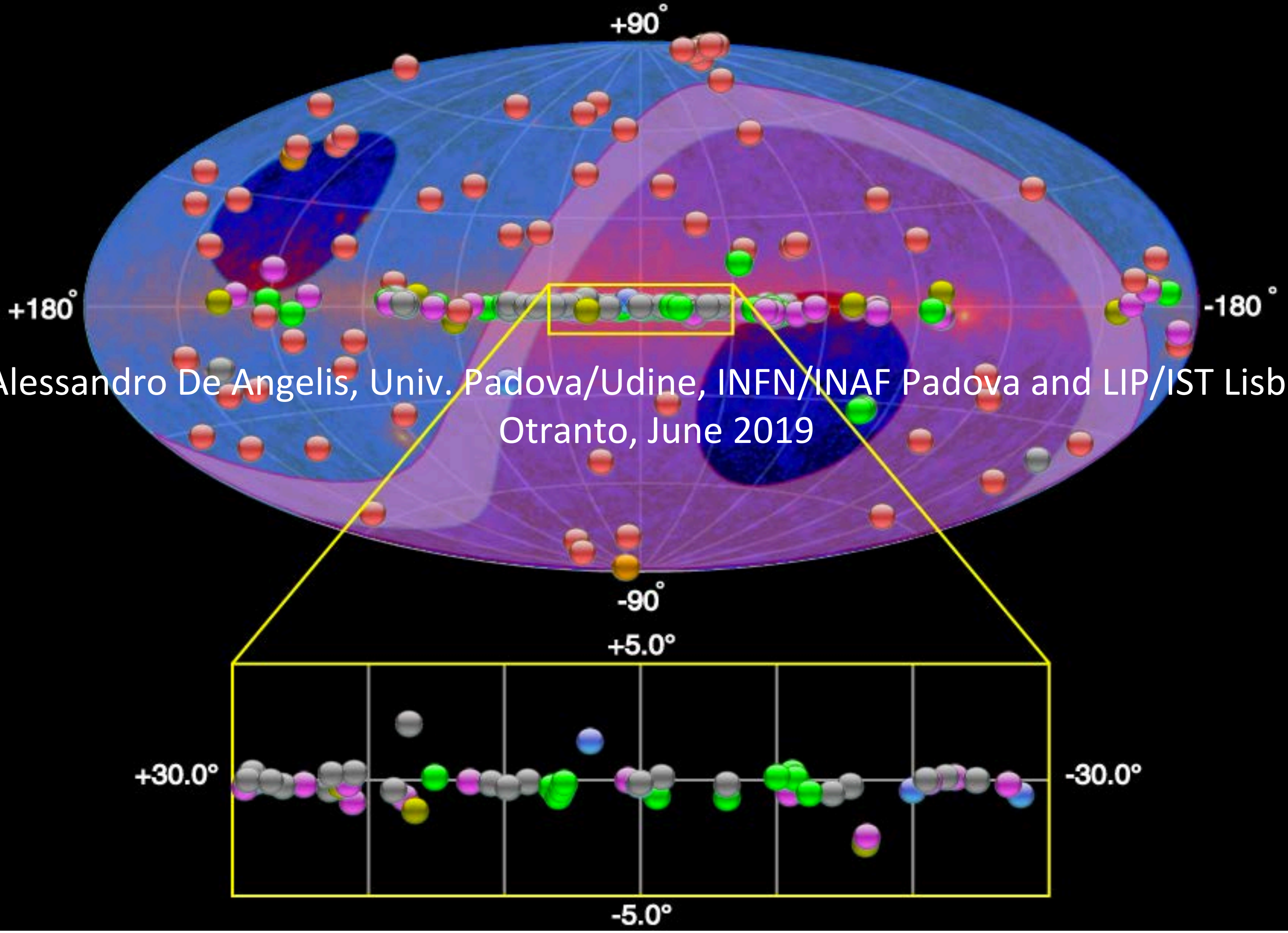
Astroparticle physics with gamma rays and neutrinos



Alessandro De Angelis, Univ. Padova/Udine, INFN/INAF Padova and LIP/IST Lisboa

Otranto, June 2019

Gaspar Barreira (1940-2019)

- Scientist with a 4π vision
- In 1986, founder of LIP
- A protagonist of the Portuguese revolution
- A friend

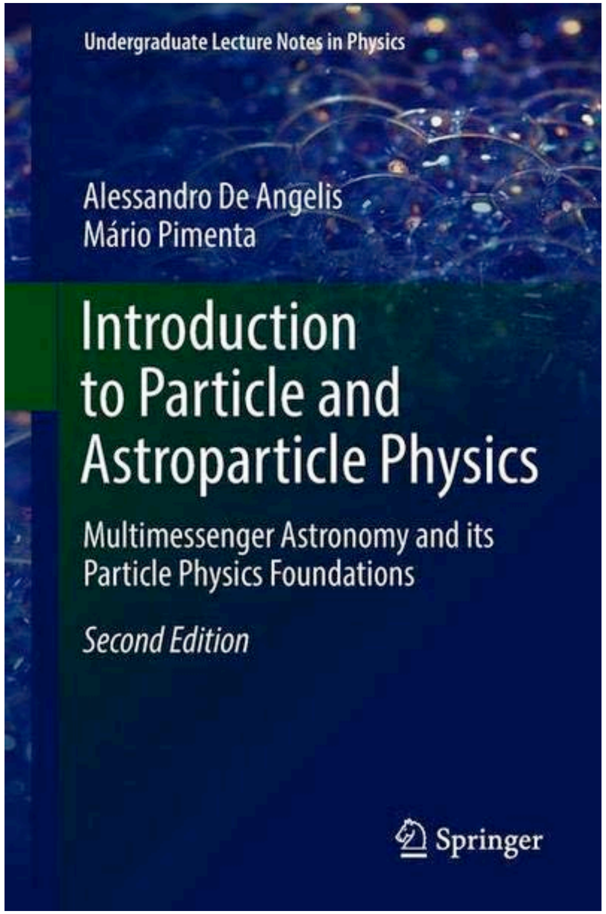
About this mini-course

What you will learn:

- Understand the basic physical processes originating the emission of high-energy gamma-rays and neutrinos from astrophysical sources
  - In particular: from accelerators in high-density regions
- Know the methods and observing techniques to study high-energy gamma and neutrino emissions.
- Describe the sky as seen with high-energy gamma-ray and neutrino detectors.
- Identify the kinds of astrophysical sources visible at high energies and relate them to relevant emission processes.
- Have insight into current research in HECR

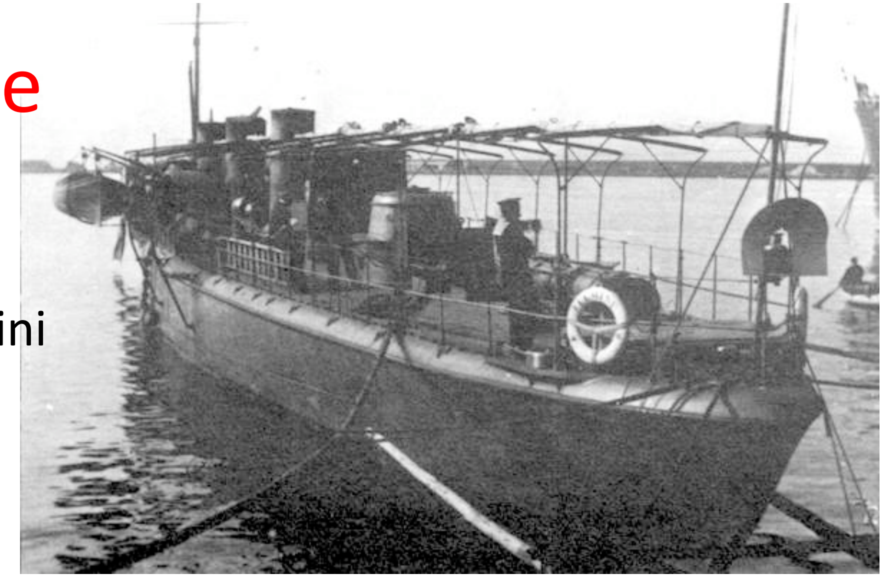
An extended version of this course (24h) is available at

https://agenda.infn.it/event/17760/



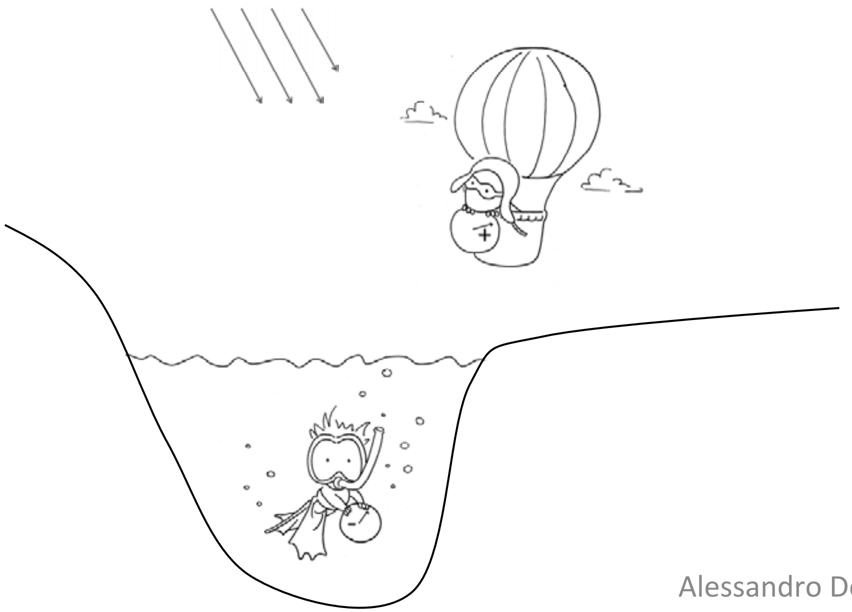
Book at SpringerLink *** FREE *** in CERN, MP, Padova, …

Messengers from the Universe

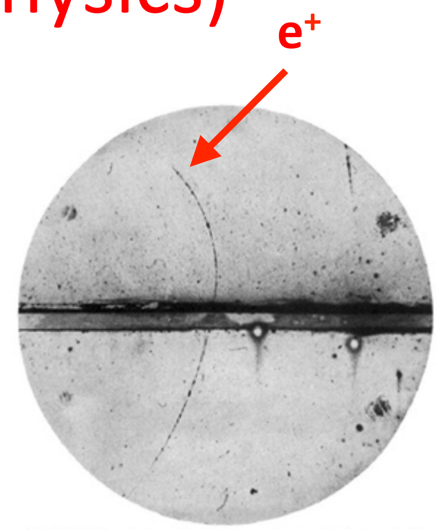


1911/12: Domenico Pacini and Victor Hess perform two complementary experiments: Pacini discovers that ionizing radiation decreases underwater, and Hess that it increases at high altitudes

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



YES (the birth of Particle Physics)



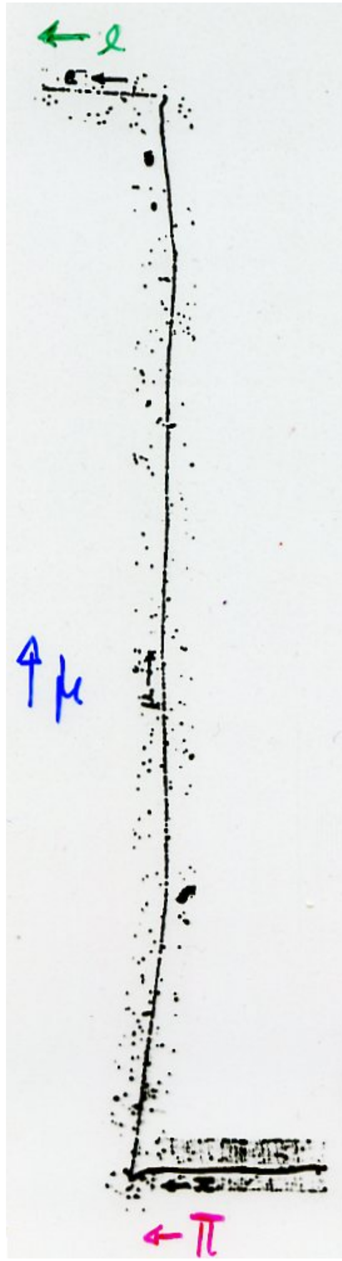
Positron (Anderson 1932)

Antimatter! (Dirac)

$\gamma \rightarrow e^+e^-$ (Einstein)

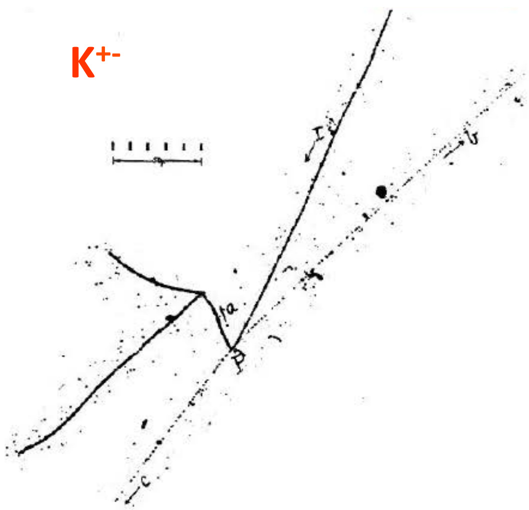
μ (Anderson 1937)

Rossi, 1940:
Muon life time.
Time dilation!



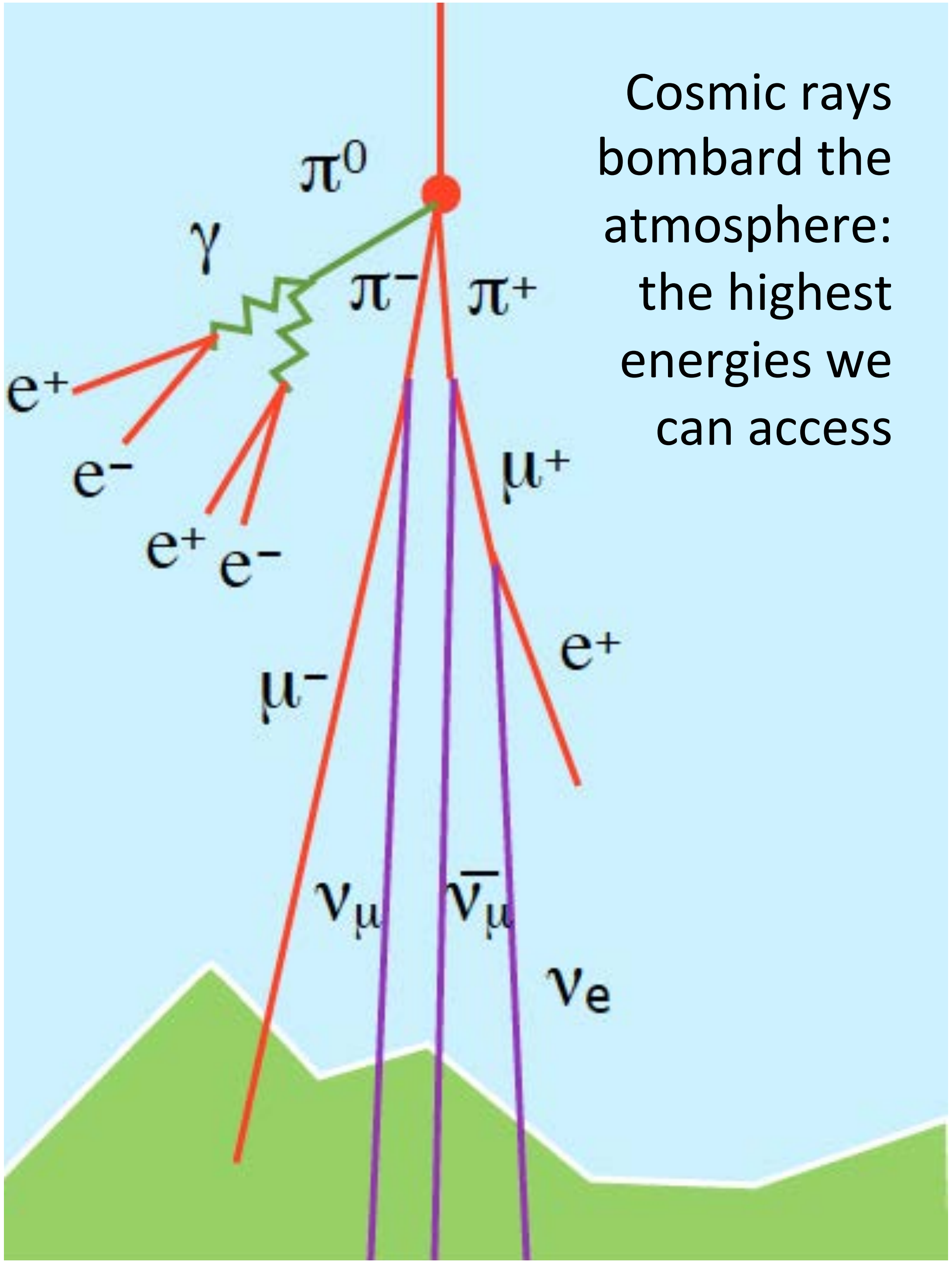
π (Lattes, Powell 1947)

Strong interactions (Yukawa)



K, Λ, ... (Leprince Ringuet 1944, Rochester , Butter 1947, ...)

Strangeness



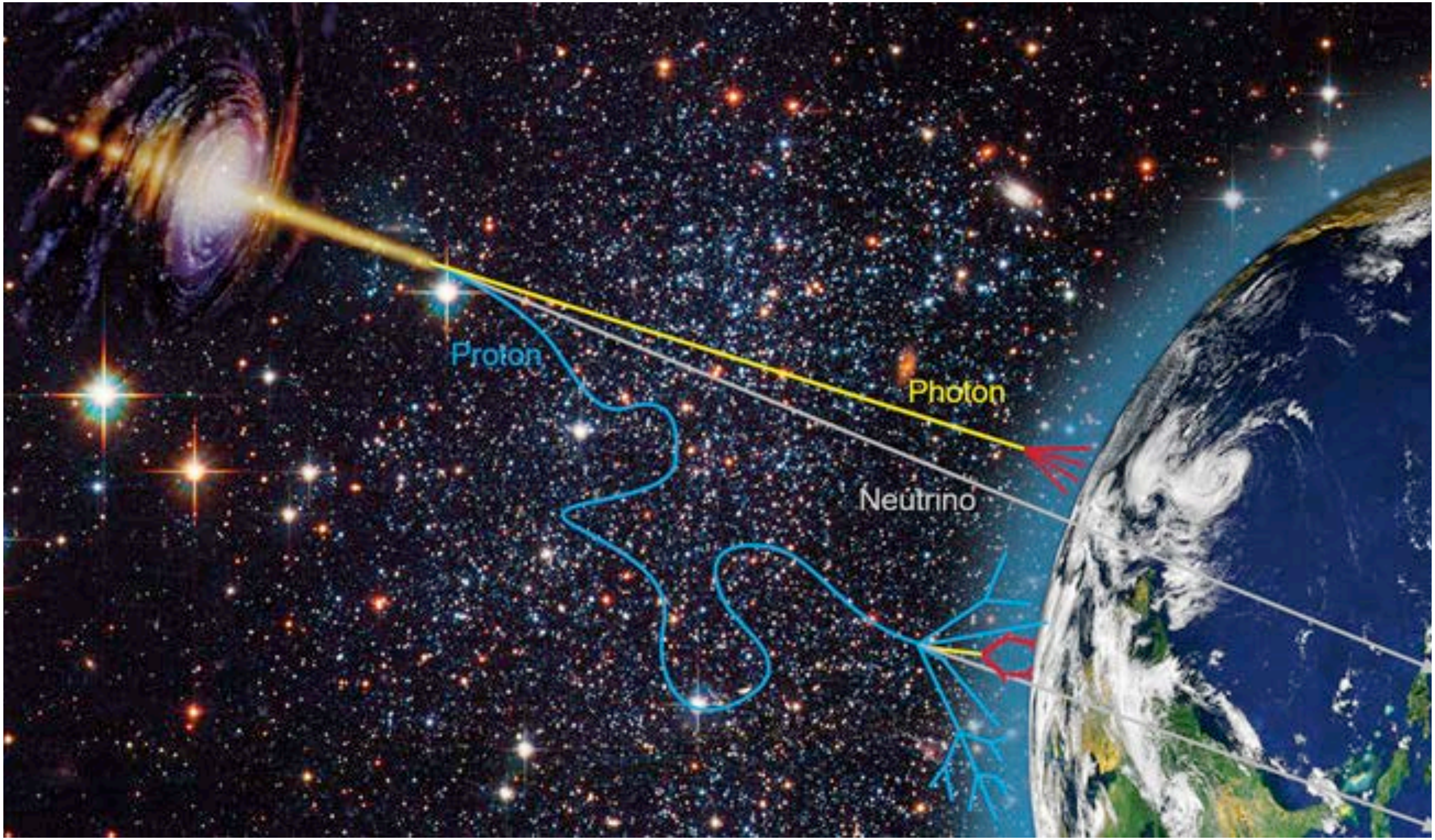
YES, and it allows accessing the highest energies

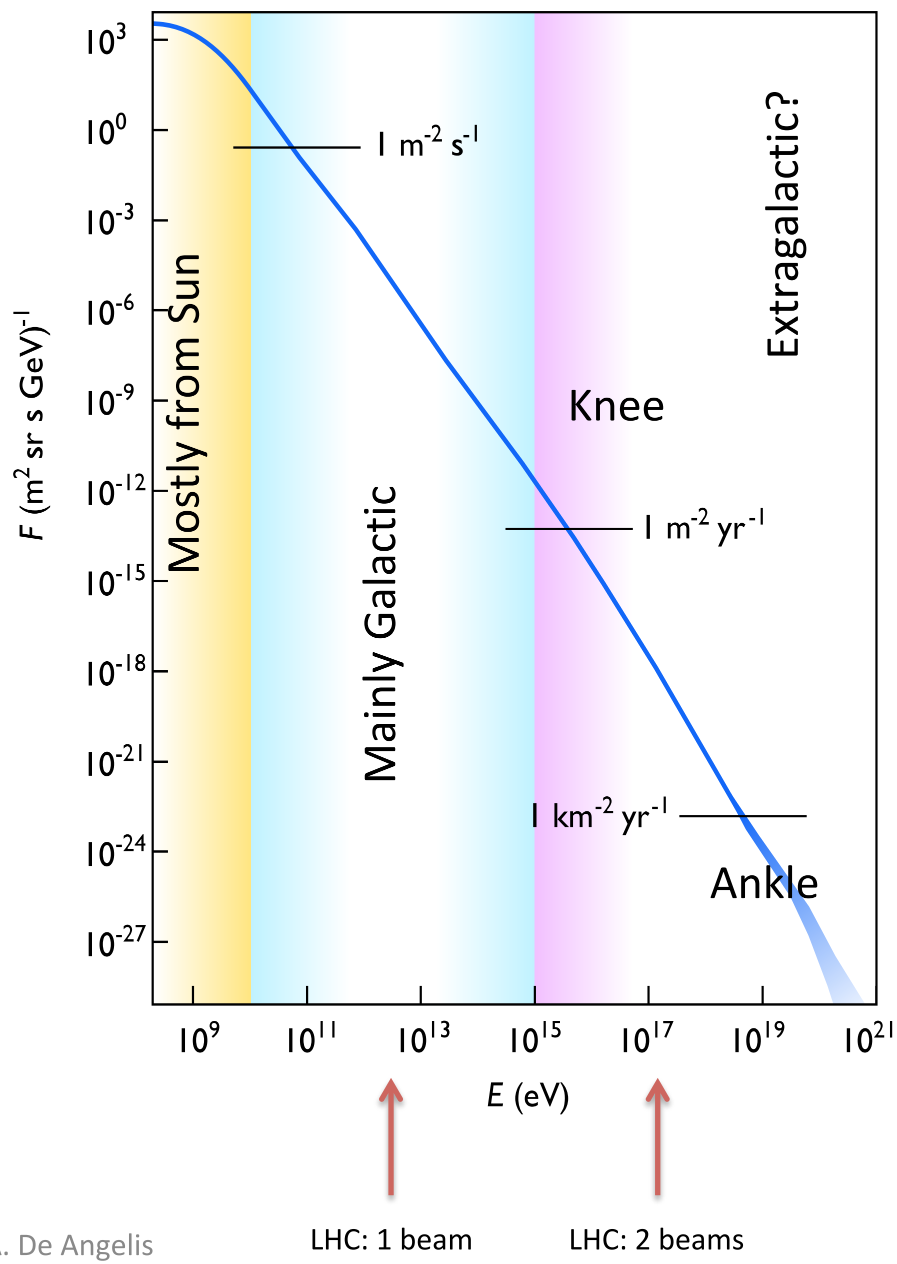
Detected protons 10^8 times more energetic than LHC

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")

- 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

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

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

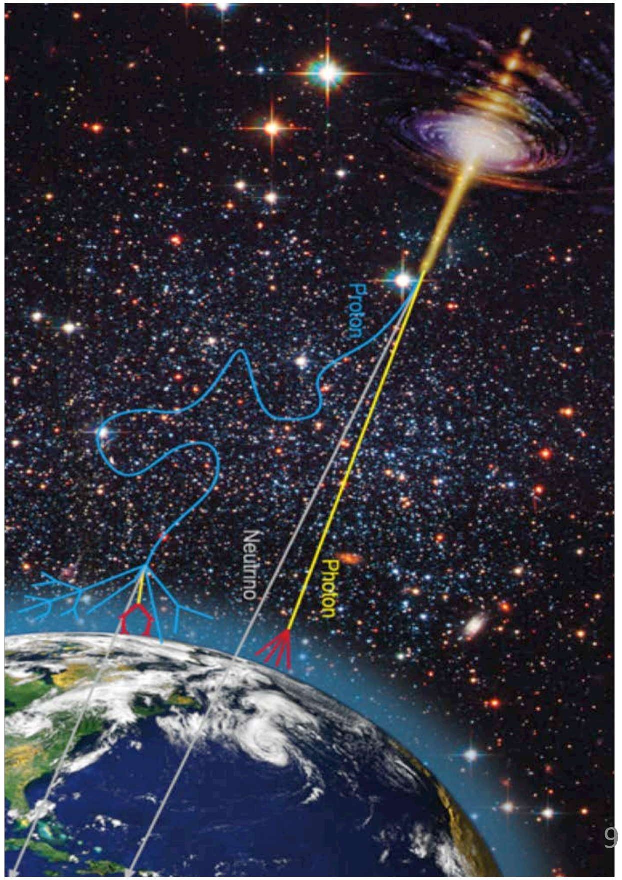
Propagation of charged CR in the Universe

- Gyroradius

  B in the Galaxy: a few μG; outside the Galaxy: 1nG > B > 1 fG

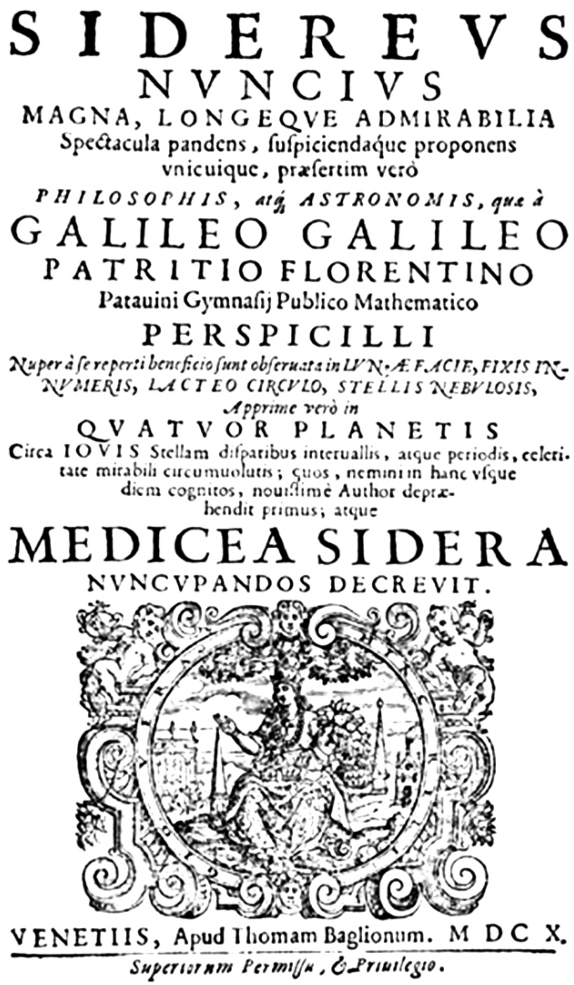
$$\frac{r}{1\ \mathrm{pc}} \cong \frac{\frac{E}{1\ \mathrm{PeV}}}{\frac{B}{1\ \mu\mathrm{G}}}$$

- 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, the Earth and the blazar TXS 0505 +056)
  - ~1 neutrino per month from astrophysical sources identified by IceCube (1km^3)!
- Gravitational waves: just started, but very important
- 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 DC X.
Superiorum Permissu, & Priuilegio.

Production / Acceleration

Possible UHECR Sources: 2 scenarios

Bottom-Up Acceleration
(Astrophysical Acceleration Mechanisms)

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

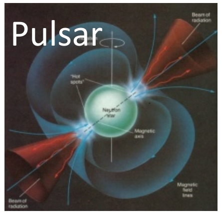
Experimental evidence:
- ✓ anisotropy in arrival directions
- ✓ Photons < ≈1%

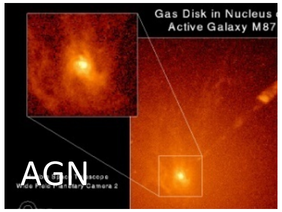
Top–Down Decay
(Physics Beyond the Standard Model)

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

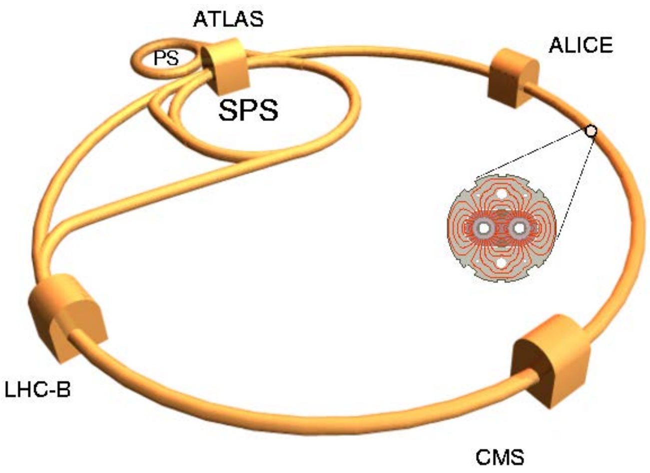
Experimental evidence:
- ✓ isotropy in arrival directions
- ✓ Photons > ≈10%

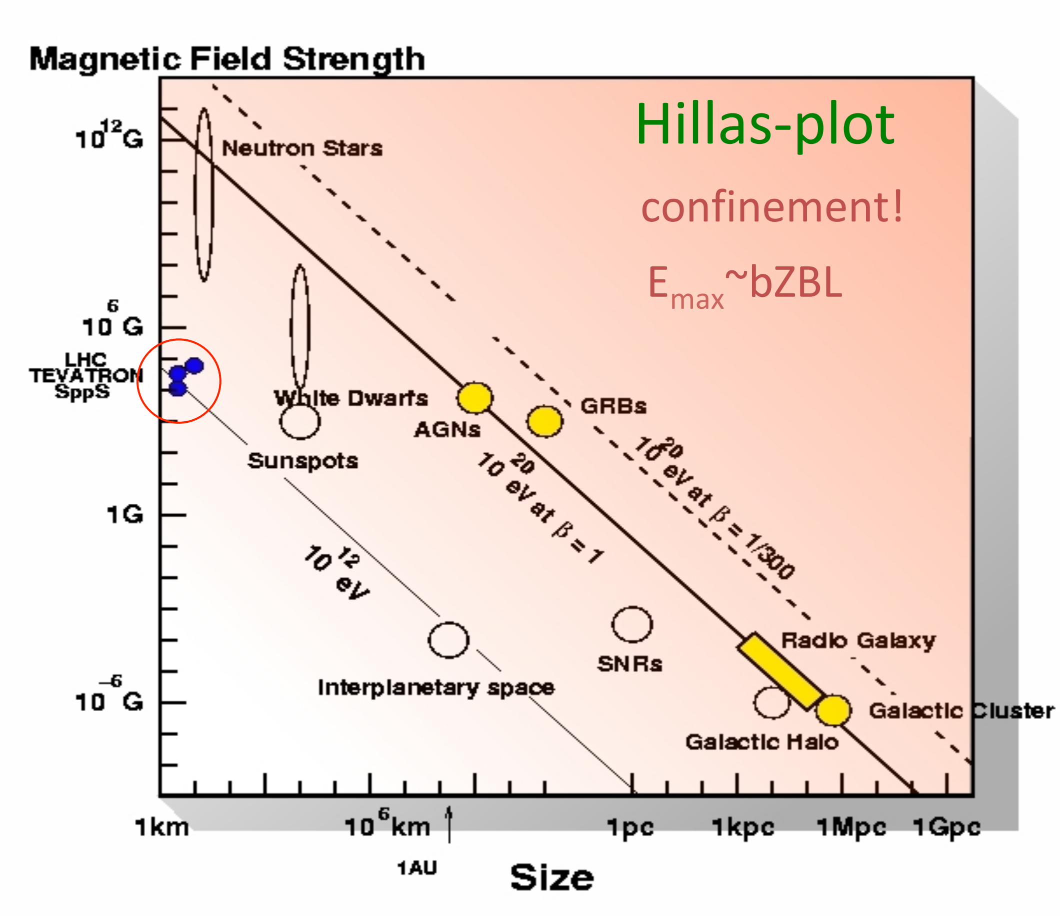
Where can be these accelerators in the Universe?





Large Hadron Collider



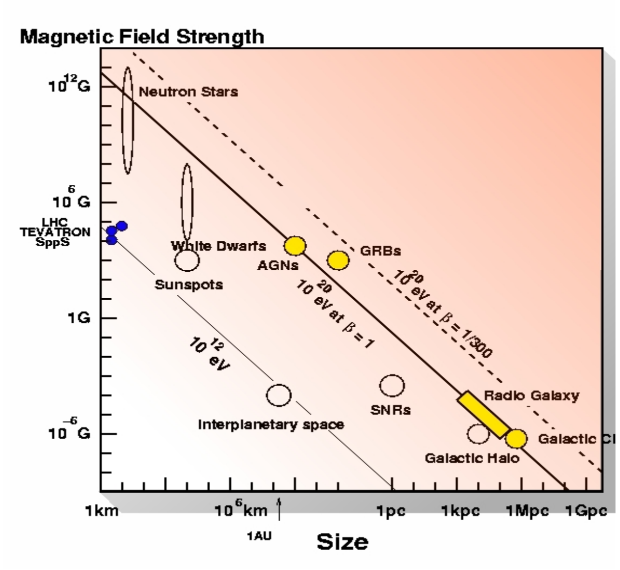


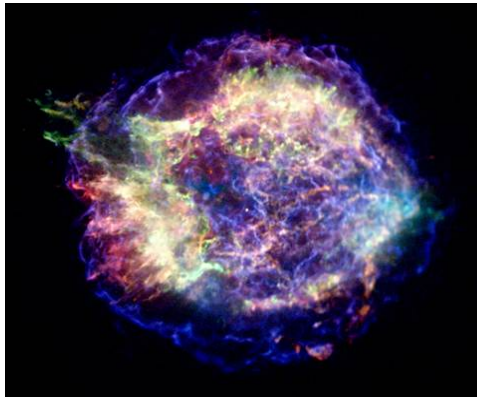
$E \propto BR$

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

A few new terms

- Stellar end-products. A star heavier than the Sun collapses at the end of its life into a neutron star (R ~ few km, which can be pulsating – a pulsar) or into a BH, and ejects material in an explosion (SuperNova, with+ possibly a Remnant).
  - Very large B fields in the pulsar; magnetic fields also in the SNR
- The centers of galaxies host black holes, often supermassive (million/billion solar masses). They might accrete at the expense of the surrounding matter, and accelerate particles in the process. When they are active, they are called Active Galactic Nuclei.





Zwicky conjectures (1933)

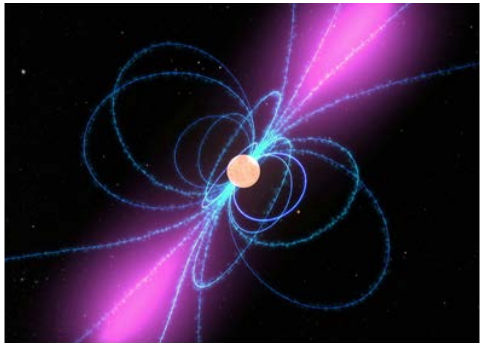
1. Heavy enough stars collapse at the end of their lives into super-novae
2. Implosions produce explosions of cosmic rays
3. They leave behind neutron stars


(Zwicky in1930)

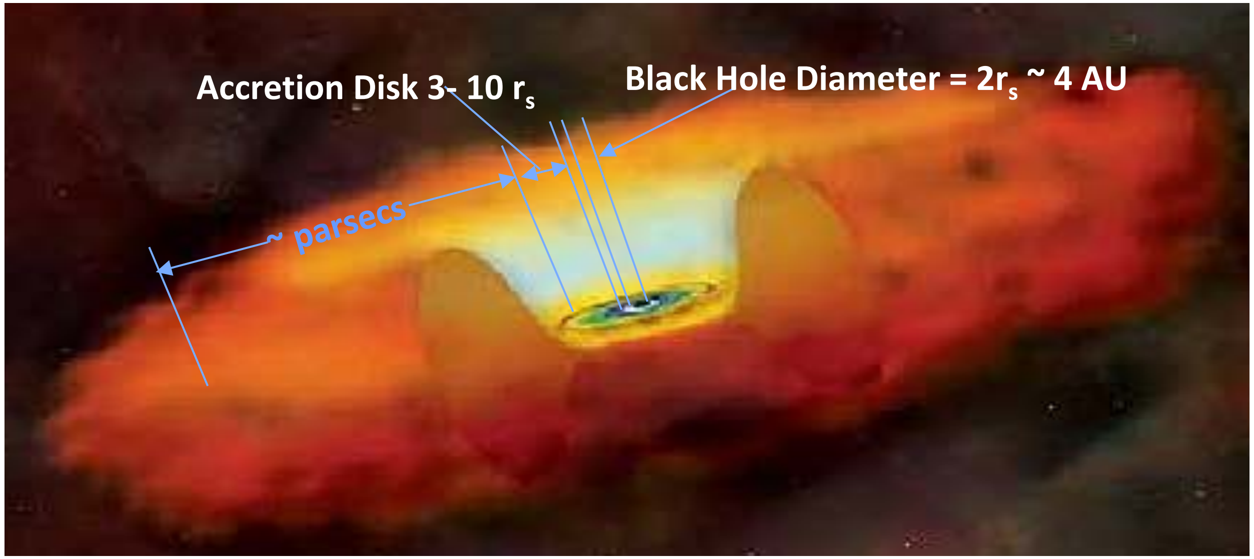
Examples of known extreme environments

GRB

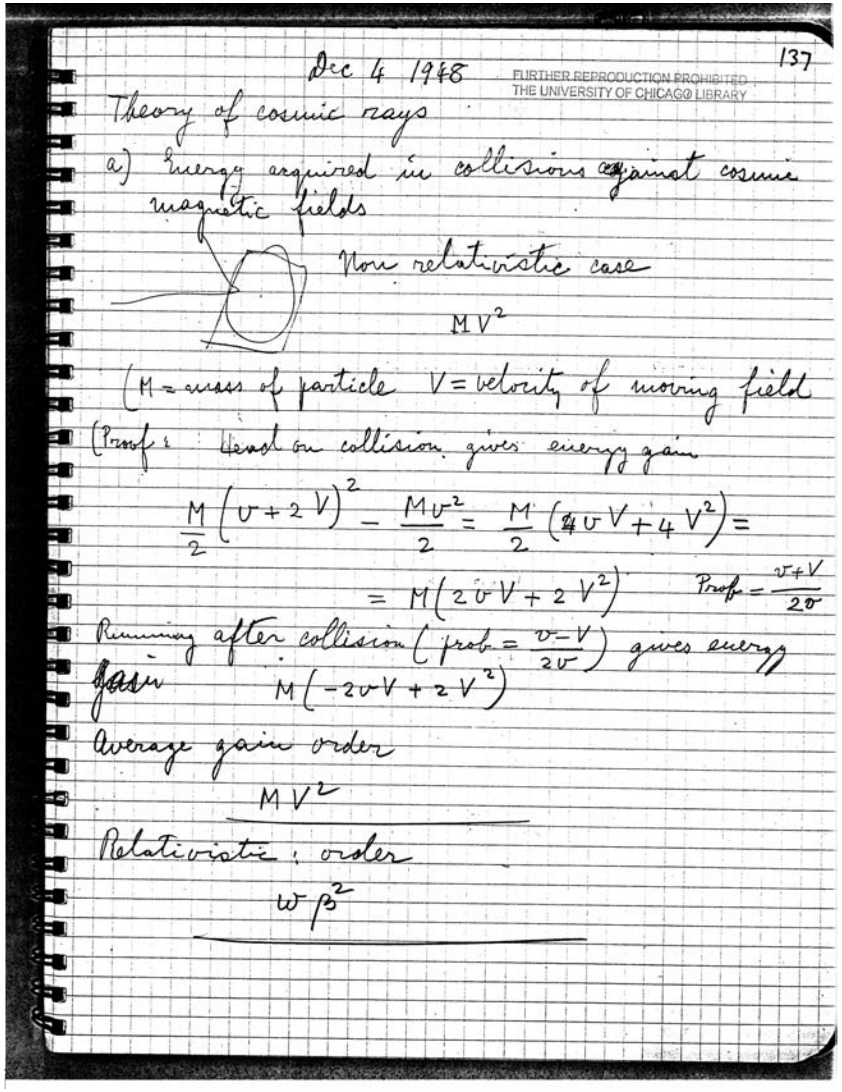
SuperNova Remnants
Pulsars



Active Galactic Nuclei



And what is the physical mechanism?



137

Dec 4 1948

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

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

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

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

$$M\left(-2vV+2V^2\right)$$

Average gain order

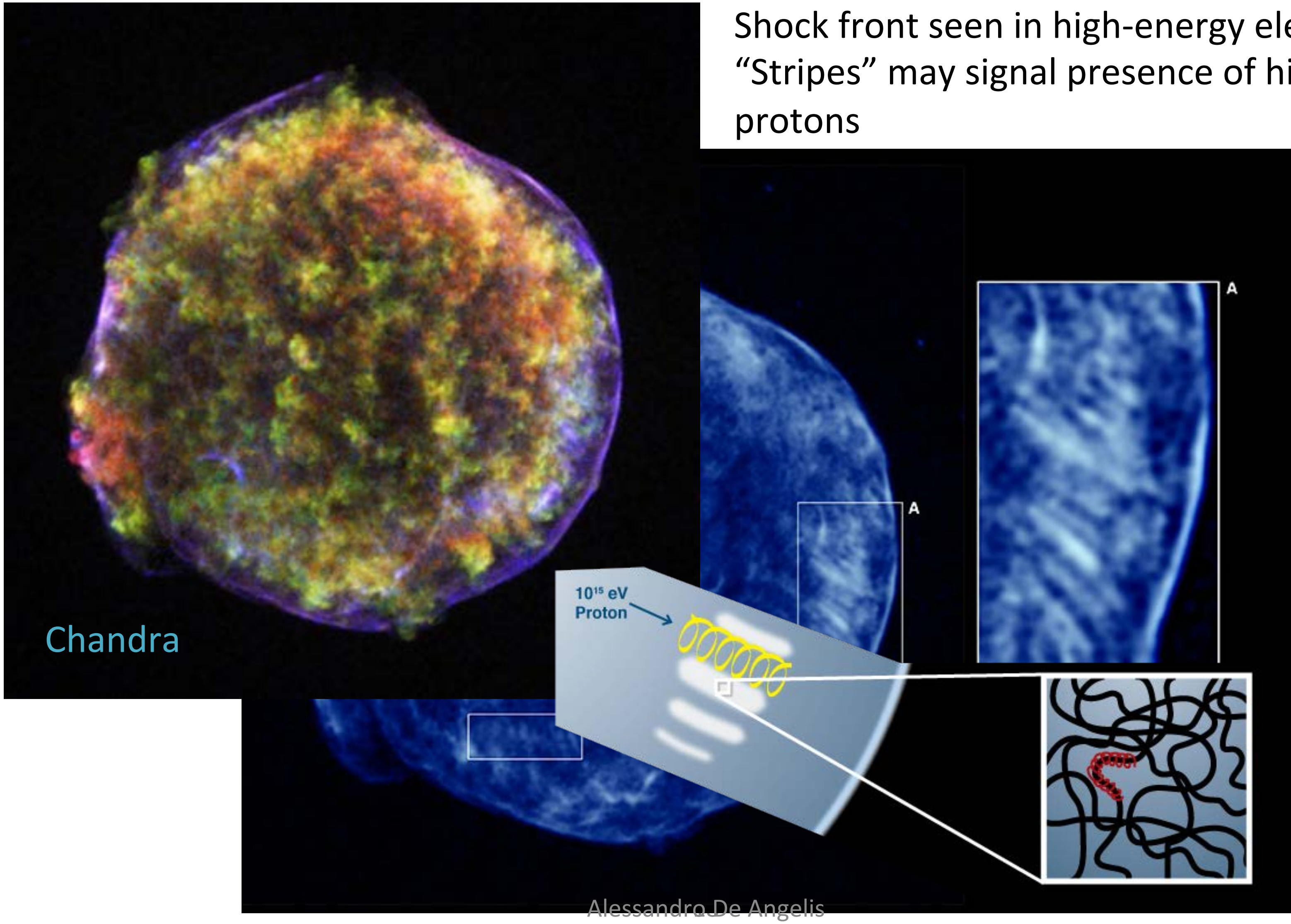
$$MV^2$$

Relativistic: order

$$w\beta^2$$

Tycho's Supernova (SN 1572)

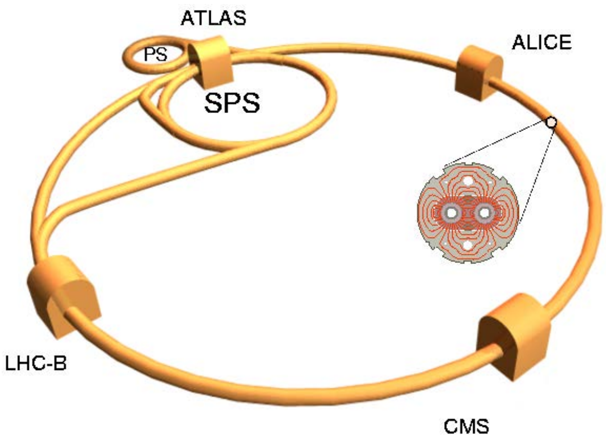
Shock front seen in high-energy electrons
"Stripes" may signal presence of high-energy protons



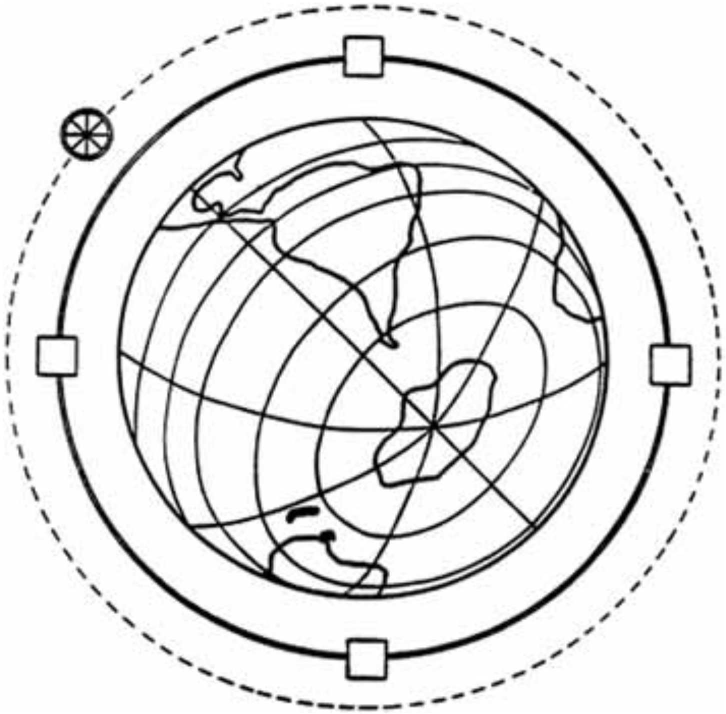
E = k BR

Whatever is the acceleration mechanism…

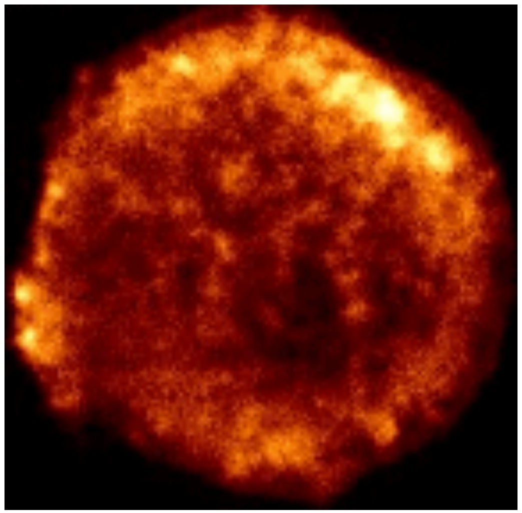
Large Hadron Collider



R ~ 10 km, B ~ 10 T
⇒ E ~ 10 TeV



Tycho SuperNova Remnant



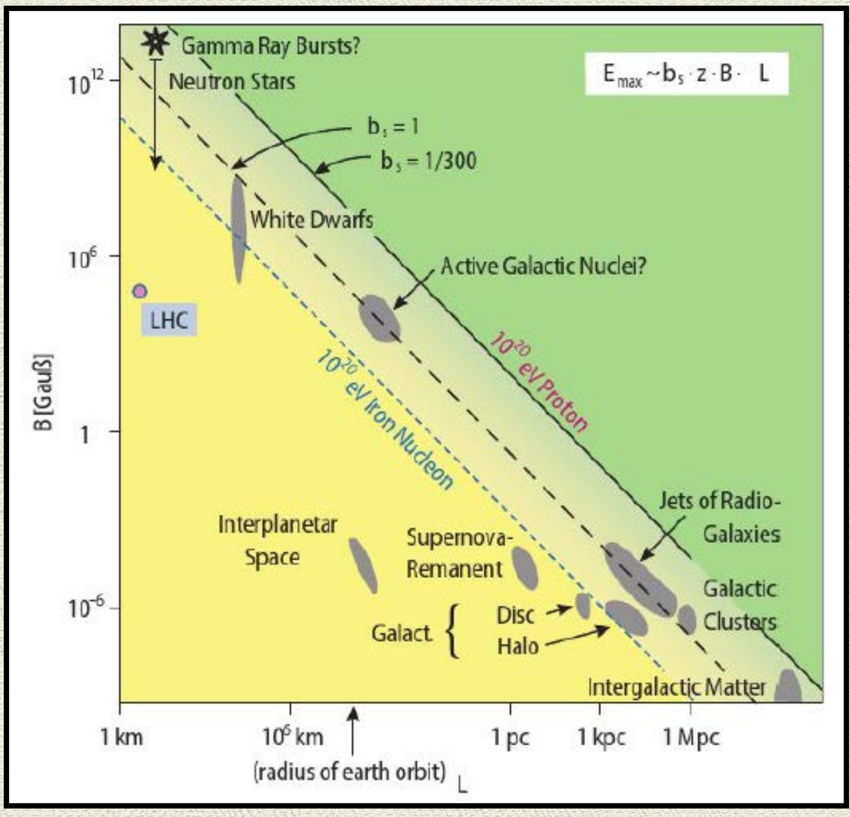
R ~ 10^{15}km, B ~ 10^{-10}T
⇒ E ~ 1000 TeV

The maximum energy possible on Earth is ~ 5000 TeV

Bottom-up models

Where do they come from?

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

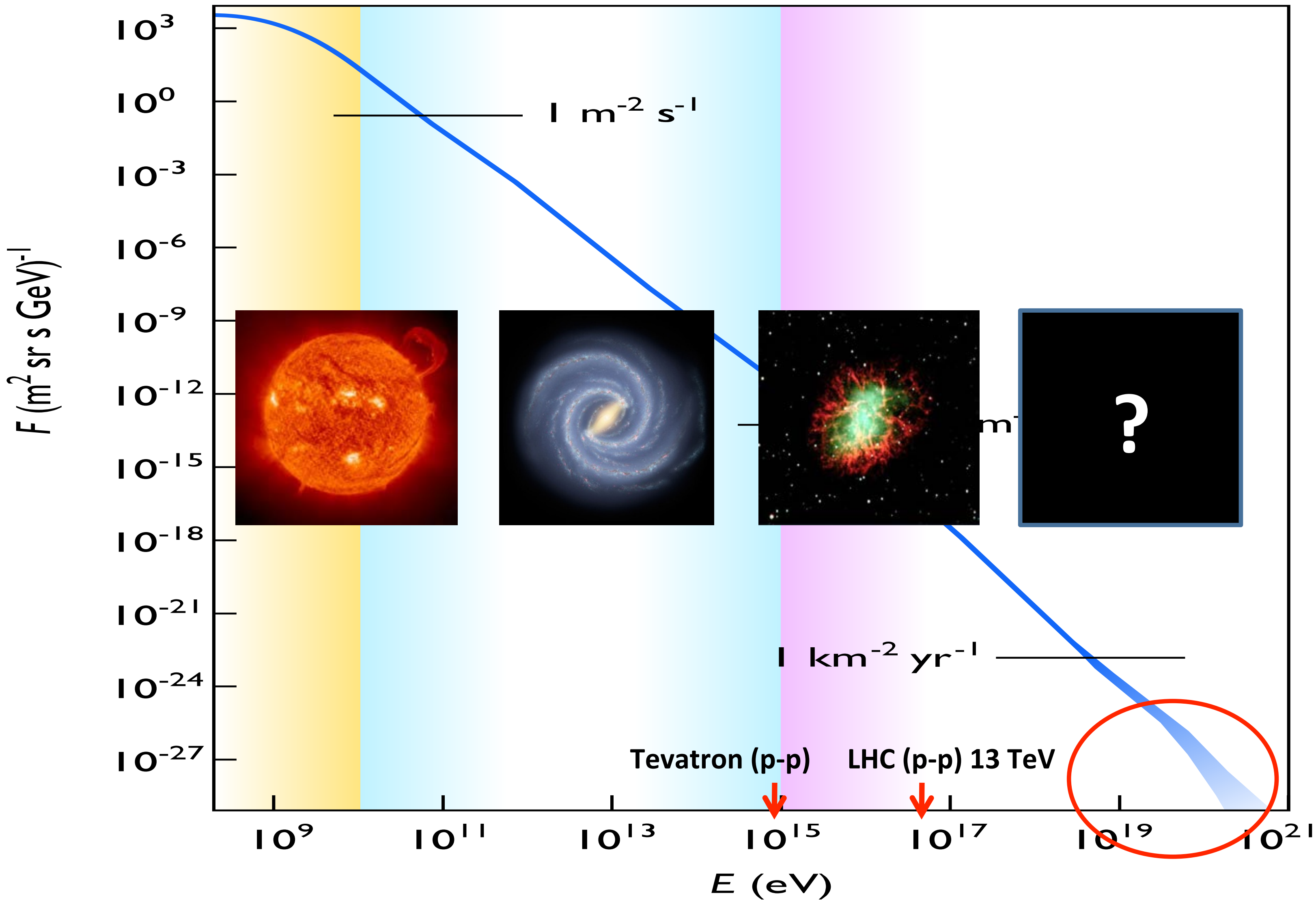


$$r_L = \frac{E_{15}}{ZB_{\mu G}}[\text{pc}]$$

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

One should consider also energy losses at the source

Origin ! ?



