Multimessenger Astroparticle Physics

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2. How to Detect High-Energy 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

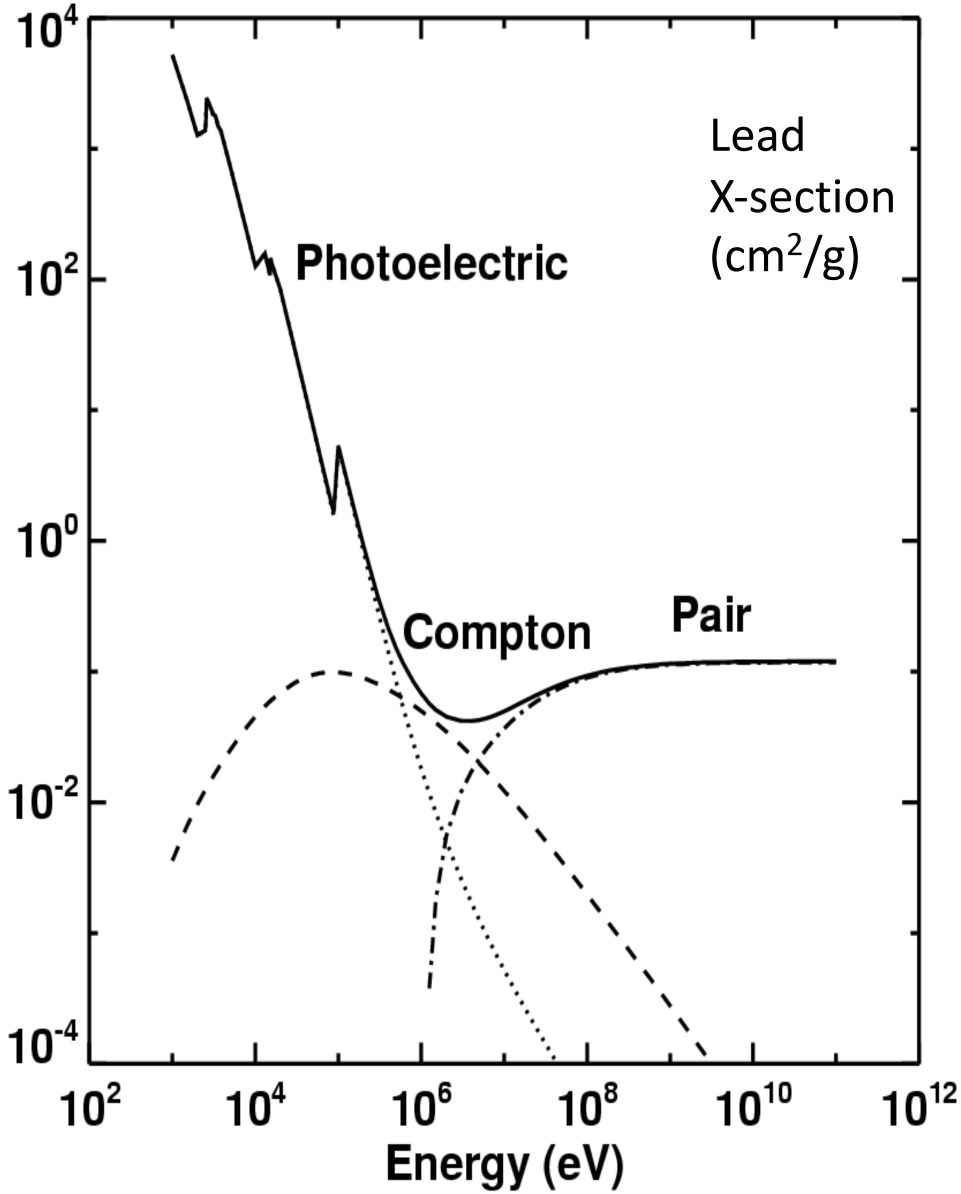
Attenuation of a beam $I = I_0 \exp(-x/\lambda)$

For materials, we often use the attenuation coefficient, μ, (cm^2/g), which is rescaled by the density (this is what you usually find in the PDG)

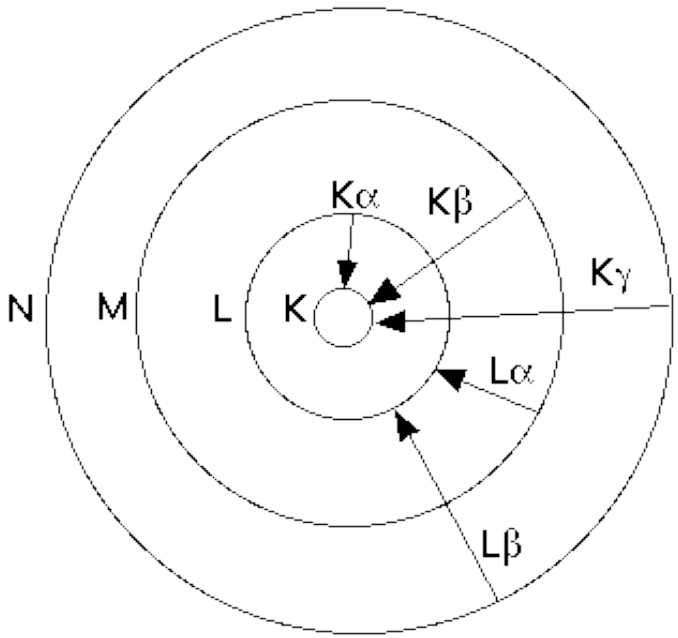
PARTICLE INTERACTIONS WITH MATTER

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

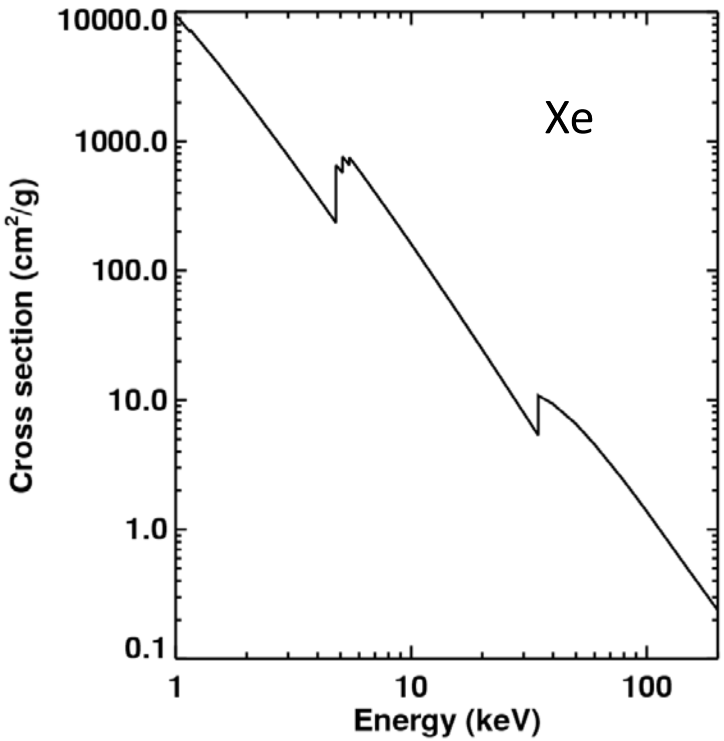


- Photons interact with matter by photoabsorption which causes excitation or ionization of atoms. Photons are absorbed.
- No simple analytic formula (guess why). "Edges" occur at the characteristic electronic transition energies. When in emission, elements produce characteristic lines at these energies

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

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.

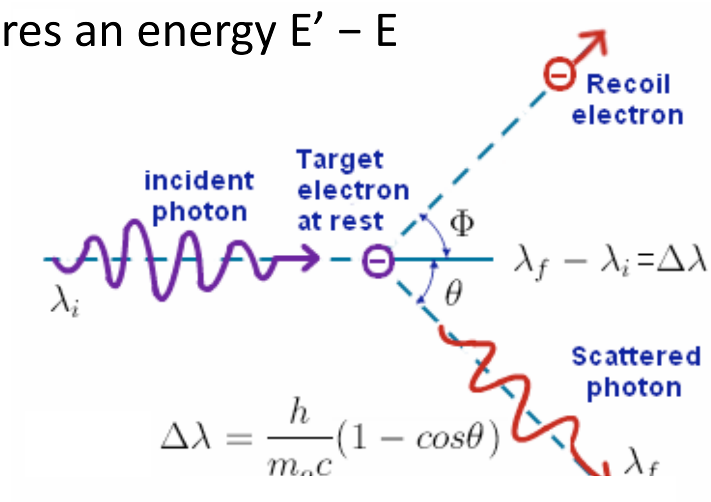


Compton scattering

- 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

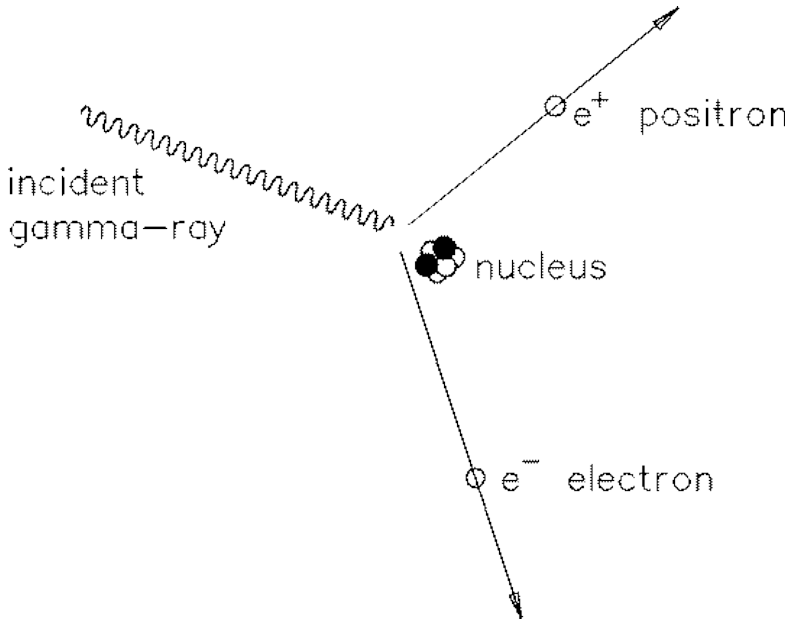


- Cross-section below $m_e c^2$ $\quad \sigma_T \simeq \frac{8\pi\alpha^2}{3(m_e c^2)^2}(\hbar c)^2$ ~ 665 mb

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

- 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

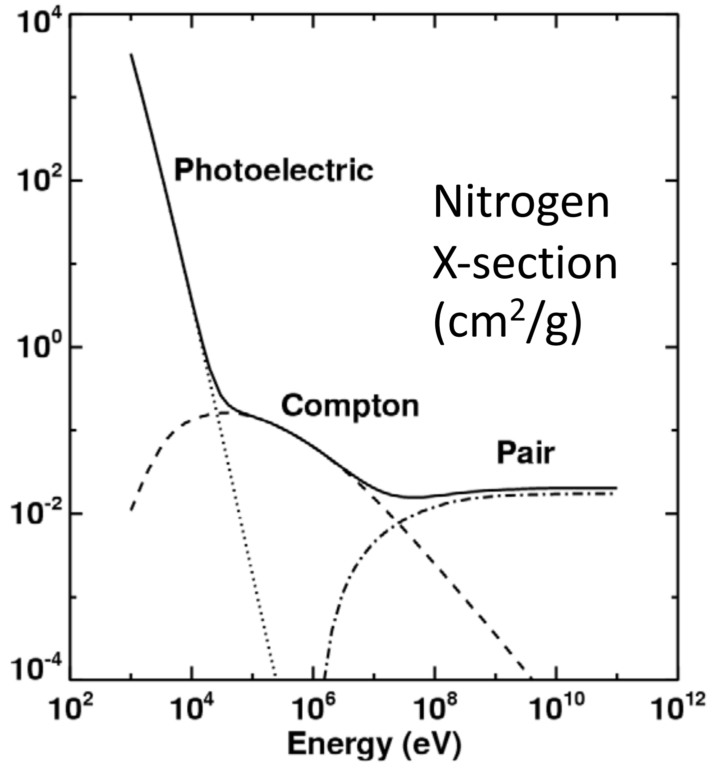
$$\sigma_{Pair} \sim \frac{7}{9}\frac{1}{n_a X_0} \Rightarrow \lambda_{Pair} \sim \frac{9}{7} X_0$$

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

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

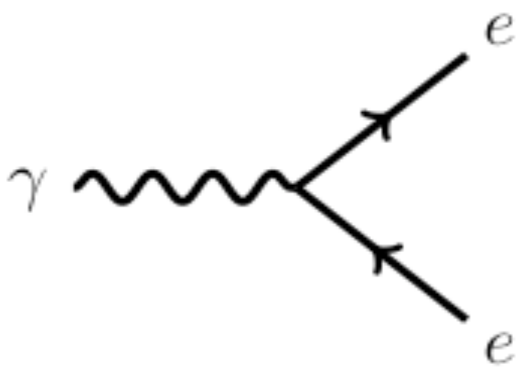
Cross section constant in this regime till 10 PeV, usually expressed in terms of the radiation length X_0- characteristic of the material

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



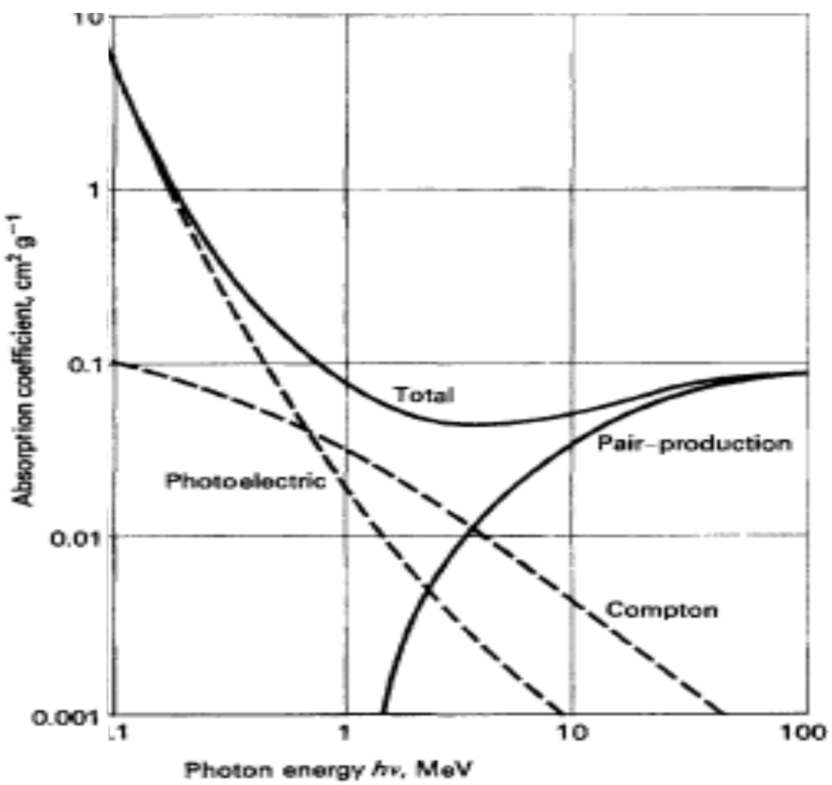
Pair Production - II

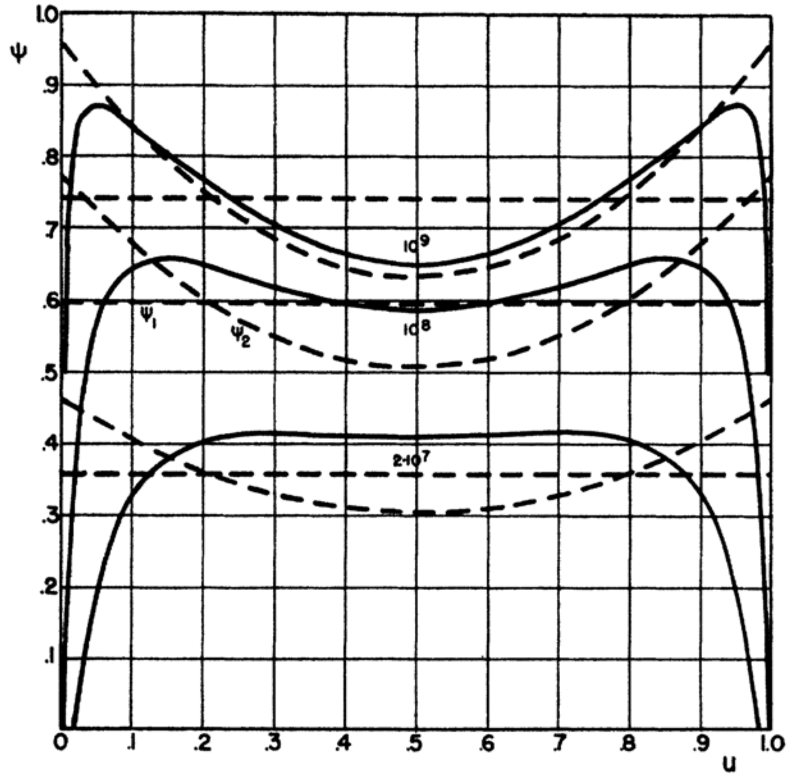
λ = (9/7) Xo for Eγ >> 2m_e



Energy spectrum ~ flat

Angular opening ~0.8 MeV/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.

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

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 $Z > 1$;

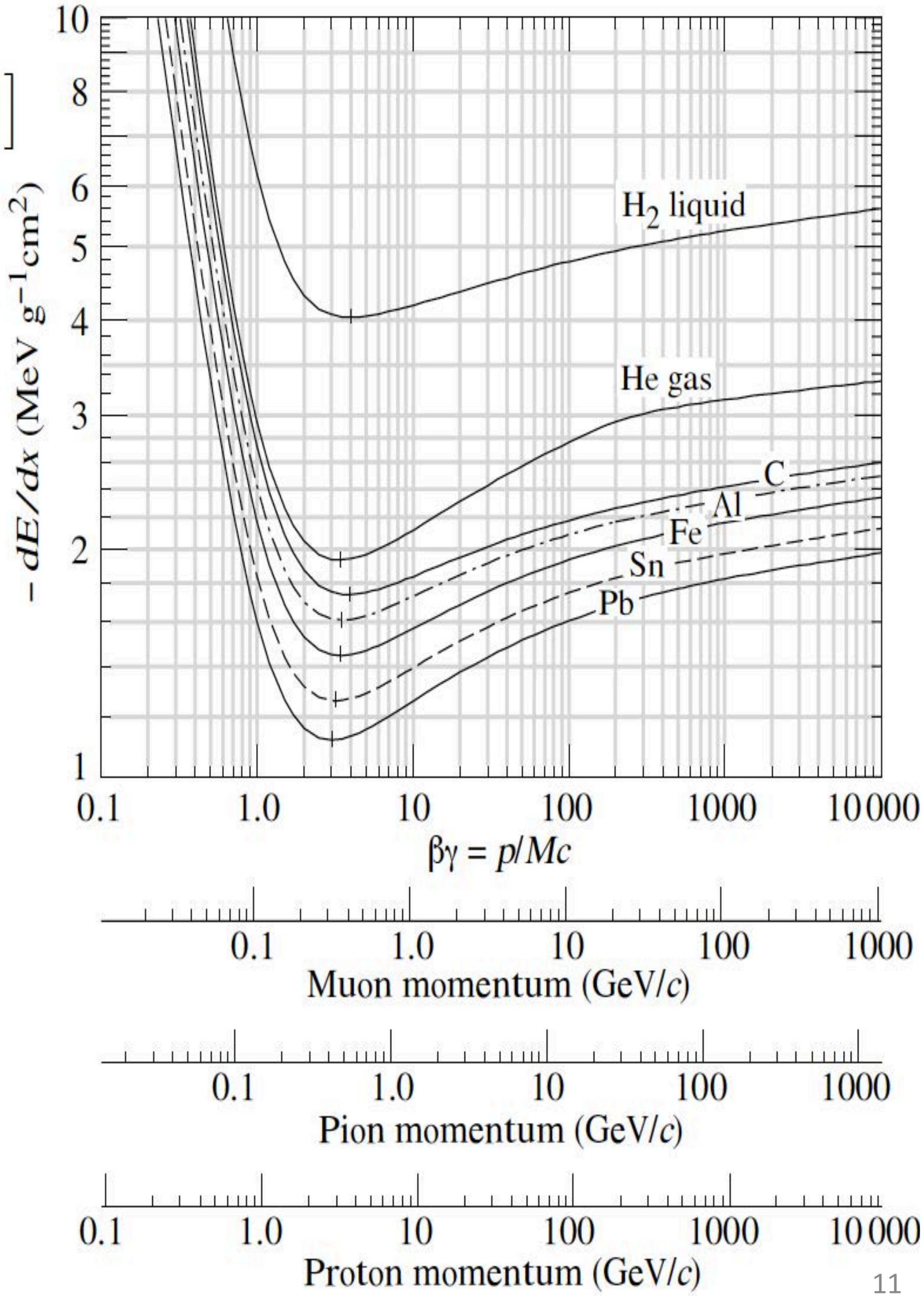
$$-\frac{dE}{dx} \simeq \rho D \left(\frac{Z}{A}\right) \frac{(z_p)^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right) - \beta^2 - \frac{\delta(\beta,\rho)}{2}\,,\right]$$

The energy loss by ionization (Fig. 4.1) in first approximation is:

- independent of the particle's mass;
- 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 $\beta\gamma \leq 3$ (the minimum of ionization: minimum ionizing particle, often just called a "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 practice, most relativistic particles (such as 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 loss from a minimum ionizing particle is well approximated as

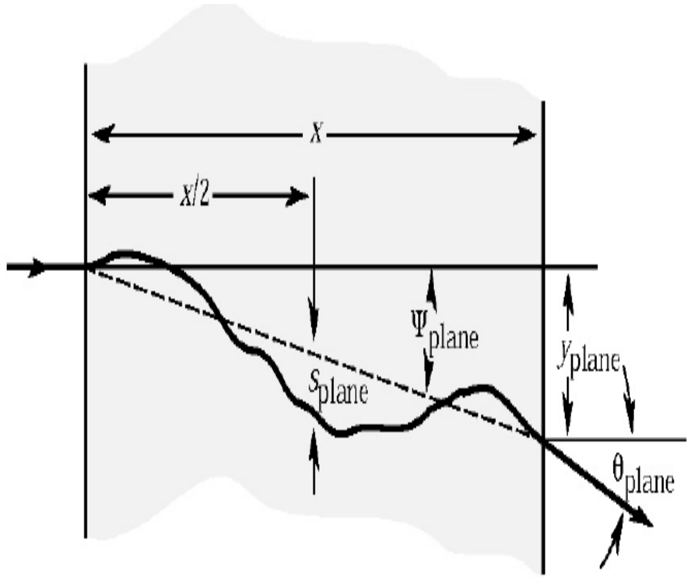
$$\frac{1}{\rho}\frac{dE}{dx} \simeq -3.5 \left(\frac{Z}{A}\right) \mathrm{MeV\,cm^2/g}\,.$$



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):



$$\theta_0 \simeq \frac{13.6\,\mathrm{MeV}}{\beta c p} z_p \sqrt{\frac{x}{X_0}}$$

Electron bremsstrahlung and radiation length

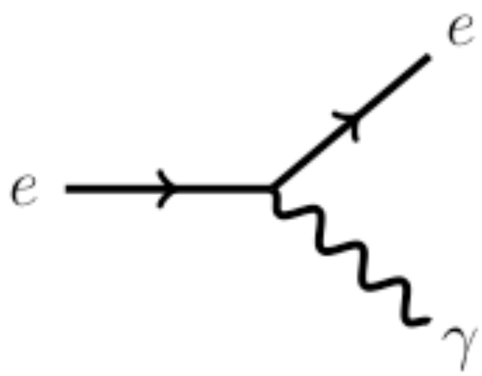
- As pair production, forbidden in vacuo by 4-momentum conservation
  - Requires interaction with the medium
- Photons of momentum $q<E_e$ emitted with probability ~proportional to 1/q
  - (and collimated: ~ m_e/E)

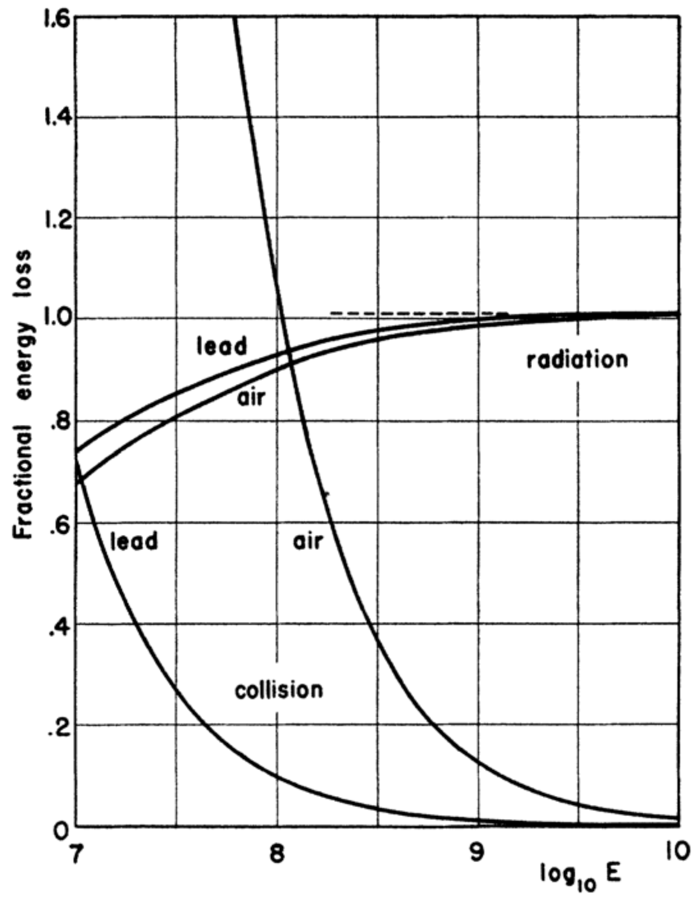
ie, energy emission is ~constant for each interval of photon energy; total is propto E

  - The dependence on the material appears through the radiation length Xo:

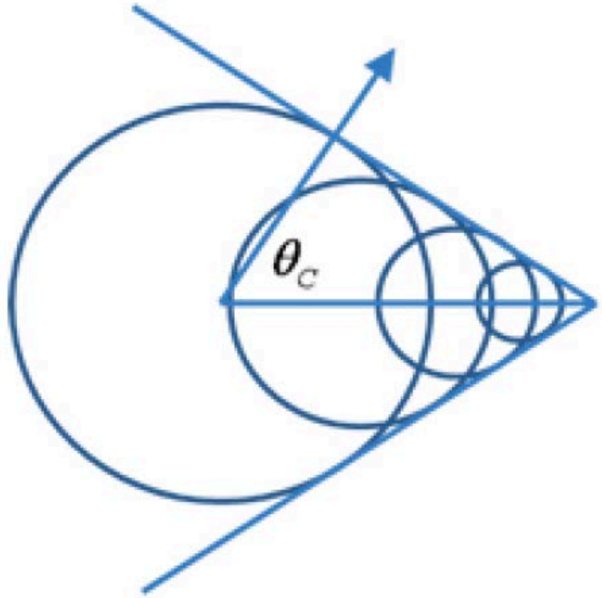
$$dE_e/dx = -1/Xo$$

  - Xo can be found in tables. It is ~400 m for air at NTP, ~43 cm for water; for density 1 g/cm^3
  - 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

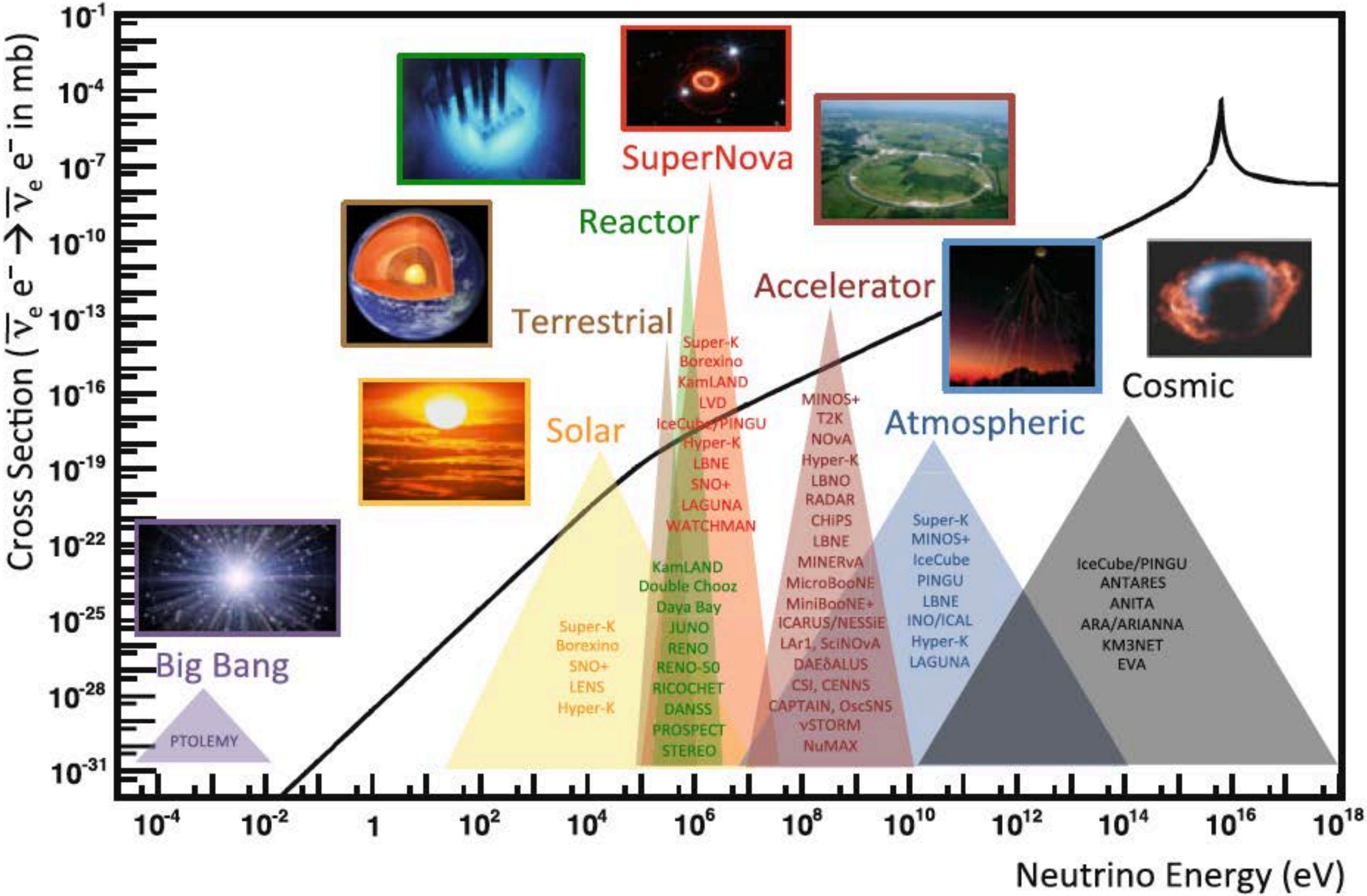
Hadronic interactions

- 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

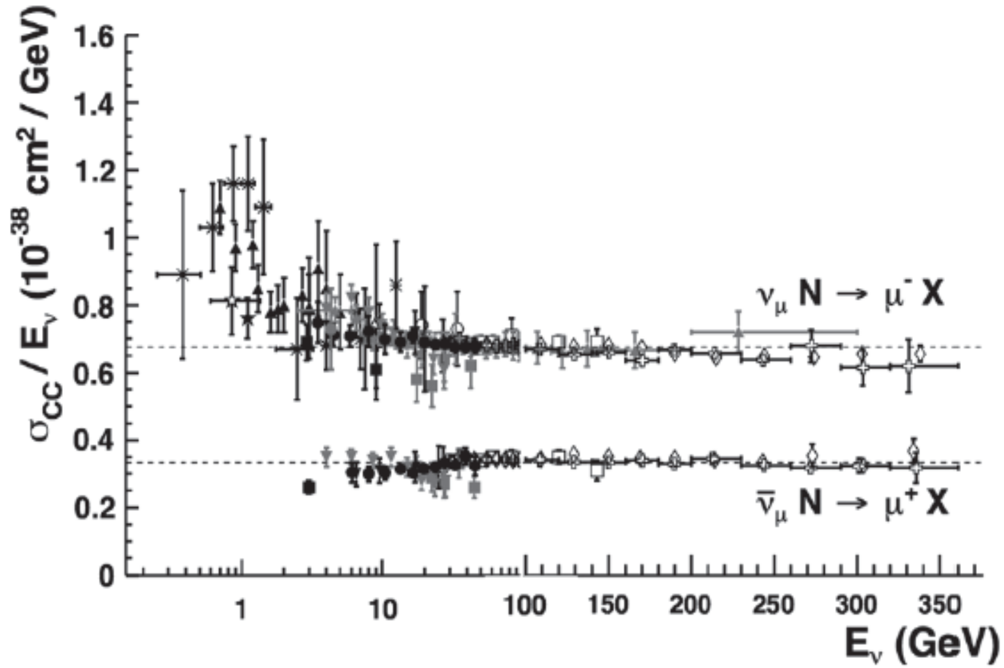
$$1/\lambda_T = 1/\lambda_H + 1/\lambda_I \ .$$

- 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.

Neutrino cross sections



Neutrino cross section: quantitative



The neutrino-nucleon cross section grows with energy. It can be parameterized for intermediate energies, 1 MeV $\lesssim E \lesssim$ 10 TeV (Fig. 4.9) as

$$\sigma_{\nu N} \simeq (0.67 \times 10^{-38} E)\,\mathrm{cm}^2 = (6.7\,E)\,\mathrm{fb}\,, \quad (4.11)$$

E being the neutrino energy in GeV. At energies between 10 TeV and 10^7 TeV (10^{19} eV), a parametrization is

$$\sigma_{\nu N} \simeq \left(0.67 \times 10^{-34} \sqrt{\frac{E}{10\,\mathrm{TeV}}}\right) \mathrm{cm}^2\,. \quad (4.12)$$

Solar neutrinos, which have MeV energies, typically cross the Earth undisturbed (see a more complete discussion in Chap. 9).

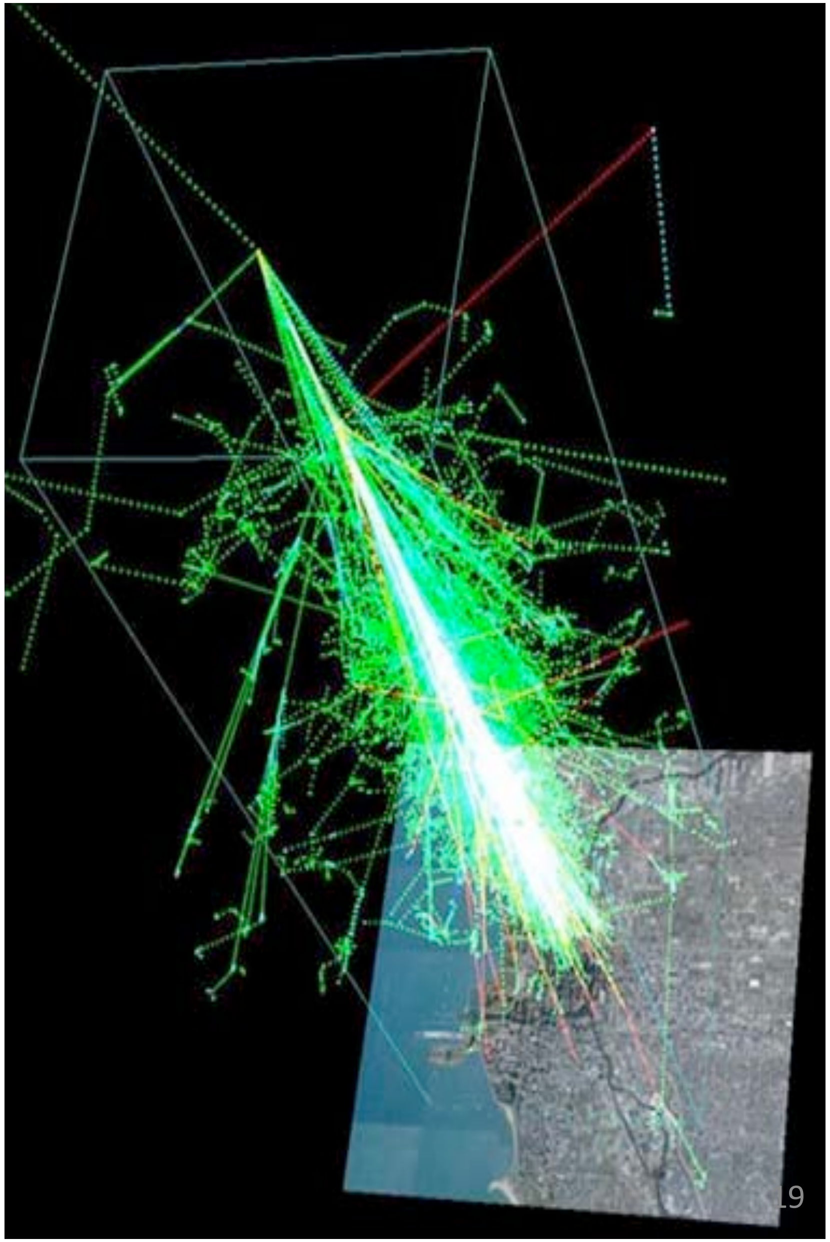
The low value of the interaction cross section makes the detection of neutrinos very difficult.

Bruno Rossi

- 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 $R_M \sim (21\ \text{MeV}/E_c)\ Xo$
    - 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

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

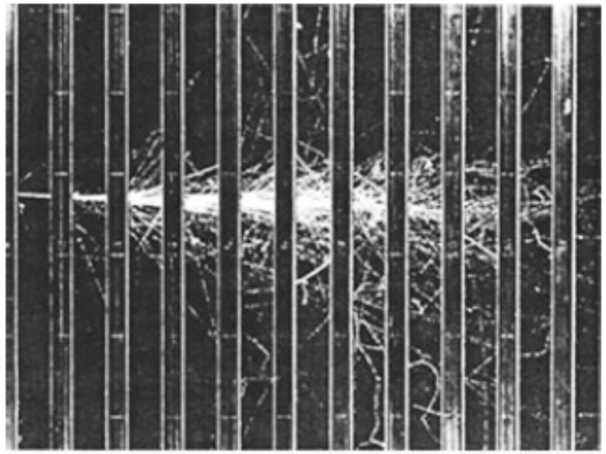
$$E(t) = E_0/2^t$$

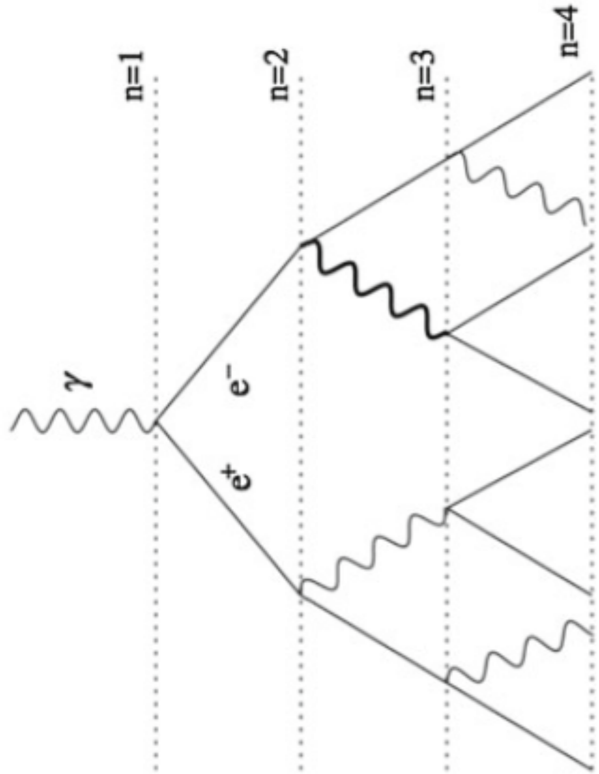
- The multiplication process will cease when $E(t)=E_C$

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

and the number of particles at this point will be

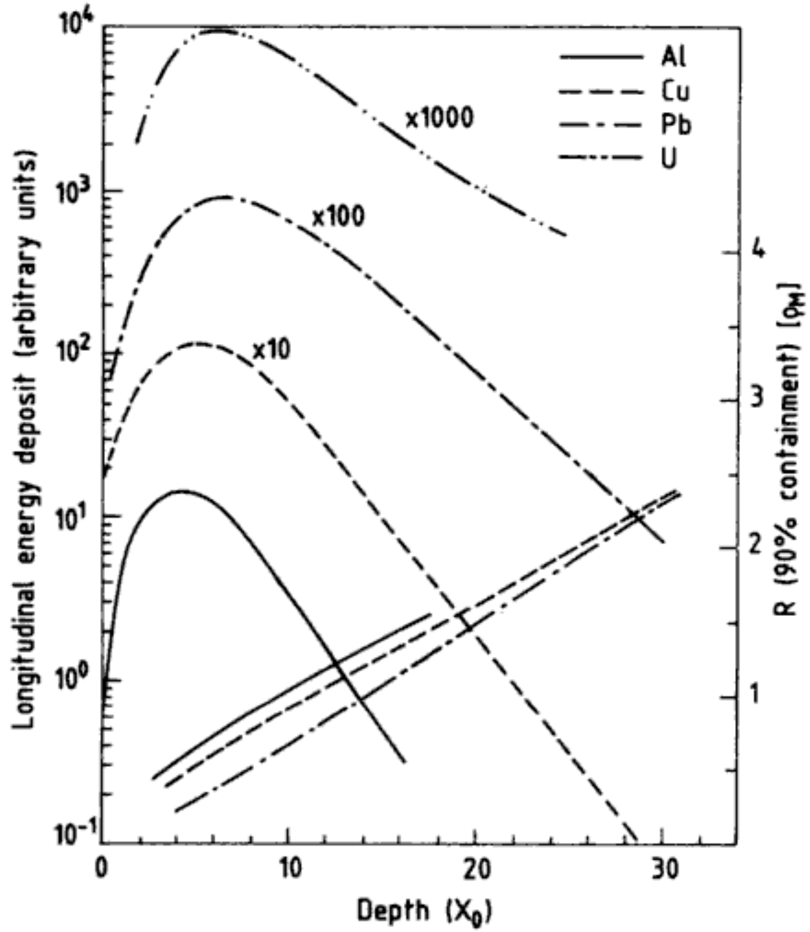
$$N_{max} = \exp\,(t_{max}\,\ln\,2) = E_0 \big/ E_C$$





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)

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

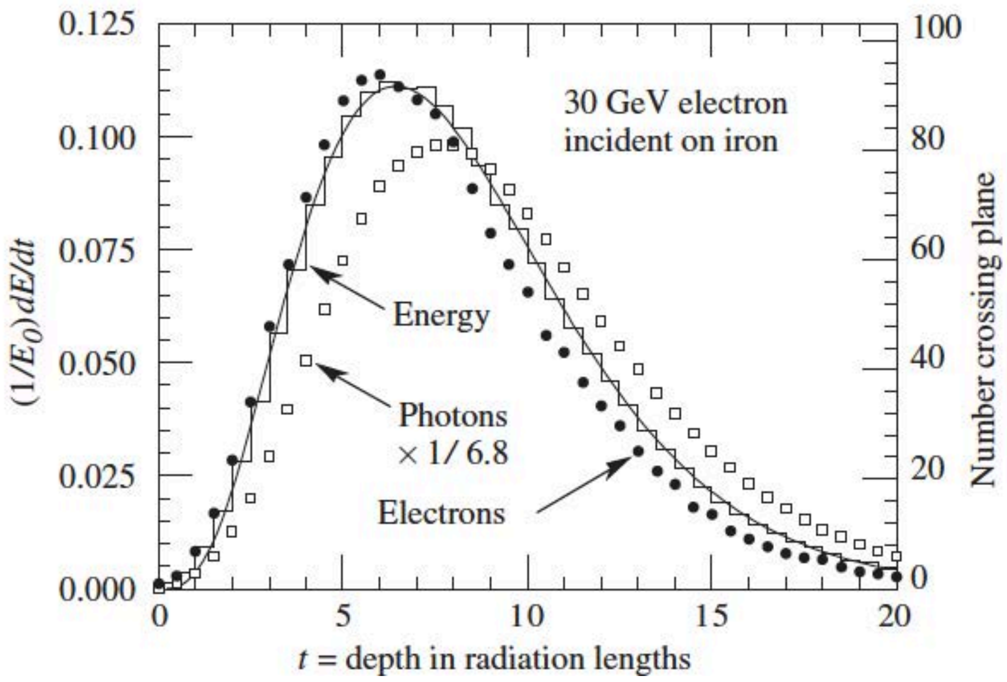
$$\frac{\partial \gamma(W,t)}{\partial t} = \int_0^1 \pi\left(\frac{W}{v}, t\right)\varphi_0(v)\frac{dv}{v} - \sigma_0\gamma(W,t)$$

A useful parametrization of the longitudinal development

A common parameterization of the longitudinal profile for a shower of initial energy E_0 is

$$\frac{dE}{dt} = E_0 \frac{\beta}{\Gamma(\alpha)} (\beta t)^{\alpha-1} e^{-\beta t} , \qquad (4.13)$$

where Γ is Euler's Gamma function $\Gamma(z) = \int_0^{+\infty} t^{z-1} e^{-t} \, dt$. In the above approximation, $t_{\max} = (\alpha - 1)/\beta$, which should be thus equal to $\ln(E_0/E_c) - C$ with $C = 1$ for an electron and $C = 0.5$ for a photon.

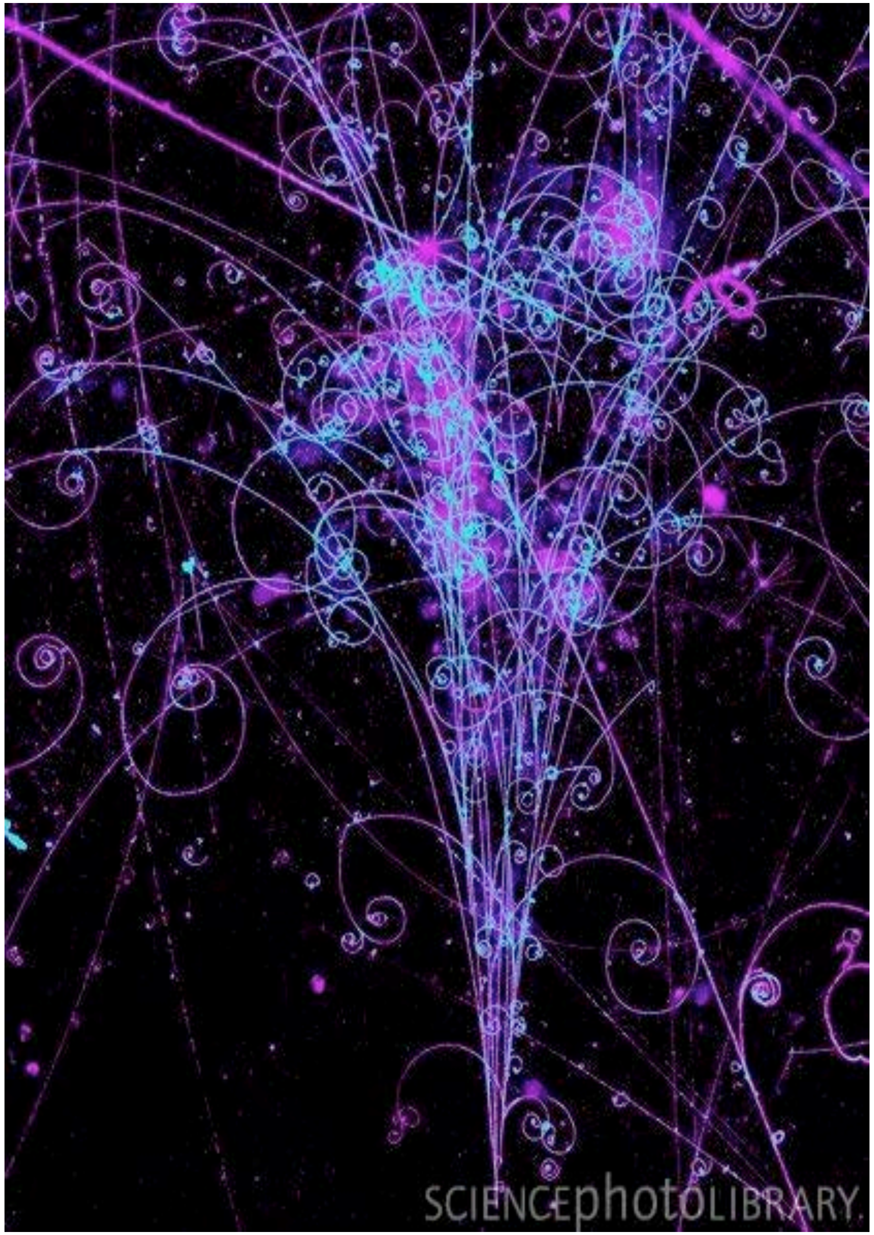


Energy measurement

- 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



Shower age; transverse profile

The description of the transverse development of a shower is more complicated. Usually the normalized lateral density distribution of electrons is approximated by the Nishimura-Kamata-Greisen (NKG) function, which depends on the "shower age" s, being 0 at the first interaction, 1 at the maximum and 3 at the death [F4.1]:

$$s = \frac{3t}{t + 2t_{\mathrm{max}}} \tag{4.14}$$

but not on its energy. The NKG function:

$$\rho_{\mathrm{NKG}}(r, s, N_e) = \frac{N_e}{R_M^2} \frac{\Gamma(4.5 - s)}{2\pi\Gamma(s)\Gamma(4.5 - 2s)} \left(\frac{r}{R_M}\right)^{s-2} \left(1 + \frac{r}{R_M}\right)^{s-4.5} \tag{4.15}$$

where N_e is the electron shower size, r is the distance from the shower axis, and R_M is a transverse scale called the Molière radius described below, is accurate for a shower age $0.5 < s < 1.5$. A variety of transverse distribution functions can be found in the literature (Greisen, Greisen–Linsley, etc.) and are mostly specific modifications of the NKG function.

