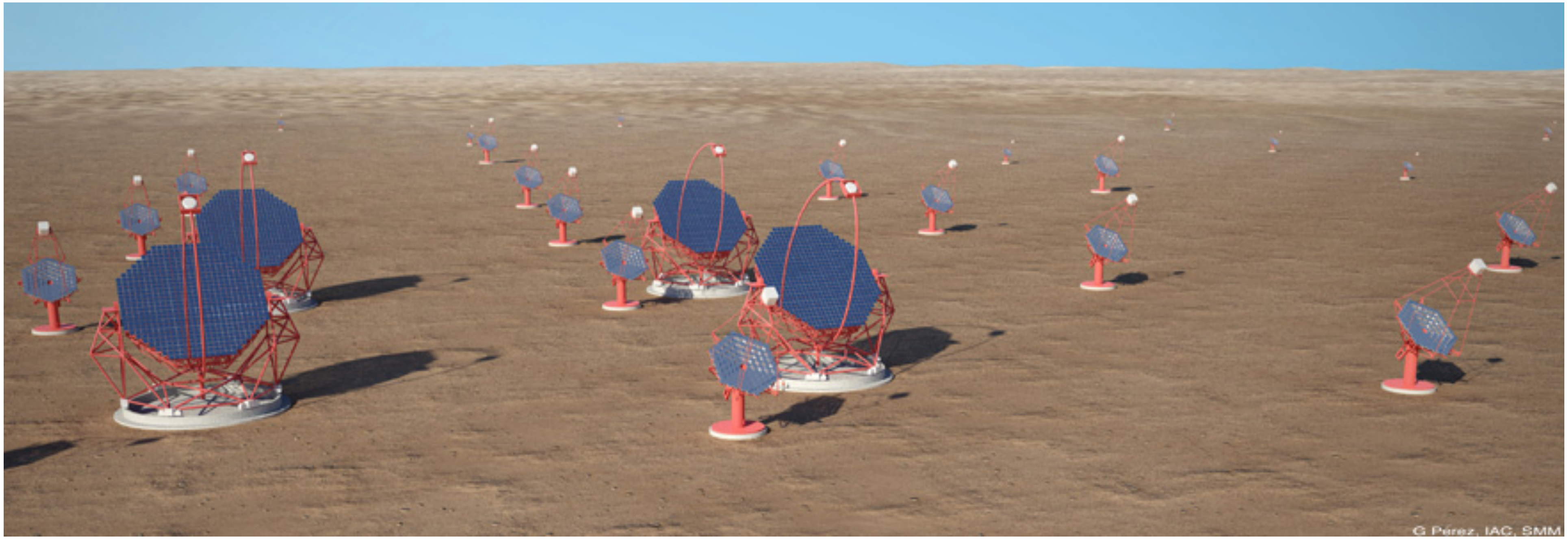
The future of very-high-energy gamma-ray astrophysics: the Cherenkov Telescope Array (CTA)



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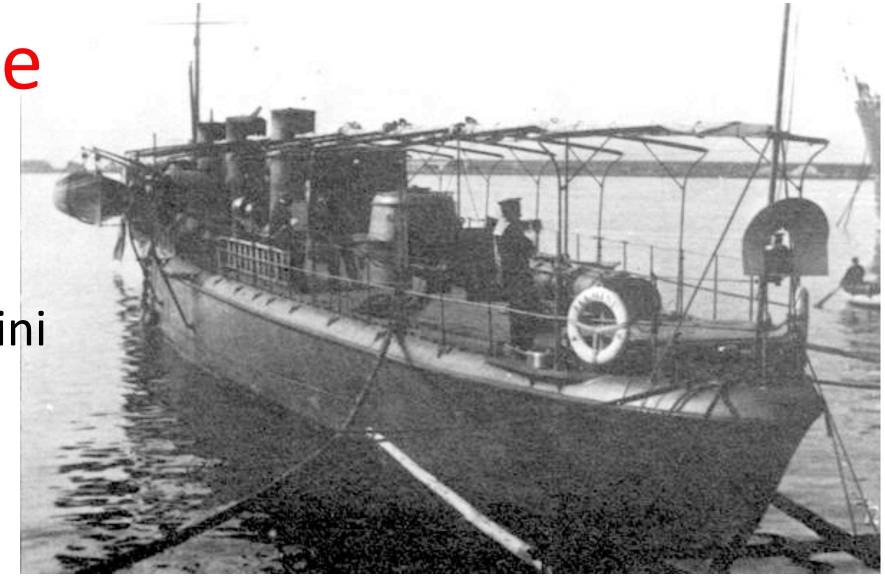
Cogne 2018

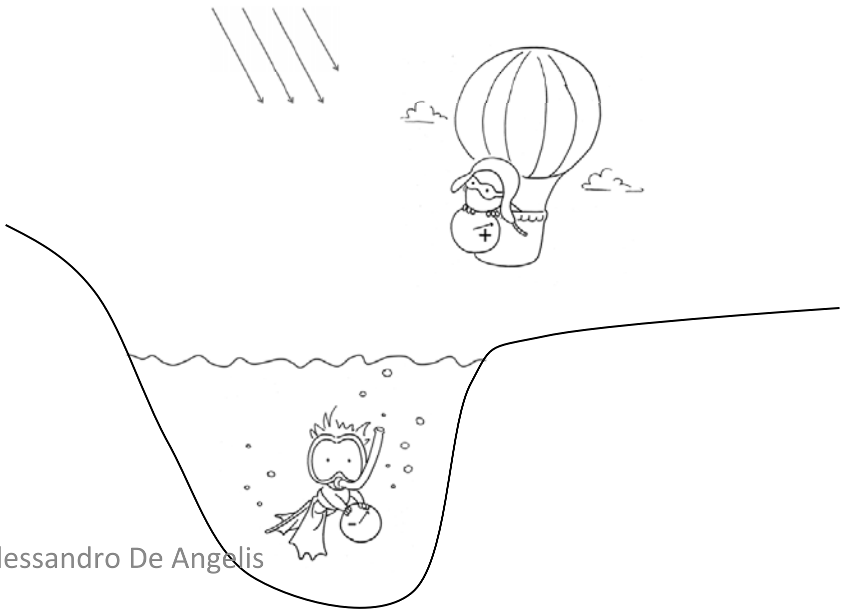
1. Gamma-ray astrophysics: the scientific context
2. Requirements for a gamma-ray detector
3. The Imaging Cherenkov technique (IACTs)
4. Requirements for a good IACT
5. The Cherenkov Telescope Array
6. Schedule and technological challenges
7. Scientific prospects
8. Opportunities

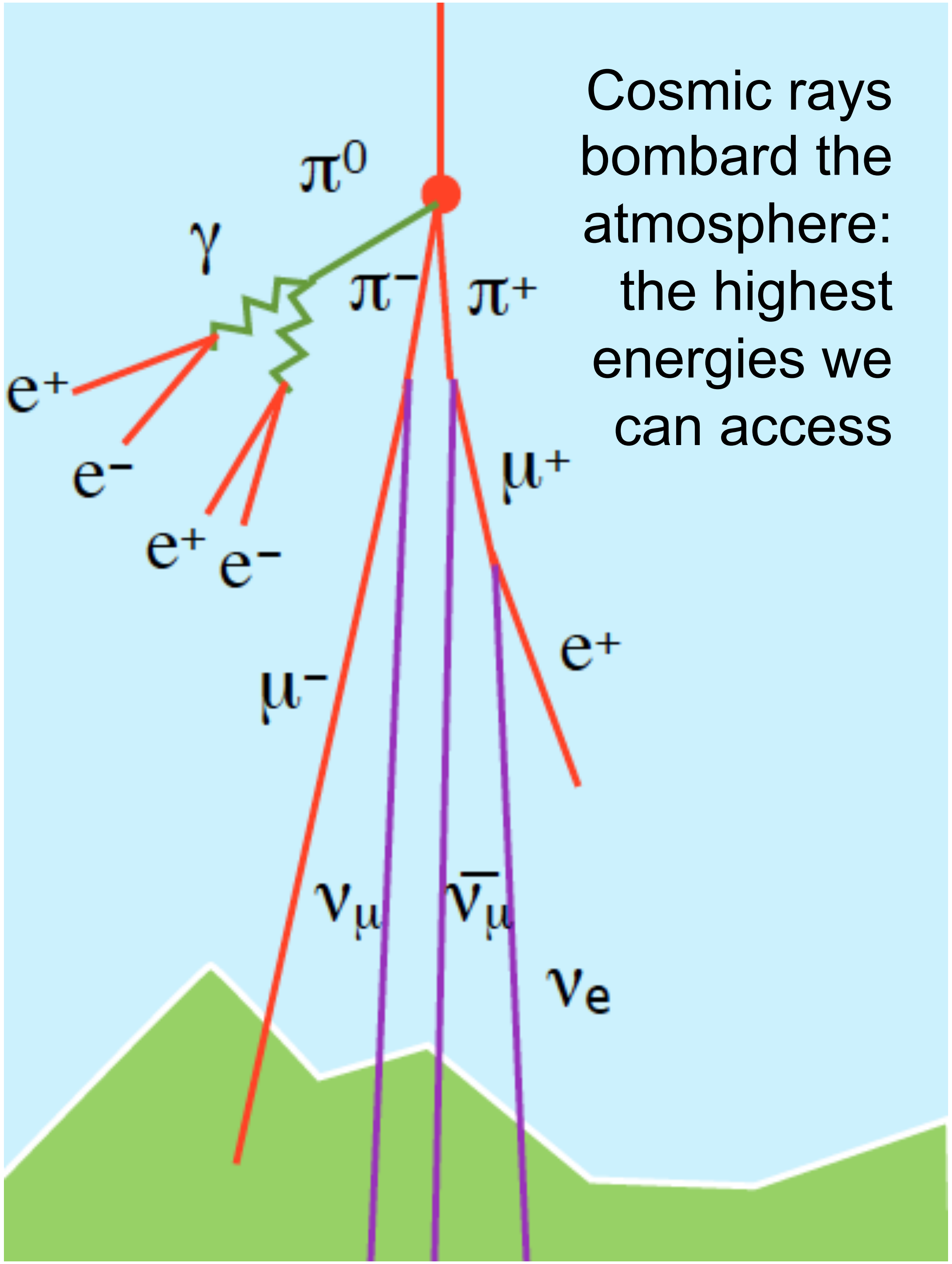
Messengers from the Universe



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?





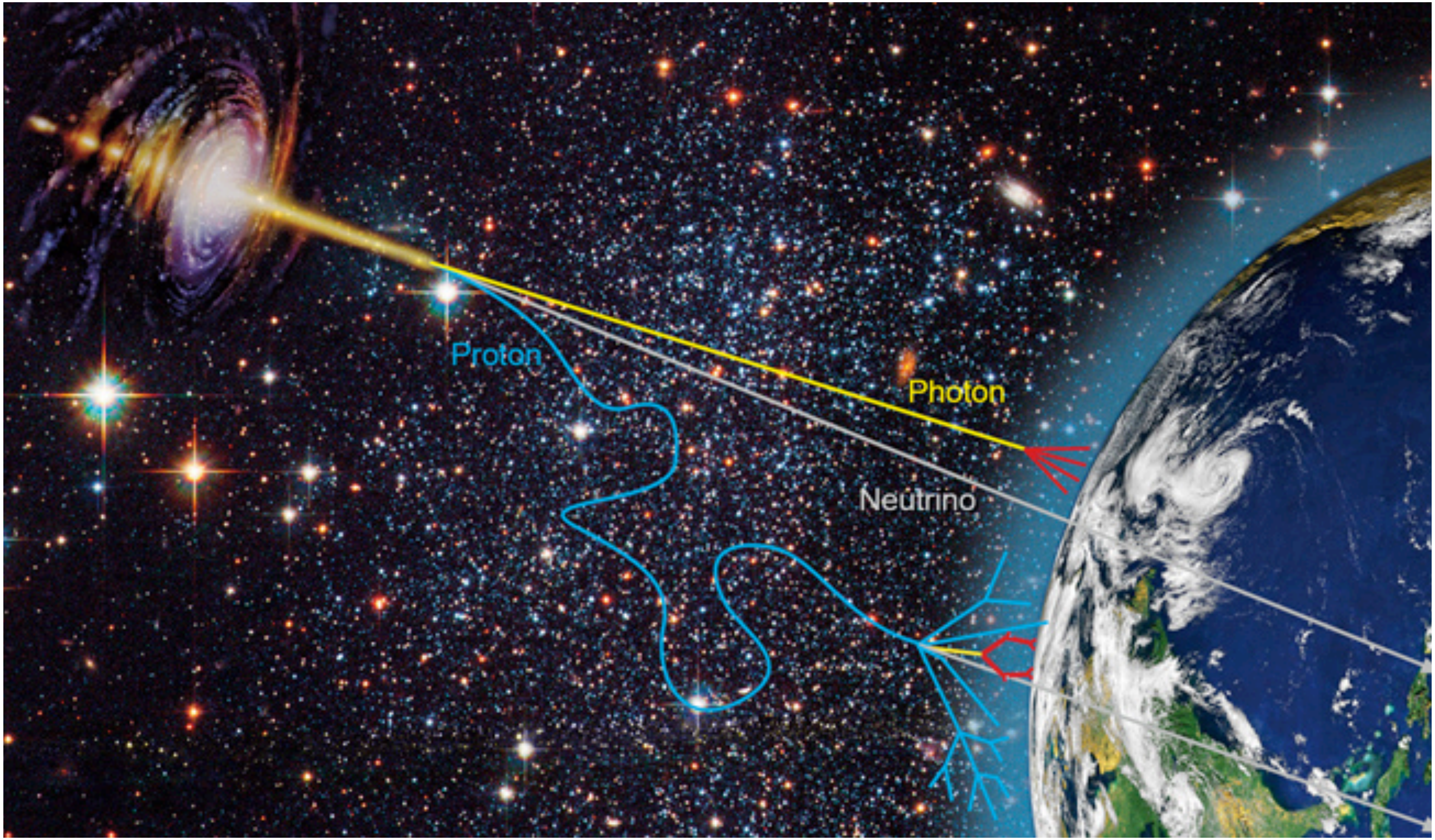
YES, and it allows accessing the highest energies

Detected protons 10^8 times more energetic than LHC

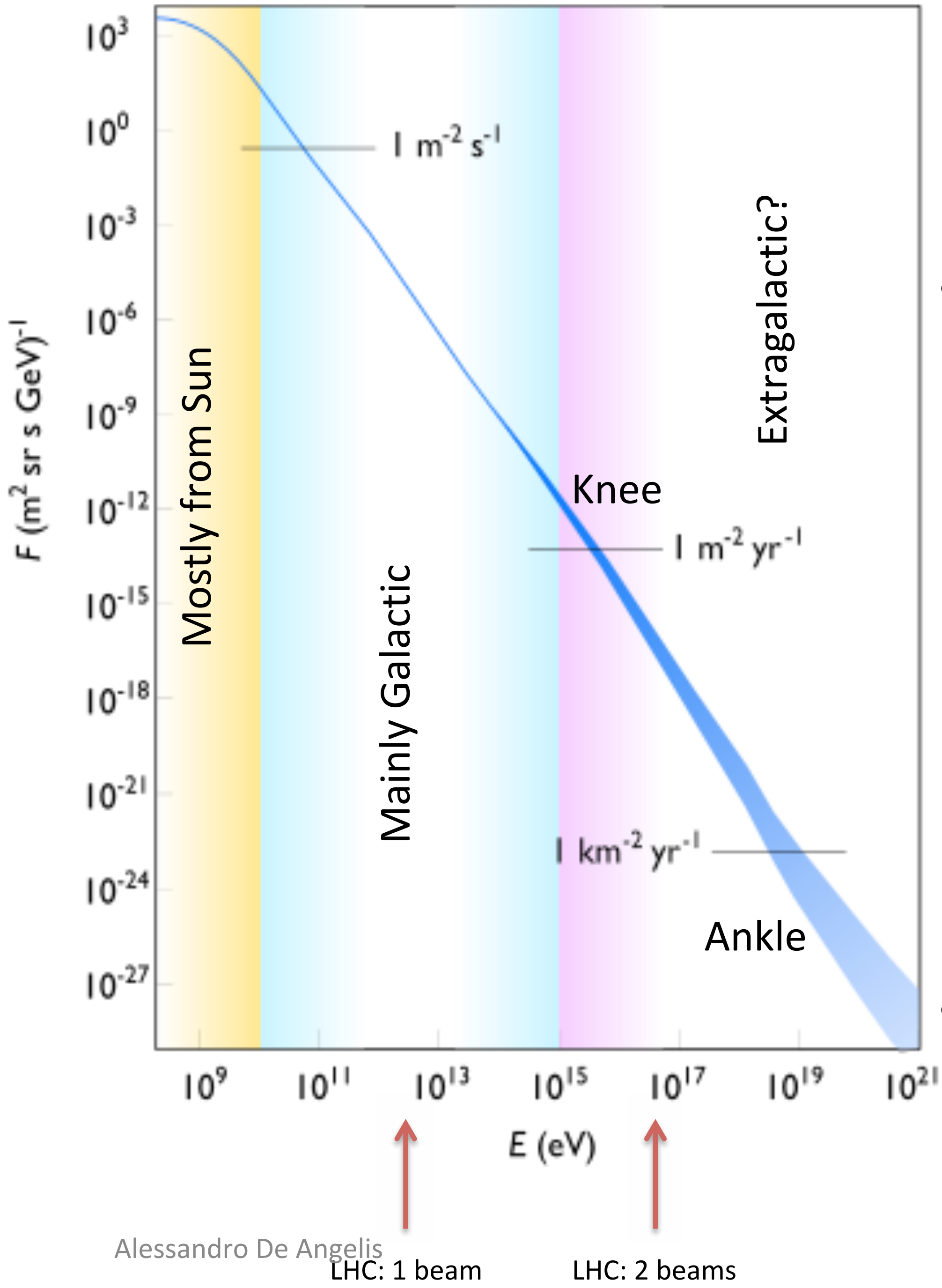
Detected gamma-rays 10000 times more energetic than human-made

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

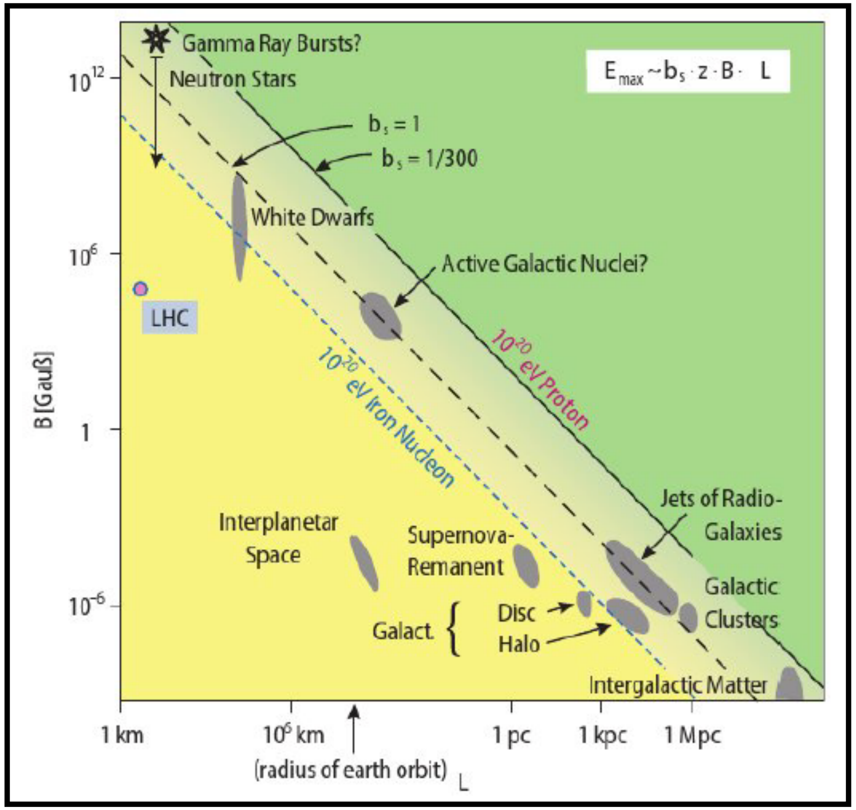
$$\frac{dN}{dE} \simeq 1.8 \times 10^4 \left(\frac{E}{\mathrm{GeV}}\right)^{-2.7} \frac{\text{particles}}{\mathrm{m^2\,s\,sr\,GeV}}$$

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

Bottom-up models

Where do they come from?

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



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

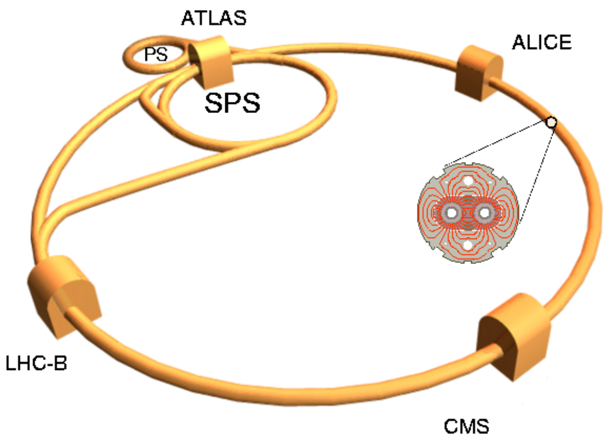
$$E_{max} \simeq ZeBL\beta$$

One should consider also energy losses at the source

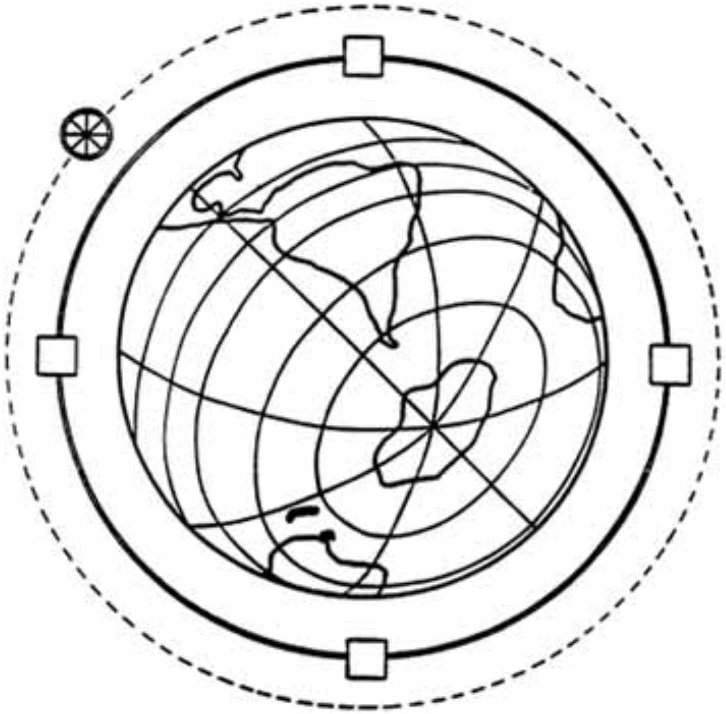
Whatever is the acceleration mechanism…

$E \propto BR$

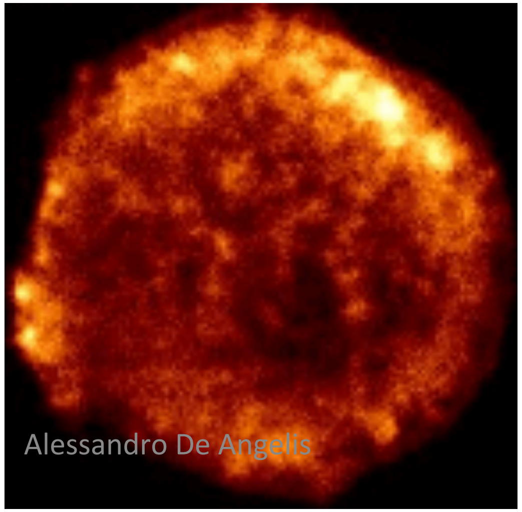
Large Hadron Collider



$R \sim 10$ 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

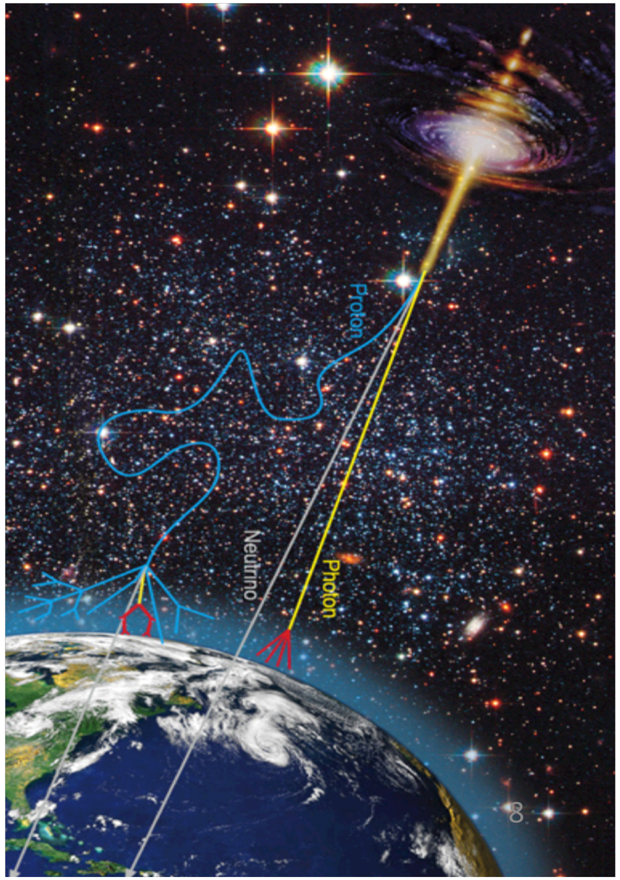
Propagation of charged CR in the Universe

- Gyroradius

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

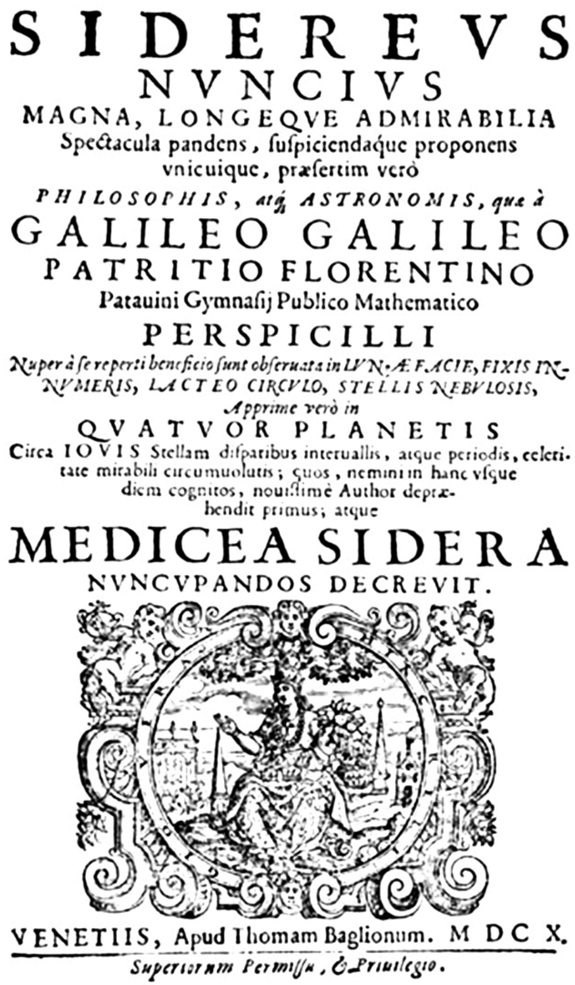
$$\frac{r}{1\ \text{kpc}} \cong \frac{\frac{E}{1\ \text{EeV}}}{\frac{B}{1\ \mu\text{G}}}$$

- 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

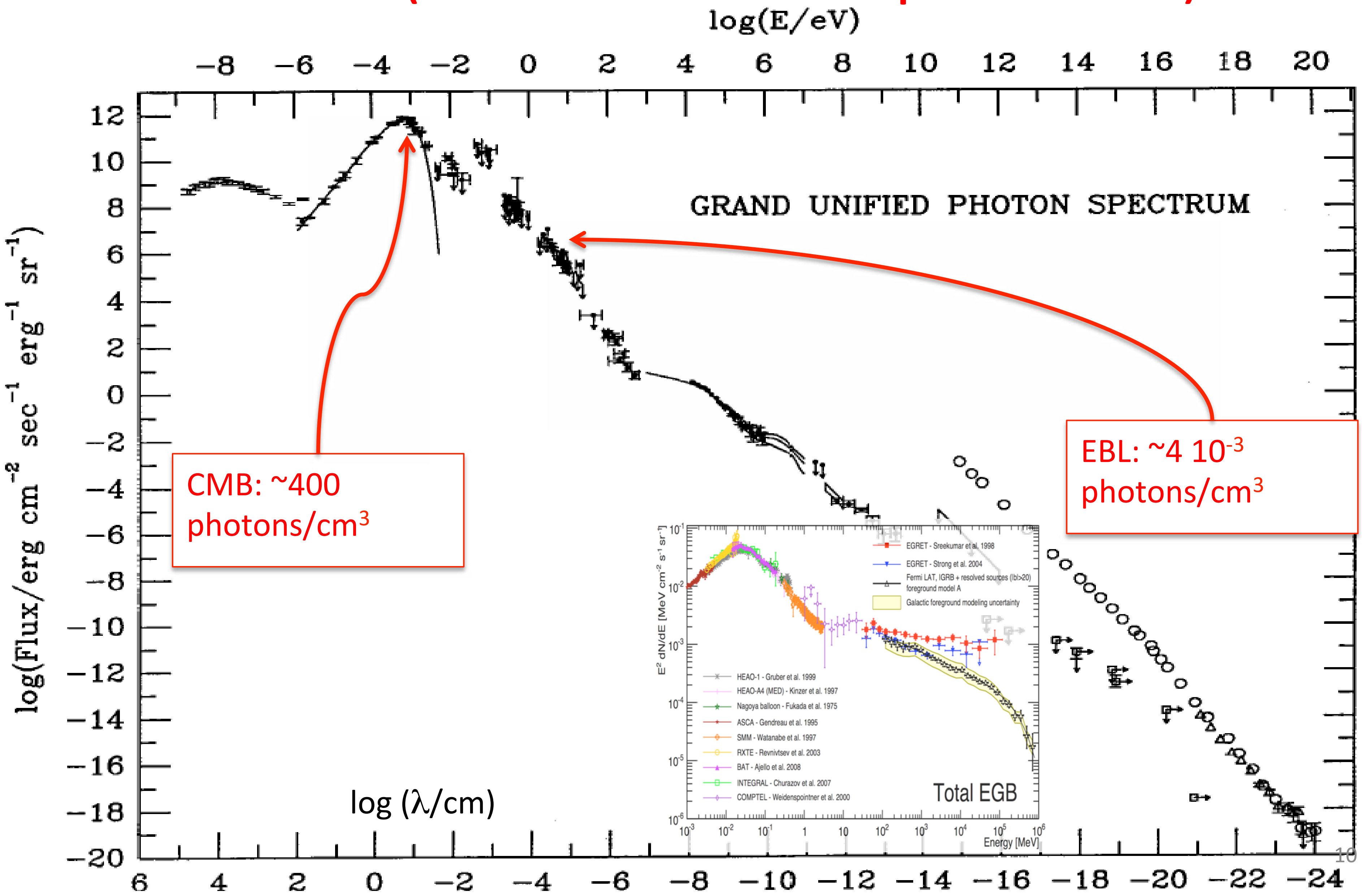


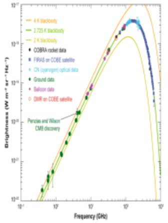
Neutral messengers must be used for astronomy & astrophysics

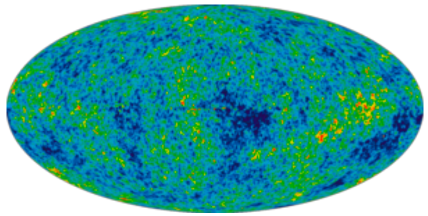
- Neutrinos: very difficult to detect due to the small interaction cross section (despite a km^3 detector in Antarctica, the only cosmic sources localized up to now are SN1987A, the Sun, the Earth, and …secret… TXS0506 +056)
  - ~1 neutrino/month from astrophysical sources identified by IceCube (1km^3)!
- 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...

