Multimessenger astroparticle physics

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Lectures 4-5

How to detect high-energy photons (and, shortly, other kinds of cosmic rays).

Detecting particles

- Particle detectors measure physical quantities related to the outcome of a collision; they should ideally identify all the outcoming (and the incoming, if unknown) particles, and measure their kinematical characteristics (momentum, energy, velocity).
- In order to detect a particle, one must make use of its interaction with a sensitive material. The interaction should possibly not destroy the particle one wants to detect; however, for some particles this is the only way to obtain information about them.
- In order to study the properties of detectors, we shall first need to review the characteristics of the interaction of particles with matter.

Some reminders of particle physics…

Cross-section = σ (normally given per particle, or per atom, in a reaction)

Frequently used unit: 1 barn = 10^{-24} cm^2 (surface of a large atom; π (0.5 fm)^2 ~ few mb)

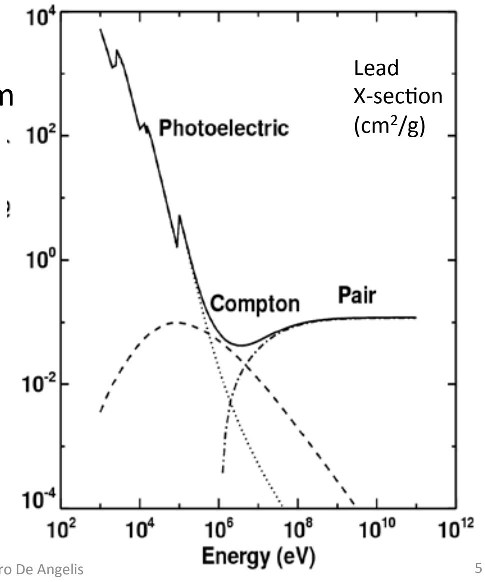
Attenuation length or "mean free path" $\lambda = 1/n\sigma$, where n is the number density of atoms

- Attenuation of a beam $I = I_0 \exp(-x/\lambda)$
- For materials, we often use the attenuation coefficient, μ, which is the cross section per mass (cm^2/g) (this is what you usually find in the PDG)
- Then attenuation length $\lambda = 1/n\sigma = 1/\mu\rho$, where ρ is density of the material

PARTICLE INTERACTIONS WITH MATTER

Interactions of photons with matter above the keV

- Photoelectric absorption
  - Photon is absorbed by atom
  - Electron is excited or ejected
- Compton scattering
  - Photon scatters off an electron
- Pair production
  - Photon interacts in electric field of nucleus and produces an $e^+ e^-$ pair



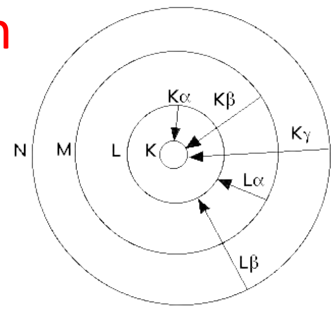
Photoelectric absorption

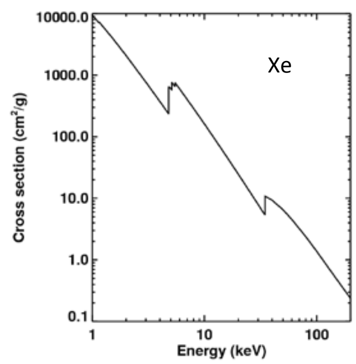
- Photons interact with matter by photoabsorption which causes excitation or ionization of atoms. Photons are absorbed.
- No simple analytic formula (guess why). "Edges" occur at the characteristic electronic transition energies. When in emission, elements produce characteristic lines at these energies

$$\sigma \propto \frac{Z^{\nu}}{E^3}$$

with ν = 4-5

- High-Z detectors are more efficient
- Above the highest edge, the cross-section scales roughly as E^{-3}. This means that photo-absorption rapidly becomes inefficient at high energies.



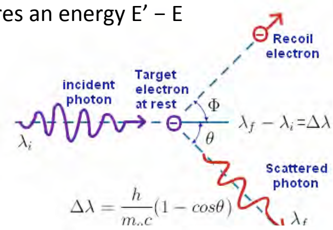


Compton scattering

- Is the scattering of a photon by an electron
- If the electron is initially free and at rest, after the collision, the photon is scattered at an angle θ and comes out with a reduced energy E' < E

$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

The electron acquires an energy E' – E

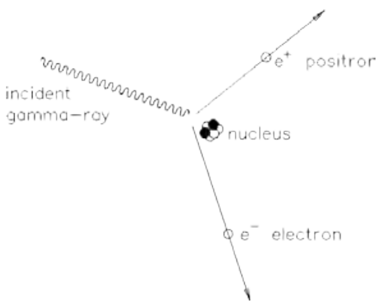


- Cross-section below $m_e c^2$ $\sigma_T \simeq \frac{8\pi\alpha^2}{3(m_e c^2)^2}(\hbar c)^2$ ~ 665 mb

  well above $m_e c^2$ $\sigma_{KN} \sim \sigma_T \frac{3}{8}\frac{m_e c^2}{E}\left[\ln\left(\frac{2E}{m_e c^2}\right) + \frac{1}{2}\right]$

- The scattering electron could also be moving: in this case, we might have E' > E ("inverse" Compton)

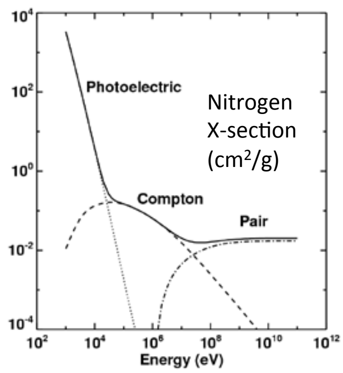
Pair Production: γ → e+e-



Nucleus is needed to conserve momentum and energy

$$\sigma_{Pair} \sim \frac{7}{9}\frac{1}{n_a X_0} \Rightarrow \lambda_{Pair} \sim \frac{9}{7} X_0$$

$$X_0 \sim \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \text{g cm}^{-2}$$



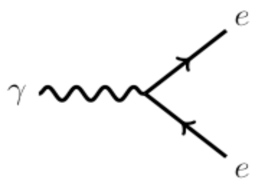
Active above 1MeV, it dominates from a few MeV to some 10^{20} eV

Cross section constant in this regime till 10 PeV, usually expressed in terms of the radiation length X_0- characteristic of the material

Above 10^{20} eV, the main interactions of the photon are strong interactions!

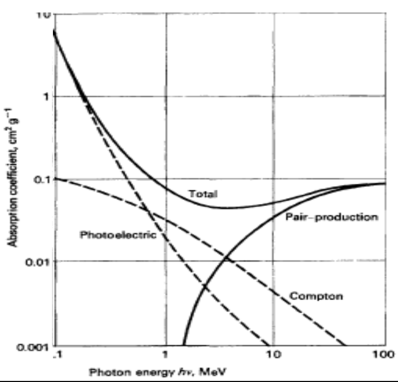
Pair Production - II

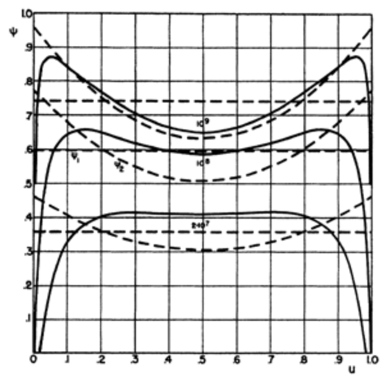
$\lambda = (9/7)\ X_0$ for $E_\gamma >> 2m_e$



Energy spectrum ~ flat

Angular opening $\sim m_e/E$





Charged particles: "Collision" energy loss

This is one of the most important sources of energy loss by charged particles. The average value of the specific (i.e., calculated per unit length) energy loss due to ionization and excitation whenever a particle goes through a homogeneous material of density ρ are described by the so-called Bethe formula[1]. This has an accuracy of a few % in the region $0.1 < \beta\gamma < 1000$ for materials with intermediate atomic number.

$$-\frac{dE}{dx} \simeq \rho D \left(\frac{Z}{A}\right) \frac{(z_p)^2}{\beta^2} \left[\frac{1}{2} \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right) - \beta^2 - \frac{\delta(\beta,\rho)}{2},\right] \quad (4.1)$$

where

- ρ is the material density, in g/cm^3;
- Z and A are the atomic and mass number of the material, respectively;
- z_p is the charge of the incoming particle, in units of the electron charge;
- $D \simeq 0.307$ MeV cm^2/g;
- $m_e c^2$ is the energy corresponding to the electron mass;
- I is the mean excitation energy in the material; it can be approximated as $I \simeq 16\text{eV} \times Z^{0.9}$ for $Z > 1$;

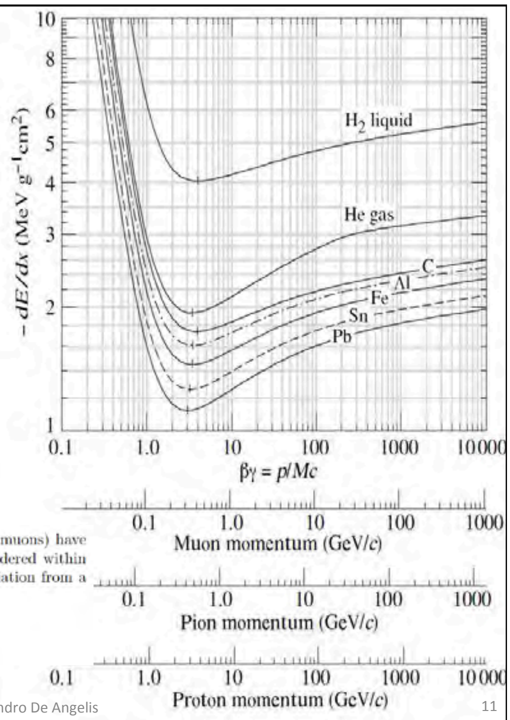
$$-\frac{dE}{dx} \simeq \rho D \left(\frac{Z}{A}\right) \frac{(z_p)^2}{\beta^2} \left[\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta(\beta, p)}{2},\right]$$

The energy loss by ionization (Figure 4.1) is thus in first approximation:

- independent of the mass of the particle;
- typically small for high energy particles (about 2 MeV/cm in water; one can roughly assume a proportionality to the density of the material);
- proportional to $1/\beta^2$ for $\beta\gamma \lesssim 3$ (the minimum of ionization: minimum ionizing particle, or mip);
- basically constant for $\beta > 0.96$ (logarithmic increase after the minimum);
- proportional to Z/A (Z/A being about equal to 0.5 for all elements but Hydrogen and the heaviest nuclei).

In practical cases, most relativistic particles (e.g., cosmic-ray muons) have mean energy loss rates close to the minimum; they can be considered within less than a factor of two as minimum-ionizing particles. The radiation from a mip is well approximated as

$$\frac{1}{\rho}\frac{dE}{dx} \simeq 3.5 \left(\frac{Z}{A}\right) \text{MeV cm}^2/\text{g}.$$

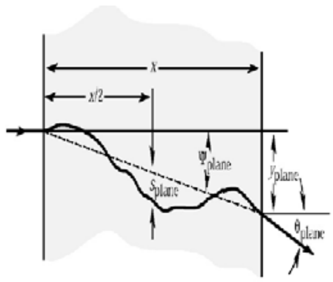


Multiple scattering

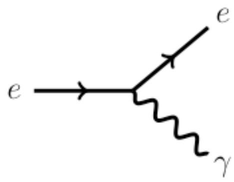
When a charged particle passes near a nucleus it undergoes a deflection which, in most cases, is accompanied by a negligible (approximately zero) loss of energy. This phenomenon, called elastic scattering, is caused by the same electric interaction between the passing particle and the Coulomb field of the nucleus. The global effect is that the path of the particle becomes a random walk (Figure 1.5), and information on the original direction is partly lost – this fact can create problems for the reconstruction of direction in tracking detectors. For very-high energy hadrons, also hadronic cross section can contribute to the effect.

Summing up many relatively small random changes of the direction of flight for a thin layer of traversed material, the distribution of the projected scattering angle of a particle of unit charge can be approximated by a Gaussian distribution of standard deviation (projected on a plane: one has to multiply by $\sqrt{2}$ to determine the variance in space):

$$\theta_0 = \frac{13.6\,\text{MeV}}{\beta c p} z_p \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \frac{x}{X_0}\right].$$



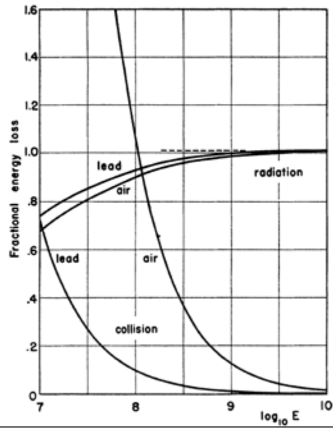
Electron bremsstrahlung and radiation length



- As pair production, forbidden in vacuo by 4-momentum conservation
  - Requires interaction with the medium
- Photons of momentum $q<E_e$ emitted with probability ~proportional to 1/q
  - (and collimated: ~ m_e/E)

  ie, energy emission is ~constant for each interval of photon energy; total is propto E
  - The dependence on the material appears through the radiation length Xo:

    $dE_e/dx = -1/Xo$
  - Xo can be found in tables. It is ~400 m for air at NTP, ~43 cm for water; for density 1 g/cm³
  - Collision energy loss is almost constant (plateau)



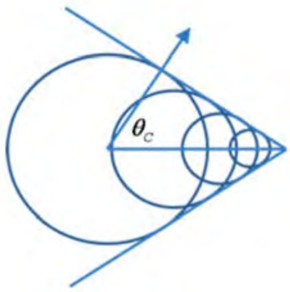
Cherenkov radiation (ß>1/n)

When ß>1/n in a medium, light is emitted in a coherent cone at an angle such that

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

from the direction of the emitting particle. The presence of a coherent wavefront can be easily derived by using the Huygens–Fresnel principle. The number of photons produced per unit path length and per unit energy interval of the photons by a particle with charge z_p at the maximum (limiting) angle is

$$\frac{d^2N}{d\lambda dx} \simeq \frac{2\pi\alpha z_p^2}{\lambda^2}\sin^2\theta_c$$



- The total energy radiated is small, some 10^{-4} times the energy lost by ionization. In the visible range (300–700 nm), the total number of emitted photons is about 40/m in air, about 500/cm in water.
- Due to the dependence on λ , it is important that Cherenkov detectors be sensitive close to the ultraviolet region. However, both n and the absorption probability of light can depend strongly on λ

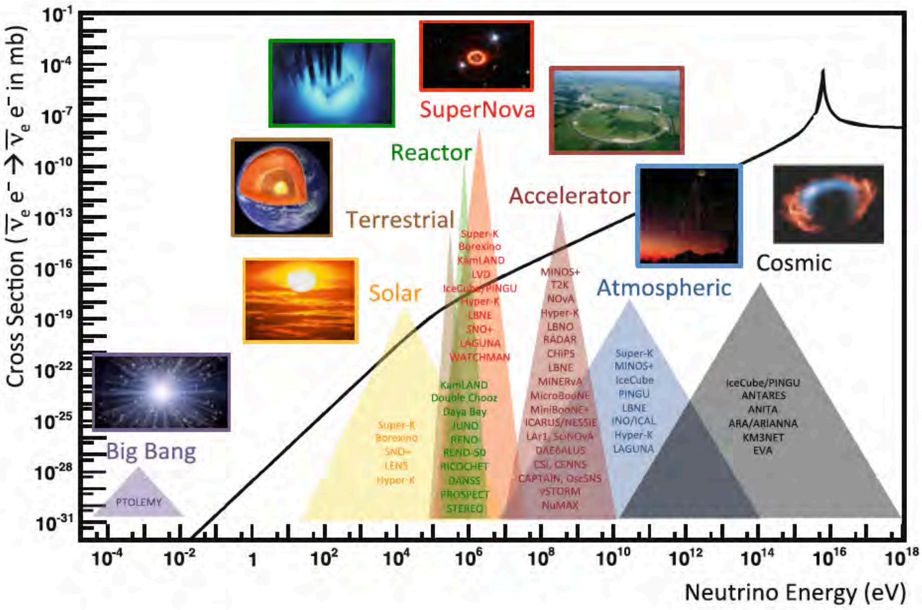
Hadronic interactions

- The nuclear or hadronic force is felt by hadrons, charged and neutral; at high energies (above a few GeV) the inelastic cross section for hadrons is dominated by nuclear interaction
  - Above some 100 EeV, the "hadronic" component of photons dominates their behavior, and this becomes also the most important interaction for photons
- High-energy nuclear interactions can be characterized by an inelastic interaction length λ_H . Values for $\rho\lambda_H$ are typically of the order of 100 g/cm^2 ; a listing for some common materials is provided in the PDG — where the inelastic length λ_I and the total length λ_T are separately listed, and the rule for the composition is

$$1/\lambda_T = 1/\lambda_H + 1/\lambda_I \ .$$

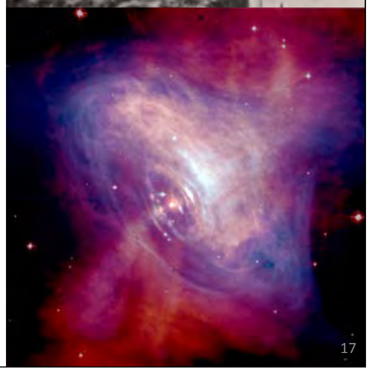
- The final state products of inelastic high-energy hadronic collisions are mostly pions, since these are the lightest hadrons. The rate of positive, negative, and neutral pions is more or less equal—as we shall see, this fact is due to an important approximate symmetry of hadronic interactions, called the isospin symmetry.