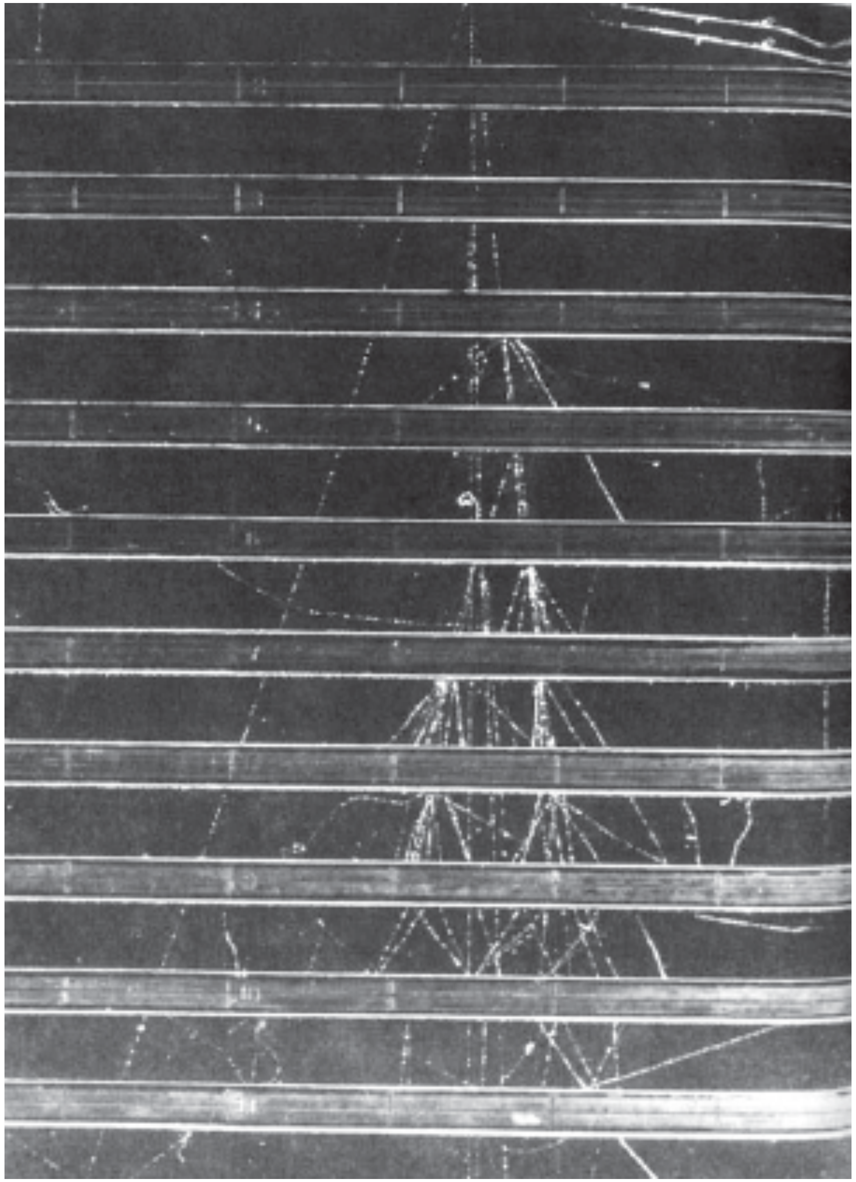
Hadronic showers and calorimeters

- 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 $\lambda_H > Xo$, 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

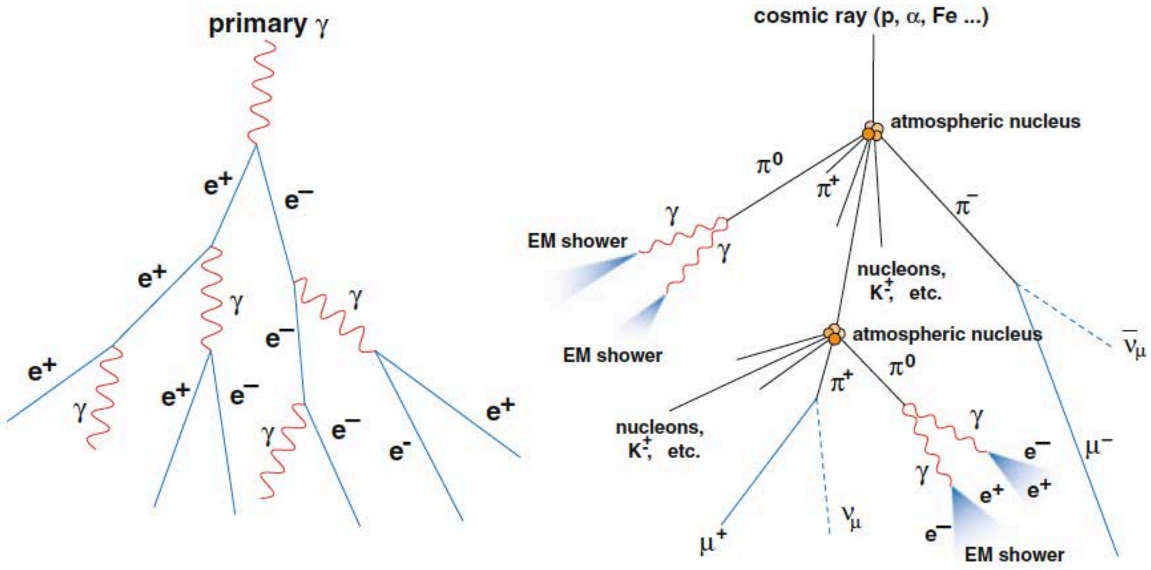
A Heitler model for hadronic showers

- Subject to large fluctuations
- At the end of a hadronic cascade, most particles are pions; 1/3 of the pions are neutral and decay almost instantaneously ($\sim 10^{-16}$ s) into a pair of photons; thus on average one-third of the hadronic cascade is indeed electromagnetic (and the fraction of energy detected in electromagnetic form is larger, since roughly three quarters of the charged pion energy is "wasted" into neutrinos)
- Although needing MC, can be in a 0th-order approximation sketched by a simple Heitler-like model: after each depth d an equal number of pions (+ - 0) are produced. Neutral pions decay into $\gamma\gamma$ and their energy is transferred to the electromagnetic cascade.



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 90 g/cm^2 for protons (750 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”

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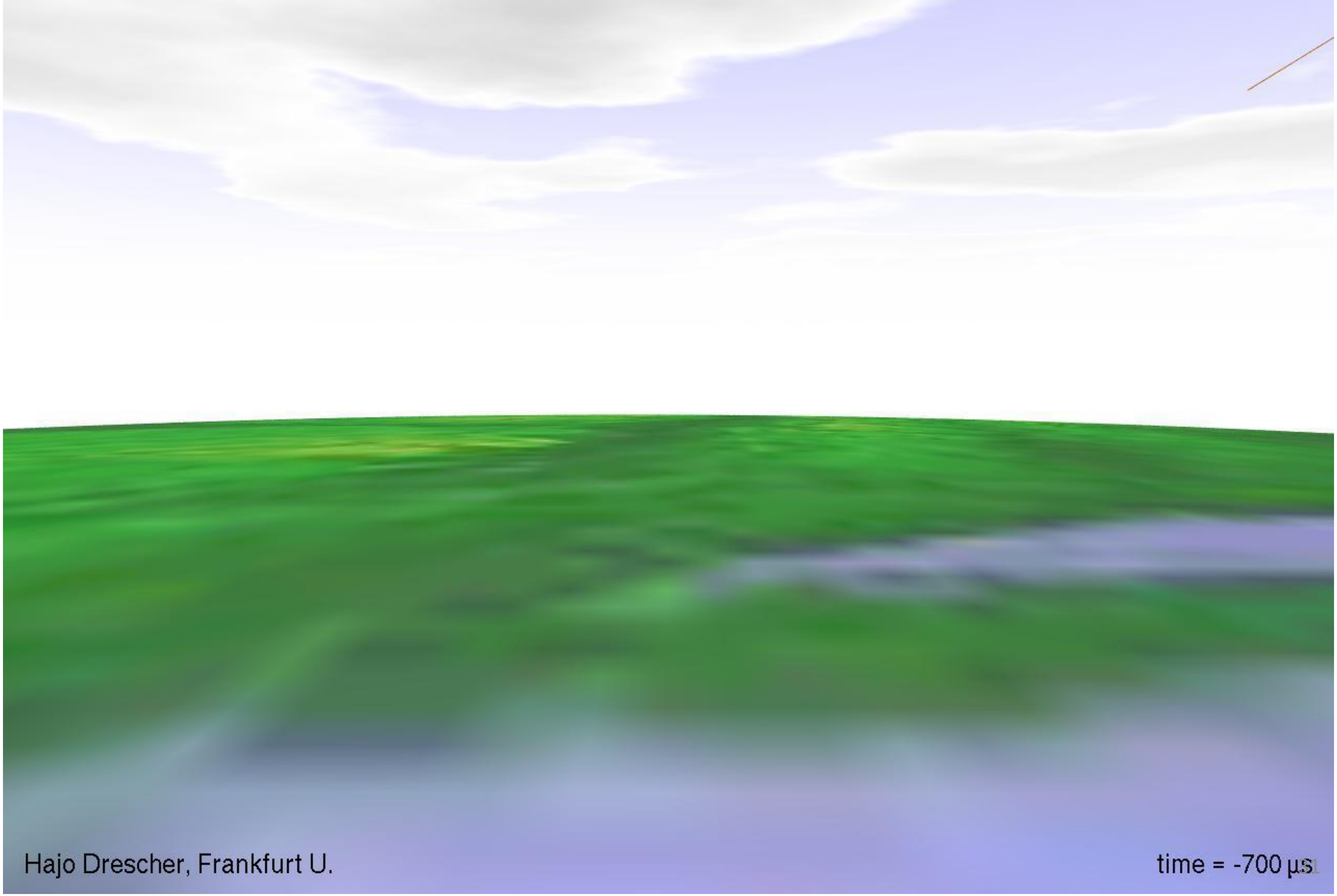
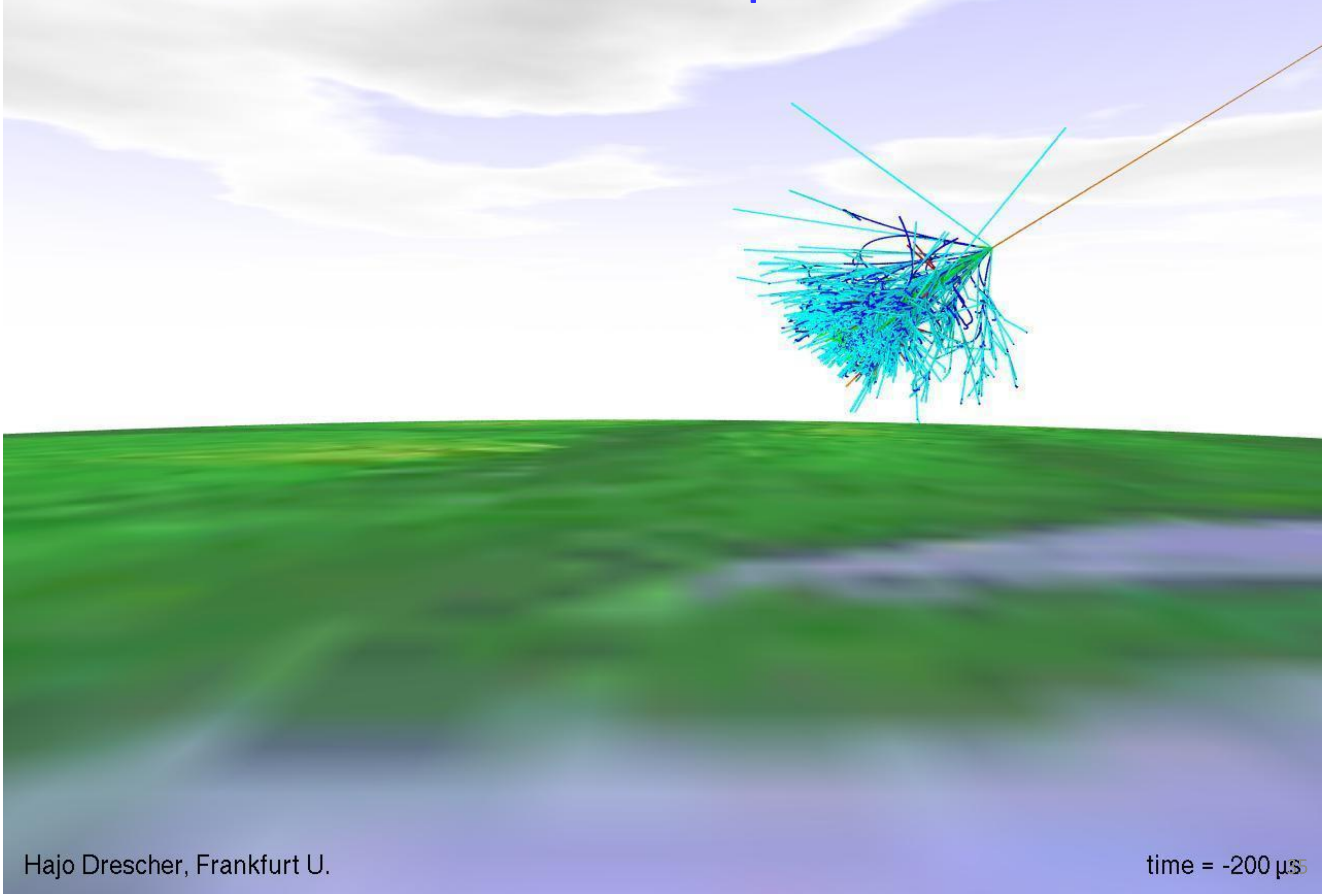


The events: Cosmic rays “rain”

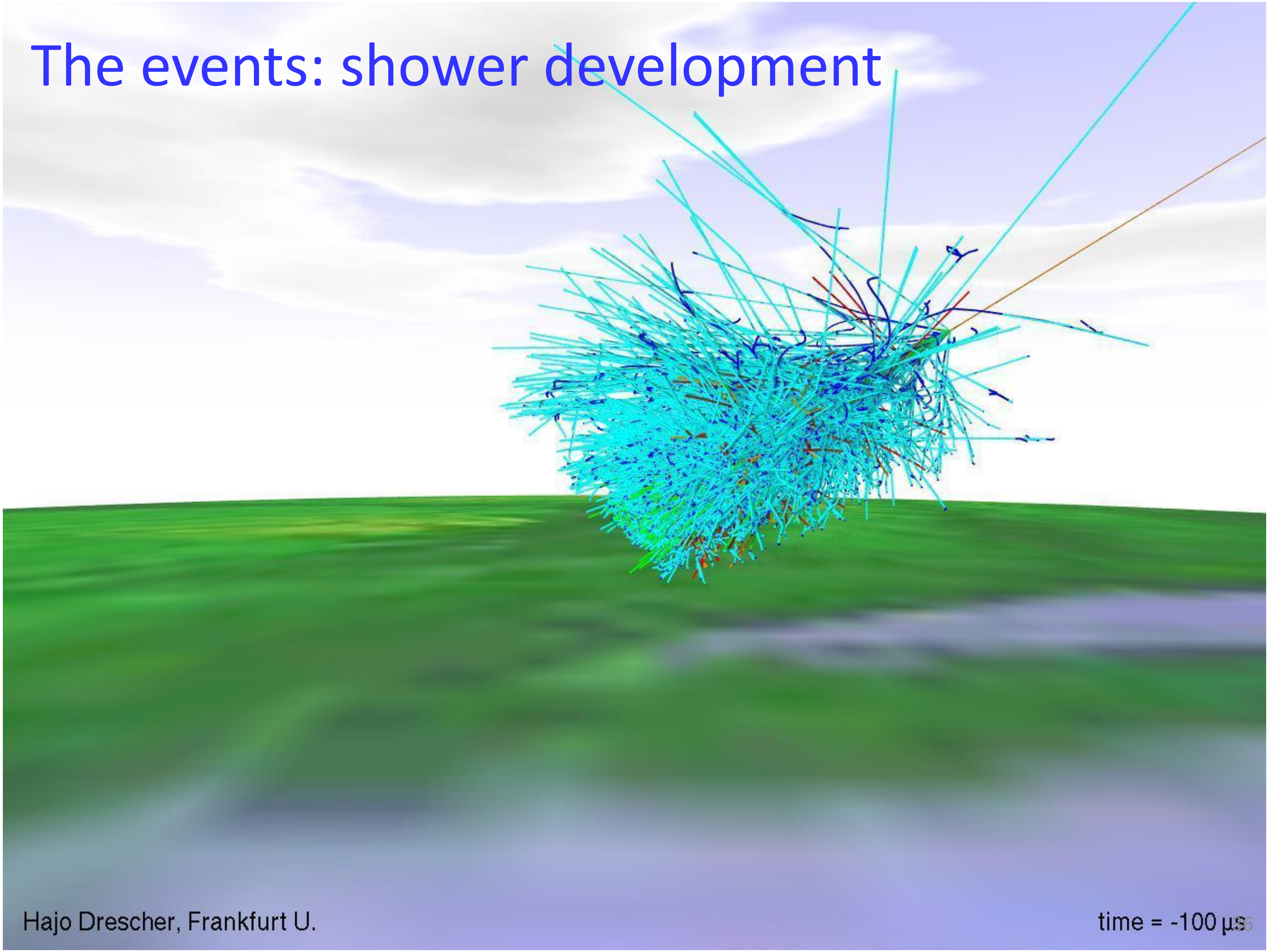
The events: Cosmic rays “rain”

The events: first interaction

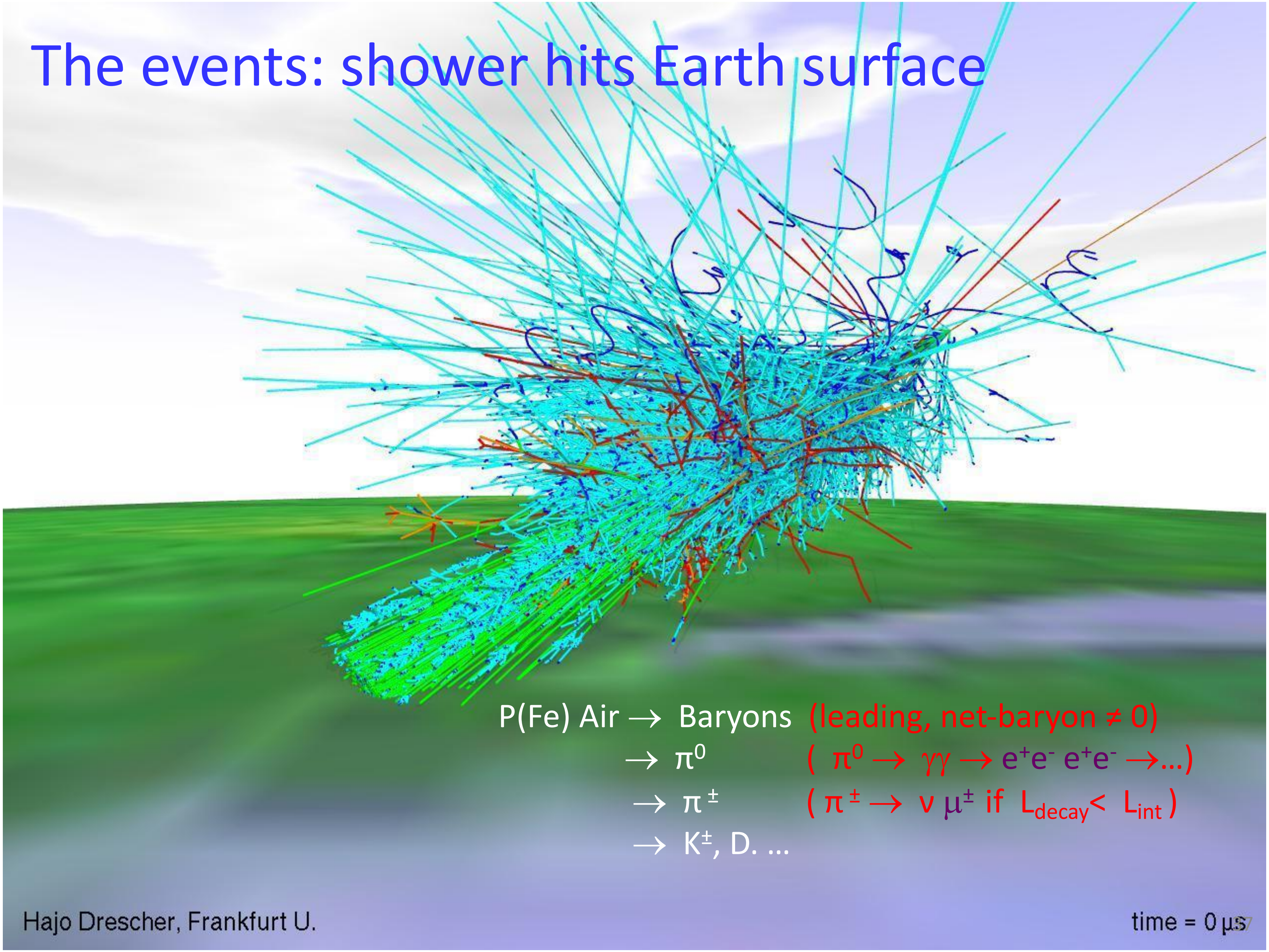
The events: shower development



The events: shower development



The events: shower hits Earth surface



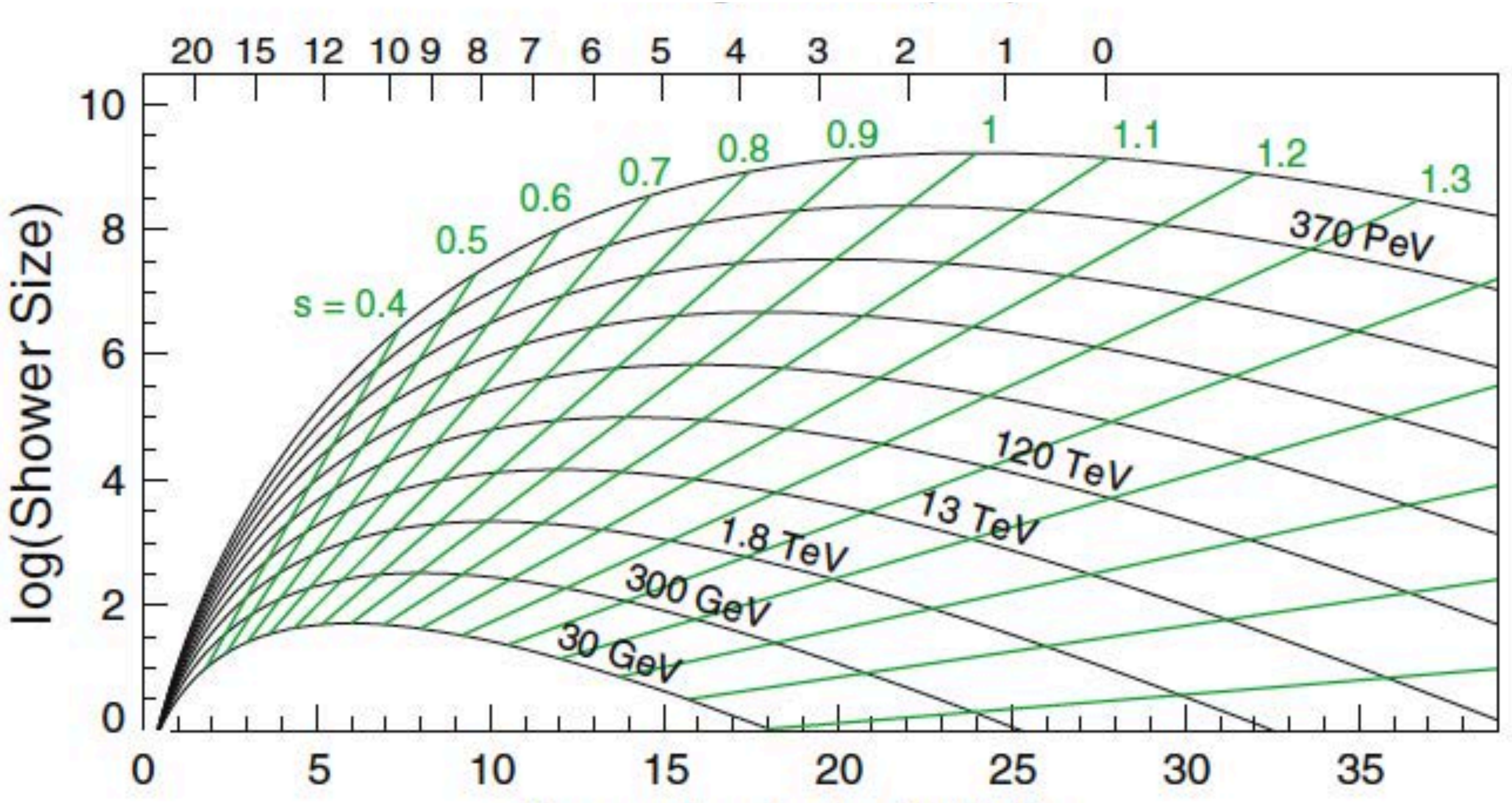
P(Fe) Air $\rightarrow$ Baryons (leading, net-baryon $\neq 0$)

$\rightarrow \pi^0$ ($\pi^0 \rightarrow \gamma\gamma \rightarrow e^+e^- \, e^+e^- \rightarrow \ldots$)

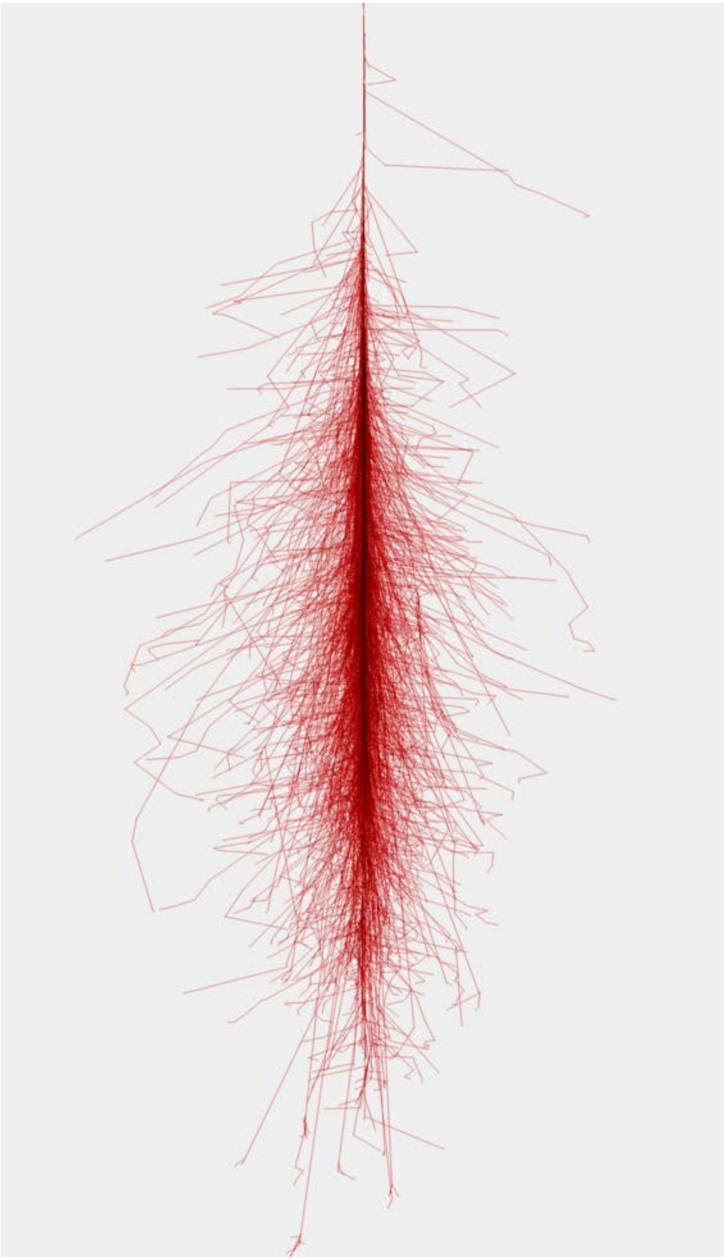
$\rightarrow \pi^\pm$ ($\pi^\pm \rightarrow \nu \, \mu^\pm$ if $L_{decay} < L_{int}$)

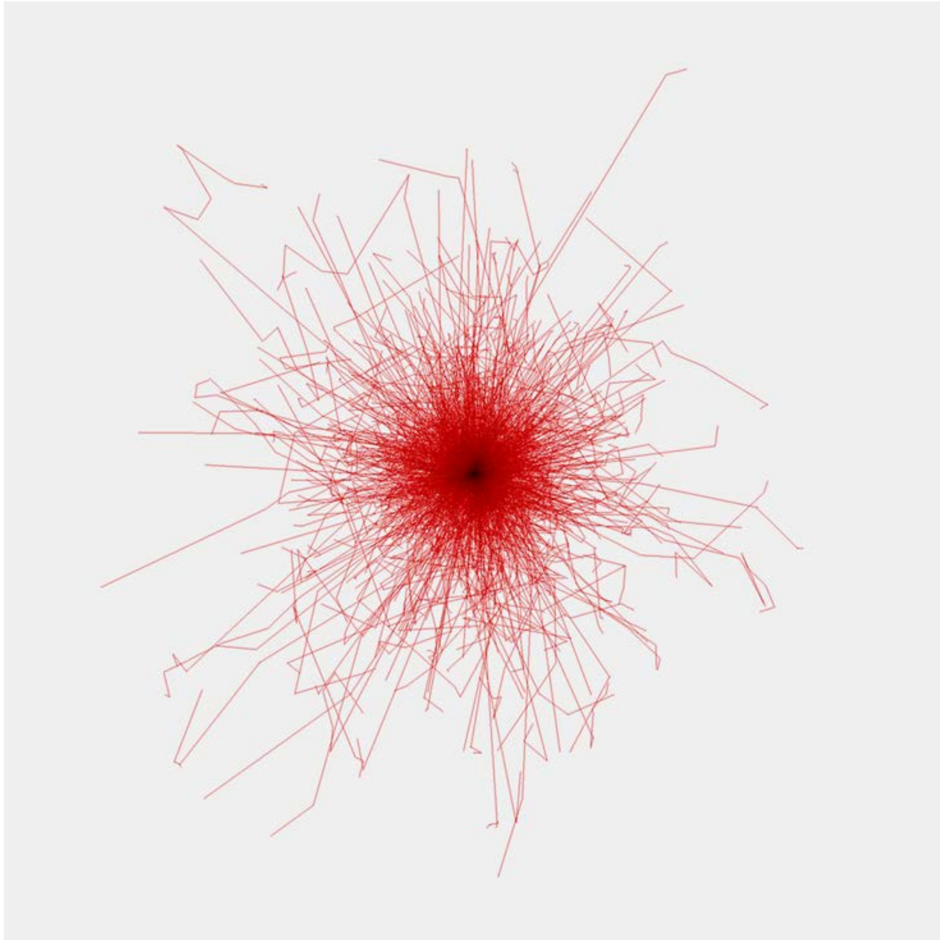
$\rightarrow K^\pm$, D. ...

Photon-initiated shower in the atmosphere



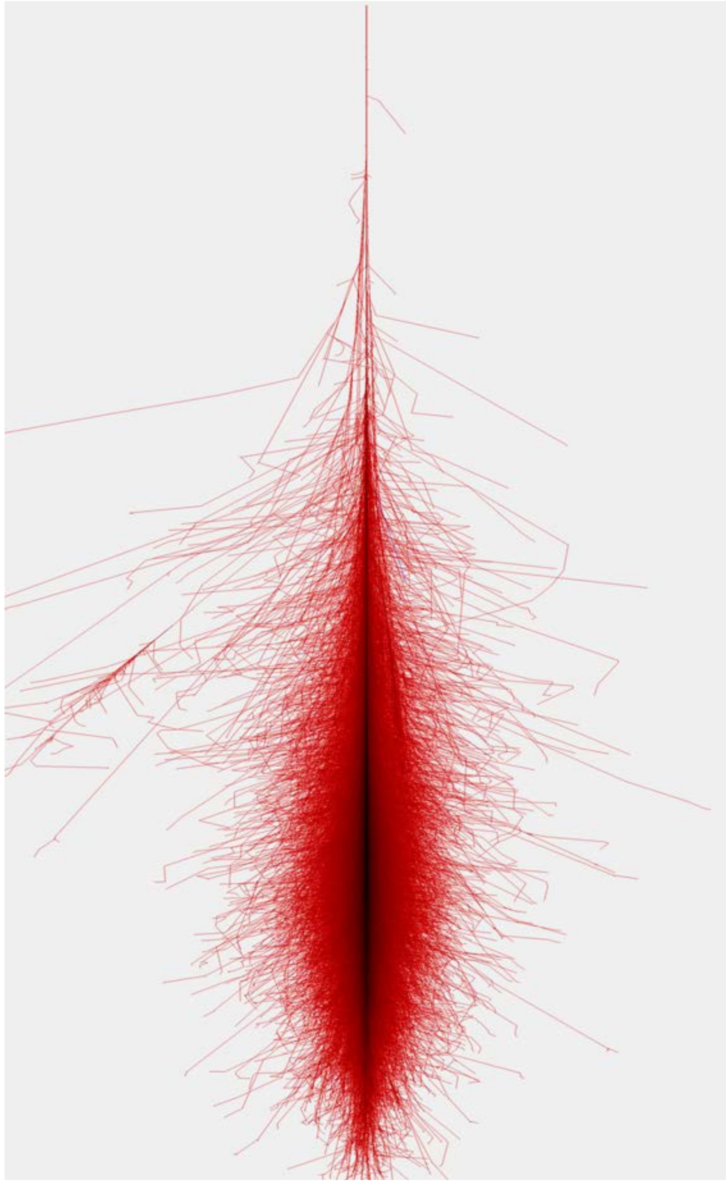
A frequent experimental problem: γ/hadron separation

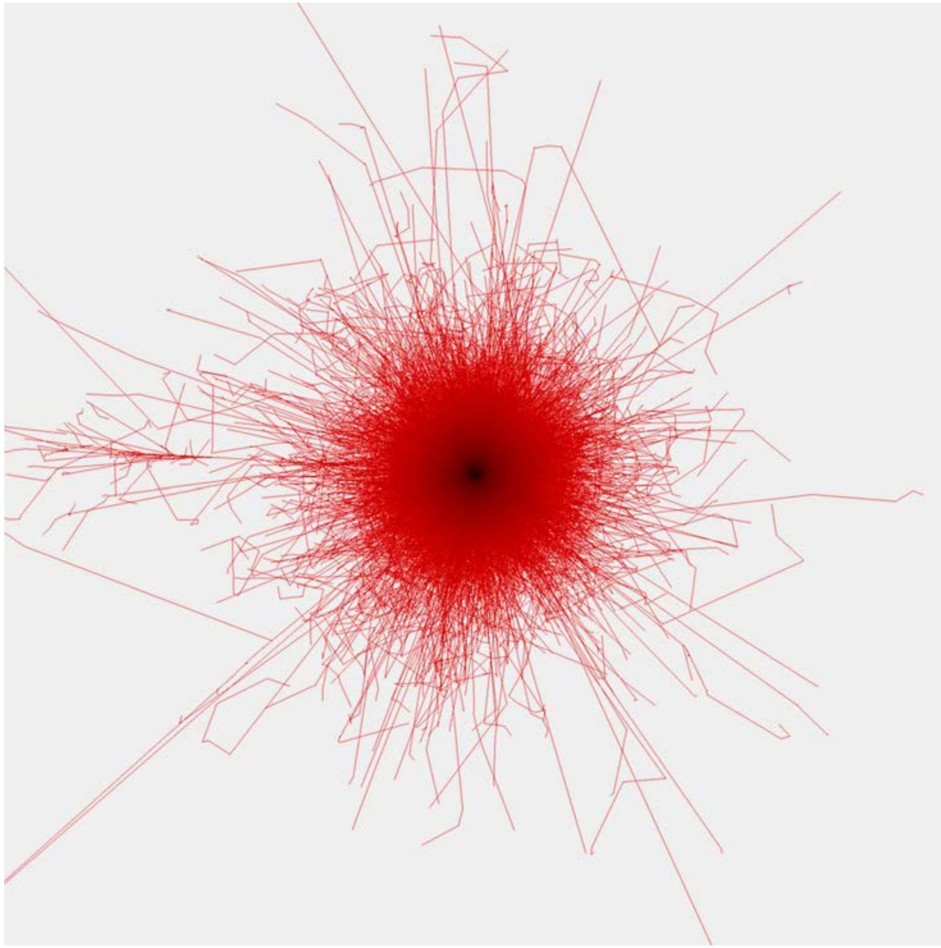




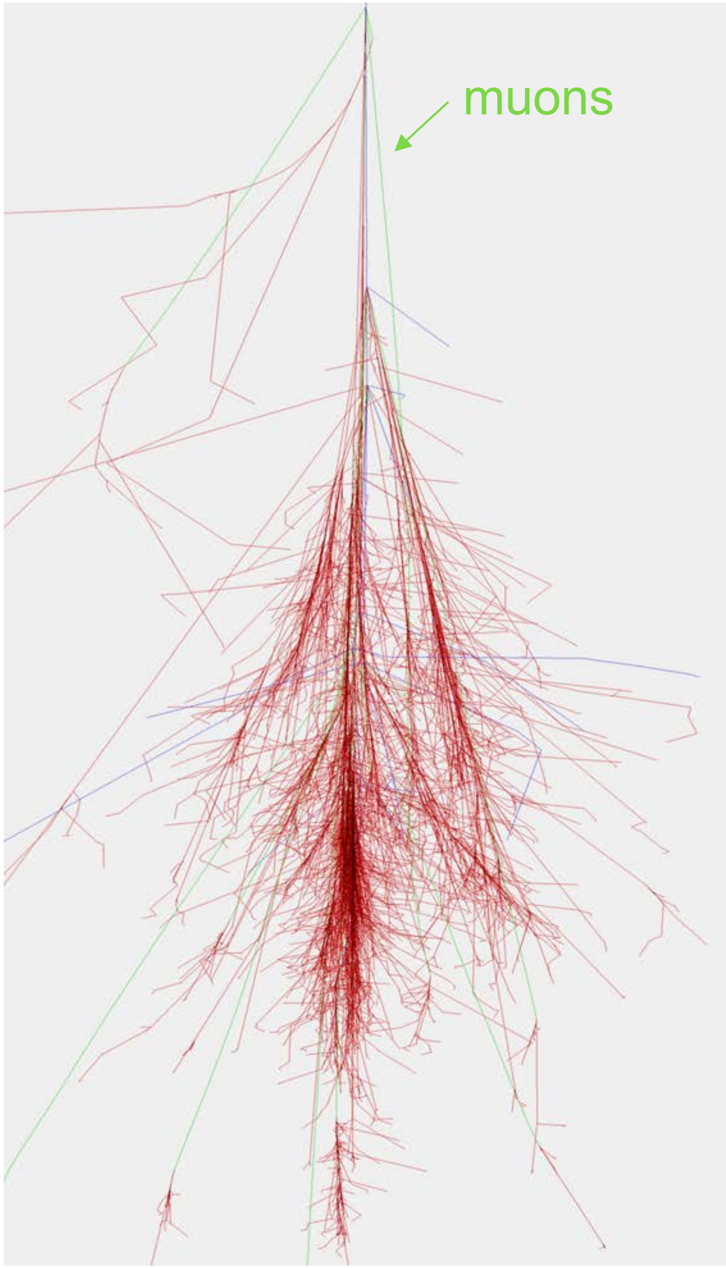
Simulated gamma
in the atmosphere:
50 GeV

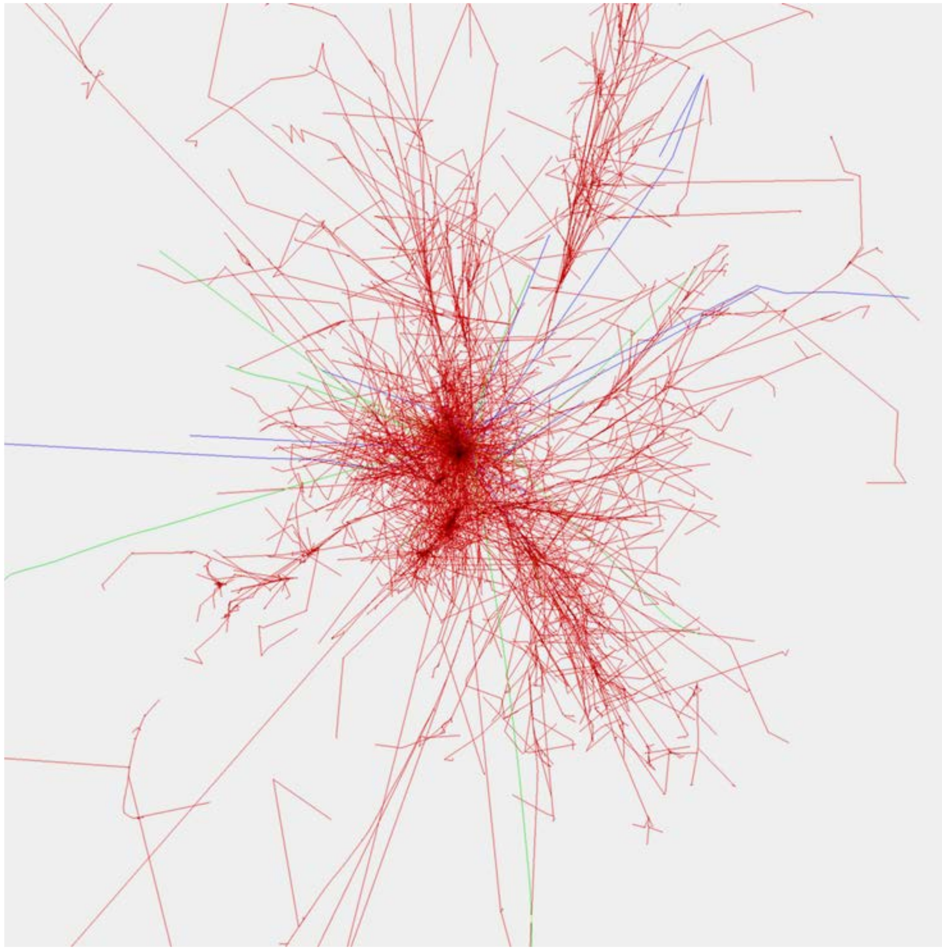
Simulated gamma
1 TeV





Simulated proton
100 GeV





LET'S DETECT

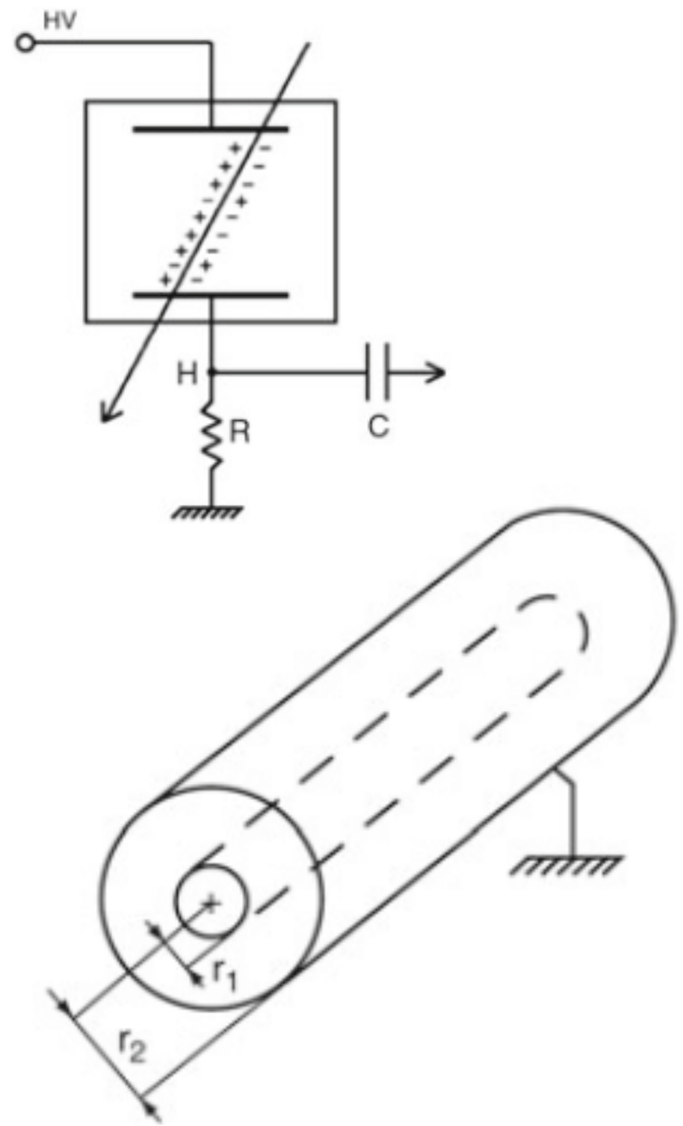
Tracking detectors (charged particles)

- 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

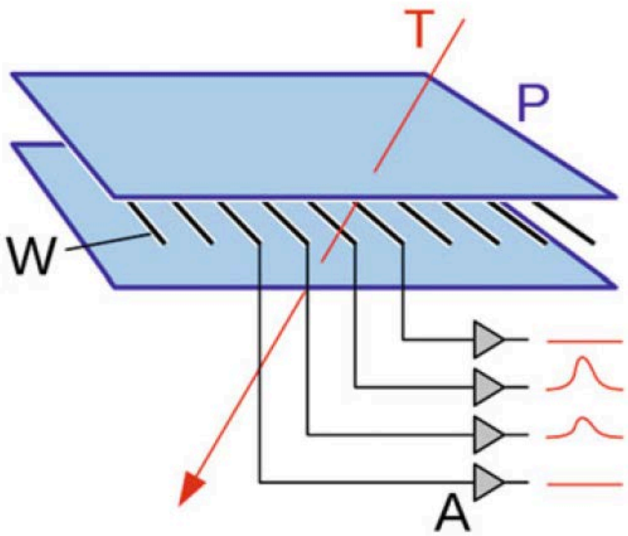
$$p\ (\mathrm{GeV}/c) \sim 0.3\ B_{\perp}(\mathrm{T})\ R\ (\mathrm{m})$$

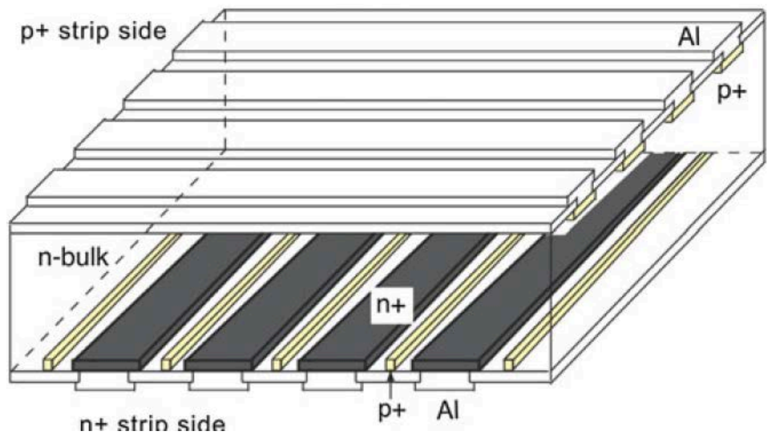
- A source of uncertainty for this determination is given by the errors in the measurement of the hits; another (intrinsic) noise is given by multiple scattering. In what follows we shall review some detectors used to determine the trajectory of charged tracks.