10^3
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-24}
10^{-27}
F (m² sr s GeV)⁻¹
1 m⁻² s⁻¹
?
1 km⁻² yr⁻¹
Tevatron (p-p)
LHC (p-p) 13 TeV
10^9
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
10^{21}
E (eV)

Production of high energy photons (and neutrinos)

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

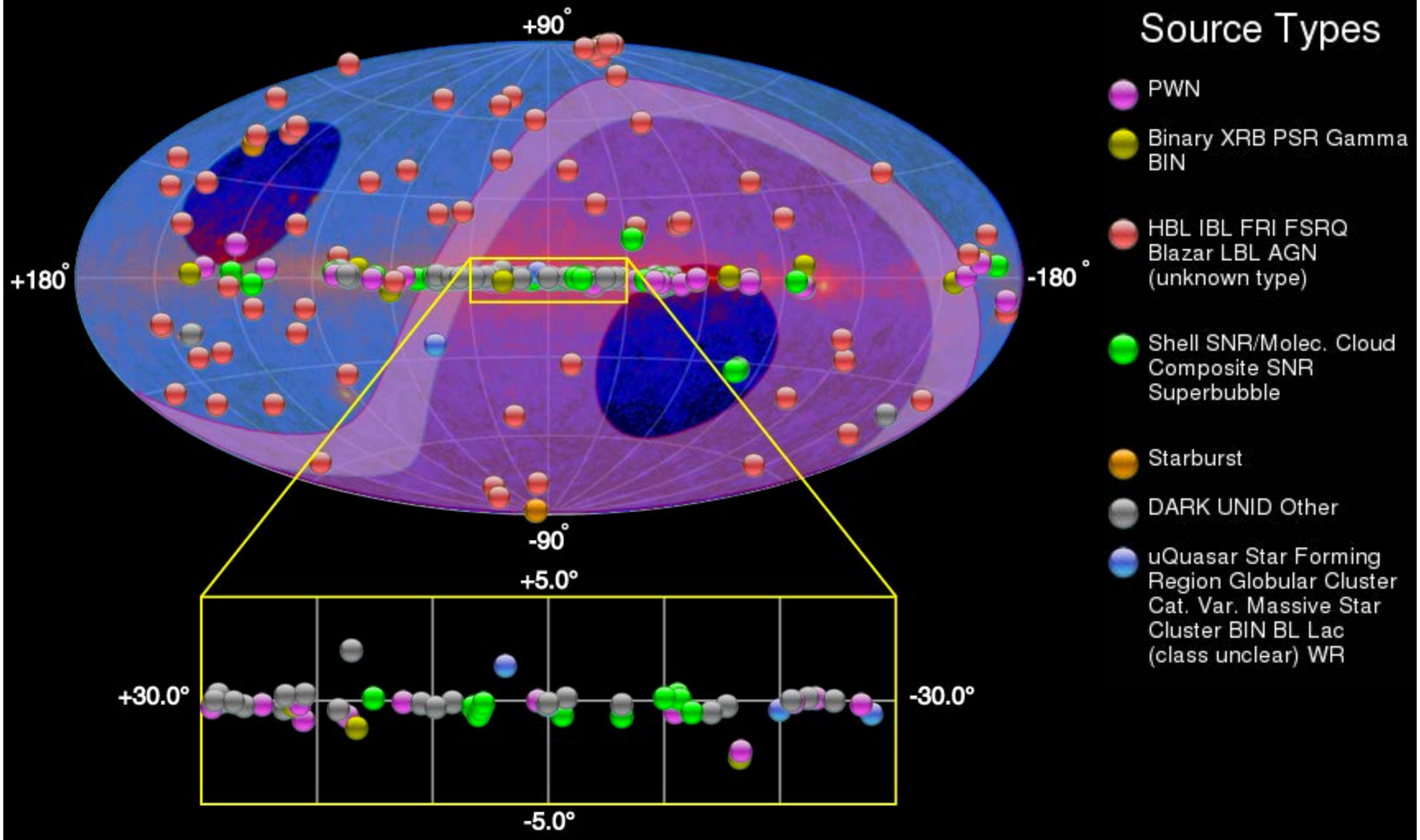
Studying Gamma Rays allows us to see different aspects of the Universe

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

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

>3k HE and >200 VHE photon emitters

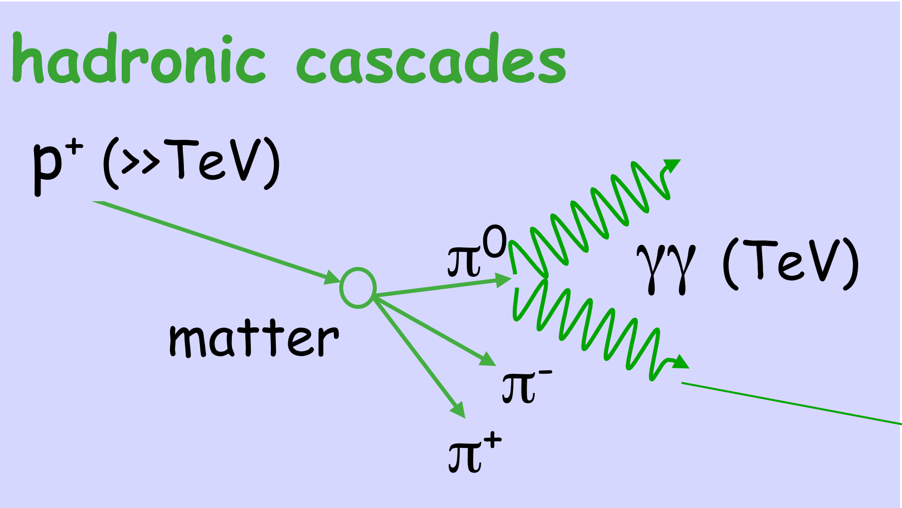


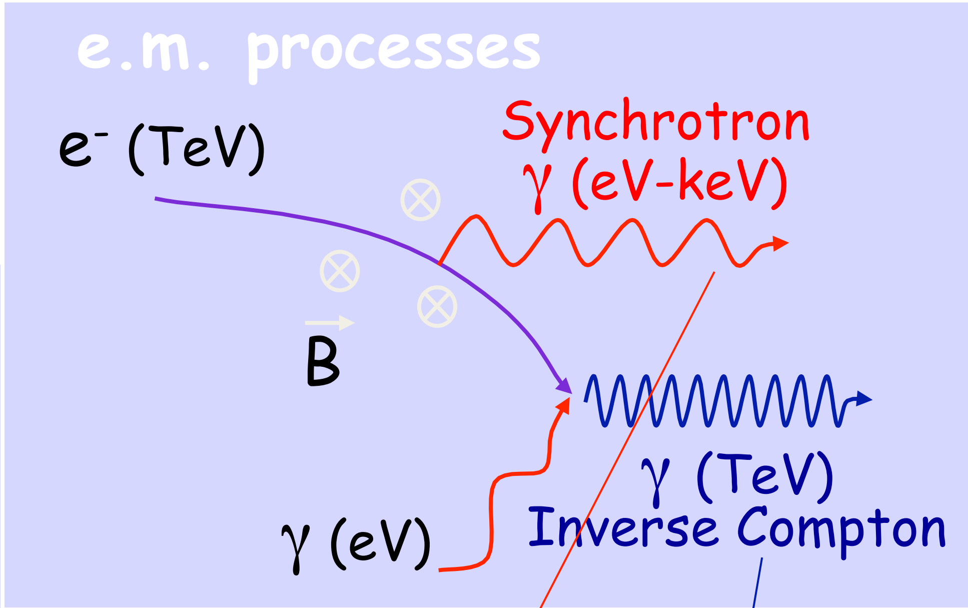
(1) Bottom-up: Interaction of accelerated particles with radiation and matter fields

- 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 (SSC) and hadronic production of gamma rays

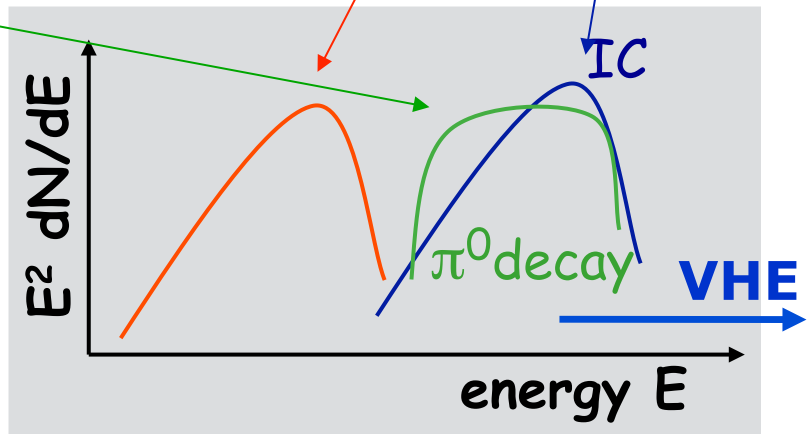
50 TeV gamma-rays hadronically produced track a pupulation of protons of energy ~ 1 PeV



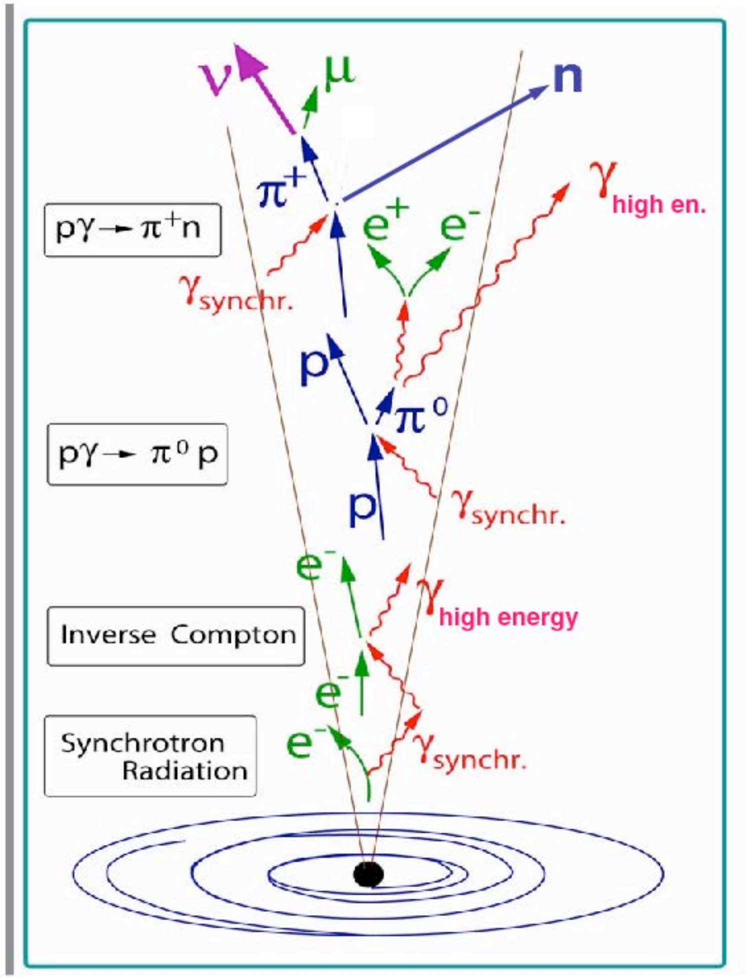


In the VHE region,
$dN/dE \sim E^{-\Gamma}$ (Γ: spectral index)

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

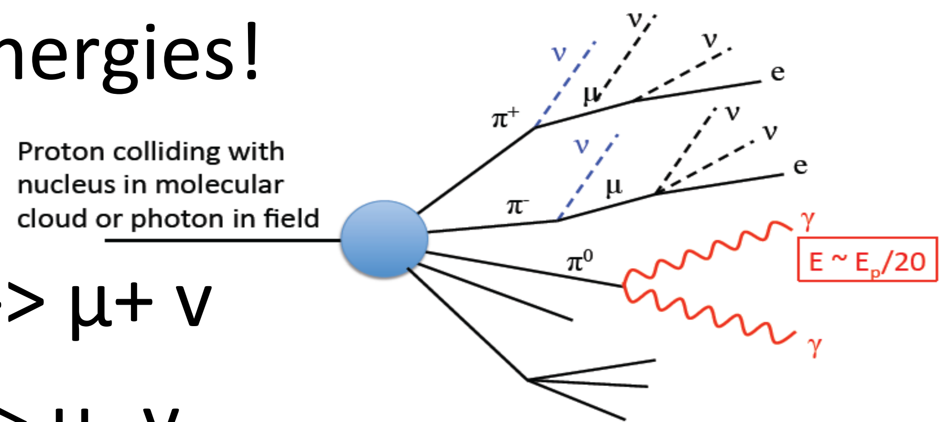


The hadronic mechanism is at work also for neutrinos…



In a hadronic process (isospin symmetry)

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



π+ -> μ+ ν

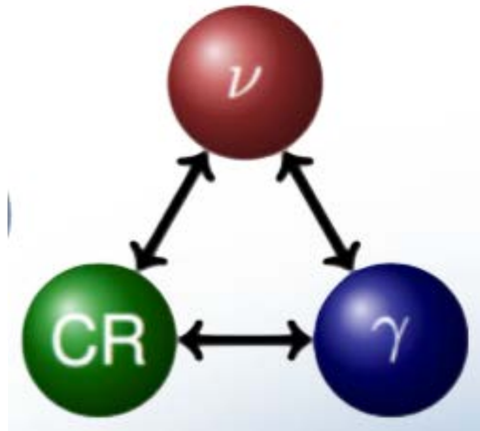
π- -> μ- ν

π^0 -> γγ

Astrophysical neutrino production

- Proton-hadron

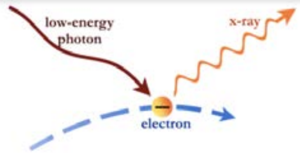
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

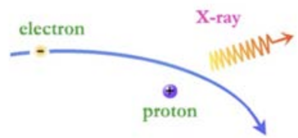


- Photoproduction

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

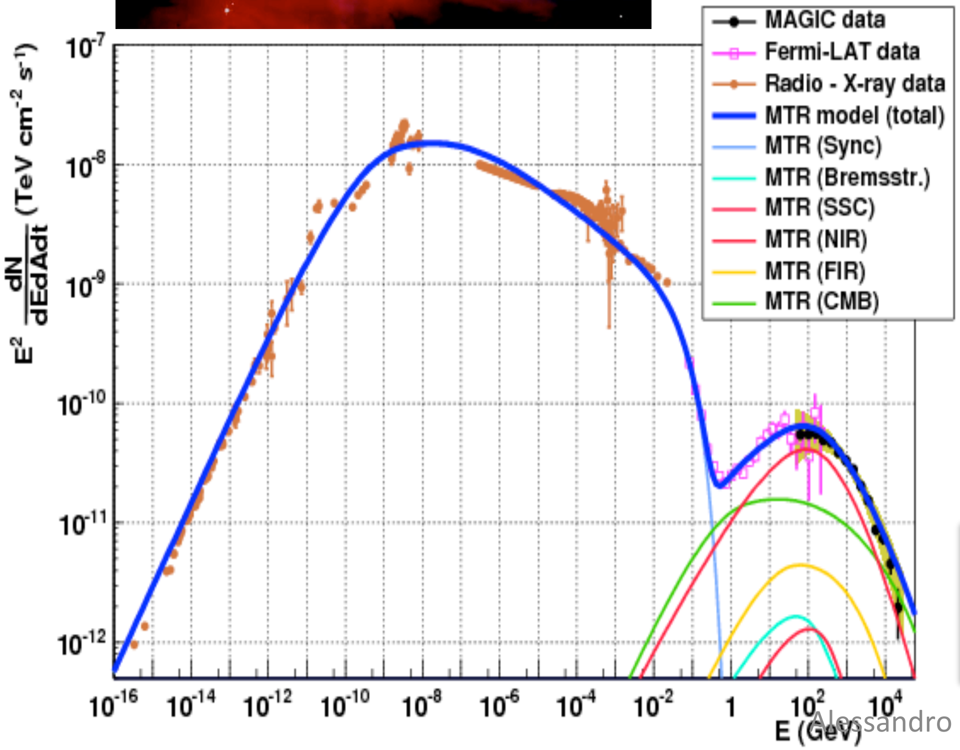
$$E_\nu^2 \frac{dN_\nu}{dE_\nu}(E_\nu) \sim \frac{3}{4} K E_\gamma^2 \frac{dN_\gamma}{dE_\gamma}(E_\gamma)\,;\; K = 1/2\;(2)\;\text{for}\;\gamma p\;(pp)$$





- HE gamma rays can also come from purely leptonic mechanisms (SSC)
- The production rate of γ-rays is not necessarily the emission rate observed: photons can be reprocessed

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

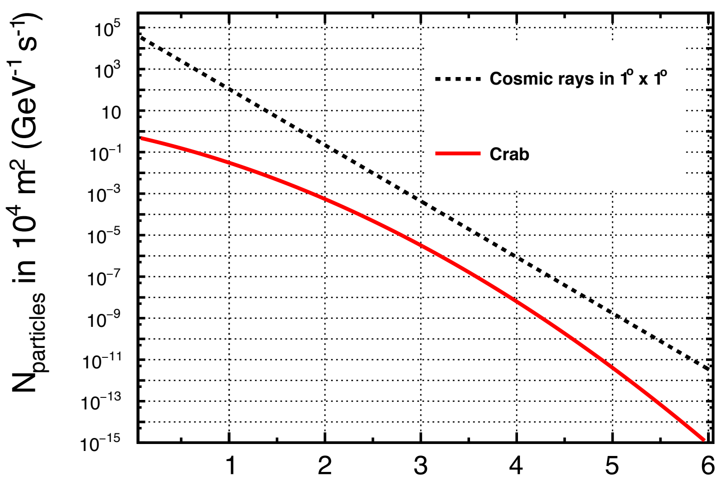


- The Crab Nebula is a nearby (~2 kpc away) PWN and the first source detected in VHE gamma-rays [Weekes 1989].
- It is the brightest steady VHE gamma-ray source, therefore it has become the so-called “standard candle” in VHE astronomy.
  - Recent observation of flares in the GeV range have however shown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

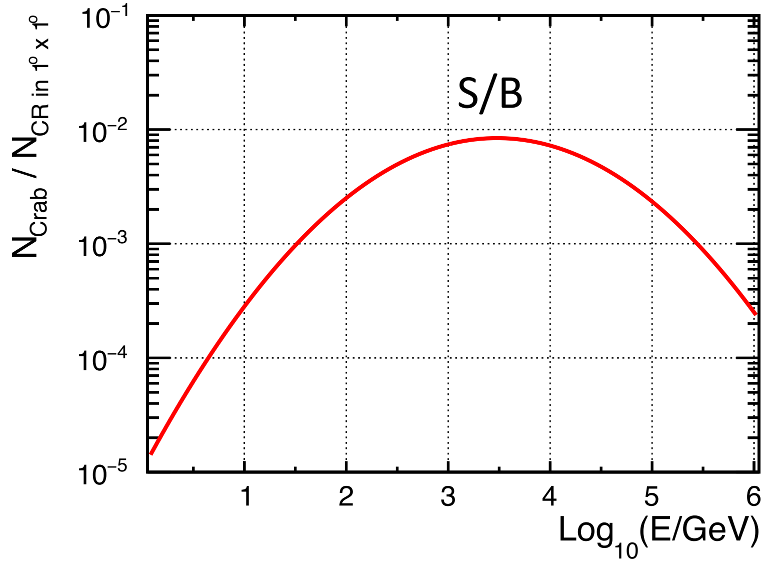
$$\frac{dN_\gamma}{dE} \simeq 3.23 \times 10^{-11} \left(\frac{E}{\mathrm{TeV}}\right)^{-2.47-0.24\left(\frac{E}{\mathrm{TeV}}\right)} \mathrm{TeV}^{-1}\mathrm{s}^{-1}\mathrm{m}^{-2}$$

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:



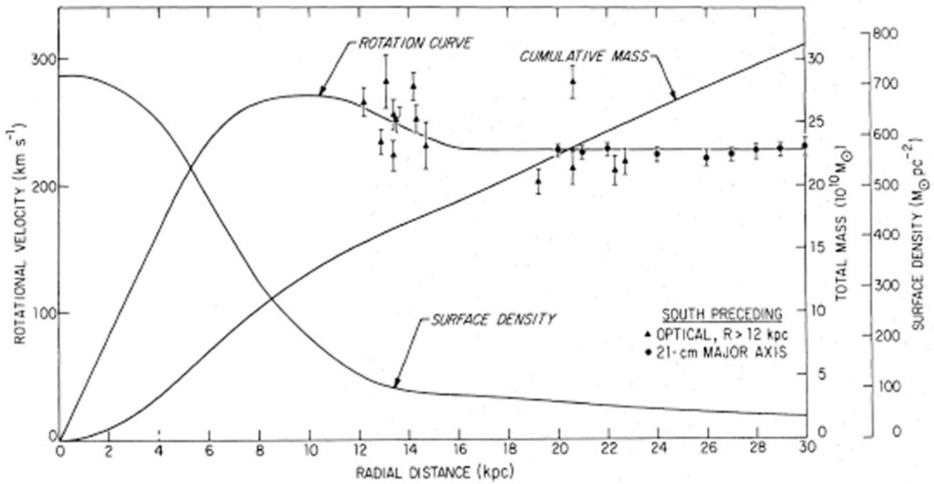
Conceicao, De Angelis, Tome+ 2016)



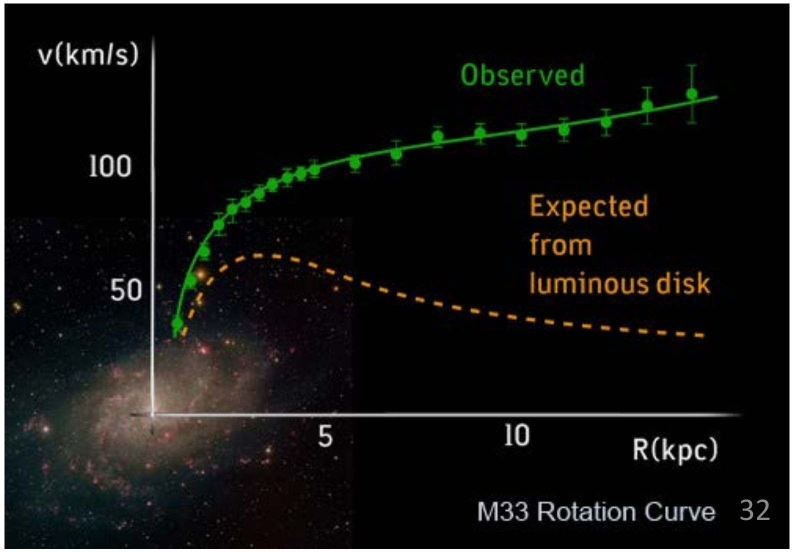
Conclusion: you need large effective area, good angular resolution, proton rejection

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

- Rotation curves of spiral galaxies

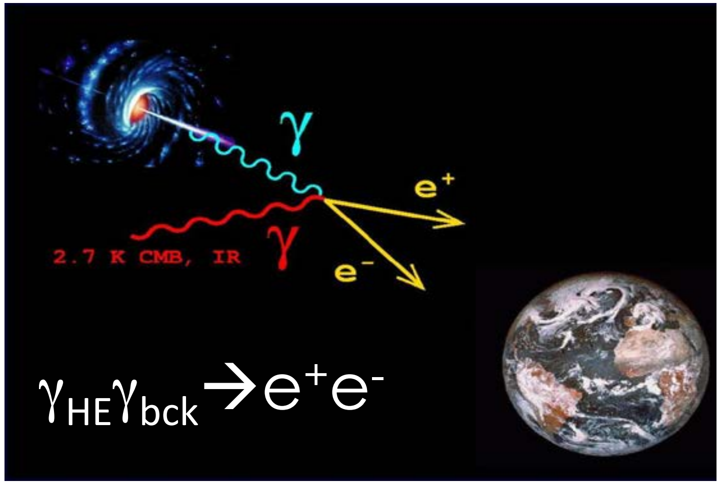


  – flat at large radii: if light traced mass we would expect them to be Keplerian at large radii, $v \propto r^{-1/2}$, because the light is concentrated in the central bulge
    - and disc light falls off exponentially
    - Zwicky had already noted in 1933 that the velocities of galaxies in the Coma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



Propagation

Attenuation of γ–rays



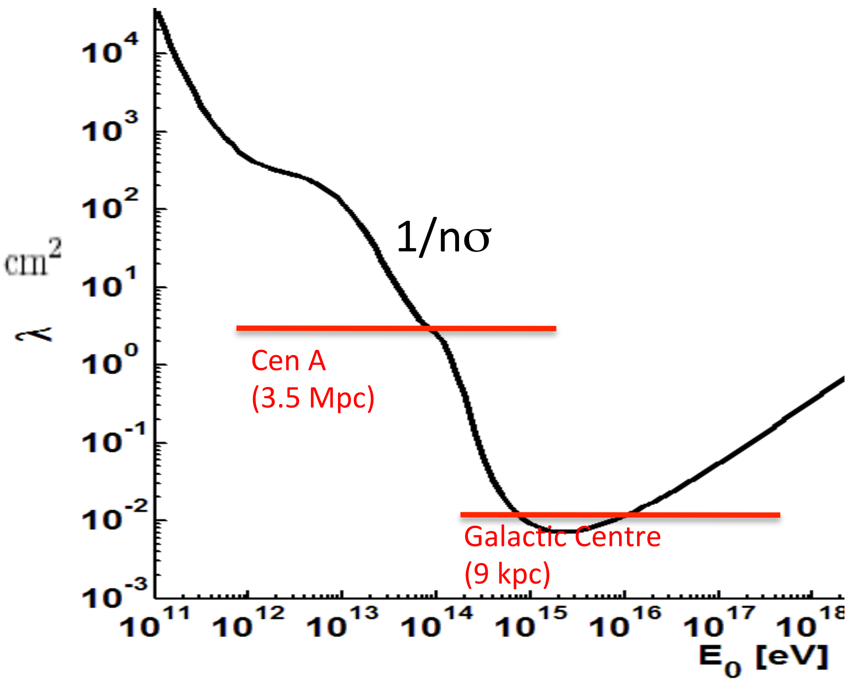
- γ-rays are effectively produced in EM and hadronic interactions
  - Energy spectrum at sources E^{-2}
- are effectively detected by space- and ground-based instruments
- effectively interact with matter, radiation ($\gamma\gamma \rightarrow e^+e^-$) and B-fields
- The interaction with background photons in the Universe attenuates the flux of gamma rays
- The "enemies" of VHE photons are photons near the optical region (Extragalactic Background Light, EBL)

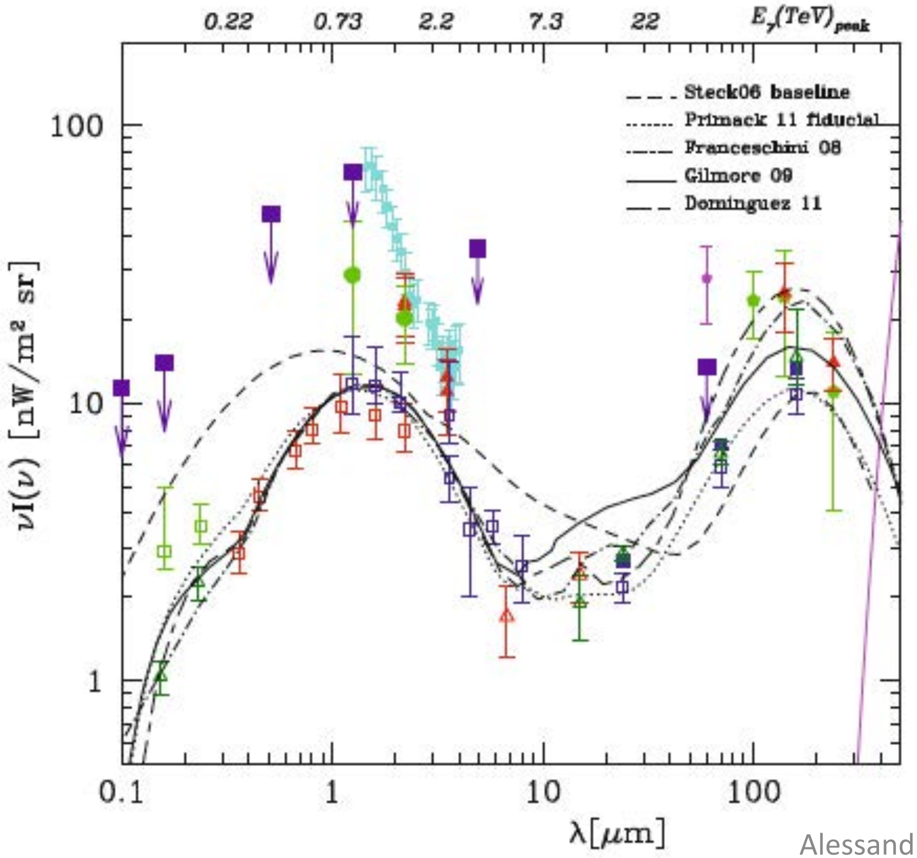
$$\gamma_{VHE}\gamma_{bck} \rightarrow e^+e^-$$

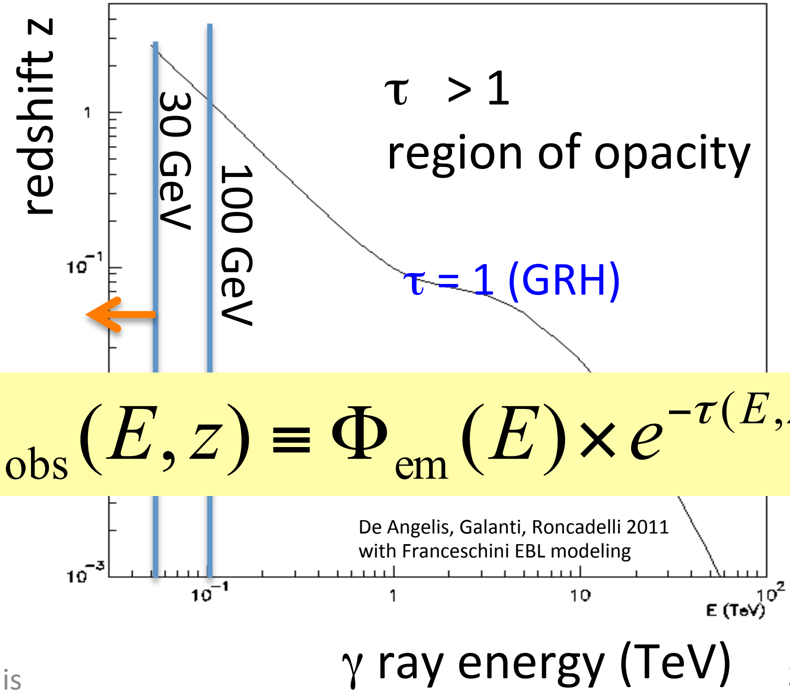
$$\sigma(\beta) \sim \quad 1.25 \cdot 10^{-25}(1-\beta^2) \cdot \left[2\beta(\beta^2-2) + (3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right] \mathrm{cm}^2$$

Max for:

$$\epsilon \simeq \frac{2m_e^2c^4}{E} \simeq \left(\frac{500\ \mathrm{GeV}}{E}\right)\mathrm{eV}$$

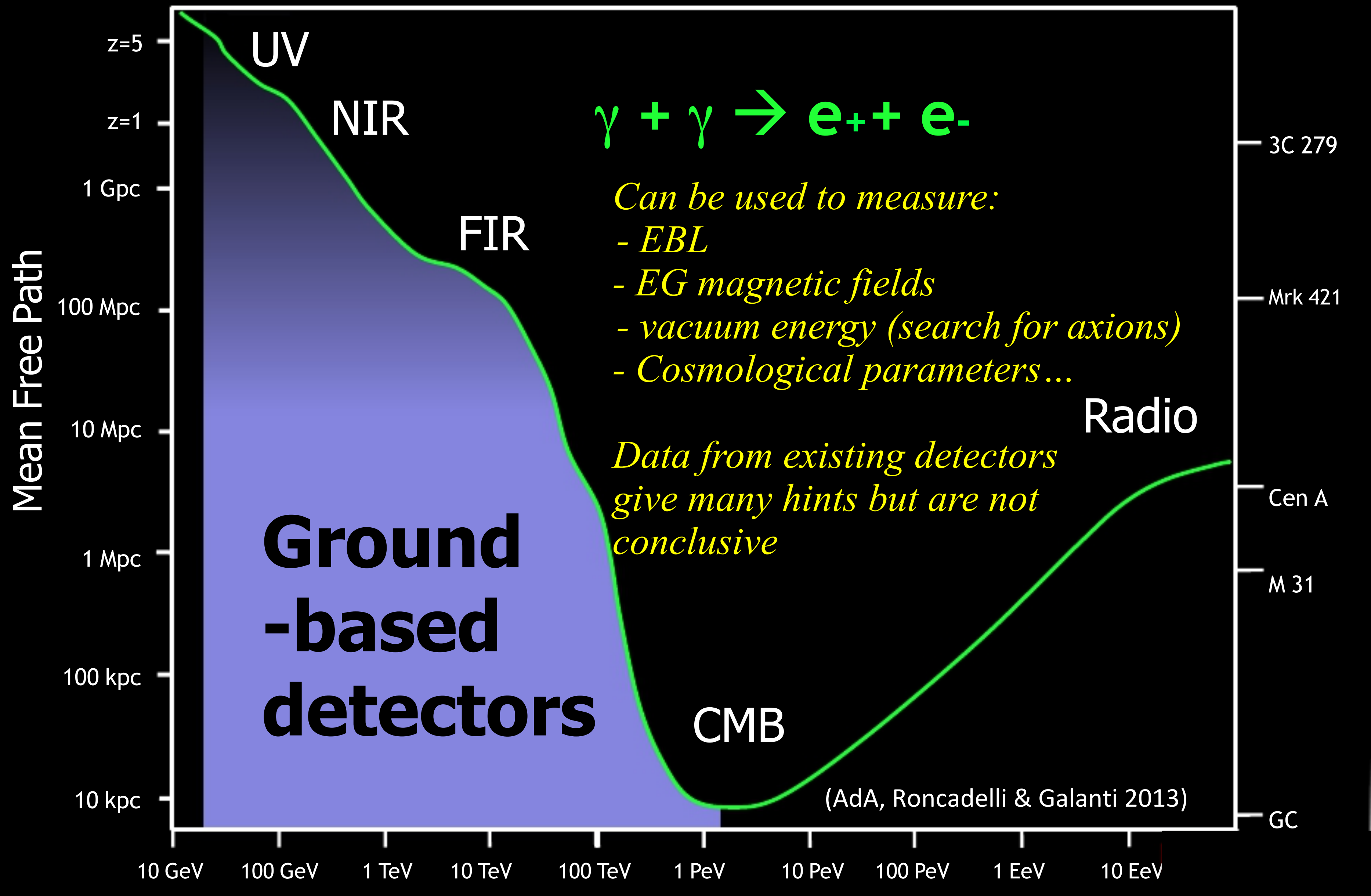




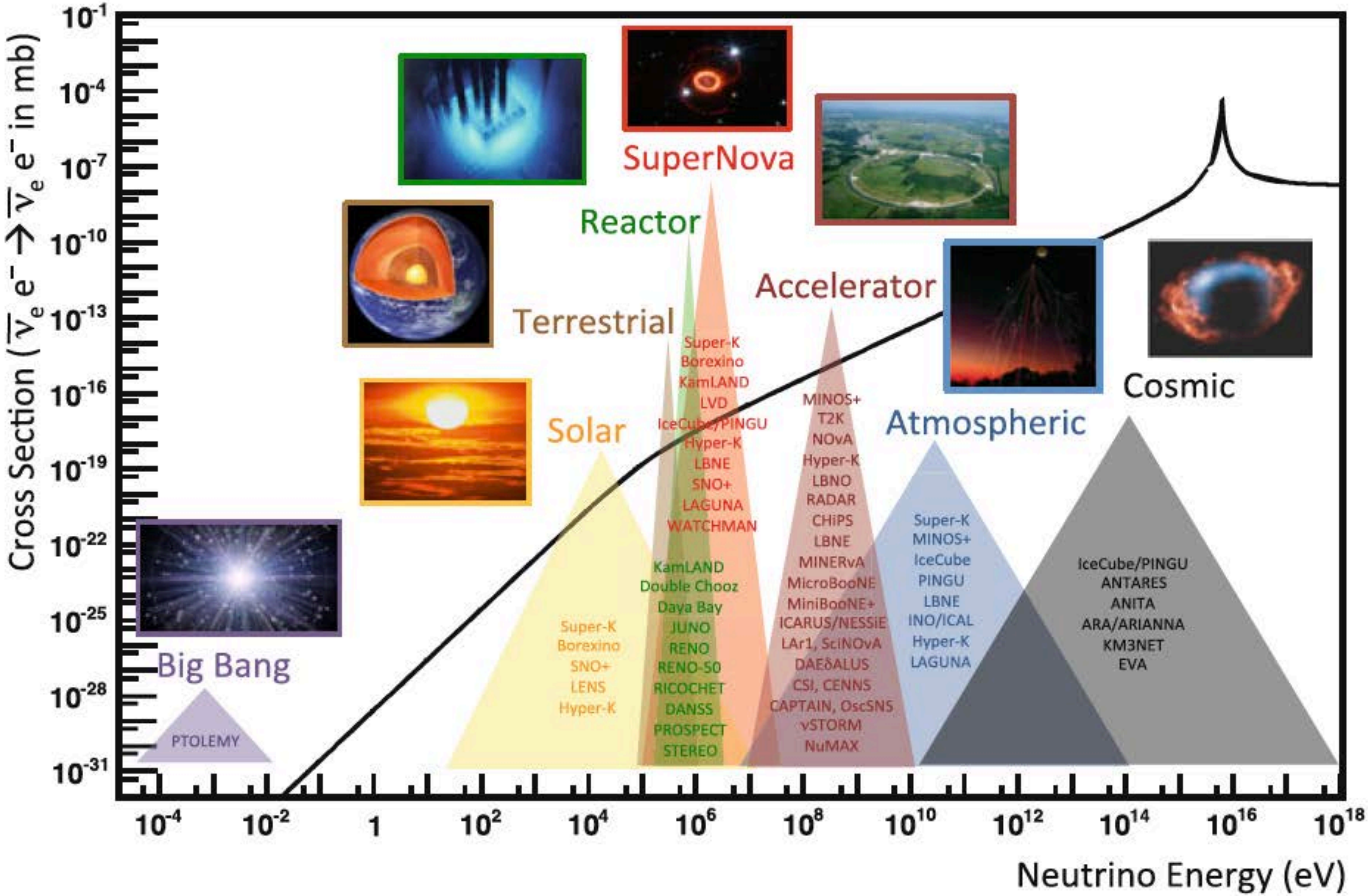


$$\Phi_{obs}(E,z) \equiv \Phi_{em}(E) \times e^{-\tau(E,z)}$$

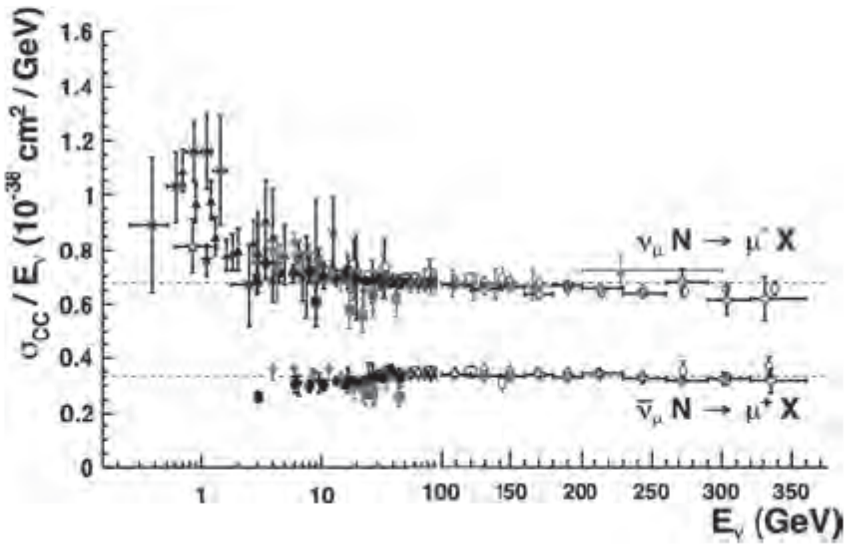
The γ horizon: nuisance and resource



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

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

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

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

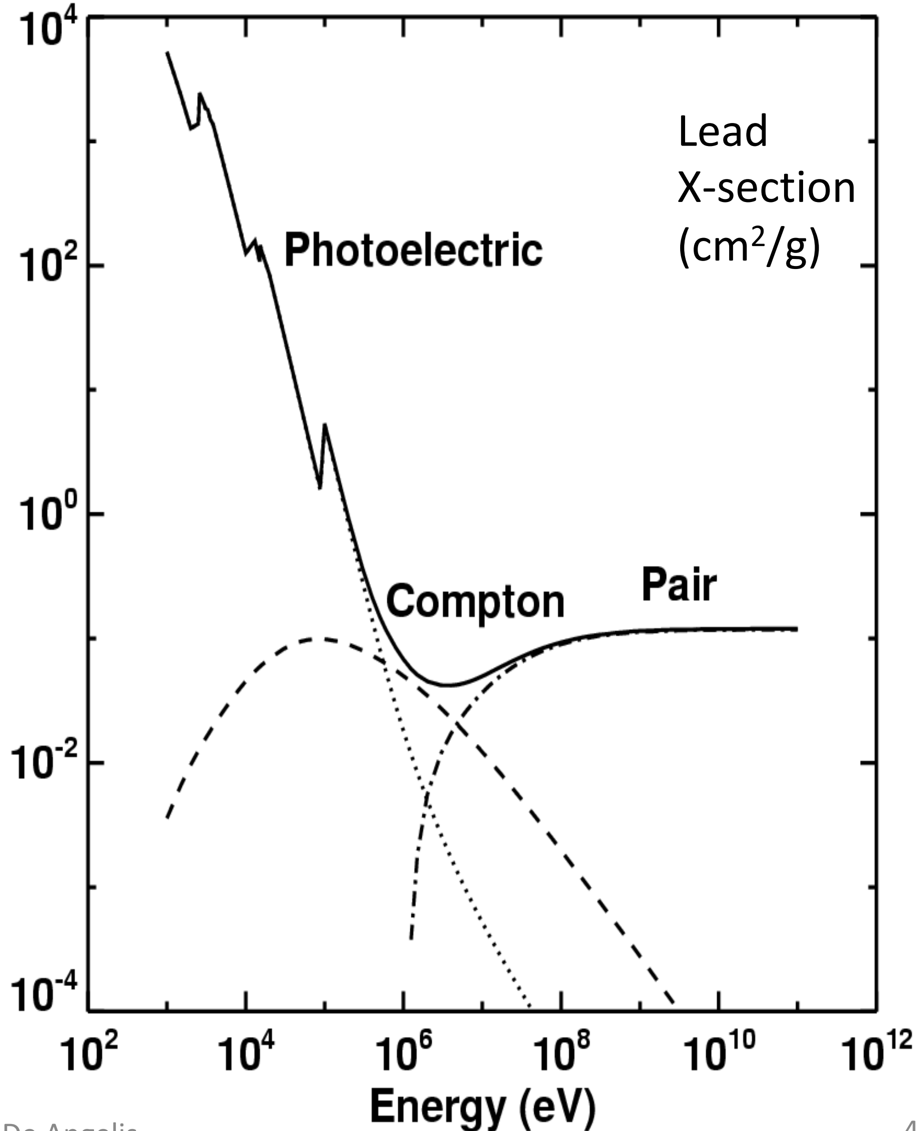
Solar neutrinos, which have MeV energies, typically cross the Earth undisturbed (see a more complete discussion in Chap. 9).

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

Interaction with matter

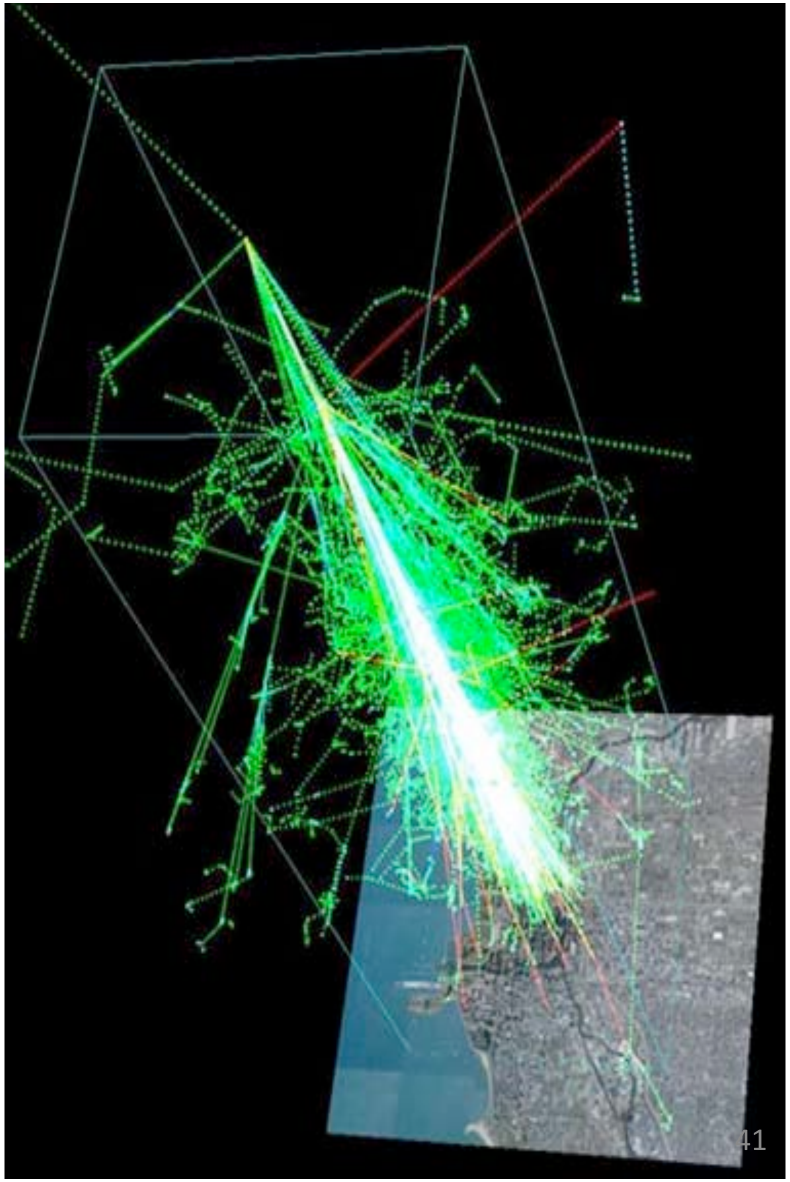
Interactions of photons with matter above the keV

- 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



Multiplicative showers (Rossi 1934)

- Cascades of particles produced as the result of a primary high-energy particle interacting with the atmosphere
  - 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

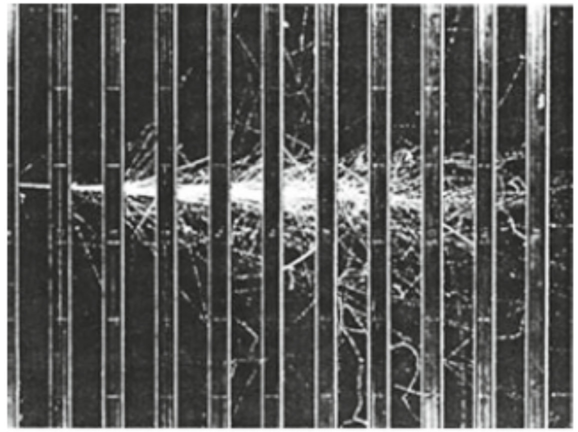
$$E(t) = E_0/2^t$$

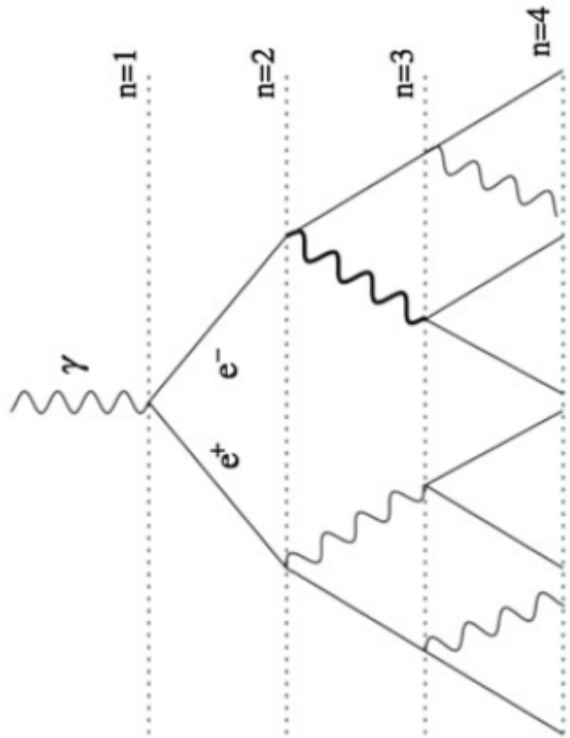
- The multiplication process will cease when $E(t)=E_C$

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

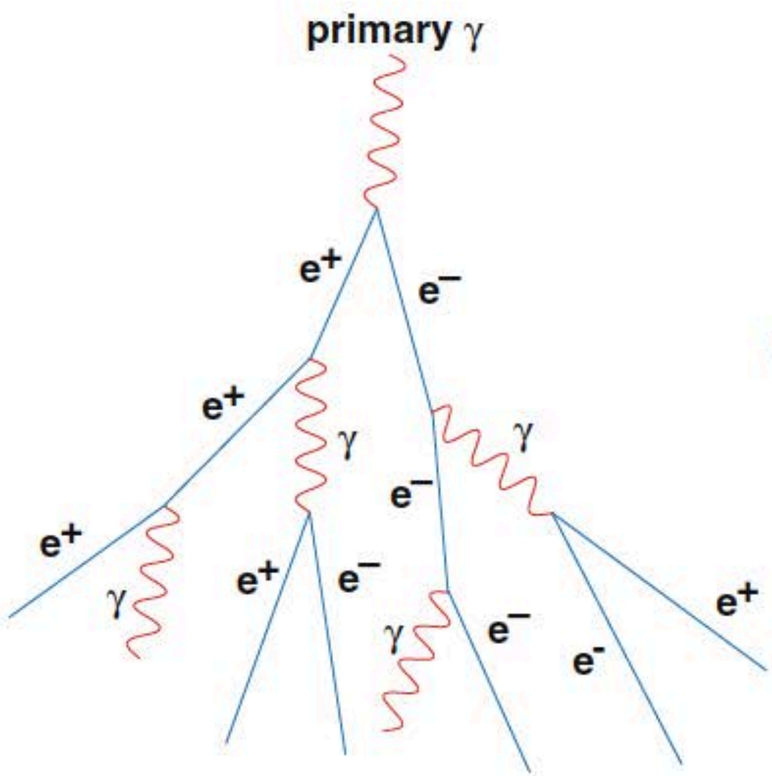
and the number of particles at this point will be

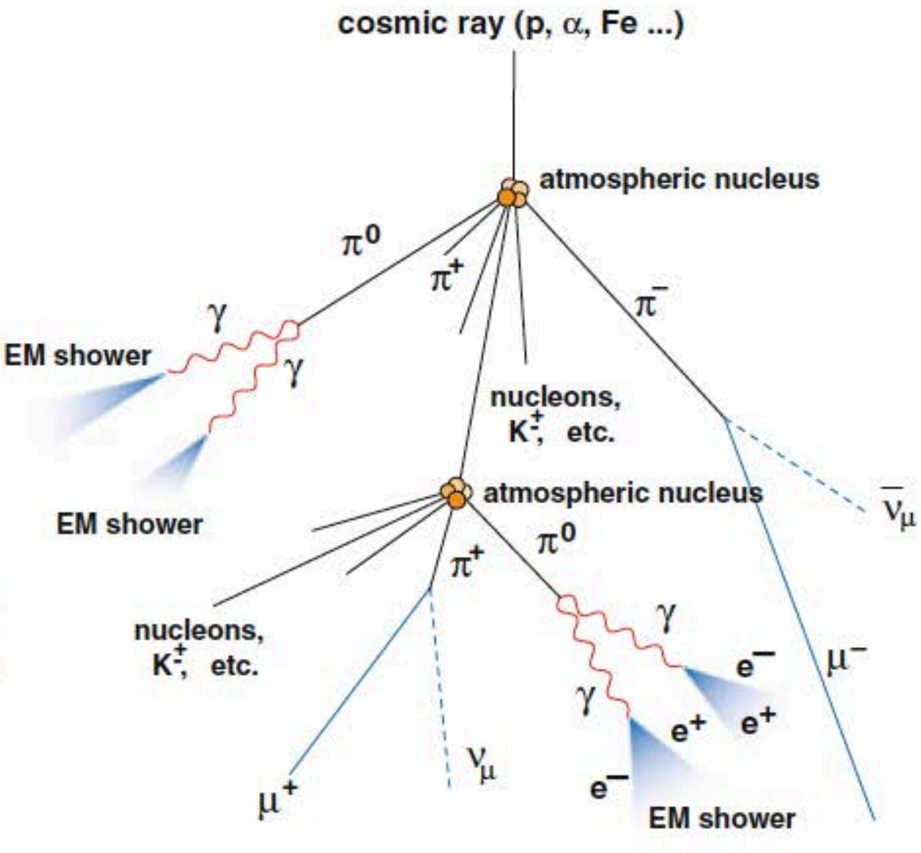
$$N_{max} = \exp(t_{max} \ln 2) = E_0 / E_C$$





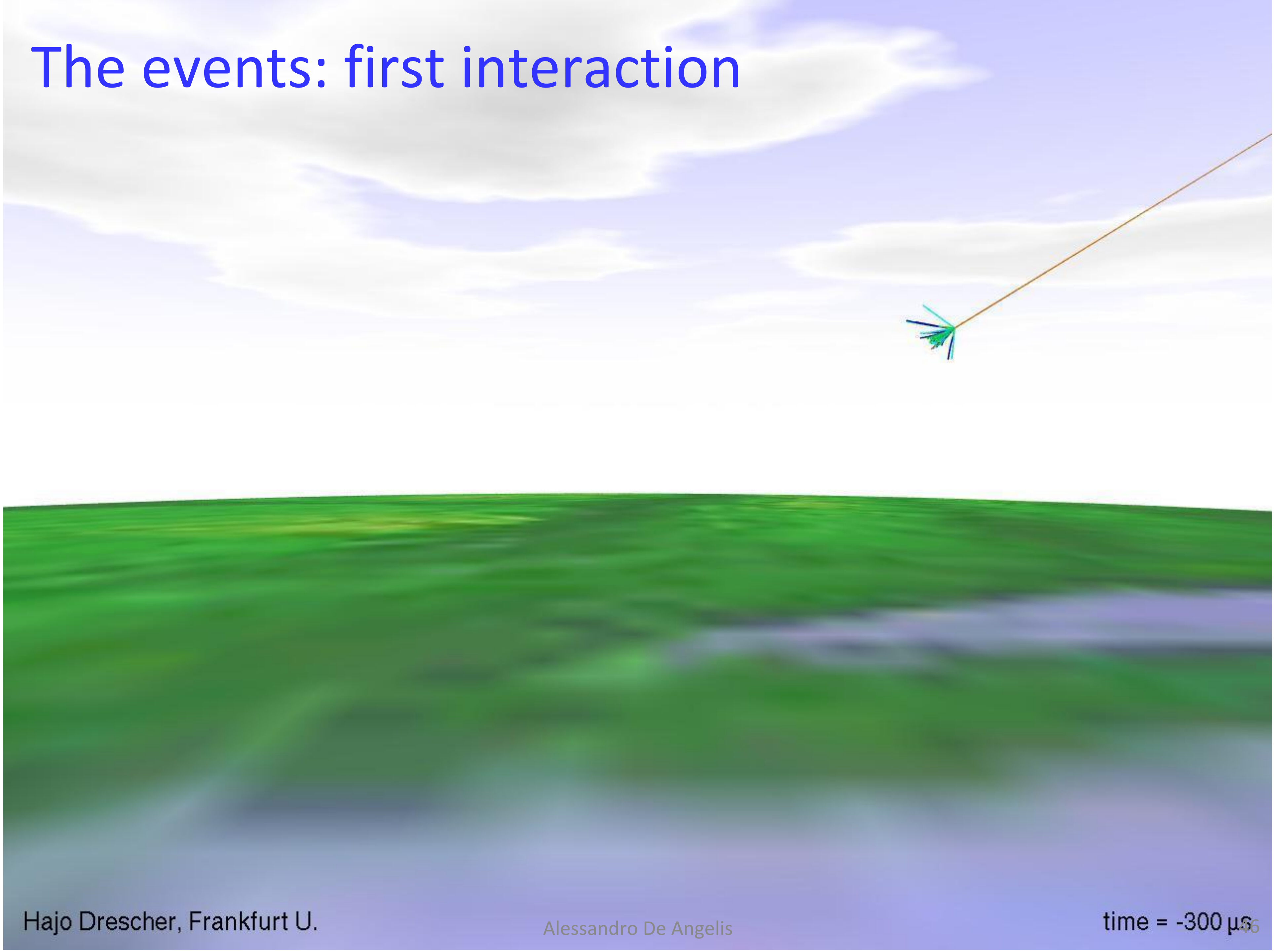
Extensive air showers (EAS)