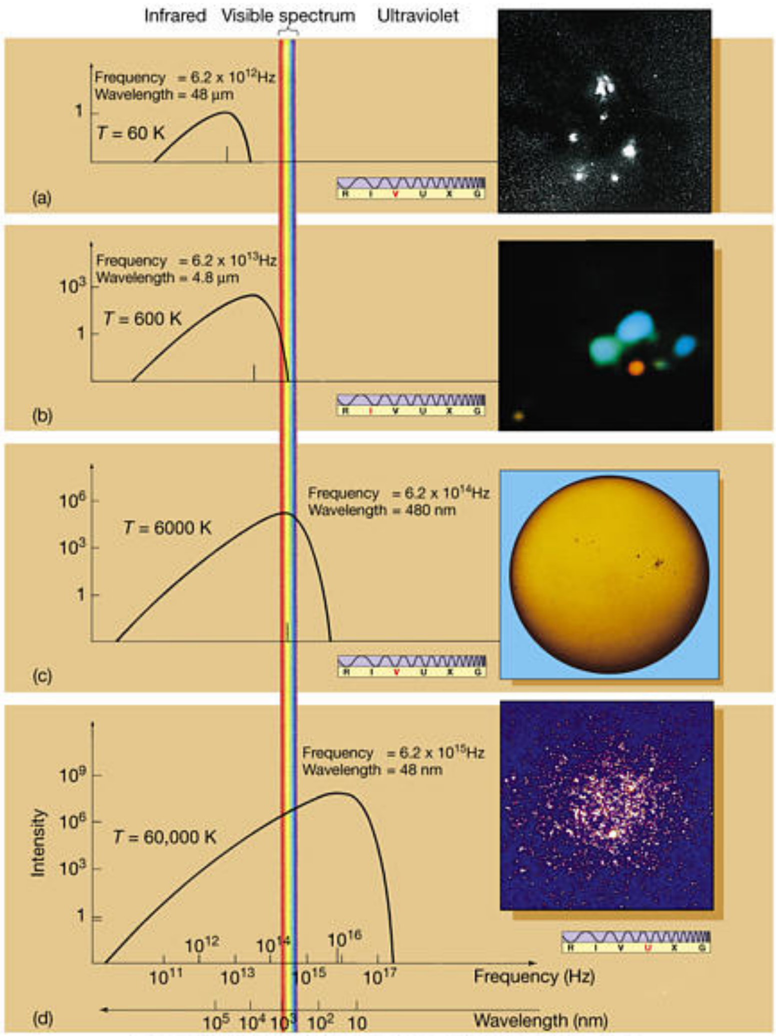

SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS 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 DC X.
Superiorum Permissu, & Priuilegio.

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









Nonthermal 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!

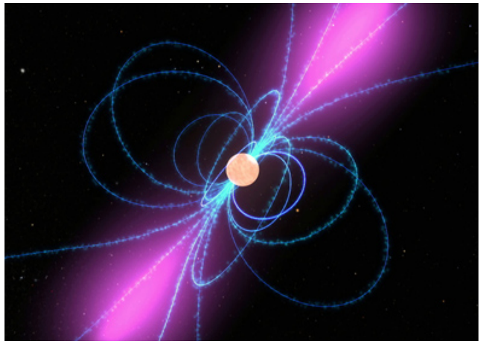
- No deflection from magnetic fields, gammas point ~ to the sources
  - Magnetic field in the galaxy: ~ 3μG
    Gamma rays can trace cosmic rays at energies ~10x
- Large mean free path
  - Regions otherwise opaque can be transparent to X/γ

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

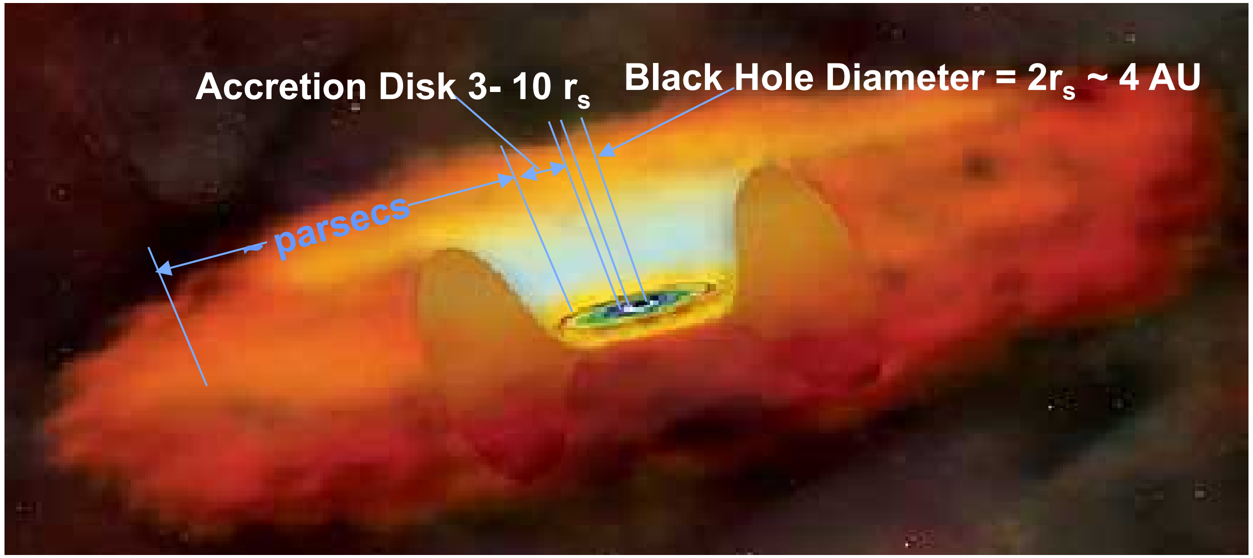
Examples of known extreme environments

GRB

SuperNova Remnants
Pulsars



Active Galactic
Nuclei



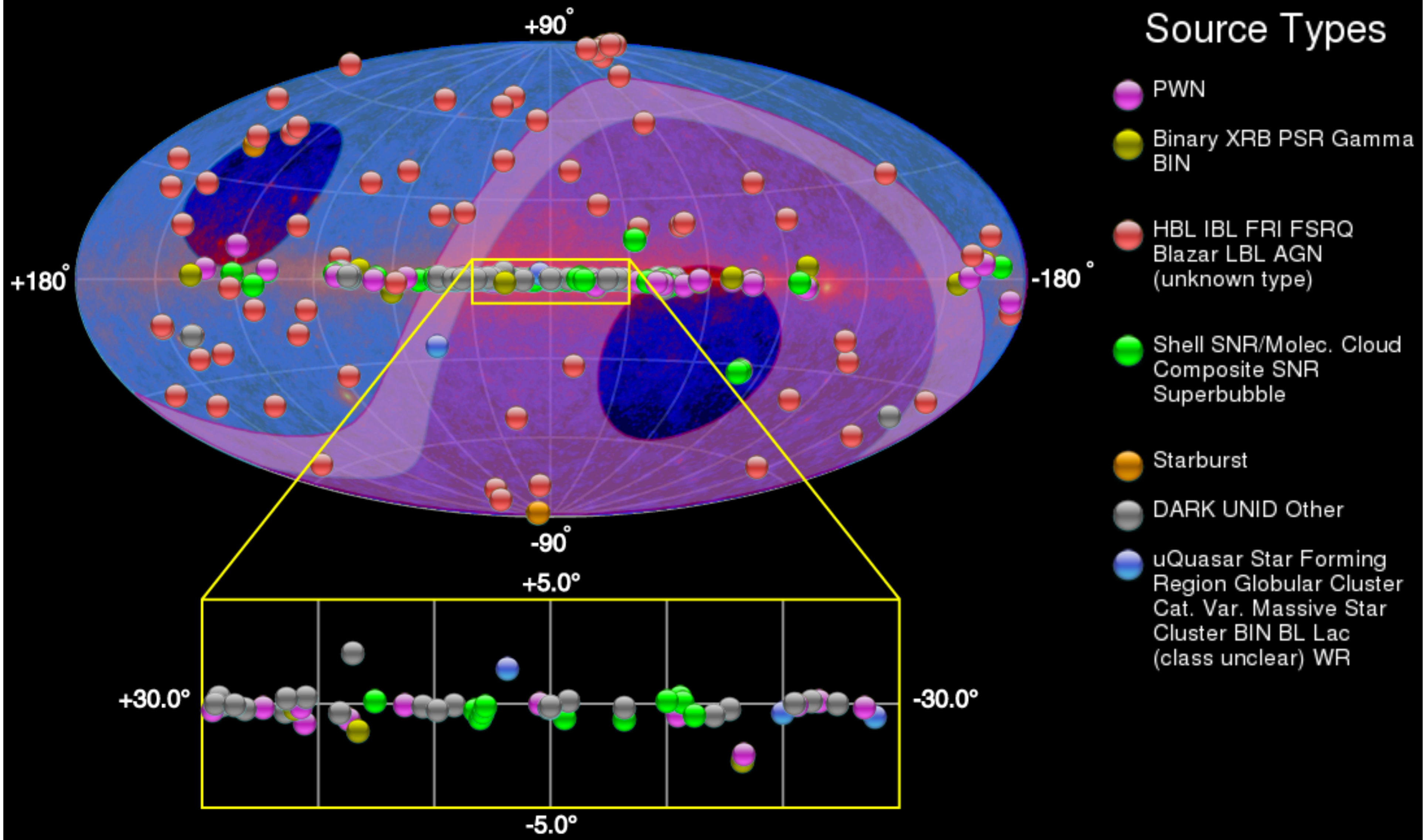
Energies above the thermal regions

- (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

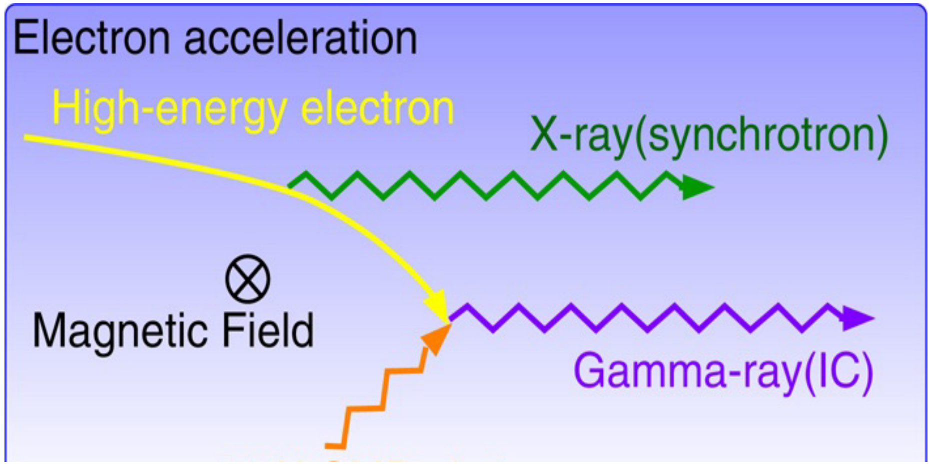
- LE,HE domain of space-based astronomy
- VHE+ domain of ground-based astronomy

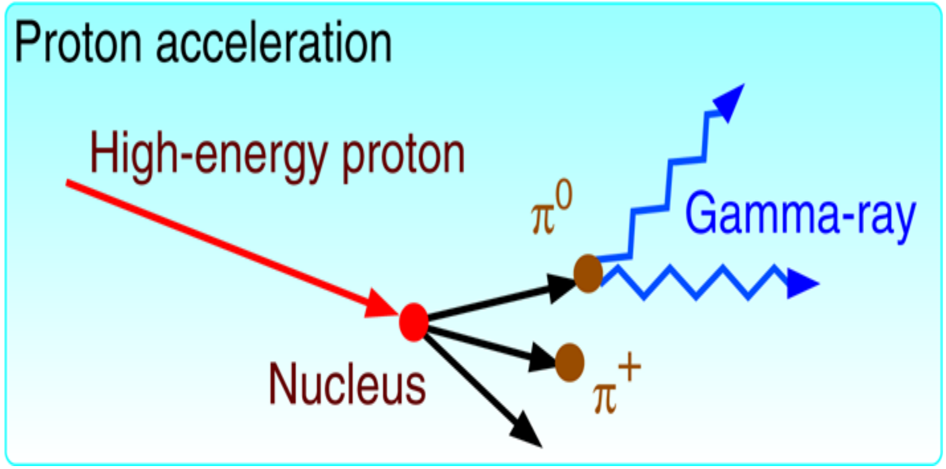
- When no ambiguity, we call "HE" all the HE and VHE+

>3k HE and >200 VHE photon emitters

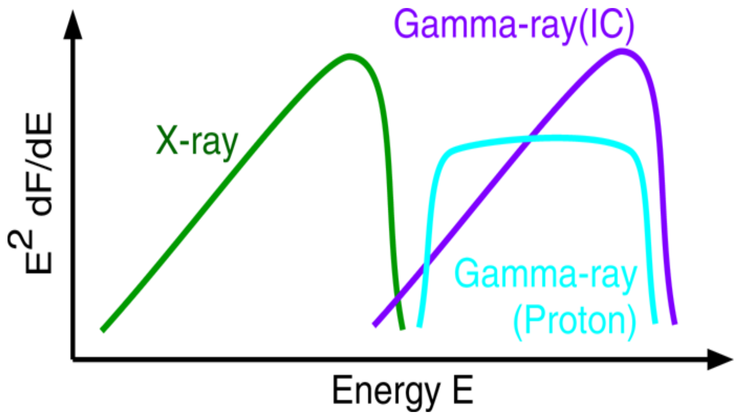


VHE (>100 GeV) gamma rays: Bottom-Up (CR acceleration)





(in astrophysical accelerators)



…or Top-Down (decay of heavier particles, e.g. WIMPs).

In addition, cosmic propagation of photons can tell us a lot on fundamental physics (cosmology, vacuum energy)

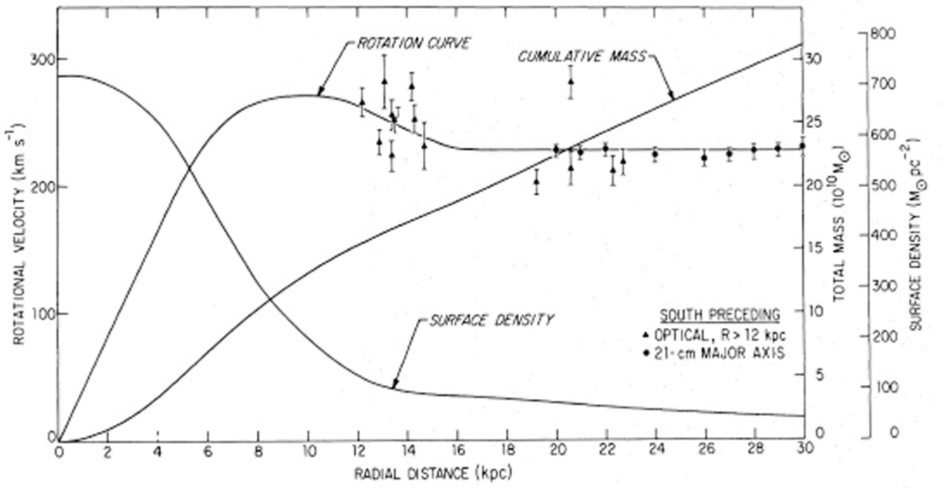
Rules of thumb in hadronic gamma ray production

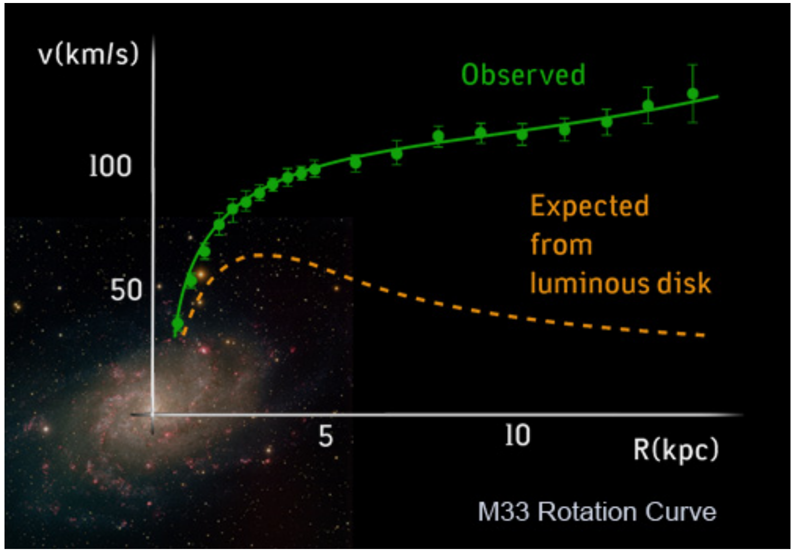
$E_p \sim (10\text{-}20)\ E_\gamma$

$\Phi(\gamma) \sim \Phi(\nu)$

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

- Rotation curves of spiral galaxies

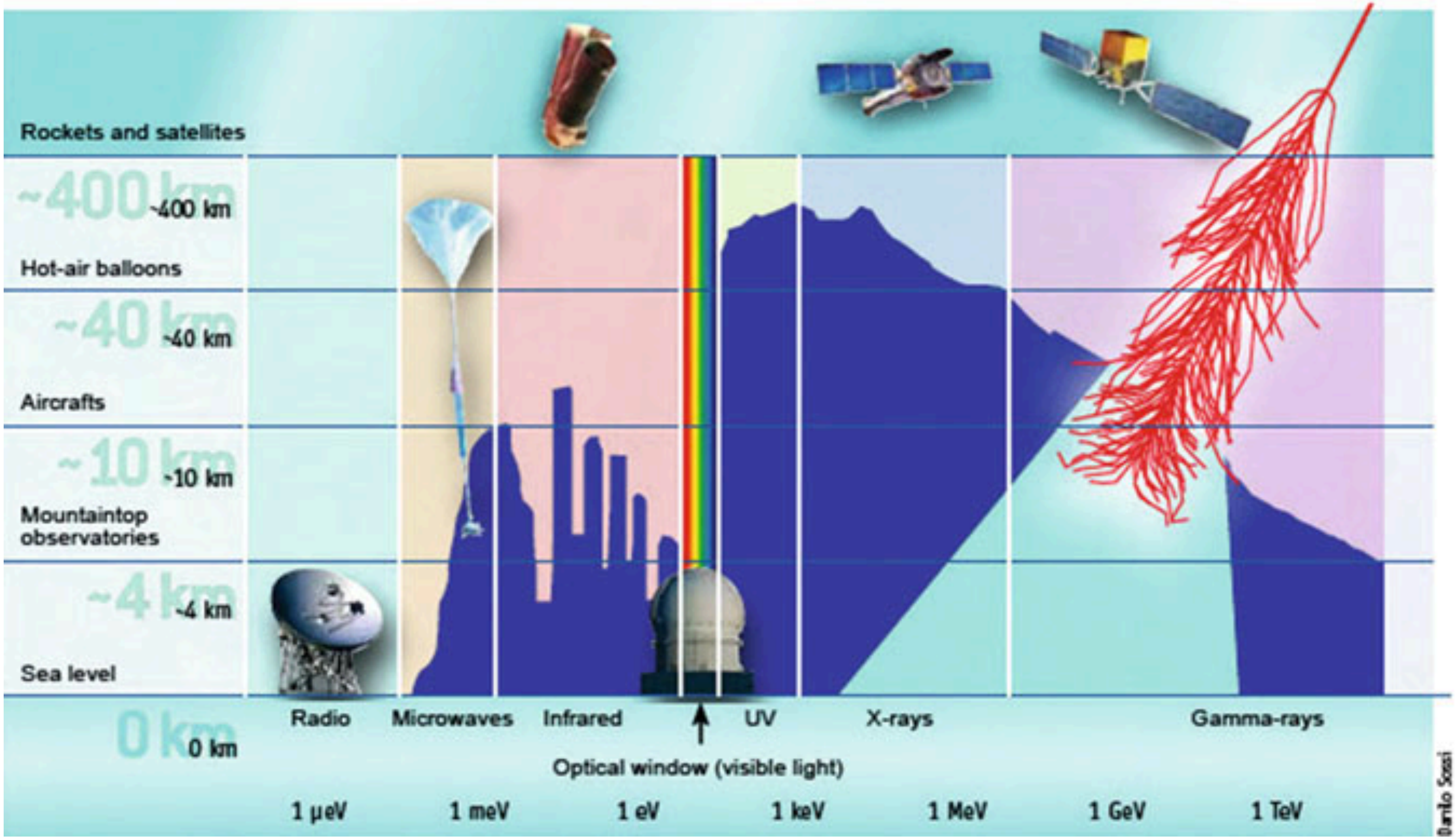




  - flat at large radii: if light traced mass we would expect them to be Keplerian at large radii, $v \propto r^{-1/2}$, because the light is concentrated in the central bulge
    - and disc light falls off exponentially
    - Zwicky had already noted in 1933 that the velocities of galaxies in the Coma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

EXPERIMENTAL PROBLEMS

Transparency of the atmosphere

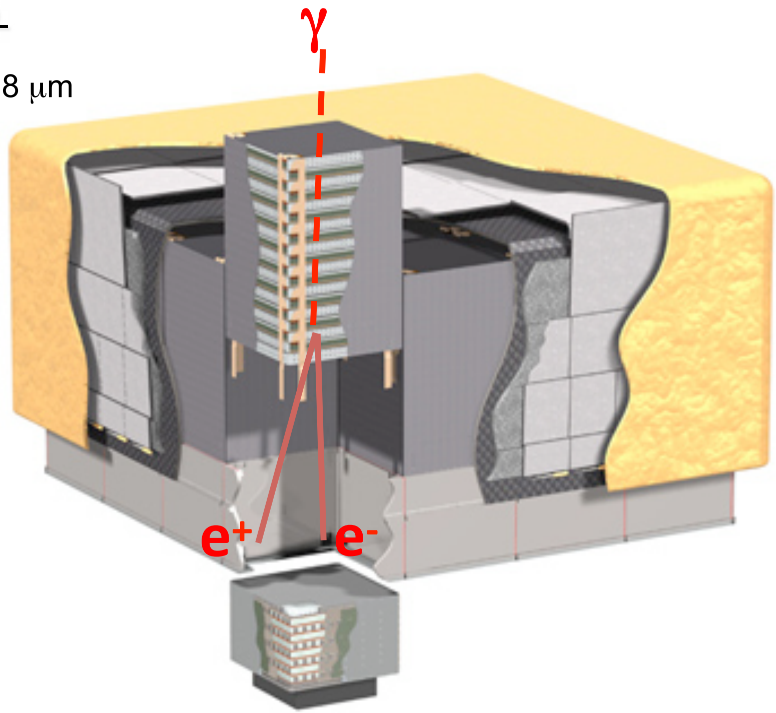


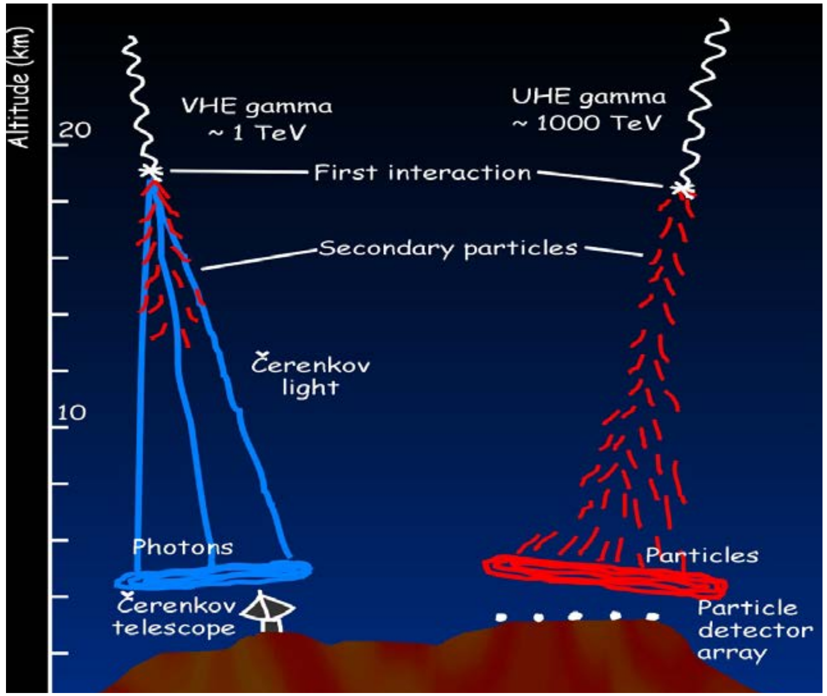
Detectors

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

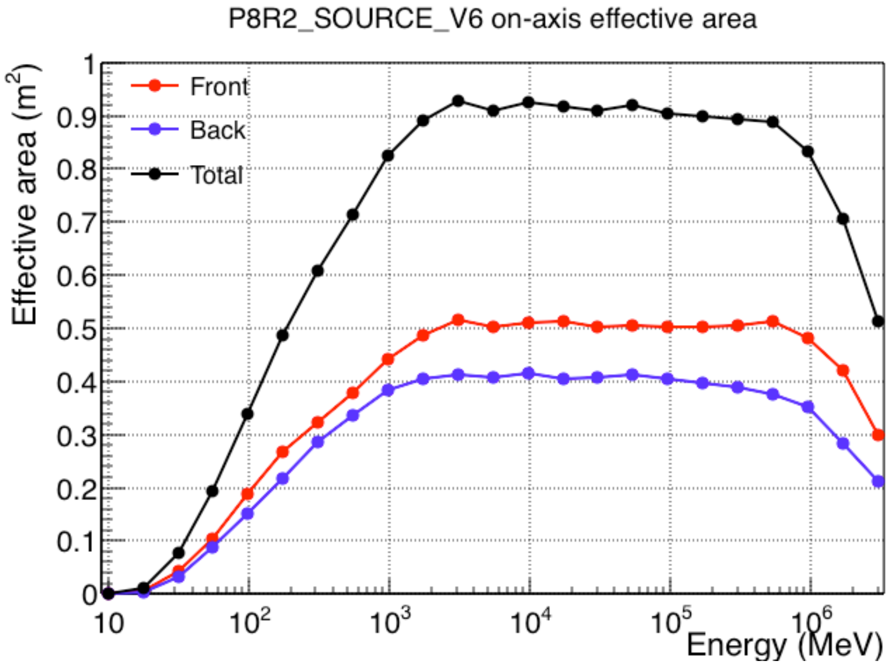
HEP detectors!