- Prototype: the ionization tube (Geiger-Muller, …)



Tracking detectors (charged particles)



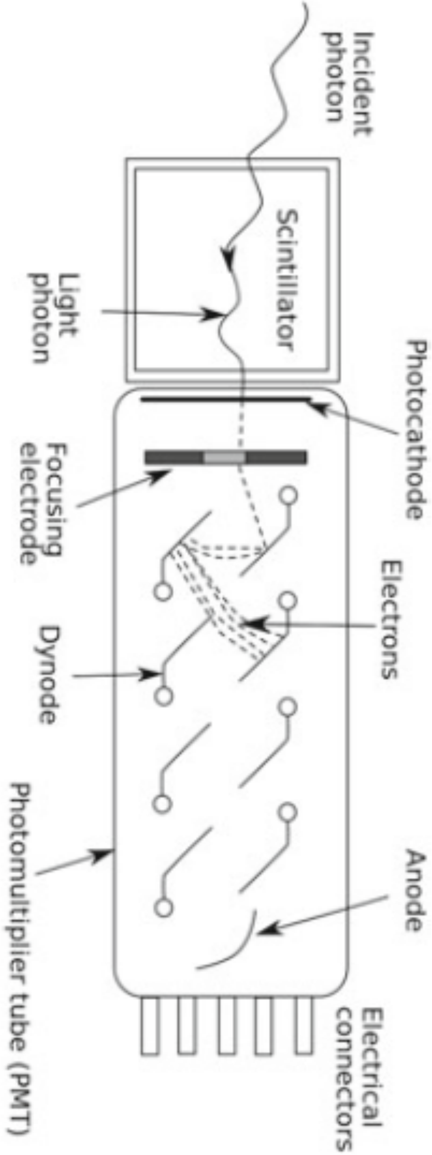


Detector type	Spatial resolution	Time resolution	Dead time
RPC	$\leq$10mm	$\sim$1ns (down to $\sim$50 ps)	–
Scintillation counter	10 mm	0.1 ns	10 ns
Emulsion	1 µm	–	–
Bubble chamber	10–100 µm	1 ms	50 ms–1 s
Proportional chamber	50–100 µm	2 ns	20–200 ns
Drift chamber	50–100 µm	few ns	20–200 ns
Silicon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

Photodetectors

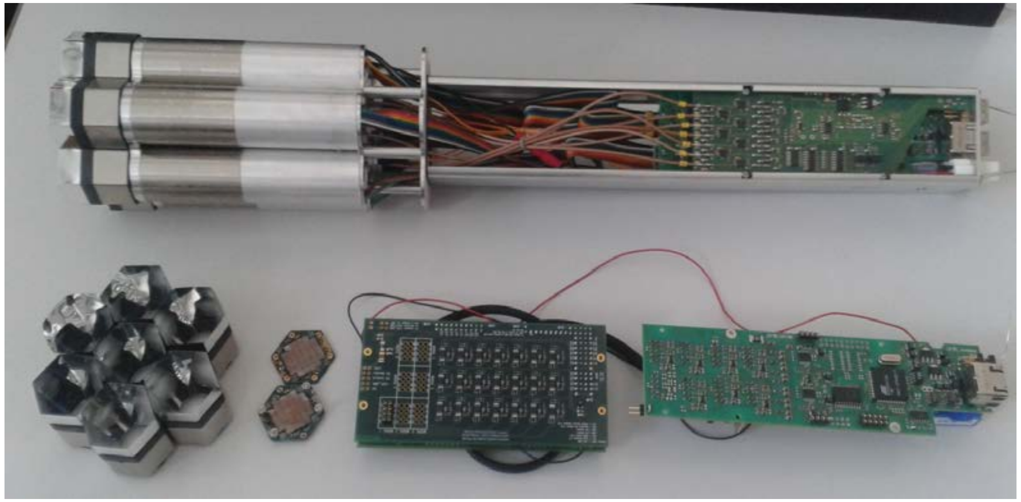
- Most detectors in particle physics and astrophysics rely on the detection of photons near the visible range, i.e., in the eV energy range. This range covers scintillation and Cherenkov radiation as well as the light detected in many astronomical observations.
- One needs to extract a measurable signal 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.

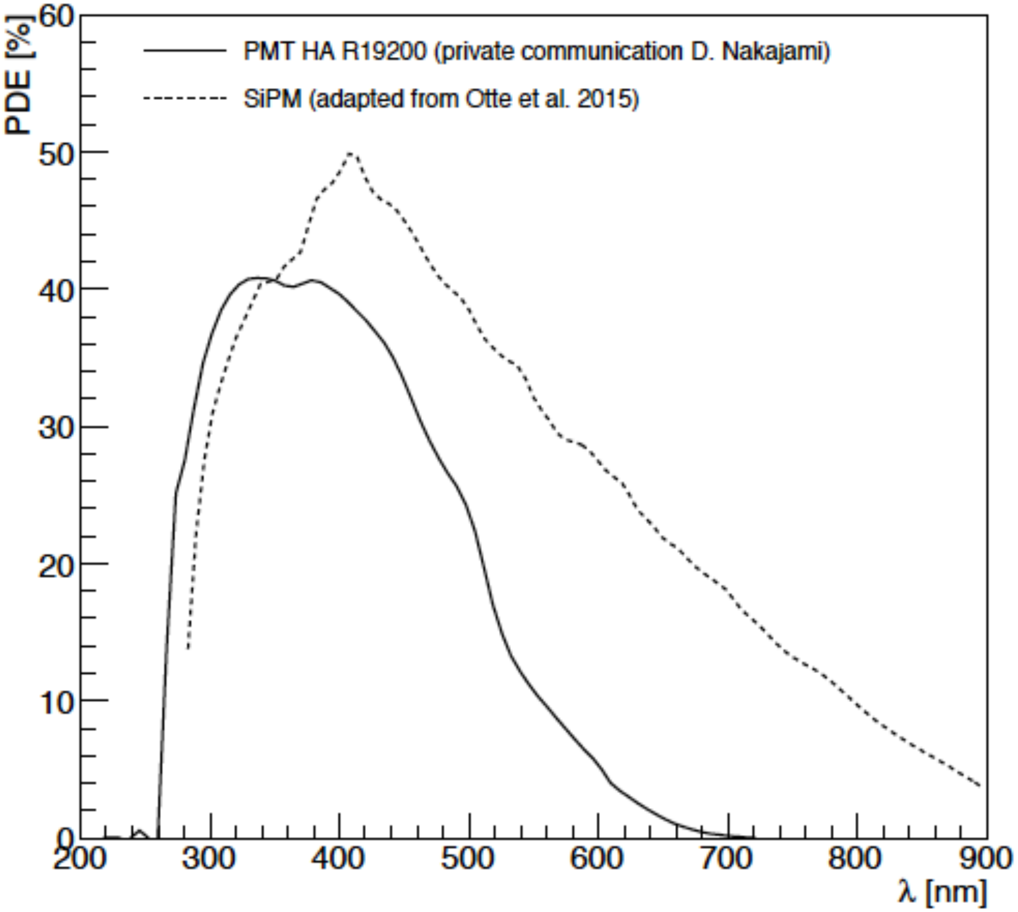
- Prototype: the avalanche photomultiplier tube (PMT)

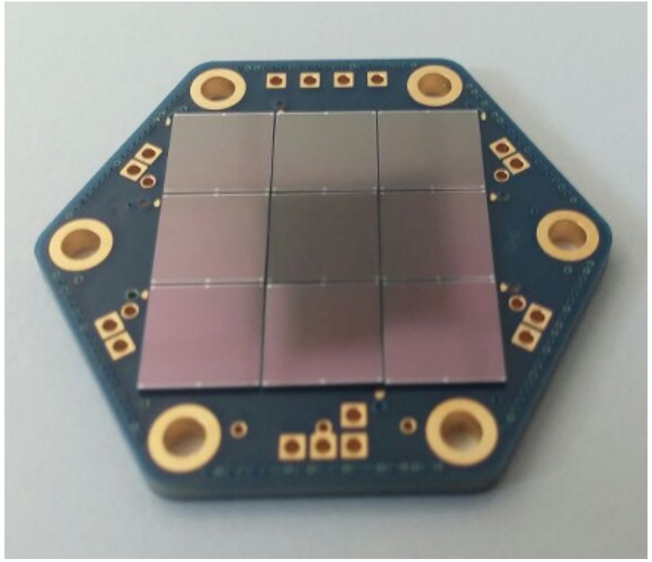


Photodetectors - II

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





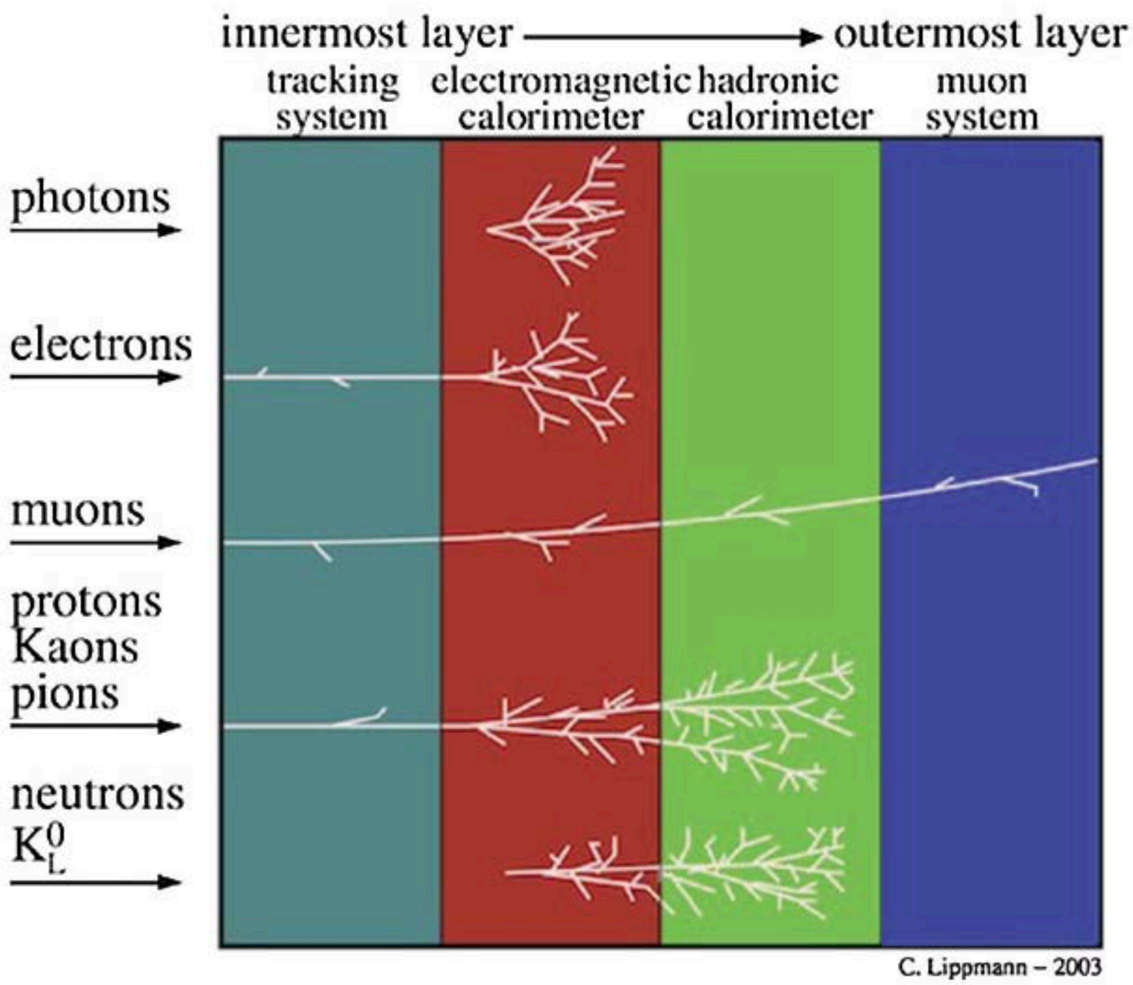


Corti, Rando+ (PD)

PART 2
LET'S BUILD COMPLEX DETECTORS, NOW!

Direct measurement of Cosmic Rays

The ideal detector: see a particle physics experiment



But:

- Heavy
- Expensive

Different setups for:

- Space (large fluxes)
- Ground (detection of EAS)

Space-based experiments

- Measure of charge, particle identification: need magnetic field?
  - If so, a technical complication
- Protons dominate the yield, maybe you want to measure different particles
  - Antimatter?
  - Low energy: TOF, Cherenkov
  - High energy: RICH, TRD, electromagnetic calorimeters

- Advanced Composition Explorer ACE, launched in 1997 and still in space: different ions (with TOF, dE/dX)
- The Balloon-borne Experiment with Superconducting Spectrometer (BESS) performed successive flights > 1993 to measure the anti-proton spectrum and to search for anti-helium
- PAMELA launched in 2006 measured charged particles and anti-particles out of the atmosphere during 6 years, with a permanent magnet of 0.43T and a silicon tracking system
- AMS-02 was installed in May 2011 on the ISS. Its concept is similar to PAMELA but with a much larger acceptance and more performing detectors
- ISS-CREAM (Cosmic Ray Energetics and Mass for the ISS) is in orbit since 2017. It uses a Si detector, timing detectors, and a TRD
- DAMPE (electrons/positrons: tracker + calorimeter) in orbit since 2017

Particle Identification

Particle identification (mass, charge, energy / momentum)

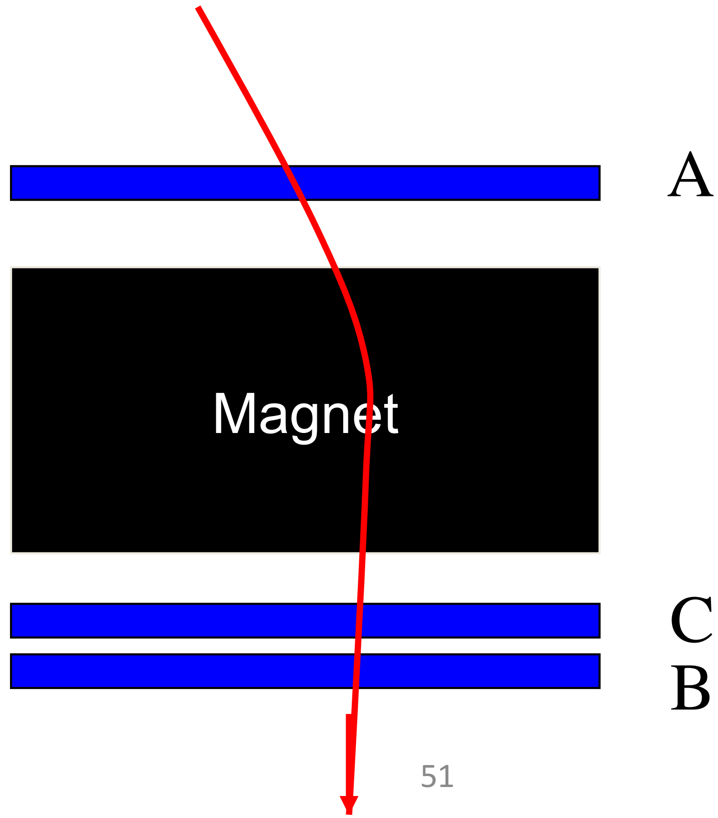
Spectrometer: instrument for measuring rigidity in the magnetic field.

B is known, Z and p can be measured

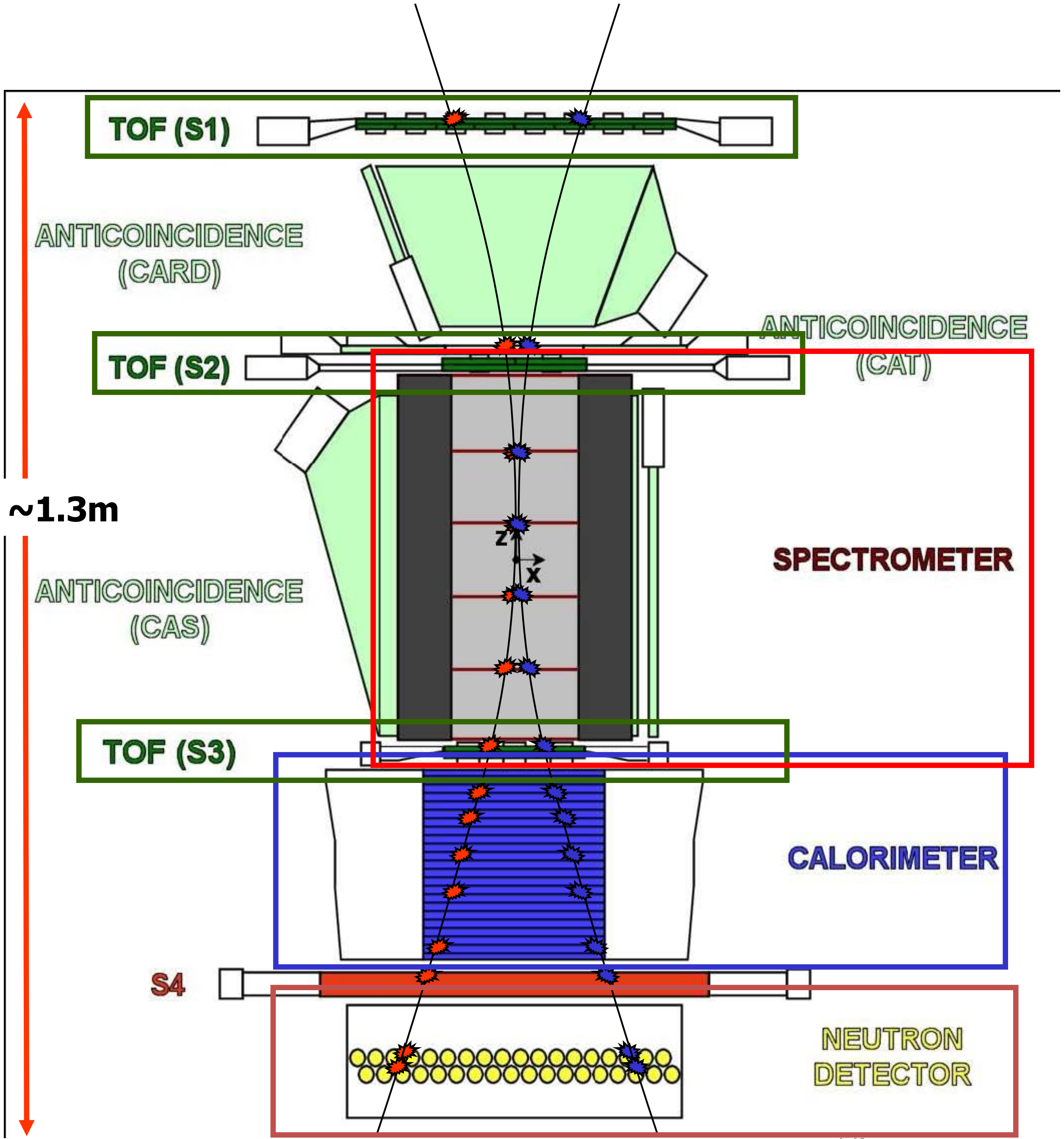
$$\mathcal{R} = r_L B c = \frac{pc}{Ze}.$$

Momentum resolution depends on the accuracy in the measurement of the track and on multiple scattering

A ToF (for example A, C are 2 scintillation counters) provides the measure of dE/dx (thus Z), time, position. The measurement of the ToF between two known positions provides v. The mass of the particle is obtained from r_L. Sometimes, a destructive detector (calorimeter) can be used to measure independently the particle energy.

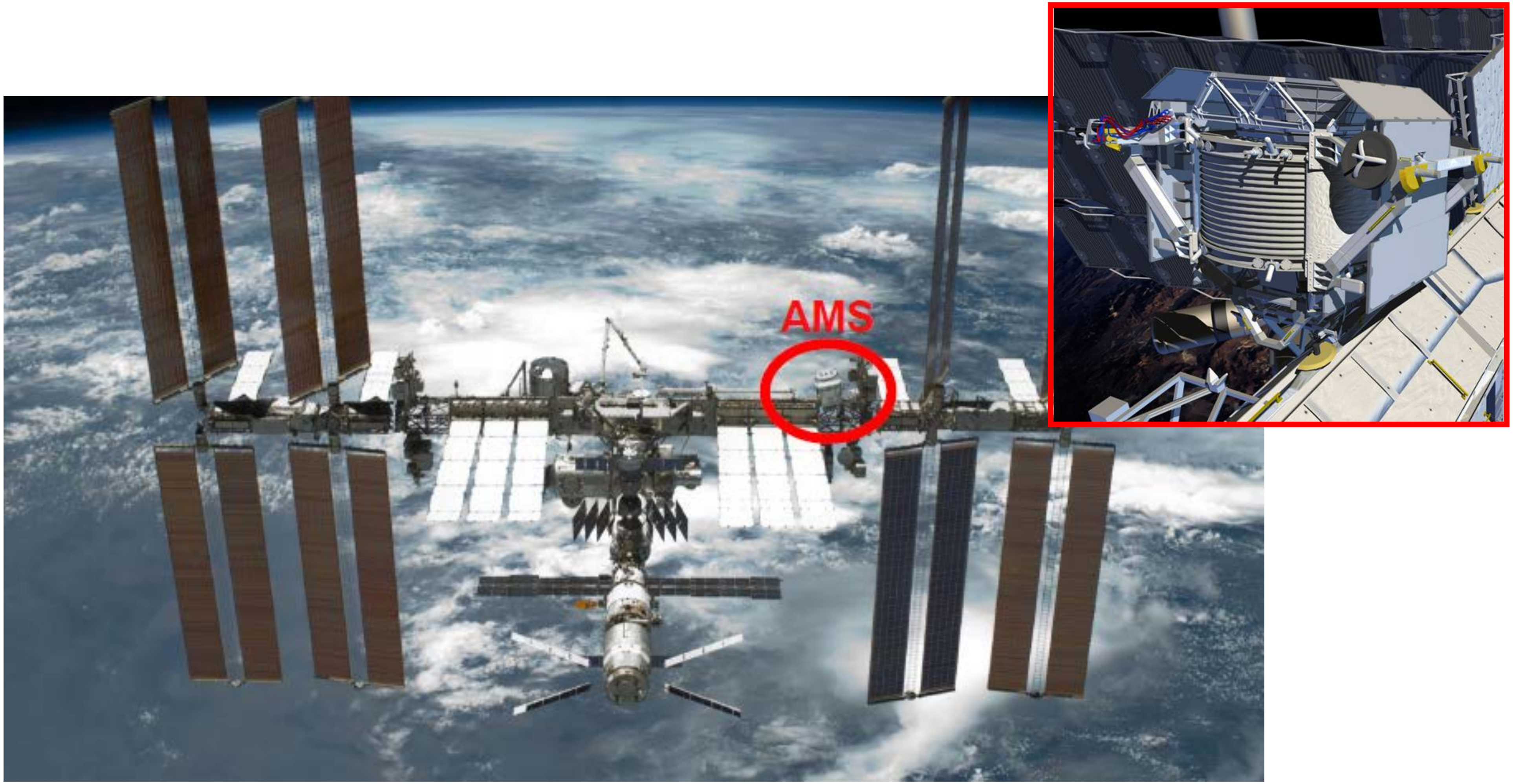


PAMELA



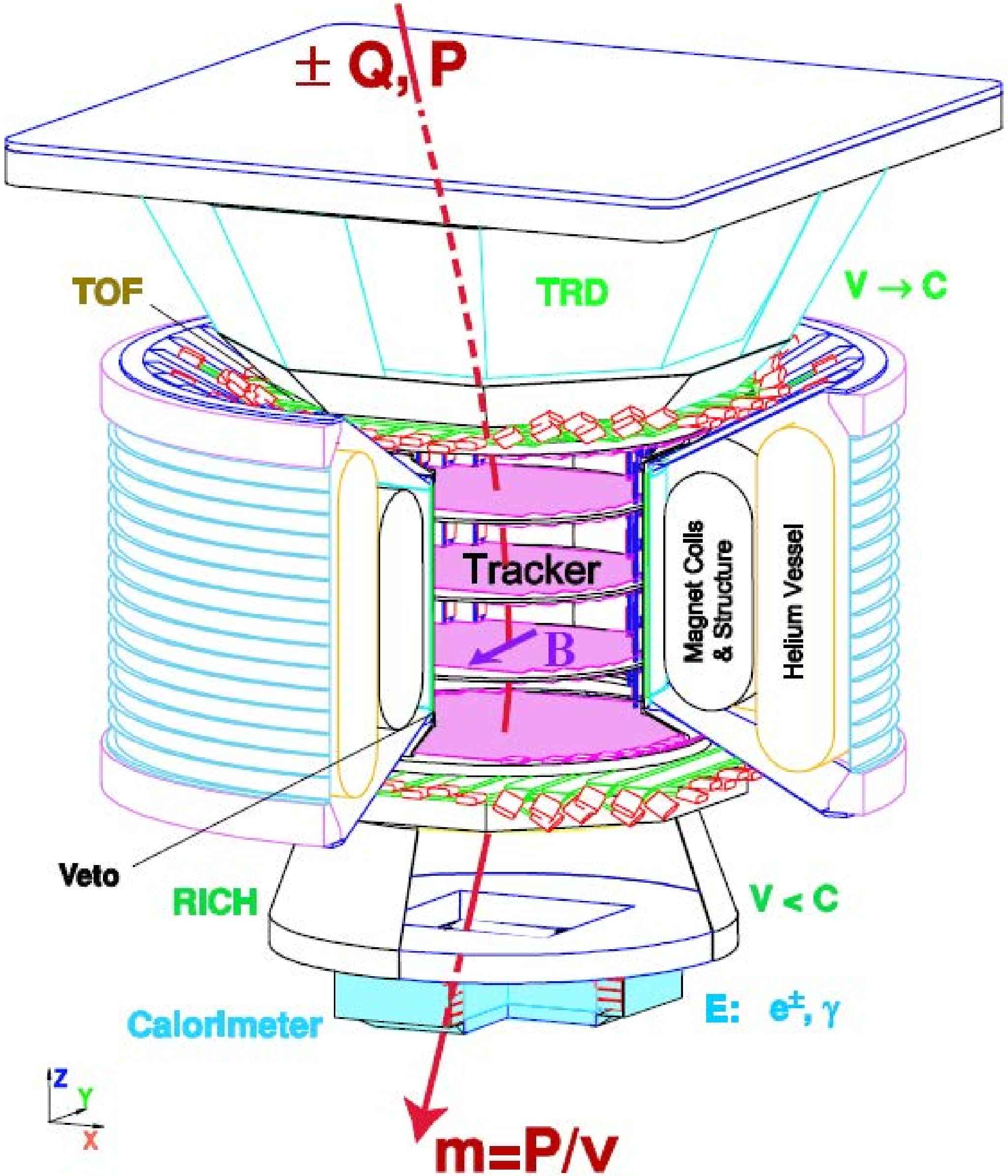
- Particle ID:
  - TOF
  - EM Calorimeter
  - Neutron detector (EM cascades vs. HAD cascades)
  - Rigidity masurement using a permanent magnet and a Si tracker

Alpha Magnetic Spectrometer Experiment



- **ISS : 108 m x 80*m*, 420 *t***
- ***orbit height 400km***

Inclination = 51.57º
15.62 revolutions/day



AMS-02: up to TeV energies

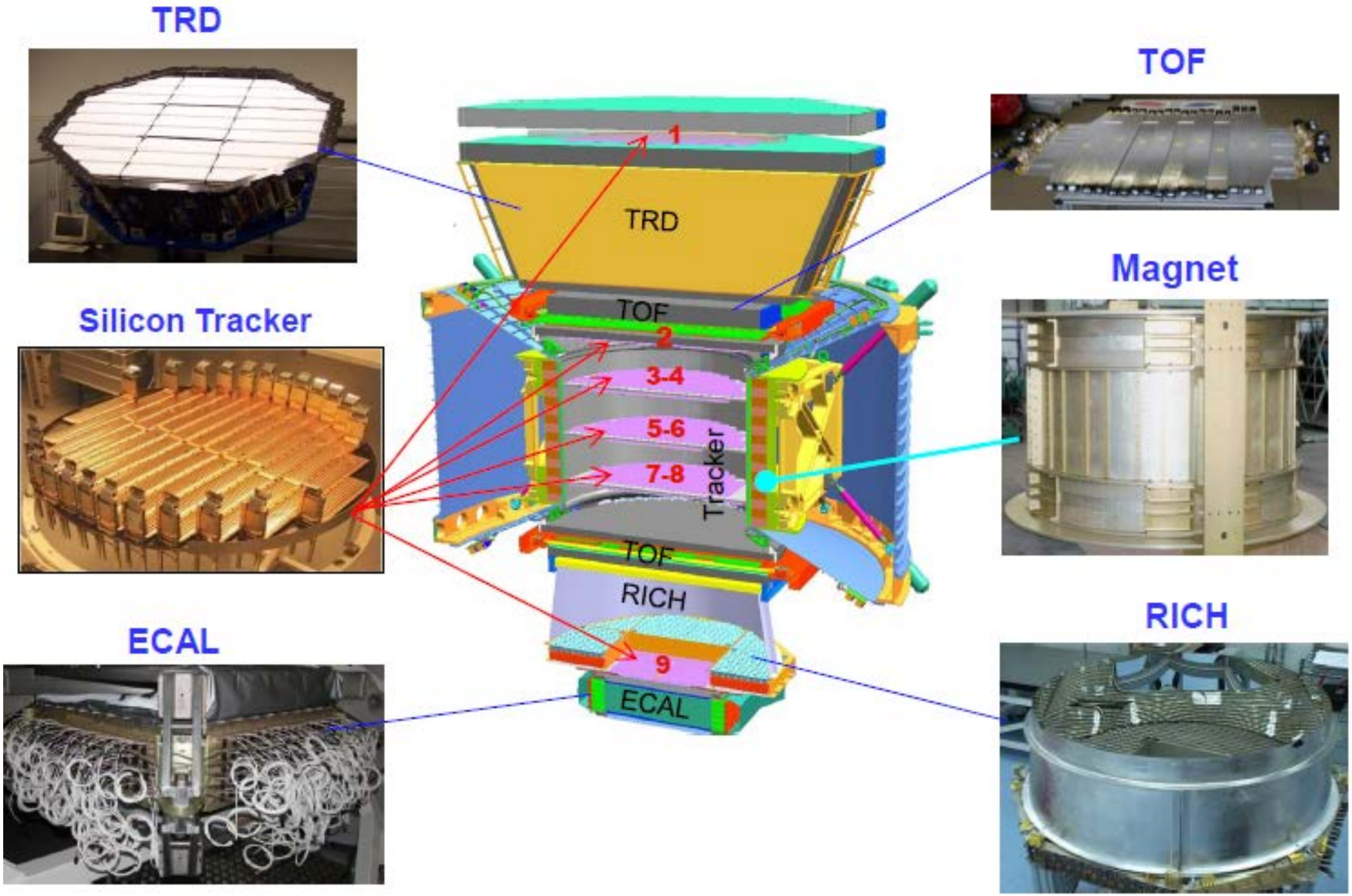
The value of |Q| is measured independently in Tracker, RICH and TOF.

The signed charge, ±Q, and the momentum of the particle, P, aremeasured by the 8 layers of doubled-sided silicon tracker in the magnet.

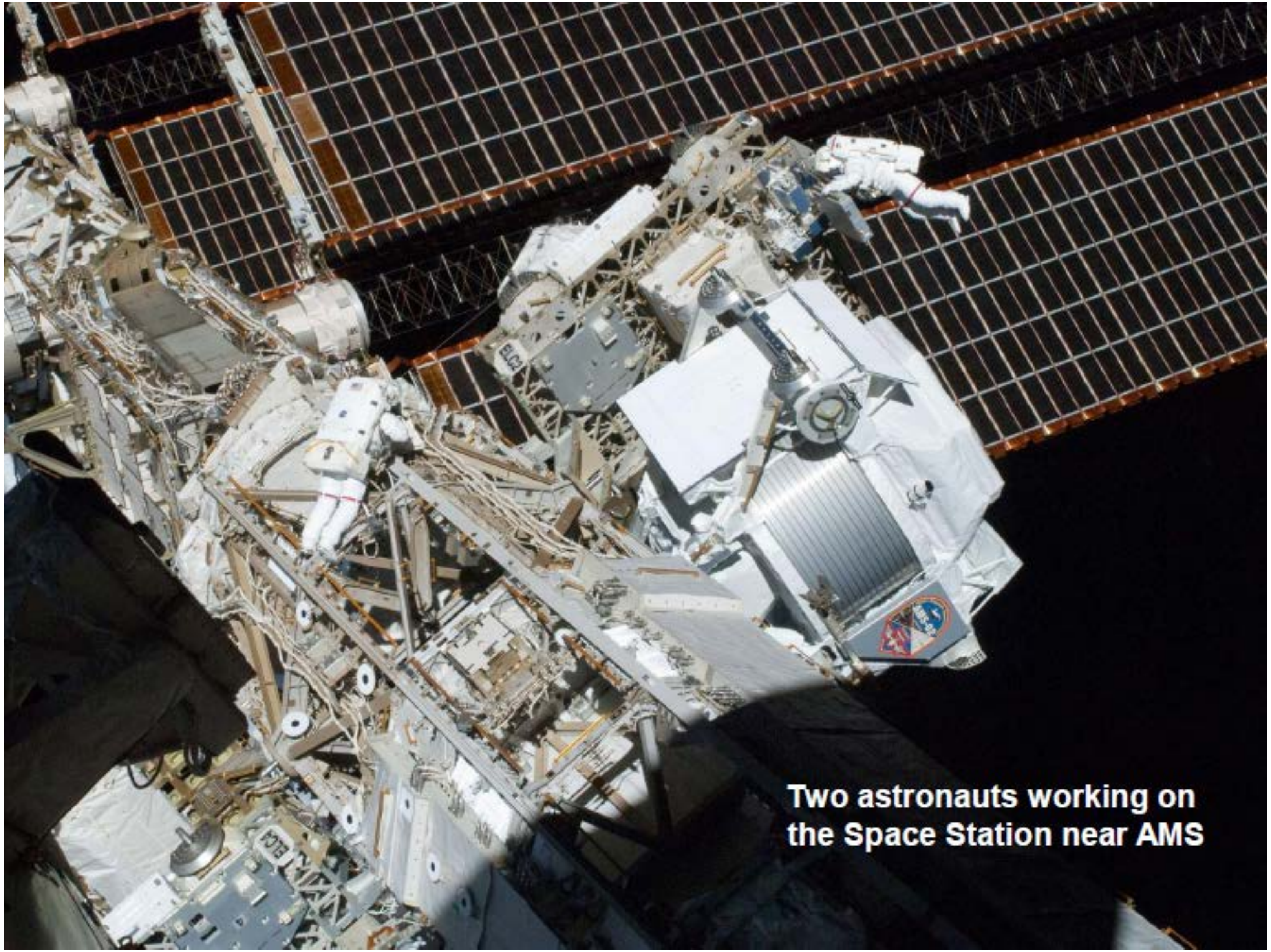
The velocity, $\beta = v/c$, is measured by the TOF, TRD and RICH.

The energy of electromagnetic particles is measured by the calorimeter.

AMS features



AMS Transfer to the Shuttle, 26 March 2011


Two astronauts working on
the Space Station near AMS
ELC2
ELC4

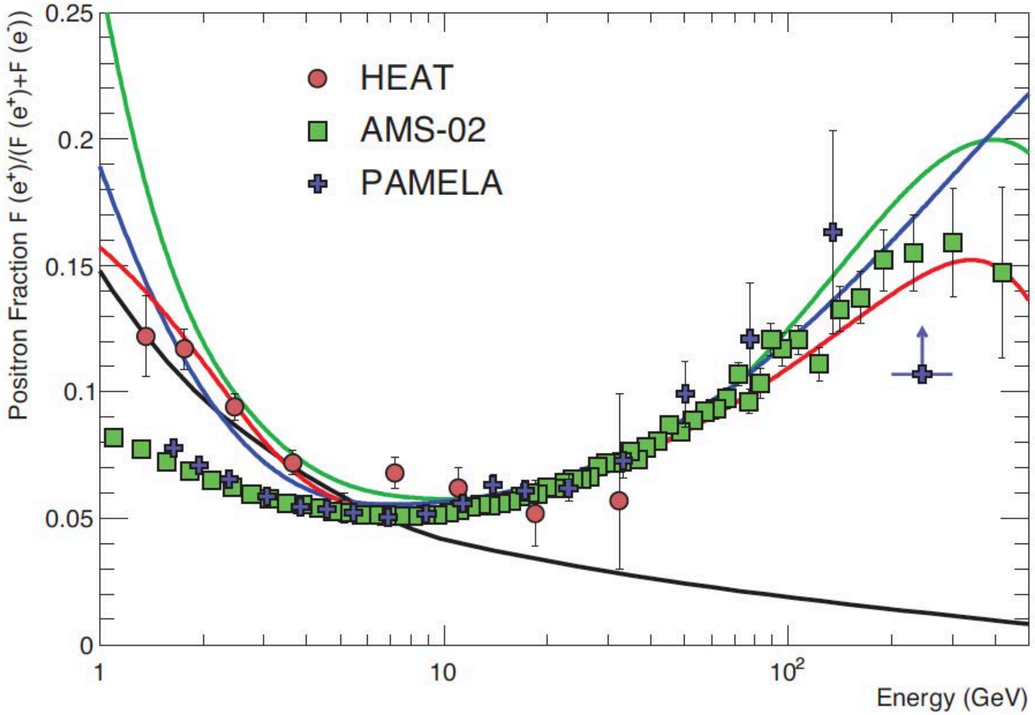
Cosmic ray studies with AMS

Goals:

- **Searches for primordial antimatter:**
  - Light anti-nuclei: $\overline{D}$, $\overline{He}$, ...
  - $\overline{p}$ / p ratio
- **Dark Matter searches:**
  - **e^{+} , $e^{\pm}$, $\overline{p}$, ...**
  - simultaneous observation of several signal channels.
- **Searches for new forms of matter:**
  - **strangelets, ...**
- **Measuring CR spectra – refining propagation models;**
- **Identification of local sources of high energy CR (~TeV):**
  - **SNR, Pulsars, PBH, ...**
- **Study effects of solar modulation on CR spectra over 11 year solar cycle**
- ...

Electron to positron ratio

- As antimatter is rare in the Universe today, all antimatter we observe are by-product of particle interactions such as Cosmic Rays interacting with the interstellar gas.
- The PAMELA and AMS-02 satellite experiments measured the positron to electron ratio to increase above 10 GeV instead of the expected decrease at higher energy.



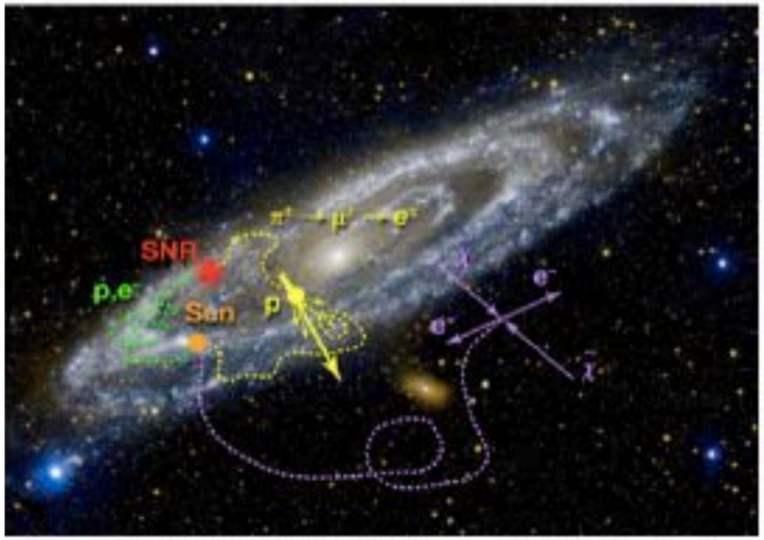


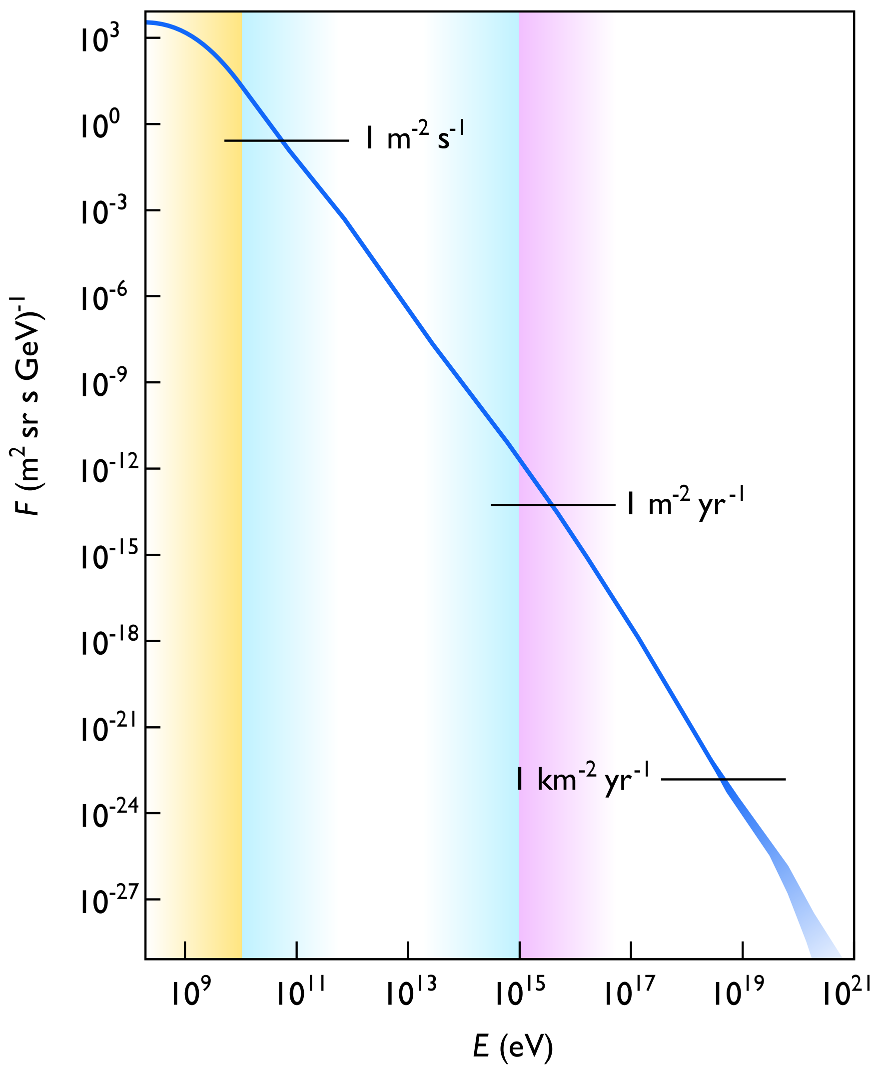
Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker

This excess might hint to to contributions from individual nearby sources (supernova remnants or pulsars) emerging above a background suppressed at high energy by synchrotron losses

Indirect measurements of Cosmic Rays: Extensive Air Showers

EHE 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

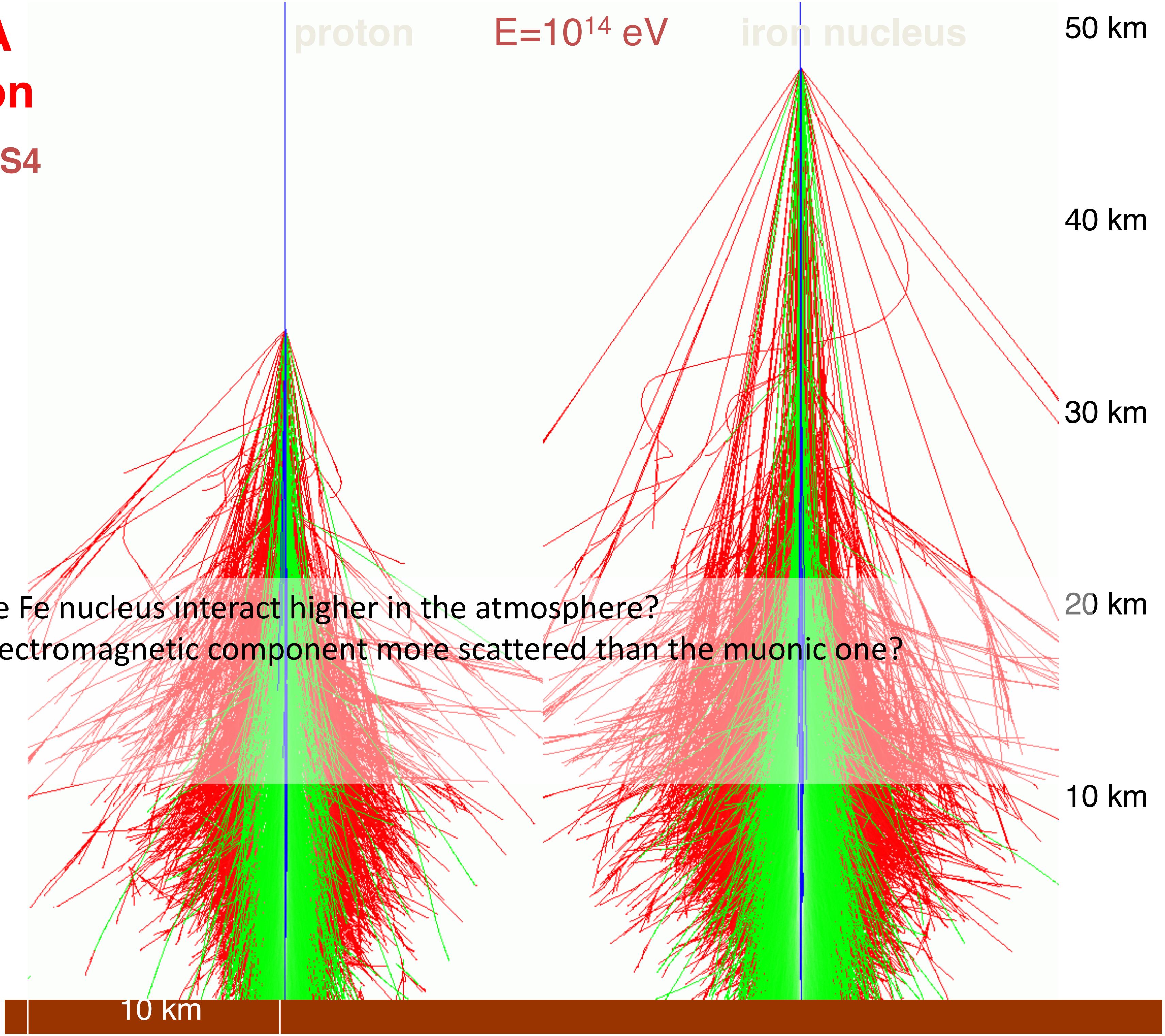


Highest energies: Extended Air Showers

- Three detectable components of EAS:
  - EM
  - Muons
  - Hadrons
- CR energies much higher than energies at accelerators (> 100 TeV in the c.m. vs. < 14 TeV)
  - Access to new phenomena
  - But: lower luminosities
  - Initial conditions unknown

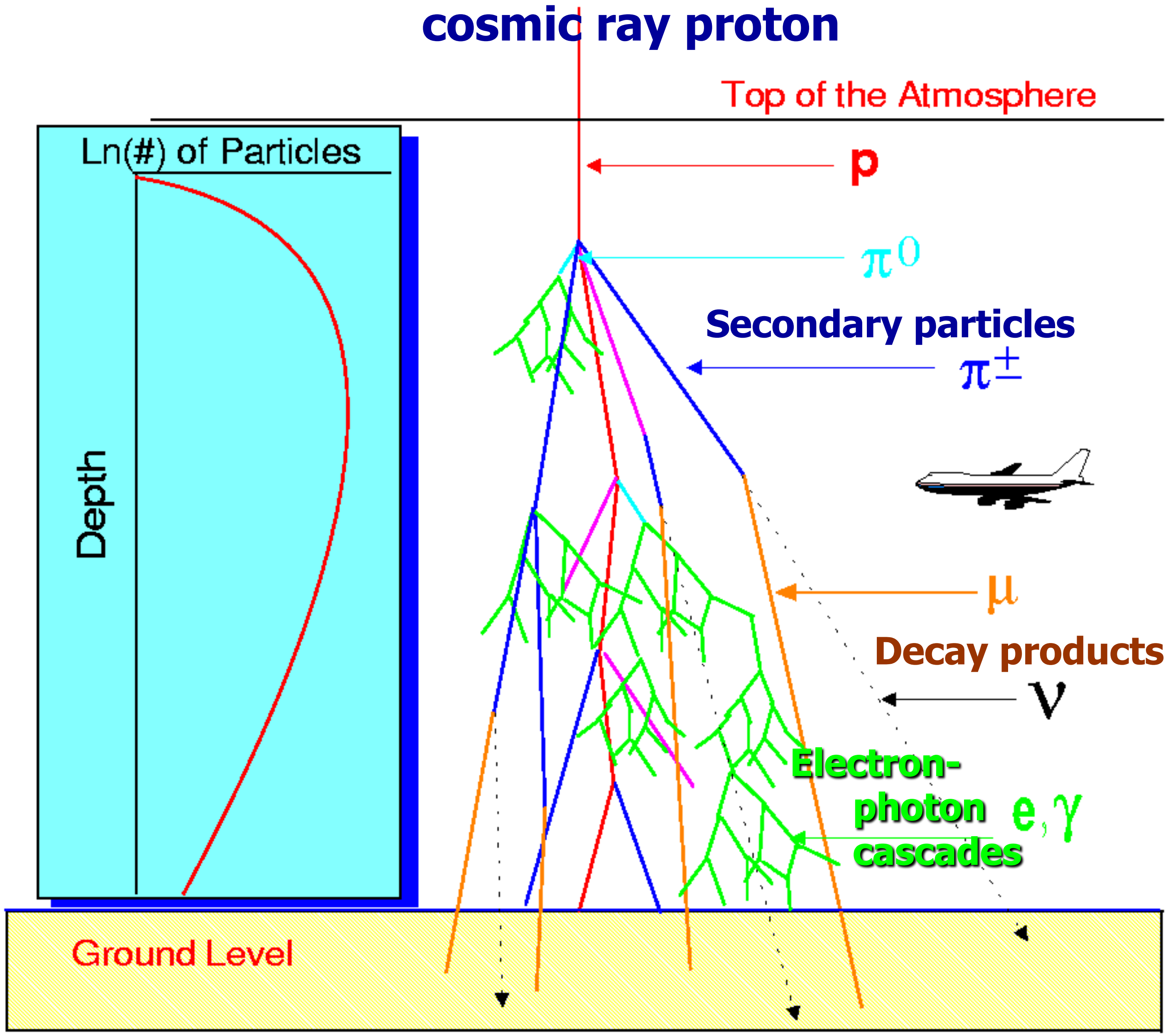
CORSIKA Simulation

QGSJET/EGS4



Why does the Fe nucleus interact higher in the atmosphere?
Why is the electromagnetic component more scattered than the muonic one?

Shower components



How to detect high energy CR?

You need:

A large collection area, S

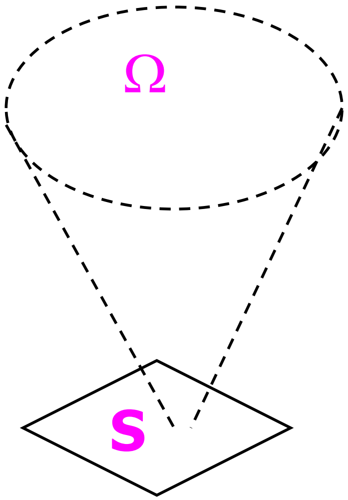
A large solid angle acceptance, Ω

A large collection time T

The quantity "exposure" $S\Omega T$ = m^2-steradian-days determines the number of detectable events

Sampling is possible!

