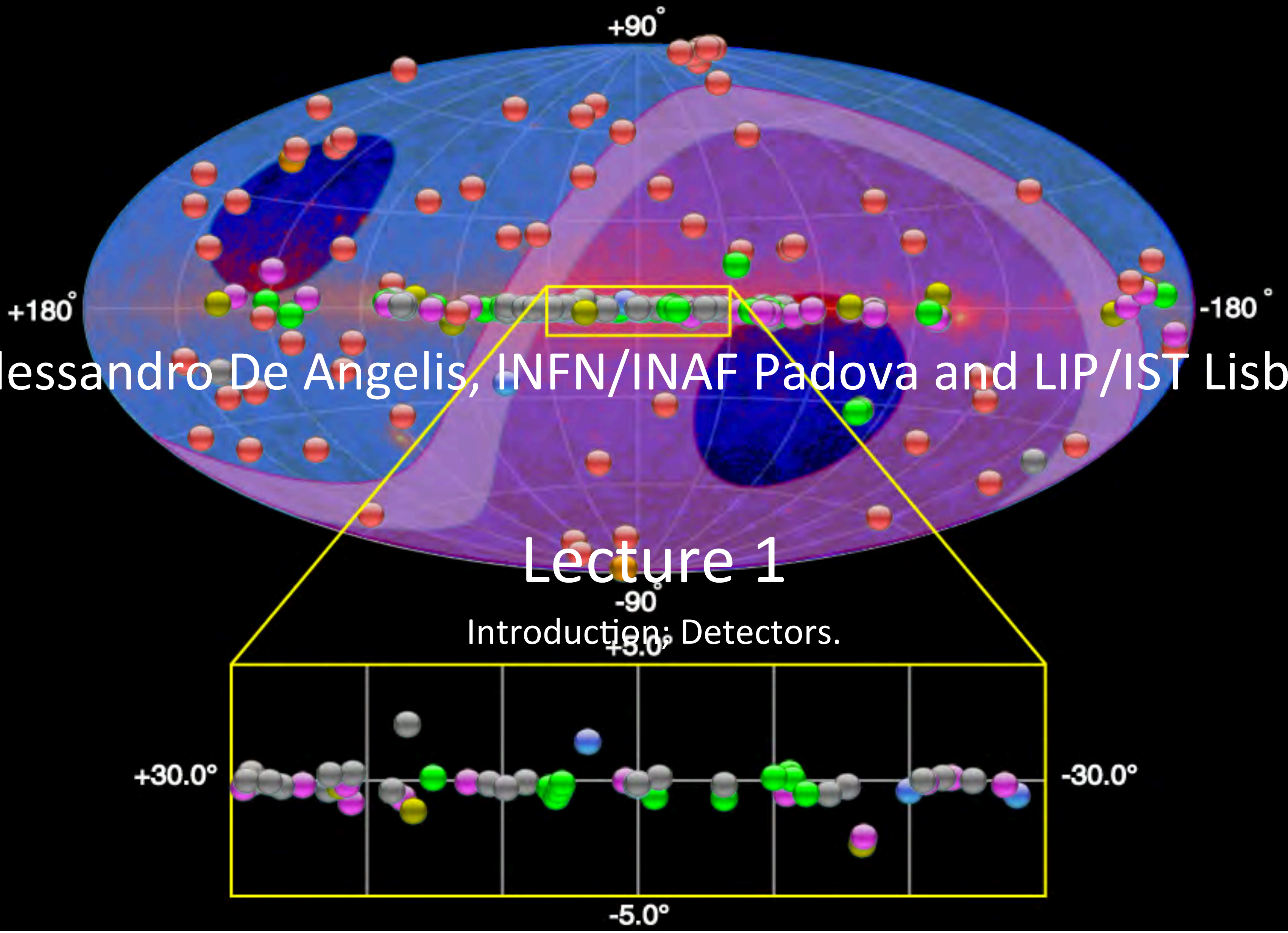
Astroparticle physics with gamma rays



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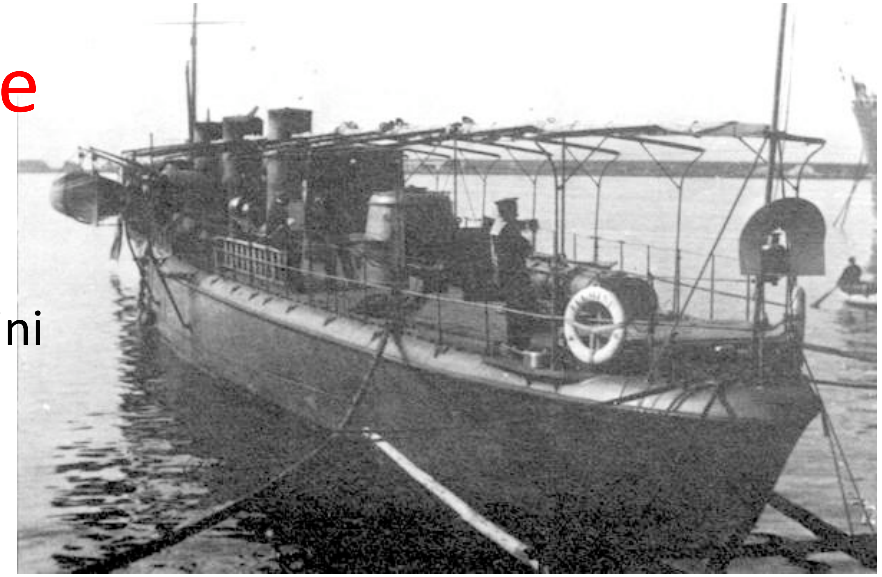
Lecture 1

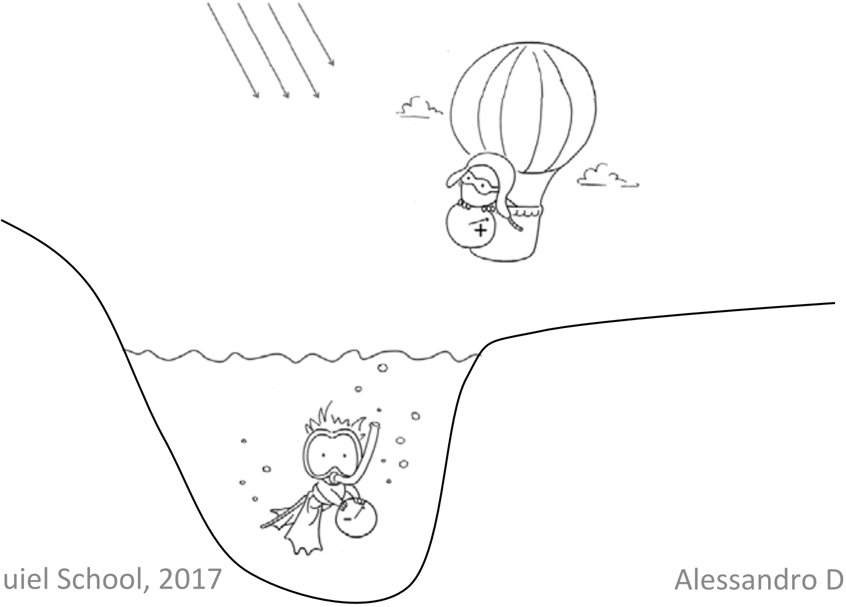
Introduction; Detectors.

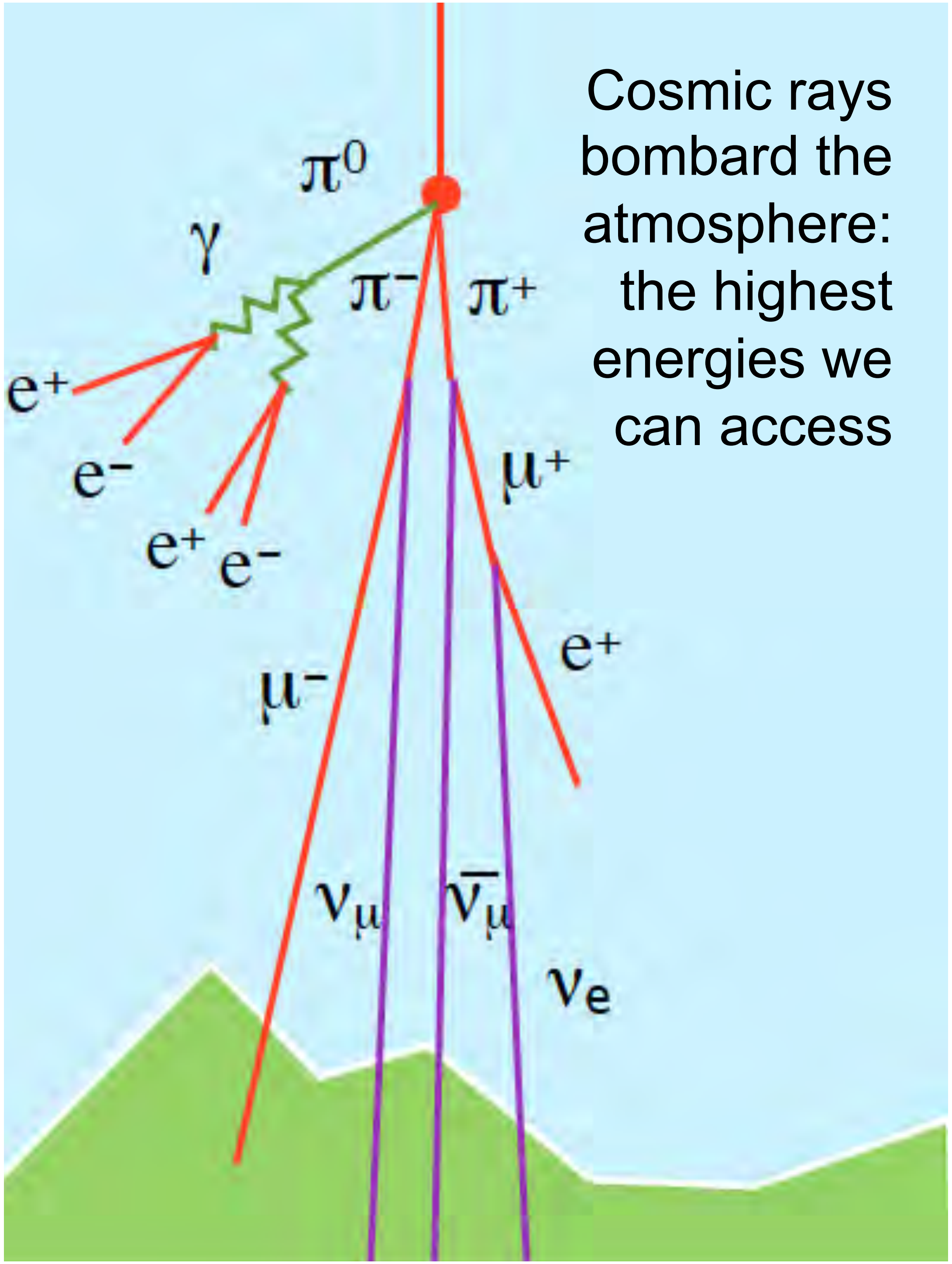
Messengers from the Universe



1911/12: Domenico Pacini and Victor Hess perform two complementary experiments: Pacini discovers that ionizing radiation decreases underwater, and Hess that it increases at high altitudes

- 20% of the natural radiation at ground is due to cosmic radiation!!! Can we use these **"cosmic rays"** for science?





Cosmic rays bombard the atmosphere: the highest energies we can access

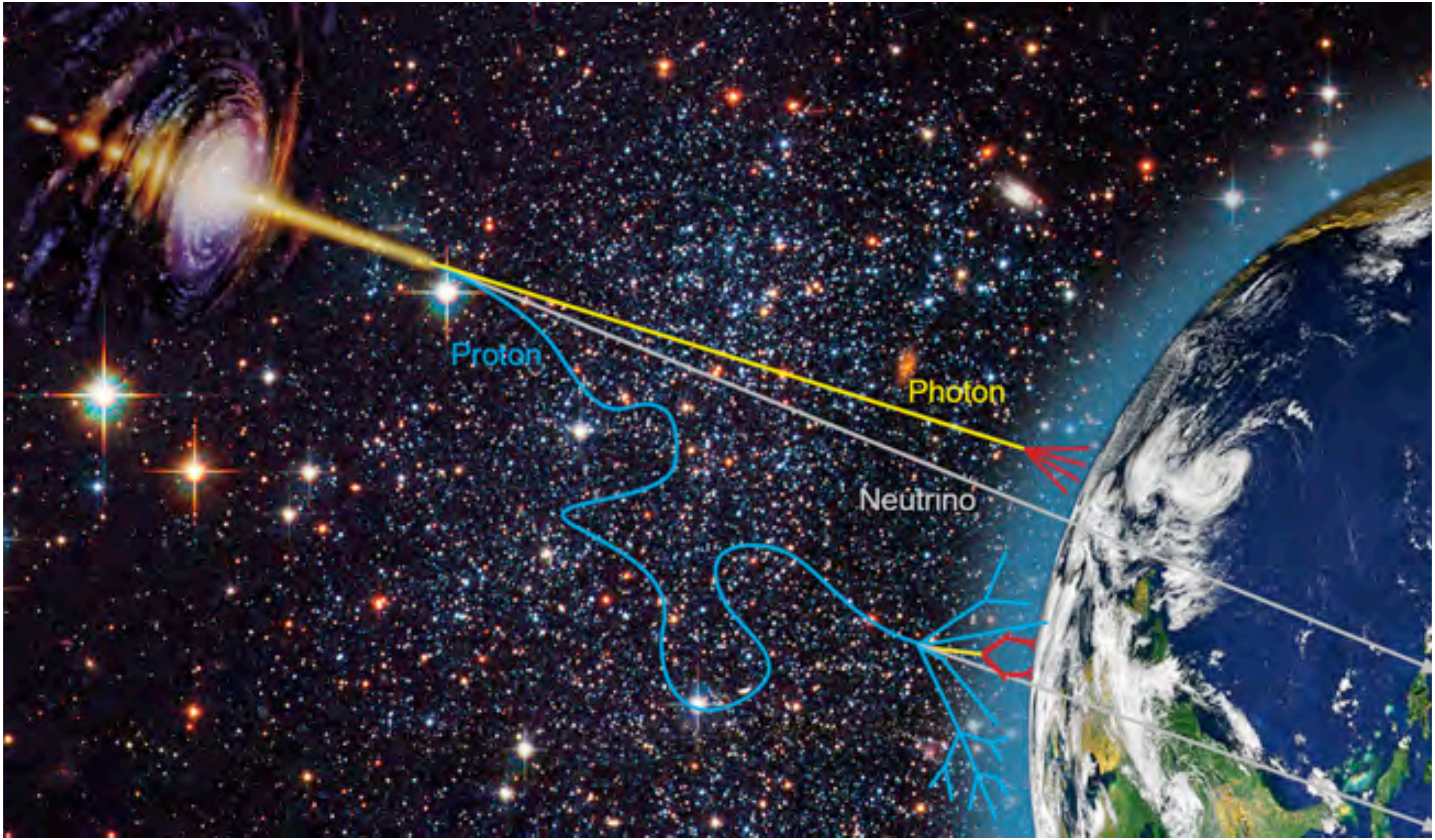
YES, and it allows accessing the highest energies

Detected protons 10^8 times more energetic than LHC

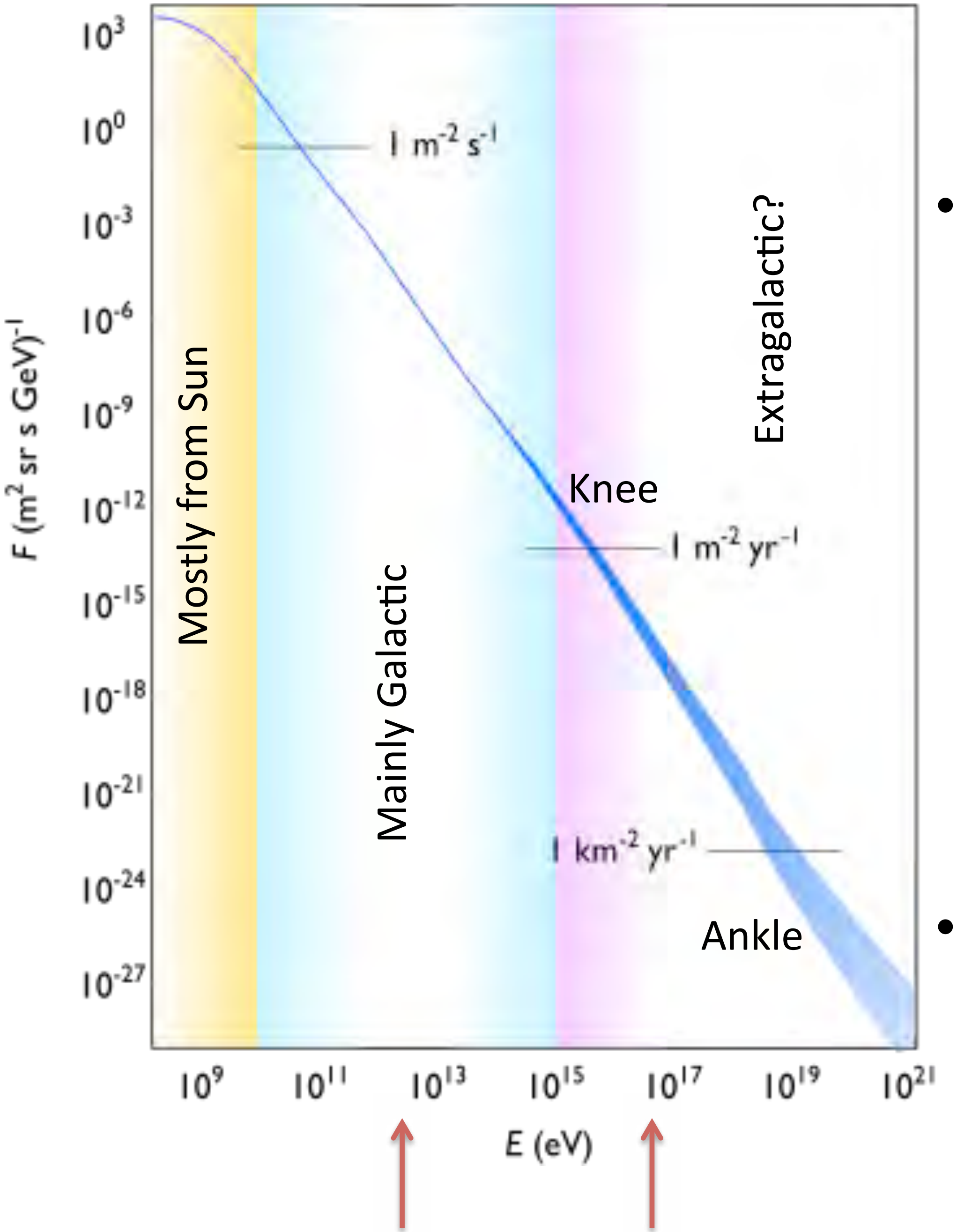
Detected gamma-rays 10000 times more energetic than human-made

Detected neutrinos 10^5 times more energetic than human-made

YES, and it allows understanding high-energy astrophysics (physics under extreme conditions)



Cosmic Rays ("astroparticles")



LHC: 1 beam

LHC: 2 beams

- Once per second per cm^2 a high-energy particle from the sky hits the Earth
  - Mostly (~89%) protons
  - He (~9%) nuclei and heavier (~1%);
  - Electrons are ~1%
  - 0.01% - 1% are gamma rays

$$\boxed{\frac{dN}{dE} \simeq 1.8 \times 10^4 \left(\frac{E}{\mathrm{GeV}}\right)^{-2.7} \frac{\text{particles}}{\mathrm{m^2\,s\,sr\,GeV}}}$$

- The flux falls as ~$E^{-2.7}$ as energy increases
  - 10^{21} eV once per second on Earth
    - The highest energies

Possible UHECR Sources: **2 scenarios**

Bottom-Up Acceleration

(Astrophysical Acceleration Mechanisms)

UHECR's are accelerated in extended objects or catastrophic events (supernova remnants, rotating neutron stars, AGNs, radio galaxies)

Experimental evidence:

- ✓ anisotropy in arrival directions
- ✓ Photons < ≈1%

Top–Down Decay

(Physics Beyond the Standard Model)

Decay of topological defects
Monopoles Relics
Supersymmetric particles
Strongly interacting neutrinos
Decay of massive new long lived particles
Etc.

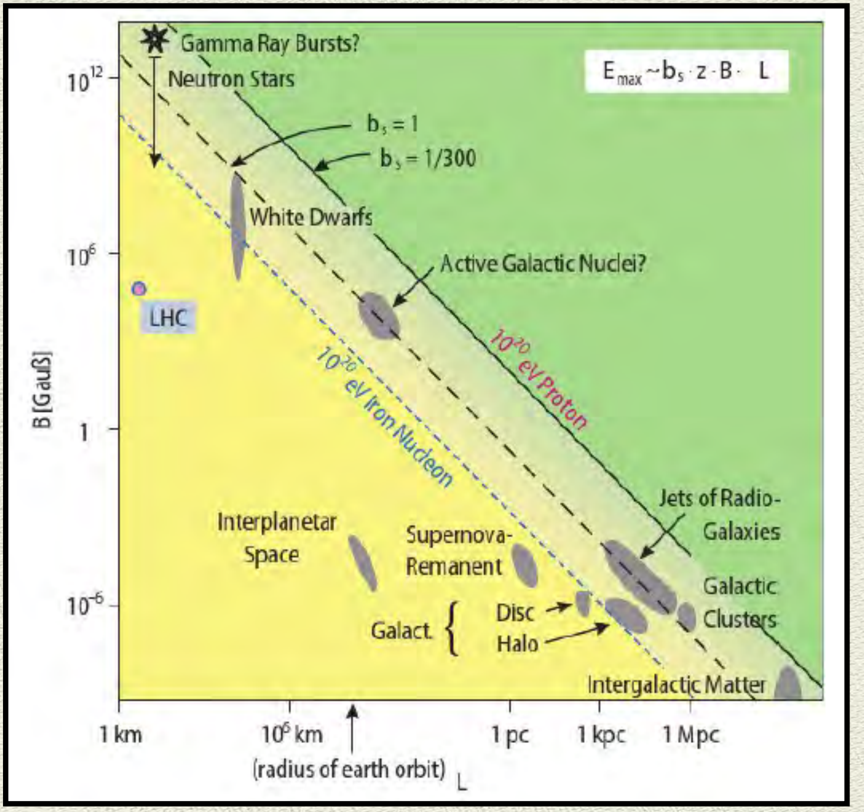
Experimental evidence:

- ✓ isotropy in arrival directions
- ✓ Photons > ≈10%

Bottom-up models

Where do they come from?

r_L must be smaller than the dimension of the source L to remain confined.



$$r_L = \frac{E_{15}}{Z B_{\mu G}} [\mathrm{pc}]$$

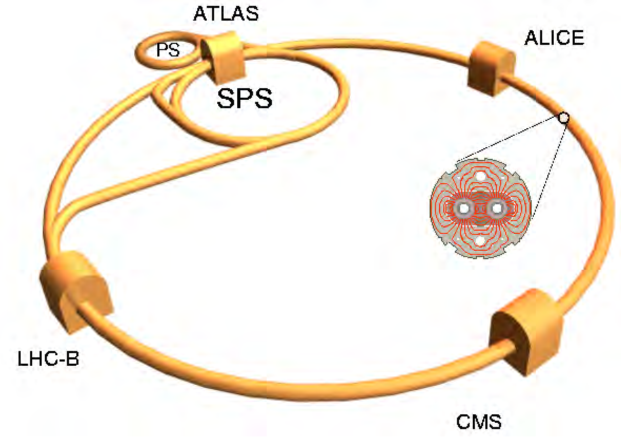
$$\boxed{E_{max} \simeq ZeBL\beta}$$

One should consider also energy losses at the source

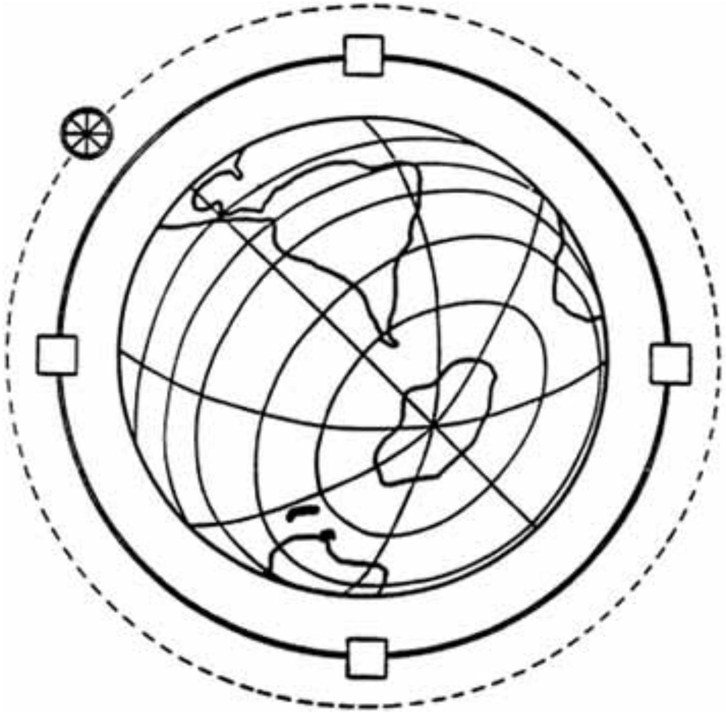
$E \propto BR$

Whatever is the acceleration mechanism…

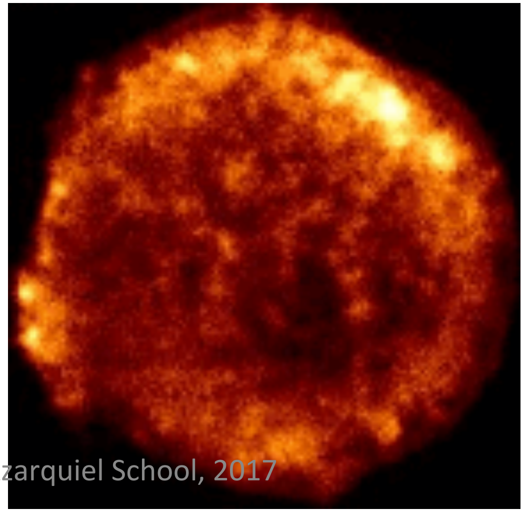
Large Hadron Collider



$R \sim 10$ km, $B \sim 10$ T
$\Rightarrow E \sim 10$ TeV



Tycho SuperNova Remnant



$R \sim 10^{15}$ km, $B \sim 10^{-10}$ T
$\Rightarrow E \sim 1000$ TeV

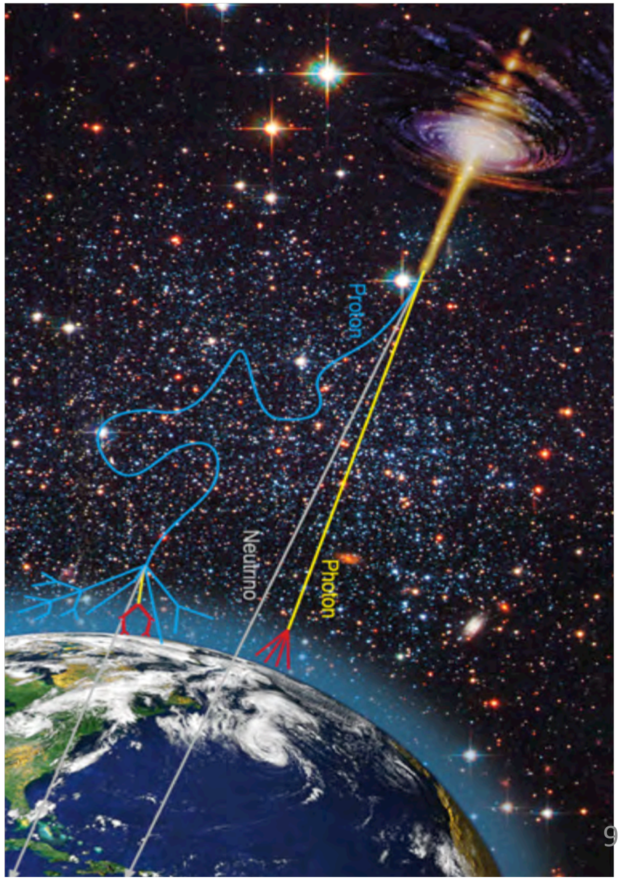
The maximum energy possible on Earth is ~ 5000 TeV