Fermi-LAT in orbit since June 2008

An important parameter is effective area

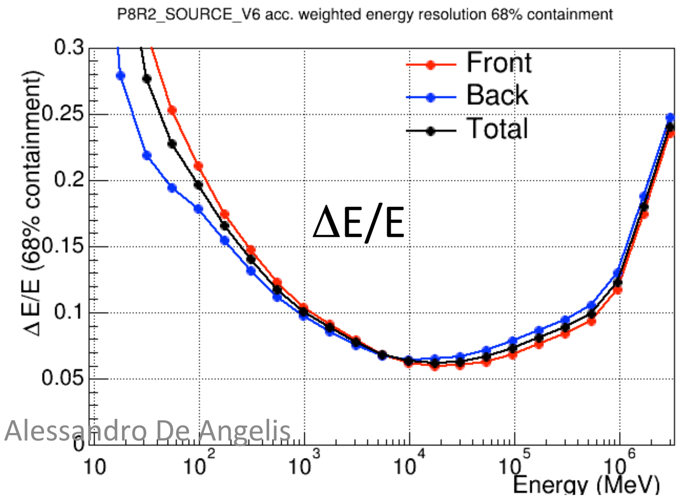


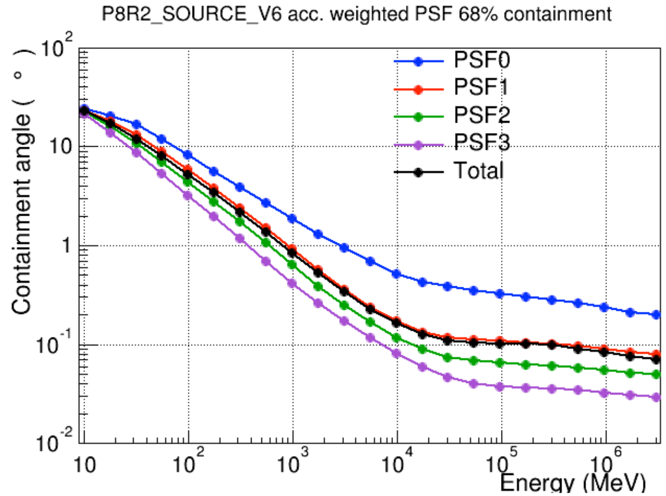
Effective area (Area x efficiency)

~ 1m^2

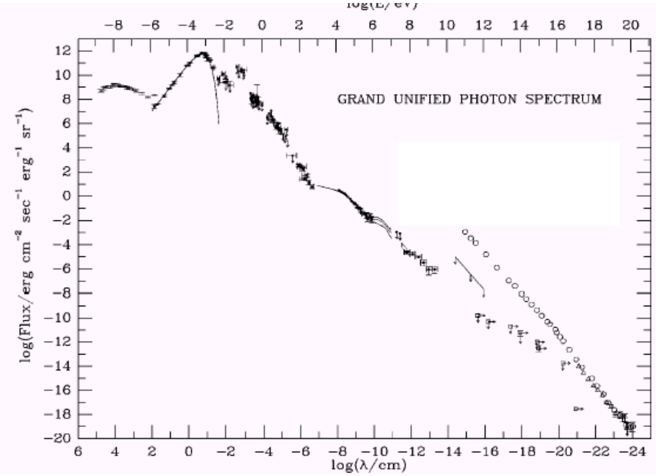
Grows as k lnE from 2 MeV to 2 GeV
Then ~0.9 m^2 from 2 GeV to 700 GeV
Then decreases as k' lnE

Acceptance: 2.5 sr

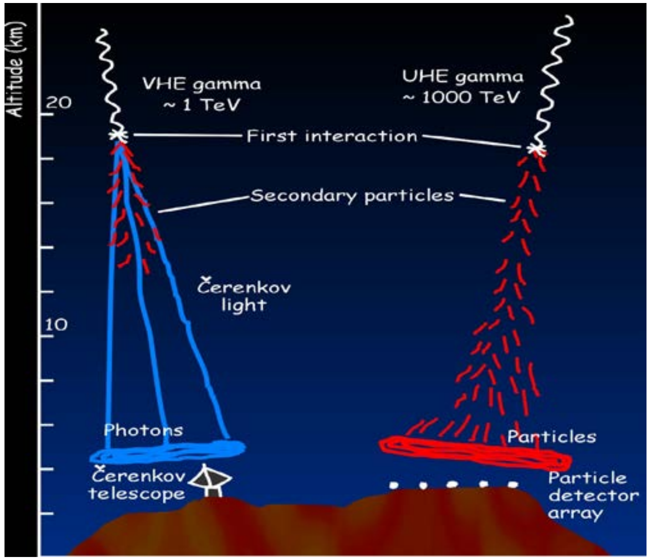




Not enough: need for detection at ground

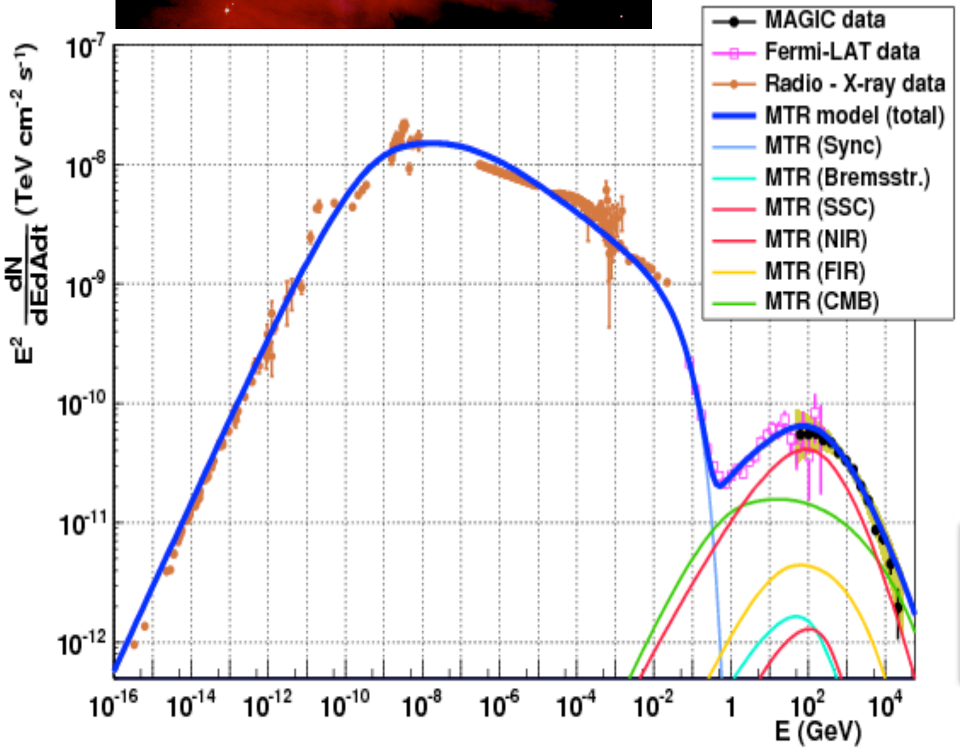


- High energies
  - Only way to build sensitive >TeV instruments
  - Maximum flux < 1 photon/h/m^2 above 200 GeV in Fermi
- High statistics /short timescales
  - Large collection areas O(km^2)
- Precision (Imaging Air Cherenkov telescopes, IACTs)
  - Superior angular resolution
- Limitations?
  - IACTs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



REQUIREMENTS
FOR A GROUND-BASED DETECTOR

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

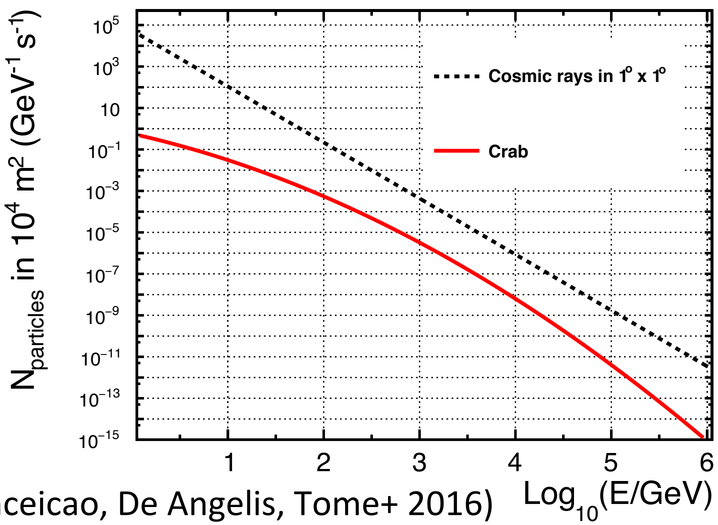


- The Crab Nebula is a nearby (~2 kpc away) PWN and the first source detected in VHE gamma-rays [Weekes 1989].
- It is the brightest steady VHE gamma-ray source, therefore it has become the so-called “standard candle” in VHE astronomy.
  - Recent observation of flares in the GeV range have however shown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

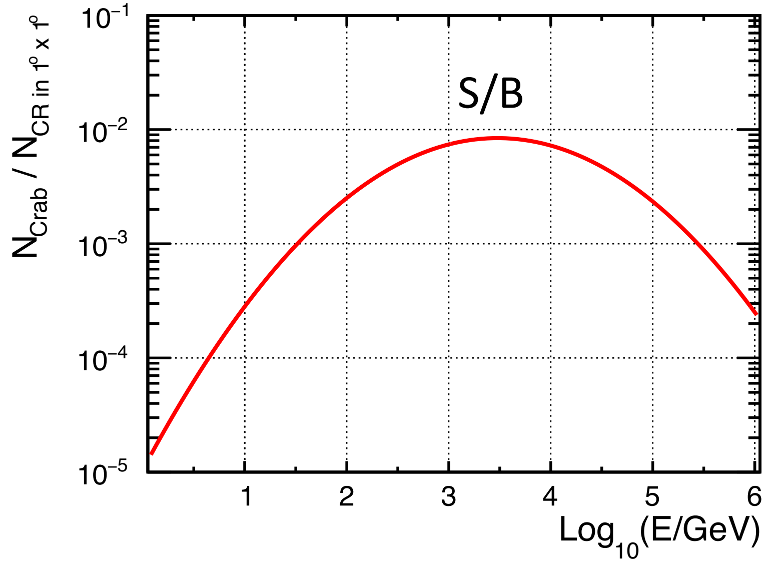
$$\frac{dN_\gamma}{dE} \simeq 3.23 \times 10^{-11} \left(\frac{E}{\mathrm{TeV}}\right)^{-2.47-0.24\left(\frac{E}{\mathrm{TeV}}\right)} \mathrm{TeV}^{-1}\mathrm{s}^{-1}\mathrm{m}^{-2}$$

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)



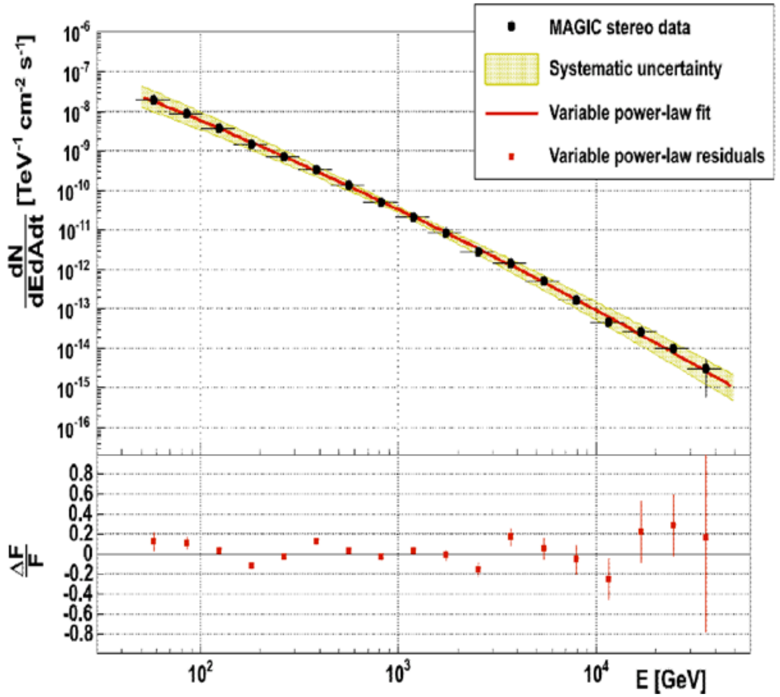
Conclusion: you need large effective area, good angular resolution, proton rejection

Gamma ray flux at high energy

The gamma ray flux decreases rapidly with the energy

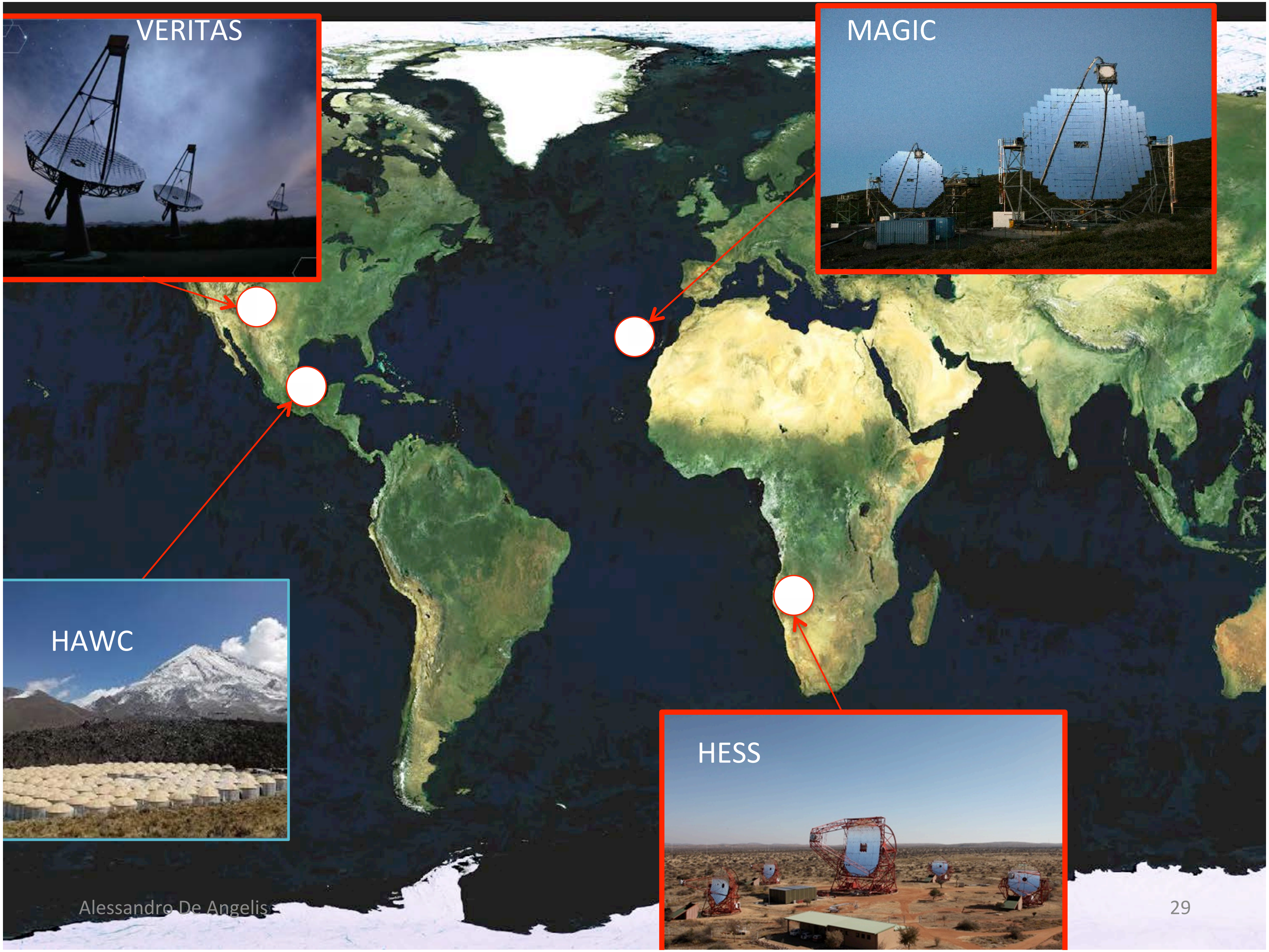
To have an Idea for CRAB nebula

Threshold		ev/h m^2
1	GeV	45
10	GeV	1
100	GeV	0.02
1	TeV	$6\ 10^{-4}$
10	TeV	$1.5\ 10^{-5}$



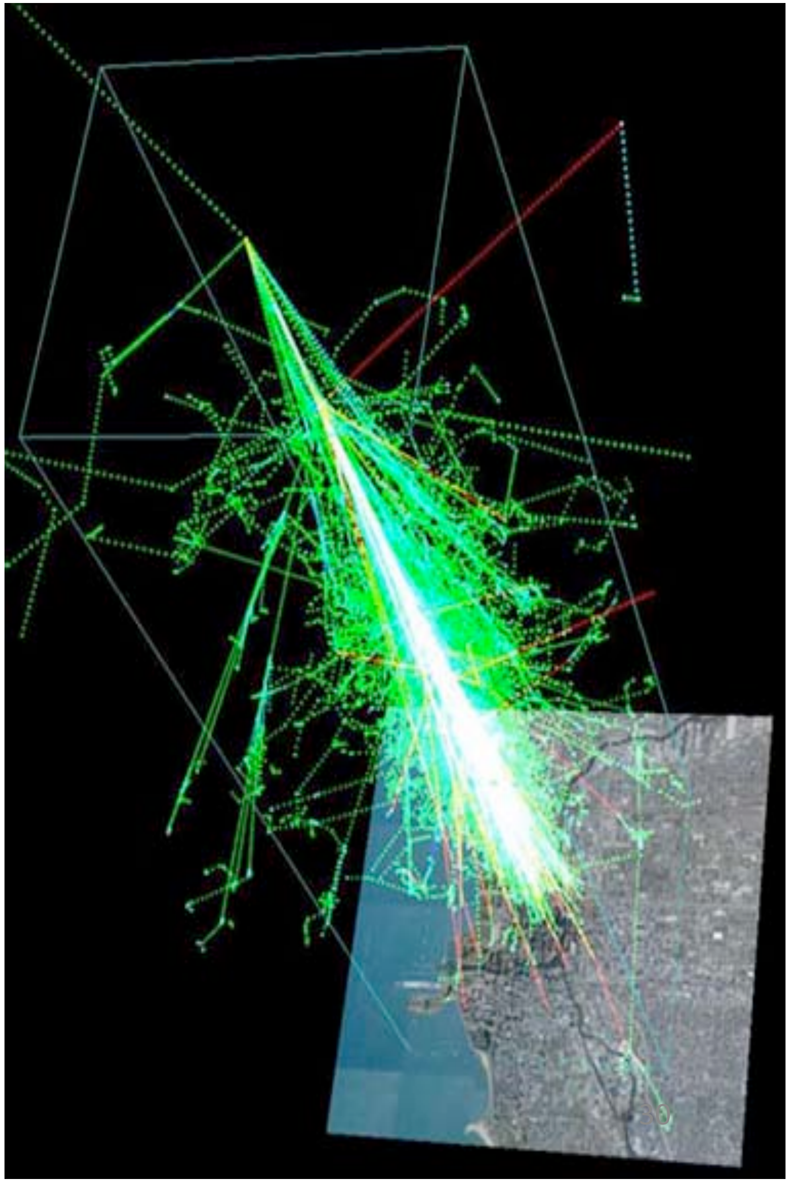
Up to now and for the near future, Cherenkov telescopes lead the field

- Threshold for EAS ~ 400 GeV
- Sensitivities od Cherenkov telescopes 10 times better than for EAS
- Logistics is easy (IACTs built in nice places al ~2000 m; possibility to correct mistakes)


VERITAS
MAGIC
HAWC
HESS

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



Bruno Rossi

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

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: $t = x/X_o$
  - The transverse development scales approximately with the Moliere radius $R_M \sim (21\ \text{MeV}/E_c)\ X_o$
    - 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

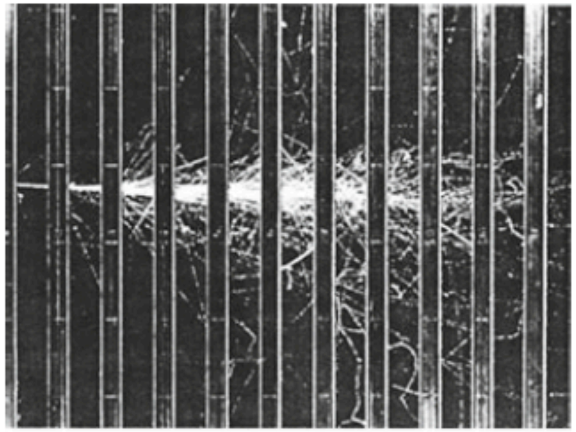
$$E(t) = E_0/2^t$$

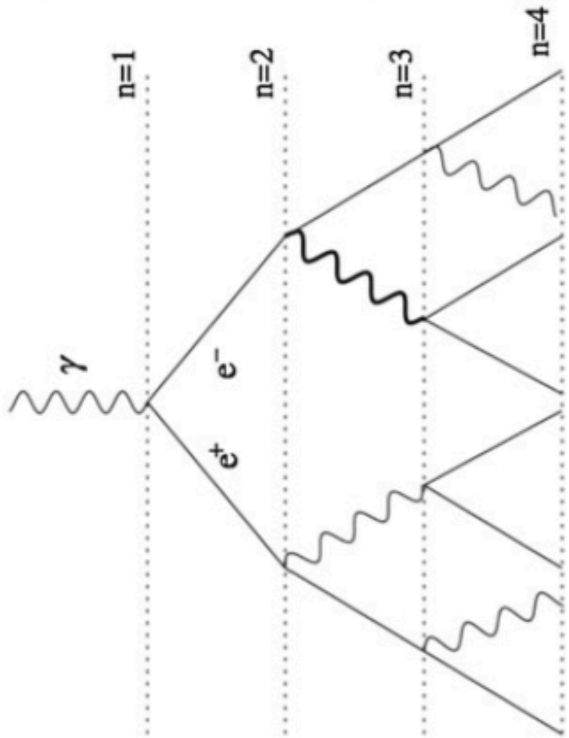
- The multiplication process will cease when $E(t)=E_C$

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

and the number of particles at this point will be

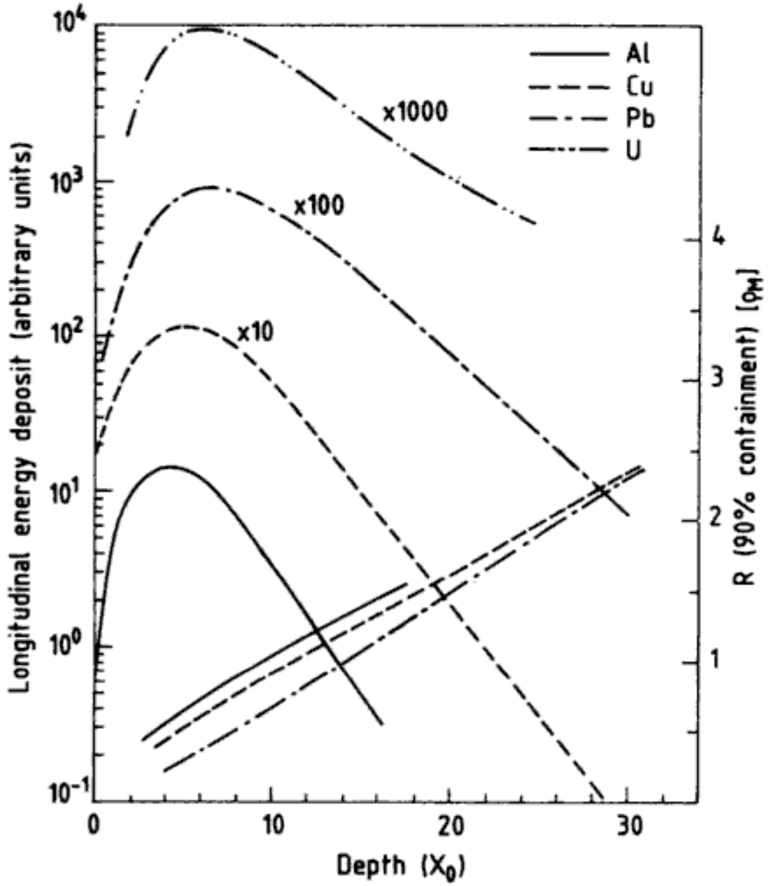
$$N_{max} = \exp\,(t_{max}\,\ln\,2) = E_0\,/\,E_C$$





An analytic model: Rossi's "approximation B"

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



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

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

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

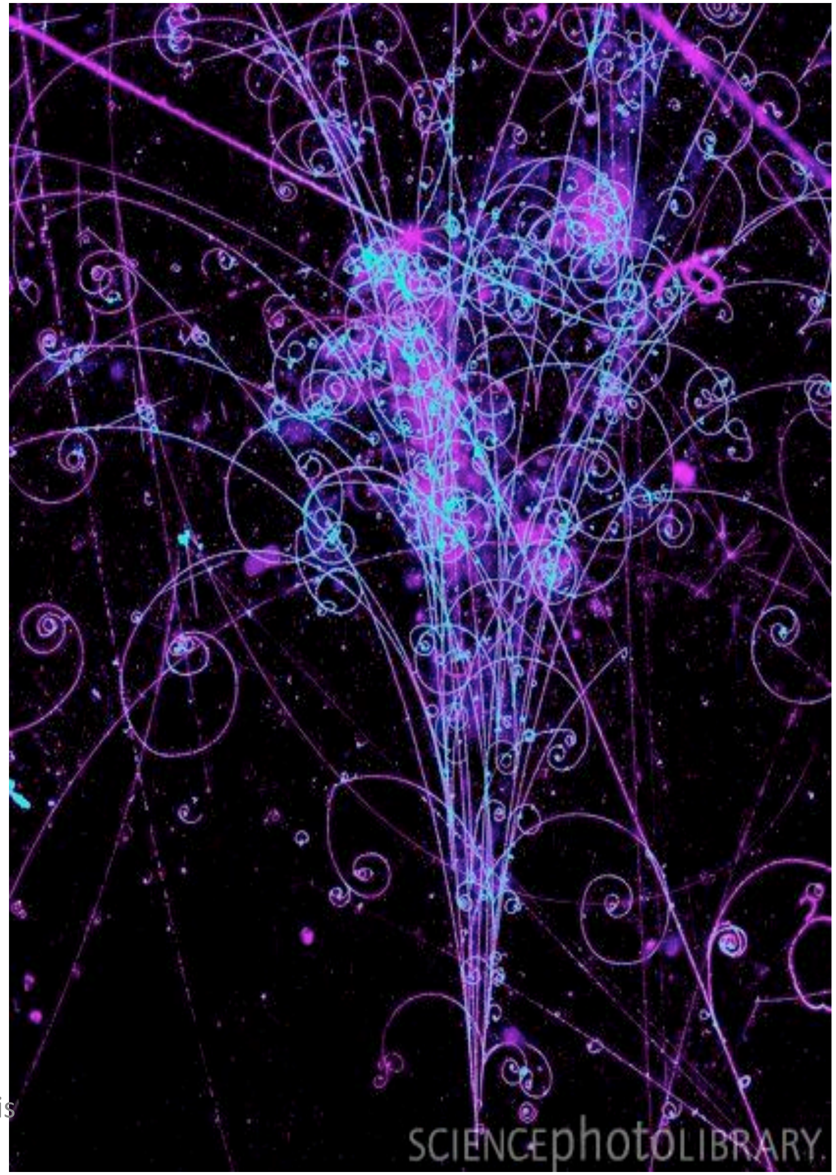
$$\frac{\partial \gamma(W,t)}{\partial t} = \int_0^1 \pi\left(\frac{W}{v},t\right)\varphi_0(v)\frac{dv}{v} - \sigma_0\gamma(W,t)$$

Energy measurement

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

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

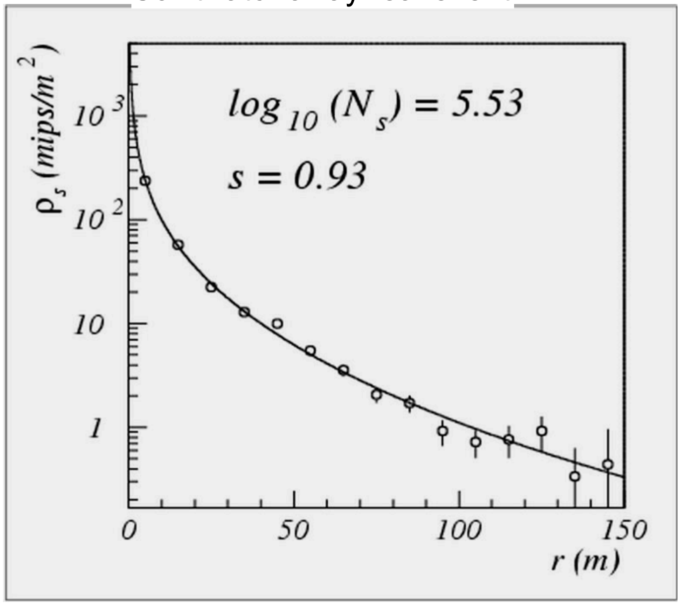
k can be a few per cent for a compact calorimeter



Lateral distribution in an EM shower:

NGK semi-empirical formula (Nishimura Kamata Greisen)

HEGRA
Scintillator array real event



r_M: Molière radius

Lateral distribution in different materials scales with r_M:

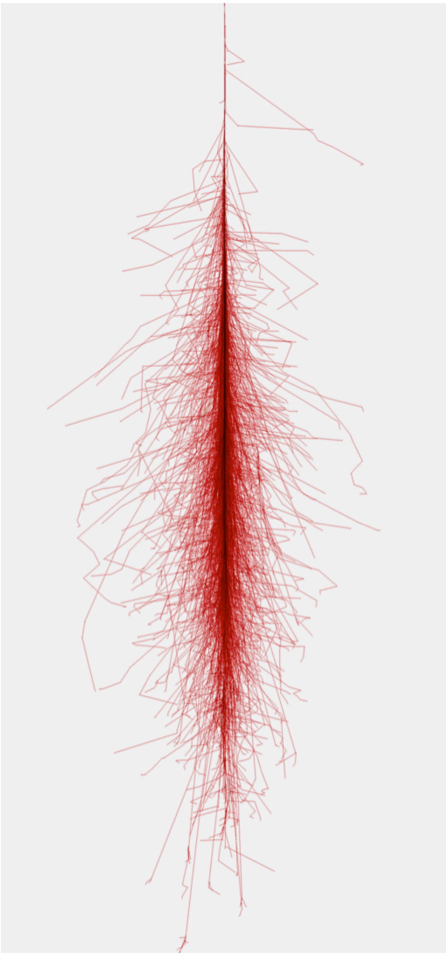
$r_M = X_0\, E_s/E_c$ (≈80 m for air at sea level)

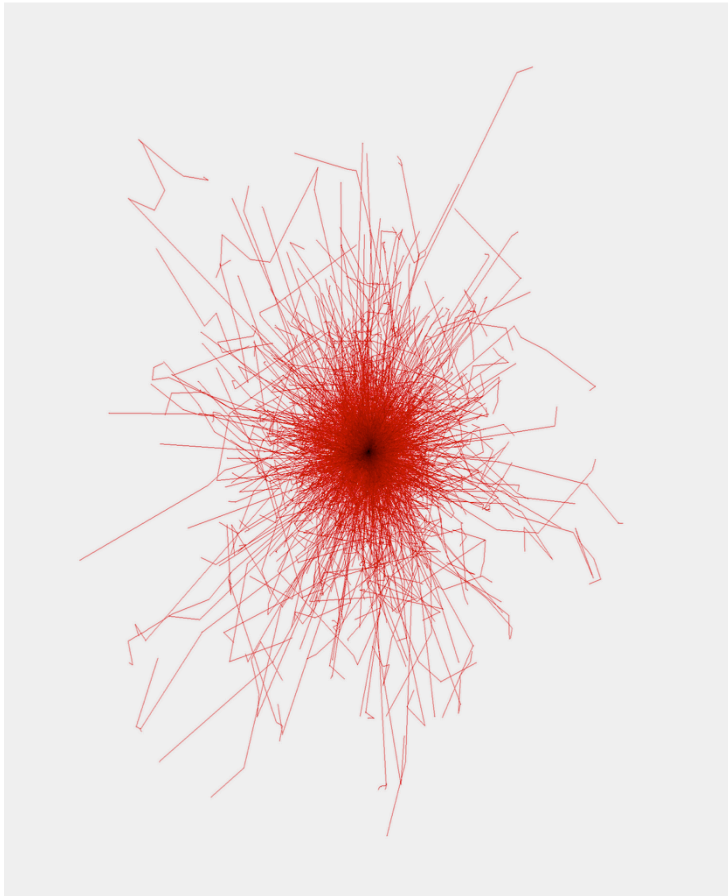
$$E_s = \sqrt{4\pi/\alpha}\; m_e c^2$$

(scale energy, 21.2052 MeV)

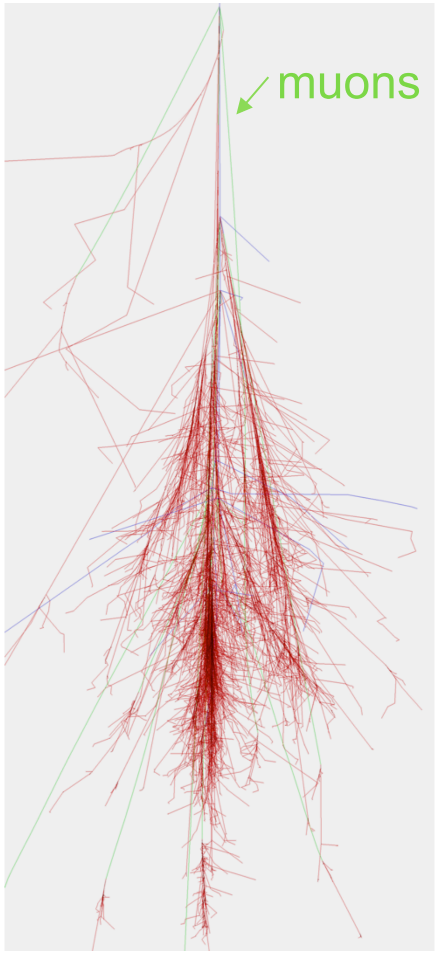
$$\rho_e(r) = \frac{N_e}{r_M^2} \cdot \left(\frac{r}{r_M}\right)^{s-2} \cdot \left(1 + \frac{r}{r_M}\right)^{s-4.5} \cdot \frac{\Gamma(4.5 - s)}{2\pi \cdot \Gamma(s) \cdot \Gamma(4.5 - 2s)}$$

