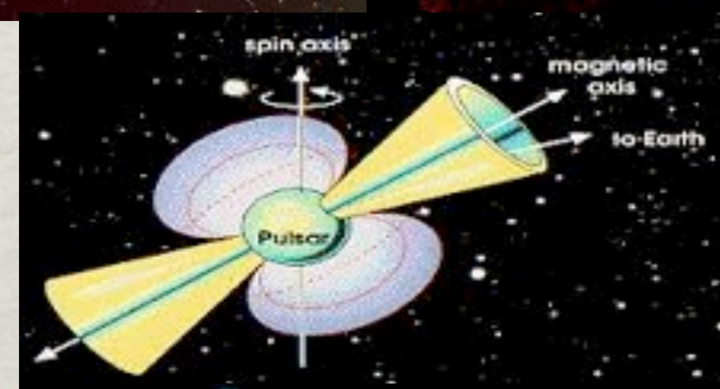
Galactic Sources

In the universe there are many violent processes that can act as particle's sources, i.e.

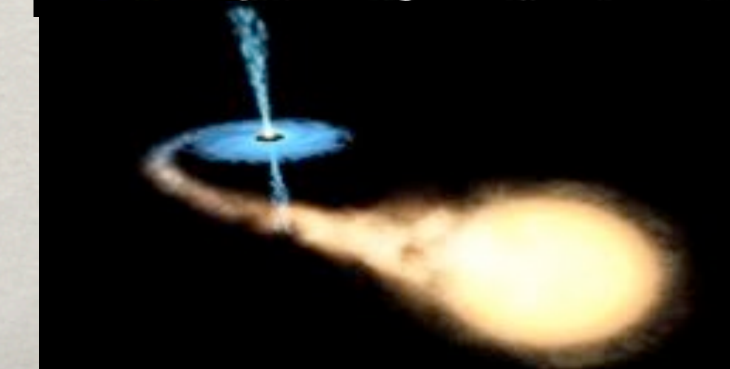
- SuperNova Remnants (SNR) (Fermi shock mechanism)



- Neutron stars/Pulsars: (very high magnetic field, up to 10^12 Gauss)



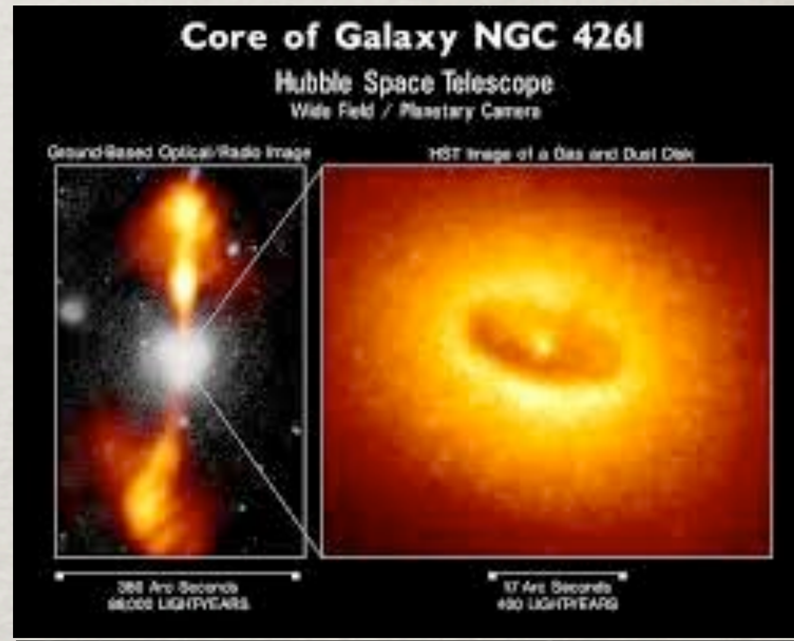
- Microquasars (Binary systems with an accreting Black Hole)



Extragalactic Sources

In the universe there are many violent processes that can act as particle's sources, i.e.

- Active Galactic Nuclei (AGN) Quasar/Blazars: Supermassive BH at centre of galaxy emitting relativistic jets



- Gamma-ray bursts (GRB): narrow beam of intense EM radiation, possibly due to an Hypernova or binary merger

High energy Cosmic rays

In general one of the main problems in astrophysics is not to produce particles, but how to give them large energy ! In general there have been two approaches:

- Bottom-up: particles of low energies are accelerated via SM physics, e.g. magnetic/electric fields within the astrophysical objects

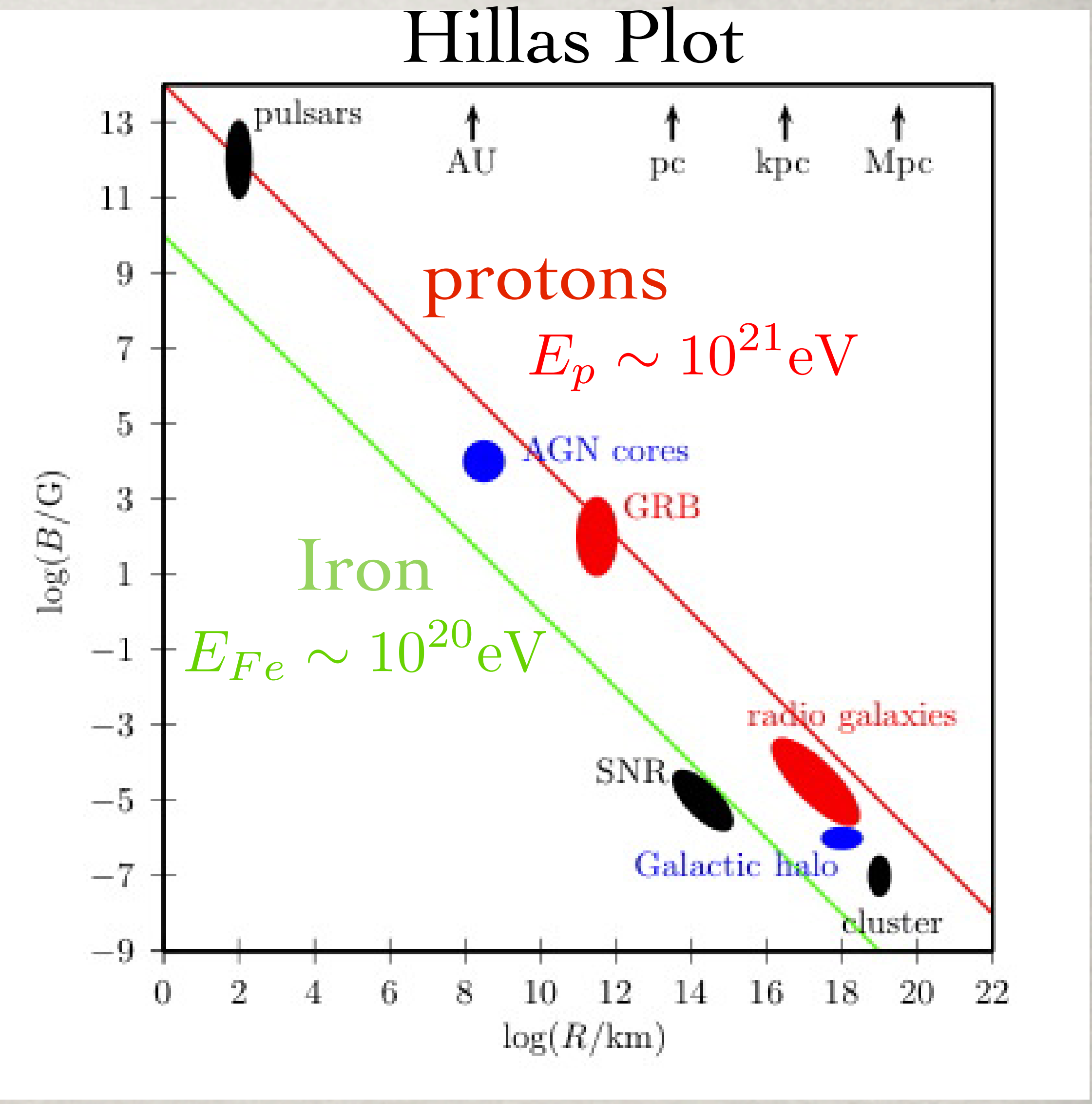
- Top-down: particles are already generated with very high energies, usually via non-SM processes, e.g. decay of (very) heavy (exotic or not so) particles

Acceleration

Hillas criterion (geometrical requirement): the maximal energy reachable within an astrophysical body is such that the corresponding Larmor radius is equal to the size of the object...

$$R \sim 2R_L = \frac{2E}{ZeB}$$

$$E_{max} = \frac{1}{2}ZeBR$$



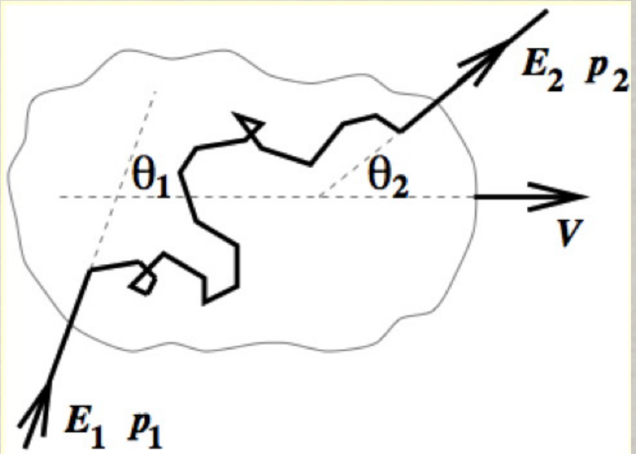
Similar maximal energy ?