Propagation of charged CR in the Universe

$$\frac{r}{1\ \mathrm{pc}} \cong \frac{\frac{E}{1\ \mathrm{PeV}}}{\frac{B}{1\ \mu G}}$$

- Gyroradius

  B in the Galaxy: a few µG; outside the Galaxy: 1nG > B > 1 fG
- If you want to look at the GC (d ~ 8 kpc) you need E > $2\ 10^{19}$ eV
  - But only 1 particle / km^2 / year
  - *And no galactic emitters expected at this energy*
- But in principle one could look outside the galaxy, were B is smaller and there are SMBHs…
  - *No: the resonant interaction with the CMB (GZK effect) provides a cutoff at E ~ 10^{19} eV*
- Conclusion: extremely difficult to use charged CR for astrophysics



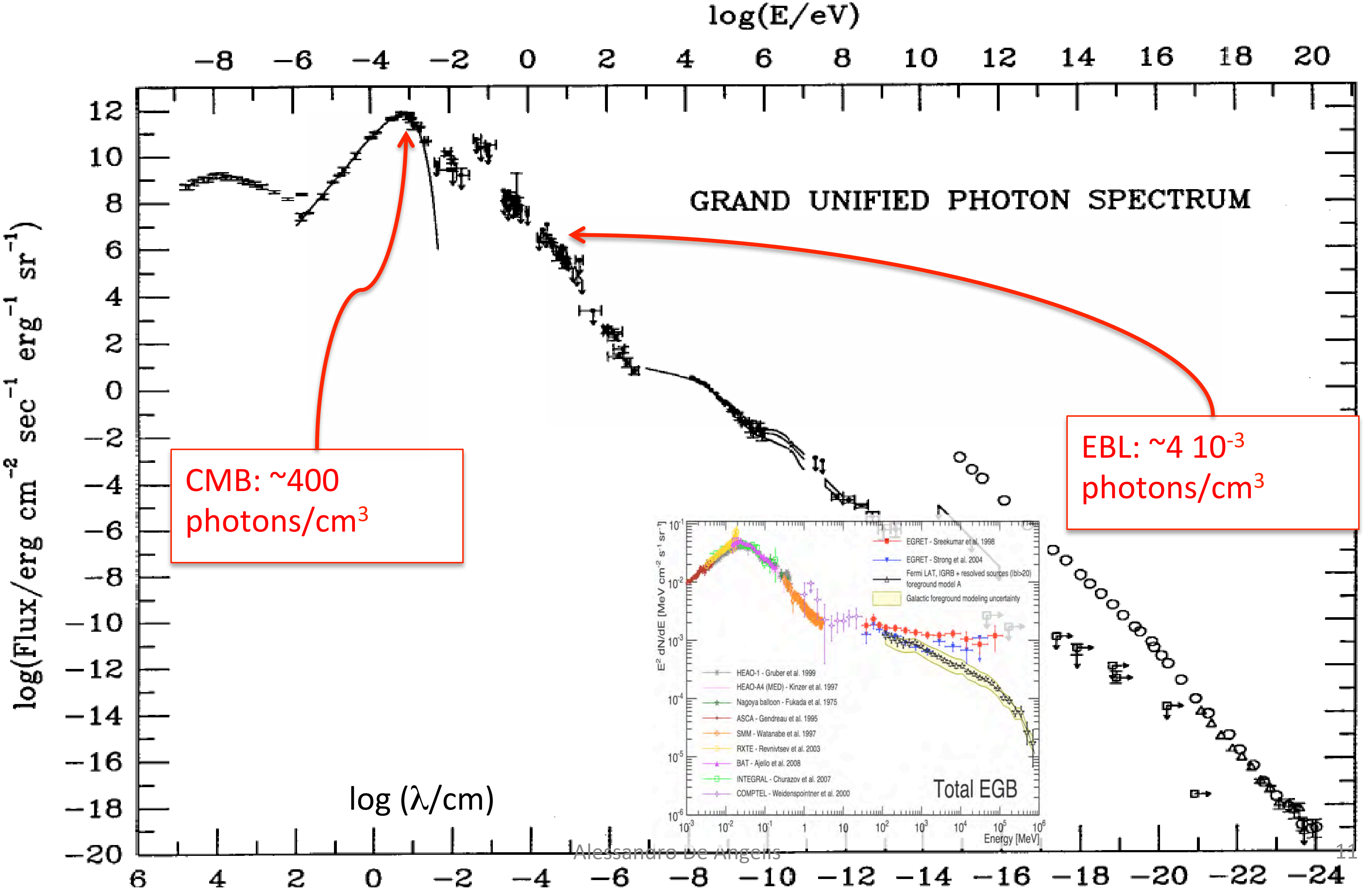
Neutral messengers must be used for astronomy & astrophysics

- Neutrinos: very difficult to detect due to the small interaction cross section (despite a km^3 detector in Antarctica, the only cosmic sources localized up to now are SN1987A, the Sun, and the Earth)
  - <10 neutrinos per year from astrophysical sources identified by IceCube (1km^3)!
- Gravitational waves: just started
- Photons: they have a long tradition in astronomy since millennia… And they are the "starry messangers" by default since 1610 at latest…

SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, ſuſpiciendaque proponens
vnicuique, præſertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnaſij Publico Mathematico
PERSPICILLI
Nuper à ſe reperti beneficio ſunt obſeruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam diſparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vſque diem cognitos, nouiſſimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M D C X.
Superiorum Permiſſu, & Priuilegio.

The observed photon spectrum extends over 30 decades (measurements up to 1 TeV)

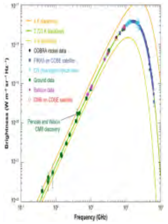


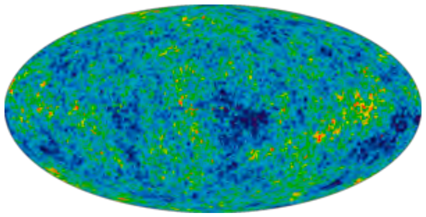
CMB: ~400 photons/cm^3

EBL: ~4 10^{-3} photons/cm^3

Thermal radiation: Blackbody Spectra

CMB:
2.7 K



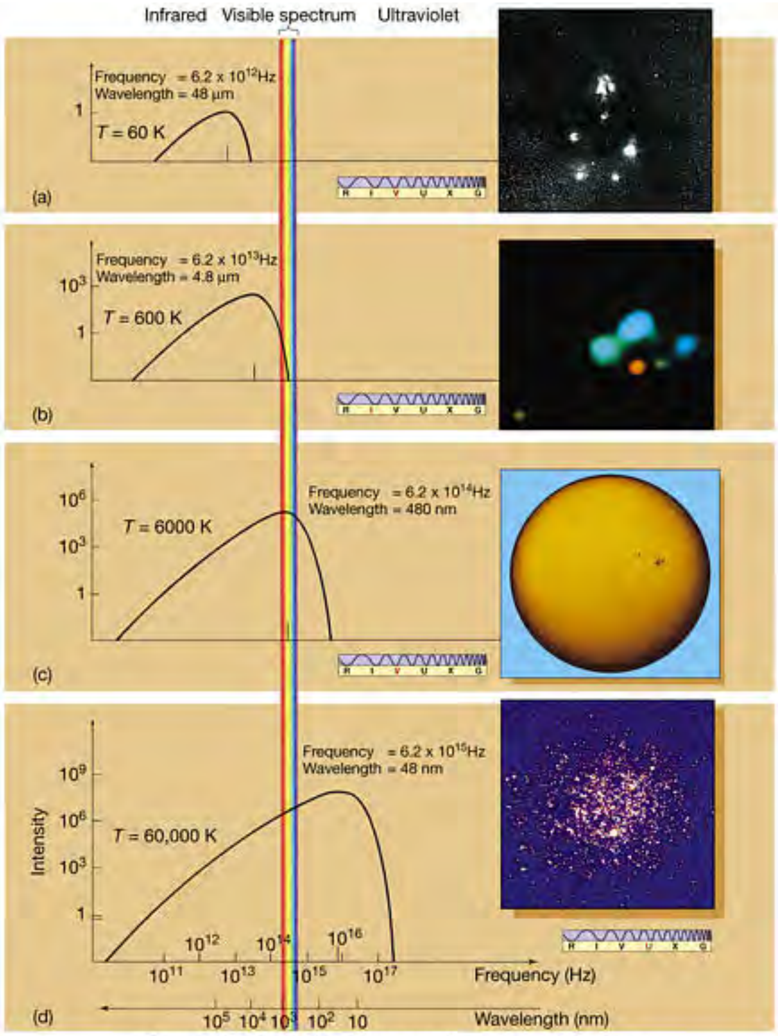


A Galactic gas cloud
60 K

Dim star in the Orion Nebula:
600 K

The Sun:
6000 K

Cluster of very bright stars, Omega Centauri:
60 000 K



Accretion near BHs: ~ the keV

γ rays: non-thermal Universe

- Particles accelerated in extreme environments interact with medium
  - Gas and dust; Radiation fields – Radio, IR, Optical, …;
    Intergalactic Magnetic Fields, …
- Gamma rays traveling to us!

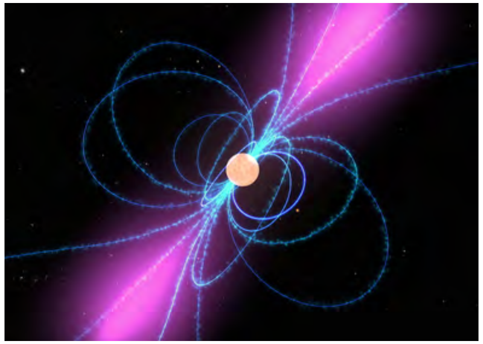
- No deflection from magnetic fields, gammas point ~ to the sources
  - Magnetic field in the galaxy: ~ 3μG
    Gamma rays can trace cosmic rays at energies ~10x
- Large mean free path
  - Regions otherwise opaque can be transparent to X/γ

Studying Gamma Rays allows us to see different aspects of the Universe

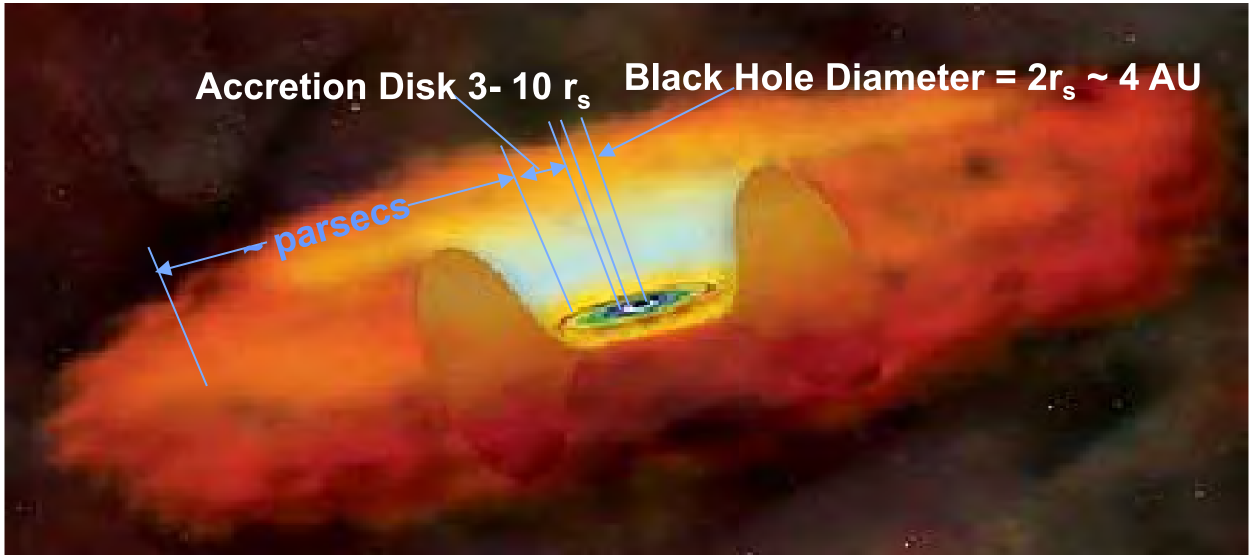
Examples of known extreme environments

GRB

SuperNova Remnants
Pulsars



Active Galactic
Nuclei



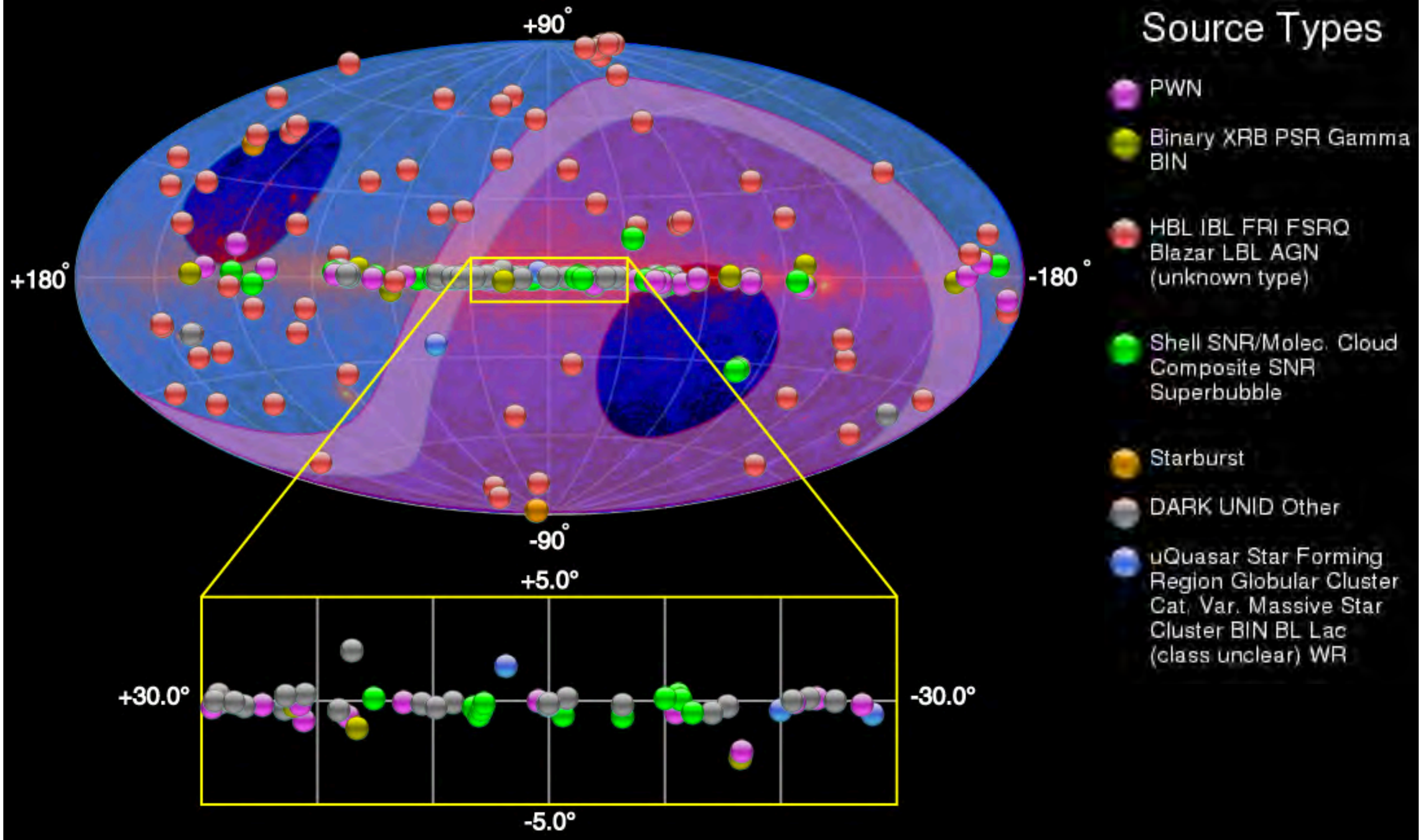
Energies above the thermal regions

- (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+

>3k HE and >200 VHE photon emitters

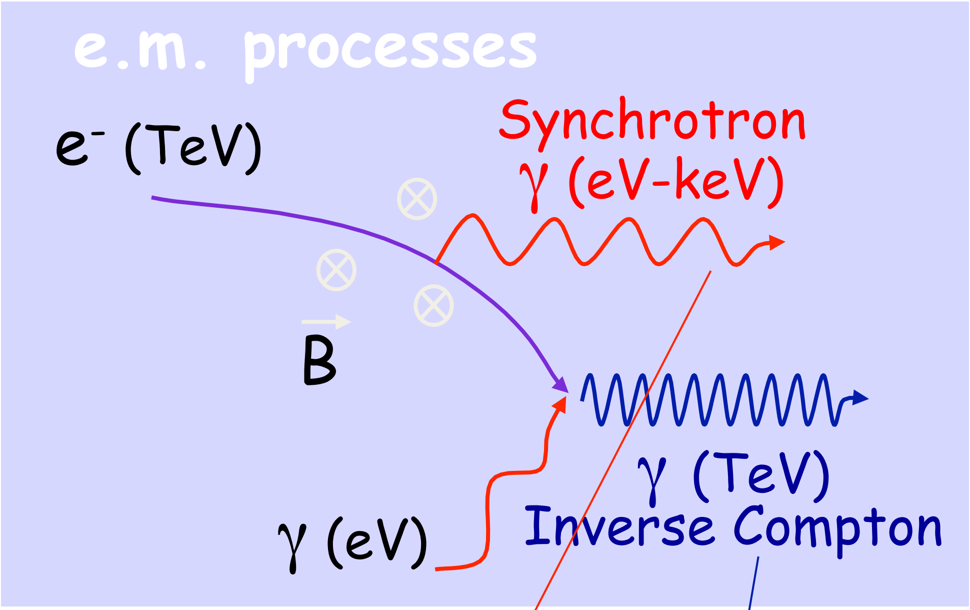


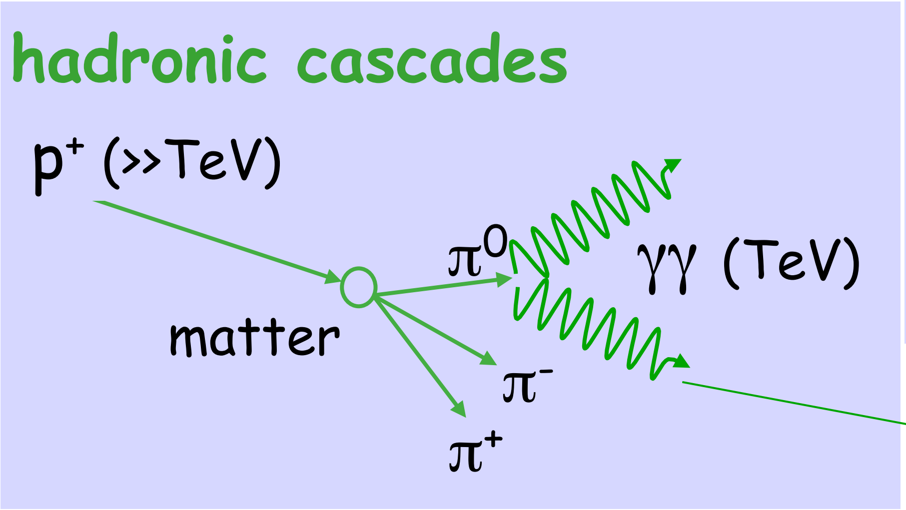
(1) Bottom-up: Interaction of accelerated particles with radiation and matter fields

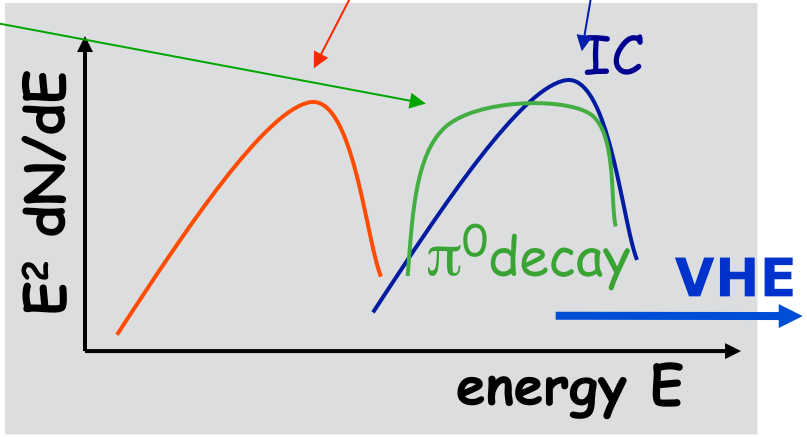
- Gamma-ray production and absorption processes: several but well studied
- These phenomena generally proceed under extreme physical conditions in environments characterized by
  - huge gravitational, magnetic and electric fields,
  - very dense background radiation,
  - relativistic bulk motions (black-hole jets and pulsar winds)
  - shock waves, highly excited (turbulent) media, etc.
- They are related to, and their understanding requires knowledge of,
  - nuclear and particle physics,
  - quantum and classical electrodynamics,
  - special and general relativity,
  - plasma physics, (magneto) hydrodynamics, etc.
  - astronomy & astrophysics

Leptonic and hadronic production of gamma rays

50 TeV gamma-rays hadronically produced track a pupulation of protons of energy ~ 1 PeV



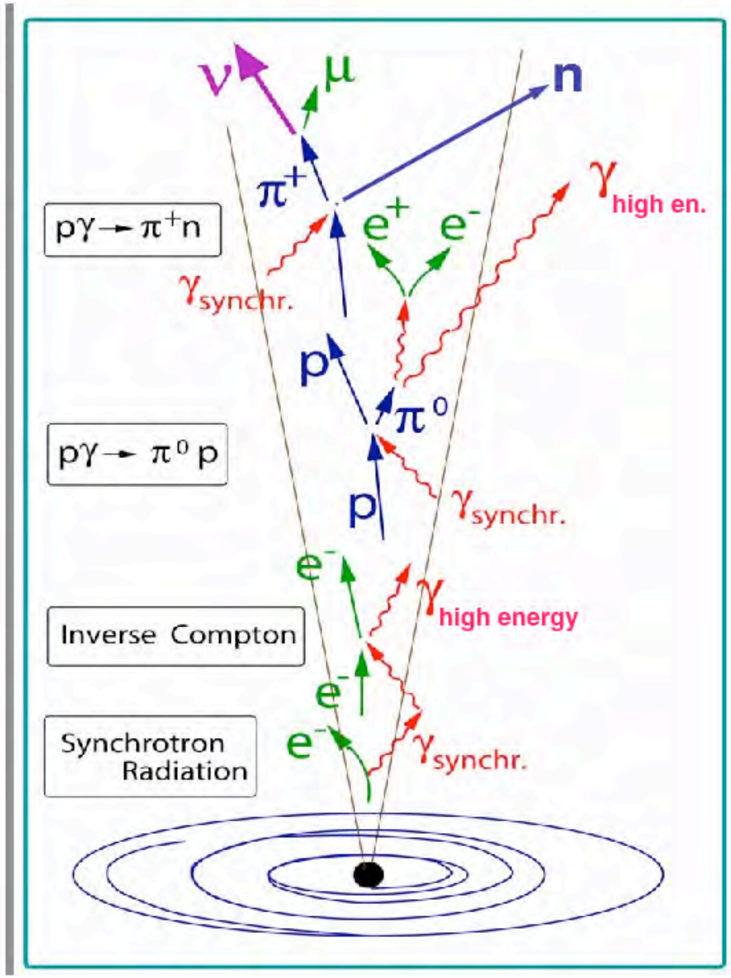




In the VHE region,
$dN/dE \sim E^{-\Gamma}$ (Γ: spectral index)

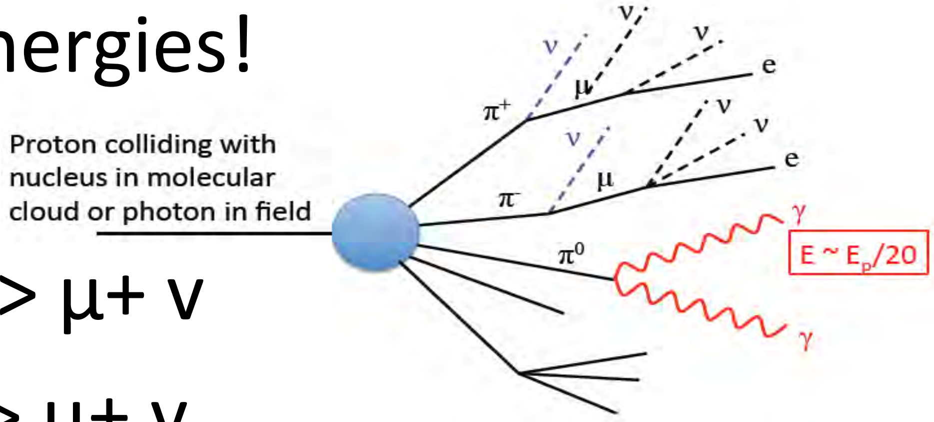
To distinguish between hadron/leptonic origin study Spectral Energy Distribution (SED):
(differential flux) · E^2

The hadronic mechanism is at work also for neutrinos…



In a hadronic process (isospin symmetry)

- N(π+) ~ N(π-) ~ N(π^0) Same energies!

