Very High Energy
γ-ray Astrophysics

Atmospheric Air Showers Seen in Particles and in Cherenkov Light

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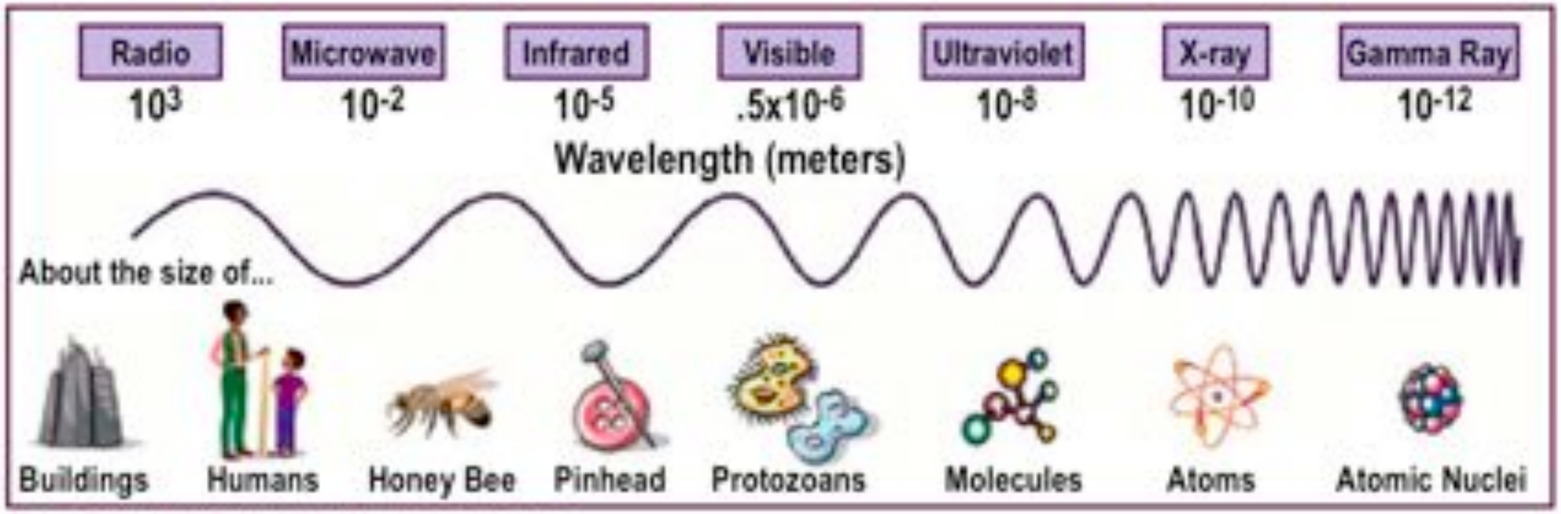
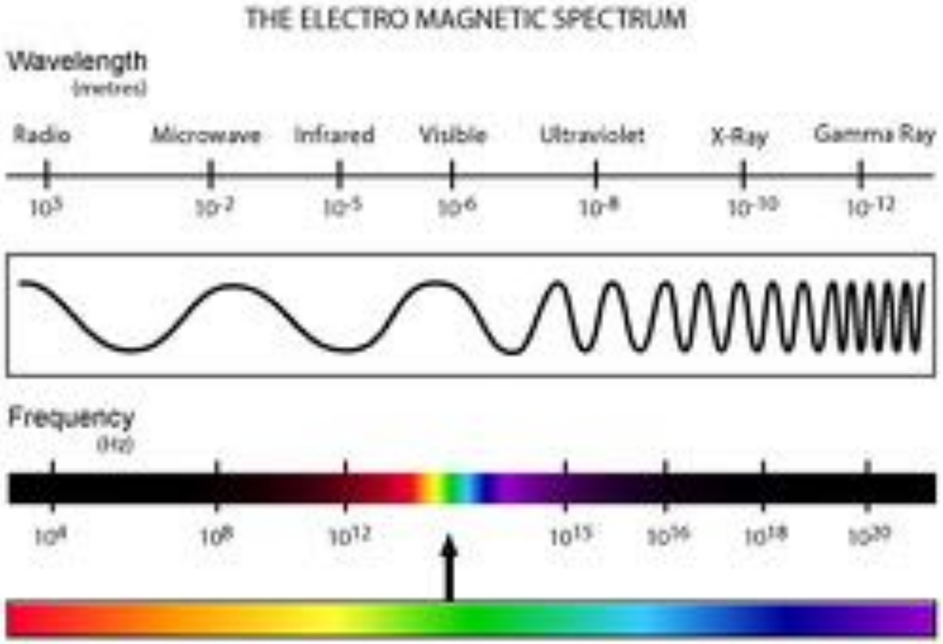
The electromagnetic spectrum

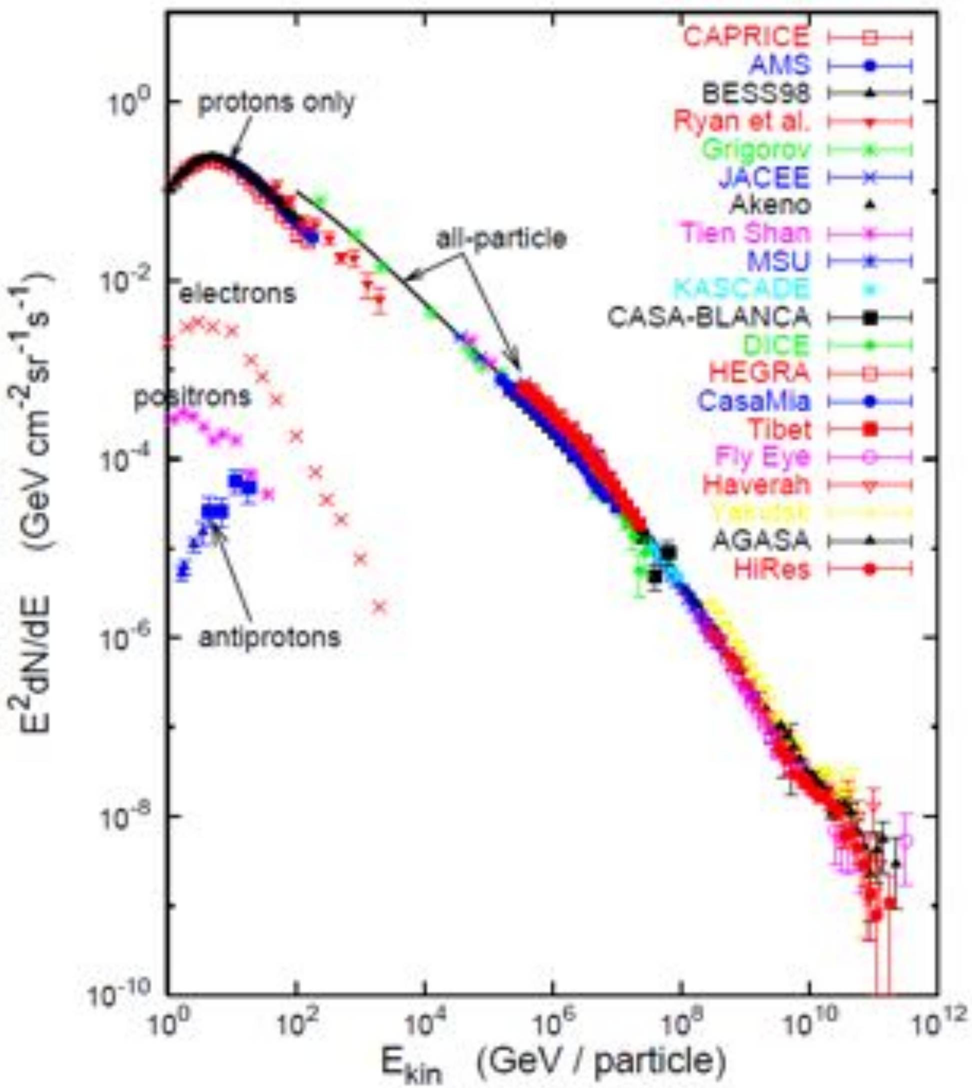


Credit: NASA / Ruth Jennings



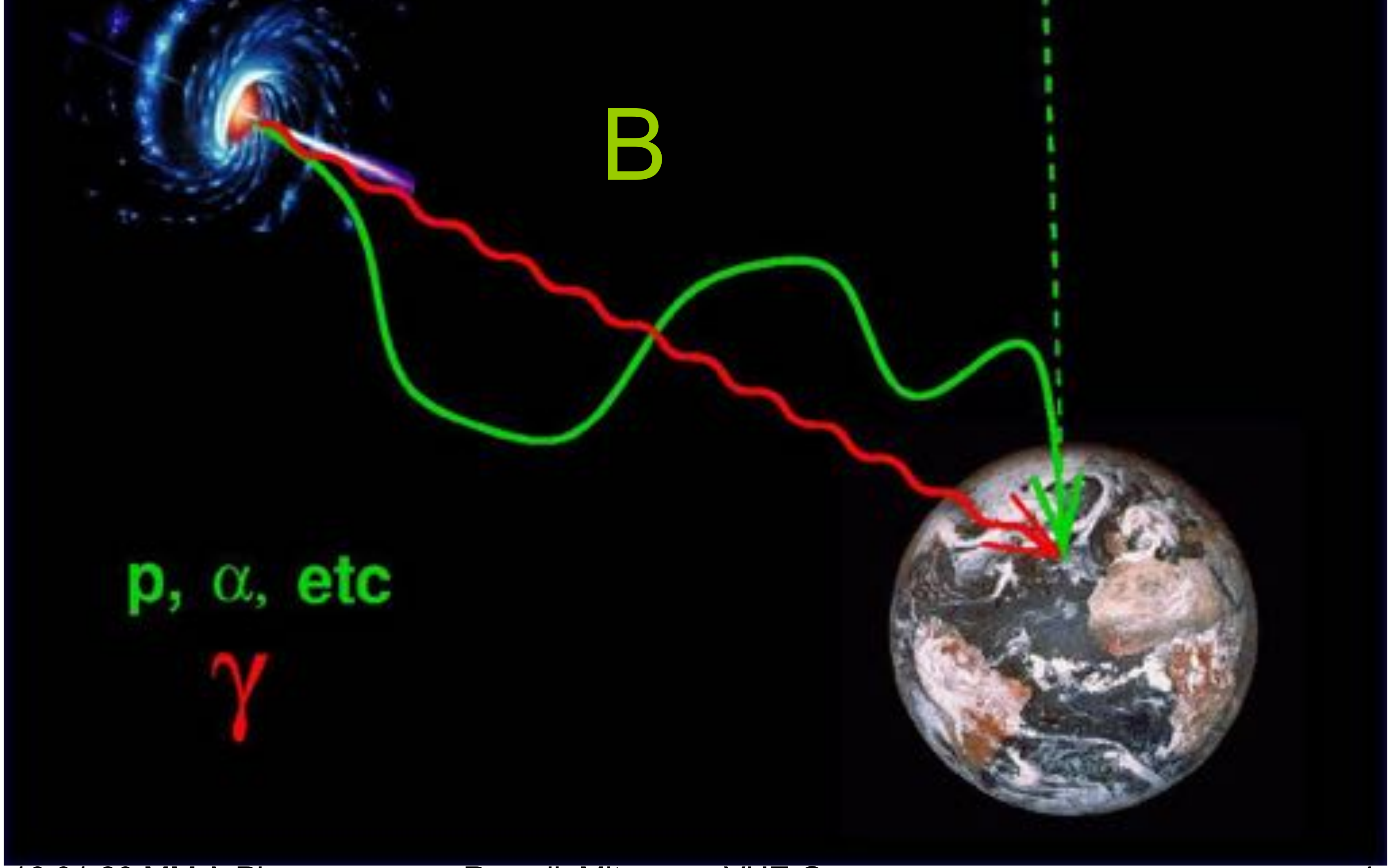
Discovery of Cosmic Rays by V. Hess in 1912

Energies and Rates of the Cosmic-Ray Particles

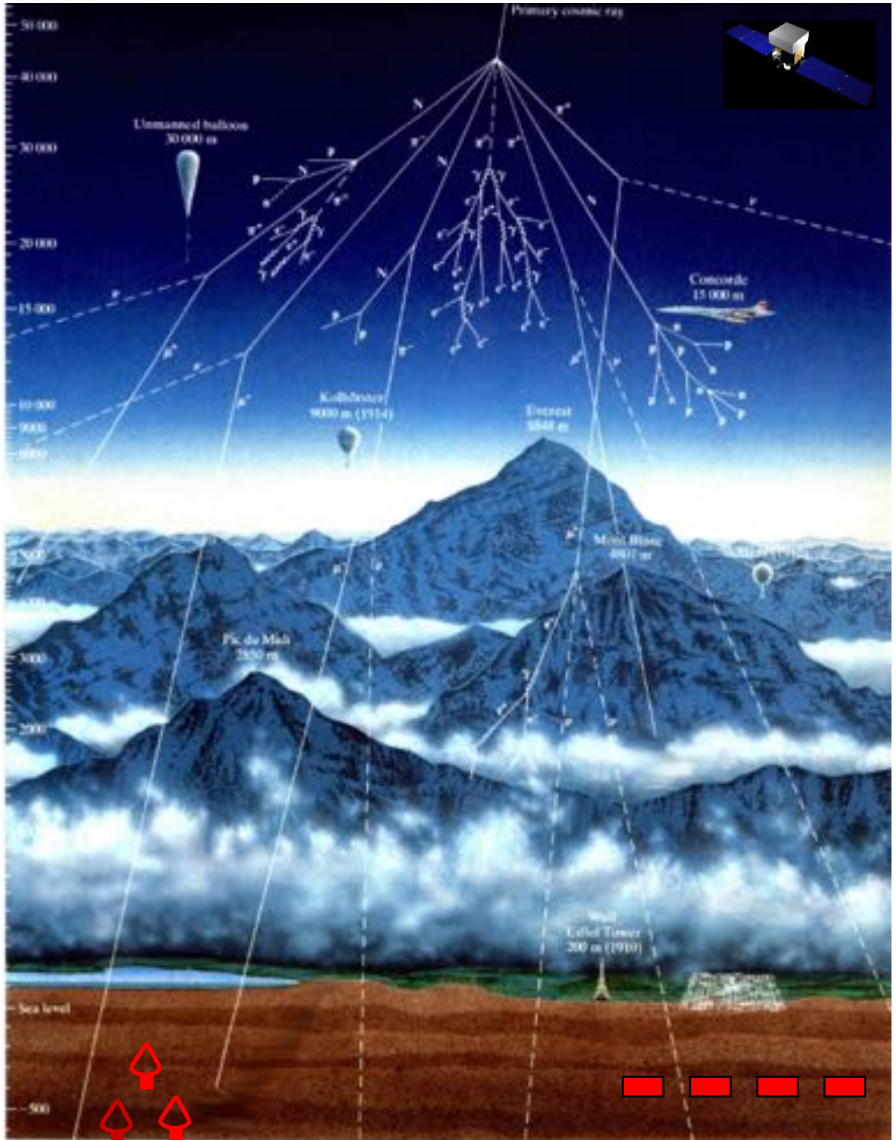


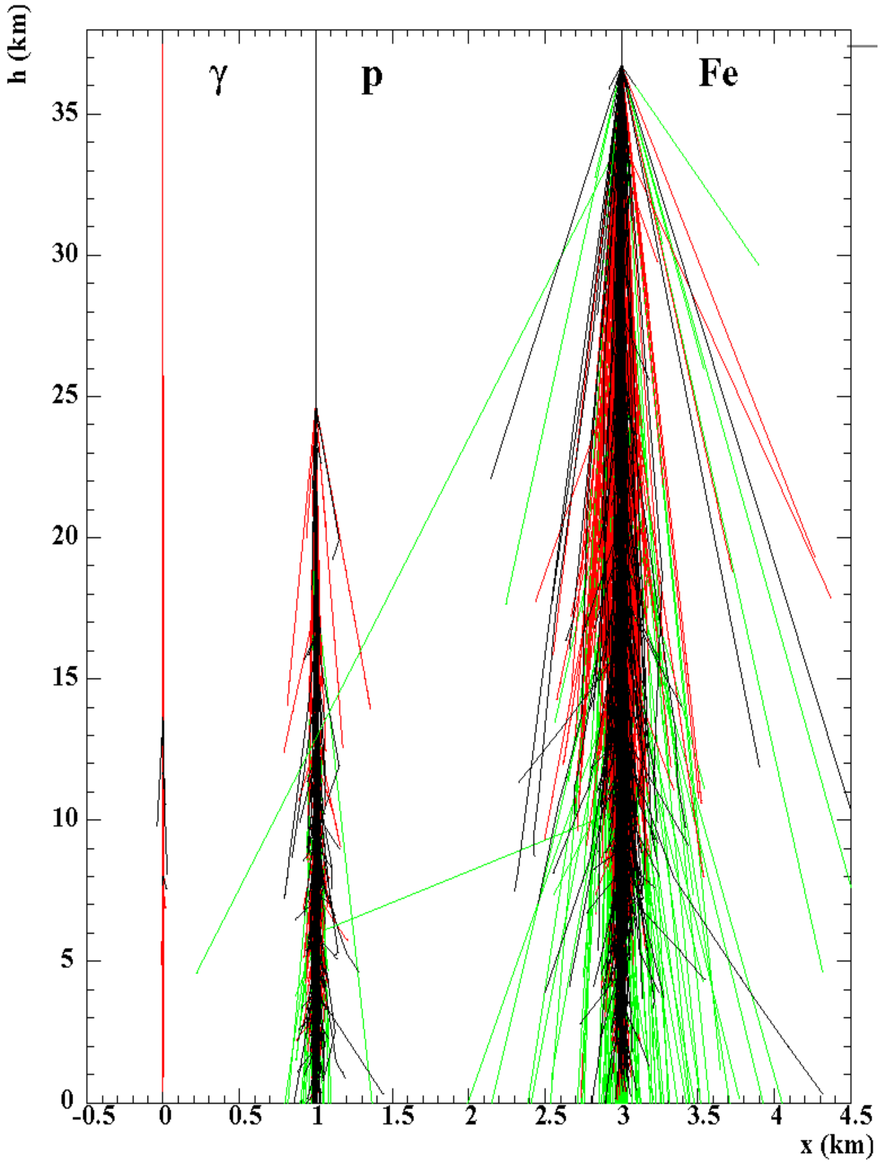
Then, why not charged CR astronomy?

Charged CR particles, deflected by magnetic fields, do not carry information on the location of the emission site (unless E is very large)



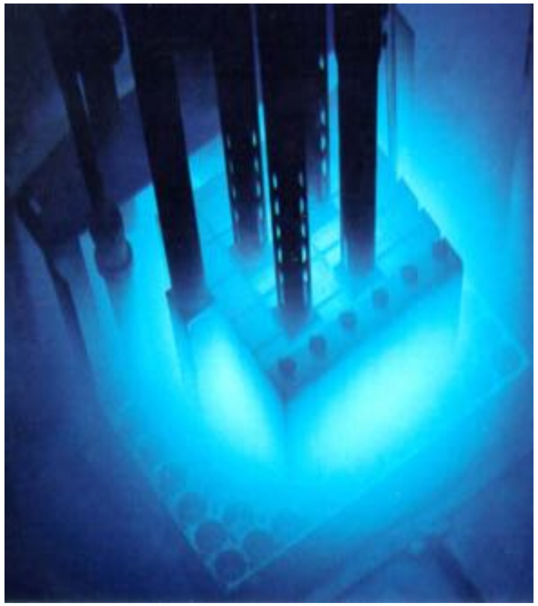
Extensive Air Showers

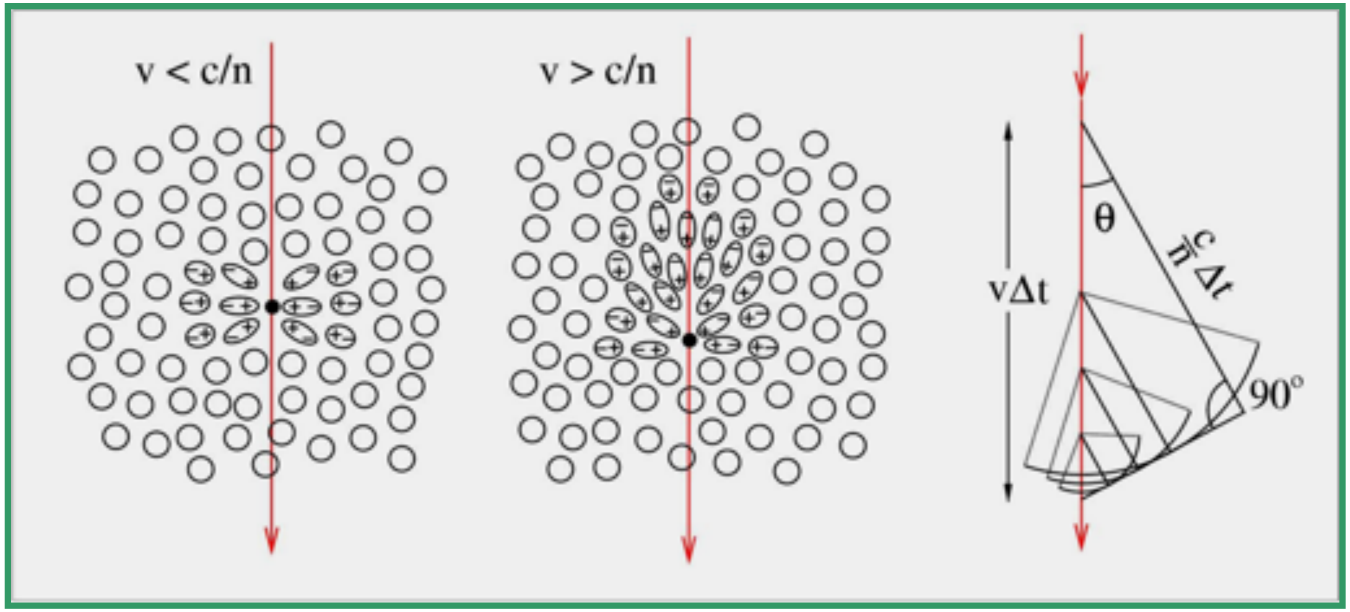




Cherenkov Radiation

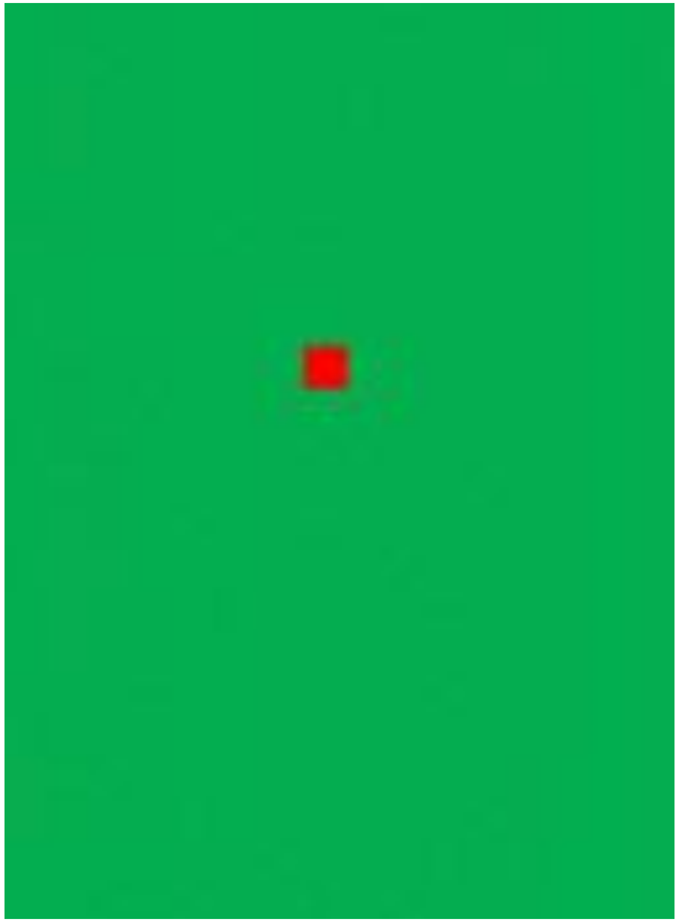
- Emitted whenever a charged particle traverses a dielectric medium at a speed larger than that of light in that medium
- The radiation results from the reorientation of electric dipoles induced by the charge in the medium. When v > c/n the contributions from different points of the trajectory arrive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