Just for fun, neutrino cross sections



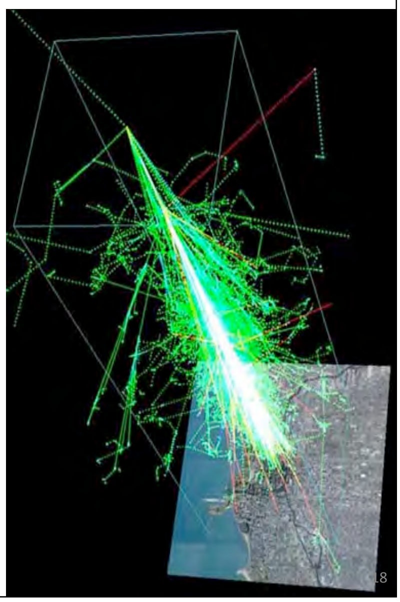
Bruno Rossi
(founder of the Dipartimento)

- Expelled from Italy in 1938 with a bad treatment, moved to US
- Toward the end of the 1950s, as accelerator experiments came to dominate particle physics, Bruno Rossi turned to space research
- At MIT he initiated a program of detector development and rocket experiments aimed astrophysics (but the excuse was the control of nuclear explosions above the atmosphere)
- To implement his ideas about X-ray astronomy, Rossi addressed the young Giacconi (Giacconi & Rossi (1960): “A ‘Telescope’ for Soft X-Ray Astronomy”) and they obtained support for rocket experiments from the Air Force. After two failures, the third satellite, launched in 1962, discovered a bright X-ray source.
- Giacconi won the Nobel prize in 2002 (Rossi died in 1993).



Multiplicative showers (Rossi 1934)

- Cascades of particles produced as the result of a primary high-energy particle interacting with matter
  - The incoming particle interacts, producing multiple new particles with lesser energy; each of these interacts in turn, a process that continues until many particles are produced. These are then stopped in the matter and absorbed
- 2 basic types of showers:
  - electromagnetic showers are produced by a particle that interacts via the electromagnetic force, a photon or electron
  - Hadronic showers are produced by hadrons, and proceed via the strong nuclear and the electromagnetic forces



Electromagnetic showers

- When a high-energy e or γ enters an absorber, it initiates an em cascade as pair production and bremsstrahlung generate more e and γ with lower energy
- The ionization loss becomes dominant < the critical energy E_c
  - E_c ~ 84 MeV in air, ~73 MeV in water; ~ (550/Z)MeV
    - Approximate scaling in $y = E/E_c$
  - The longitudinal development ~scales as the radiation length in the material: $t = x/Xo$
  - The transverse development scales approximately with the Moliere radius R_M ~ (21 MeV/E_c) Xo
    - In average, only 10% of energy outside a cylinder w/ radius R_M
    - In air, R_M ~ 80 m; in water R_M ~ 9 cm
- Electrons/positrons lose energy by ionization during the cascade process
- Not a simple sequence: needs Monte Carlo calculations

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A simplified approach (Heitler)

- If the initial electron has energy $E_0 >> E_C$, after t Xo the shower will contain 2^t particles. ~equal numbers of e+, e-, γ, each with an average energy

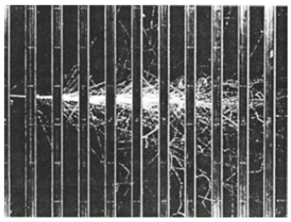
  $E(t) = E_0/2^t$

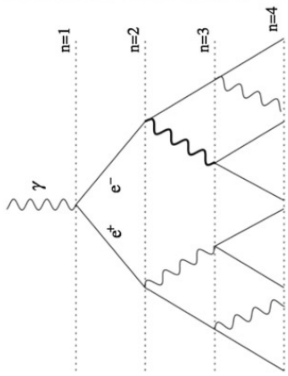
- The multiplication process will cease when $E(t)=E_C$

$$t_{max} = t(E_C) \equiv \frac{\ln(E_0/E_C)}{\ln 2},$$

and the number of particles at this point will be

$$N_{max} = \exp(t_{max} \ln 2) = E_0 / E_C$$





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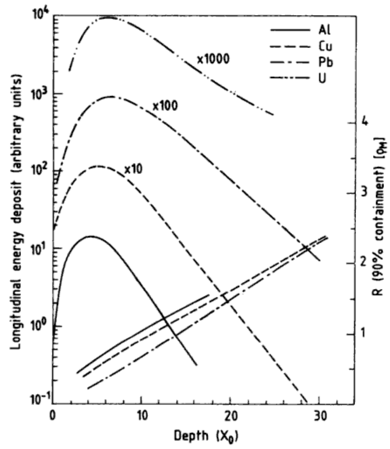
An analytic model: Rossi's "approximation B"

- Rossi in 1941 published an analytical formulation for the shower development as a set of 2 integro-differential equations under the approximation that:
  - Electrons lose energy by ionization & bremsstrahlung; asymptotic formulae hold
  - Photons undergo pair production only; asymptotic formulae hold ($E > 2 m_e$)
- Very good approximation until $E \sim E_c$



	Incident electron	Incident photons
Peak of shower, t_{max}	$1.0 \times (\ln y - 1)$	$1.0 \times (\ln y - 0.5)$
Centre of gravity, t_{med}	$t_{max} + 1.4$	$t_{max} + 1.7$
Number e^+ and e^- at peak	$0.3\, y \times (\ln y - 0.37)^{-1/2}$	$0.3\, y \times (\ln y - 0.31)^{-1/2}$
Total track length T	y	y

(Rossi-Greisen 1941, Rev. Mod. Phys. 13, 240)

$$\frac{\partial \pi(E,t)}{\partial t} = 2\int_0^1 \gamma\left(\frac{E}{u},t\right)\psi_0(u)\frac{du}{u} - \int_0^1\left[\pi(E,t) - \frac{1}{1-v}\pi\left(\frac{E}{1-v},t\right)\right]\varphi_0(v)dv + \epsilon\frac{\partial \pi(E,t)}{\partial E}.$$

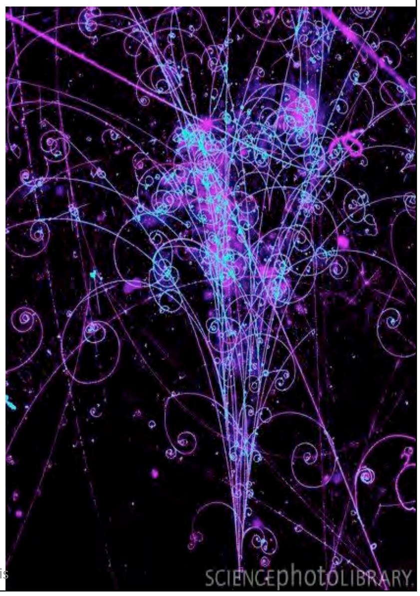
$$\frac{\partial \gamma(W,t)}{\partial t} = \int_0^1 \pi\left(\frac{W}{v},t\right)\varphi_0(v)\frac{dv}{v} - \sigma_0\gamma(W,t)$$

Energy measurement

- The calorimetric approach: absorb the shower
  - As much as possible… But the logarithmic behavior helps
  - Typically (20-30) Xo give an almost full containment up to hundreds of GeV
    - But sometimes it is difficult (calorimeters in space)
  - Errors asymptotically dominated by statistical fluctuations:

$$\frac{\sigma_E}{E} \cong \frac{k_E}{\sqrt{E}} \oplus c$$

k can be a few per cent for a compact calorimeter

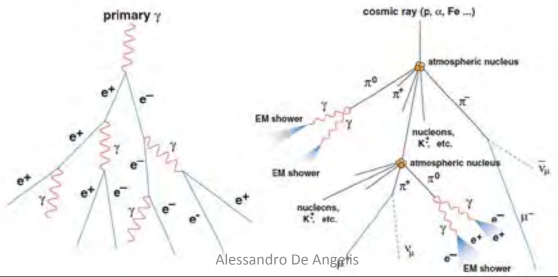


Hadronic showers and calorimeters

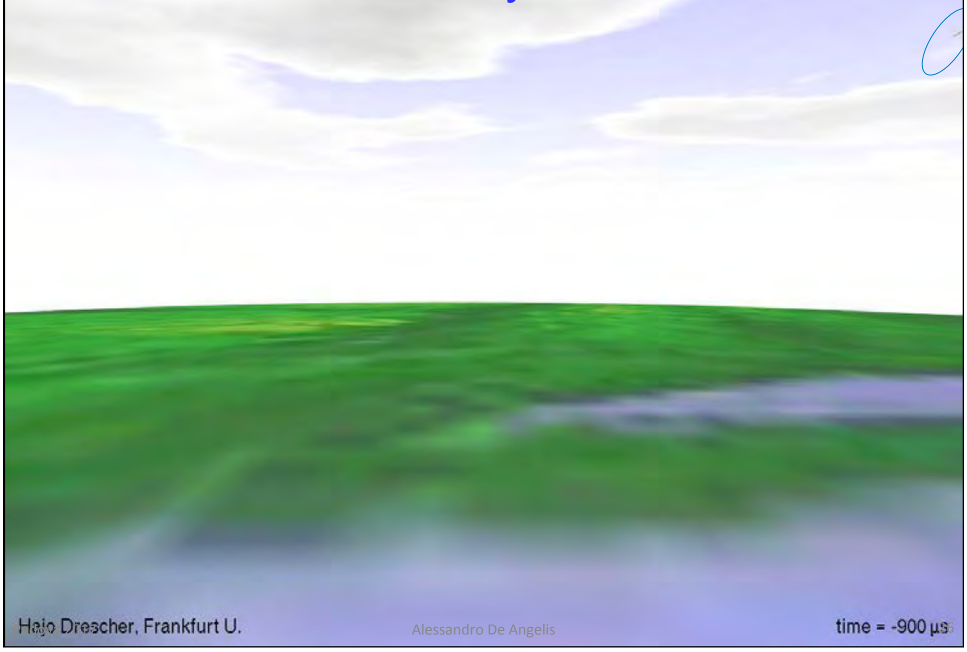
- Although hadronic showers are qualitatively similar to em, shower development is more complex because many different processes contribute
  - Larger fluctuations
- Some of the contributions to the total absorption may not give rise to an observable signal in the detector
  - Examples: nuclear excitation and leakage of secondary muons and neutrinos
- Depending on the proportion of π^0s produced in the early stages of the cascade, the shower may develop predominantly as an electromagnetic one because of the decay $\pi^0 \rightarrow \gamma\ \gamma$
- The scale of the shower is determined by the nuclear absorption length λ_H
  - Since typically λ_H > Xo, hadron calorimeters are thicker than em ones
- The energy resolution of calorimeters is in general much worse for hadrons than for electrons and photons
  - Energy resolution typically a factor of 5–10 poorer than in em calorimeters

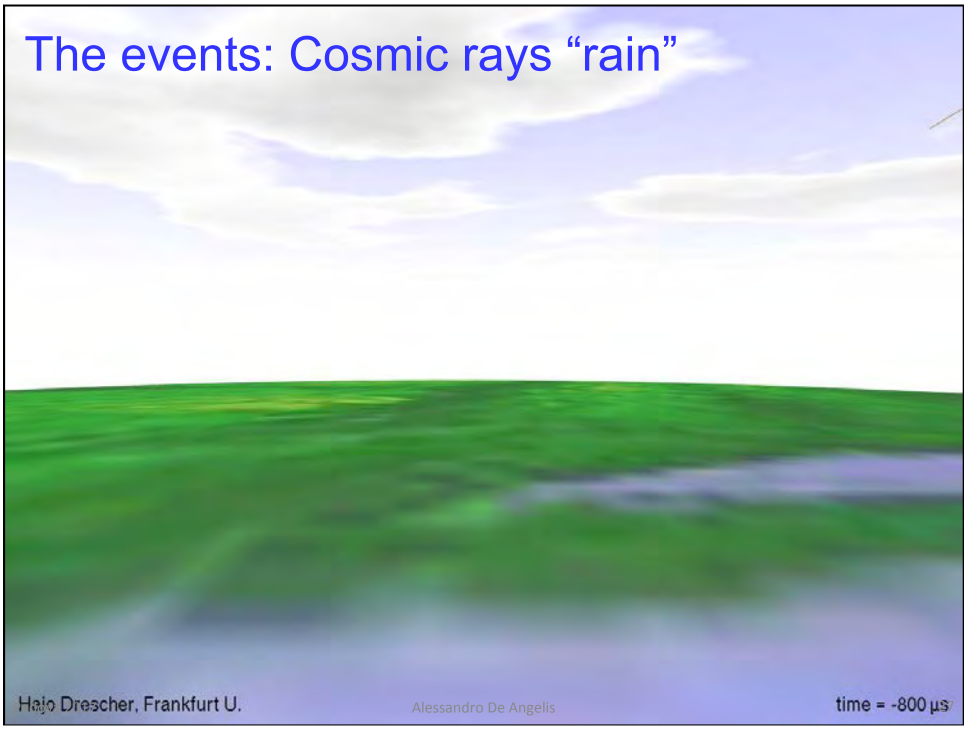
Extensive air showers (EAS)

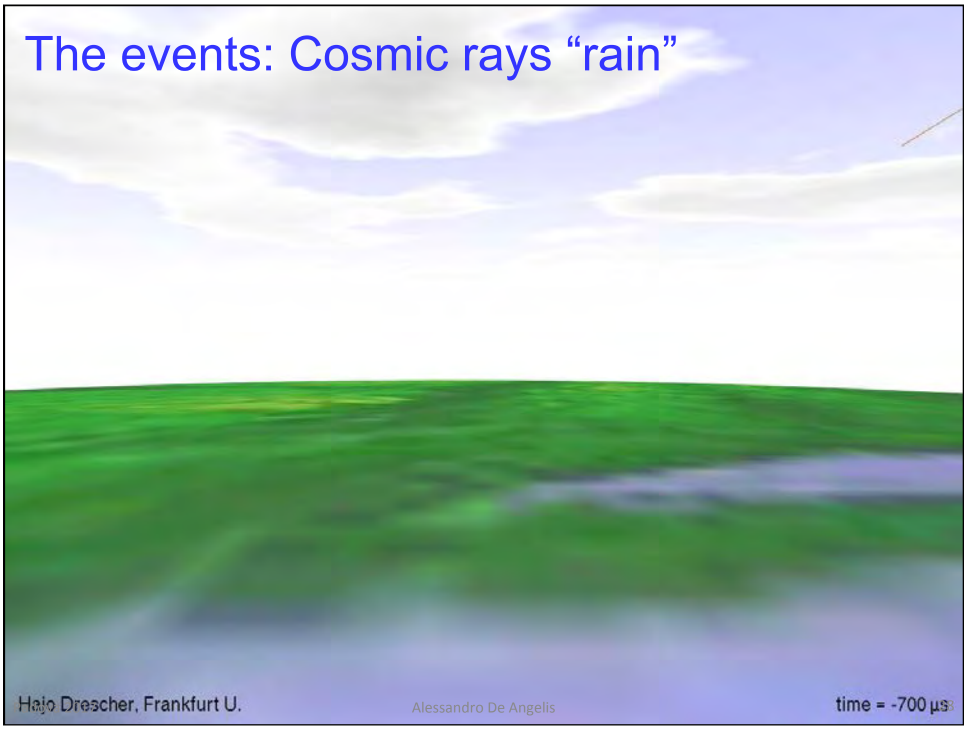
- Showers due to the interaction of HE particles with the atmosphere.
- High-energy hadrons, photons, and electrons interact in the high atmosphere. The process is conceptually similar.
- For photons and electrons above a few hundred MeV, the cascade process is dominated by the pair production and the bremsstrahlung mechanisms.
- The maximum shower size occurs approximately ln(E/Eo) radiation lengths, the radiation length for air being about 37 g/cm^2 (approximately 300m at sea level and NTP). The critical energy is about 80 MeV in air.
- The hadronic interaction length in air is about 61 g/cm^2 for protons (500 meters for air at NTP), being shorter for heavier nuclei—the dependence of the cross section on the mass number A is approximately $A^{2/3}$.
- The transverse profile of hadronic showers is in general wider than for electromagnetic showers, and fluctuations are larger.
- Particles release energy in the atmosphere, which acts like a calorimeter, through different mechanisms—which give rise to a measurable signal.