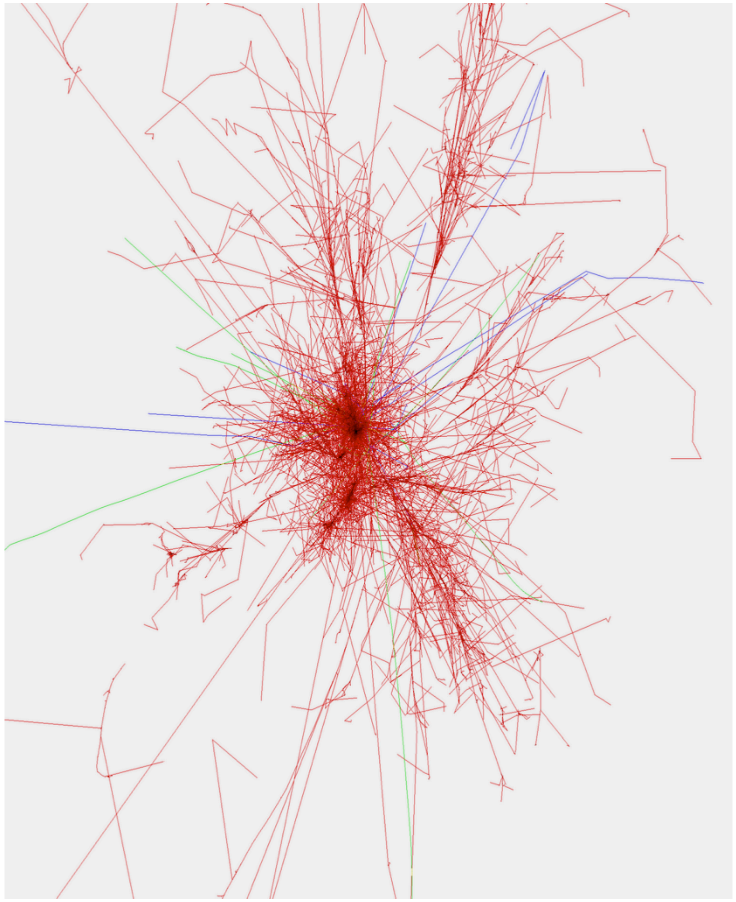
Simulated 50 GeV EM shower





Simulated 100 GeV hadronic shower

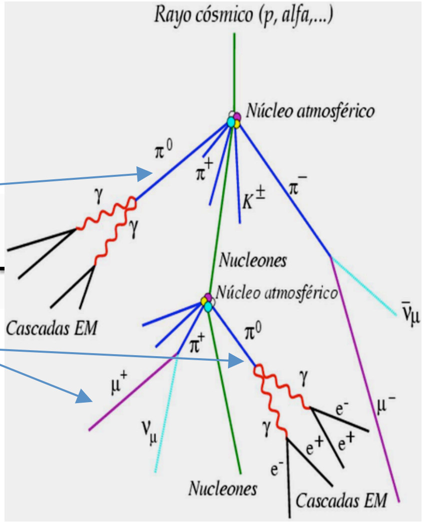




Hadron initiated showers

- Muons, resulting mainly from charged pions, have a half-life of 2.2 μs in their own reference frame ⇒ many arrive at the ground before decaying (and account for 75% of all secondary CR detected at sea level)

- Neutral pions decay (most often) in 2 γ, resulting in EM sub-showers at some angle w.r.t. the shower axis

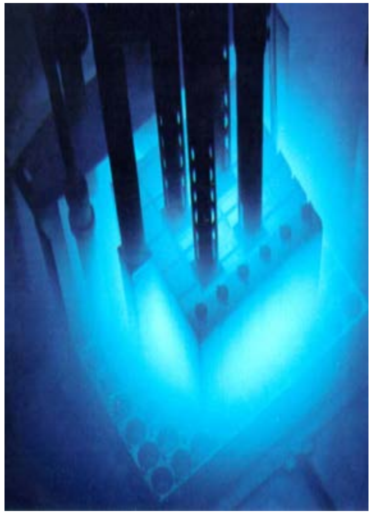


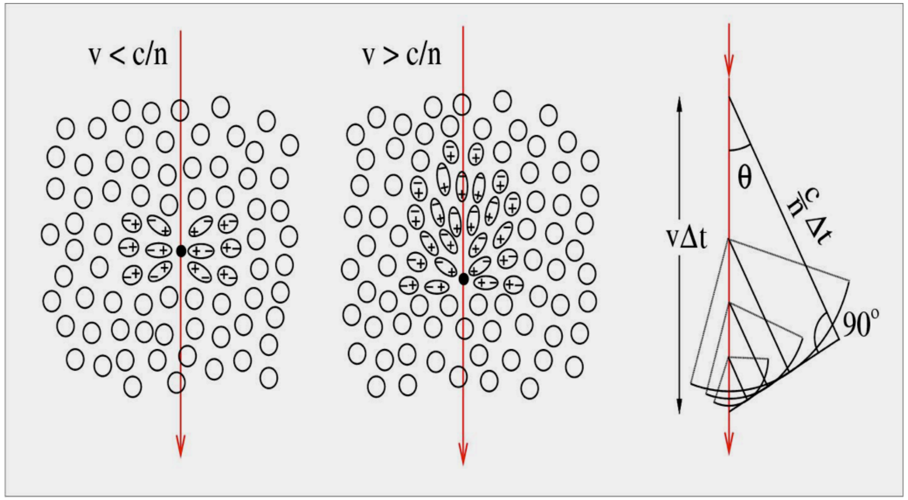
- **Shape is different from EM: more irregular**

- Detailed study requires a full Monte Carlo simulation

Cherenkov radiation (Vavilov & Cherenkov 1934, Nobel to Cherenkov in 1958)

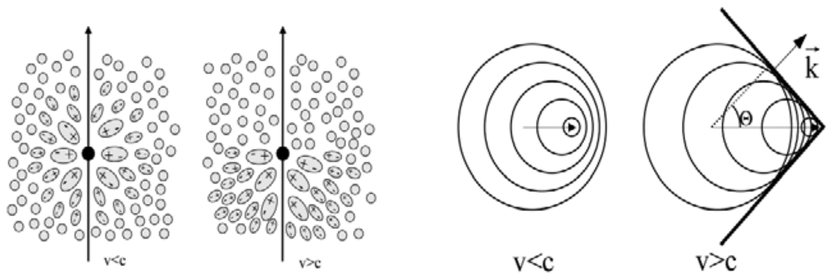
- Emitted whenever a charged particle traverses a medium at a speed larger than that of light in the medium
- The radiation results from the reorientation of electric dipoles induced by the charge in the medium. When v > c/n the contributions from different points of the trajectory arrive in phase at the observer as a narrow light pulse

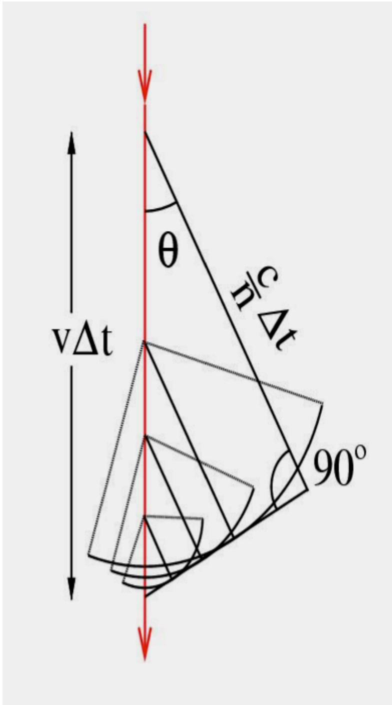




Cherenkov radiation

Analogous to “sonic bang”





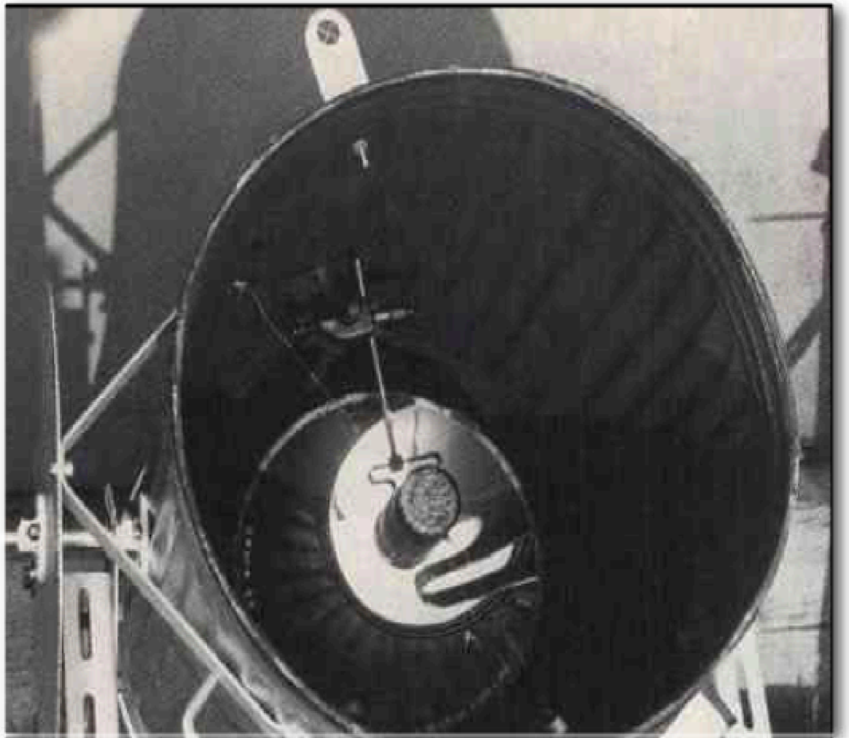
$$\frac{d^2N}{d\lambda dx} = 2\pi\alpha\frac{\sin^2\theta}{\lambda^2}$$

$\cos\theta = 1 / (\beta n)$

For $\beta=1$ =>

$\theta_{max} = \cos^{-1}(1/n)$

The Very Beginning of the Atmospheric Air Cherenkov Telescope Technique….

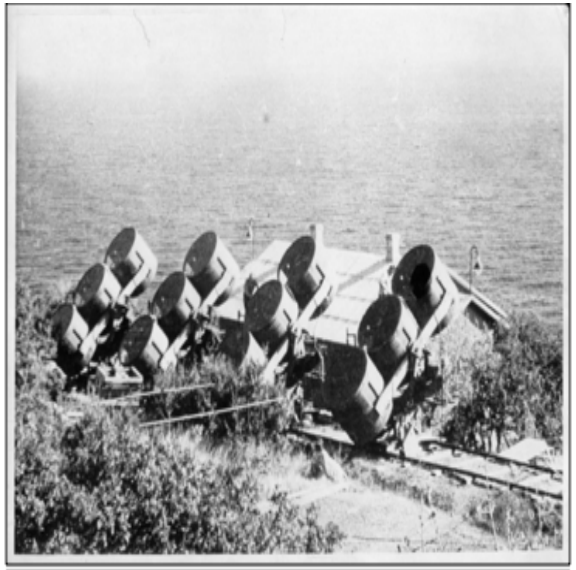


In 1948, P.M.S. Blackett suggested that secondary CR's should produce Cherenkov radiation which would account for a fraction 10^{-4} of the total night sky light

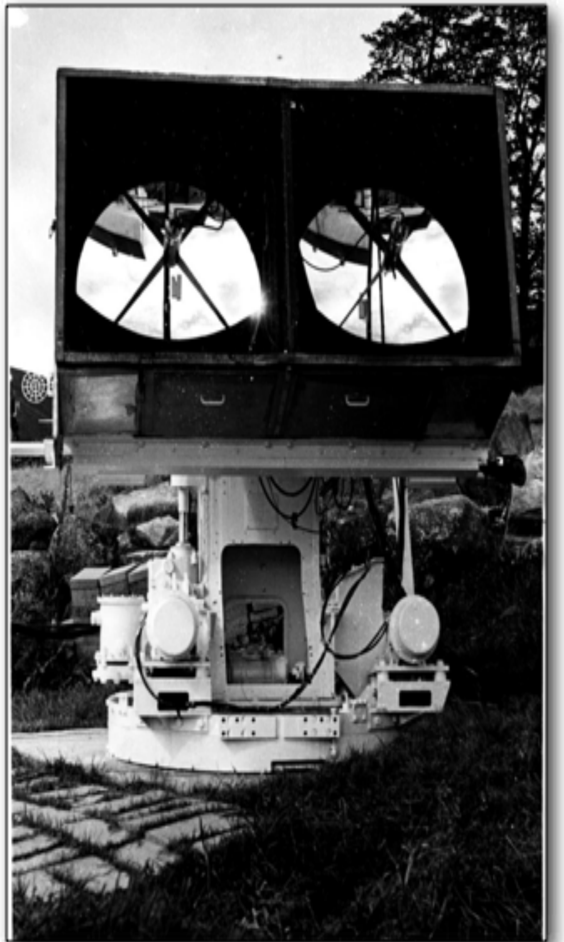
Pulses of Cherenkov light from air showers were first recorded by Galbraith and Jelley in 1953

1953 By using a garbage can, a 60 cm diameter mirror in it and a PMT in its focus Galbraith and Jelley had discovered the Cherenkov light pulses from the extensive air showers.

The Very Beginning of the Atmospheric Air Cherenkov Telescope Technique



Crimea Experiment 1959-1965, Chudakov, et al., (SNR, radio galaxies)



Telescope Glencullen, Ireland ~1962-66University College, Dublin group led by Neil Porter(in collaboration with J.V.Jelley)

Cherenkov radiation in the atmosphere

Air density: $$\rho(h) = \rho_0 \cdot e^{-\frac{h}{h_0}}$$ h_0 = 7.8 km

Refractive index: $$n = 1 + \eta_h = 1 + \eta_0 \cdot e^{-\frac{h}{h_0}}$$, with $\eta_0 = 2.9 \cdot 10^{-4}$

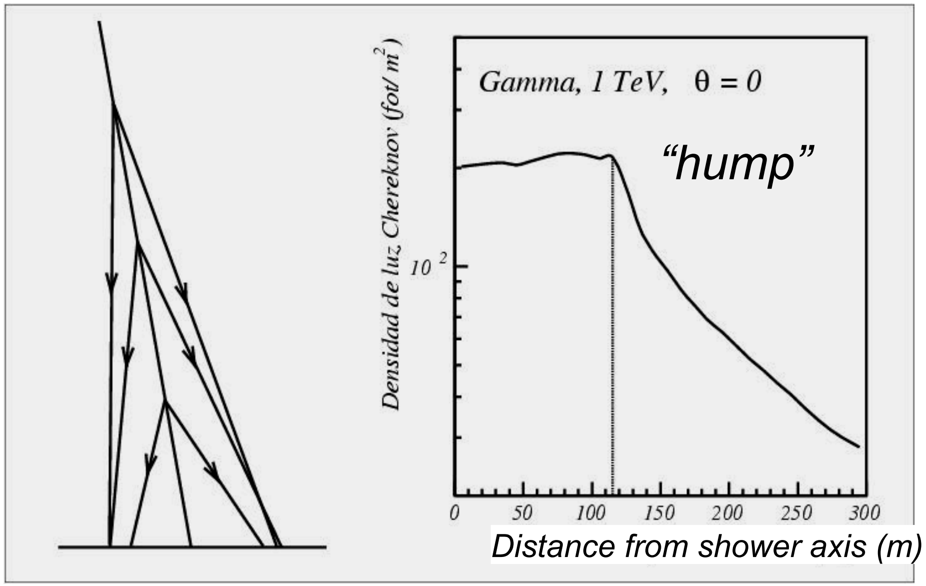
Threshold for Cherenkov emission: $$E_{min} = \frac{m_e c^2}{\sqrt{1-\beta_{min}^2}} = \frac{m_e c^2}{\sqrt{1-n^{-2}}} \simeq \frac{0.511\ MeV}{\sqrt{2\ \eta_h}}$$ (≈ 21 MeV at sea level, for electron)

Cherenkov angle for $\beta = 1$: $$\cos\theta_{max} = \frac{1}{n} = \frac{1}{1+\eta_h} \simeq 1 - \eta_h$$ ~1 deg at sea level

The concept of "light pool"

R_c: Distance from shower trajectory at which the C-photons hit the ground

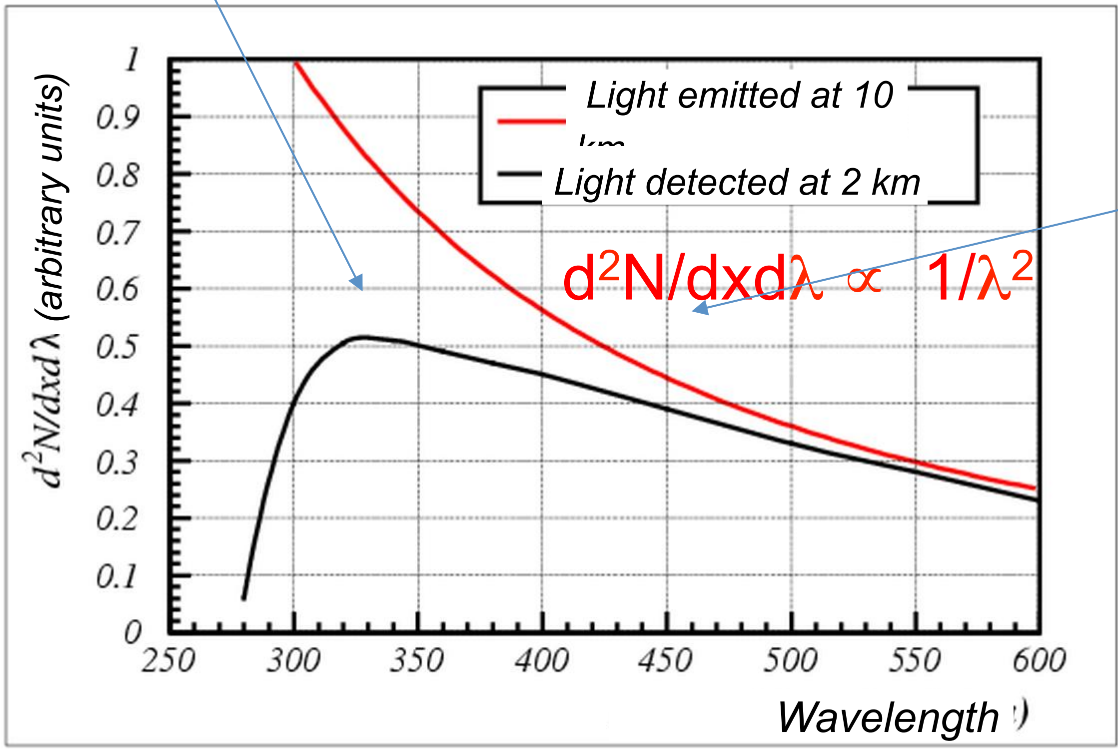
$$R_c \equiv (h - h_{obs}) \cdot \tan \theta_{max}$$ for $\beta = 1$



Hump position depends on observation altitude (indirectly on E_0)

Observed Cherenkov spectrum

Transparency of the atmosphere absorption effect



$$\frac{d^2N}{d\lambda dx} = 2\pi\alpha\frac{\sin^2\theta}{\lambda^2}$$

Three relevant processes of absorption:

- Mie scattering (by dust particles)
- Rayleigh scattering (by air molecules)
- Absorption by Ozone (but EAS develops mostly below O_3 layer)

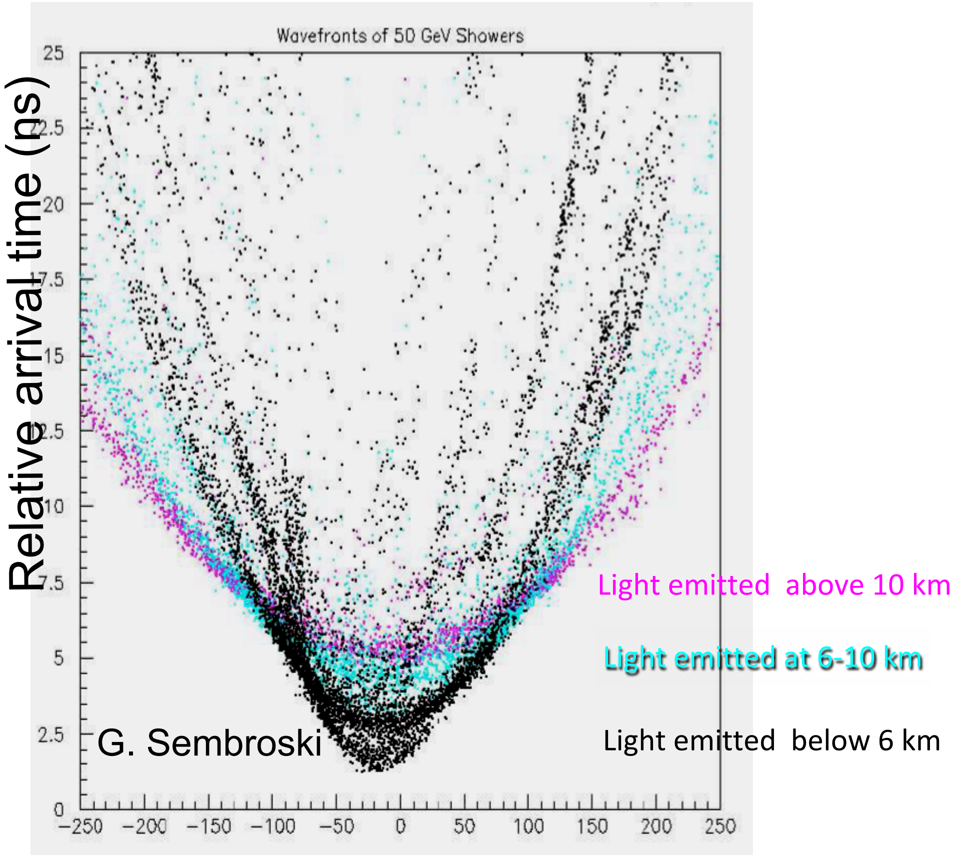
- From 1 TeV, ~ 200 photons/m2

Constraint on the photodetector: should be sensitive in the NUV

Cherenkov light in the atmosphere:

Time structure of the C-light front

C-light front is shaped as a rather flat, narrow cone, sharper than the charged particles front



Constraint on the electronics: better than 1 GHz

The first Imaging Atmospheric Telescope: the IACT era

Whipple observatory: the first ever succesful ground based experiment

30h for 20 sigma signal from Crab

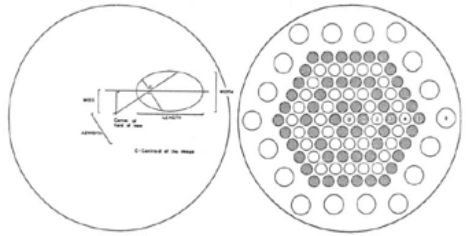


Fig. 2. Definition of image parameters.

Fig. 3. The layout of the photomultipliers in the focal plane of the reflector. The inner pixel spacing is 0.25°. The numbers refer to the zones, the convention used to designate the position of the images relative to the center of the camera.

Observations of TeV Photons at the Whipple Observatory

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Abstract

The Whipple Observatory 10 m gamma-ray telescope has been used to search for TeV gamma-ray emission from a number of objects. This paper reports observations of six galactic and three extragalactic objects using the Cherenkov image technique. With the introduction of a high-resolution camera (1/4° pixel) in 1988, the Crab Nebula was detected at a significance level of 20 σ in 30 hours of on-source observation. Upper limits at a fraction of the Crab flux are set for most of the other objects, based on the absence of any significant dc excess or periodic effect when an *a priori* Monte Carlo determined imaging selection criterion (the "azwidth cut") is employed. There are weak indications that one source, Hercules X-1, may be an episodic emitter. The Whipple detection system will be improved shortly with the addition of a second reflector 11 m in diameter (GRANITE) for stereoscopic viewing of showers. The combination of the two-reflector system should have a signal-to-noise advantage of 10^3 over a simple nonimaging Cherenkov receiver.

The IACT technique

Incoming

γ-ray

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

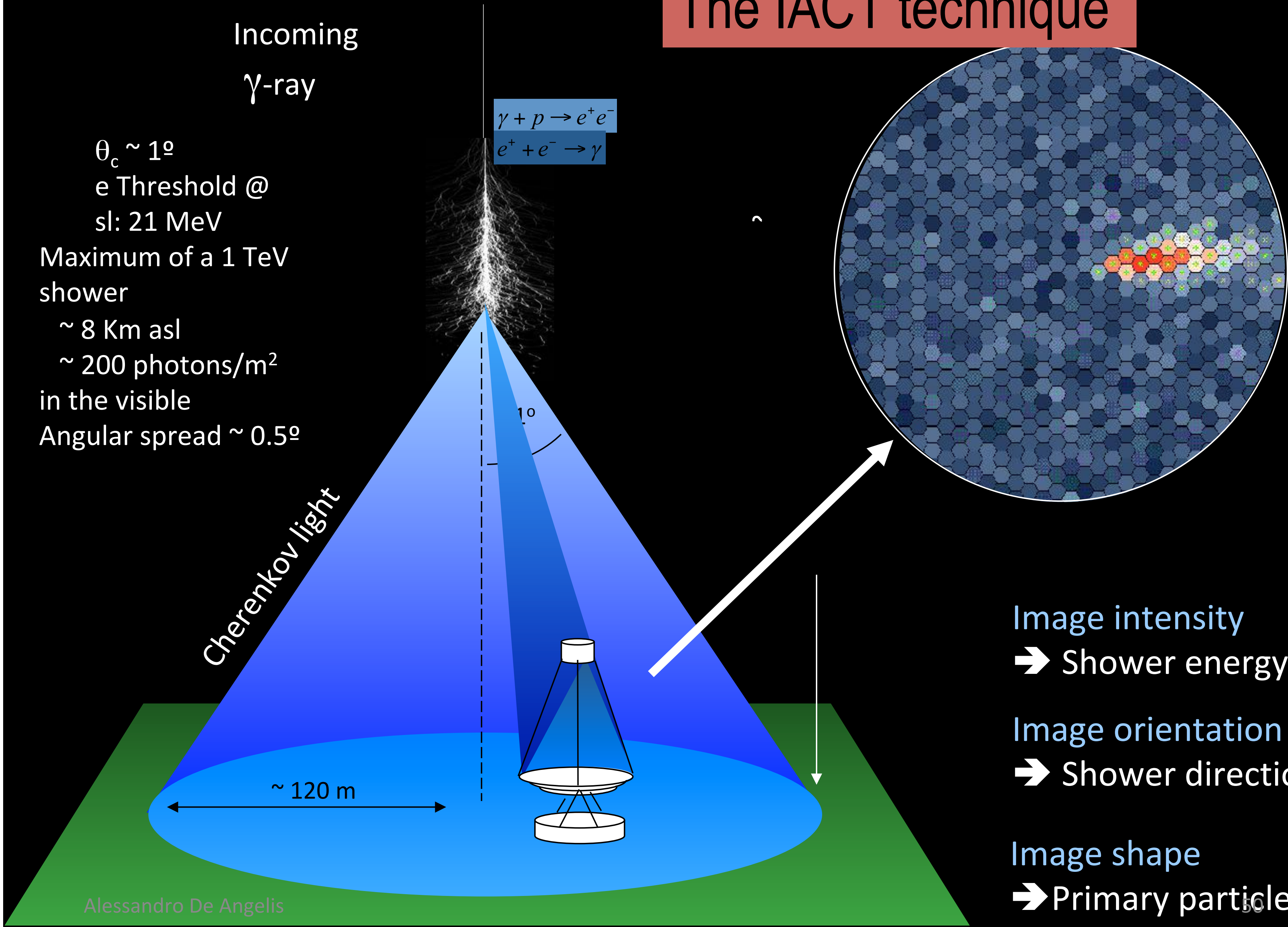
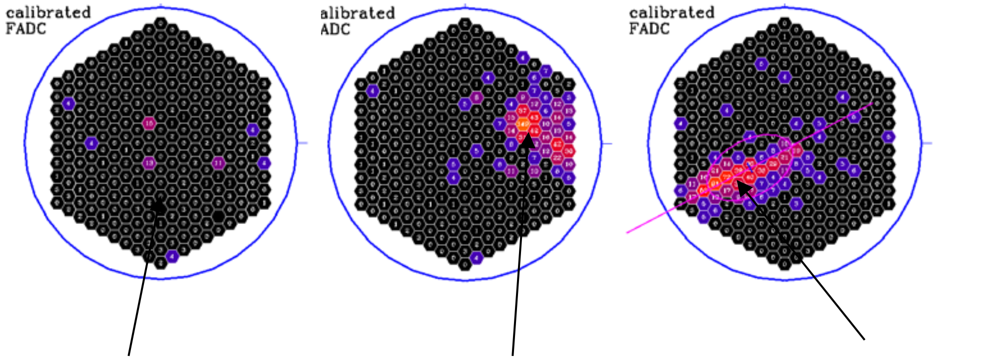