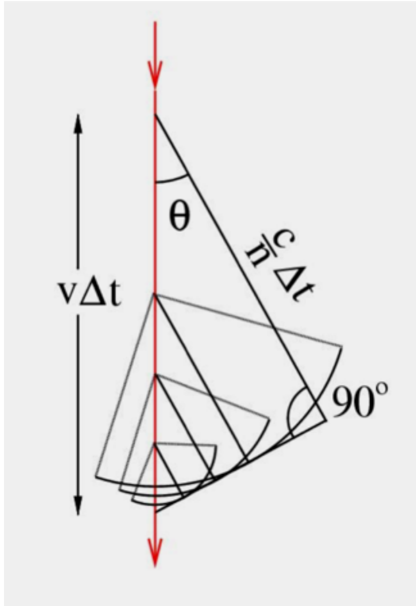




Cherenkov radiation

Analogous to “sonic boom”





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

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

Cherenkov radiation in the atmosphere

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

Cherenkov radiation in the atmosphere; simple model

Air density: $$\rho(h) = \rho_0 \cdot e^{-\frac{h}{h_0}}$$ $h_0 = 7.1$ km

Air density exponentially reduces with increasing height

Refractive index:

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

at sea level

So, for example, at the height of 7.1km the air density is (1/e) times less, i.e. only ~37 % of its value at sea level

Definition of refractive index: $n = c/v$ (c-speed of light; v-speed of electromagnetic interaction in a given medium)

Definition of β: $\beta = v/c = 1/n = n^{-1}$;

$\beta^2 = n^{-2}$;

$n = 1 + \eta_h$

$n^{-2} = (1 + \eta)^{-2} = 1 - 2\eta + \eta^2$; $\eta << 1$; $\rightarrow n^{-2} = 1 - 2\eta$

Threshold for Cherenkov emission for $e^{\pm}$:

$$E_{min} = \frac{m_e c^2}{\sqrt{1 - \beta^2_{min}}} = \frac{m_e c^2}{\sqrt{1 - n^{-2}}} \simeq \frac{0.511\ MeV}{\sqrt{2\ \eta_h}}$$

(≈ 21 MeV at sea level)

Cherenkov angle for $\beta = 1$:

$$\cos\theta_{max} = \frac{1}{n} = \frac{1}{1 + \eta_h} \simeq 1 - \eta_h$$

Cherenkov emission threshold in atmosphere

Let us estimate Cherenkov light emission threshold energy for $e^{\pm}$, $\mu^{\pm}$ and p for few height levels in the atmosphere

particle type	$e^{\pm}$	$\mu^{\pm}$	p
$E_{thr.}$ @ sea level, GeV	0.021	4.4	38.9
@ 2 km a.s.l.	0.024	5.1	44.8
@ 10 km a.s.l.	0.043	8.9	78.6
@ 15 km a.s.l.	0.061	12.6	111.5

Cherenkov emission threshold in water and in glass

- Water: $n = 1.33$;

  $\theta_{max} = 41.2°$

  for $e^{\pm}$ $E_{thr} = 775$ KeV

  for $\mu^{\pm}$ $E_{thr} = 160$ MeV

  $N_{photons/mm} = 36$ for λ in (300 – 600) nm

- Plexiglas: $n = 1.50$;

  $\theta_{max} = 48.2°$

  for $e^{\pm}$ $E_{thr} = 686$ KeV

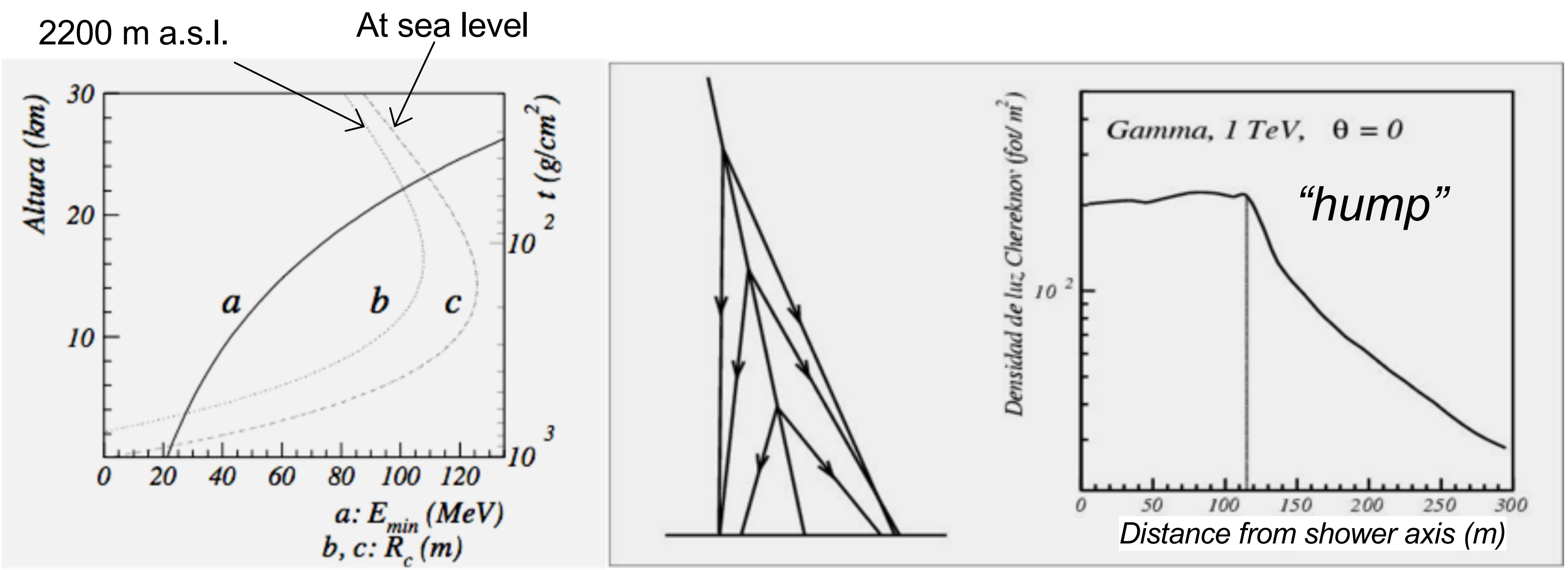
  for $\mu^{\pm}$ $E_{thr} = 142$ MeV

  $N_{photons/mm} = 46$ for λ in (300 – 600) nm

Cherenkov radiation in the atmosphere

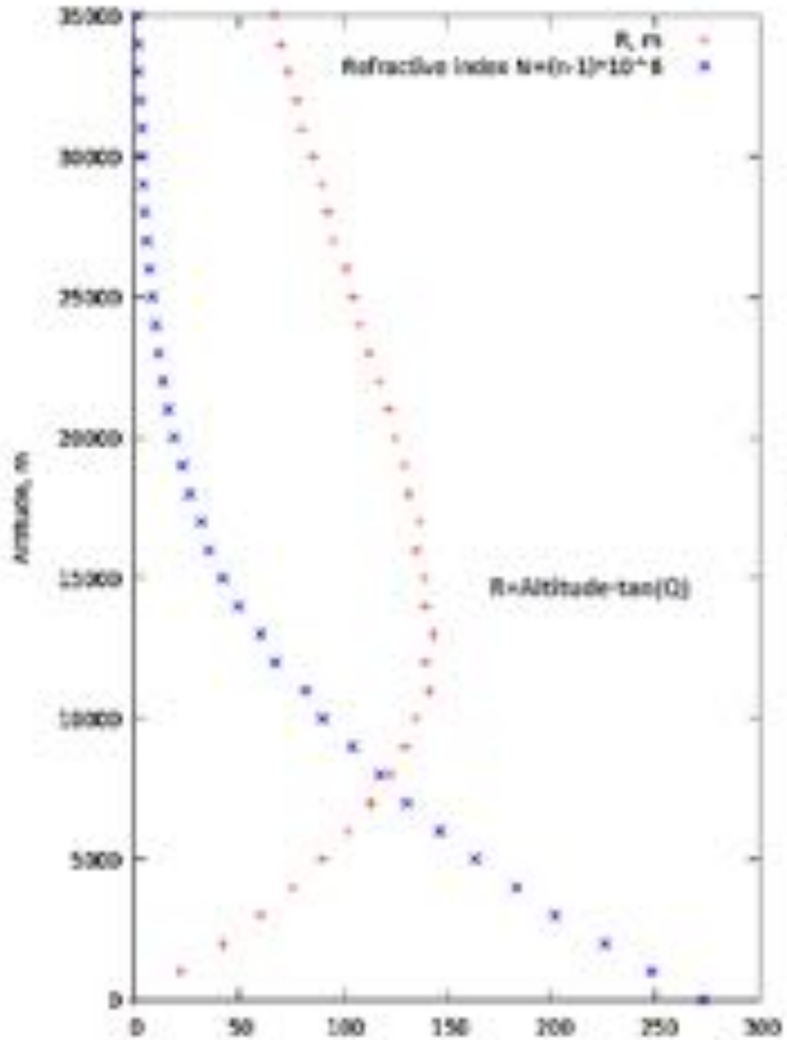
R_c: Distance from shower trajectory at which the C-photons hit the ground

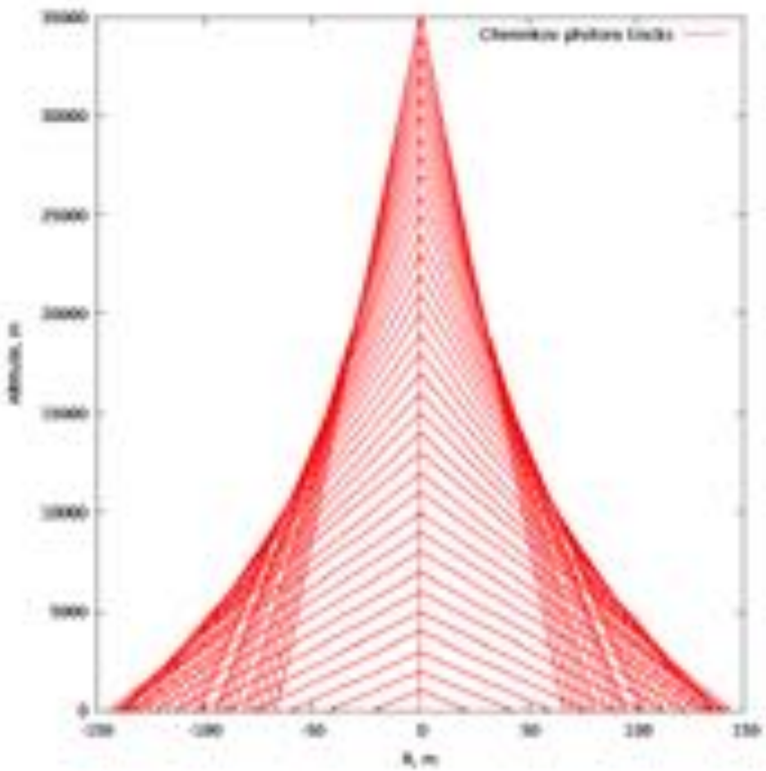
$$R_c \equiv (h - h_{obs}) \cdot \tan\theta_{max} \quad \text{for } \beta = 1$$



Hump position depends on observation altitude (but not on E_0)

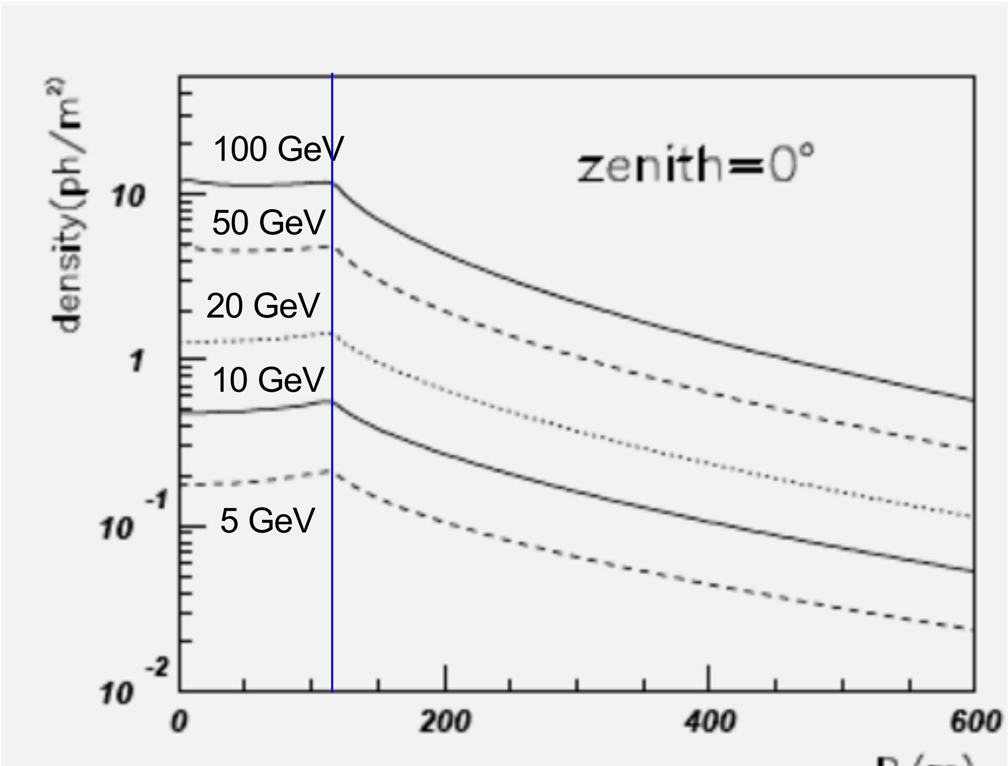
Index of Refraction and Cherenkov Emission Angle versus Altitude





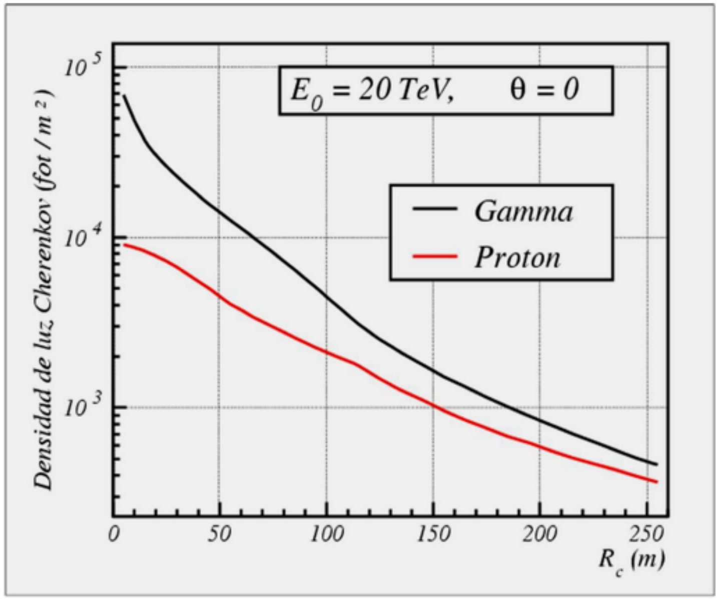
Lateral distribution of C-light

If e$^{\pm}$ shower extinguishes before reaching observation level (E< a few TeV) : Plateau up to the hump, then fast drop



D. Sobczynska, CORSIKA simulations

Else, C-light density is maximum at shower core and drops exponentially with R



Note above: for a given E_0, a γ-ray produces far less light than a hadron!

Number of emitted Cherenkov photons

An electron traveling at speed β in a medium of refractive index n emits, between wavelengths λ_1 and λ_2, per unit length:

$$\frac{dN}{dx} = 2\pi\alpha \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \cdot \left(1 - \frac{1}{\beta^2 n^2}\right)$$

For $\lambda_1 = 300$ nm, $\lambda_2 = 600$ nm (this is the usual sensitivity range of classical PMTs), in air, $\beta = 1$, for exponential atmosphere ρ profile:

$$dN/dx \sim 45 \cdot e^{-h/h0} \text{ photons/m} = 45 \cdot t/t_0 \text{ photons/m}$$

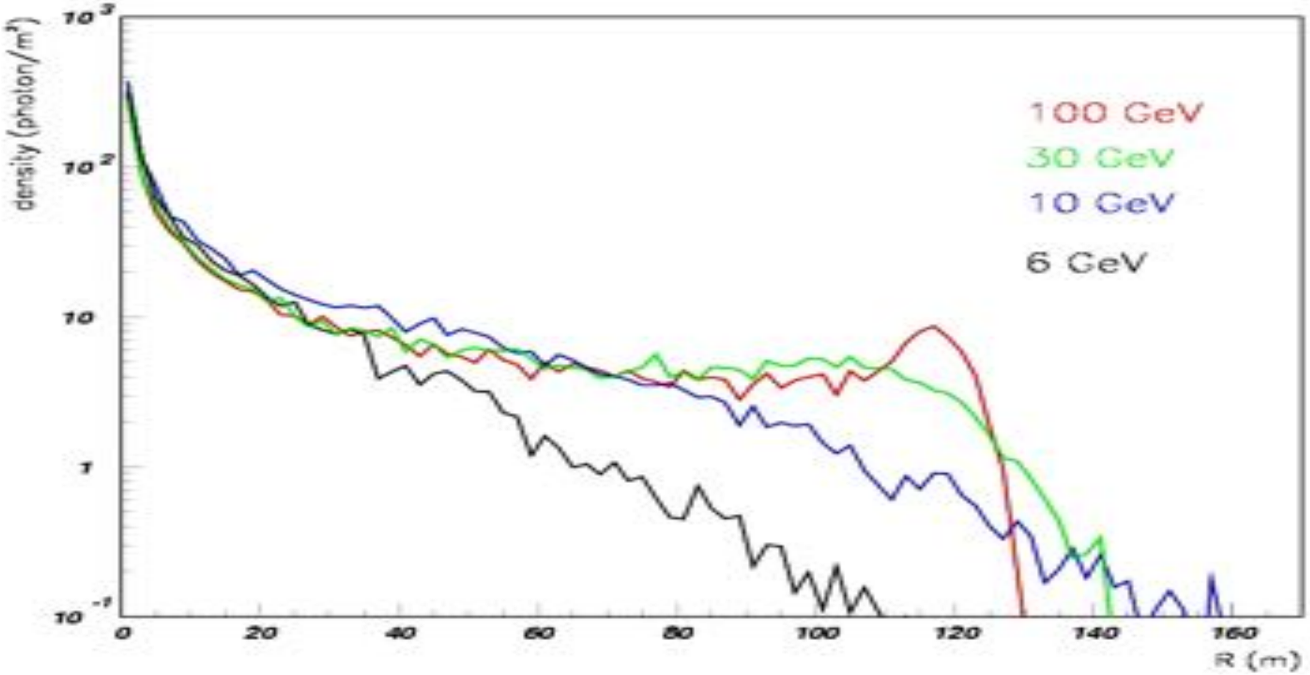
t-slanth depth at given atmospheric height, $t_0 = 1036$ g/cm^2

Number of emitted Cherenkov photons in the atmosphere

- A relativistic particle at a given height (slanth depth) a.s.l. will emit in the atmosphere, in the wavelength range of 300-600 nm, the following number of photons per 1m path length:

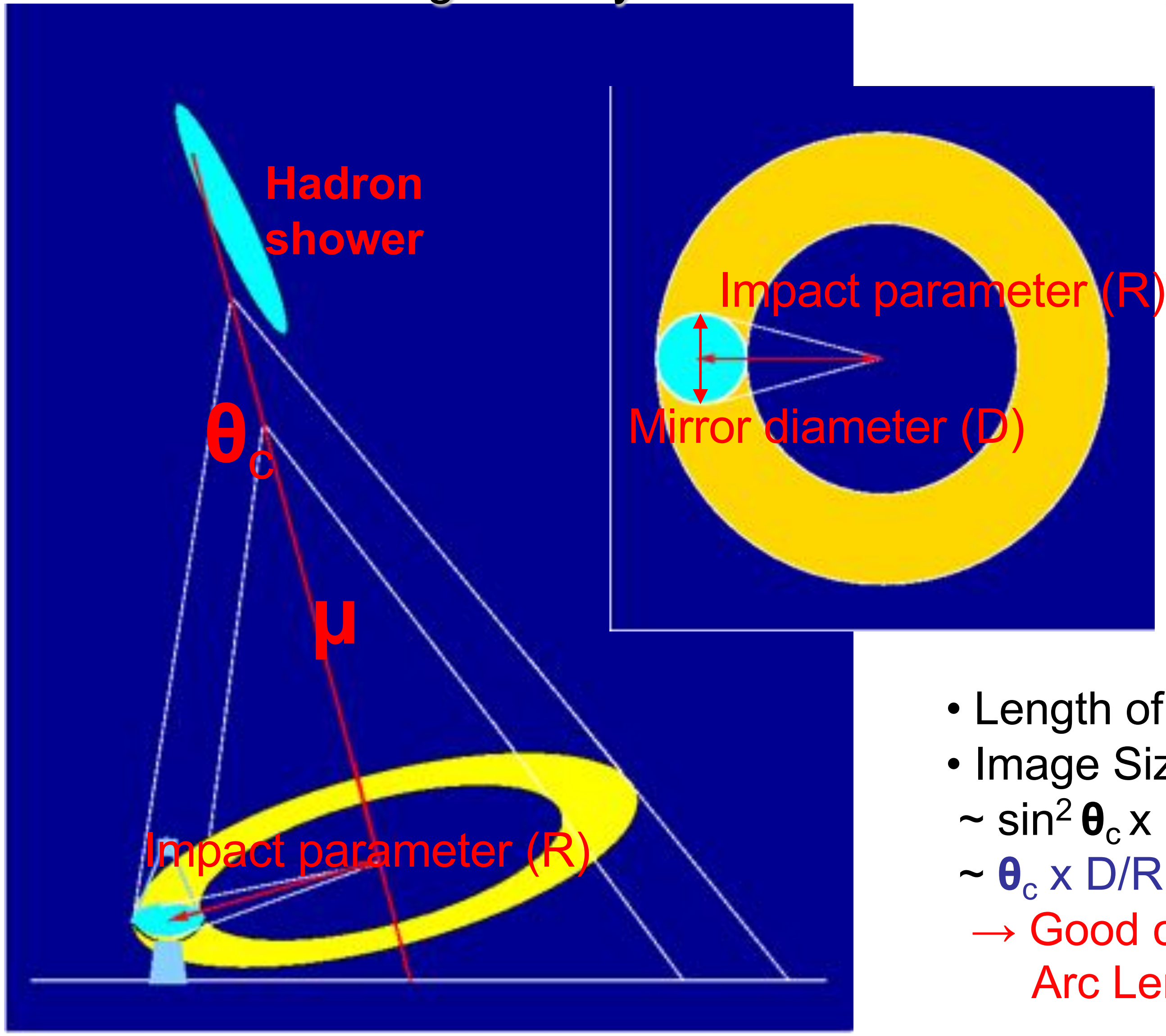
Slanth depth, g/cm²	100	300	800	1036
Height a.s.l., km	16	10	2.2	0
Number of emitted C-photons/m	4.5	13	35	45