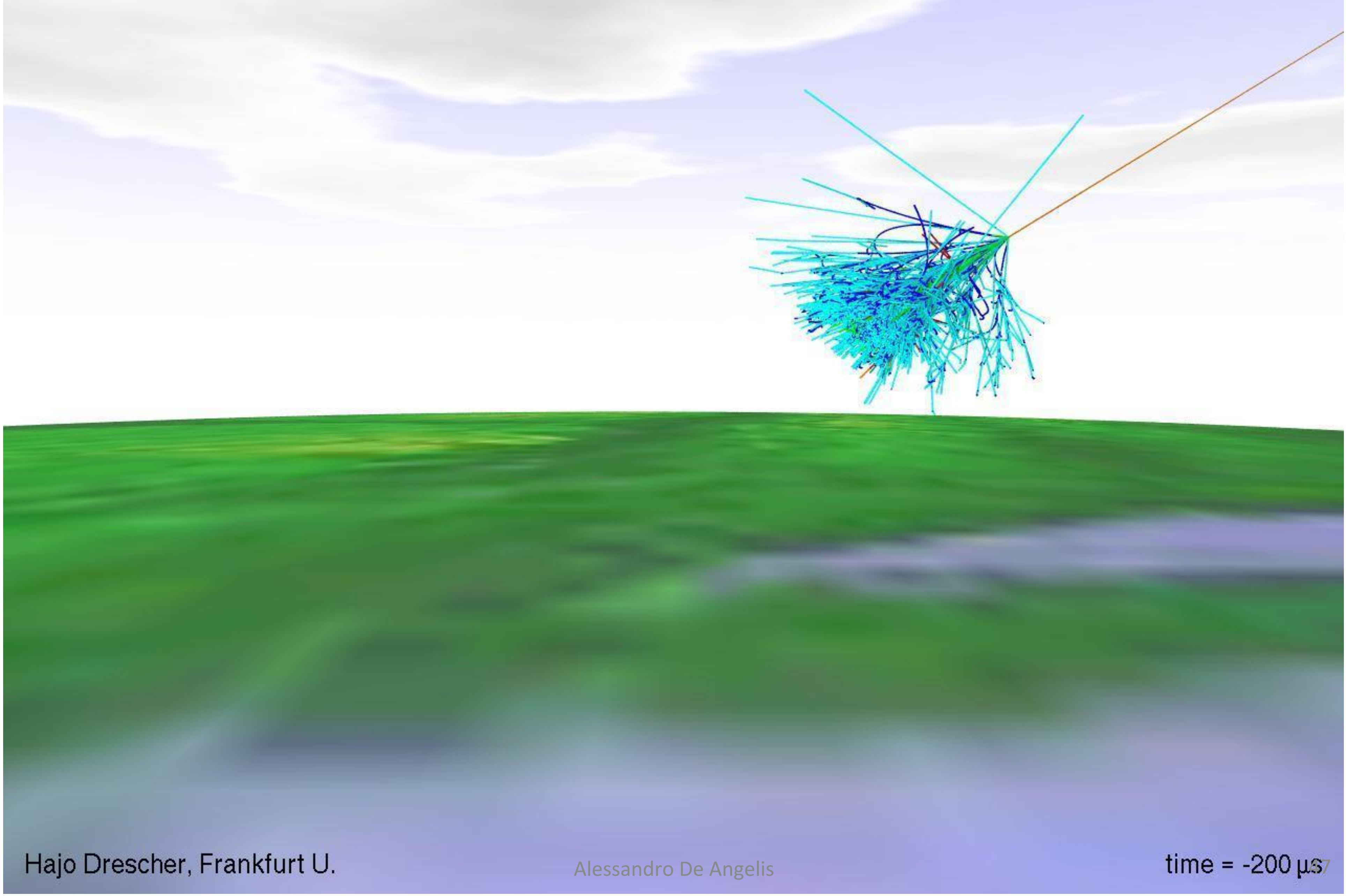


The events: Cosmic rays “rain”

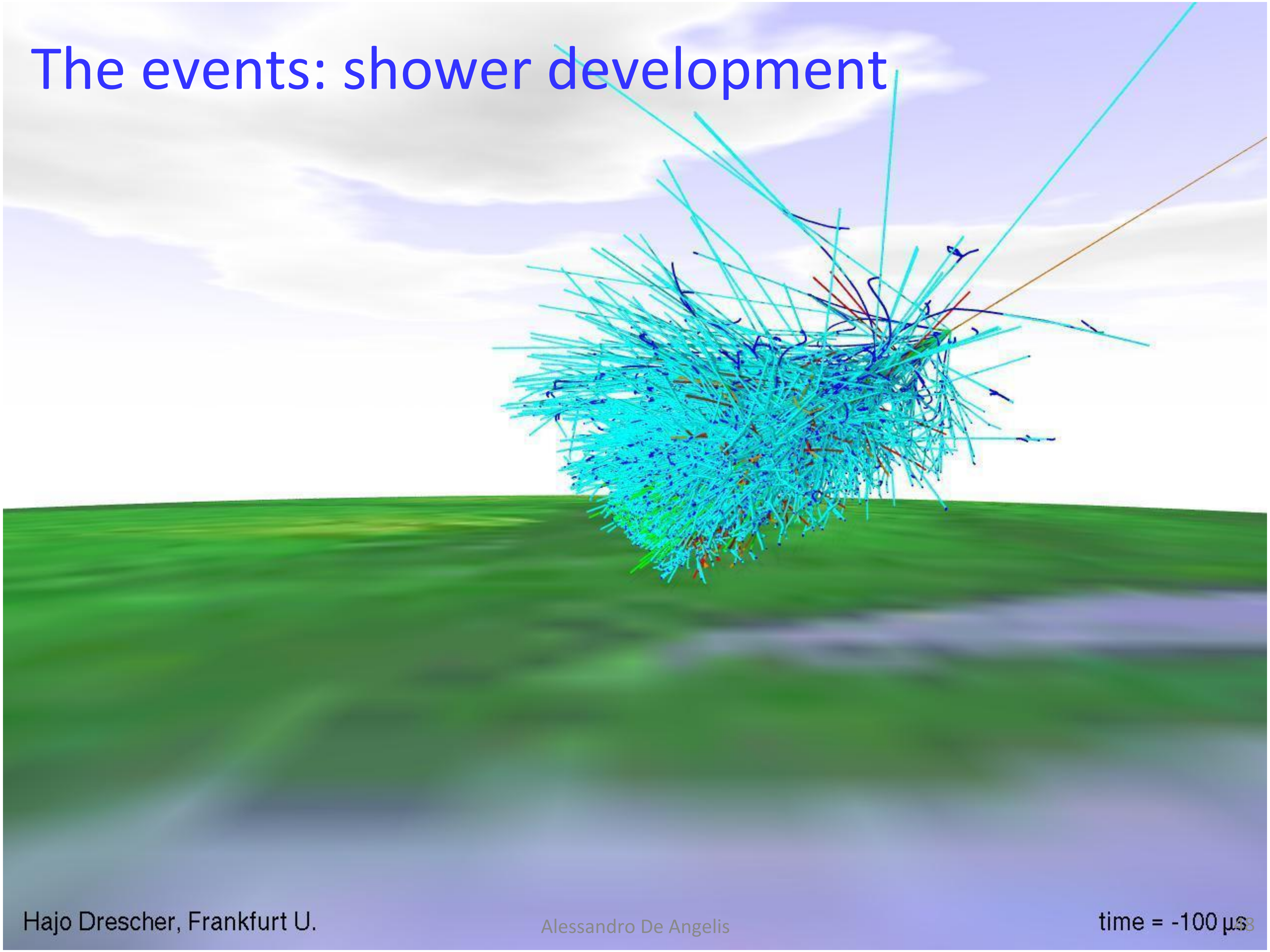
The events: first interaction



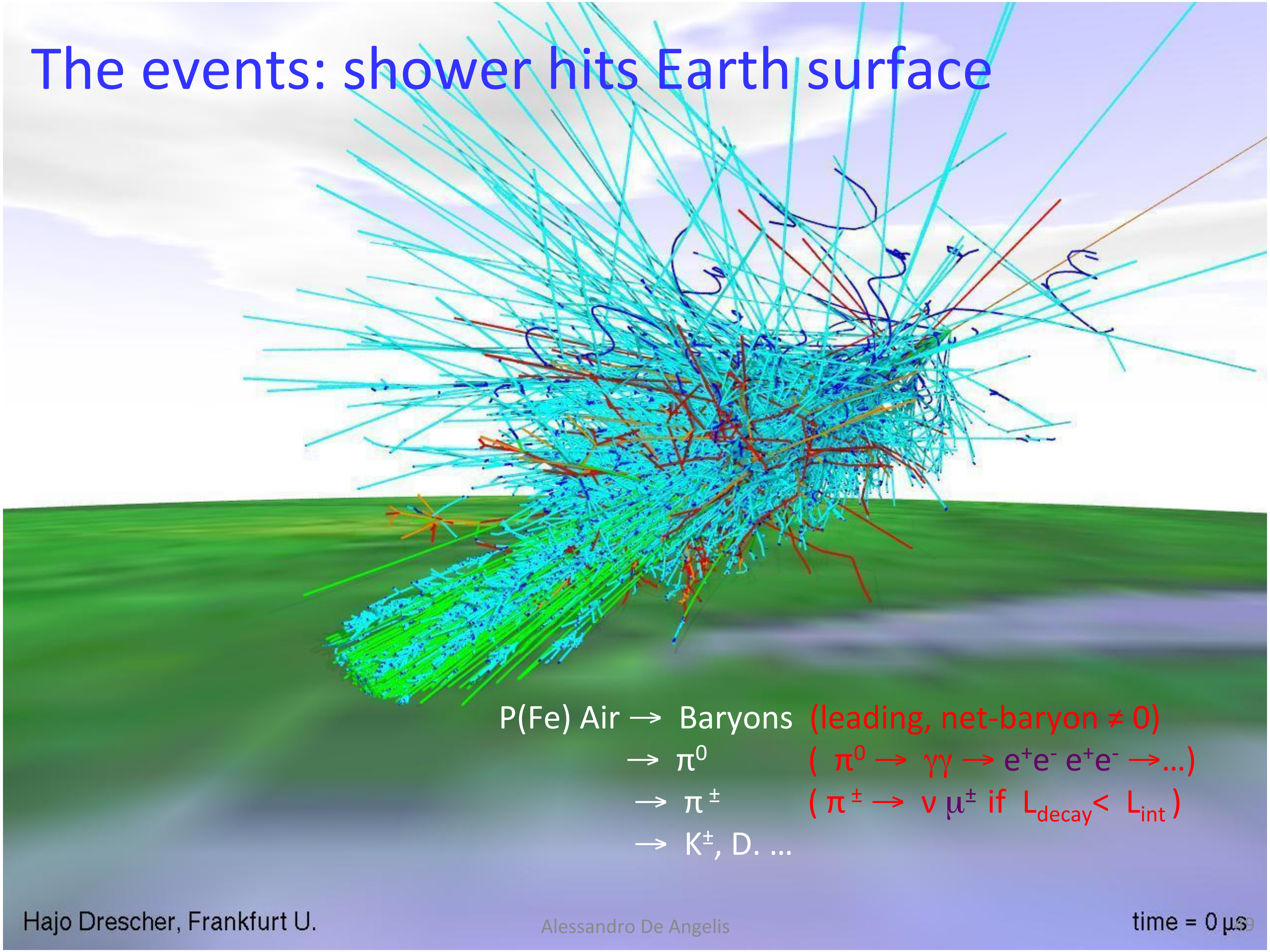
The events: shower development



The events: shower development



The events: shower hits Earth surface



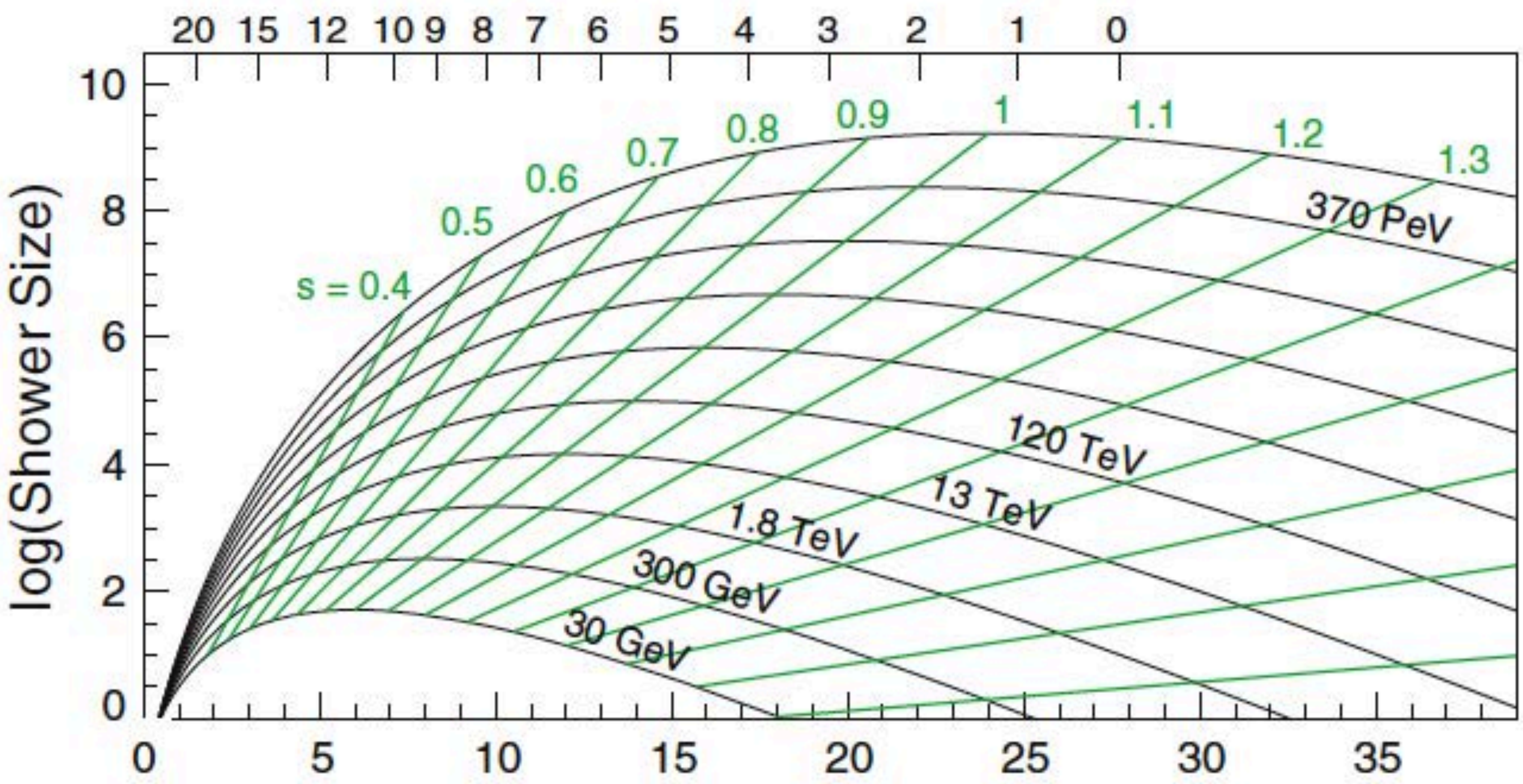
P(Fe) Air $\rightarrow$ Baryons (leading, net-baryon ≠ 0)

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

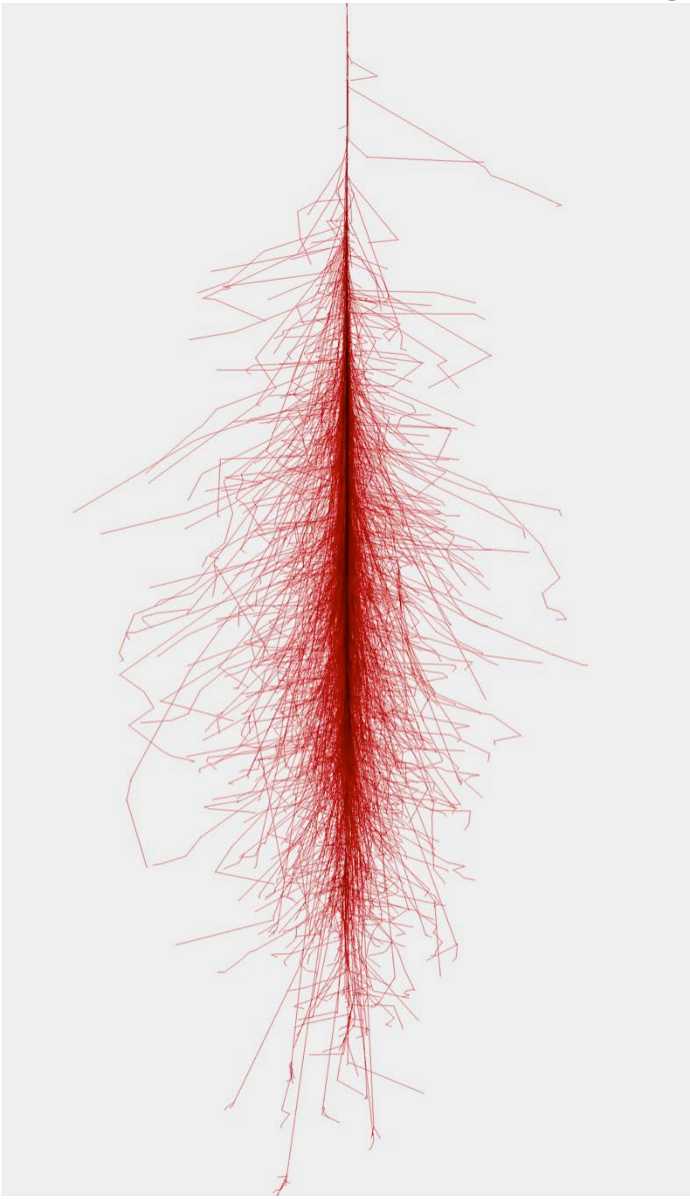
$\rightarrow \pi^\pm$ ($\pi^\pm \rightarrow \nu\, \mu^\pm$ if $L_{decay} < L_{int}$)

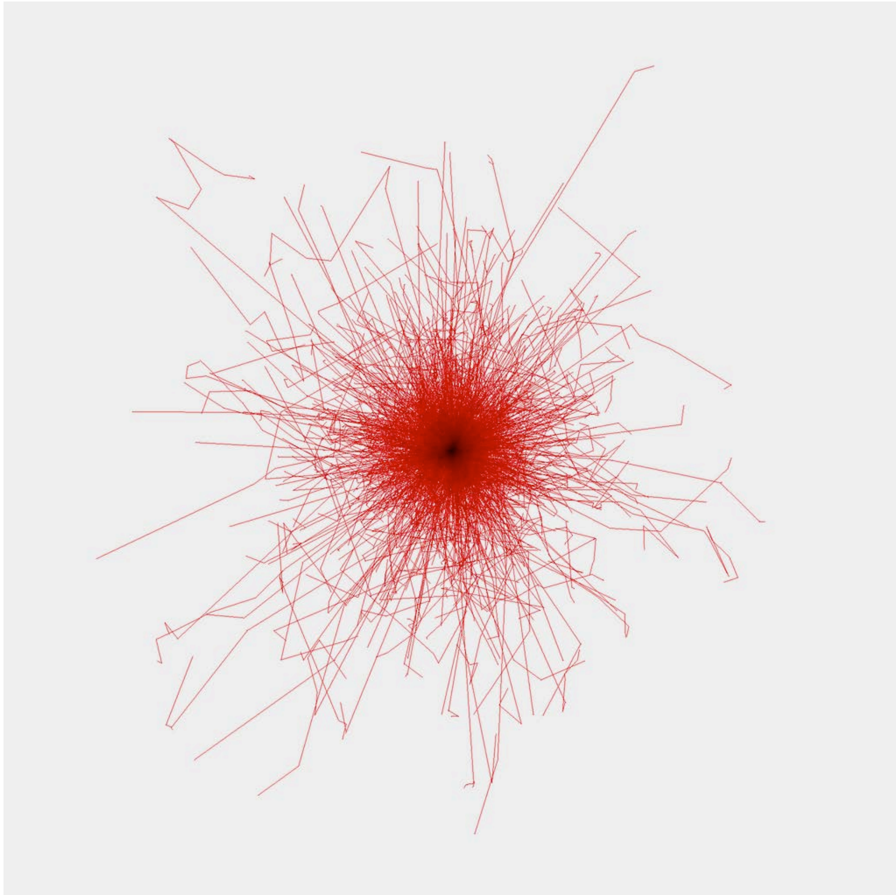
$\rightarrow K^\pm$, D. …

Photon-initiated shower in the atmosphere



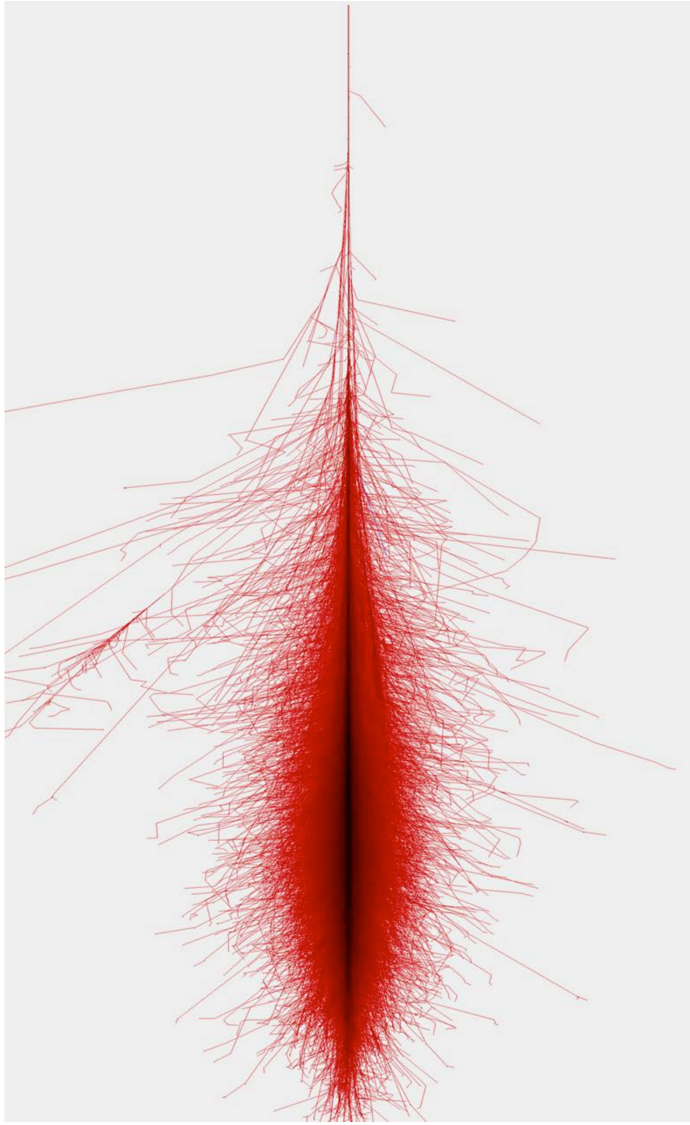
A frequent experimental problem: γ/hadron separation

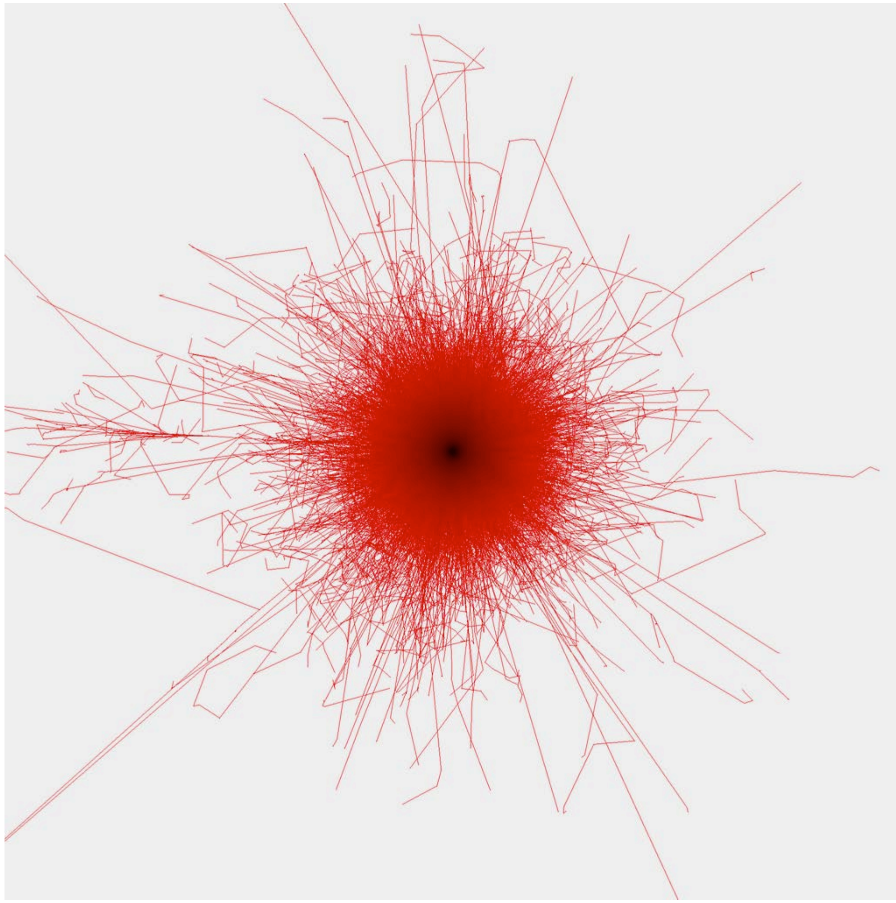




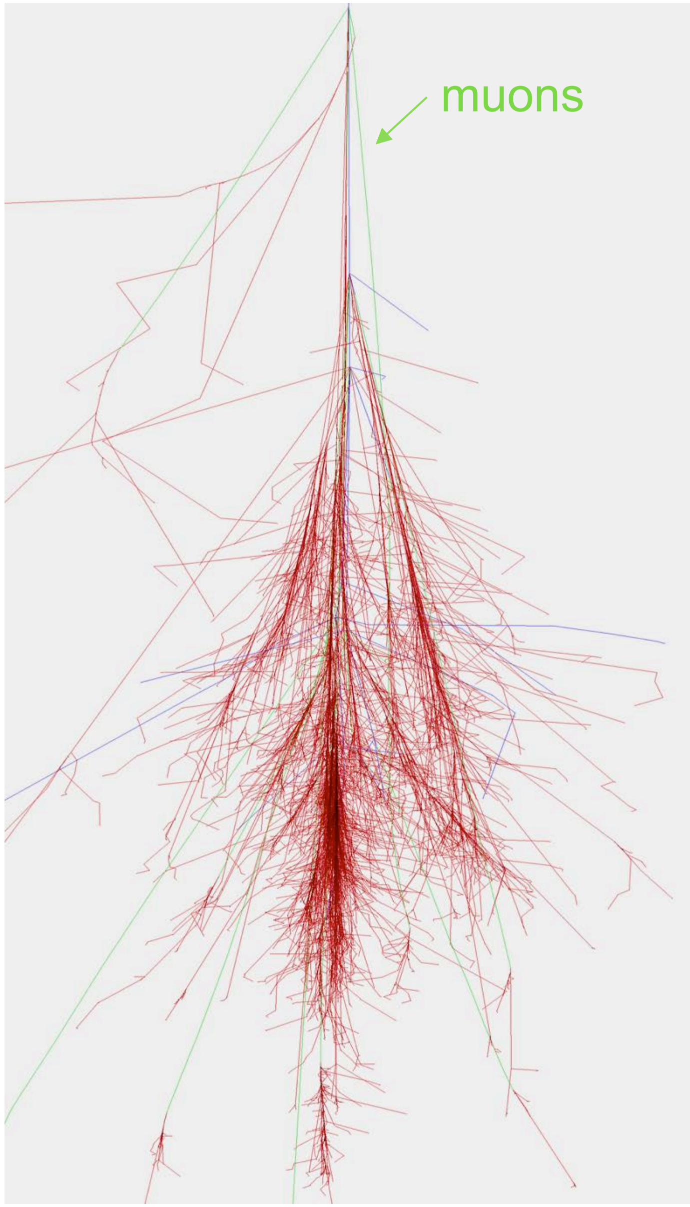
Simulated gamma
in the atmosphere:
50 GeV

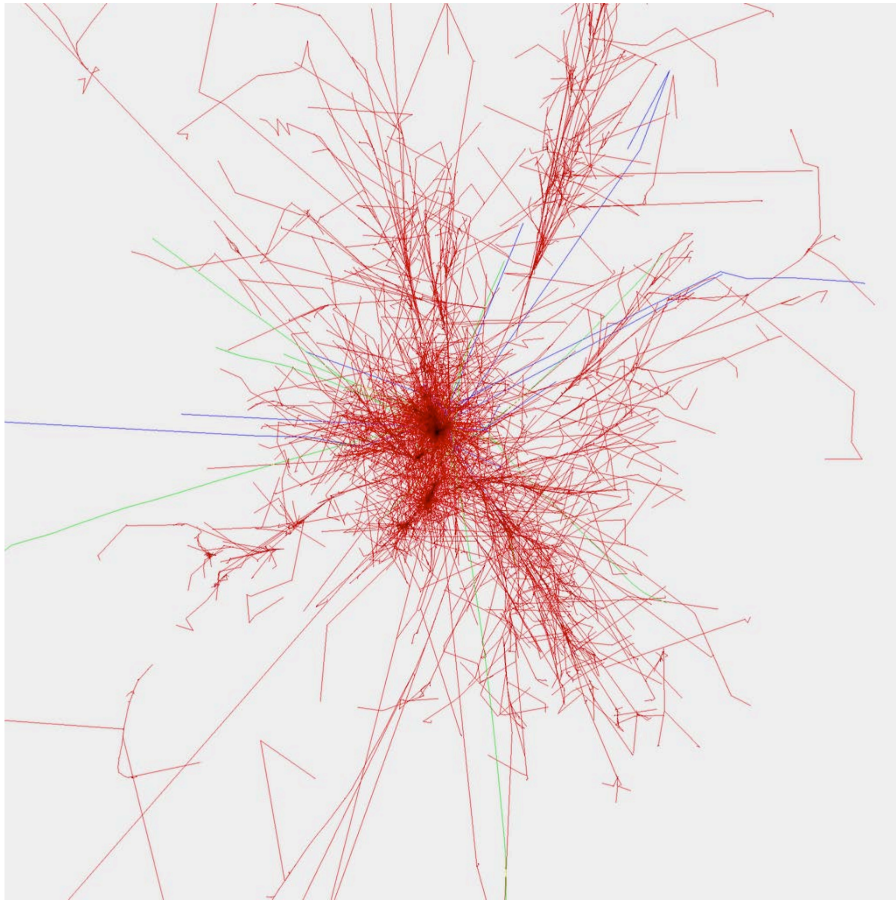
Simulated gamma
1 TeV





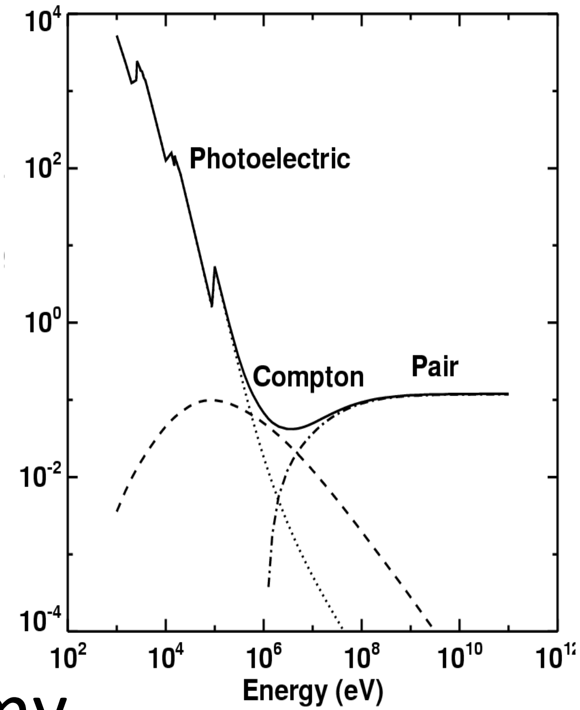
Simulated proton 100 GeV (the ennemy)





Photons in the nonthermal region

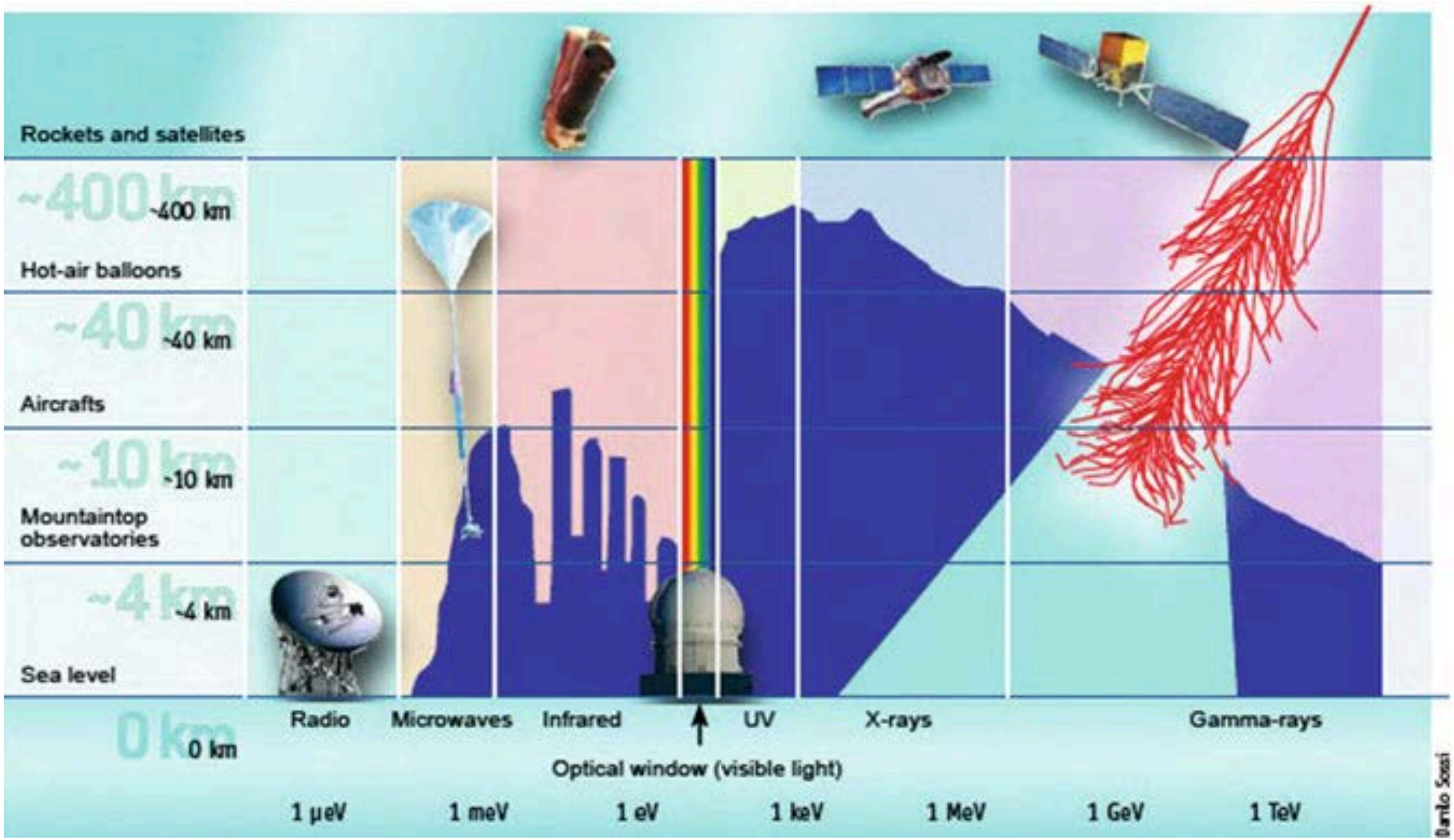
- LE or MeV : 0.1 (0.03) -100 (30) MeV
- HE or GeV : 0.1 (0.03) -100 (30) GeV
- VHE or TeV : 0.1 (0.03) - 100 (30) TeV
- UHE or PeV : 0.1 (0.03) -100 (30) PeV



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

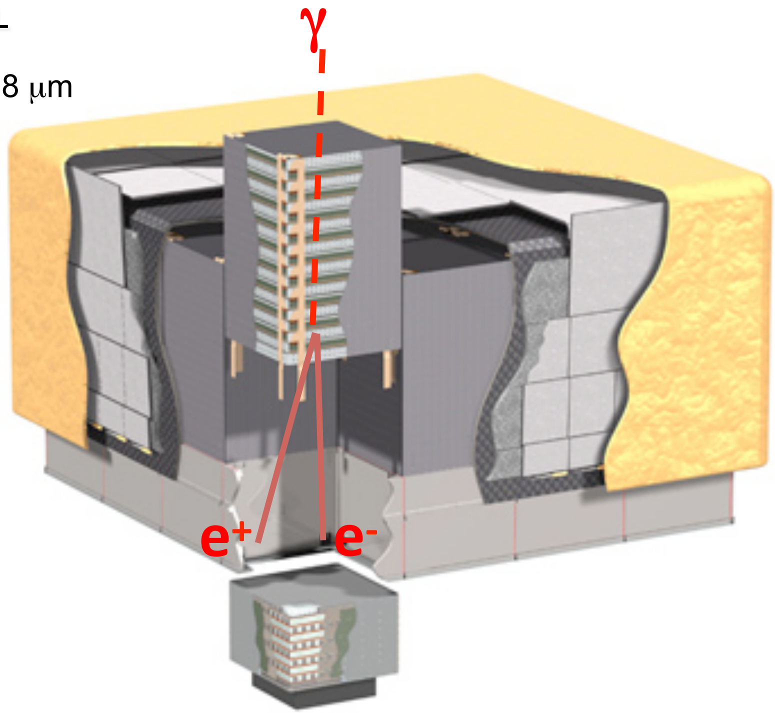
- When no ambiguity, we call "HE" all the HE and VHE+

Transparency of the atmosphere

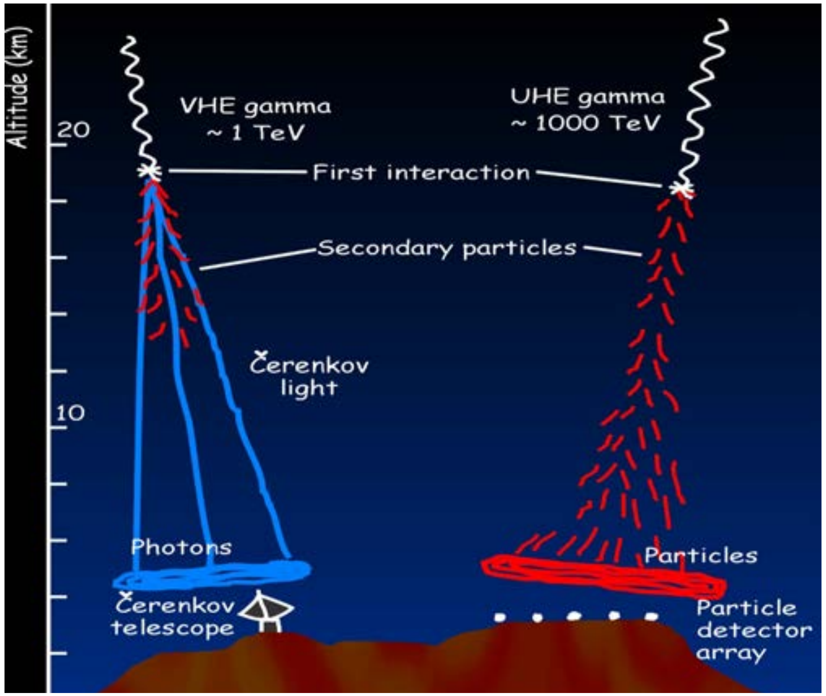


Detectors

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



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

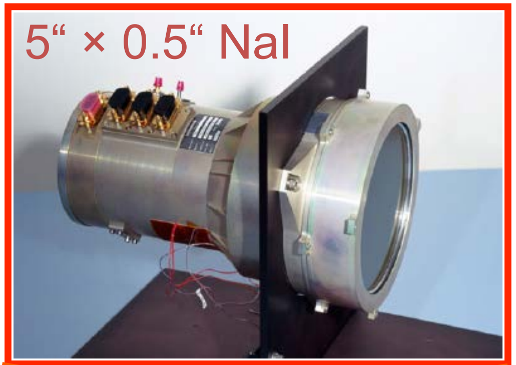


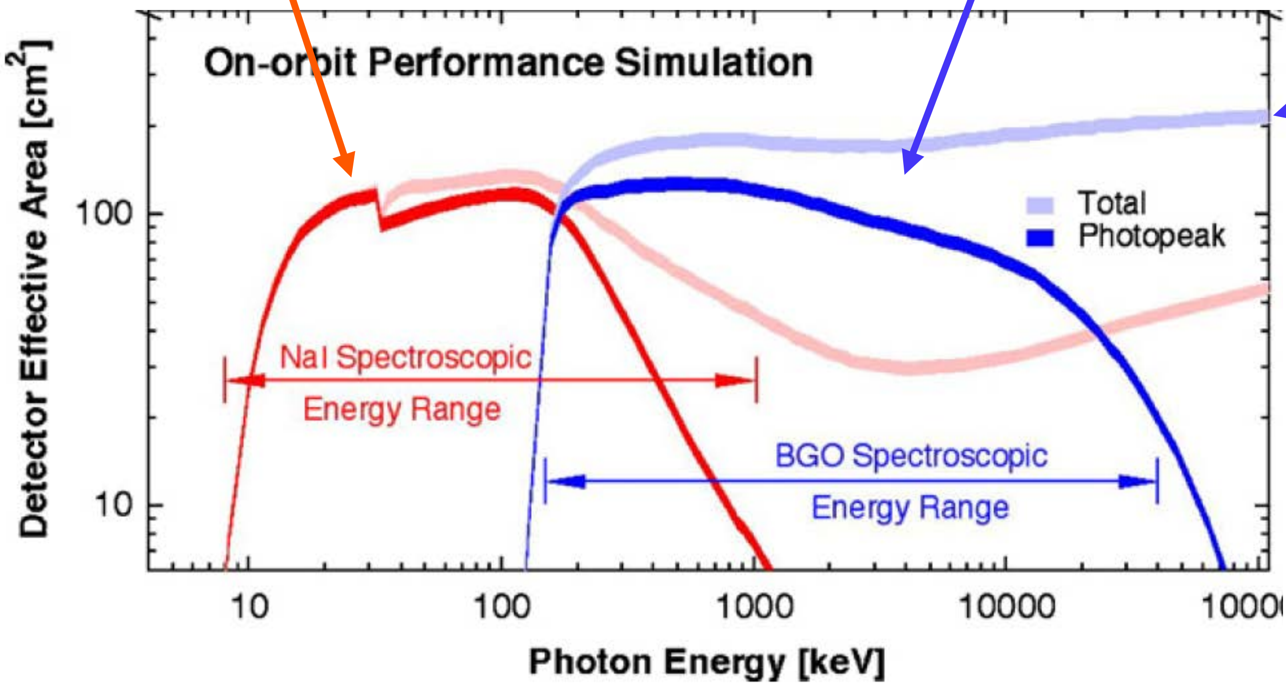
HEP detectors!

MeV photon detectors

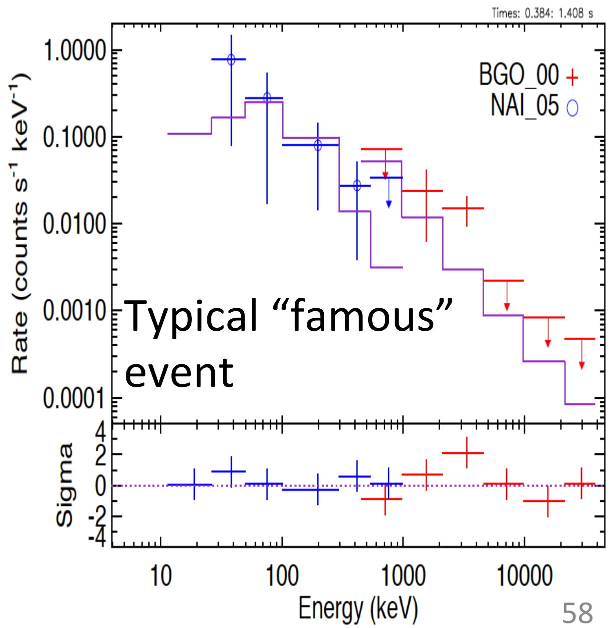
- The MeV region is crucial for nuclear physics
- An “easy” way to do MeV photon detectors
  - Scintillating crystals
- But:
  - Bad directionality
  - No polarization information
- Typically used in Gamma-Ray Burst monitors

Fermi GBM detectors





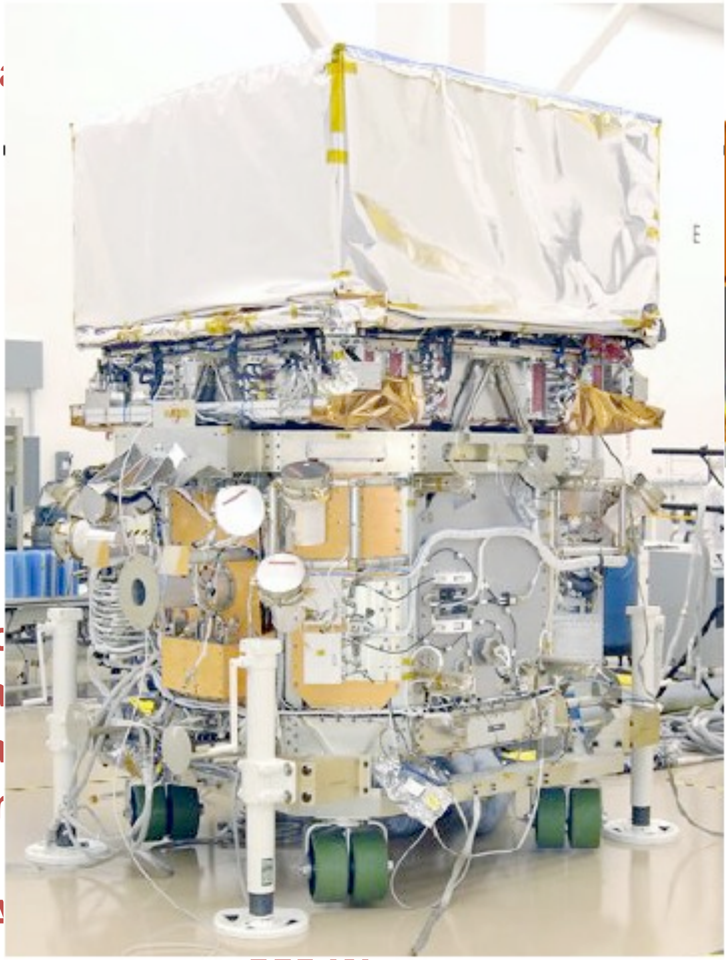
effective area
≈ 160 cm^2

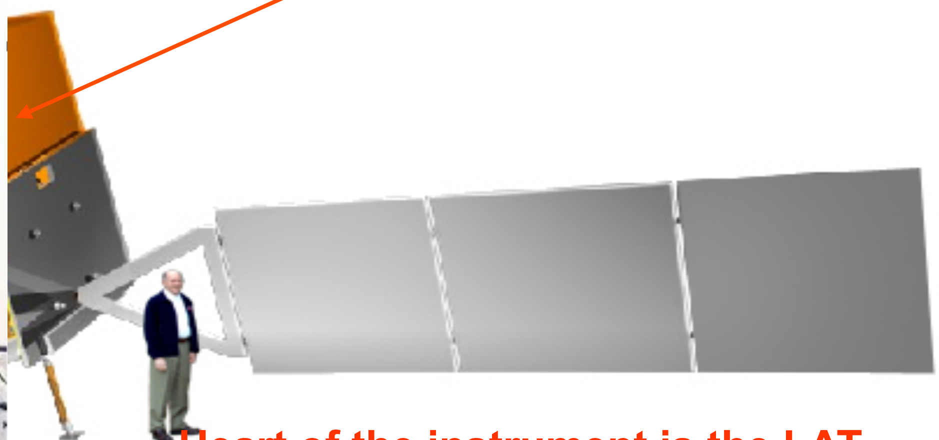


C. Meegan et al. 2009, ApJ, 702,

The GeV (pair production): Fermi and the LAT (June 2008)

Ga

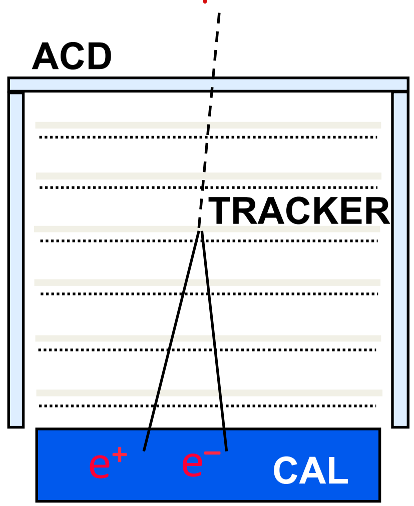




Ro
La
La
Or

LA
Power 650 W

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



LAT overview

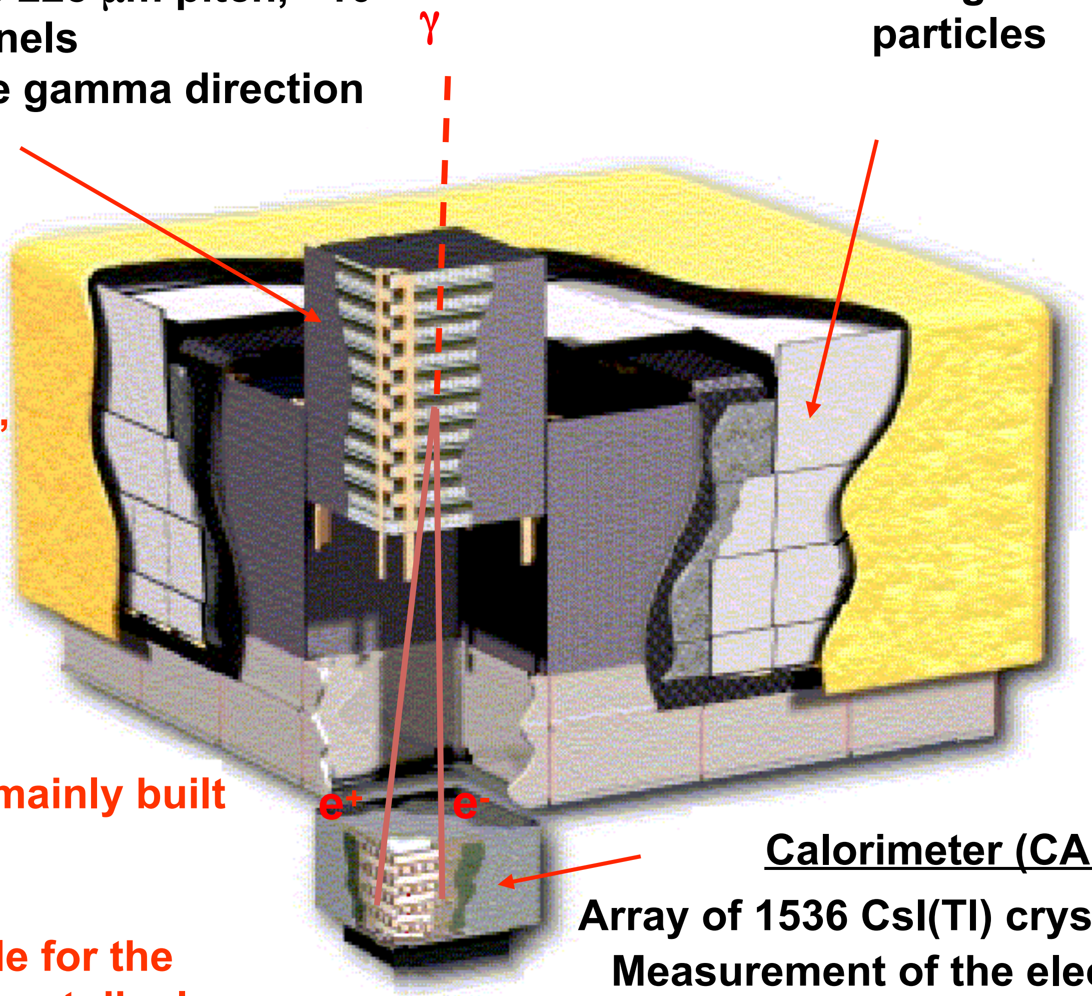
Si-strip Tracker (TKR)

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



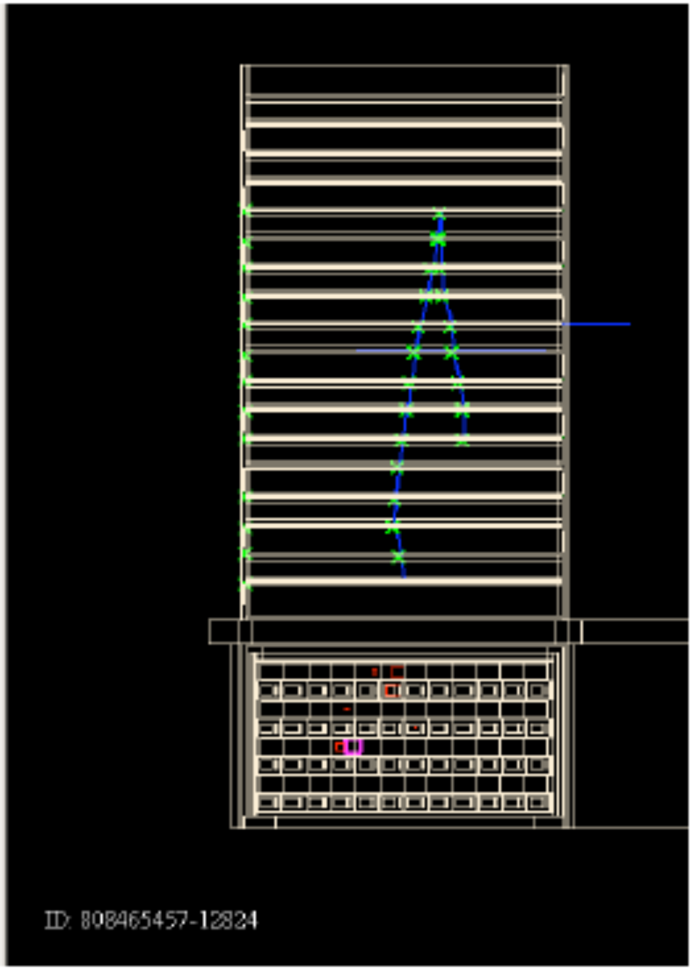
The Silicon tracker is mainly built in Italy

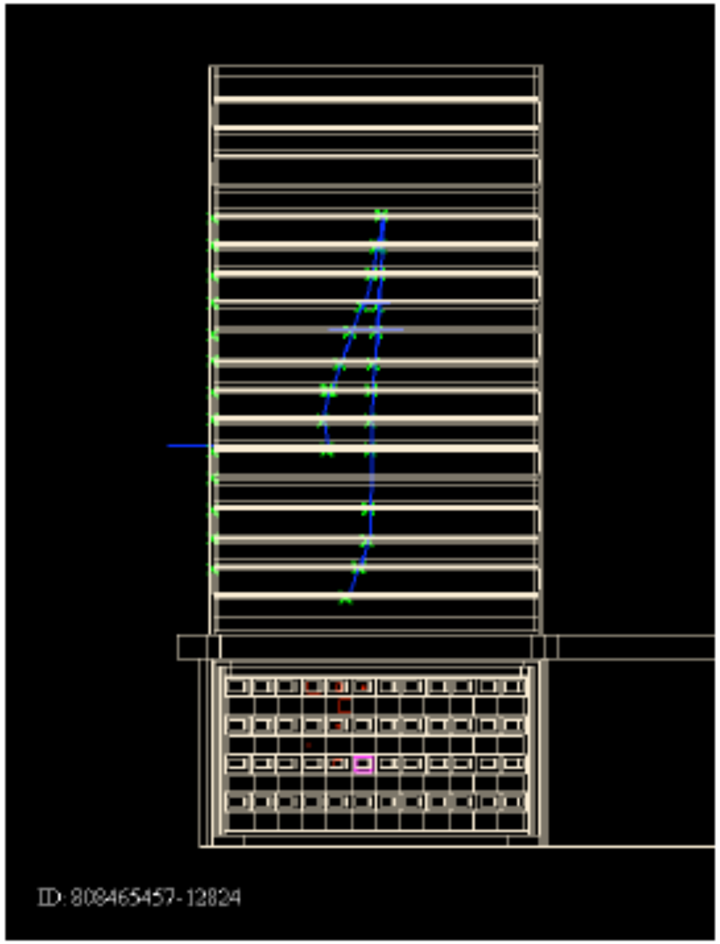
Italy is also responsible for the detector simulation, event display and GRB physics

Calorimeter (CAL)