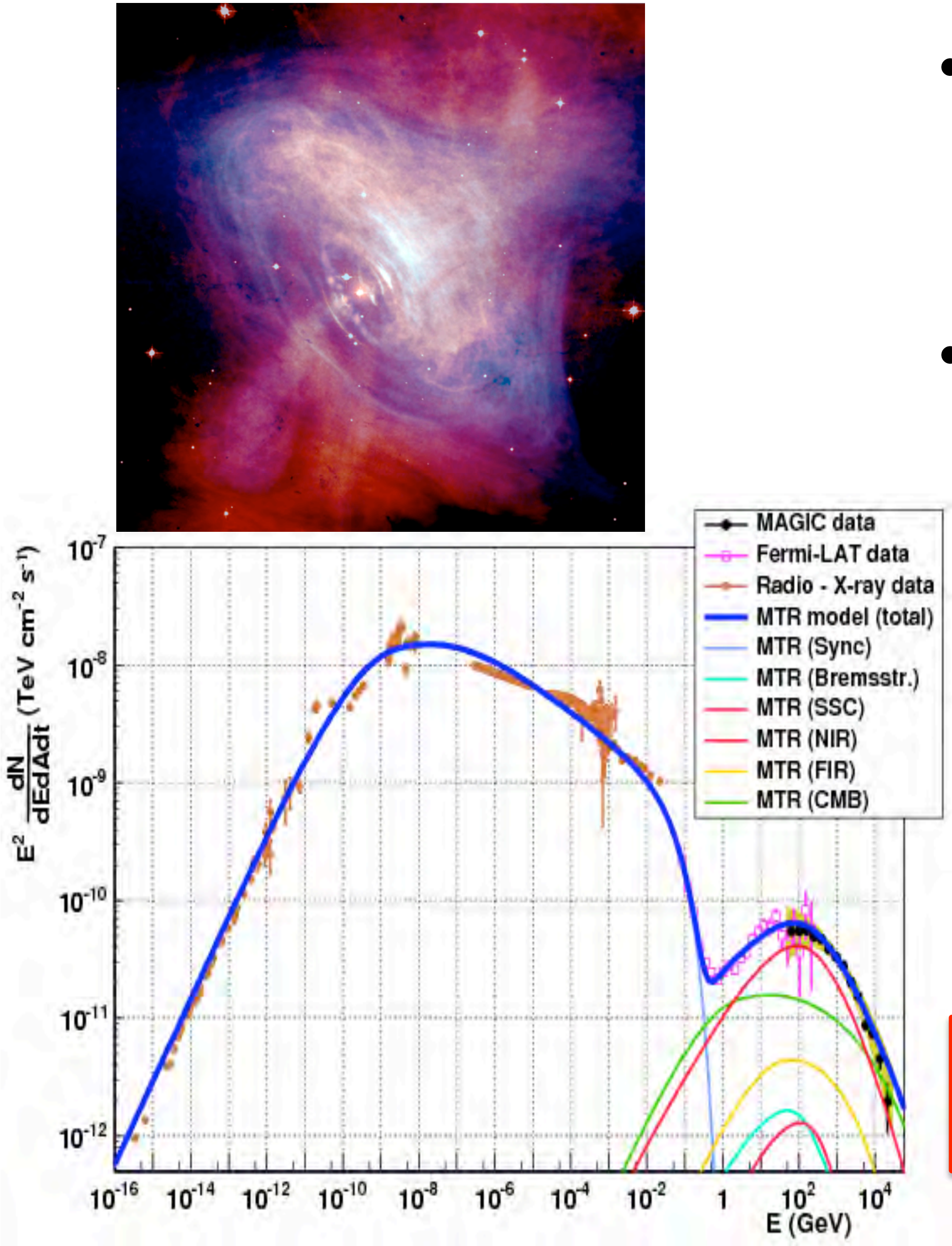


$\pi^+ \to \mu^+ \nu$

$\pi^- \to \mu^+ \nu$

$\pi^0 \to \gamma\gamma$

A “typical” (V)HE γ source: Crab Nebula

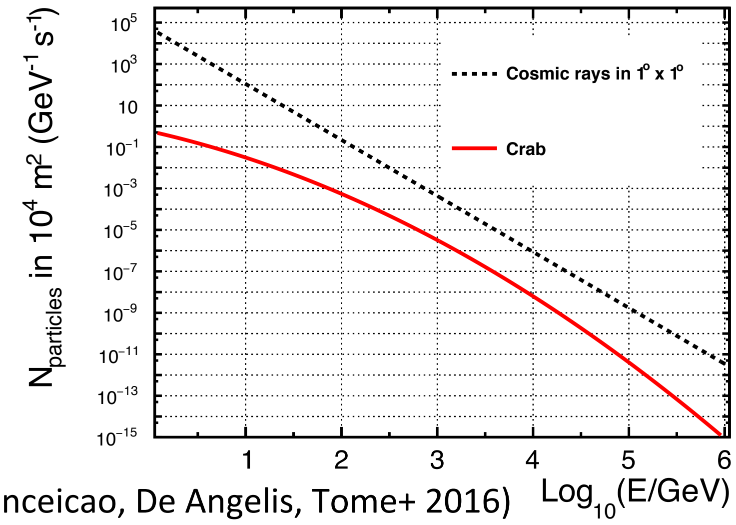


- The Crab Nebula is a nearby (~2 kpc away) PWN and the first source detected in VHE gamma-rays [Weekes 1989].
- It is the brightest steady VHE gamma-ray source, therefore it has become the so-called “standard candle” in VHE astronomy.
    - Recent observation of flares in the GeV range have however shown that occasionally the Crab flux can vary.

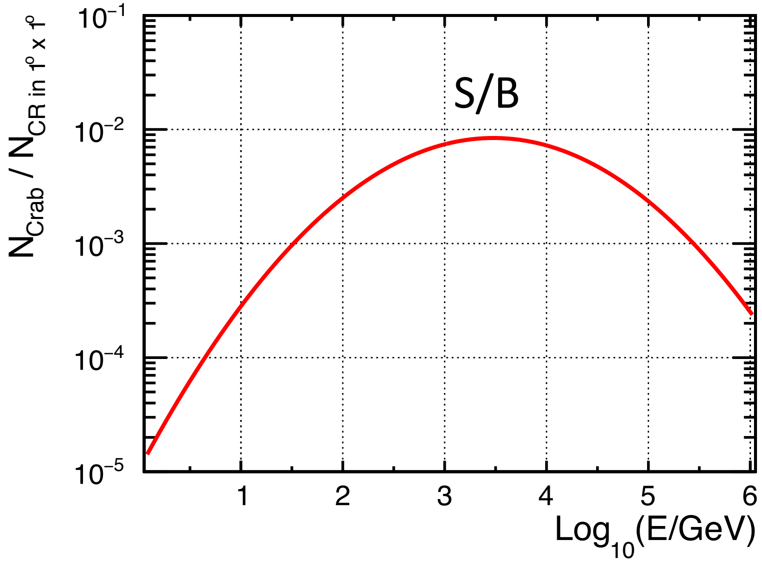
$$\frac{dN_\gamma}{dE} \simeq 3.23 \times 10^{-11} \left(\frac{E}{\mathrm{TeV}}\right)^{-2.47-0.24\left(\frac{E}{\mathrm{TeV}}\right)} \mathrm{TeV}^{-1}\mathrm{s}^{-1}\mathrm{m}^{-2}$$

γ-ray detection: signal vs. background

- Is Crab Nebula easy to detect?
- Suppose to have a 100 x 100 m^2 detector with a resolution of 1 square degree:

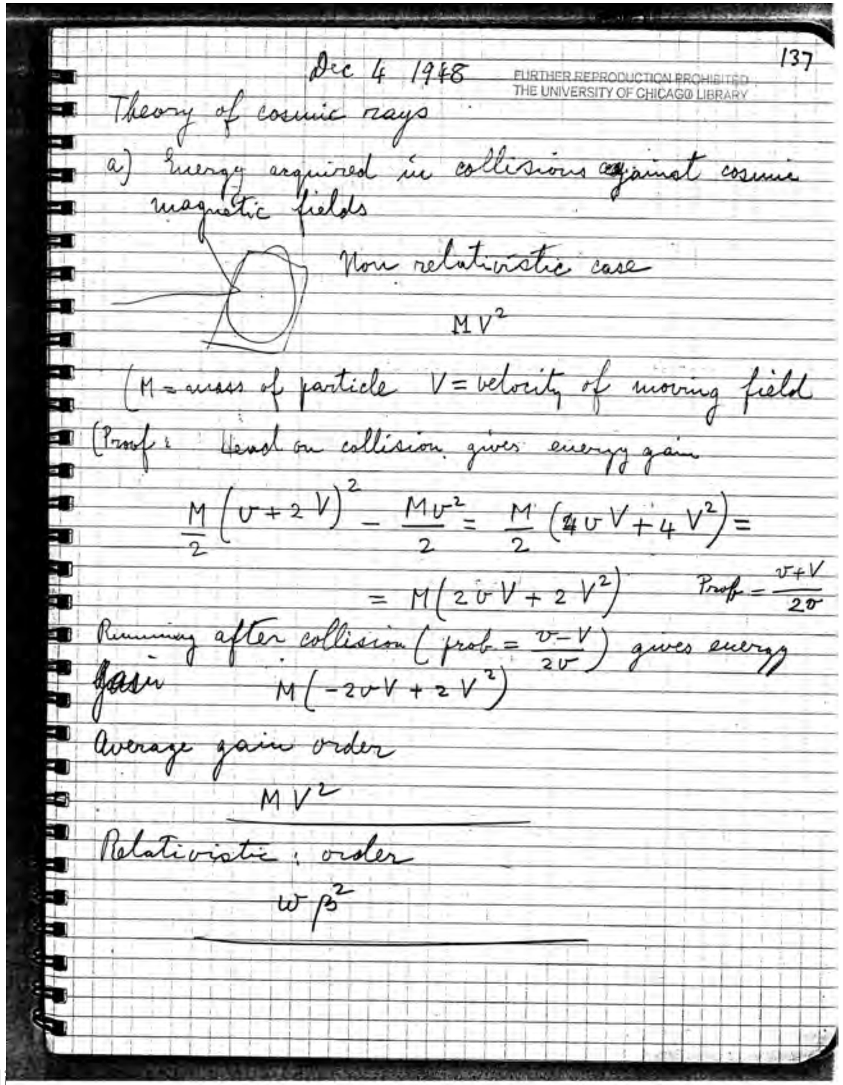


Conceicao, De Angelis, Tome+ 2016)



Conclusion: you need large effective area, good angular resolution, proton rejection

How to generate bottom-up energies much higher than thermal?



Dec 4 1948

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Theory of cosmic rays

a) Energy acquired in collisions against cosmic magnetic fields

Non relativistic case

MV^2

(M = mass of particle V = velocity of moving field

(Proof: Head on collision gives energy gain

$$\frac{M}{2}(v+2V)^2 - \frac{Mv^2}{2} = \frac{M}{2}(4vV+4V^2) =$$

$$= M(2vV+2V^2) \qquad \text{Prob} = \frac{v+V}{2v}$$

Running after collision (prob = $\frac{v-V}{2v}$) gives energy gain

$$M(-2vV+2V^2)$$

Average gain order

MV^2

Relativistic: order

$w\beta^2$

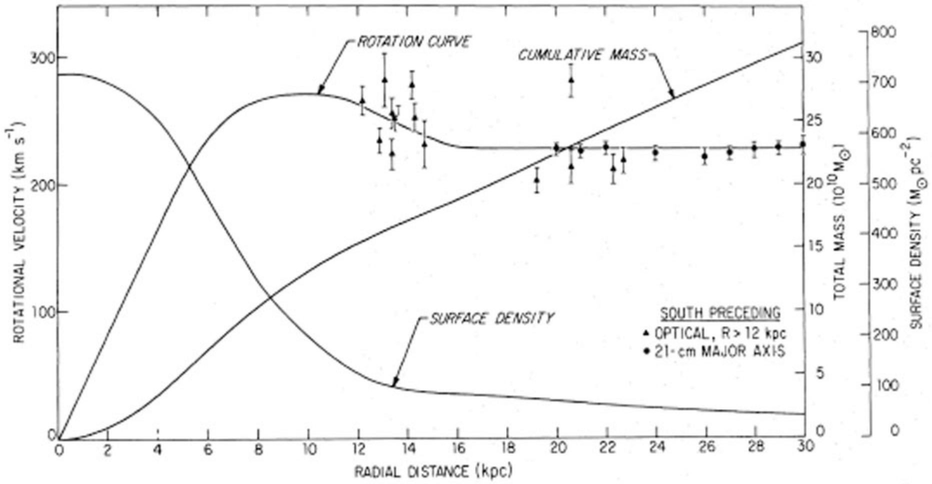
Zwicky conjectures (1933)

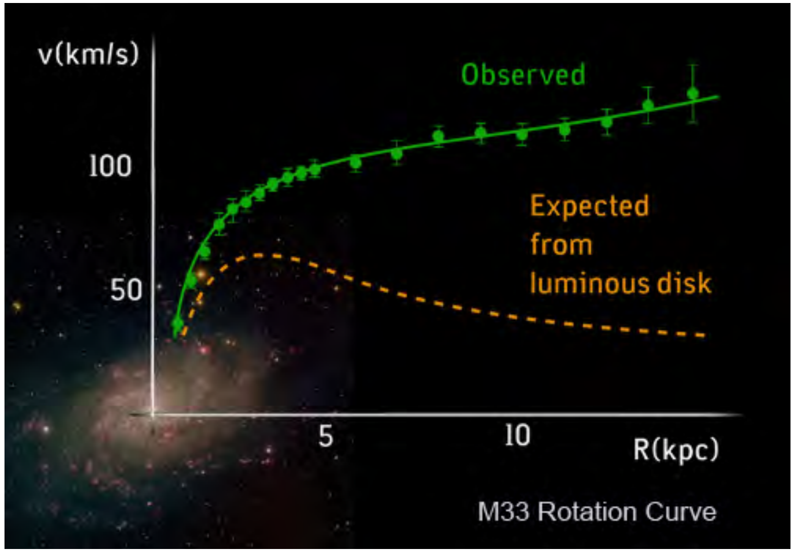
1. Heavy enough stars collapse at the end of their lives into super-novae
2. Implosions produce explosions of cosmic rays
3. They leave behind neutron stars


(Zwicky in1930)

(2) Top-down: are there new (heavy) particles which can produce HE photons?

- Rotation curves of spiral galaxies





  - flat at large radii: if light traced mass we would expect them to be Keplerian at large radii, $v \propto r^{-1/2}$, because the light is concentrated in the central bulge
    - and disc light falls off exponentially
    - Zwicky had already noted in 1933 that the velocities of galaxies in the Coma cluster were too high to be consistent with a bound system
    - Observed for many galaxies, including the Milky Way

The currently favored solution

To assume that in and around the Galaxies there is

Dark Matter

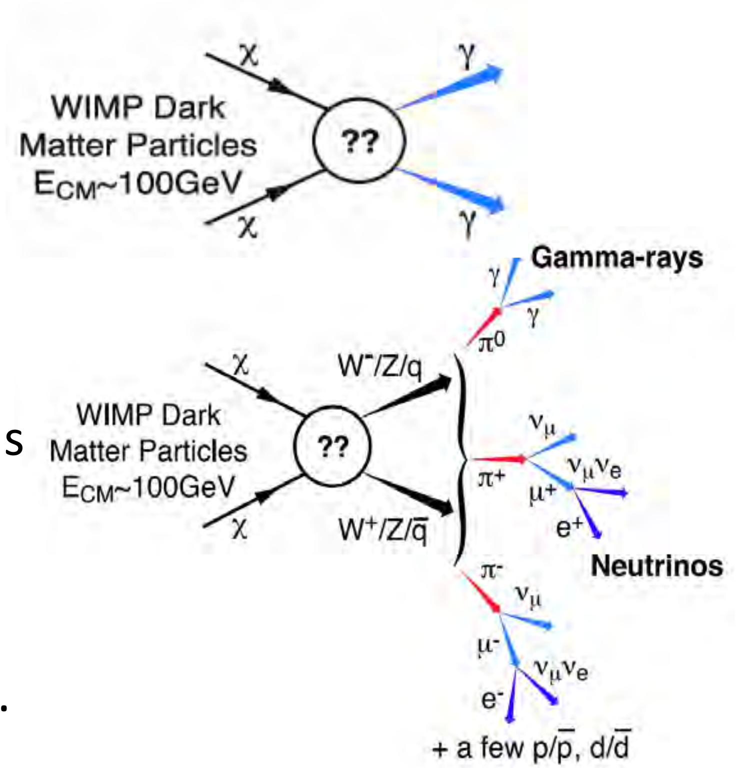
subject to gravitational interaction but no electromagnetic interaction

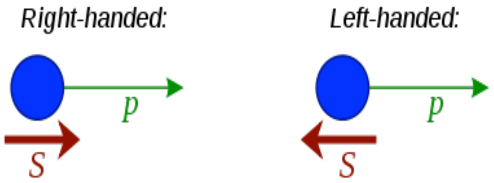
$$M(r) \propto r \Rightarrow v_{rot} = \sqrt{\frac{GM(r)}{r}} = const.$$

- Must be "cold", i.e., non-relativistic (it is trapped by the gravitational field), and "weakly" interacting: WIMP
- The hypothesis is not odd: remember that the existence of Neptune was suggested on the basis of the irregular motions of Uranus
- How much DM do we need? results to be 5 times more than luminous matter (astrophysics, evolution of the Universe)

How do WIMPs produce photons?

- The energy “blob” from χχ annihilation might decay:
  - Directly into 2γ, or into Zγ if kinematically allowed. Clear experimental signature (photon line), but not very likely (requires one loop). In SUSY, the BR depends on what is the lightest neutralino composition.
  - Into a generic f-fbar pair, then generating a hadronic cascade with π^0 decaying into photons in the final state. Remind that flavors are left-handed and anti-flavors are right-handed with amplitude $[1+|p|/(E+m_f)]/2 \sim v/c$, and in this case for an s-wave you need to “force” one of the decay products to have the “wrong” elicity.

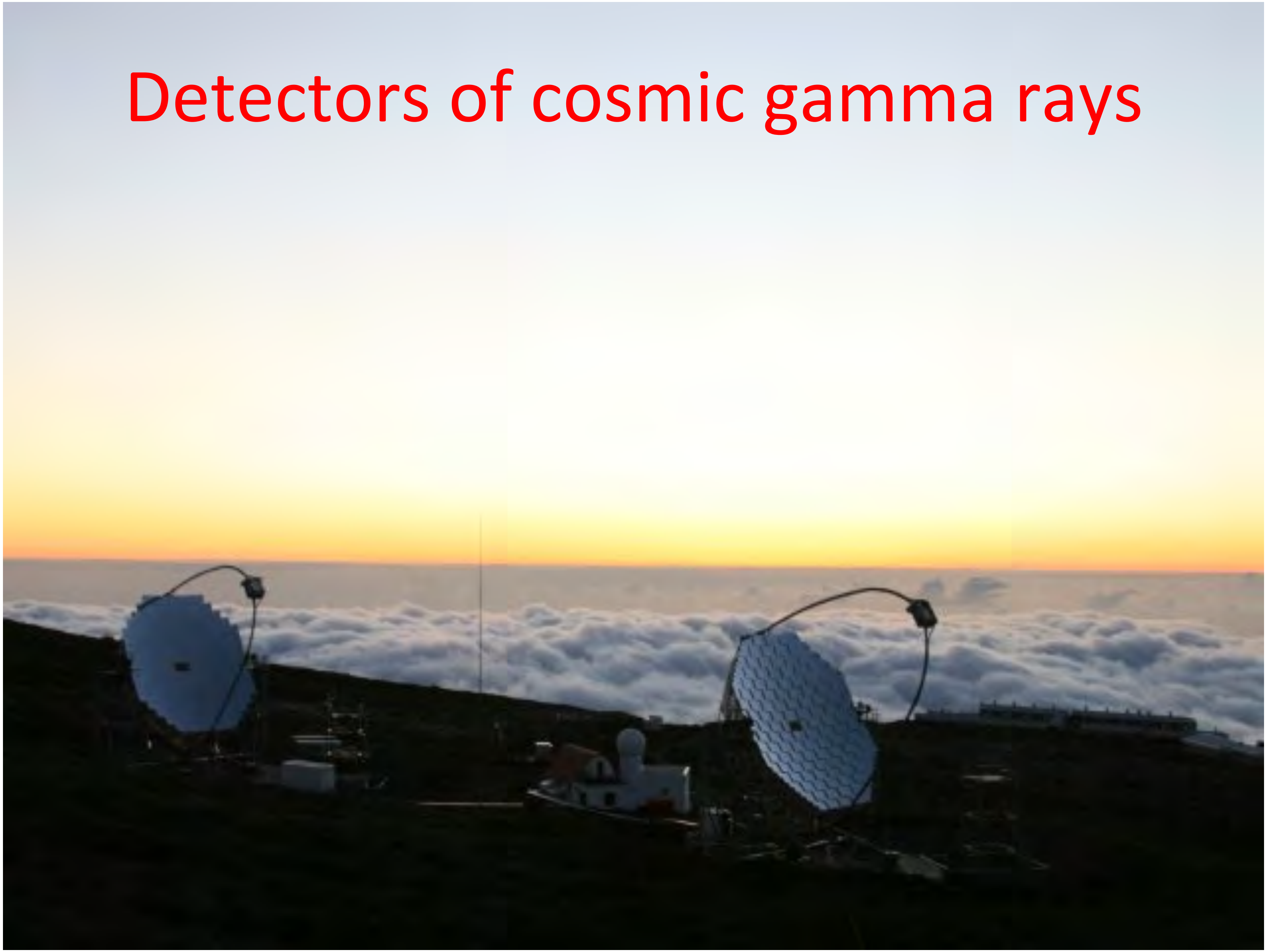




$$M_{fi} \propto \frac{1}{2}\left(1-\frac{|p|}{E+m_f}\right)=\frac{m_f}{2m_\chi+m_f}$$

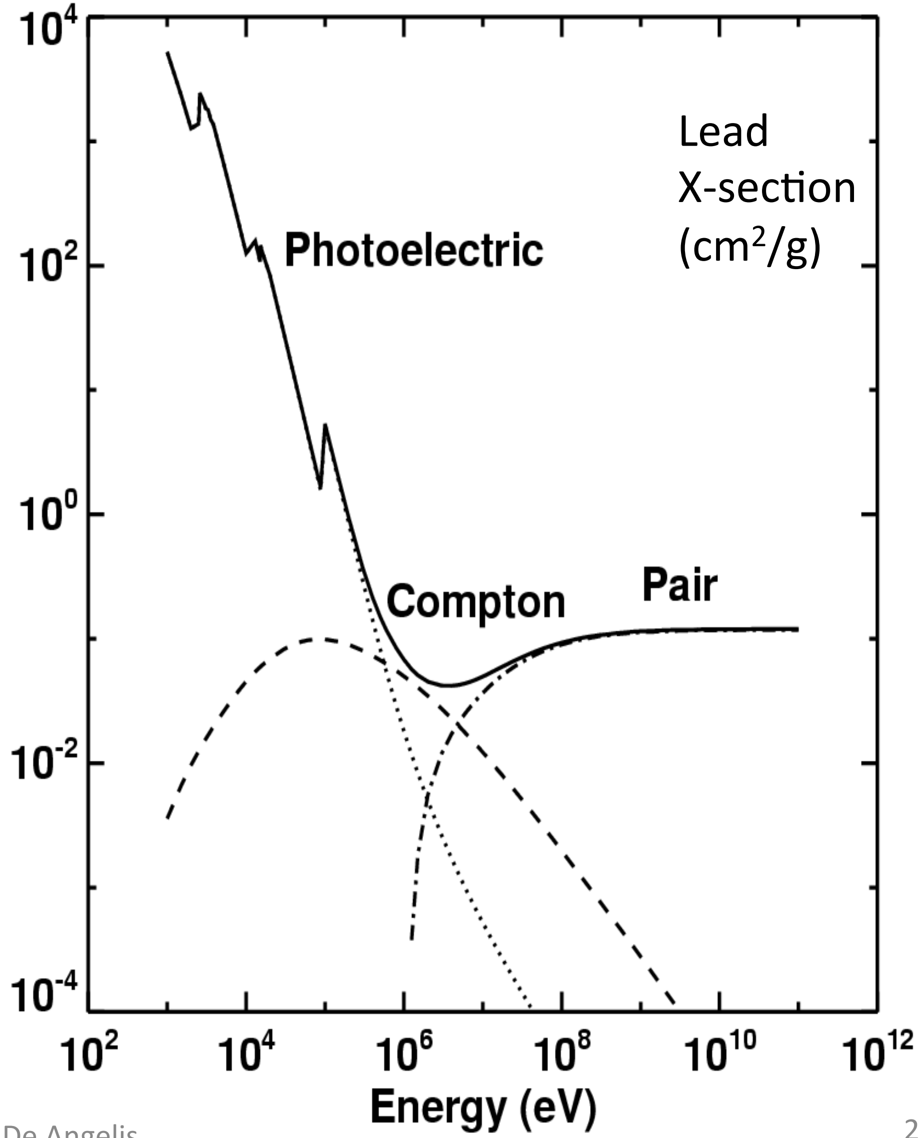
=> The χχ pair will prefer to decay into the heaviest available pair – i.e., if 20 GeV < m_χ < 80 GeV, into b-bbar

Detectors of cosmic gamma rays



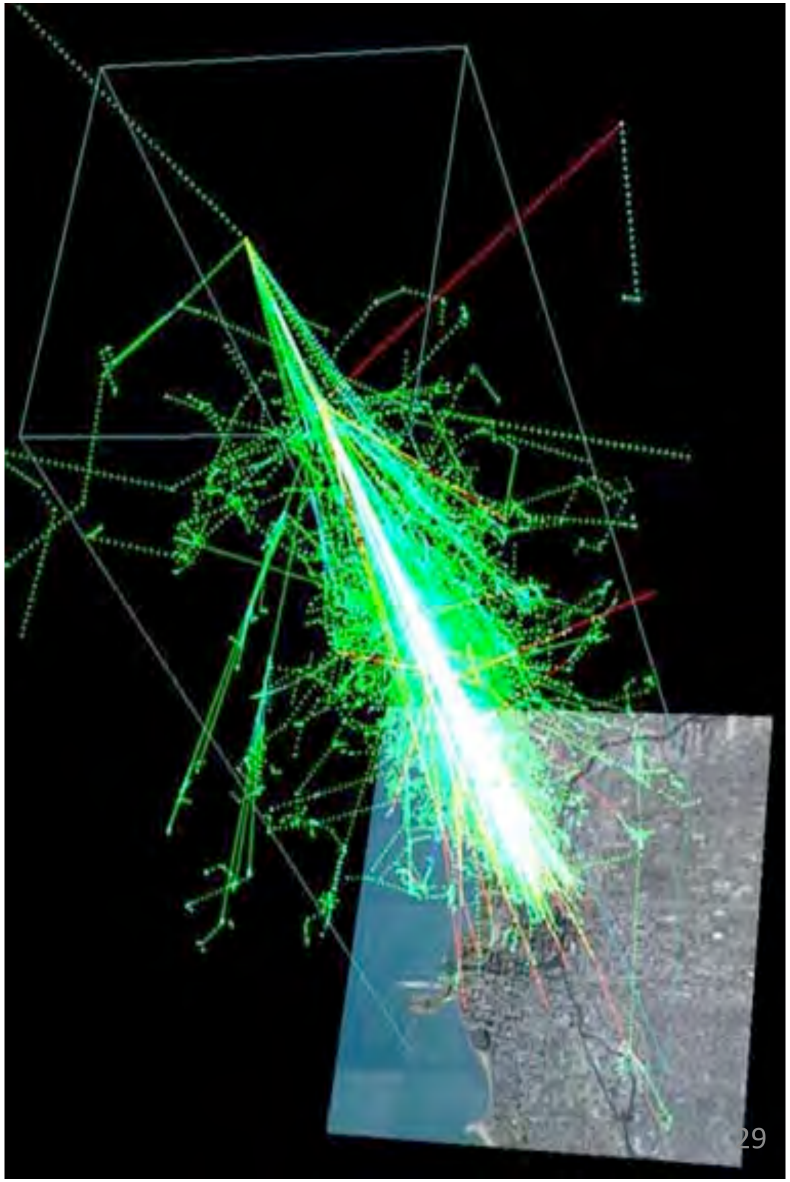
Interactions of photons with matter above the keV

- 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



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

A simplified approach (Heitler)

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

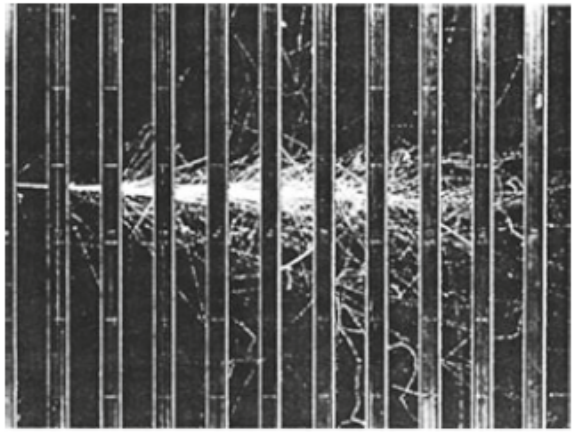
$$E(t) = E_0/2^t$$

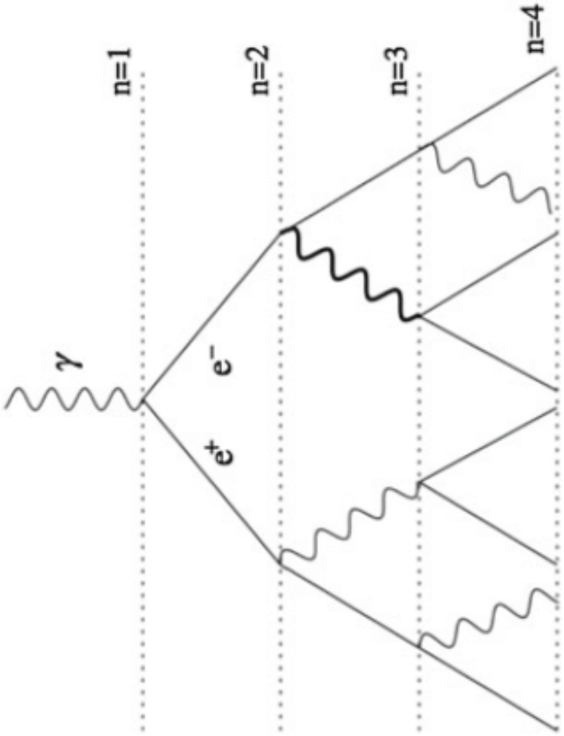
- The multiplication process will cease when $E(t)=E_C$