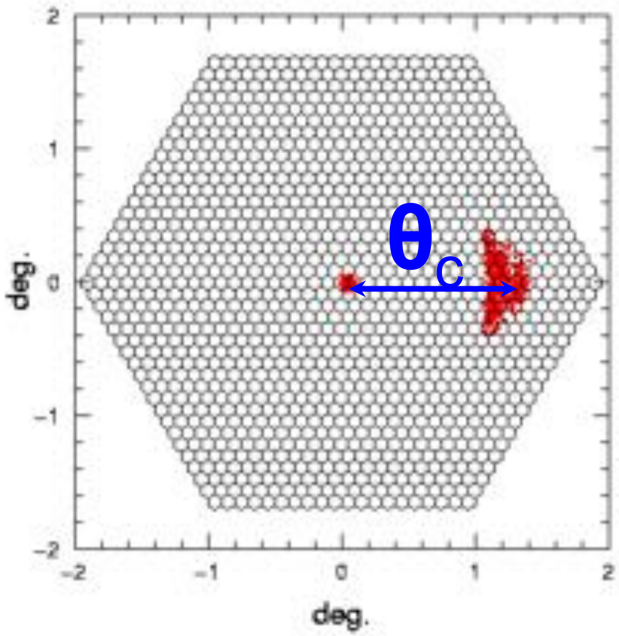
Lateral distribution of Cherenkov light emission from a single μ



Muons

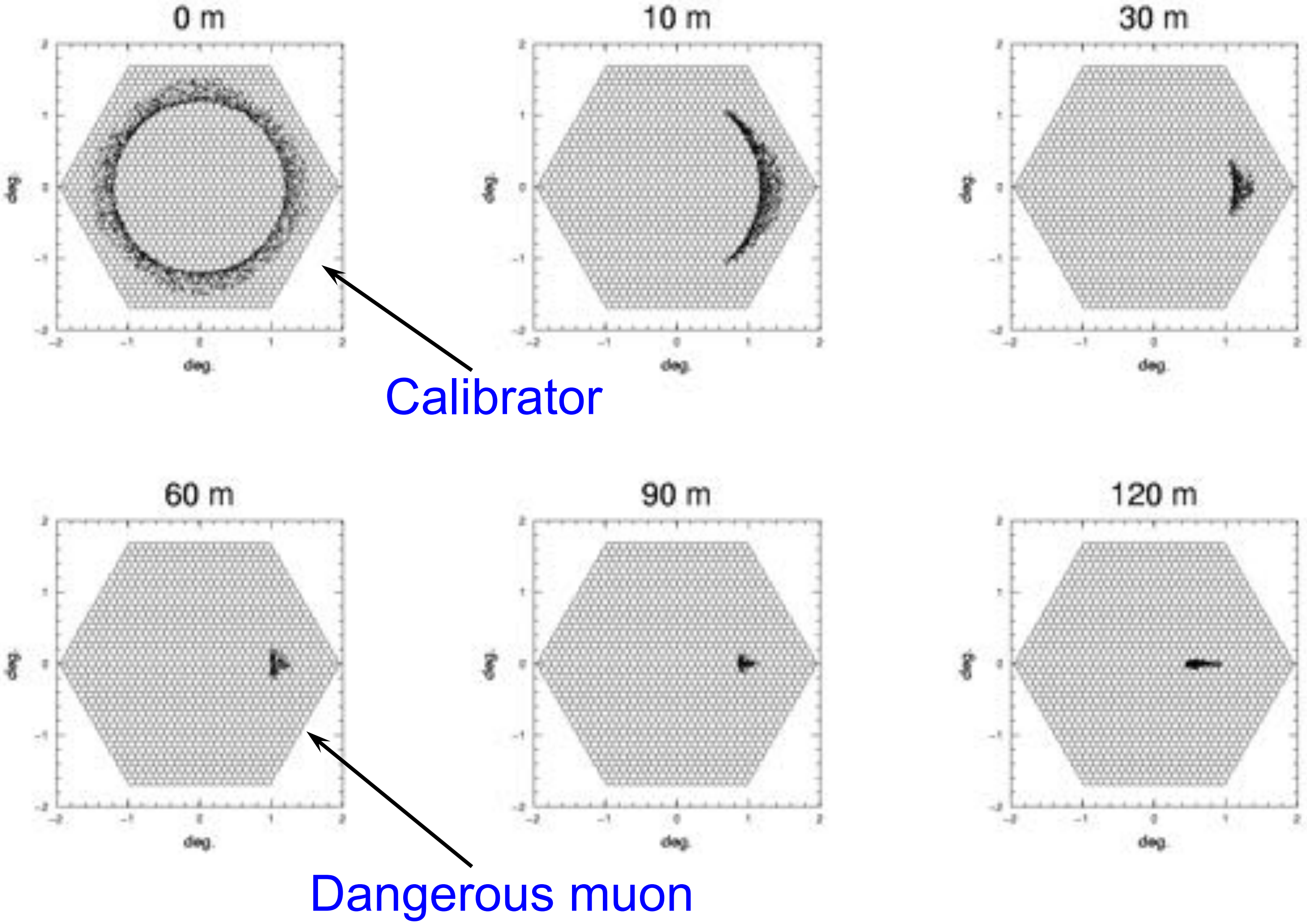
Muon images is simply determined by the geometry.
The geometry can be reconstructed by the image.

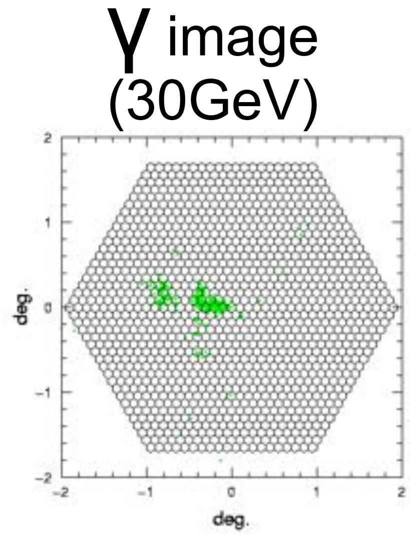




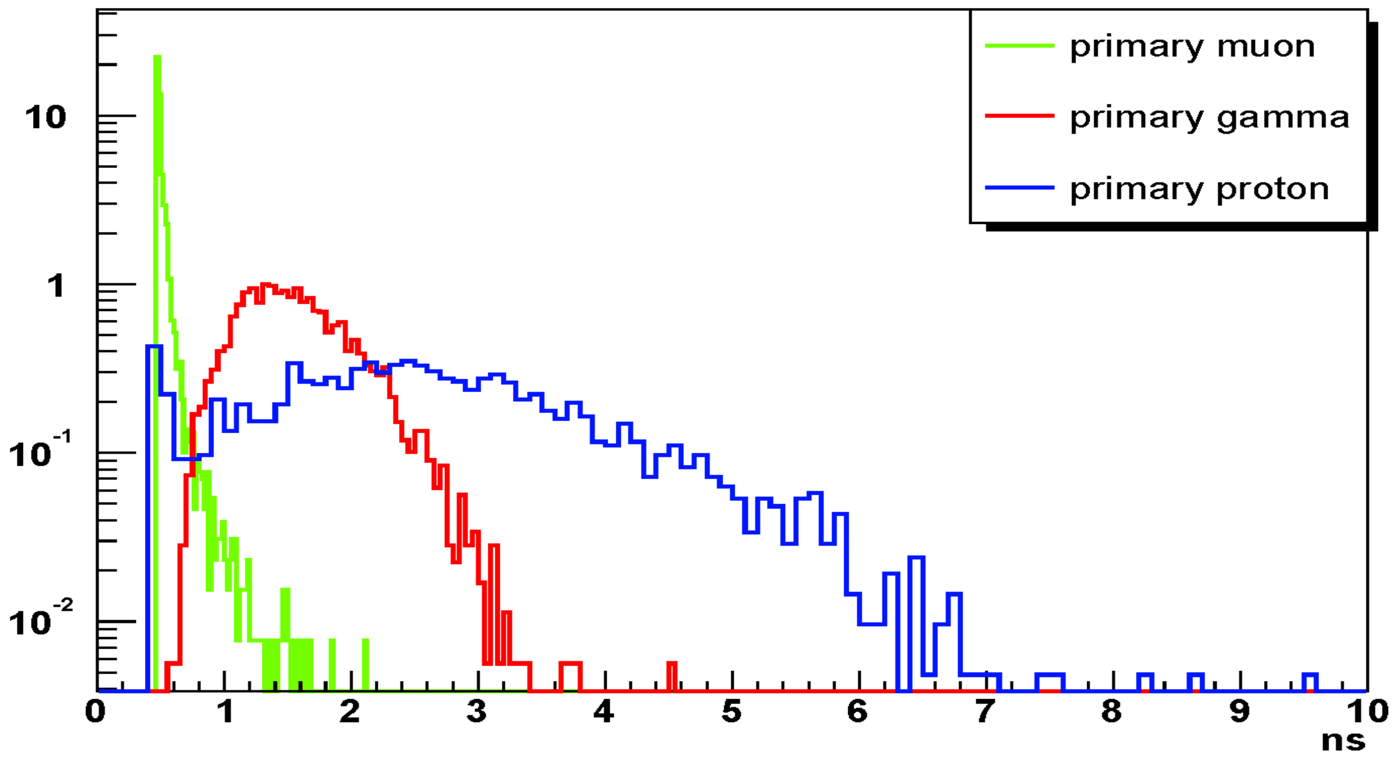
- Length of the arc ~ θ_c x D/R
- Image Size(Total photons)
  ~ $\sin^2 \theta_c \times 1/\tan \theta_c \times D/R$
  ~ θ_c x D/R
  → Good correlation between Arc Len. and SIZE

Muon Images depending on the impact parametre

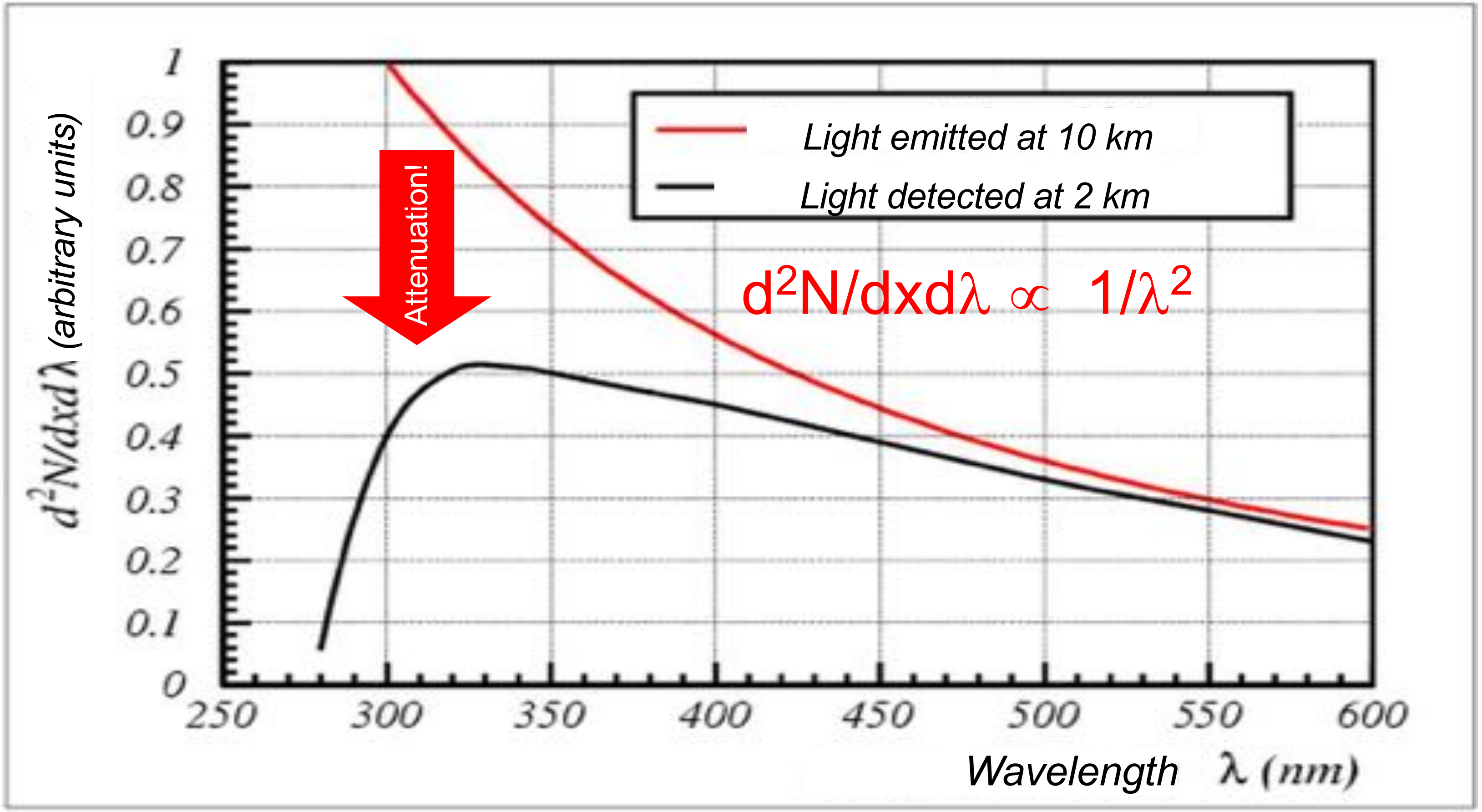




Arrival time distribution of Cherenkov photons

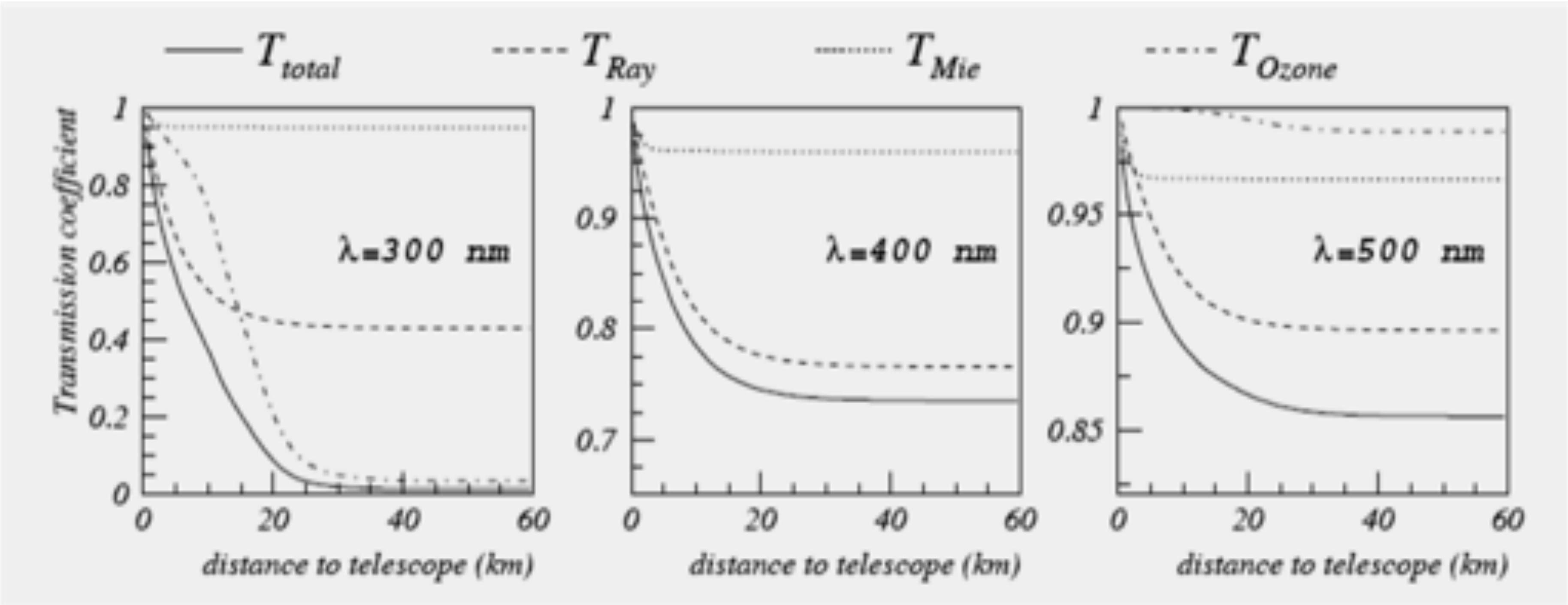


Spectrum of atmospheric Cherenkov light



Attenuation of C-light in the atmosphere

3 processes: Mie scattering (by dust particles); Rayleigh scattering (by air molecules); absorption by Ozone
(but EAS develops mostly below O_3 layer)

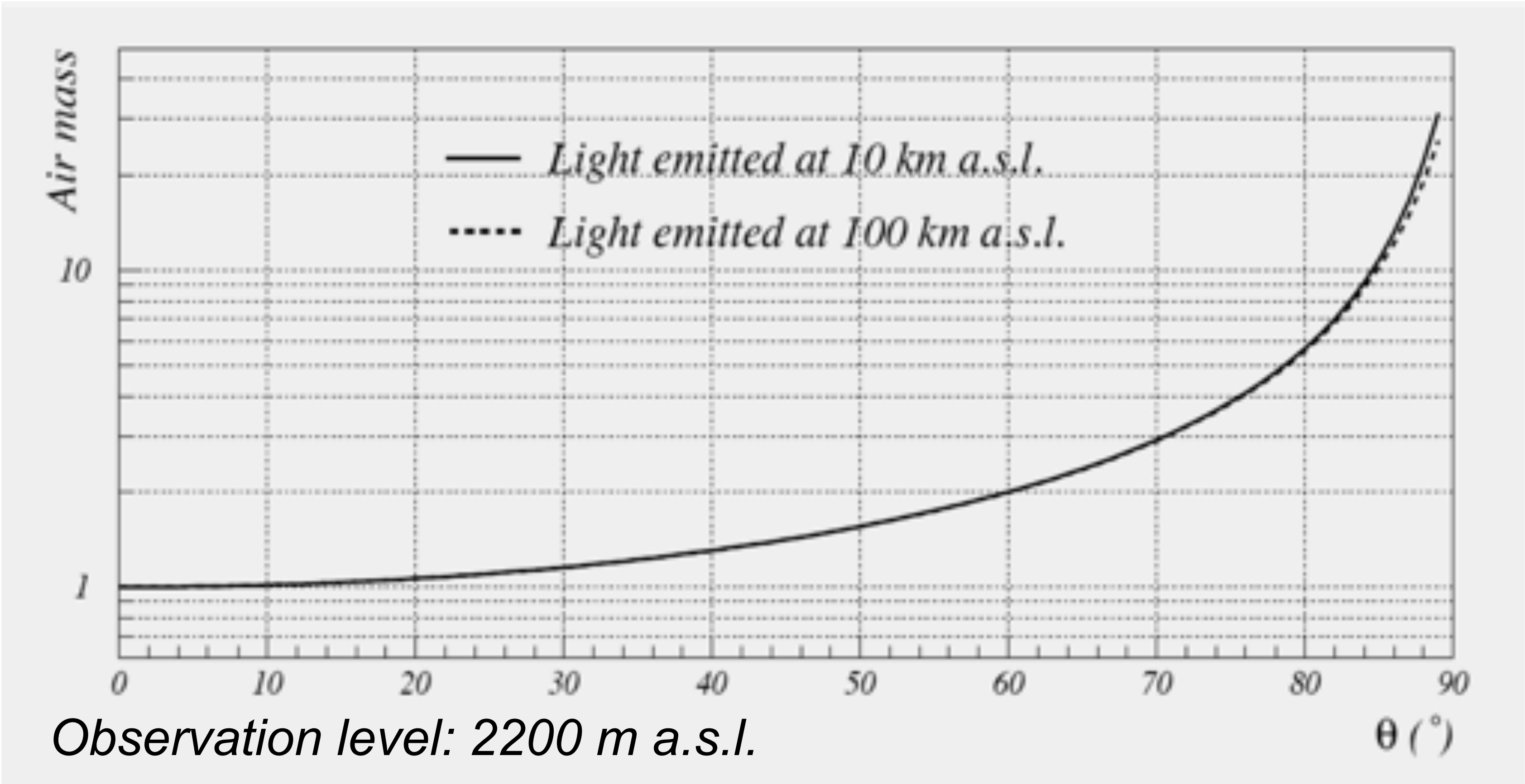


Total atmospheric transmission coefficients for vertically incident light, for the “standard clear atmosphere”

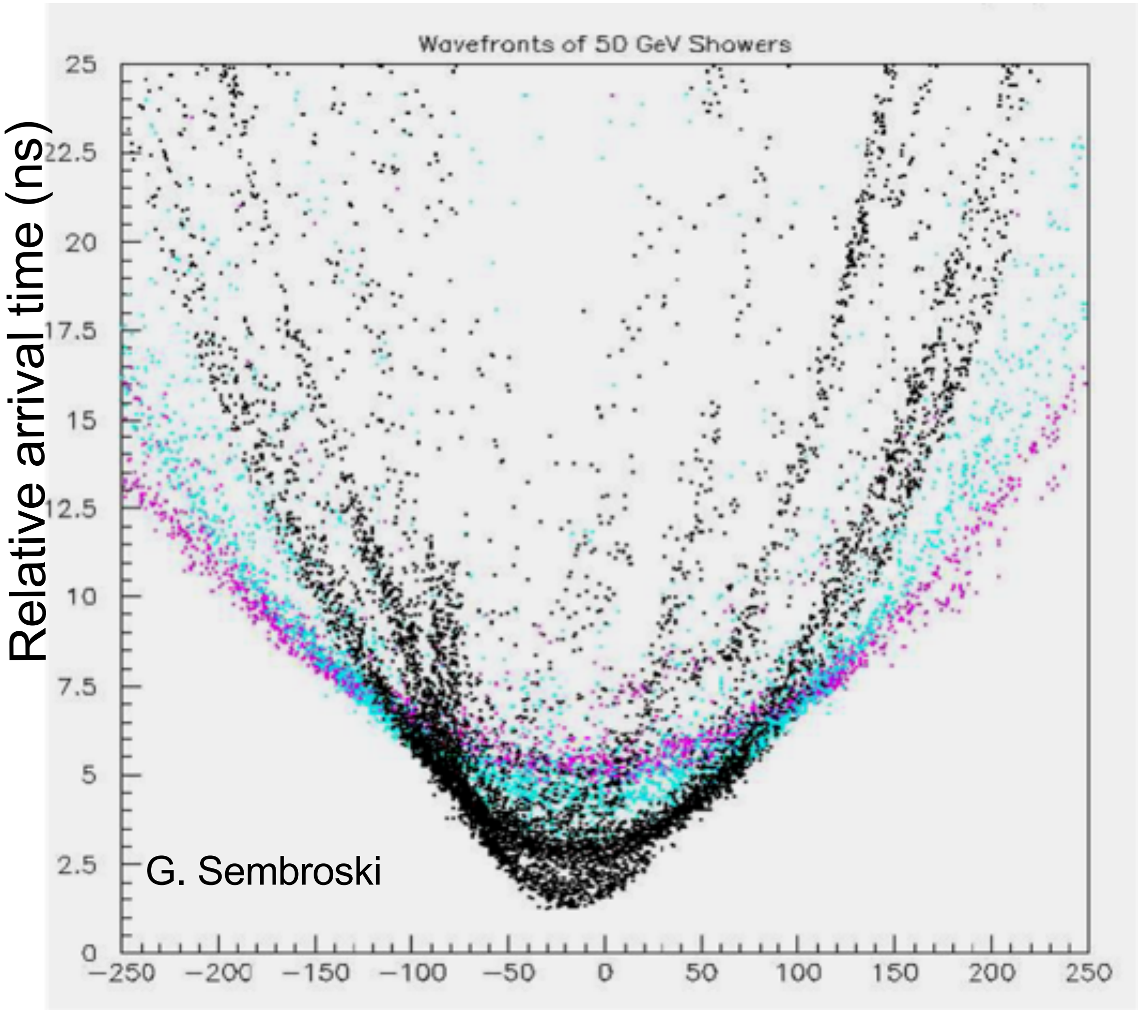
Attenuation of C-light in the atmosphere