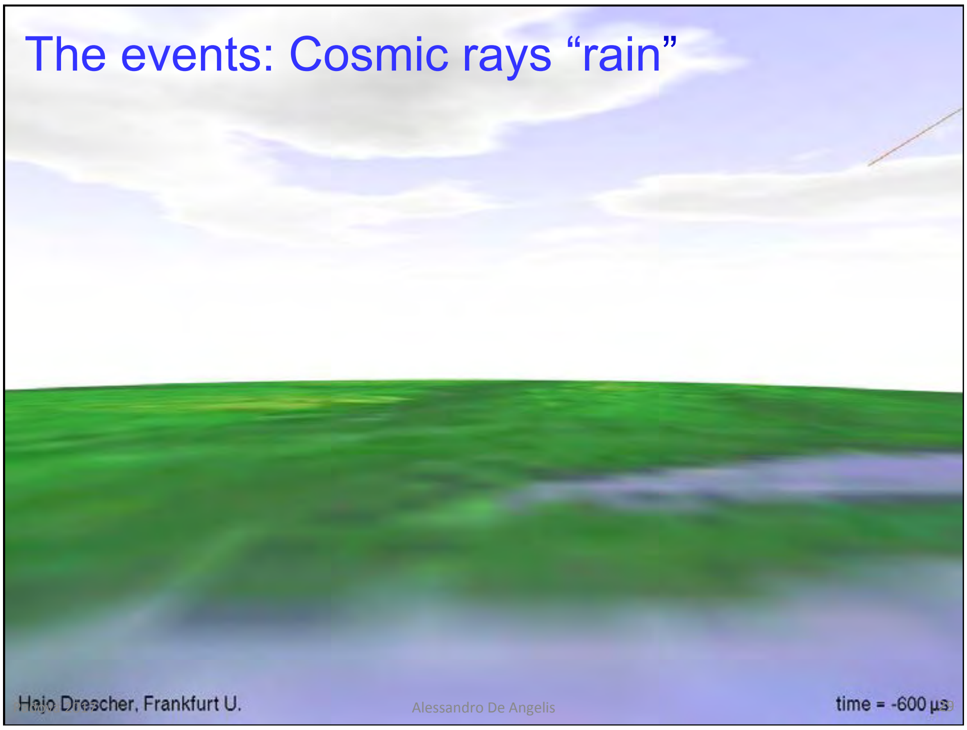


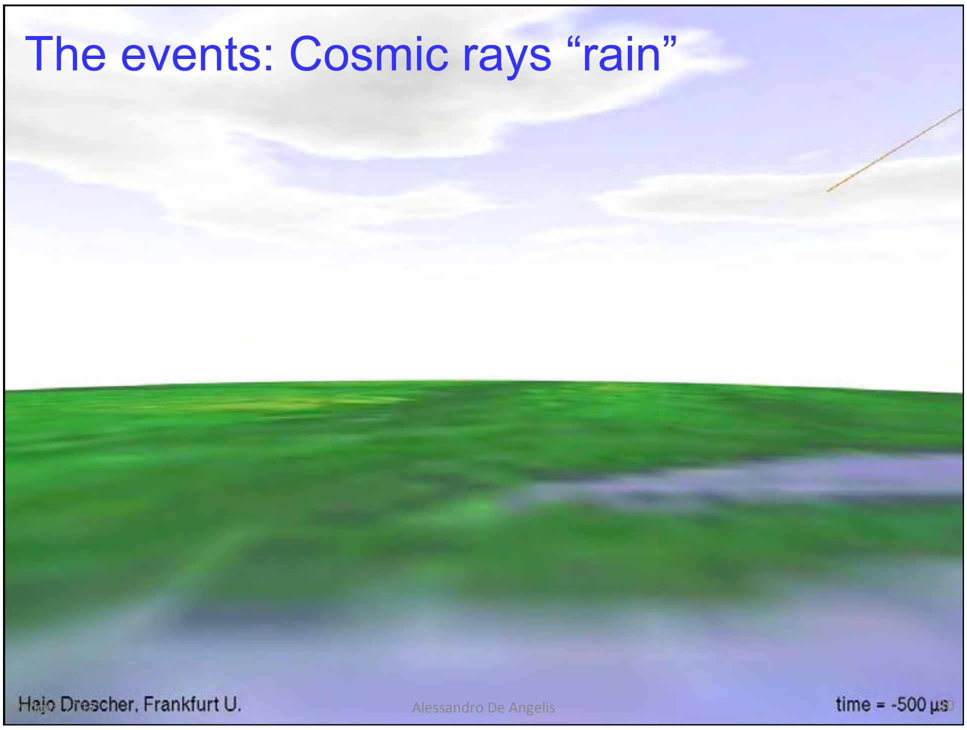
The events: Cosmic rays "rain"

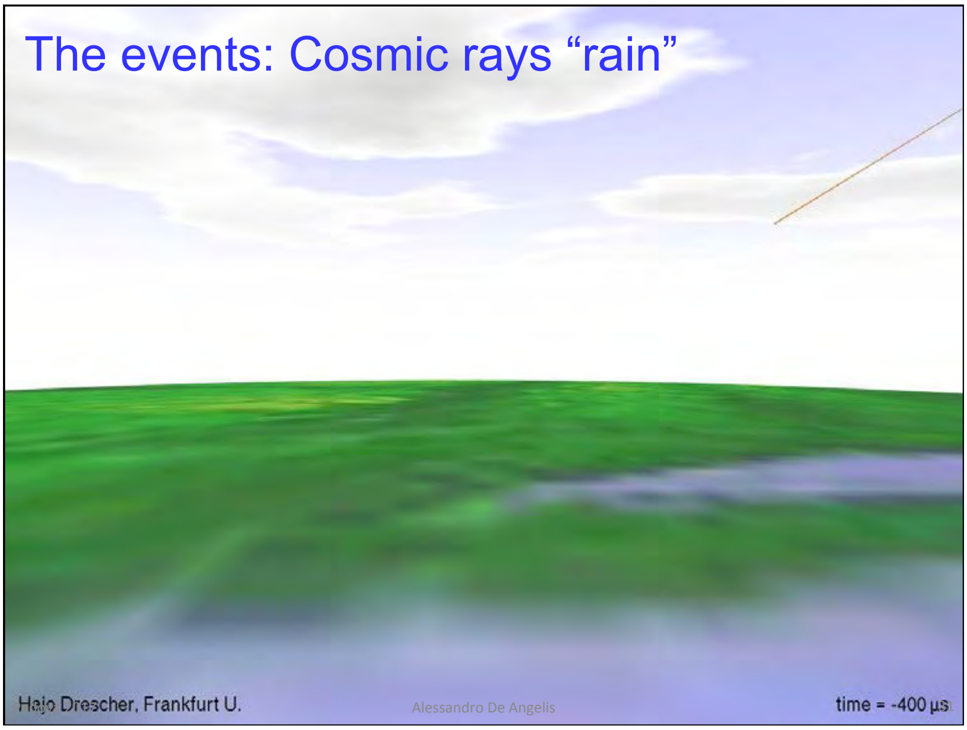


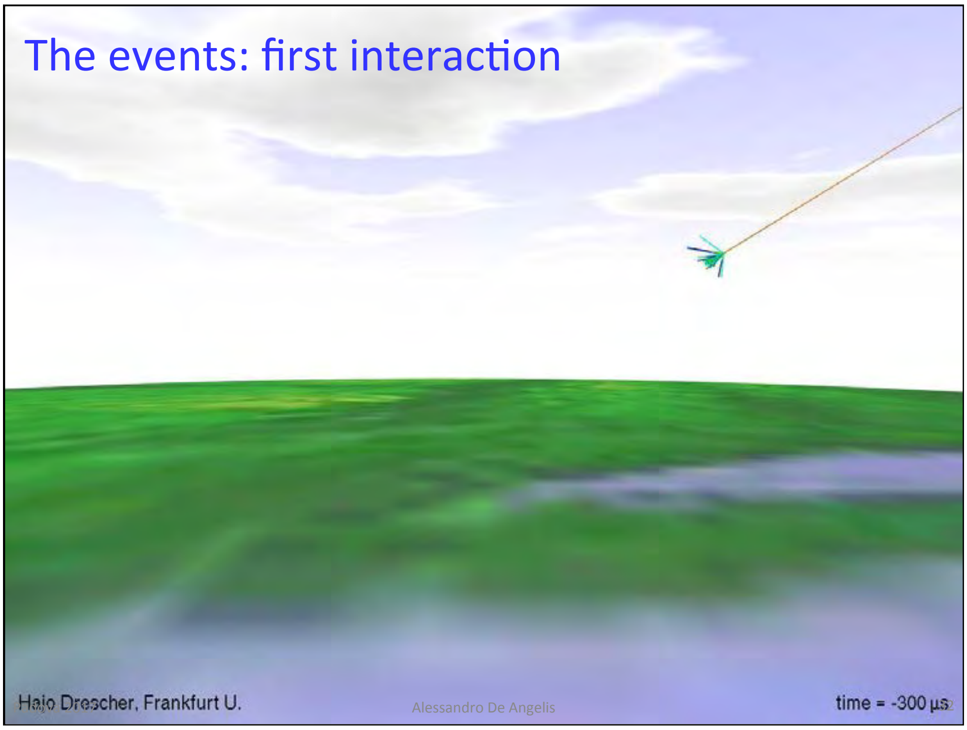

The events: Cosmic rays “rain”
Hajo Drescher, Frankfurt U.
Alessandro De Angelis
time = -800 µs

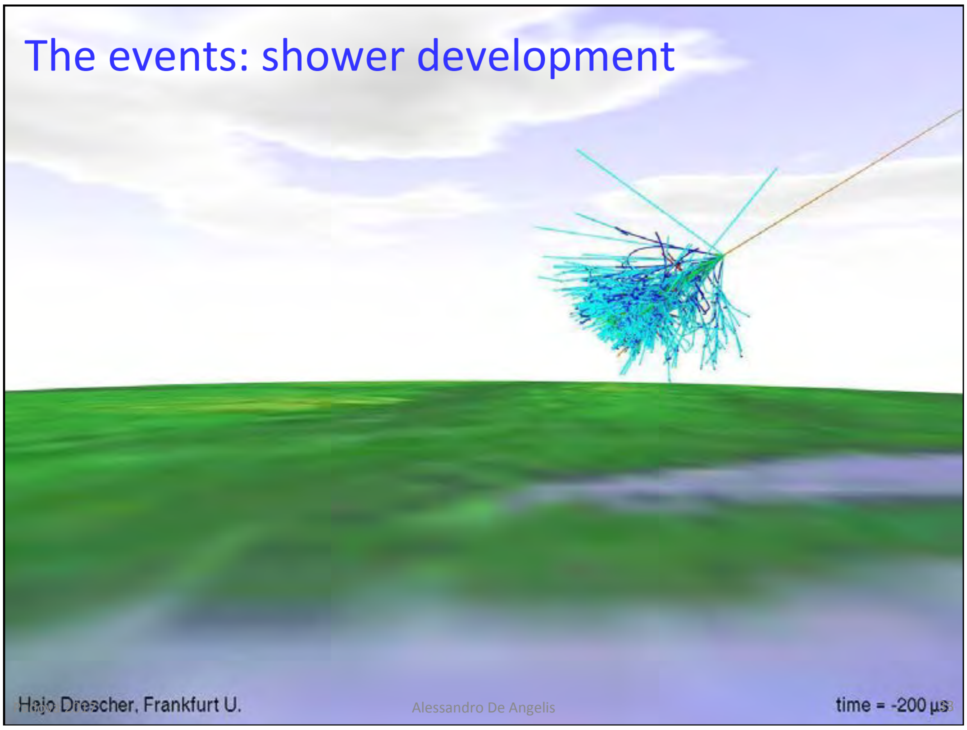

The events: Cosmic rays “rain”
Hajo Drescher, Frankfurt U.
Alessandro De Angelis
time = -700 µs

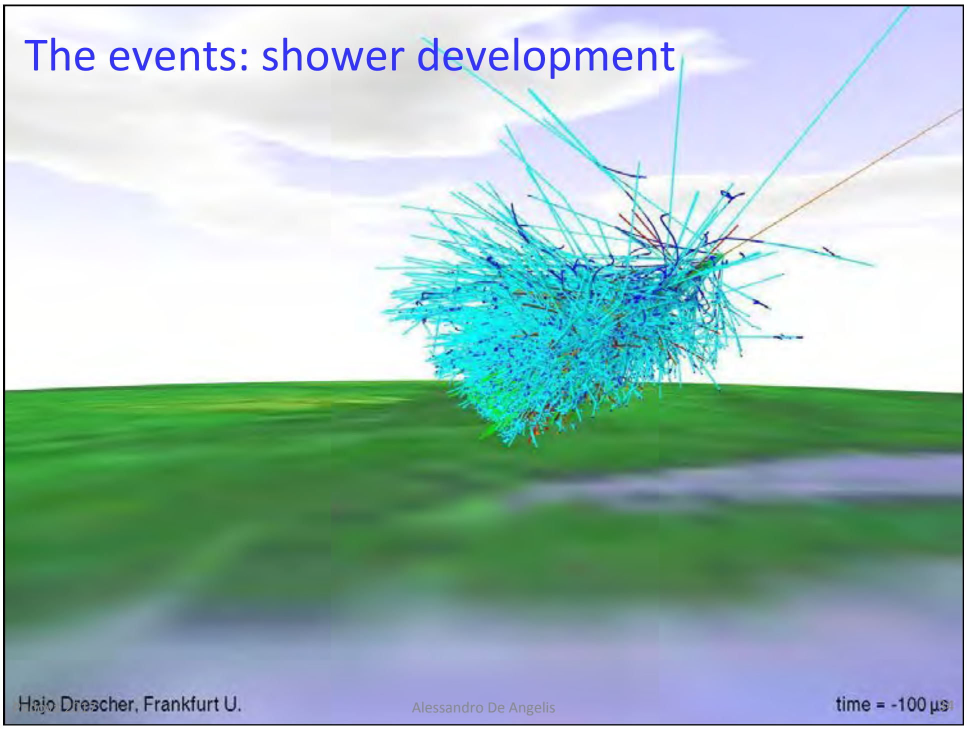

The events: Cosmic rays "rain"
Hajo Drescher, Frankfurt U.
Alessandro De Angelis
time = -600 µs