FERMI ACCELERATION I

Already long ago Enrico Fermi tried to answer the question of how to accelerate particles in astrophysics. He considered the collision of a particle with a moving magnetized cloud:

$$E_1' = \gamma E_1 (1 - \beta \cos\theta_1)$$

Cloud frame "Lab" frame



After elastic deflection: $E_2' = E_1'$

$$E_2 = \gamma E_1' (1 + \beta \cos\theta_2)$$

"Lab" frame Cloud frame

Energy gain: $\dfrac{\Delta E}{E} = \gamma^2(\beta^2 - \beta(\cos\theta_1 - \cos\theta_2) - \beta^2 \cos\theta_1 \cos\theta_2)$

On average:

$\langle \cos\theta_1 \rangle = -\beta/3$

$\langle \cos\theta_2 \rangle = 0$

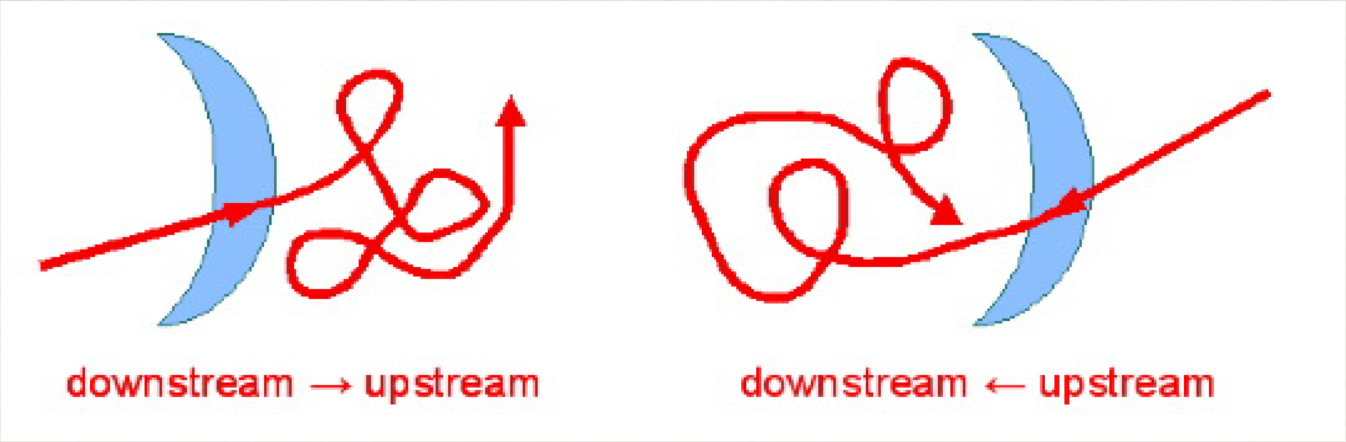
$$\frac{\Delta E}{E} = \gamma^2(\beta^2 + \beta^2 \frac{1}{3}) \sim \frac{4}{3}\beta^2$$

2nd Order

FERMI ACCELERATION II

The second order Fermi acceleration is not sufficient to explain the high energies in the CRs...
Actually possible to gain more by crossing a shock front (first order Fermi acceleration) or exploiting relativistic velocities and large γ

Shock front Shock front



$$\frac{\Delta E}{E} \sim \frac{4}{3}\beta$$

Power-law spectrum

Any mechanism like the Fermi one generates a power-law particle spectrum. Indeed assuming the source produces particles with energy E_0 and that the energy increases by the factor α after each shock-crossings, we have after many such crossings: $E = E_0\alpha^n$.

Moreover given a probability P_{esc} to escape the accelerating region after each shock crossing, we also have

$$N = N_0(1 - P_{esc})^n$$

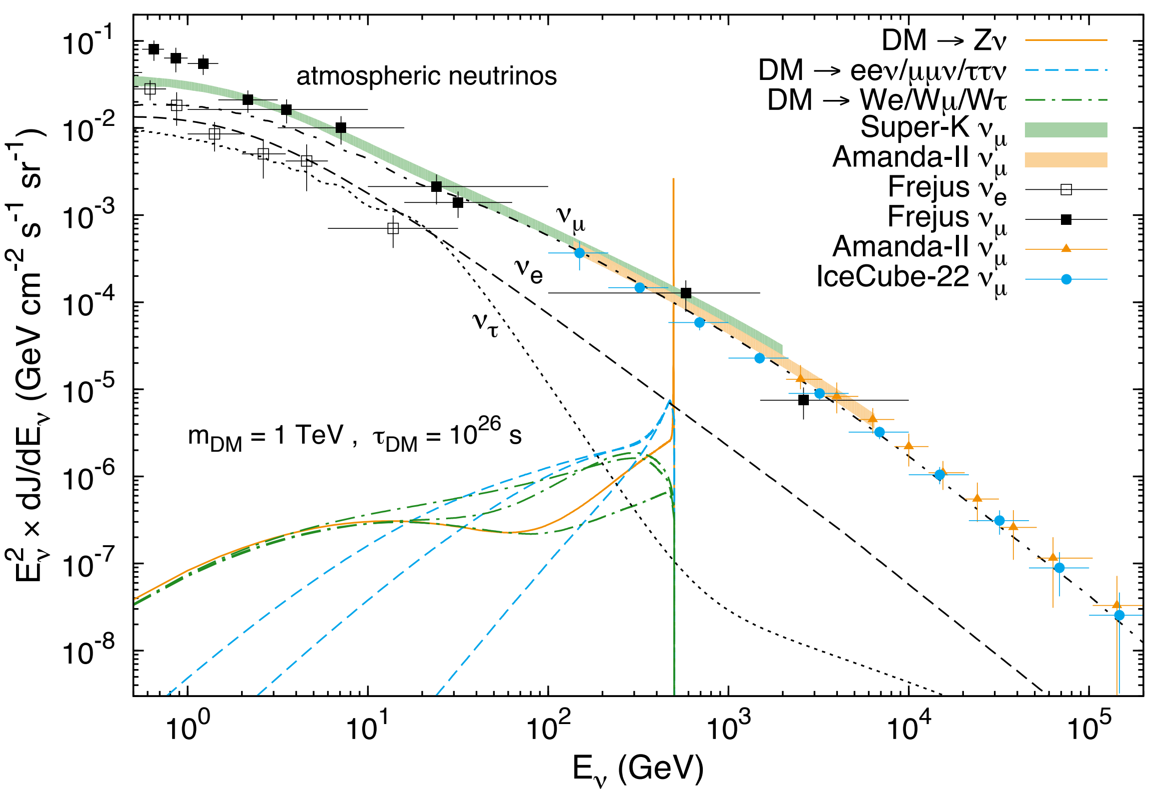
$$\rightarrow \quad \frac{dN}{dE} \propto E^{-1+\frac{\ln(1-P_{esc})}{\ln\alpha}} \sim E^{-1-\frac{P_{esc}}{\alpha-1}}$$

Observed spectrum goes like $E^{-2.7}$

Exotic particle decay

Depending on the final state, the decay of a non-relativistic particle can give different daughter particles spectra...

[LC, Grefe, Ibarra & Tran 09]



In general no power-law, but "bump-like" spectrum, cut-off at the mother particle mass (at least before propagation !)

Basics: Propagation

Propagation

In general propagation of the cosmic rays from the source to the Earth can change their energy spectrum and if the particles are charged also their direction...

- Scatterings with the intergalactic/interstellar medium: they can change the energy spectrum of the particles
- Deflection due to magnetic fields and energy loss due to synchrotron emission

Neutral particles like photons and neutrinos are less affected, but still not completely safe...