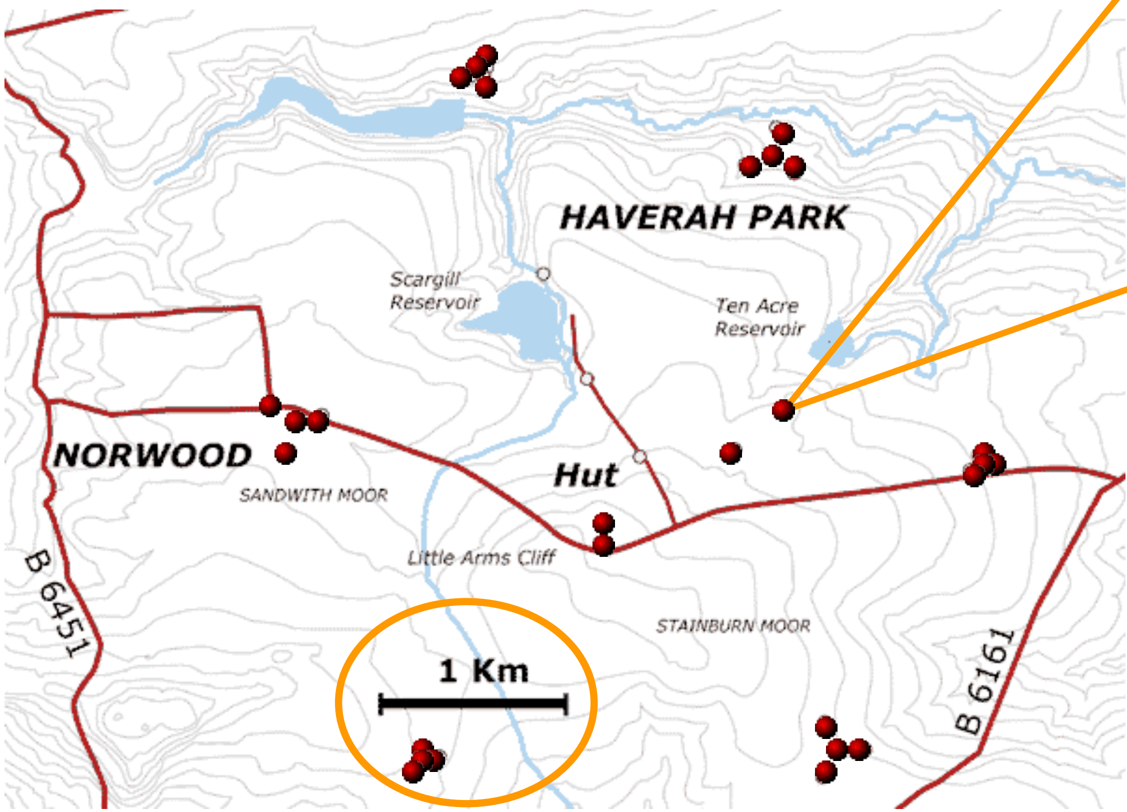
Flux for $E_o > 10^{19}$ eV
~0.5 particles per km^2-sr-<u>year</u>

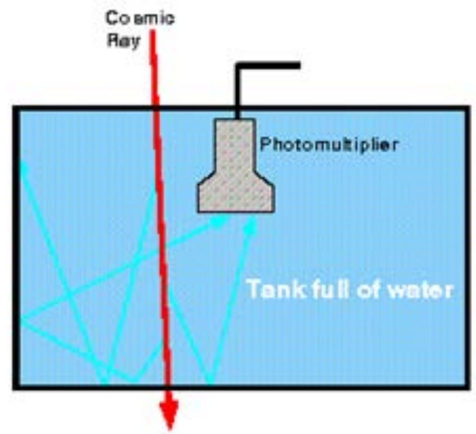


EAS detectors

- Experimental apparatus (Extensive Air Shower Arrays, EAS) are in general located at high altitude
- Measure showers“sampling”

  on a large surface



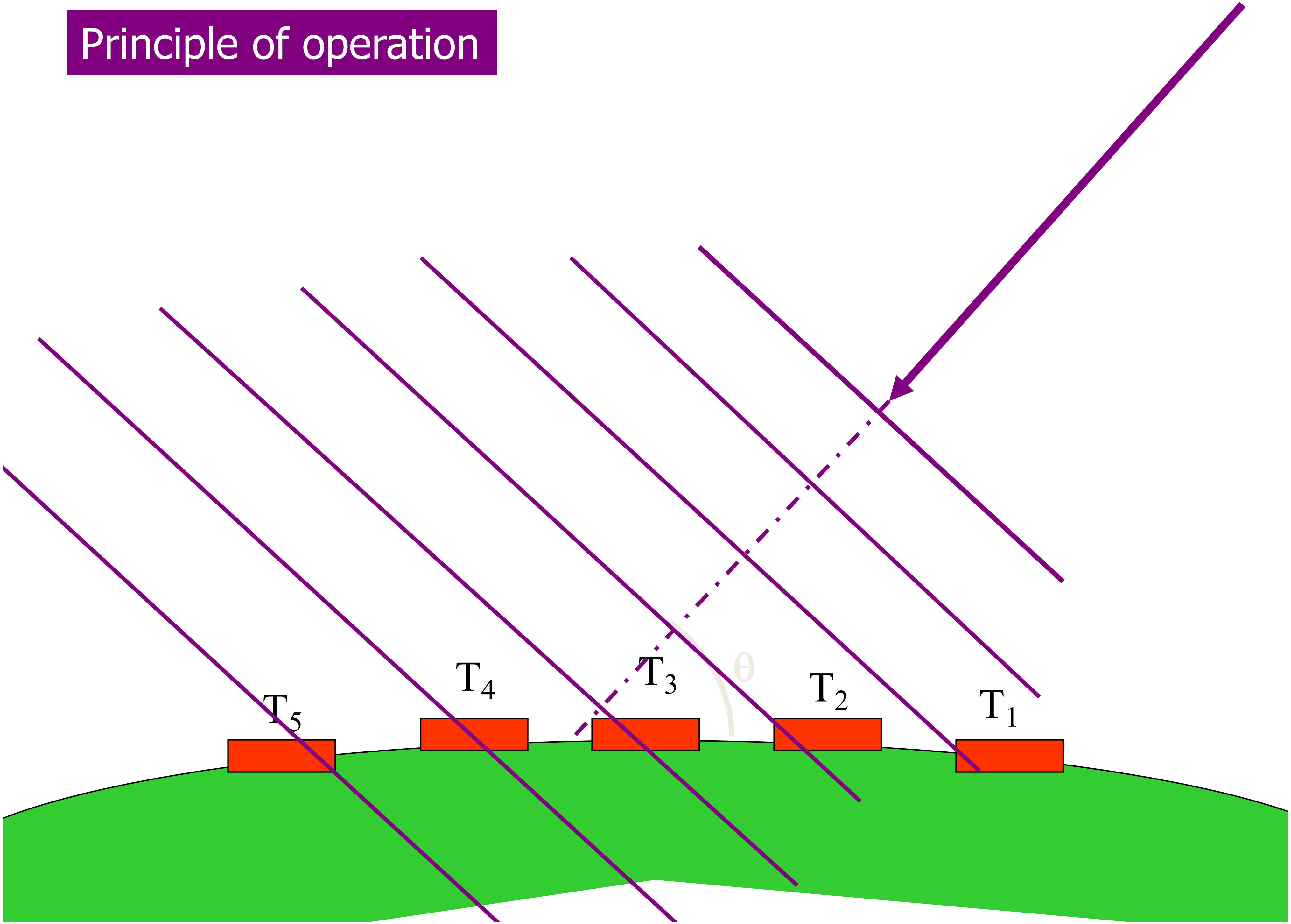


Which counters?

- Scintillators
- RPCs
- Water tanks detecting the Cherenkov light of superluminal particles in water through PMTs

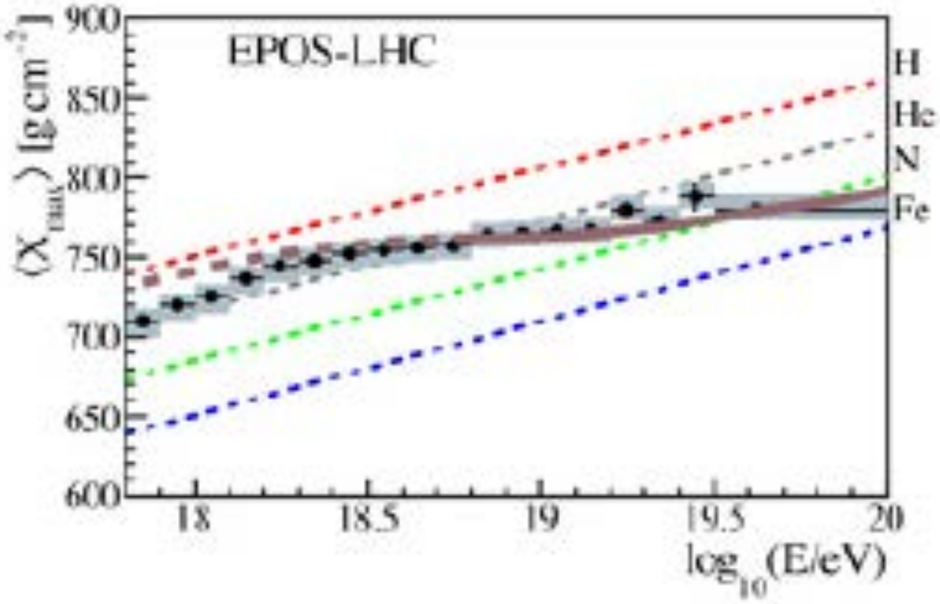
- The average distance between the counters determines the minimum energy of the detectable shower
- The number of counters, the accuracy of the measurement
- The total area covered determines the maximum measurable energy
- Each counter measures the energy loss of the particles passing through it; we can derive the number of incident particles
- From the particle density measurements in each counter of the array, we infer the lateral distribution D(r).
- From the measurement of D(r), from the reconstruction of the height of first interaction and from the hits count we go back to the energy of the primary, and from the frequency of the number of counts we go back to the flow.
- The direction of the shower can be determined by the measurement of the delay time in the arrival of the swarm on different counters

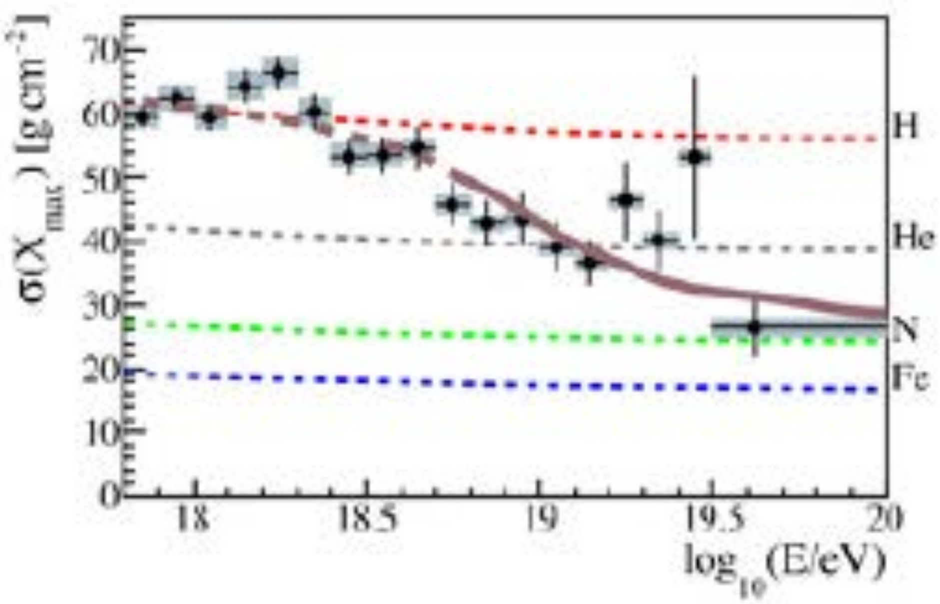
Principle of operation



Chemical composition?

- We expect to see heavier ioins at higher energies
- Not easy for EAS to measure <A>





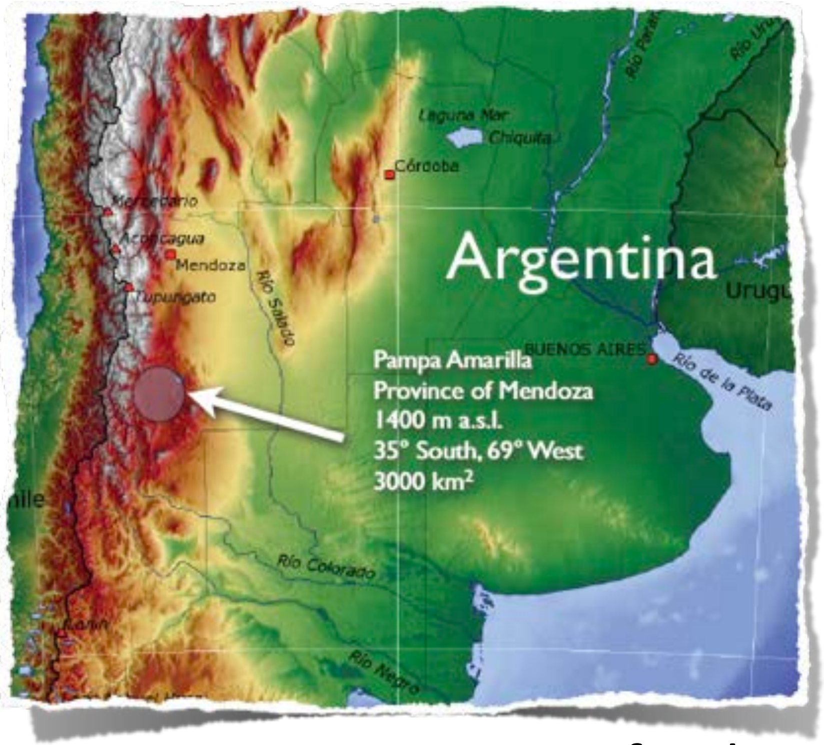
Additional detection methods

Charged particles in EAS also produce light in the atmosphere due to Cherenkov effect (electrons with E> 20�30 MeV).

Cherenkov light can be revealed (Cherenkov telescopes) on moonless nights by special detectors on the ground.

EAS also induce the excitation of atmospheric nitrogen, which re-emits by irradiating light. This fluorescence can be detected on the ground (Fluorescence detectors).

The muon component can be revealed by "underground" detectors.



Large hybrid detectors needed!

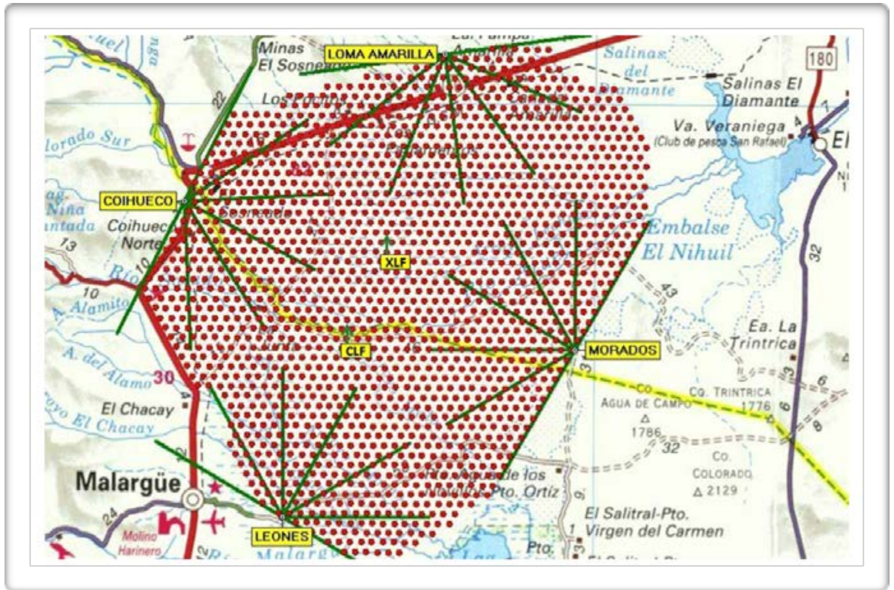
Located in the southern hemisphere, Auger is the **world's largest experiment for UHECRs** with its extension of **3000 km^2**

Powerful **hybrid detection** technique

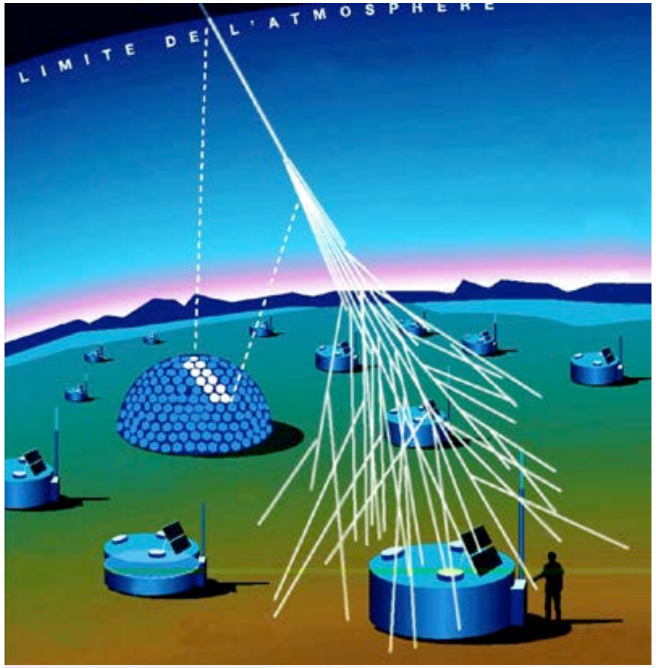
Main components of the observatory:

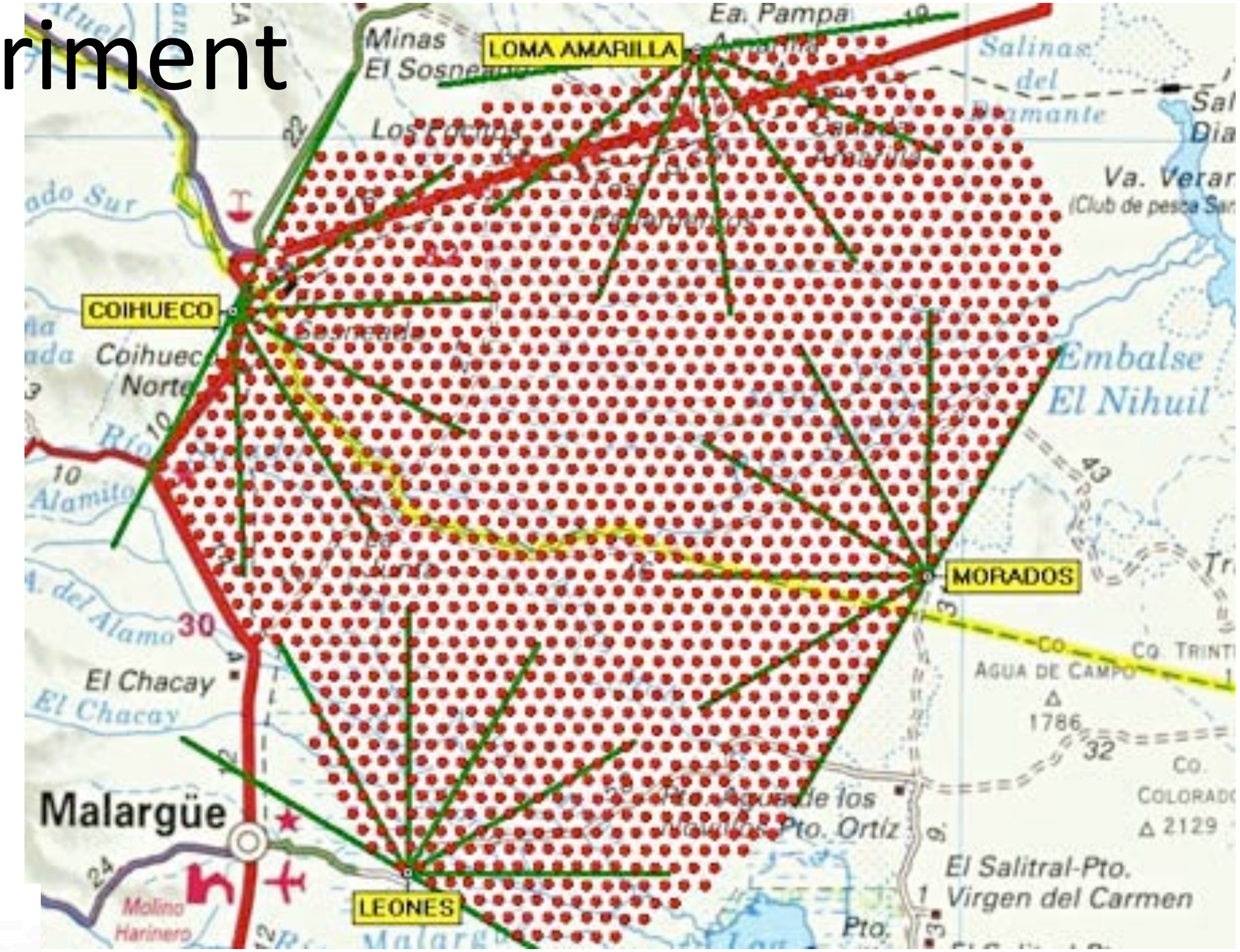
- **Surface detector (SD)**: array of 1600 water-Cherenkov tanks, spaced by 1.6 km

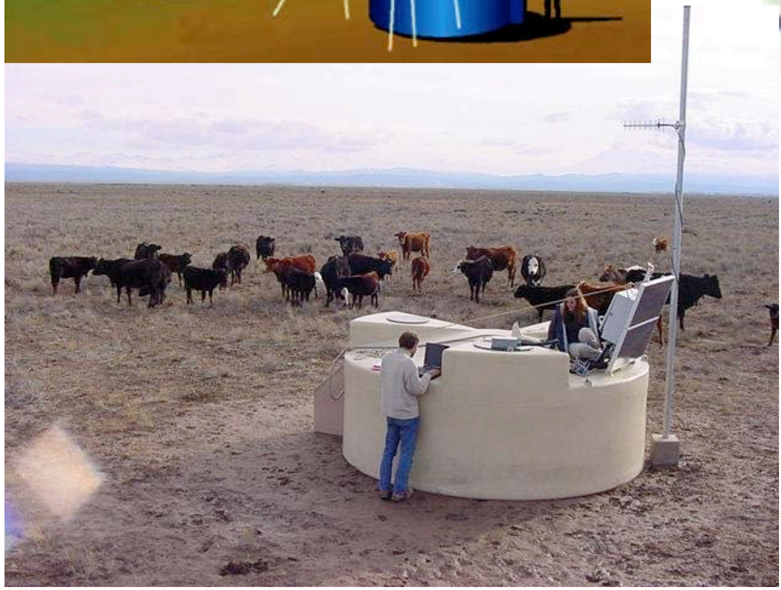
- **Fluorescence detector (FD)**: 24 telescopes in 4 buildings



The Auger experiment in Argentina







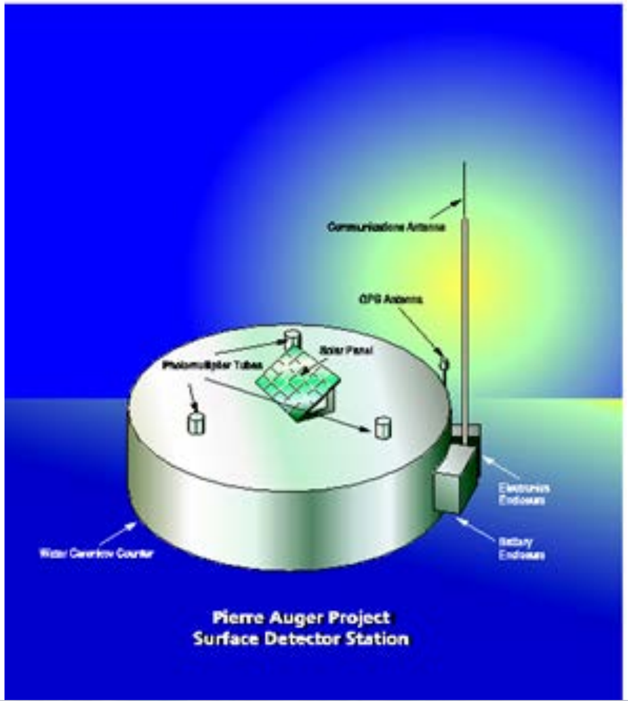
The largest in the world: surface of 3000 km^2
(Veneto: 18000 km^2)

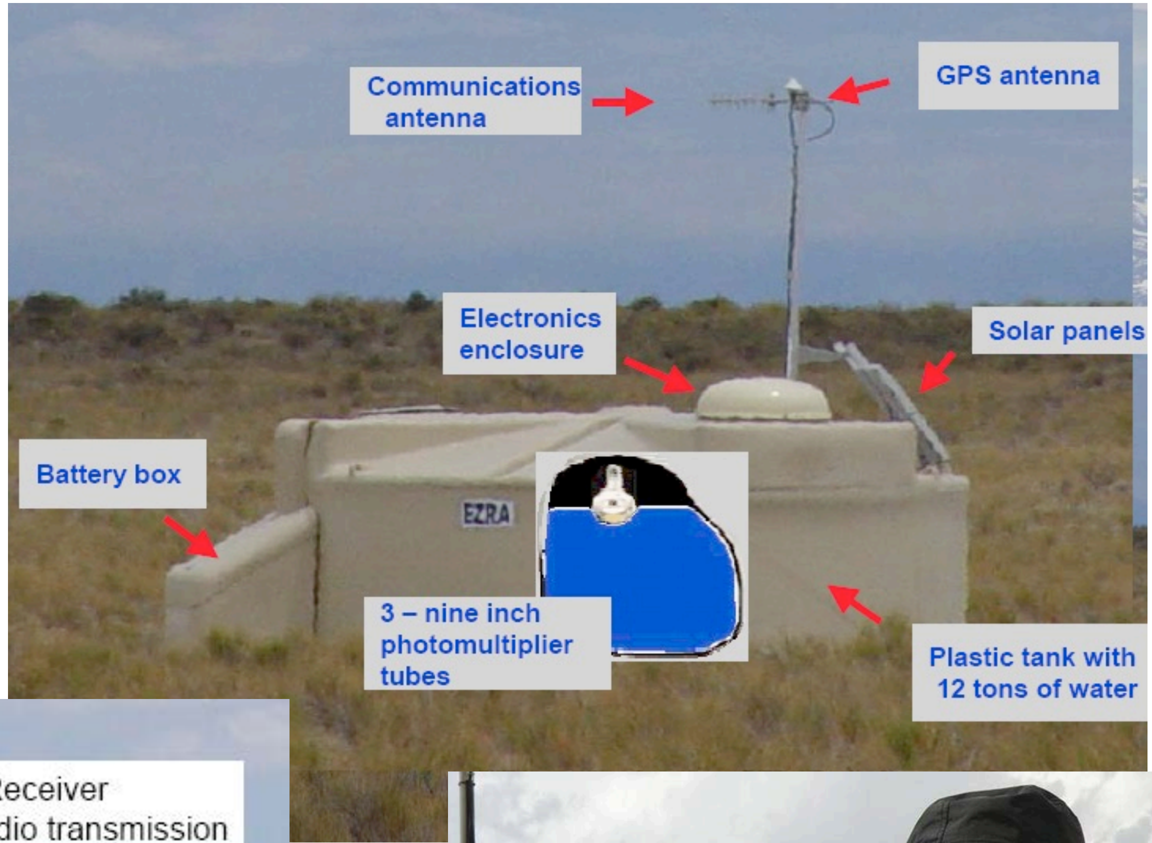
1600 surface detectors & 4 telescopes

Still not enough for astronomy

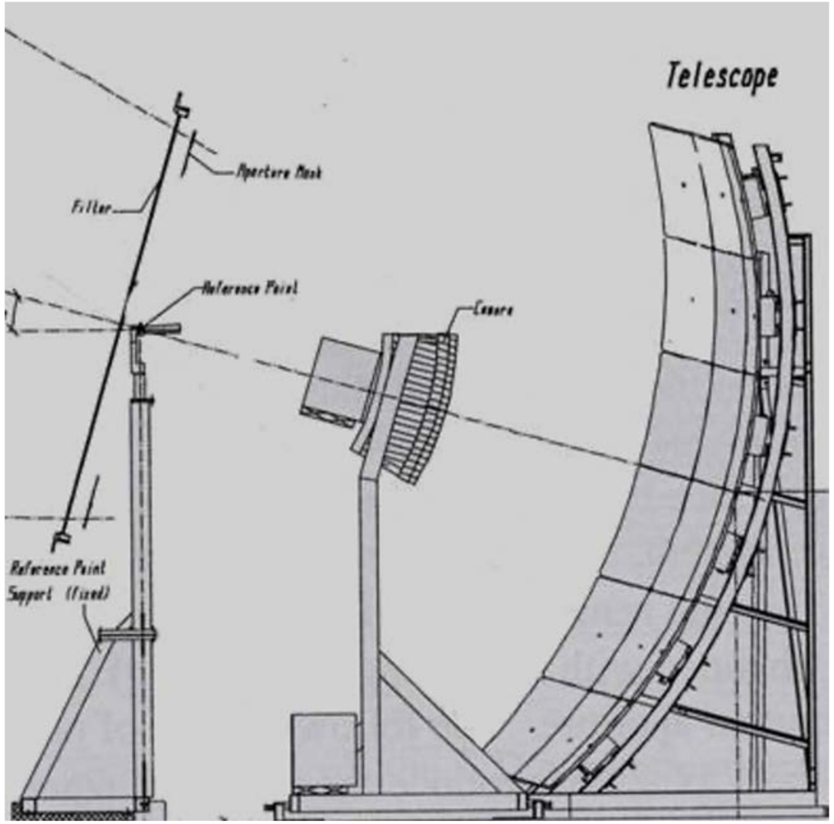
The Surface Detector Array

Čerenkov detectors in AUGER

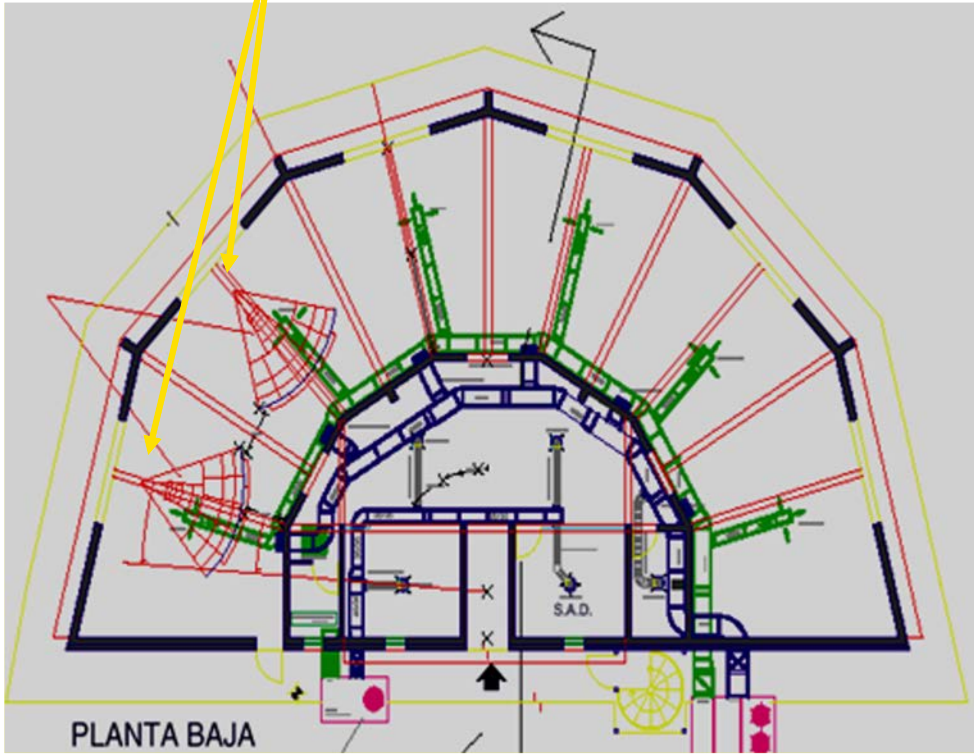


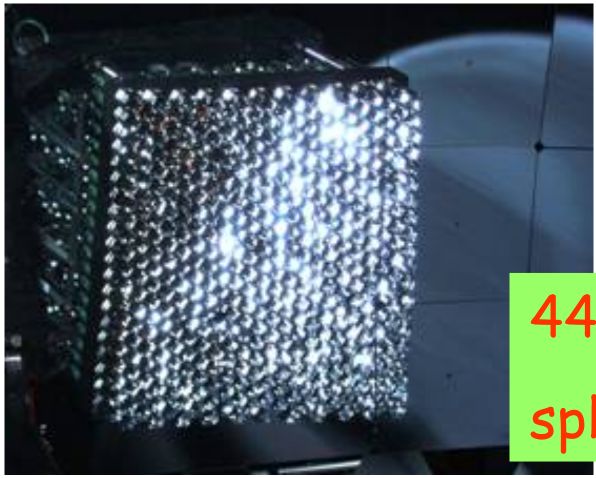


Fluorescence Detectors

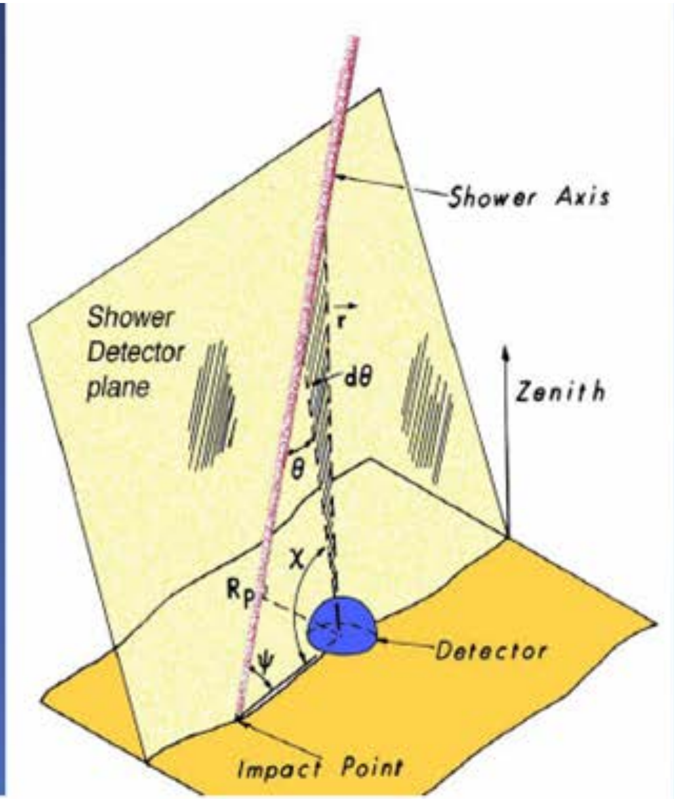


2 FD Telescopes



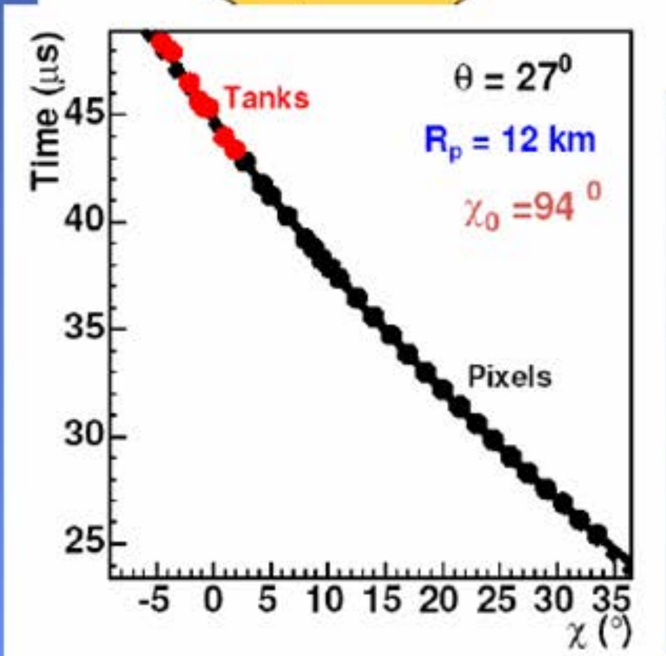


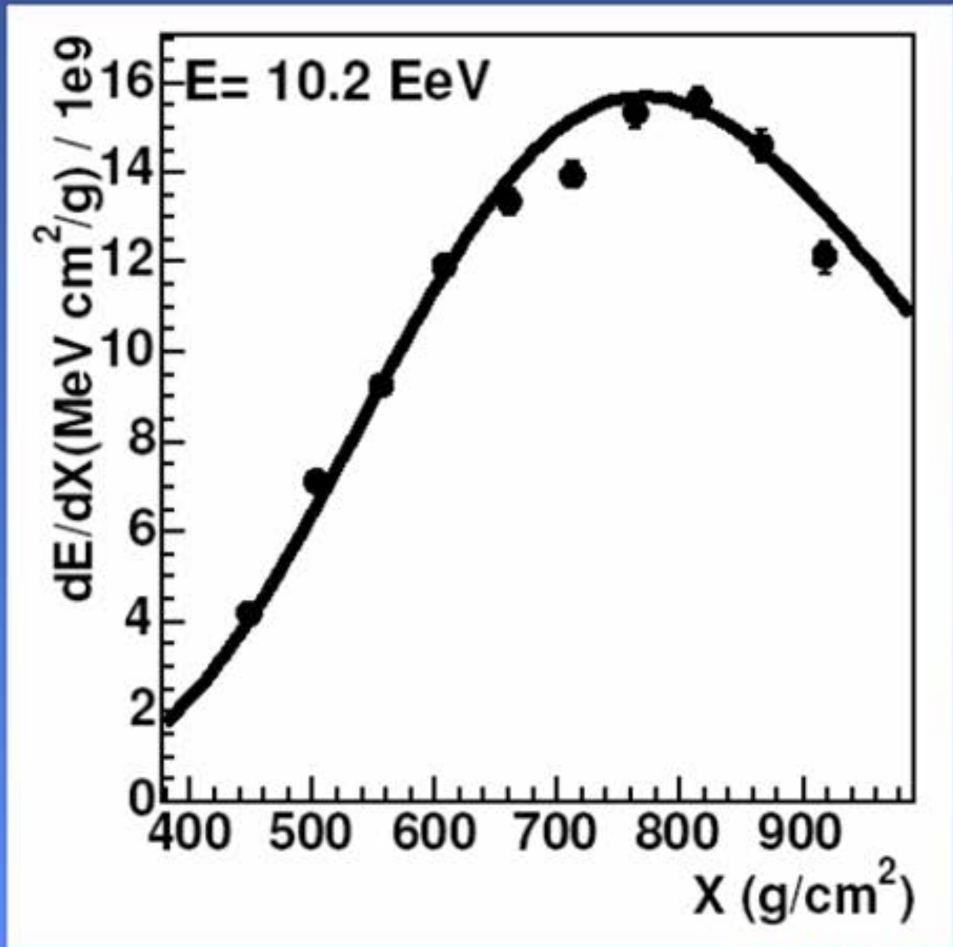
440 photomultipliers upon a spherical cup of 1.741 m ray

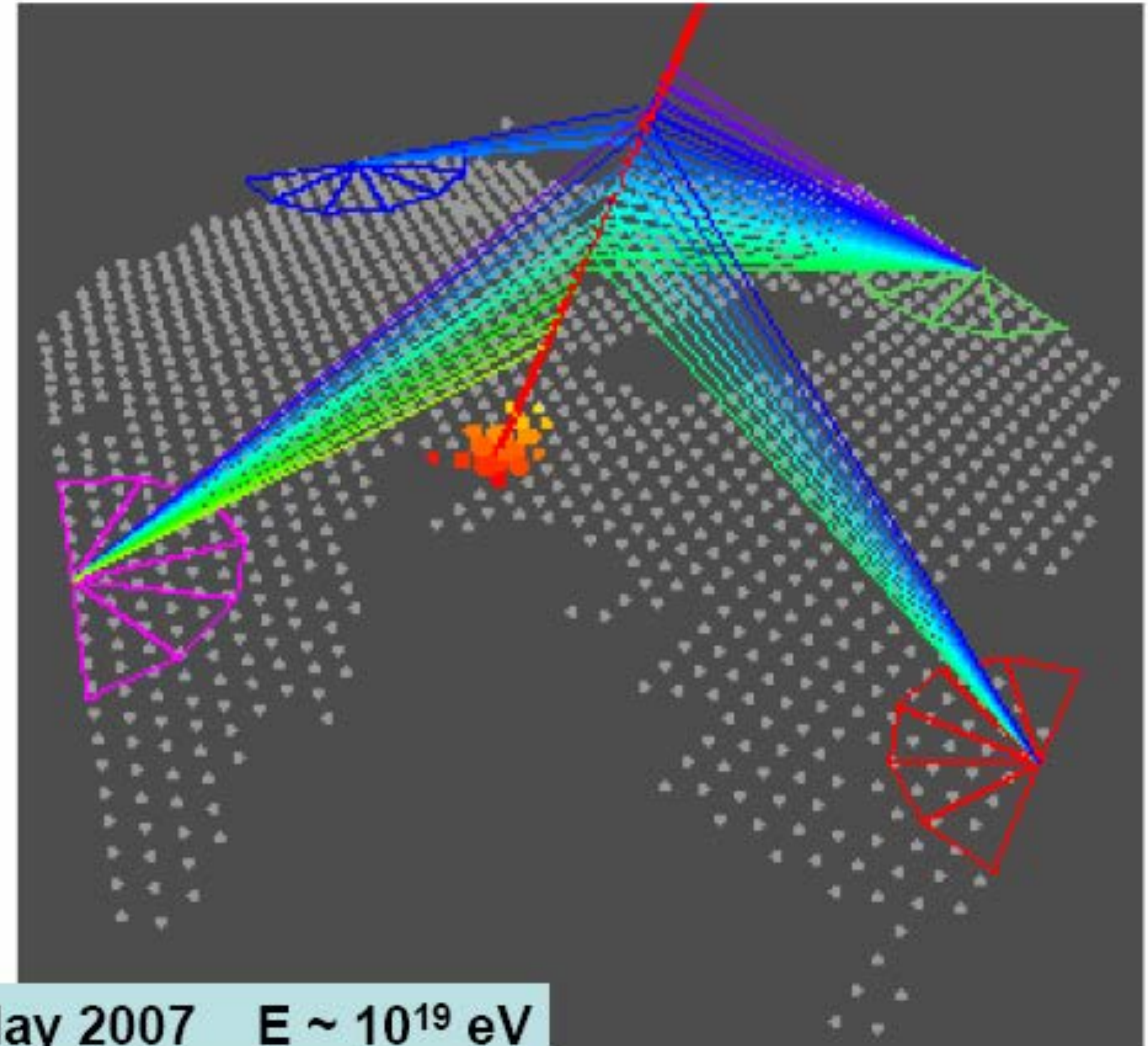


Hybrid Event (FD view)

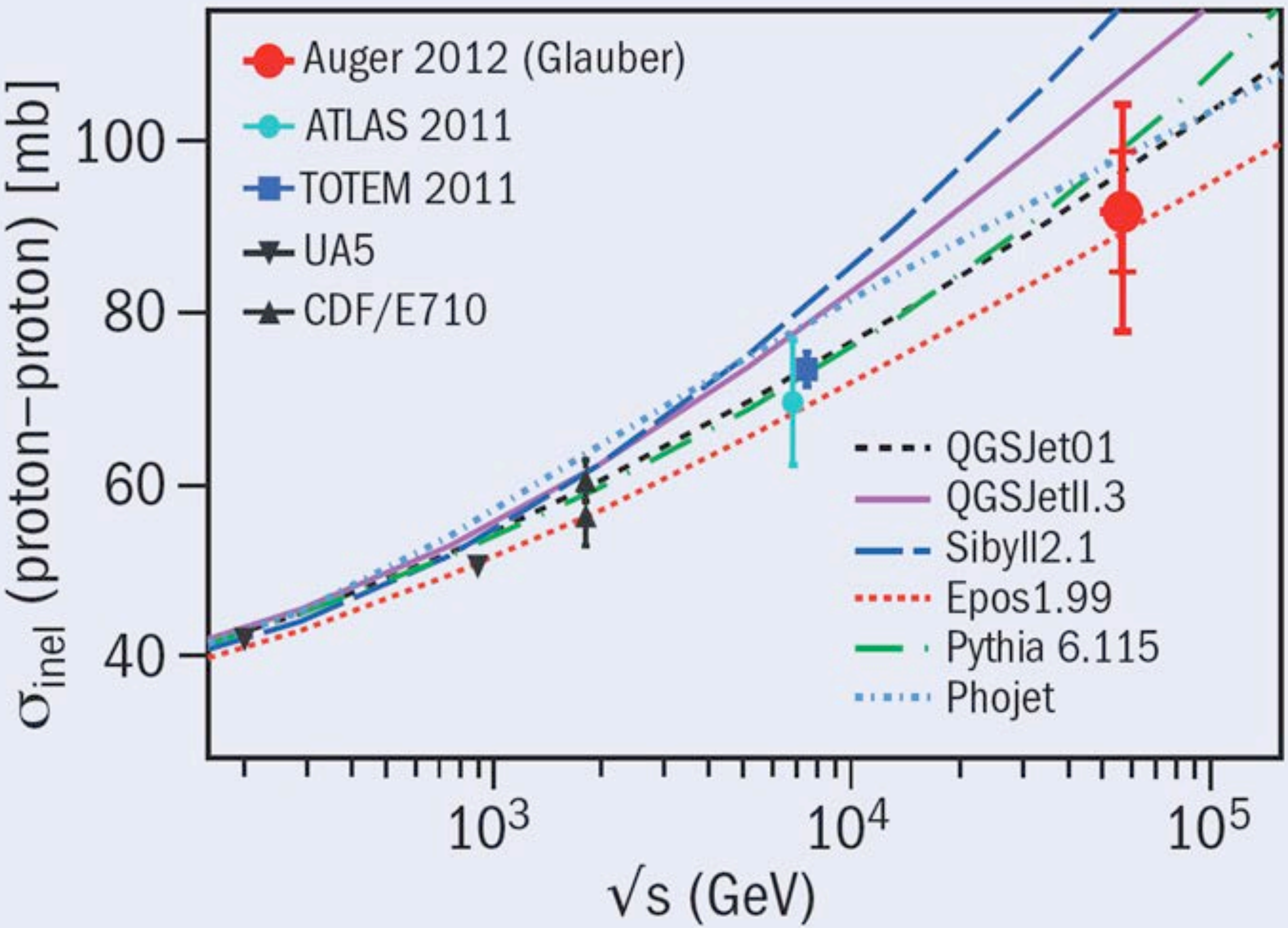
A hybrid event – 1021302
Zenith angle ~ 30º, Energy ~ 10 EeV





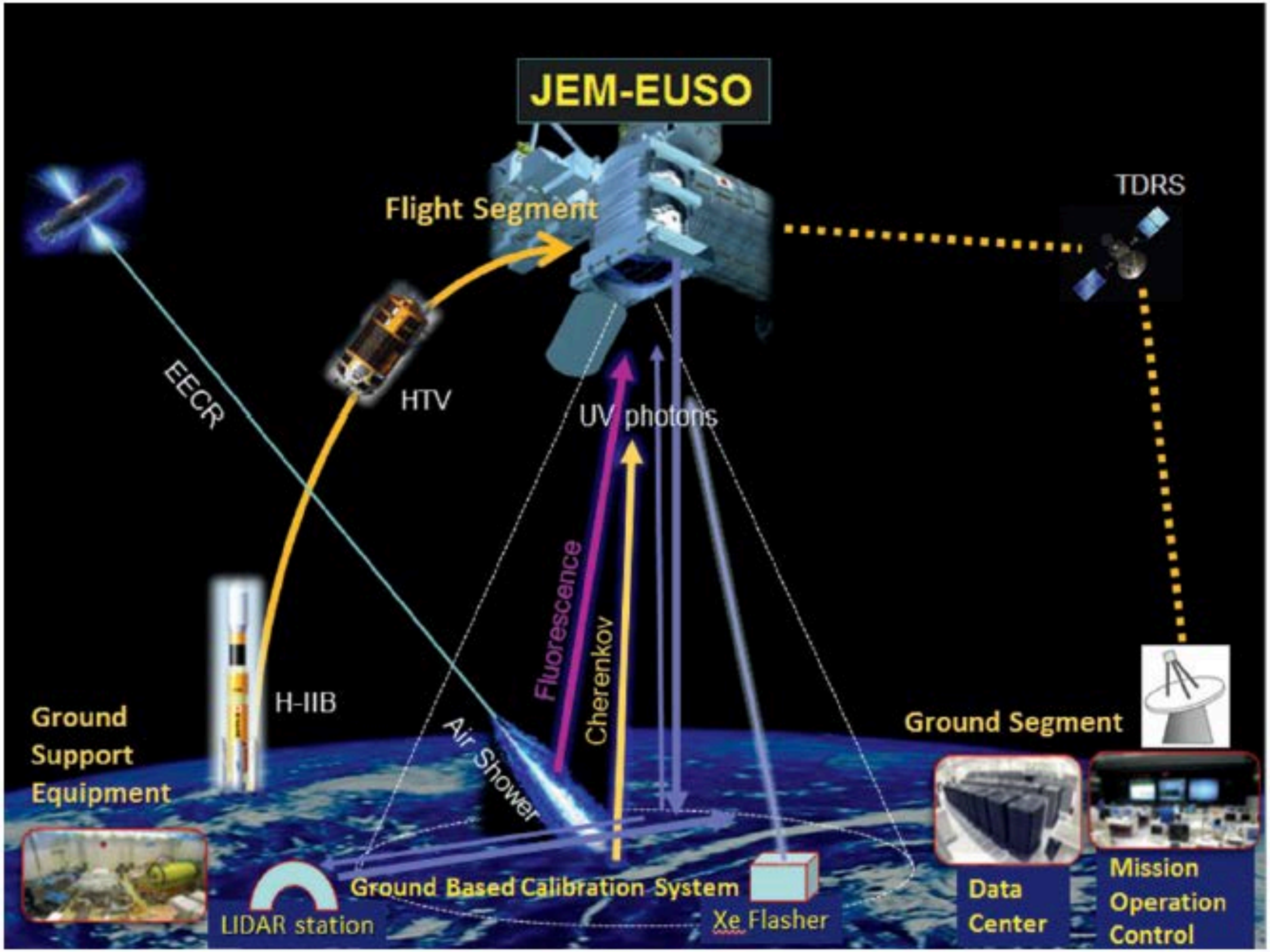


20 May 2007 E ~ 10^{19} eV



Auger 2012 (Glauber)
ATLAS 2011
TOTEM 2011
UA5
CDF/E710
QGSJet01
QGSJetII.3
Sibyll2.1
Epos1.99
Pythia 6.115
Phojet
σinel (proton–proton) [mb]
100
80
60
40
10³
10⁴
10⁵
√s (GeV)

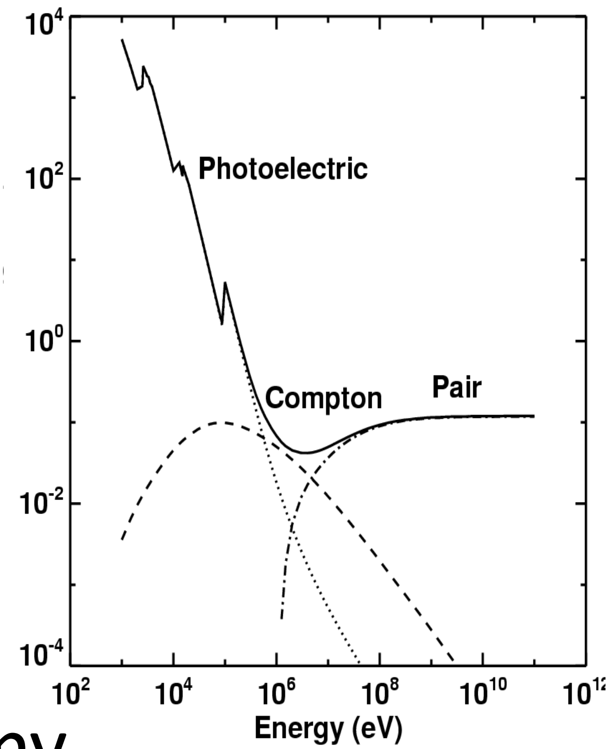
Future: the EUSO concept?