The events: Cosmic rays "rain"
Hajo Drescher, Frankfurt U.
Alessandro De Angelis
time = -500 µs

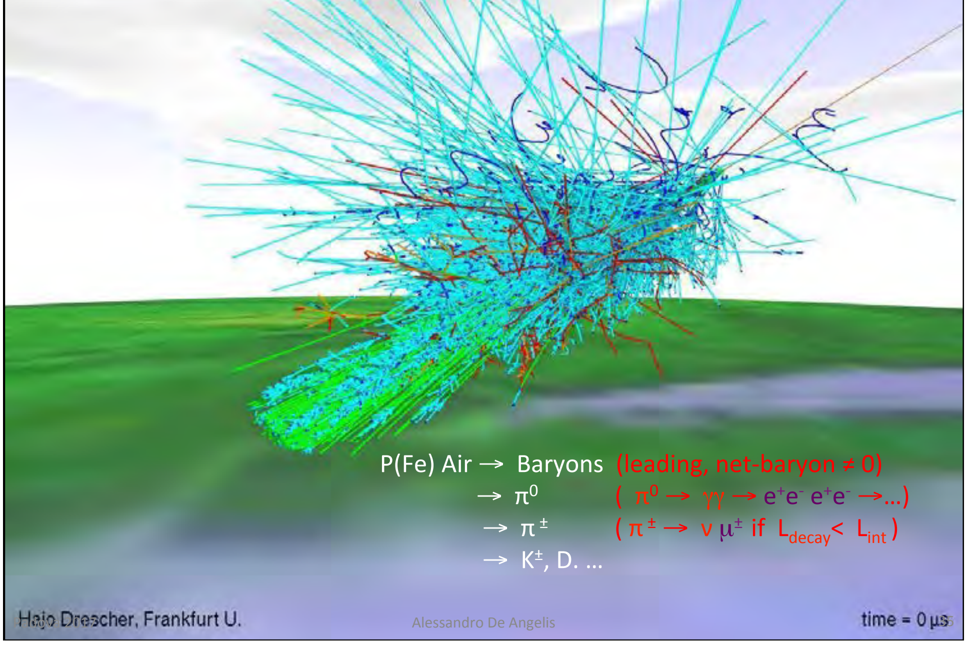

The events: Cosmic rays "rain"
Hajo Drescher, Frankfurt U.
Alessandro De Angelis
time = -400 µs


The events: first interaction
Hajo Drescher, Frankfurt U.
Alessandro De Angelis
time = -300 µs


The events: shower development
Hajo Drescher, Frankfurt U.
Alessandro De Angelis
time = -200 µs

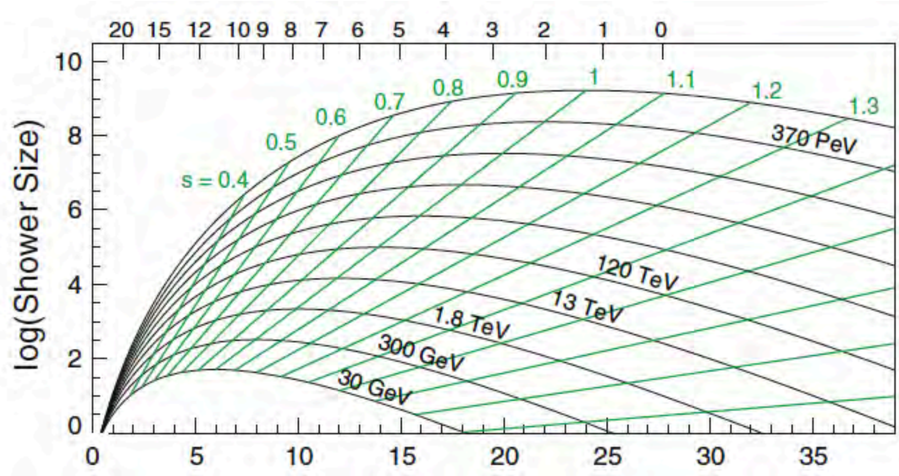

The events: shower development
Hajo Drescher, Frankfurt U.
Alessandro De Angelis
time = -100 µs

The events: shower hits Earth surface

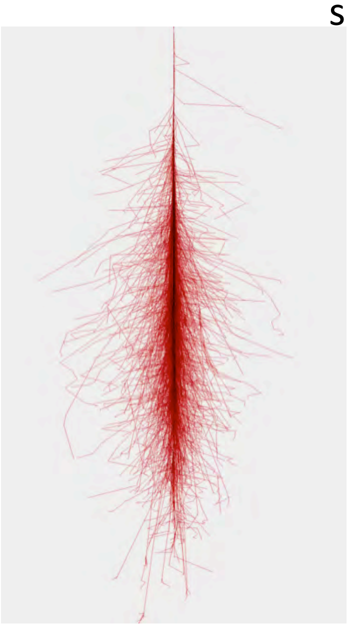
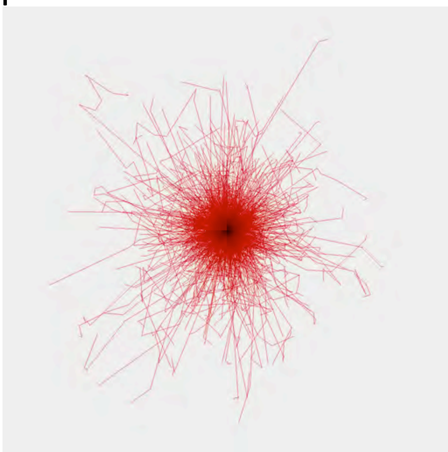


Alessandro De Angelis

Photon-initiated shower in the atmosphere

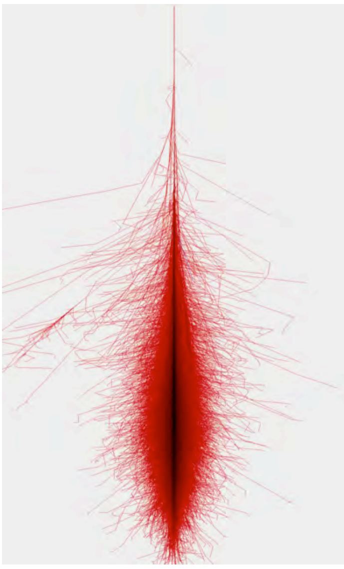
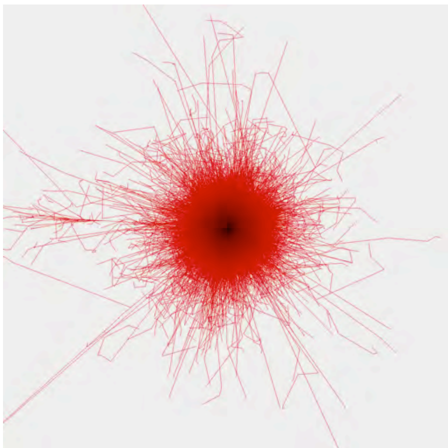


A frequent experimental problem: γ/hadron separation

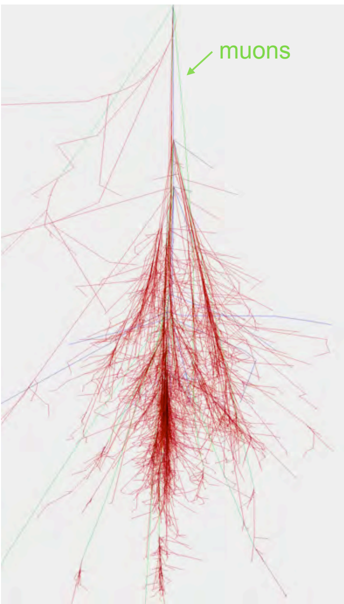



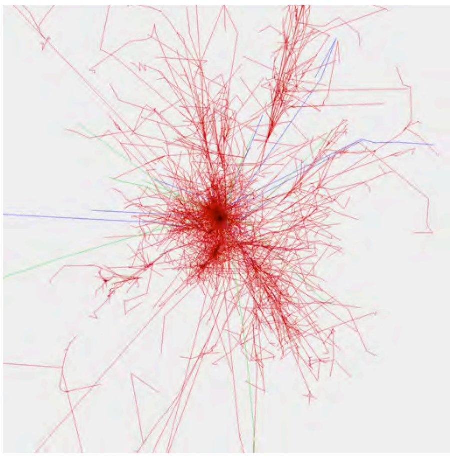
Simulated gamma
in the atmosphere:
50 GeV

Simulated gamma
1 TeV

Simulated proton
100 GeV (the ennemy)





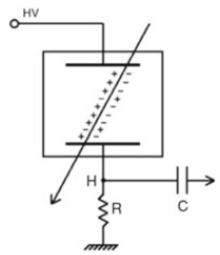
LET'S DETECT

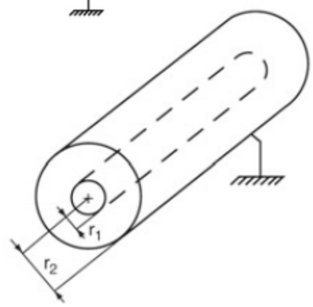
Tracking detectors (charged particles)

- A tracking detector reveals the path taken by a charged particle by measurements of sampled points (hits). Momentum measurements can be made by measuring the curvature of the track in a magnetic field, which causes the particle to curve into a spiral orbit with a radius proportional to the momentum of the particle. This requires the determination of the best fit to a helix of the hits (particle fit). For a particle of unit charge

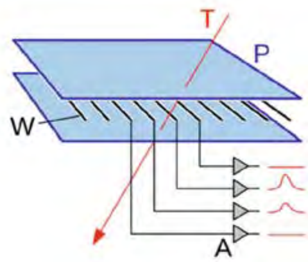
$$p\ (\mathrm{GeV}/c) \sim 0.3\ B_{\perp}(\mathrm{T})\ R\ (\mathrm{m})$$

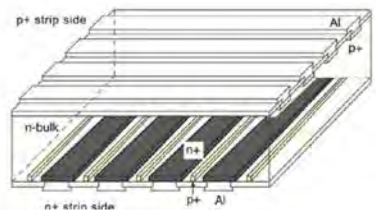
- A source of uncertainty for this determination is given by the errors in the measurement of the hits; another (intrinsic) noise is given by multiple scattering. In what follows we shall review some detectors used to determine the trajectory of charged tracks.
- Prototype: the ionization tube (Geiger-Muller, …)





Tracking detectors (charged particles)

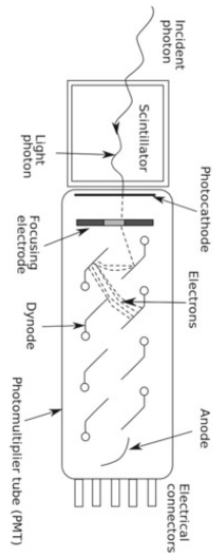




Detector type	Spatial resolution	Time resolution	Dead time
RPC	$\leq$10mm	~1ns (down to ~50 ps)	–
Scintillation counter	10 mm	0.1 ns	10 ns
Emulsion	1 µm	–	–
Bubble chamber	10–100 µm	1 ms	50 ms–1 s
Proportional chamber	50–100 µm	2 ns	20–200 ns
Drift chamber	50–100 µm	few ns	20–200 ns
Silicon strip	Pitch/5 (few µm)	few ns	50 ns
Silicon pixel	10 µm	few ns	50 ns

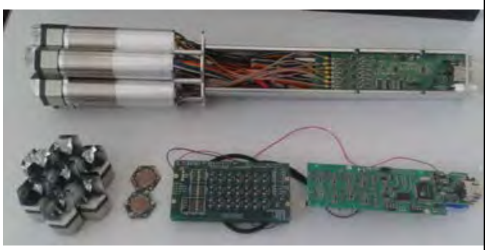
Photodetectors

- Most detectors in particle physics and astrophysics rely on the detection of photons near the visible range, i.e., in the eV energy range. This range covers scintillation and Cherenkov radiation as well as the light detected in many astronomical observations.
- One needs to extract a measurable signal from a small number of incident photons. This can be achieved by generating a primary photoelectron or electron–hole pair by an incident photon (typically by photoelectric effect), amplifying the signal to a detectable level (usually by a sequence of avalanche processes), and collecting the secondary charges to form an electrical signal.
- The important characteristics of a photodetector include:
    - the quantum efficiency QE
    - the overall collection efficiency
    - the gain G
    - the dark noise DN , i.e. the electrical signal when there is no incoming photon;
    - the intrinsic response time of the detector.

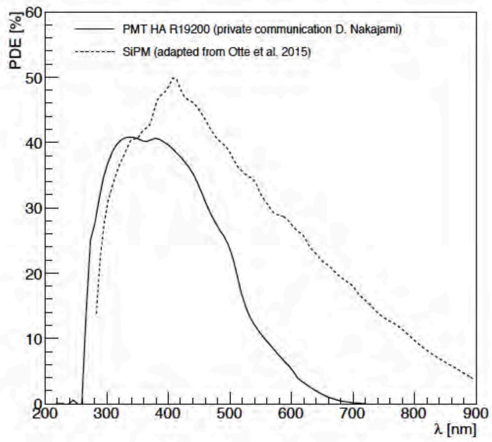


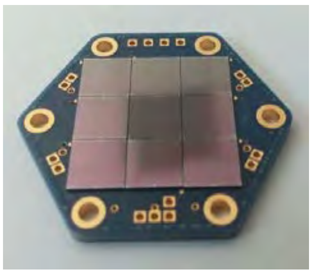
- Prototype: the avalanche photomultiplier tube (PMT)

Photodetectors - II



- Other photodetectors:
    - Gaseous detectors
    - Solid-state detectors (SiPM) – high fashion now





Corti, Rando+ (PD)

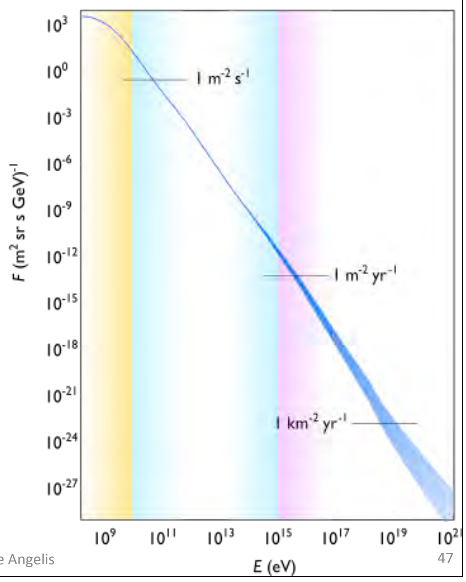
Exercises

1. *Cherenkov radiation.* A proton with momentum 1.0 GeV/c passes through a gas at high pressure. The index of refraction of the gas can be changed by changing the pressure. Compute: (a) the minimum index of refraction at which the proton will emit Cherenkov radiation; (b) the Cherenkov radiation emission angle when the index of refraction of the gas is 1.6.
2. *Photodetectors.* What gain would be required from a photomultiplier in order to resolve the signal produced by three photoelectrons from that due to two or four photoelectrons? Assume that the fluctuations in the signal are described by Poisson statistics, and consider that two peaks can be resolved when their centers are separated by more than the sum of their standard deviations.
3. *Cherenkov counters.* Estimate the minimum length of a gas Cherenkov counter used in the threshold mode to be able to distinguish between pions and kaons with momentum 20GeV. Assume that 200 photons need to be radiated to ensure a high probability of detection and that radiation covers thewhole visible spectrum (neglect the variation with wavelength of the refractive index of the gas).
4. Electromagnetic showers. If a shower is generated by a gamma ray of E = 1 TeV penetrating the atmosphere vertically, considering that the radiation length X0 of air is approximately 37 g/cm2 and its critical energy Ec is about 88 MeV, calculate the height hM of the maximum of the shower in the Heitler model and in the Rossi approximation B.
5. *Electromagnetic calorimeters.* Electromagnetic calorimeters have usually 20 radiation lengths of material. Calculate the thickness (in cm) for a calorimeters made of of BGO, $PbWO_4$ (as in the CMS experiment at LHC), uranium, iron, tungsten and lead. Take the radiation lengths from Appendix B or from the Particle Data Book.
6. *Muon energy loss.* A muon of 100 GeV crosses a layer of 1 m of iron. Determine the energy loss and the expected scattering angle.