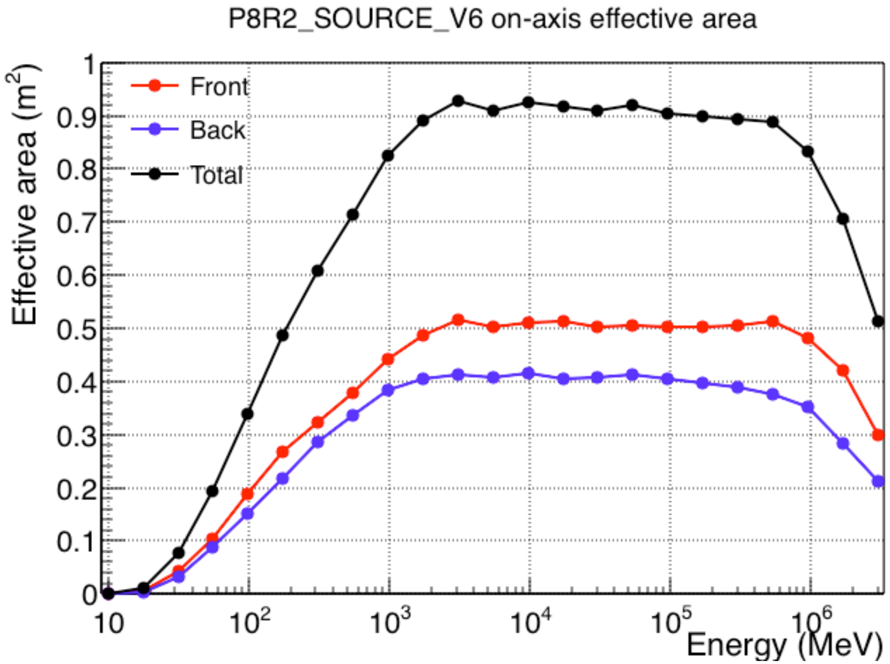
Array of 1536 CsI(Tl) crystals in 8 layers
Measurement of the electron energy

Detection of a gamma-ray





Performance of Fermi (Pass 8)

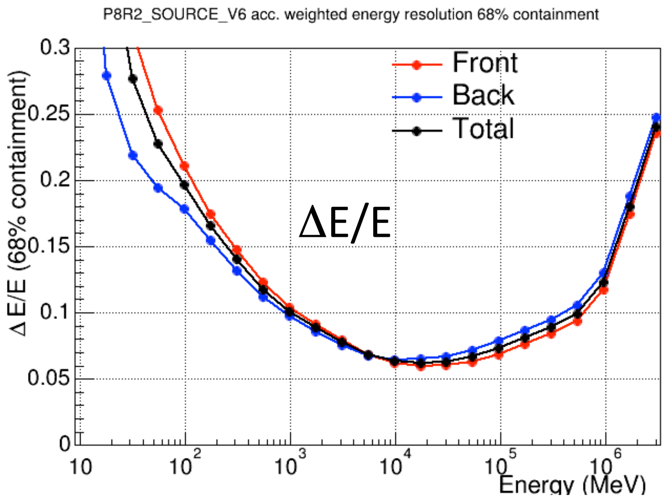


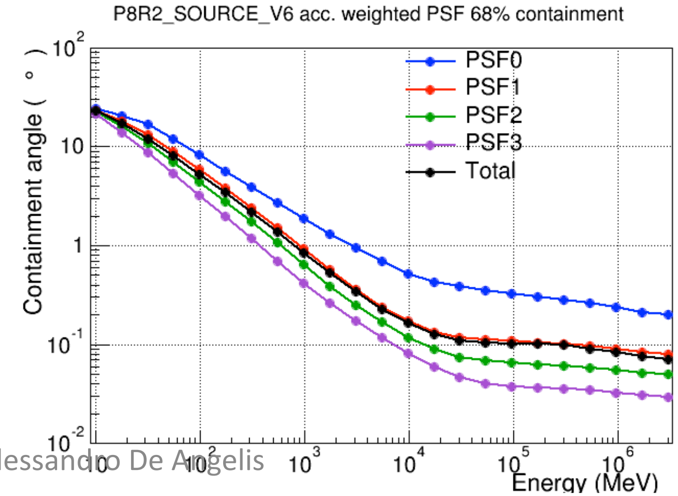
Effective area (Area x efficiency)

~ 1m^2

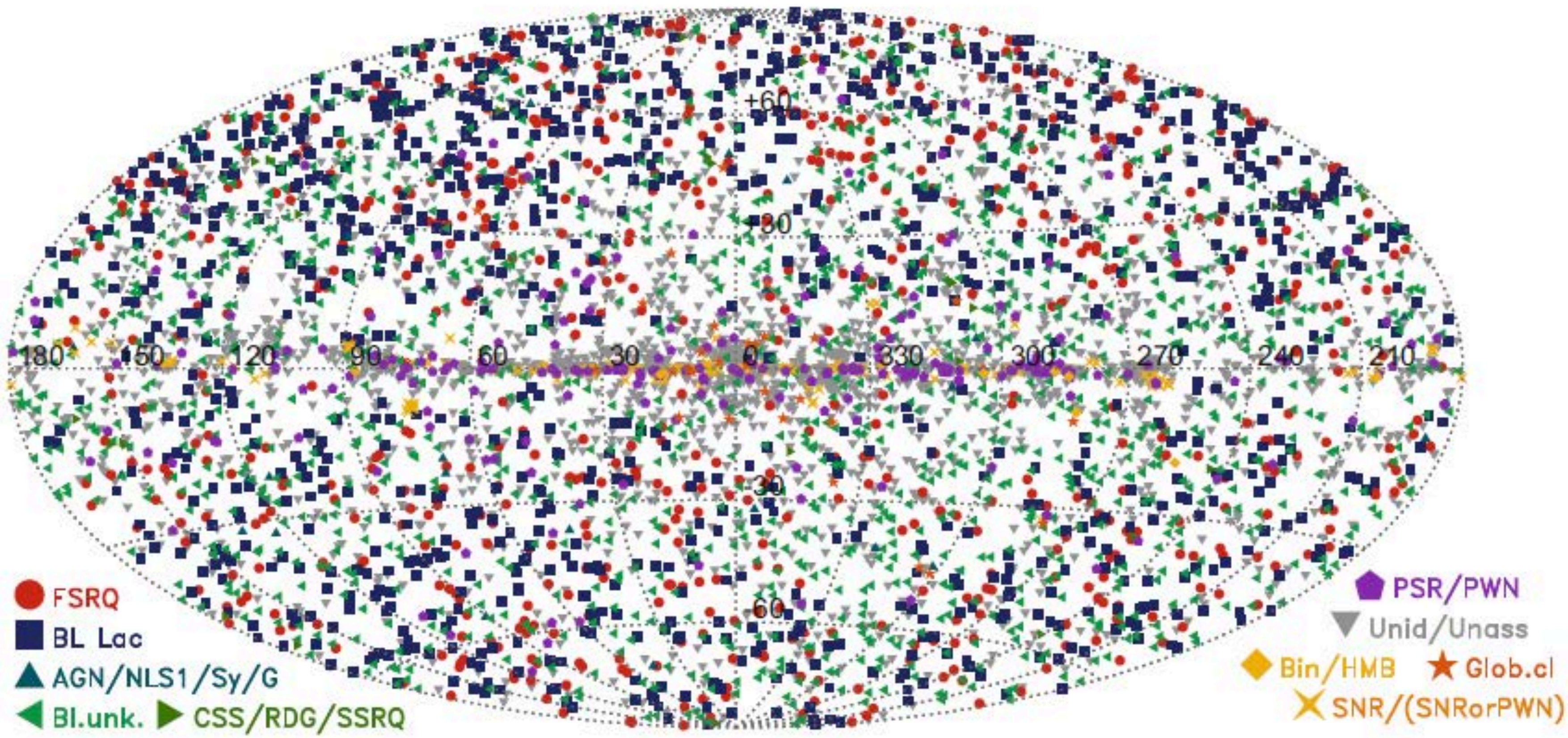
Grows as k lnE from 2 MeV to 2 GeV
Then ~0.9 m^2 from 2 GeV to 700 GeV
Then decreases as k' lnE

Acceptance: 2.5 sr



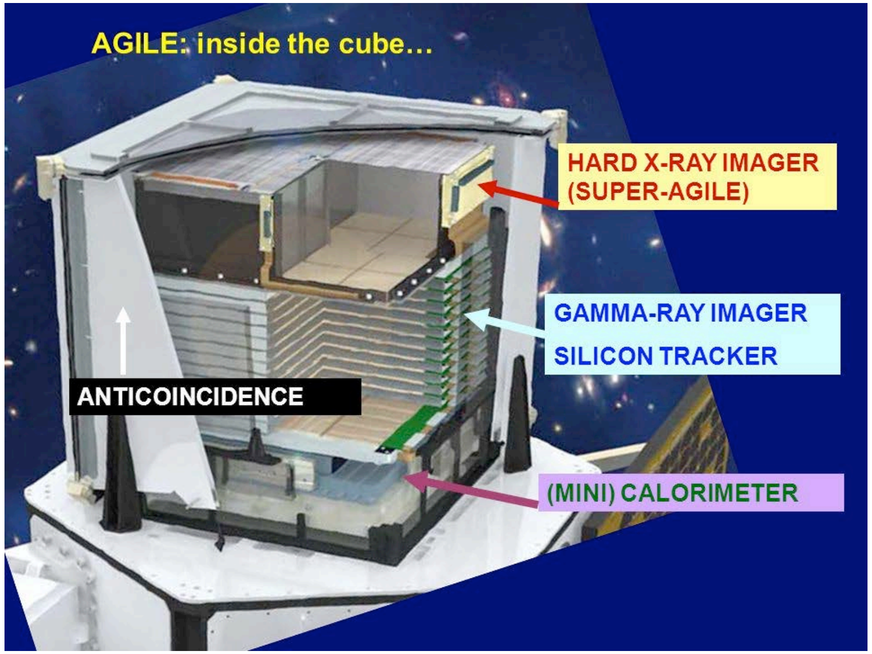


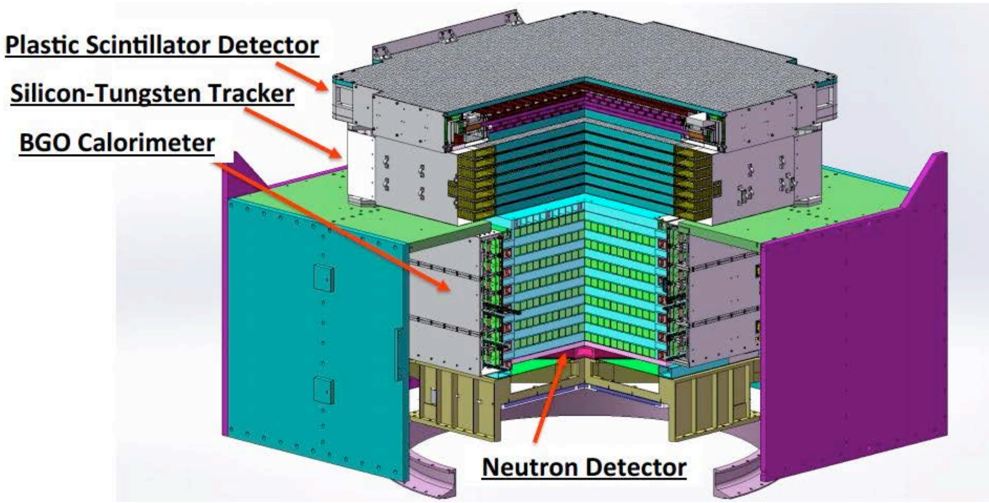
LAT 8-year Point Source Catalog (4th)
> 5000 sources above 100 MeV



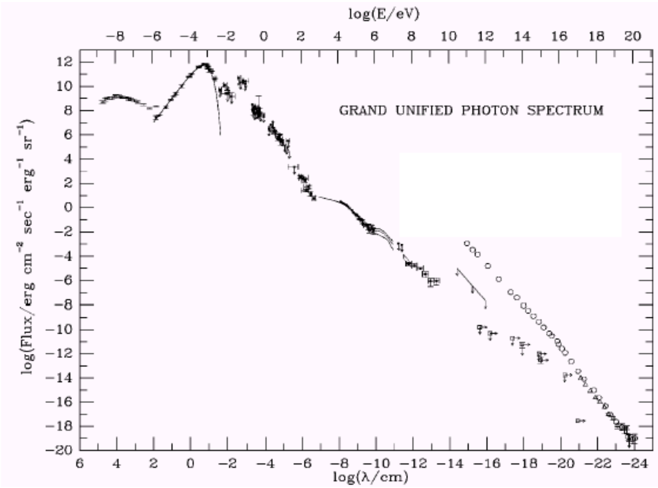
AGILE & DAMPE

- 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

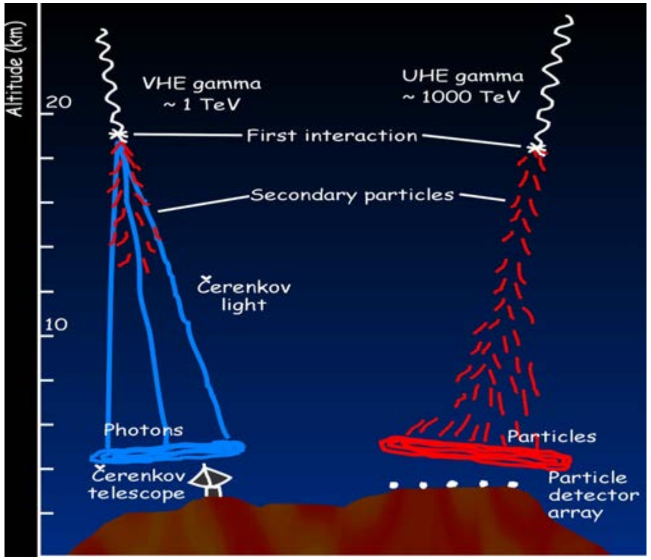


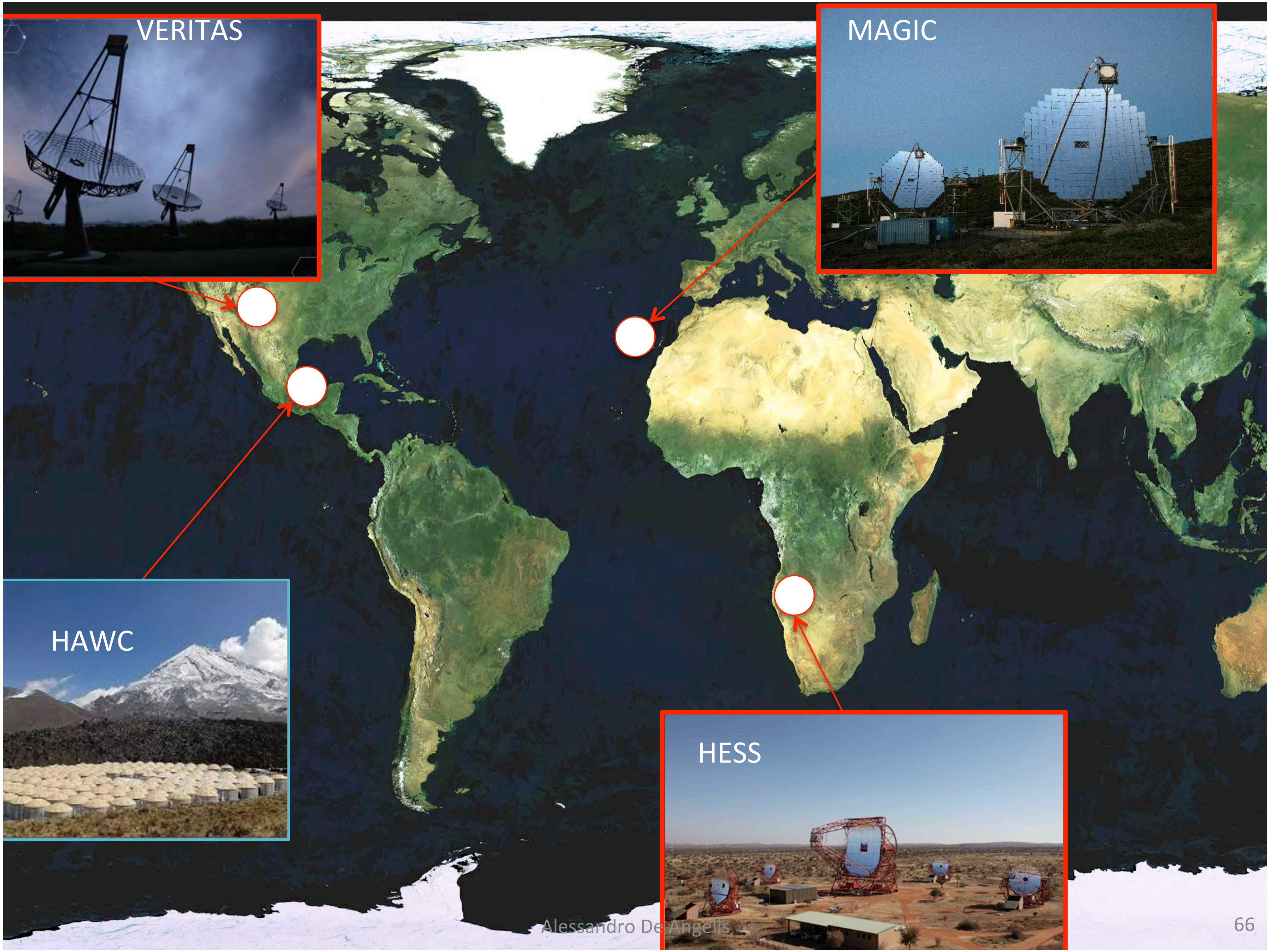


Why detection at ground?



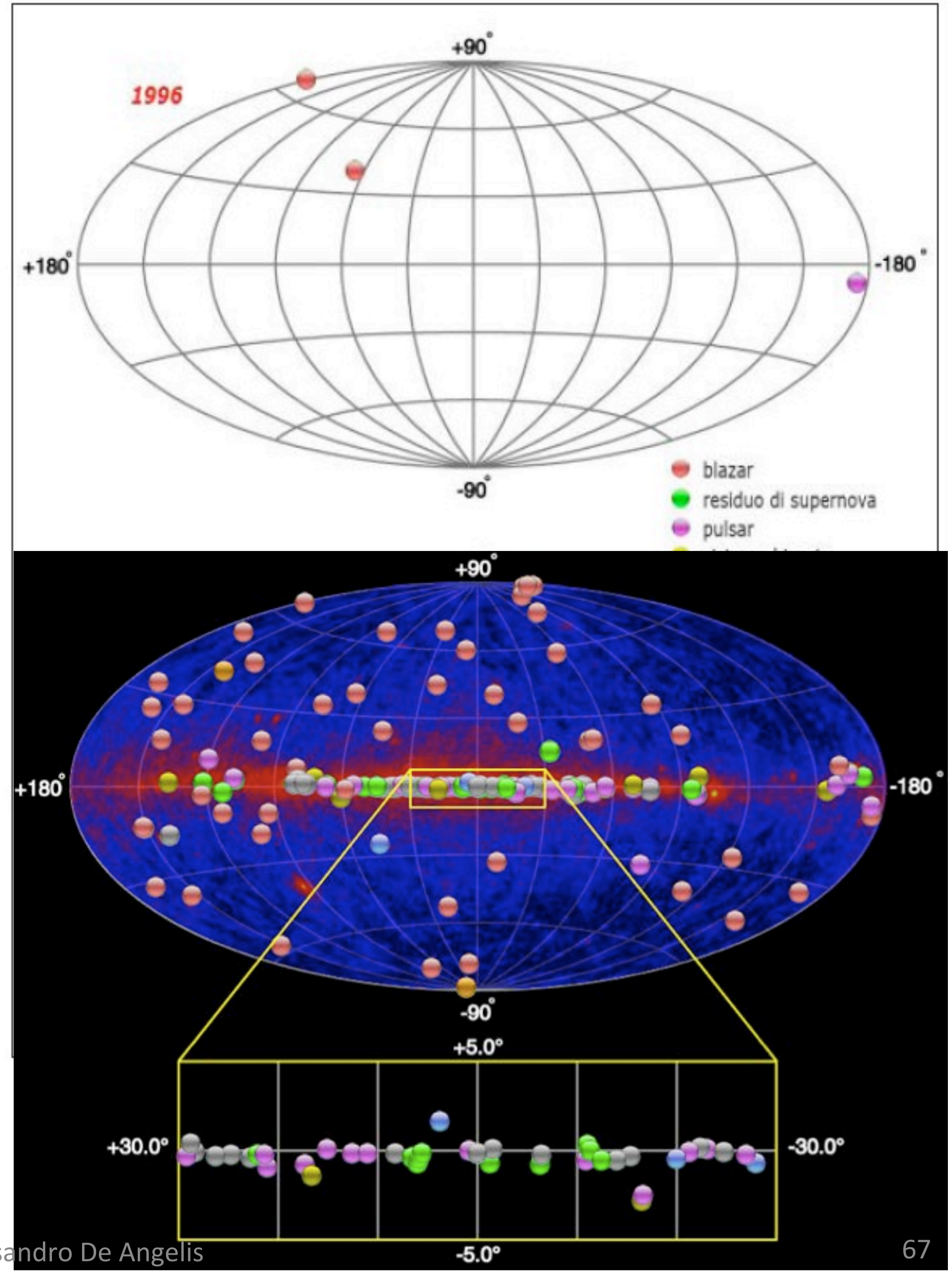
- High energies
  - Only way to build sensitive >TeV instruments
  - Maximum flux < 1 photon/h/m^2 above 200 GeV in Fermi
- High statistics /short timescales
  - Large collection areas O(km^2)
- Precision (Imaging Air Cherenkov telescopes, IACTs)
  - Superior angular resolution
- Limitations?
  - IACTs
    - 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

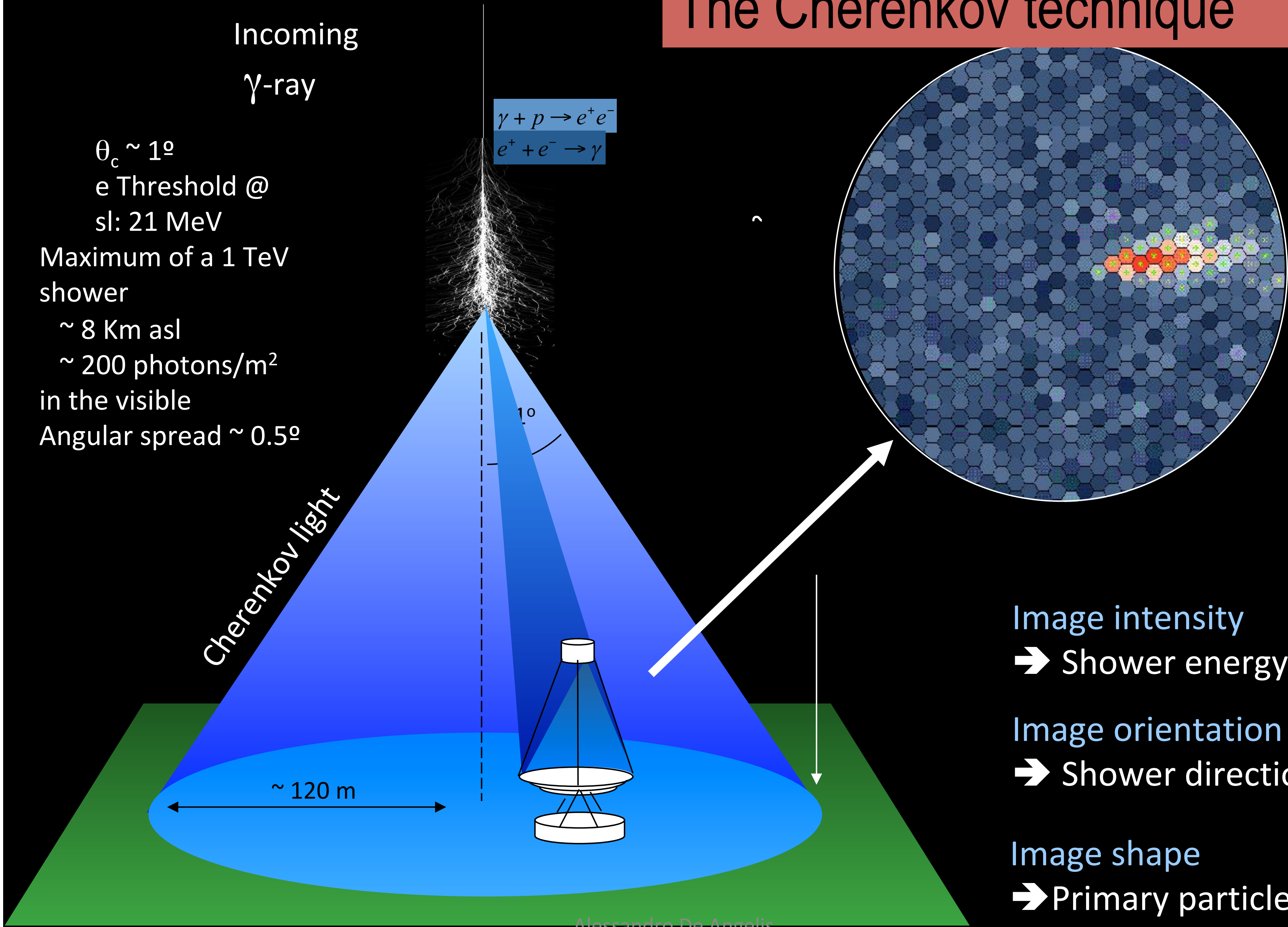


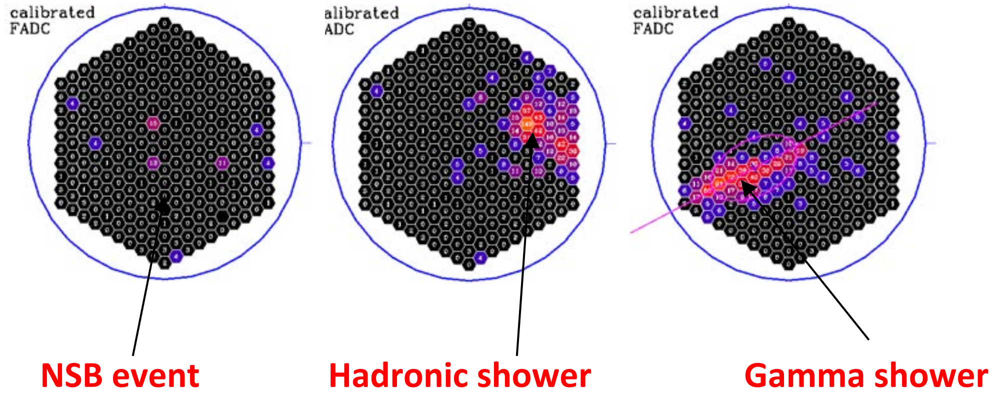
Image intensity
➔ Shower energy

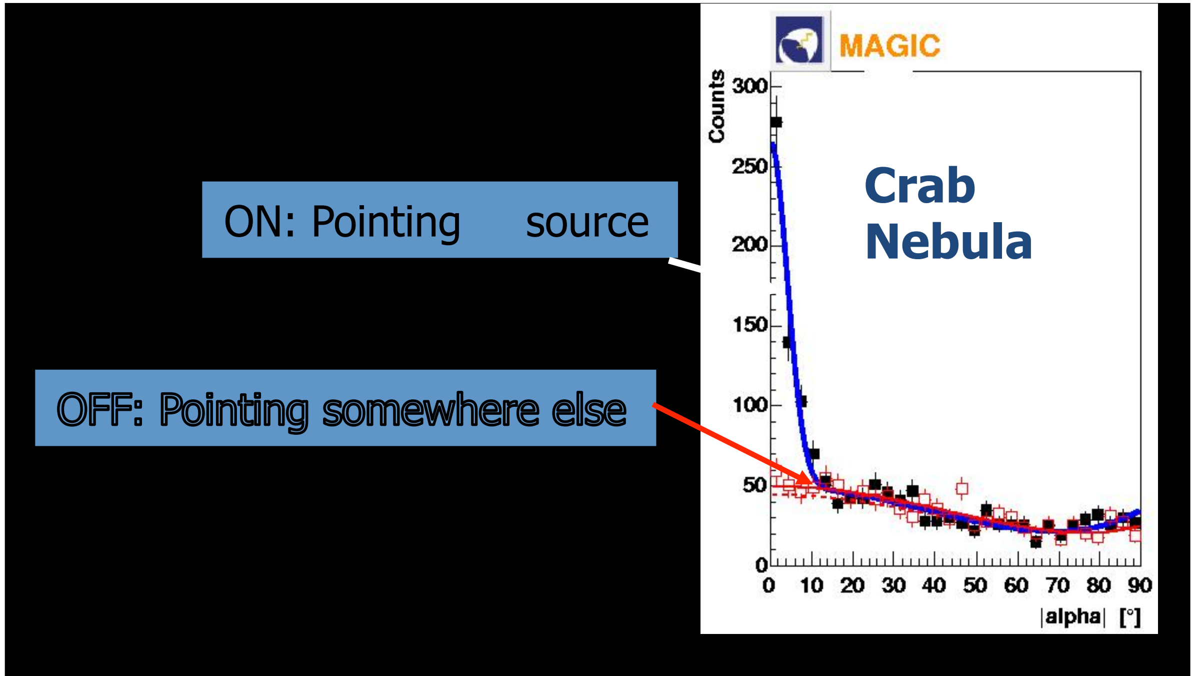
Image orientation
➔ Shower direction

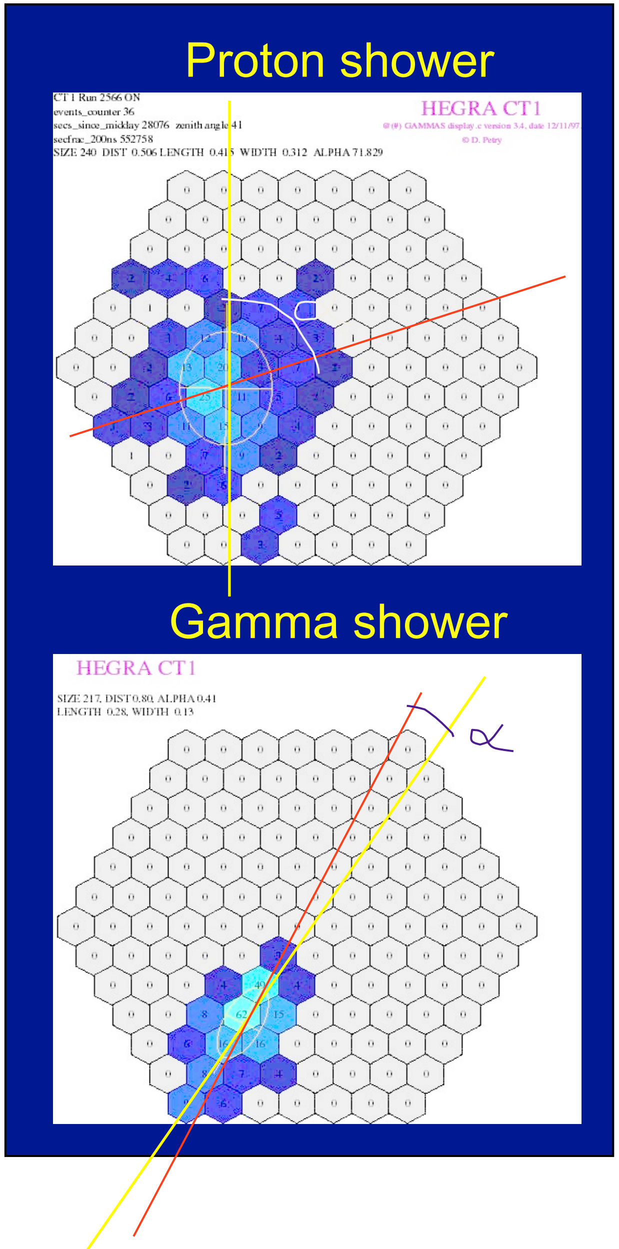
Image shape
➔Primary particle

Signal duration: ~ 3ns

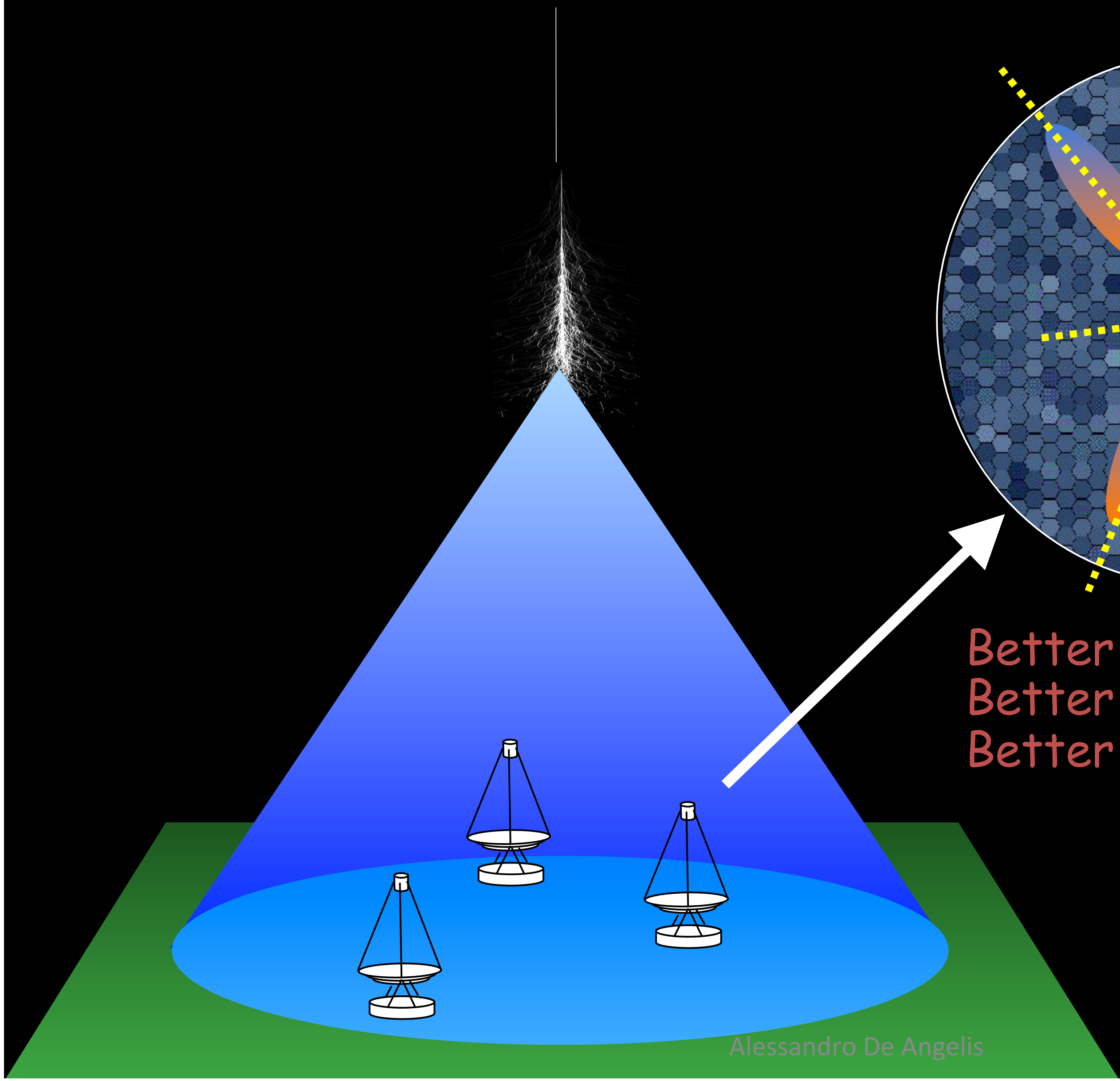
γ/h Separation

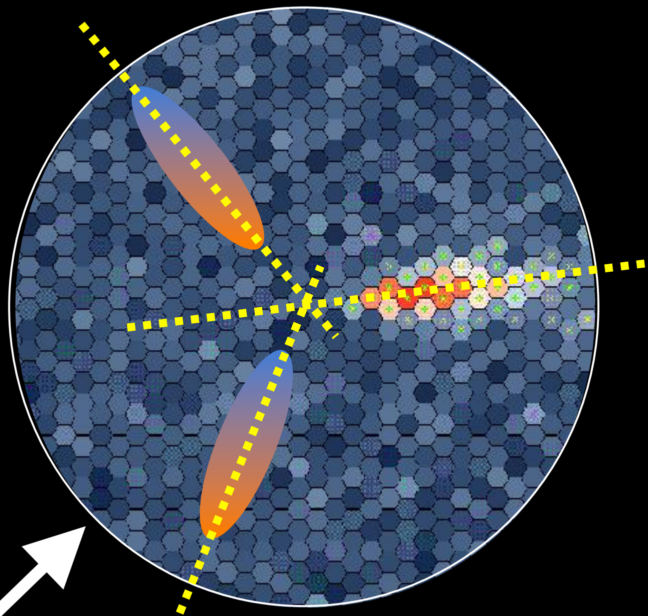






Systems of Cherenkov telescopes





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

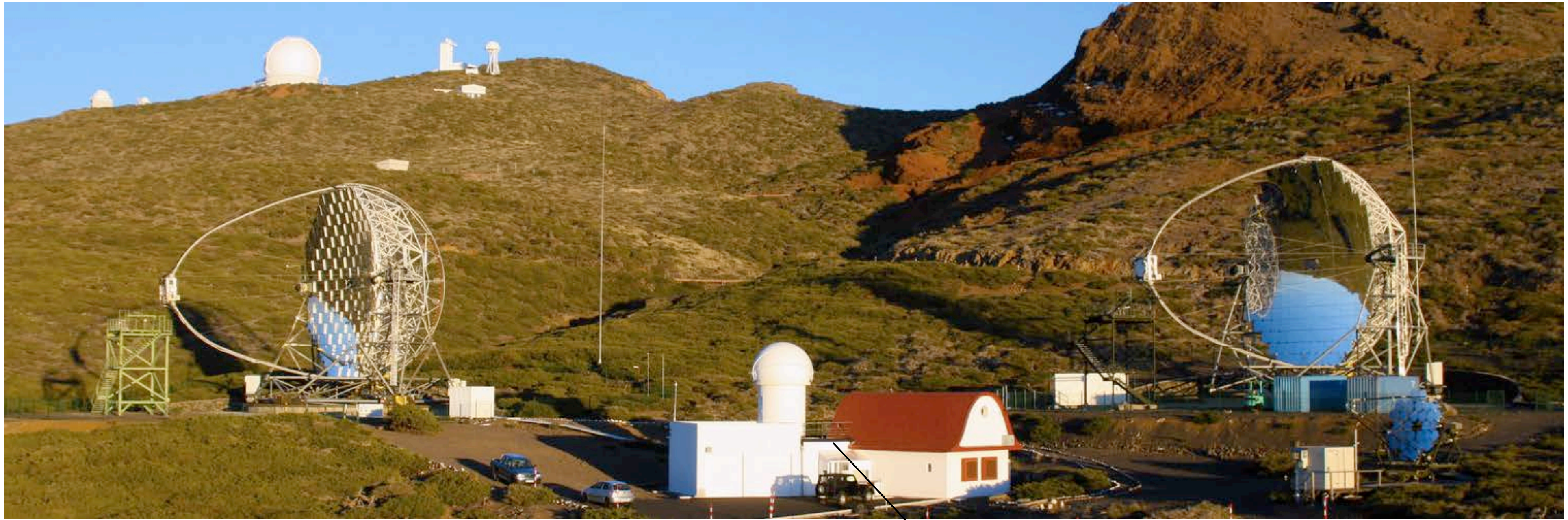
HESS (Namibia)

4 telescopes (~12m) operational since 2003

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

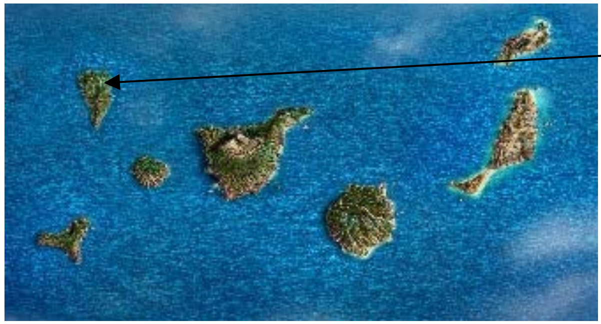
MAGIC: Two 17m Ø Imaging Atmospheric Cherenkov Telescopes
1st telescope since 2004, 2nd since 2009, upgrade in 2013

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

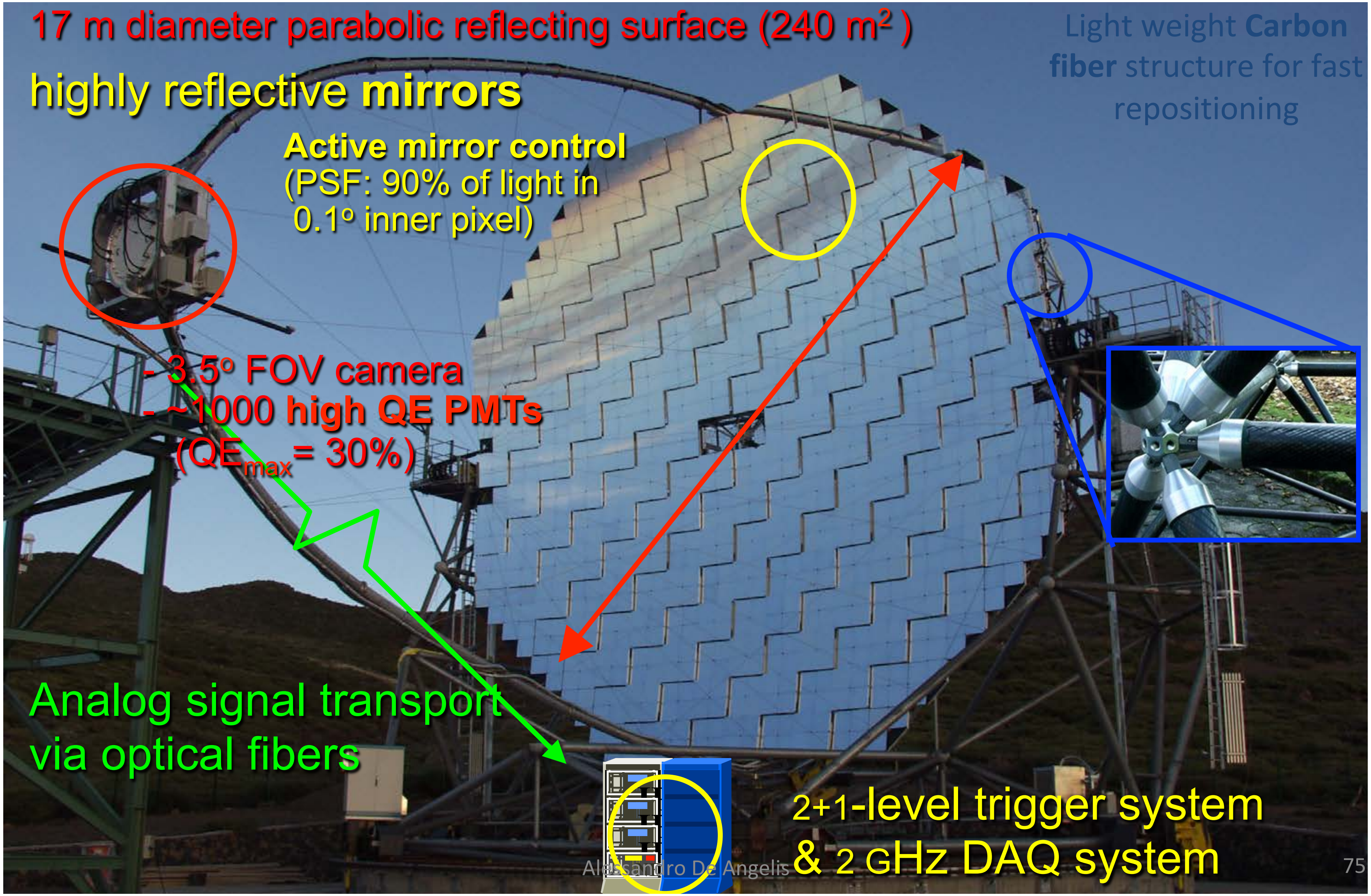


Canary island of La Palma

at 2400 m a.s.l.



Key elements



Fast and smooth repointing (< 30 s)

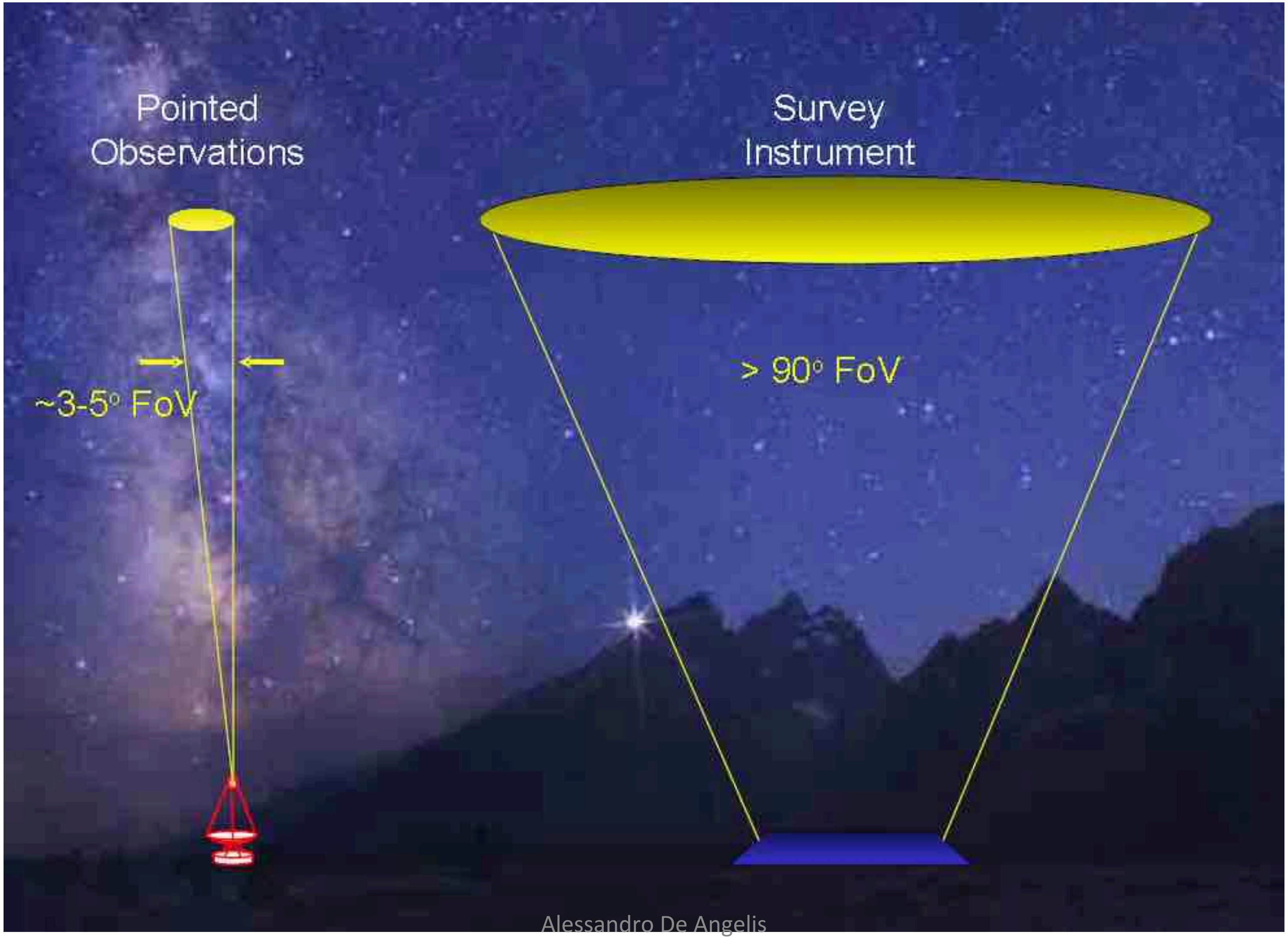
Why bigger and bigger?

Figures of merit of a Cherenkov telescope

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

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

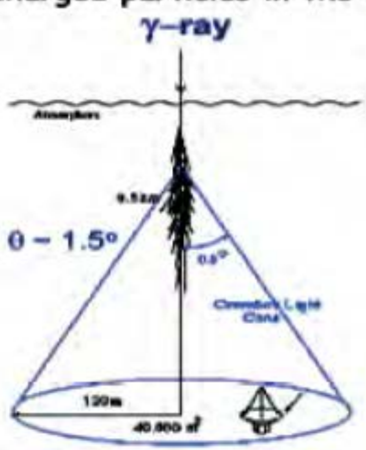
Cherenkov vs. EAS



EAS-type designs
(serendipity => GRB, unexpected…)

Air Cherenkov Telescopes

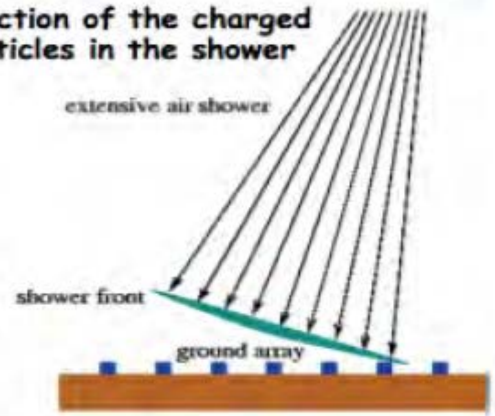
detection of the Cherenkov light from charged particles in the EAS



Very low energy threshold (≈50 GeV)
Excellent bkg rejection (>99%)
Excellent angular resolution (≈0.05 deg)
Good energy resolution (≈15%)
High Sensitivity (< % Crab flux)
Low duty-cycle (≈10%)
Small field of view (4-5 deg)

EAS arrays

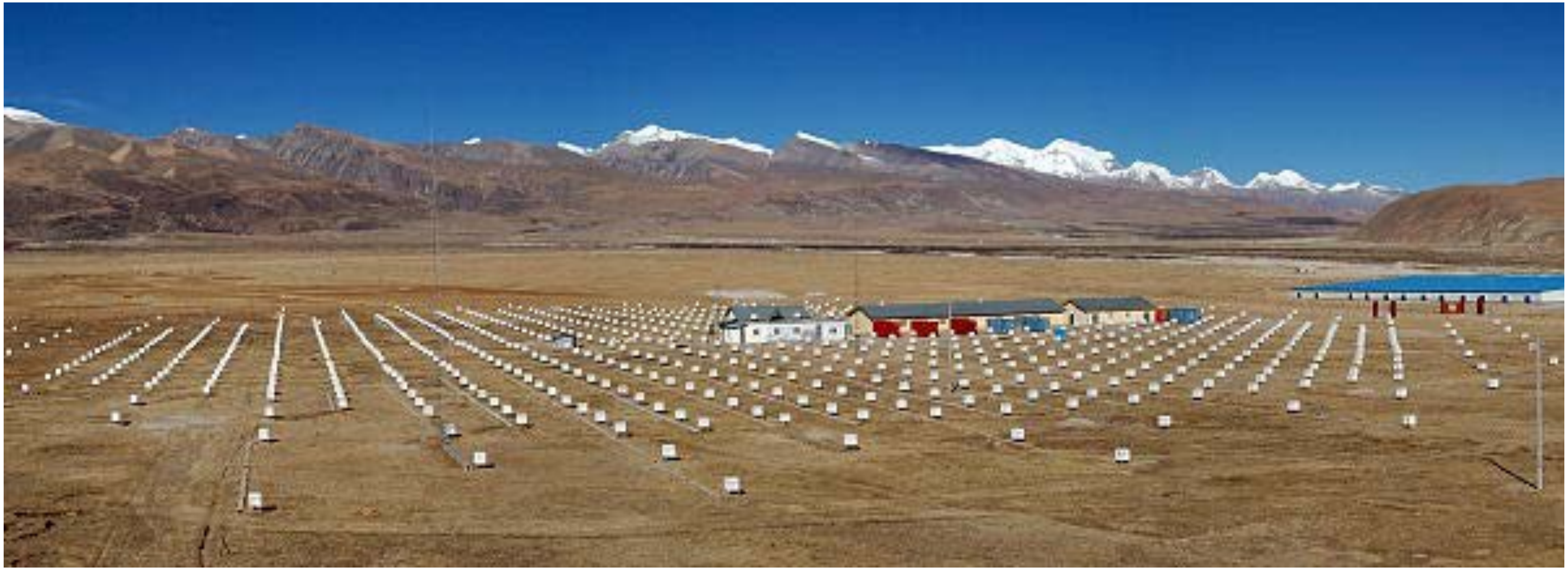
detection of the charged particles in the shower



Higher energy threshold (≈300 GeV)
Good bkg rejection (>80%)
Good angular resolution (0.2-0.8 deg)
Modest energy resolution (≈50%)
Good Sensitivity (5-10% Crab flux)
High duty-cycle (≈100%)
Large field of view (≈2 sr)