Gamma Rays

Photons in the nonthermal region

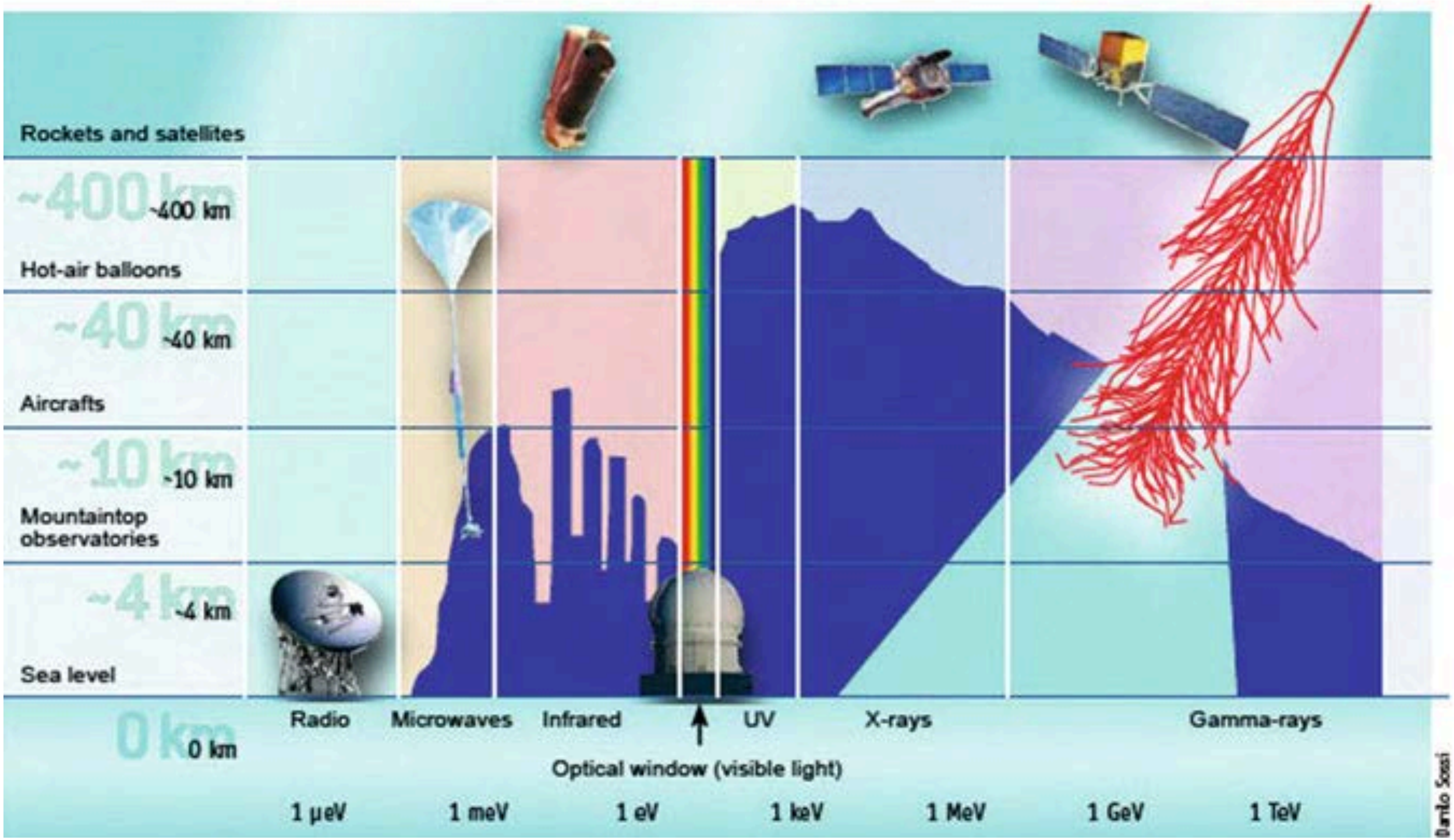
- LE or MeV : 0.1 (0.03) -100 (30) MeV
- HE or GeV : 0.1 (0.03) -100 (30) GeV
- VHE or TeV : 0.1 (0.03) - 100 (30) TeV
- UHE or PeV : 0.1 (0.03) -100 (30) PeV



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

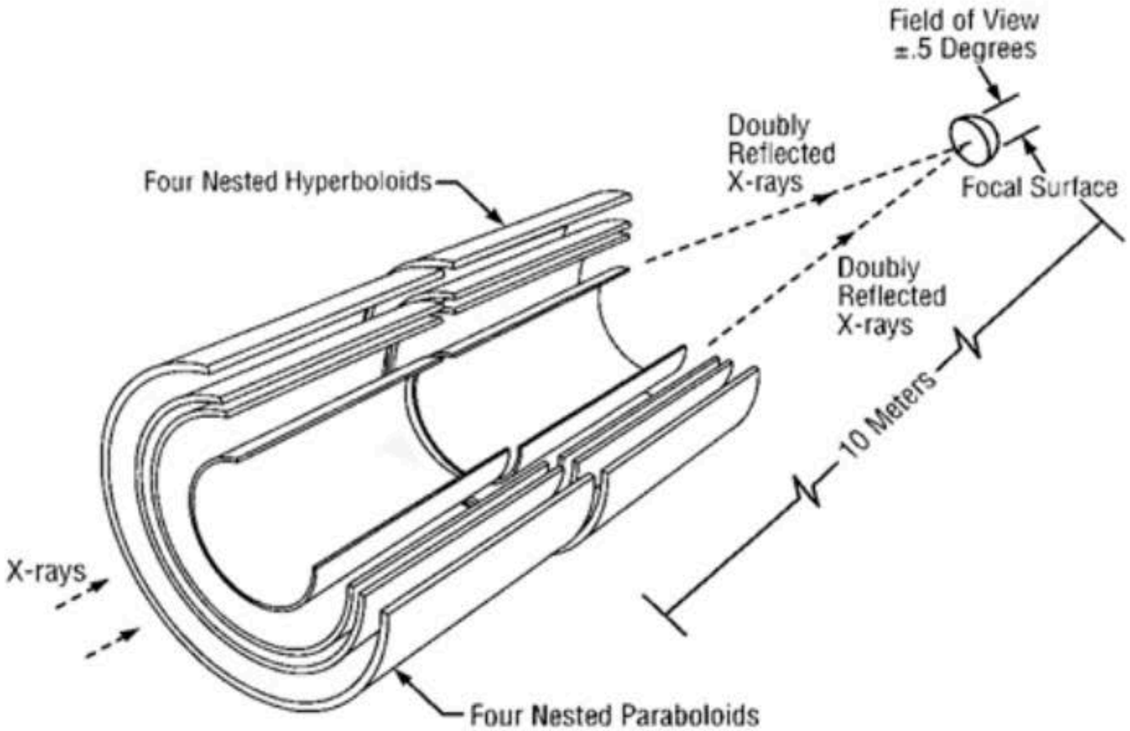
- When no ambiguity, we call “HE” all the HE and VHE+

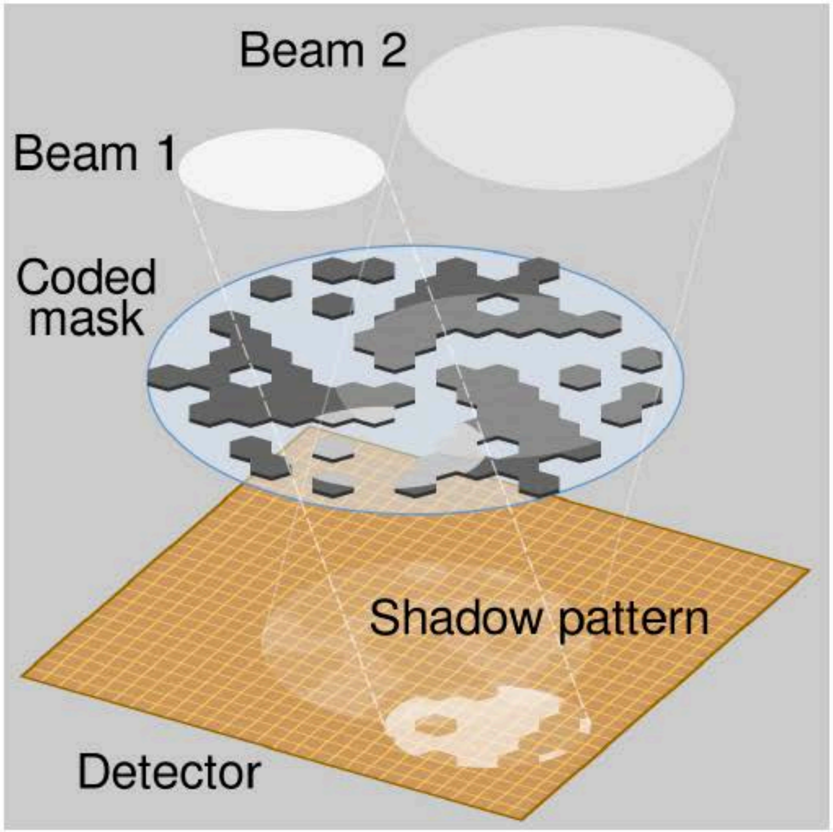
Transparency of the atmosphere



keV instruments (satellite)

- Detection must be based on photoelectric effect
- Very difficult to track
- Two designs: sacrifice acceptance or sensitivity
- INTEGRAL, Swift, Chandra, NuSTAR

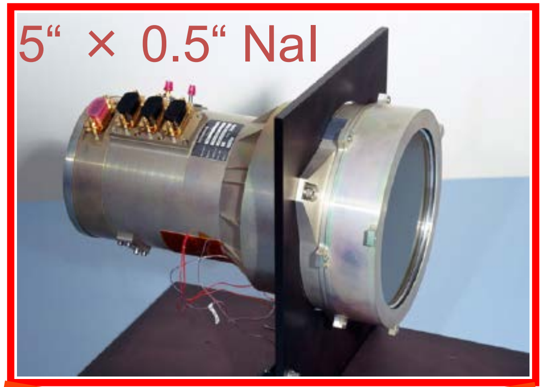


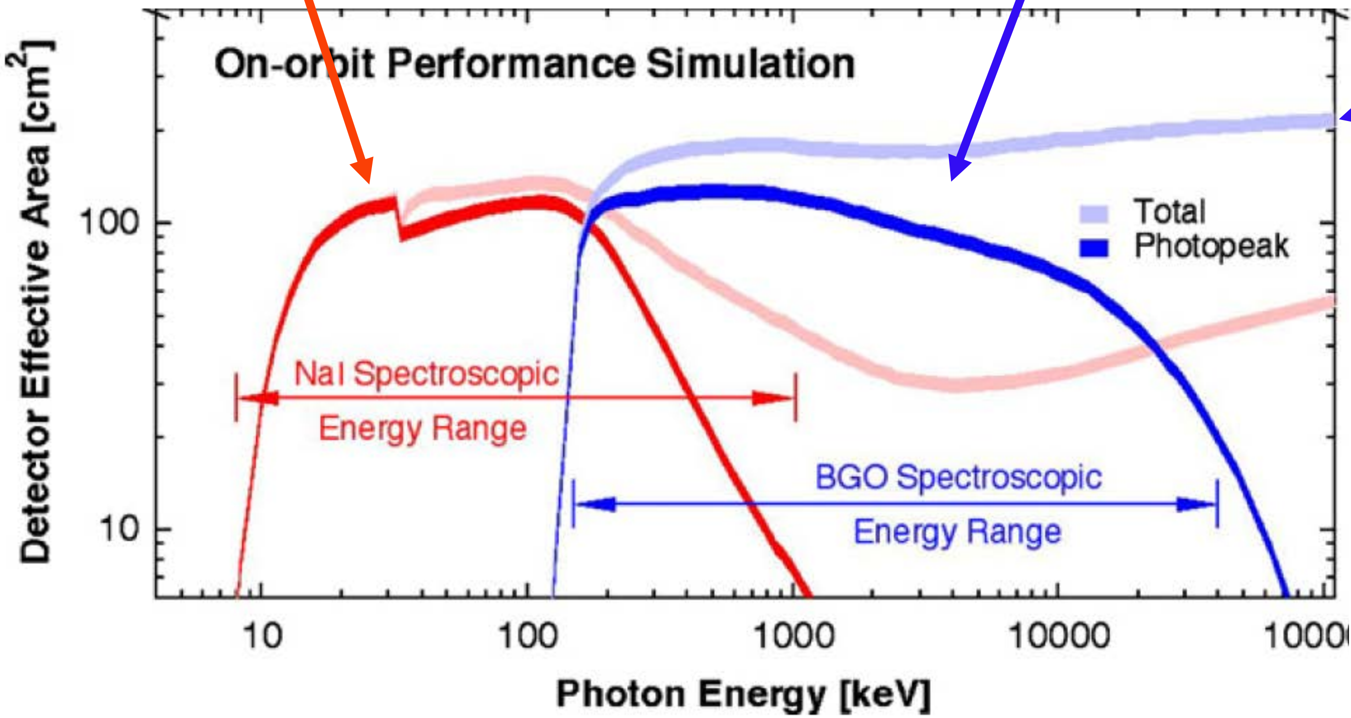


MeV photon detectors (satellite)

- The MeV region is crucial for nuclear physics, and for the study of high-energy emitters
- An "easy" way to do MeV photon detectors
  - Scintillating crystals
- But:
  - Bad directionality
  - No polarization information
- Typically used in Gamma-Ray Burst monitors
- No tracking instrument since COMPTEL (1990)

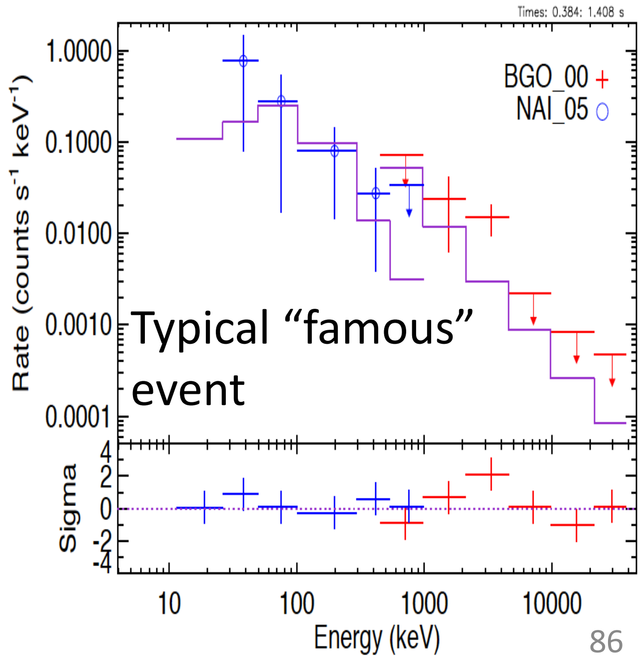
Fermi GBM detectors





effective area
≈ 160 cm^2

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



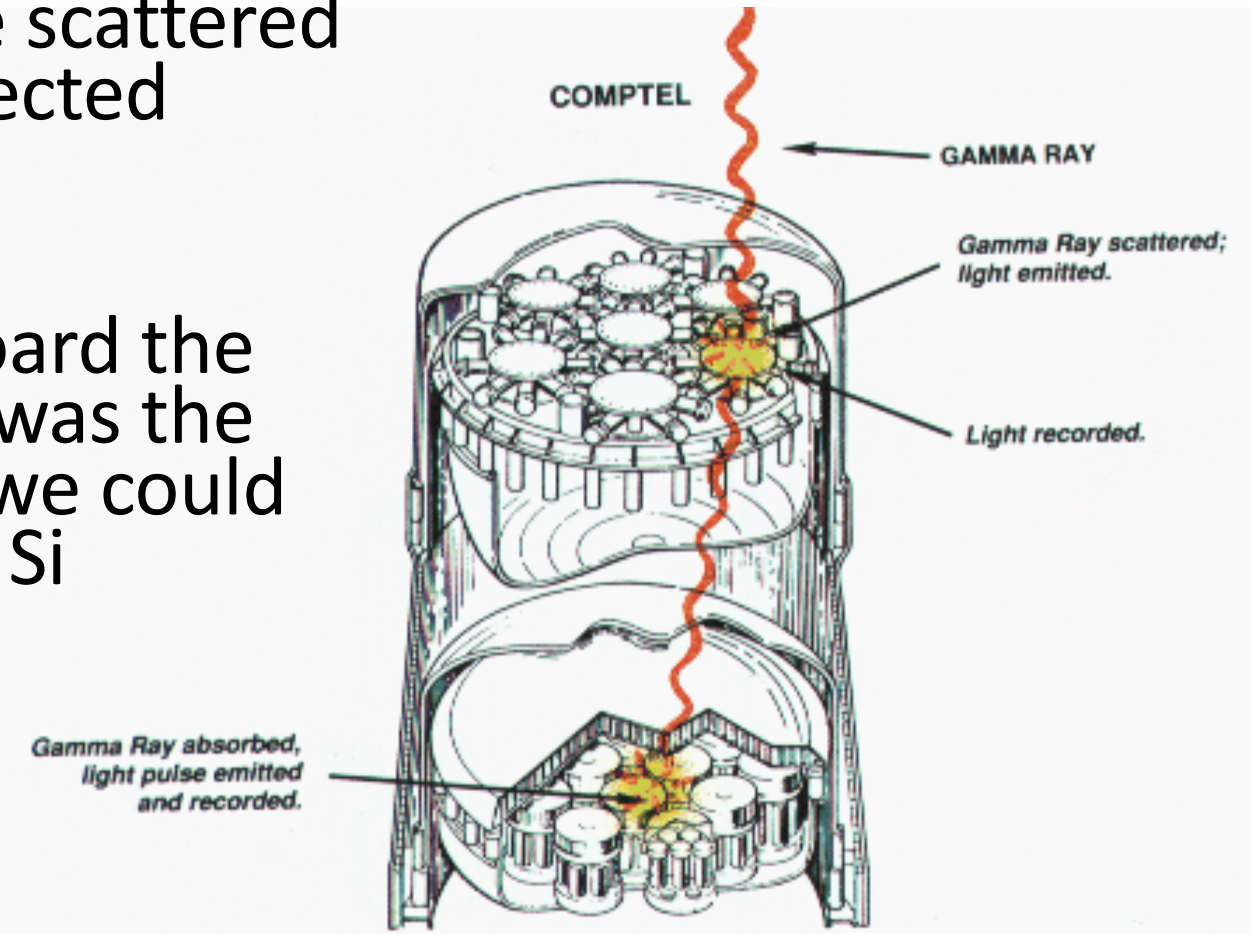
Typical "famous" event

MeV photon detectors: the hard way

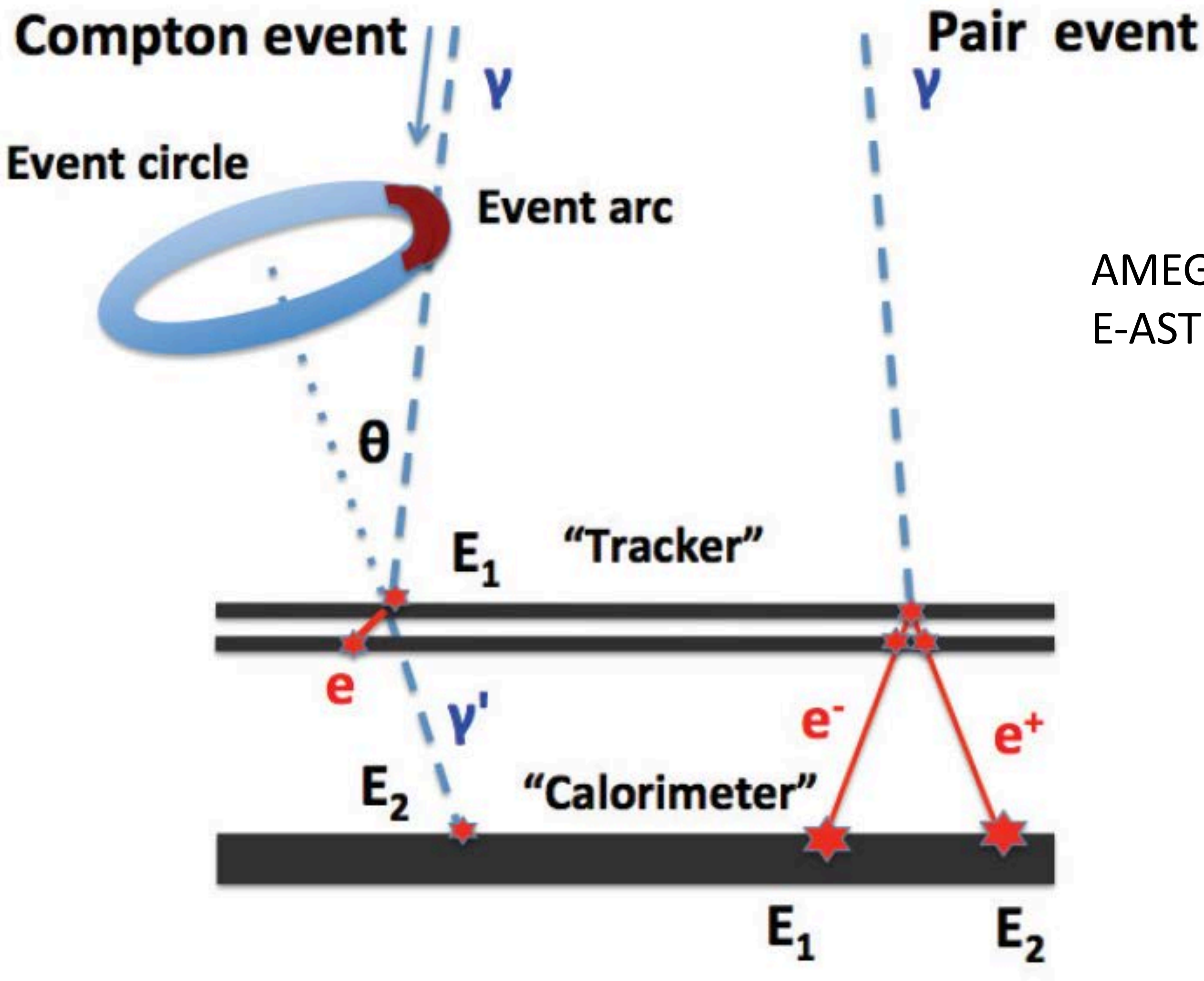
- Specific Compton detectors

- 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…



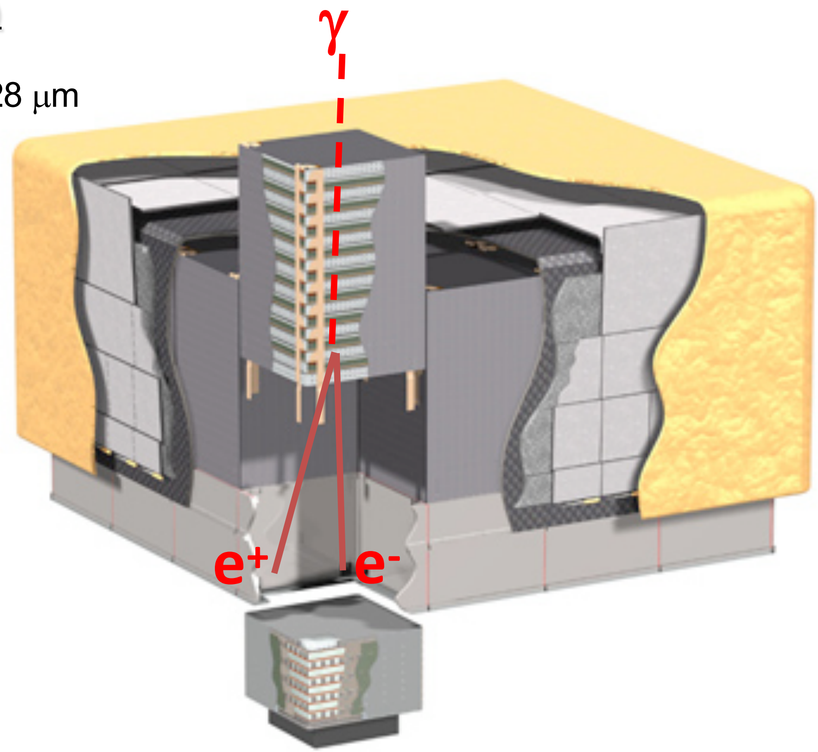
How to do it with today’s technology?



AMEGO (NASA, Mc ENERY at al.)
E-ASTROGAM (ESA, De Angelis et al.)

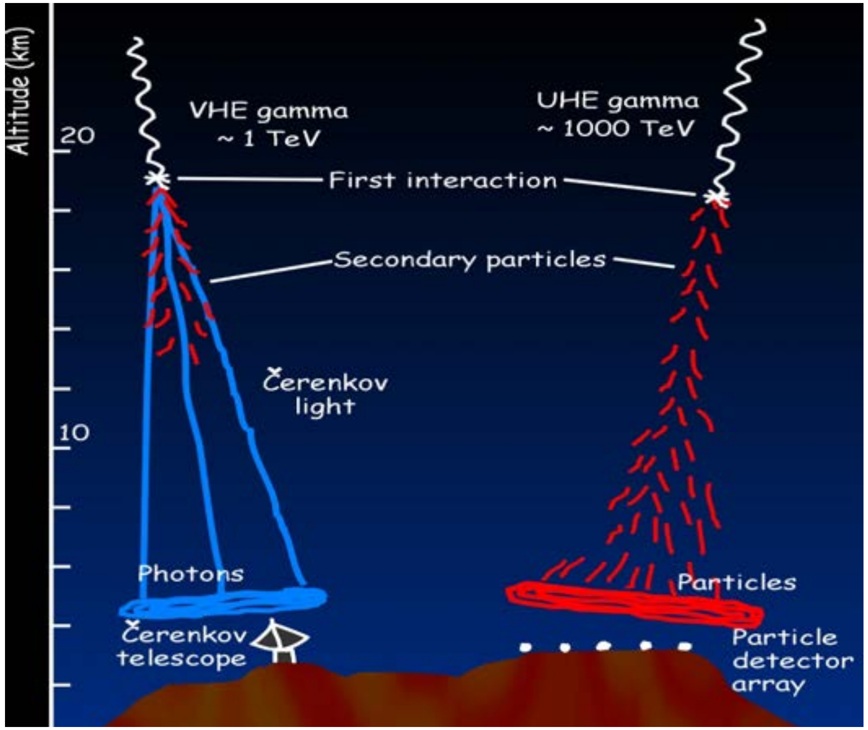
Higher Energies

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



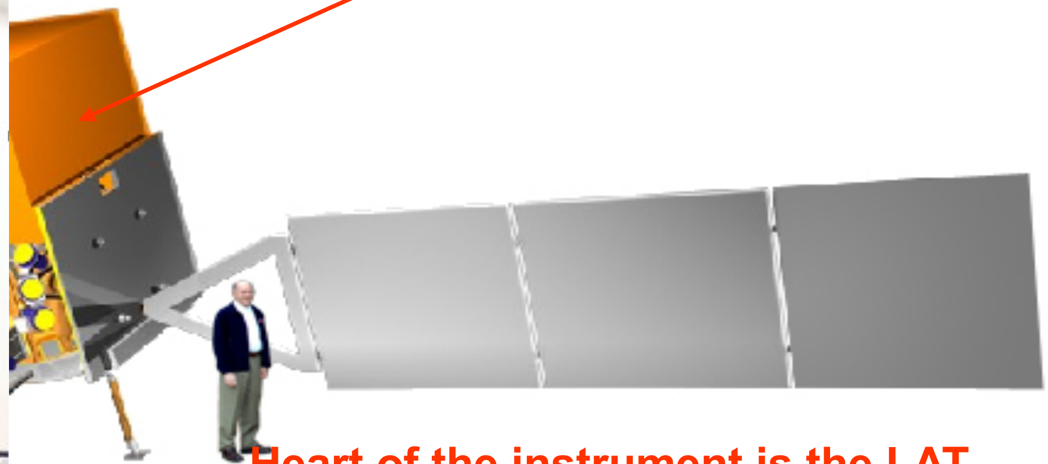
- GeV Satellites (AGILE, Fermi, DAMPE)
  - Silicon tracker (+calorimeter)
- Cherenkov telescopes (H.E.S.S., MAGIC, VERITAS)
- Extensive Air Shower detectors (HAWC, LHAASO):
  RPC, scintillators, water Cherenkov

  HEP detectors!



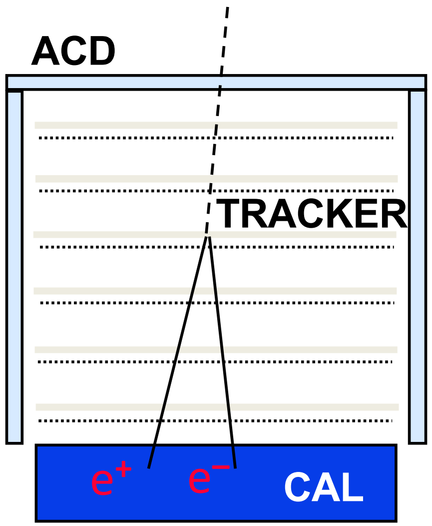
The GeV (pair production): Fermi and the LAT

Gamma Ray Burst Monitor (GBM)



er

Heart of the instrument is the LAT, detecting gamma conversions γ



Fermi-LAT launched June 2008

LAT overview

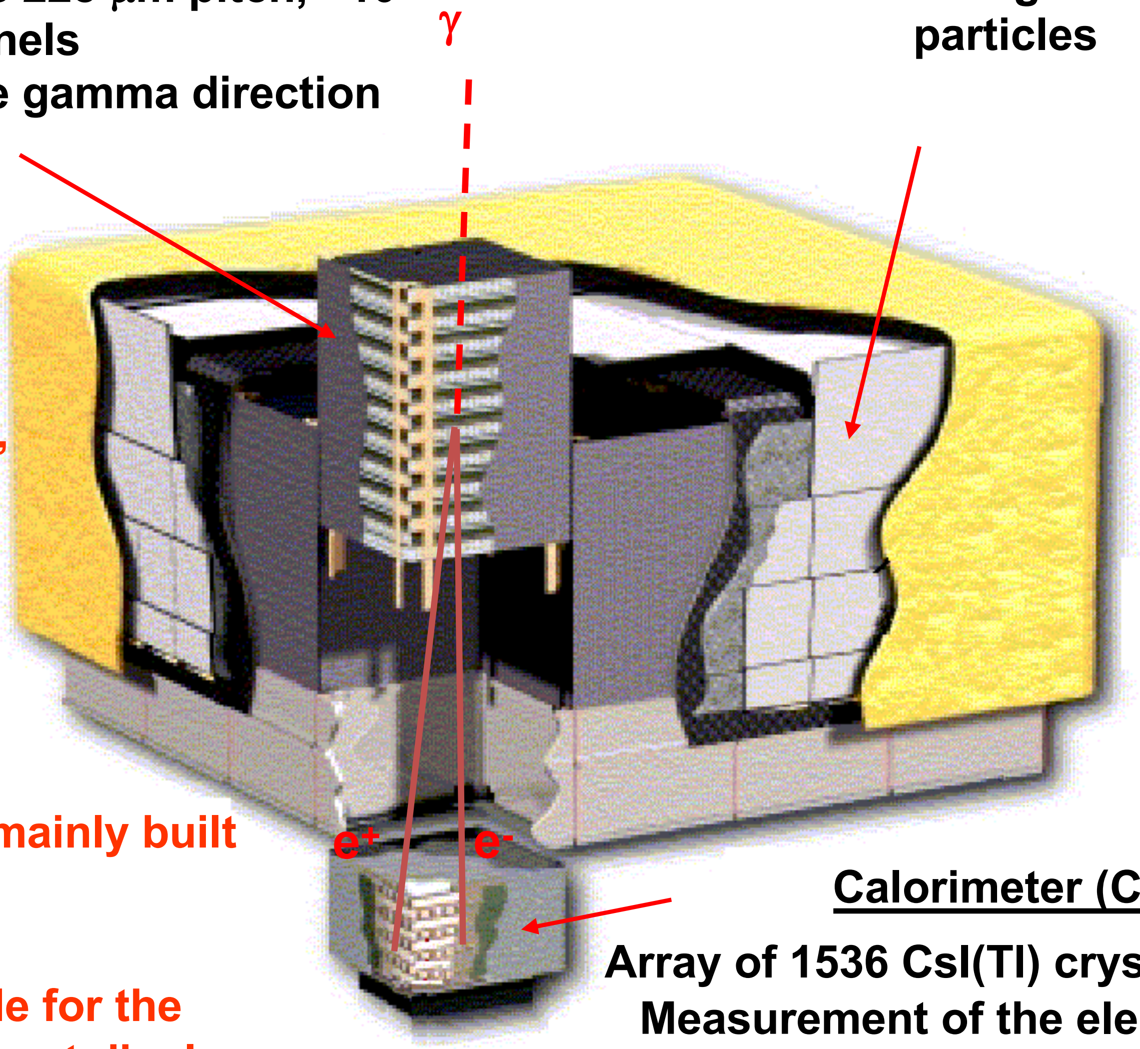
Si-strip Tracker (TKR)

18 planes XY ~ 1.7 x 1.7 m² w/ converter
Single-sided Si strips 228 μm pitch, ~10^6 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

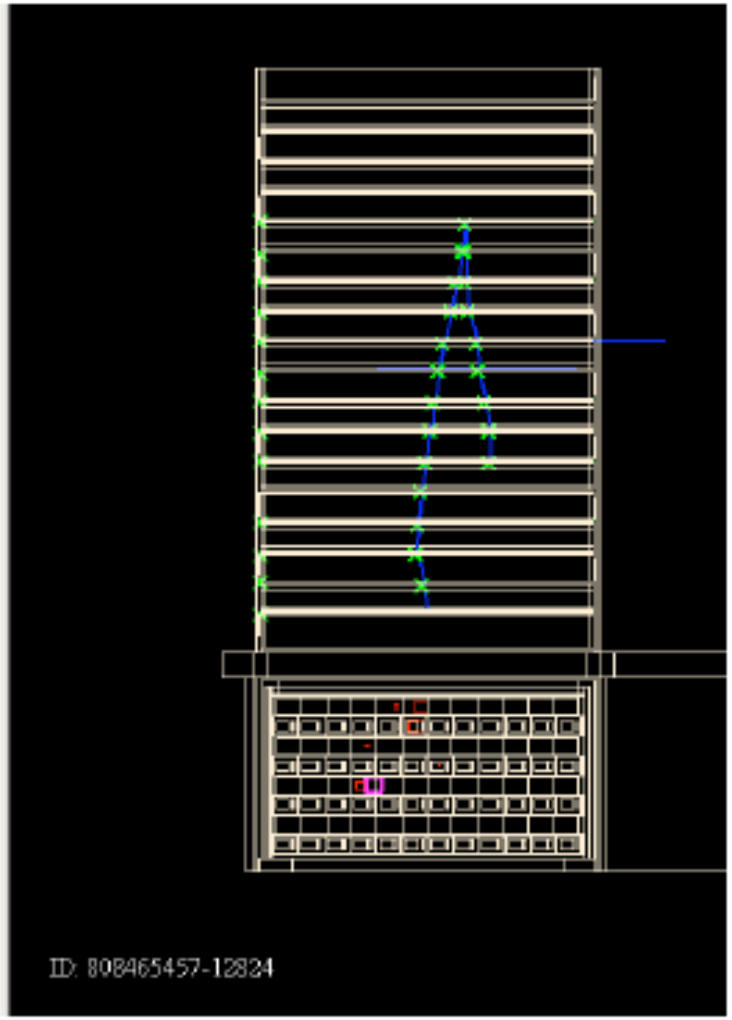
Calorimeter (CAL)

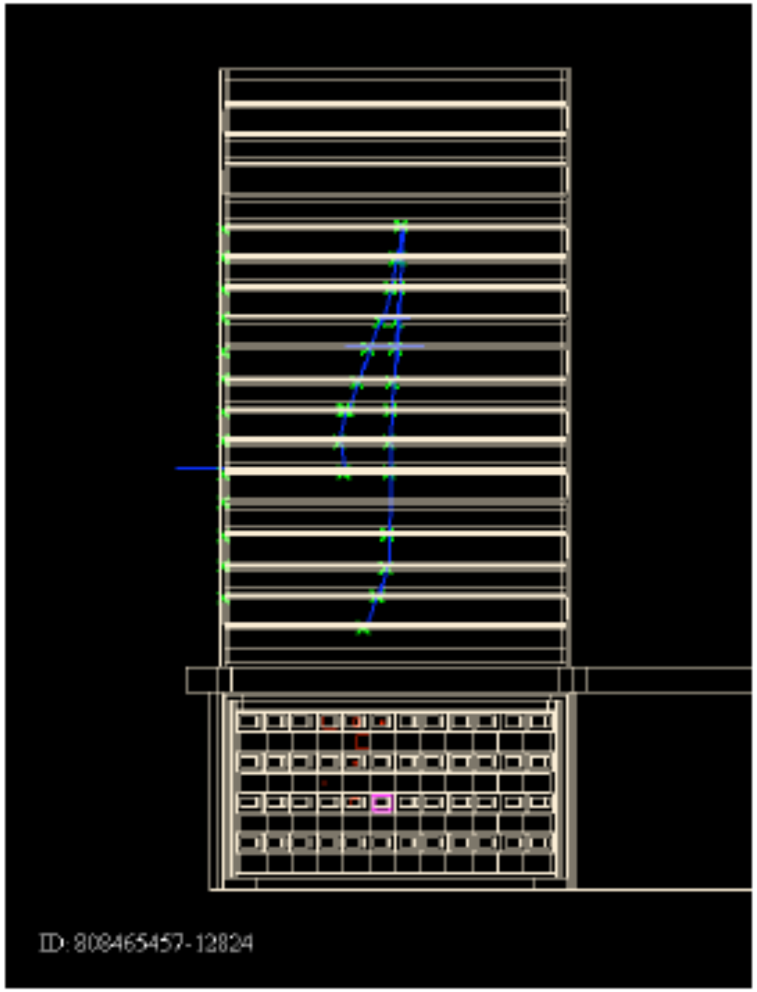
Array of 1536 CsI(Tl) crystals in 8 layers
Measurement of the electron energy

The Silicon tracker is mainly built in Italy

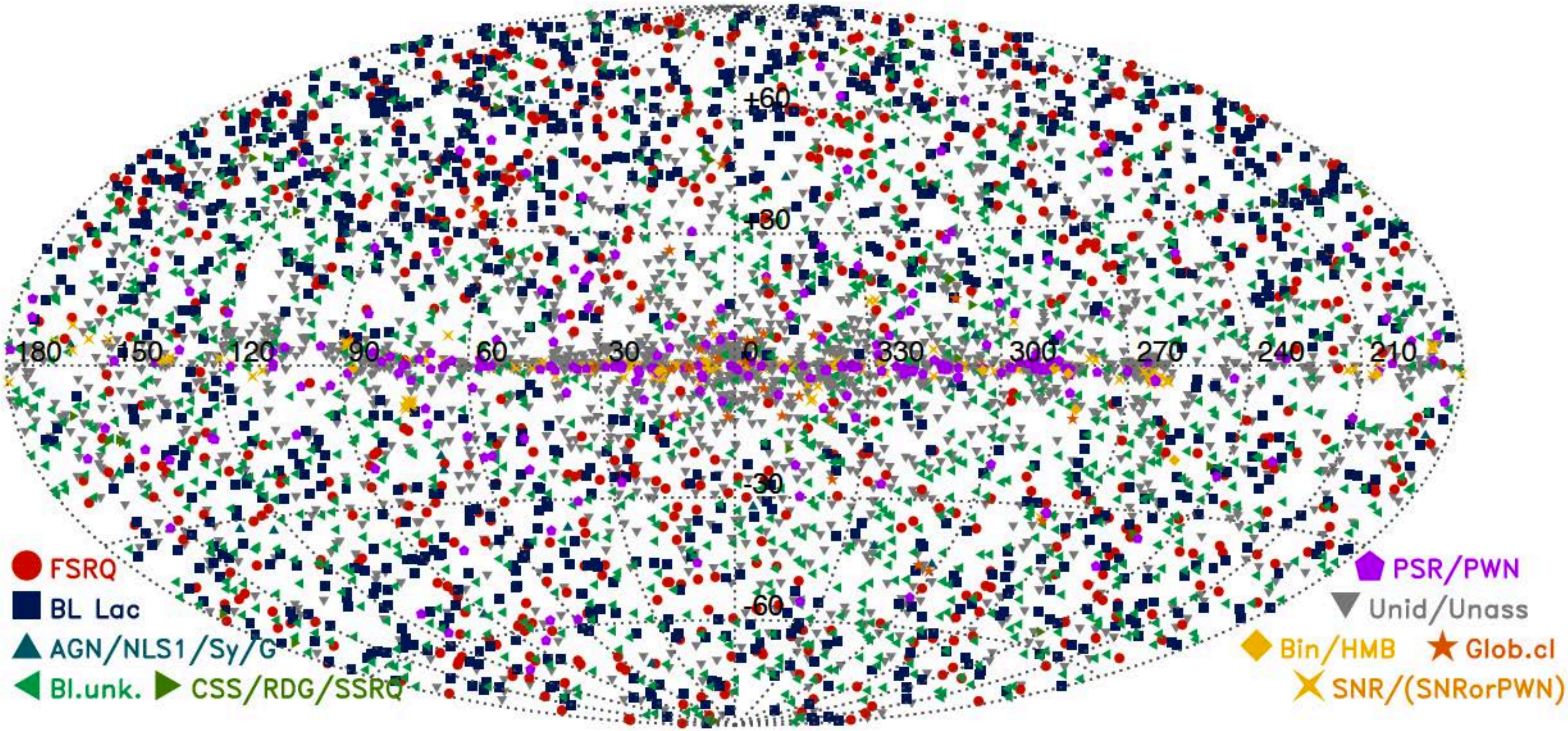
Italy is also responsible for the detector simulation, event display and GRB physics

Detection of a gamma-ray



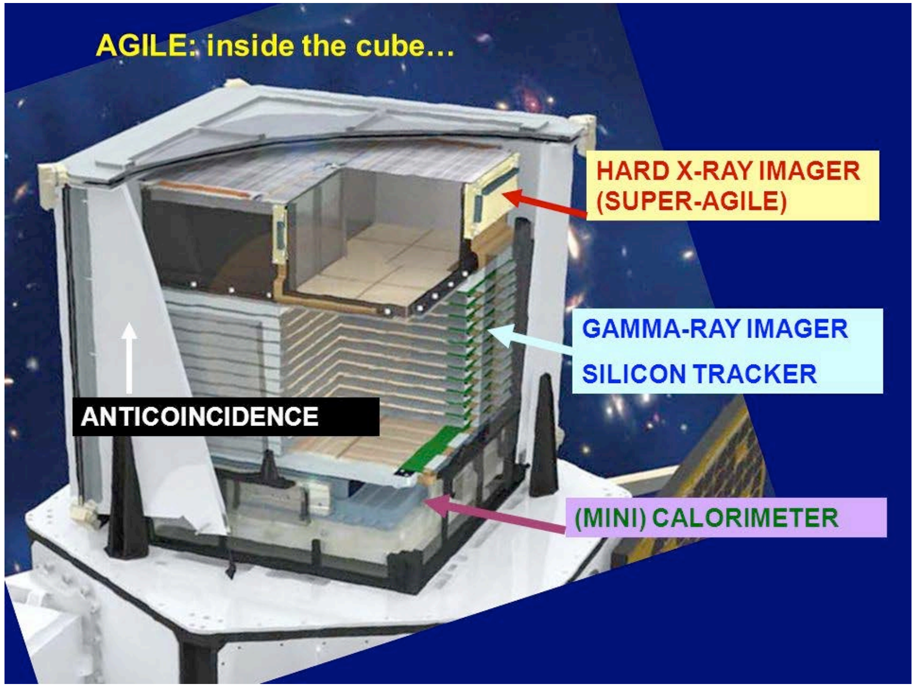


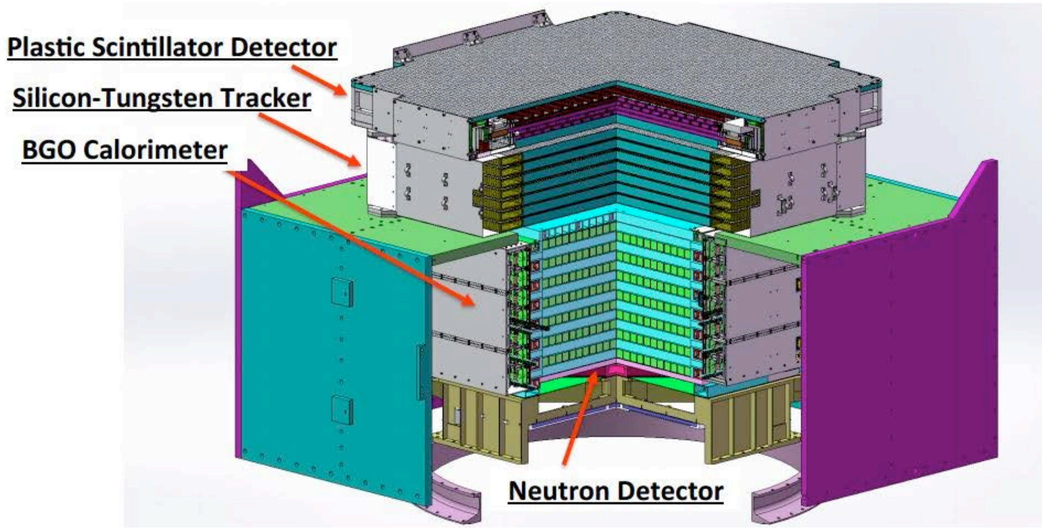
LAT 8-year Point Source Catalog (4FGL)