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

and the number of particles at this point will be

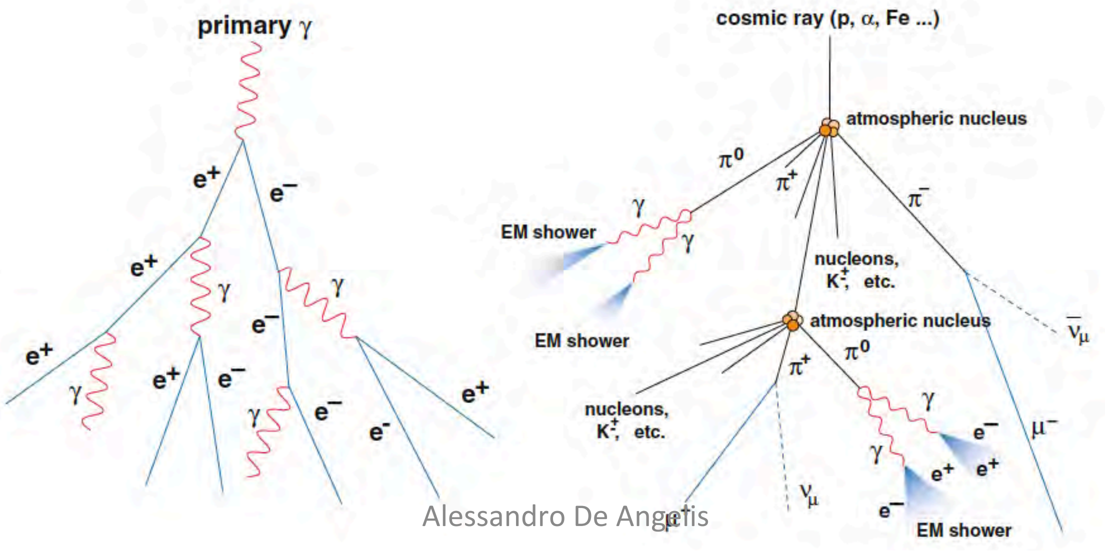
$$N_{max} = \exp(t_{max} \ln 2) = E_0 / E_C$$





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”

The events: Cosmic rays "rain"

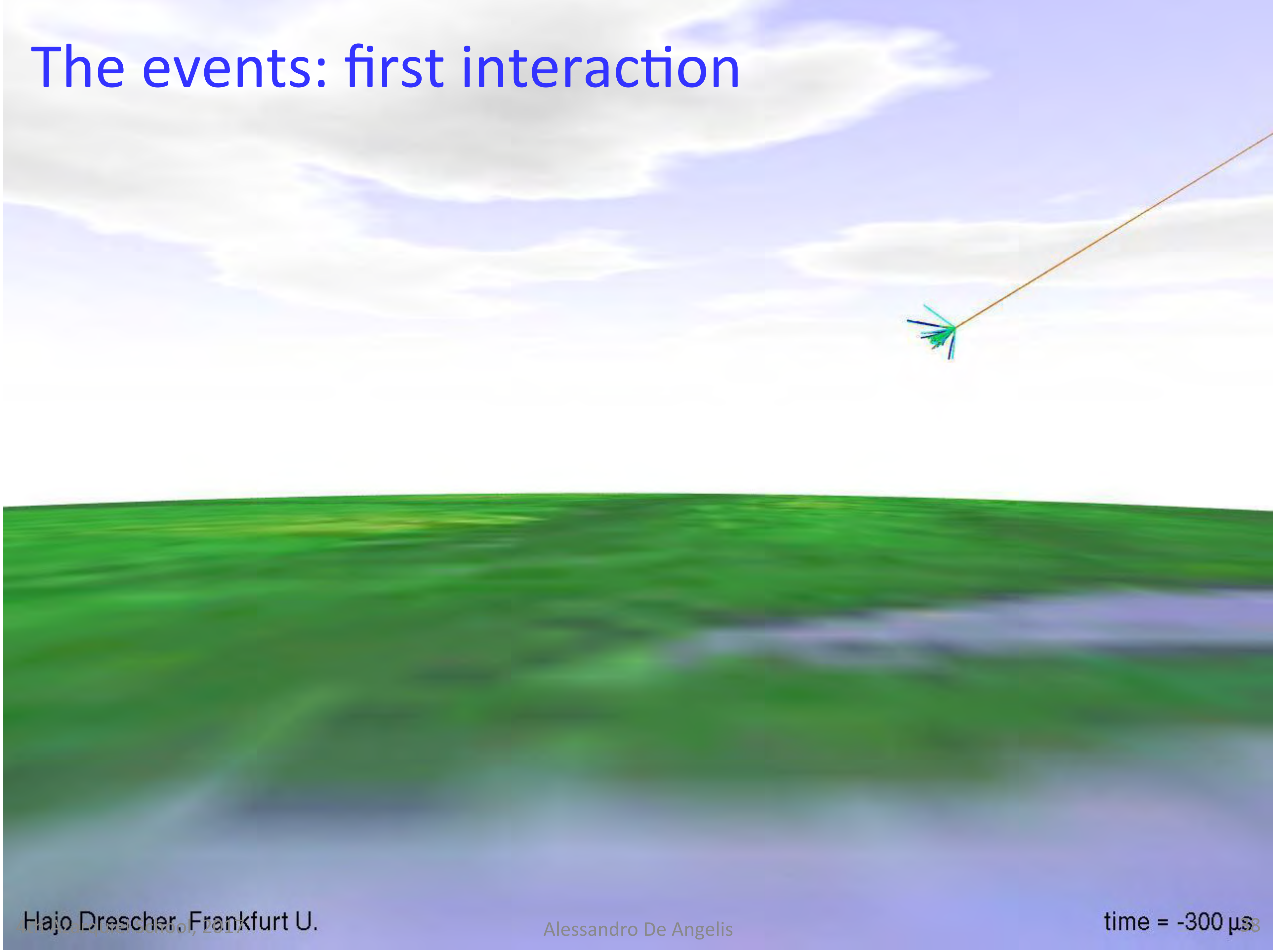
Hajo Drescher, Frankfurt U.

The events: Cosmic rays “rain”

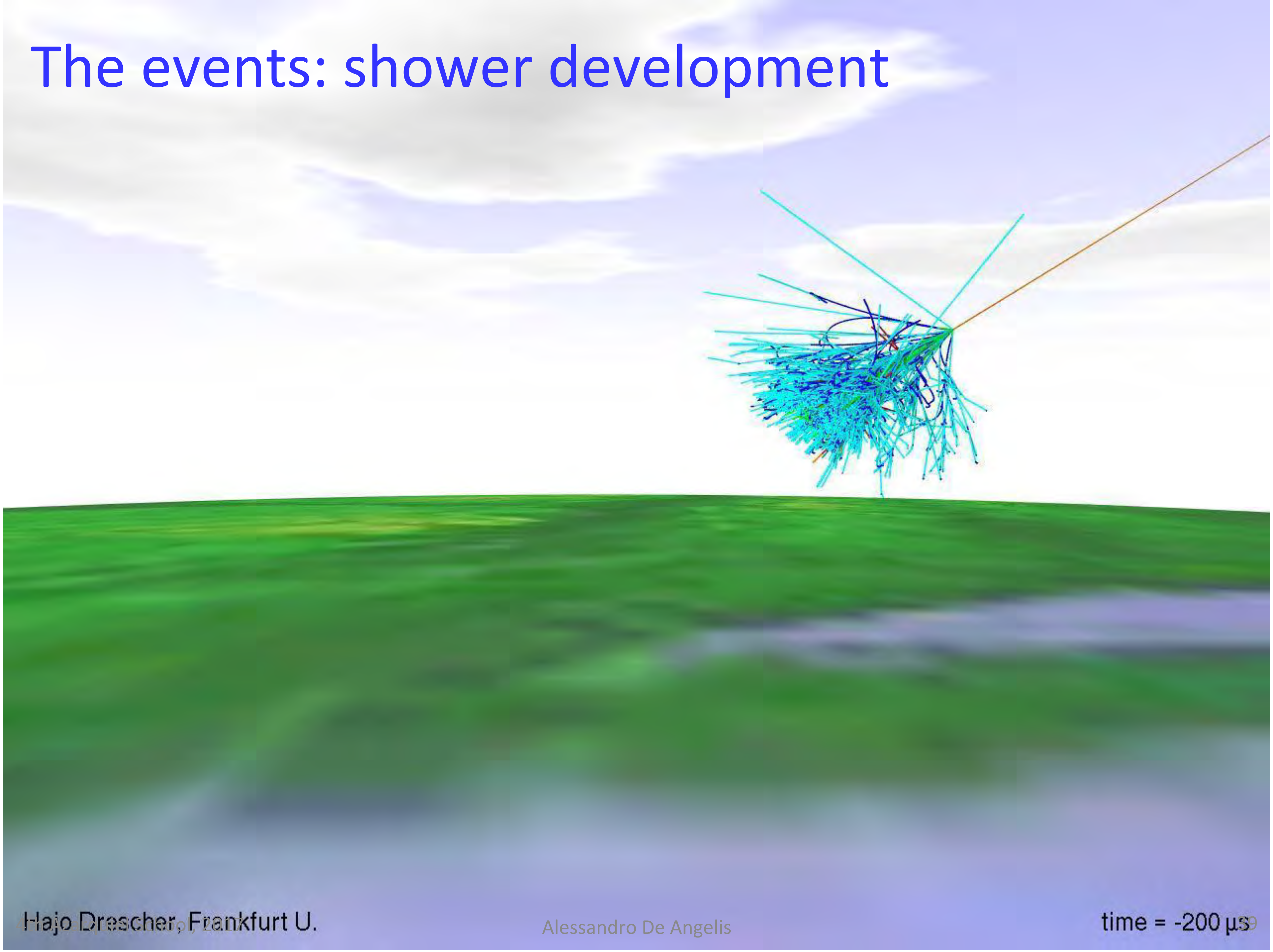
The events: Cosmic rays “rain”

Hajo Drescher, Frankfurt U.

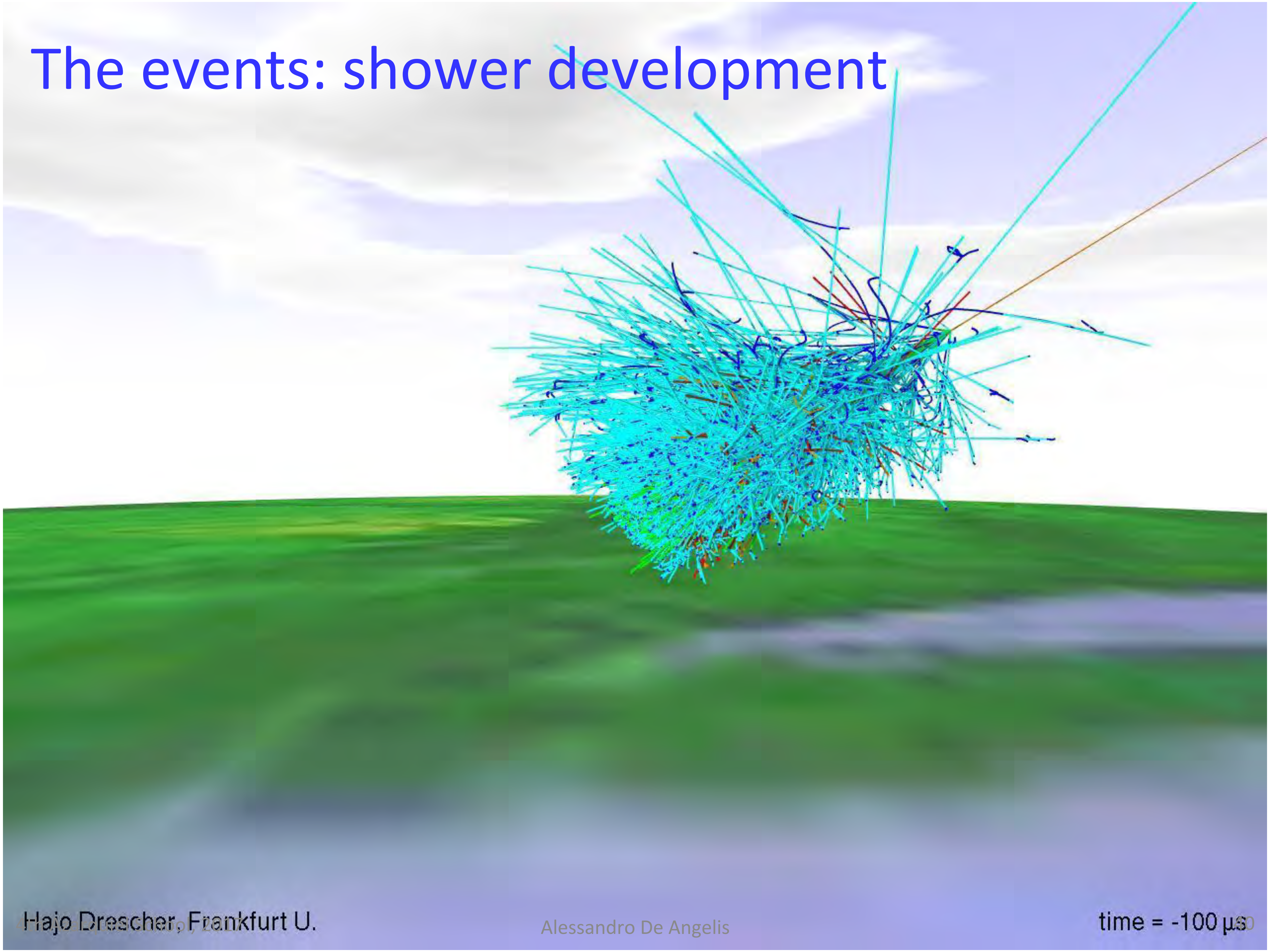
The events: first interaction



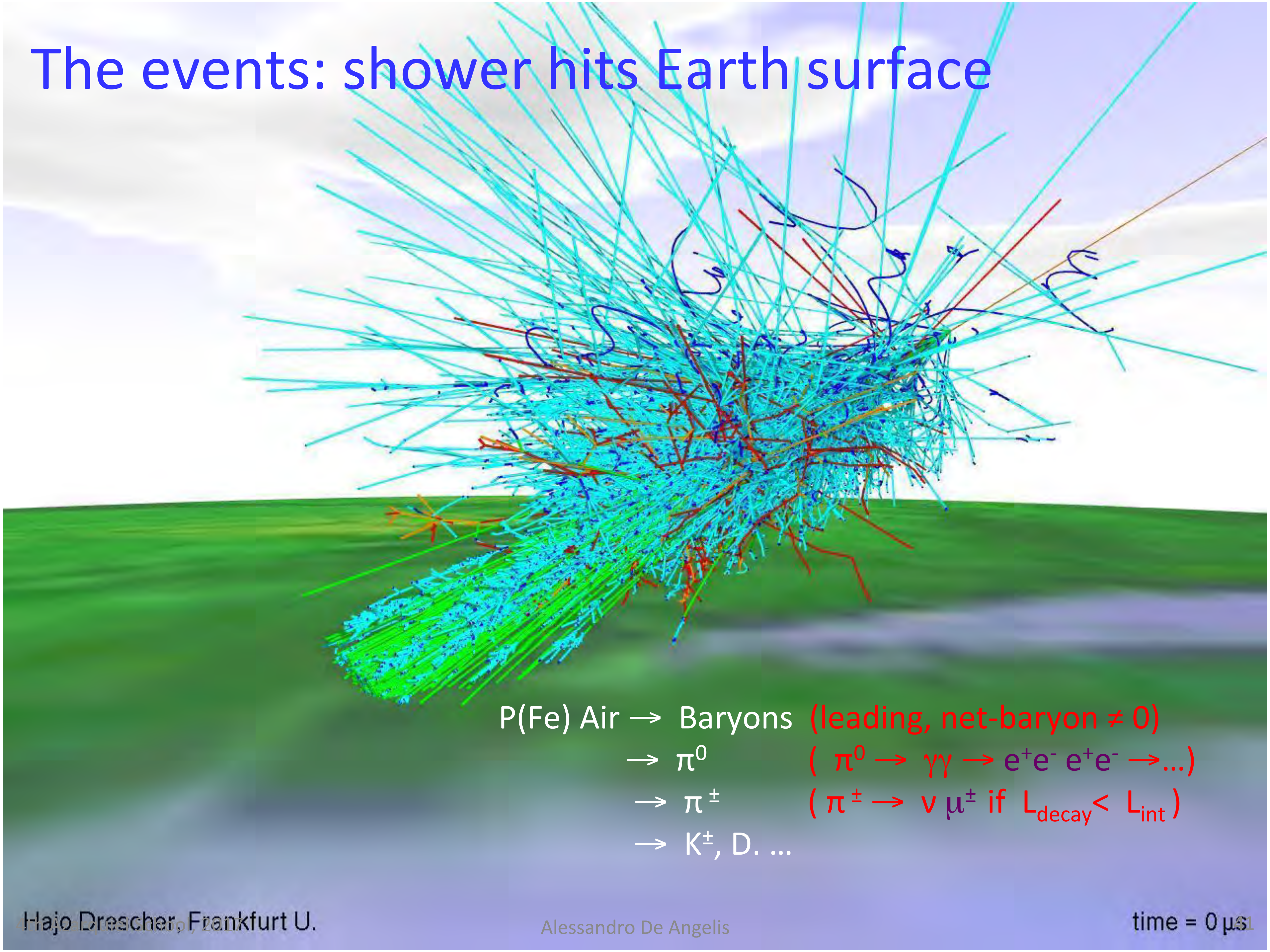
The events: shower development



The events: shower development



The events: shower hits Earth surface



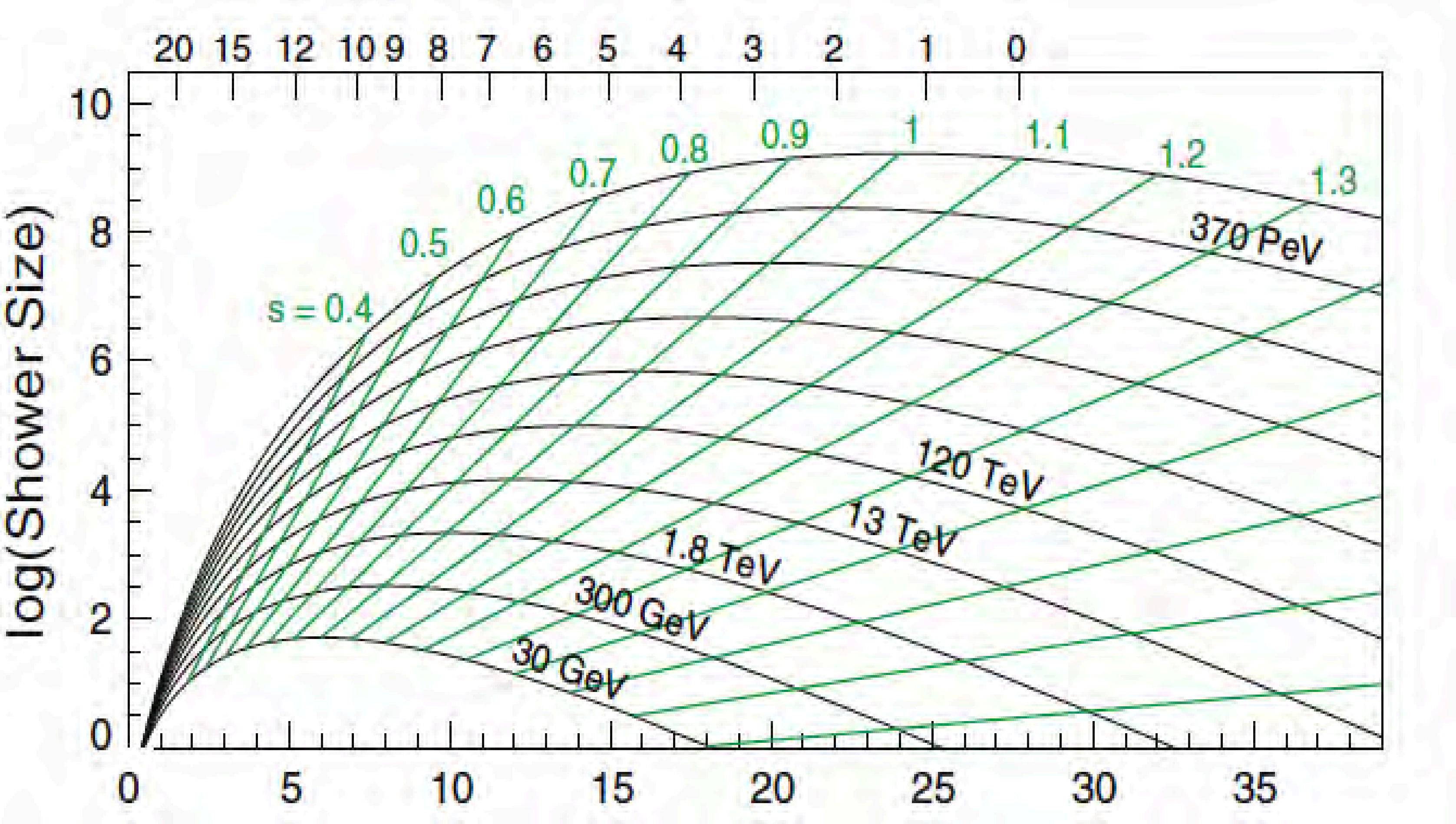
P(Fe) Air → Baryons (leading, net-baryon ≠ 0)

→ π^0 ($\pi^0 \to \gamma\gamma \to e^+e^- e^+e^- \to \ldots$)

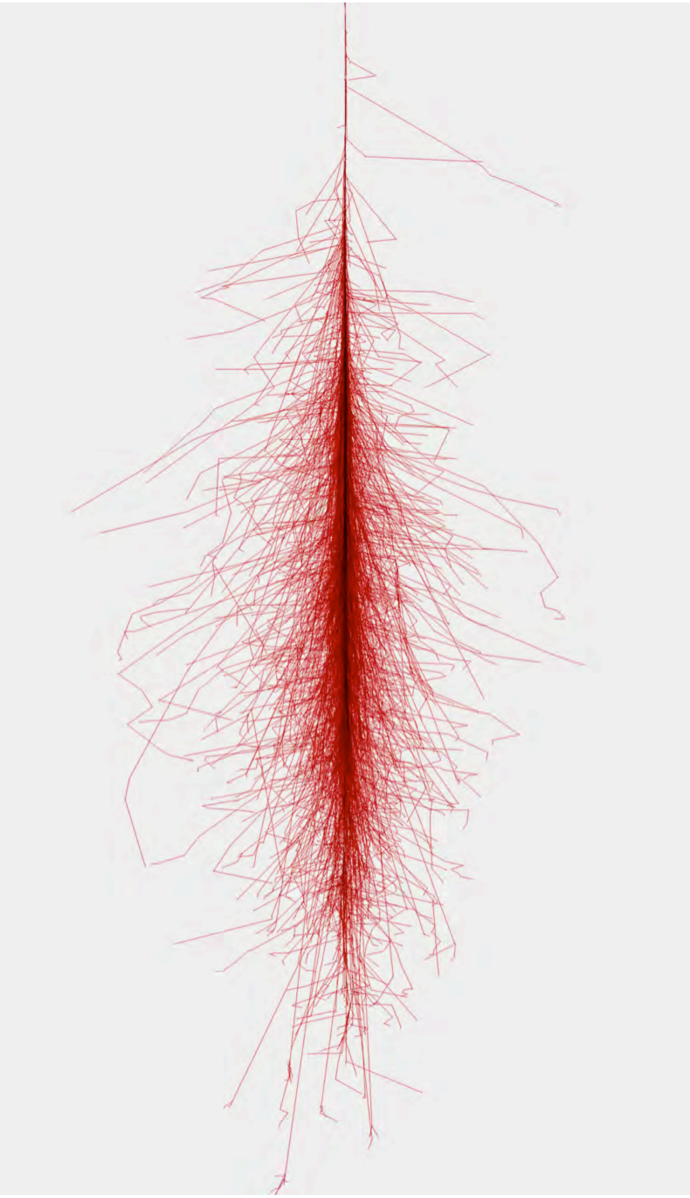
→ $\pi^\pm$ ($\pi^\pm \to \nu\, \mu^\pm$ if $L_{decay} < L_{int}$)