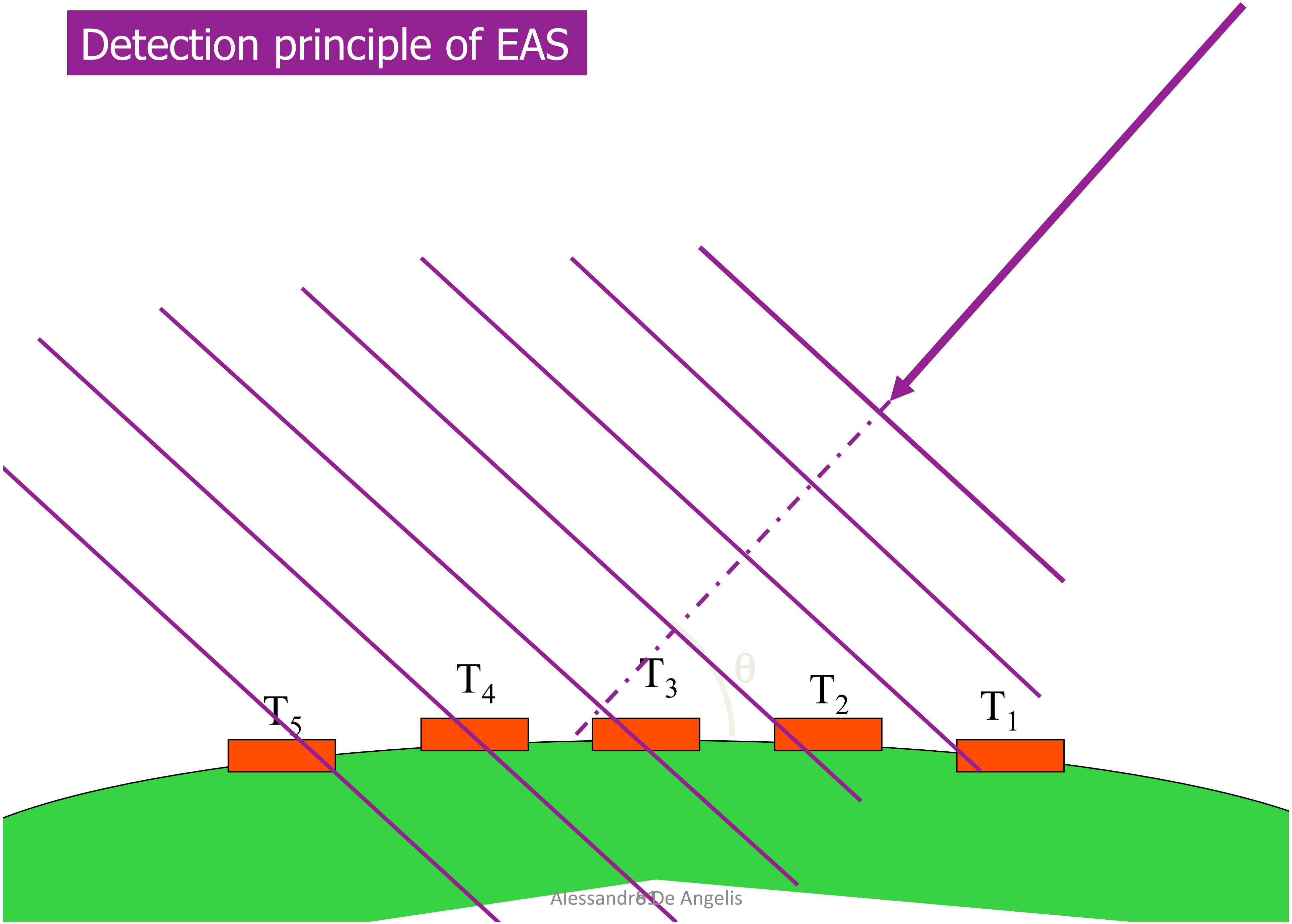
Higher energies: EAS detectors

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



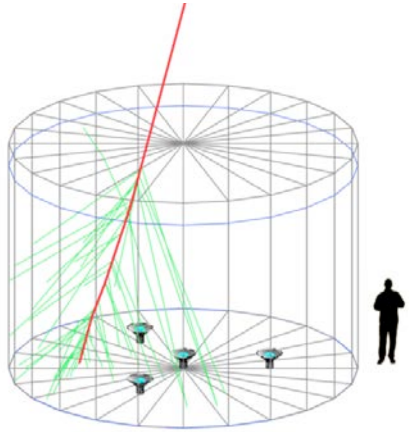
Tibet – AS gamma: scintillators

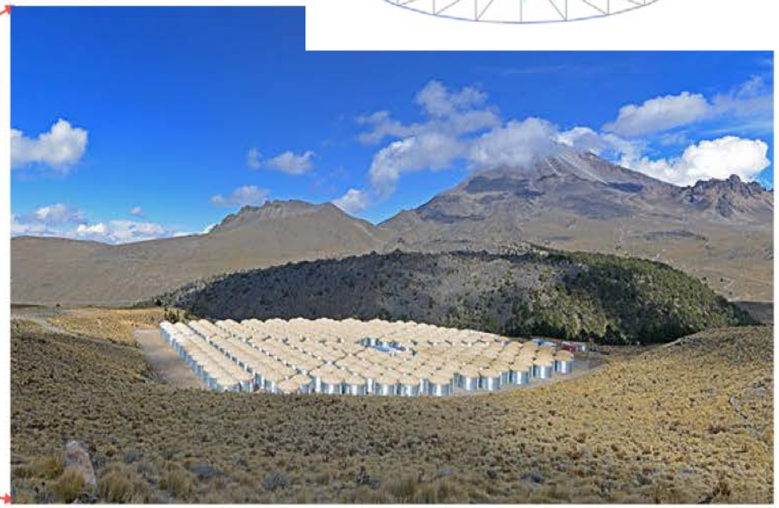
Detection principle of EAS



The present

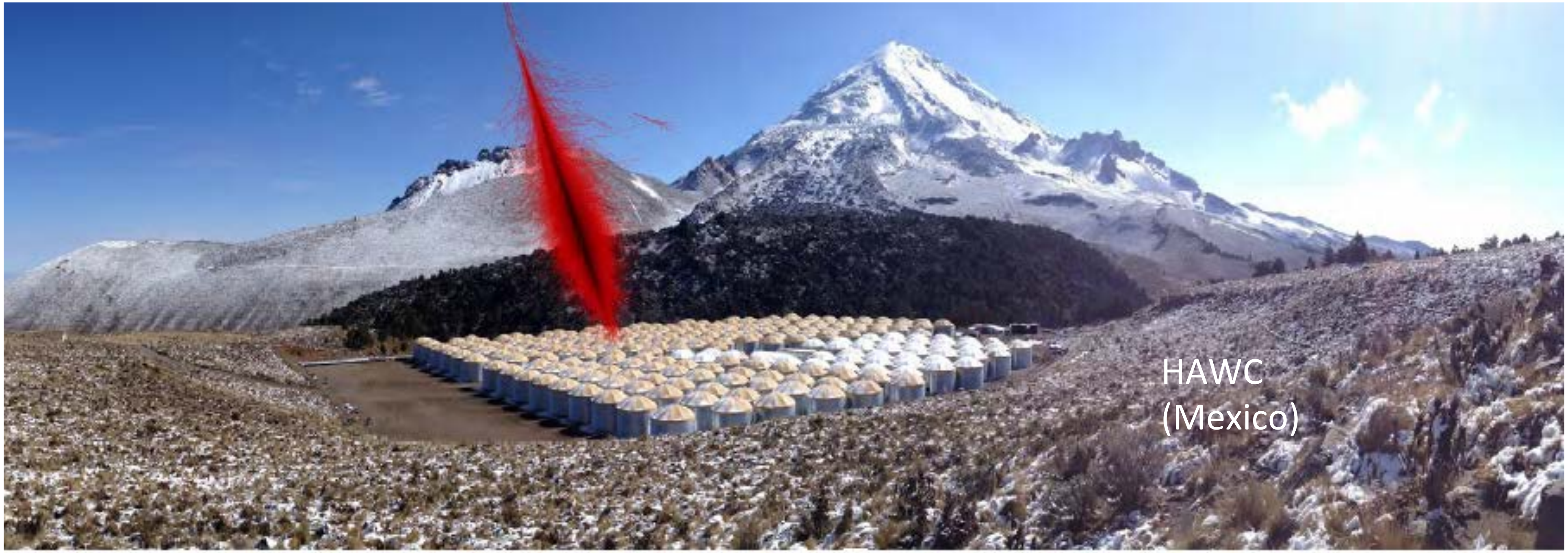
The HAWC Observatory





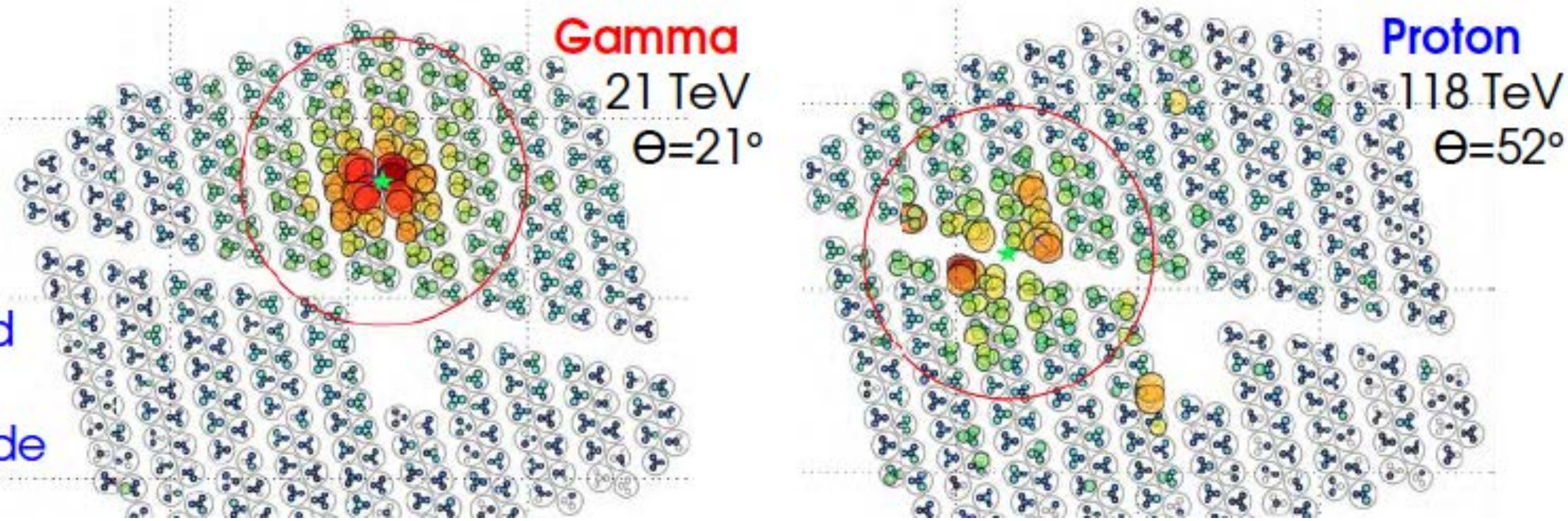
- Located at **4100 m** a.s.l. in Mexico near Pico de Orizaba at 19ºN
- Effective Area: **~22,000 m²**
- Instantaneous field of view **2 sr**; daily coverage of **2/3** of the sky.
- 300 Water Cherenkov Detectors (WCDs)
- Declinations from **-26° to 64°** (***Part of Northern Fermi Bubble visible***)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

Very-high-energies (above 200 GeV)

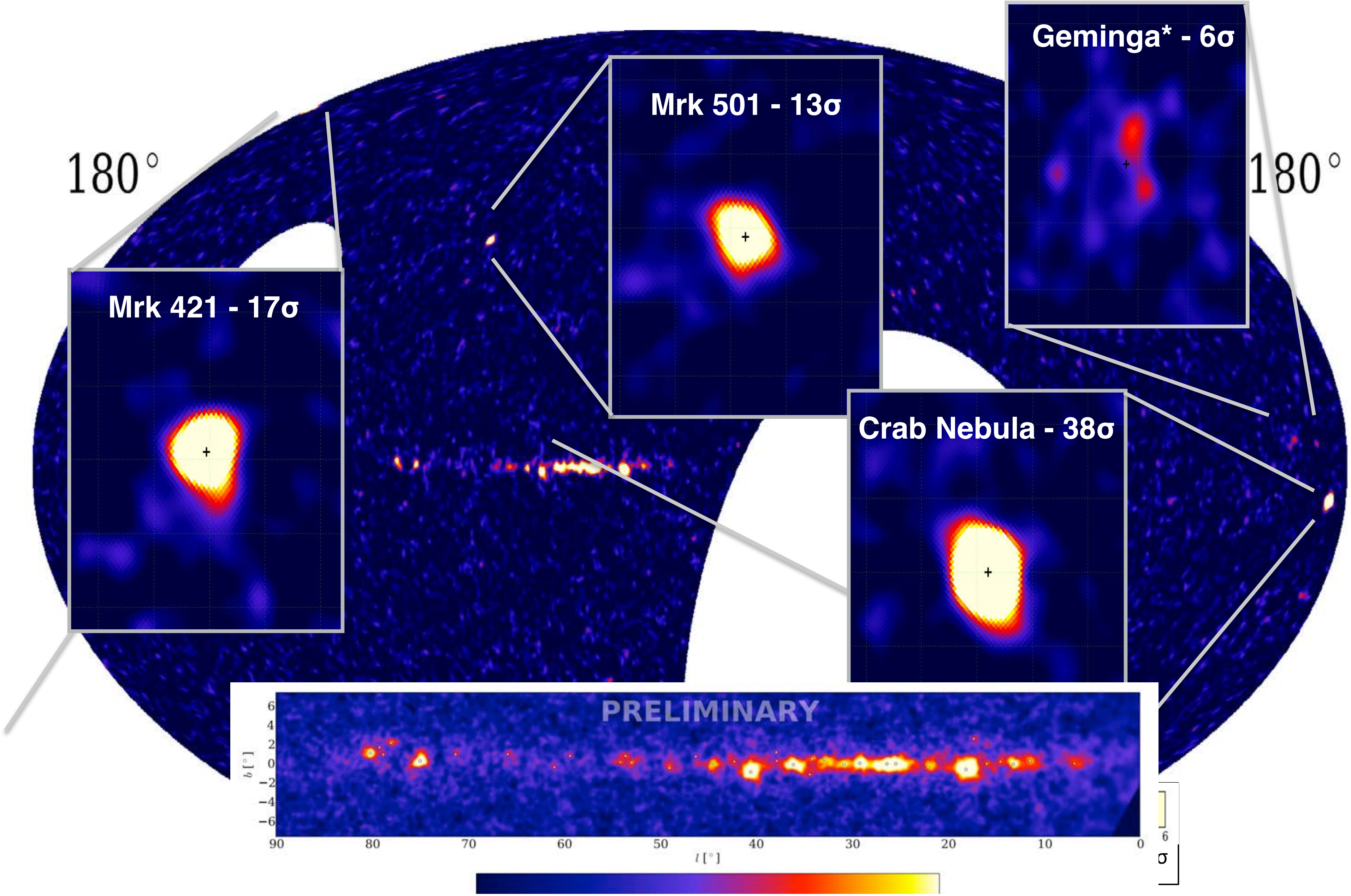


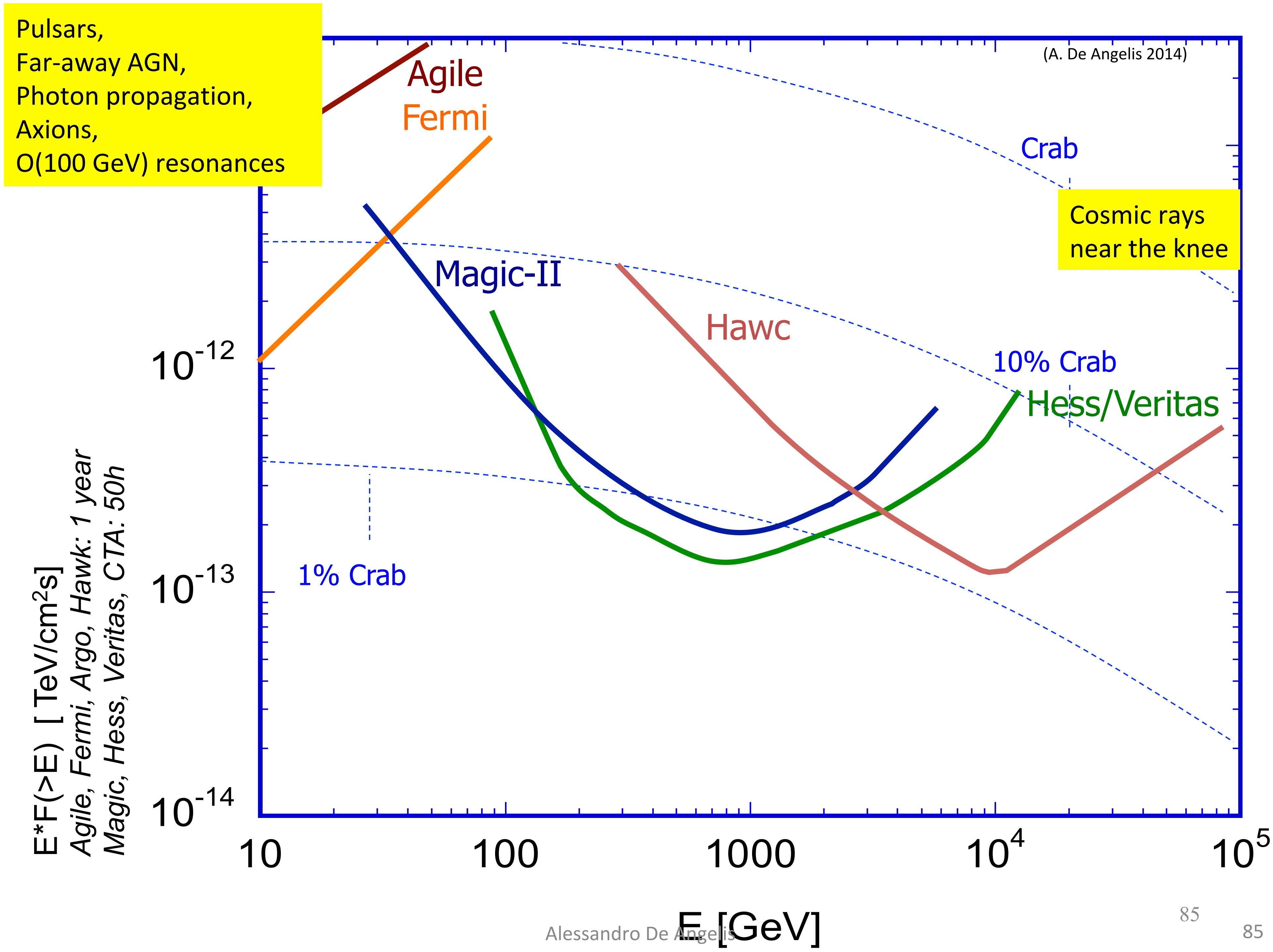
Reconstruct air showers based on PMT hit times and charges

Reject charged primaries via bright hits outside the core



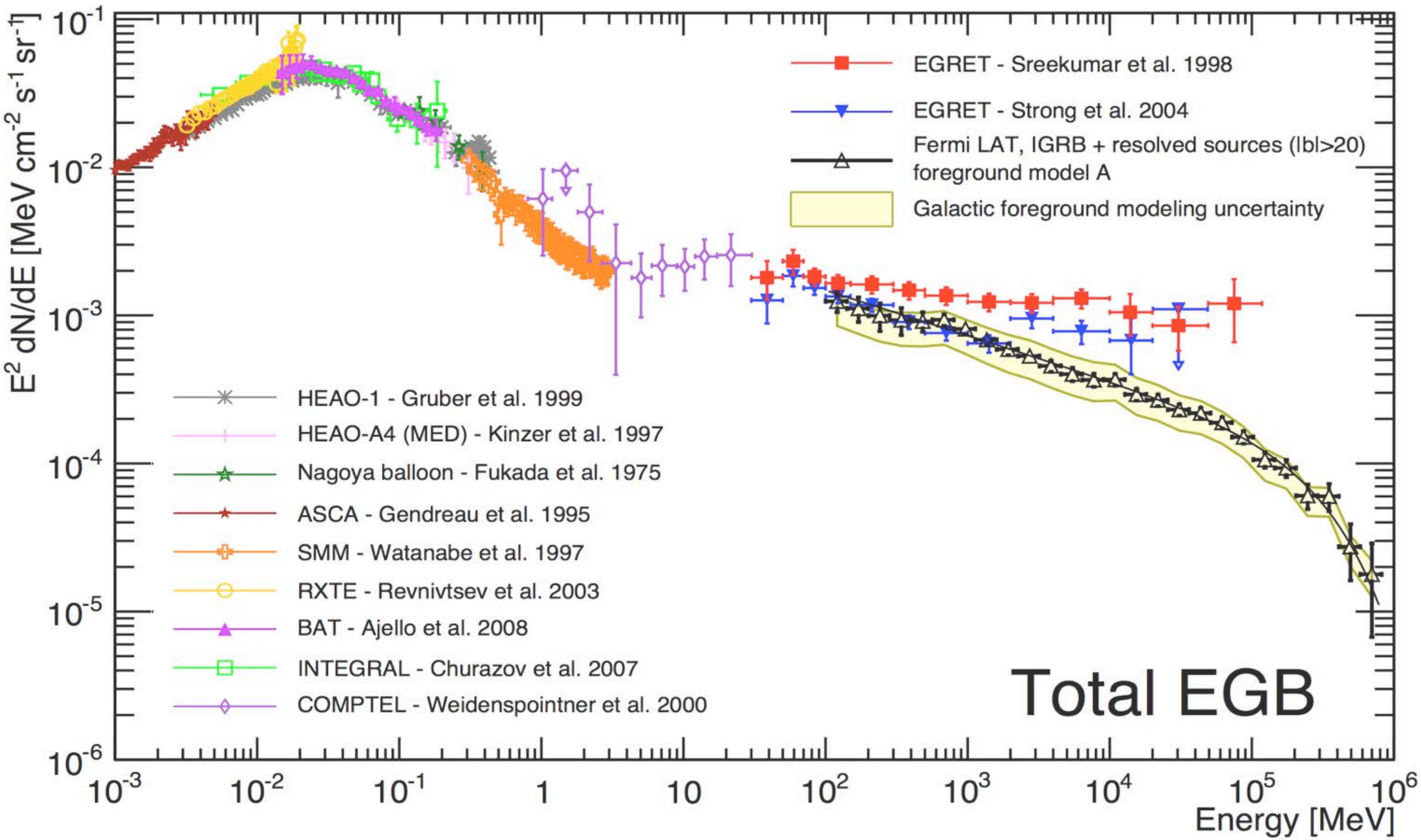
HAWC-250 150-Day TeV Sky Survey (38σ Crab)

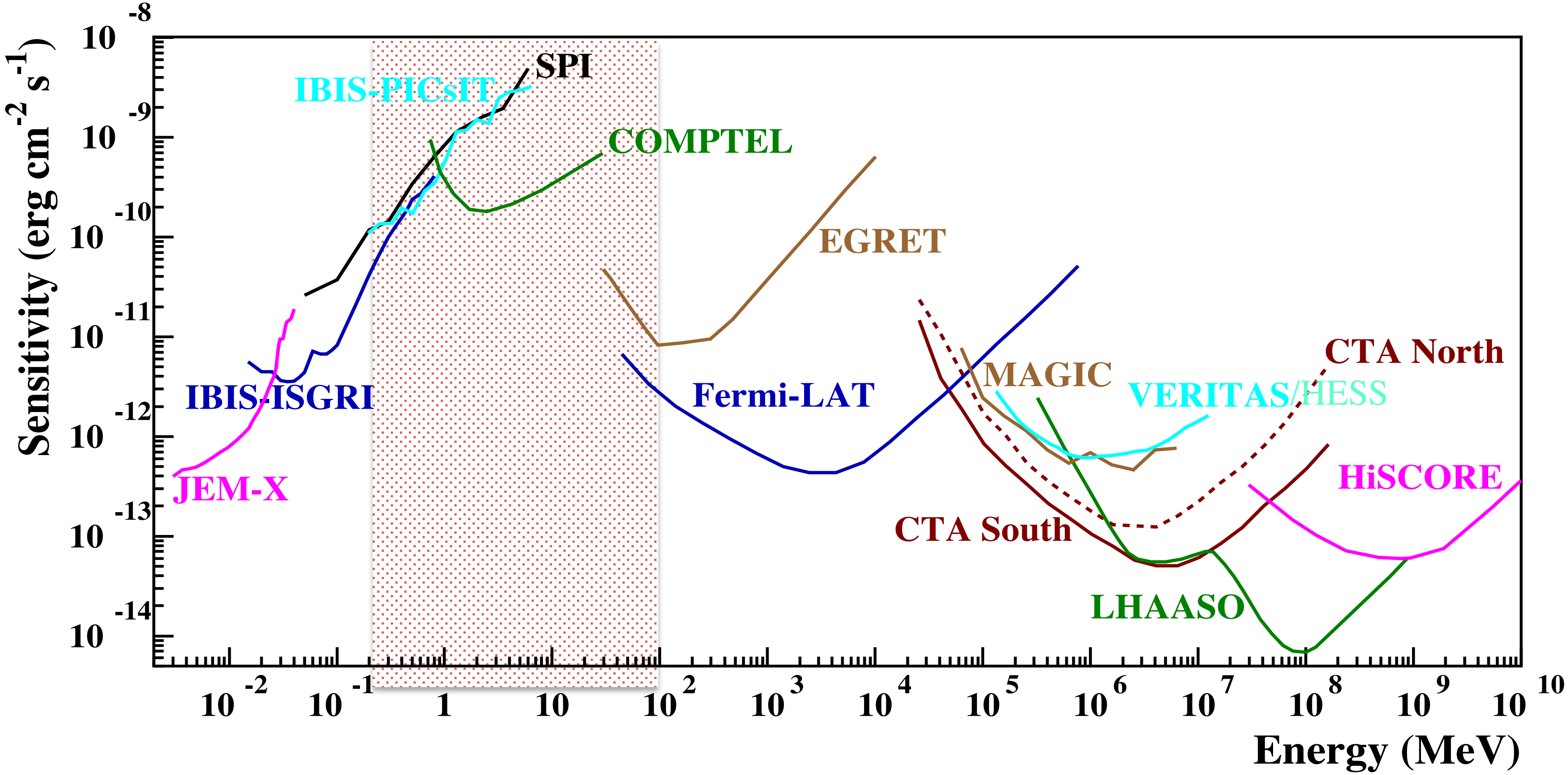




Pulsars,
Far-away AGN,
Photon propagation,
Axions,
O(100 GeV) resonances
(A. De Angelis 2014)
Agile
Fermi
Crab
Cosmic rays
near the knee
Magic-II
Hawc
10% Crab
Hess/Veritas
1% Crab
10^-12
10^-13
10^-14
E*F(>E) [TeV/cm^2s]
Agile, Fermi, Argo, Hawk: 1 year
Magic, Hess, Veritas, CTA: 50h
10
100
1000
10^4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

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

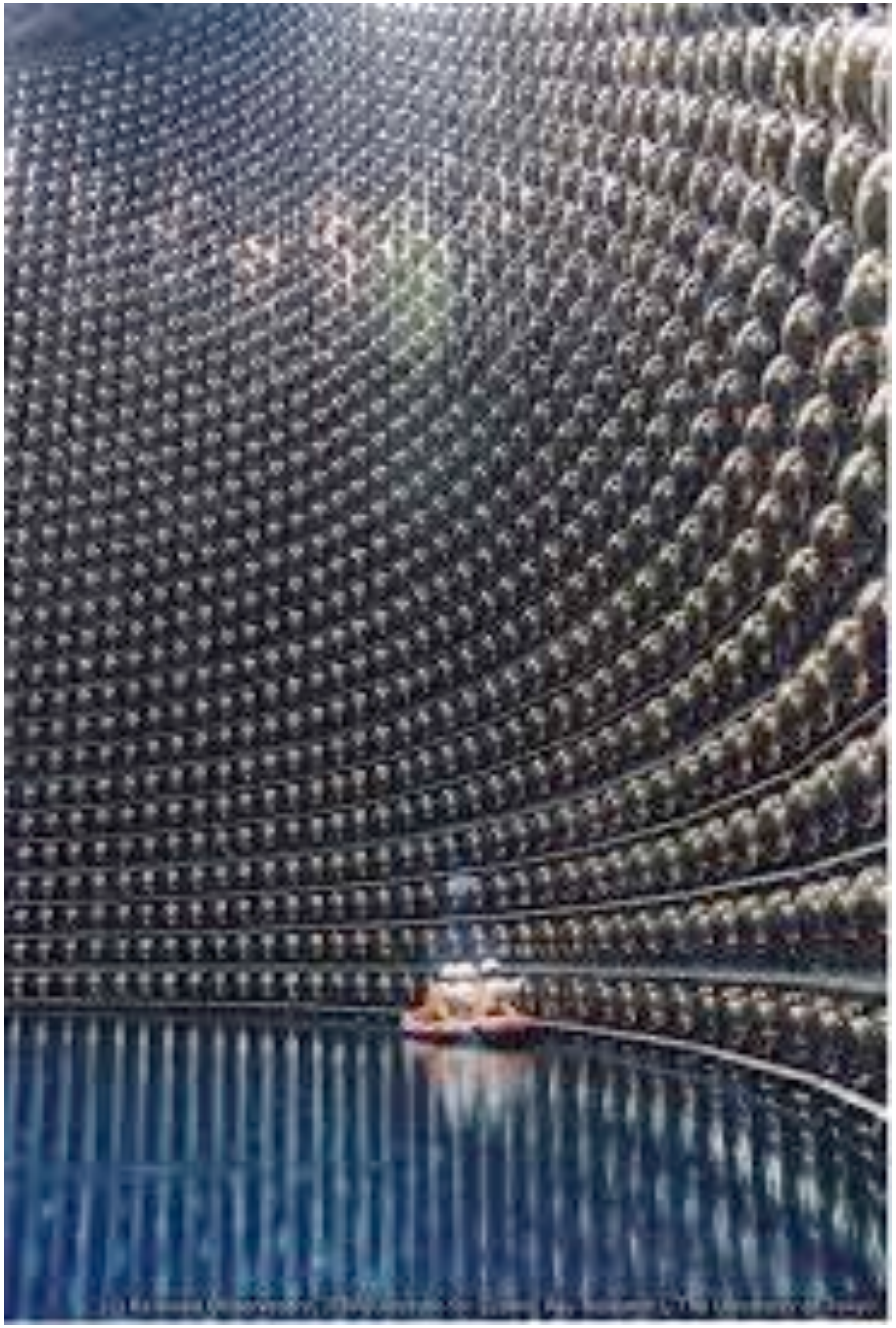
Neutrino detectors

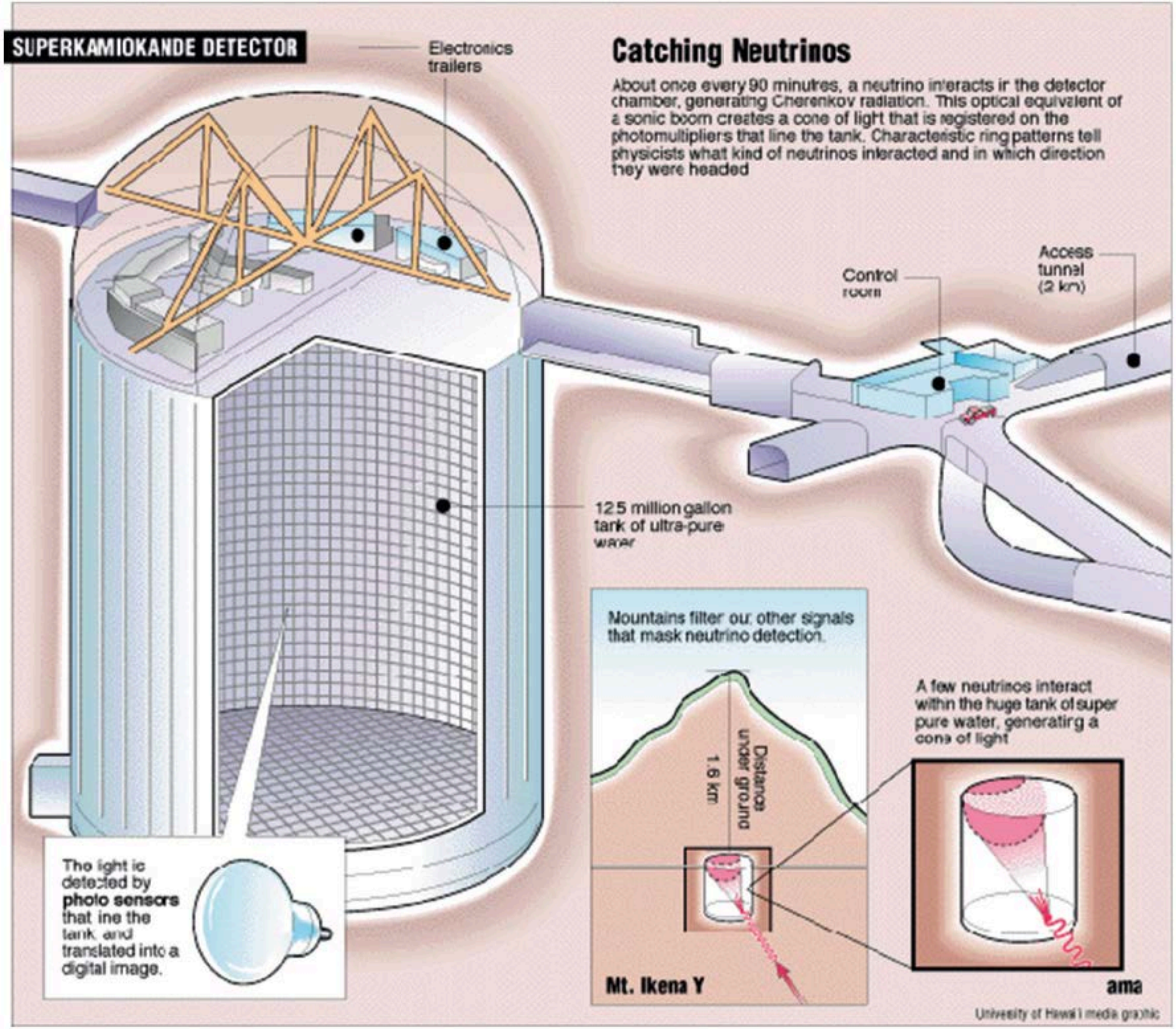
MeV neutrinos

- 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

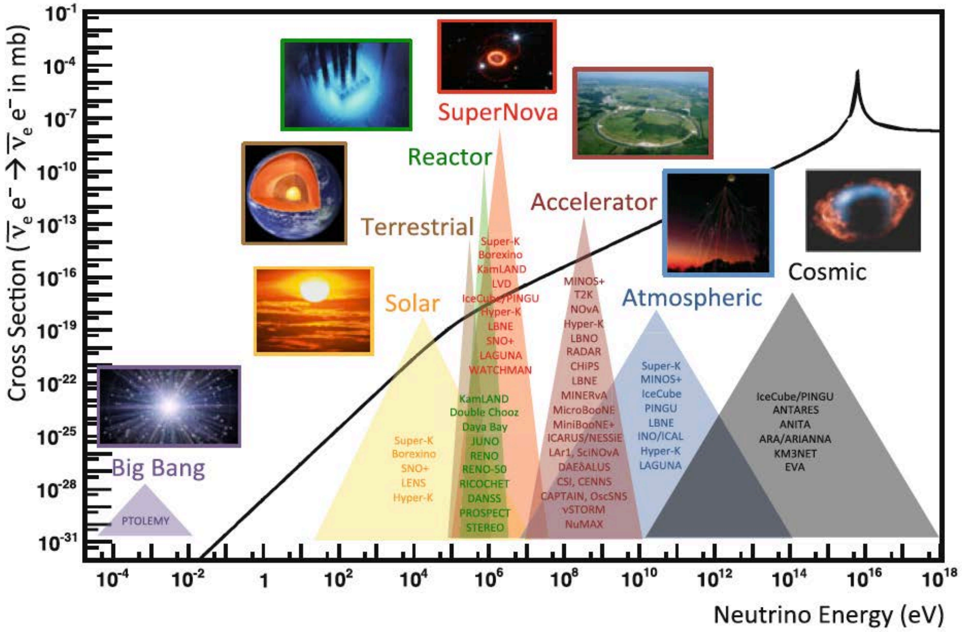
- Very important: fusion processes in stars, atmospheric neutrinos
- Needs large volumes: (Super)Kamiokande
  - SK: 50000 tons
  - Hyper-K: 20 x SK?
- Water instrumented with large PMTs; detection of Cherenkov photons
- Two Nobel prizes

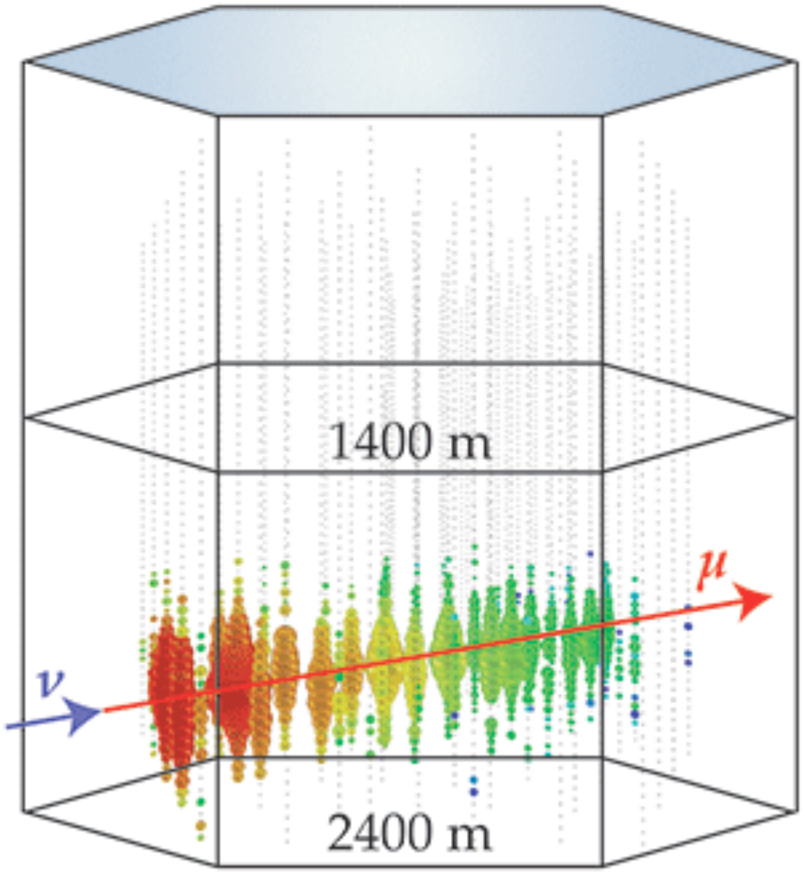



SUPERKAMIOKANDE DETECTOR
Electronics trailers
Catching Neutrinos
About once every 90 minutes, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic 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 Hawai'i media graphic

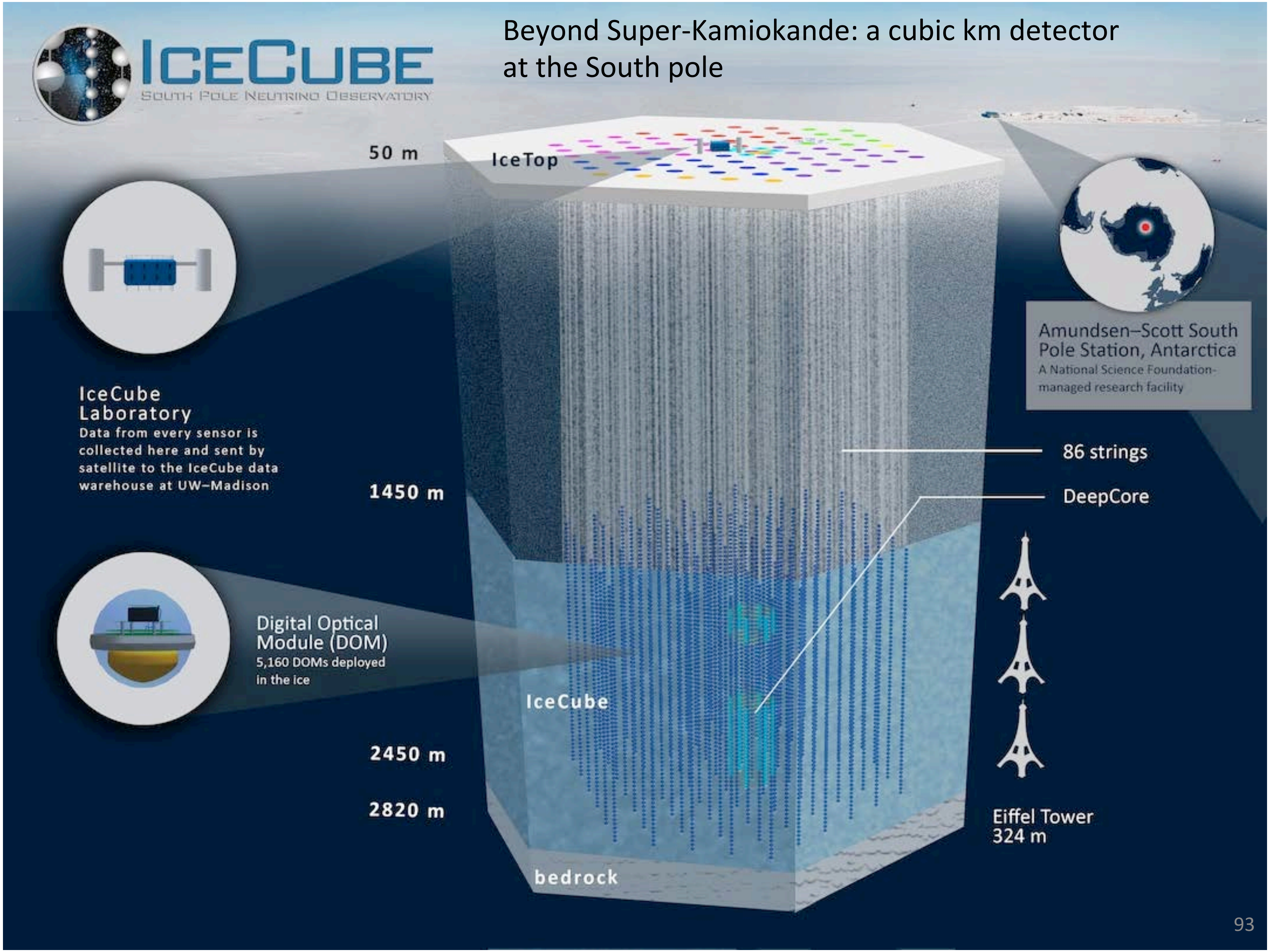
Do you aim at astrophysical neutrinos?

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





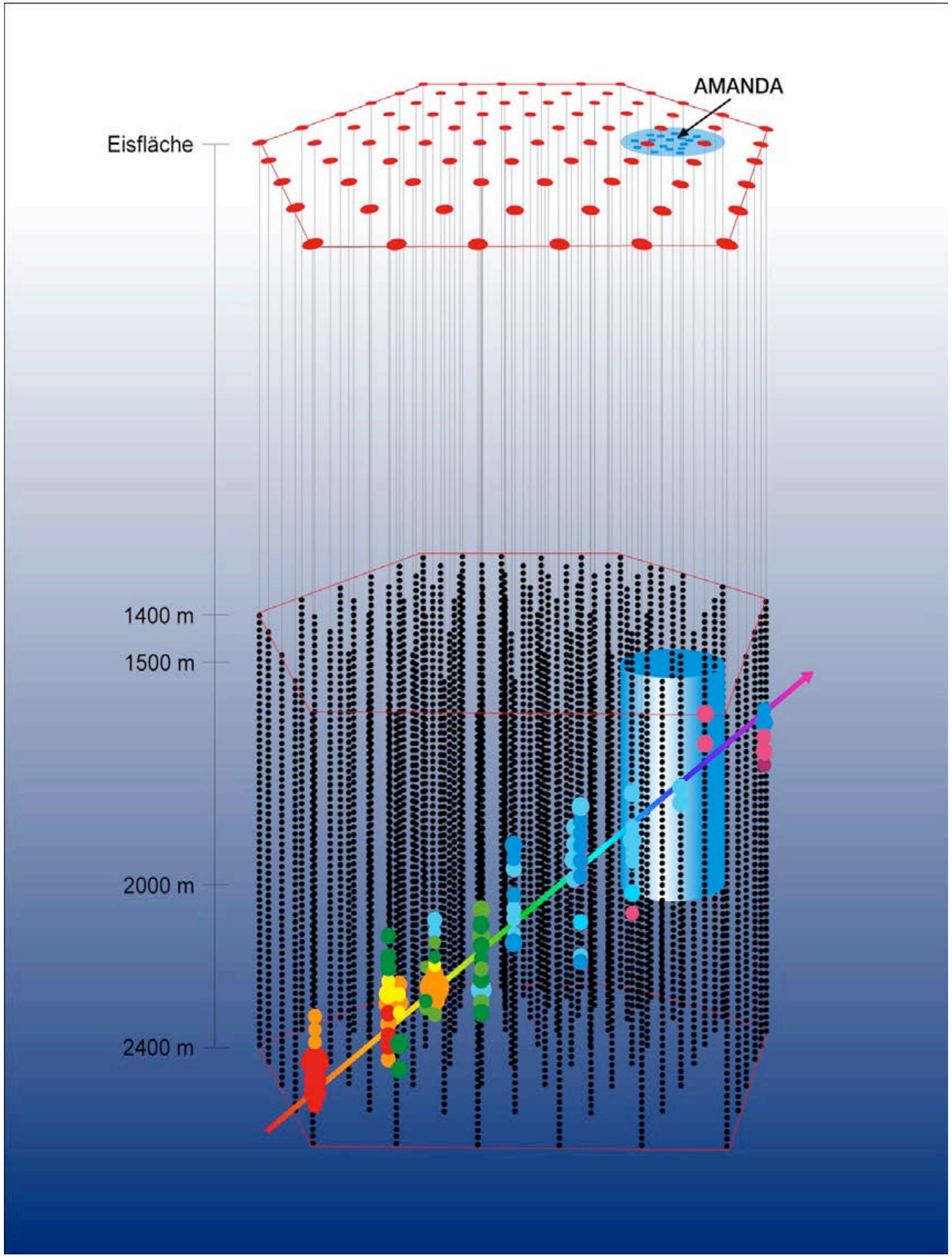
Beyond Super-Kamiokande: a cubic km detector at the South pole



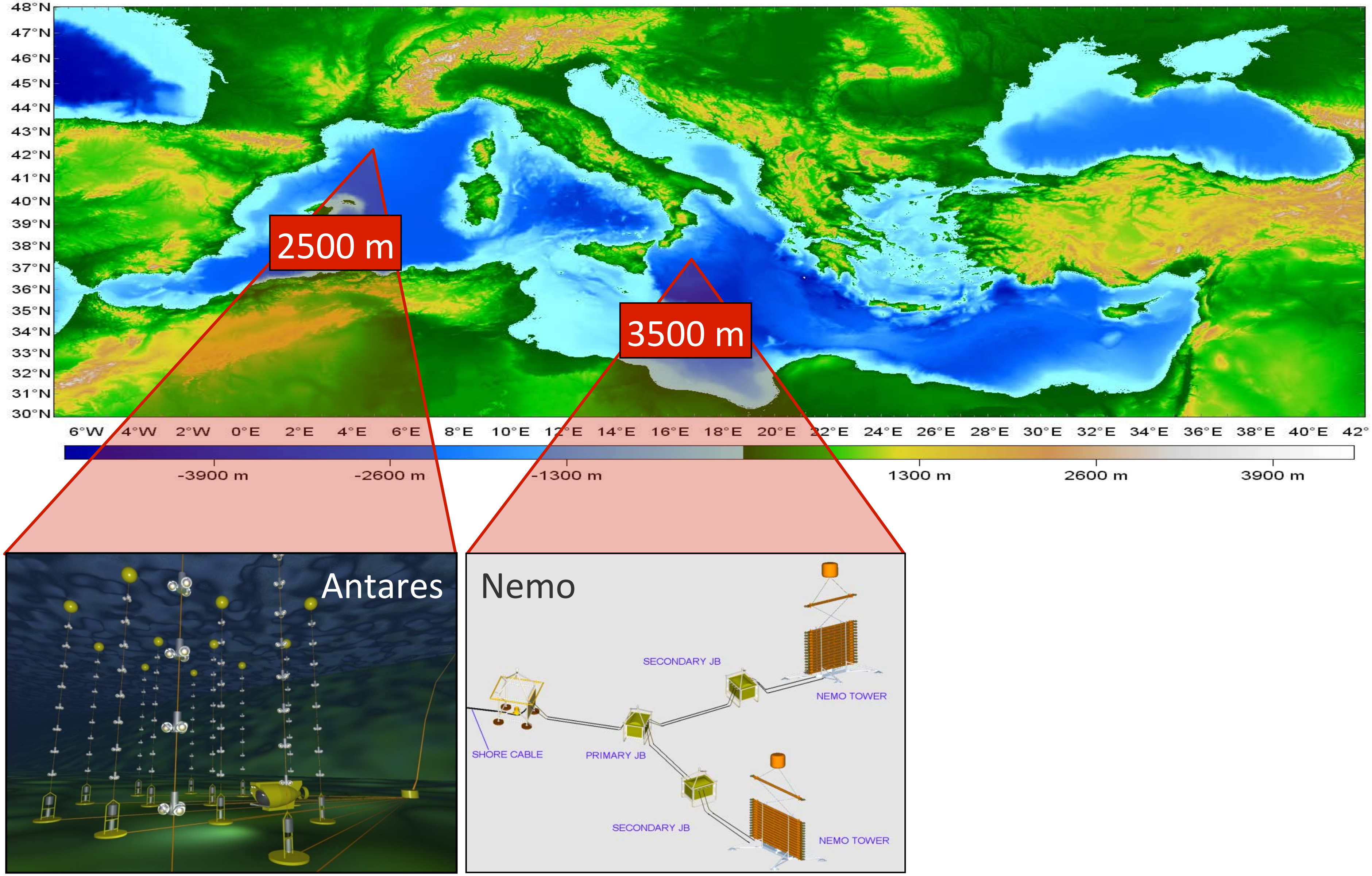
Deploying a (string of) photosensors

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



First detection of (HE, VHE) gamma-ray excess positionally and temporally consistent with an IceCube EHE neutrino (EHE170922). Astronomer telegrams:

IceCube-170922A: IceCube observation of a high-energy neutrino candidate event

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

Further Swift-XRT observations of IceCube 170922A

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

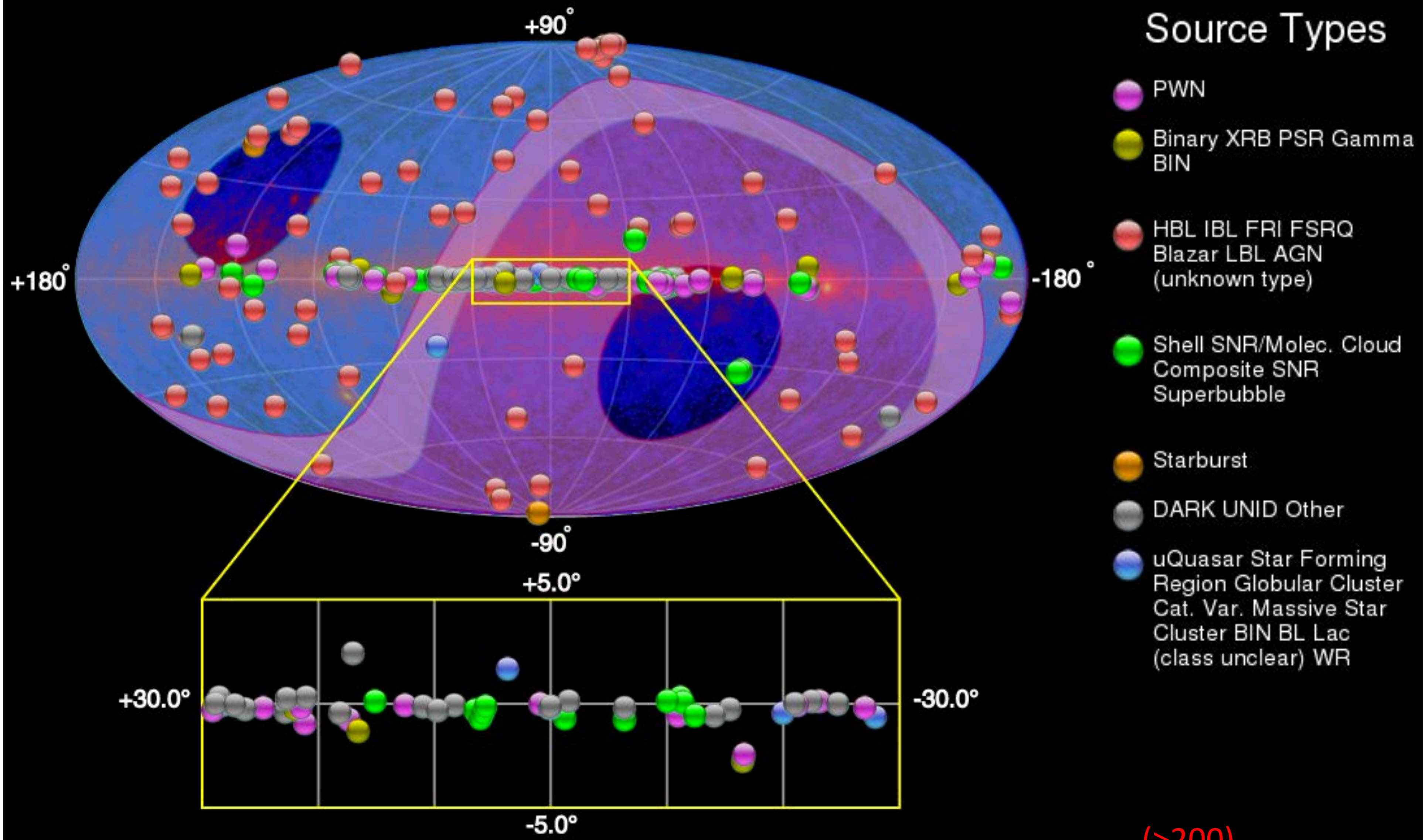
Related

10845	Joint Swift XRT and NuSTAR Observations of TXS 0506+056
10844	Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
10840	VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
10838	MAXI/GSC observations of IceCube-170922A and TXS 0506+056
10833	VERITAS follow-up observations of IceCube neutrino event 170922A
10831	Optical photometry of TX0506+056
10830	SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
10817	First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A
10802	HAWC gamma ray data prior to IceCube-170922A
10801	AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
10799	Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
10794	ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
10792	Further Swift-XRT observations of IceCube 170922A
10791	Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
10787	H.E.S.S. follow-up of IceCube-170922A
10773	Search for counterpart to IceCube-170922A with ANTARES

Most ϒ-ray detections > 5σ

GAMMA RAYS
the right tool to locate sources, up to now
(with at least one very important exception)

TeV sources tevcat.uchicago.edu

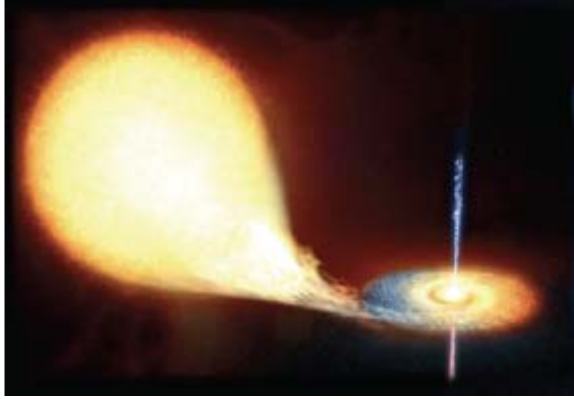


(>200)

TeV Impact

Highlights from HESS, MAGIC, VERITAS & MILAGRO

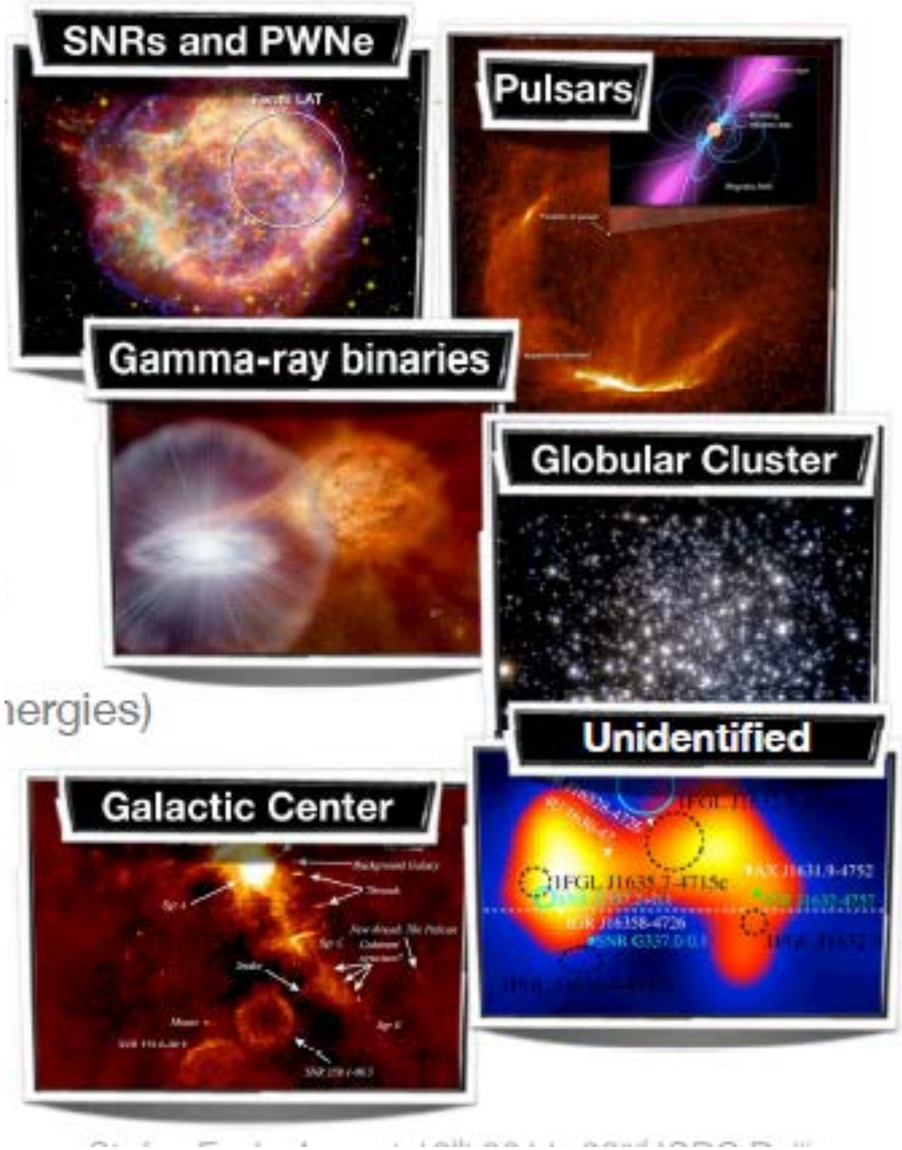
- *Microquasars:* Science 309, 746 (2005), Science 312, 1771 (2006)
- *Pulsars:* Science 322, 1221 (2008), Science 334, 69 (2011)
- *Supernova Remnants:* Nature 432, 75 (2004)
- *The Galactic Centre:* Nature 439, 695 (2006)
- *Surveys:* Science 307, 1839 (2005), PRL 95, 251103 (2005)
- *Starbursts:* Nature 462, 770 (2009), Science 326,1080 (2009)
- *AGN:* Science 314,1424 (2006), Science 325, 444 (2009)
- *EBL:* Nature 440, 1018 (2006), Science 320, 752 (2008)
- *Dark Matter:* PRL 96, 221102 (2006), PRL 106, 161301 (2011)
- *Lorentz Invariance:* PRL 101, 170402 (2008)
- *Cosmic Ray Electrons:* PRL 101, 261104 (2009)