Image intensity
➔ Shower energy

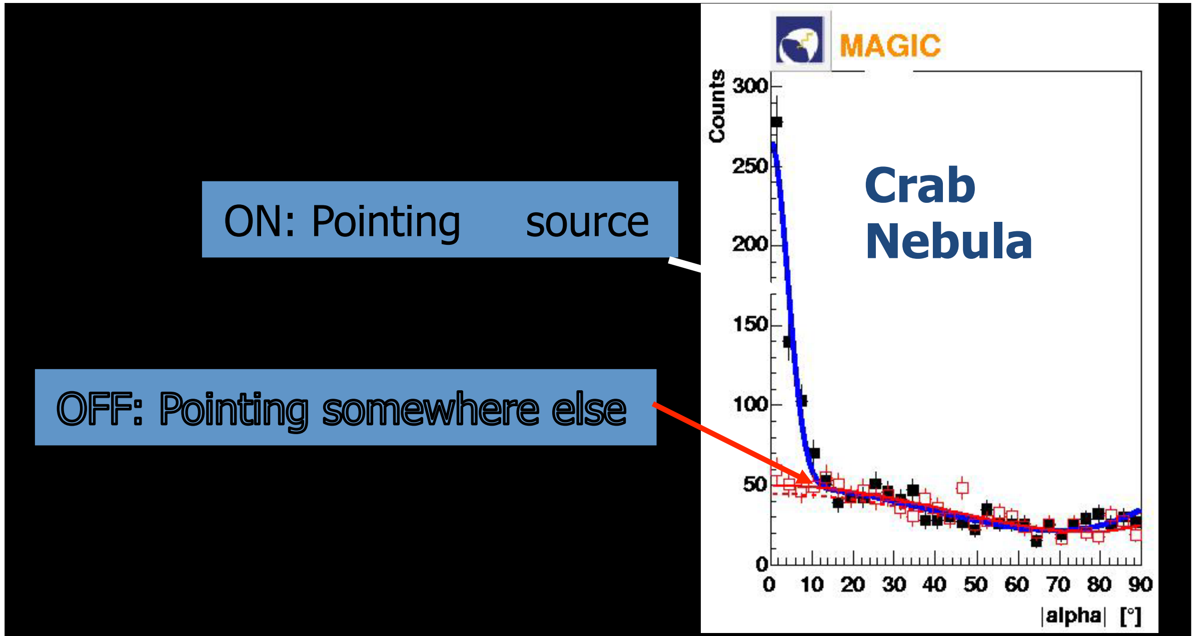
Image orientation
➔ Shower direction

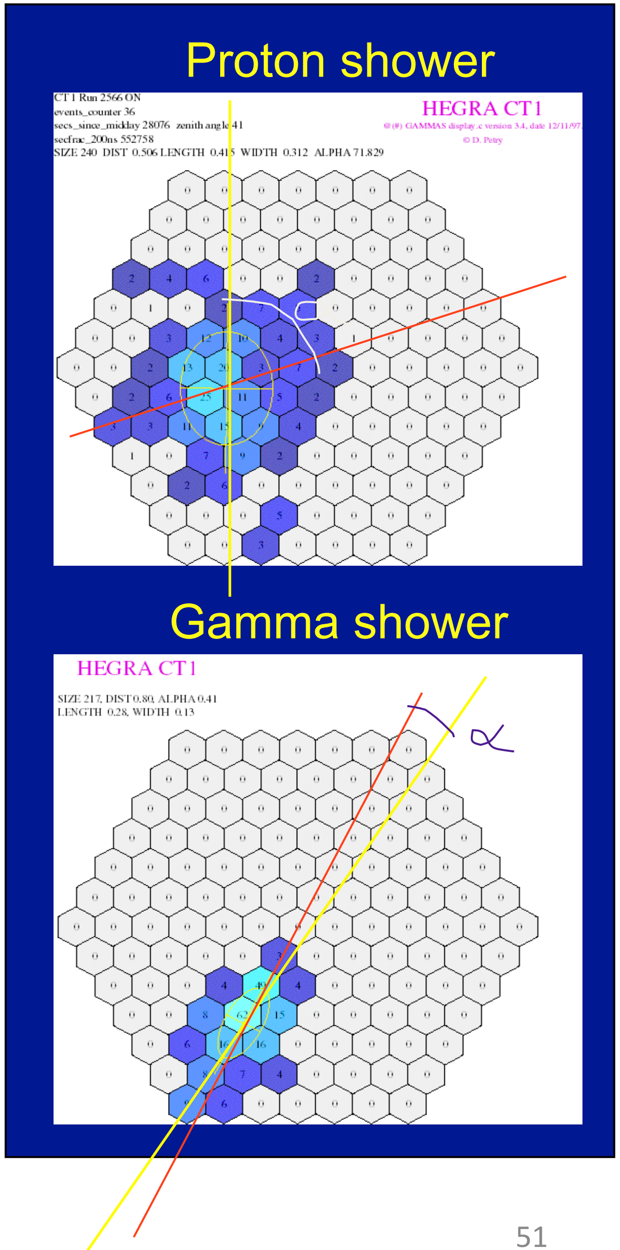
Image shape
➔ Primary particle

γ/h Separation

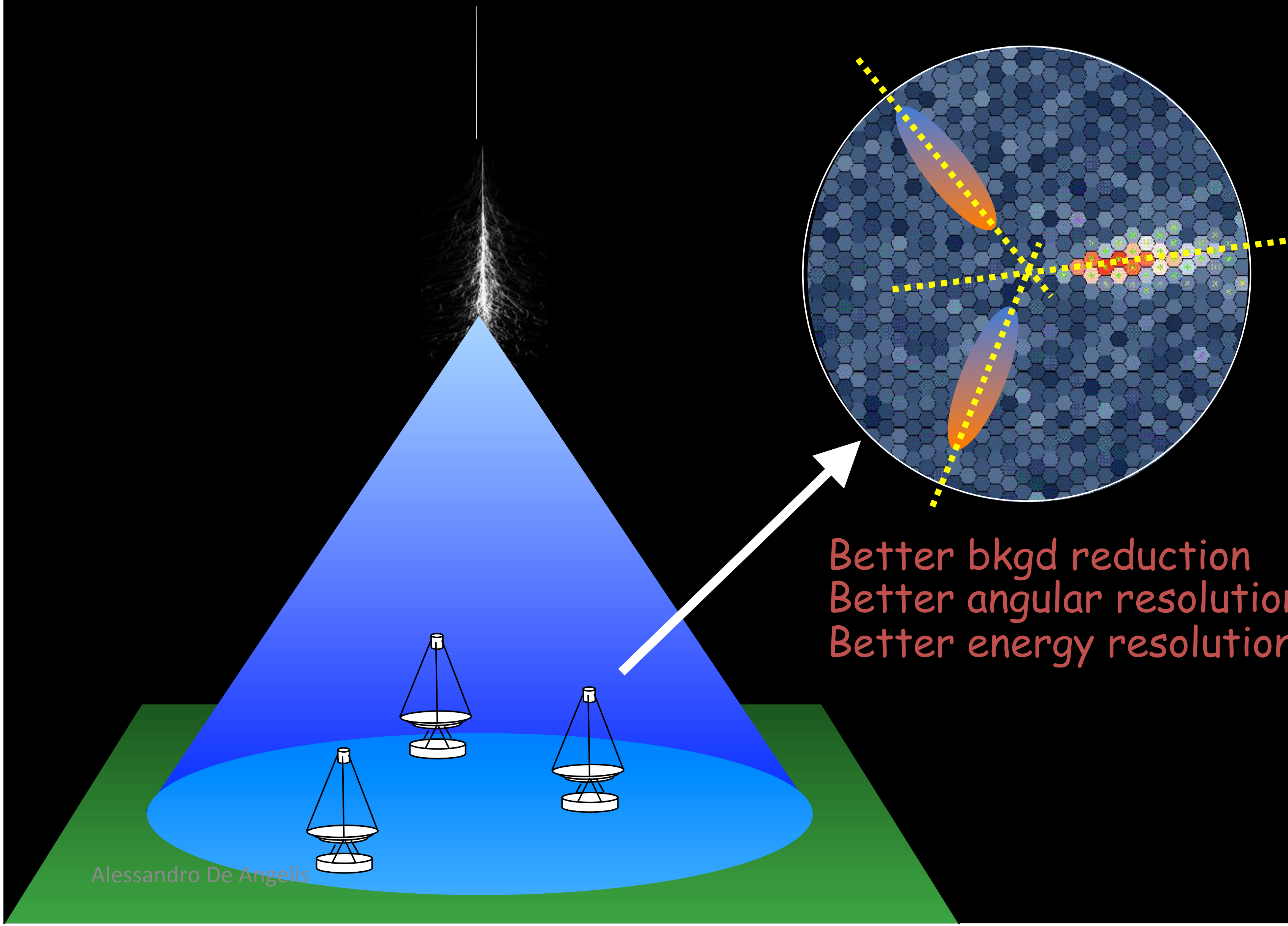


NSB event **Hadronic shower** **Gamma shower**





Systems of Cherenkov telescopes

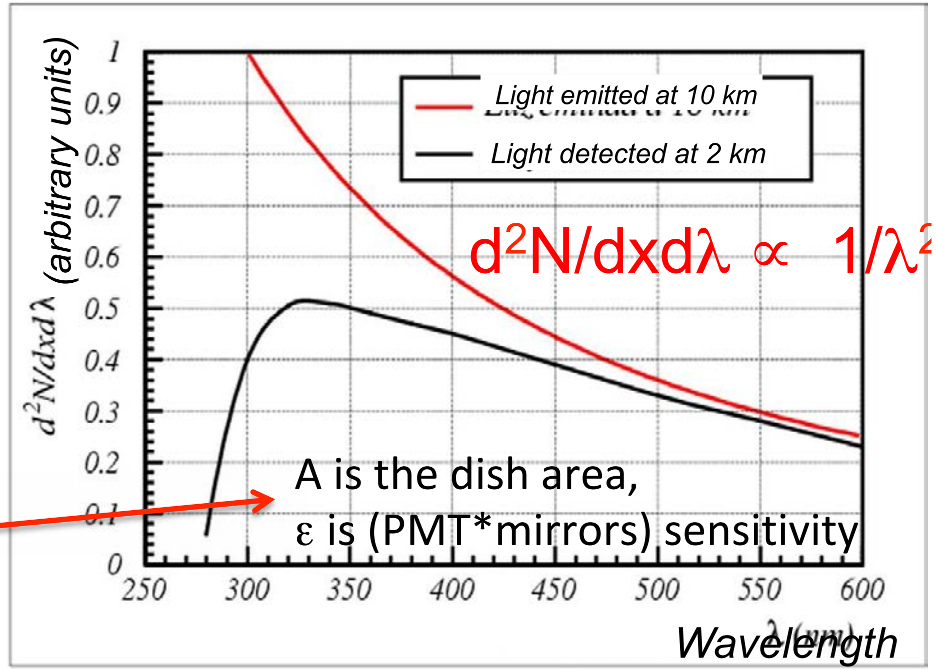


Better bkgd reduction
Better angular resolution
Better energy resolution

Figures of merit of a Cherenkov telescope

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

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 have small N (cost: 1-10 MEUR/telescope)

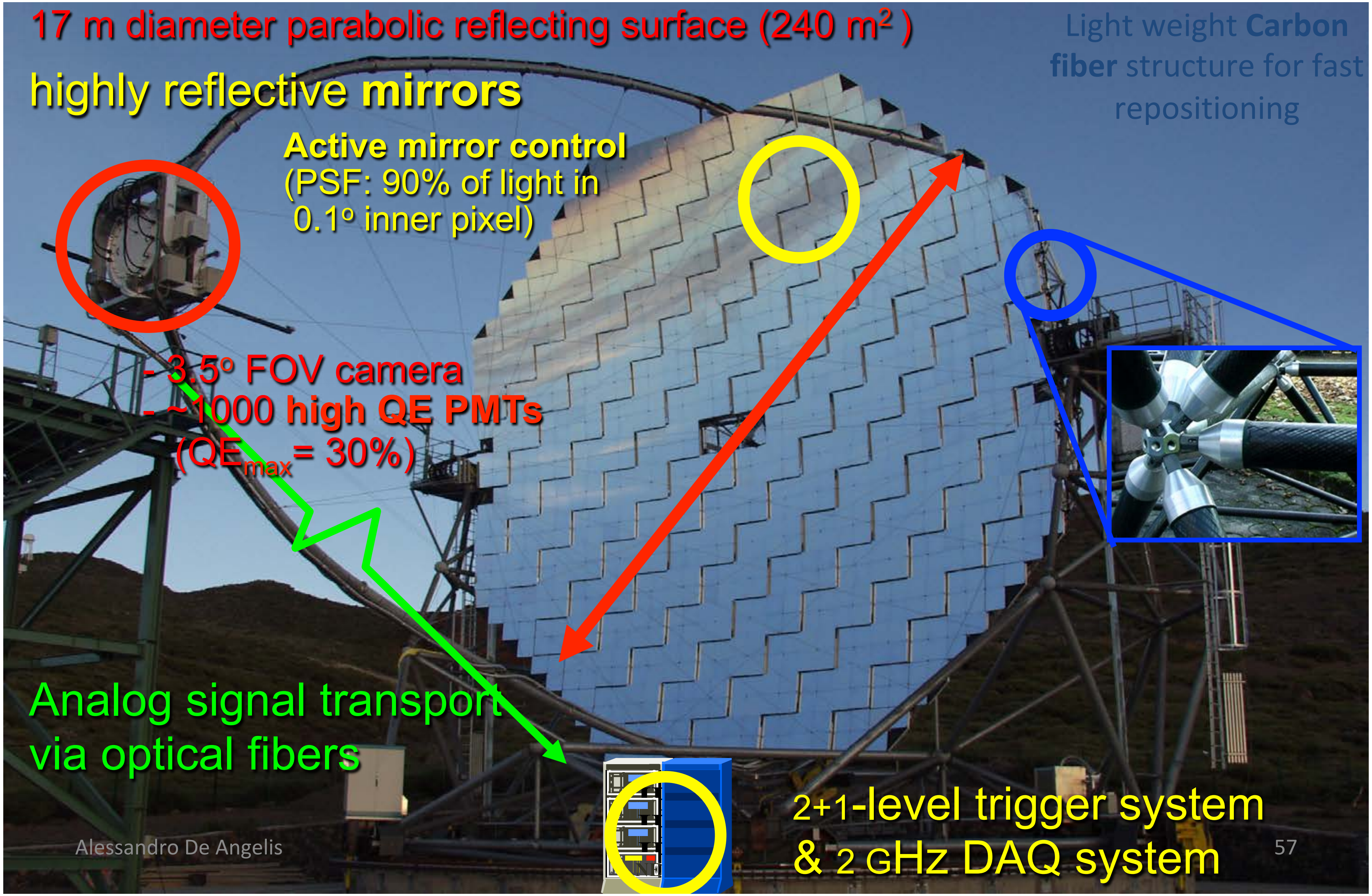
And you need a dark dark place…

Canary island of La Palma

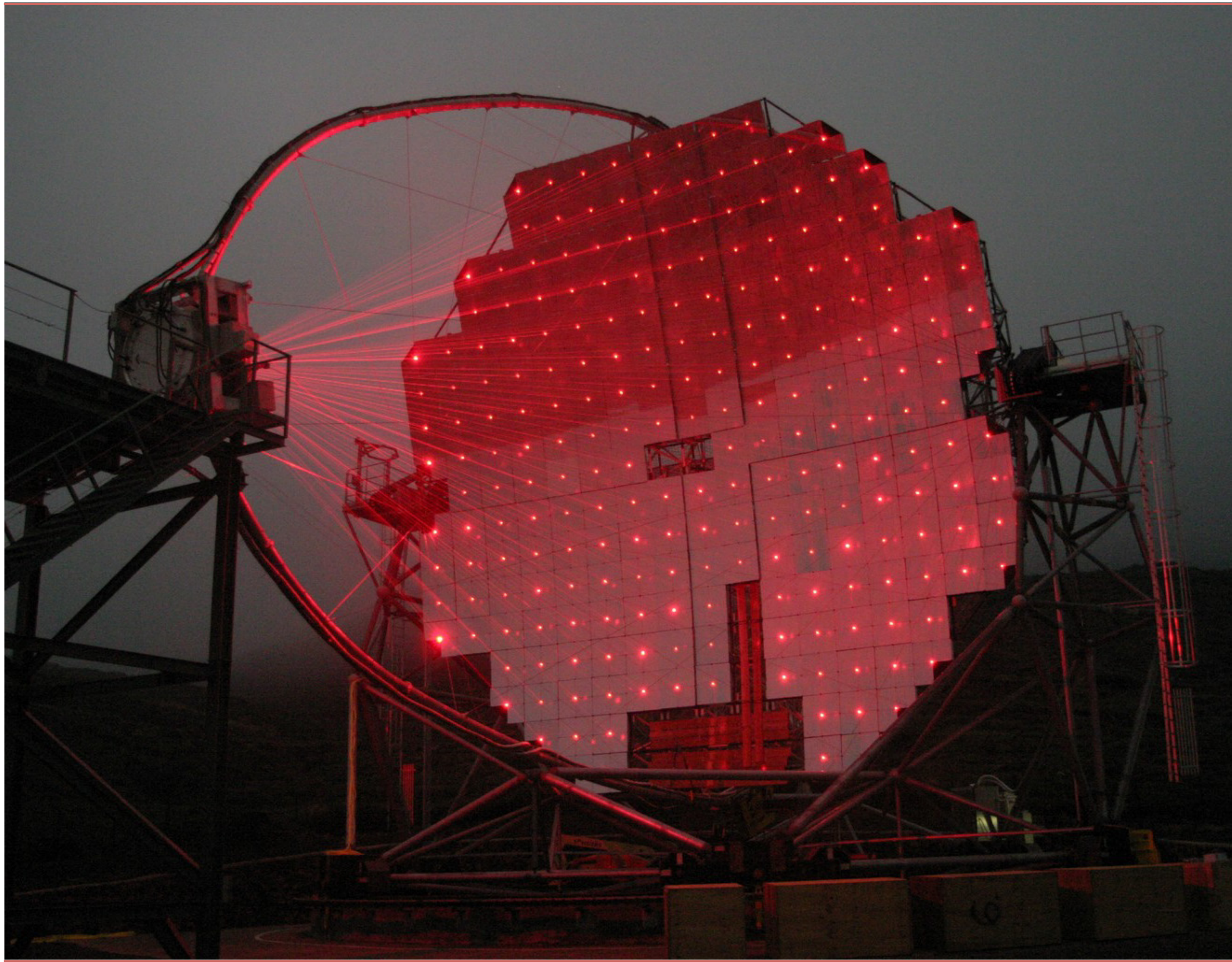
at 2400 m a.s.l.

The level of clouds is 1600 m => 650 m below

Key elements of a current detector



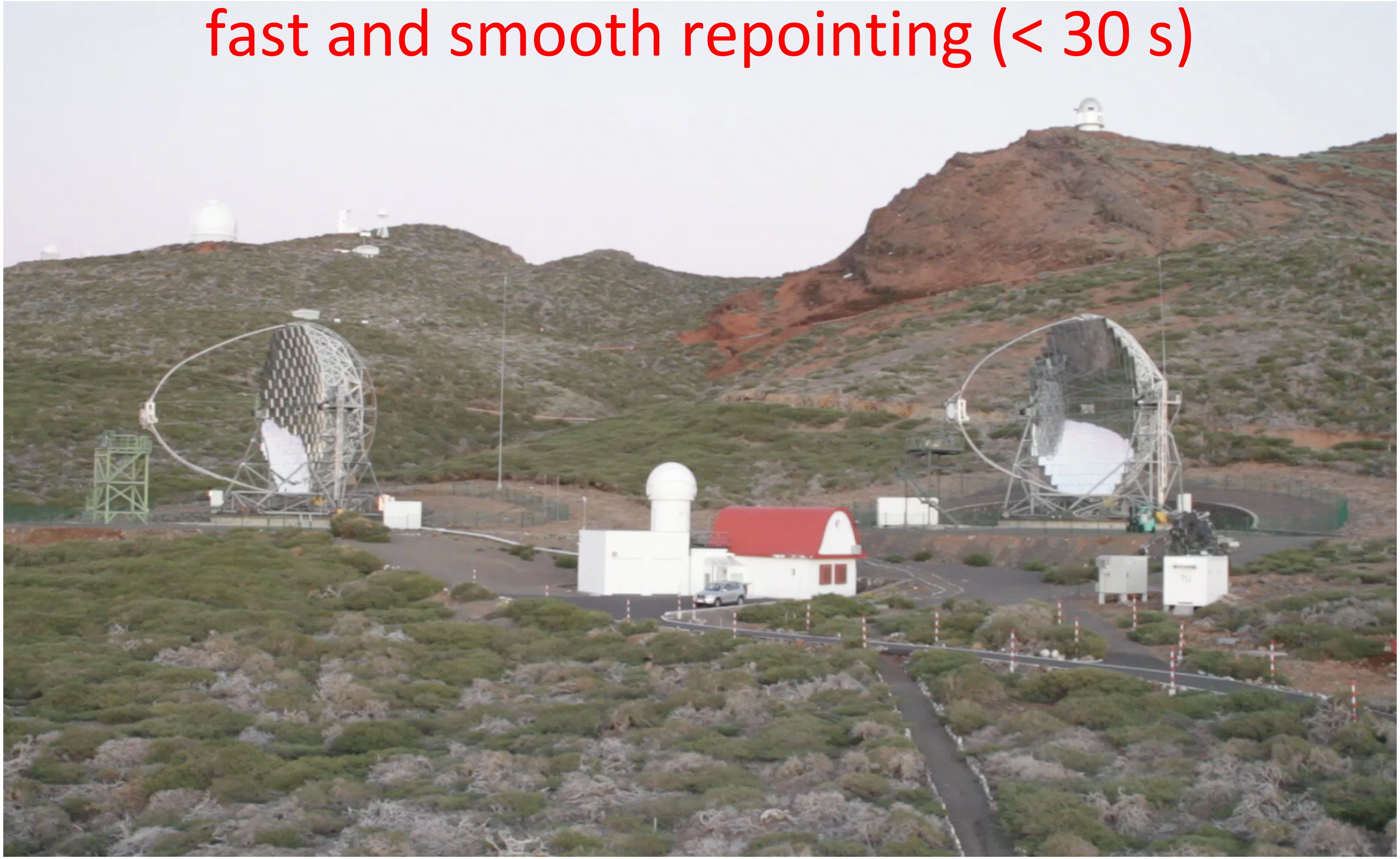
Adjustement (active control)



All AMC Lasers switched on during foggy night

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

Many sources are transient =>
fast and smooth repointing (< 30 s)



IACT data analysis:

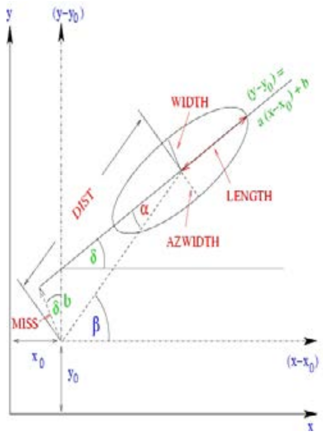
from shower images to photon flux and spectrum reconstruction

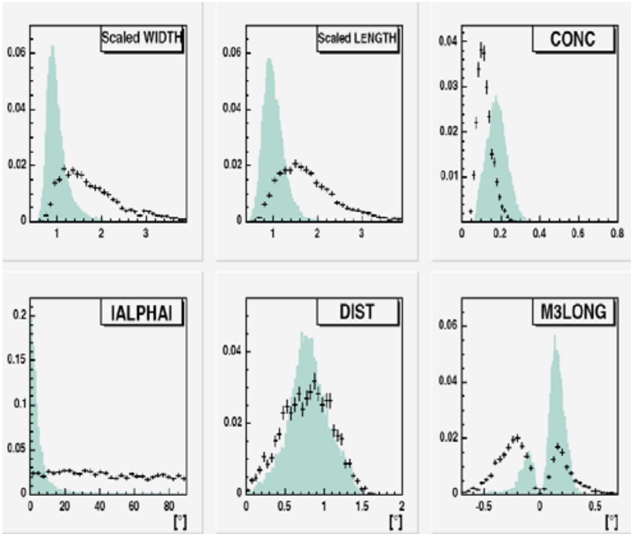
Data analysis steps:

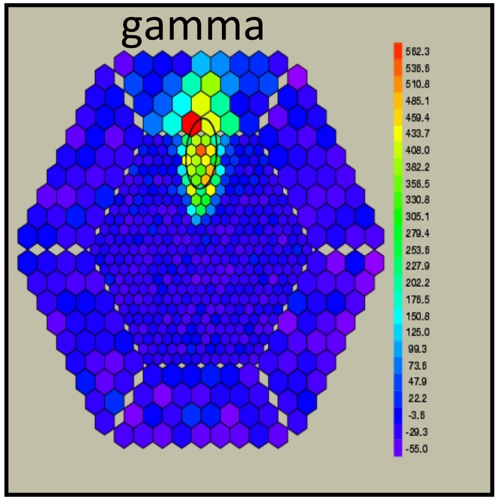
1. Signal extraction and image analysis
2. Gamma-hadron separation
3. Energy reconstruction
4. Photon (shower) direction
5. Photon flux measurement
6. Spectrum reconstruction

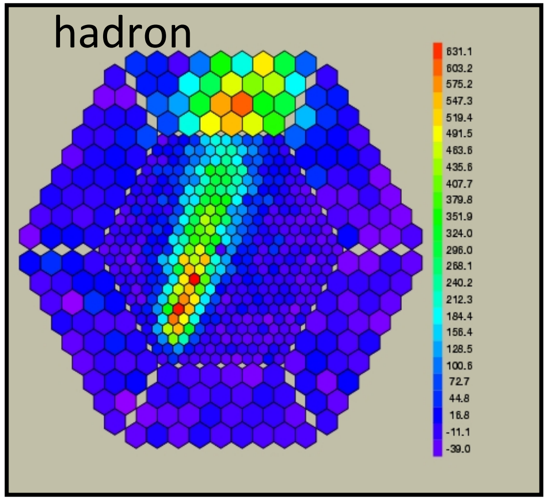
Image analysis

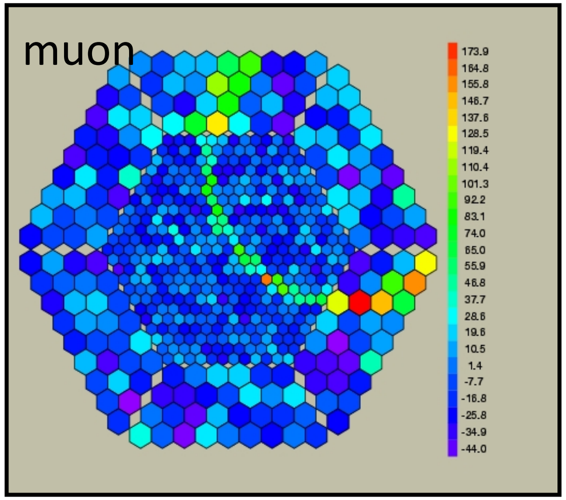
Hillas image parameters







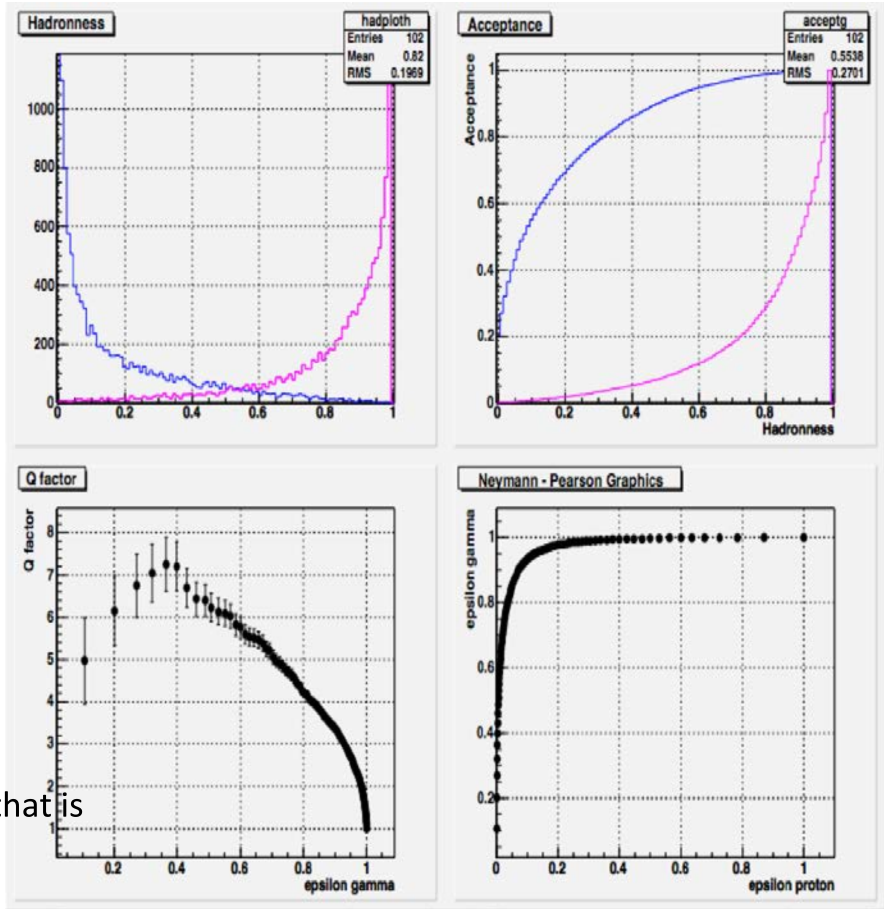




Gamma/Hadron separation

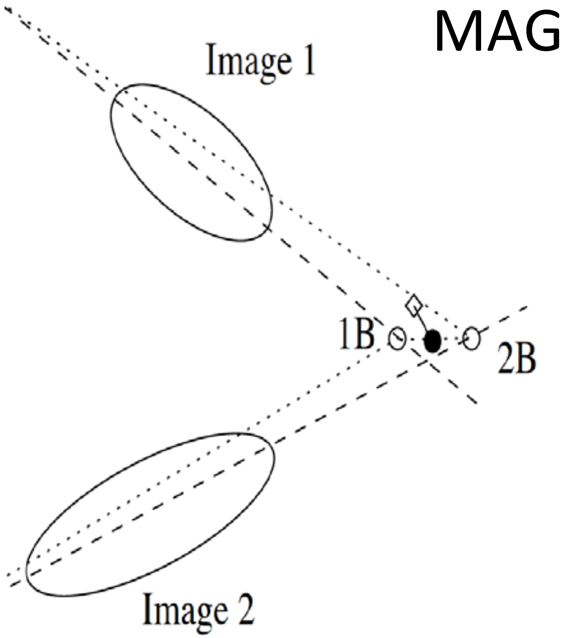
Random forest classification method

- Classification algorithm:
- No a priori parameterization
- Using "decision trees", constructed through training samples of known typology events
- It can combine multiple parameters taking into account any correlations between them
- Label each event with a "coefficient of adronnes"



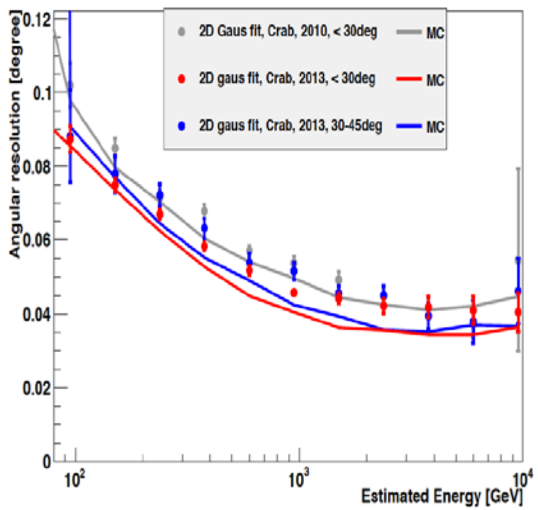
Every event is labeled with "hadronnes" Coefficient that is related with the probability do be background

Direction and angular resolution

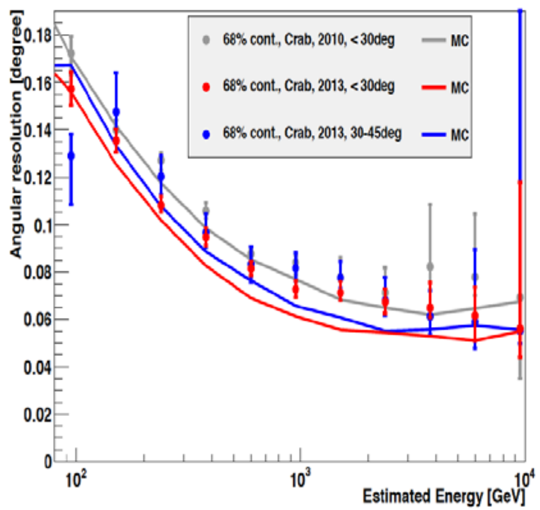


MAGIC performance as an example

stereo



mono

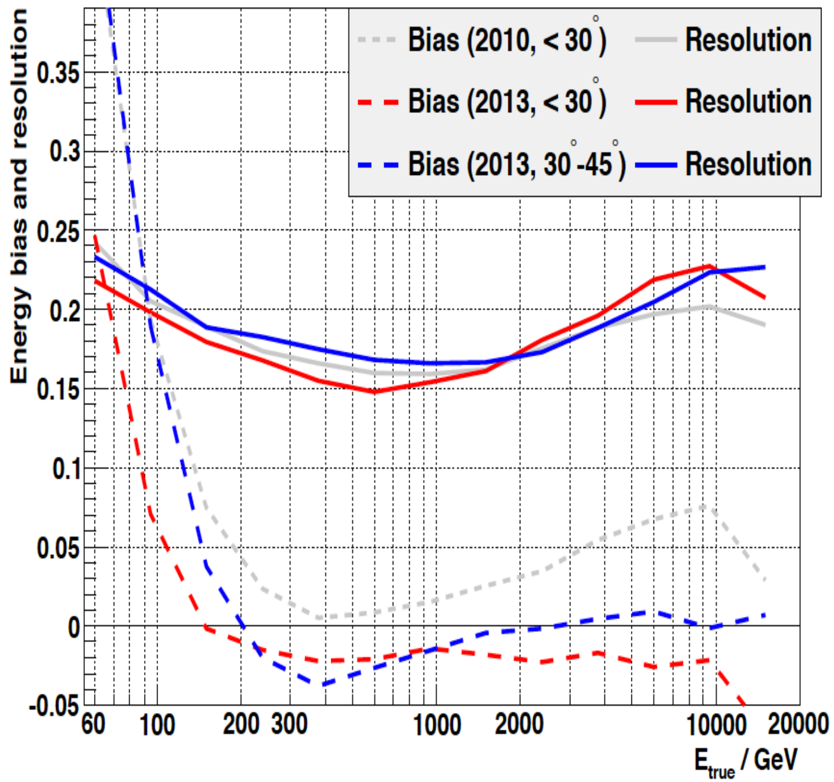


Energy resolution

Energy is very much related with the images intensity (we call it “size” of the event).
The primary energy estimation is calculated by comparing the collected light with the expected from simulation.