The GZK Cut-off

[Greisen '66, Zatsepin & Kuzmin '66]

Since the universe is not completely empty, interactions that stop or slow down the CR may happen !
The particles with highest density are the CMB photons...

$$\gamma_{CMB} + p \to \Delta \to n + \pi^+, p + \pi^0$$

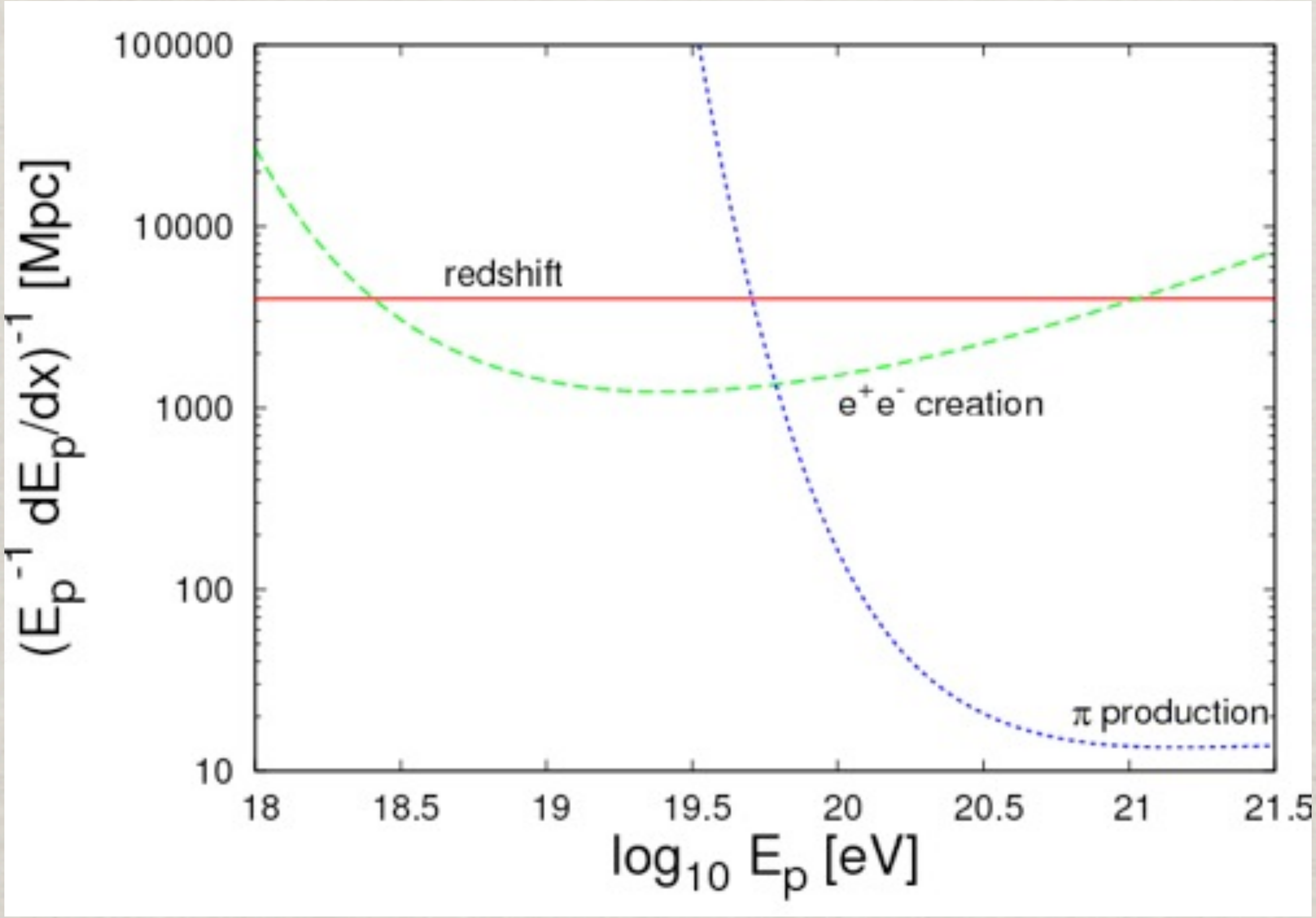
This process has a threshold, since sufficient energy should be present to produce a pion of mass

$$E_p \geq \frac{m_\pi^2}{4E_\gamma} \sim 3 \times 10^{20} eV$$

If allowed, the scattering causes an energy loss of about 20% and cuts off the energy spectrum of protons above threshold.

The GZK Cut-off

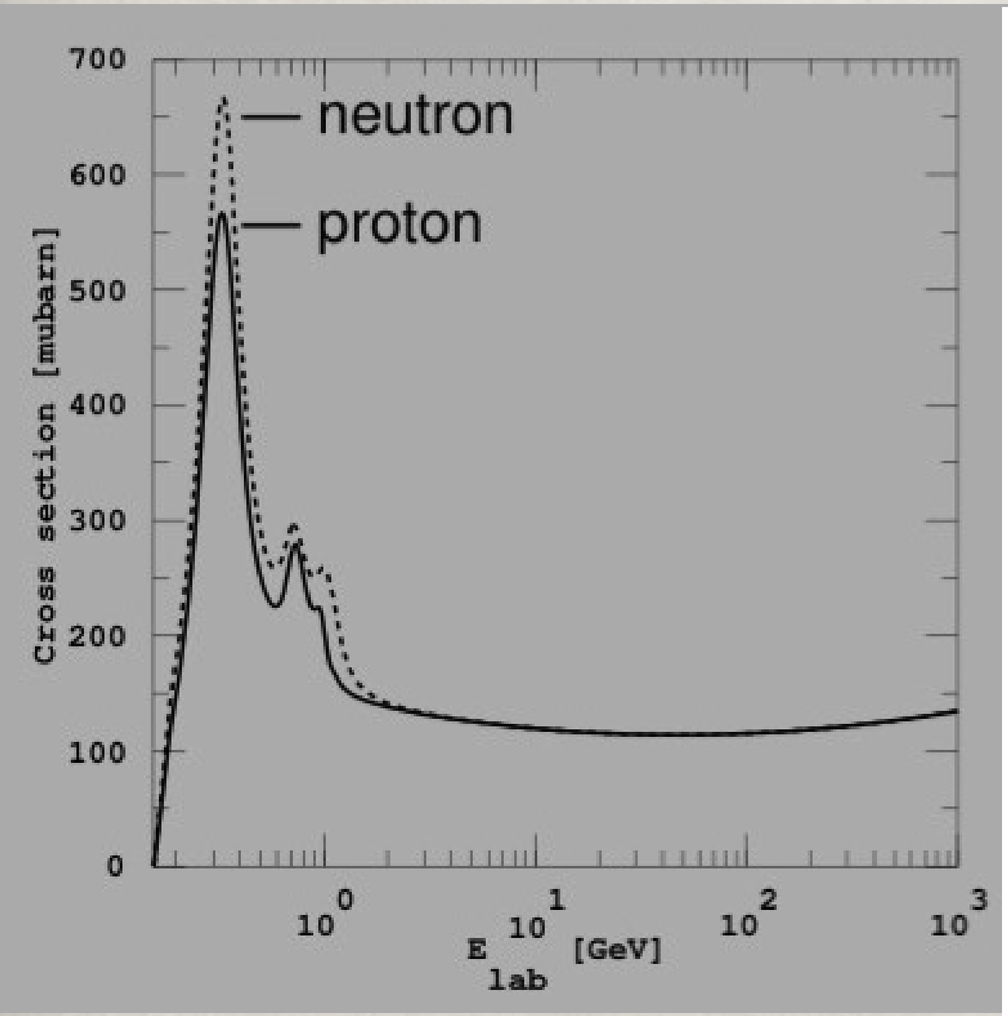
[Greisen '66, Zatsepin & Kuzmin '66]