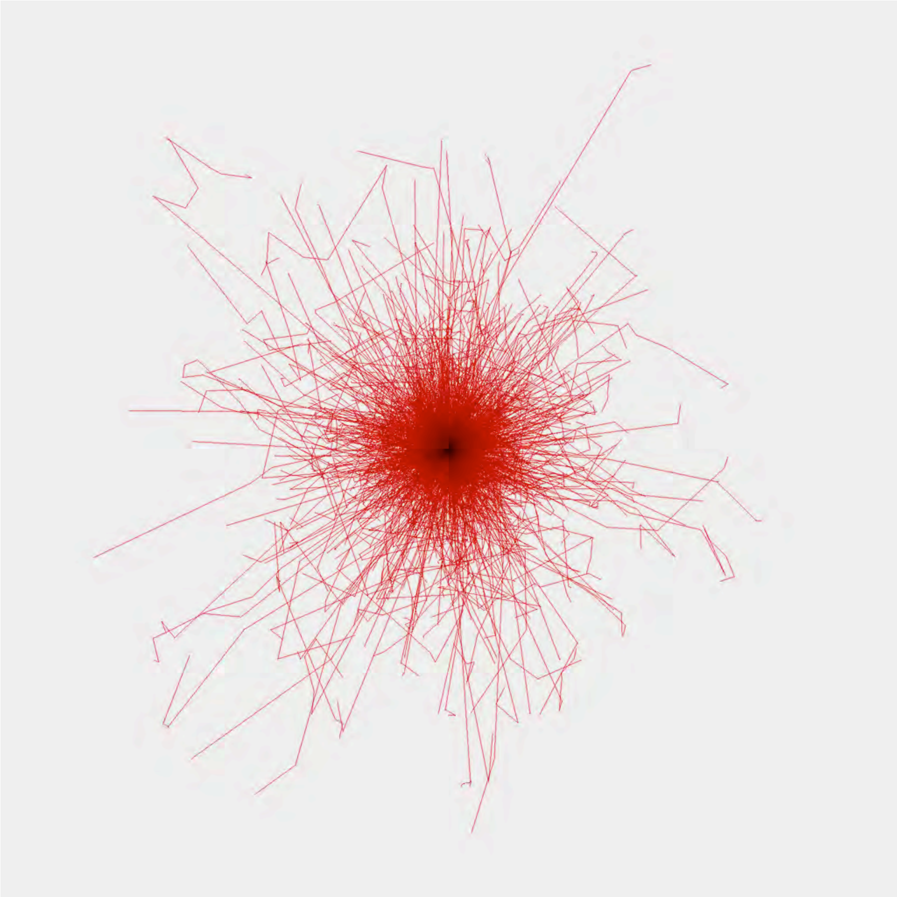
→ $K^\pm$, D. …

Photon-initiated shower in the atmosphere

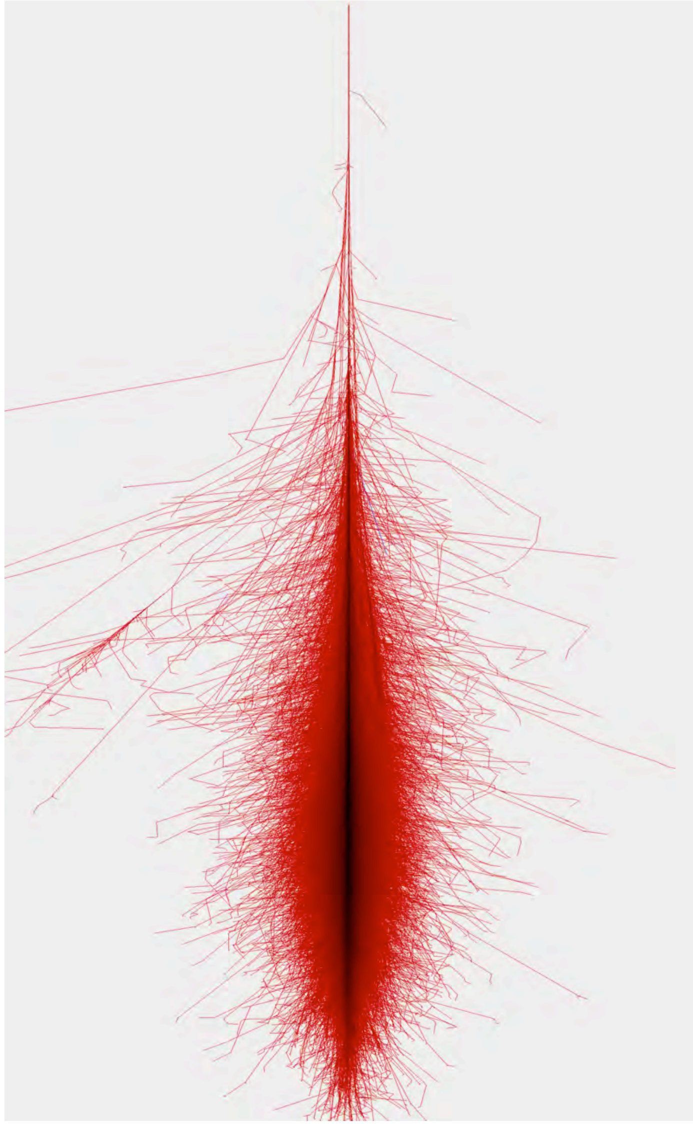


A frequent experimental problem: γ/hadron separation

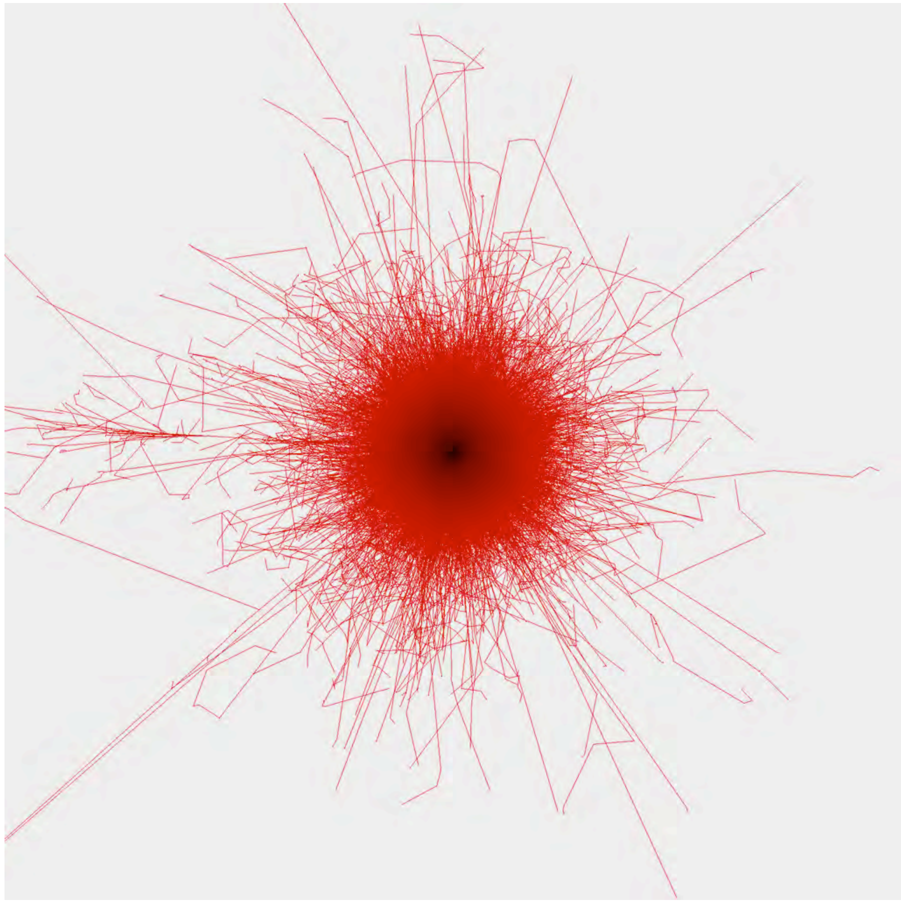




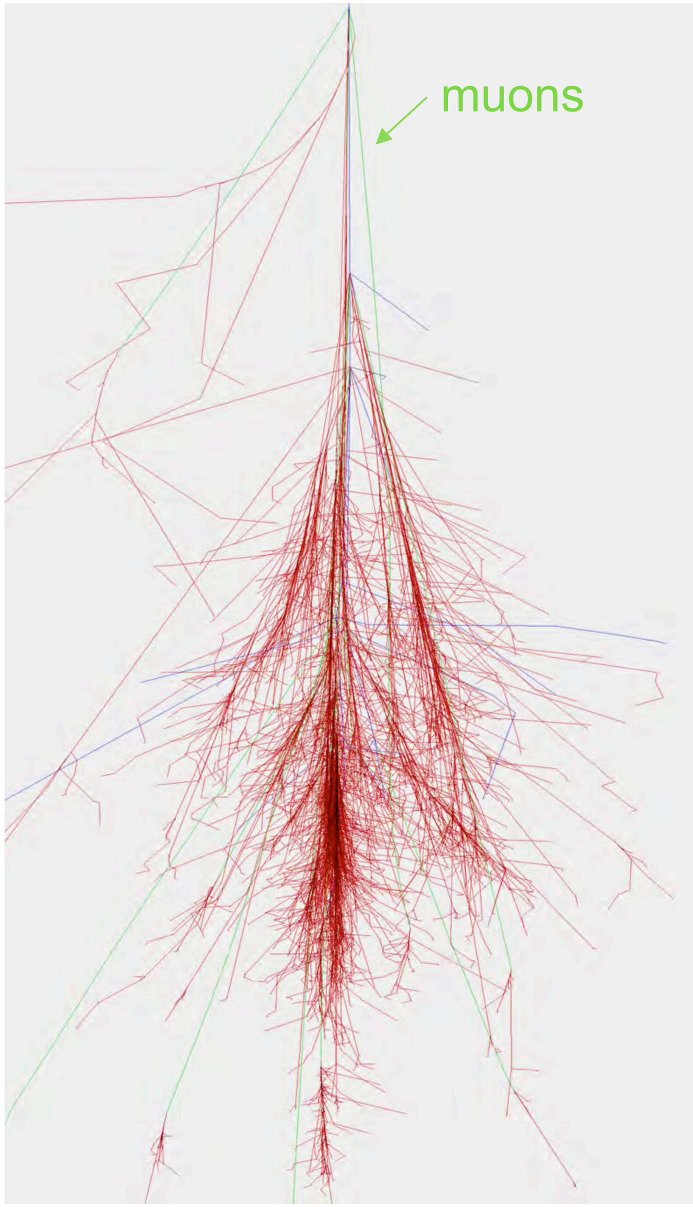
Simulated gamma
in the atmosphere:
50 GeV

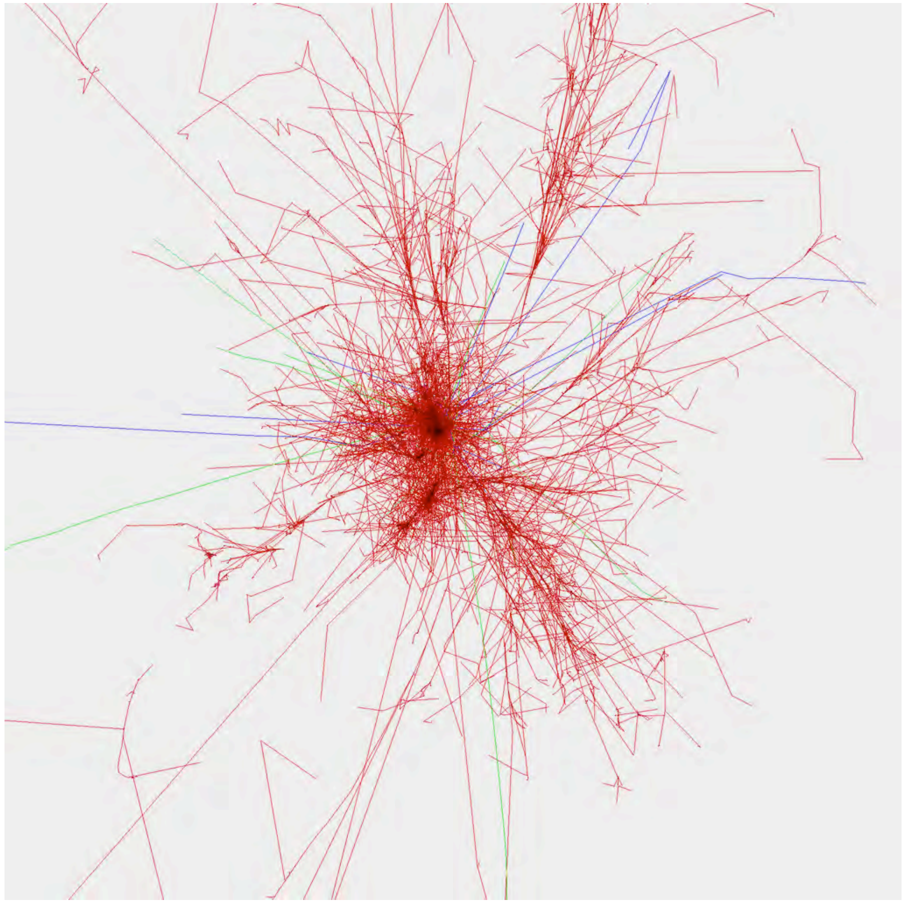


Simulated gamma
1 TeV

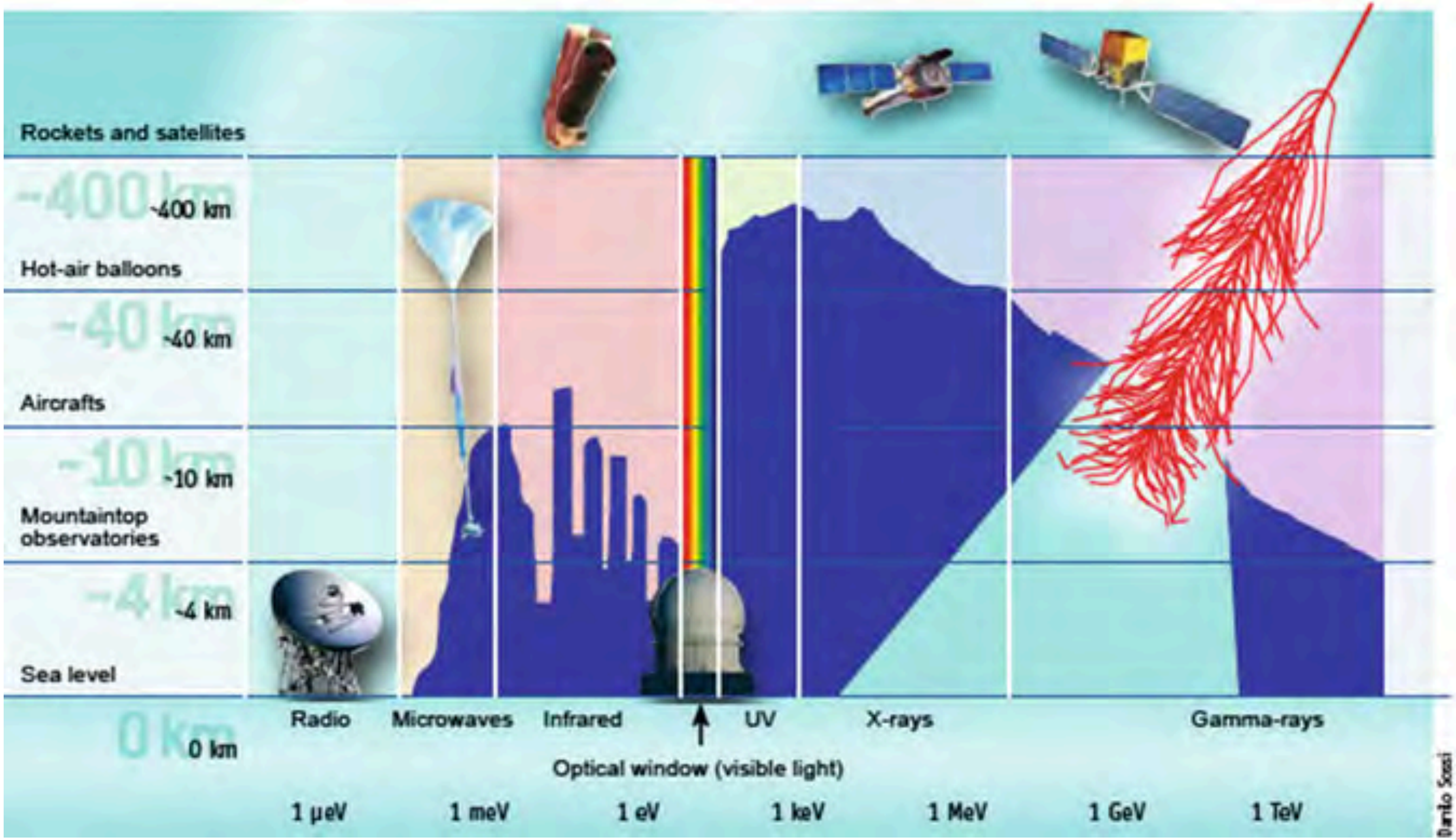


Simulated proton 100 GeV (the ennemy)





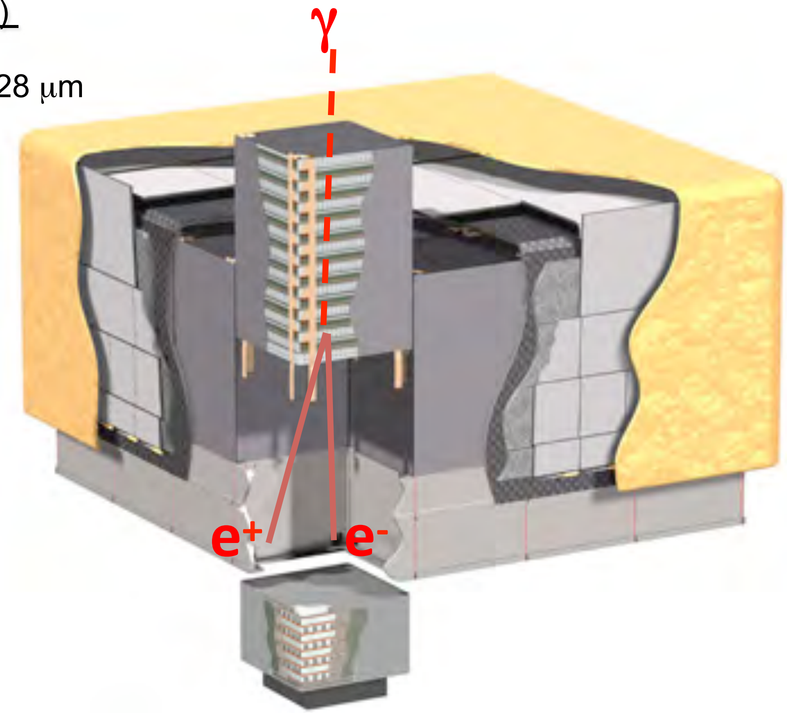
Transparency of the atmosphere



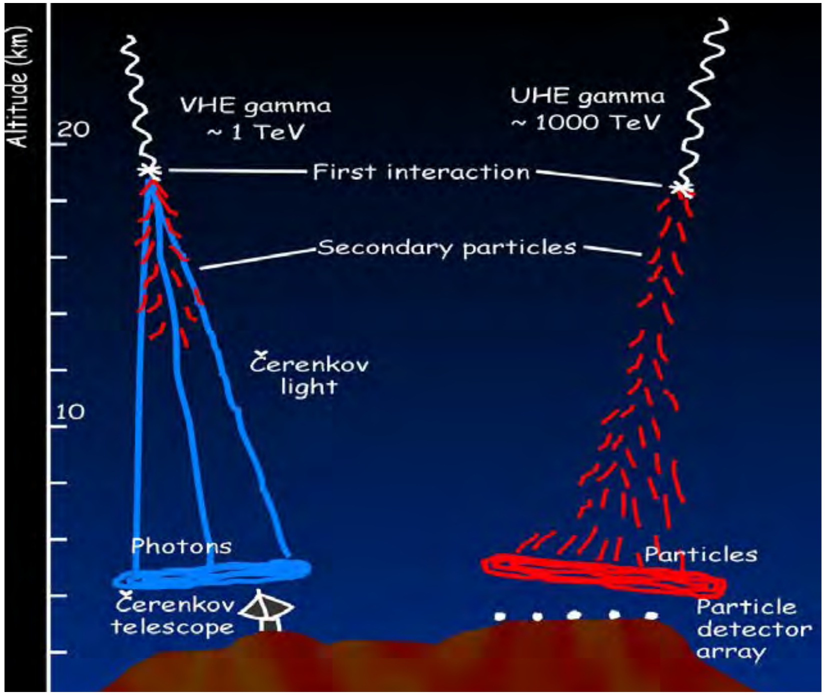
Detectors

- 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!



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



MeV photon detectors

- The MeV region is crucial for nuclear (astro)physics

- An "easy" way to do MeV photon detectors
  - Scintillating crystals

- But:
  - Bad directionality
  - No polarization information

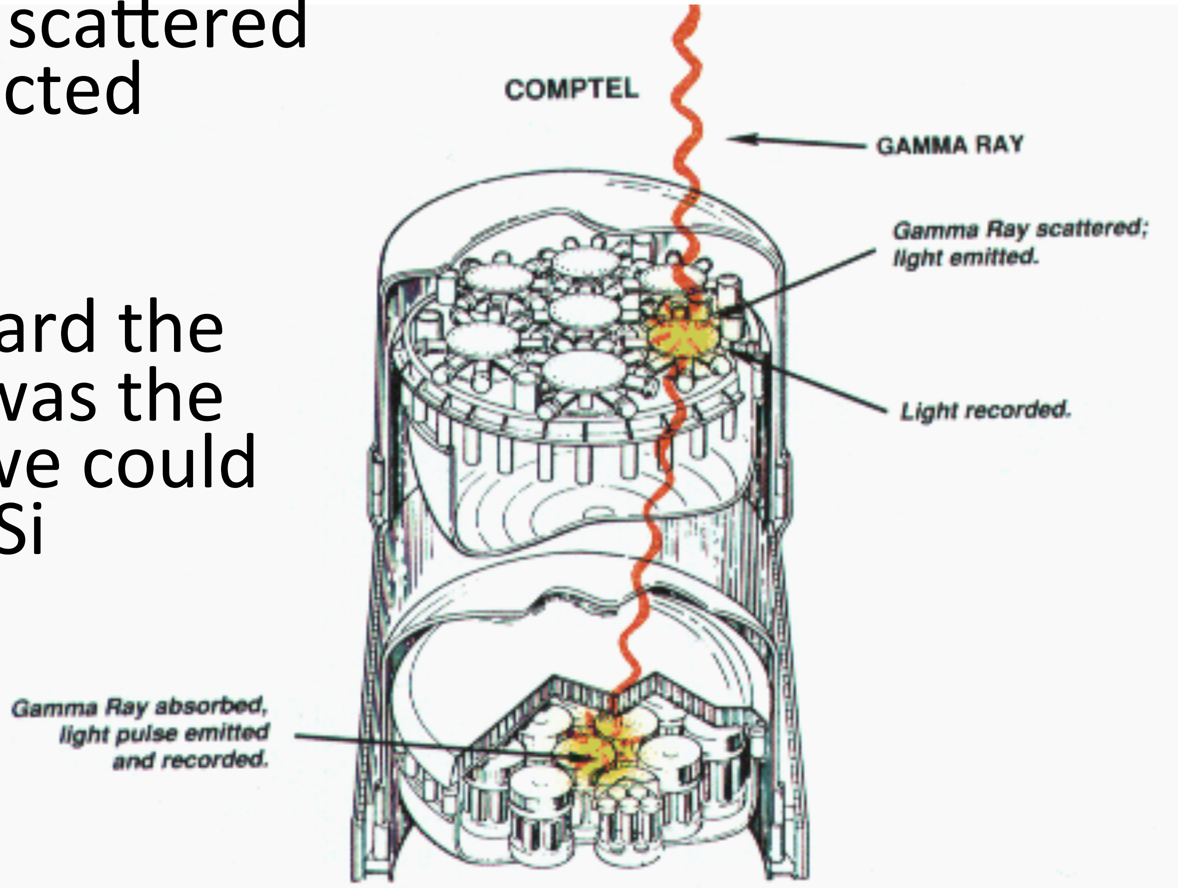
- Typically used in Gamma-Ray Burst monitors

MeV photon detectors: the hard way

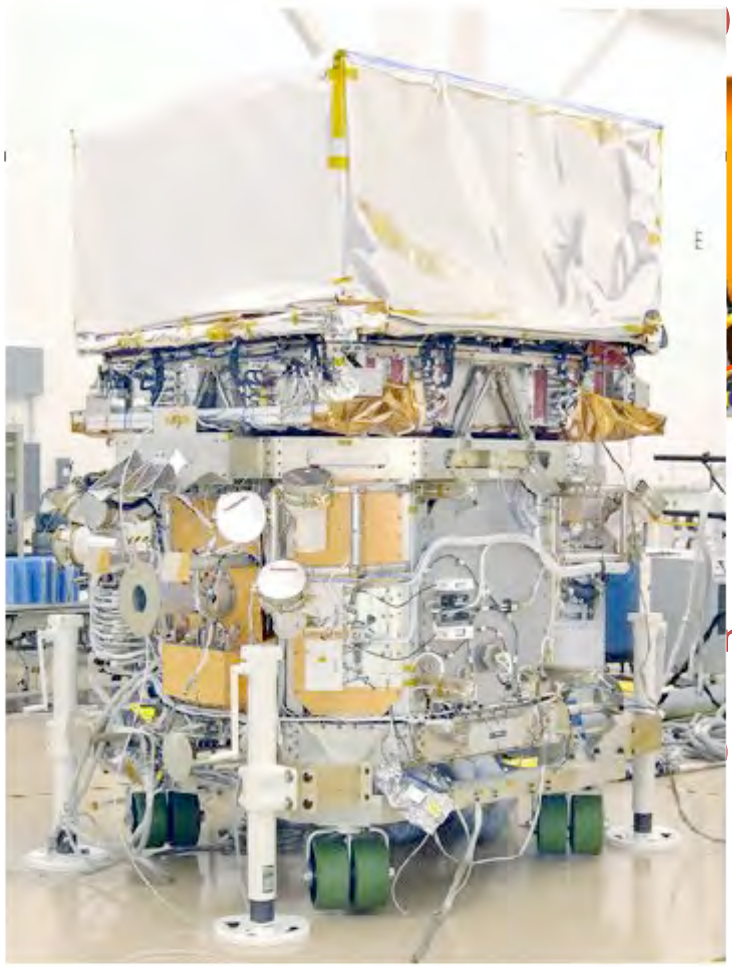
- Specific Compton detectors

- 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…



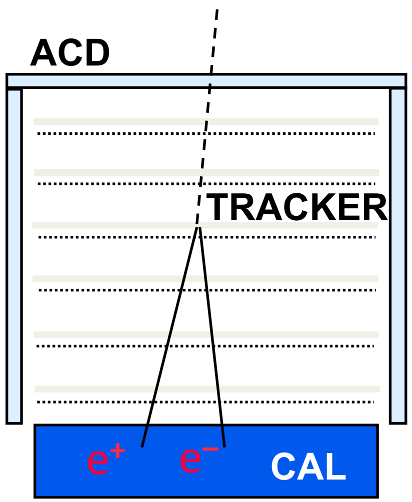
The GeV (pair production): Fermi and the LAT



Large Area Telescope (LAT)

nter

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



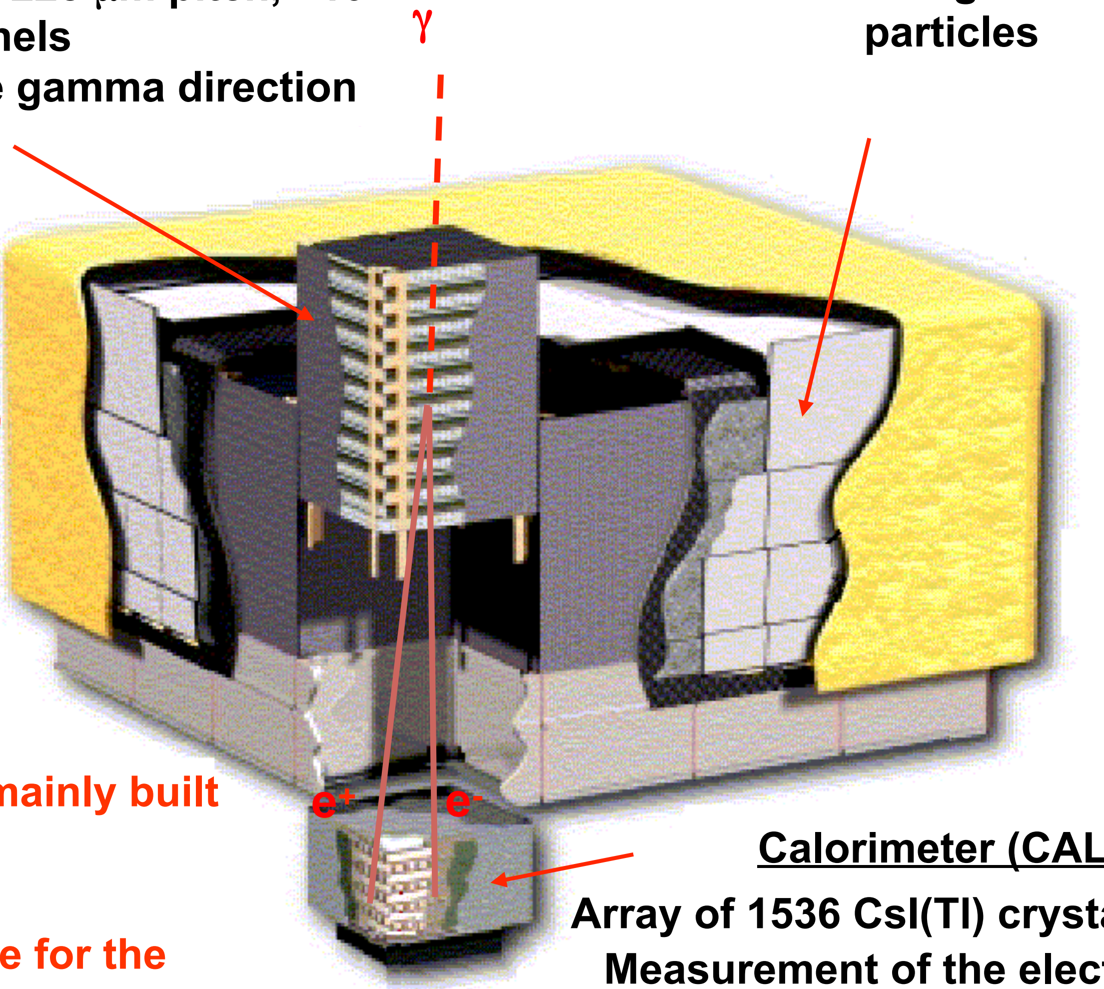
LAT overview

Si-strip Tracker (TKR)
18 planes XY ~ 1.7 x 1.7 m^2 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