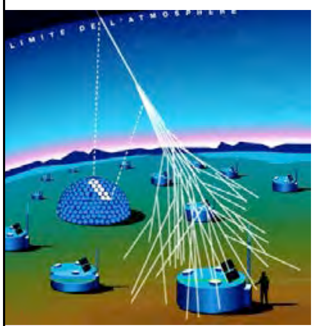
PART 2
LET'S BUILD COMPLEX DETECTORS, NOW!

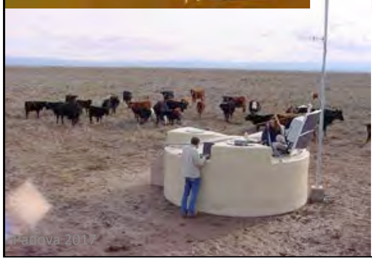
Charged particles: for astrophysics, the bigger the better

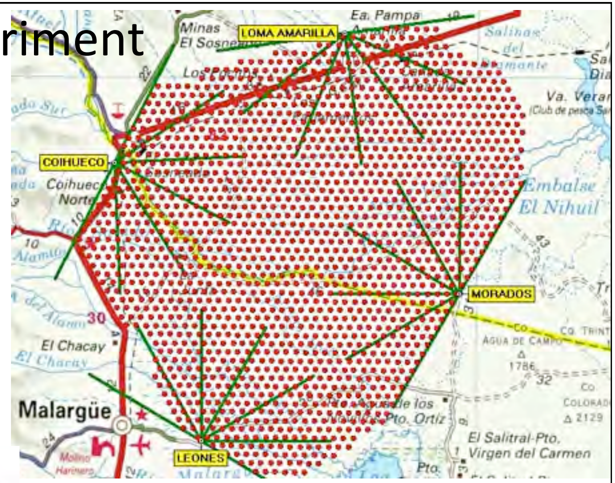
- Detect EAS at ground (mostly detect the charged particles in the shower)
- Go as high as possible (~4km)
- You can sample
- You can use simple detector units
  - Water pools (Cherenkov effect in water) with PMT(s)
  - Scintillators
  - RPC
- Your results are “dirty”: difficult to identify the cosmic ray – also its charge



The Auger experiment in Argentina







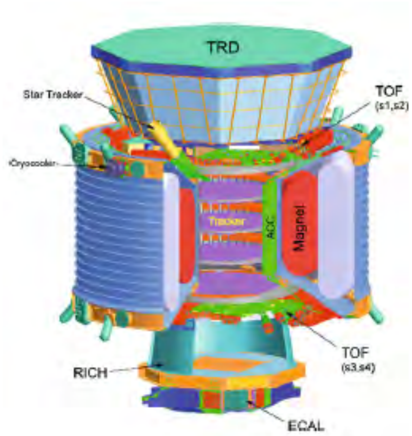
The largest in the world: surface of 3000 km^2 (Veneto: 18000 km^2)

1600 surface detectors & 4 telescopes

Still not enough for astronomy

If you want to identify particles (eg for DM studies), the only solution is going to space

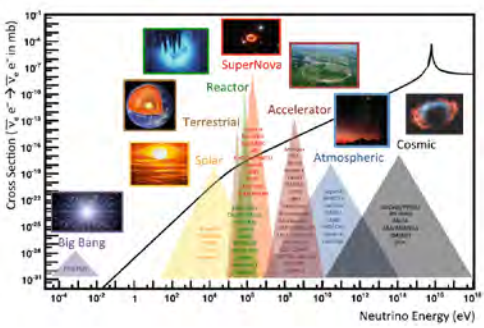
- Need magnetic field
- Need power
- Maximum area ~ $1m^{2}$,
  Maximum weight ~ 1 ton
  Maximum power ~ 1kW
  => Maximum E ~ 1 TeV

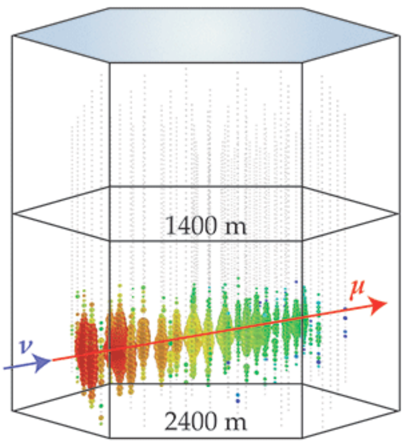


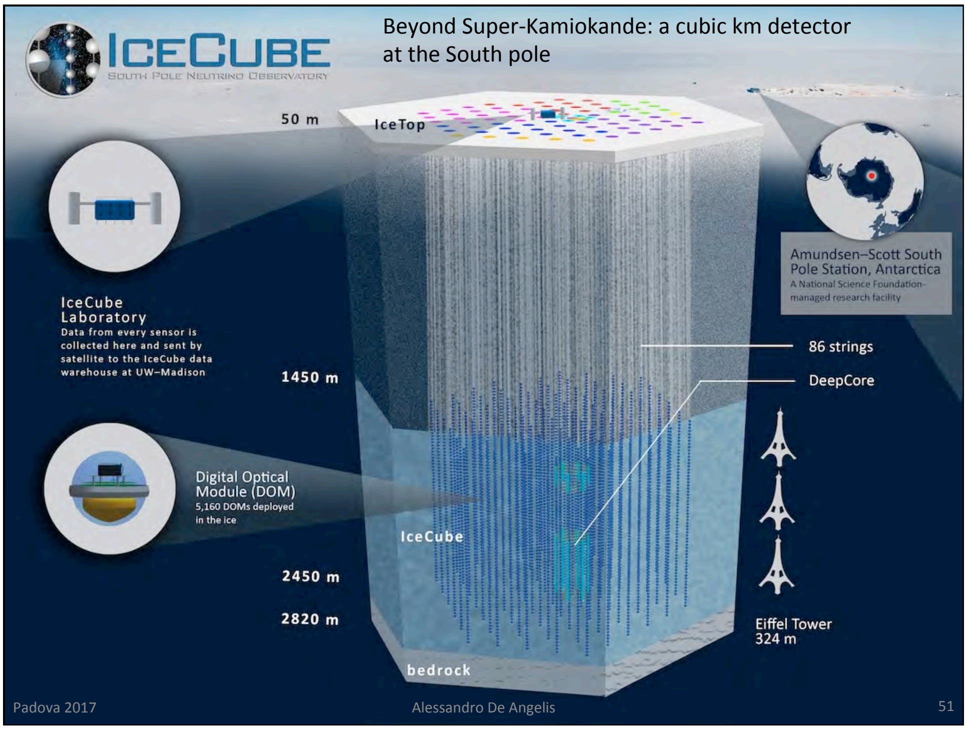
AMS-02 onboard the ISS
Launched by the Space Shuttle
May 2011

Another frontier of large detectors: neutrinos

- You need cubic kilometers to (possibly) do astrophysics…

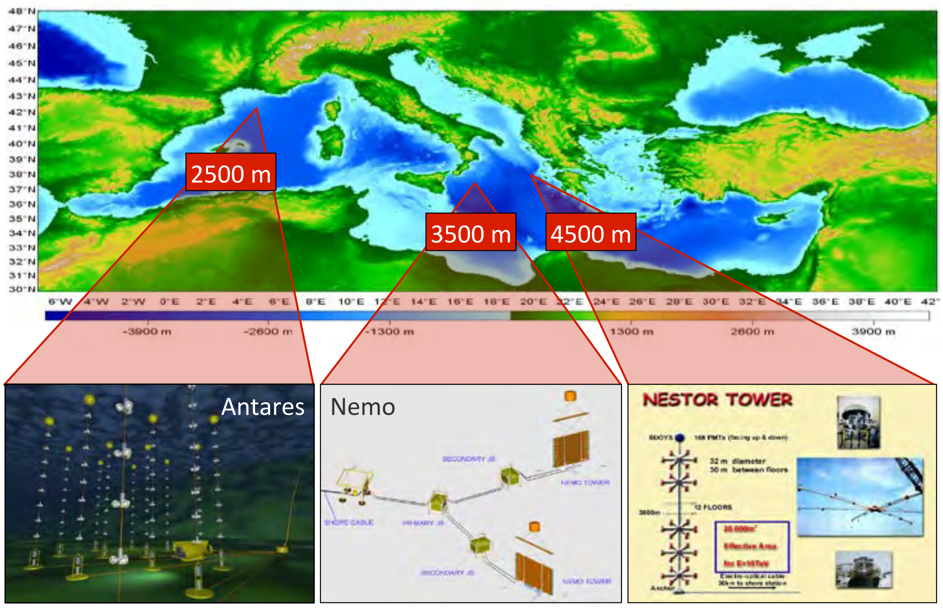






Deploying a (string of) photosensors

…and in the Mediterranean sea



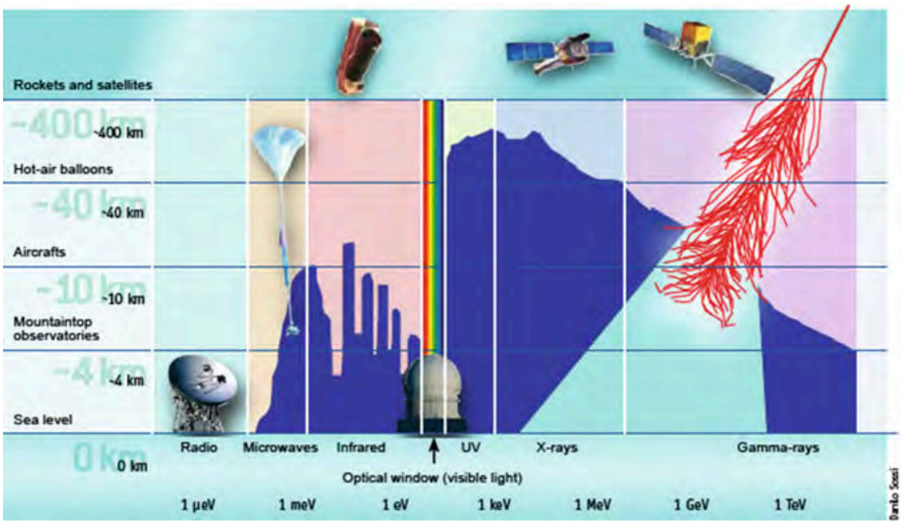
Photons in the nonthermal region

- LE or MeV : 0.1 (0.03) -100 (30) MeV
- HE or GeV : 0.1 (0.03) -100 (30) GeV
- VHE or TeV : 0.1 (0.03) - 100 (30) TeV
- UHE or PeV : 0.1 (0.03) -100 (30) PeV

- LE,HE domain of space-based astronomy
- VHE+ domain of ground-based astronomy

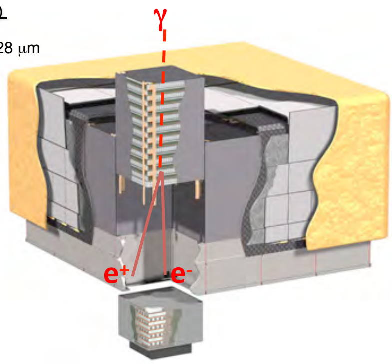
- When no ambiguity, we call “HE” all the HE and VHE+

Transparency of the atmosphere



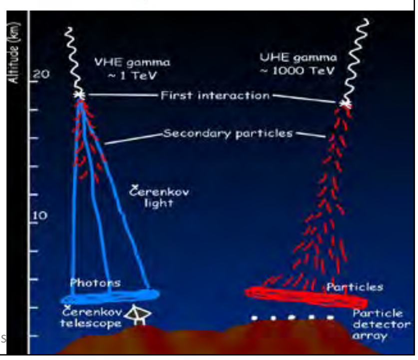
Detectors

Precision Si-strip Tracker (TKR)
18 XY tracking planes
Single-sided silicon strip detectors 228 μm pitch, 8.8 10^5 channels
Measure the photon direction



- MeV satellites
- GeV Satellites (AGILE, Fermi, DAMPE)
  - Silicon tracker (+calorimeter)
- Cherenkov telescopes (H.E.S.S., MAGIC, VERITAS)
- Extensive Air Shower detectors (HAWC): RPC, scintillators, water Cherenkov

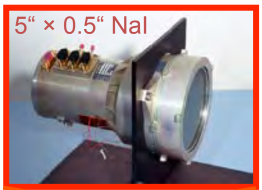
HEP detectors!

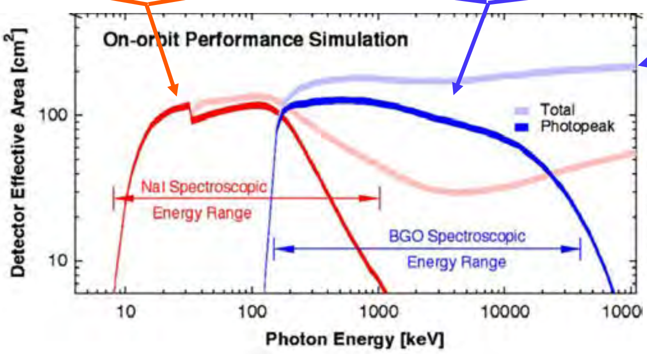


MeV photon detectors

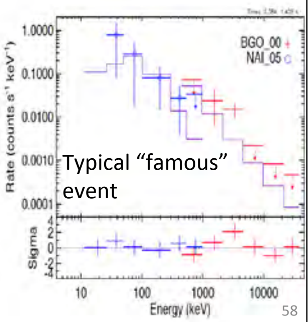
- The MeV region is crucial for nuclear physics
- An “easy” way to do MeV photon detectors
  - Scintillating crystals
- But:
  - Bad directionality
  - No polarization information
- Typically used in Gamma-Ray Burst monitors

Fermi GBM detectors





effective area $\approx$ 160 cm^2

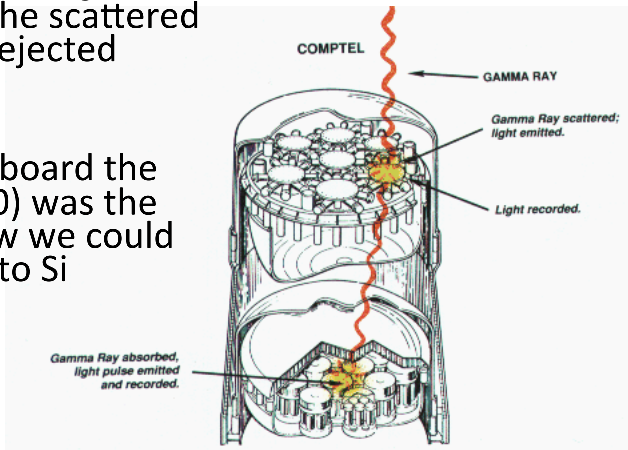


Typical “famous” event

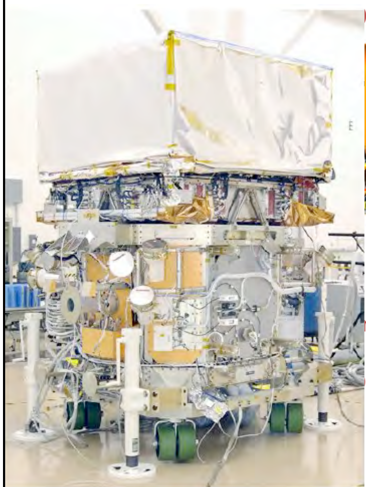
C. Meegan et al. 2009, ApJ, 702,

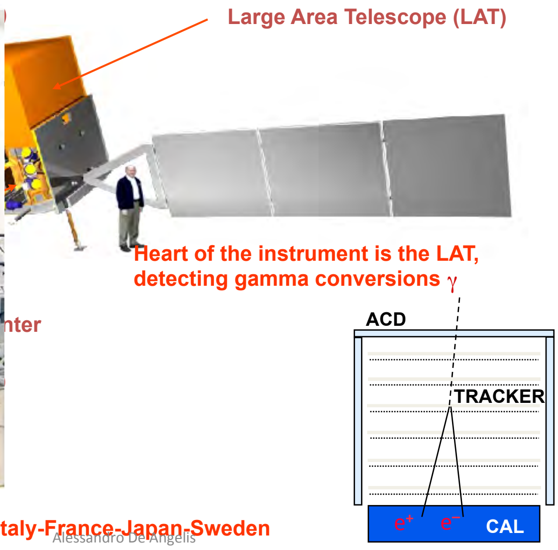
MeV photon detectors: the hard way

- Specific Compton detectors
- Need accurate tracking of the directionality of the scattered photon or of the ejected electron, if any
- The COMPTEL onboard the CGRO (1991-2000) was the last example. Now we could do better thanks to Si technology…