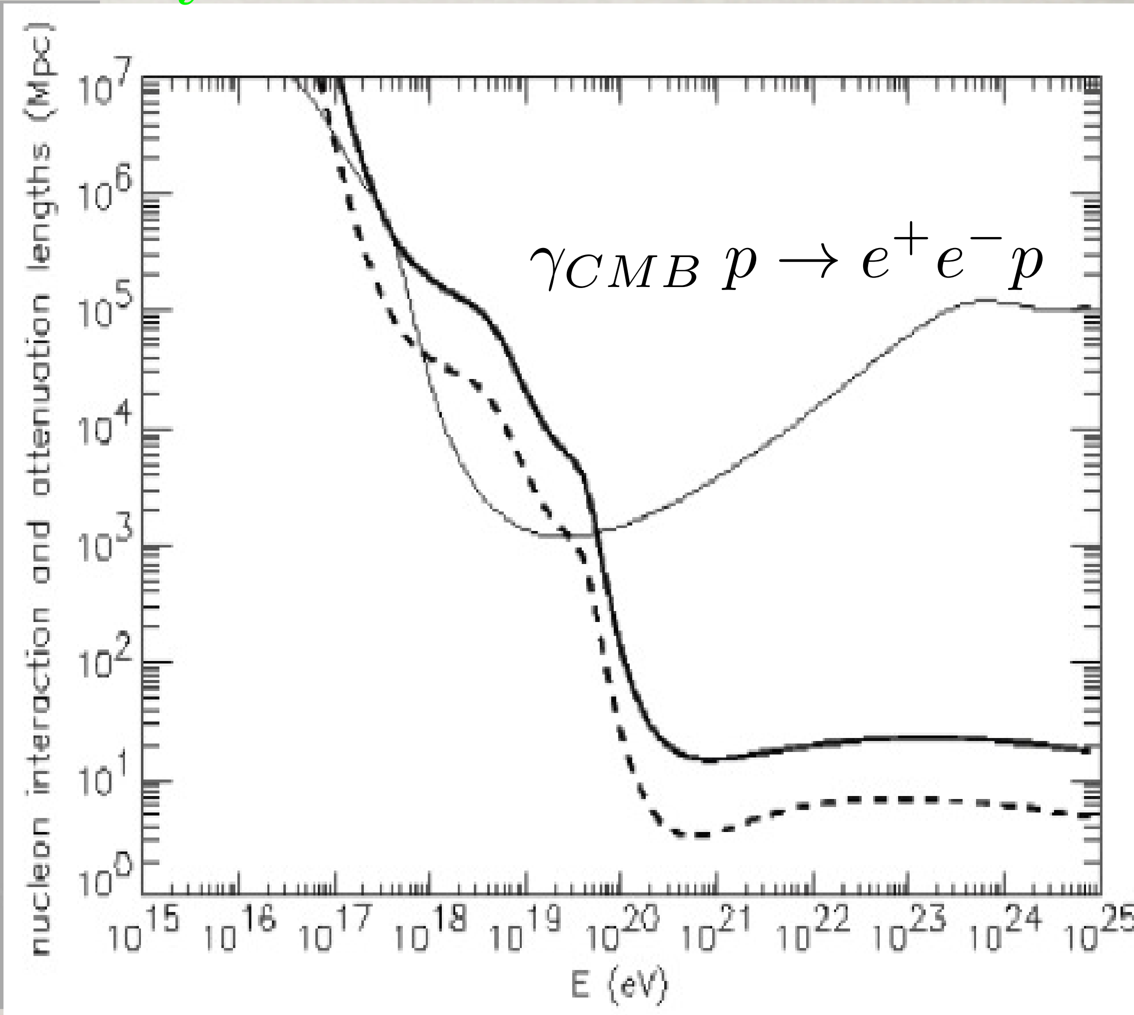


The GZK Cut-off

[Greisen '66, Zatsepin & Kuzmin '66]

P. Tinyakov, Odense Winter School 2012





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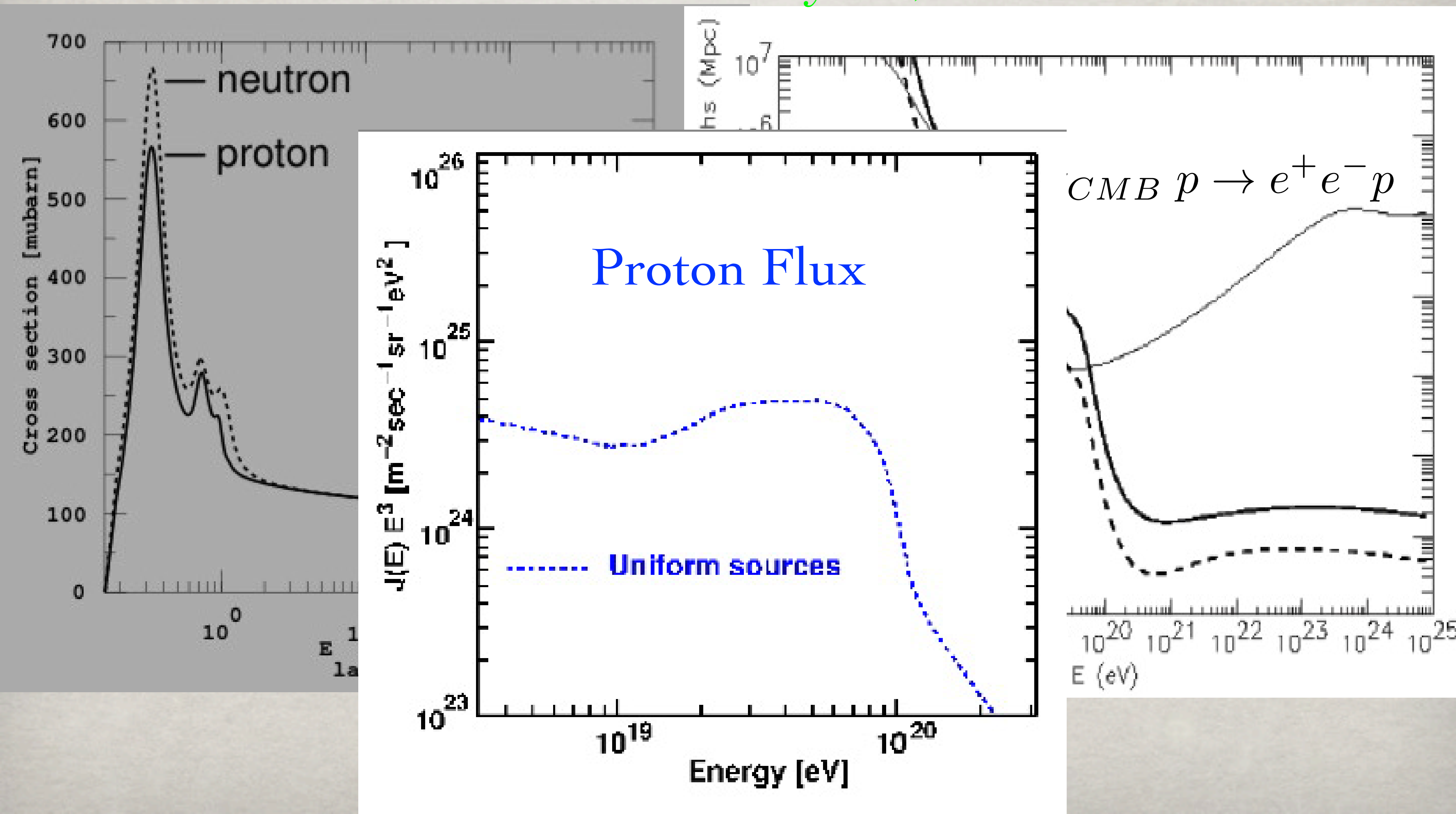


Magnetic fields

The deflection of a charged particle in a magnetic field is just given by the Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

In the relativistic limit we have for constant B field:

$$\theta \sim 0.52^o\, q \left(\frac{E}{10^{20} eV}\right)^{-1} \left(\frac{R}{1kpc}\right) \left(\frac{B_\perp}{10^{-6} G}\right)$$

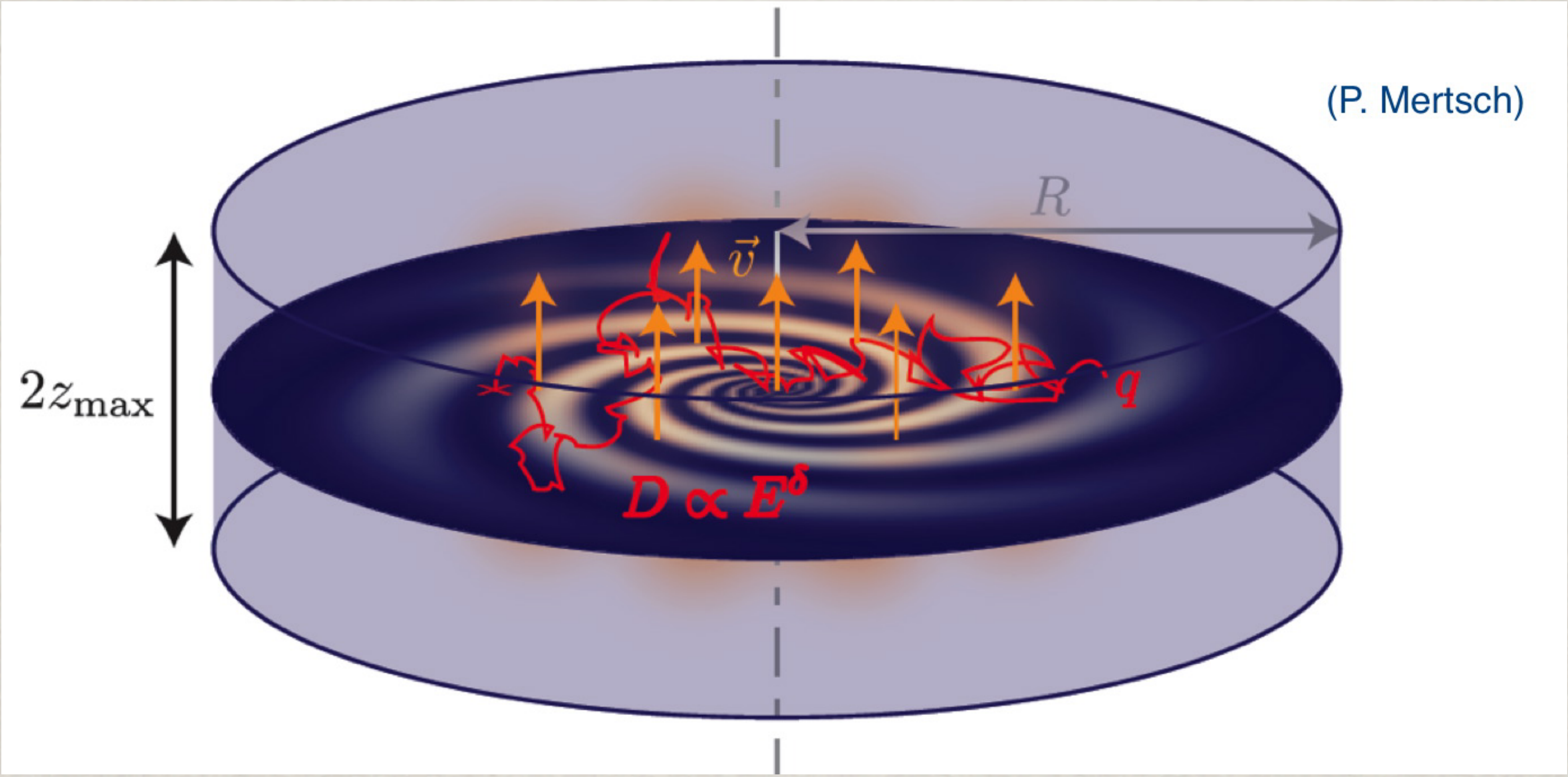
For random B field coherent over a distance ℓ_c:

$$\theta \sim 1.8^o\, q \left(\frac{E}{10^{20} eV}\right)^{-1} \left(\frac{\ell_c R}{50 Mpc^2}\right)^{1/2} \left(\frac{B_\perp}{10^{-9} G}\right)$$

Crucial to know the magnetic fields !!!