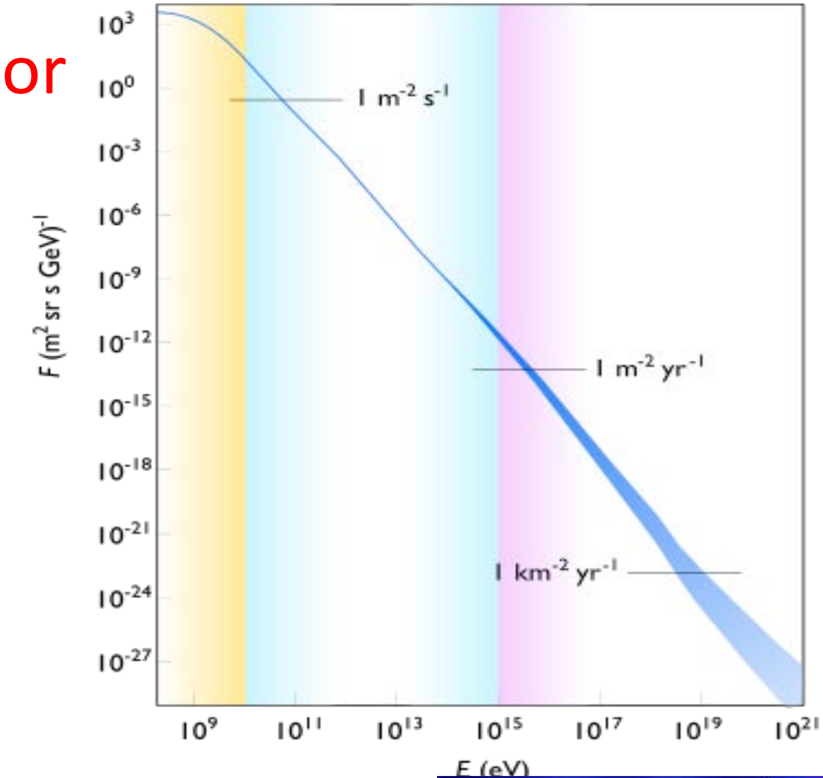

Galactic sources of gamma rays

- Remnants of SN explosions (shells, pulsar wind nebulae, pulsars themselves)
- Gamma-rays binaries
- The Galactic Center

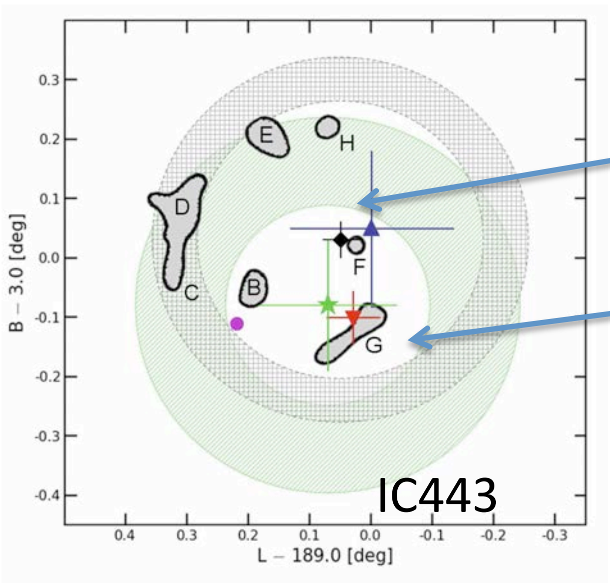
- Many unassociated sources



Interaction with molecular clouds or gammas in the ambient

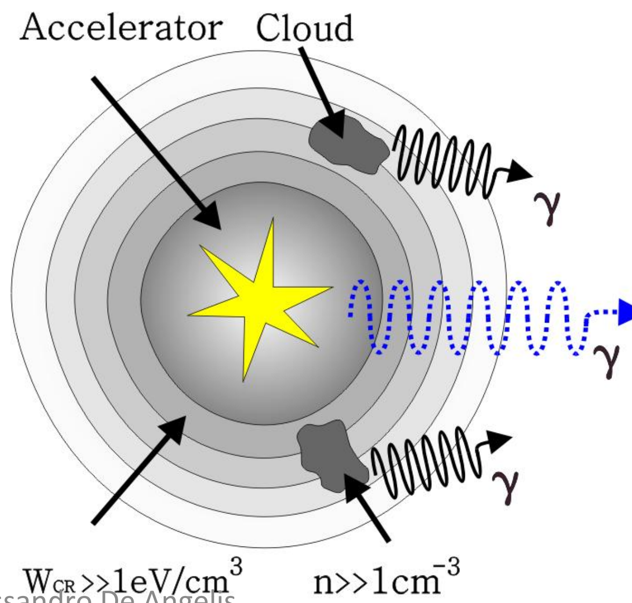


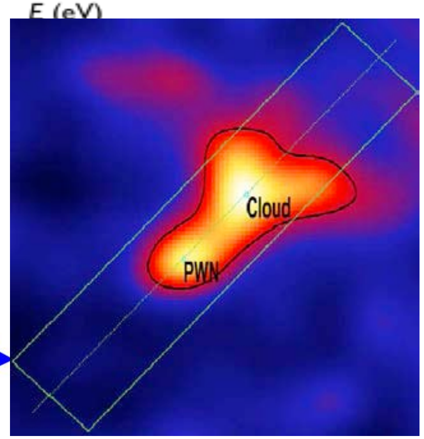
- Evidence that SNR are sources of CR up to ~1000 TeV (almost the knee) came from morphology studies of RX J1713-3946 (H.E.S.S. 2004) with photons
- Striking evidence from the morphology of SNR IC443 (MAGIC + Fermi/Agile 2010)



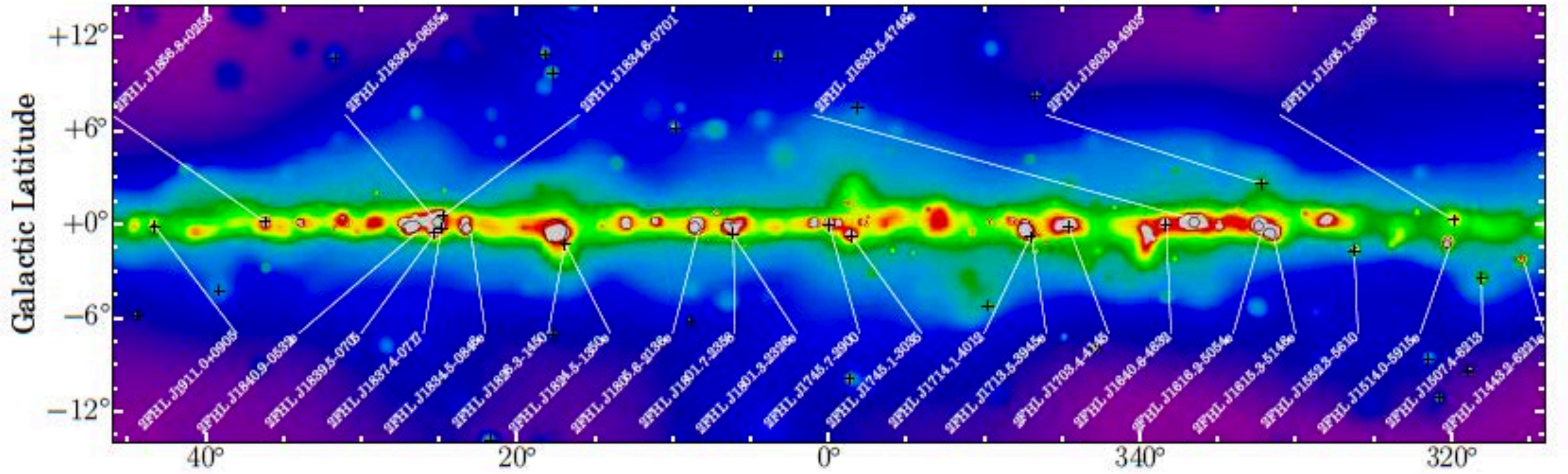
Fermi, Egret

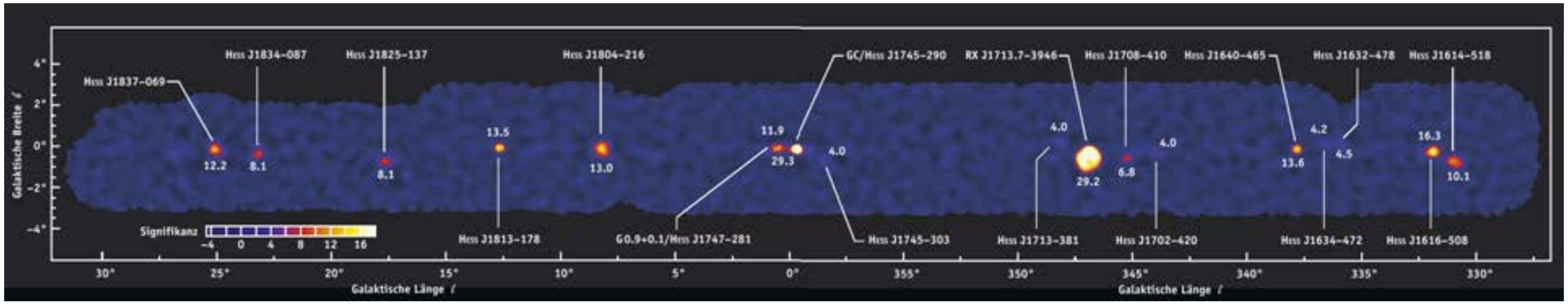
Magic, Veritas



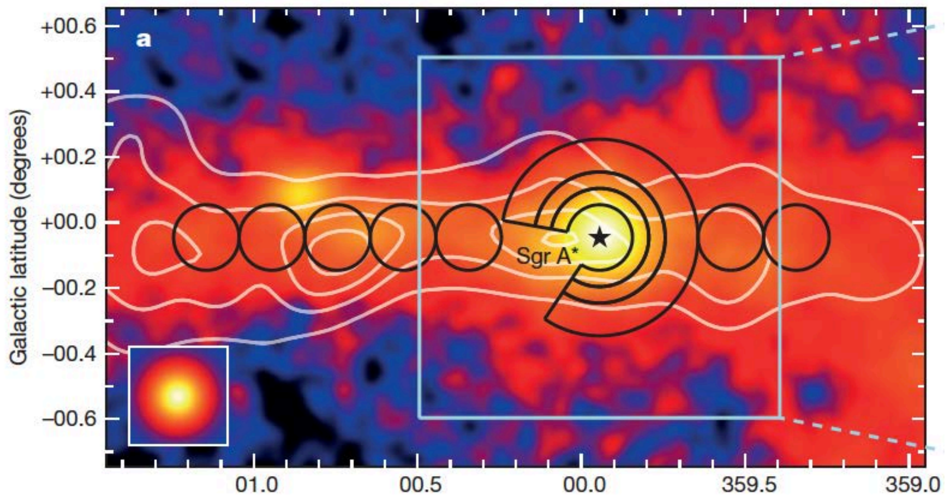


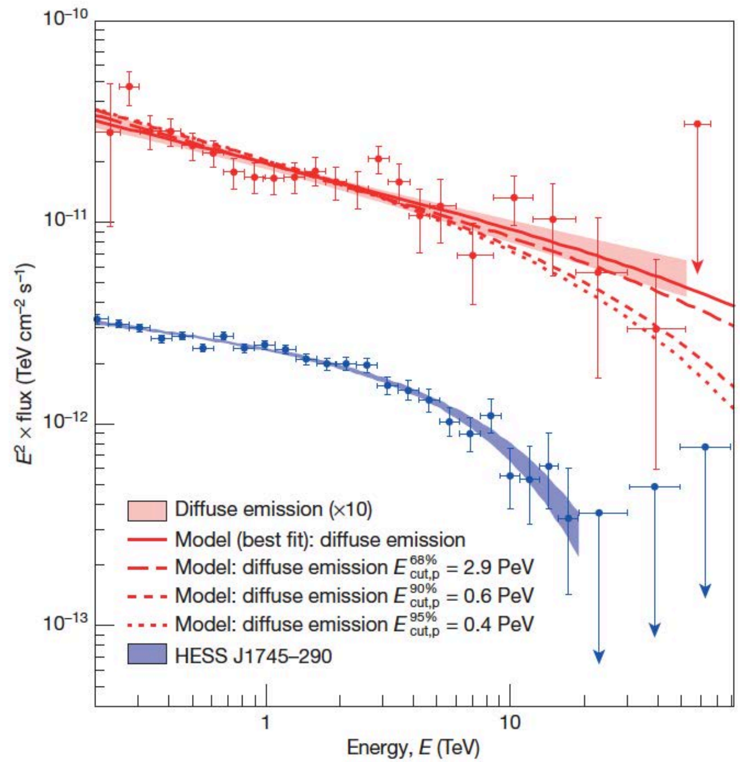
The Galactic center above 50 GeV (Fermi) and in TeV (HESS)





A PeVatron in the GC? (HESS, Nature 2016)

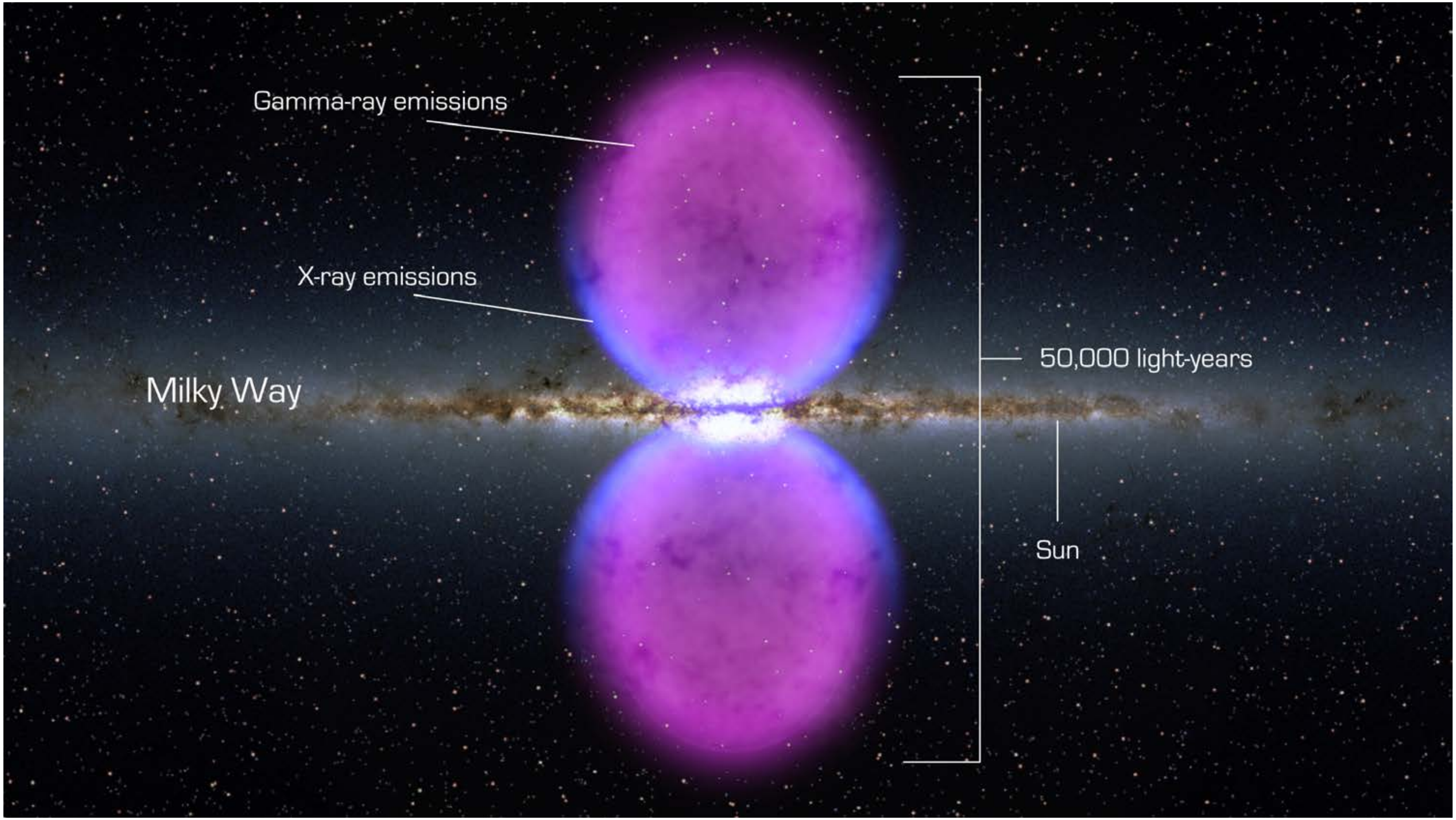




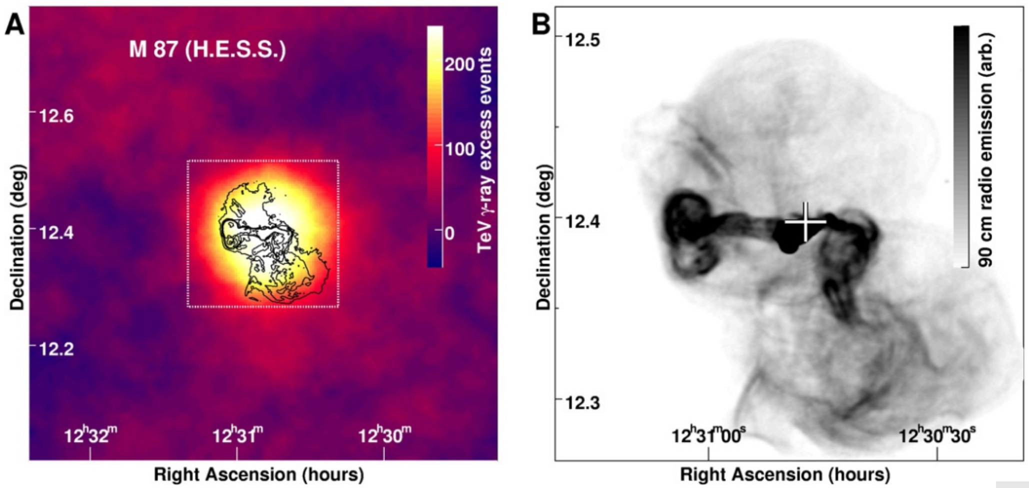
- Diffuse emission from the decay of π^0 produced in pp interactions can reach some 50 TeV => primary energy ~ 1 PeV

A PeVatron in Crab? (MAGIC, HAWC 2019)

Something special: the Fermi bubbles

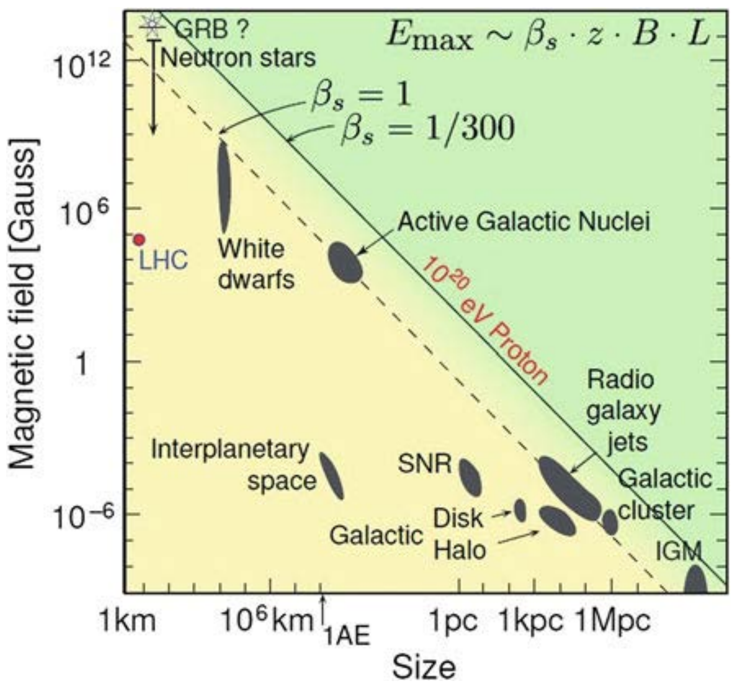


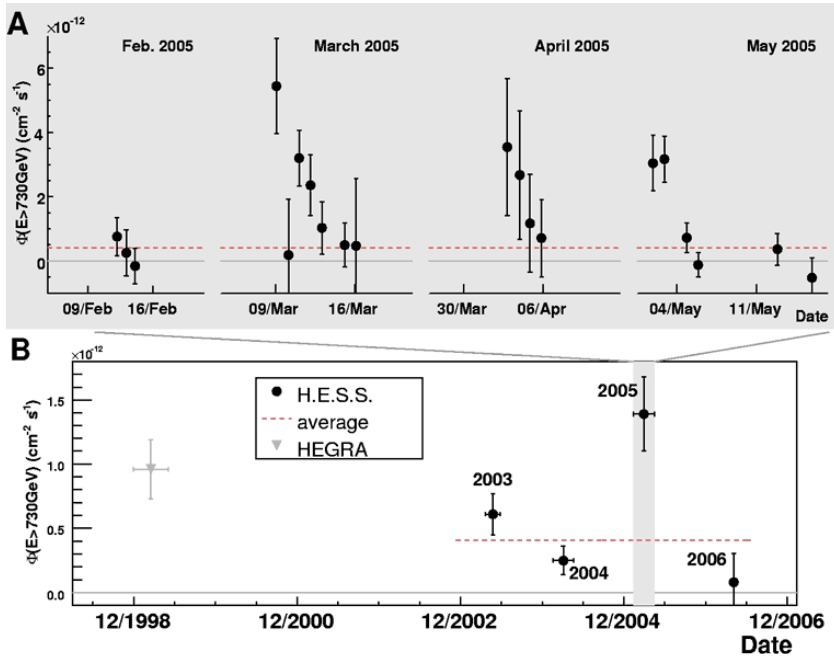
Extragalactic emitters: AGN
(IACT don’t have the resolution to see structures)



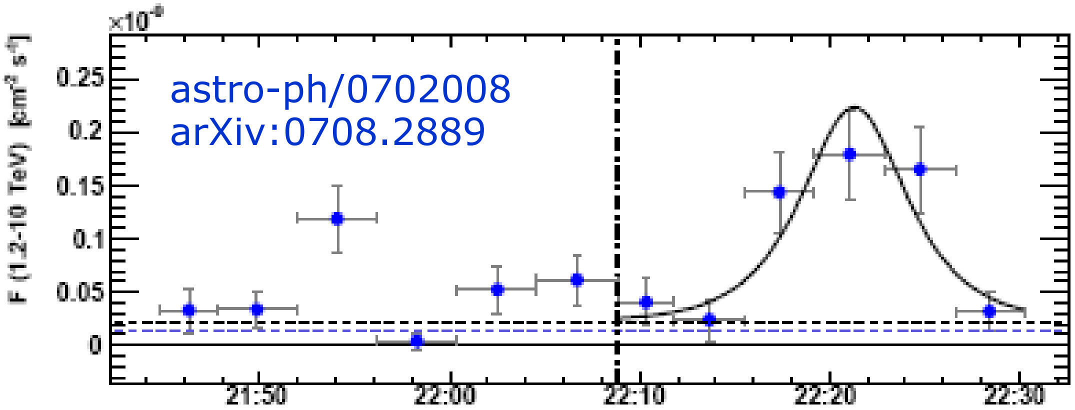
M87: Image from HESS and radio image

M87 variability in the TeV

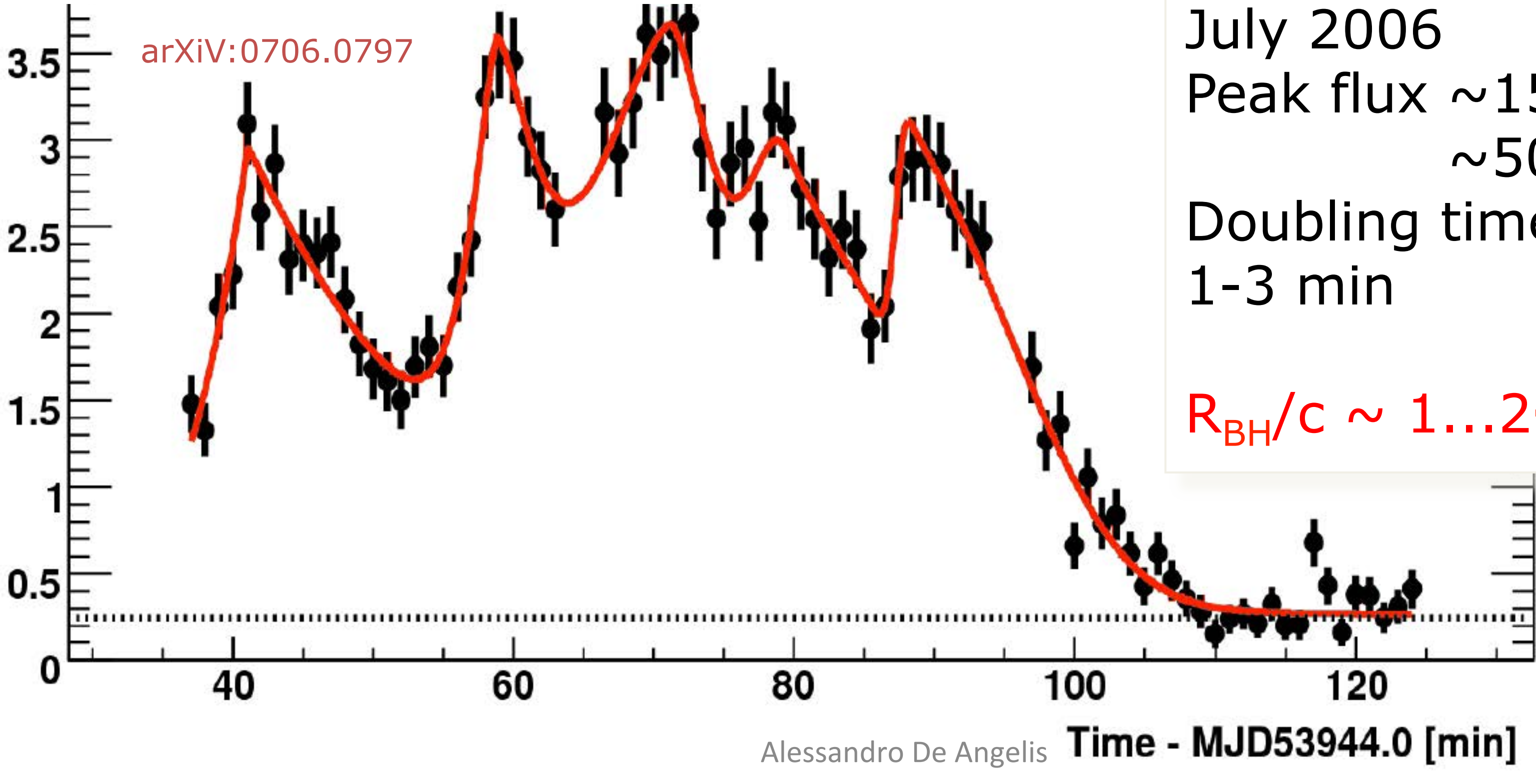




Rapid variability



MAGIC, Mkn 501
Doubling time ~ 2 min

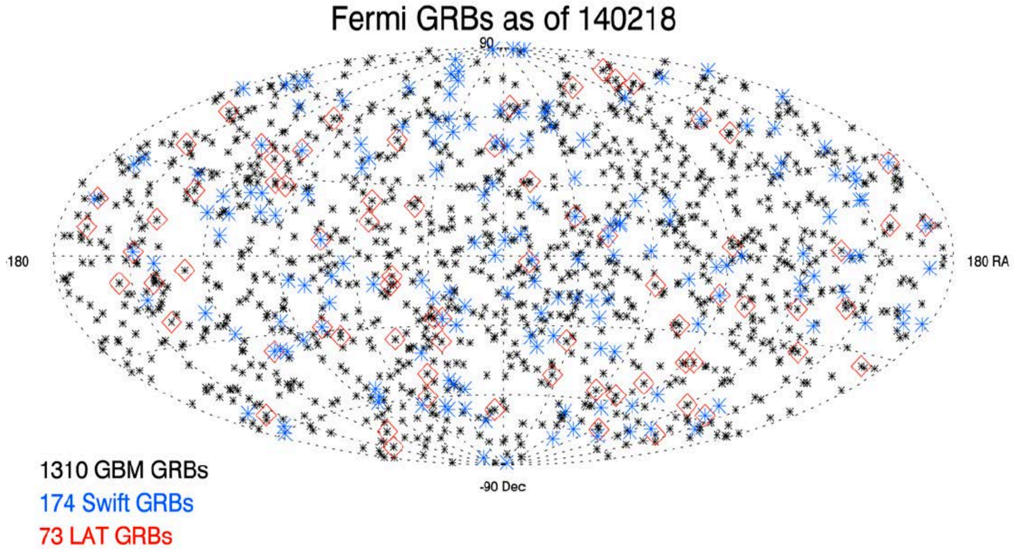


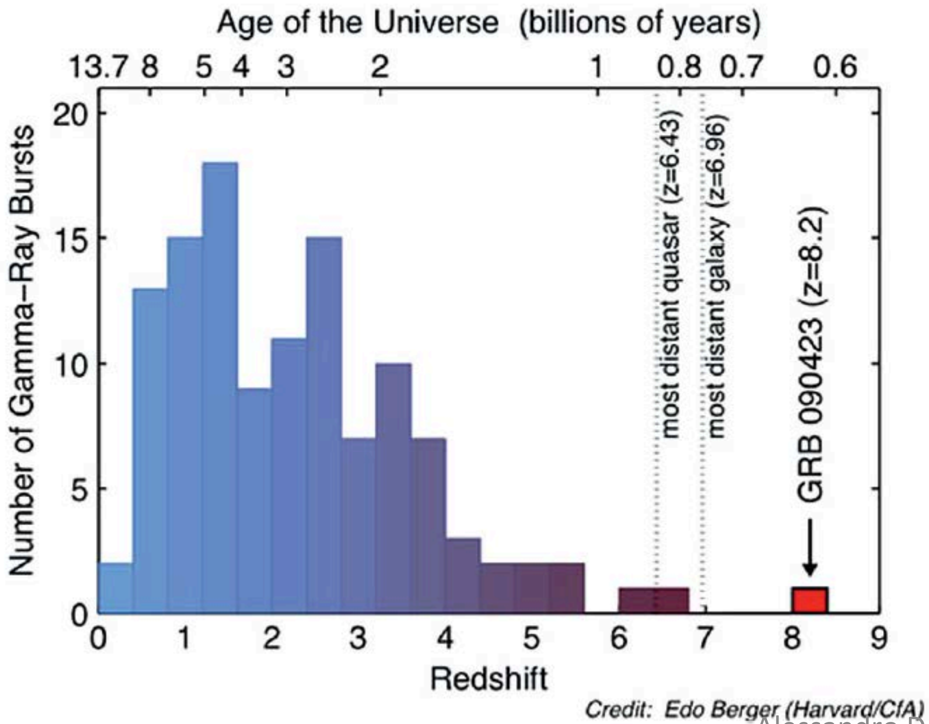
HESS PKS 2155
z = 0.116

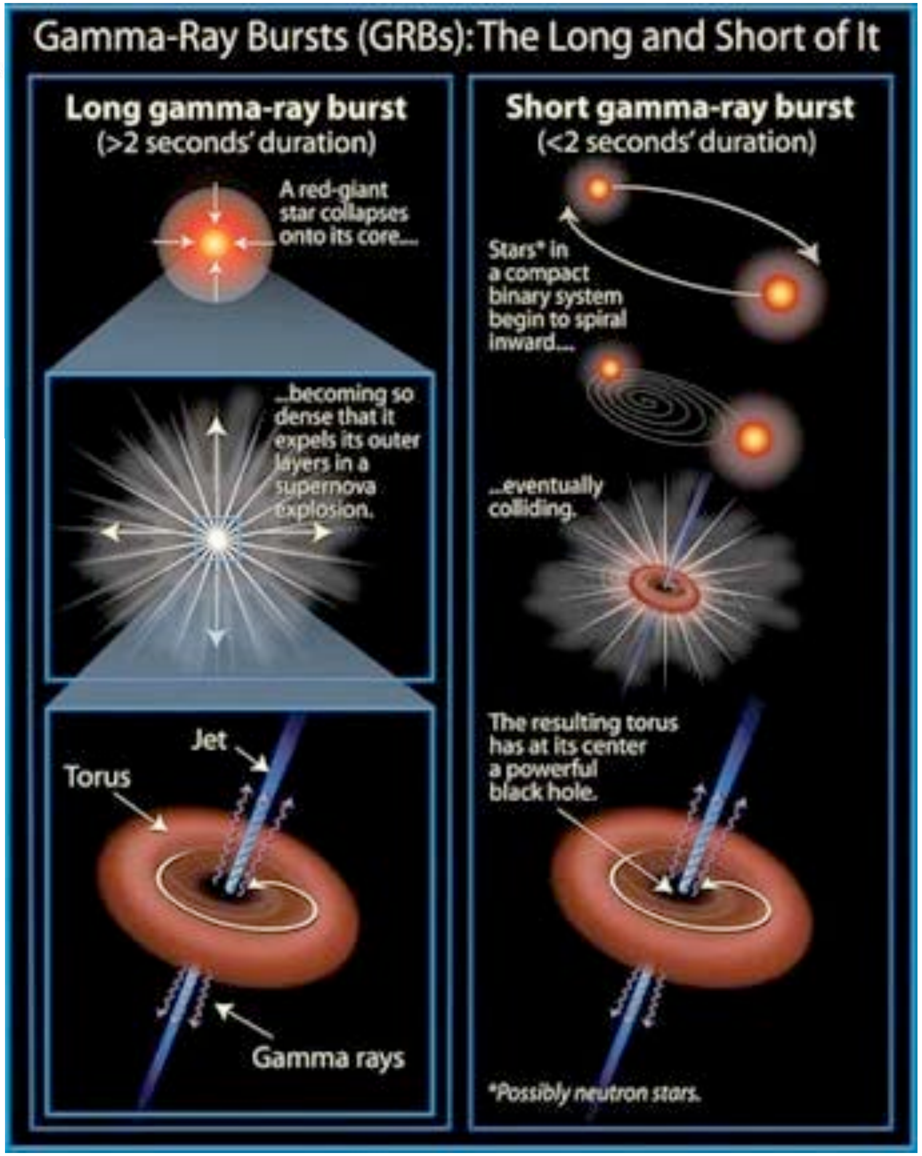
July 2006
Peak flux ~15 x Crab
~50 x average
Doubling times
1-3 min

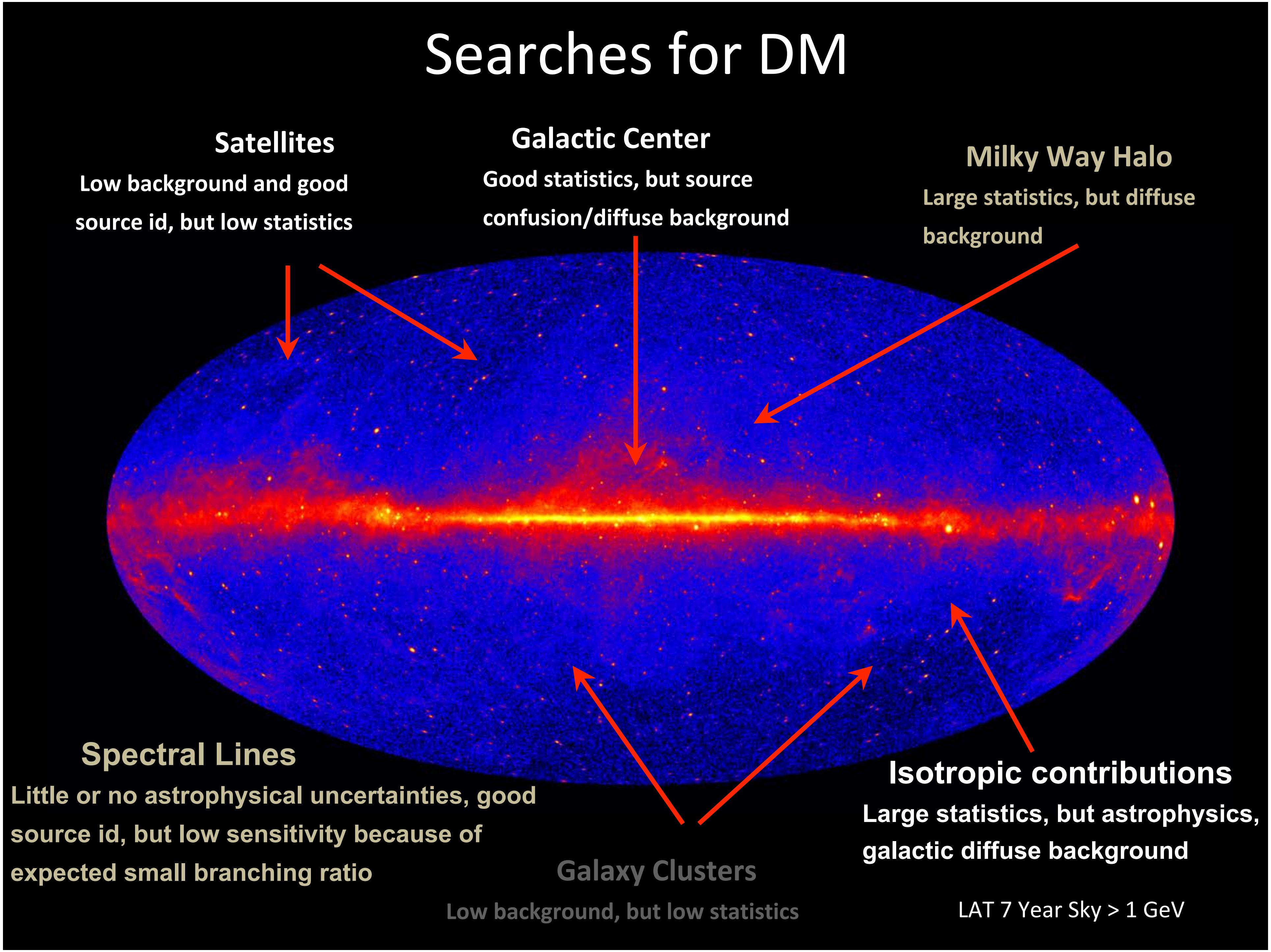
$R_{BH}/c \sim 1\ldots2 \cdot 10^4$ s

GRBs


Fermi GRBs as of 140218
90
-180
180 RA
-90 Dec
1310 GBM GRBs
174 Swift GRBs
73 LAT GRBs

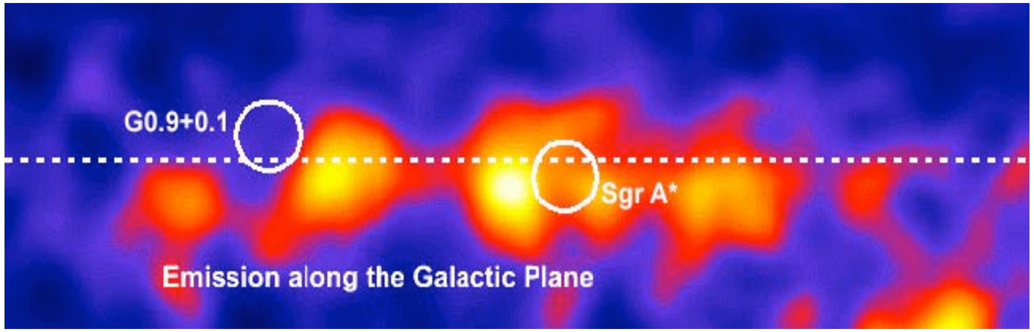

Age of the Universe (billions of years)
13.7 8 5 4 3 2 1 0.8 0.7 0.6
Number of Gamma-Ray Bursts
Redshift
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
Credit: Edo Berger (Harvard/CfA)

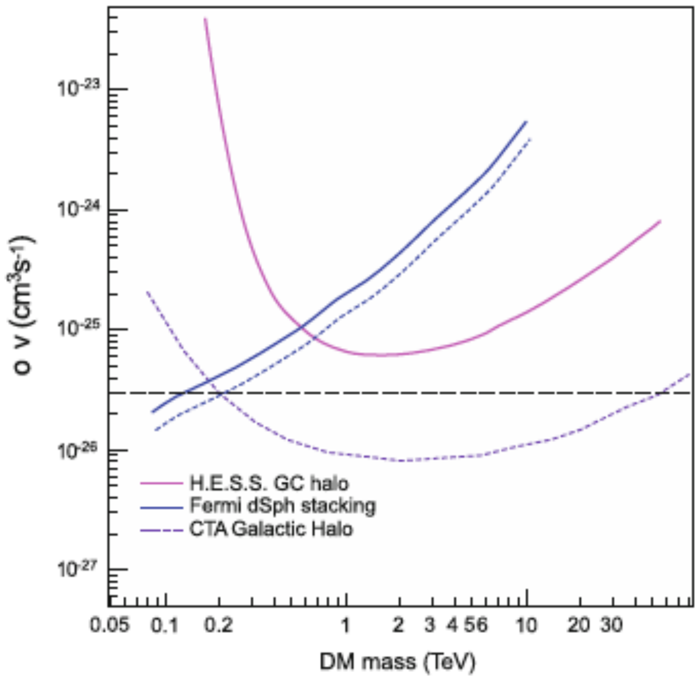

Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core...
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward...
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

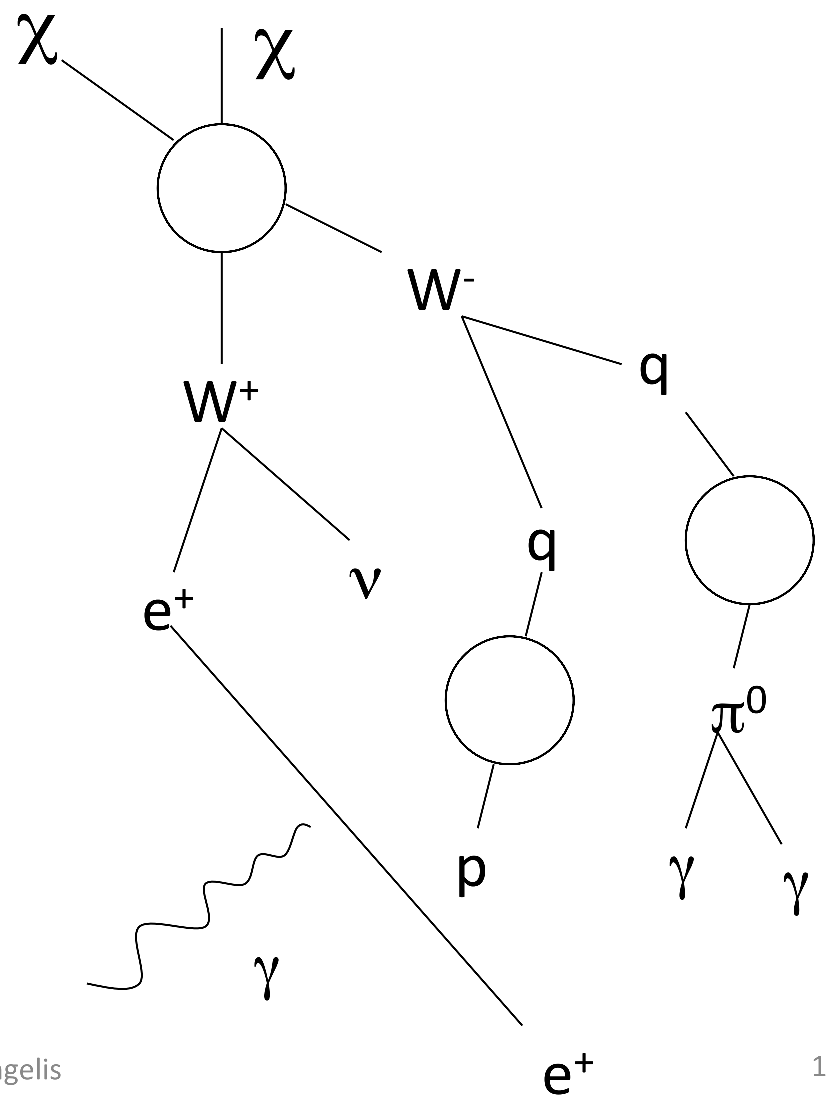

Searches for DM
Satellites
Low background and good source id, but low statistics
Galactic Center
Good statistics, but source confusion/diffuse background
Milky Way Halo
Large statistics, but diffuse background
Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio
Galaxy Clusters
Low background, but low statistics
Isotropic contributions
Large statistics, but astrophysics, galactic diffuse background
LAT 7 Year Sky > 1 GeV

Searches for DM

- Something marginal (maybe 0) from the GC at ~ 40 GeV (but very confuse region)
- No signal from dwarf satellites
- Room for sensitivity improvement







NEUTRINOS

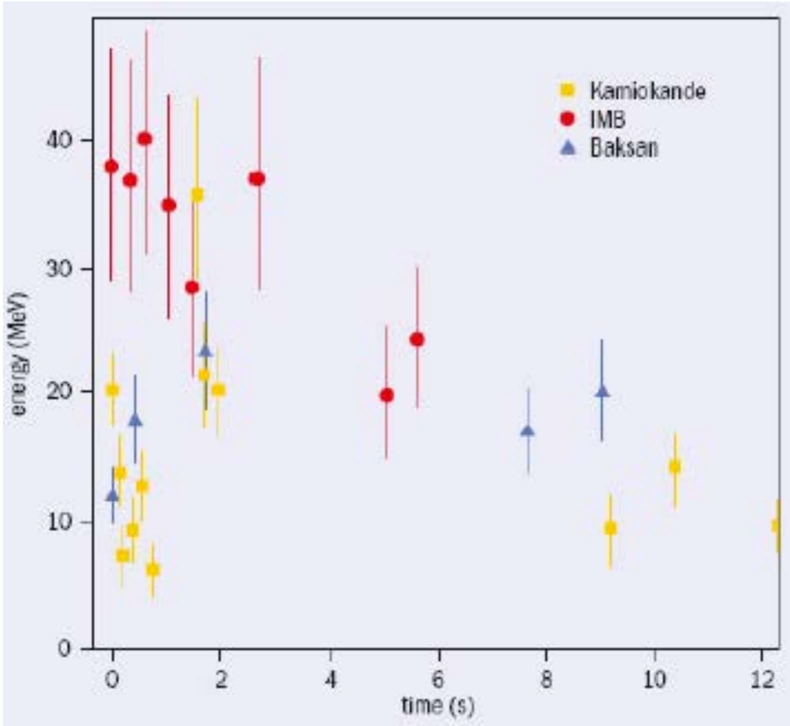
Astrophysical neutrinos

- Experimental data on astrophysical neutrinos are scarce: their small cross section makes the detection difficult.

- Up to now we detected astrophysical ν from
  - the Sun
  - the center of the Earth
  - the supernova SN1987A
  - one EHE neutrino from the blazar TXS 0506 +056
  - diffuse VHE astrophysical νs that we are can't locate the origin of

SN1987A in the Large Magellanic Cloud

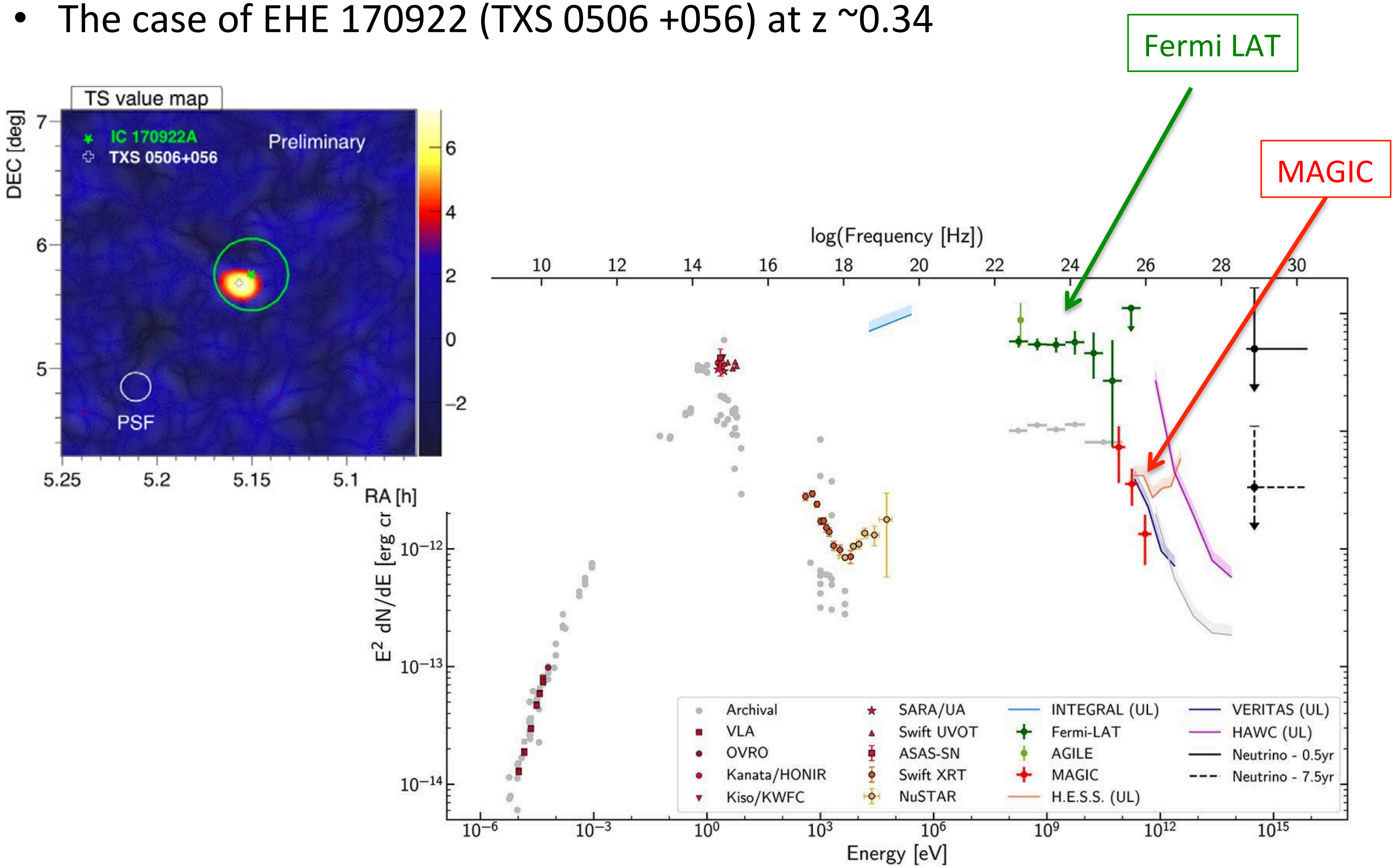
- On Feb 23, 1987, a SN was observed in the LMC, a satellite of the Milky Way (about ~1% of the mass of our Galaxy), about 50 kpc away
  - Also the first SN since 1604 visible with naked eye
  - Collapse of the star Sanduleak-69202, of mass ~20 M_S
- ~3h before optical detection, a bunch of neutrinos was observed on Earth.
- Three water Cherenkov detectors: Kamiokande, IMB, and the Baksan, observed 12, 8, and 5 neutrino interaction events, respectively, over a 13 s interval
- Within the limited statistics achieved by these 1st-generation detectors, number of events and burst duration consistent with standard estimates of the energy release and cooling time of a SN. Energy of neutrinos inferred from the energy of the recoil electrons ~10 MeV range, consistent with the origin from a collapse of a star of that mass
- No (V)HE gamma rays



- Fundamental properties of neutrinos:
  - ν arrival time distribution => $m_\nu < 10$ eV
  - No spread: $\mu < 10^{-12}\ \mu_B$
  - Optical delay: $|v-c|/c < 2\ 10^{-9}$

September 2017: the first identified AGN

- Are AGN sources of VHE neutrinos and thus of UHECR?
- The case of EHE 170922 (TXS 0506 +056) at z ~0.34



Neutrinos in an AGN

- Although $\sigma_{\gamma p} \sim 0.3$ mb $\sim \sigma_{pp}/100$, photoproduction is favored in jets because the photon density is expected to be larger

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+\,\nu_\mu \rightarrow n\,e^+\,\nu_e\,\bar{\nu}_\mu\,\nu_\mu \end{cases}$$

- This process has obviously a threshold, and is dominated by the Δ pole:

$$E_p \sim 350 \text{ PeV} / (\varepsilon/\text{eV})$$

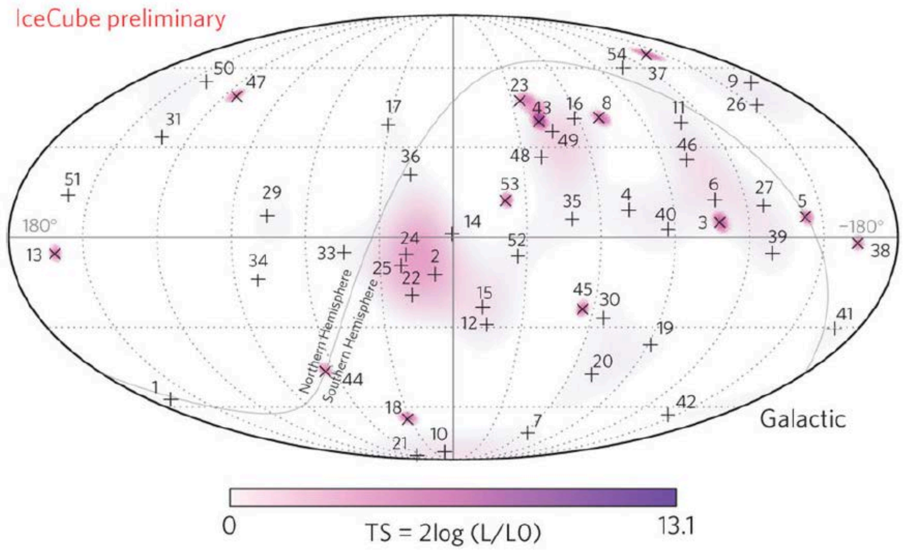
=> The creation of a neutrino (or gamma ray) from a photon gas at 5-10 eV requires protons at $E_p >\sim 50$ PeV

- E^{-p} in protons => E^{-p} in photons and neutrinos, rescaled by a factor ~10 – 20
  - By the way, a factor of ~20 also in hadroproduction around the PeV

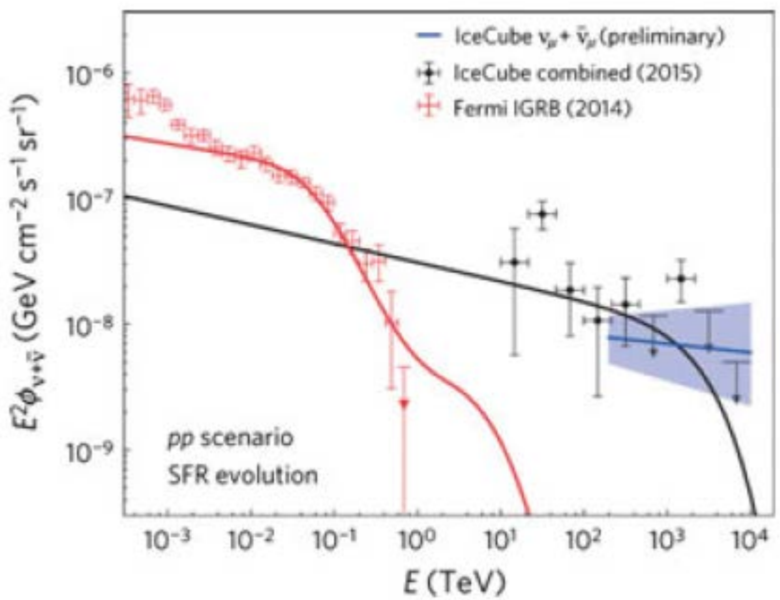
Diffuse VHE astrophysical neutrinos

- IceCube reported in 2013 the detection of astrophysical νs; now ~1 astrophysical neutrino/month collected
- The experimental problem is linked to the large background from atmospheric muons, which are recorded, even at a depth of 1450 m, at a rate of about 3000 per second. Two methods are used to identify genuine ν :
  - Use the Earth as a filter remove the huge background of CR muons. i.e., look only to events from the bottom
  - Identify νs interacting inside the detector: divide the instrumented volume of ice into an outer veto and a 500 megaton inner fiducial volume.

$$\Phi_\nu \simeq (0.9 \pm 0.3) \times 10^{-18} \left(\frac{E}{100\,\mathrm{TeV}}\right)^{2.13\pm0.13} \mathrm{GeV^{-1}cm^{-2}sr^{-1}}$$



- Physics result:
  - No evidence for clustering



Clear relation with gamma rays

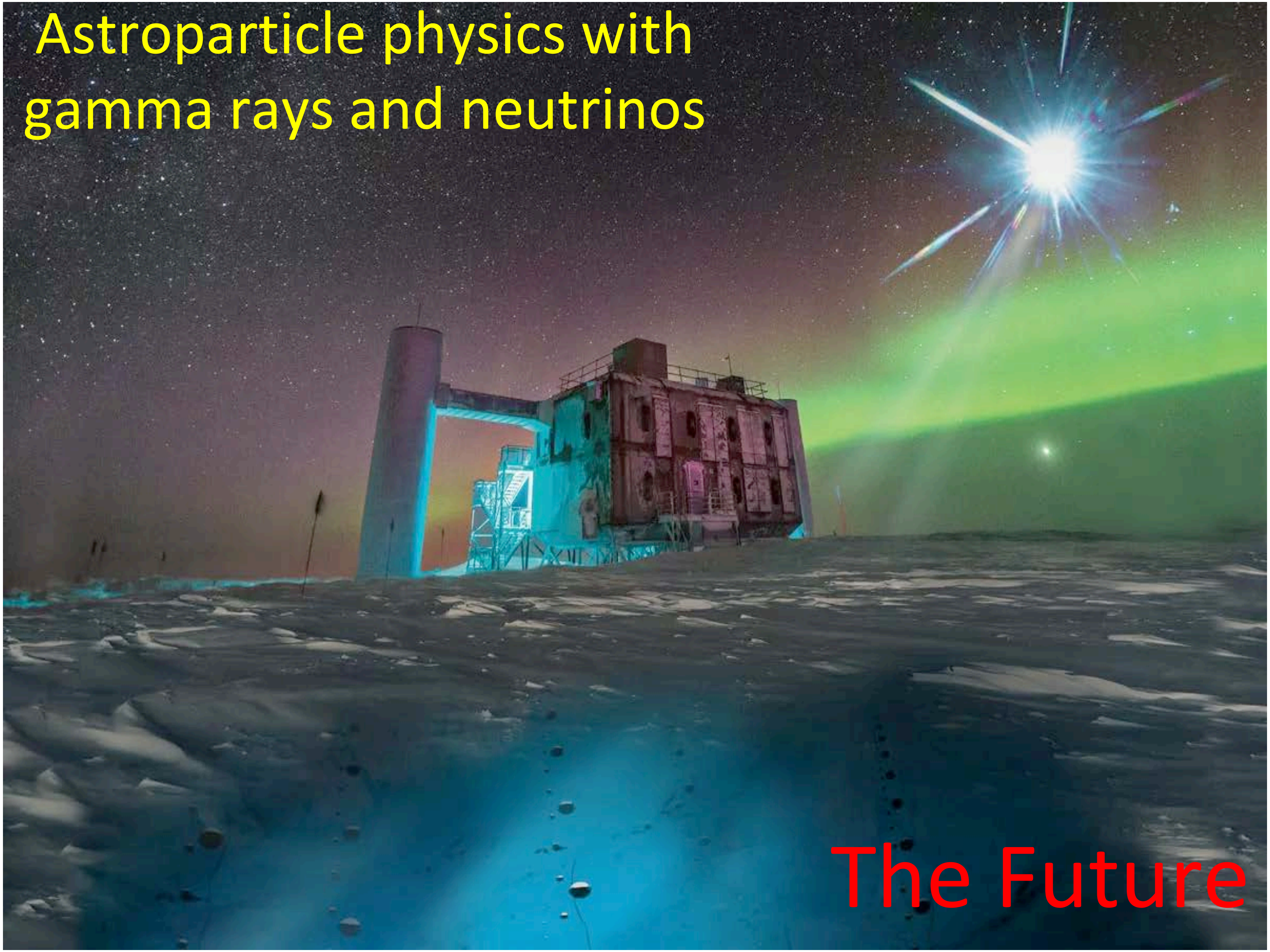
Summary: what data tell us on sources

- Neutrinos are markers of hadronic accelerators
  - One AGN found above the knee
- Gamma rays are markers of hadronic acceleration if
  - π^0 peak or
  - PeV acceleration or
  - Orphan flares

=> Many SNRs, few AGN

- Other classes of sources of gamma rays (pulsars, binaries, GRBs without hadronic identification)
  - If hadronic acceleration, both neutrinos and gamma rays
- < 6% of IceCube neutrinos are coincident with GRBs
  - GRBs are not the dominant source of CRs

- Still a lot of work, but already many hints during the last 10 years

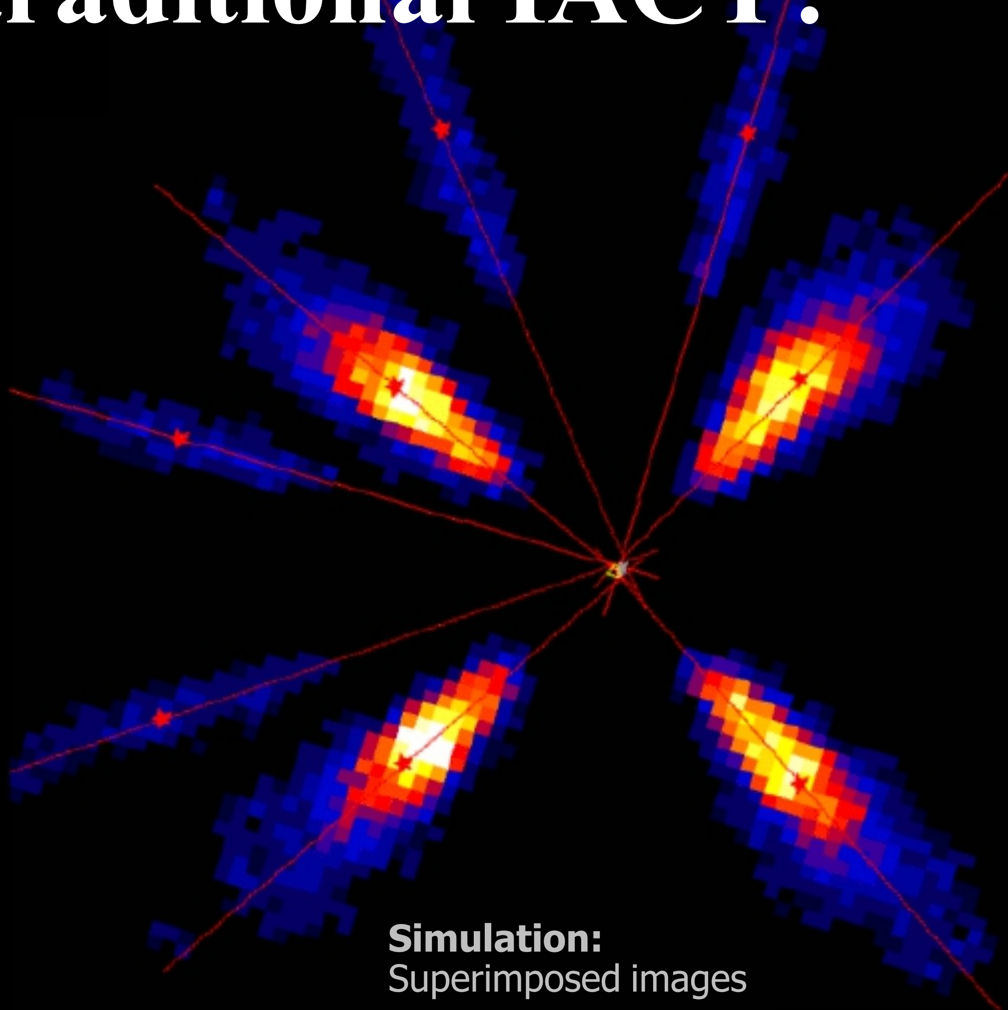

Astroparticle physics with
gamma rays and neutrinos
The Future

The TeV gamma-ray region: CTA & friends

The 20 GeV- 100 TeV region: how to do better with traditional IACT?