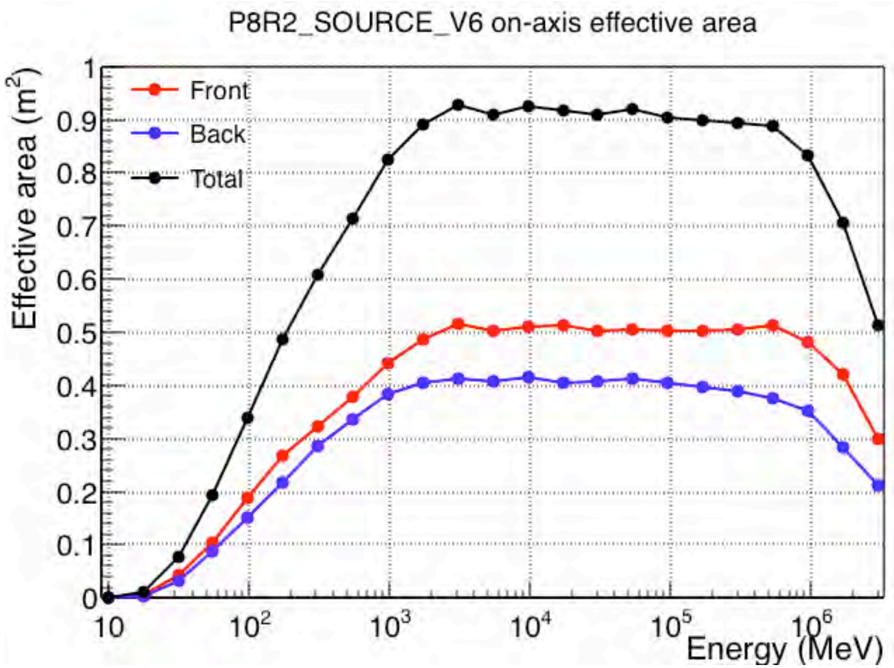
🇺🇸 🇫🇷 🇸🇪

The Silicon tracker is mainly built in Italy

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

Fermi-LAT launched June 2008

Performance of Fermi (Pass 8)

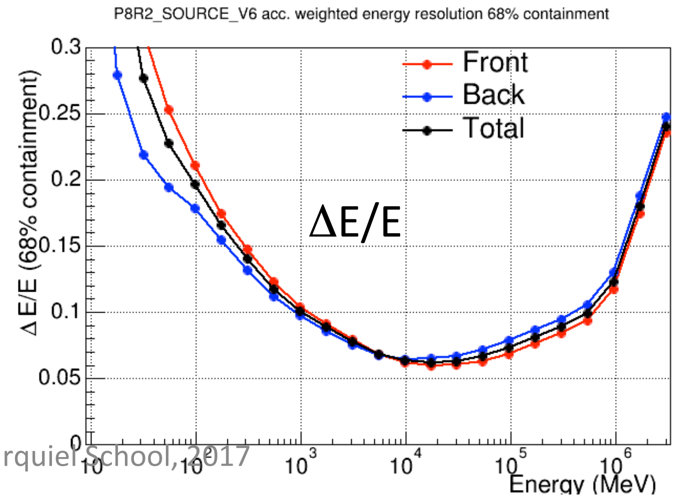


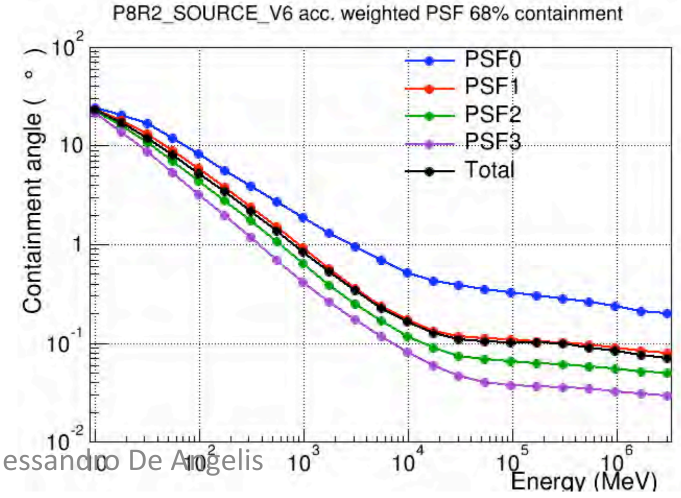
Effective area (Area x efficiency)

~ 1m^2

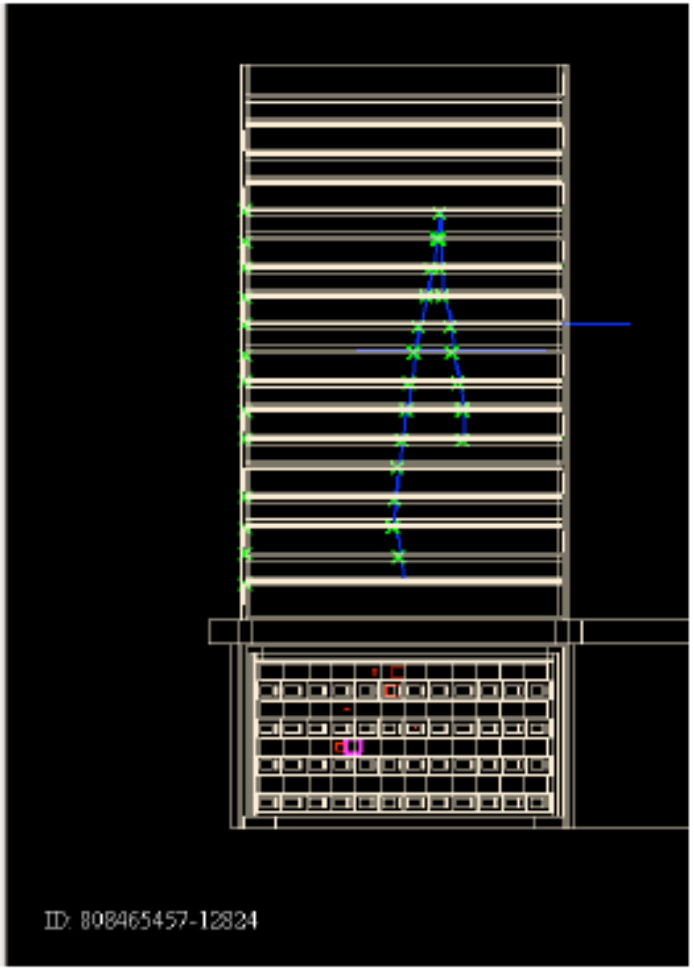
Grows as k lnE from 2 MeV to 2 GeV
Then ~0.9 m^2 from 2 GeV to 700 GeV
Then decreases as k' lnE

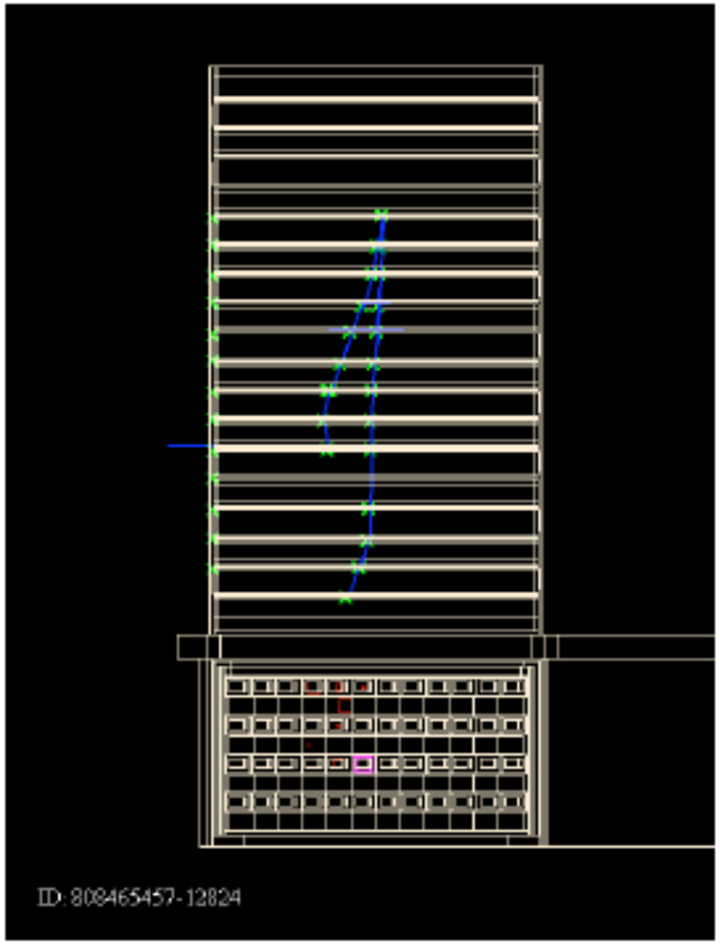
Acceptance: 2.5 sr



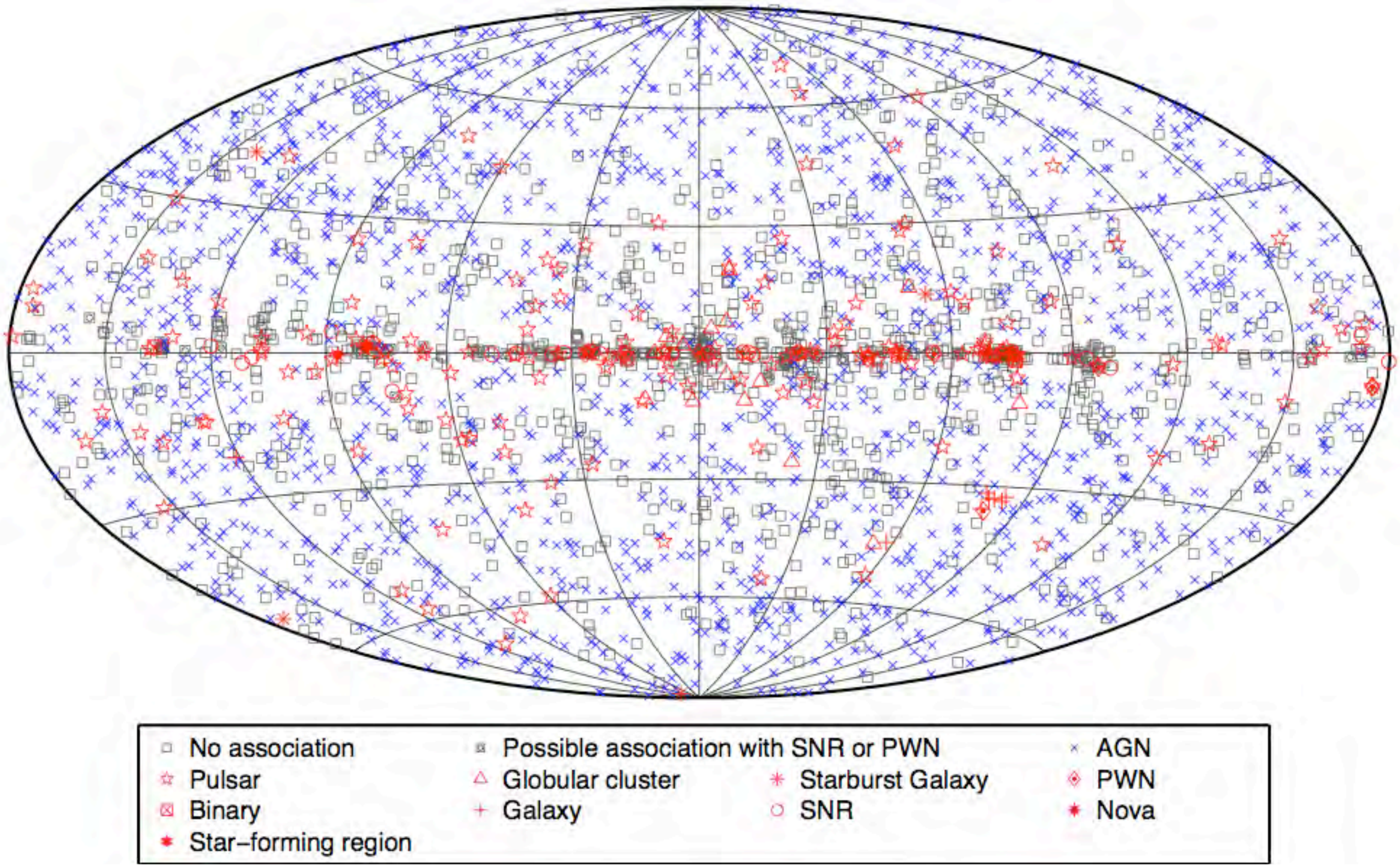


Detection of a gamma-ray



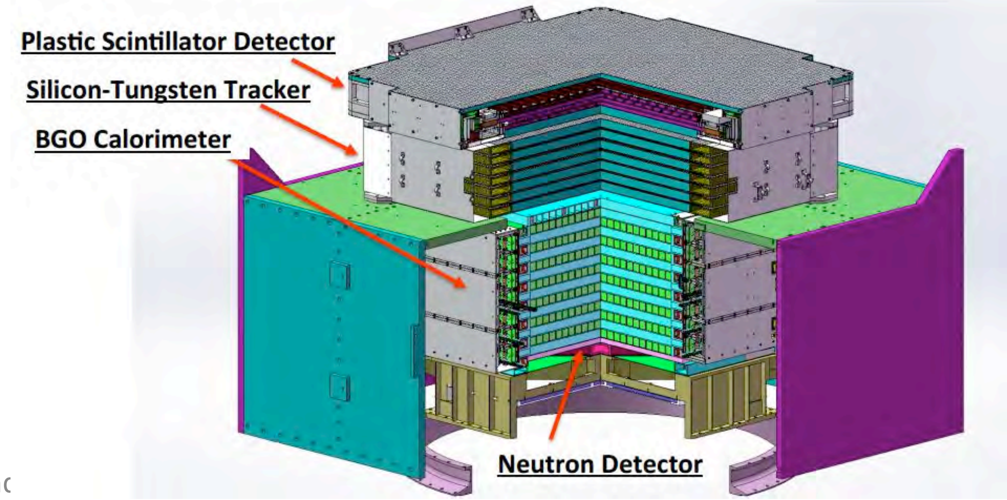


LAT 4-year Point Source Catalog (3FGL)

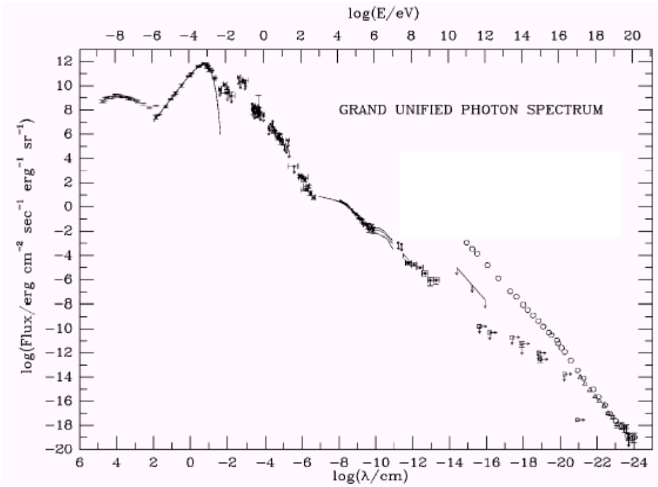


AGILE & DAMPE

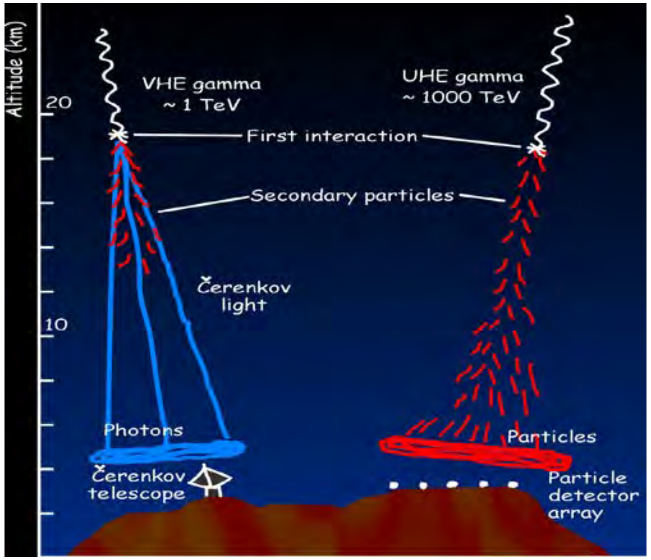
- 2 more instruments in space
- The all-Italian telescope AGILE
  - A Fermi precursor: see Fermi, 16 times smaller
  - Launched April 2007
  - Pointing systems has some problems
- The Chinese-Italian-Swiss DAMPE
  - ~AGILE
  - Launched December 2015
  - Better calorimetry than Fermi

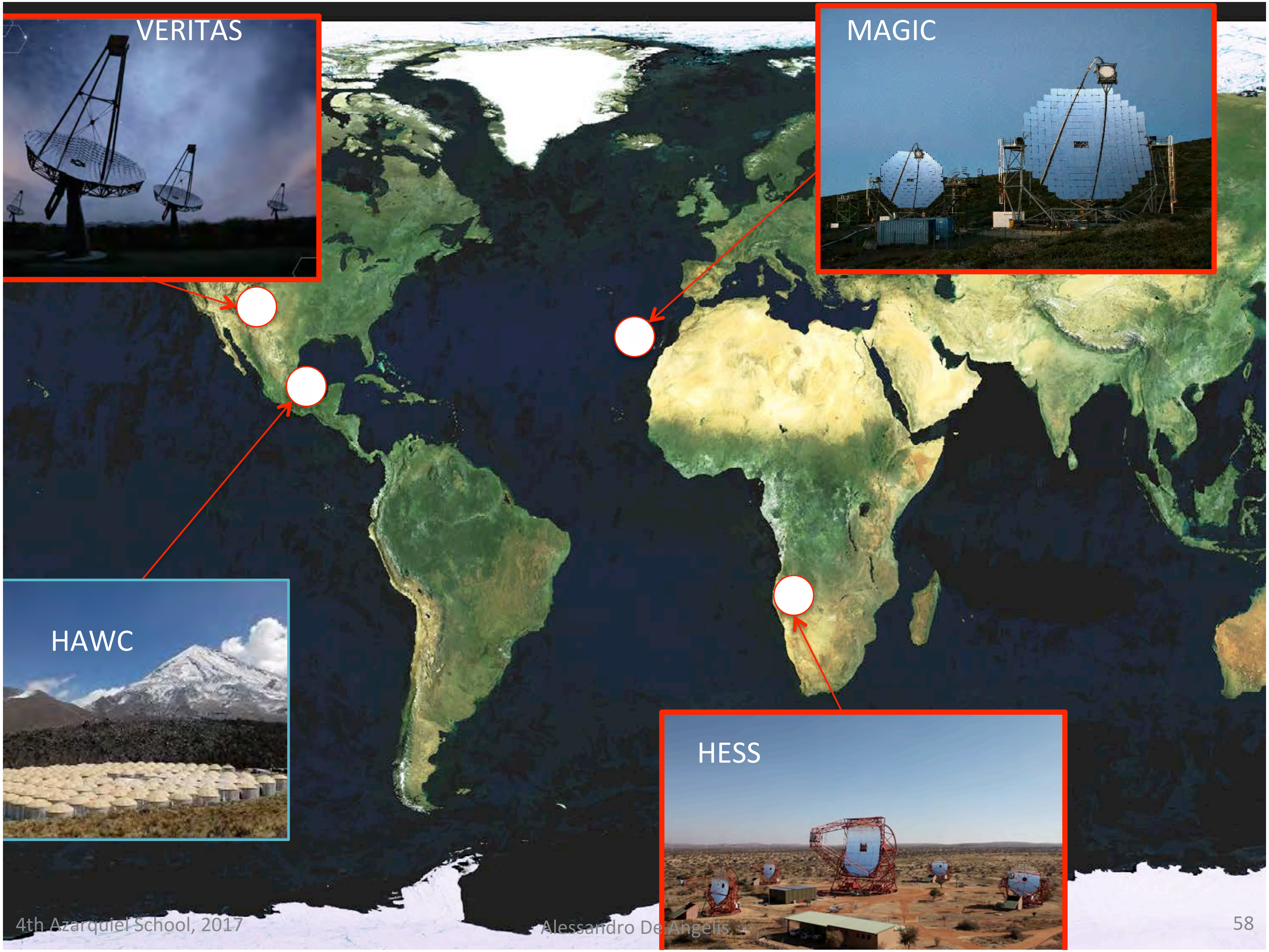


Why detection at ground?



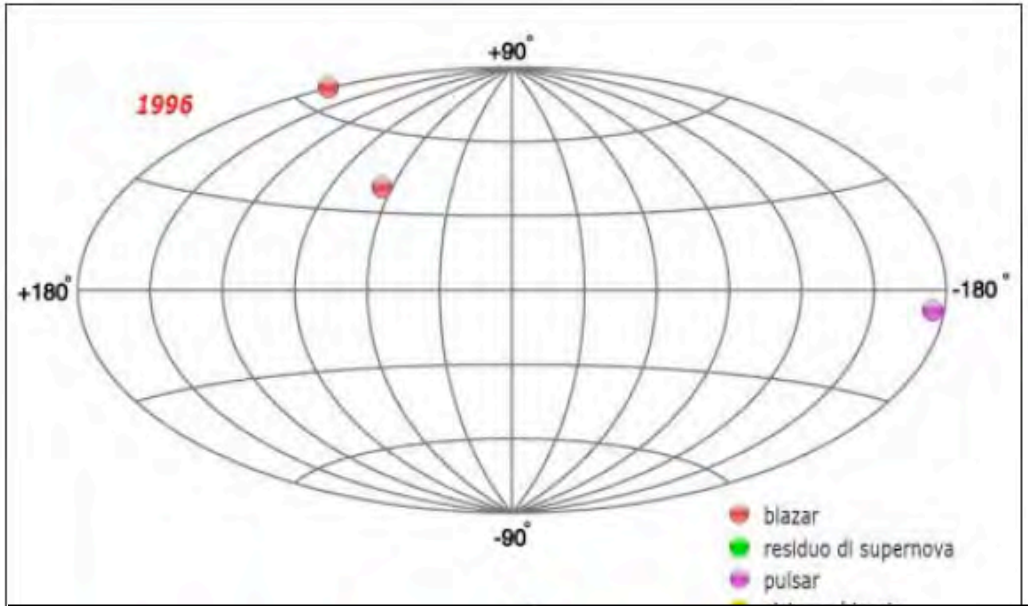
- High energies
  - Only way to build sensitive >TeV instruments
  - Maximum flux < 1 photon/h/m^2 above 200 GeV in Fermi
- High statistics /short timescales
  - Large collection areas O(km^2)
- Precision (Imaging Air Cherenkov telescopes, IACTs)
  - Superior angular resolution
- Limitations?
  - IACTs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

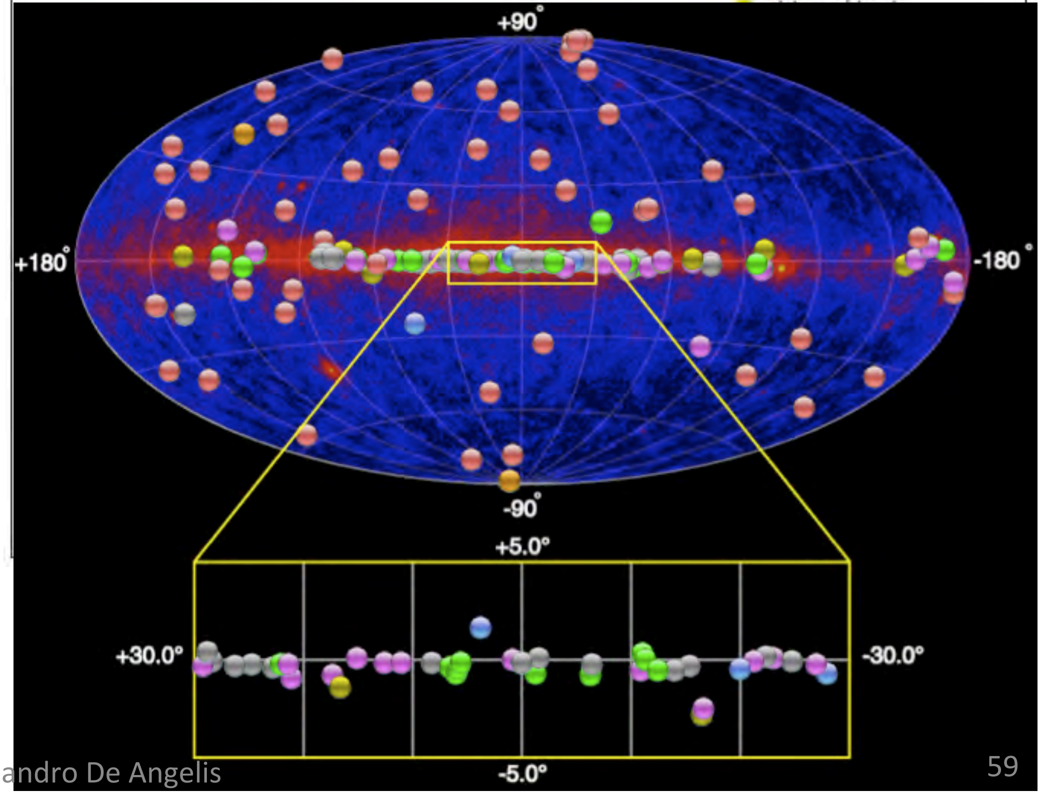



VERITAS
MAGIC
HAWC
HESS

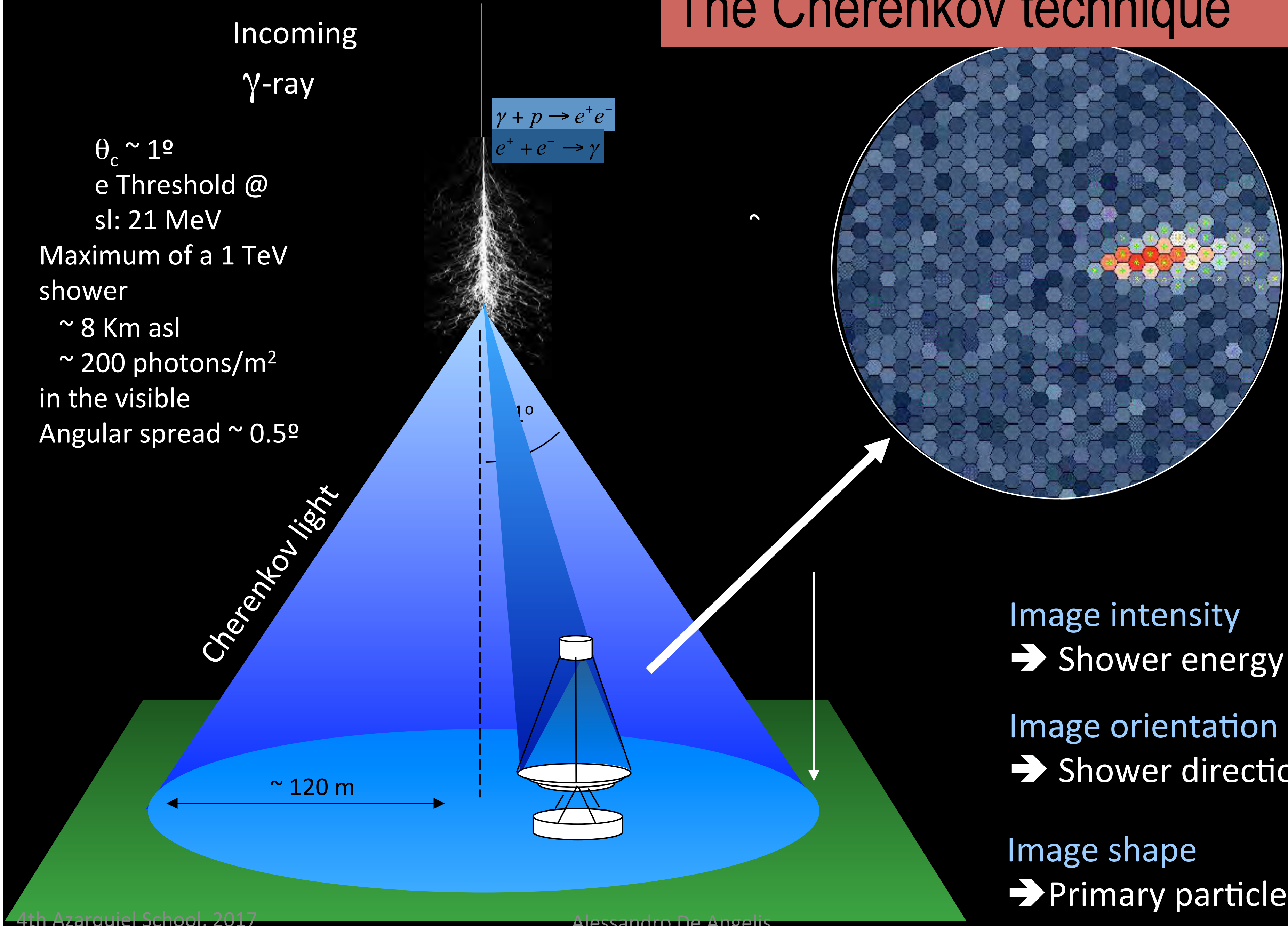
Highlight in γ-ray astrophysics (mostly HESS, MAGIC, VERITAS)