The GeV (pair production): Fermi and the LAT





International collaboration USA-Italy-France-Japan-Sweden

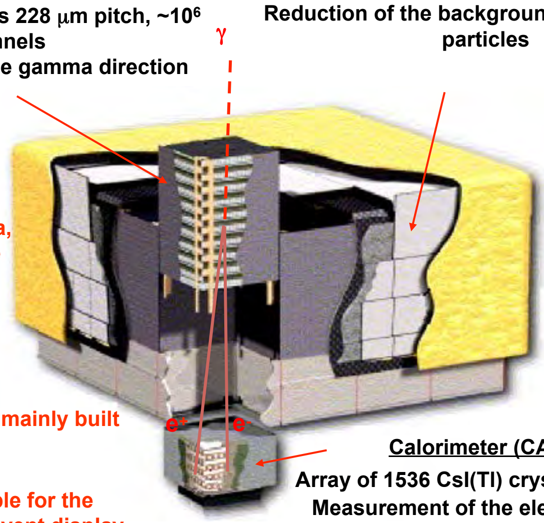
Fermi-LAT launched June 2008

LAT overview

Si-strip Tracker (TKR)
18 planes XY ~ 1.7 x 1.7 m² w/ converter
Single-sided Si strips 228 μm pitch, ~10⁶ channels
Measurement of the gamma direction

AntiCoincidence Detector (ACD)
89 scintillator tiles around the TKR
Reduction of the background from charged particles

Astroparticle groups INFN/University Bari, Padova, Perugia, Pisa, Roma2, Udine/Trieste

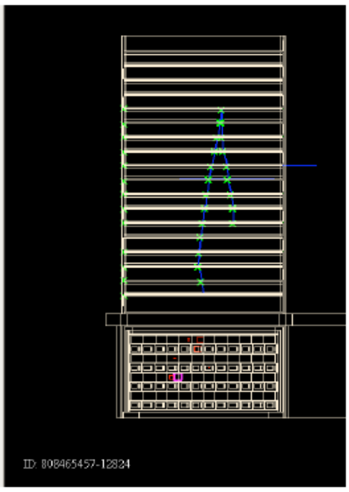


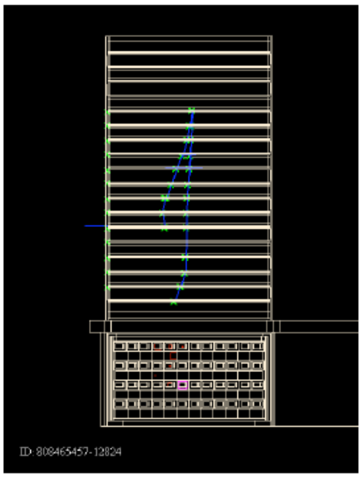
The Silicon tracker is mainly built in Italy

Italy is also responsible for the detector simulation, event display and GRB physics

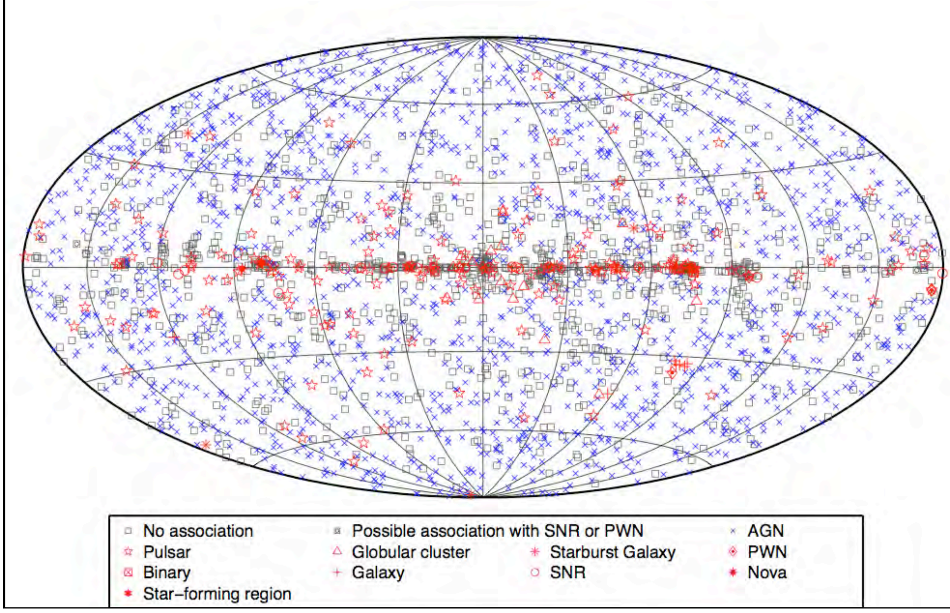
Calorimeter (CAL)
Array of 1536 CsI(Tl) crystals in 8 layers
Measurement of the electron energy

Detection of a gamma-ray



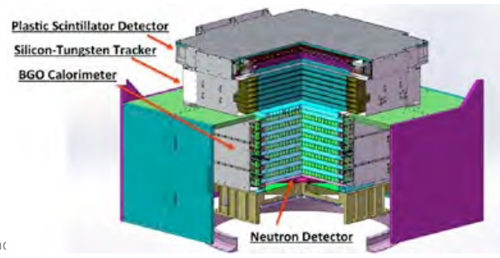


LAT 4-year Point Source Catalog (3FGL)

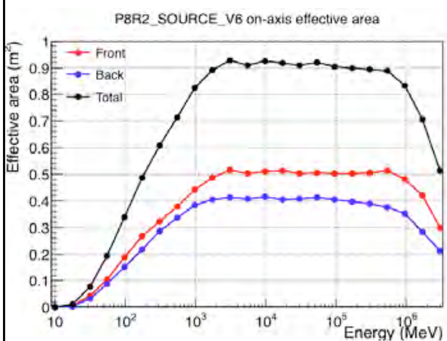


AGILE & DAMPE

- 2 more instruments in space
- The all-Italian telescope AGILE
  - A Fermi precursor: see Fermi, 16 times smaller
  - Launched April 2007
  - Pointing systems has some problems
- The Chinese-Italian-Swiss DAMPE
  - ~AGILE
  - Launched December 2015
  - Better calorimetry than Fermi



Performance of Fermi (Pass 8)

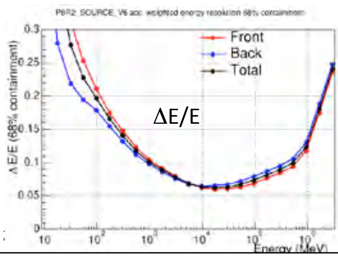


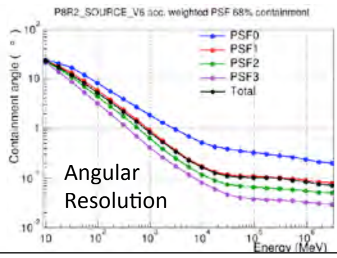
Effective area (Area x efficiency)

~ 1m²

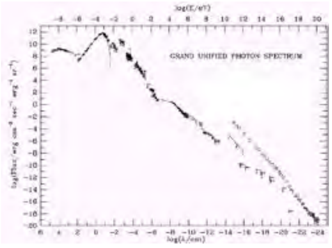
Grows as k lnE from 2 MeV to 2 GeV
Then ~0.9 m² from 2 GeV to 700 GeV
Then decreases as k' lnE

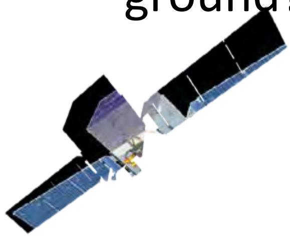
Acceptance: 2.5 sr



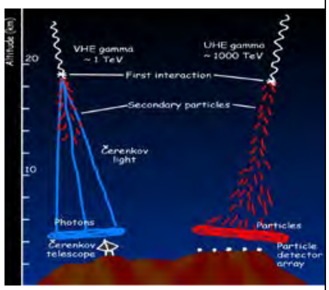


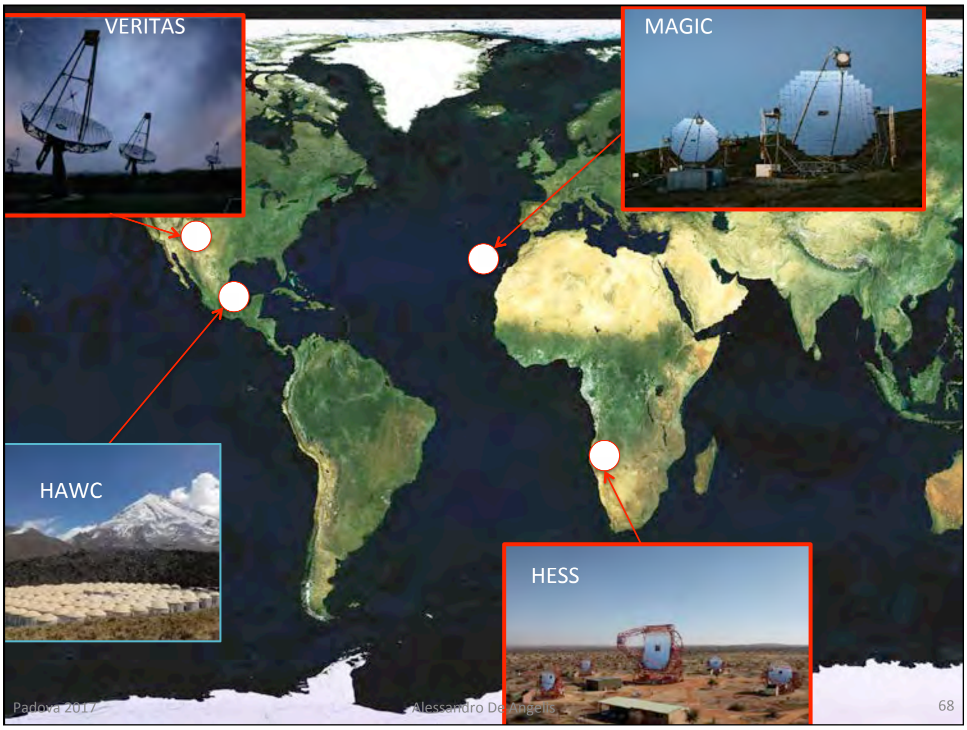
Why detection at ground?





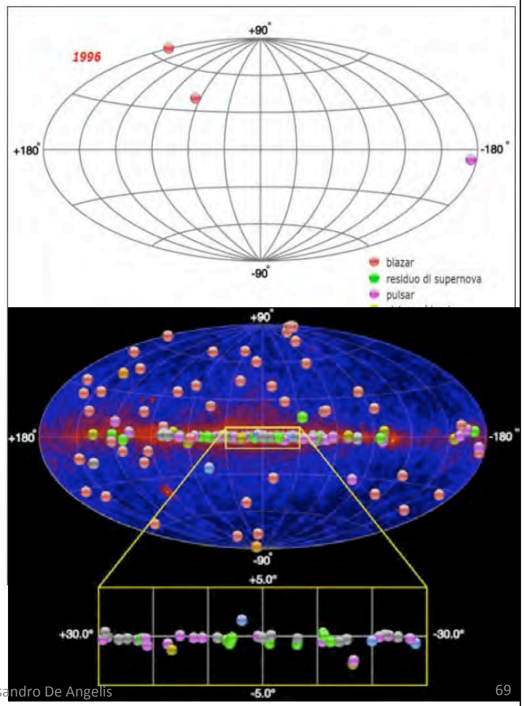
- High energies
  - Only way to build sensitive >TeV instruments
  - Maximum flux < 1 photon/h/m^2 above 200 GeV in Fermi
- High statistics /short timescales
  - Large collection areas O(km^2)
- Precision (Imaging Air Cherenkov telescopes, IACTs)
  - Superior angular resolution
- Limitations?
  - IACTs
    - Smaller duty cycle
    - Smaller field of view
  - EAS ground particle detectors
    - Modest resolution and background rejection power
  - Complementary approaches

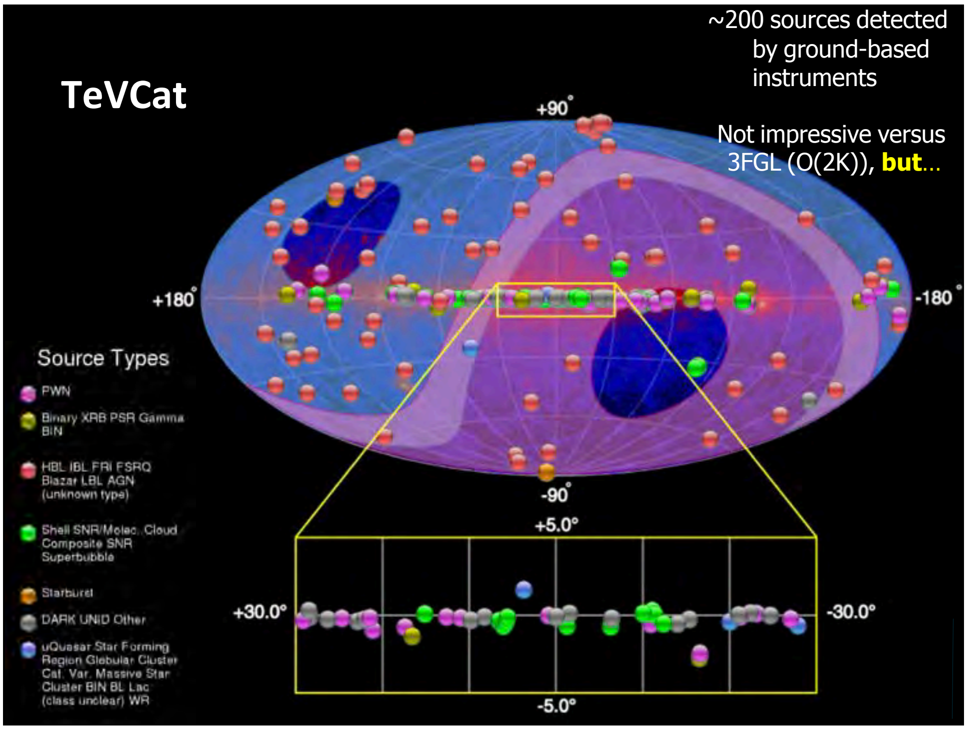


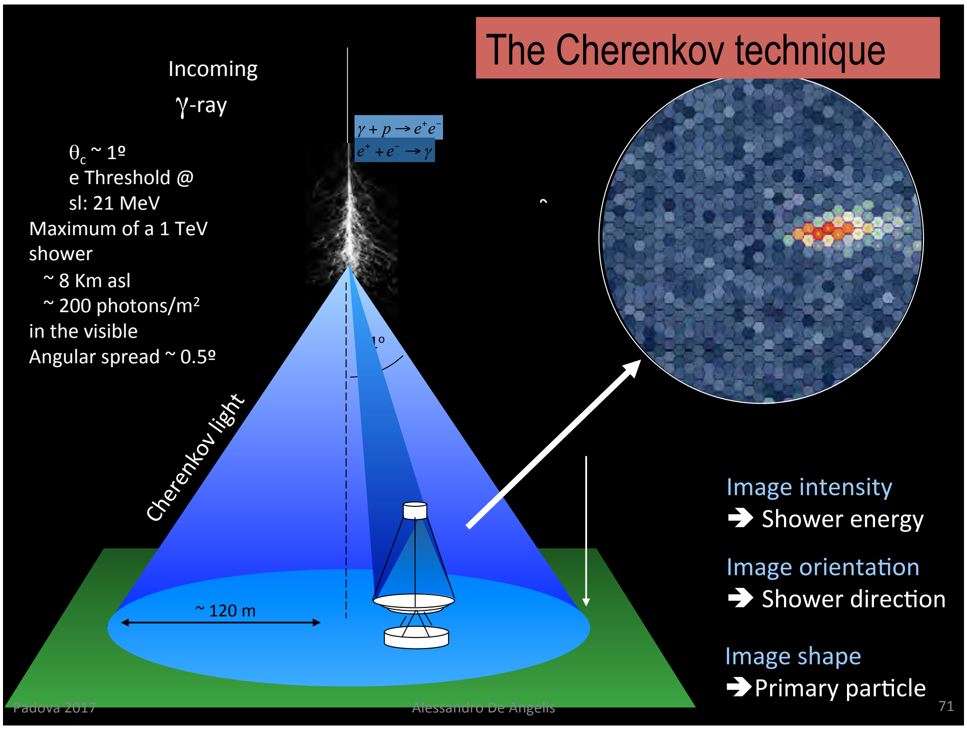


Highlight in γ-ray astrophysics (mostly HESS, MAGIC, VERITAS)