Gets more severe at larger zenith angles, as the optical path through the atmosphere increases:

Air mass: ratio between the traversed atmospheric mass (g/cm^2) at z.a. θ and that at vertical incidence



Time structure of the C-light front



Light emitted above 10 km

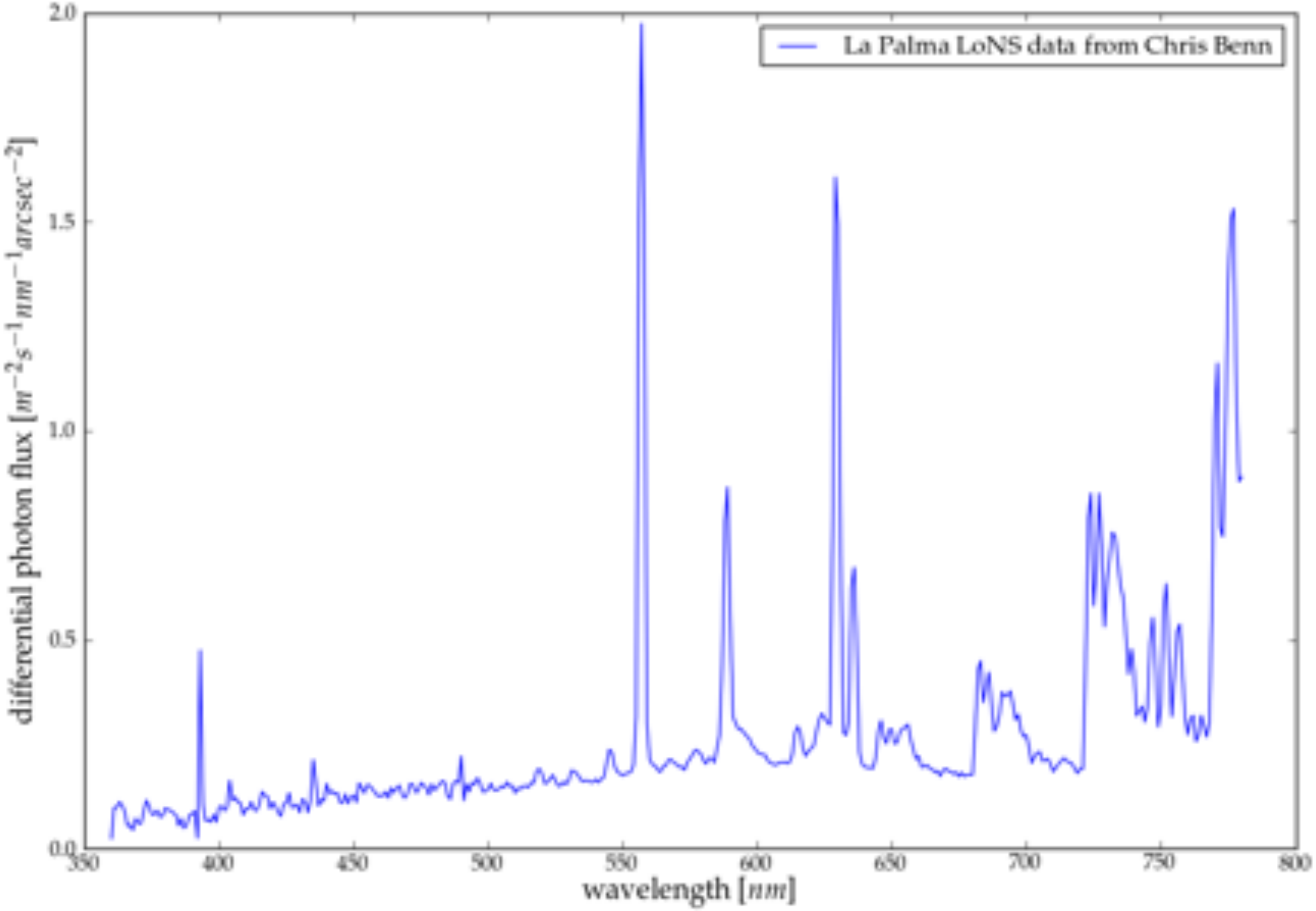
Light emitted at 6-10 km

Light emitted below 6 km

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

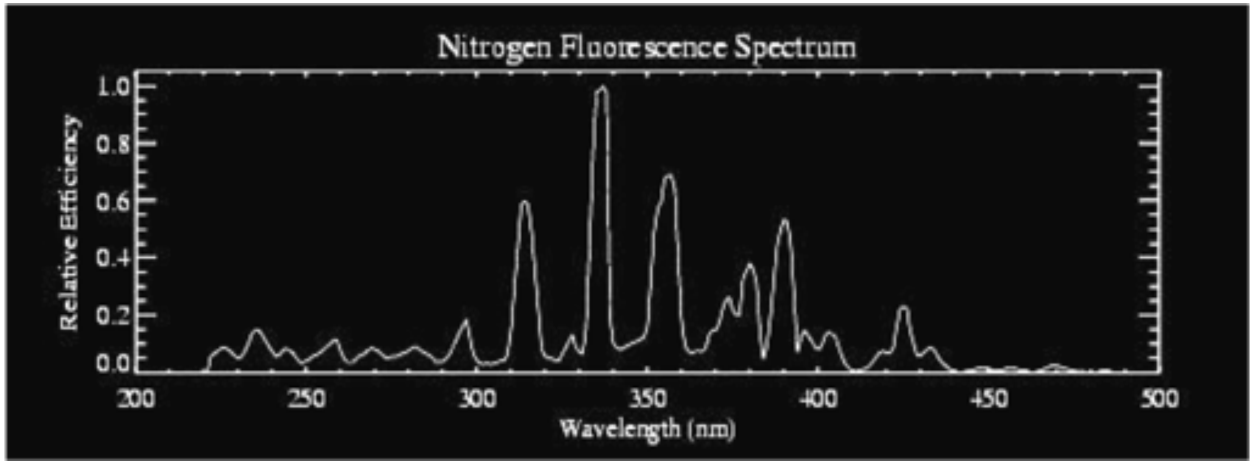
Light of Night Sky (LoNS) is a strong background emission

Integral of LoNS in 300-600nm: 2×10^{12} ph/m²·sr·s



More light from EAS: Air fluorescence

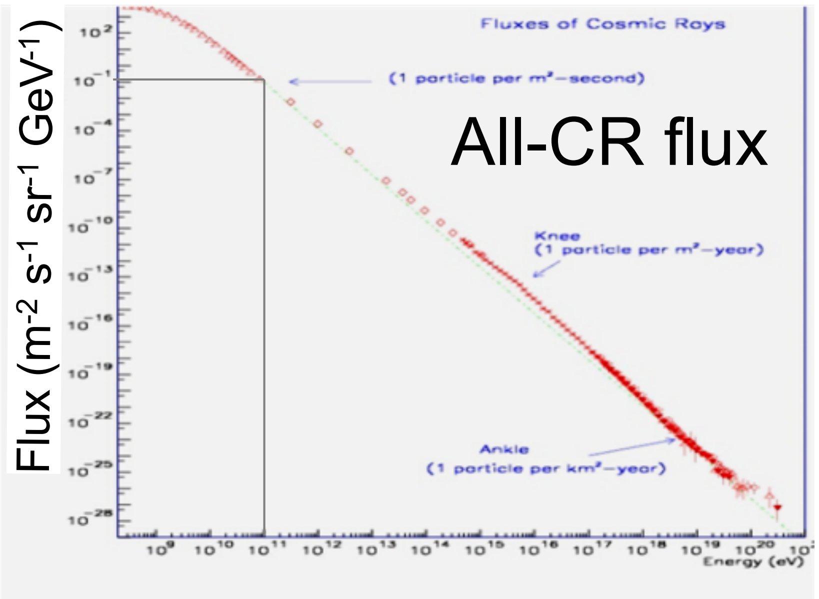
Particles of the air shower excite air molecules, which fluoresce in the UV: $N_2^* \rightarrow N_2 + h\nu$, in competition with $N_2^* + N_2 \rightarrow 2N_2$ (the excited state may also be collisionally quenched).

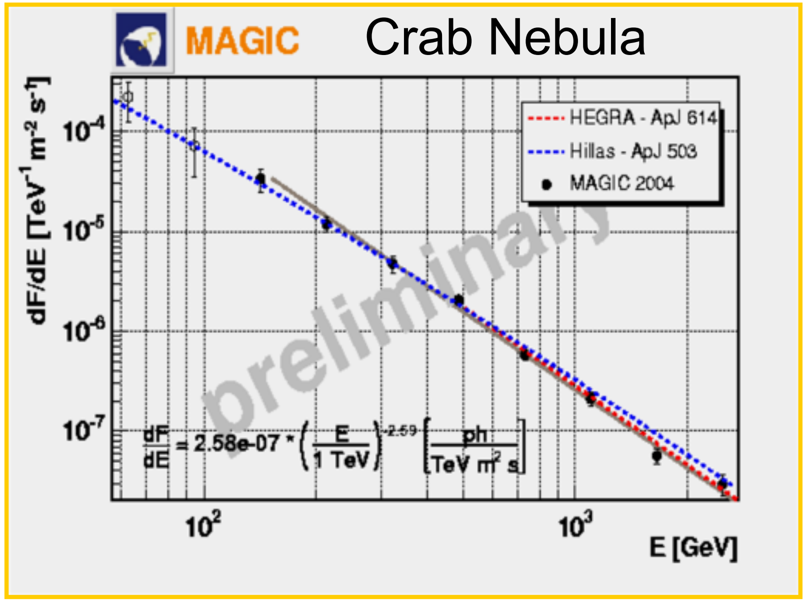


The emitted isotropic light is proportional to the number of electrons at all depths: as dE / dx per unit length goes up with higher atmospheric pressure, the efficiency of light production decreases linearly with pressure $\Rightarrow$ a fast electron produces roughly the same amount of light per unit path length at all altitudes. The downside - it is rather dim (isotropy) and is affected by atmospheric absorption.

Good news: the effects of the interaction of a VHE γ-ray in the atmosphere are spread over a large area on the ground $\Rightarrow$ very large effective areas are achievable $\Rightarrow$
VHE γ-ray astronomy is feasible despite the low fluxes

Drawback of ground-based γ-ray astronomy:





Charged CR showers are much more numerous than gamma showers (x 10^3 – 10^5), even for strong sources!

Air shower detection techniques

Detected shower component

- Cherenkov light *"Atmospheric Cherenkov detectors"*

Imaging (IACTs)

Sampling

Narrow FOV
(i.e. solar arrays)

Wide FOV
(AIROBICC, BLANCA)

- Particles (and secondary γ's) *"Air shower detectors"*

Dense sampling
(Milagro, HAWC, ARGO)

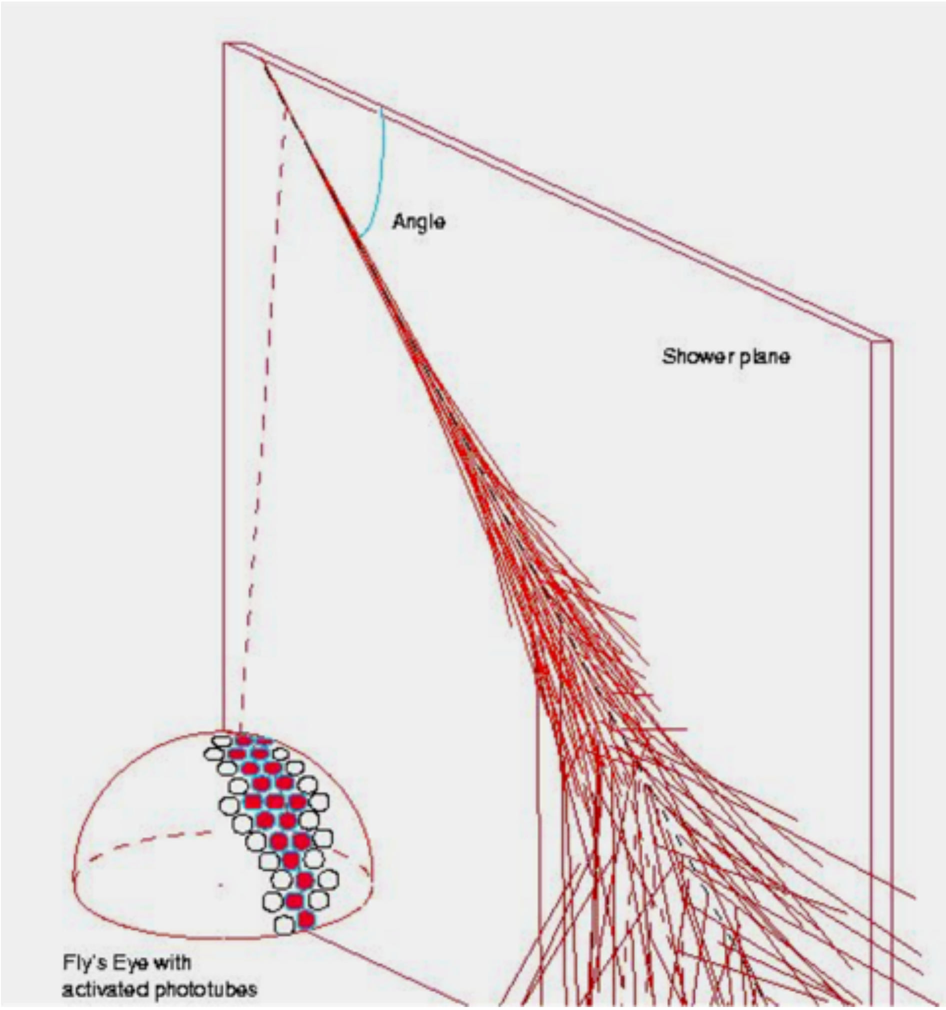
LHAASO

Coarse sampling
(Tibet AS, HEGRA, CASA)

- Fluorescence light

i.e. Fly's eye, HiRes, AUGER
Not used for γ-astronomy

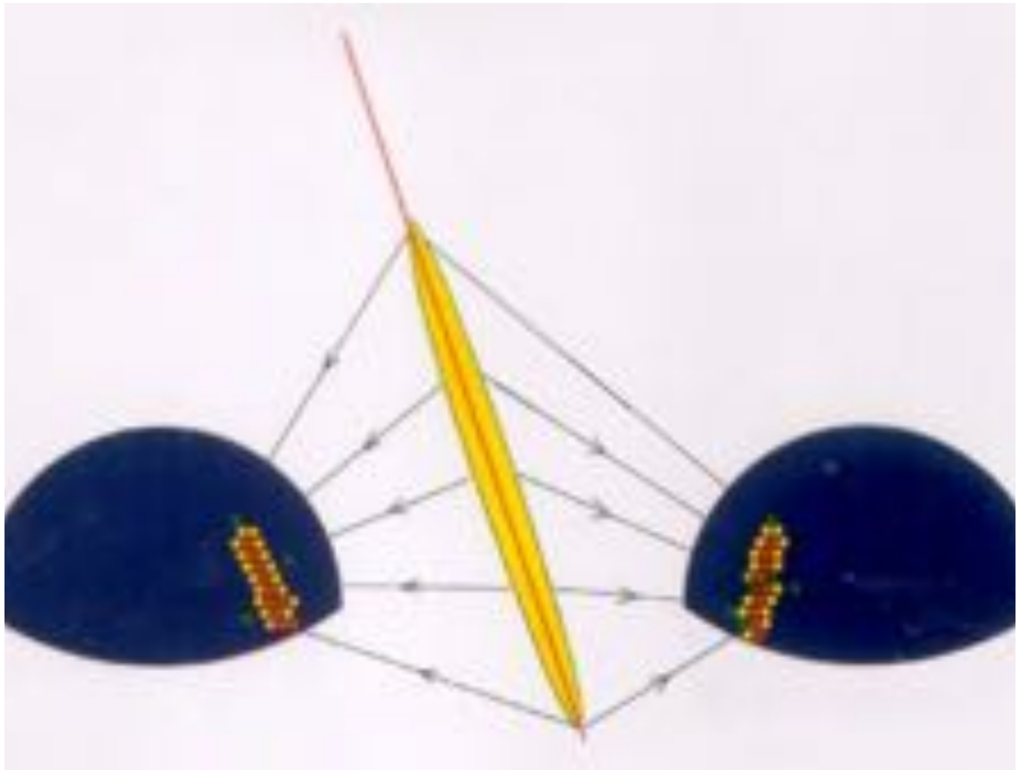
Fluorescence detectors

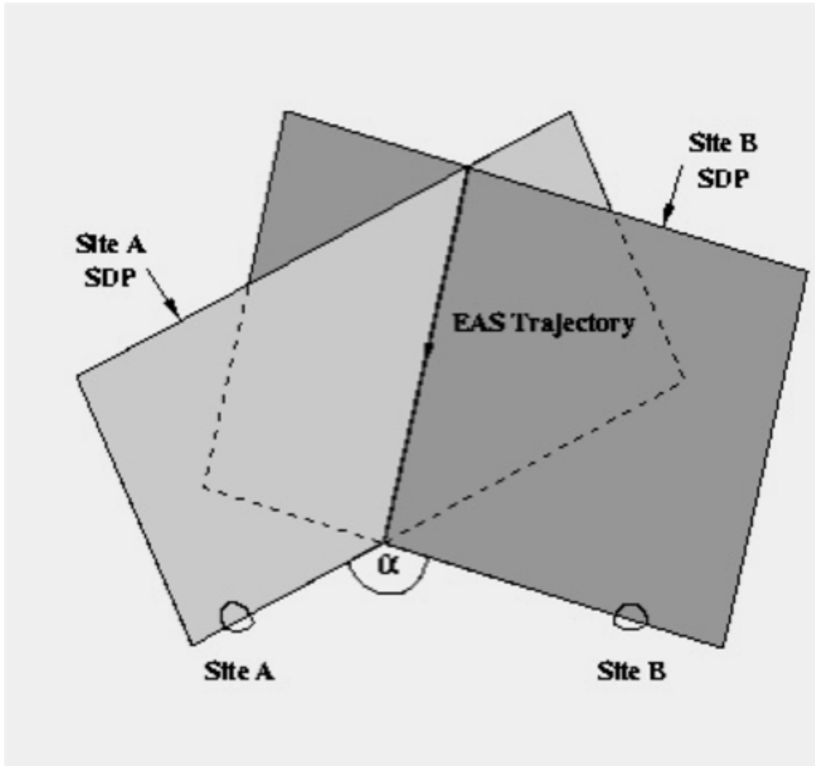


Wide field of view imaging light detector viewing the EAS "sideways" $\Rightarrow$ determination of a plane containing the shower

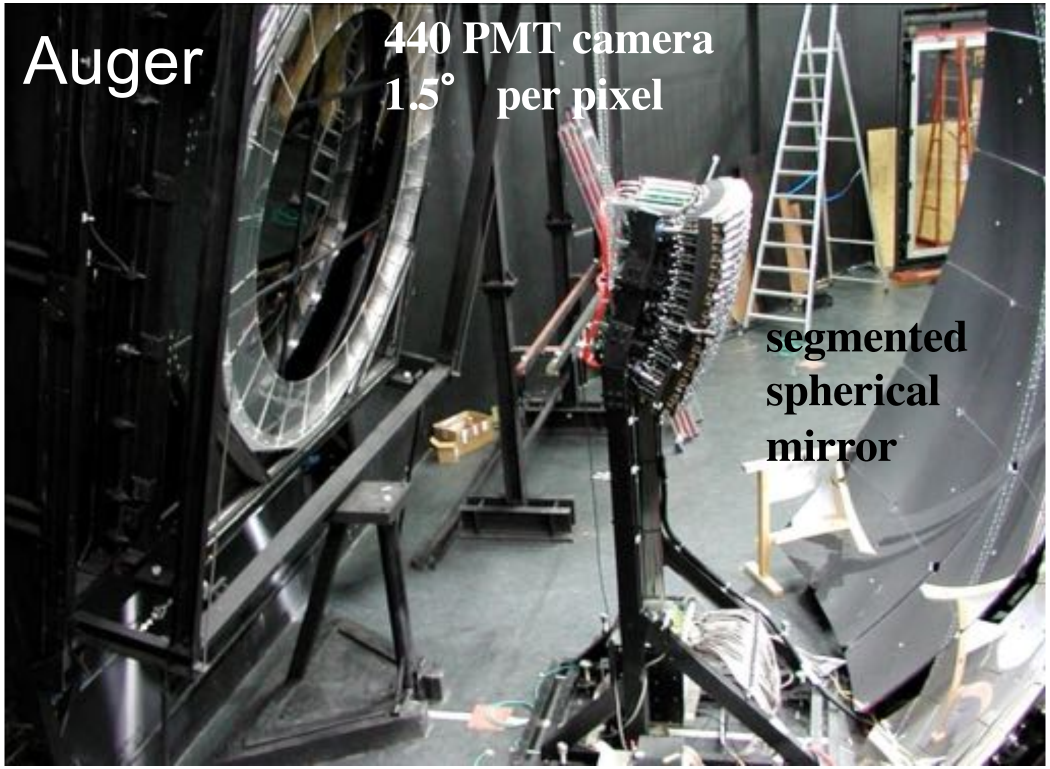
Fluorescence detectors

Stereo observations: better determination of shower direction and impact point

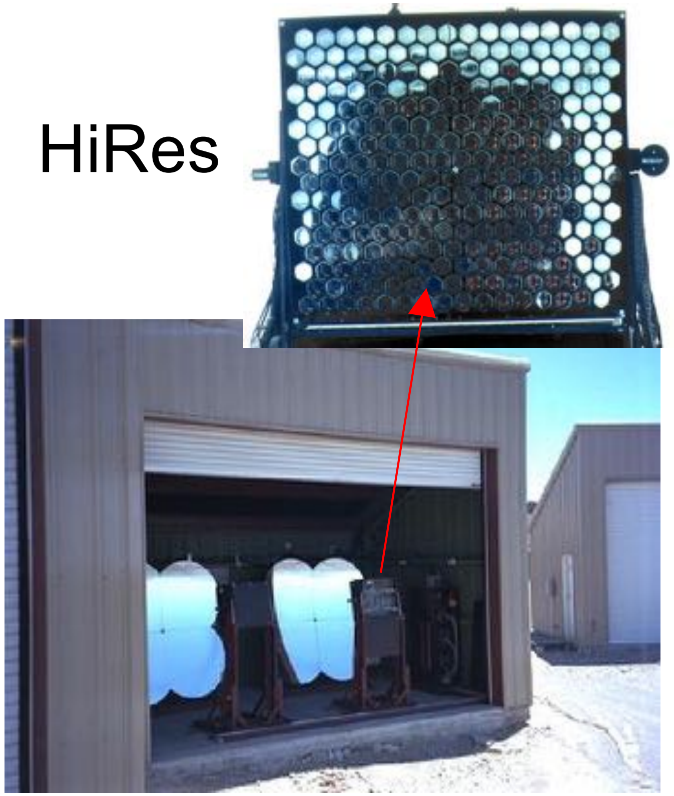




Fluorescence detectors



HiRes



Due to the low intensity of fluorescence light, these instruments are only sensitive to showers of $E > 10^{18}$ eV