Propagation in our galaxy

Charged particles travel in the galaxy along complex paths:



To obtain the spectrum need to solve a complicated diffusion equation including energy losses, spallation, convective winds and possibly sources...

Propagation in our galaxy

Diffusion equation for the charged particles:

$$\frac{\partial f}{\partial t} - K(E)\vec{\nabla}^2 f - \frac{\partial}{\partial E}(b(E)f) + \frac{\partial}{\partial z}(v_c f) = Q_s - 2h\delta(z)\Gamma_{spall} f$$

Diffusion — Energy loss — Convective Wind — Source — Spallation

The equation is not easy to solve... Usually try to obtain the steady state solution for different species at the same time to compare with the data !

Usually the solution for secondaries (no source !) is a (negative) power-law.

Basics: detection

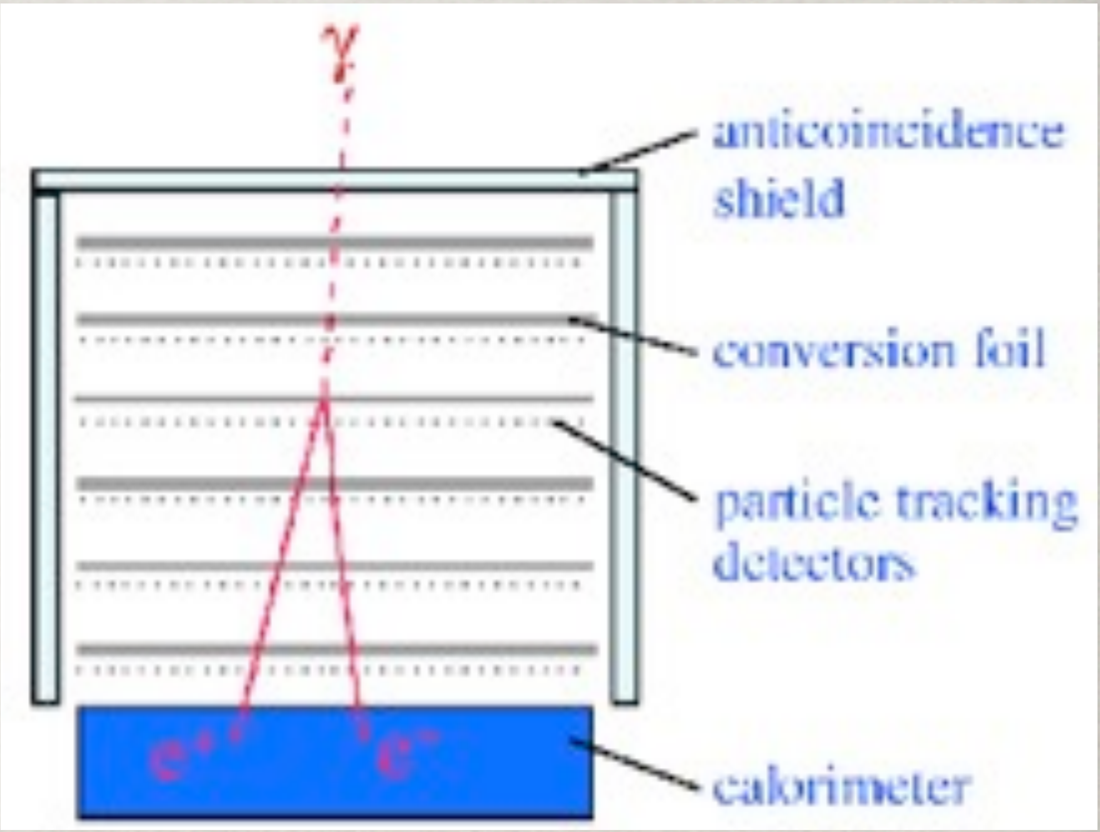
How to detect Cosmic rays

The basic ideas for cosmic rays detectors are the same as any particle physics detector: → Detector lectures by I. Wingerter

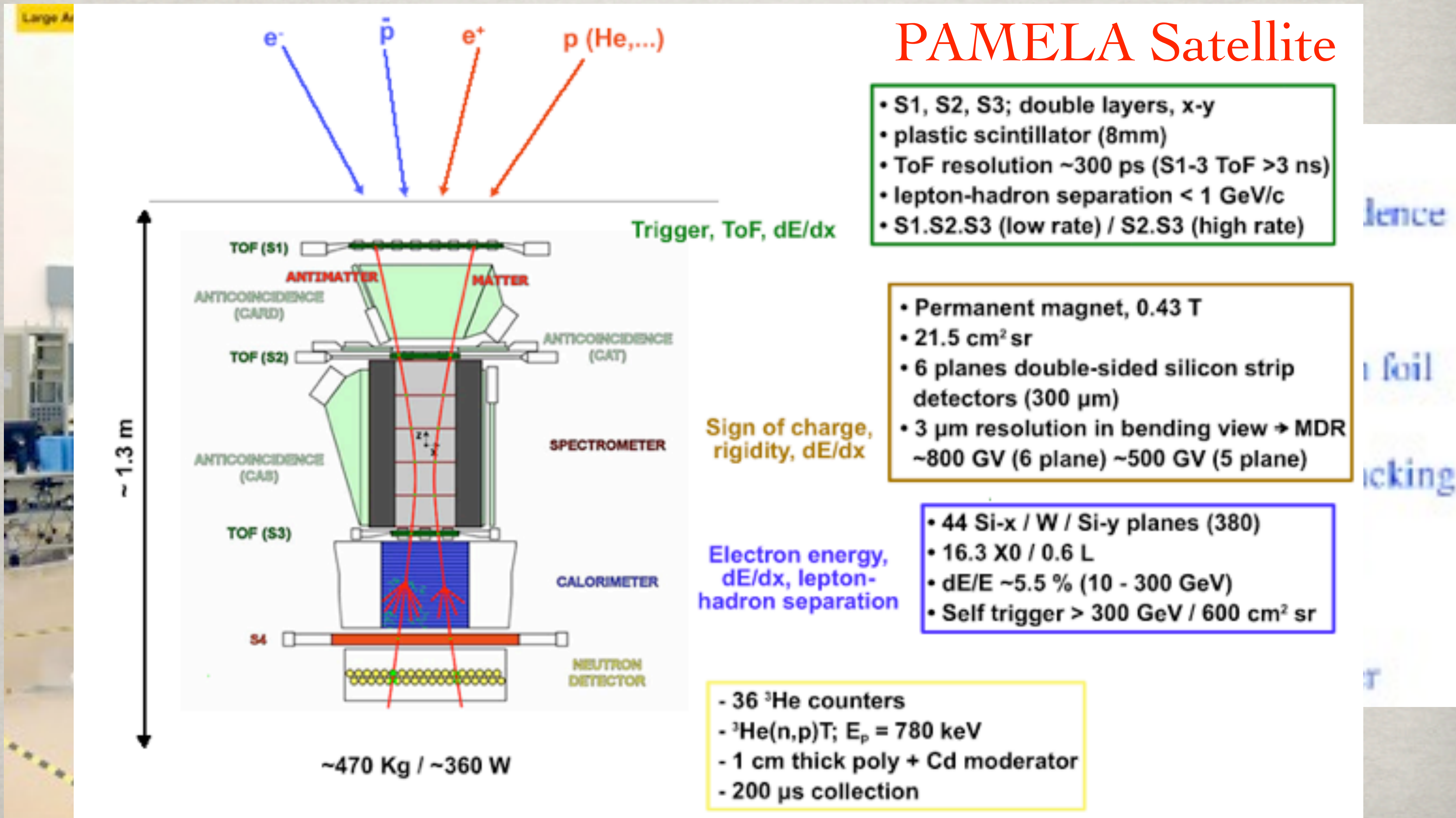
- Charged Particles: To reconstruct charge/mass by spectrometry need a magnetic field !
- Charged Particles: since they are highly relativistic, one can exploit Cherenkov light !
- Neutral Particles (gamma-rays and neutrinos): turn them into charged ones and measure those...
- Neutral Particles (DM): look for energy deposited by elastic scattering with matter.

PARTICLE DETECTORS IN SPACE !