- Thanks mostly to Cherenkov telescopes, imaging of VHE (> 30 GeV) galactic sources and discovery of many new galactic and extragalactic sources: ~ 200 (and >200 papers) in the last 9 years
  - And also a better knowledge of the diffuse gammas and electrons
- A comparable success in HE (the Fermi realm); a 10x increase in the number of sources
- A new tool for cosmic-ray physics and fundamental physics

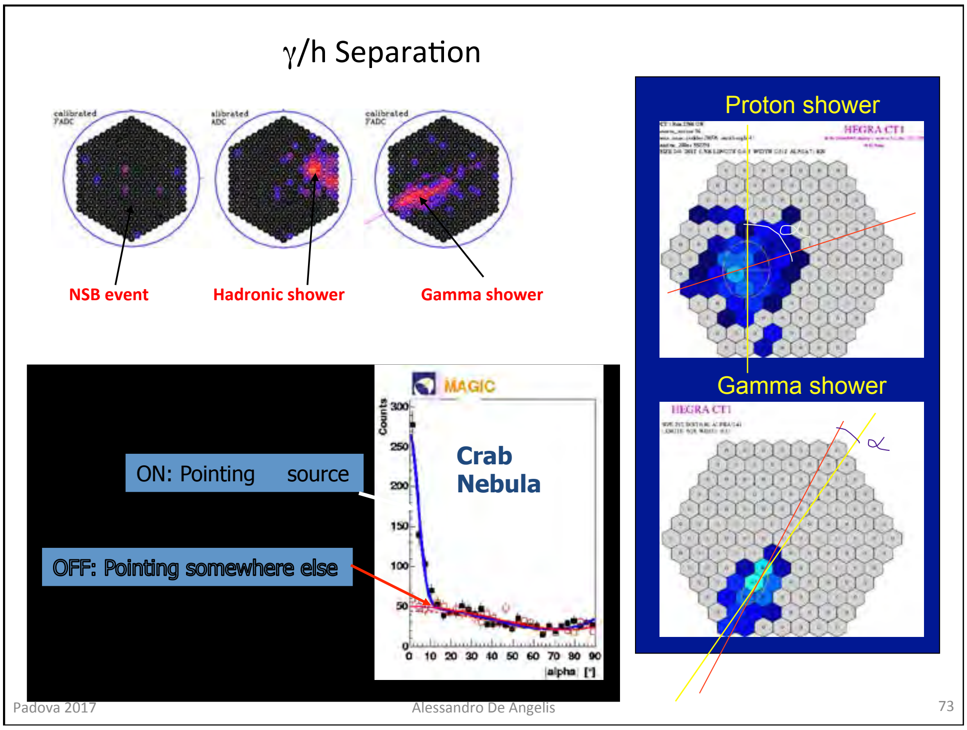






Signal duration: ~ 3ns

Padova 2017 Alessandro De Angelis 72


γ/h Separation
NSB event
Hadronic shower
Gamma shower
ON: Pointing source
OFF: Pointing somewhere else
MAGIC
Crab Nebula
Counts
alpha [°]
Proton shower
HEGRA CT1
Gamma shower
HEGRA CT1
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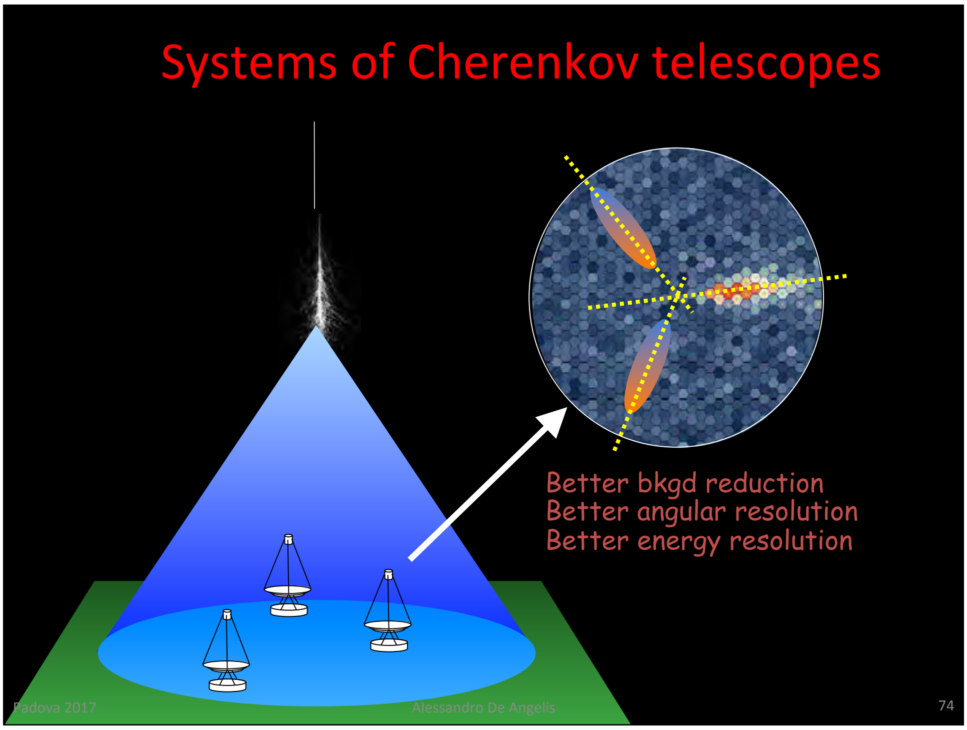
Systems of Cherenkov telescopes
Better bkgd reduction
Better angular resolution
Better energy resolution
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Instr.	Tels. #	Tel. A (m^2)	FoV (°)	Tot A (m^2)	Thresh. (TeV)	PSF (°)	Sens. (%Crab)
H.E.S.S.	4	107	5	428	0.1	0.06	0.7
MAGIC	2	236	3.5	472	0.05(0.03)	0.06	0.8
VERITAS	4	106	4	424	0.1	0.07	0.7

Plus a 600 m2 telescope (CT5) operating since 2015

(0.03 for CT5)

VERITAS: 4 telescopes (~12m) in Arizona operational since 2006

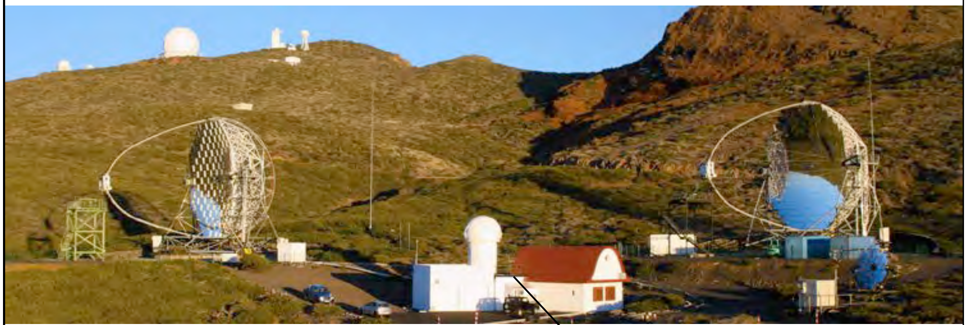
HESS (Namibia)

4 telescopes (~12m) operational since 2003

HESS 2: 5th telescope (26-28m) commissioned in 2015

MAGIC: Two 17m Ø Imaging Atmospheric Cherenkov Telescopes
1st telescope since 2004, 2nd since 2009, upgrade in 2013

~160 physicists from 10 countries:
Bulgaria, Croatia, Finland, Germany, India, Italy, Japan, Poland, Spain, Switzerland

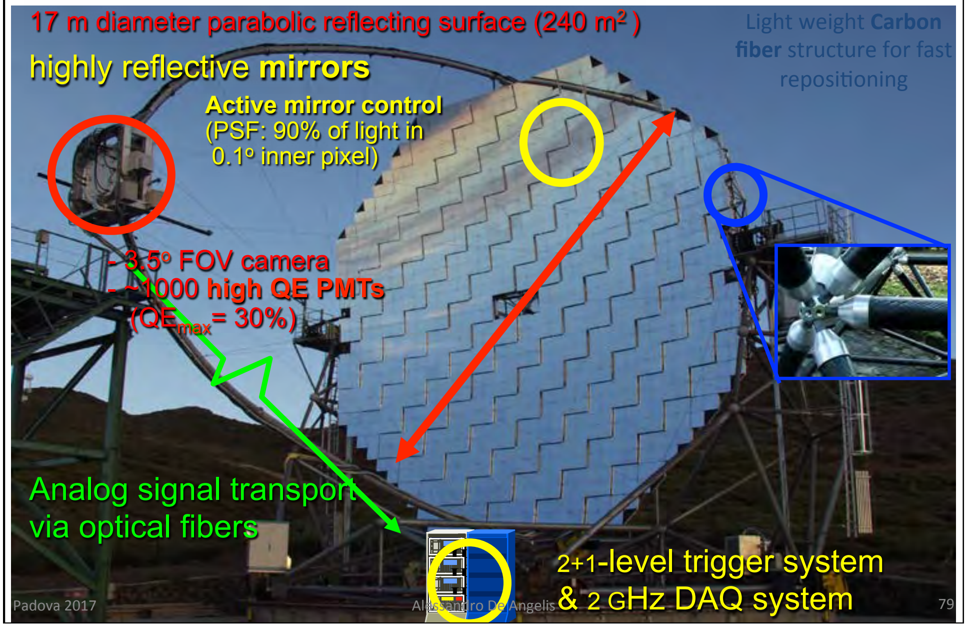


Canary island of La Palma

at 2400 m a.s.l.

The level of perturbations is 1600 m => 650 m b

Key elements



Padova 2017 Alessandro De Angelis 79

Operated from a control room

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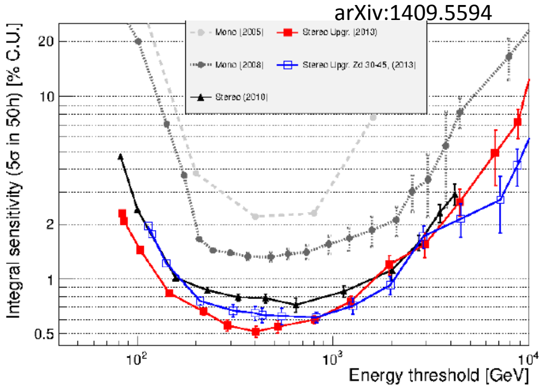
Main parameters & performance

- **Light-weight**: ~60 T
- **Fast re-positioning** to any coordinates in the sky: ~ 25 s /180°
- Optimized electro-optical design providing ~ 2.5 ns FWHM pulses
- Data digitized by using 2 GSample/s DRS4 chips
- Producing ~ 1 TB data per observation night

arXiv:1409.5594



Energy threshold:
50 GeV
30 GeV Sum-Trigger

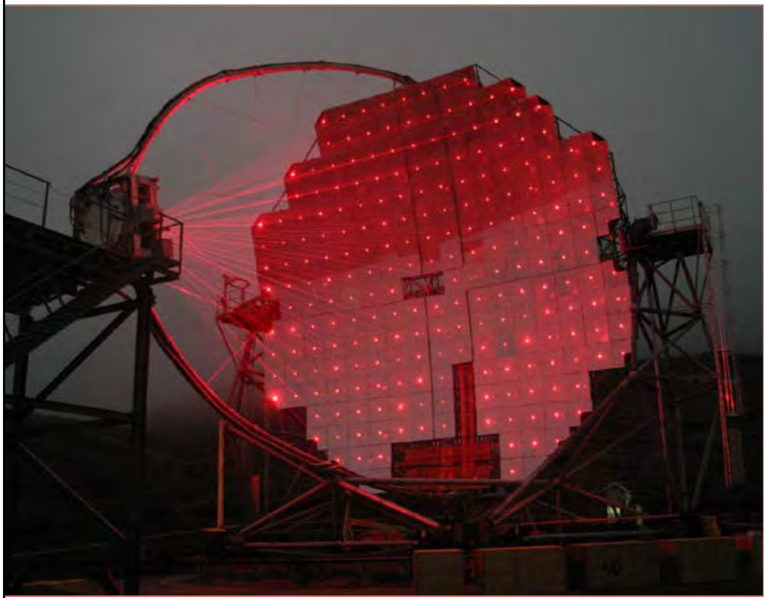
Energy resolution:
15% (@ 1 TeV) – 20% (@100 GeV)

Angular resolution:
0.06° @ 1 TeV , 0.1° @ 100 GeV

Best **sensitivity**: 0.5% of Crab Nebula flux
in 50 hours obs. @ E ~ 400 GeV

Fast and smooth repointing (< 30 s)

Adjustement (active control)



All AMC Lasers switched on during foggy night

(nice propaganda picture; does never look like that during operation …)

Why bigger and bigger?