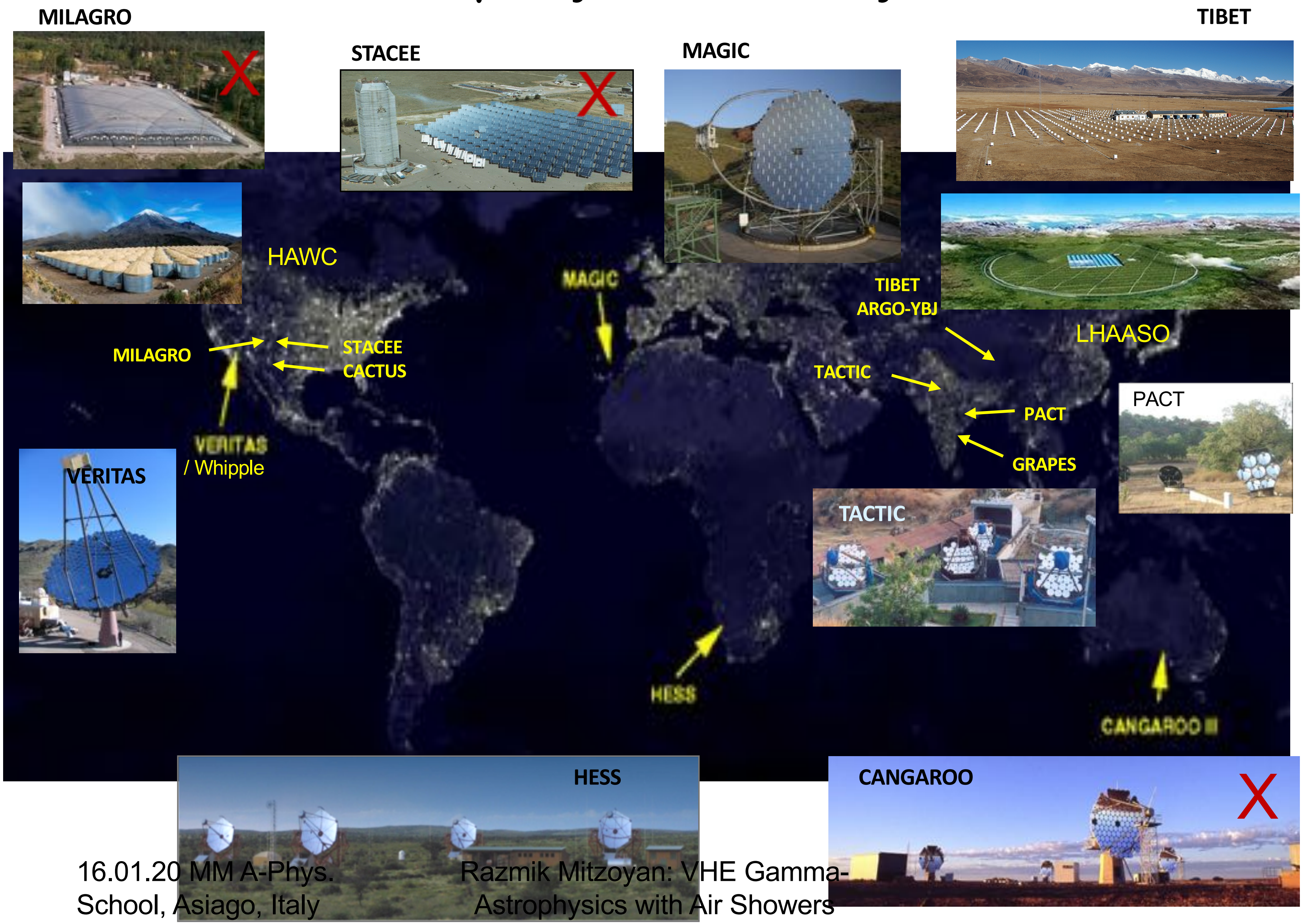
Too high a threshold for γ-ray astronomy! (but good for CR studies)

Ground-based γ-ray astronomy in the World

Experiment	Type	Location	Altitude	Specifications
~~CACTUS~~	~~AC-Sampling~~	~~Barstow, USA~~	~~640 m~~	~~144 x 42 m²~~
~~CANGAROO-III~~	~~AC-Imaging~~	~~Woomera, Australia~~	~~165 m~~	~~4 x 78 m²~~
HESS	AC-Imaging	Gamsberg, Namibia	1800 m	4 x 110 m^2
MAGIC	AC-Imaging	La Palma, Spain	2250 m	1 x 226 m^2
PACT	AC-Sampling	Pachmarhi, India	1075 m	25 x 4.5 m^2
~~SHALON~~	~~AC-Imaging~~	~~Tien Shan, Kazakhstan~~	~~3338 m~~	~~1 x 11 m²~~
~~STACEE~~	~~AC-Sampling~~	~~Albuquerque, USA~~	~~1700 m~~	~~64 x 37 m²~~
TACTIC	AC-Imaging	Mt. Abu, India	1400 m	1 x 9.5 m^2
VERITAS	AC-Imaging	Mt. Hopkins, USA	1275 m	2 x 110 m^2
~~Whipple~~	~~AC-Imaging~~	~~Mt. Hopkins, USA~~	~~2250 m~~	~~1 x 78 m²~~
ARGO-YBJ	Air Shower	Yangbajing, Tibet	4300 m	4000 m^2
GRAPES-III	Air Shower	Ooty, India	2200 m	288 x 1 m^2
~~Milagro~~	~~Air Shower~~	~~Los Alamos, USA~~	~~2630 m~~	~~4800 m²~~
Tibet	Air Shower	Yangbajing, Tibet	4300 m	761 x 0.5 m^2
		LHAASO	4400	~1 km²

Rene Ong, 2005

Ground-based γ-ray astronomy in the World

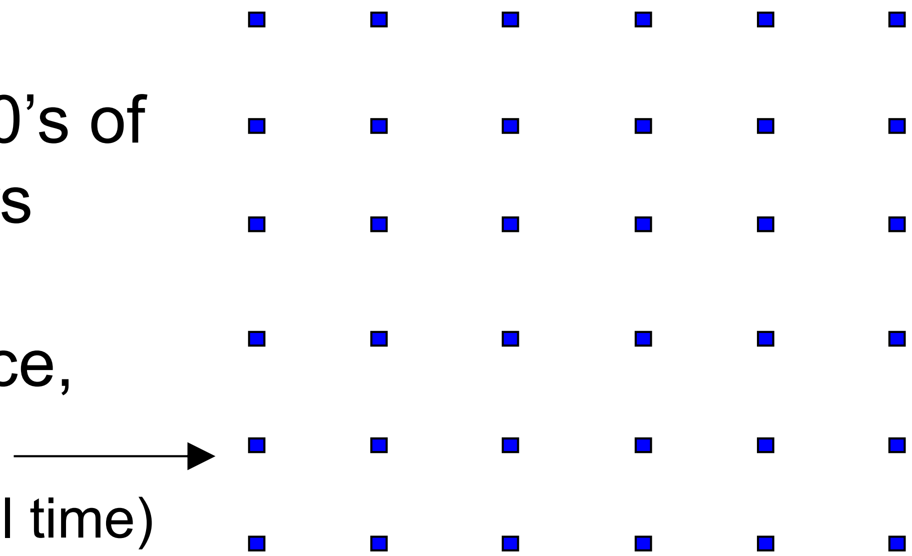


“Air Shower” detectors

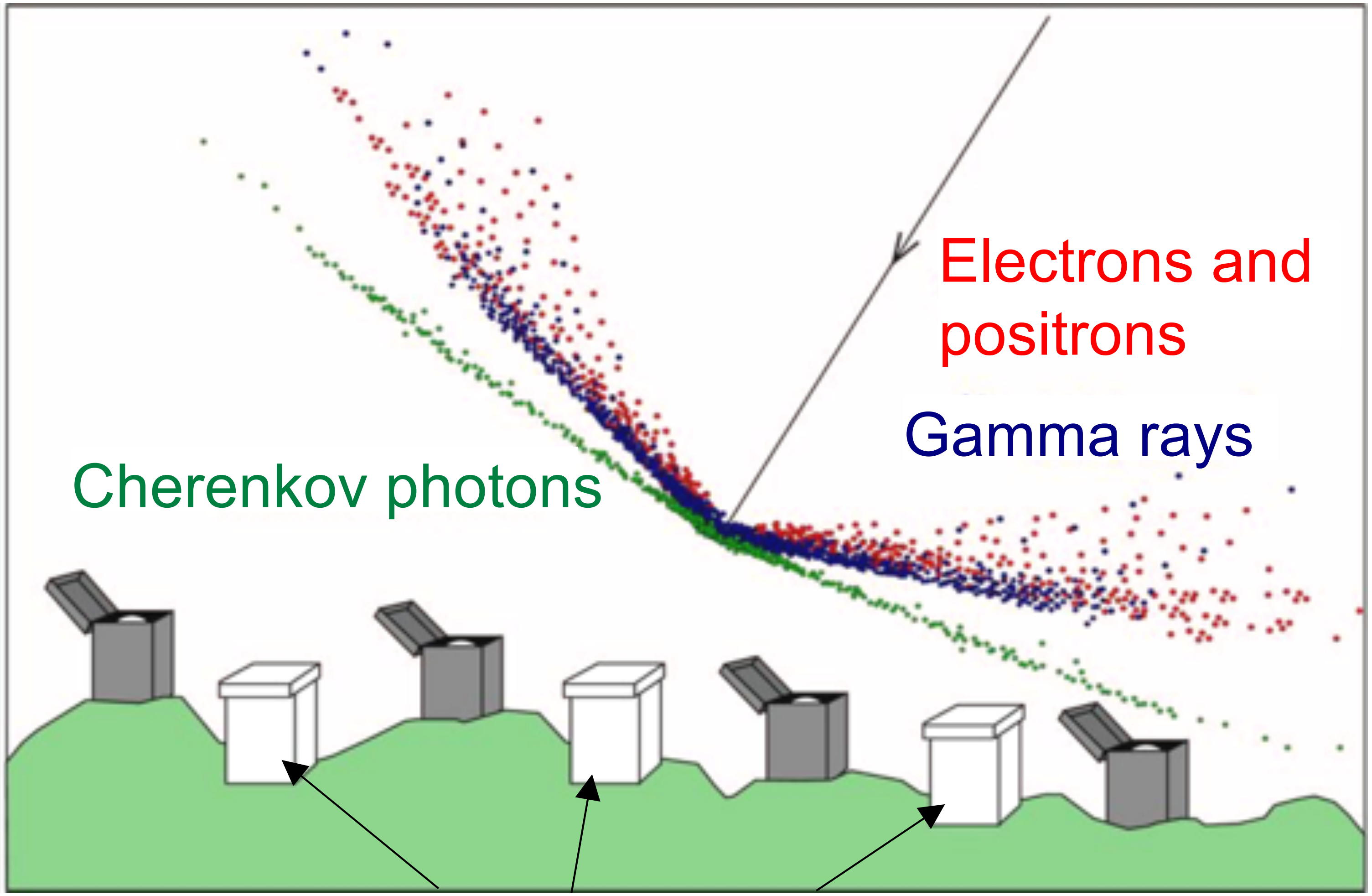
By this name we refer to instruments based on the *direct* detection of the shower secondary particles and gamma rays

By *direct* I mean that the $e^{\pm}$ and the secondary gamma rays actually enter the man-made artifacts (hence excluding atmospheric Cherenkov devices)

Typical air shower detector: array of ~100’s of ~1m^2 particle detectors spread over >10^4 m^2 operated in coincidence, measuring $\rho(x_i, y_i, t_i)$
(particle density and arrival time)

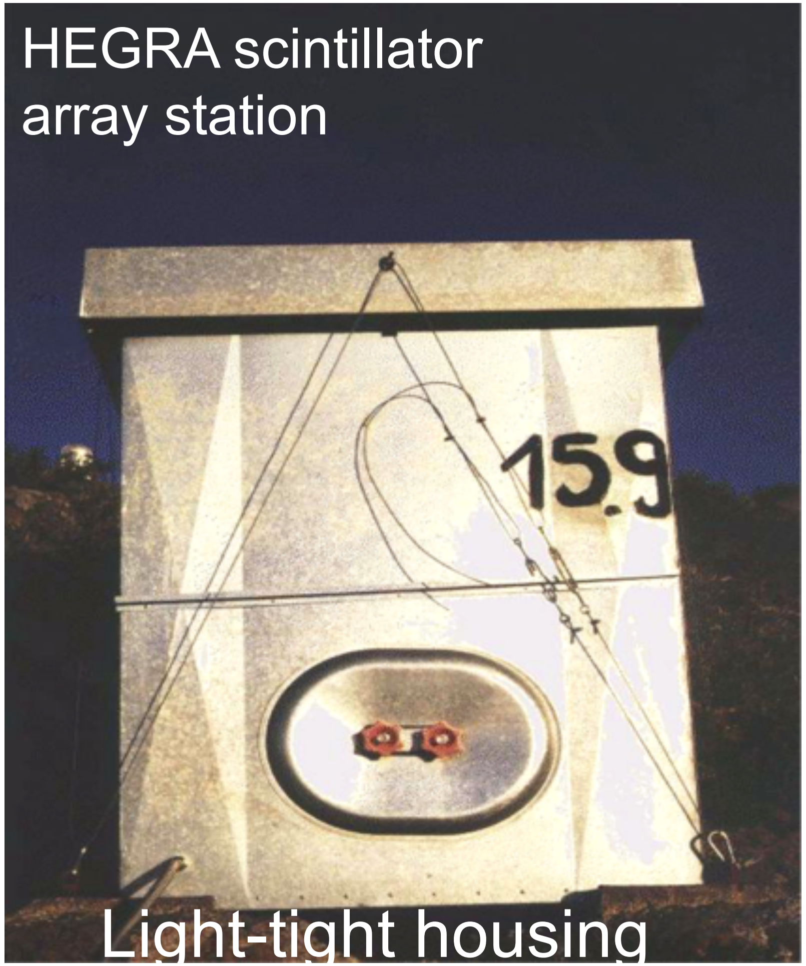


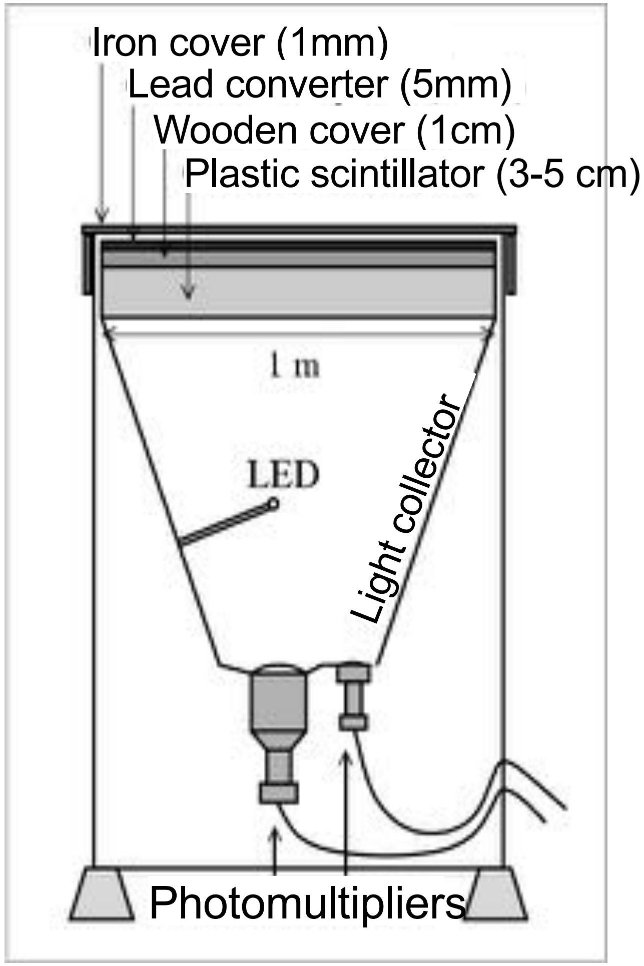
Air Shower arrays



Particle detectors

Typical AS array detector station: Scintillator + PMT(s)





Measured light $\propto$ number of charged particles.

Led converter (~1 R.L.) to turn γ's into detectable $e^{\pm}$ pairs

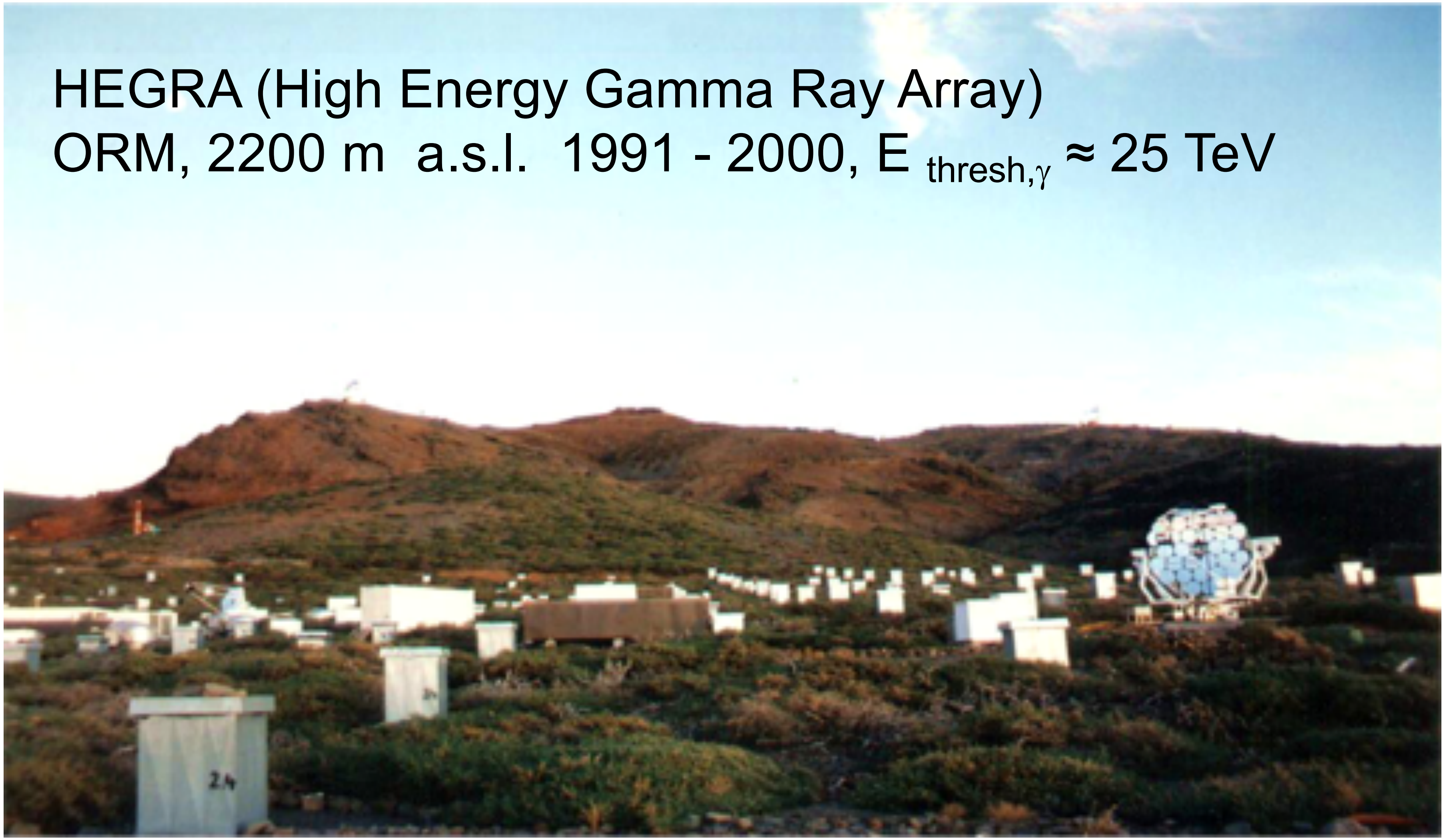
Air Shower arrays

Common additional component of AS arrays: muon detectors, aiming at the discrimination of hadron-initiated showers through their muon content

One just needs a particle detector protected from γ's and $e^{\pm}$ by a thick shield