Many parameters like atmosphere transparency, mirror reflectivity, photosensor efficiency have to be taken into account

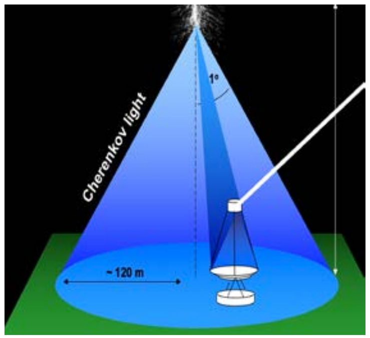
The calibration/simulation of the detector is a crucial element, and has to be updated frequently

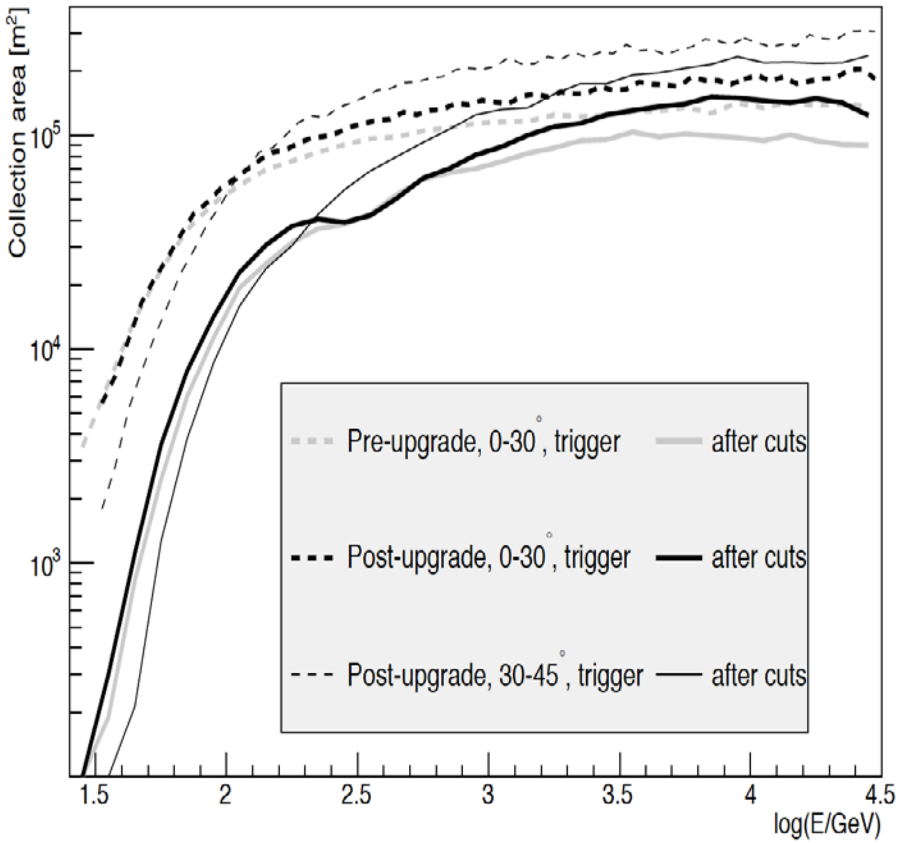


Effective area of a Cherenkov telescope

The effective area is the **integral of the observation surface weighted** with the **probability** that a **shower** with a given **energy** can **trigger**, trigger and pass some given analysis cuts.

Note that effective area exceeds by far the telescope surface!!





Sensitivity

Integral MAGIC sensitivity

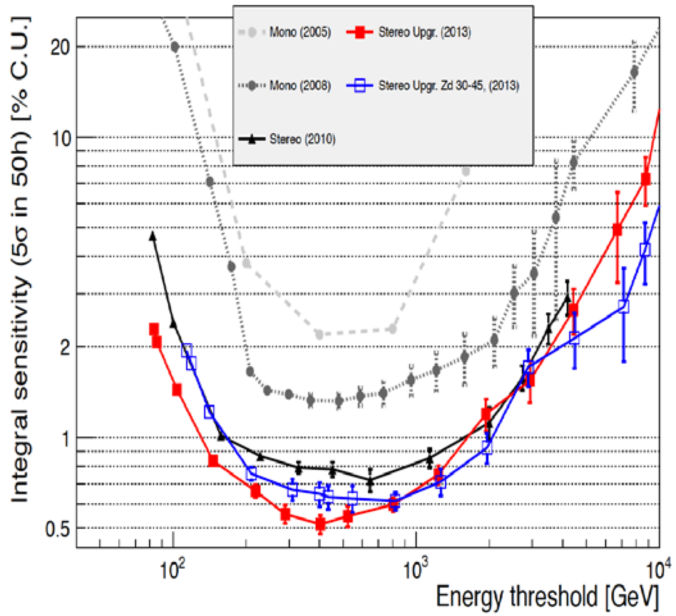


Figure 17: Evolution of integral sensitivity of the MAGIC telescopes, i.e. the integrated flux of a source above a given energy for which $N_{excess}/\sqrt{N_{bkg}} = 5$

Differential MAGIC sensitivity

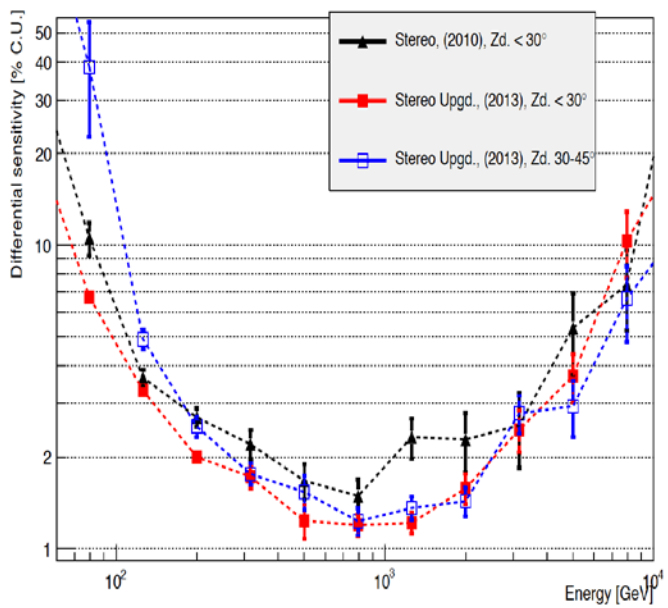


Figure 18: Differential (5 bins per decade in energy) sensitivity of the MAGIC Stereo system. We compute the flux of the source in a given energy range for which $N_{excess}/\sqrt{N_{bkg}} = 5$ with $N_{excess} > 10$, $N_{excess} > 0.05 N_{bkg}$ after 50 h of effective time. For better visibility the data points are joined with broken dotted lines.

Evolution of sensitivity

Crab discovery Wipple	5 sigma Crab in 2h
HEGRA	5 sigma Crab in 6 min
MAGIC, HESS, Veritas	5 sigma Crab <20 s

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)

Main scientific discoveries

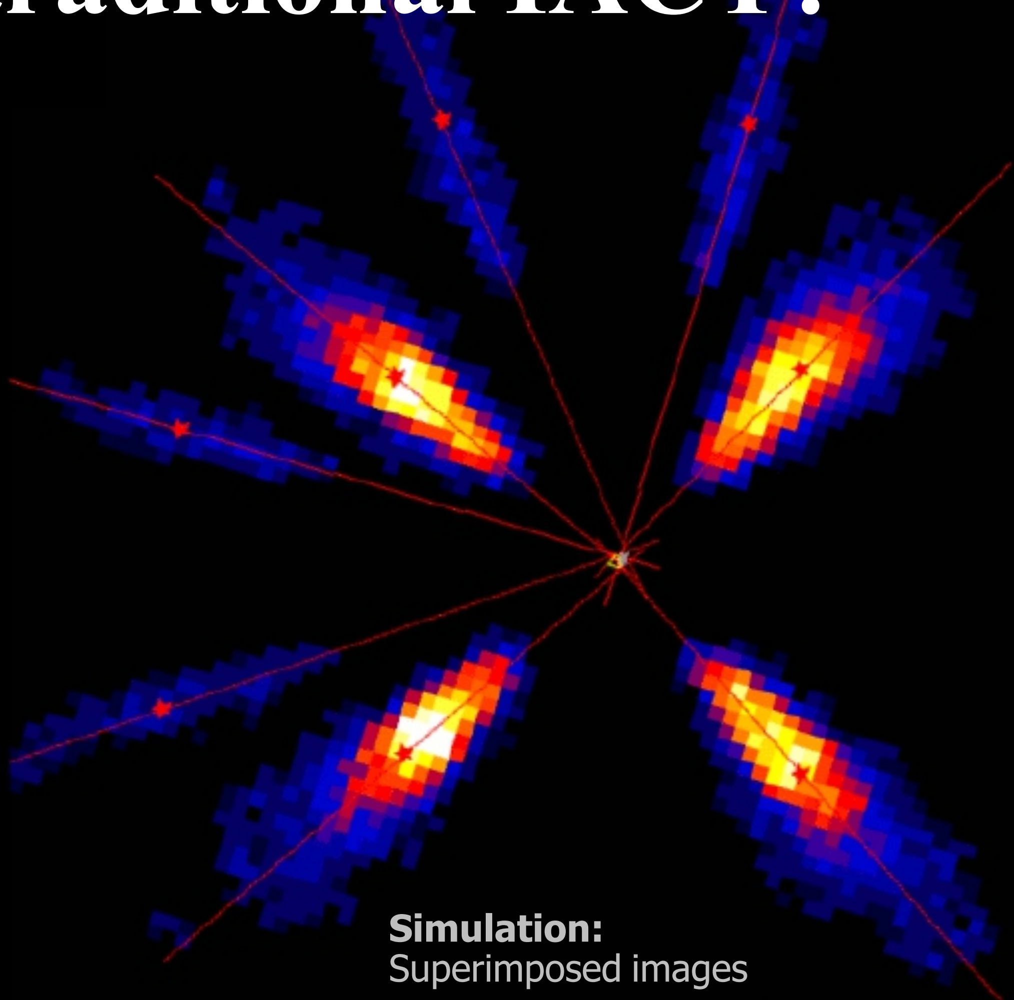
- A handful of Galactic hadronic accelerators at energies < 1 PeV
- Probably, 2 Galactic PeVatrons (one in the Galactic center region, the other is Crab)
- 1 extragalactic accelerator above the knee
- Acceleration near a Kerr black hole
- “Measurement” of the intergalactic magnetic field (1nb-1fb)
- Measurement of density and spectrum of the background intergalactic photons in the visible

- Plus many astronomical discoveries on source population etc.
  – Many new sources and source types

The FUTURE
The TeV gamma region: CTA

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

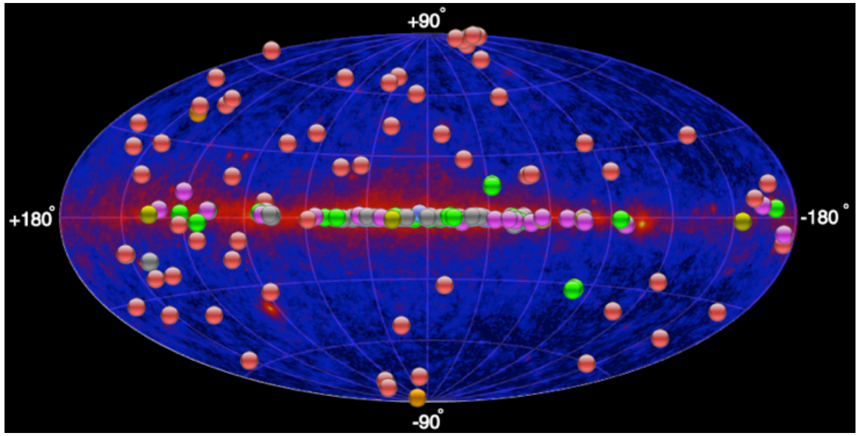
- More events
  - More photons = better spectra, images, fainter sources
    - Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary gammas
    - Improved angular resolution
    - Improved background rejection power

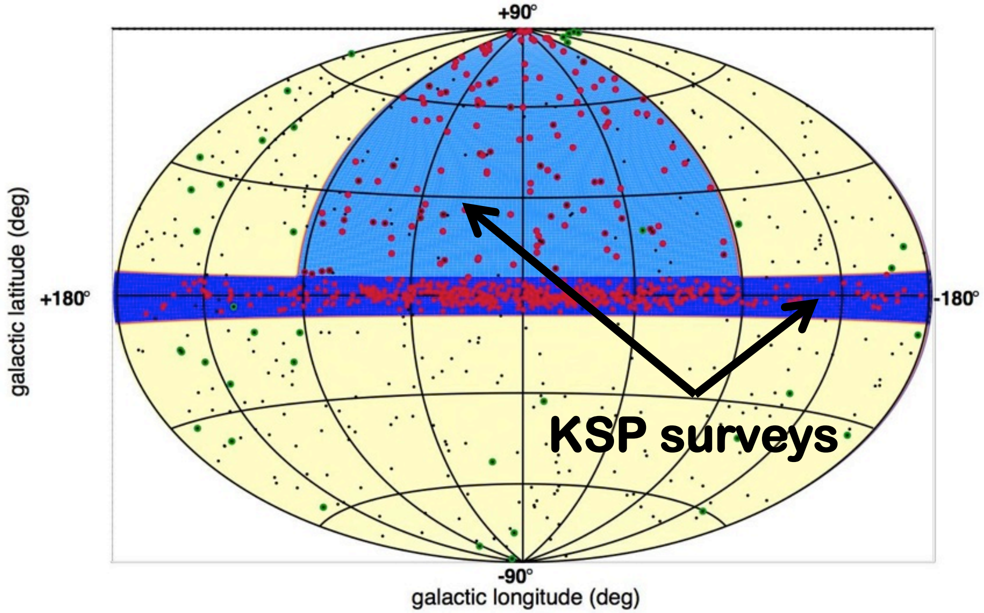


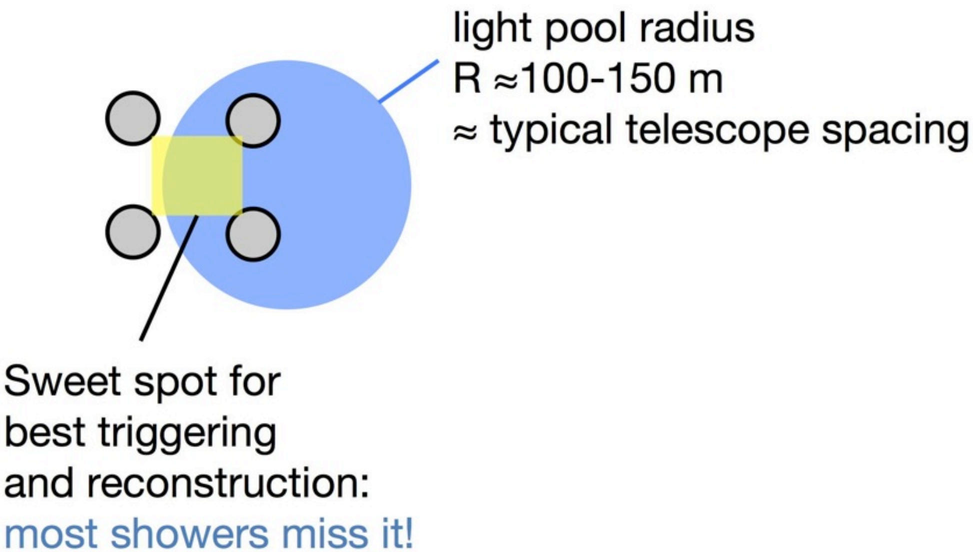
Simulation:
Superimposed images from 8 cameras

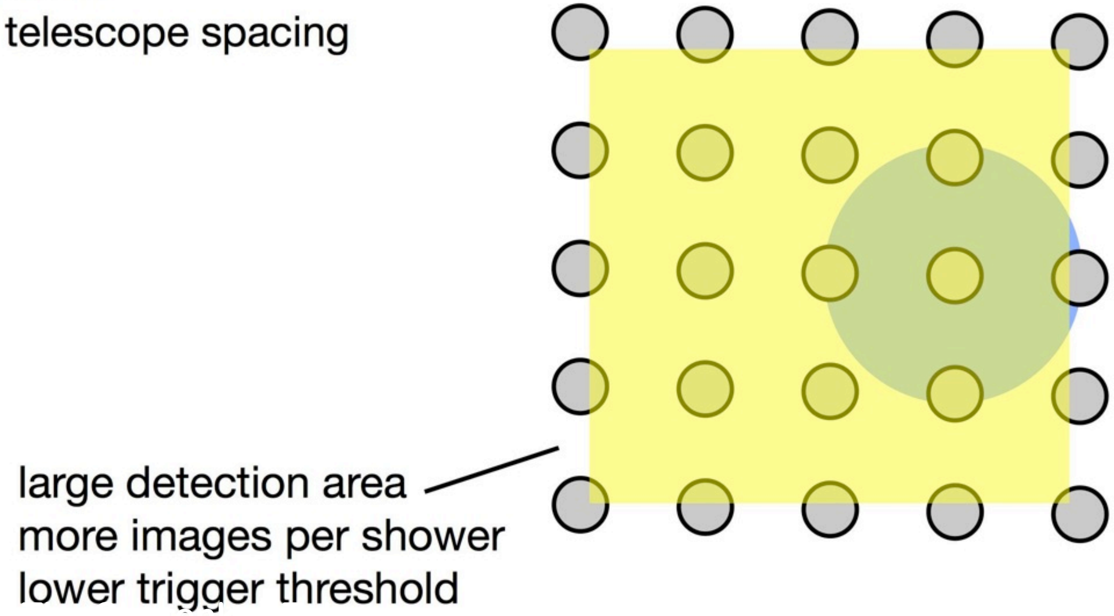
☛ The CTA solution: More telescopes !

From current arrays to CTA

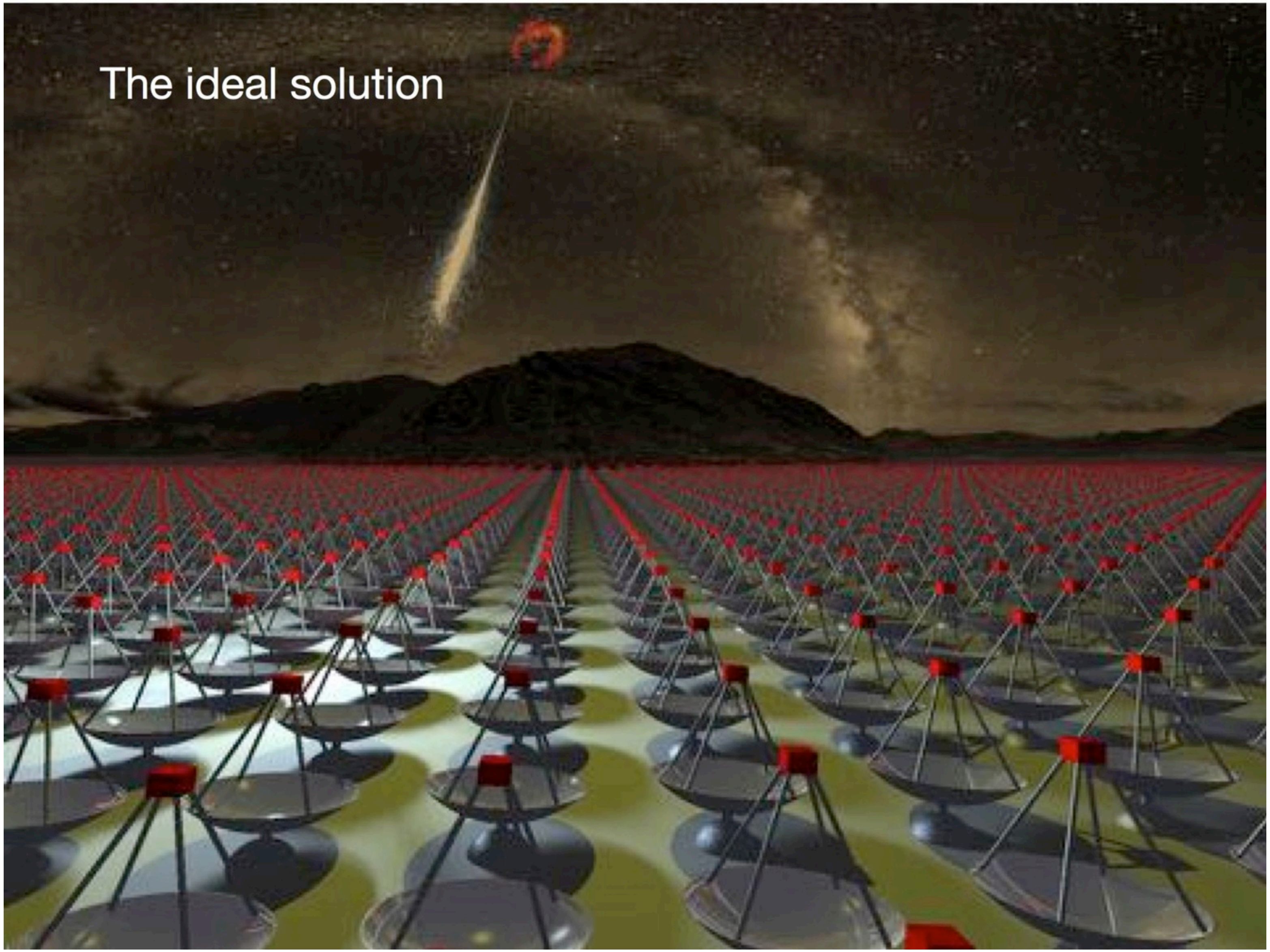






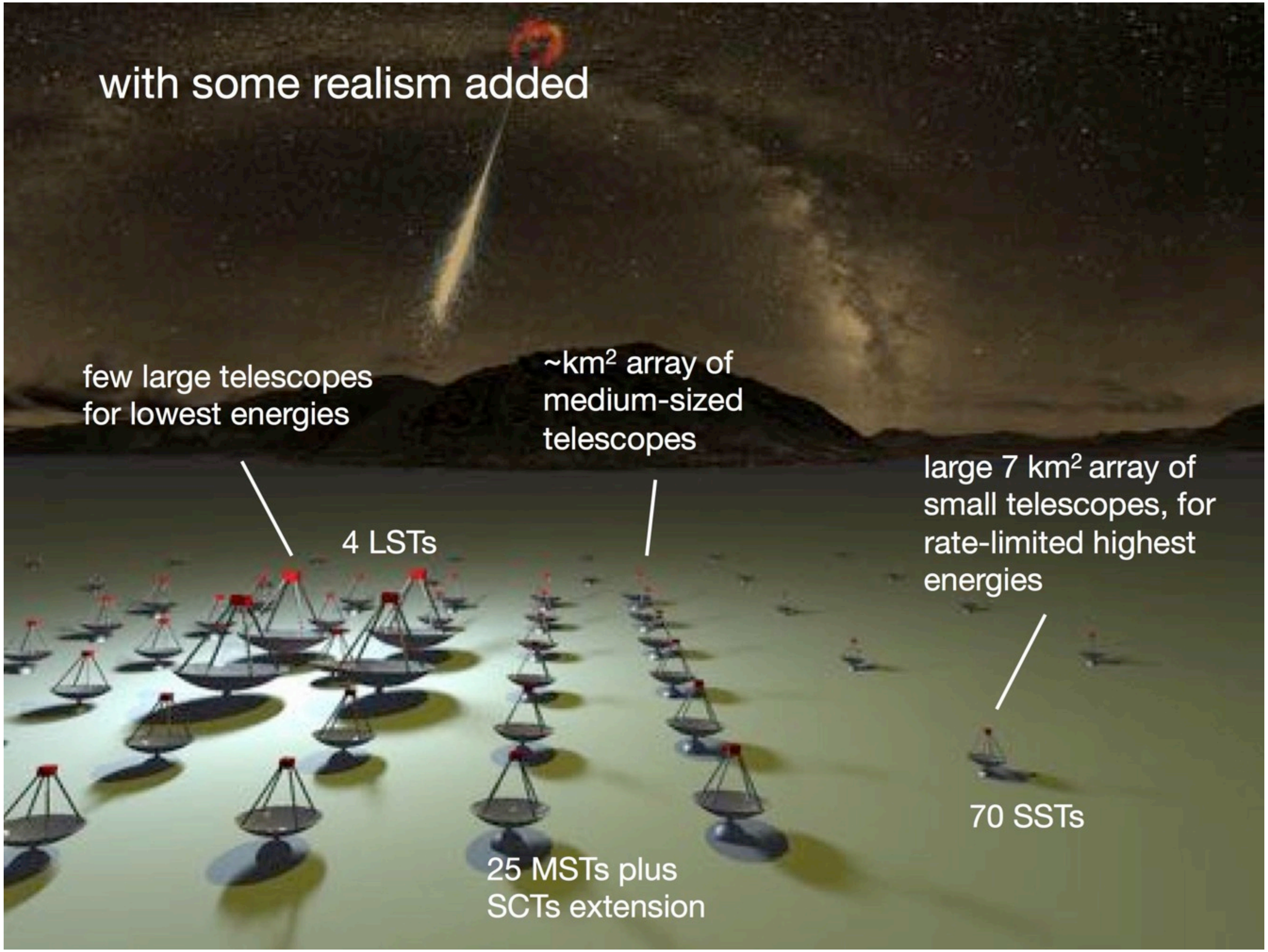


A next generation VHE facility



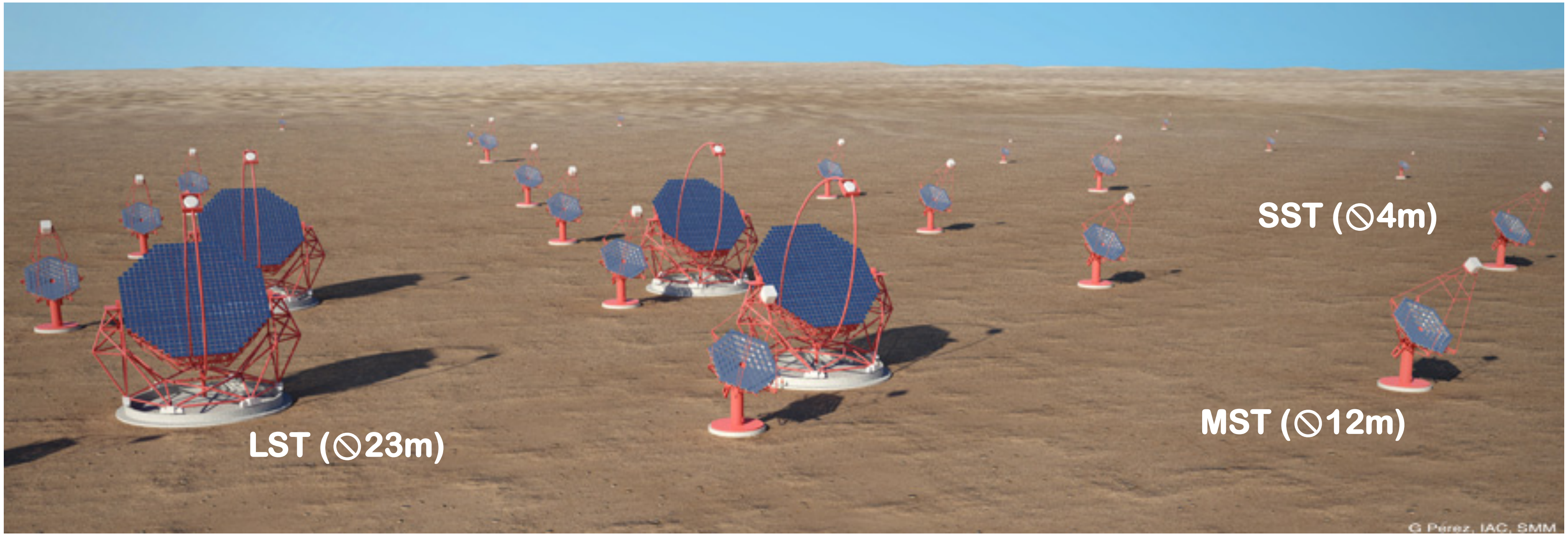
W. Hofmann

A next generation VHE facility

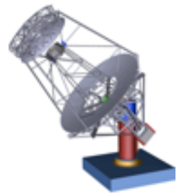


W. Hofmann

The CTA Observatory

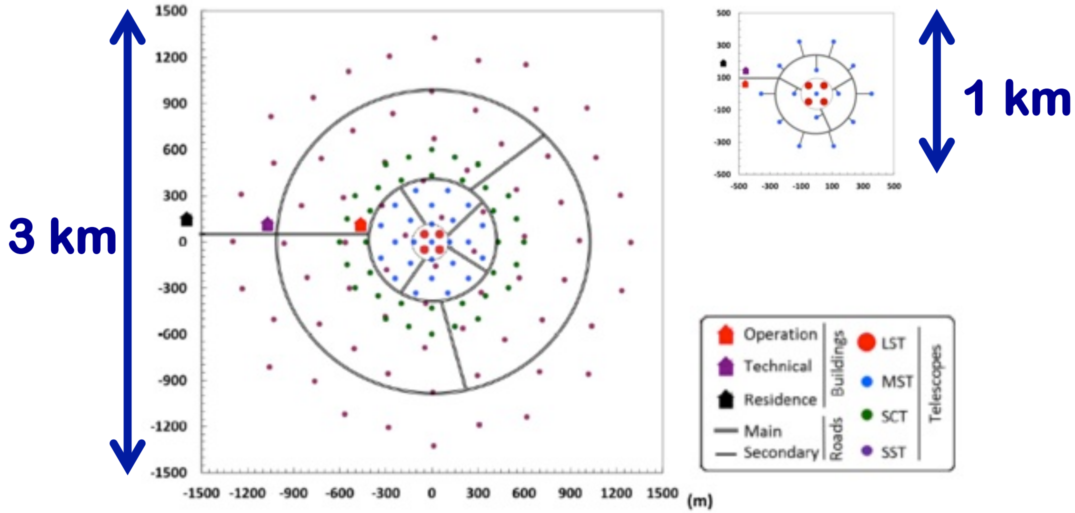


SCT (⌀10m)