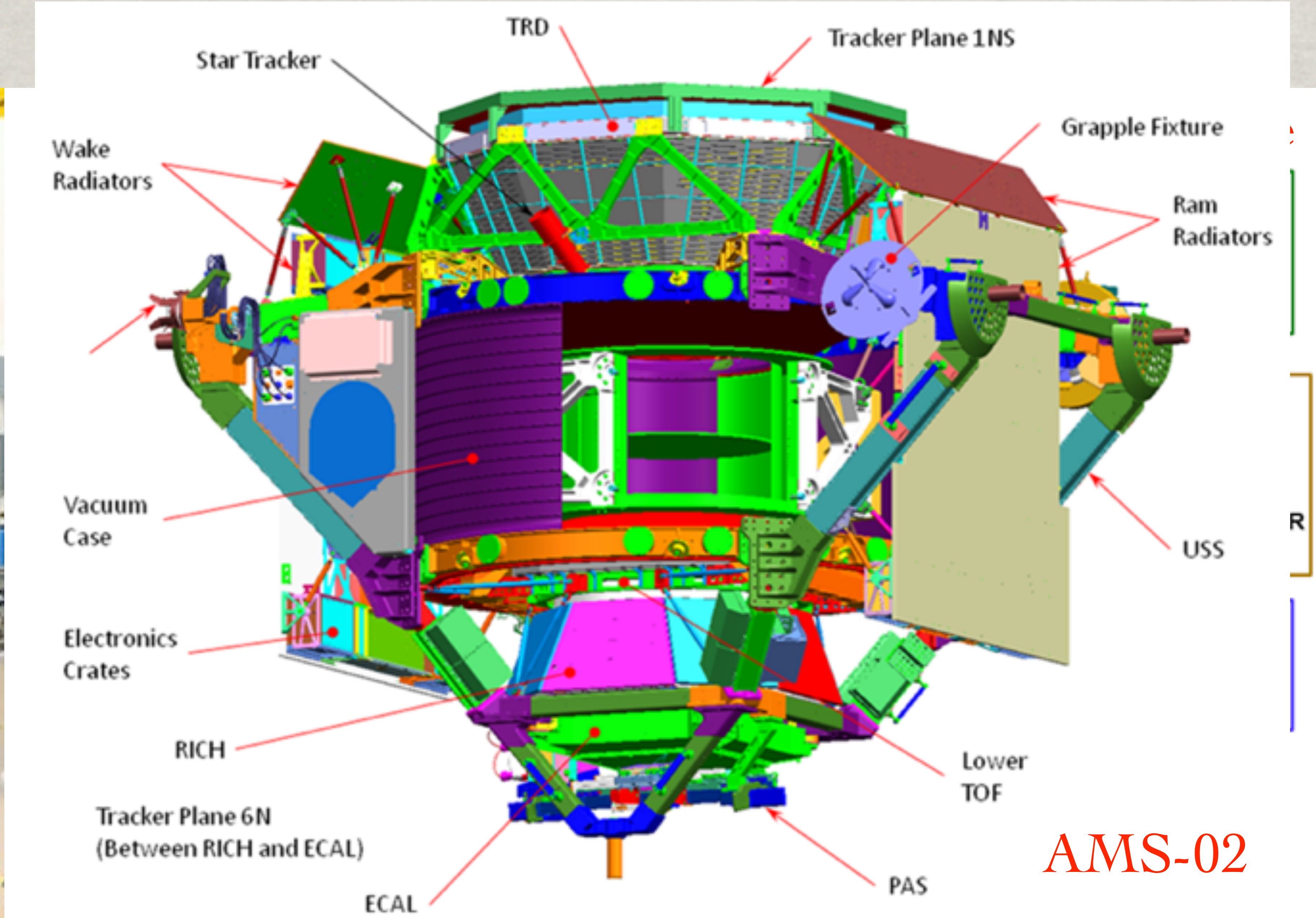
FERMI-LAT



PARTICLE DETECTORS IN SPACE !

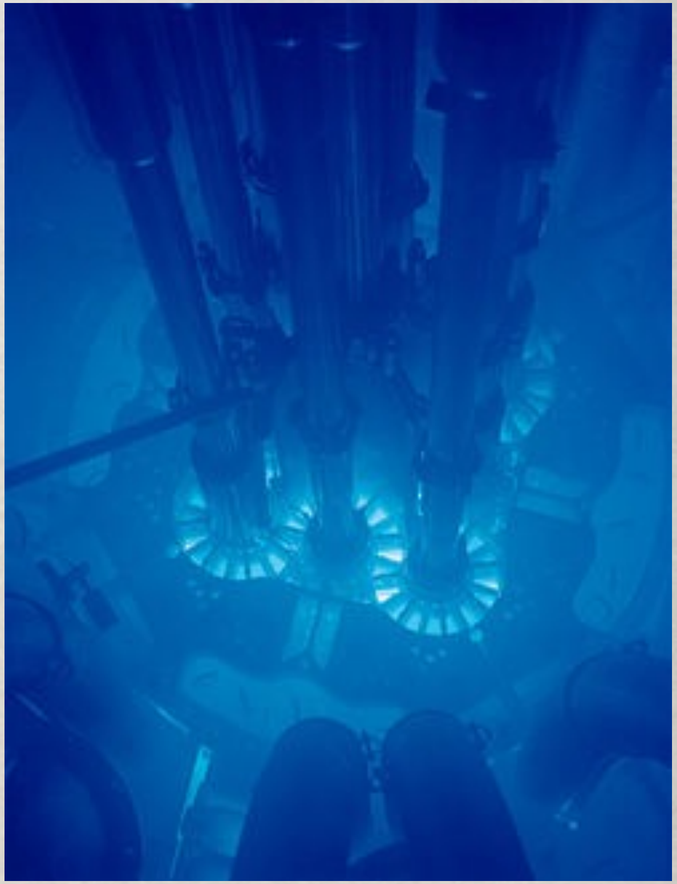


PARTICLE DETECTORS IN SPACE !



Cherenkov radiation I

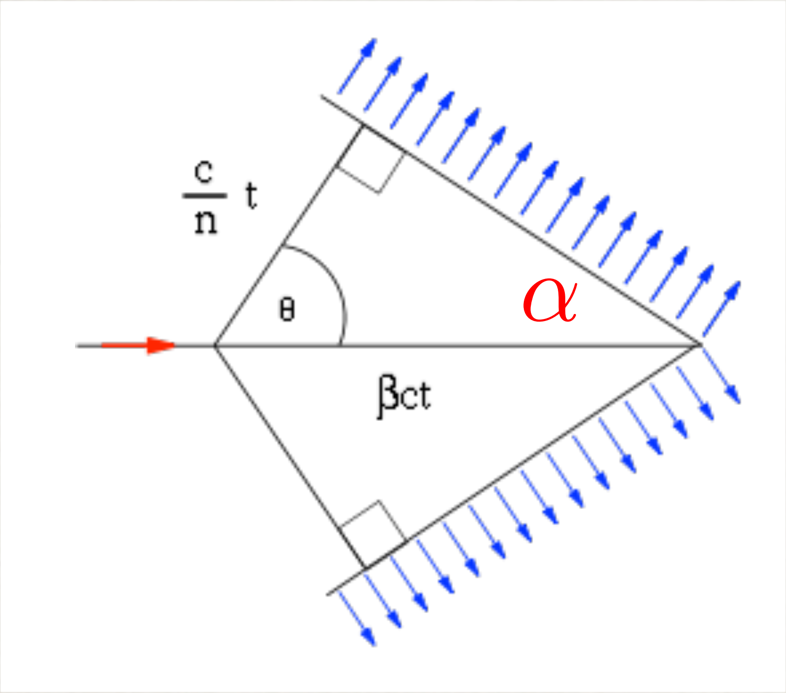
Blue light first observed by P. Cherenkov in liquids under radiation in 1934. I can be seen also as glow around nuclear reactors as shown here...



I. Frank and I. Tamm explained the phenomenon already in 1937:
the effect is analogous to the sonic boom of an aircraft travelling faster than the sound speed, only for electromagnetic waves instead of sound waves !