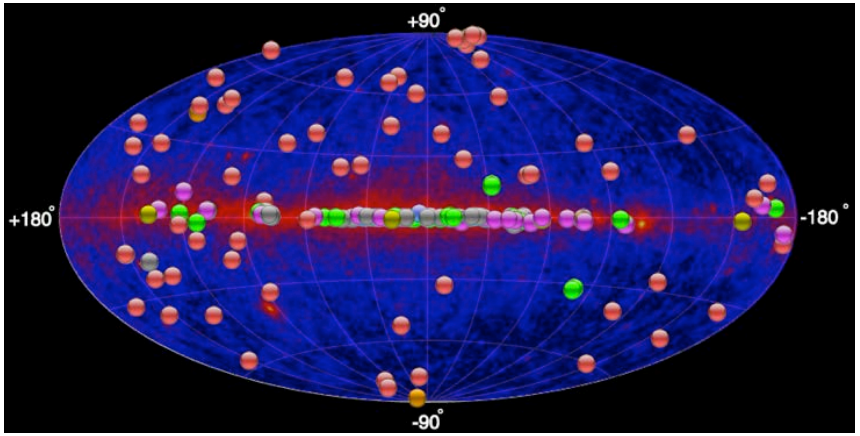
- More events
  - More photons = better spectra, images, fainter sources
    - Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - Improved angular resolution
    - Improved background rejection power

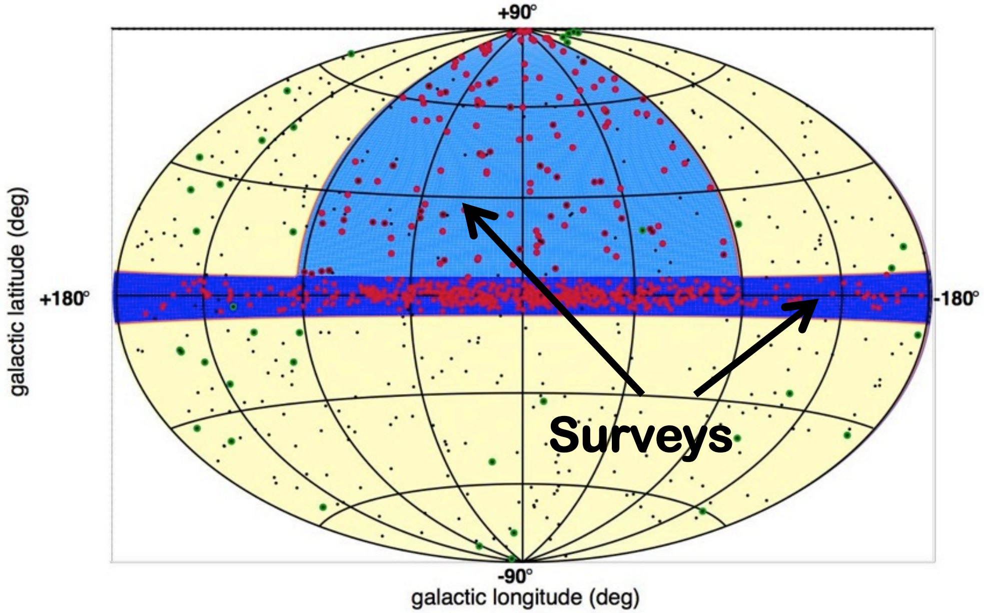
☛ The CTA solution: More telescopes !

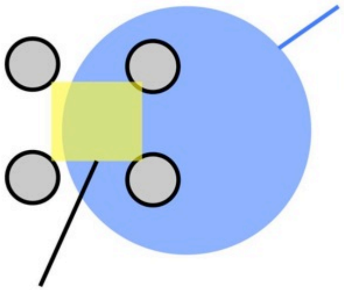


Simulation: Superimposed images from 8 cameras

From current arrays to CTA

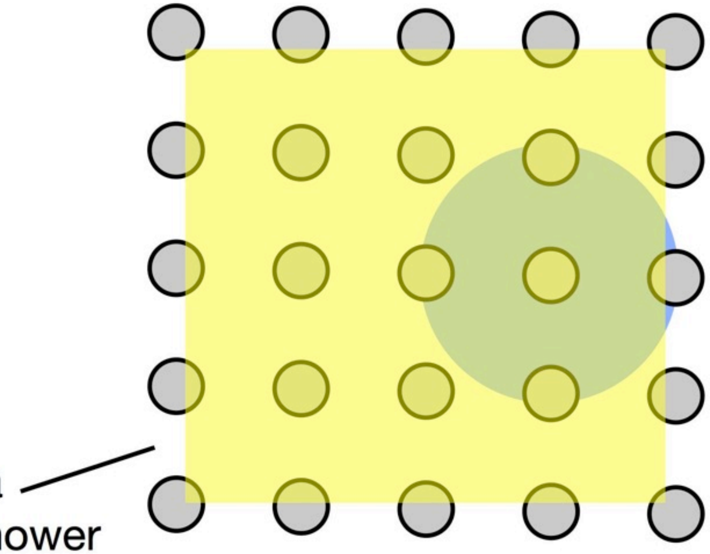






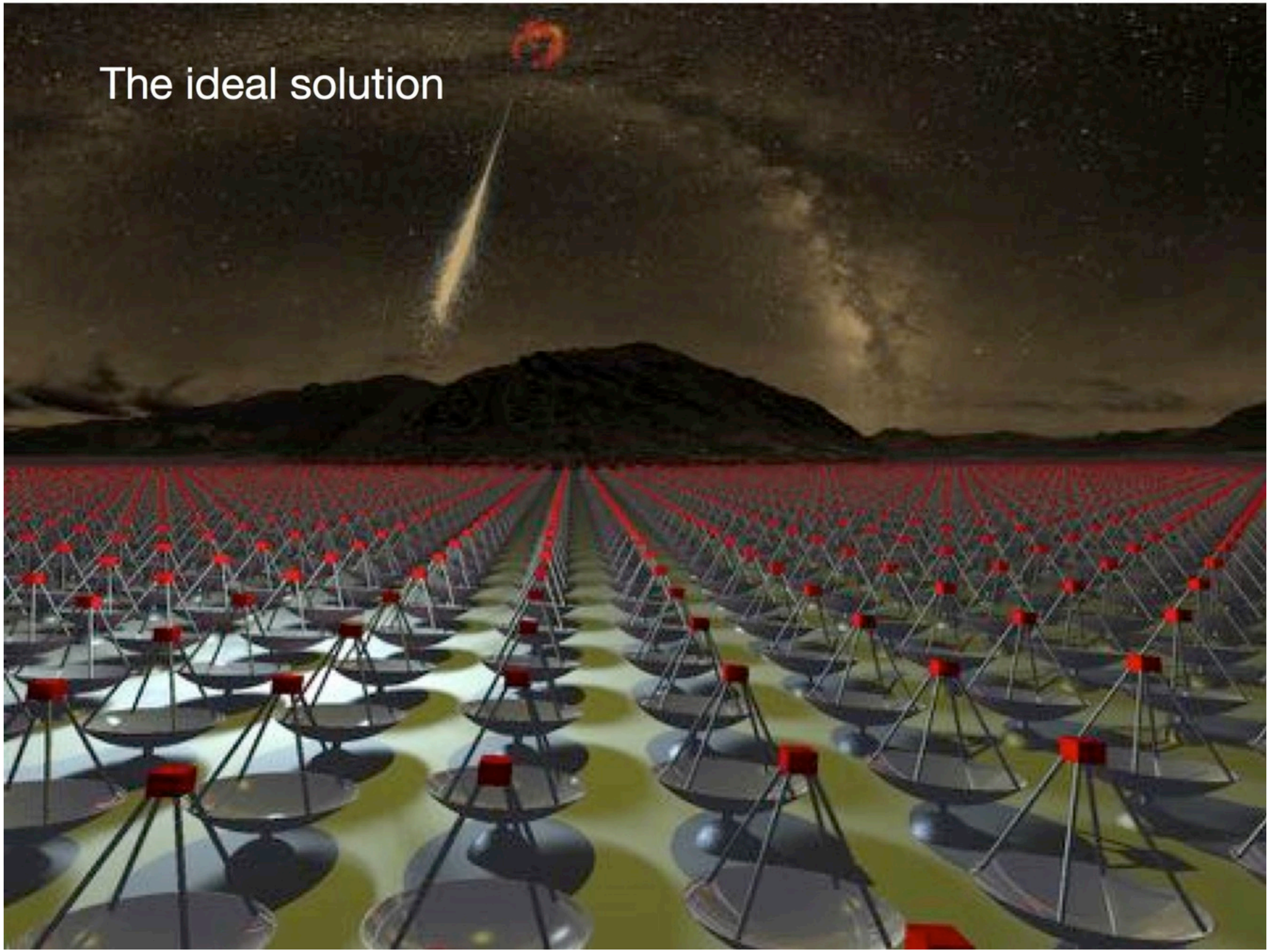
light pool radius
R ≈100-150 m
≈ typical telescope spacing

Sweet spot for
best triggering
and reconstruction:
most showers miss it!

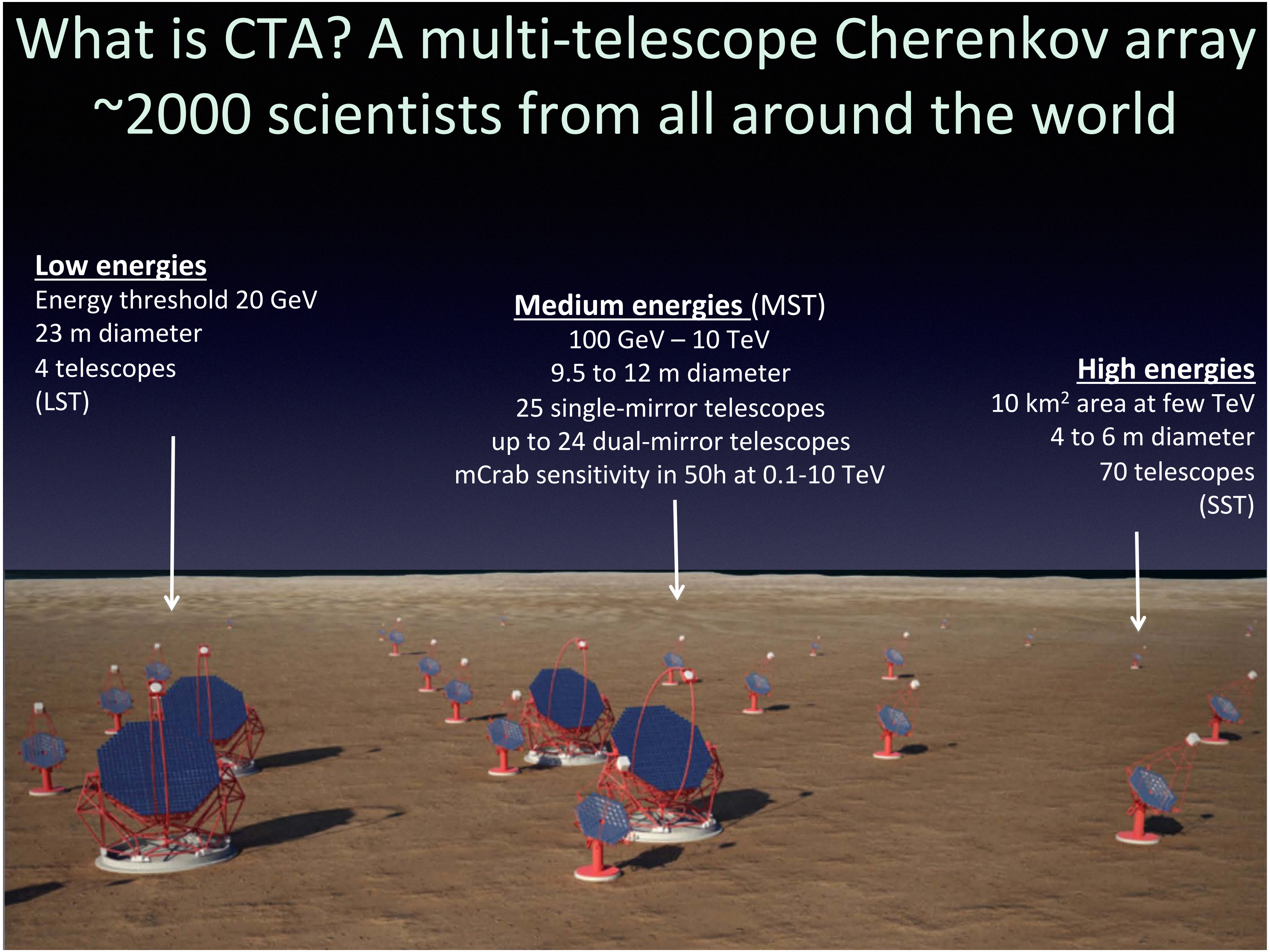


large detection area
more images per shower
lower trigger threshold

A next generation VHE facility

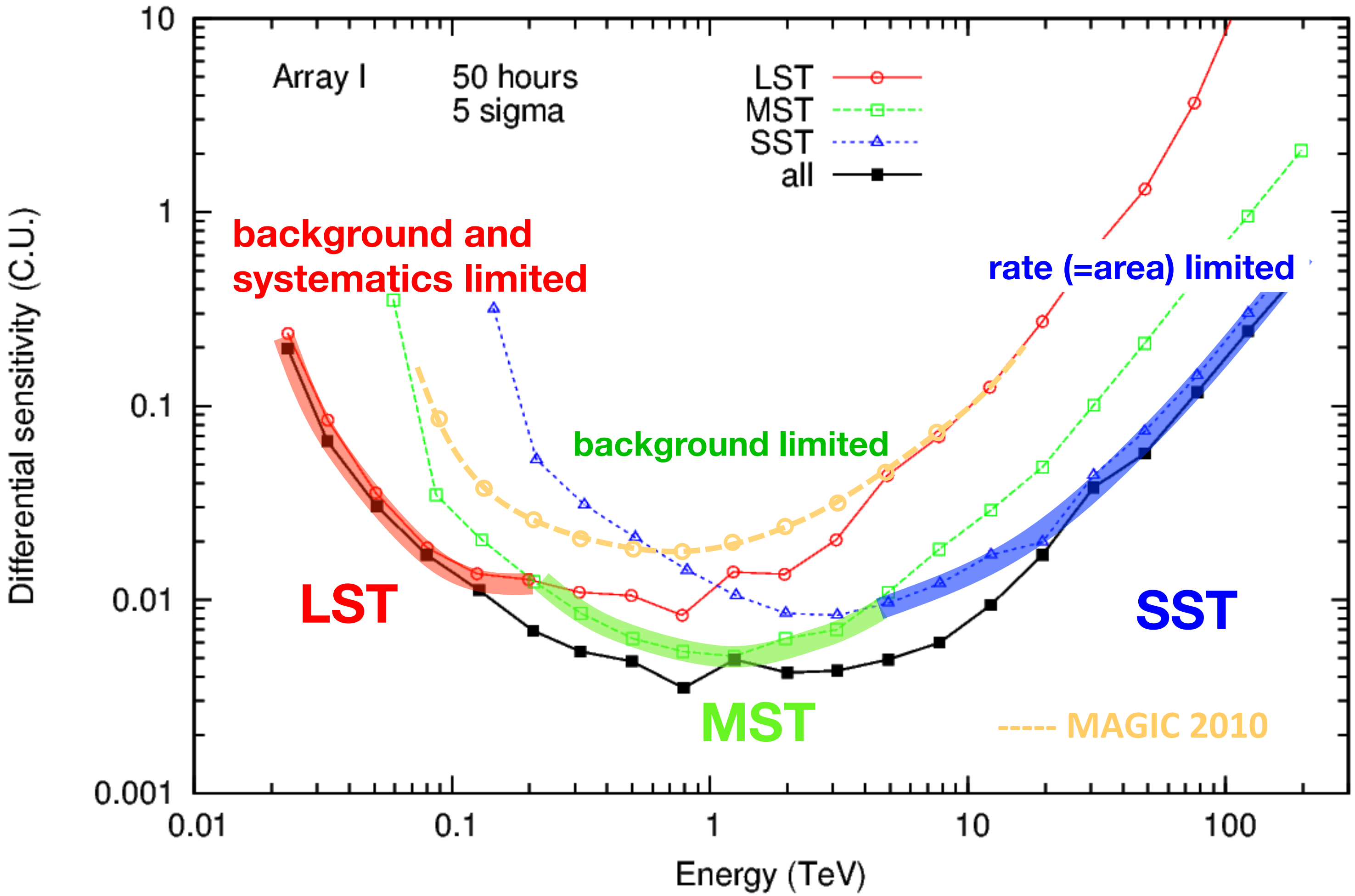


W. Hofmann

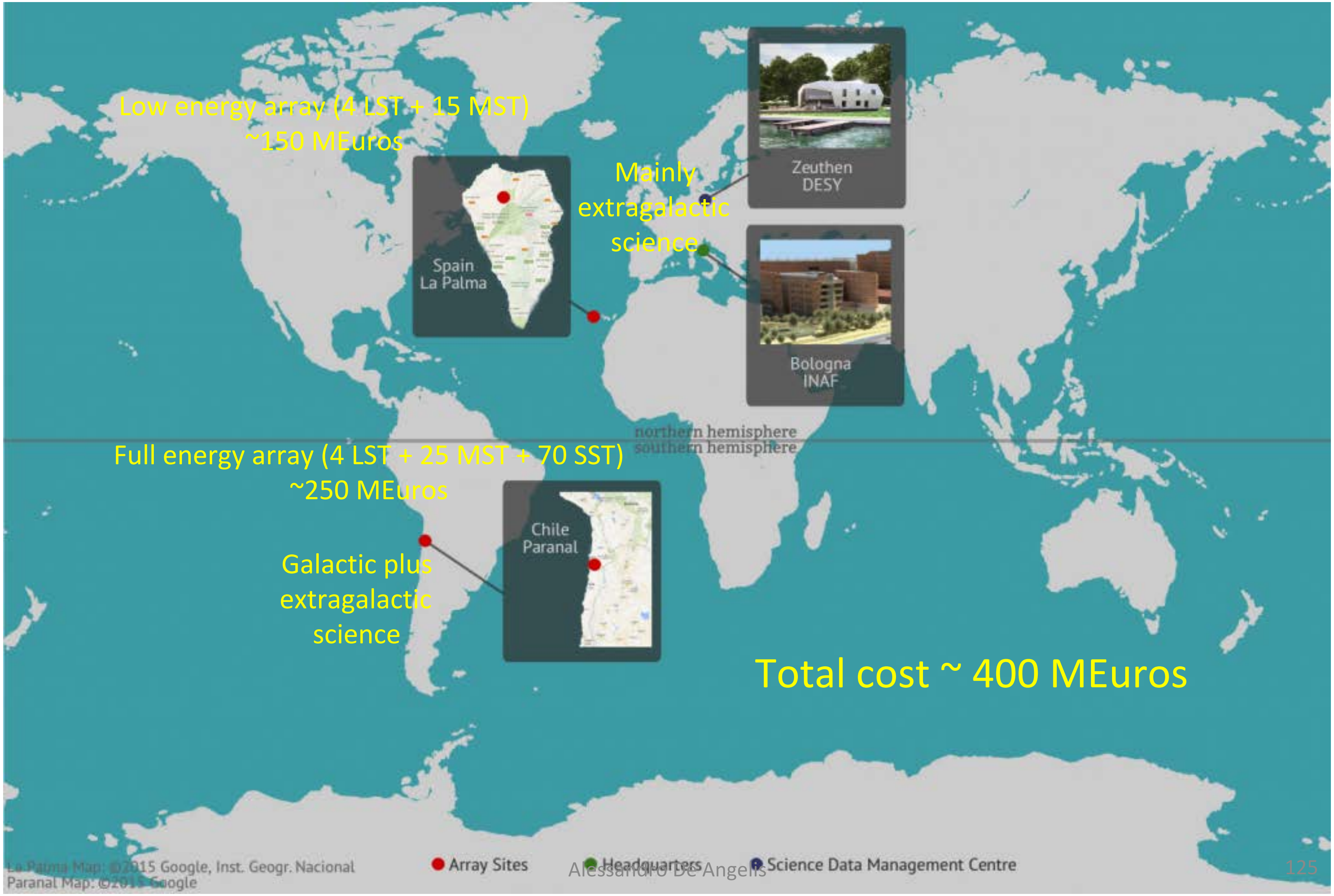

What is CTA? A multi-telescope Cherenkov array
~2000 scientists from all around the world
Low energies
Energy threshold 20 GeV
23 m diameter
4 telescopes
(LST)
Medium energies (MST)
100 GeV – 10 TeV
9.5 to 12 m diameter
25 single-mirror telescopes
up to 24 dual-mirror telescopes
mCrab sensitivity in 50h at 0.1-10 TeV
High energies
10 km² area at few TeV
4 to 6 m diameter
70 telescopes
(SST)

CTA sensitivity in units of Crab flux

for 5 σ detection & $N_\gamma > 10$ in each 0.2-dex bin in E, in 50 h



All-sky coverage: two observatories

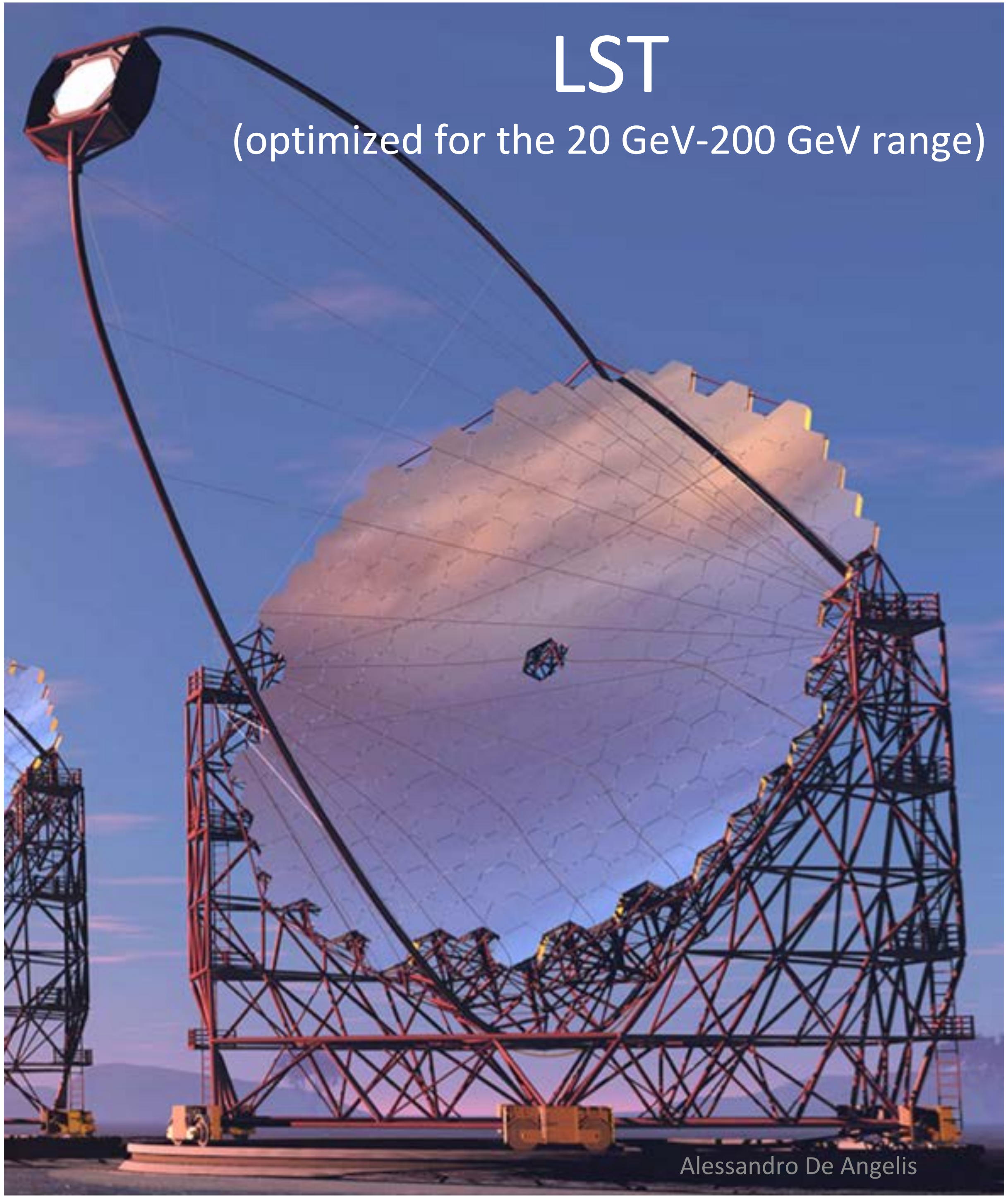


CTA-N: rendering

LST1 under commissioning in 2019 (inaugurated October 10, 2018)
LST2-4 deployed in 2020-22?
First 5 MST deployed in 2022-23?

LST

(optimized for the 20 GeV-200 GeV range)



- 23 m diameter (400 m^2 dish area)
- 28 m focal length
- 200x2m^2 hexagonal mirrors

- 4.5 deg FoV

- 0.1° pixels, camera diam. 2m
- Light structure for 20 s positioning
- AMC

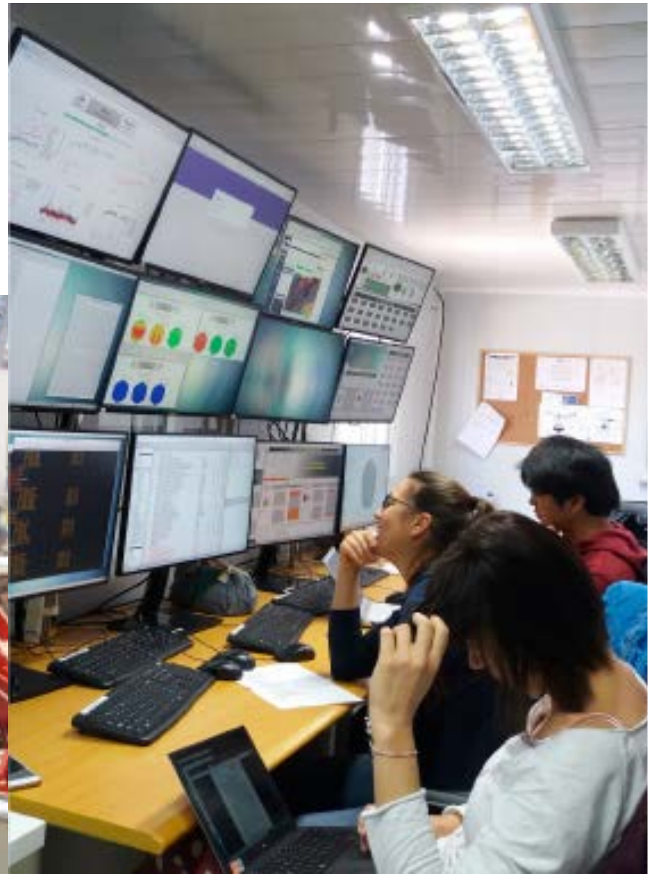
- 4 LSTs on North site, 4 LSTs on South site

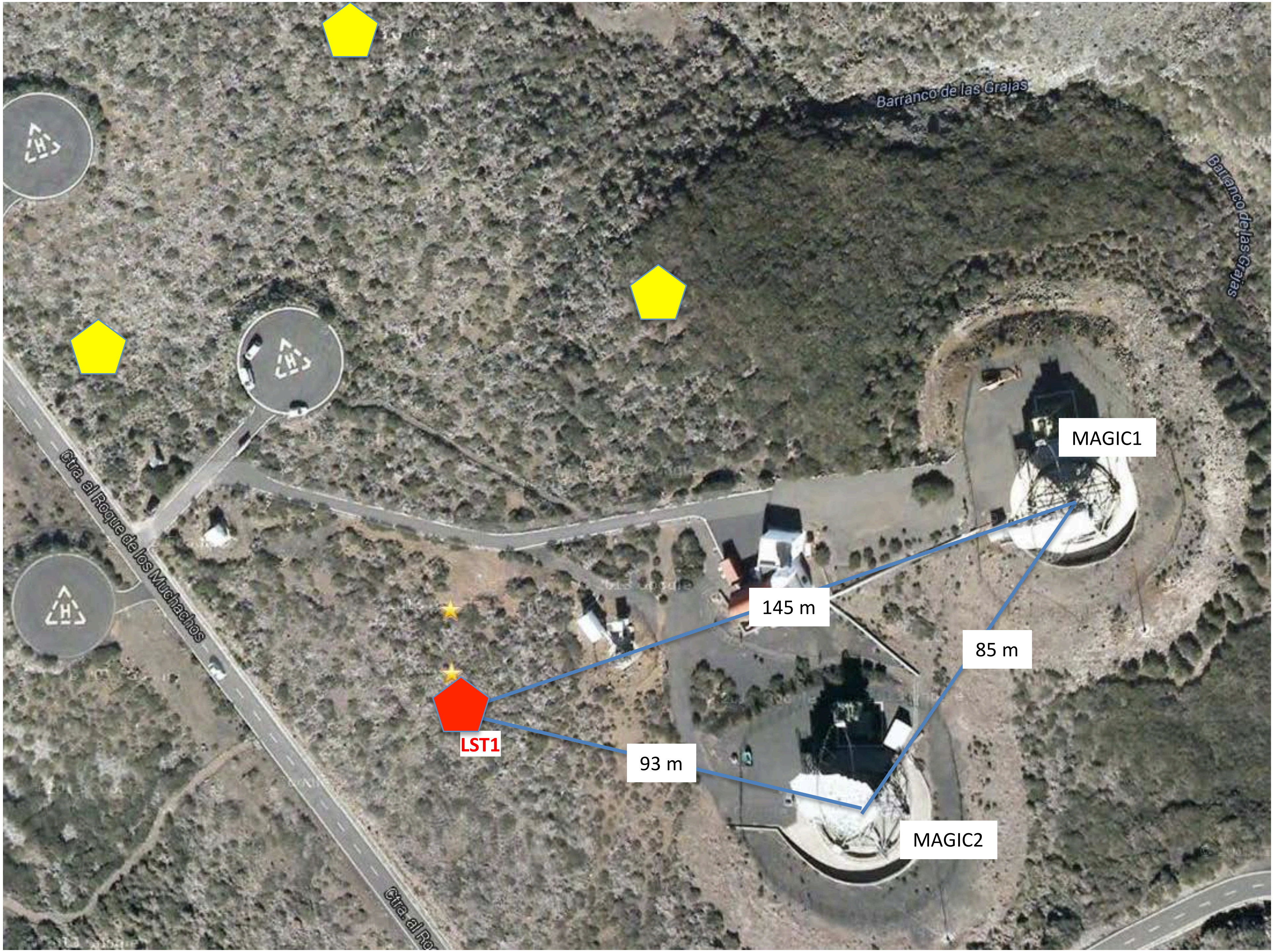
- Prototype = 1st telescope at La Palma.
- Foundations end 2016
- Inaugurated Oct 10, 2018
- First signals detected
- First source in ~1 month?

- Japan, Germany, INFN Italy, Spain, IN2P3 France, India, Brazil, Croatia, Sweden

LST1 at La Palma (near MAGIC)

Commissioning in progress,
~20 people in the field

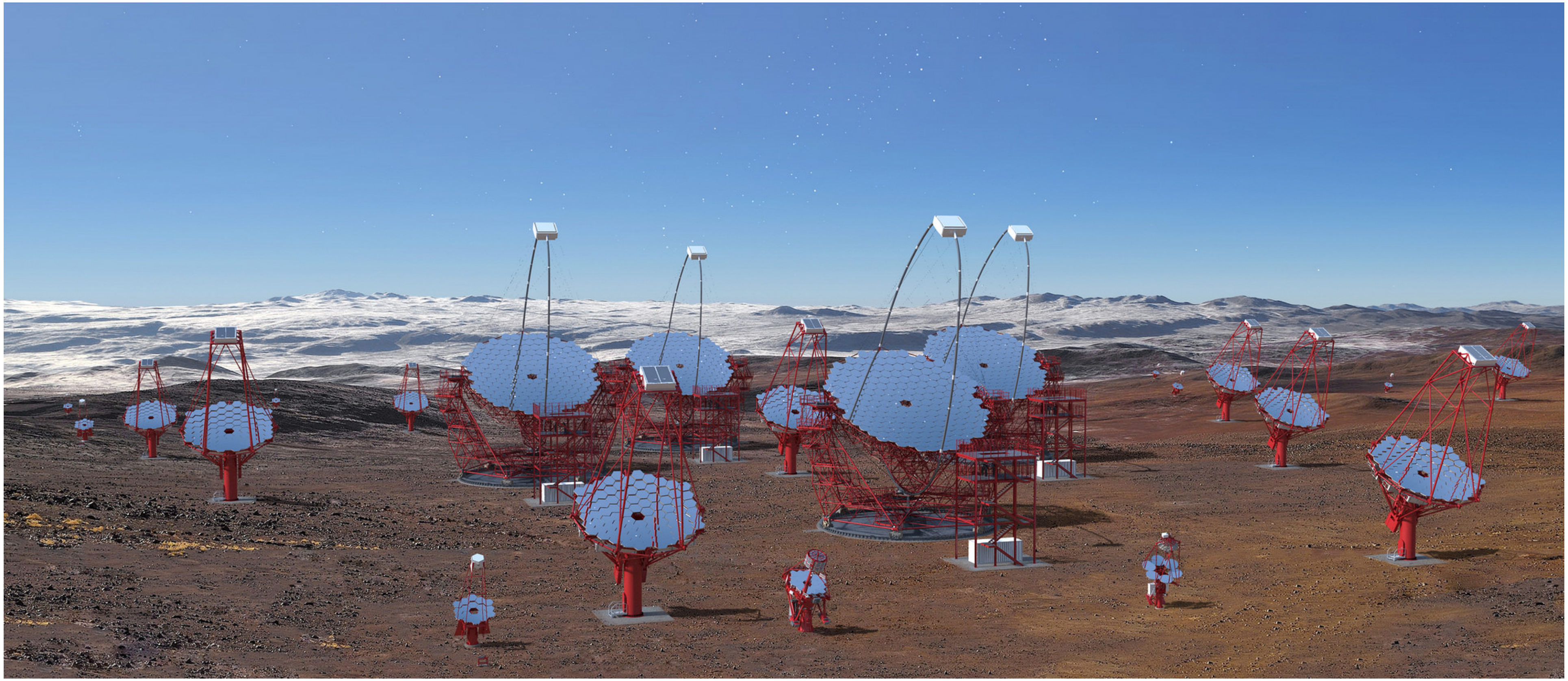


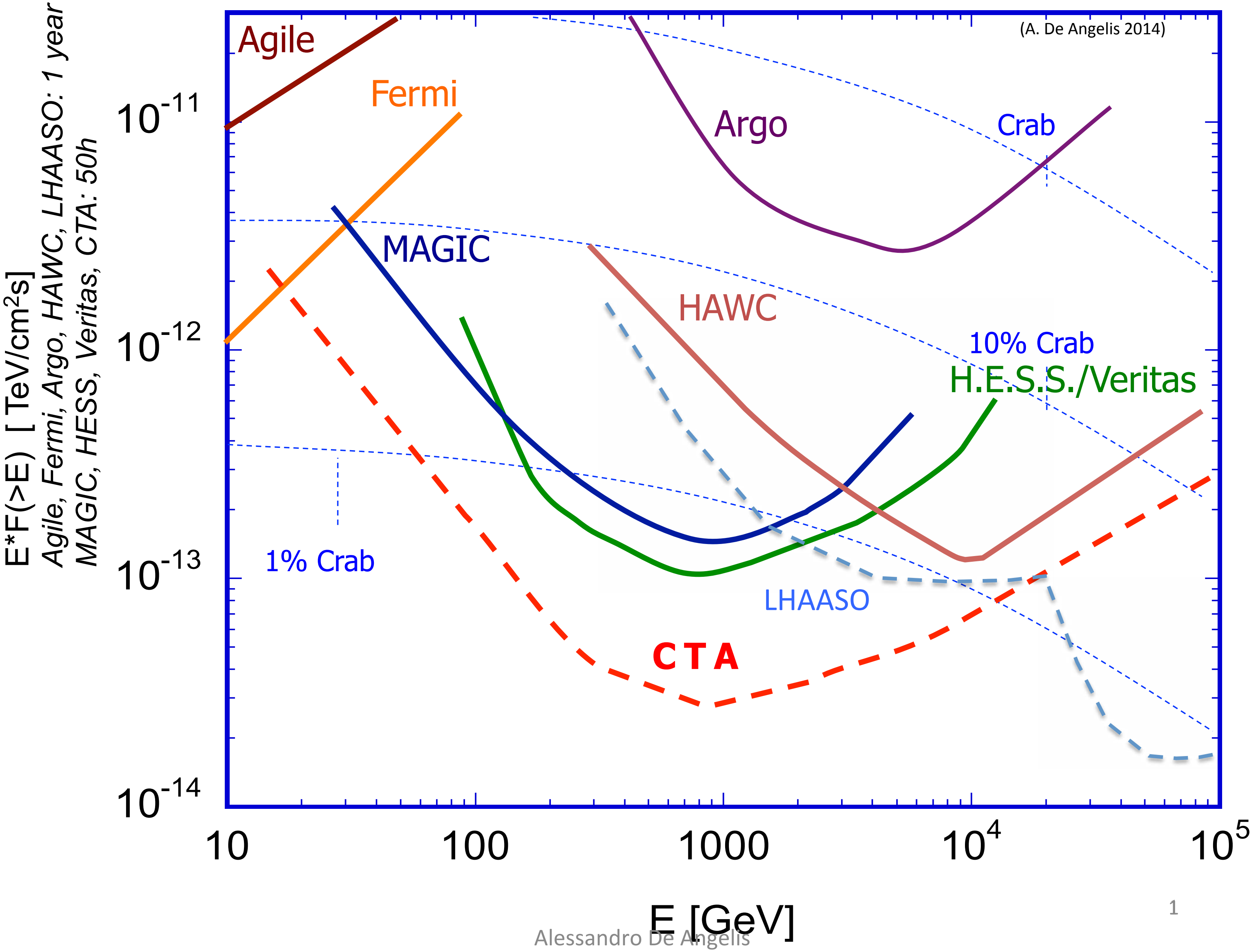

Barranco de las Grajas
Barranco de las Grajas
Ctra. al Roque de los Muchachos
Ctra. al Ro
MAGIC1
MAGIC2
LST1
145 m
85 m
93 m

MST: 2 designs

SST: 3 designs

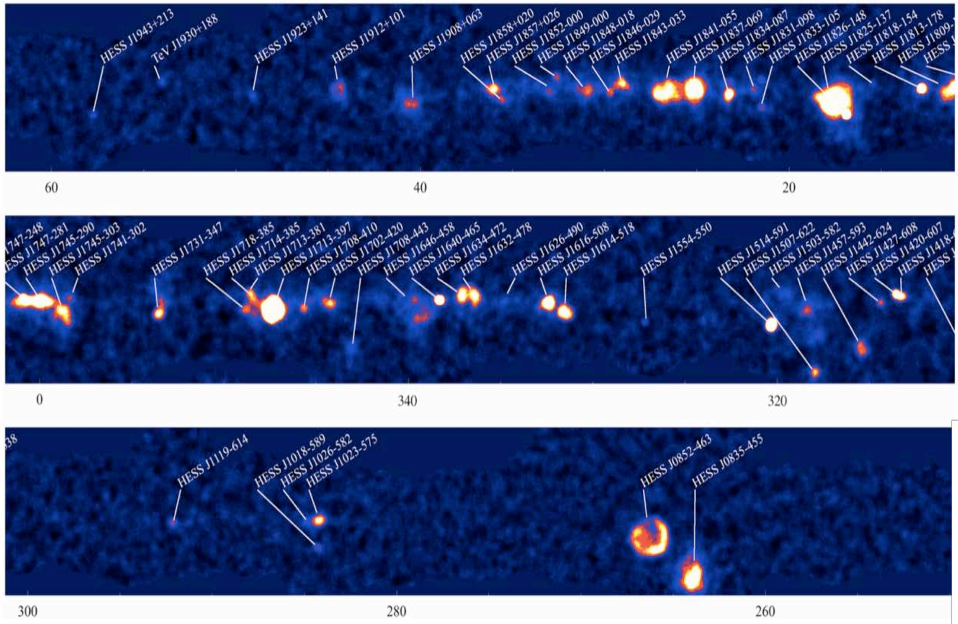
CTA-S in Paranal: rendering (deployment starting in 2022?)

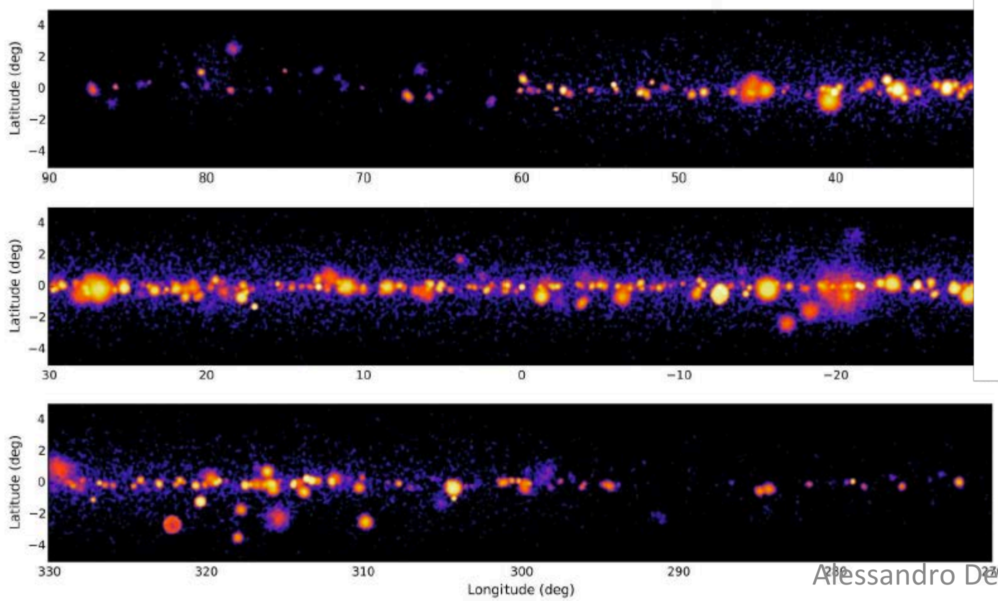


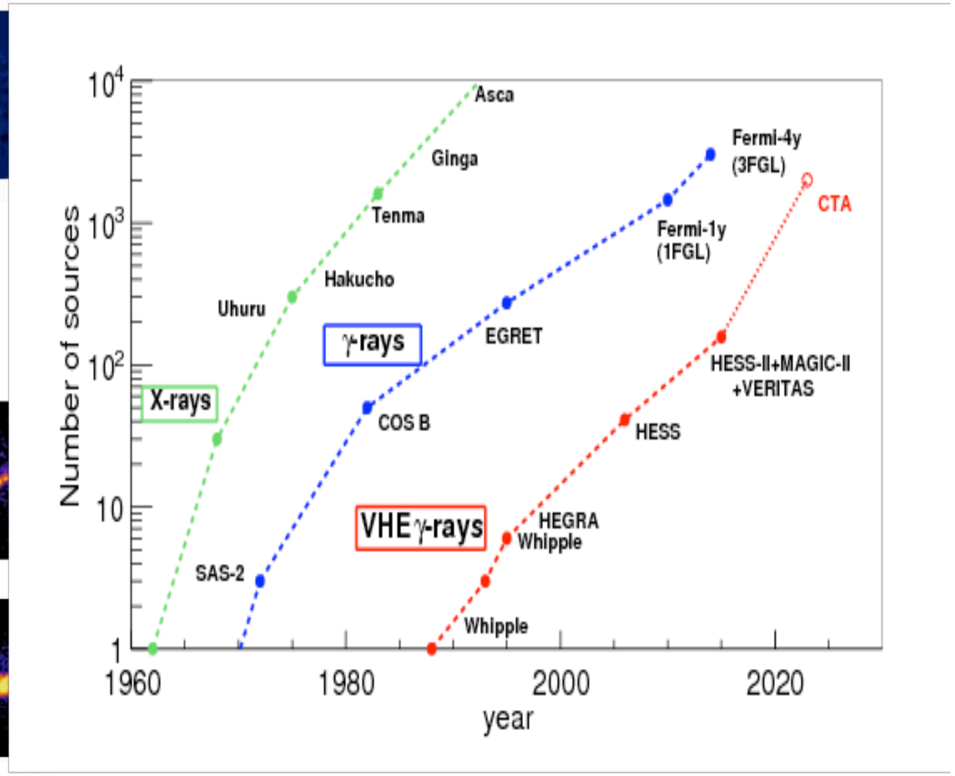


E*F(>E) [TeV/cm2s]
Agile, Fermi, Argo, HAWC, LHAASO: 1 year
MAGIC, HESS, Veritas, CTA: 50h
(A. De Angelis 2014)
Agile
Fermi
Argo
Crab
MAGIC
HAWC
10% Crab
H.E.S.S./Veritas
1% Crab
LHAASO
CTA
10-11
10-12
10-13
10-14
10
100
1000
104
105
E [GeV]
1

Huge physics case for CTA





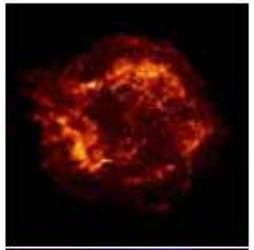


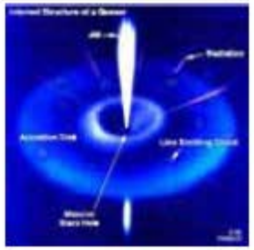
Guaranteed Science with CTA

An advanced Facility for ground-based gamma-ray Astronomy

~200 -> ~2000 sources above 100 GeV

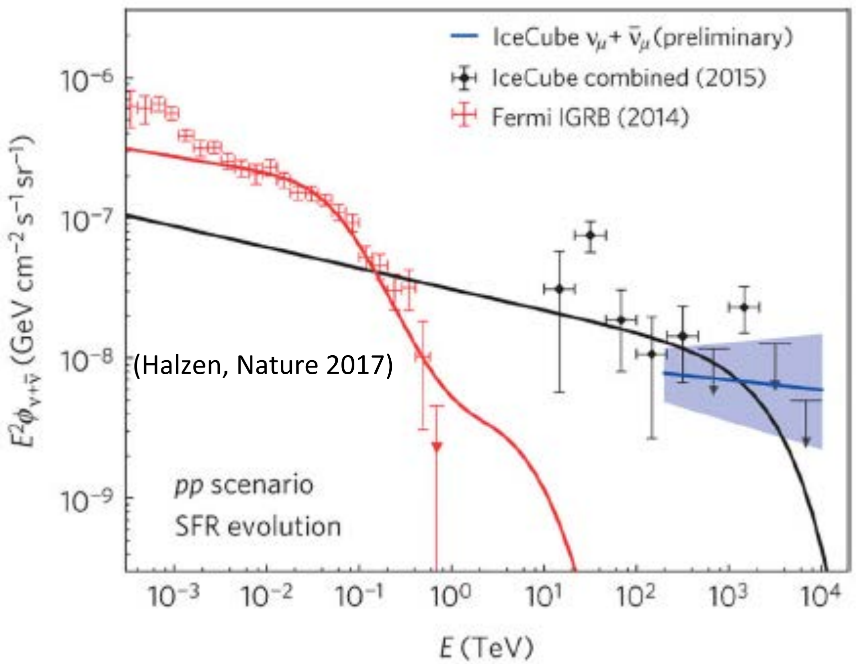
- Study of sources and propagation of high energy particles in the Cosmos, on scales ranging from compact objects to large scale structures
  - Pulsars
  - Pulsar wind nebulae
  - Stellar winds
  - Supernova remnants
  - Diffuse emission
  - Galactic center region
  - Starburst galaxies
  - Clusters of galaxies
- Black holes and their environment
  - Stellar-mass black holes
  - Supermassive black holes



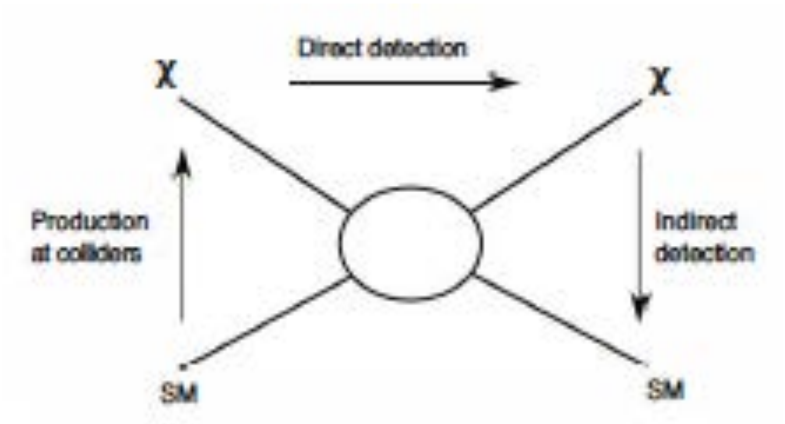
Gravity near compact objects (in particular through multimessenger astronomy)

- Astrophysics has recently became multimessenger thanks to the simultaneous observations of GW/gamma rays and of neutrino/gamma ray events
- While the counterparts of GW events seem out of reach for IACTs (~MeV), IACTs are perfect for the counterparts of neutrino events

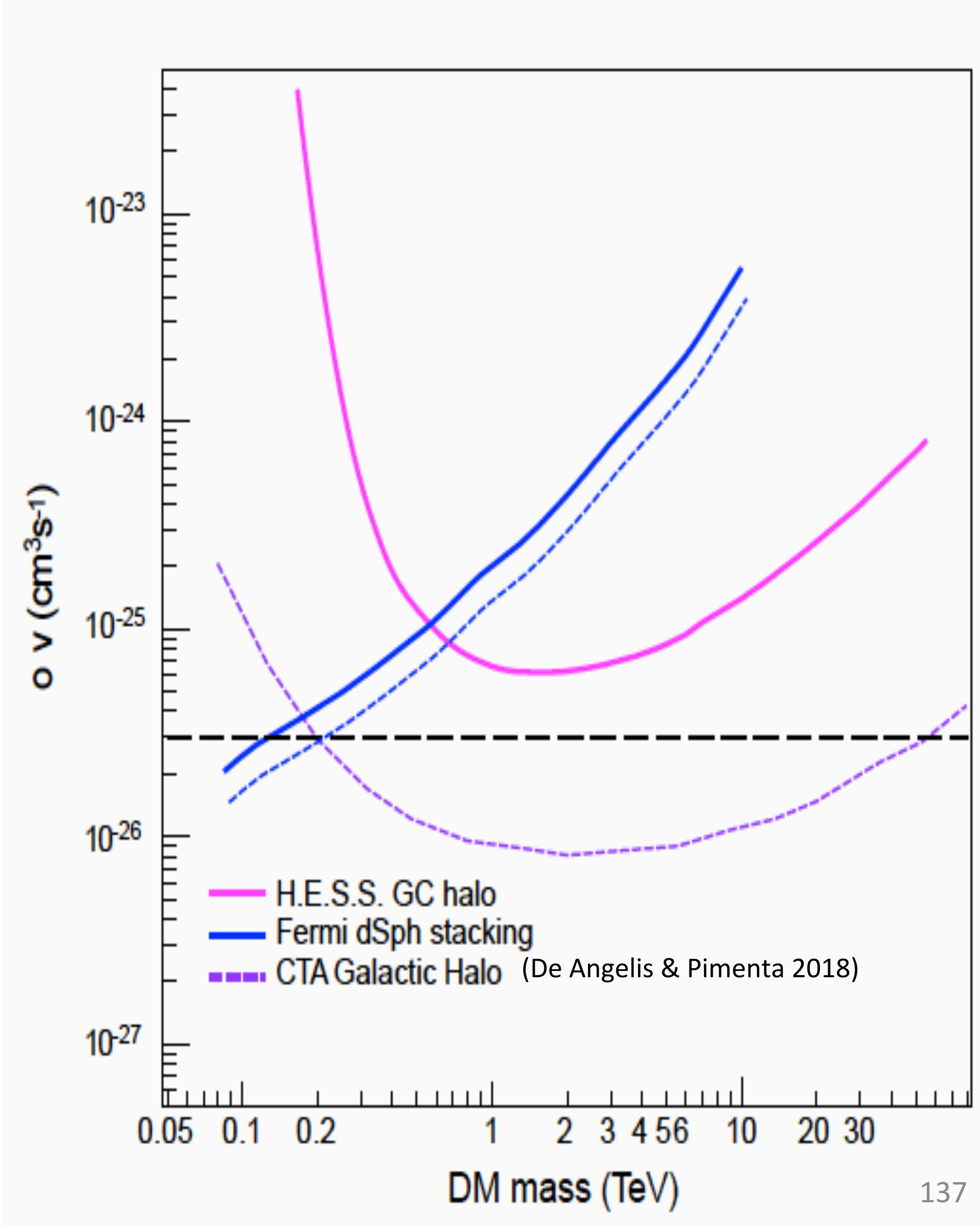


(Halzen, Nature 2017)

Dark Matter and New Particles



- Indirect detection of DM: CTA will reach the "thermal cross section" in 3 years
- Photon propagation: explore new regions in the axion m/coupling plane

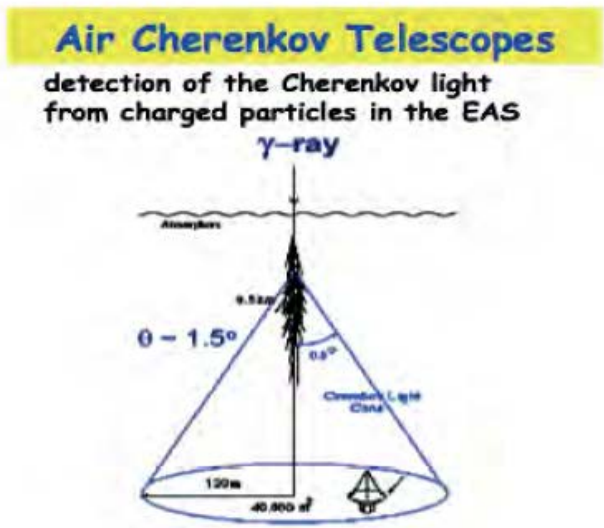


The unexpected

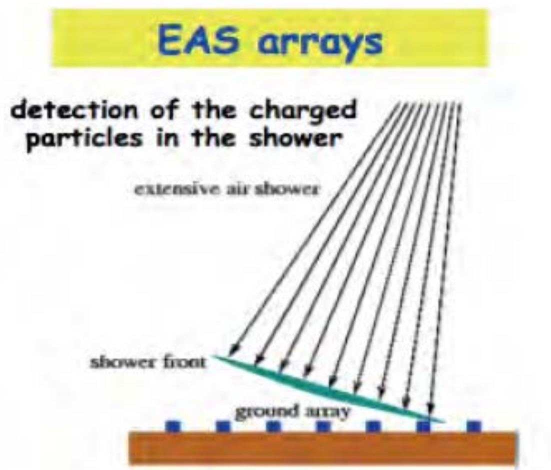
- A number 10x of sources detected
- Access to unexpected science (fast transients, new compact objects, etc.)
- Tests of fundamental symmetries of Nature in an unexplored regime

EAS-type designs (serendipity => GRB, unexpected...)