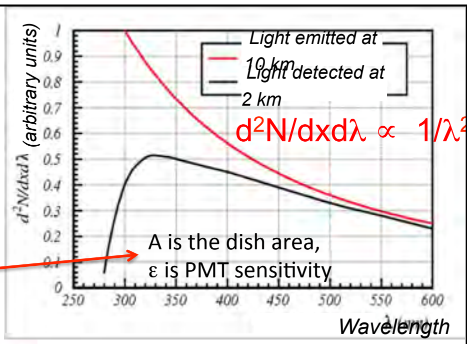
Figures of merit of a Cherenkov telescope

- Sensitivity: effective area (effective area covered, => ~ number of telescopes)
- Angular resolution: number N of telescopes
- Serendipity: FoV, Duty Cycle
- Still we use small N (cost: 1-10 MEUR/telescope)

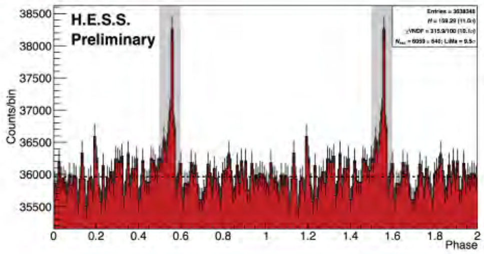
Figures of merit - II

- The threshold is

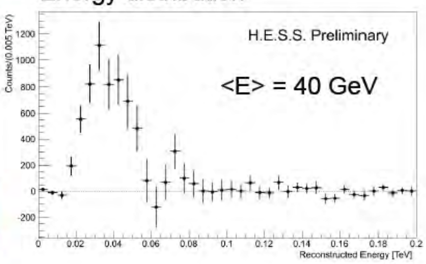
$$E_{threshold} \propto \sqrt{\frac{\phi \Omega \tau}{\epsilon A}}$$



The Vela pulsar seen with CT5

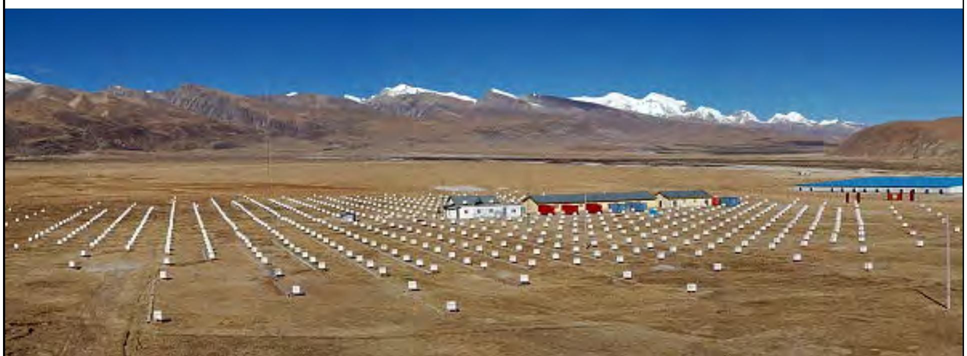


Energy distribution



Higher energies: EAS detectors

(Cost of covering 1 km² with Cherenkov telescopes > 100 MEUR)

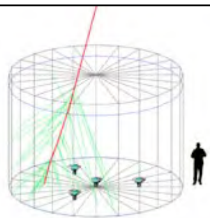


Tibet – AS gamma: scintillators

EAS detectors

- Pro: wide field of view, continuous operation, cheap to instrument large areas
- Minus: Resolution is worse => more background, higher threshold
- Transients: plus is serendipity, can be the trigger; minus is sensitivity

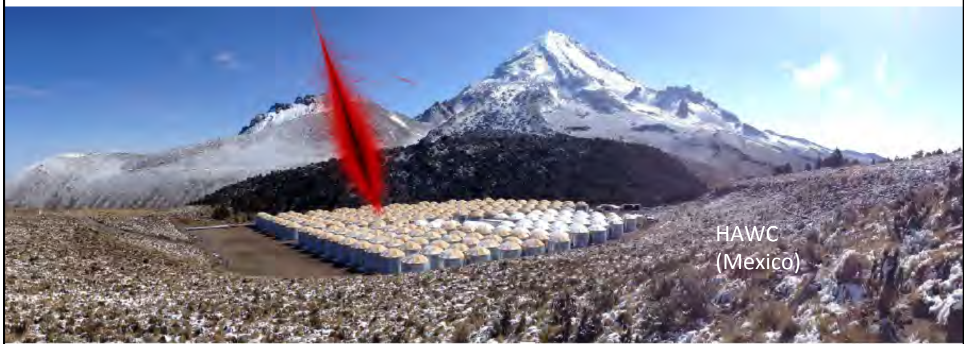
The present



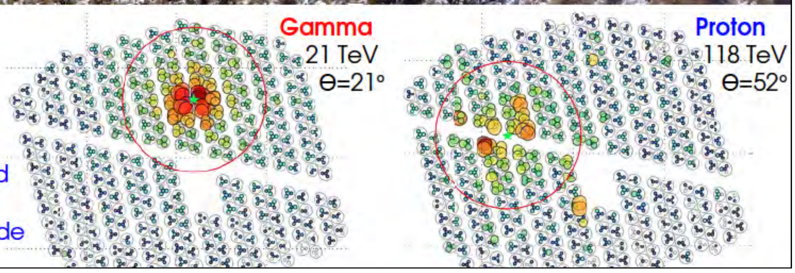
The HAWC Observatory

- Located at **4100 m** a.s.l. in Mexico near Pico de Orizaba at 19ºN
- Effective Area: **~22,000 m²**
- Instantaneous field of view **2 sr**; daily coverage of **2/3** of the sky.
- 300 Water Cherenkov Detectors (WCDs)
- Declinations from **-26º to 64º** (***Part of Northern Fermi Bubble visible***)
- Inaugurated in **March 2015**, taking science data since **2013**.

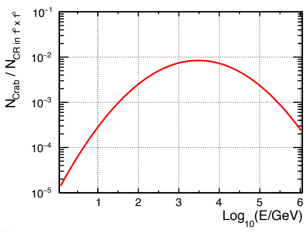
Very-high-energies (above 200 GeV)



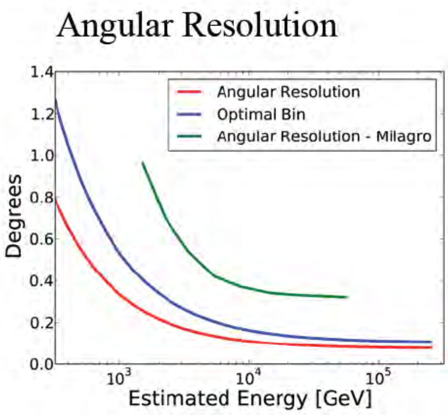
Reconstruct air showers based on PMT hit times and charges
Reject charged primaries via bright hits outside the core

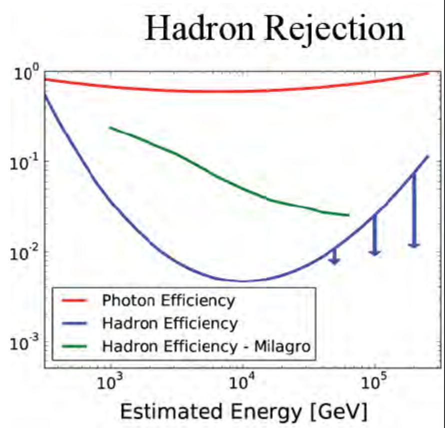


Performance

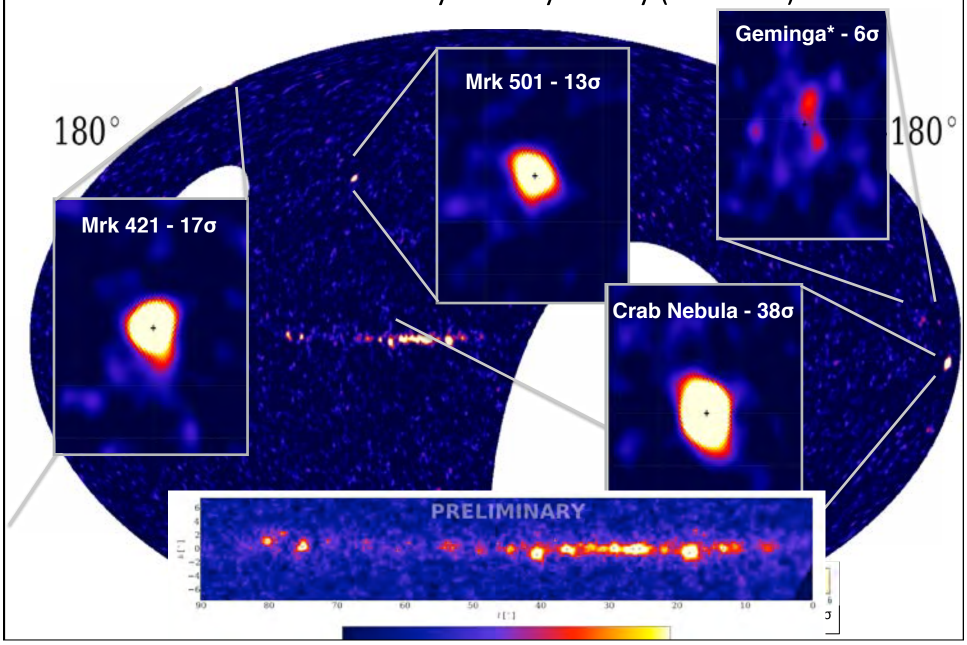


S/B from Crab
Resolution of 1 degree





HAWC-250 150-Day TeV Sky Survey (38σ Crab)



Detection of Cherenkov radiation vs. direct sampling

$$\theta_c = \frac{1}{n\beta}$$

from the direction of the emitting particle. The threshold velocity is thus $\beta = 1/n$, where n is the refractive index of the medium.

The number of photons produced per unit path length and per unit energy interval of the photons by a particle with charge $z_p e$ is

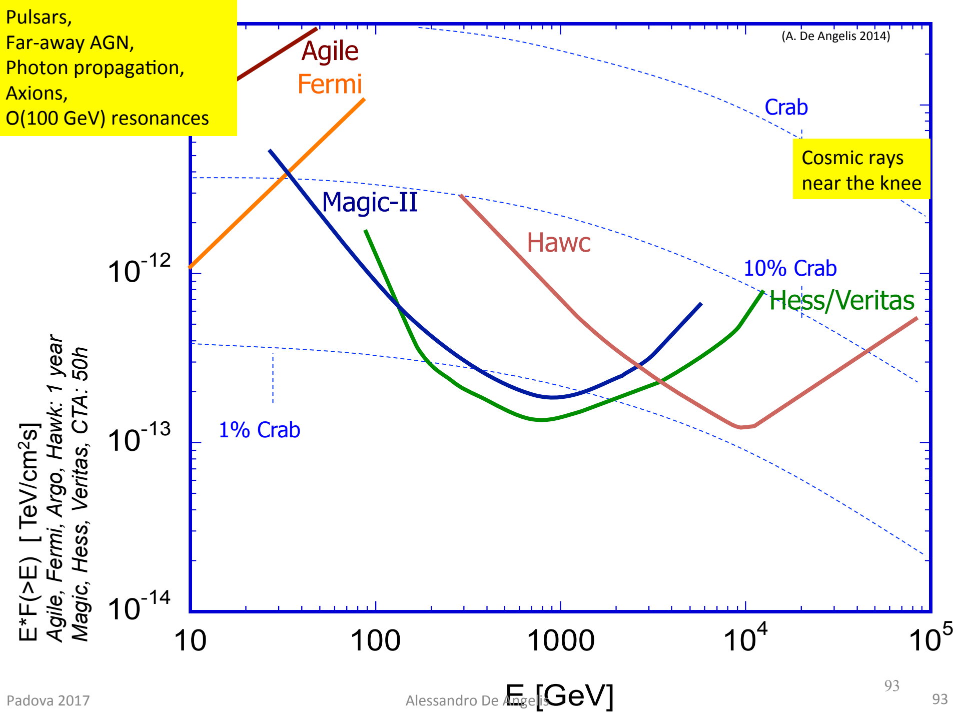
$$\frac{d^2N}{dEdx} \simeq \frac{\alpha z_p^2}{\hbar c} \sin^2\theta_c \simeq 370 \sin^2\theta_c \, \mathrm{eV}^{-1}\mathrm{cm}^{-1} \qquad (4.6)$$

or equivalently

$$\frac{d^2N}{dEd\lambda} \simeq \frac{2\pi\alpha z_p^2}{\lambda^2} \sin^2\theta_c \qquad (4.7)$$

(the index of refraction n is in general a function of photon energy E).

- For a particle unit charge: ~40 photons/m between 300nm and 700nm in air
  Total energy loss is about 10^{-4} the ionization loss
- Attenuation length is ~ 3 km
  The scale of attenuation of the shower is 10 times smaller!!! Direct sampling disfavored

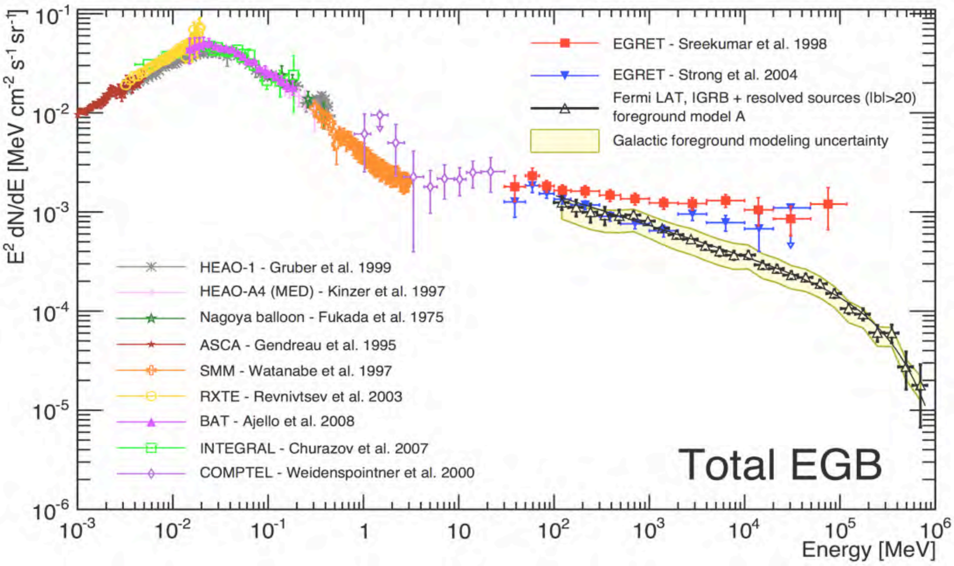


Performance of different types of HE gamma detectors

Table 4.5 A comparison of the characteristics of Fermi, the IACTs and of the EAS particle detector arrays. Sensitivity computed over one year for Fermi and the EAS, and over 50 h for the IACTs

Quantity	Fermi	IACTs	EAS
Energy range	20 MeV – 200 GeV	100 GeV – 50 TeV	400 GeV – 100 TeV
Energy res.	5–10 %	15–20 %	∼ 50 %
Duty cycle	80 %	15 %	> 90 %
FoV	$4\pi/5$	5 deg × 5 deg	$4\pi/6$
PSF (deg)	0.1	0.07	0.5
Sensitivity	1 % Crab (1 GeV)	1 % Crab (0.5 TeV)	0.5 Crab (5 TeV)

Gamma rays above the keV: an overall picture



Summary of lectures 2 and 3

- Detectors for charged cosmic rays: (1) need large effective area for the UHE, (2) smart instruments on satellite for particle identification. For (1) we are close to the limit (Auger) unless we change technology, for (2) we are close to the limit
- Astrophysical neutrino detectors: we need several km3; we are close to the limit (Icecube) but still improving (Antares -> km3)
- Photons:
  - In the MeV region, instruments did not reach the technological limit, yet
  - In the GeV region, Fermi is close to the technological limit
  - In the TeV region, the Cherenkov technique reigns. HESS, MAGIC and VERITAS have still potential, and there is room for improvement by "brute force"
  - In the PeV region, only one detector presently active, and there is room for improvement by "brute force".

Exercises - II

1. *Cherenkov telescopes.* Suppose you have a Cherenkov telescope with 7m diameter, and your camera can detect a signal only when you collect 100 photons from a source. Assuming a global efficiency of 0.1 for the acquisition system (including reflectivity of the surface and quantum efficiency of the PMT),what is the minimum energy (neglecting the background) that such a system can detect at a height of 2 km a.s.l.?
2. *Cherenkov telescopes.* Show that the image of the Cherenkov emission from a muon in the focal plane of a parabolic IACT is a conical section (approximate the Cherenkov angle as a constant).
3. *Energy loss.* In the Pierre Auger Observatory the surface detectors are composed by water Cherenkov tanks 1.2m high, each containing 12 tons of water. These detectors are able to measure the light produced by charged particles crossing them. Consider one tank crossed by a single vertical muon with an energy of 5 GeV. The refraction index of water is n 1.33 and can be in good approximation considered constant for all the relevant photon wavelengths. Determine the energy lost by ionization and compare it with the energy lost by Cherenkov emission.