Every particle travelling in a dielectric with velocity larger than the speed of light produces Cherenkov light from the medium ionization

Cherenkov radiation II



Cherenkov radiation is emitted with a wavefront forming an angle $\alpha = 90^o - \theta$ with the direction of motion of the particle where

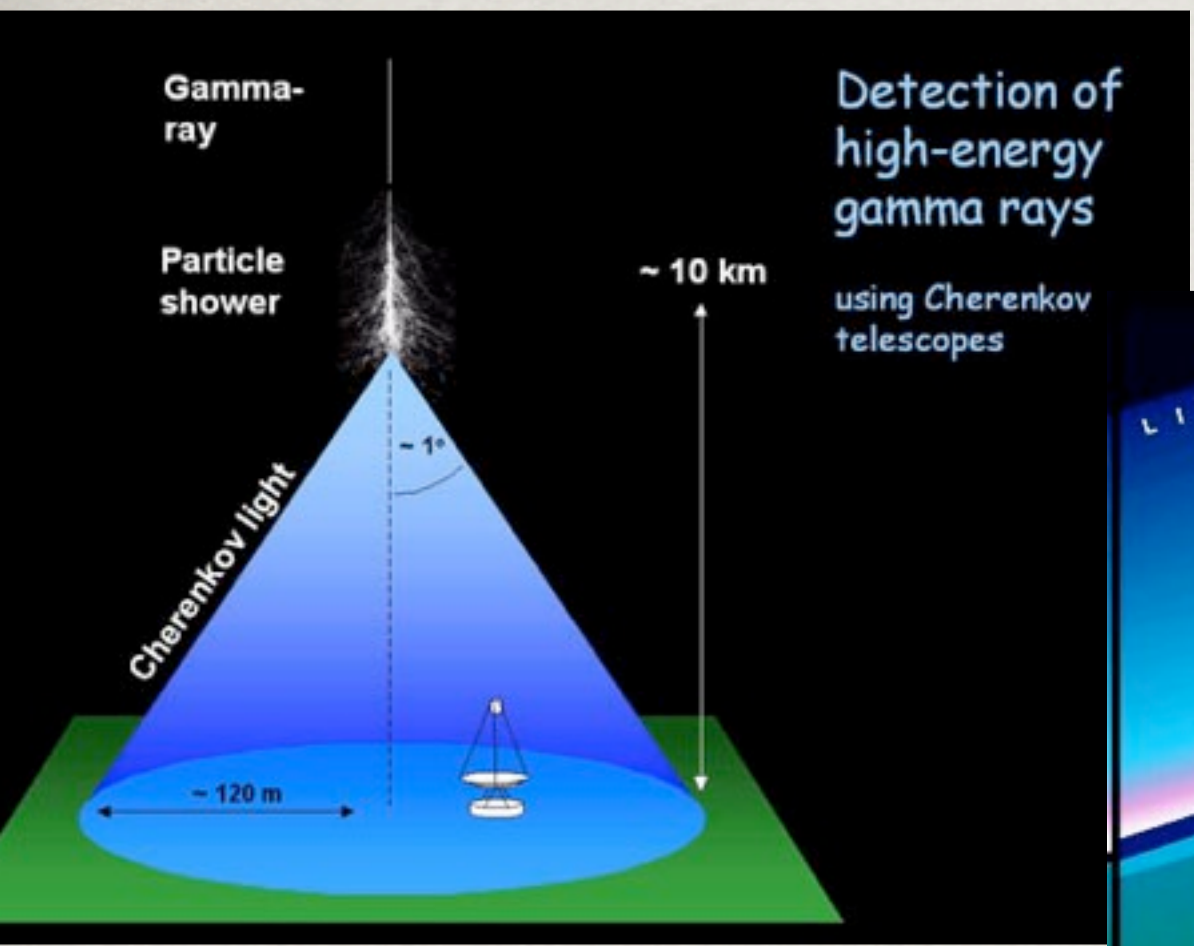
$$\cos\theta = \frac{1}{\beta n}$$

Different angles depending on *n*, i.e. the medium:

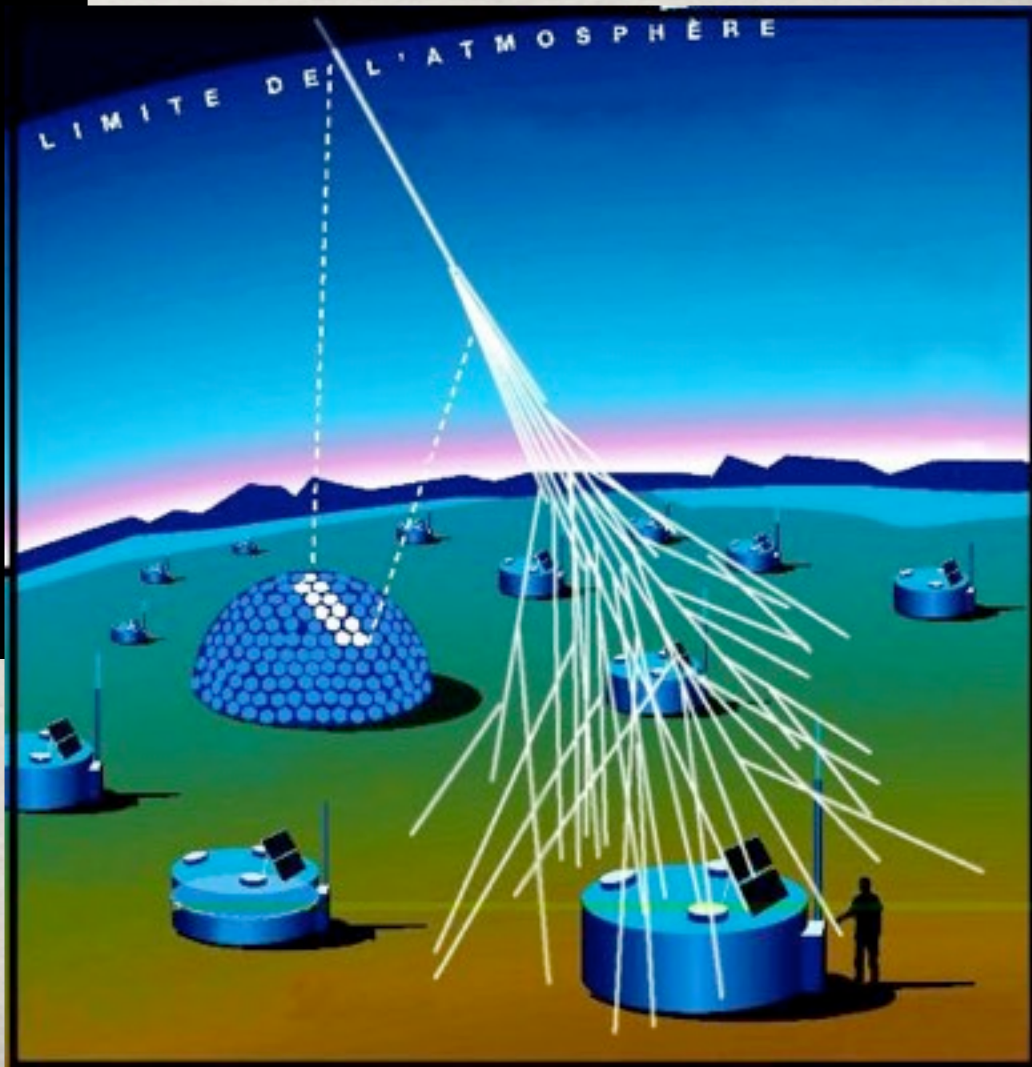
Air: $n \sim 1,0003$ $\alpha \sim 1^o$

Water: $n \sim 1,33$ $\alpha \sim 42^o$

Cherenkov detectors



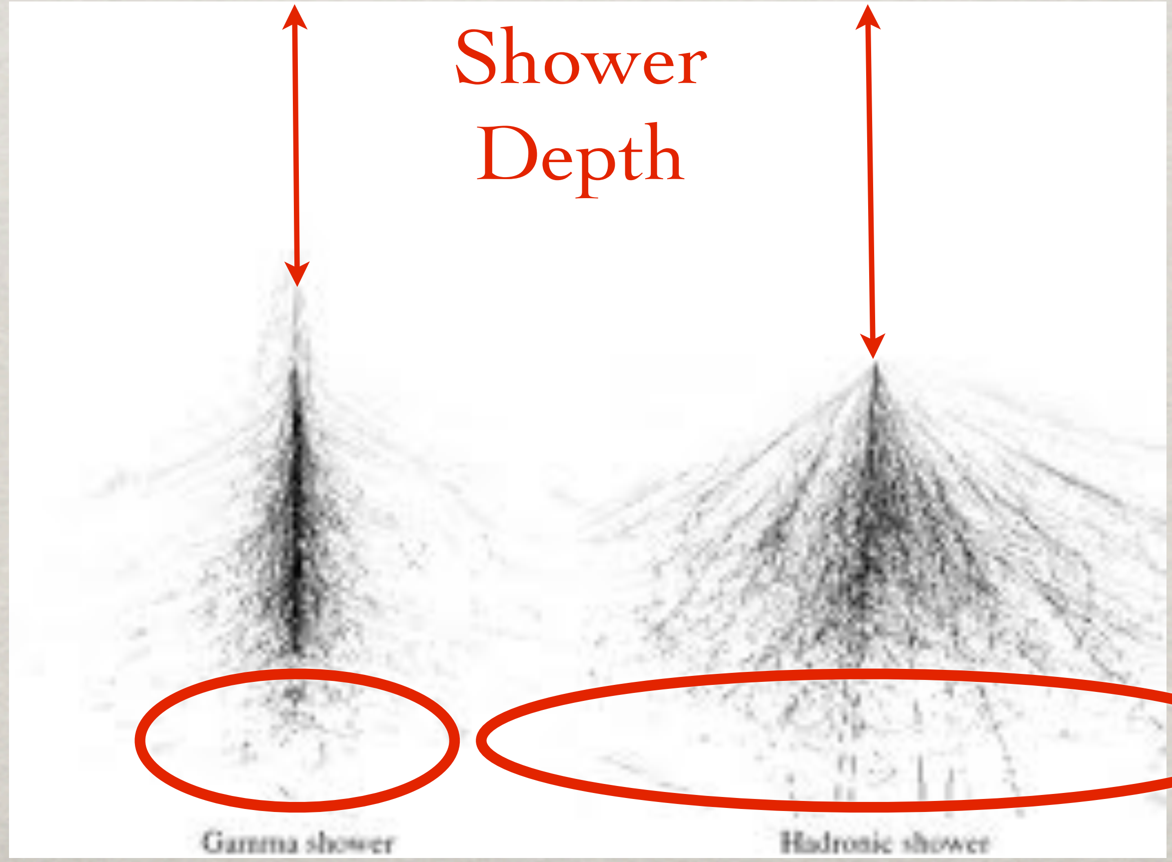
The atmosphere as a calorimeter !