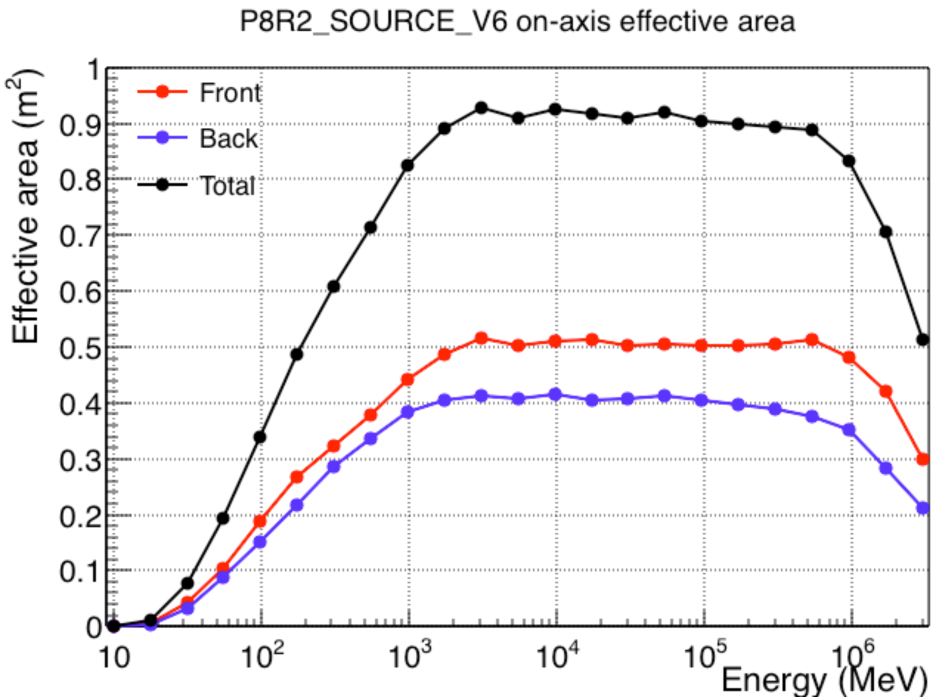
AGILE & DAMPE

- 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

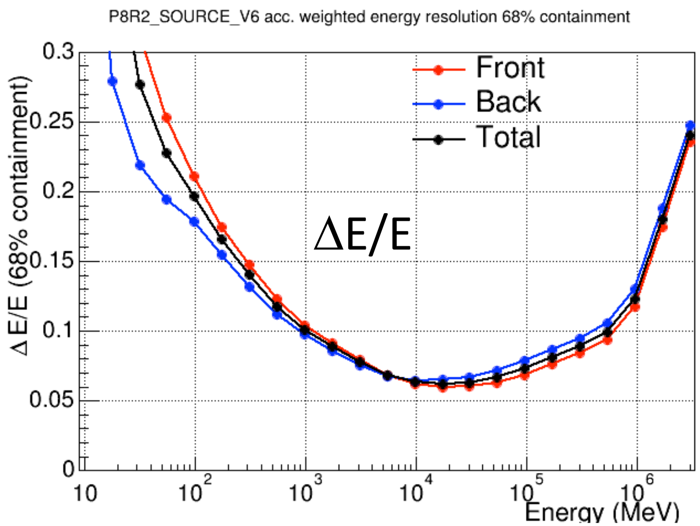


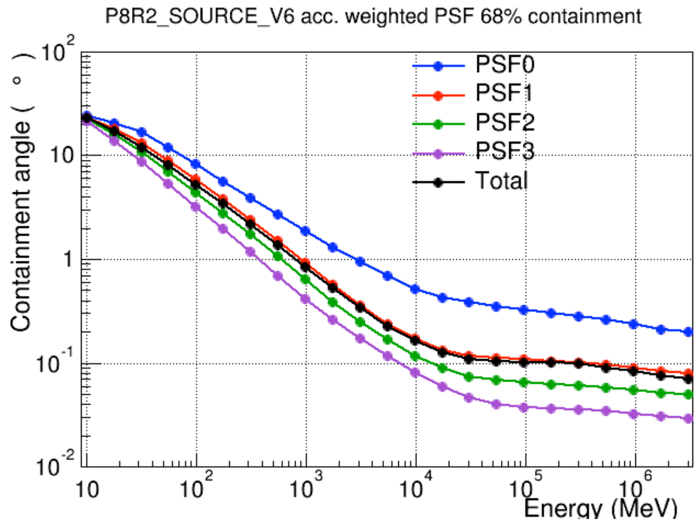
Effective area (Area x efficiency)

~ $1 m^2$

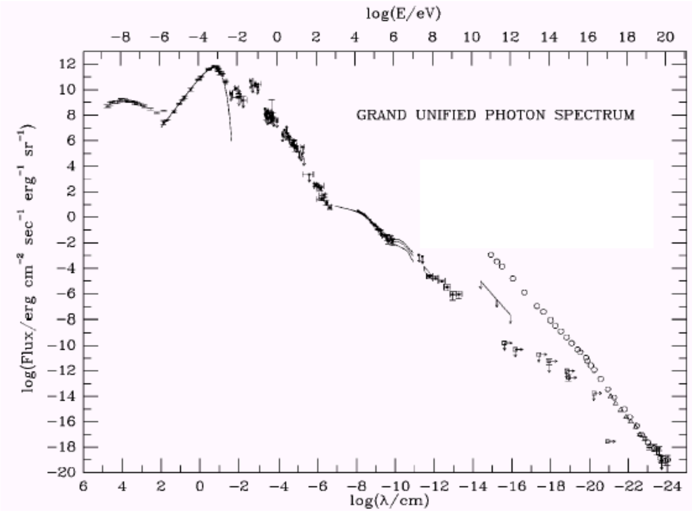
Grows as k lnE from 2 MeV to 2 GeV
Then ~$0.9 m^2$ from 2 GeV to 700 GeV
Then decreases as k' lnE

Acceptance: 2.5 sr

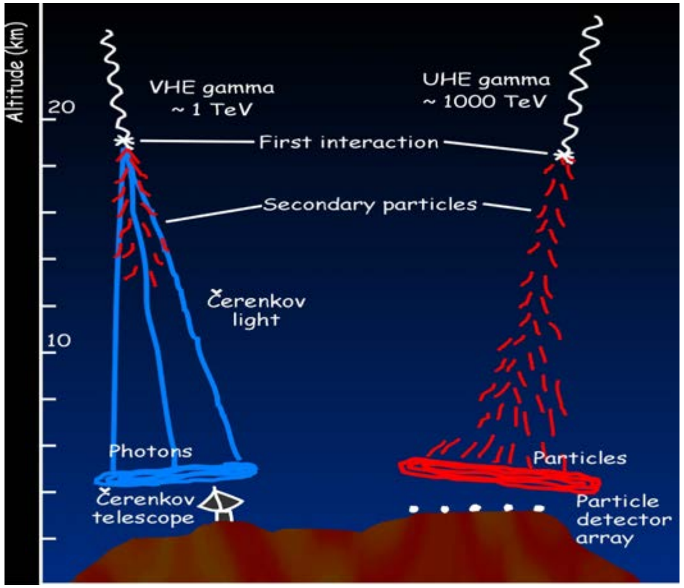


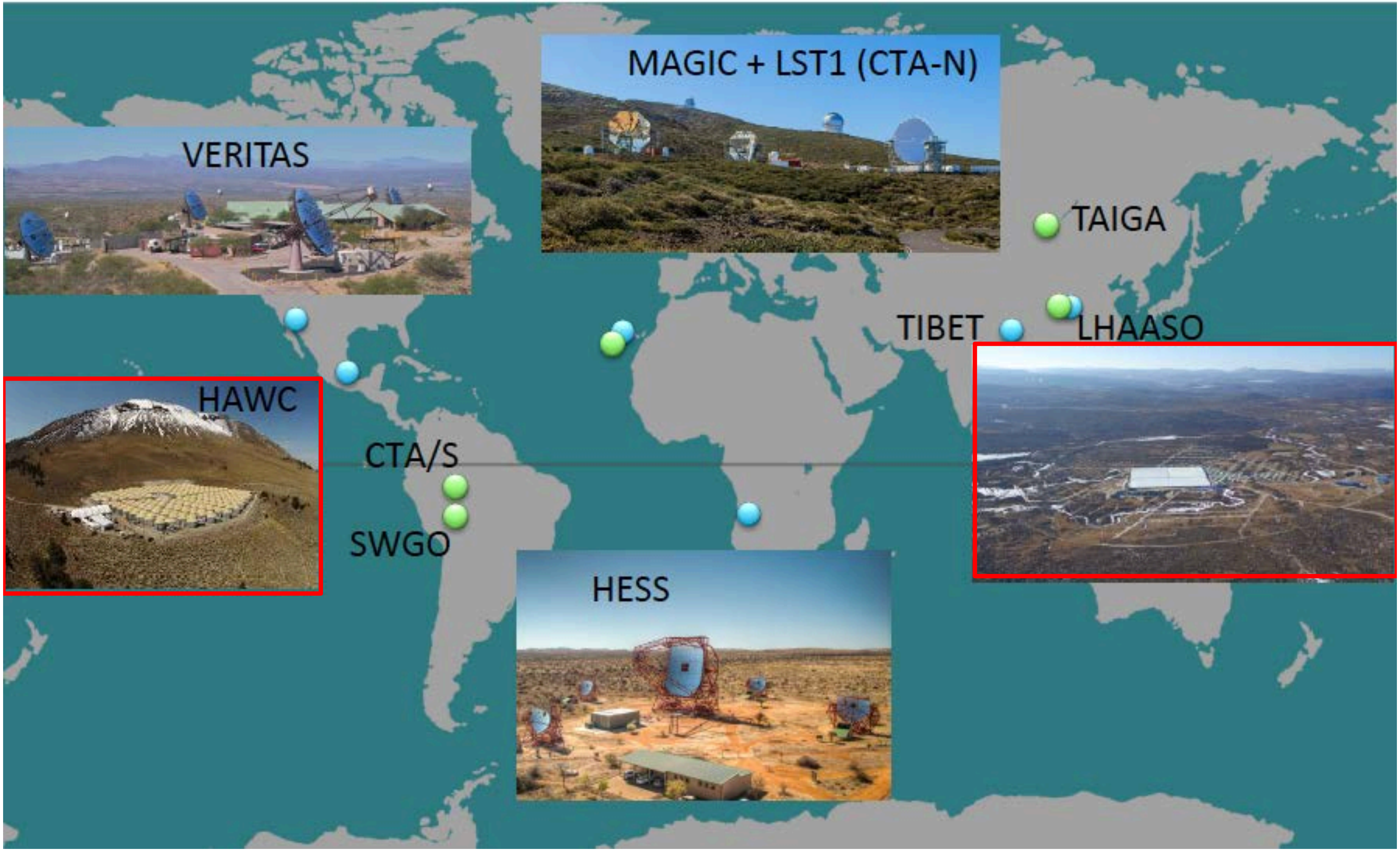


Why detection at ground?



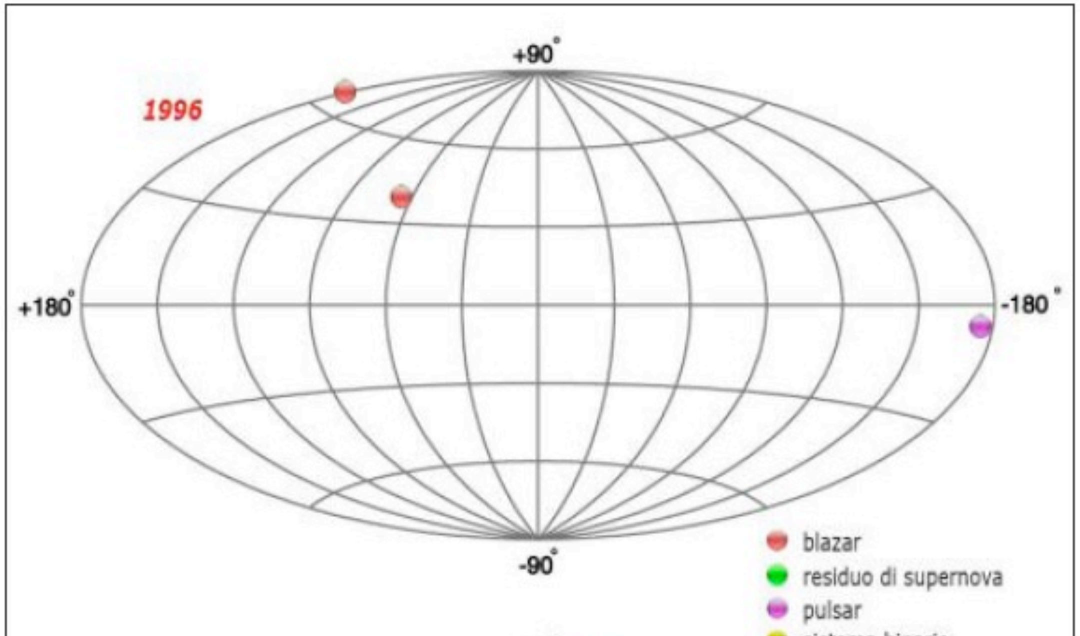
- High energies
  - Only way to build sensitive >TeV instruments
  - Maximum flux < 1 photon/h/m^2 above 200 GeV in Fermi
- High statistics /short timescales
  - Large collection areas O(km^2)
- Precision (Imaging Air Cherenkov telescopes, IACTs)
  - Superior angular resolution
- Limitations?
  - IACTs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

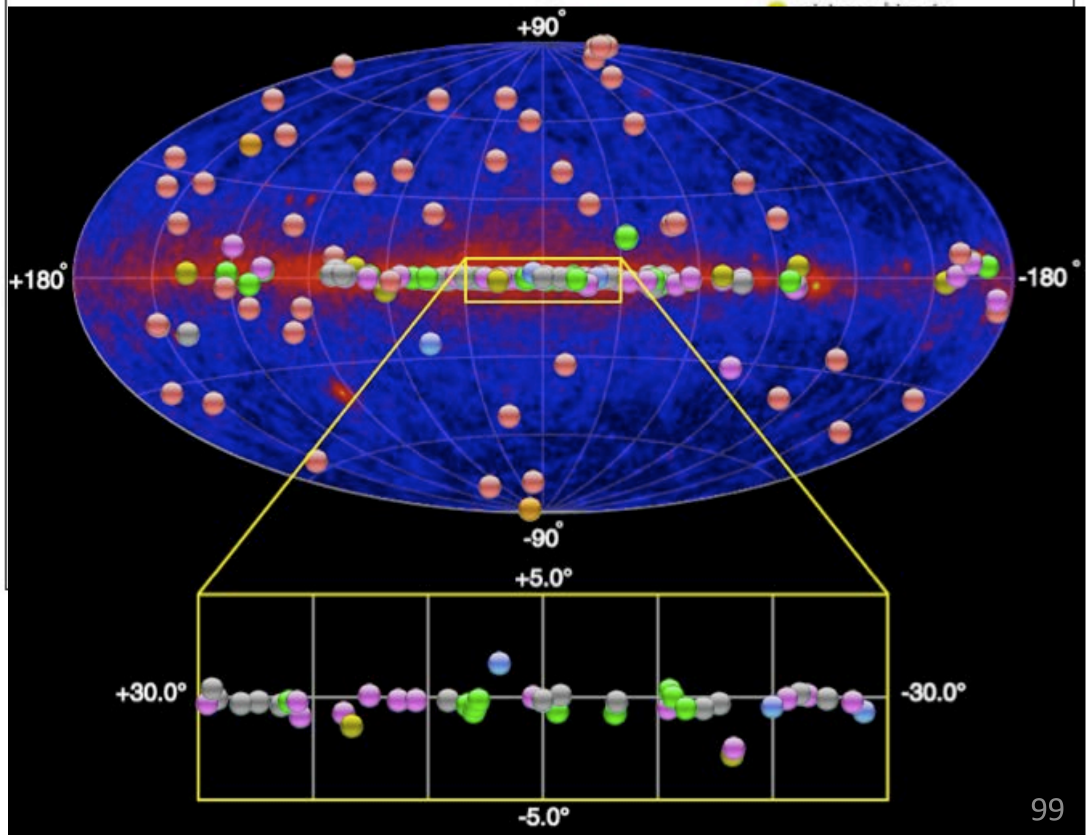



MAGIC + LST1 (CTA-N)
VERITAS
TAIGA
TIBET
LHAASO
HAWC
CTA/S
SWGO
HESS

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
  - **TeVCAT**
- 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

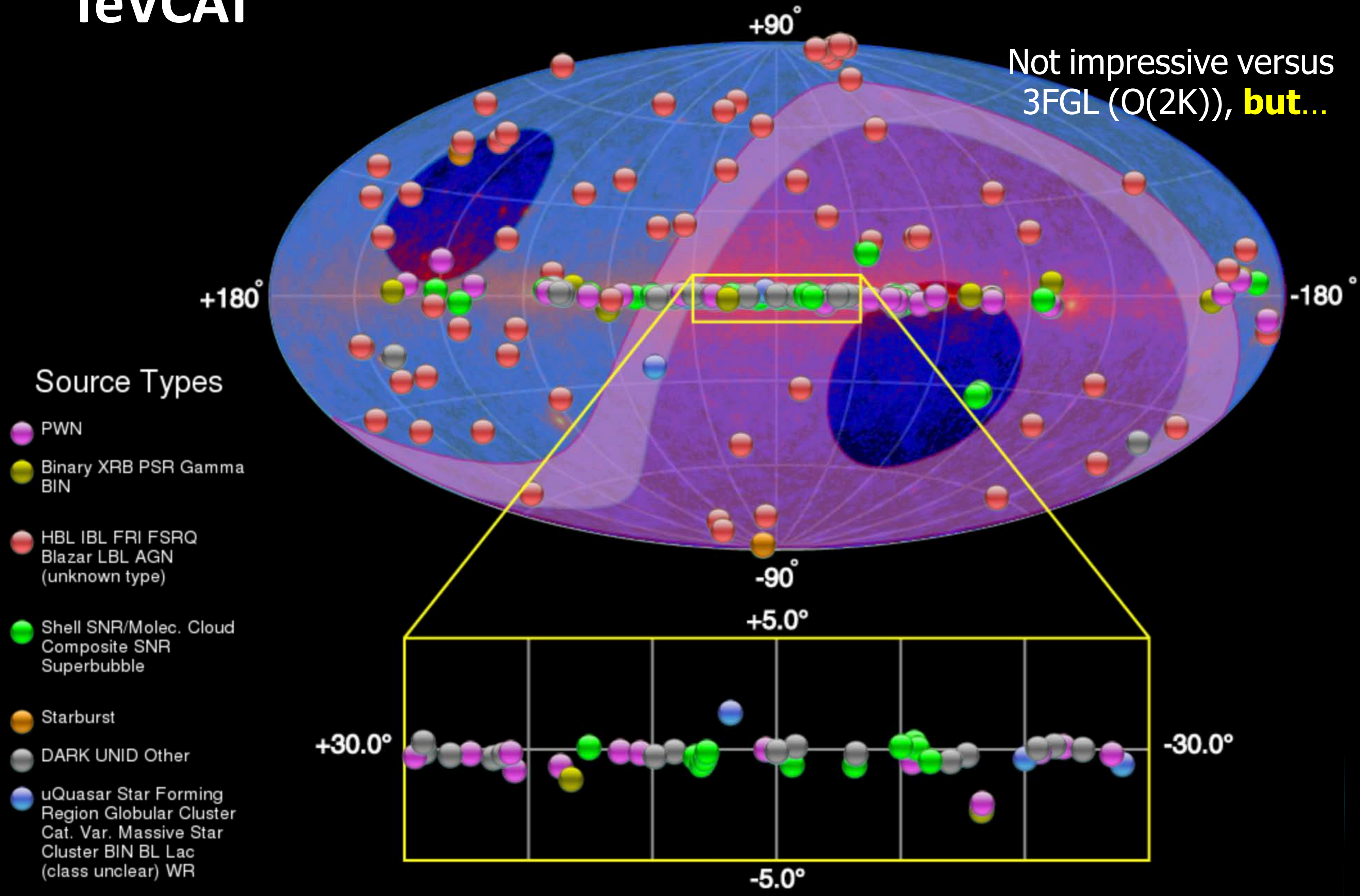




TeVCAT

>200 sources detected by ground-based instruments

Not impressive versus 3FGL (O(2K)), **but**…



The Cherenkov technique

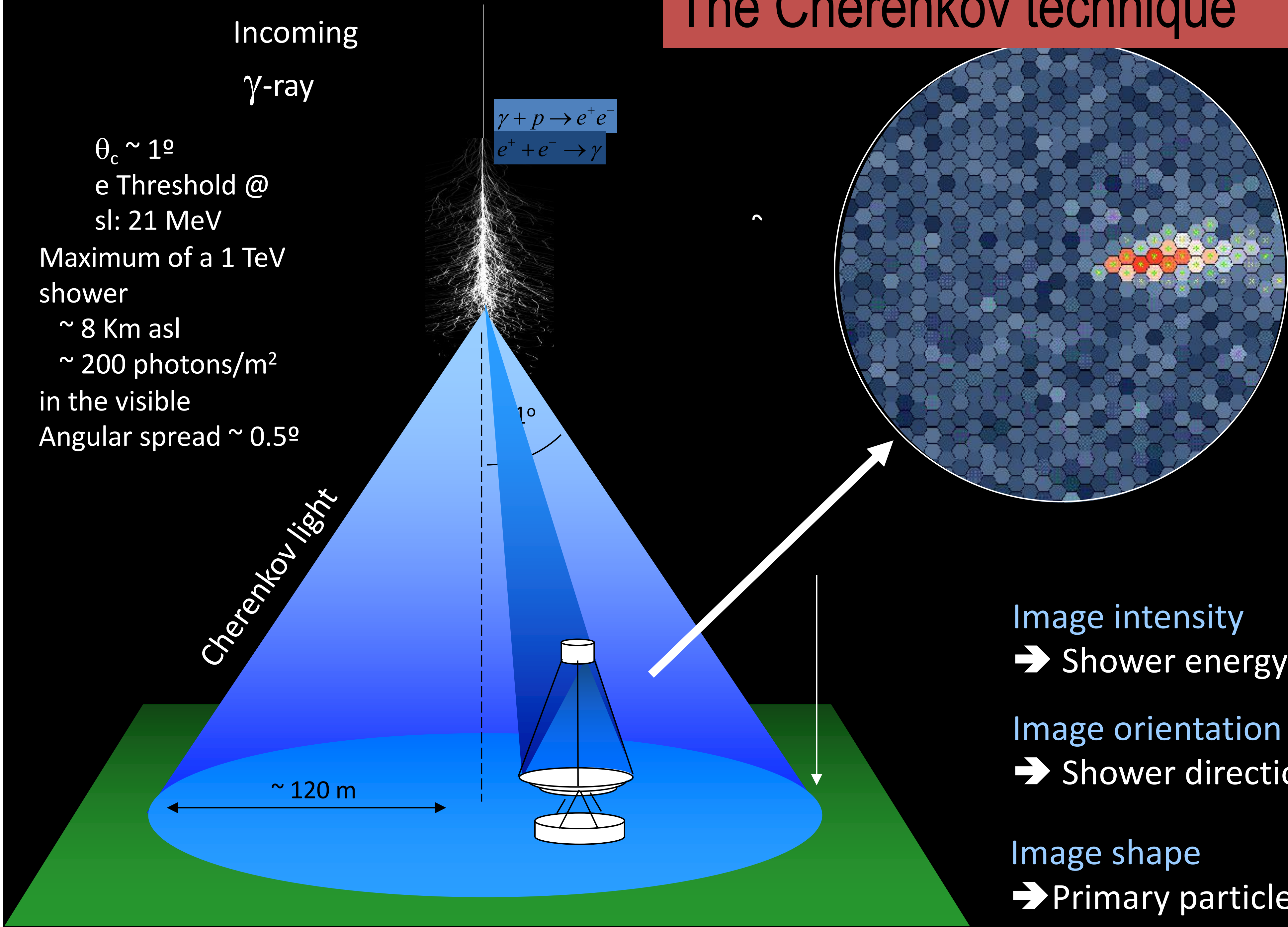
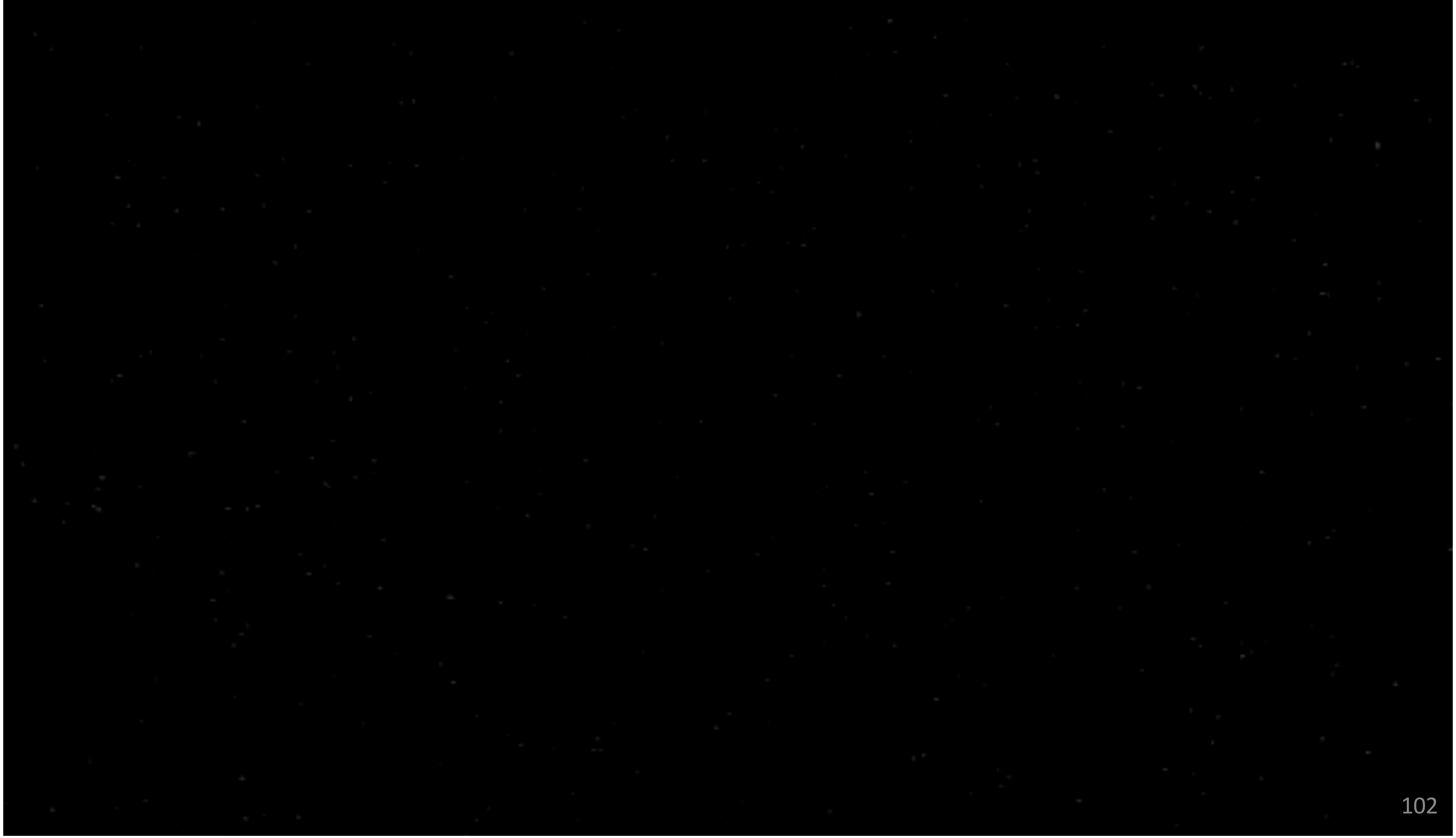


Image intensity
➔ Shower energy

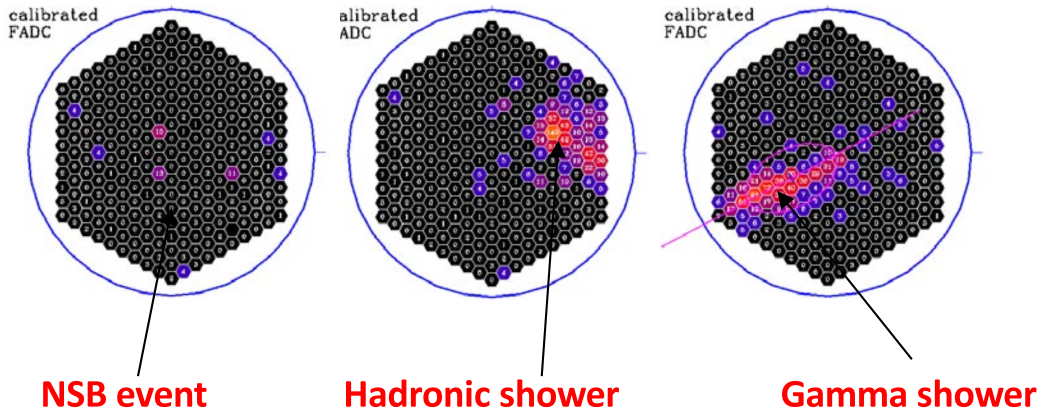
Image orientation
➔ Shower direction

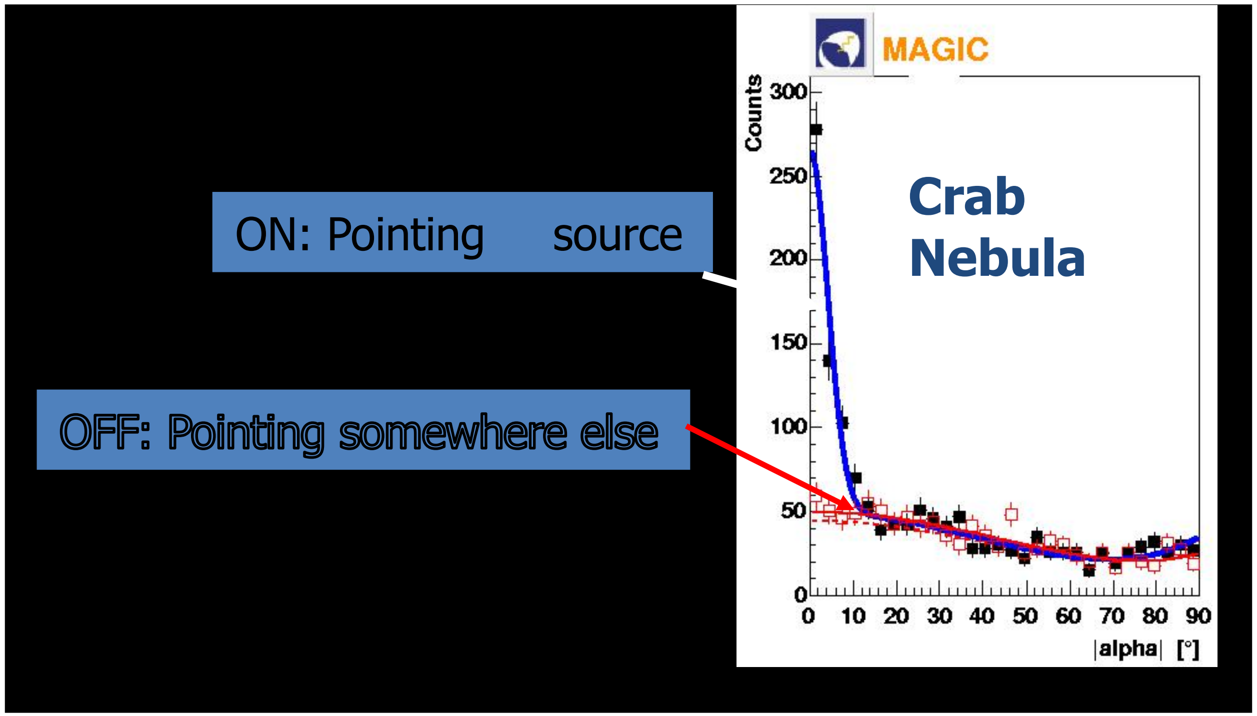
Image shape
➔ Primary particle

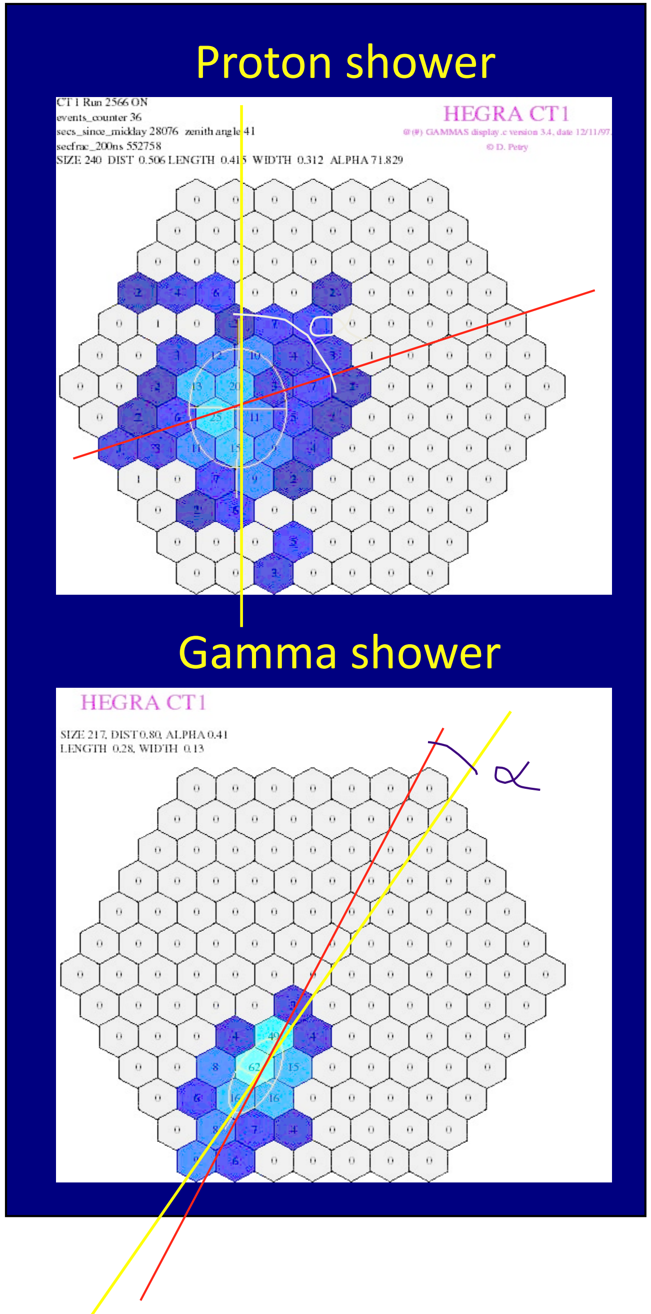
Signal duration: ~ 3ns



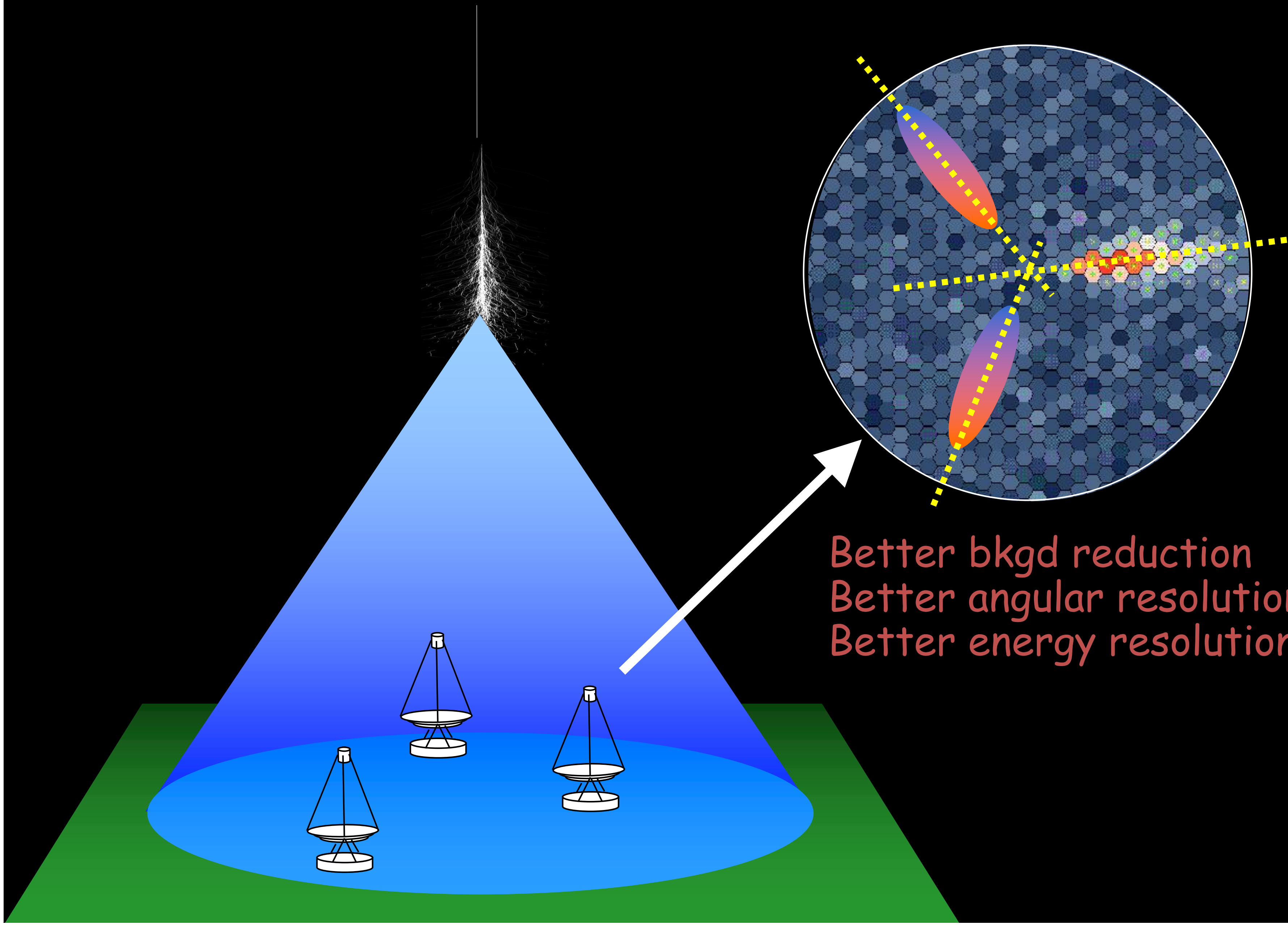
γ/h Separation







Systems of Cherenkov telescopes



Better bkgd reduction
Better angular resolution
Better energy resolution

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)

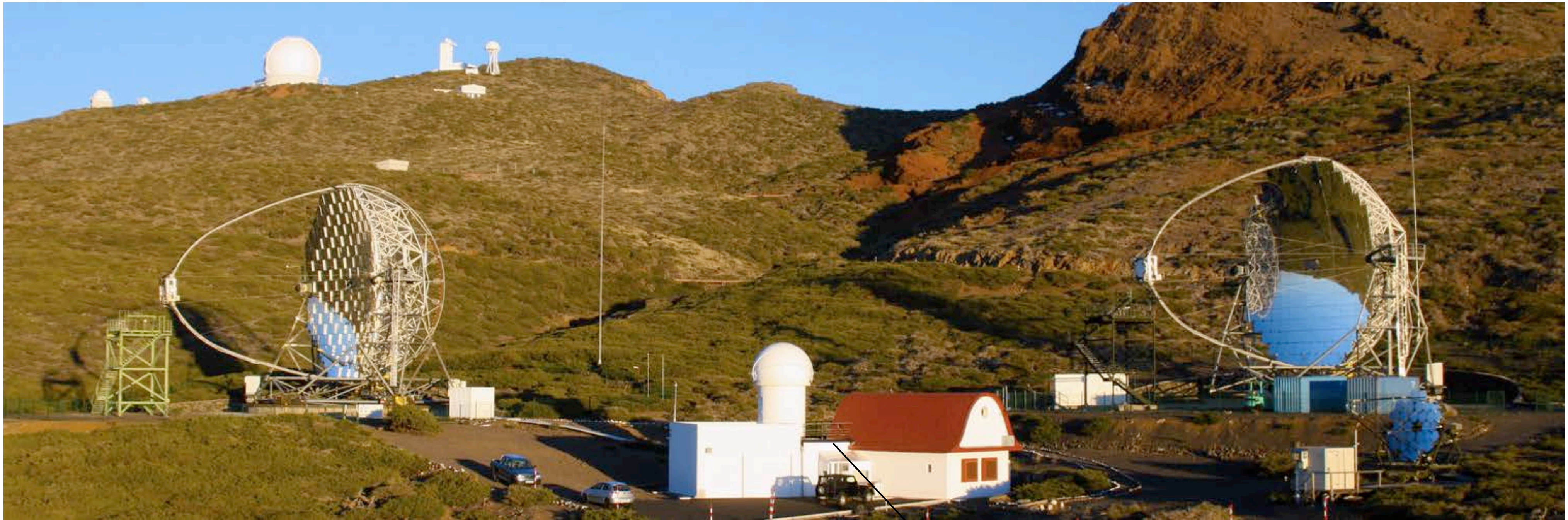
4 telescopes (~12m) operational since 2003

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

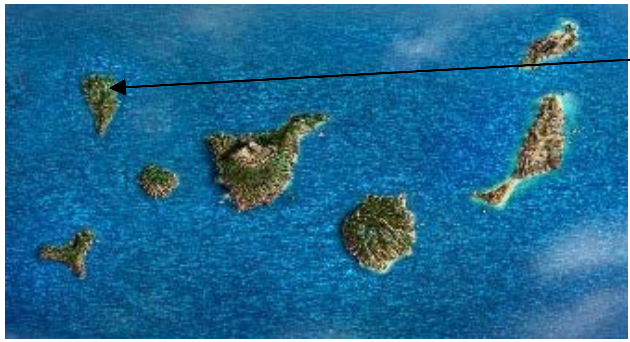
~160 physicists from 10 countries:

Bulgaria, Croatia, Finland, Germany, India, Italy, Japan, Poland, Spain, Switzerland



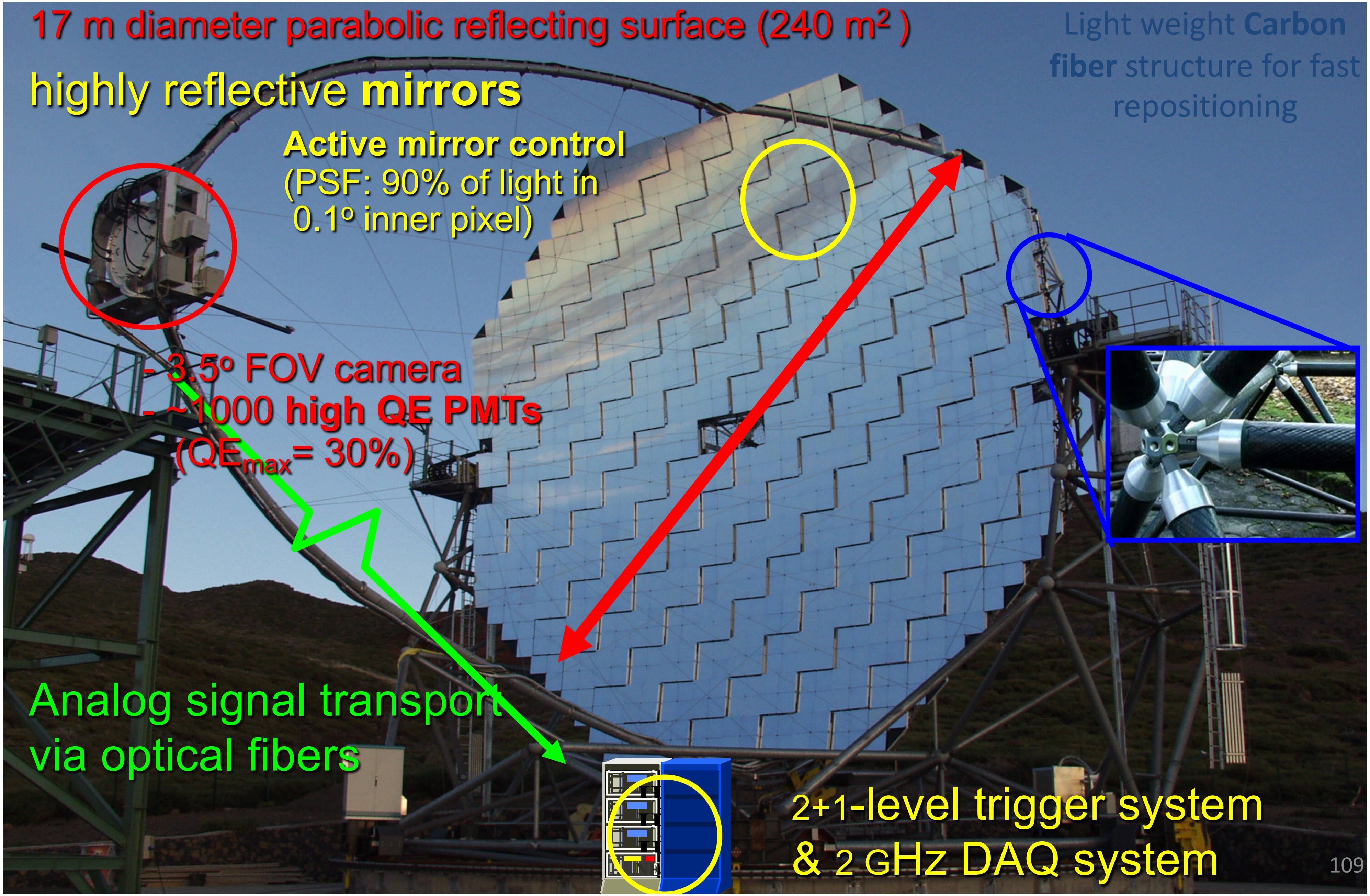
Canary island of La Palma

at 2400 m a.s.l.



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

Key elements

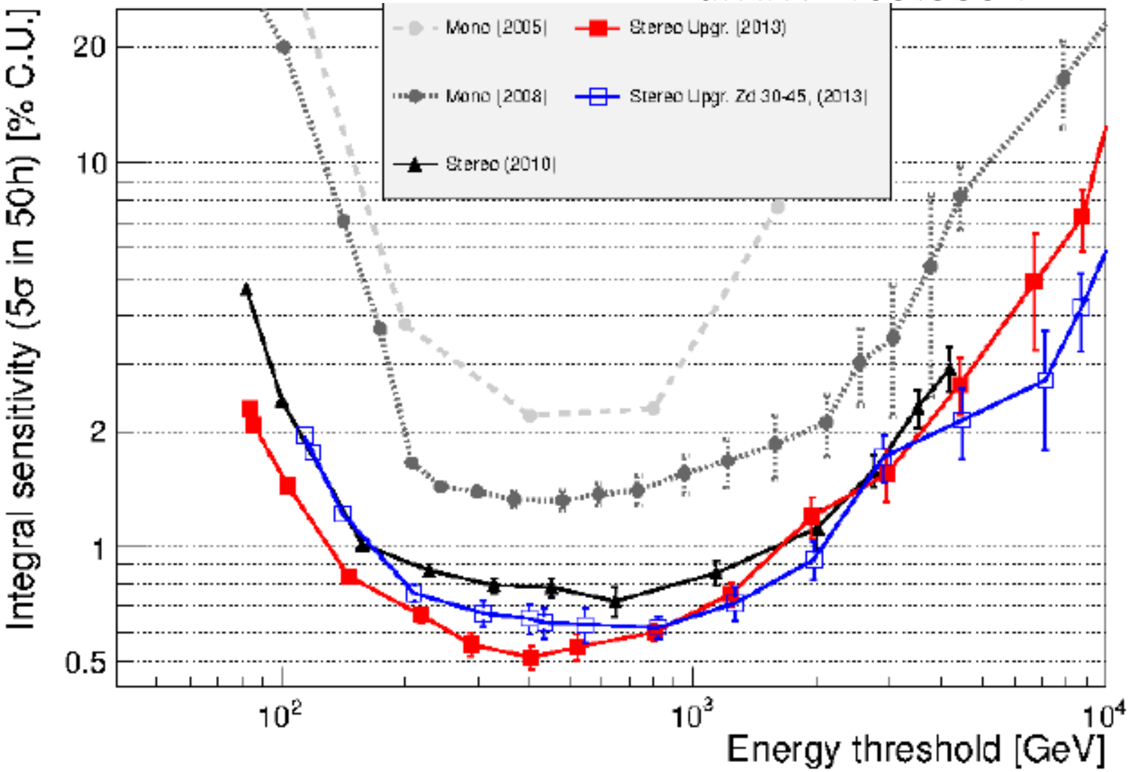


Operated from a control room

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

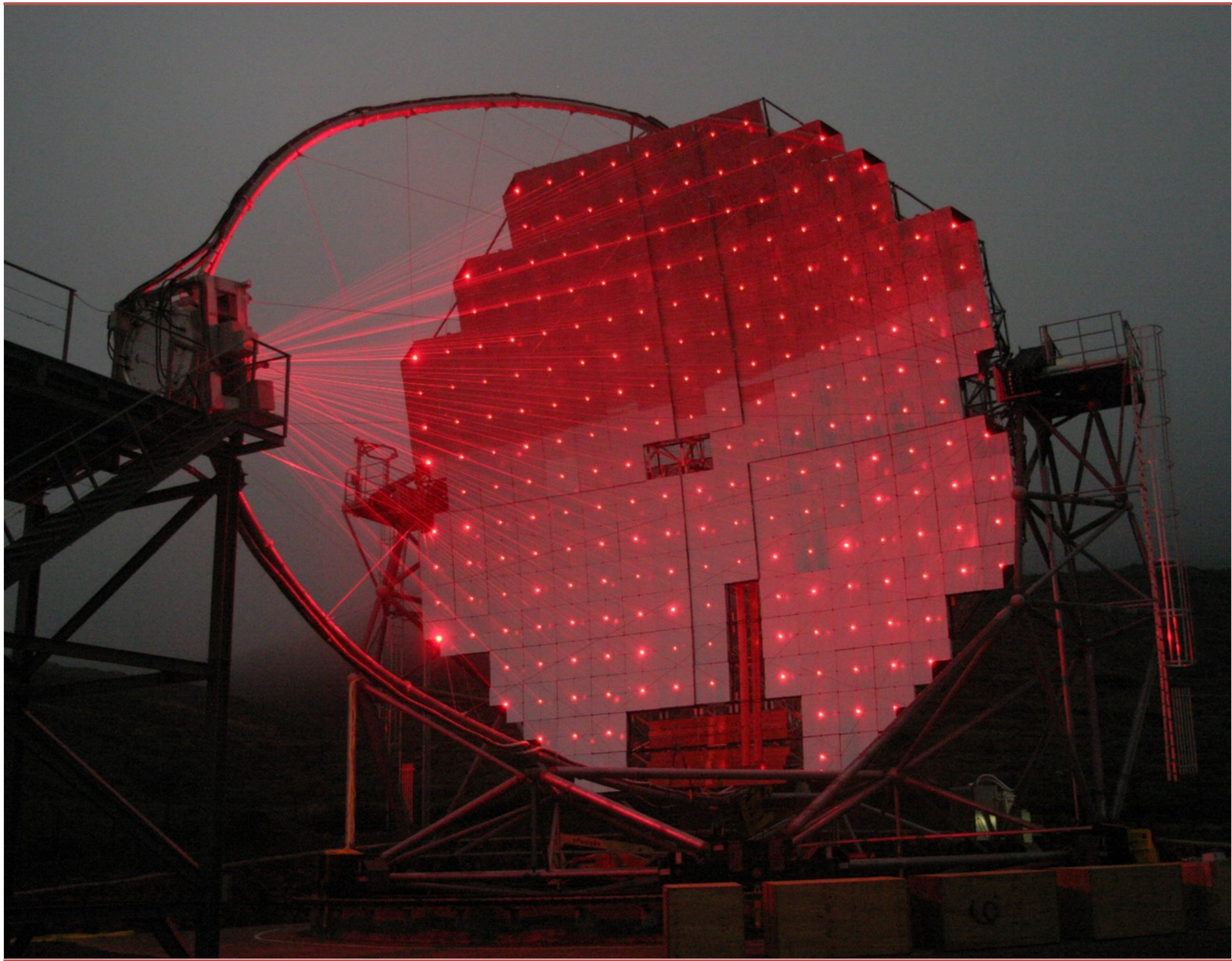
Energy resolution:
15% (@ 1 TeV) – 20% (@100 GeV)

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?