- 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





The Cherenkov technique



θ_c ~ 1º
e Threshold @
sl: 21 MeV
Maximum of a 1 TeV shower
~ 8 Km asl
~ 200 photons/m^2
in the visible
Angular spread ~ 0.5º

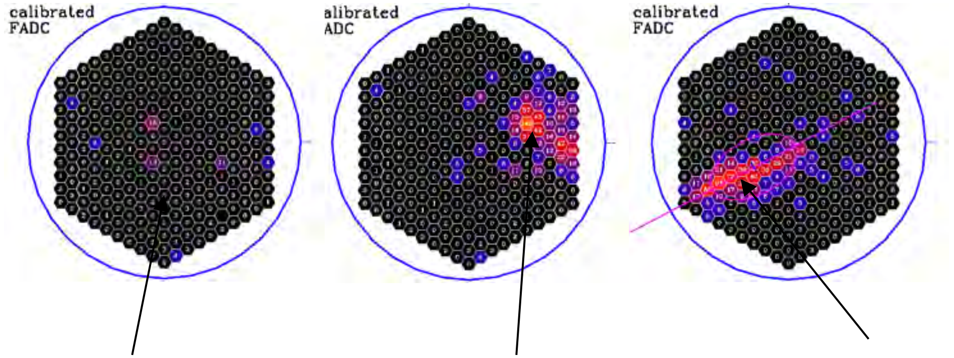
Image intensity
➔ Shower energy

Image orientation
➔ Shower direction

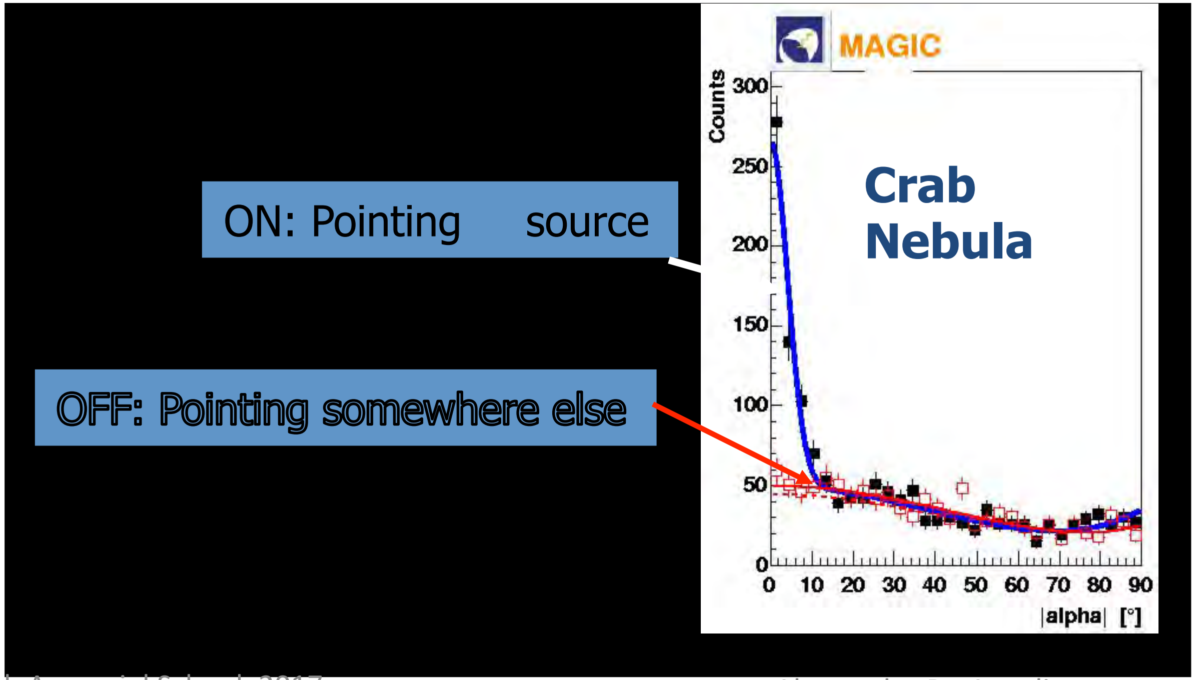
Image shape
➔ Primary particle

Signal duration: ~ 3ns

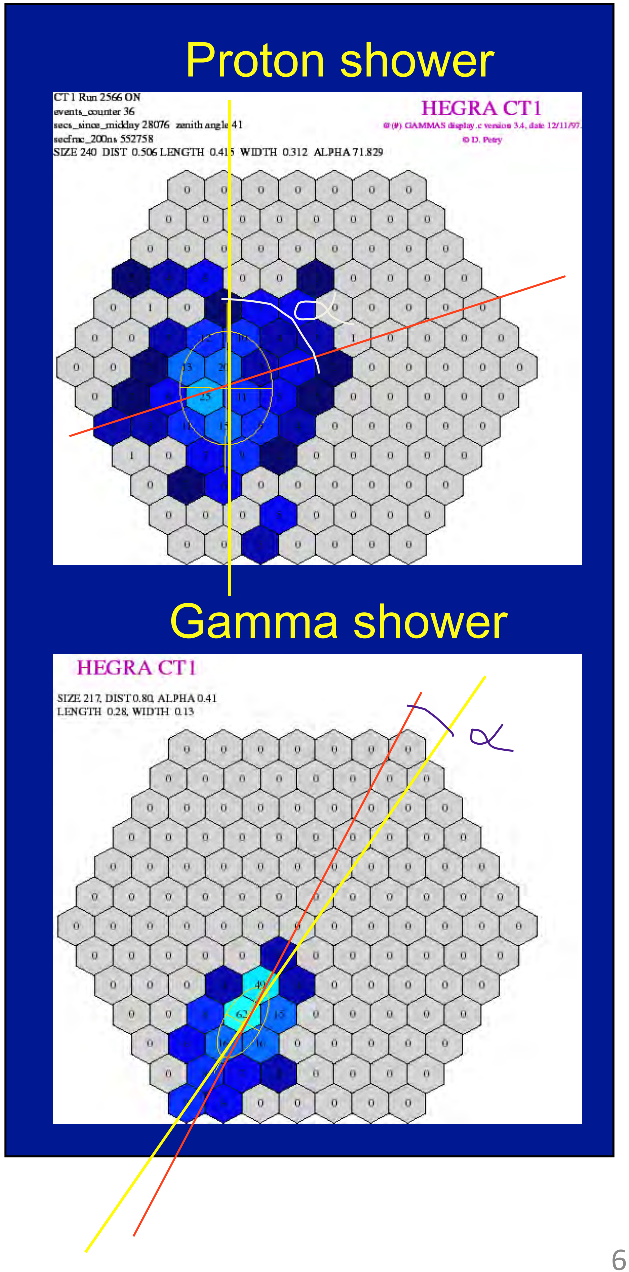
γ/h Separation



NSB event **Hadronic shower** **Gamma shower**

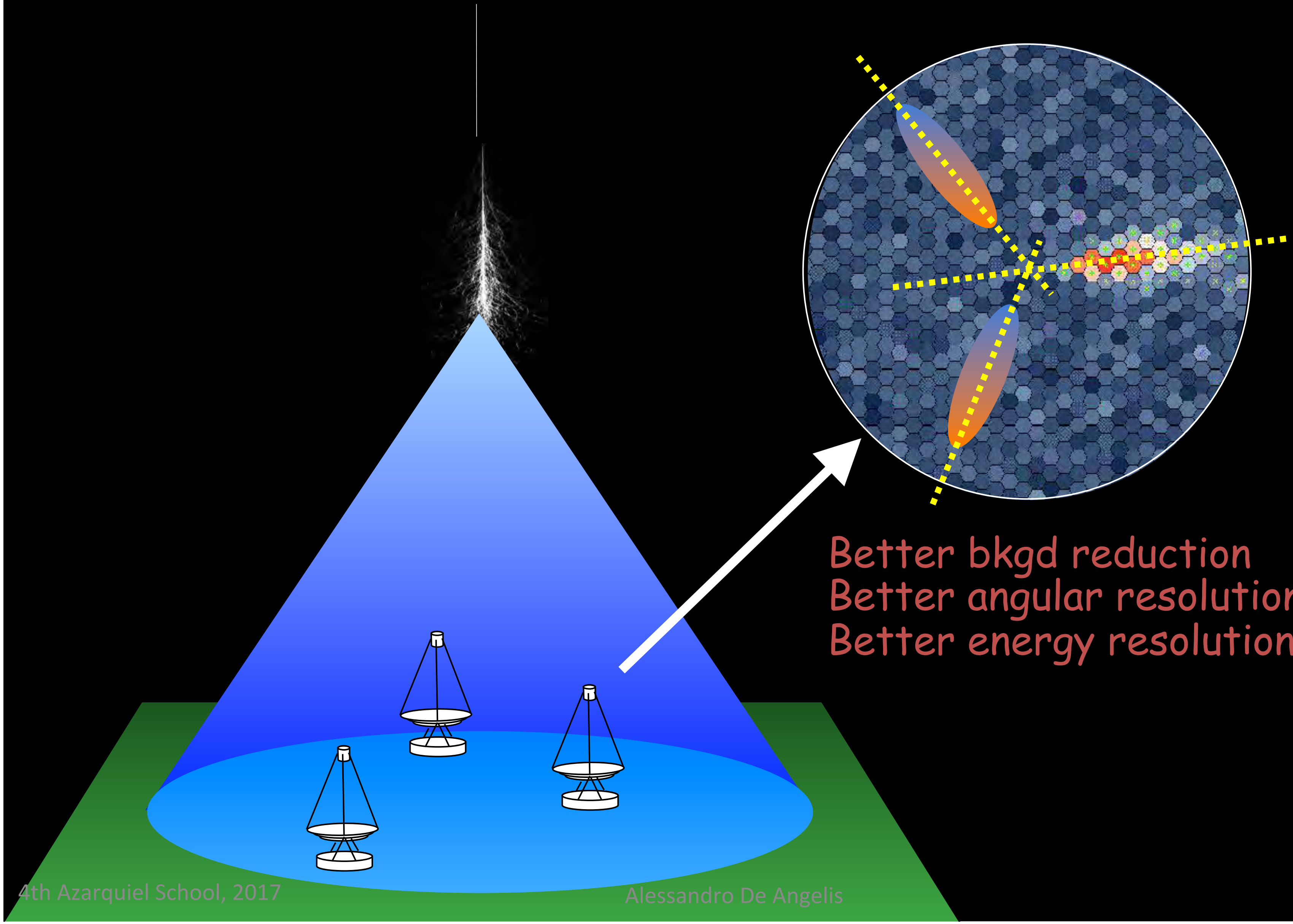

ON: Pointing source

OFF: Pointing somewhere else

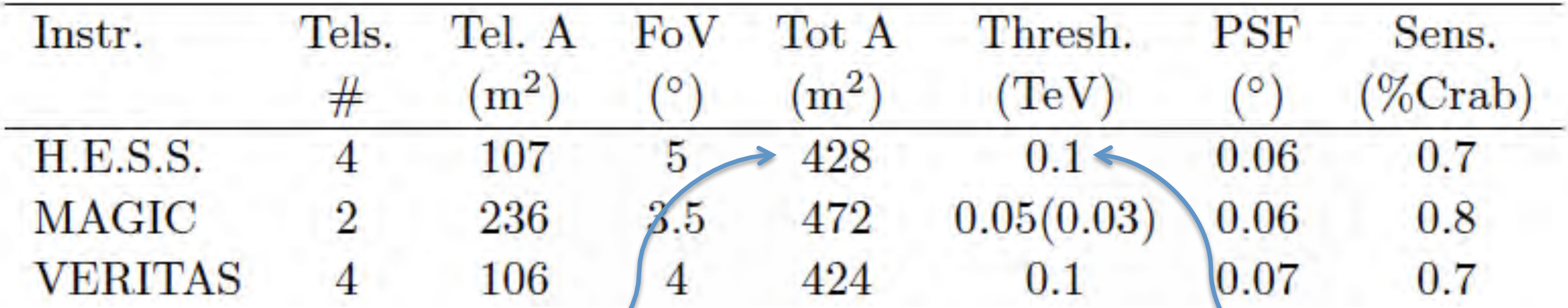

Proton shower

Gamma shower

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

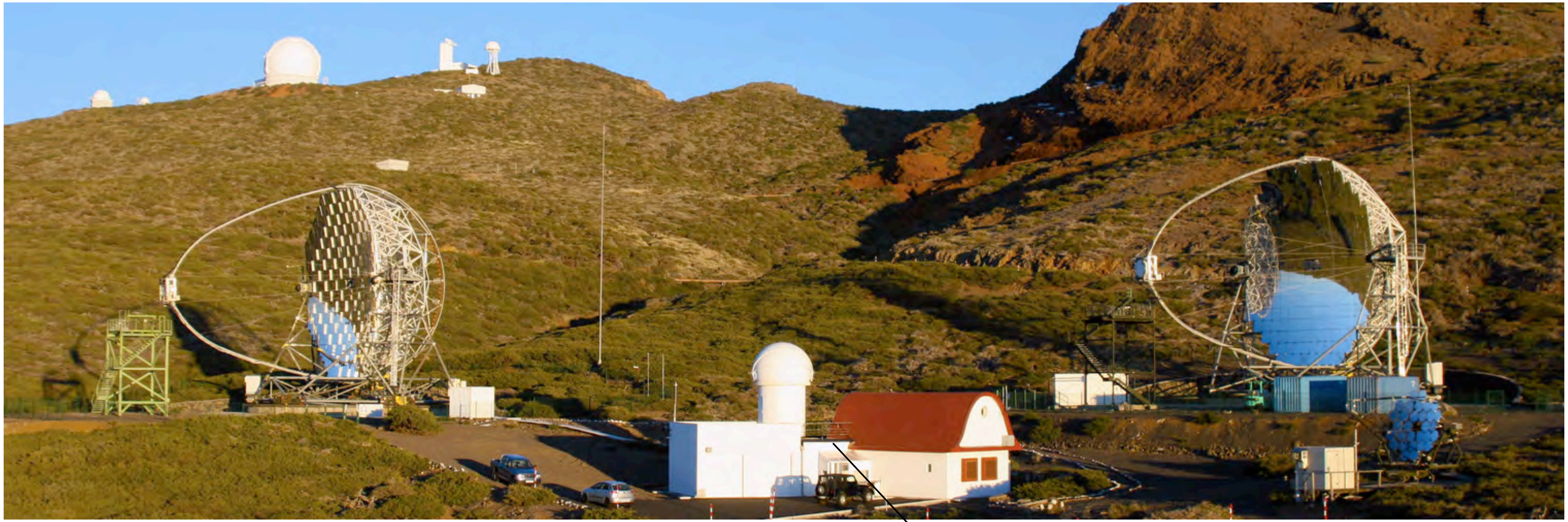
(0.03 for CT5)

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

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

~160 physicists from 10 countries:

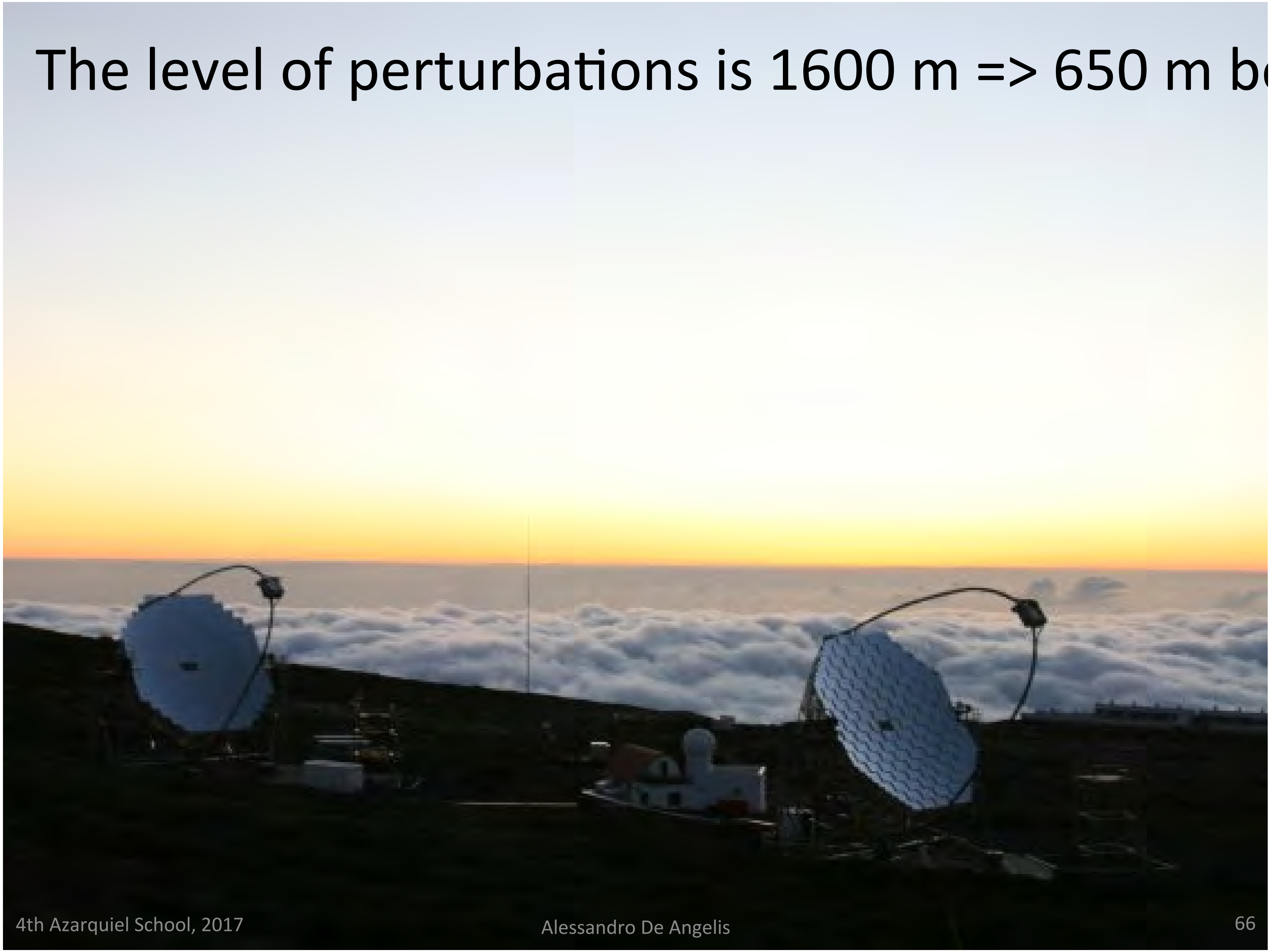
Bulgaria, Croatia, Finland, Germany, India, Italy, Japan, Poland, Spain, Switzerland



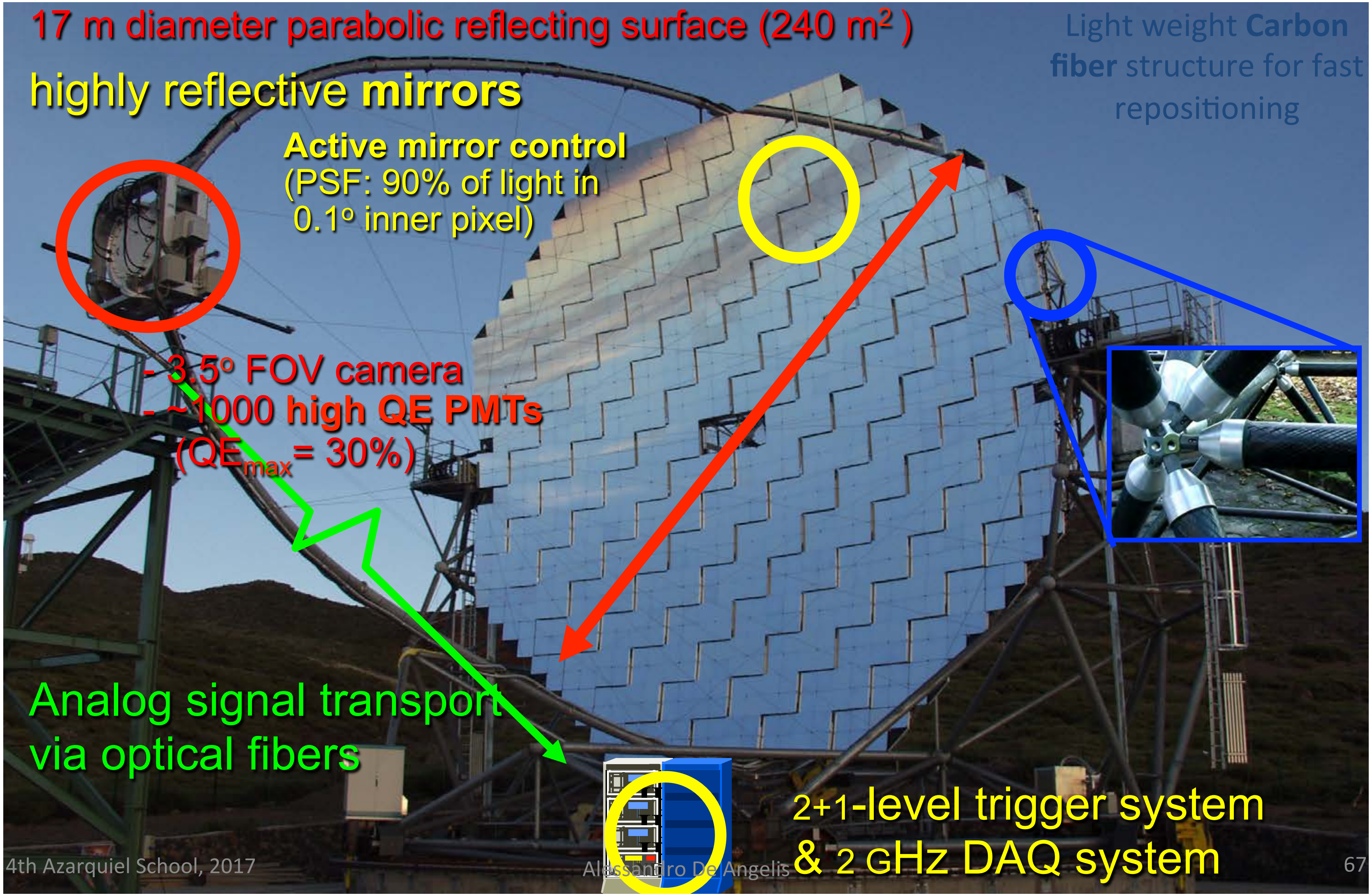
Canary island of La Palma

at 2400 m a.s.l.