South

North

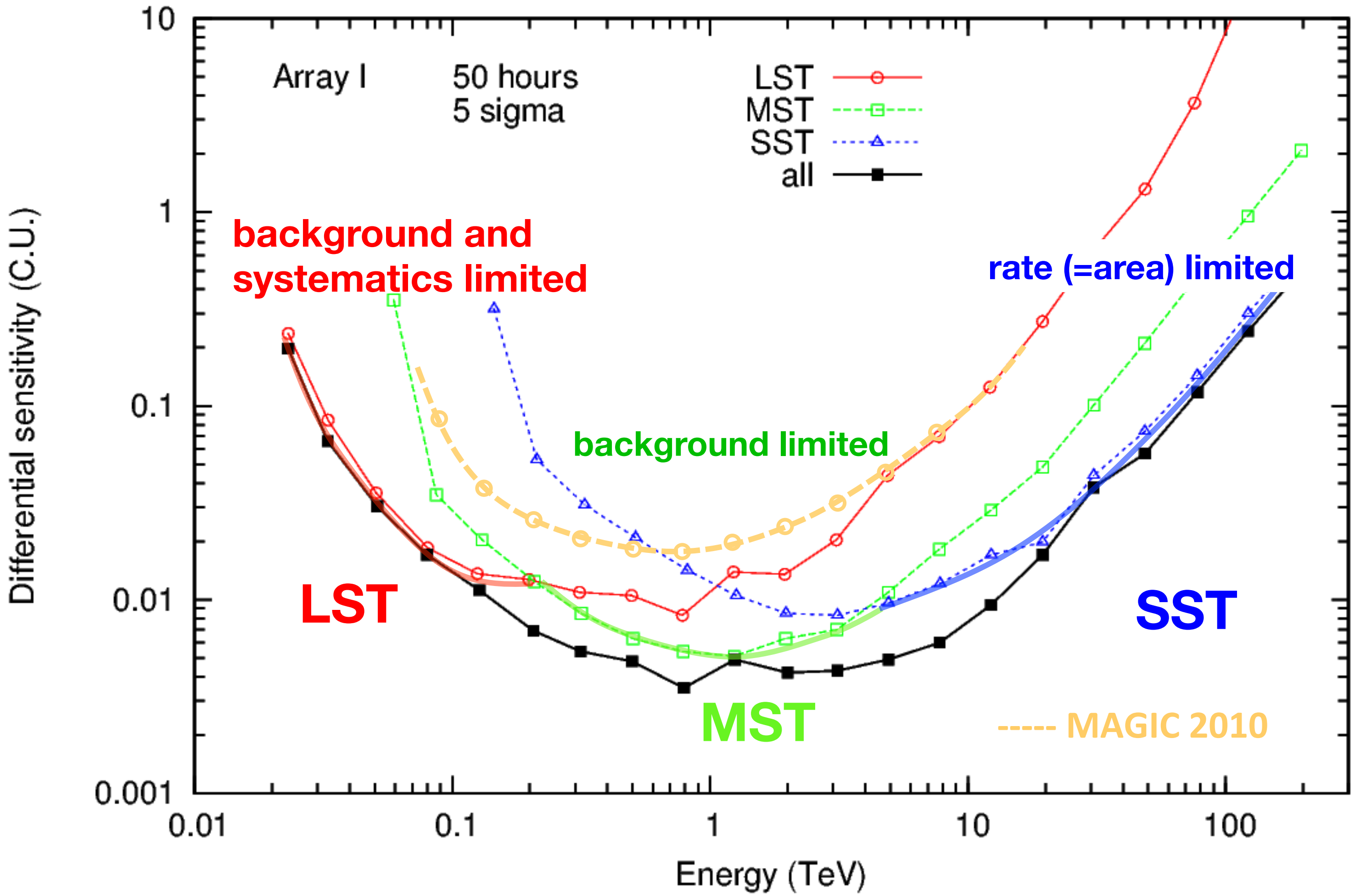


Characteristics

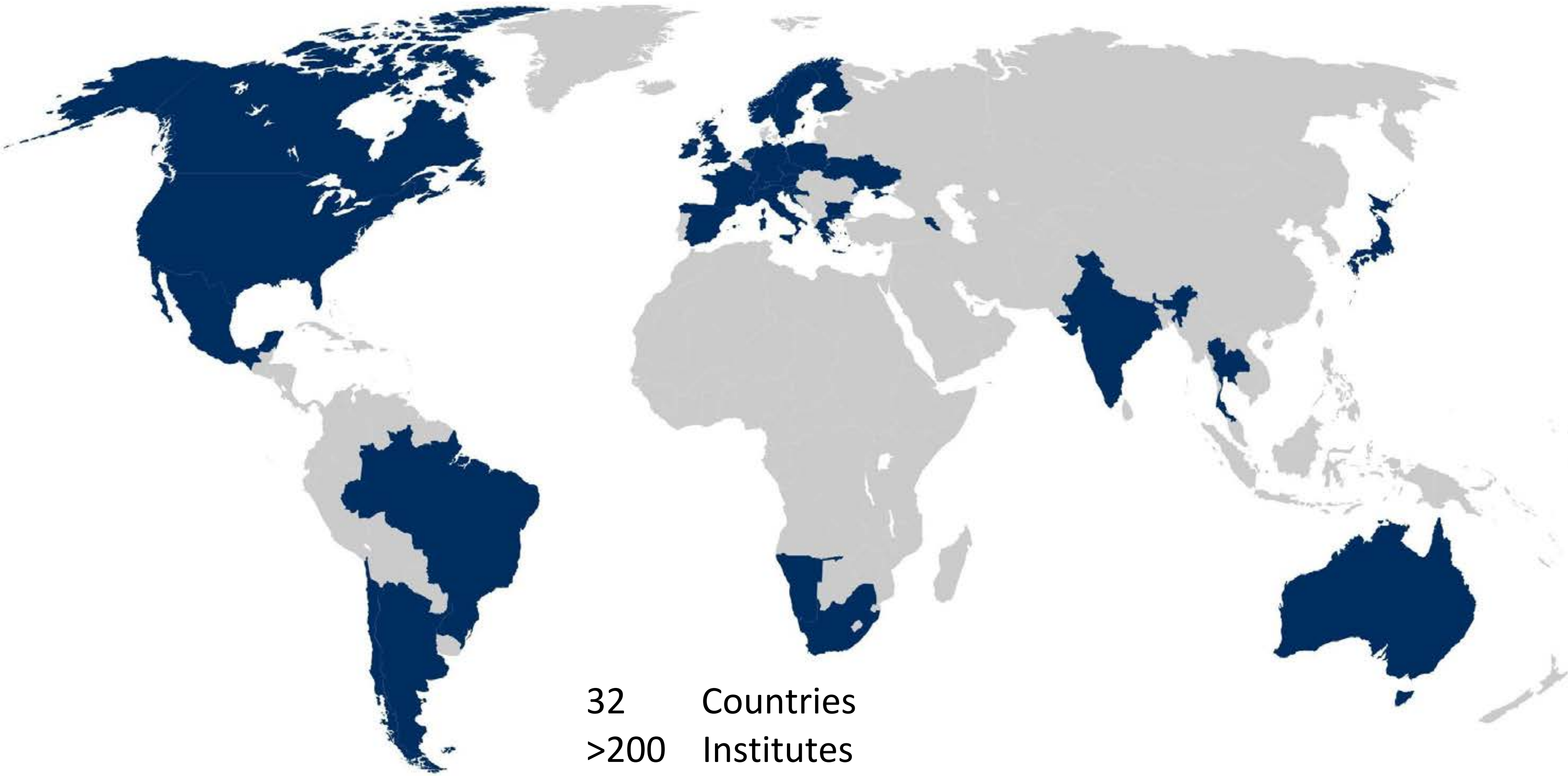
2 sites (north & south)
3 telescope size classes
About 120 telescopes in total
South U.S. extension with about 25 SCT telescopes

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

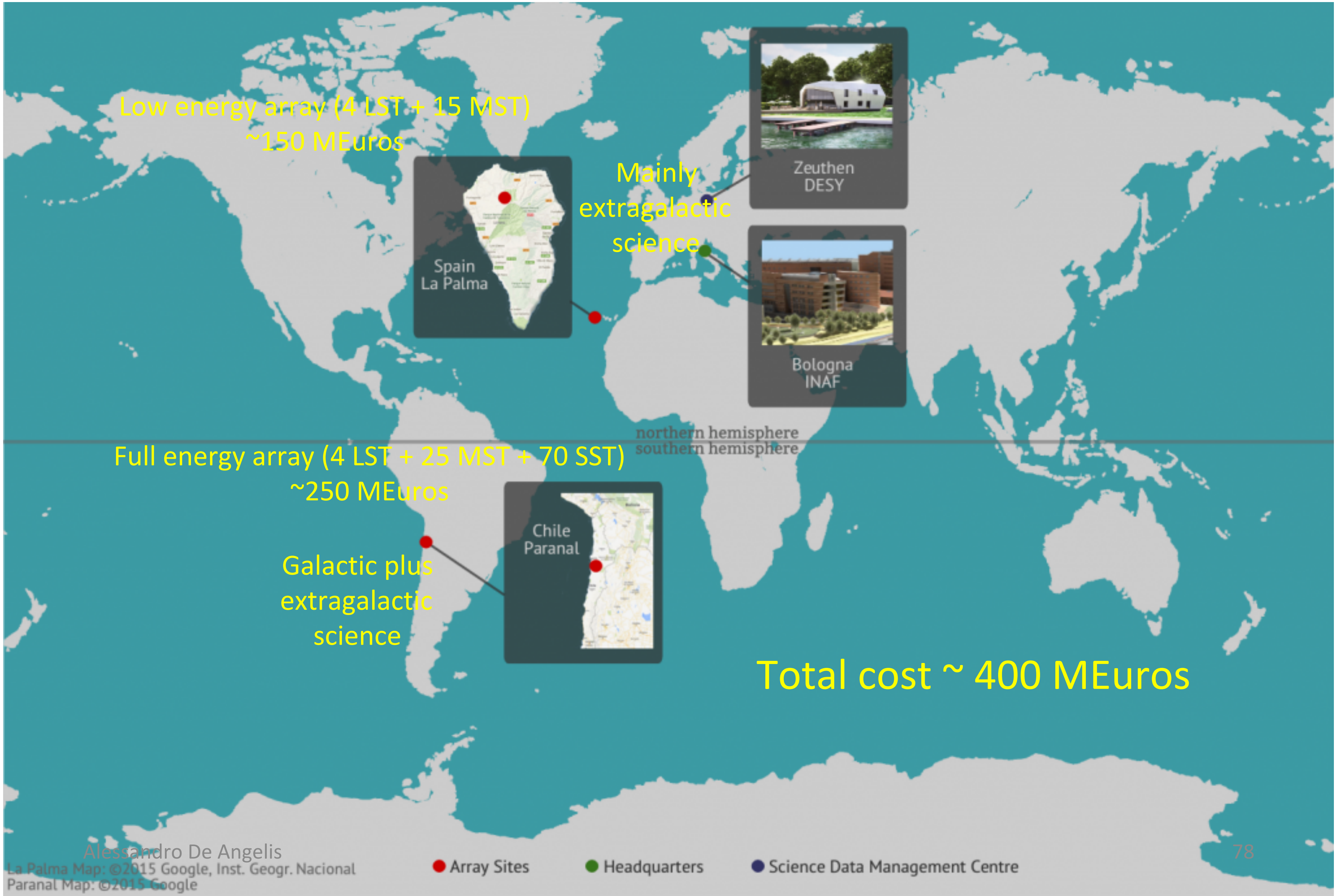


CTA consortium: a world-wide effort

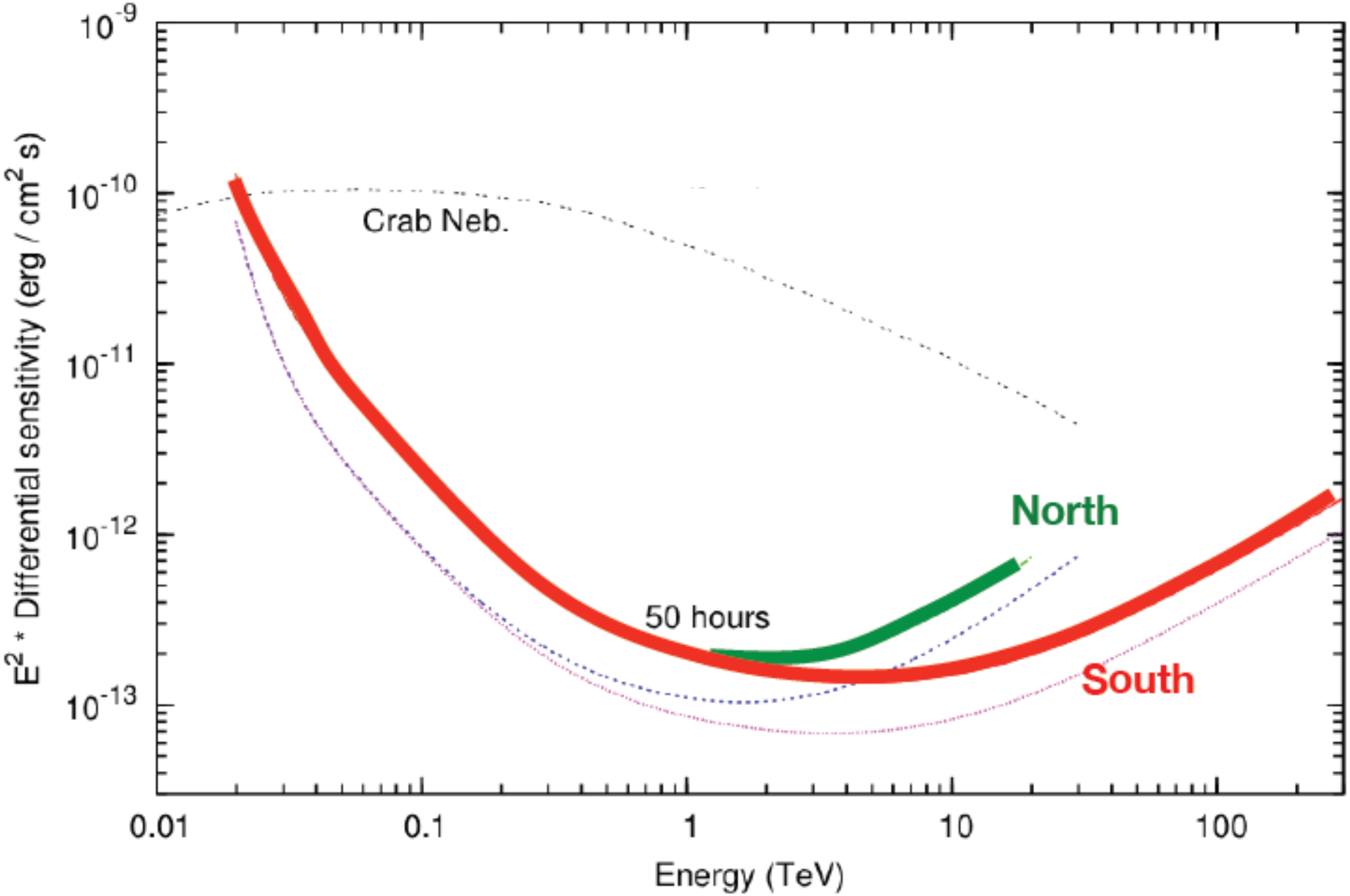


32 Countries
>200 Institutes
>1500 Members

All-sky coverage: two observatories

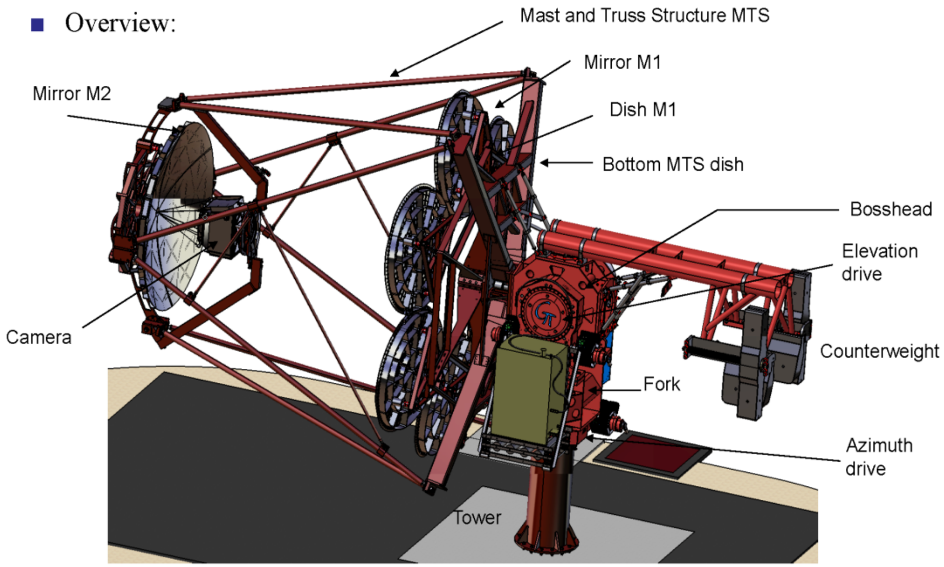


Sensitivity for North and South

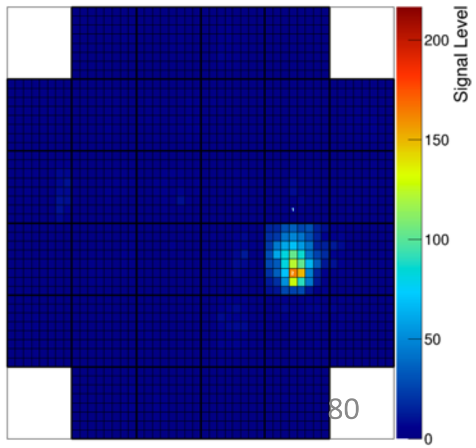


Small Telescope 2-mirror (SST-2M)

SST-2M –ASTRI MECHANICAL PROTOTYPE
INAUGURATION, 24 SEPT 2014
(SERRA LA NAVE, SICILY)



SST-2M-GCT (GATE TELESCOPE)
INAUGURATED IN JUNE 2016
SAW ALREADY 1ST LIGHT



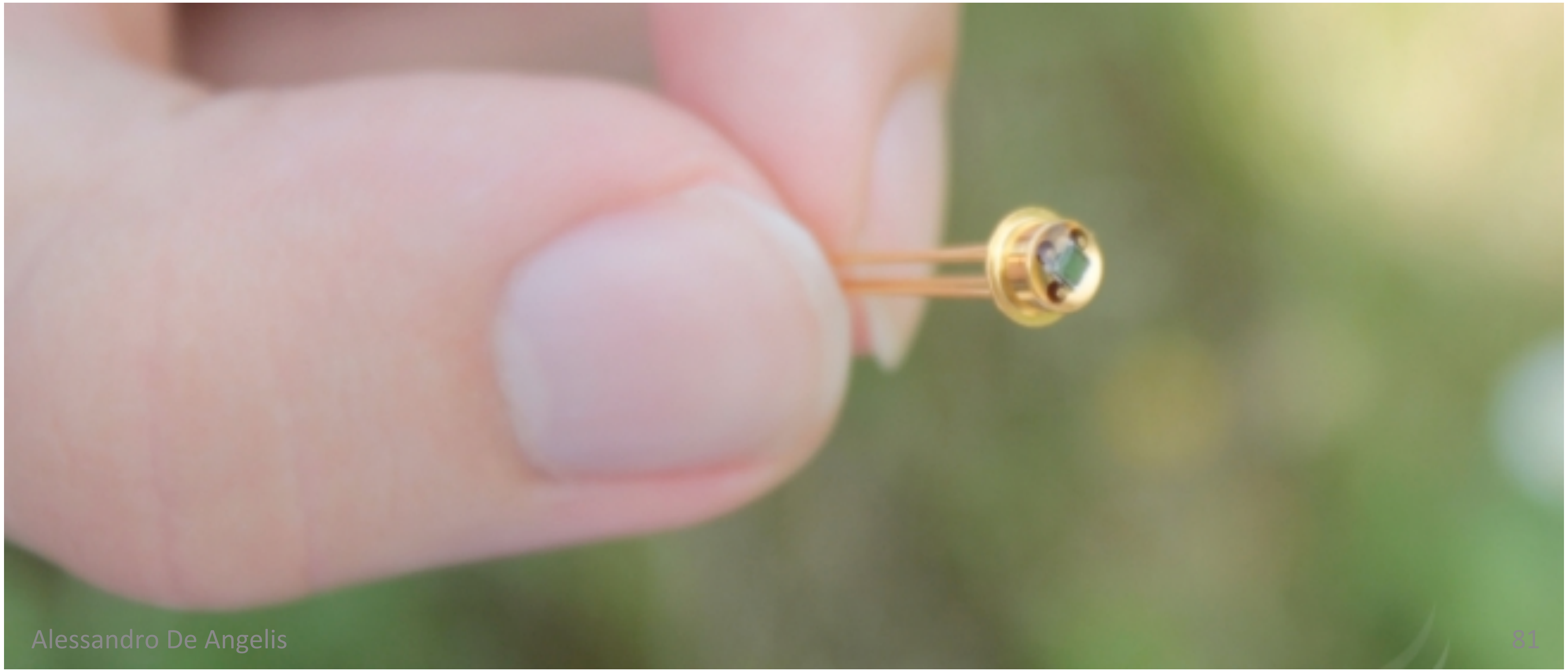
BOTH 2-MIRROR SST DESIGNS: COMPACT CAMERAS

LARGE FoV (~10 DEG) IN COMPACT SPACE (40 cm) =>
NEED FOR ~5 mm PHOTOSENSOR

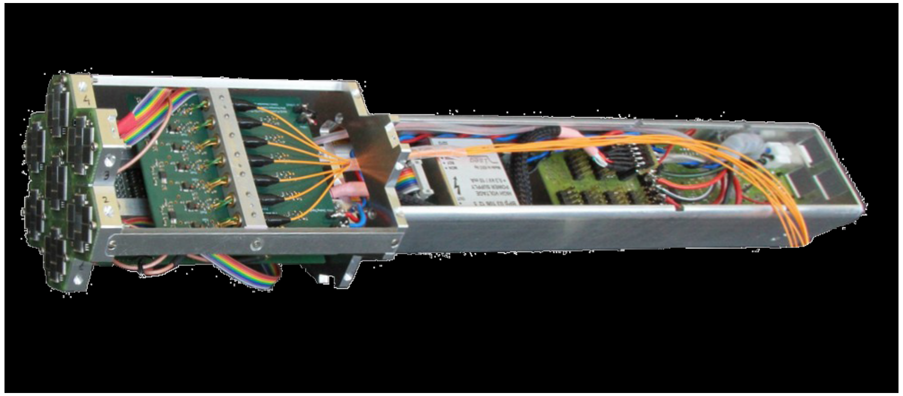
SiPM: the technological challenge for small cameras

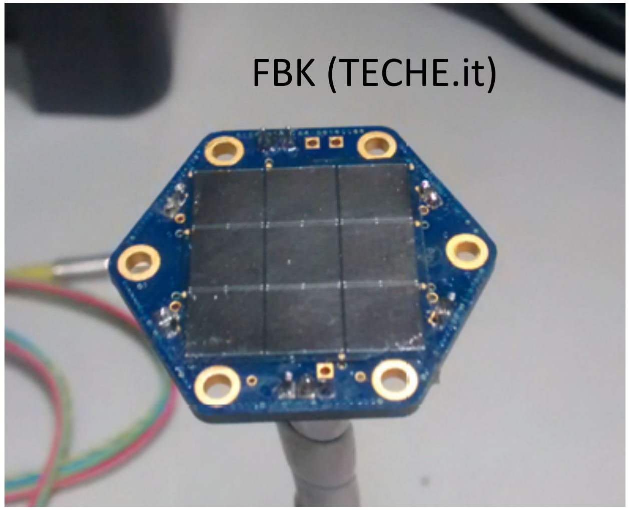
Cameras need high granularity, and typical PMT size of 5-6 mm

Difficult to do with standard PMT

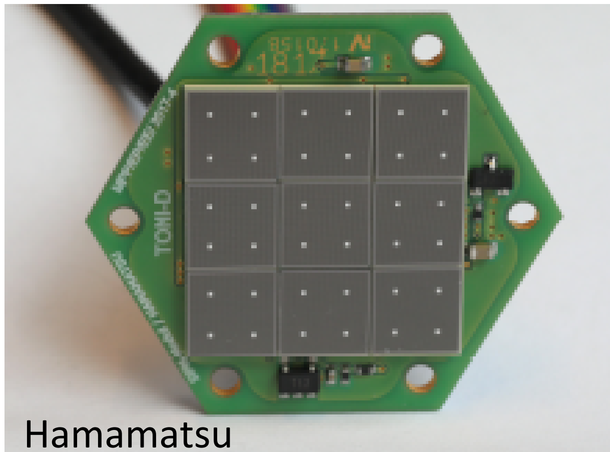


But also working on advanced photosensors for LSTs: SiPM clusters with 1” prototypes from various manufacturers (Excelitas, FBK, Hamamatsu, SensL) under test in the MAGIC-I camera (MPI, INFN)





FBK (TECHE.it)



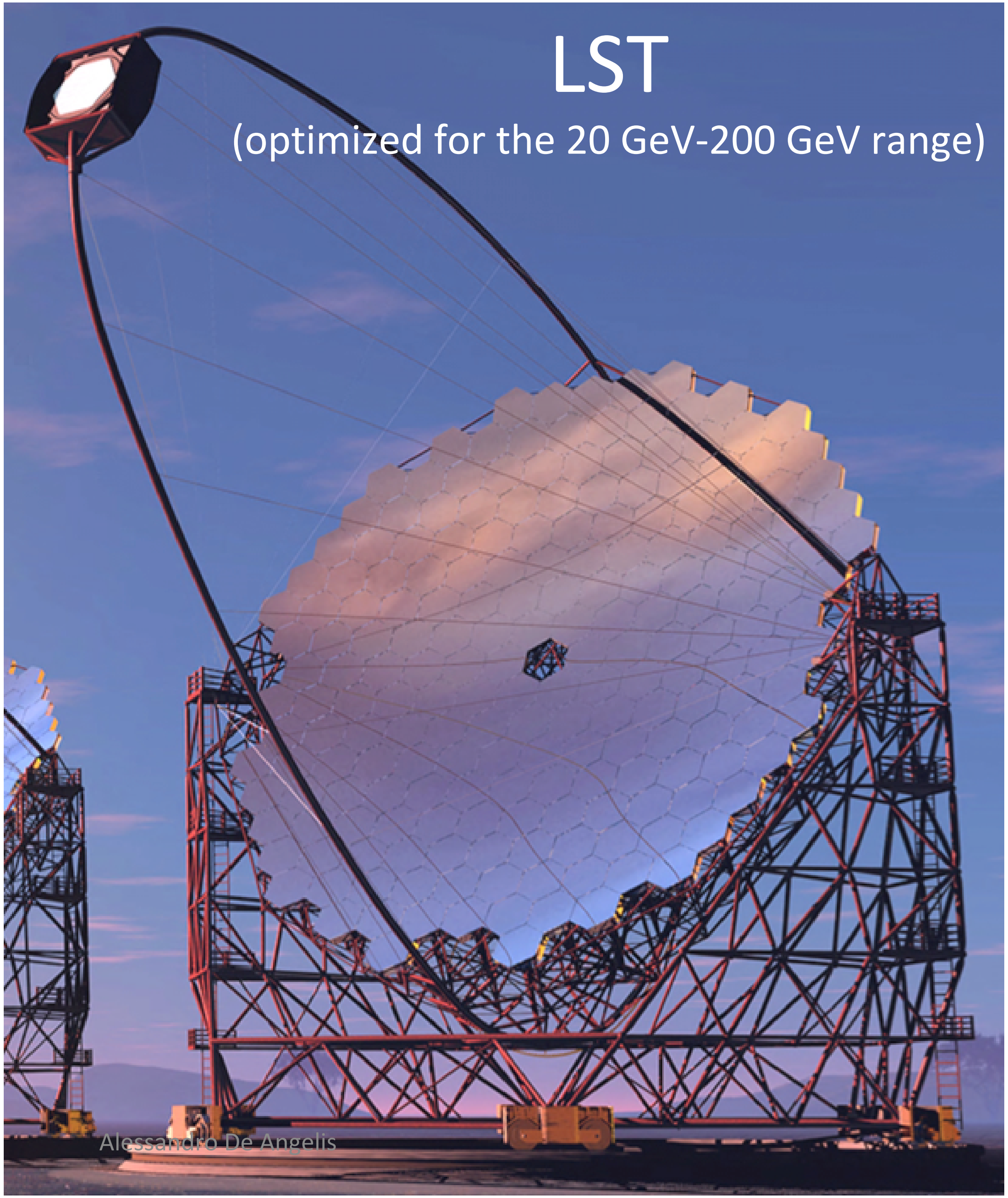
Hamamatsu

CTA-N: rendering

LST1 to be commissioned in 2018 (inauguration October 10, 2018)
LST2-4 commissioned in 2020?
First 5 MST commissioned in 2022?