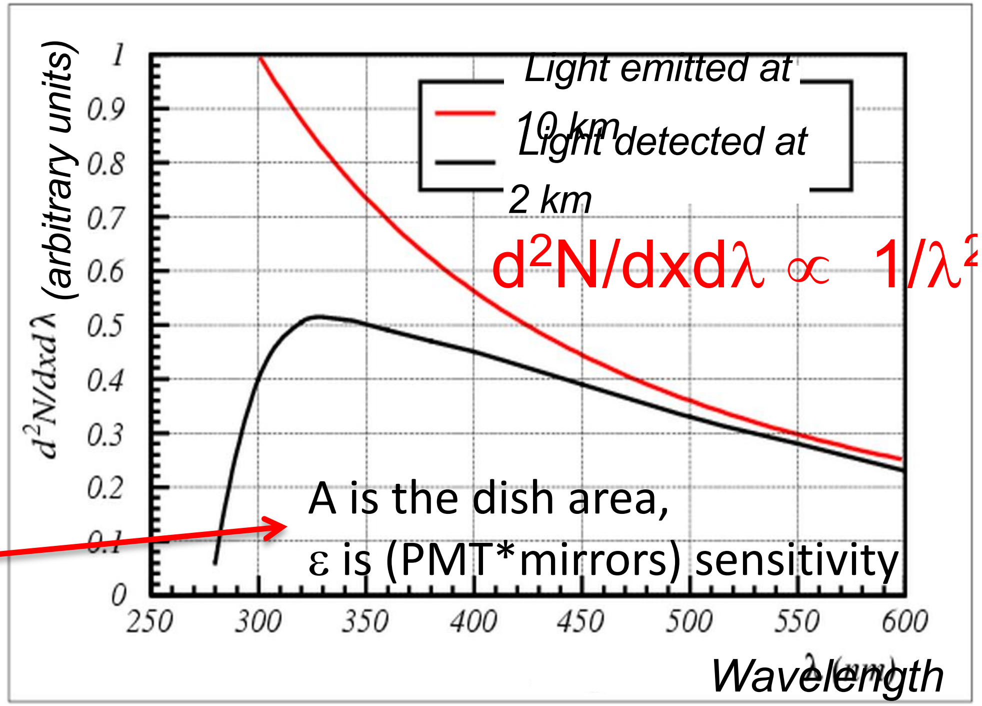
Figures of merit of a Cherenkov telescope

- 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)

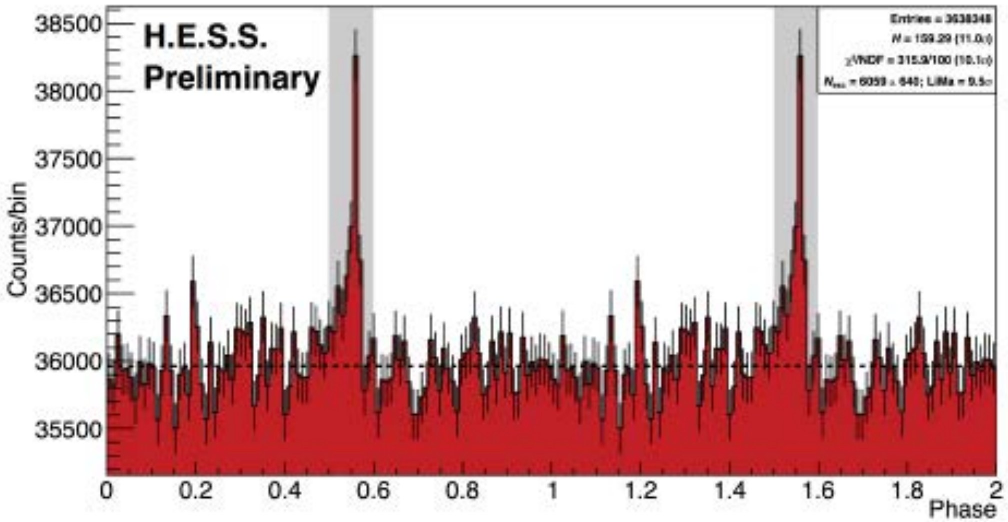
Figures of merit - II

- The threshold is

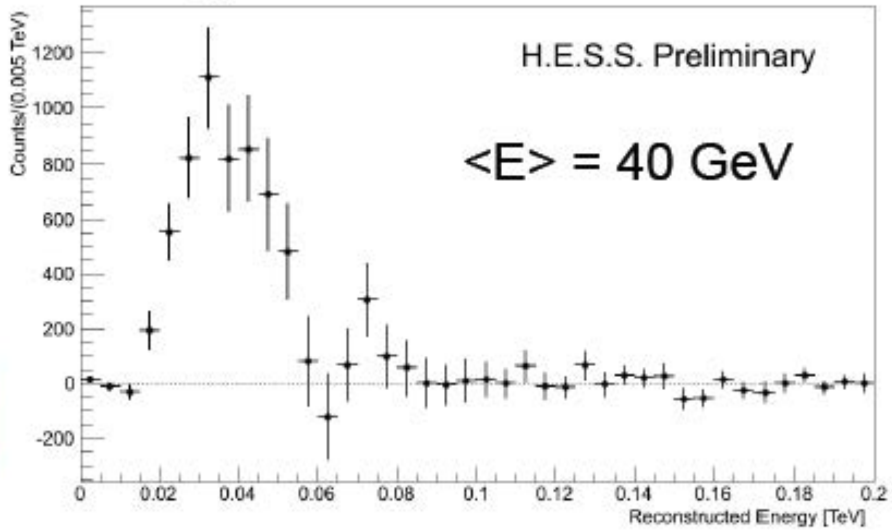
$$E_{threshold} \propto \sqrt{\frac{\phi\Omega\tau}{\epsilon A}}$$



The Vela pulsar seen with CT5



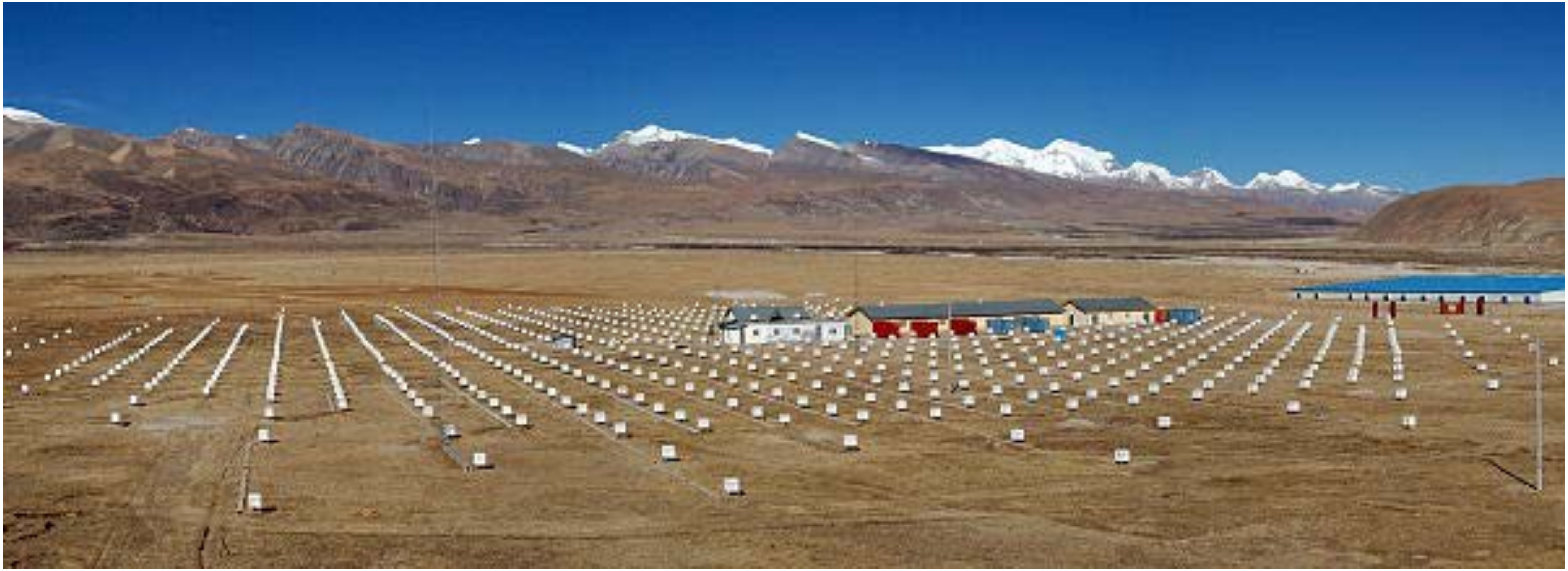
Energy distribution




cta

Higher energies: EAS detectors

(Cost of covering 1 km^2 with Cherenkov telescopes > 100 MEUR)



Tibet – AS gamma: scintillators

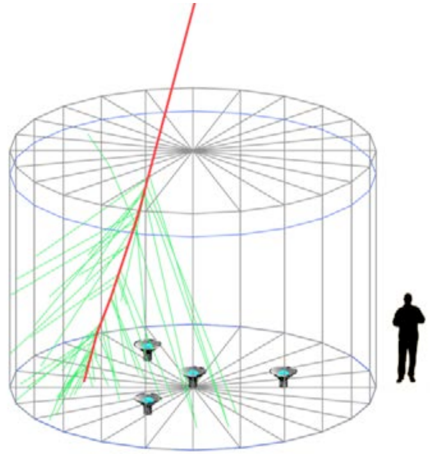
EAS detectors

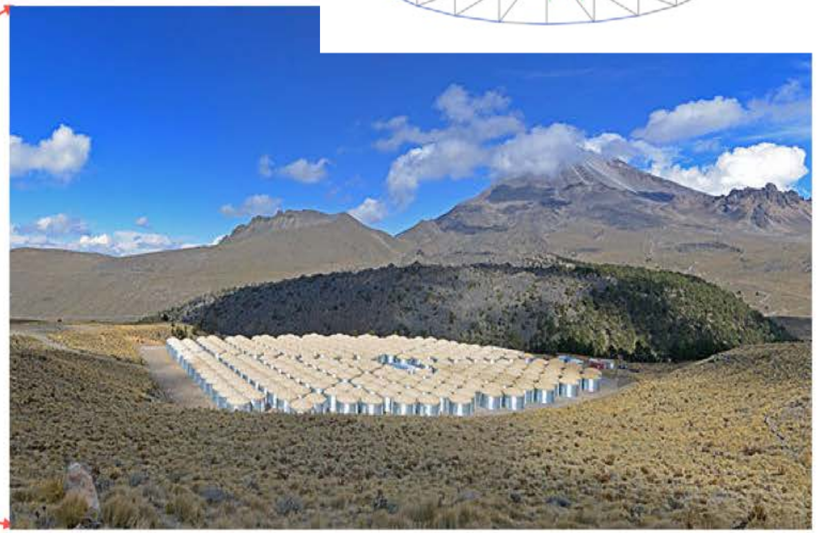
- Pro: wide field of view, continuous operation, cheap to instrument large areas
- Minus: Resolution is worse => more background, higher threshold

- Transients: plus is serendipity, can be the trigger; minus is sensitivity

The present

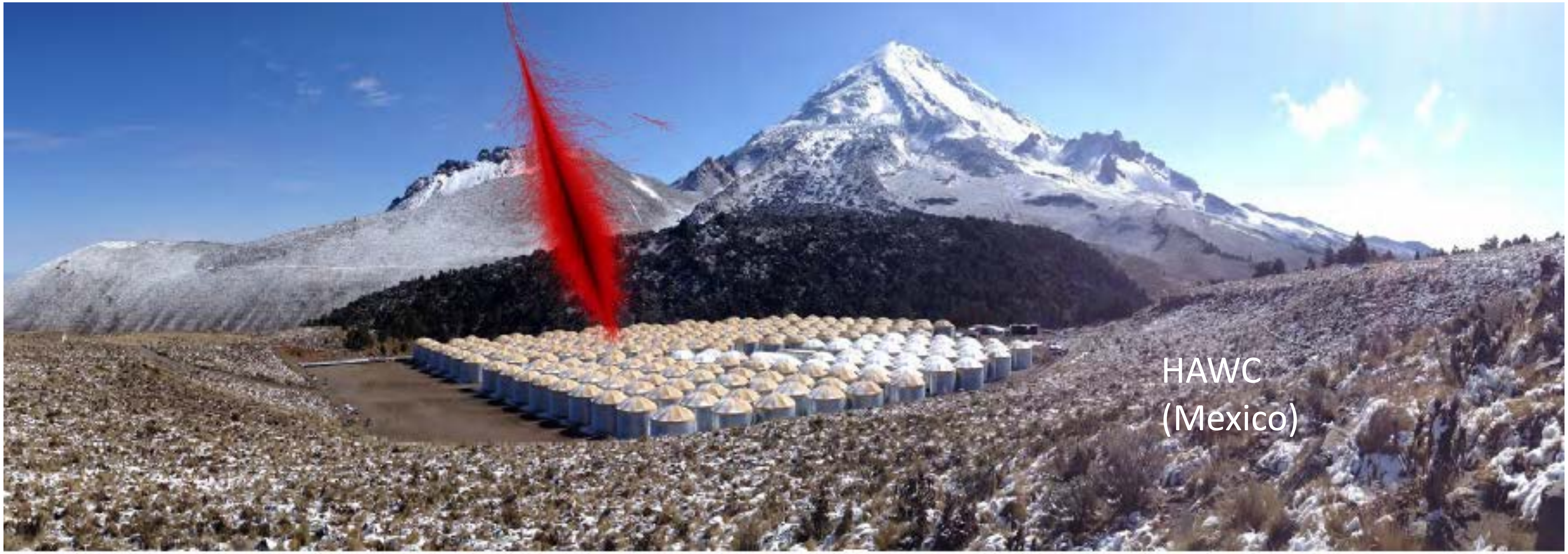
The HAWC Observatory





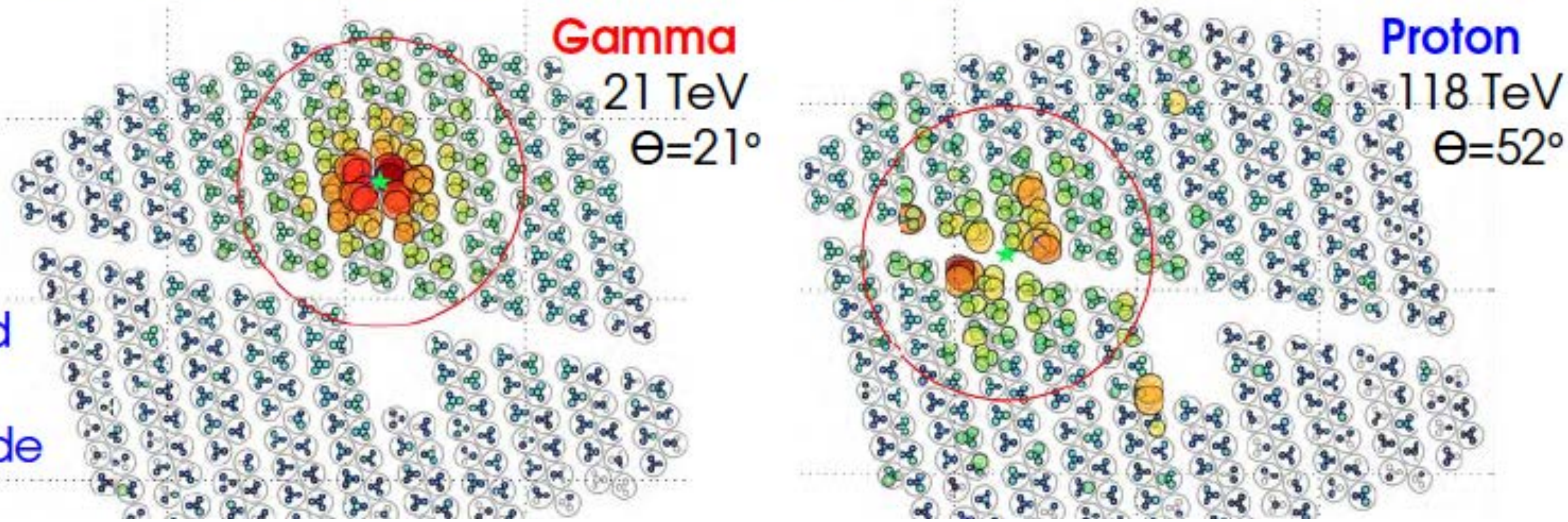
- Located at **4100 m** a.s.l. in Mexico near Pico de Orizaba at 19ºN
- Effective Area: **~22,000 m^2**
- Instantaneous field of view **2 sr**; daily coverage of **2/3** of the sky.
- 300 Water Cherenkov Detectors (WCDs)
- Declinations from **-26º to 64º** (***Part of Northern Fermi Bubble visible***)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

Very-high-energies (above 200 GeV)

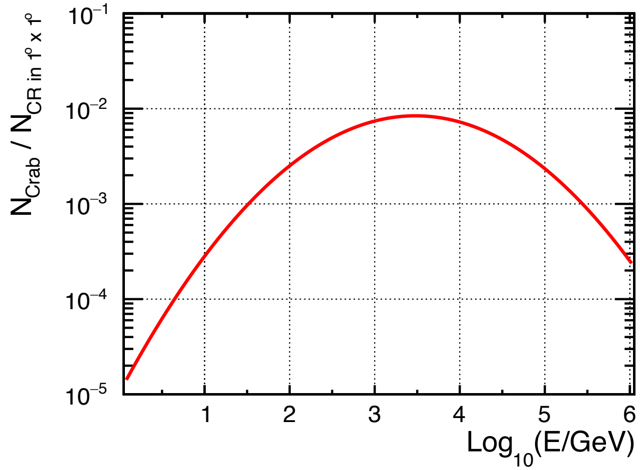


Reconstruct air showers based on PMT hit times and charges

Reject charged primaries via bright hits outside the core

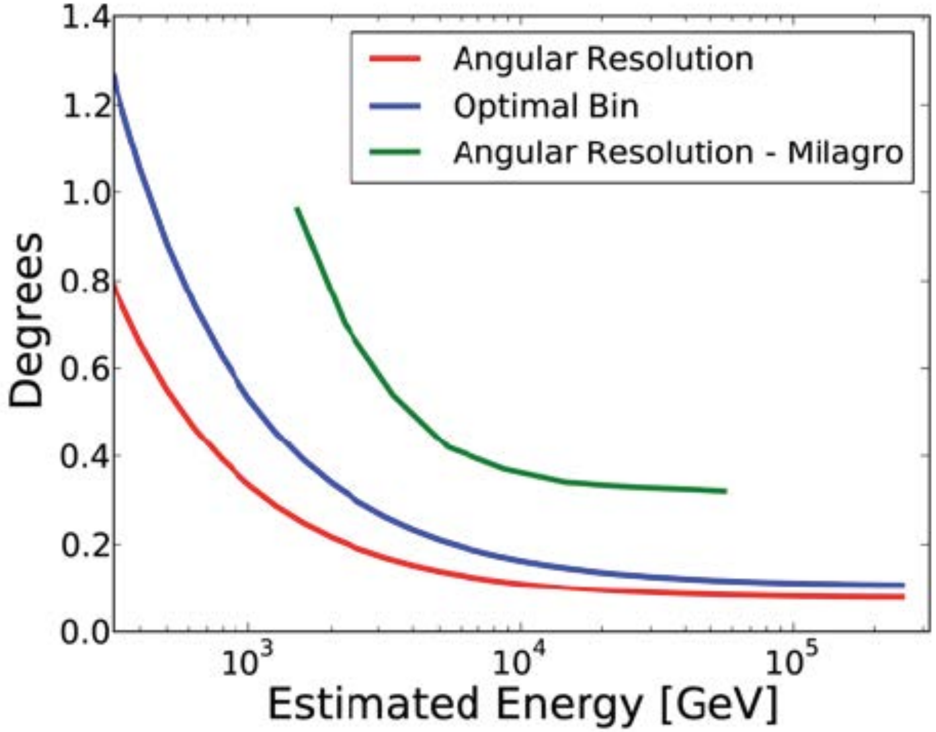


Performance

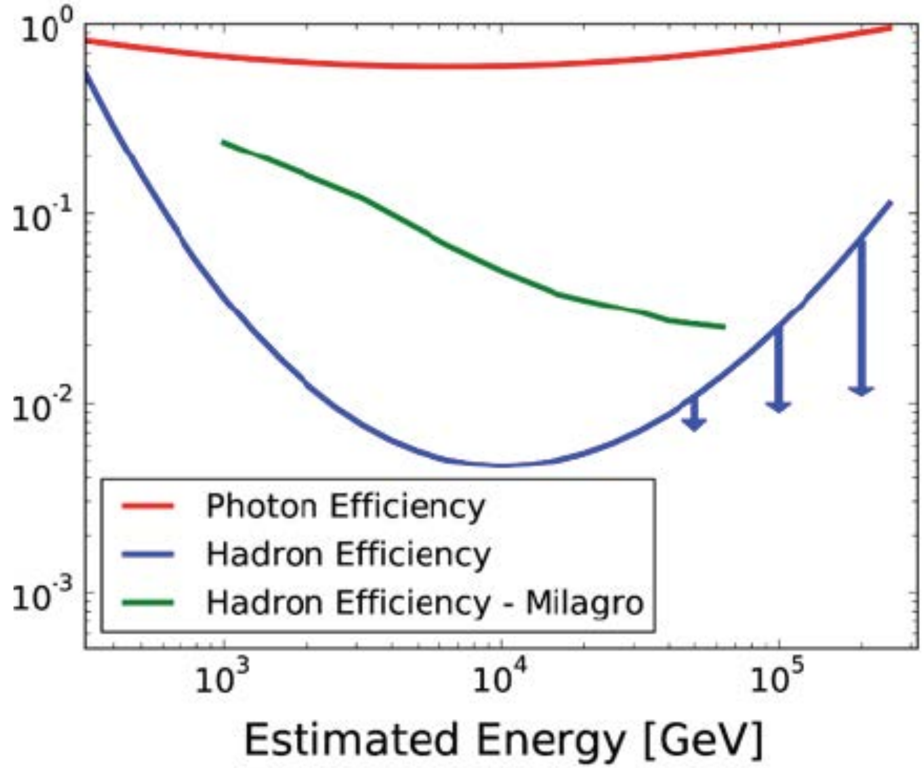


S/B from Crab
Resolution of 1 degree

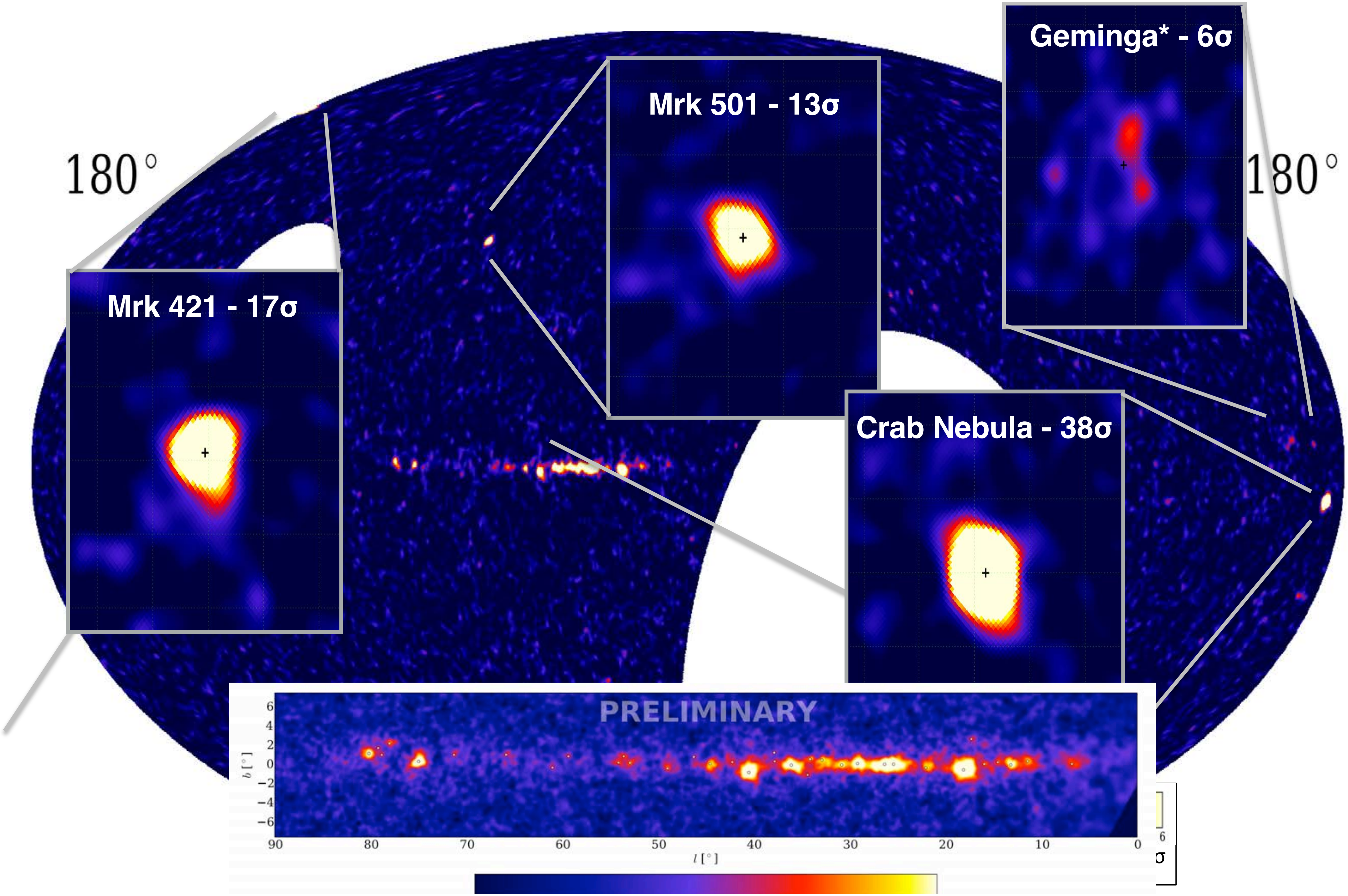
Angular Resolution

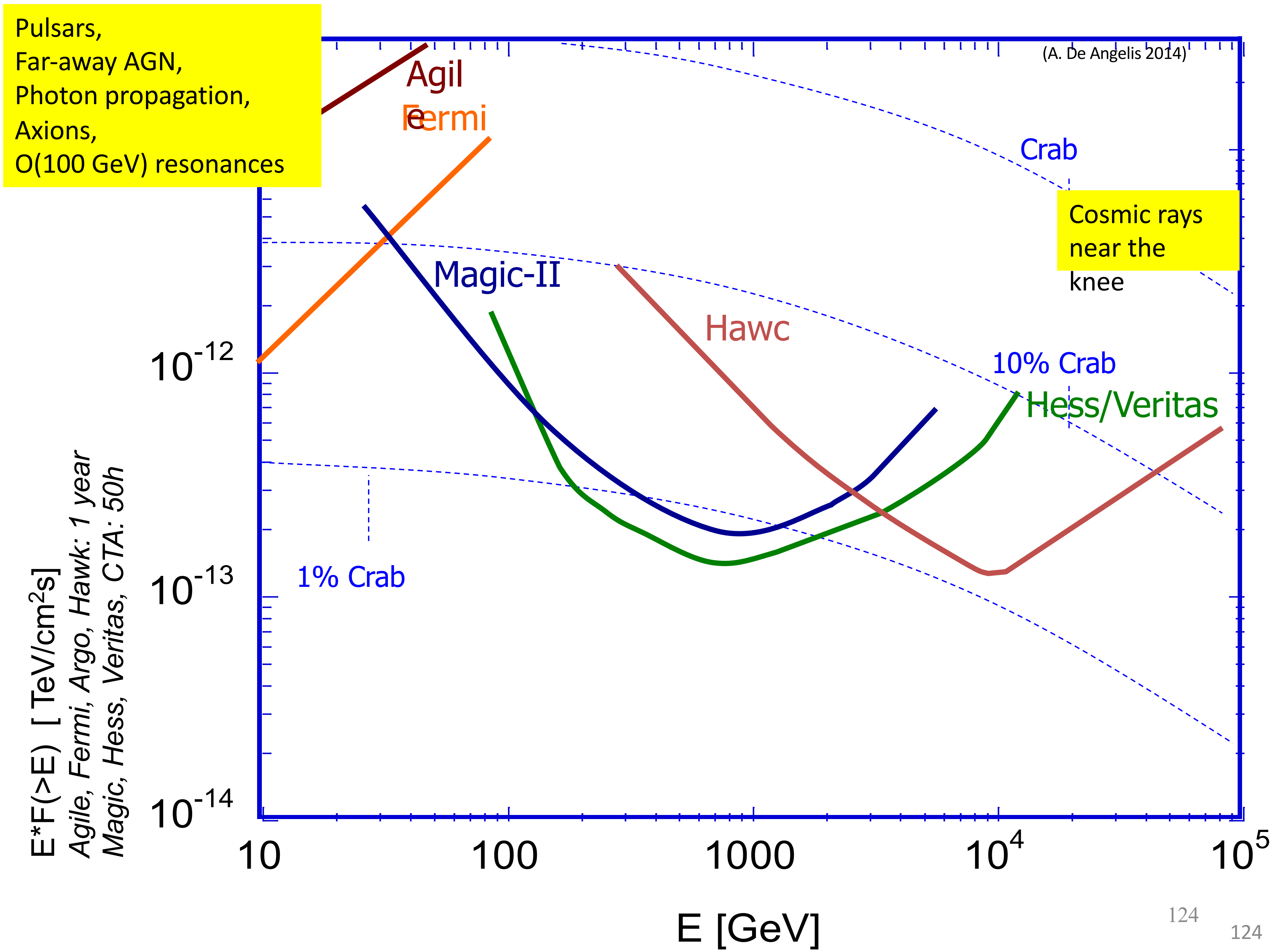


Hadron Rejection



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




Pulsars,
Far-away AGN,
Photon propagation,
Axions,
O(100 GeV) resonances
Agil
Fermi
Crab
(A. De Angelis 2014)
Cosmic rays
near the
knee
Magic-II
Hawc
10% Crab
Hess/Veritas
1% Crab
10-12
10-13
10-14
10
100
1000
10^4
10^5
E*F(>E) [TeV/cm^2s]
Agile, Fermi, Argo, Hawk: 1 year
Magic, Hess, Veritas, CTA: 50h
E [GeV]

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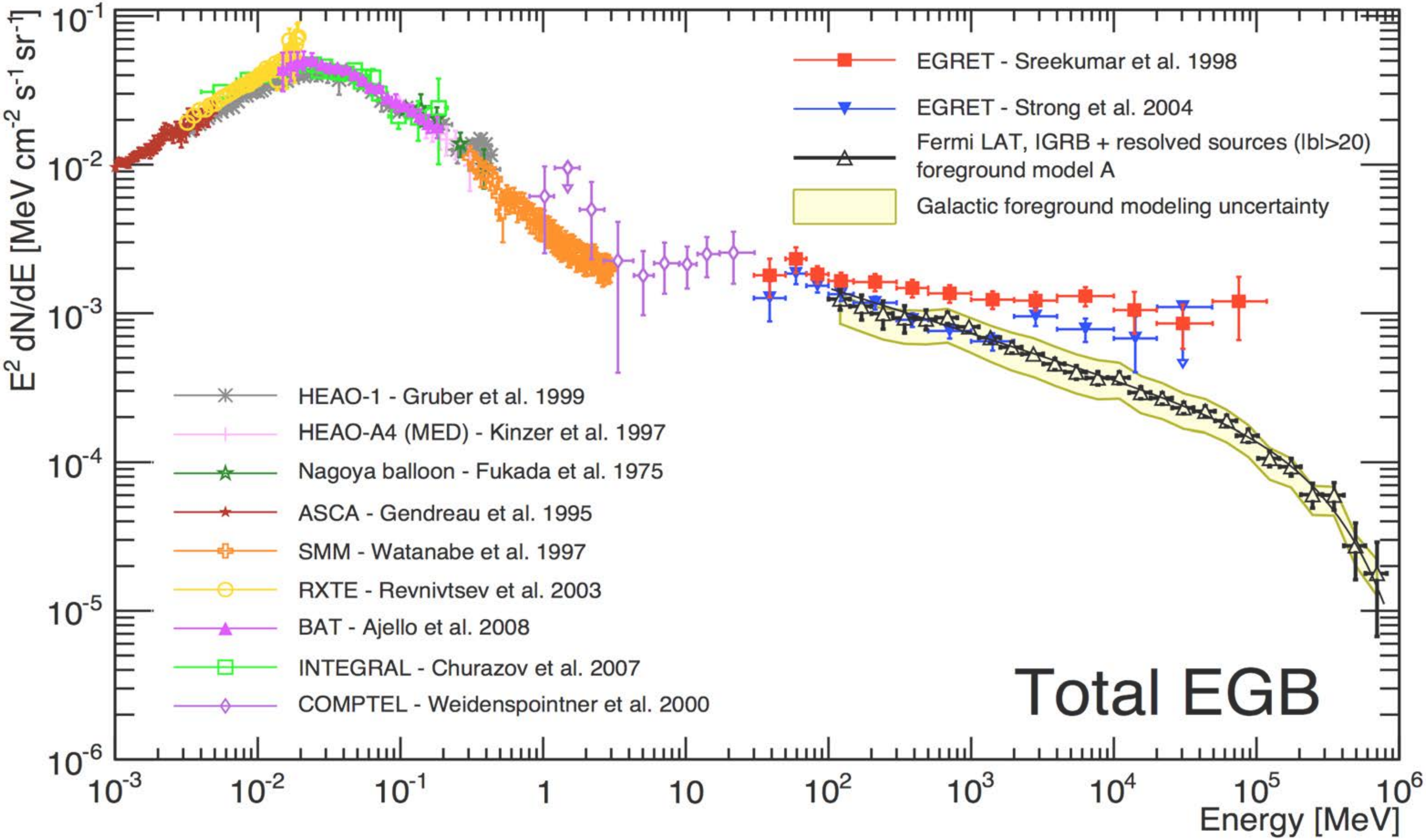
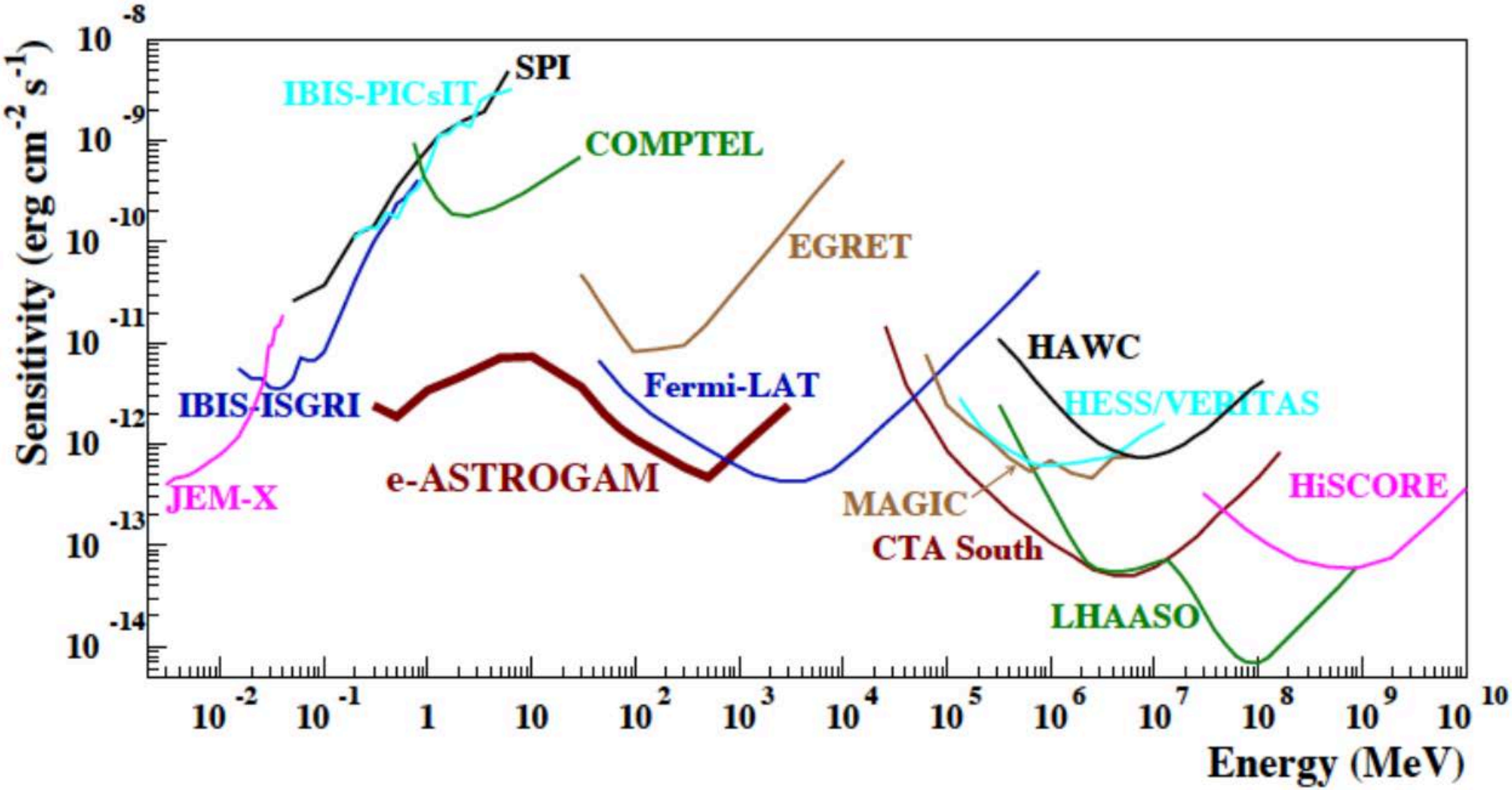
Performance of different types of HE gamma detectors

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 %	$\sim$ 50 %
Duty cycle	80 %	15 %	$>$ 90 %
FoV	$4\pi/5$	5 deg $\times$ 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





- MeV/GeV worst covered part of the electromagnetic spectrum (only a few tens of steady sources detected so far between 0.2 and 30 MeV)
- Binding energies of atomic nuclei fall in this range, which therefore is as important for HE astronomy as optical astronomy is for phenomena related to atomic physics

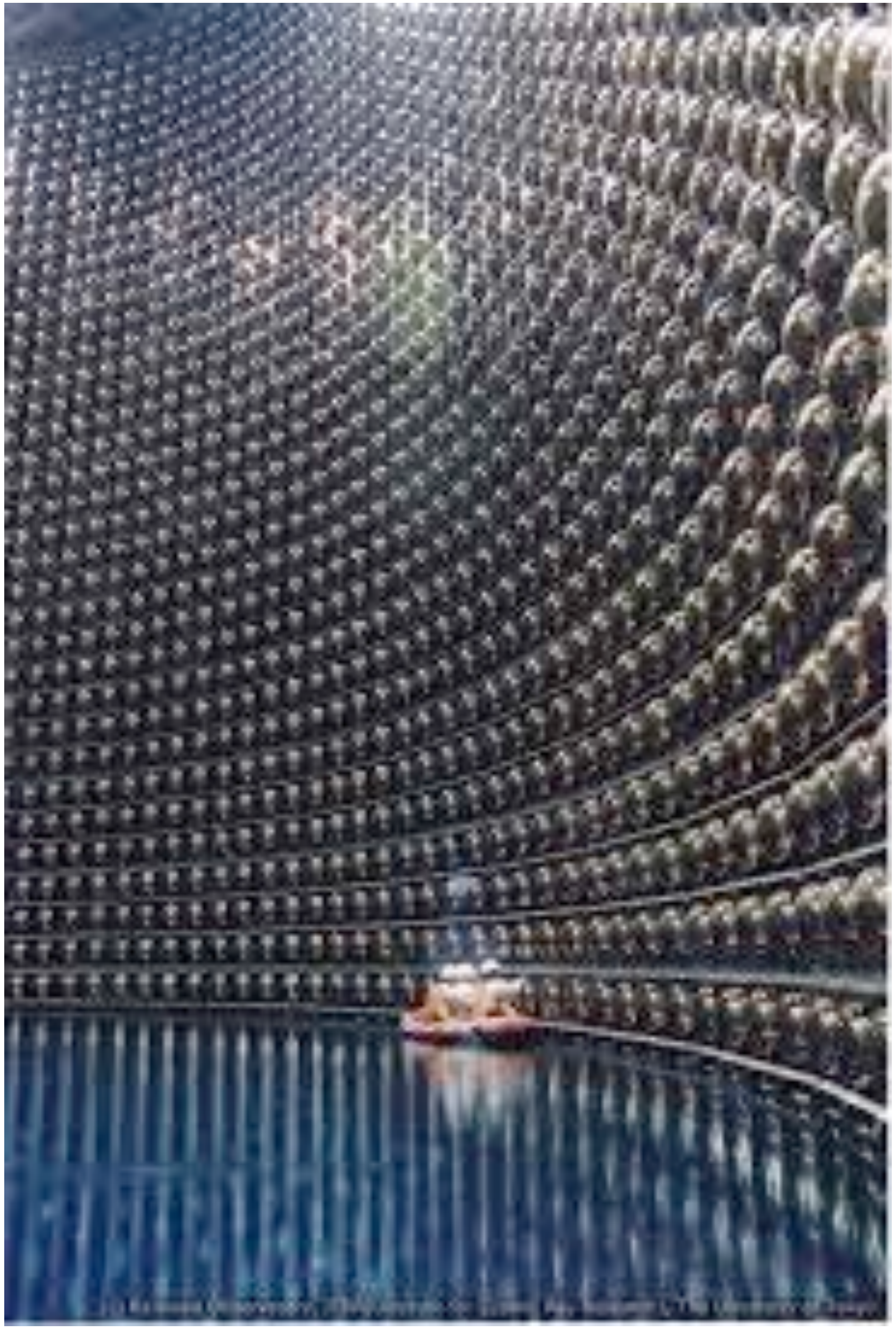
Neutrinos

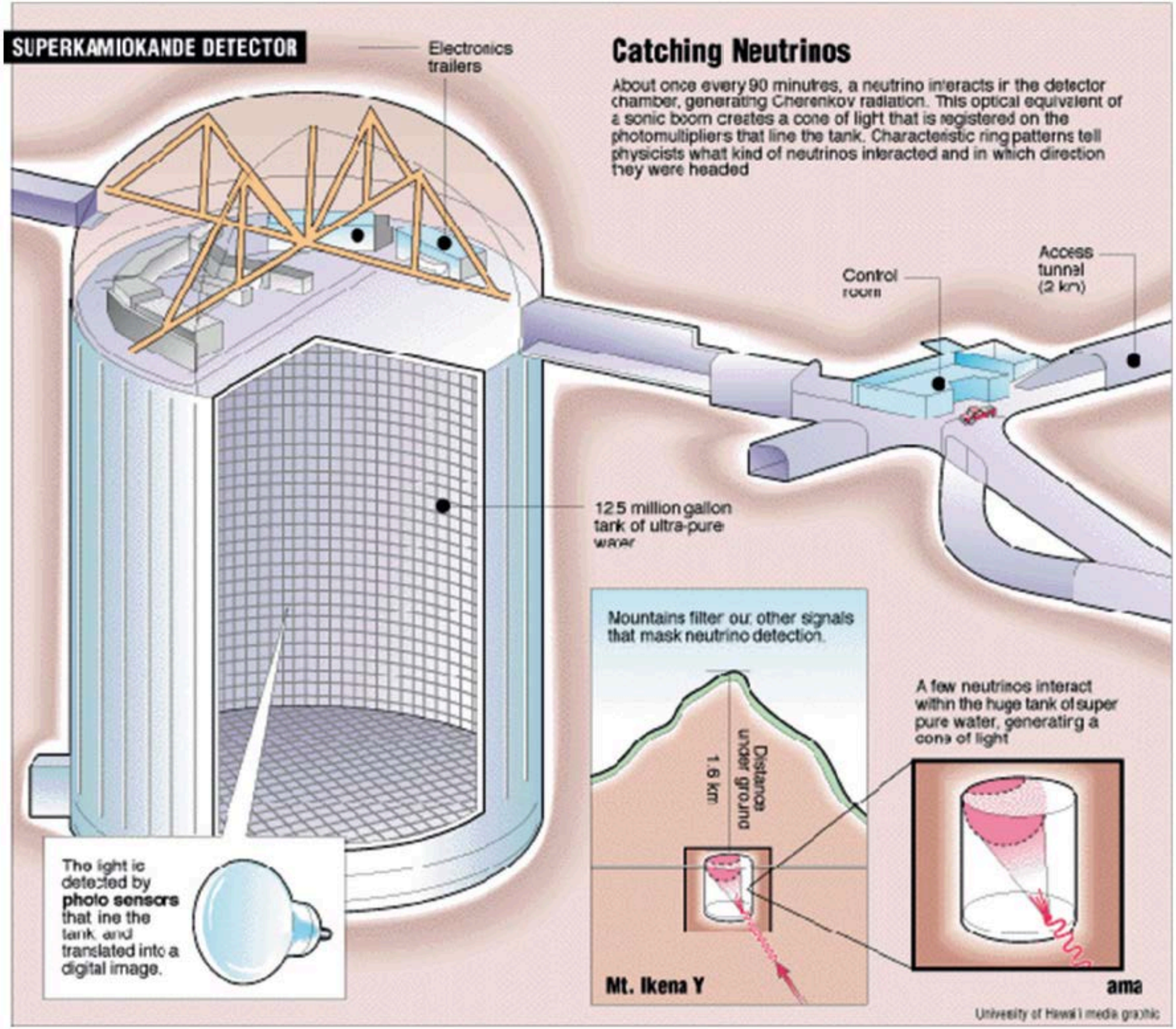
MeV neutrinos

- Very important: fusion processes in stars
- Cross section is low, but flux is very large (compute the flux from the Sun through your body)
- The first setups used a solution of cadmium chloride in water and two scintillation detectors as a veto against charged CRs. Antineutrinos with an energy above the 1.8MeV threshold can cause charged inverse beta-decay interactions with the protons in the water, producing a positron which in turn annihilates, generating photon pairs that can be detected.
- Radiochemical chlorine detectors consist instead of a tank filled with a chlorine solution in a fluid. A neutrino converts a 37Cl atom into a 37Ar; the threshold neutrino energy for this reaction is 0.8 MeV. Nobel Prize to Davis in 2002 (Homestake, 470 tons)
- Also Ga -> Ge

MeV to GeV

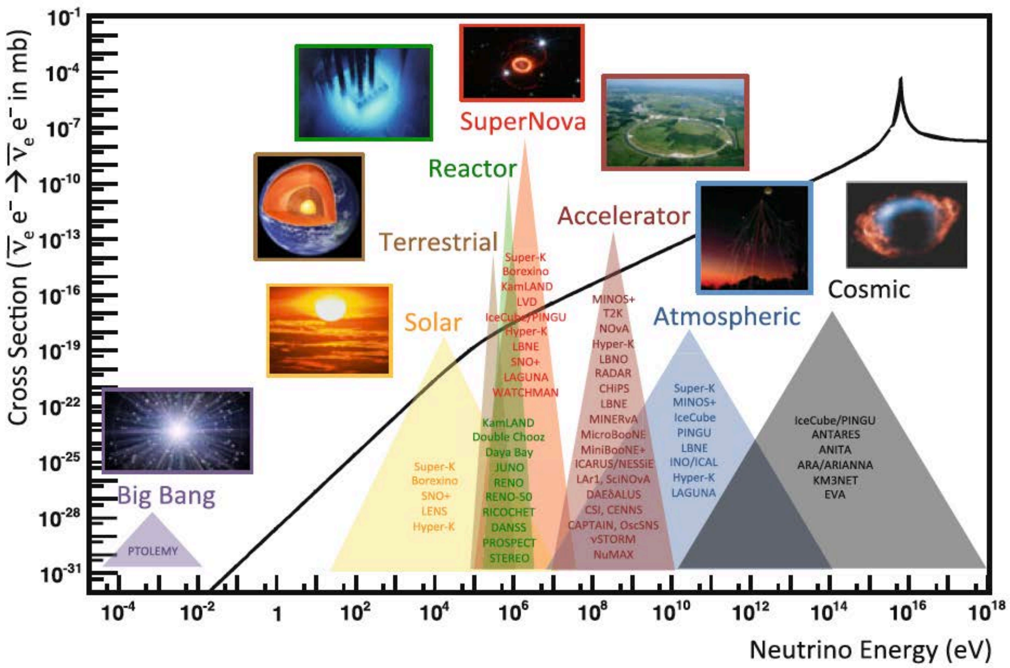
- Very important: fusion processes in stars, atmospheric neutrinos
- Needs large volumes: (Super)Kamiokande
  - SK: 50000 tons
  - Hyper-K: 20 x SK?
- Water instrumented with large PMTs; detection of Cherenkov photons
- Two Nobel prizes

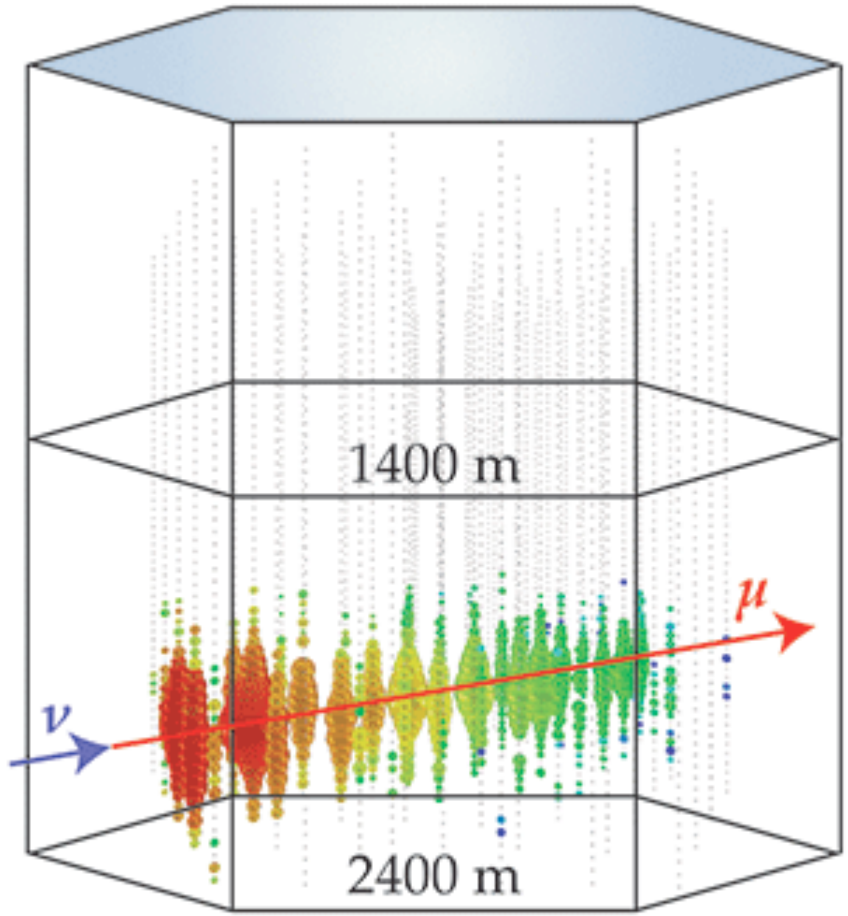



SUPERKAMIOKANDE DETECTOR
Electronics trailers
Catching Neutrinos
About once every 90 minutes, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed
Control room
Access tunnel (2 km)
12.5 million gallon tank of ultra-pure water
Mountains filter out other signals that mask neutrino detection.
Distance under ground
1.6 km
A few neutrinos interact within the huge tank of super pure water, generating a cone of light
The light is detected by photo sensors that line the tank and translated into a digital image.
Mt. Ikena Y
ama
University of Hawaii media graphic

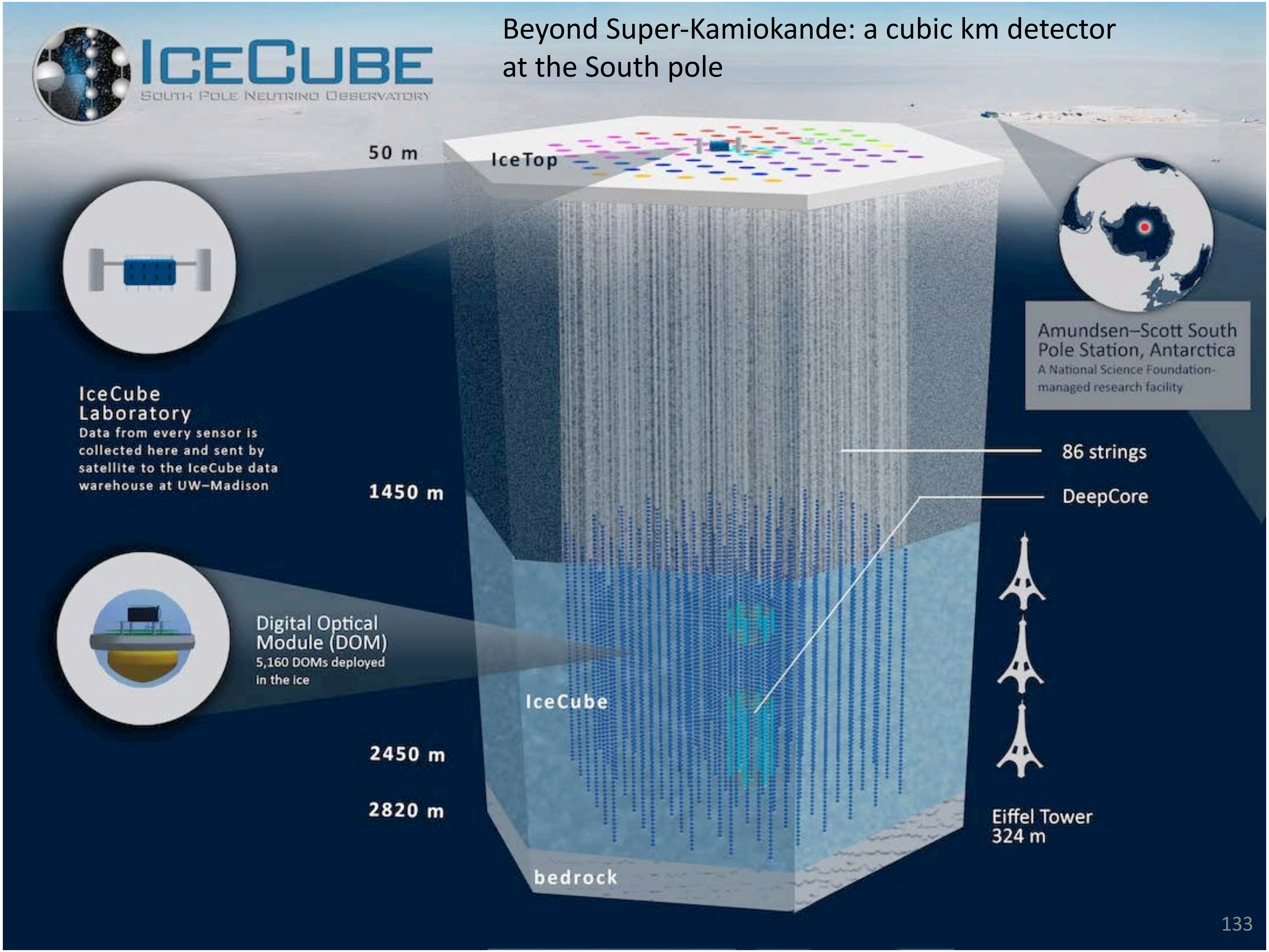
Do you aim at astrophysical neutrinos?