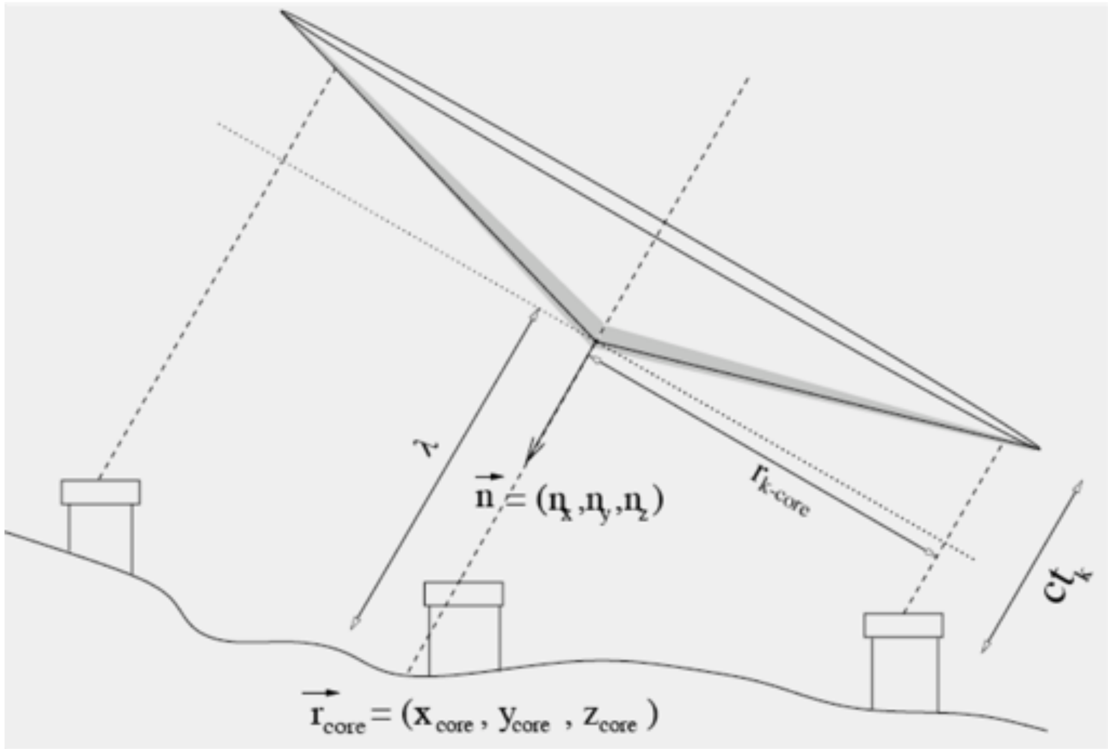
The HEGRA scintillator array

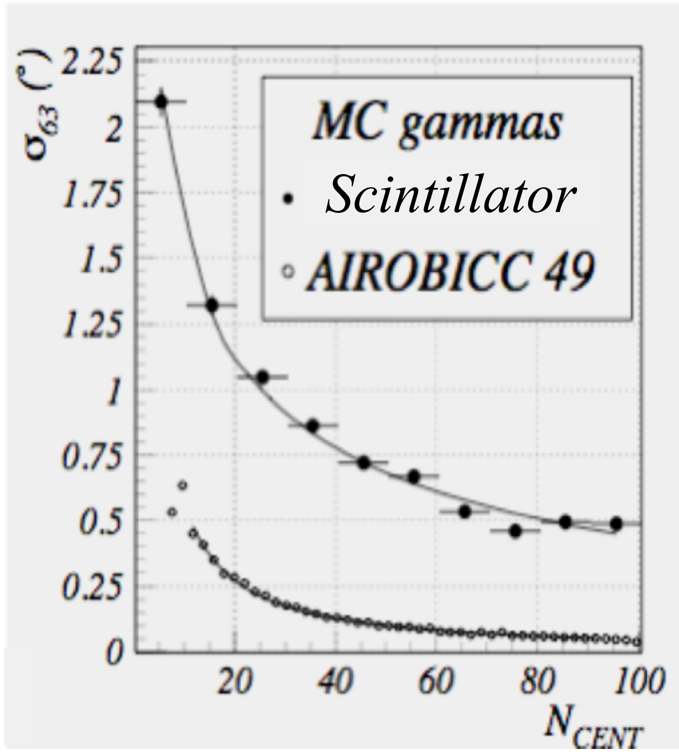
HEGRA (High Energy Gamma Ray Array)
ORM, 2200 m a.s.l. 1991 - 2000, $E_{thresh,\gamma} \approx 25$ TeV



Reconstruction of the shower direction

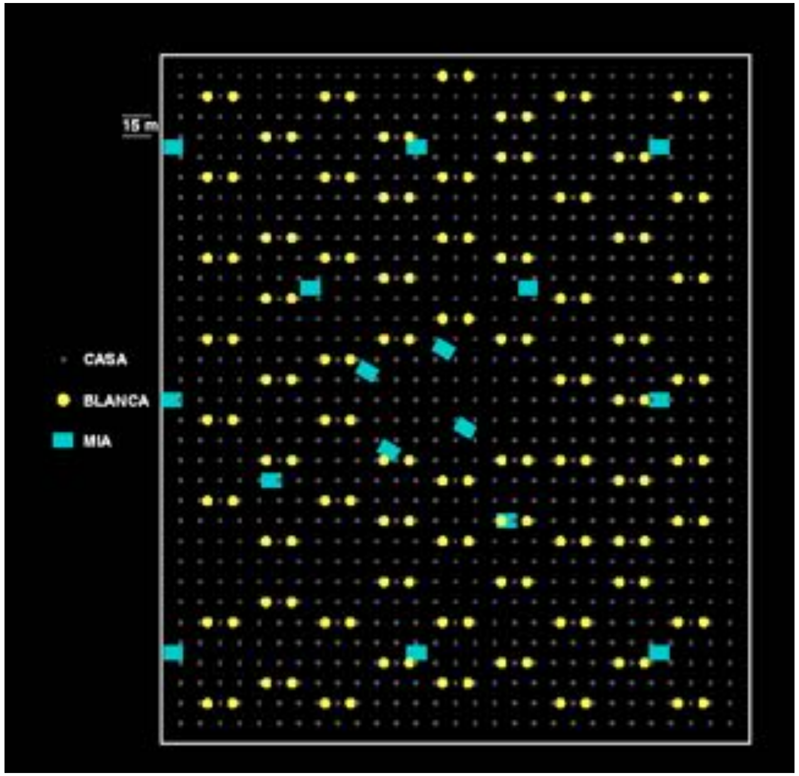
Relies on the determination of the arrival time at the stations with ~ns precision, and on fitting the shower front to a t(x,y) model (a cone for instance). Achievable angular resolution 0.5 - 1° , energy dependent





CASA-MIA

Ground array - Chicago Air Shower Array (Dugway, Utah)

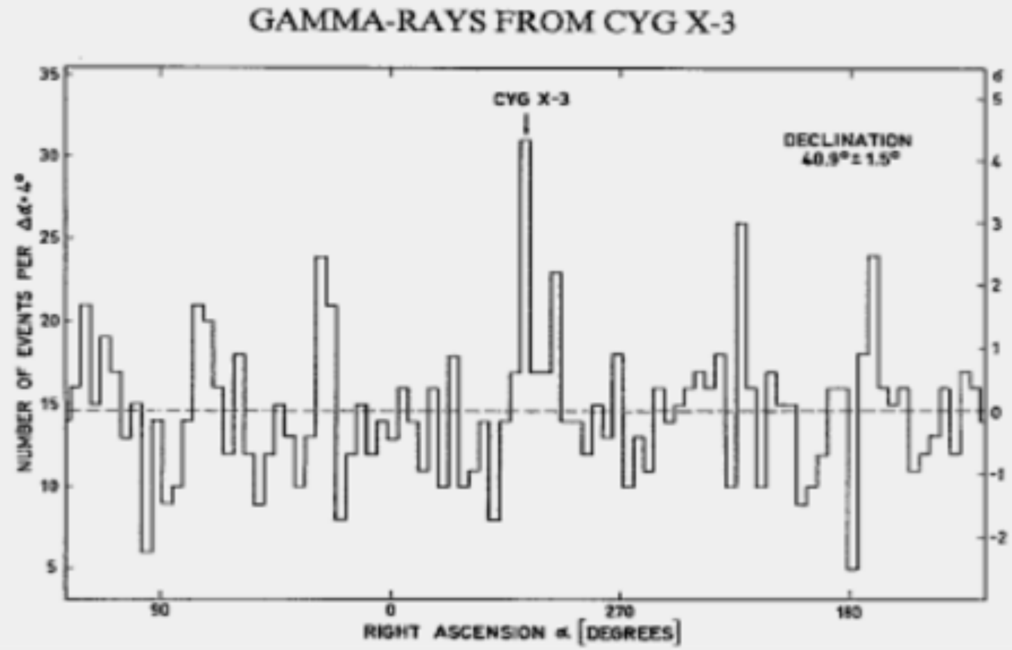


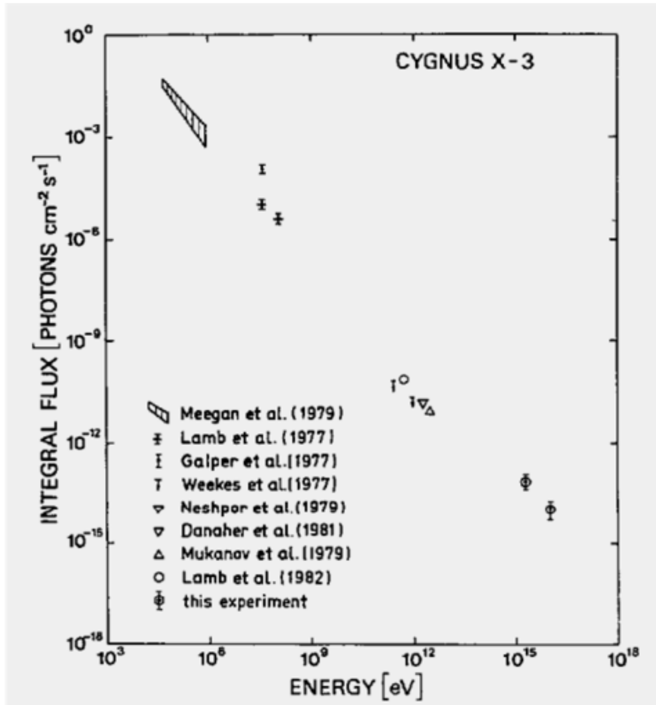
Early results from AS arrays

Air shower experiment at Kiel (HEGRA predecessor) : signal ($4.4\ \sigma$) from Cygnus X-3 above 10^{15} eV, modulated with the 4.8 h period of the system

This and other early claims of source detections by AS arrays were **not** confirmed by later, more sensitive experiments

Samorski and Stamm, ApJ 268 (1983)



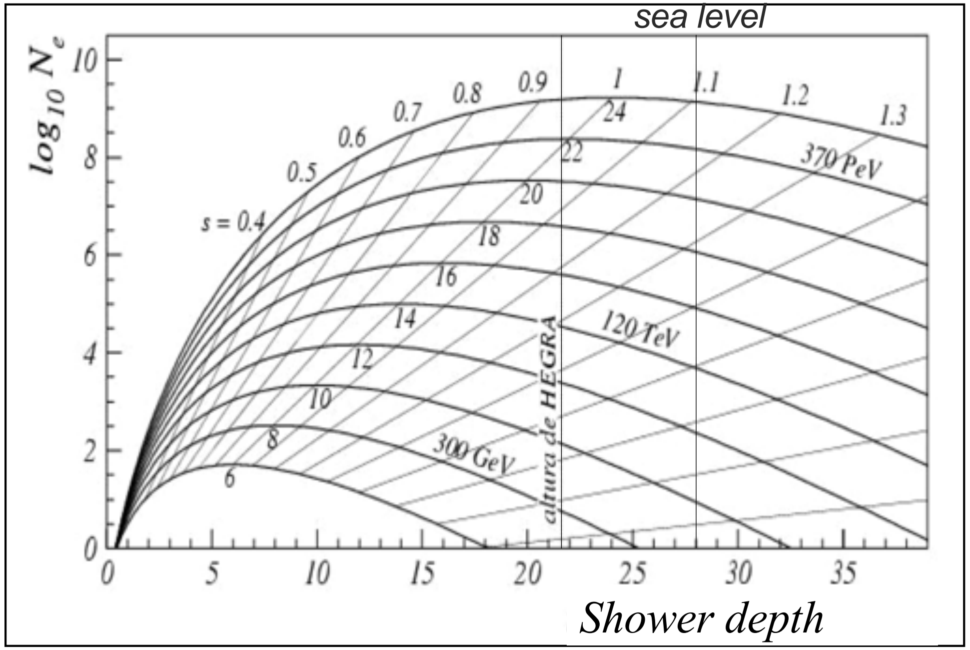


Early results from AS arrays

- Despite the many claims of various sources, no AS experiment detected the Crab Nebula with > 5 σ statistical significance until the late 90's (Tibet AS array)
- This was achieved mainly through a reduction in energy threshold (resulting in more events, both signal and background)

How to lower the threshold of an Air Shower detector?

The threshold of an AS detector is dictated by the number of detected particles. Two ways to increase this number:

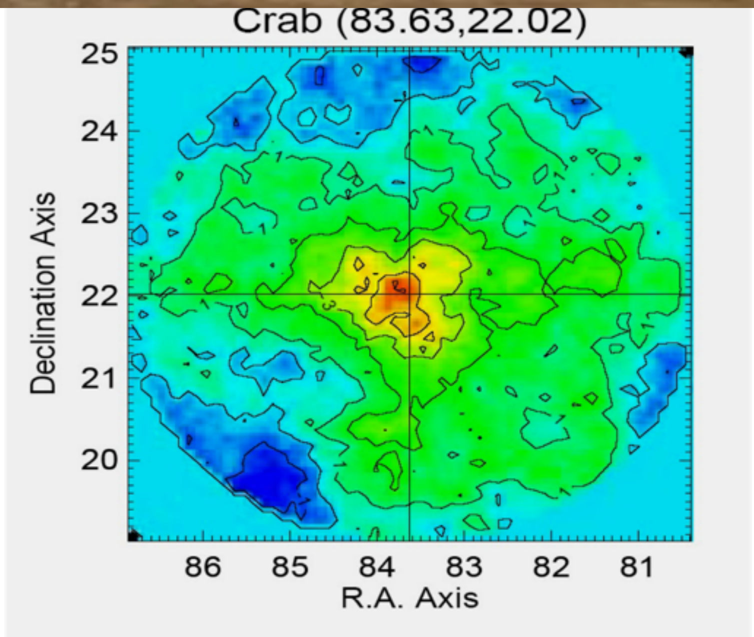


- Put the detector higher in the atmosphere

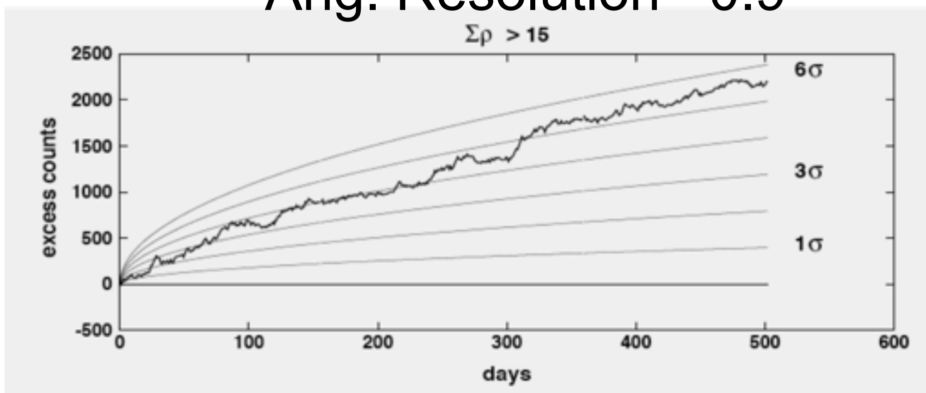
- Make a denser sampling of the shower front (1% or less active area in a typical scintillator array)

Tibet Air Shower array

4300 m a.s.l., Yangbajing



Ang. Resolution ~0.9˚

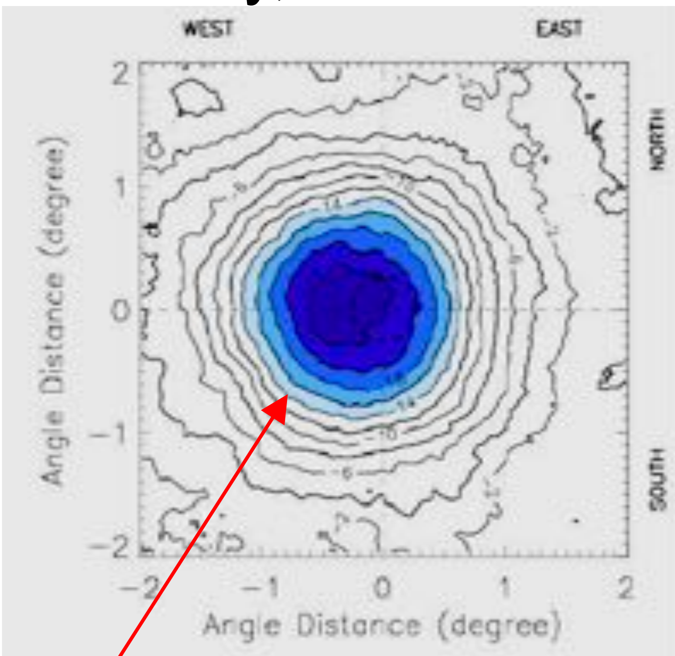


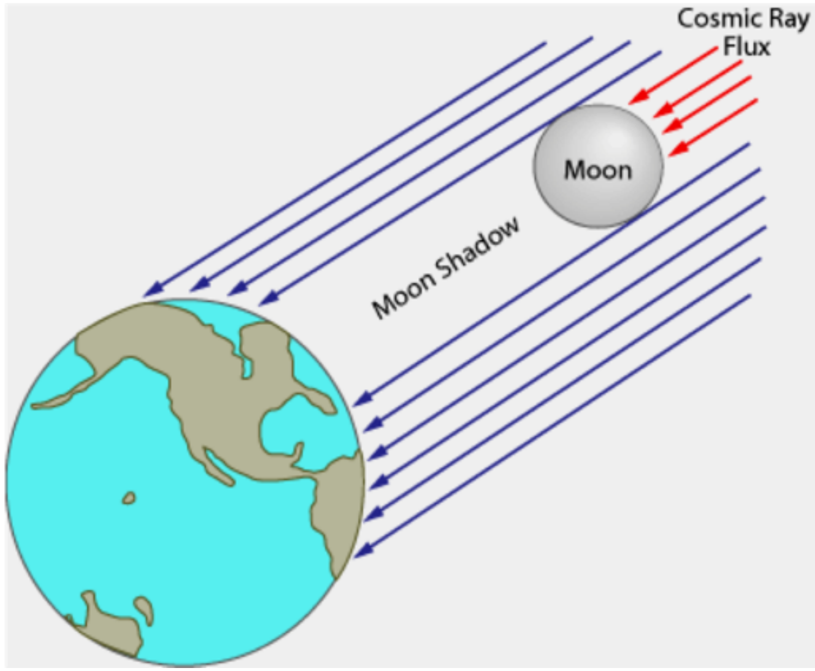
1999: Crab detection above 3 TeV (5.5 σ) in 500 days

Checking the pointing of an AS detector

Both the Moon and the Sun shadow the flux of charged CR. This is used by AS detectors (with ~100% duty cycle) to check their pointing

Tibet array, Moon shadow

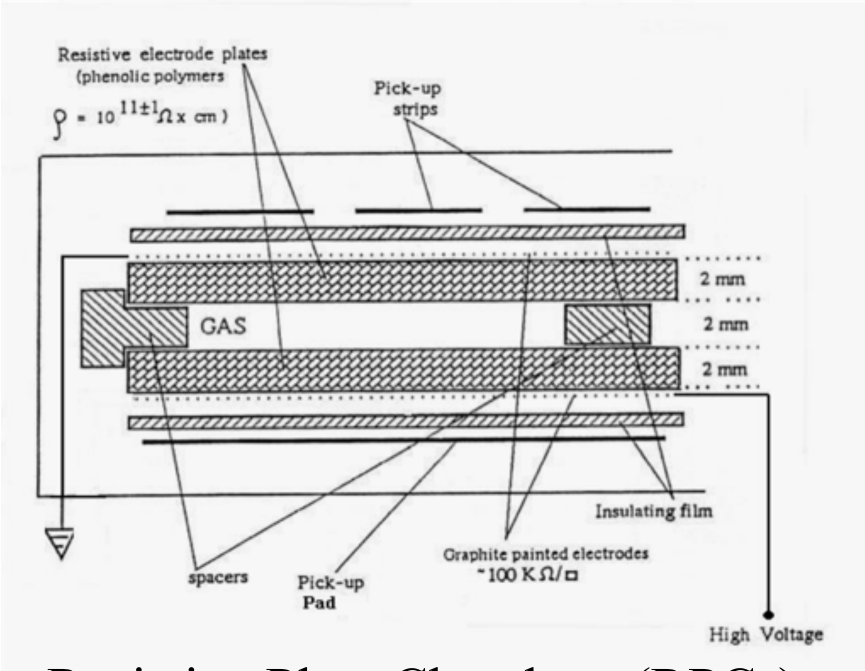




Shifted to the W due to the Earth's magnetic field

ARGO-YBJ

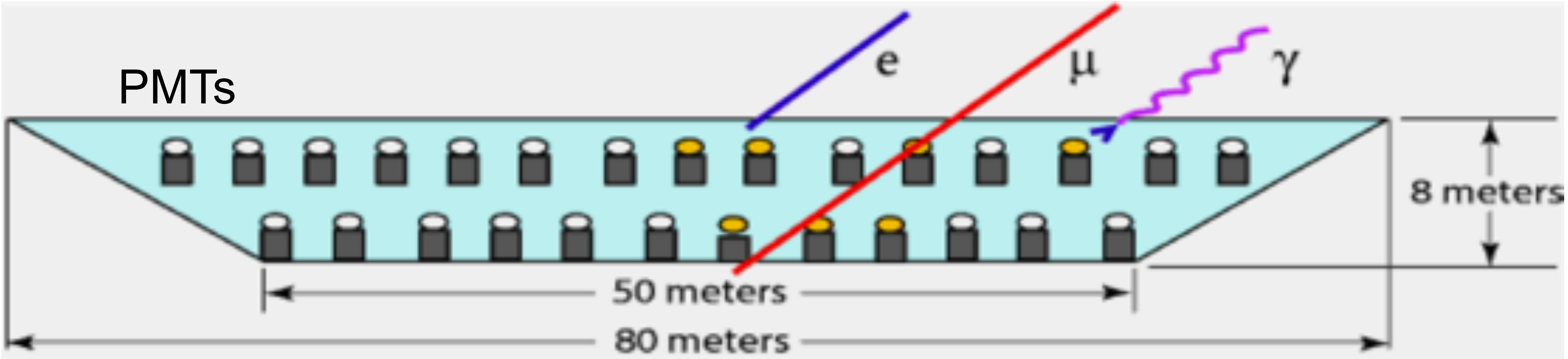
Going further down in E: better coverage of the detection area

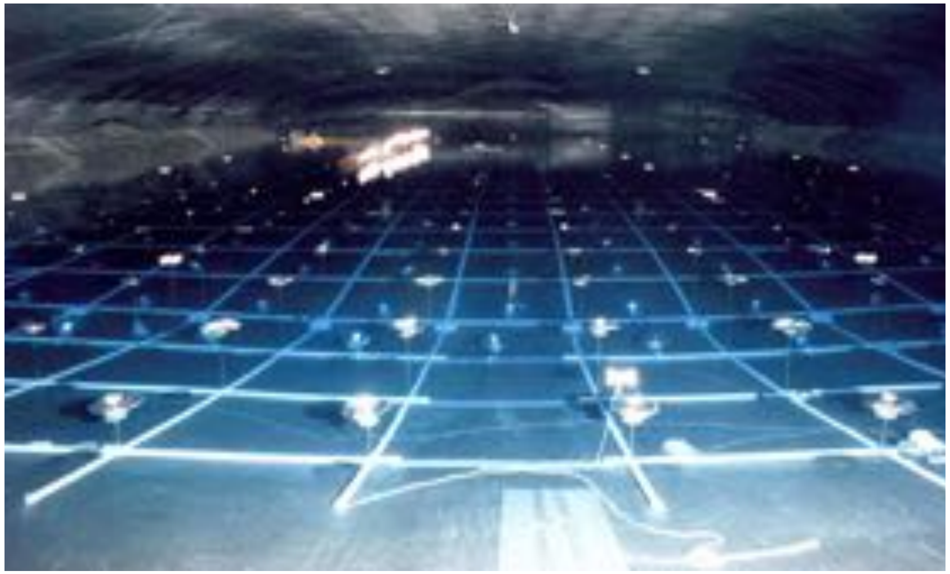


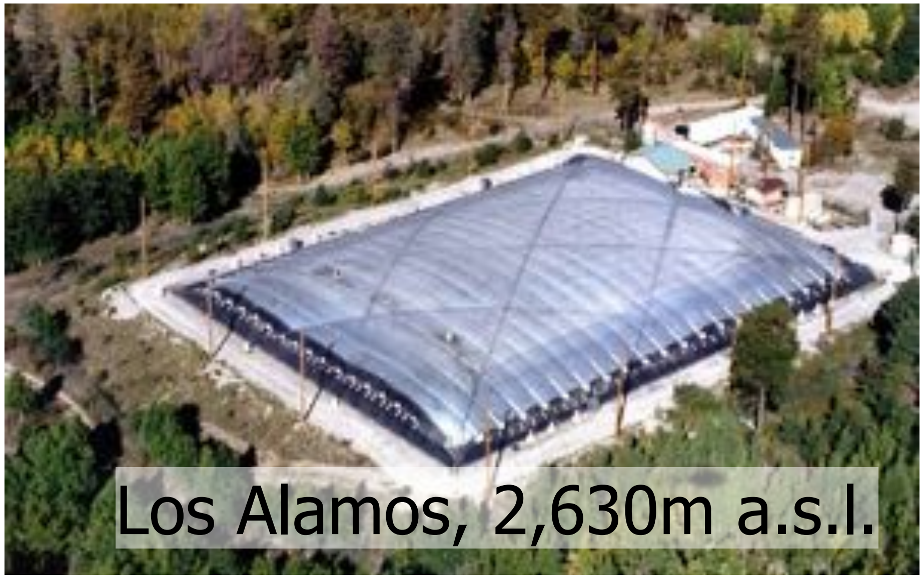
Resistive Plate Chambers (RPCs) are gaseous ionisation detectors with parallel resistive electrodes
Good time and spatial resolution