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

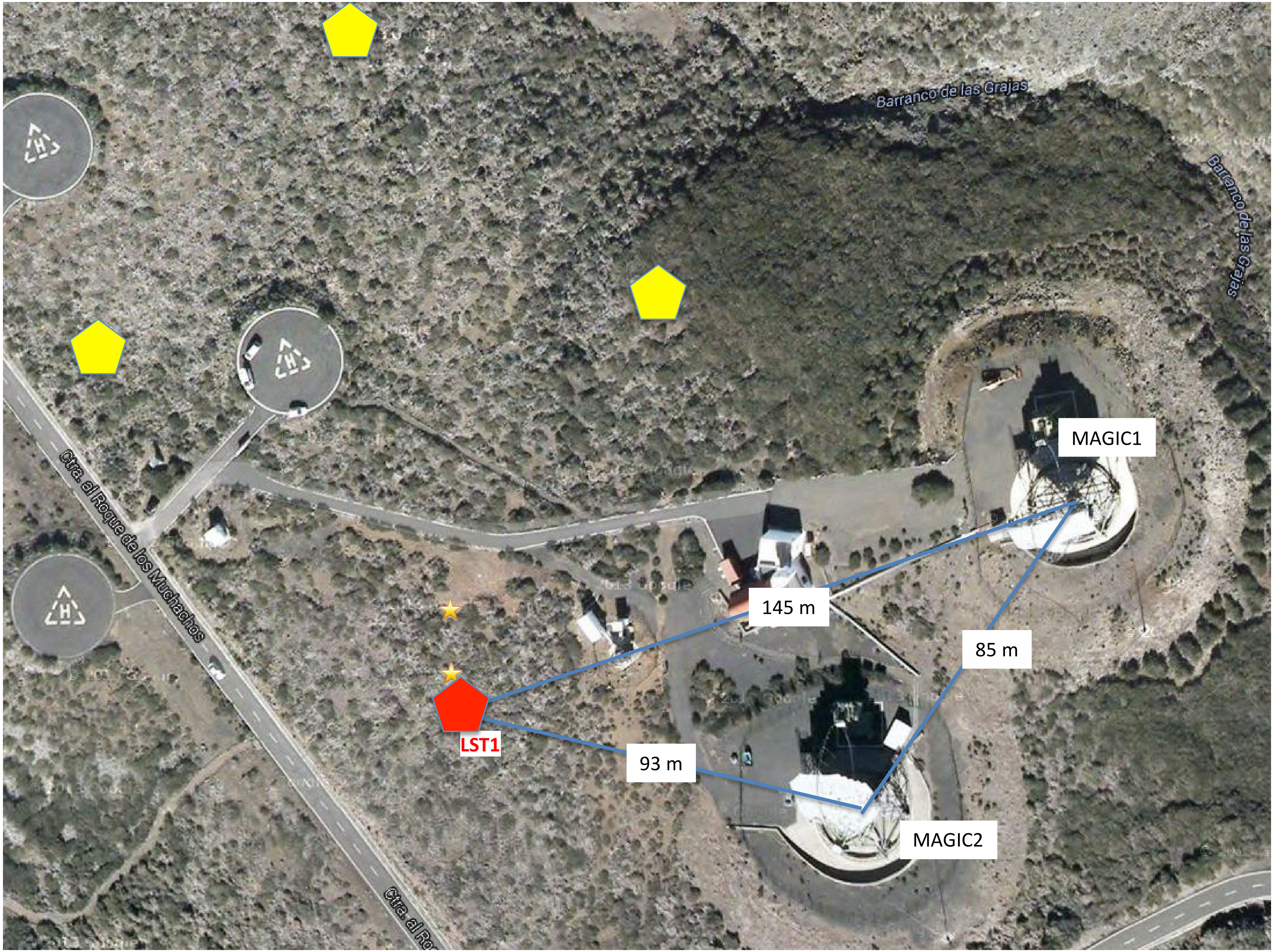
- 0.1° pixels, camera diam. 2m
- Light structure for 20 s positioning
- AMC

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

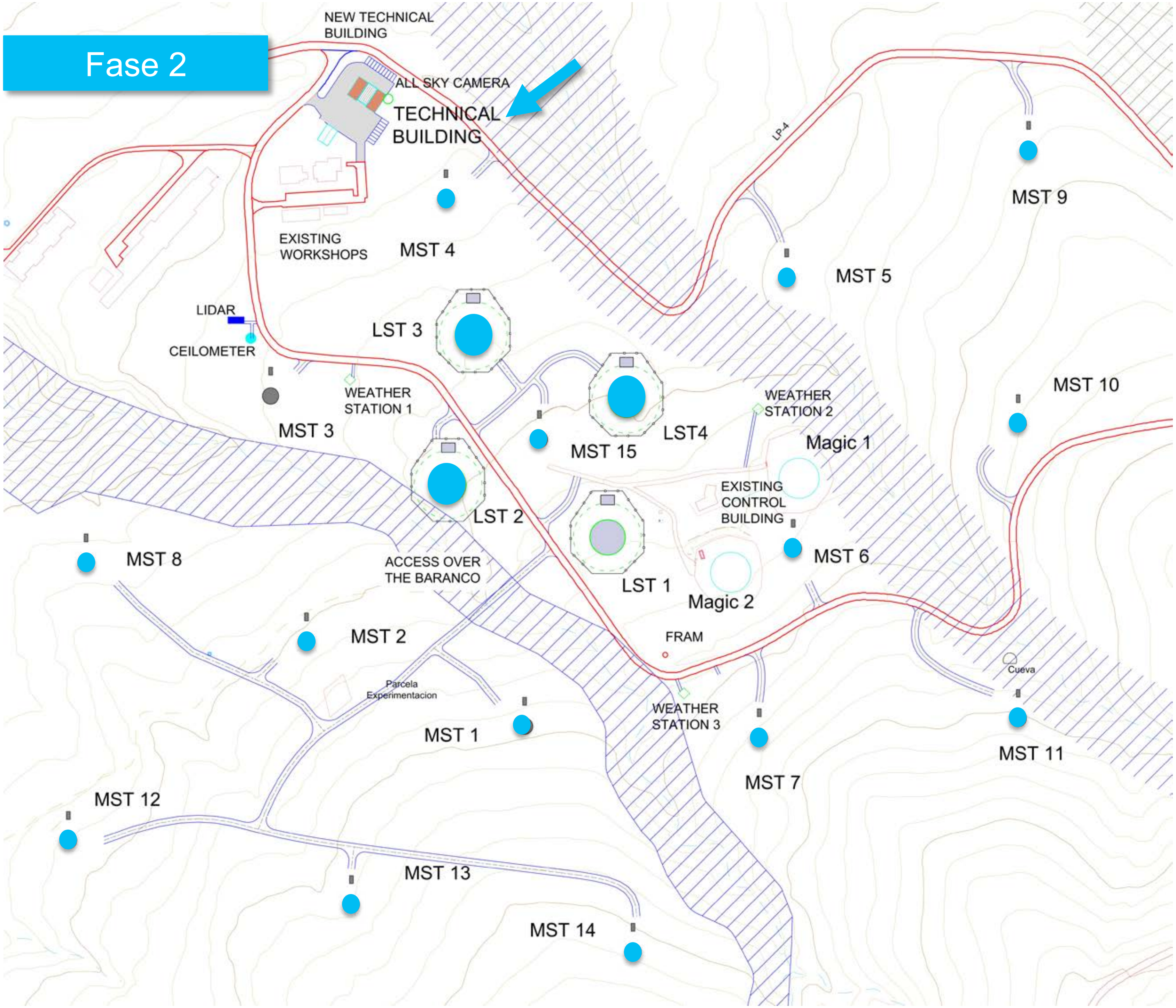
- Prototype = 1st telescope at La Palma.
- Foundations finished end 2016
- Inauguration fixed Oct 10, 2018

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

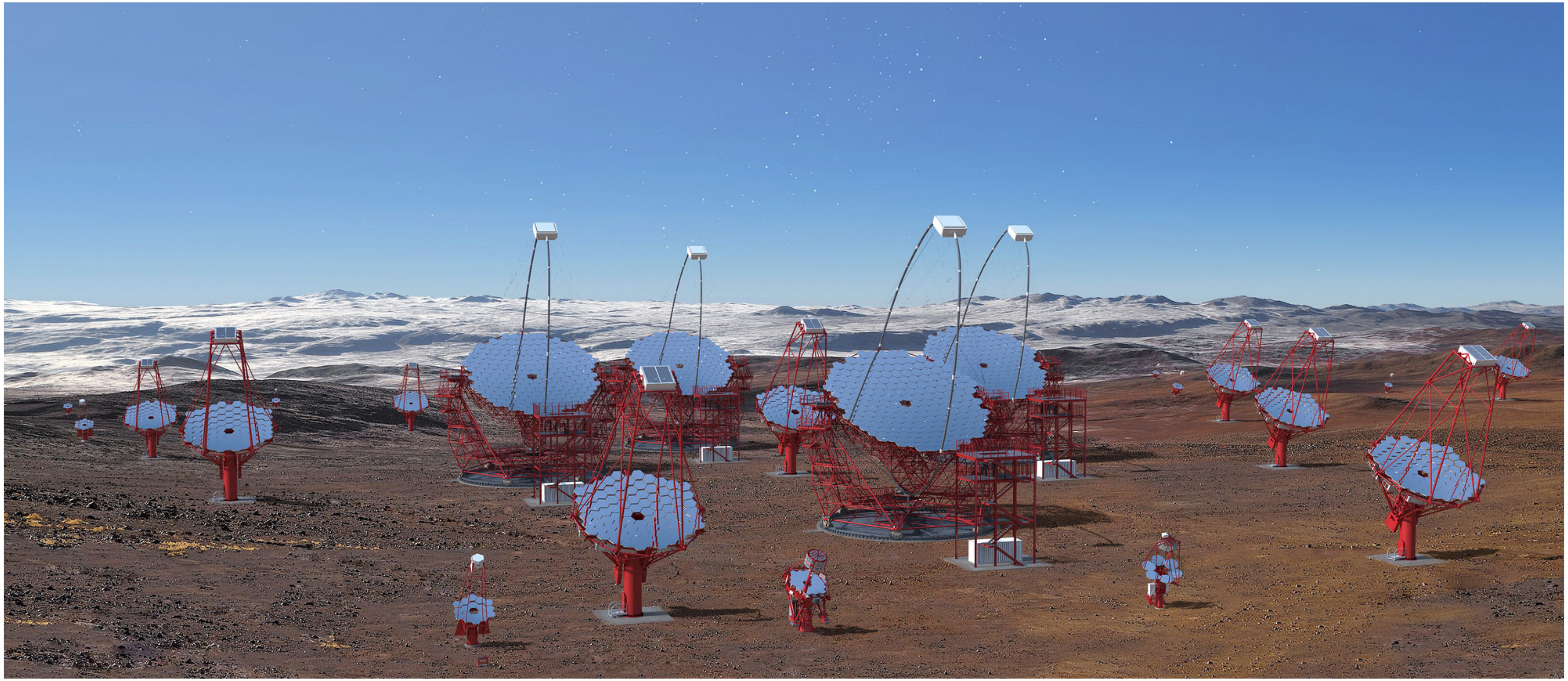
LST Webcam. Inauguration October 10, 2018

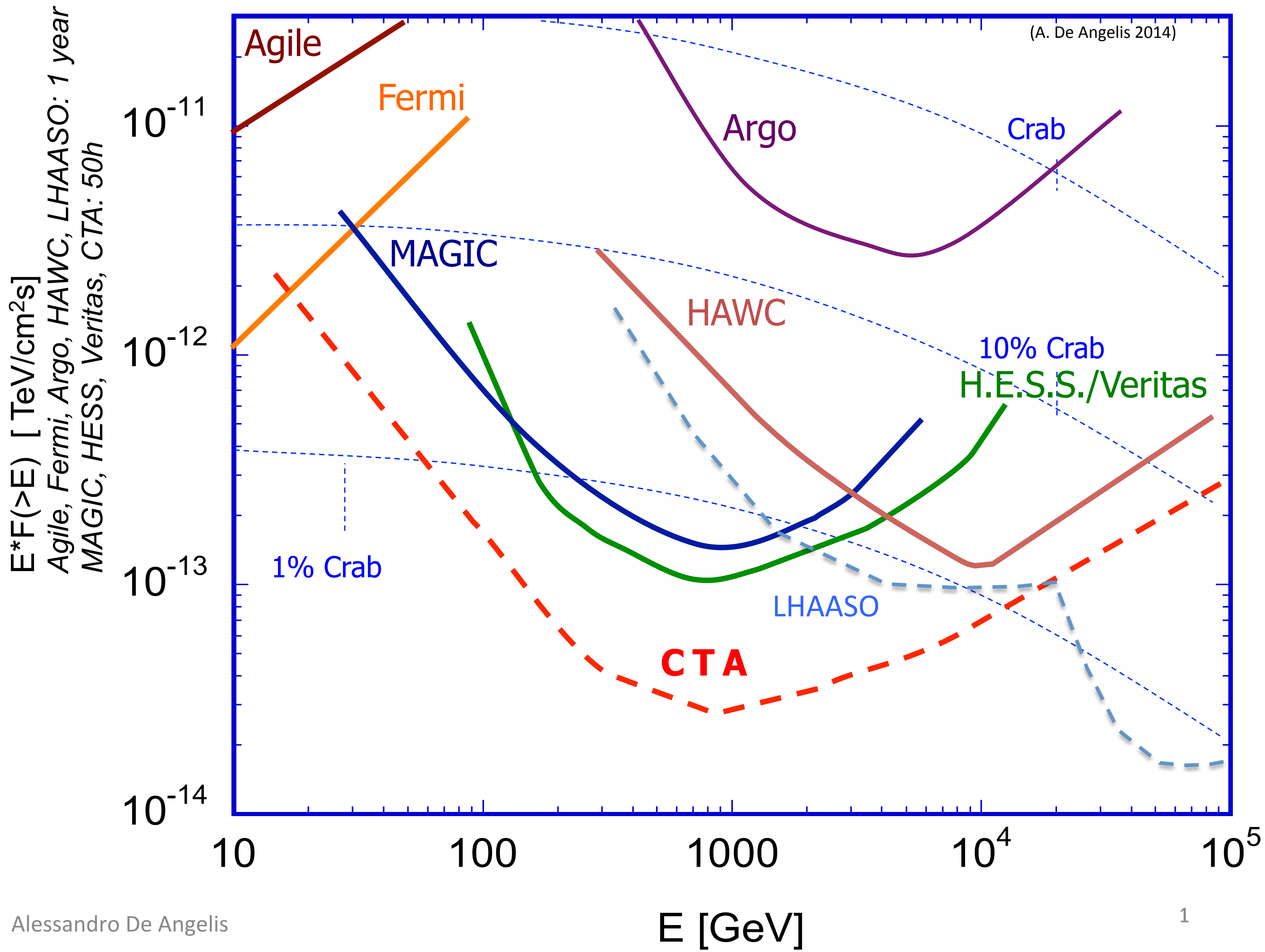

Barranco de las Grajas
Barranco de las Grajas
Ctra. al Roque de los Muchachos
Ctra. al Ro
MAGIC1
145 m
85 m
LST1
93 m
MAGIC2

Fase 2

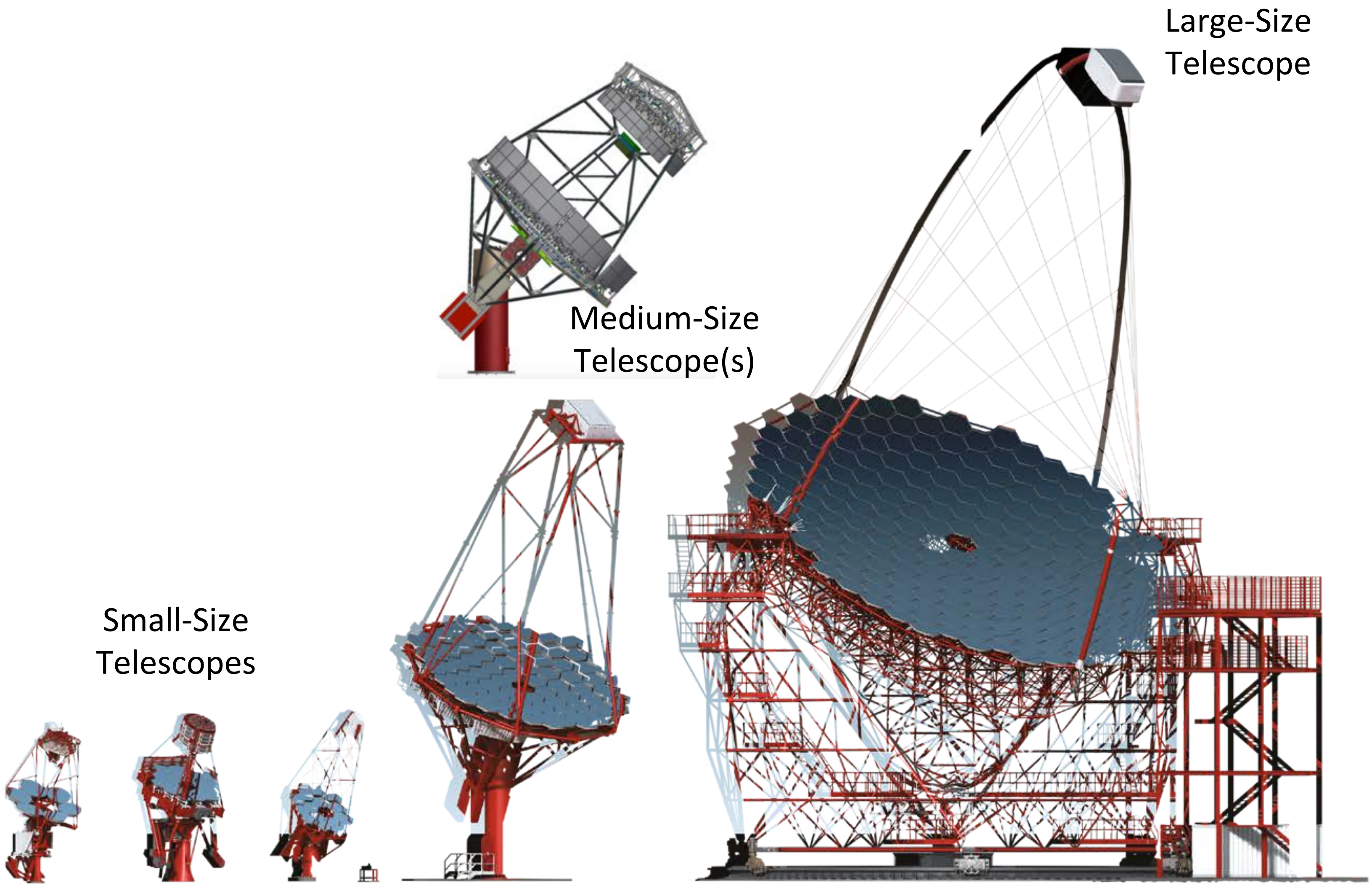

NEW TECHNICAL BUILDING
ALL SKY CAMERA
TECHNICAL BUILDING
LP-4
MST 9
MST 4
EXISTING WORKSHOPS
MST 5
LIDAR
CEILOMETER
LST 3
WEATHER STATION 1
MST 3
MST 10
WEATHER STATION 2
LST4
MST 15
Magic 1
EXISTING CONTROL BUILDING
LST 2
MST 6
MST 8
ACCESS OVER THE BARANCO
LST 1
Magic 2
MST 2
FRAM
Cueva
Parcela Experimentacion
WEATHER STATION 3
MST 1
MST 11
MST 7
MST 12
MST 13
MST 14

CTA-S in Paranal: rendering (contracts starting in June 2019?)



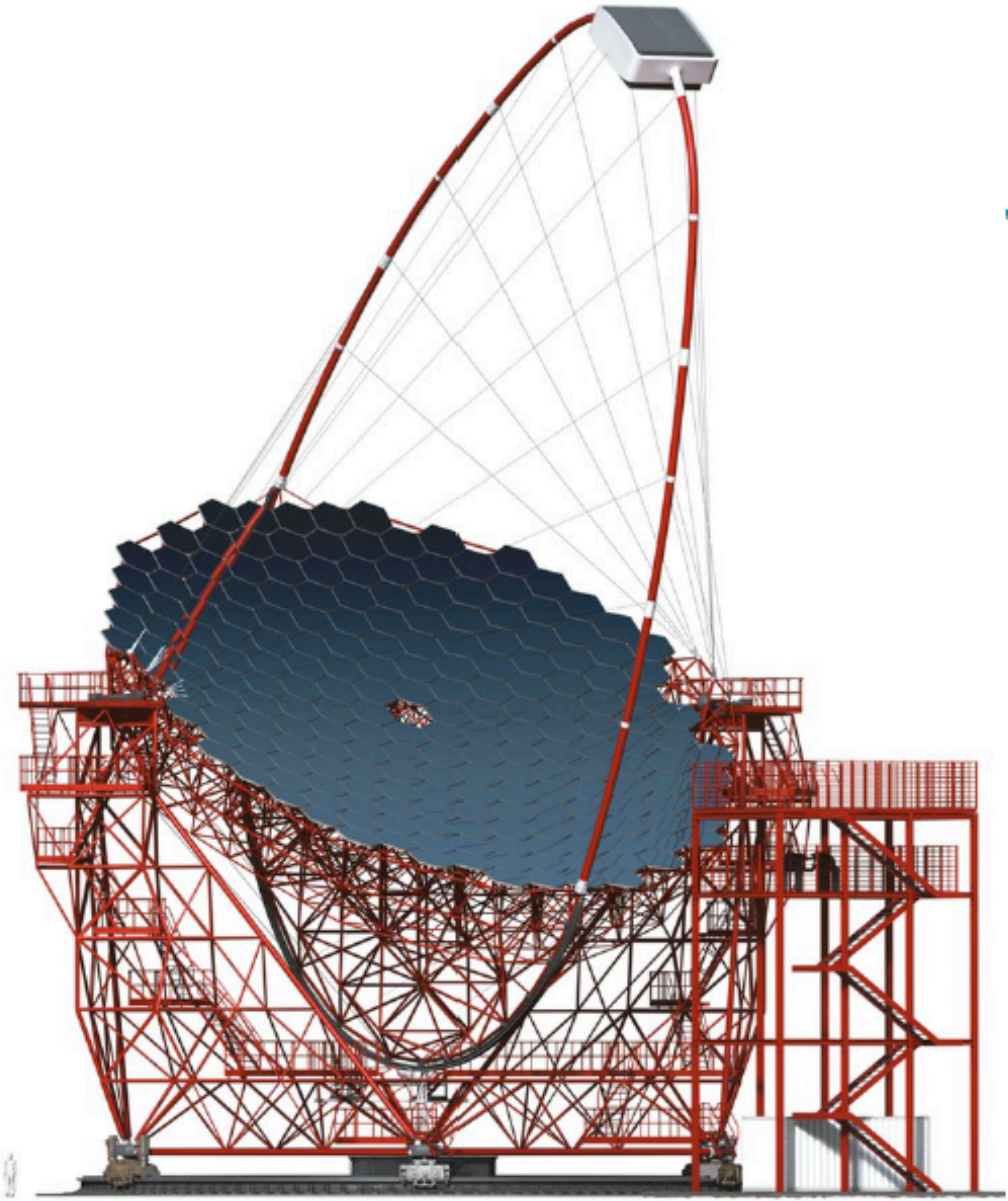

(A. De Angelis 2014)
Agile
Fermi
Argo
Crab
MAGIC
HAWC
10% Crab
H.E.S.S./Veritas
1% Crab
LHAASO
CTA
E*F(>E) [TeV/cm2s]
Agile, Fermi, Argo, HAWC, LHAASO: 1 year
MAGIC, HESS, Veritas, CTA: 50h
10-11
10-12
10-13
10-14
10
100
1000
104
105
E [GeV]

Telescopes



(Rendering credit: Gabriel Pérez Diaz, IAC)

STATUS OF THE CONSTRUCTION



LST cta

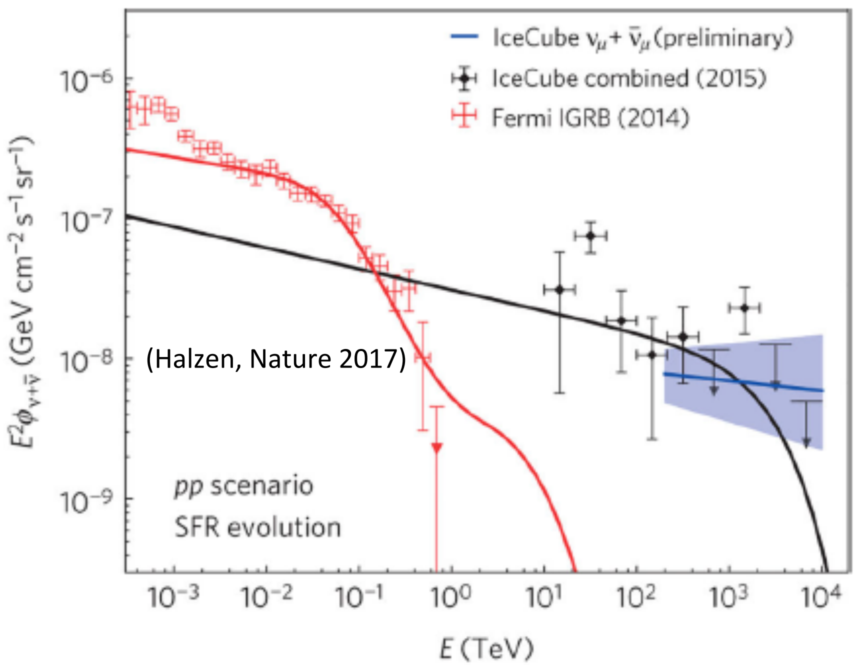
If (crossing fingers) LST1 successful, CTA-N will proceed fast

And also other prototipes…

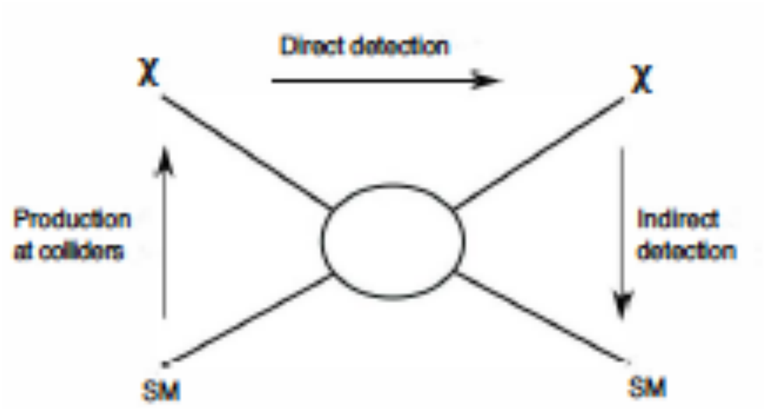
PHYSICS PROSPECTS

Gravity near compact objects (in particular through multimessenger astronomy)

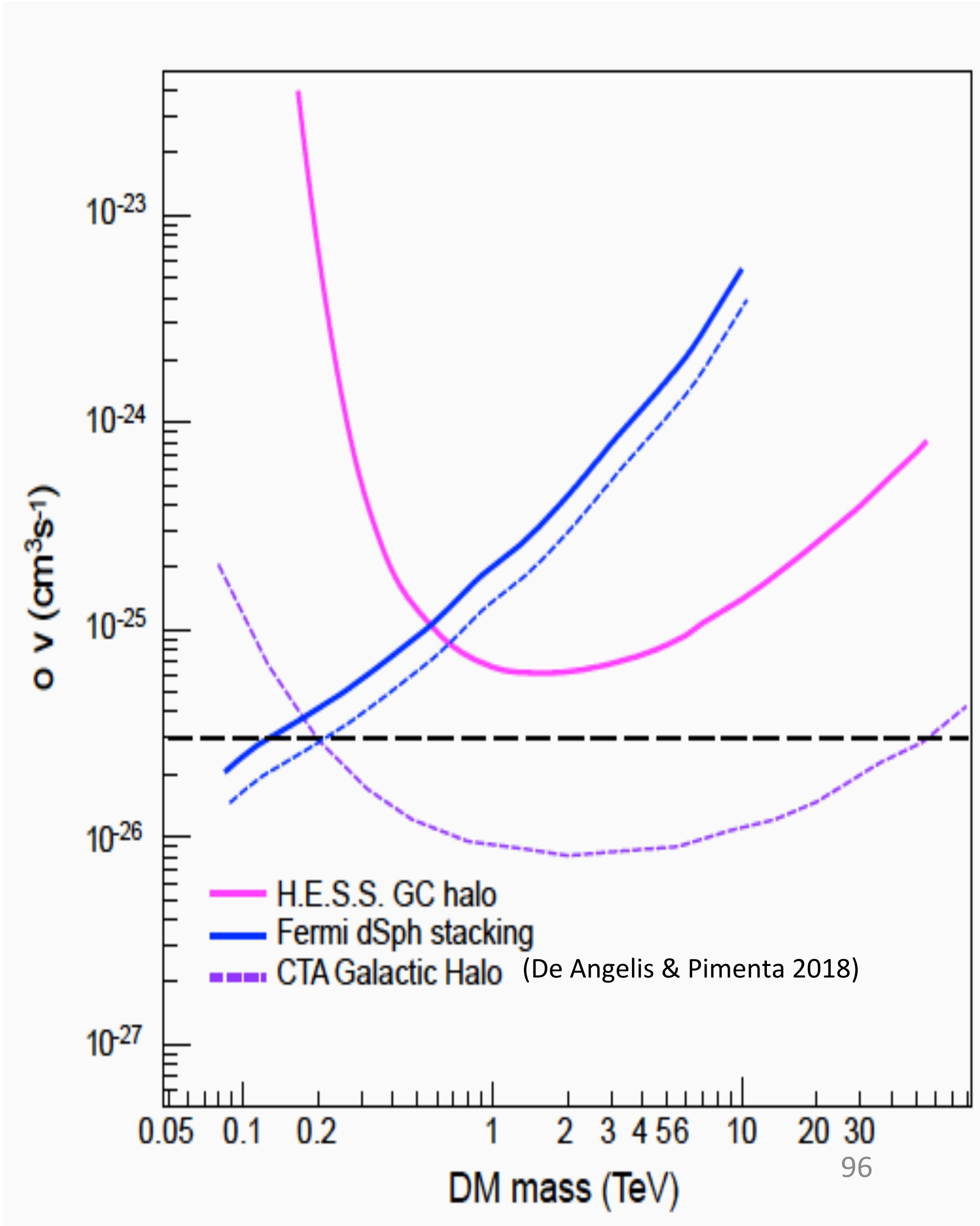
- Astrophysics has recently became multimessenger thanks to the simultaneous observations of GW/gamma rays and of neutrino/gamma ray events
- While the counterparts of GW events seem out of reach for IACTs (~MeV), IACTs are perfect for neutrino events



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

THE ROLE OF A YOUNG EXPERIMENTAL SCIENTIST IN CTA

Opportunities!

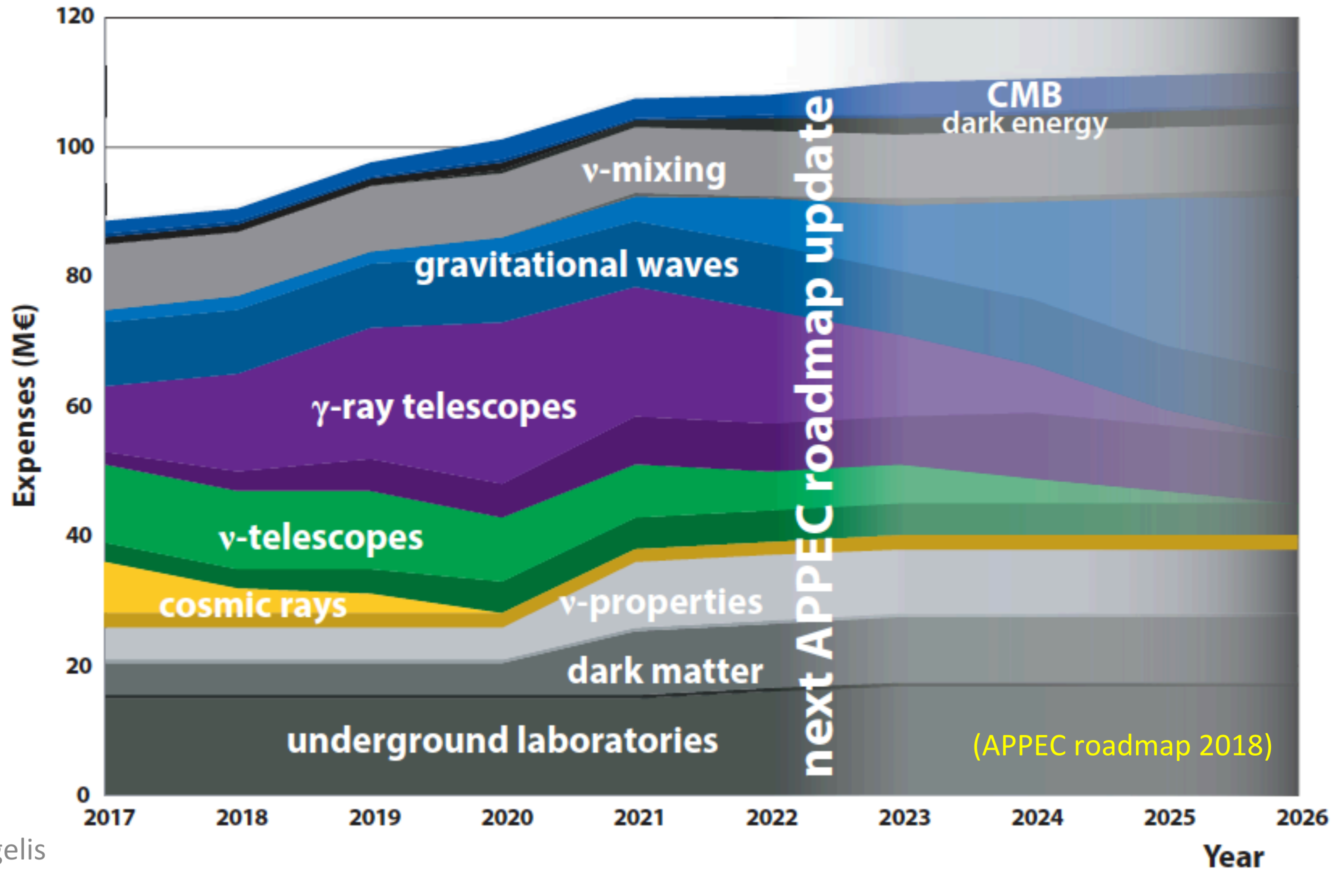
- Many positions are opening in CTA
- Many opportunities to study new phenomena and develop new technologies, on the pure hardware and computation sides
- CTA headquarters are in Italy (Bologna)

- BTW, the position of LST manager opened yesterday

CTA is the main 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)



Summary

- Astroparticle physics guarantees the best science for the future, and it is an essential ingredient of multimessenger astrophysics
- We are confident that this interplay between fundamental physics and astrophysics will be useful for both fields, as history of science has demonstrated

Alessandro De Angelis and Mário Pimenta

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2nd Edition

February 14, 2018

Springer