Extended air showers (EAS) produce Cherenkov light in air or water...

Cherenkov detectors

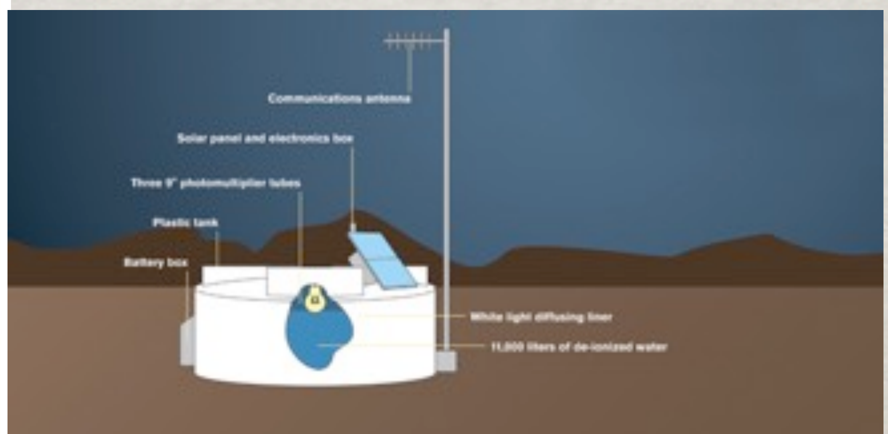
At high enough energy practically ANY (SM) particle produces a shower in the atmosphere.
How to distinguish between them ?
Through the Shape and Depth of the shower !



Spread of EAS

DETECTORS ON EARTH !

Cherenkhov Telescopes

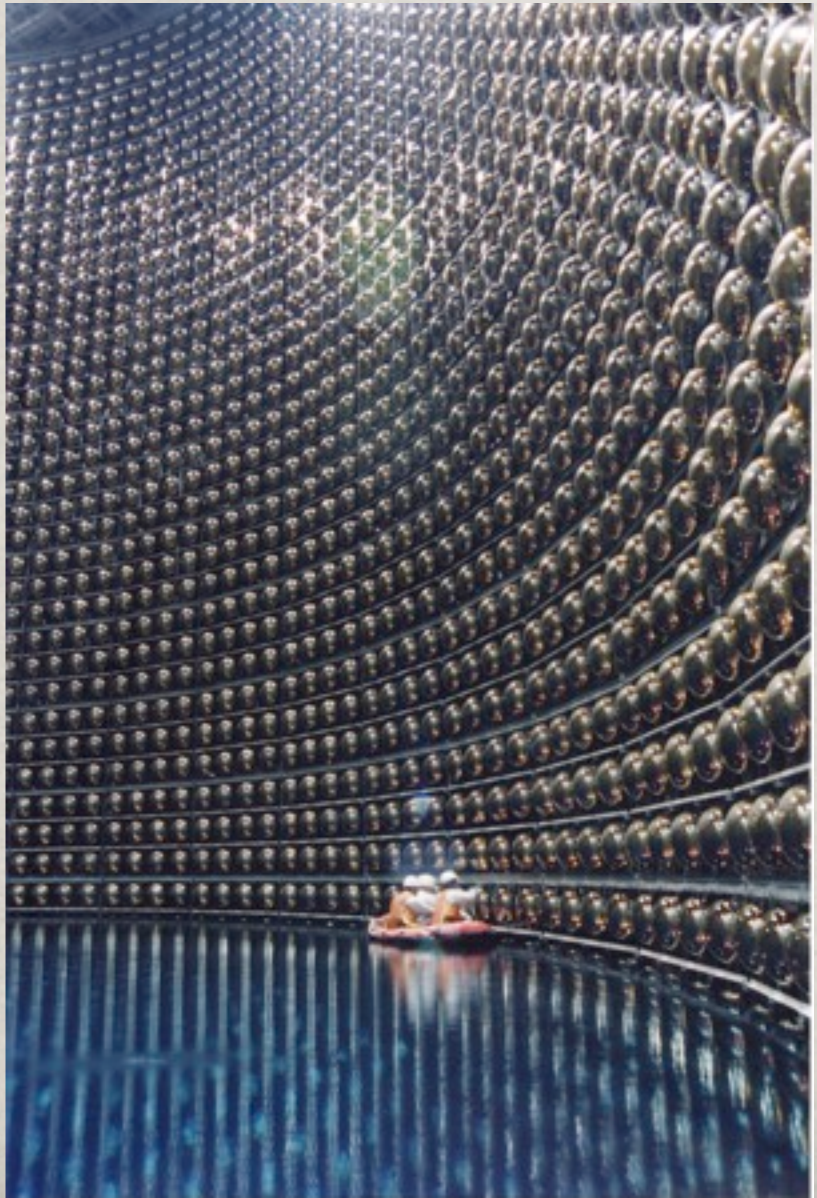


Cosmic rays Observatory

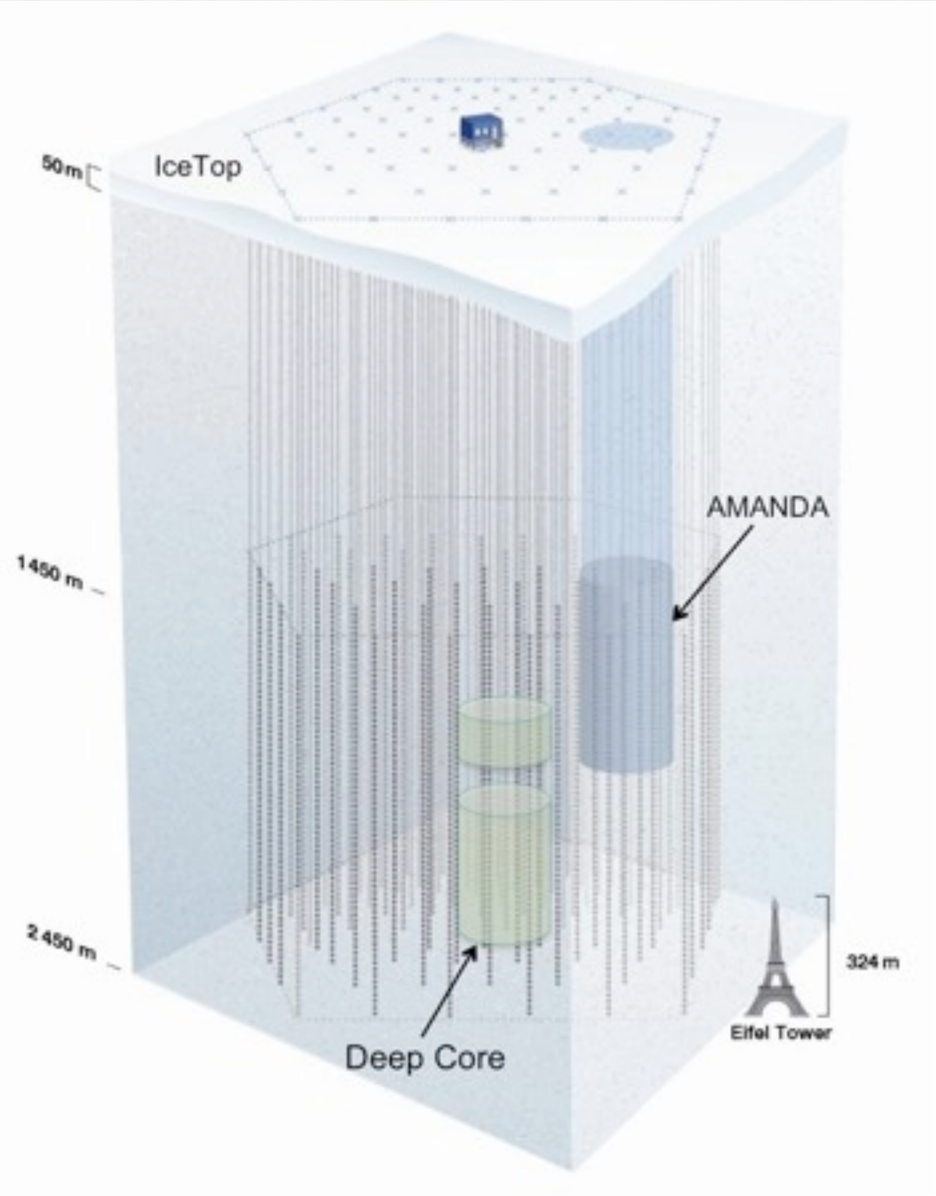
http://www.auger.org

DETECTORS UNDERGROUND !

SuperKamiokande



Icecube



Dark Matter