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



Key elements



17 m diameter parabolic reflecting surface (240 m^2)

highly reflective **mirrors**

Active mirror control
(PSF: 90% of light in
0.1° inner pixel)

Light weight **Carbon fiber** structure for fast repositioning

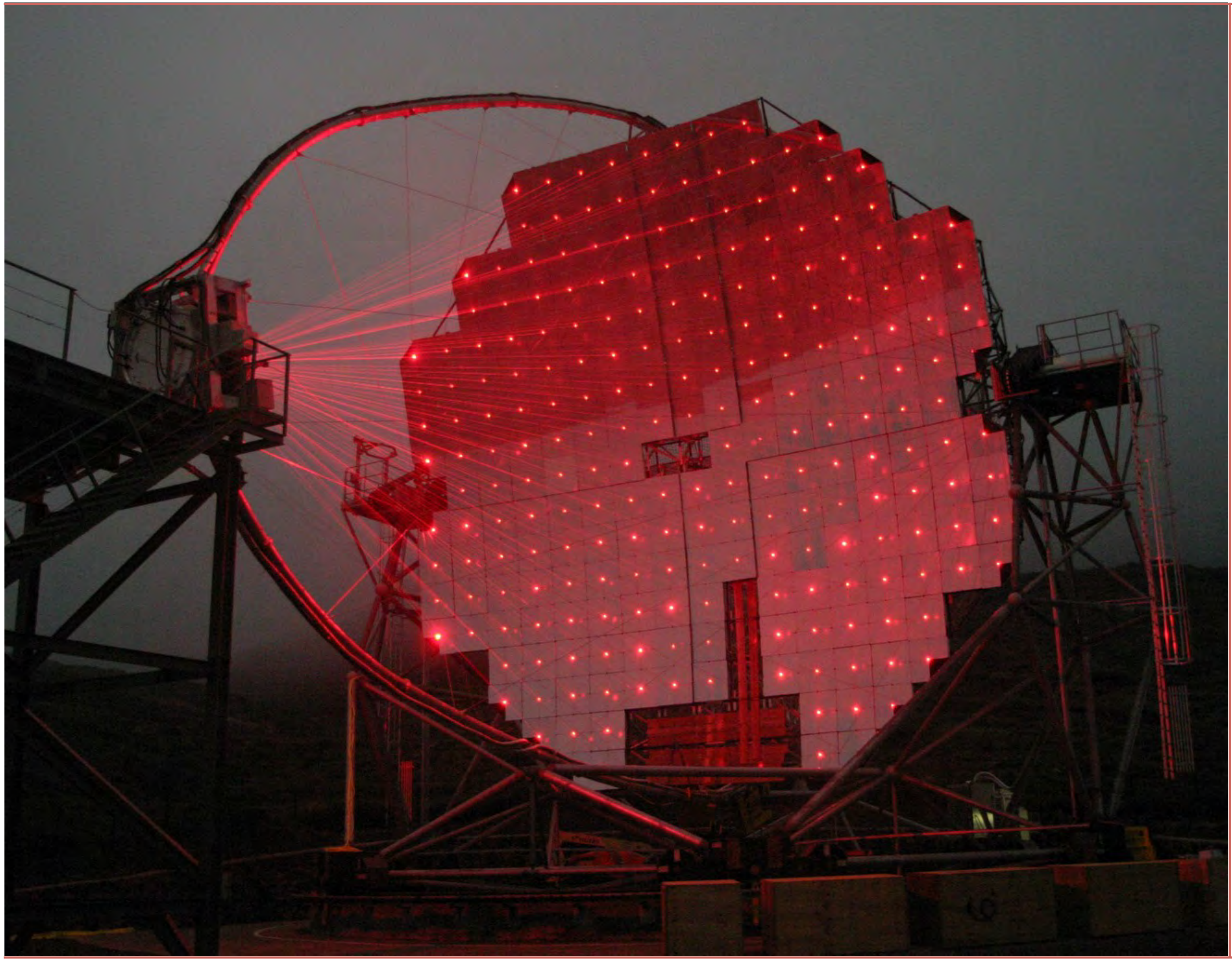
- 3.5° FOV camera
- ~1000 **high QE PMTs**
(QE$_{max}$ = 30%)

Analog signal transport
via optical fibers

2+1-level trigger system
& 2 GHz DAQ system

Fast and smooth repointing (< 30 s)

Adjustement (active control)

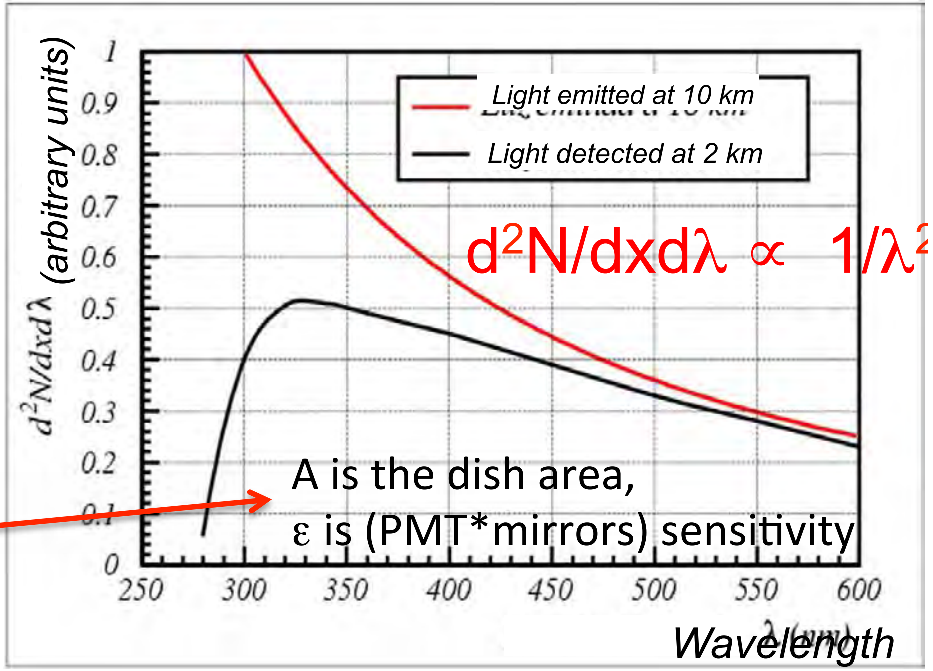


All AMC Lasers switched on during foggy night

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

Figures of merit of a Cherenkov telescope

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



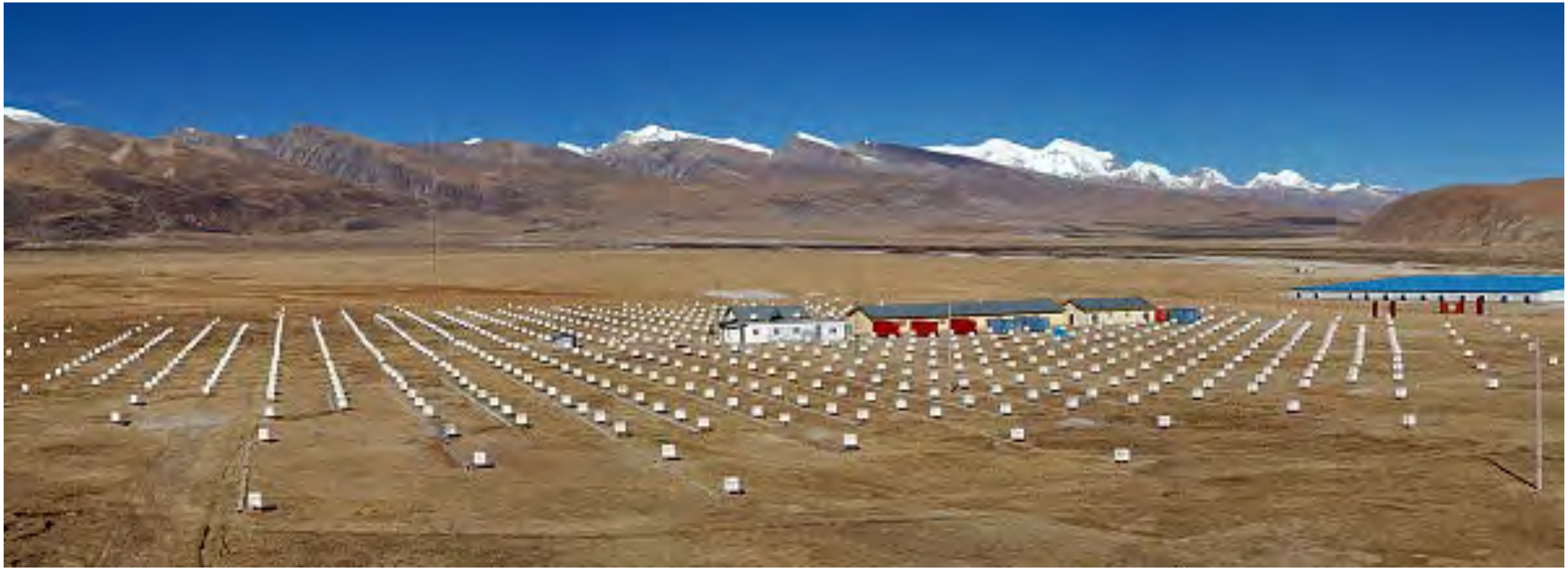
$d^2N/dxd\lambda \propto 1/\lambda^2$

A is the dish area,
ε is (PMT*mirrors) sensitivity

- 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)

Higher energies: EAS detectors

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



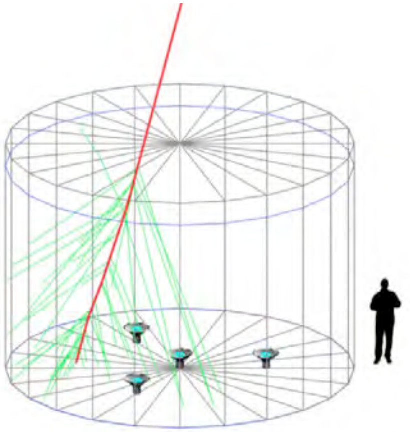
Tibet – AS gamma: scintillators

EAS detectors

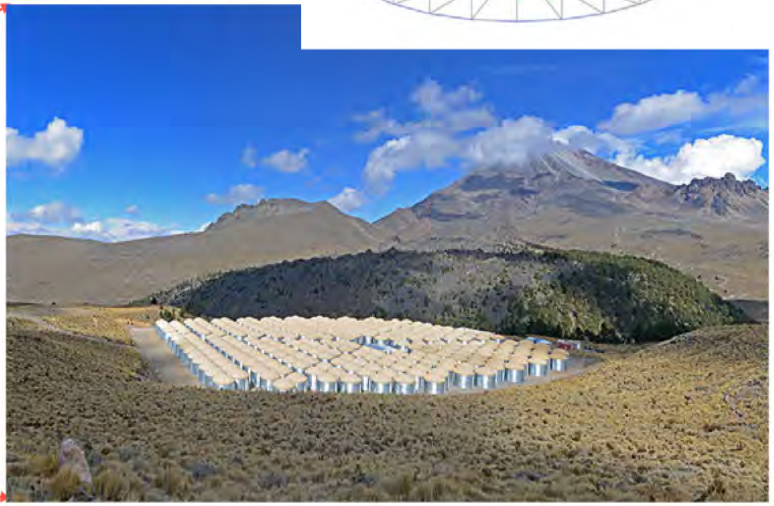
- Pro: wide field of view, continuous operation, cheap to instrument large areas
- Minus: Resolution is worse => more background, higher threshold

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

The present

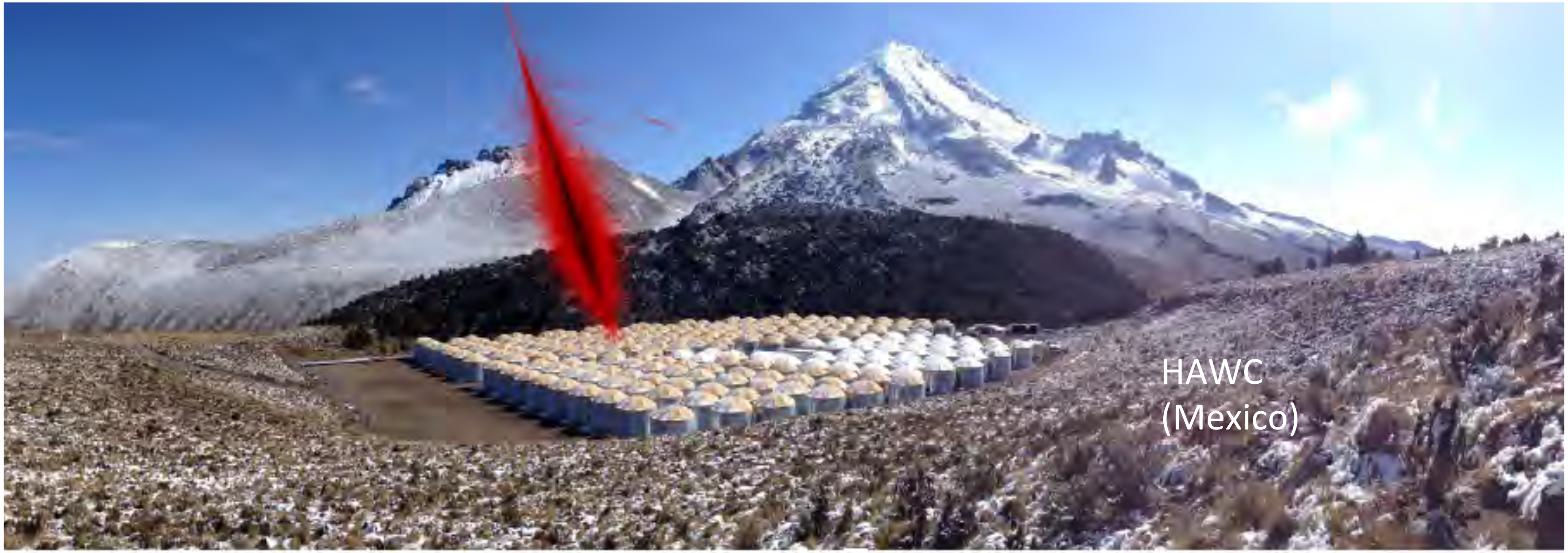


The HAWC Observatory



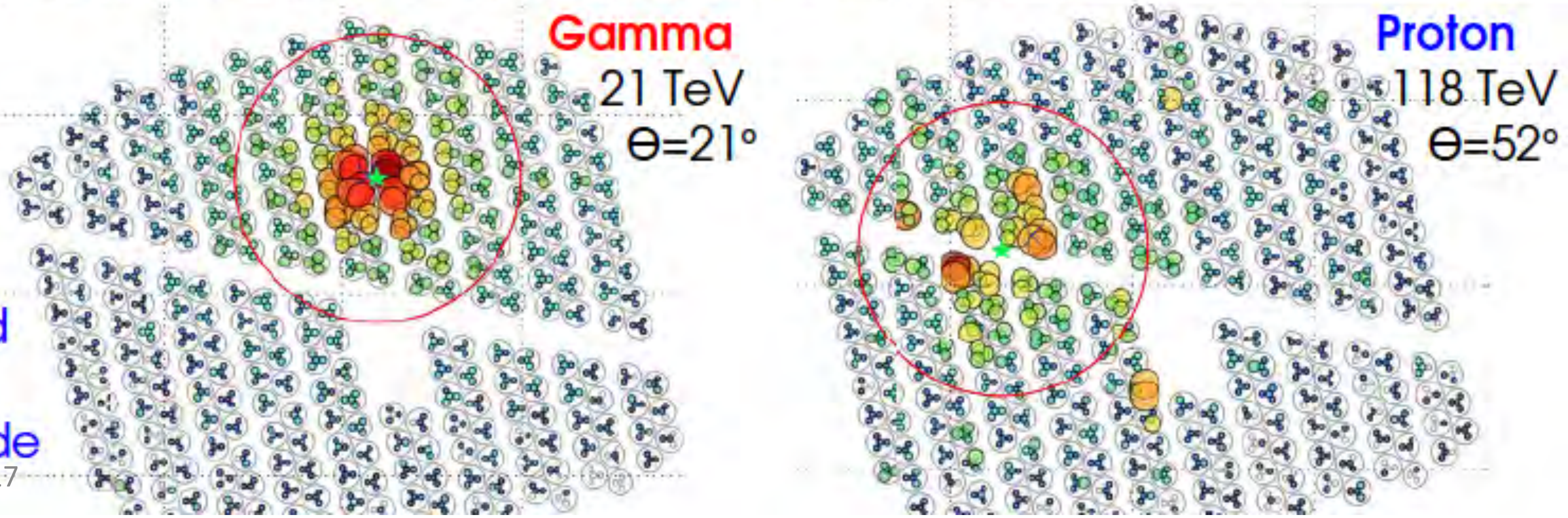
- Located at **4100 m** a.s.l. in Mexico near Pico de Orizaba at 19ºN
- Effective Area: **~22,000 m^2**
- Instantaneous field of view **2 sr**; daily coverage of **2/3** of the sky.
- 300 Water Cherenkov Detectors (WCDs)
- Declinations from **-26º to 64º** (***Part of Northern Fermi Bubble visible***)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

Very-high-energies (above 200 GeV)

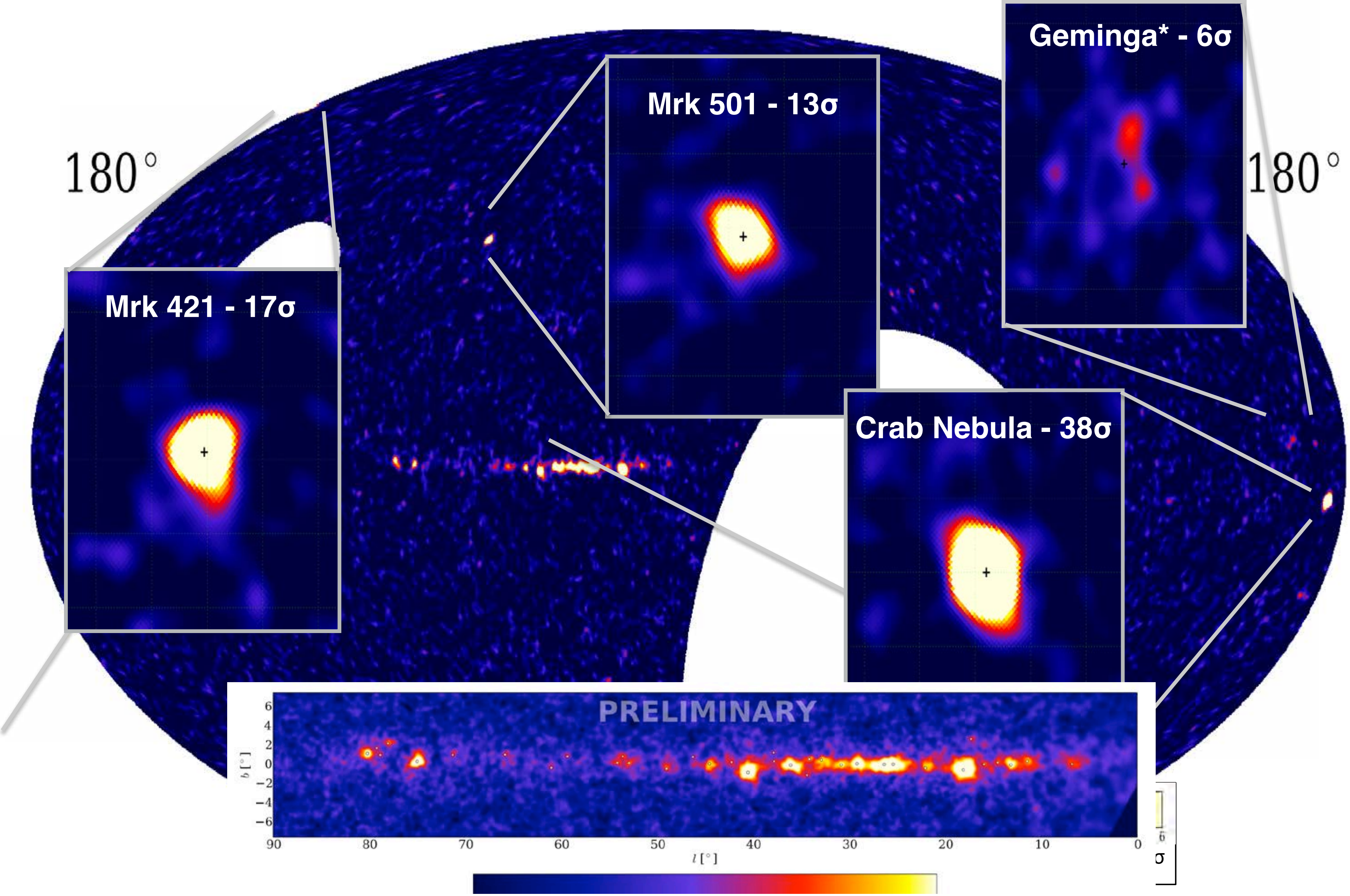


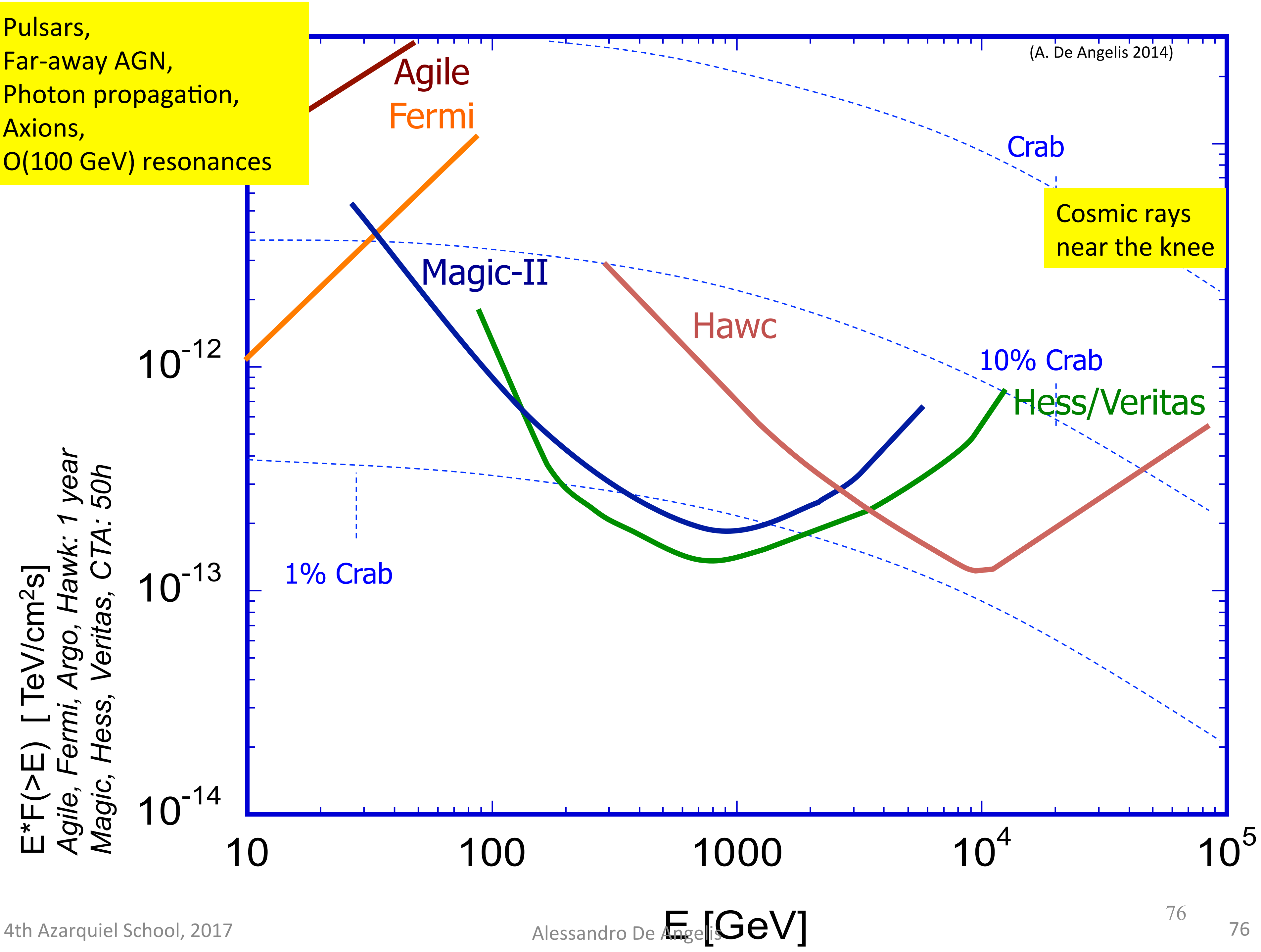
Reconstruct air showers based on PMT hit times and charges

Reject charged primaries via bright hits outside the core



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





Pulsars,
Far-away AGN,
Photon propagation,
Axions,
O(100 GeV) resonances

Cosmic rays
near the knee

Performance of different types of HE gamma detectors

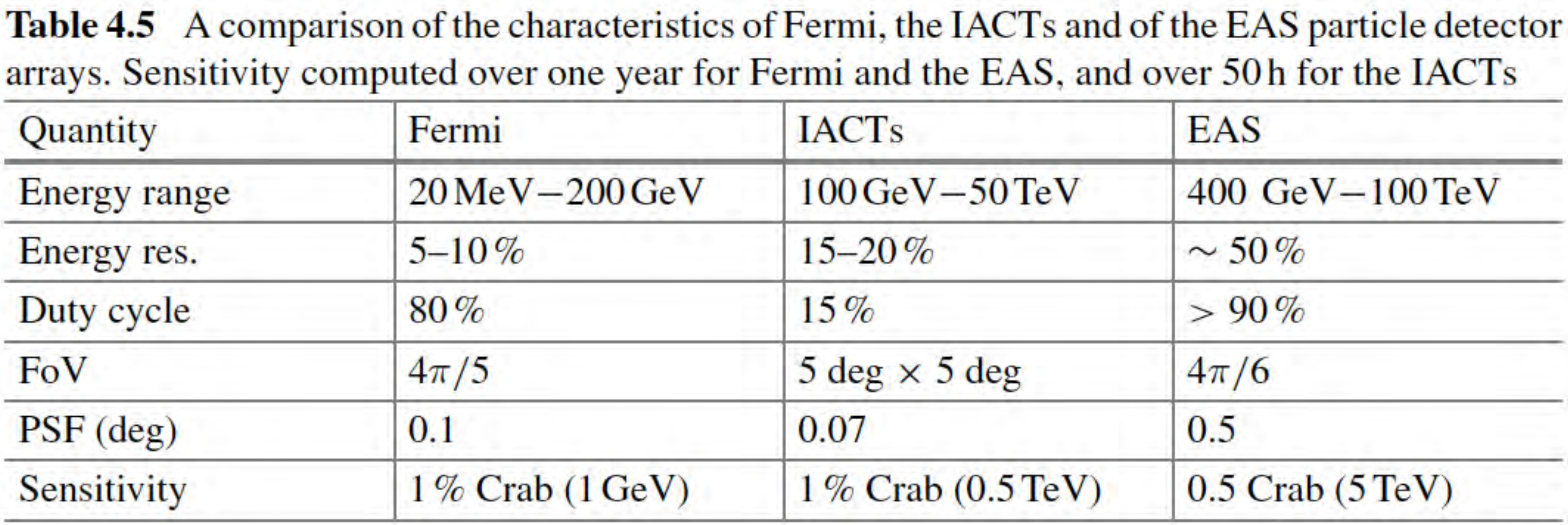
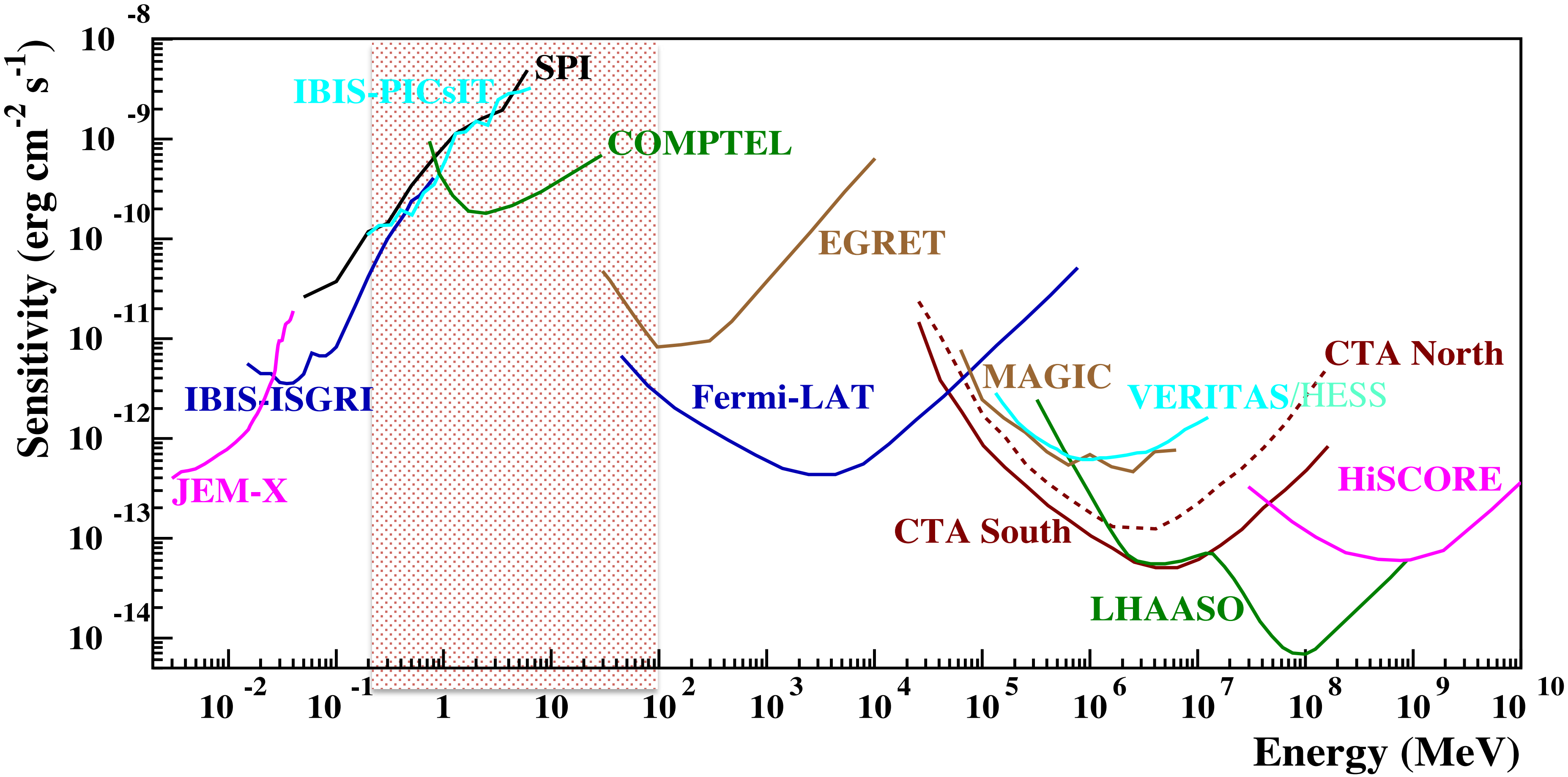


Table 4.5 A comparison of the characteristics of Fermi, the IACTs and of the EAS particle detector arrays. Sensitivity computed over one year for Fermi and the EAS, and over 50 h for the IACTs

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 × 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)



- 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

Detectors: summary

- 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 (HAWC), and there is room for improvement by “brute force”.