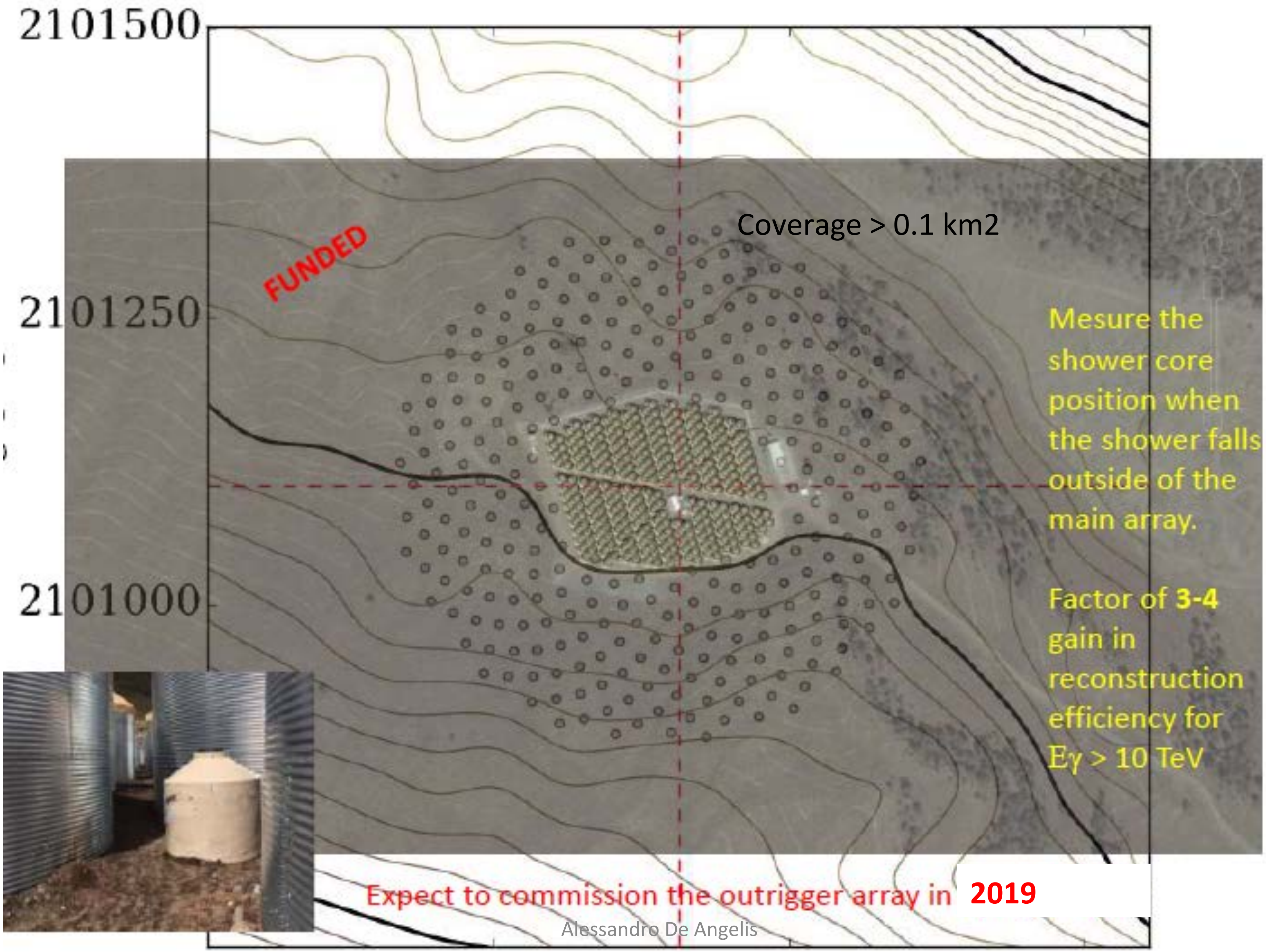
- CTA can be non optimal for PeV detection
  - EAS can be the key for Pevatron studies
- CTA not optimal for VHE transients



Very low energy threshold (≈50 GeV)
Excellent bkg rejection (>99%)
Excellent angular resolution (≈0.05 deg)
Good energy resolution (≈15%)
High Sensitivity (< % Crab flux)
Low duty-cycle (≈10%)
Small field of view (4-5 deg)



Higher energy threshold (≈300 GeV)
Good bkg rejection (>80%)
Good angular resolution (0.2-0.8 deg)
Modest energy resolution (≈50%)
Good Sensitivity (5-10% Crab flux)
High duty-cycle (≈100%)
Large field of view (≈2 sr)

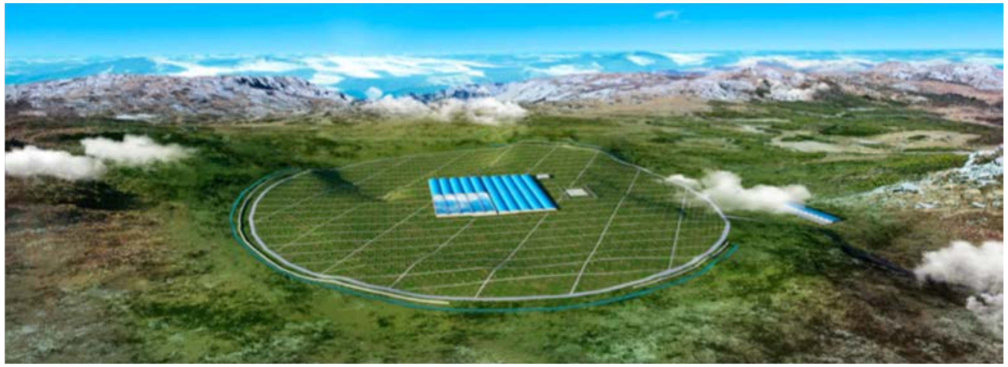


Coverage > 0.1 km2

Mesure the shower core position when the shower falls outside of the main array.

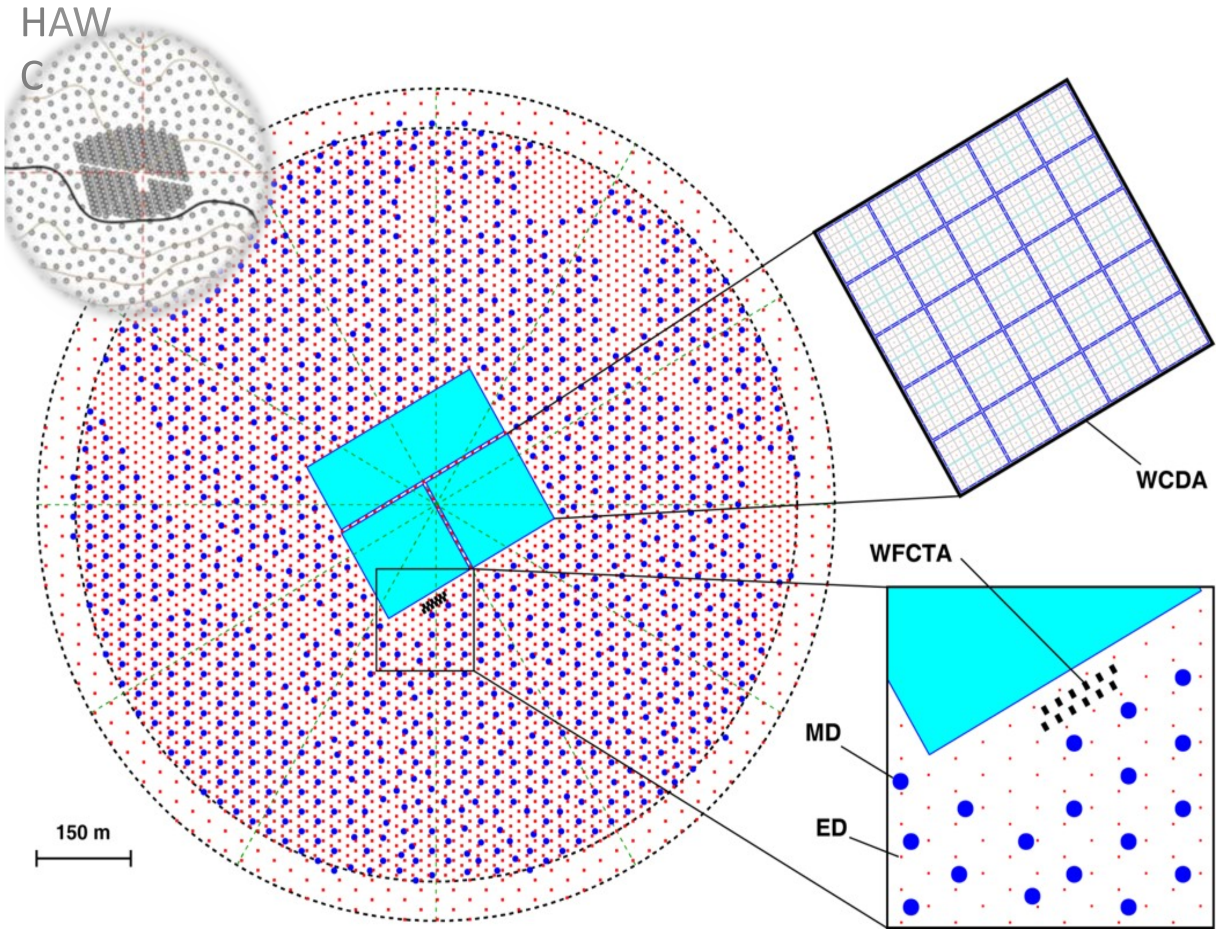
Factor of **3-4** gain in reconstruction efficiency for Eγ > 10 TeV

Expect to commission the outrigger array in **2019**



LHAASO

Sichuan, China, 4410 m asl
25% ready in 2020



5195 Scintillators
- 1 m^2 each
- 15 m spacing

1171 Muon Detectors
- 36 m^2 each
- 30 m spacing

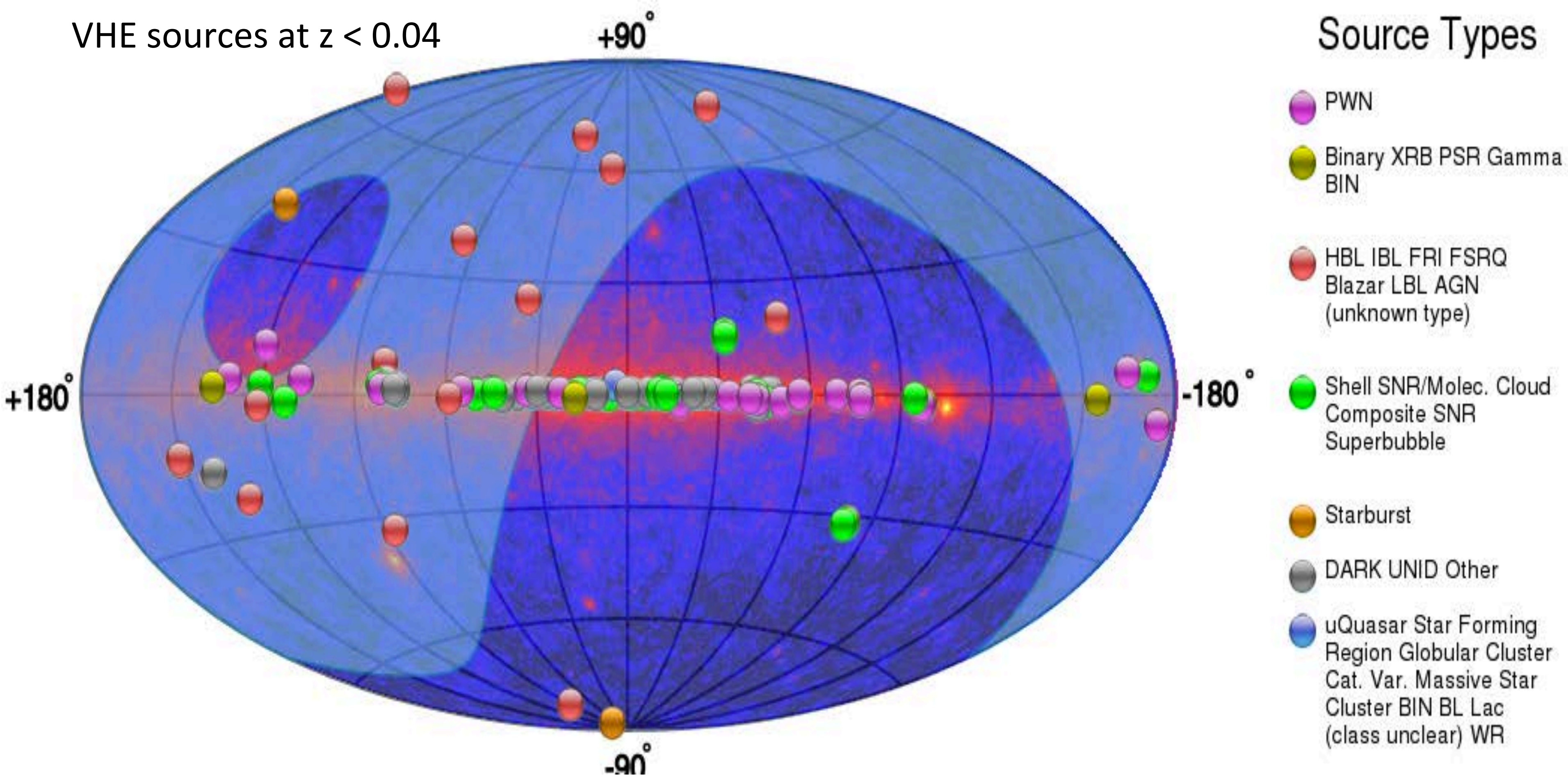
3000 Water Cherenkov Cells
- 25 m^2 each

12 Wide Field Cherenkov Telescopes

¼ ready in 2019

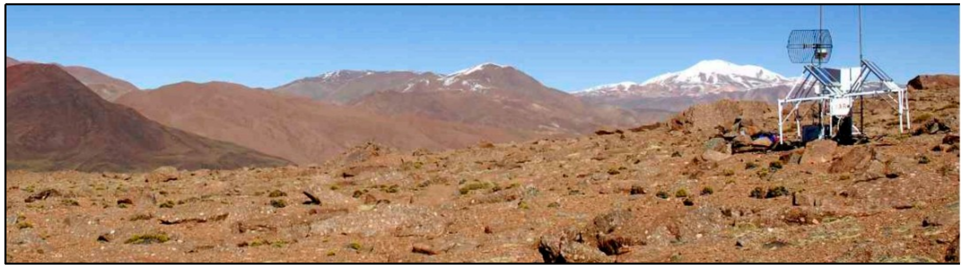
HAWC+, LHAASO ~ funded, but there is a strong case for a **wide-field experiment in the Southern hemisphere**

VHE sources at z < 0.04



Where? Site Considerations

- Host country
  - Legal, political, economic, security, …
  - Local partners
- Local Infrastructure
  - Road access, water access, power, network
- Altitude
  - >4.5 km
- Longitude
  - Not much choice given high altitude
- Latitude

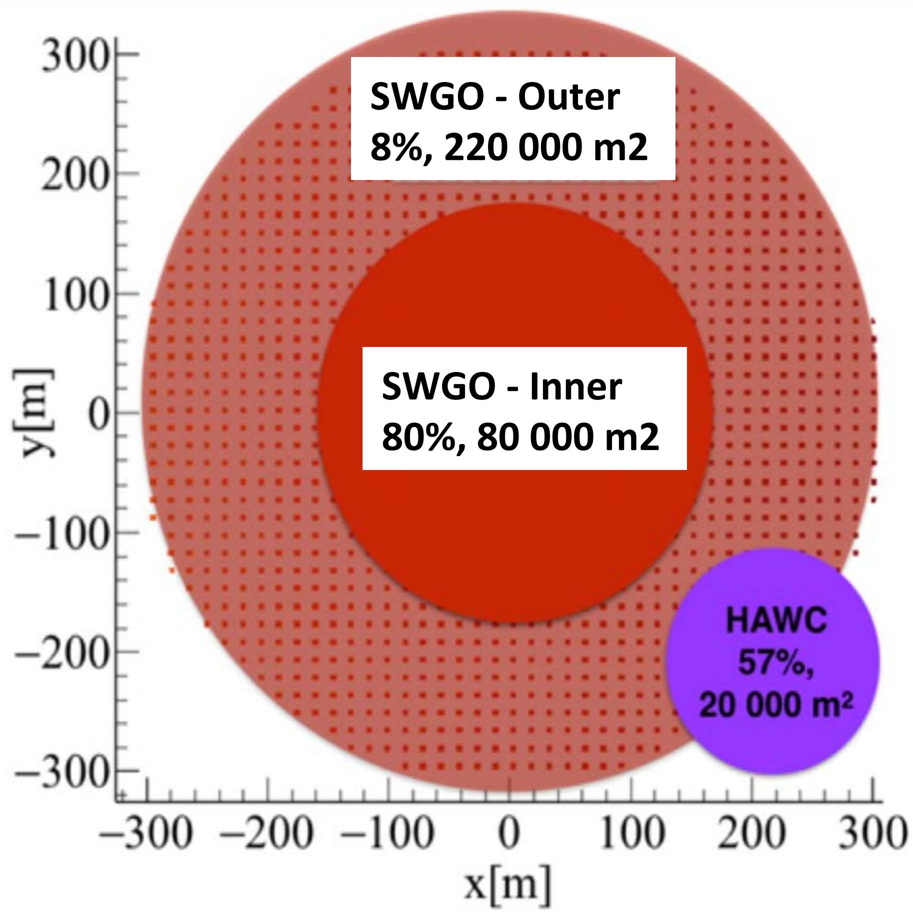


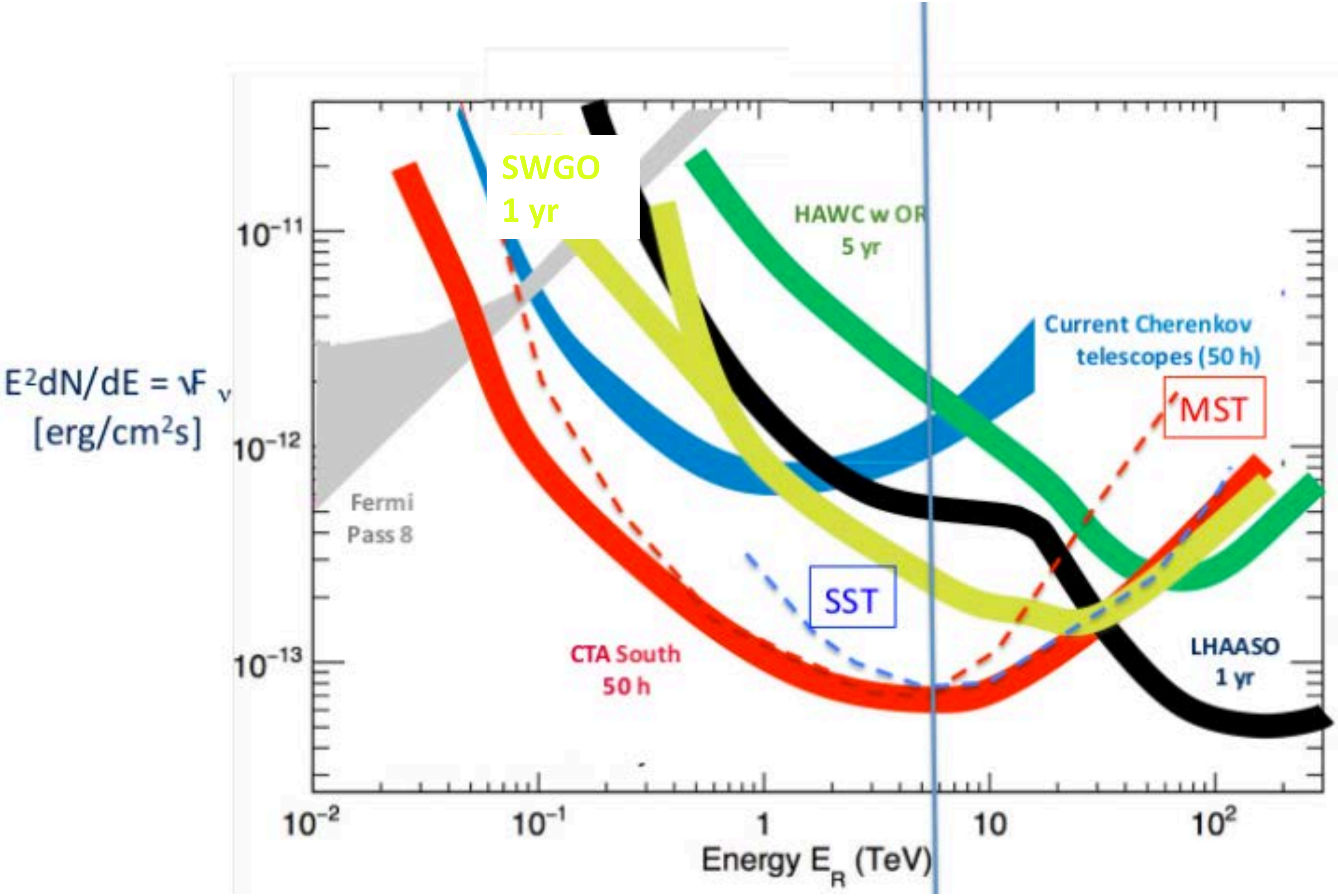
Sites in Argentina, Chile, Peru

SWGO: a world-based project for the R&D of the Southern Wide-field Gamma-ray Observatory

- A 3-year project starting on July 1st, 2019

- Signed by Parties in Brazil, Germany, Italy, Portugal, US (groups interested and negotiations ongoing with Argentina, Chile, China, Czech Republic, France, Japan, Spain, Sweden, UK, Peru)



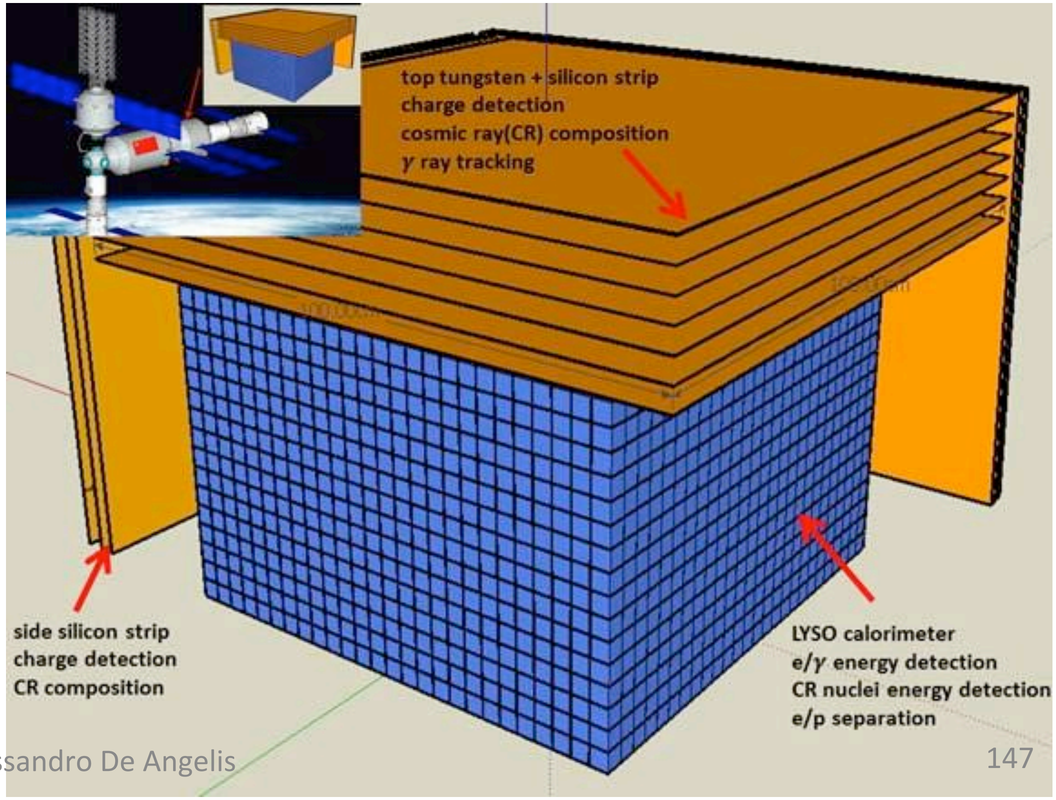


SWGO
1 yr
HAWC w OR
5 yr
Current Cherenkov
telescopes (50 h)
MST
SST
CTA South
50 h
LHAASO
1 yr
Fermi
Pass 8
E²dN/dE = νF ν
[erg/cm²s]
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻²
10⁻¹
1
10
10²
Energy E_R (TeV)

Lower Energies (GeV and MeV)

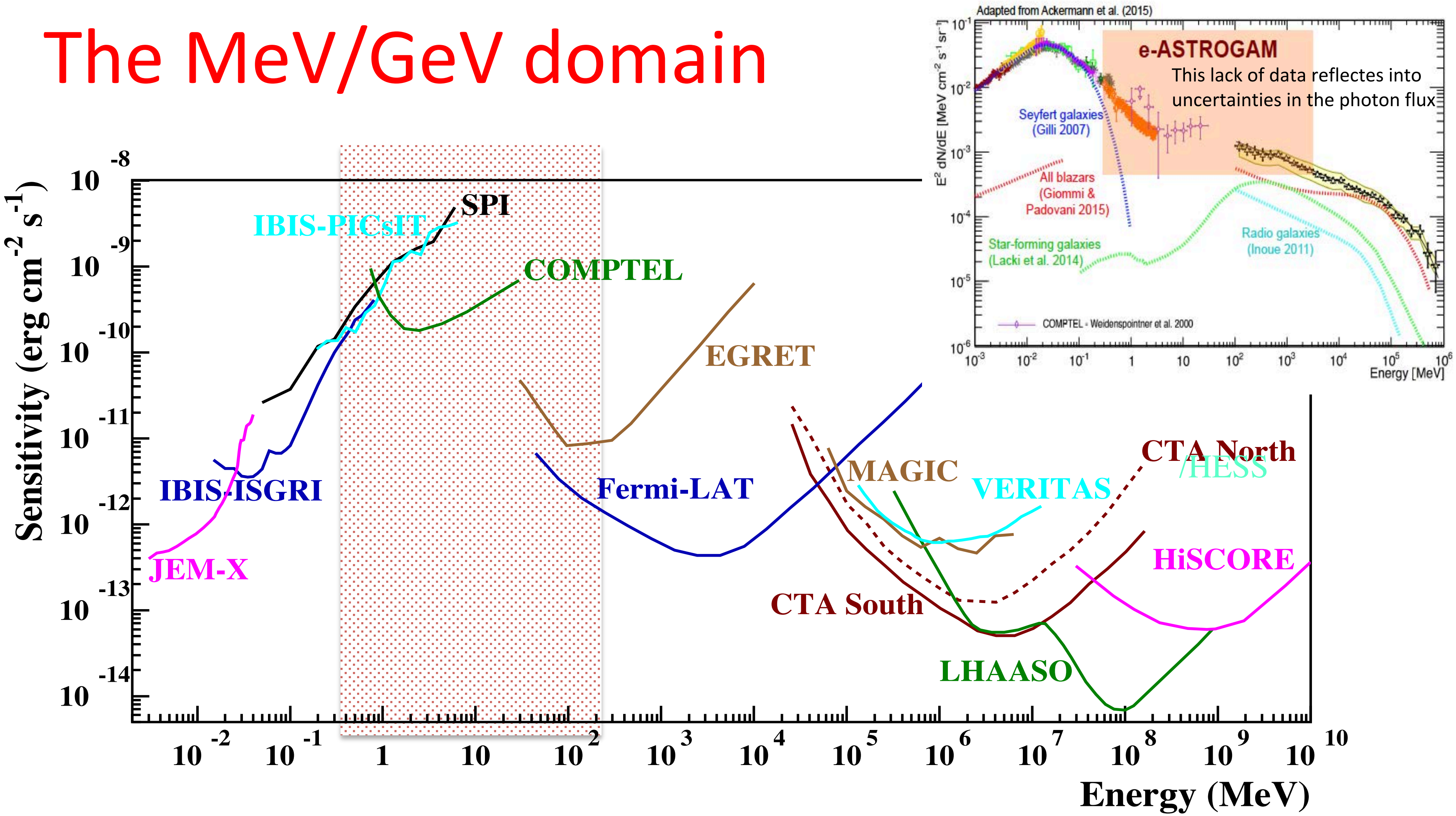
GeV region from space

- Fermi can fly till 2028 (granted till 2020)
- Difficult to find a successor…
- Only one super-Fermi project on the field: the Chinese-Italian HERD
  - A Fermi with better calorimetry
  - A few years after the CSS
  - Approved in 2017



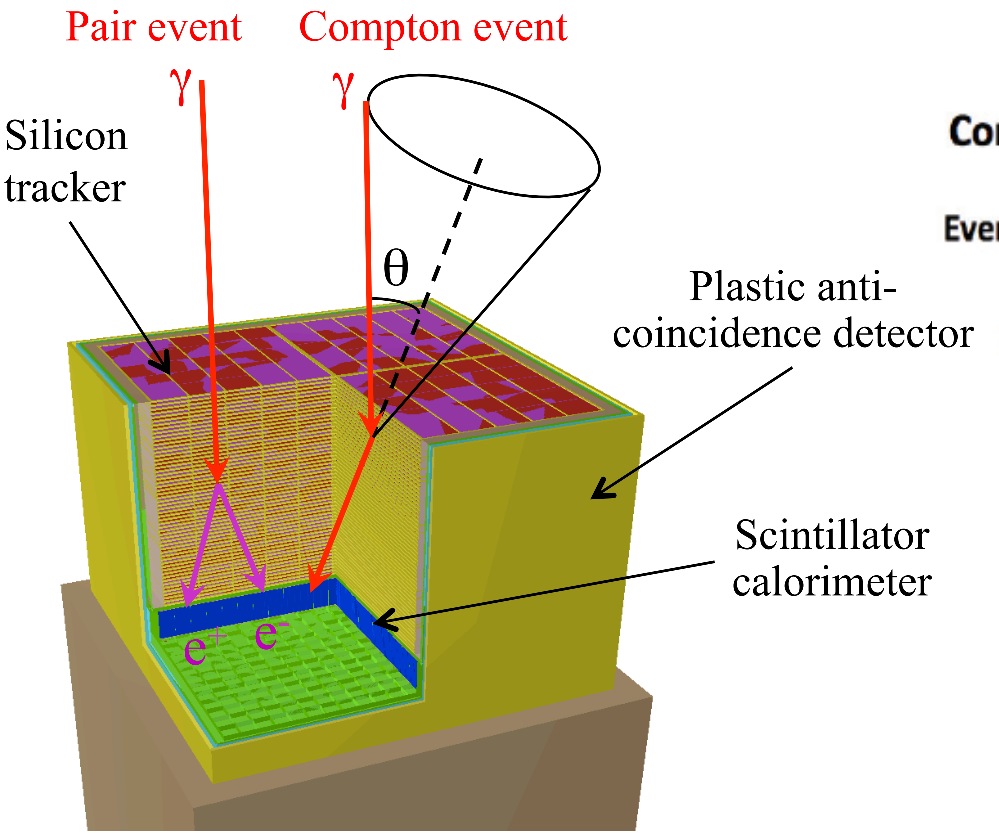
- Also useful for observing charged cosmic rays up to ~ the knee

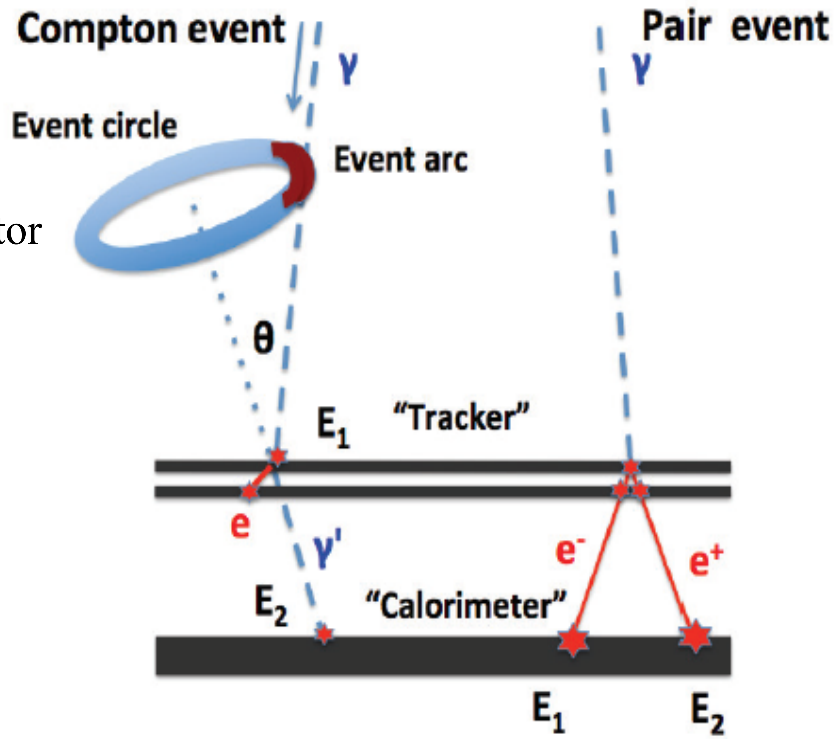
The MeV/GeV domain



- Worst covered part of the electromagnetic spectrum (only a few tens of steady sources detected so far between 0.2 and 30 MeV)
- Many objects have their peak emissivity in this range (GRBs, blazars, pulsars...)
- Binding energies of atomic nuclei fall in this range, which therefore is as important for HE astronomy as visible light is for phenomena related to atomic physics

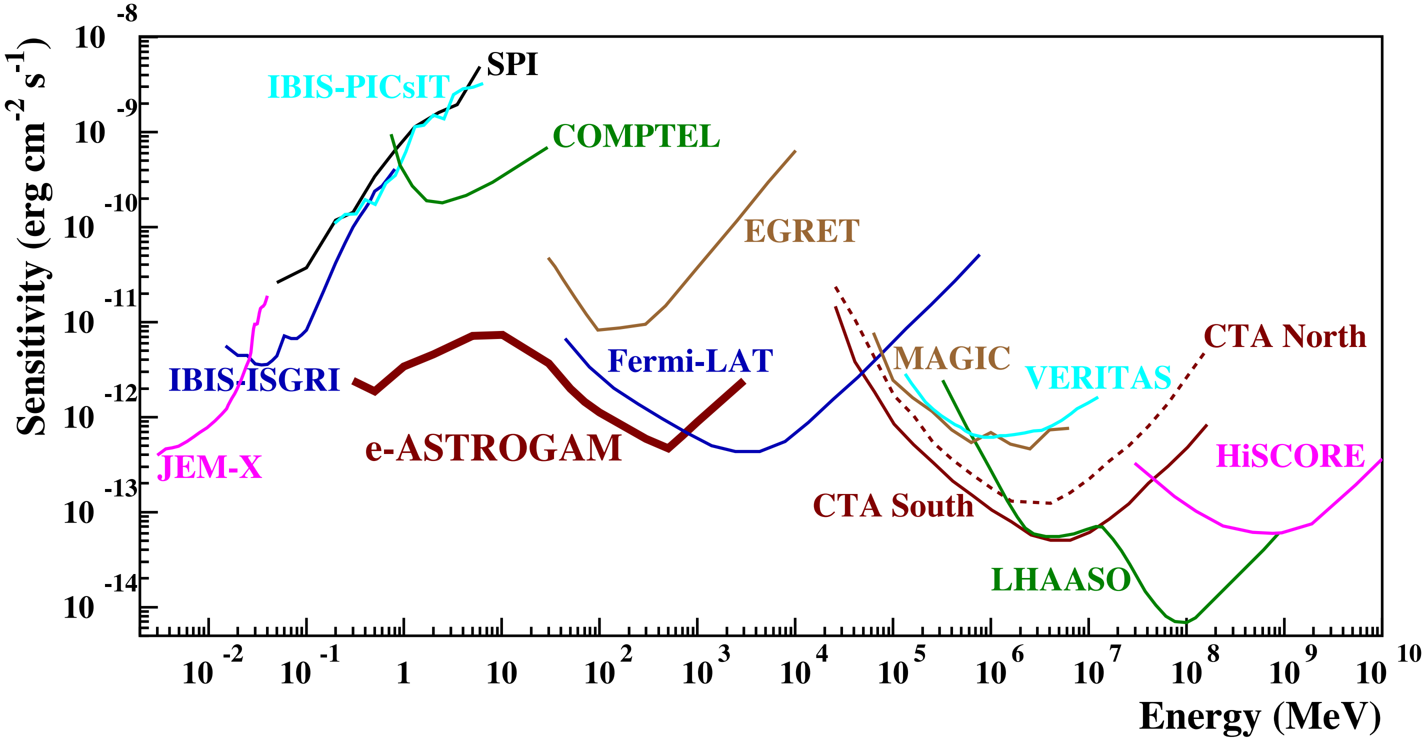
How to measure gamma rays in the MeV-GeV?
The ASTROGAM concept





ASTROGAM, AMEGO performance

1. Achieve a sensitivity better than INTEGRAL/CGRO/COMPTEL by a factor of 20 - 50 – 100 in the range 0.2 – 30 MeV
2. Fully exploit gamma-ray polarization for both transient and steady sources
3. Improve significantly the angular resolution (to reach, e.g., ~ 10' at 1 GeV)
4. Achieve a very large field of view (~ 2.5 sr) ⇒ efficient monitoring of the γ-ray sky
5. Enable sub-millisecond trigger and alert capability for transients

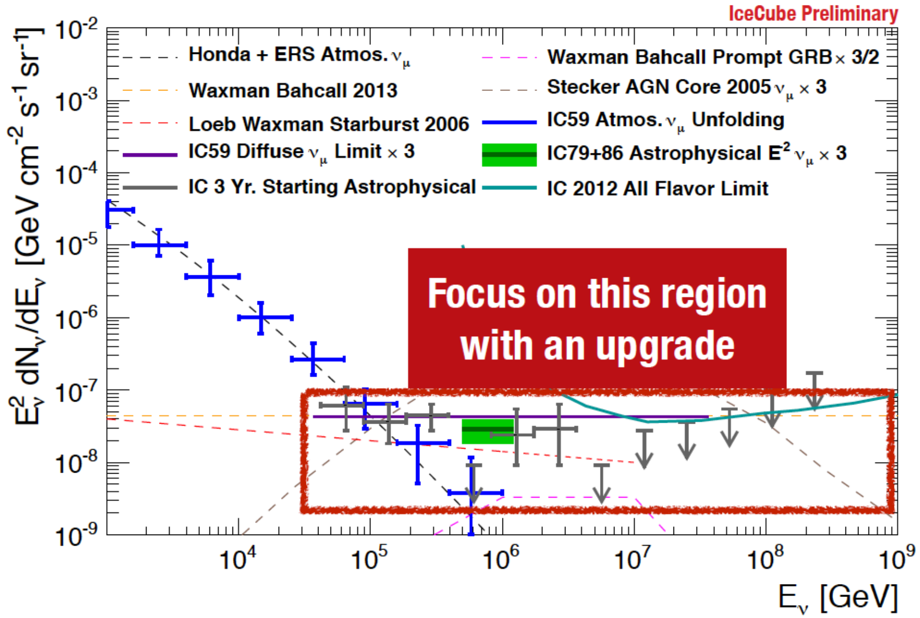


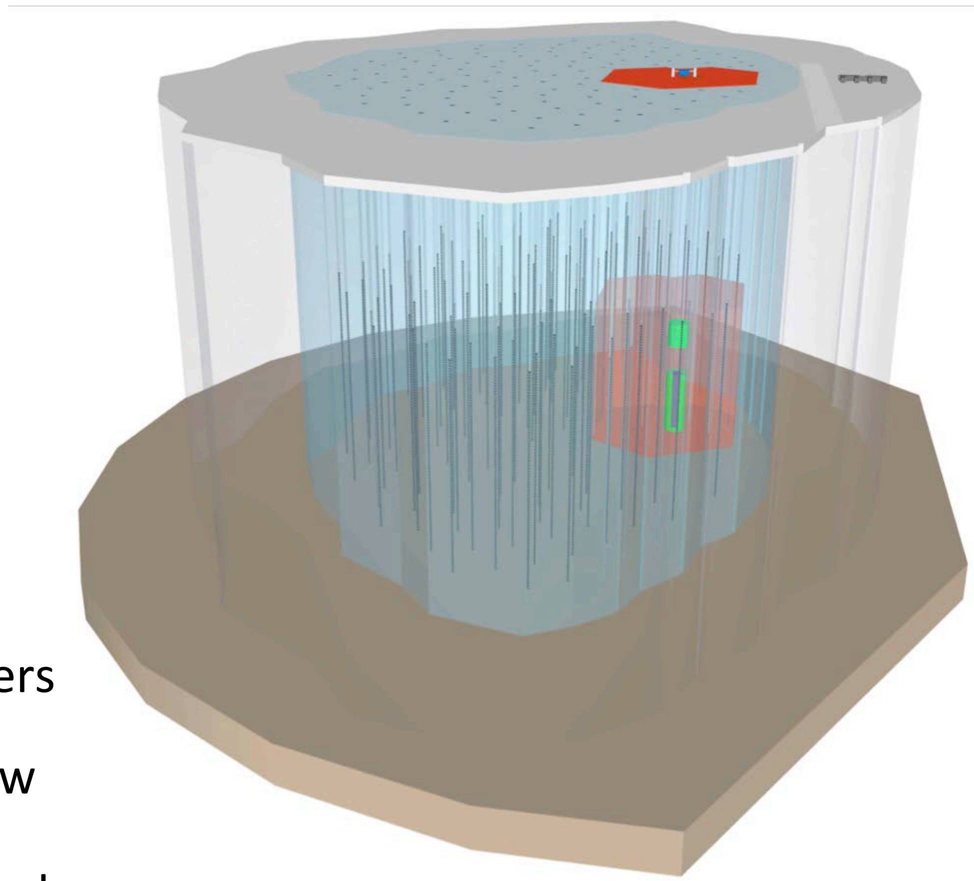
Neutrinos

Astrophysical neutrinos: the future

- Three lines of development:
  1. Large volume
  2. High precision
  3. New technologies
- ν Astronomy has just started and a rich physics program is ahead of us. A global neutrino network (IceCube-Gen2 in the South Pole, Gigaton Volume Detector (GVD) in the lake Baikal and KM3NeT in the Mediterranean sea) will operate.

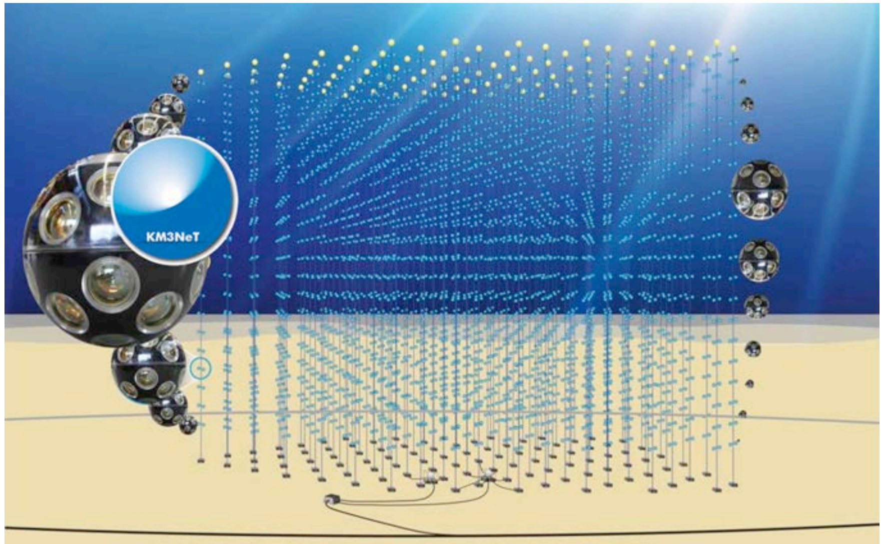
IceCube-Gen2, a ~10-cubic-kilometer detector

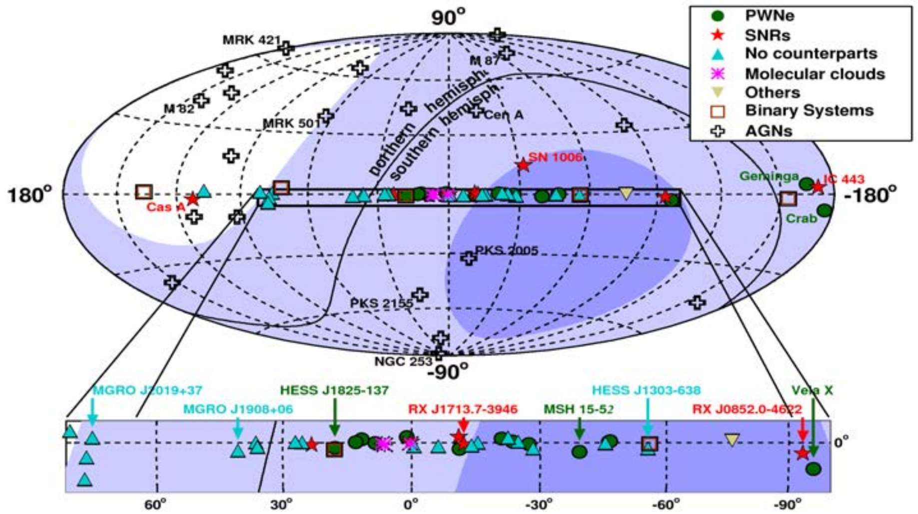




- Spacing between light sensors ~ 250 meters, instead of the current 125 meters in IceCube. The IceCube-Gen2 instrumented volume might rapidly grow at modest costs.
- By ~ doubling the instrumentation already deployed, the telescope will achieve a tenfold increase in volume to about 10 cubic kilometers, aiming at a 10x increase in neutrino detection rates.

Km3Net in the Mediterranean Sea





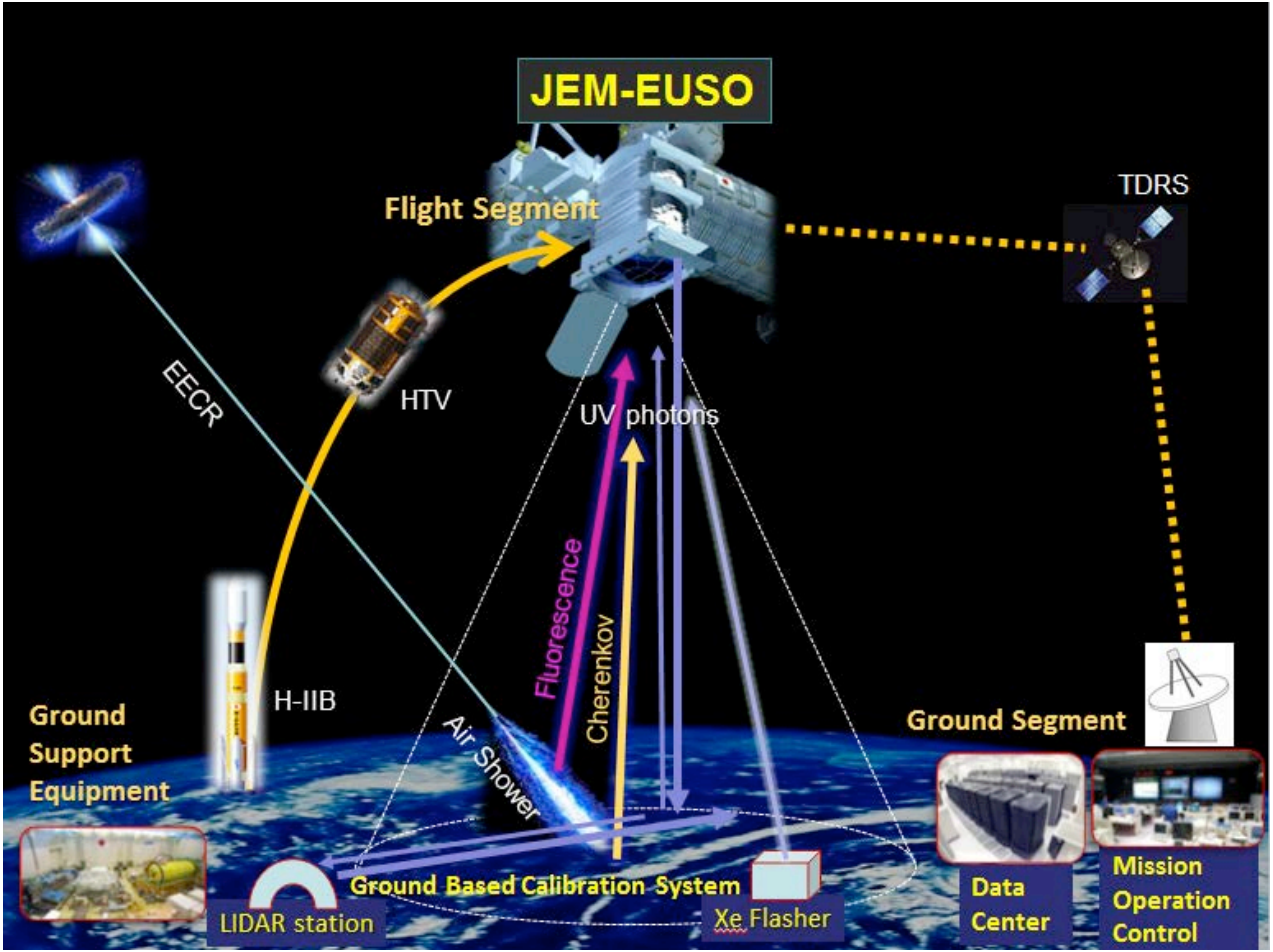
- Plan to reach ~3km^3
- Better angular resolution
- Better visibility of the GC region

Source Name	Source radius (°)	Visibility	Number of events per year For $E_\nu > 5$ TeV	
			Signal ν	Atm ν
RX J1713.7−3946	0.7	0.74	4 – 11	6.4
RX J0852.0−4622	1.0	0.84	2 – 6	17
HESS J1745−303	0.2	0.66	0 – 22	1.4
HESS J1626−490	< 0.1	0.91	4 – 9	1.6
Vela X	0.4	0.81	4 – 15	3.5
Crab Nebula	< 0.1	0.39	1 – 3	0.8

New technologies

- At extremely high energies, above 100 PeV, a cosmogenic neutrino flux is expected from the interaction of highest energy cosmic-ray protons with the CMB. Predicted are in a range of approximately 1 event/year/km^3 or lower. The idea to increase the effective volume of detectors to be sensitive to such rates seems feasible only:
  - By adopting the EUSO concept (see later)
  - By detecting coherent radio emission up to GHz originated by the ν interaction in dense, radio-transparent media (Askar'yan effect).

    Several prototype detectors are being developed.



JEM-EUSO
Flight Segment
TDRS
EECR
HTV
UV photons
Fluorescence
Cherenkov
H-IIB
Air Shower
Ground Support Equipment
Ground Segment
Ground Based Calibration System
LIDAR station
Xe Flasher
Data Center
Mission Operation Control

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
- Gravitational waves: a great success
- Astrophysical neutrino detectors: we need several km3; we are close to the limit (Icecube) but still improving (Antares -> Km3NeT; IceCube Gen2)
- Photons:
  - In the MeV region, instruments did not reach the technological limit, yet
  - In the GeV region, Fermi is close to the technological limit
  - In the TeV region, the Cherenkov technique reigns. HESS, MAGIC and VERITAS have still potential, and there is room for improvement by “brute force” (CTA)
  - In the PeV region, only one detector presently active; there is room for improvement by “brute force” + exploiting the Southern point of view

Planned investment in astroparticle physics for the next years

(budget excluding manpower, labs, regional funds, and competitive calls by NASA/ESA)

(M/L space missions approved can be ~50 MEUR/year on top of this)