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





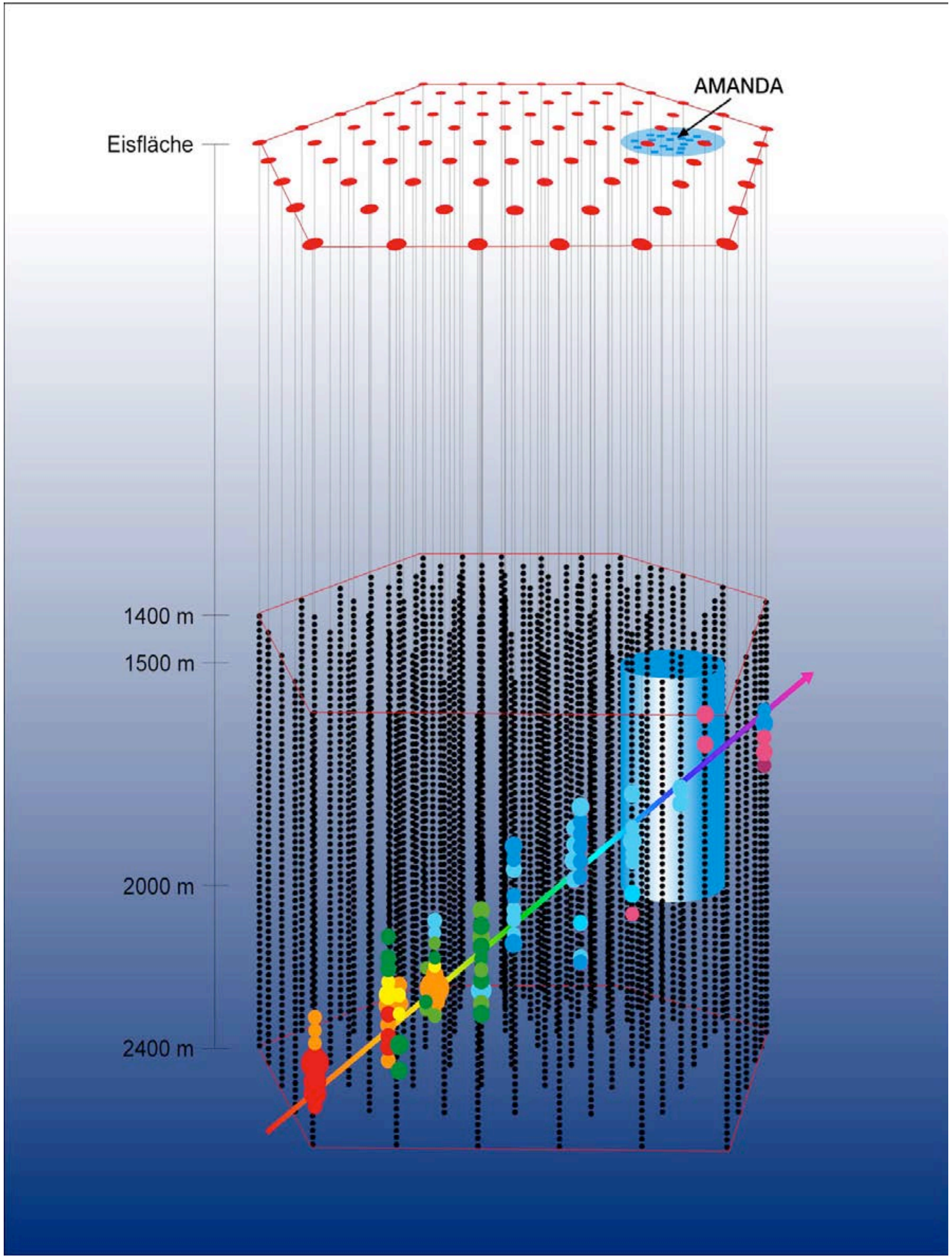
Beyond Super-Kamiokande: a cubic km detector at the South pole



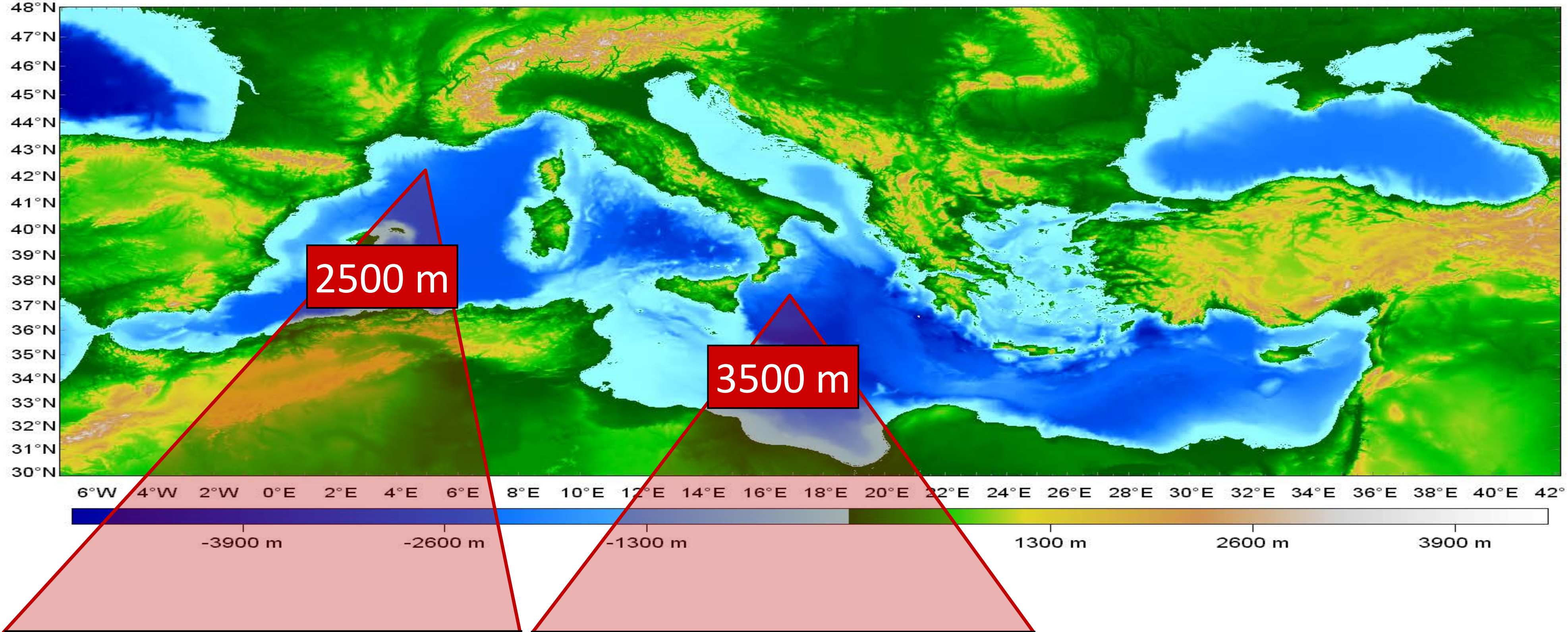
Deploying a (string of) photosensors

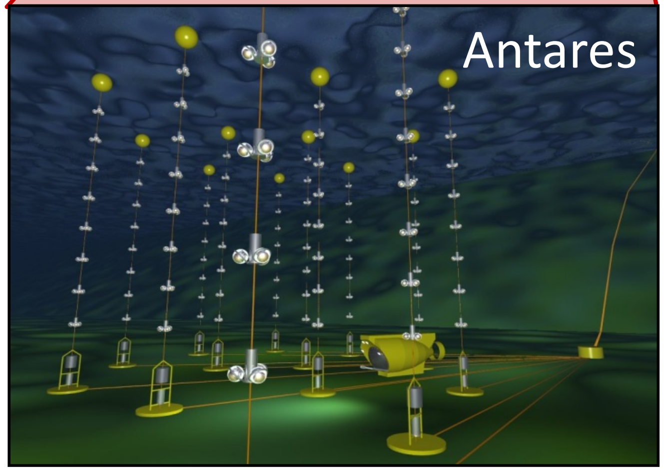
Principle of operation

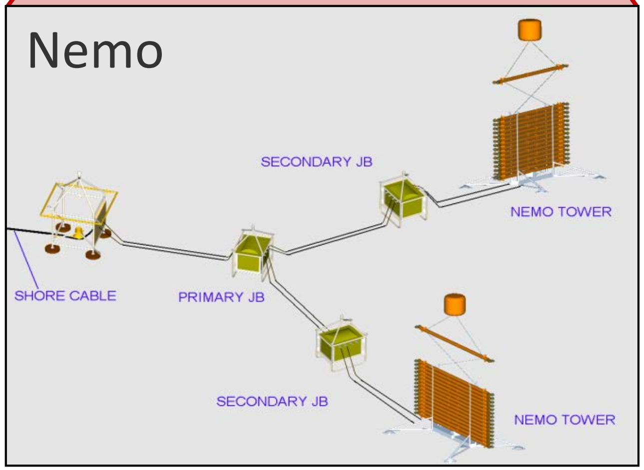
- Energy depositions: muon energy & direction
- Translate into neutrino energy
- 2 classes of events, according o the trigger



...and in the Mediterranean sea







MULTIMESSENGER ASTROPHYSICS:

GRAVITATIONAL WAVES

Gravitational waves: physics

- Einstein field equations:

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

- Far from the source: metric is flat with small perturbation

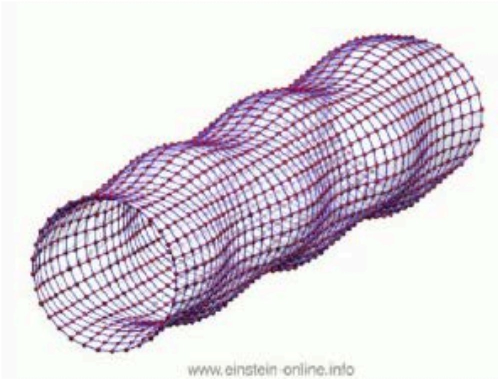
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

- Far from the source: Einstein equations reduce to wave equation for the perturbation:

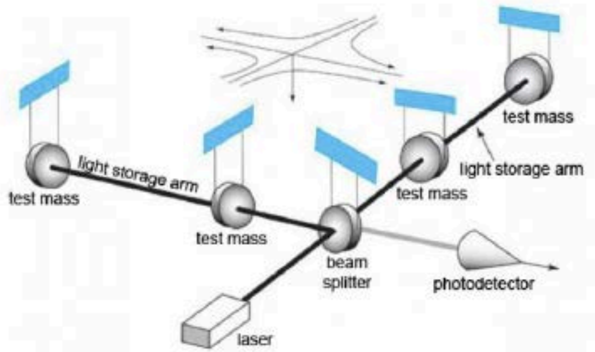
$$\left(-\frac{\partial^2}{c^2\partial t^2} + \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) h_{\mu\nu}^{\mathrm{TT}} = 0$$

Gravitational waves

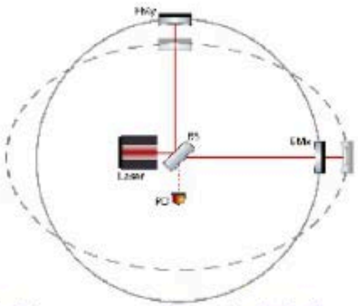
- Gravitational waves have the effect of traveling tidal waves



- Laser interferometer:



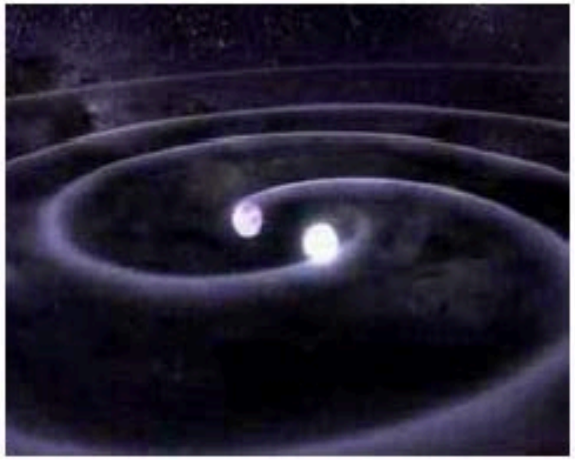
- Arms are periodically stretched and compressed by passing gravitational wave:



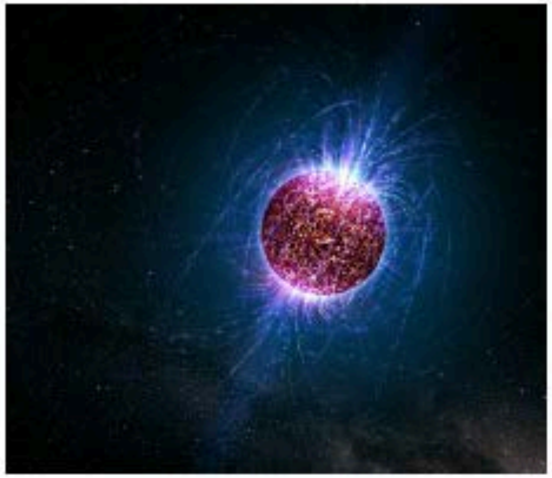
- Extreme sensitivities required: $\Delta L/L \sim 10^{-23}$

Sources of gravitational waves: needs asymmetry

Coalescing binary neutron stars and black holes



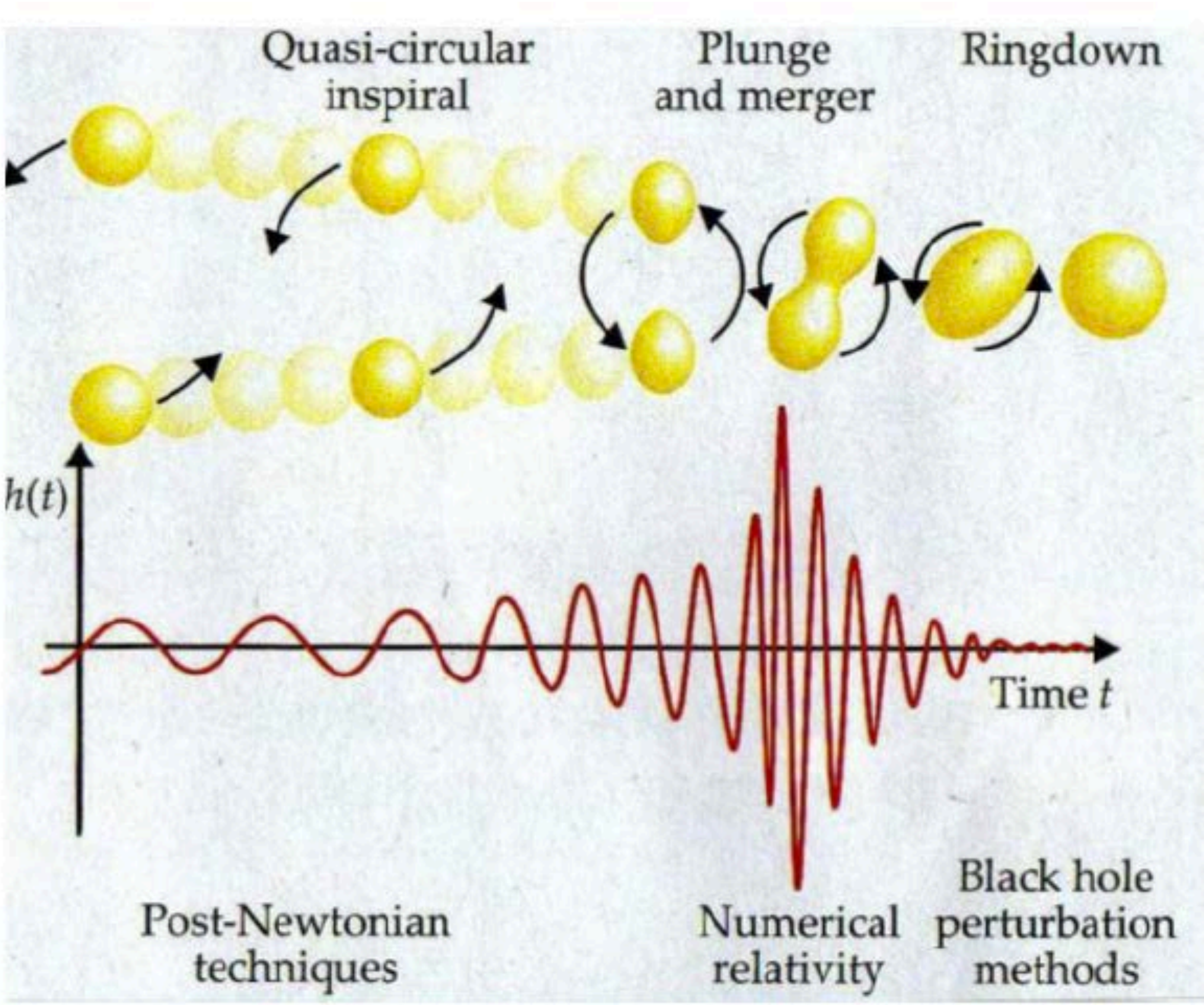
Fast-spinning neutron stars



Bursts (e.g. supernovae)

Effect is deformation of spacetime

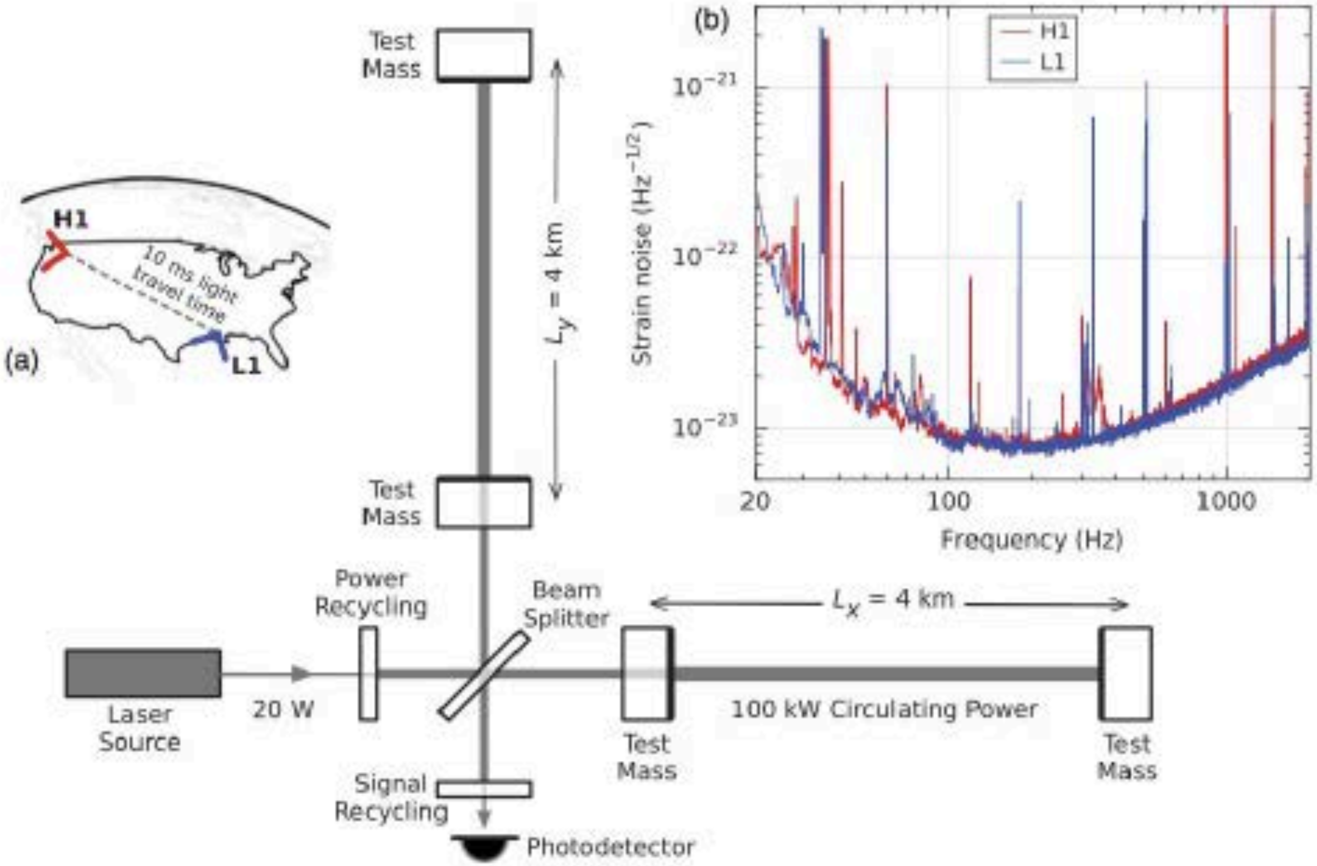
Time evolution of GW



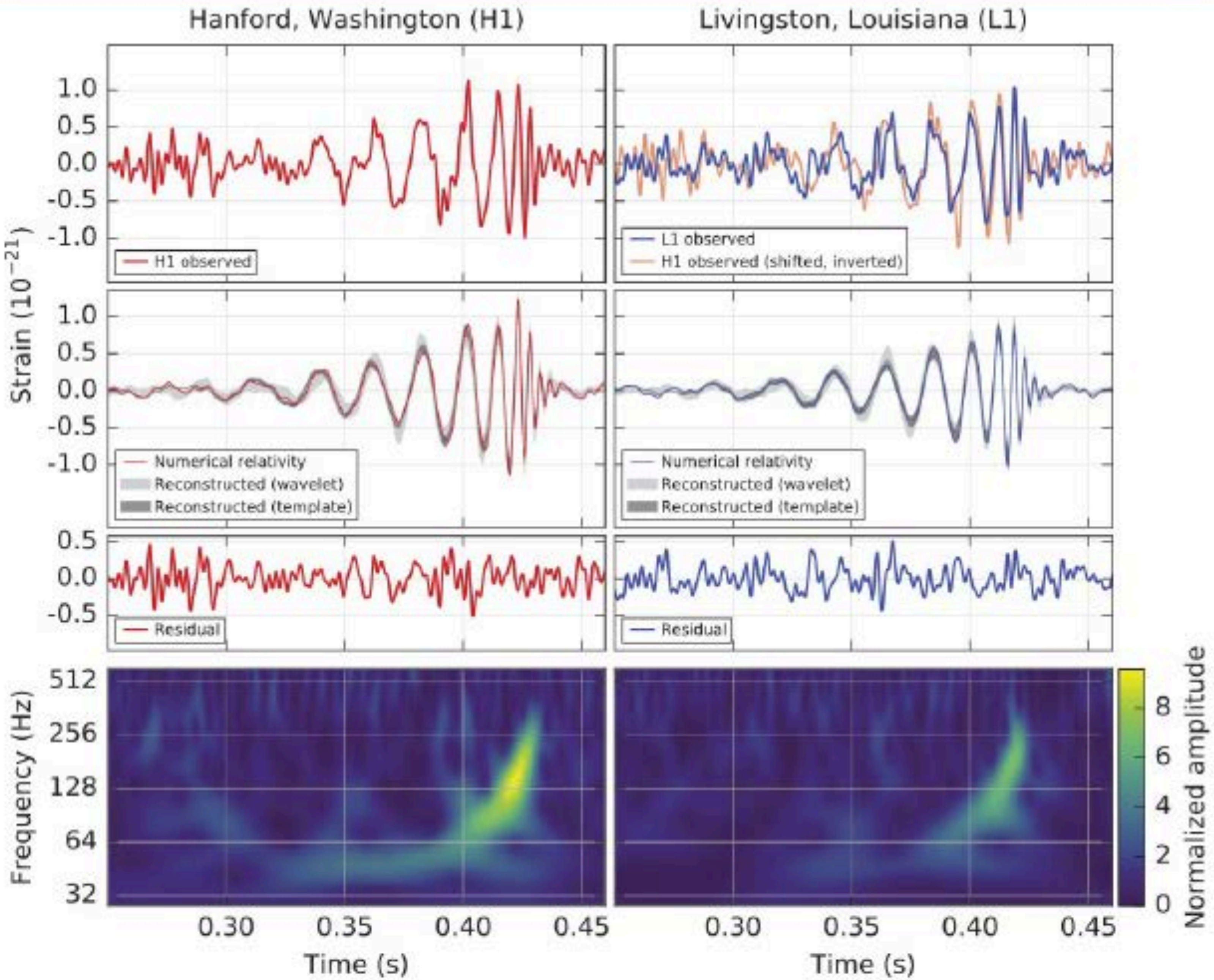
Gravitational wave detectors

- Need to measure strain ∂L/L
- Strain affects space, not light
- For typical sources can be very low: ~ 10^{-22}
  - 1 atom over 10^{12} m
- Technique can be interferometry, but needs resonant cavities

The Advanced LIGO detectors

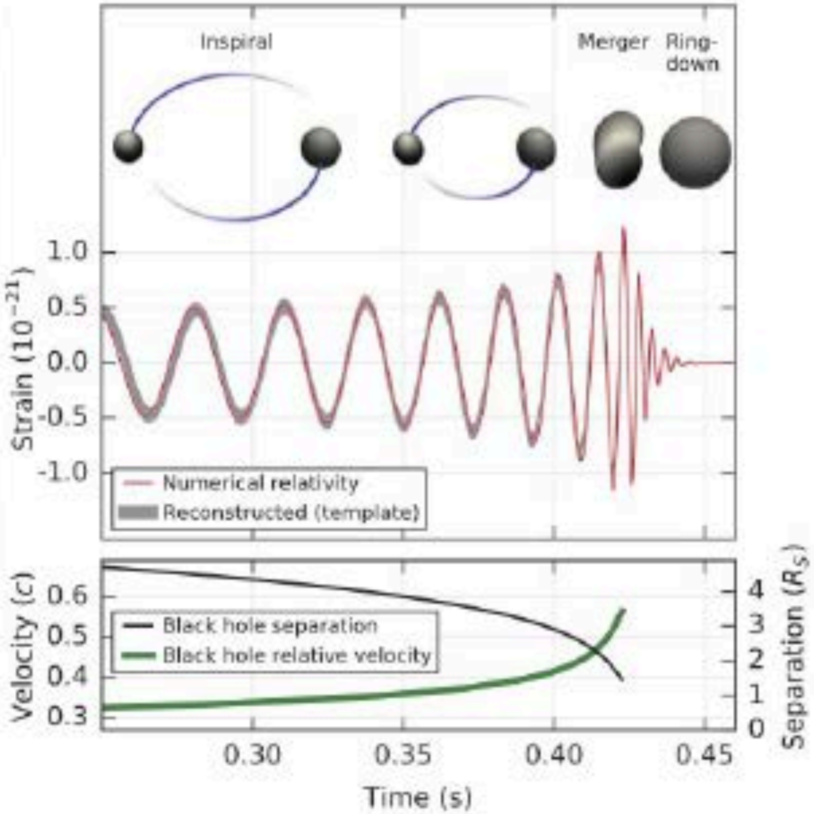


The first detection



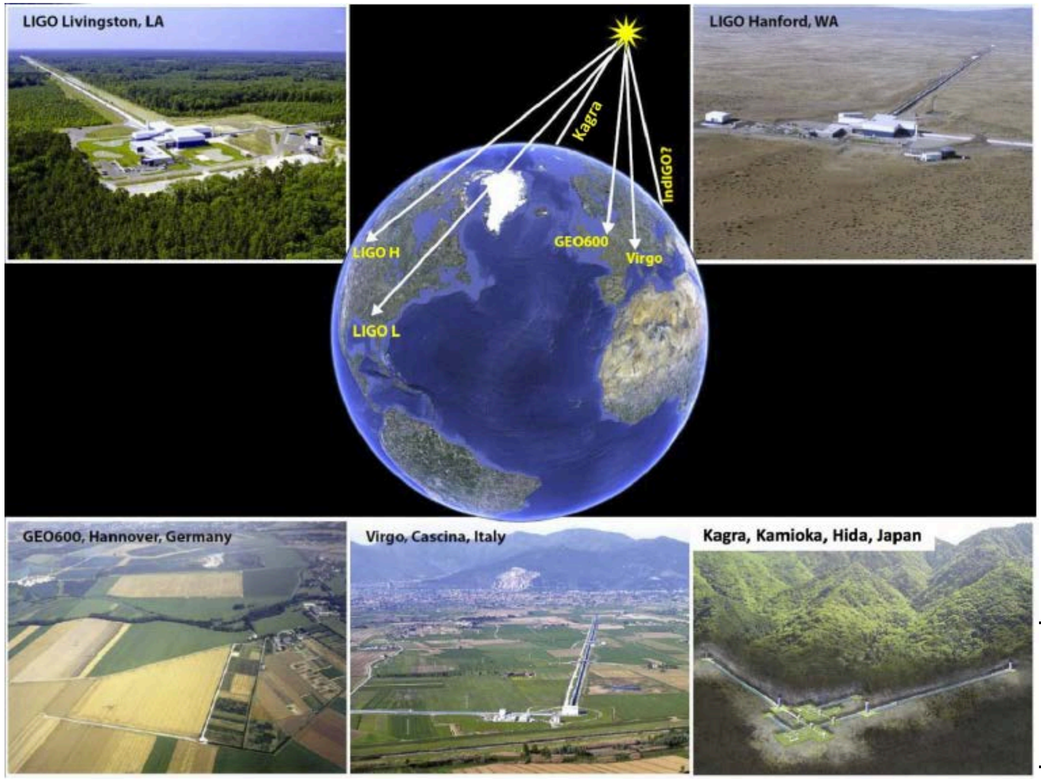
The first detection

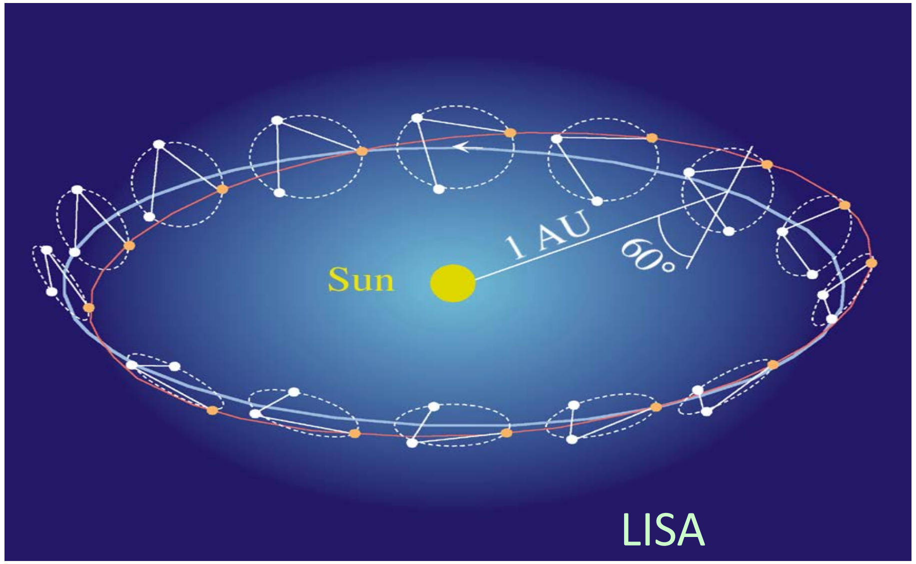
- Signal consistent with binary black hole merger
- Parameters measured by matching millions of trial waveforms in 15-dimensional parameter space



Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

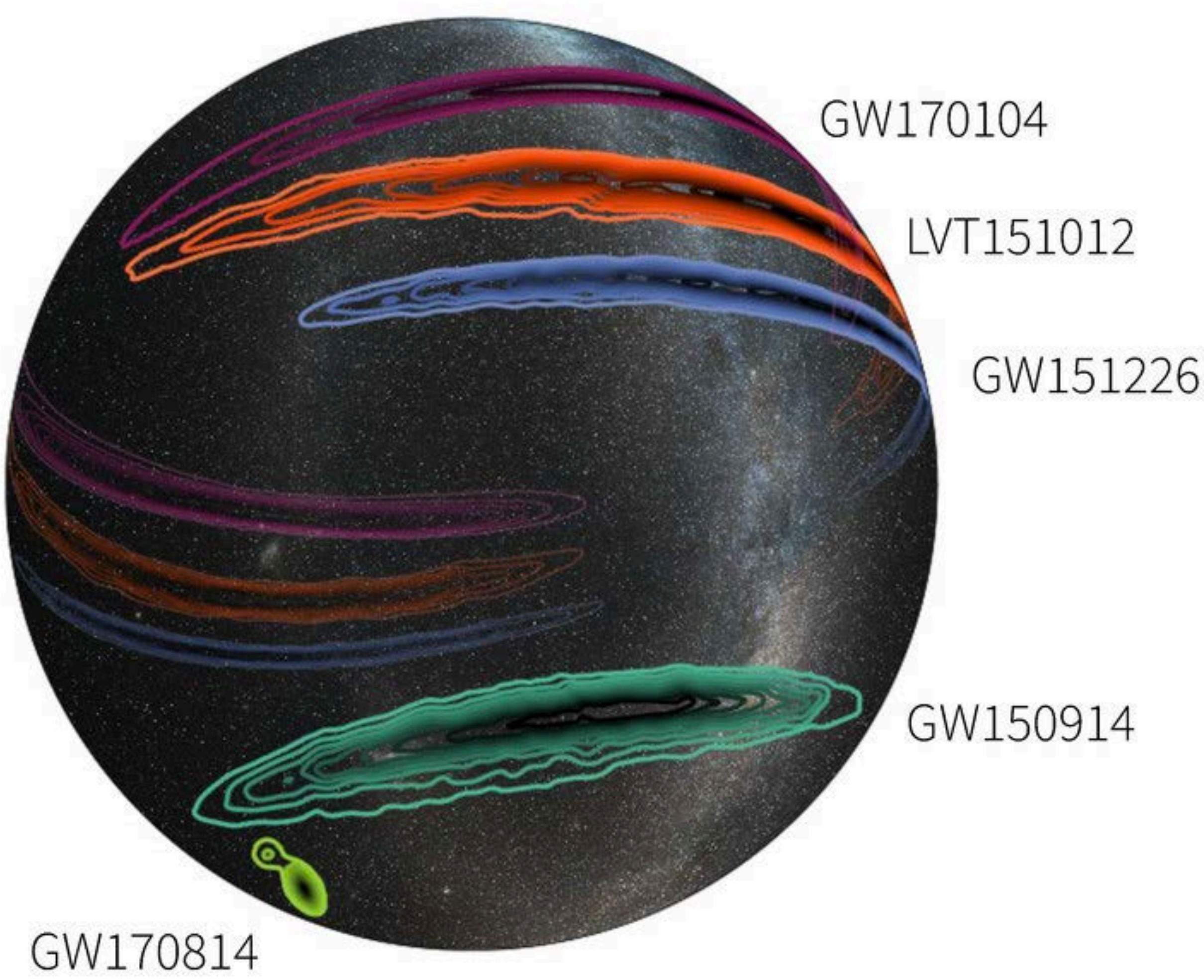
In the future: more detectors, bigger detectors



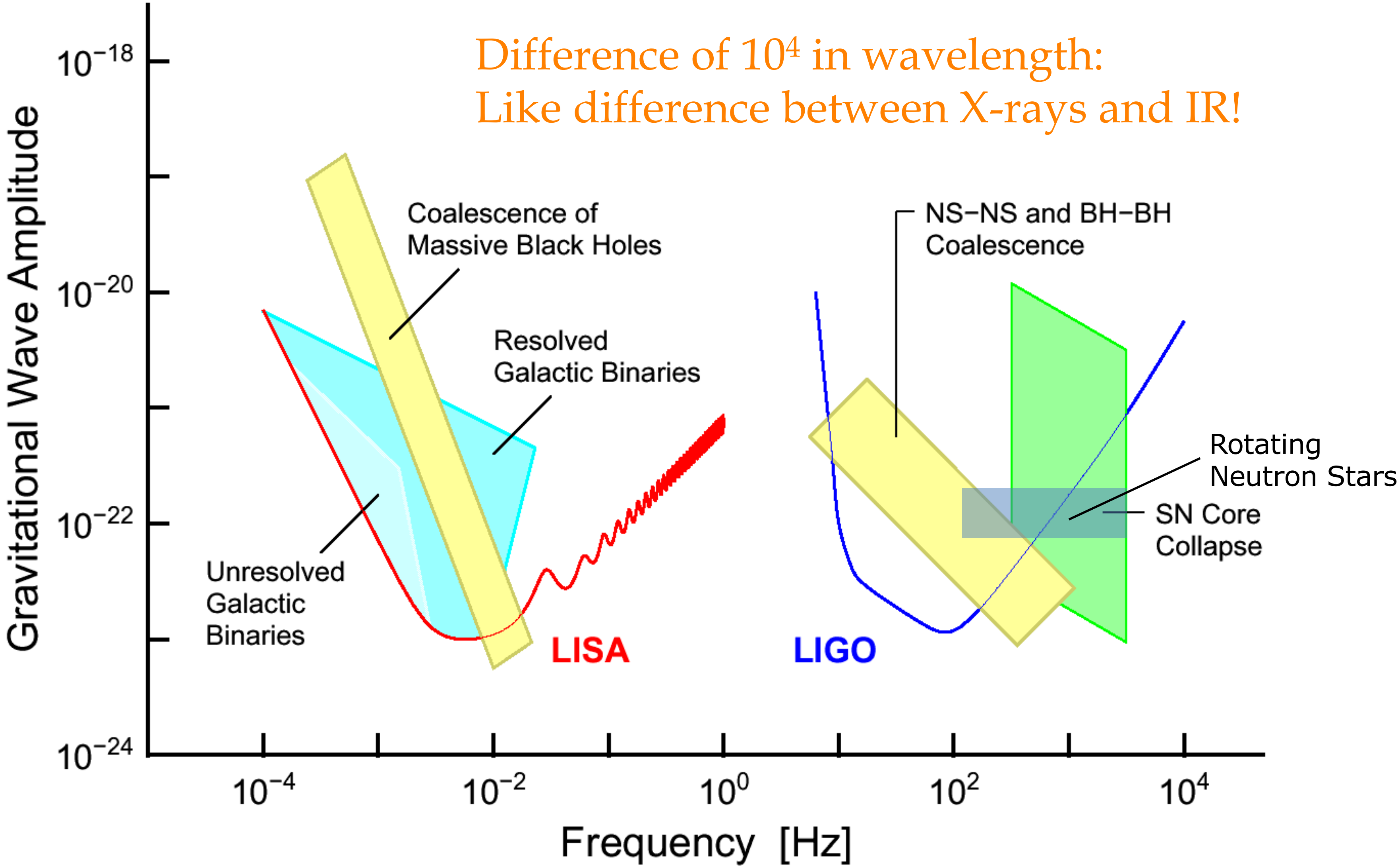


- *3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.*
- *Measure changes in distance between fiducial masses in each spacecraft*
  – *Partnership between NASA and ESA*
  – *Launch date 2034*

More detectors: improved localization

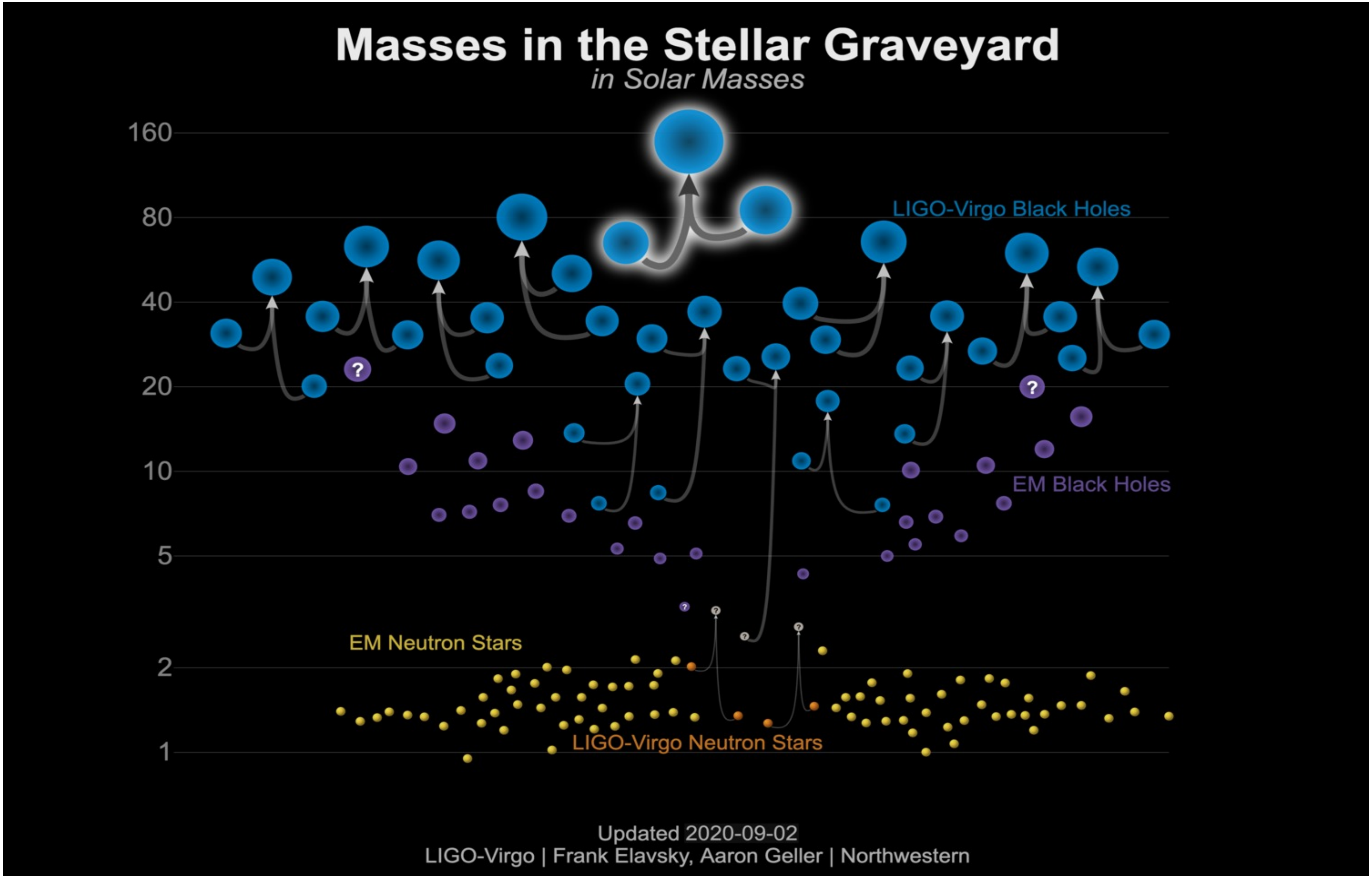


Different arm lengths, different frequencies, different processes



LISA will see all the compact white-dwarf and neutron-star binaries in the Galaxy

Up to now, BH-BH mergers without electromagnetic counterpart and a NS/NS fusion with EM companion



Summary

- 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
- Photons:
  - The keV region is a standard
  - 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 two detector presently active (both in the Northern hemisphere), and there is room for improvement by "brute force", South.
- Astrophysical neutrino detectors: we need several km3; we are close to the limit (IceCube -> Gen2) but still improving (Antares -> km3NET)
- Gravitational waves: the present and near future

Exercises

1. *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).