MILAGRO (moved to → HAWC)

Achieves full coverage in a different way: Cherenkov light emission in water

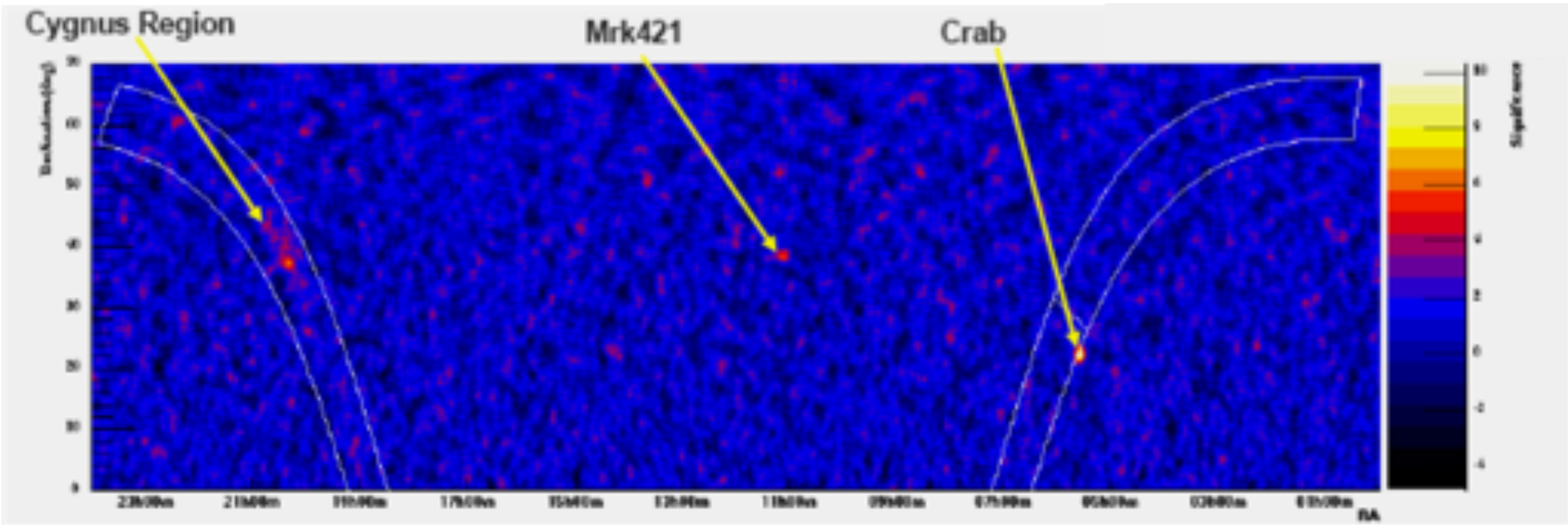






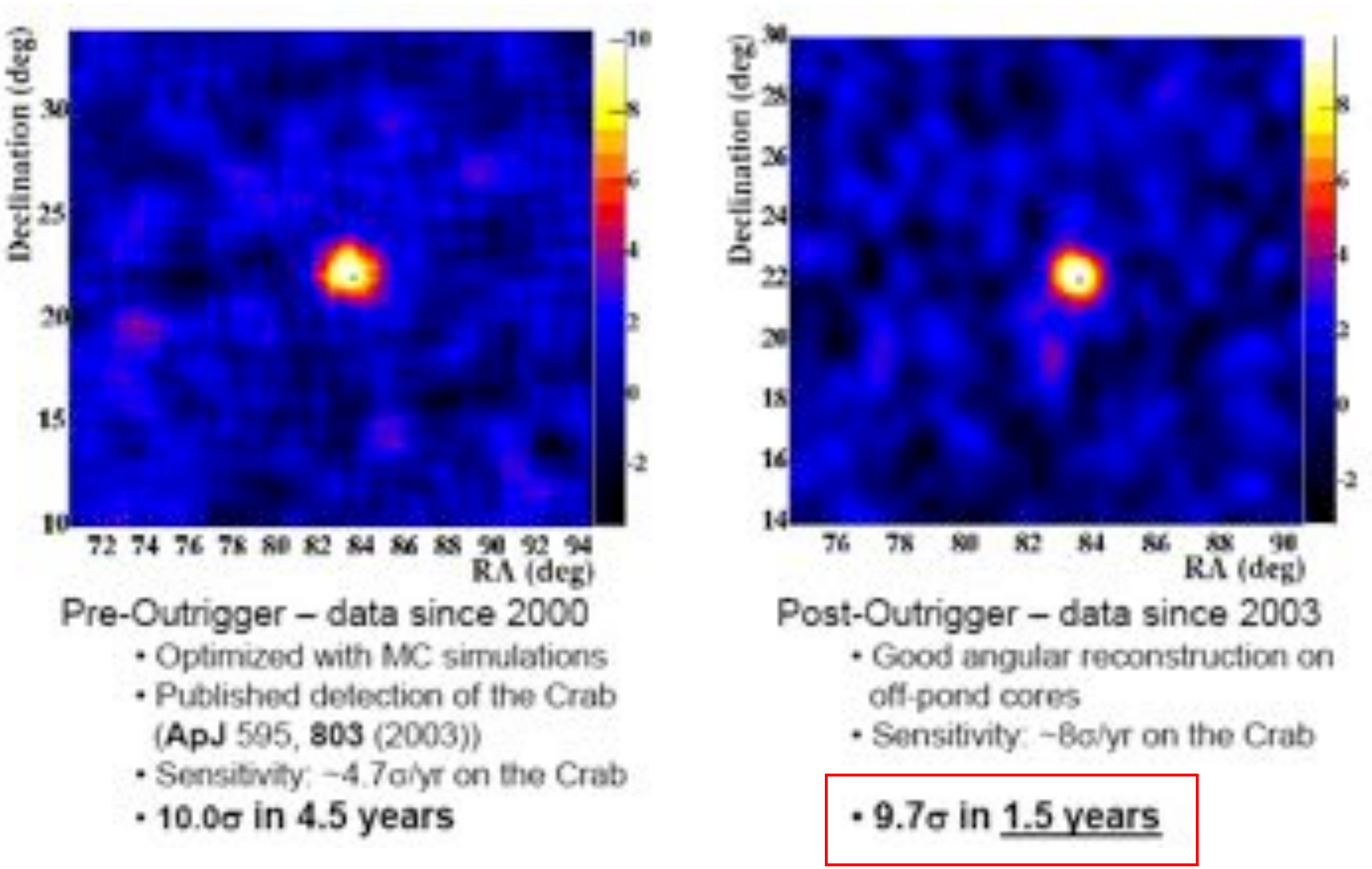
MILAGRO

Some suppression of the background of hadron-initiated showers is possible through the so-called *compactness* parameter. MILAGRO has successfully detected Crab and Mrk 421, and claims an extended source in the Cygnus region



4.5 years of data, $E_{thresh} \approx 2$ TeV

MILAGRO sensitivity



HAWC

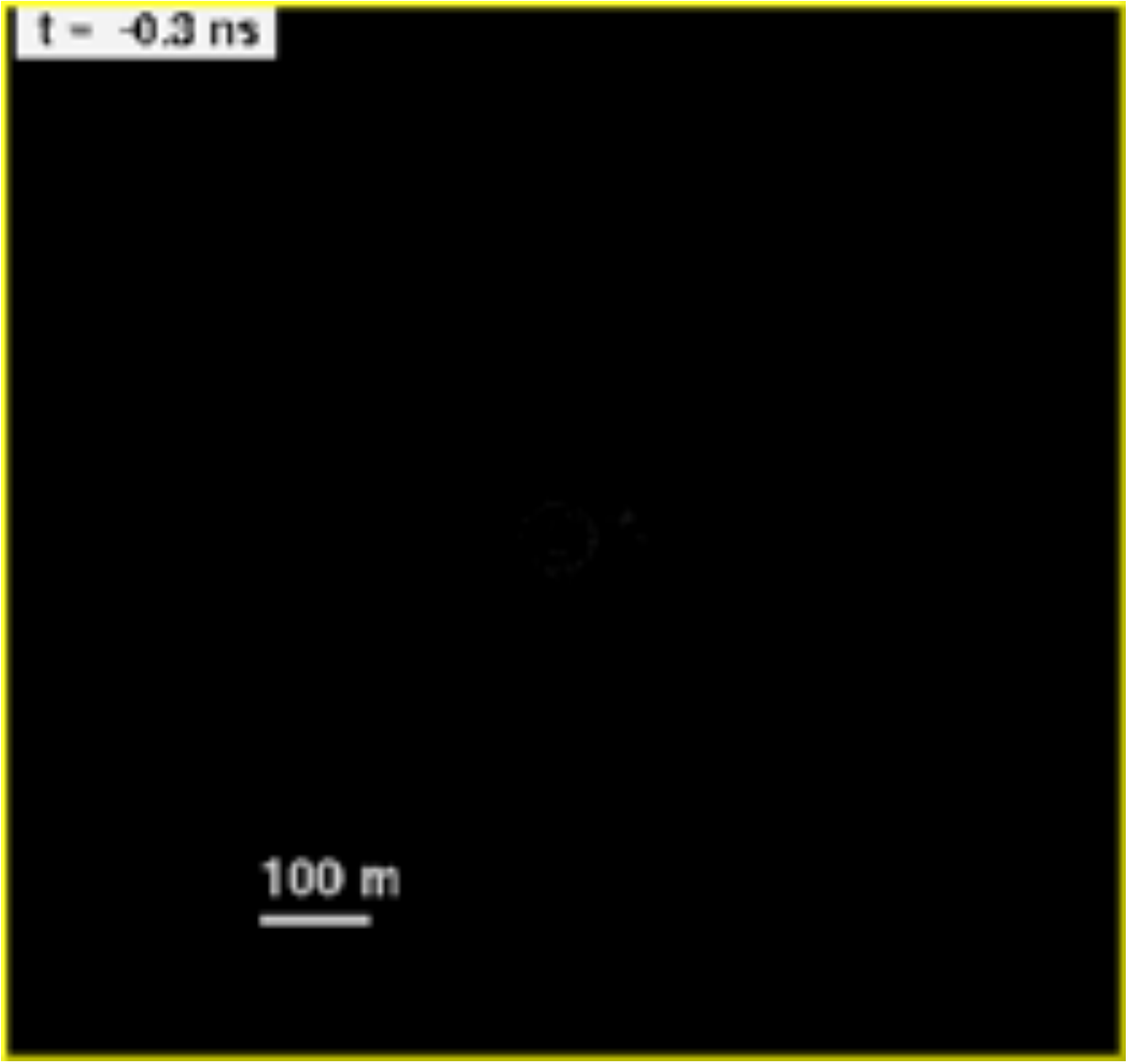
HAWC

HAWC is located at an altitude of 4100 meters on the slope of the Volcanoes Sierra Negra and Pico de Orizaba at the border between the states of Puebla and Veracruz in Mexico.

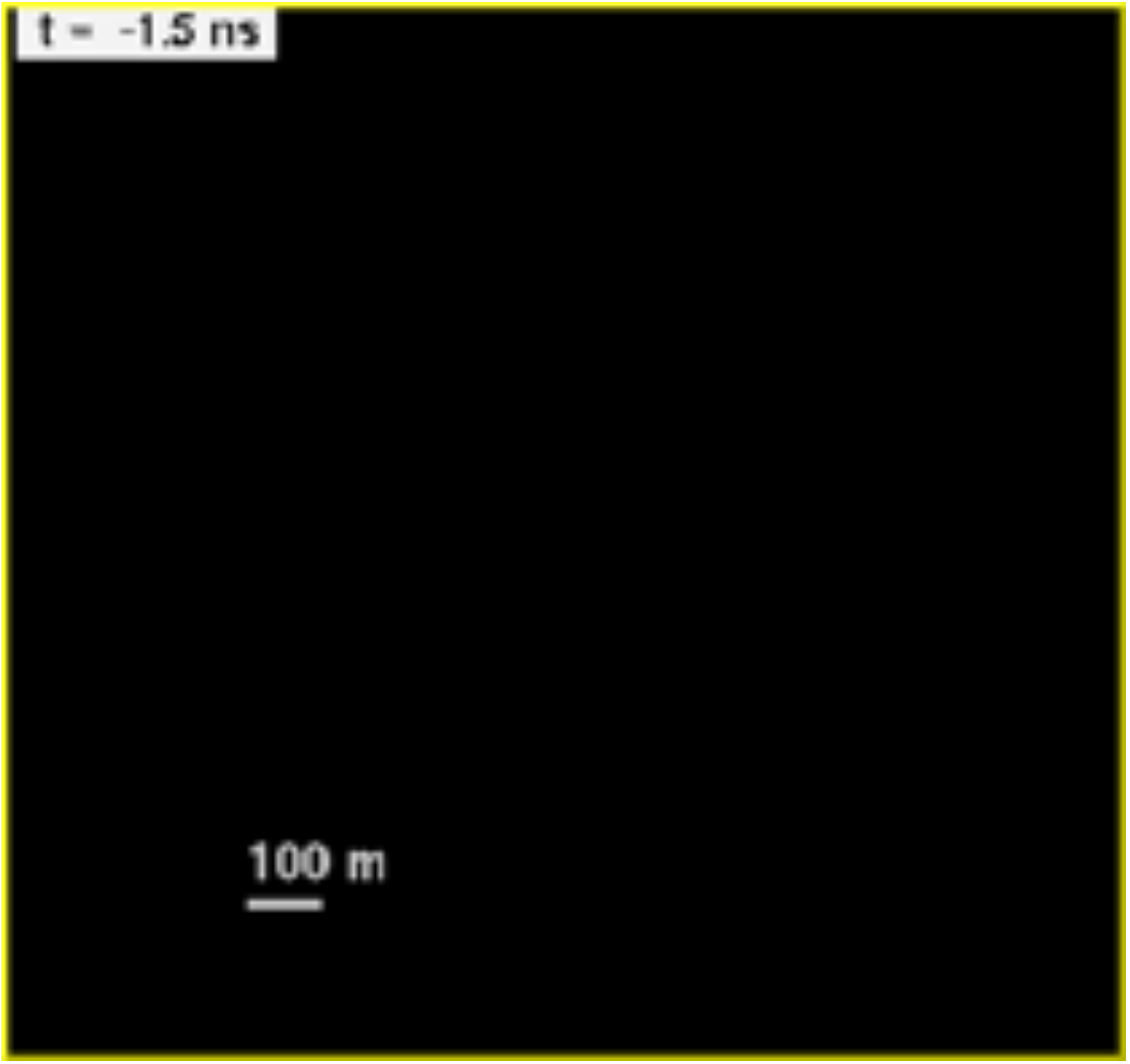
Currently all 300 Cherenkov detectors are deployed and taking data. Each Cherenkov detector consists of 180,000 liters of extra pure water stored inside an enormous tank (5 meters high and 7.3 meters in diameter) with four highly sensitive light sensors fixed to the bottom of the tank

Inauguration of HAWC, Mexico, 20.03.15

A 100 GeV γ-ray event on the ground

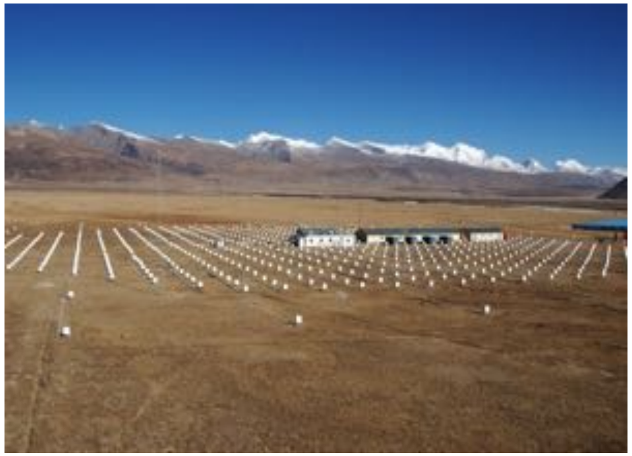


A 200 GeV proton on the ground

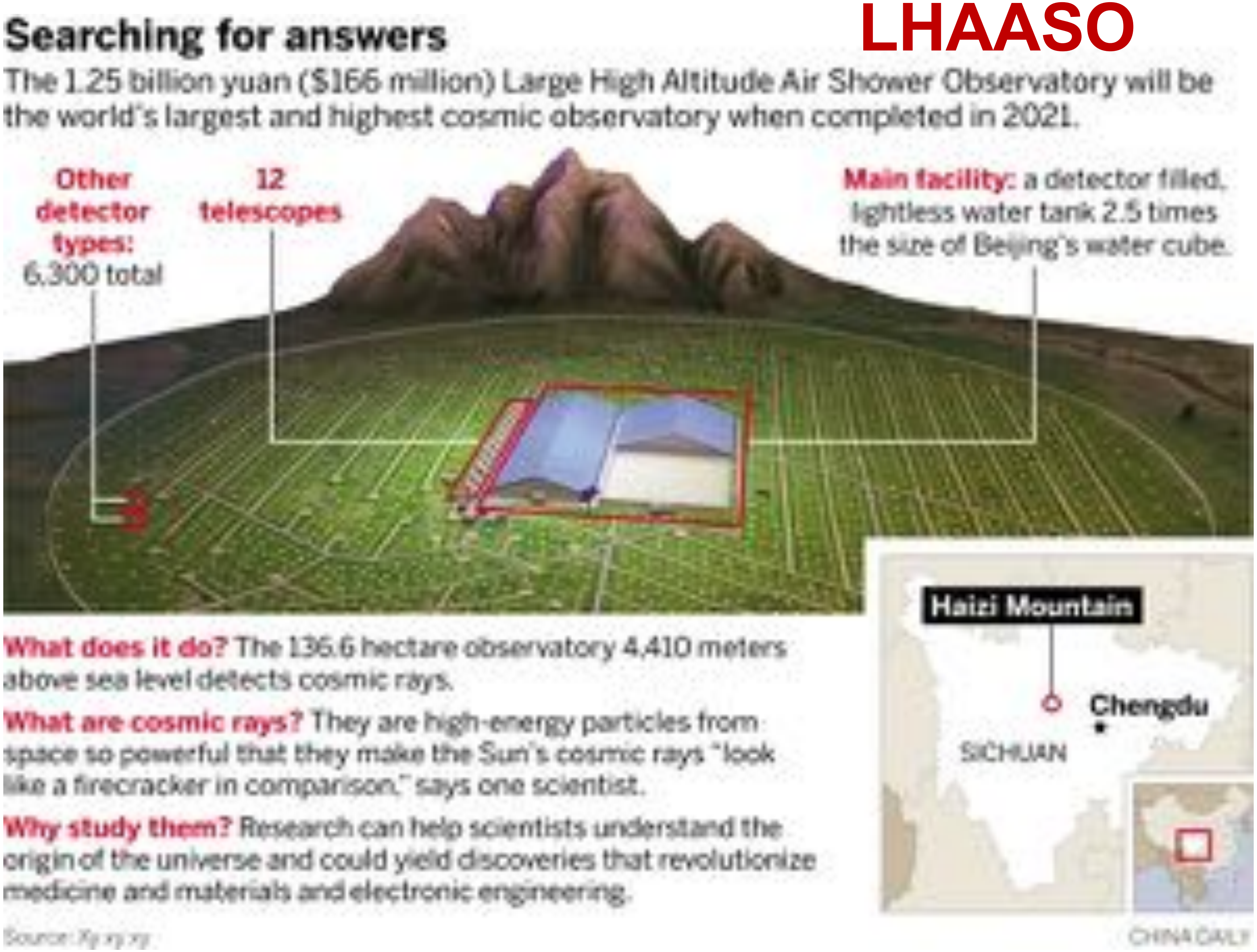


Flux sensitivities of Wide-angle AS instruments

	Threshold	Sens. (1 yr)
Milagro	~ 2 TeV	~ 0.5 Crab
(HAWC:		x 20 Milagro)
Tibet III shower array	~ 3 TeV	~ 1 Crab
ARGO YBJ	0.5 – 1 TeV	~ 0.3 Crab



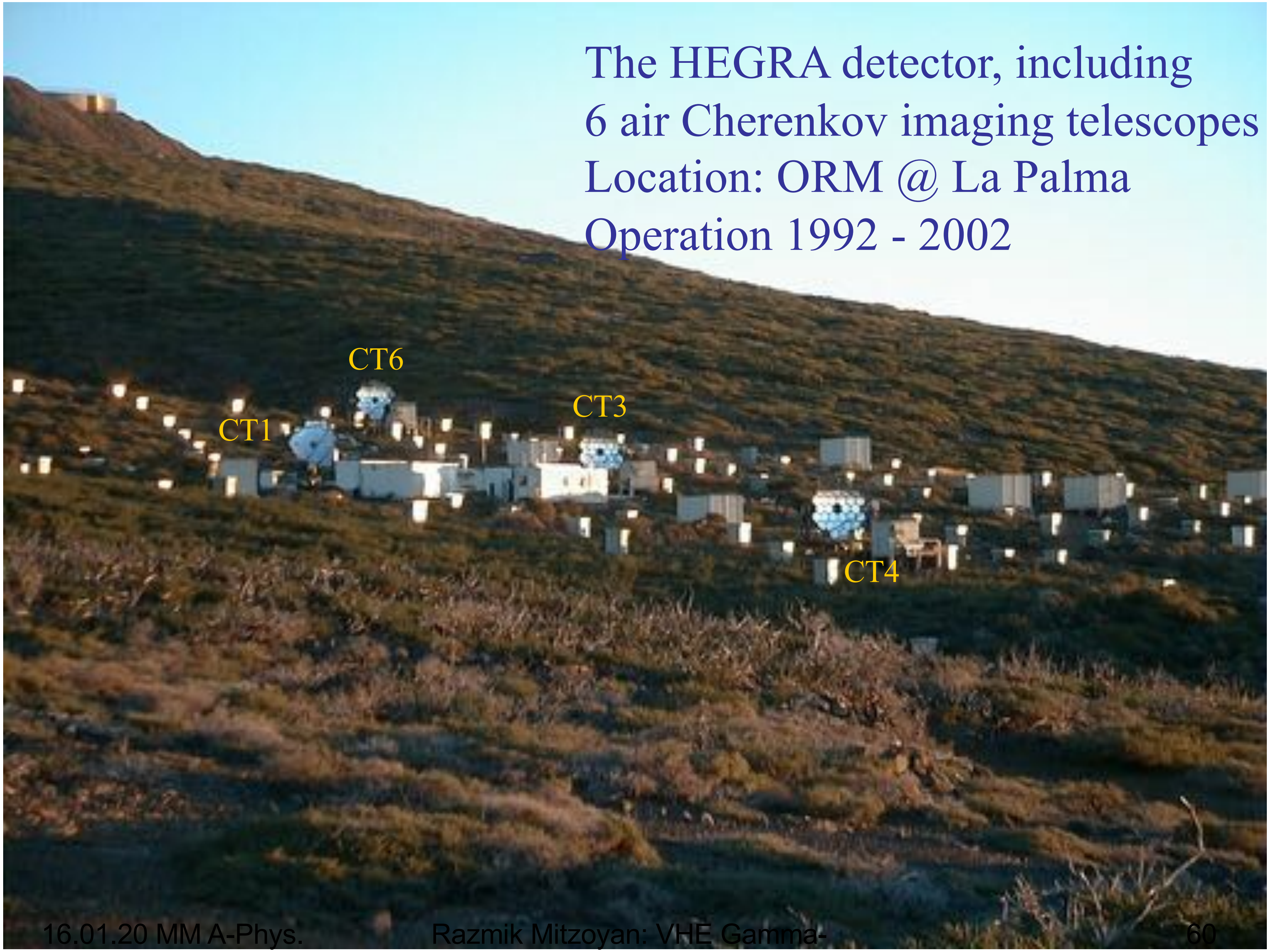
LHAASO


Searching for answers
The 1.25 billion yuan ($166 million) Large High Altitude Air Shower Observatory will be the world's largest and highest cosmic observatory when completed in 2021.
Other detector types: 6,300 total
12 telescopes
Main facility: a detector filled, lightless water tank 2.5 times the size of Beijing's water cube.
What does it do? The 136.6 hectare observatory 4,410 meters above sea level detects cosmic rays.
What are cosmic rays? They are high-energy particles from space so powerful that they make the Sun's cosmic rays "look like a firecracker in comparison," says one scientist.
Why study them? Research can help scientists understand the origin of the universe and could yield discoveries that revolutionize medicine and materials and electronic engineering.
Haizi Mountain
Chengdu
SICHUAN
CHINA DAILY

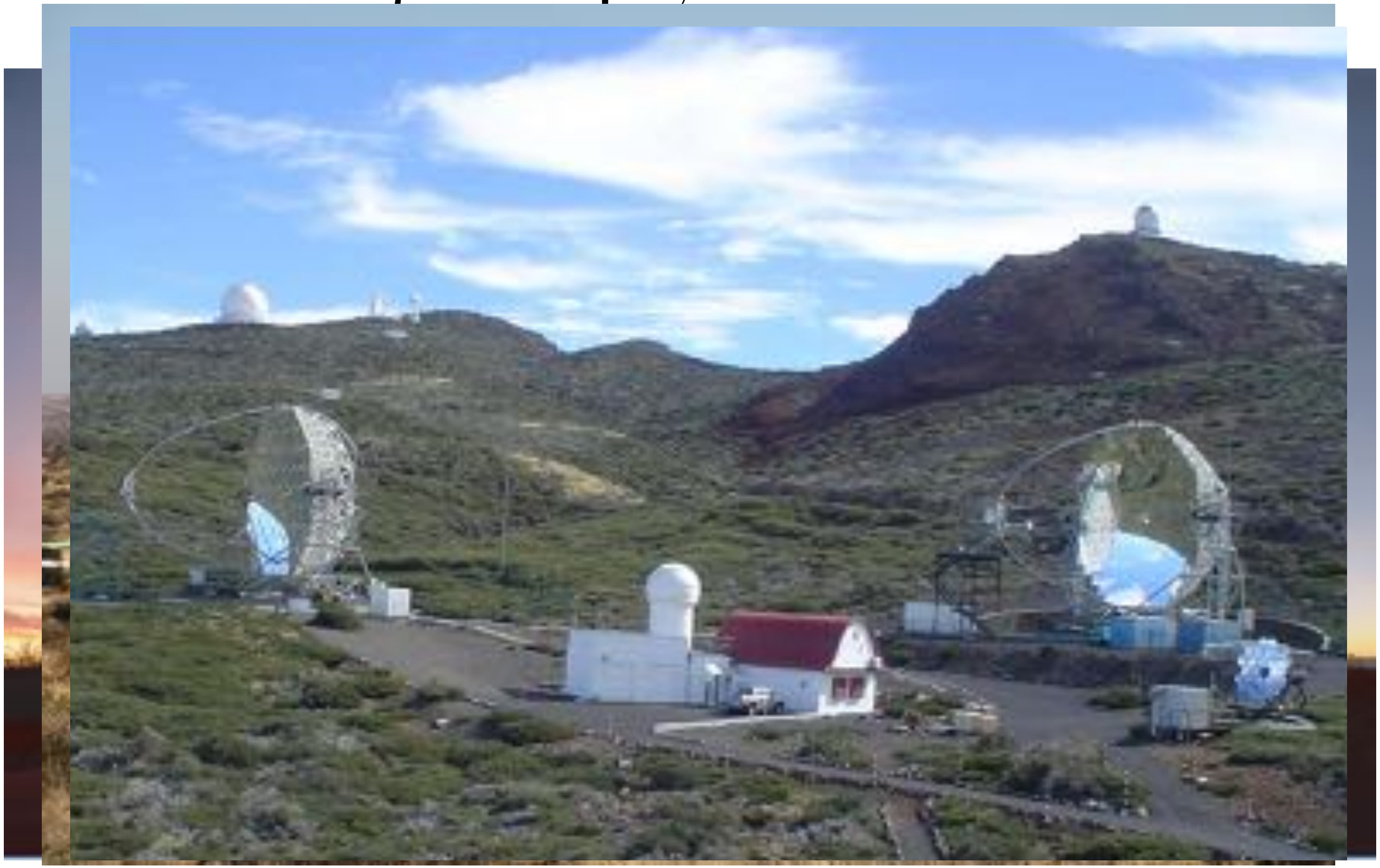
The Pioneer Trevor Weekes and his 10m Ø Whipple telescope gave birth to γ-ray astrophysics: 9σ from Crab Nebula in 1988 !

„If a telescope can within a few s evaporate a solid piece of steel, it can also measure gamma rays“ ;-)

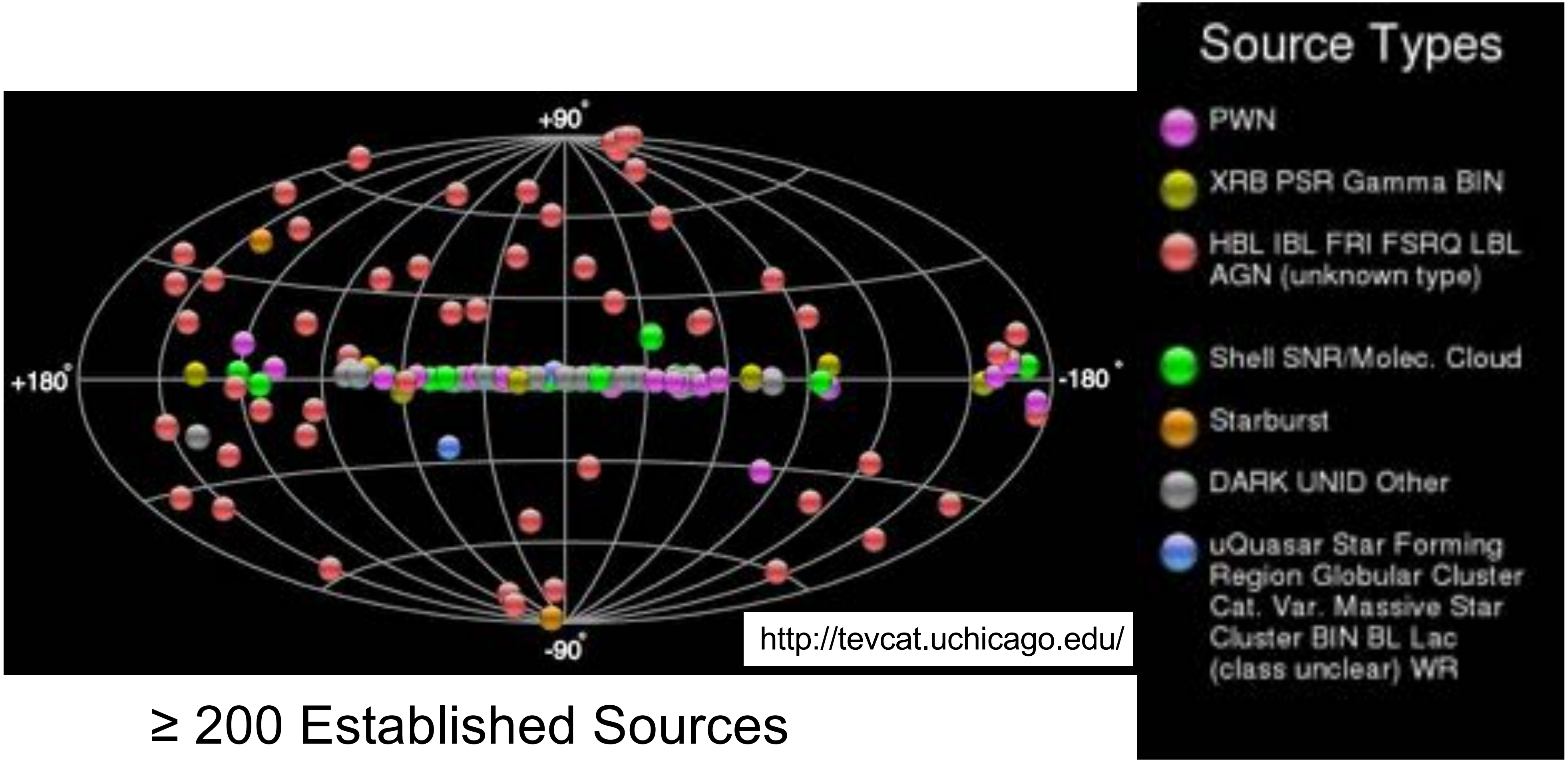
The 1st telescope (of 5 planned) we´ve built: 1989


The HEGRA detector, including
6 air Cherenkov imaging telescopes
Location: ORM @ La Palma
Operation 1992 - 2002
CT6
CT1
CT3
CT4

VERITAS, H.E.S.S. & MAGIC: pushing the VHE γ-astro-physics to its limits



Today‘s VHE γ–ray Sources in the Sky



≥ 200 Established Sources

Outlook : the next 5-7 years

Next generation VHE γ ray Observatory: CTA

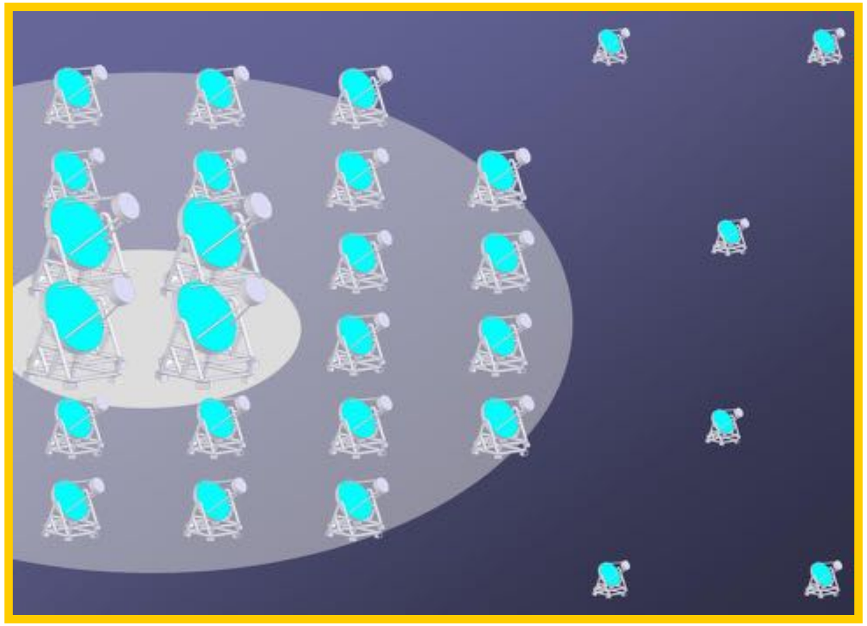
MAGIC

HESS Phase II

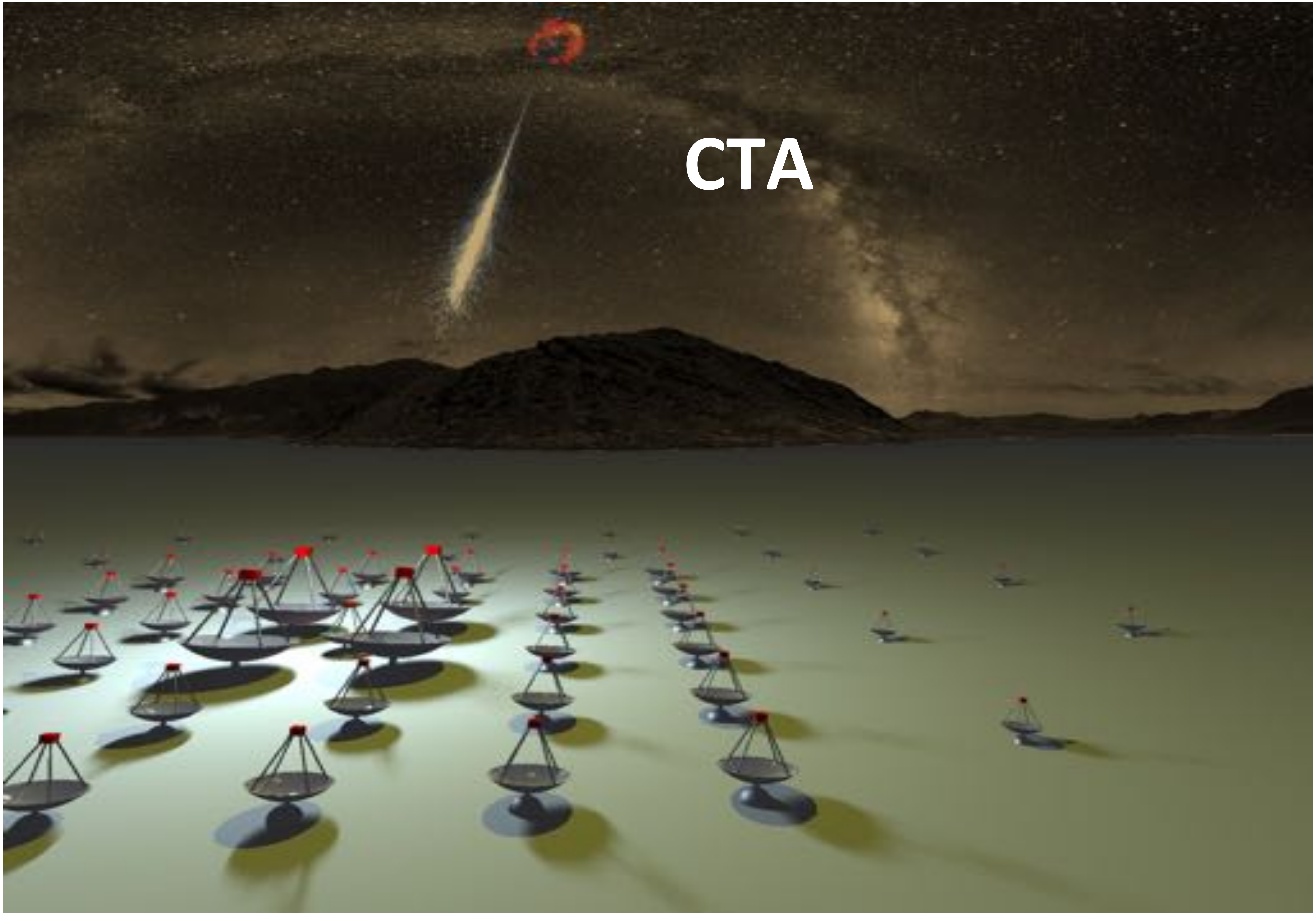
>1500 scientists
~130 institutions

CTA

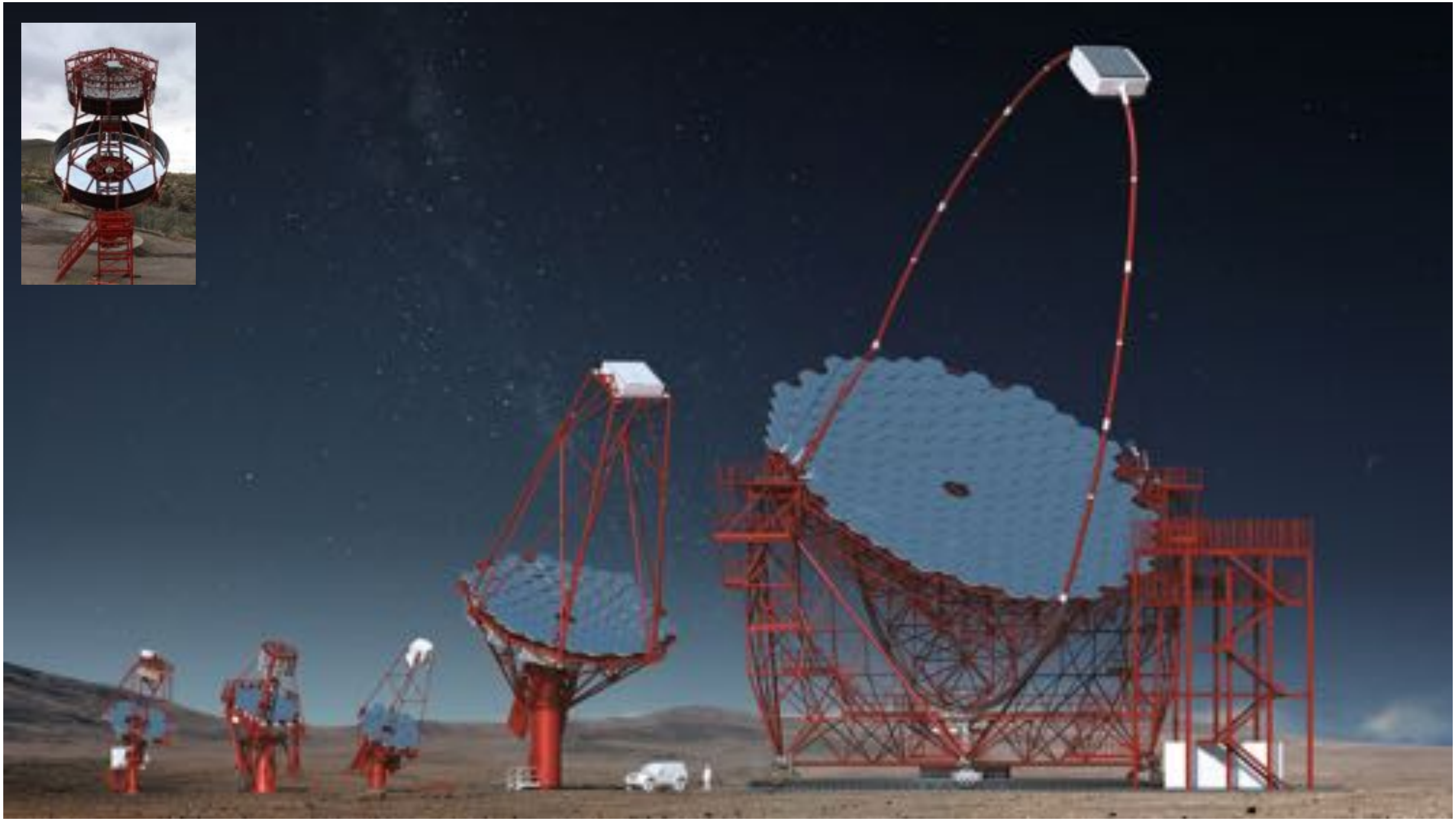
Cherenkov Telescope Array
~1000 sources will be discovered



EU, US, JAPAN, India, Brazil,…

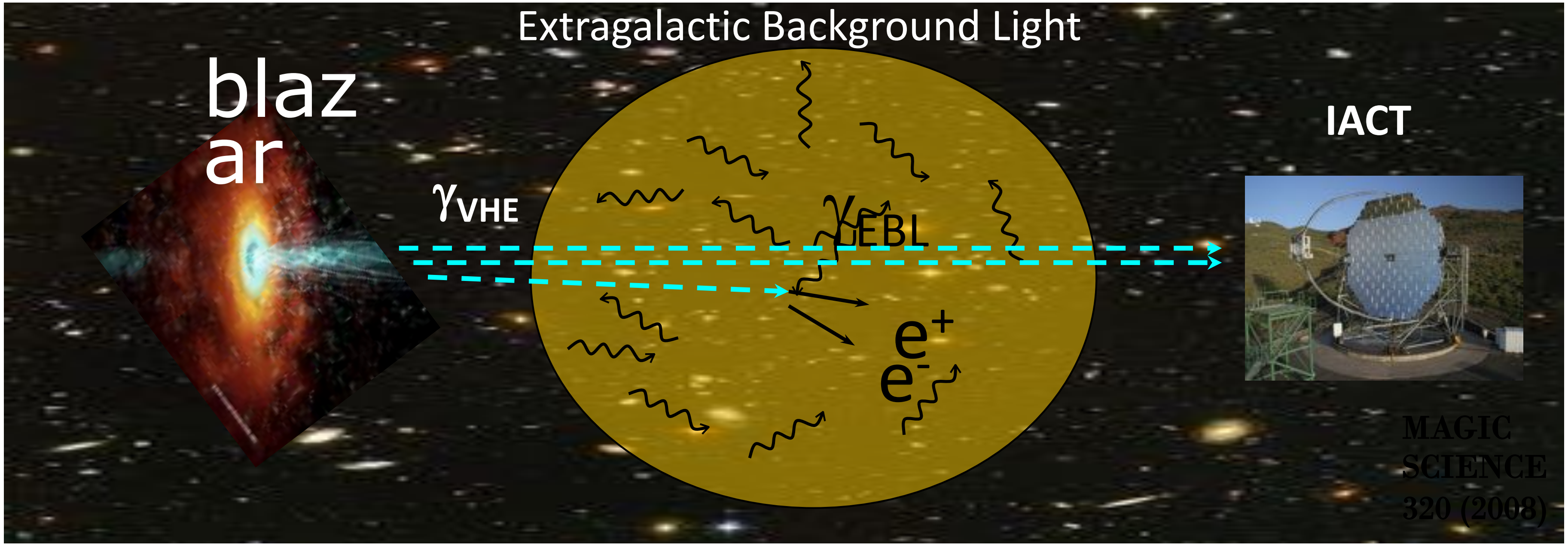

CTA

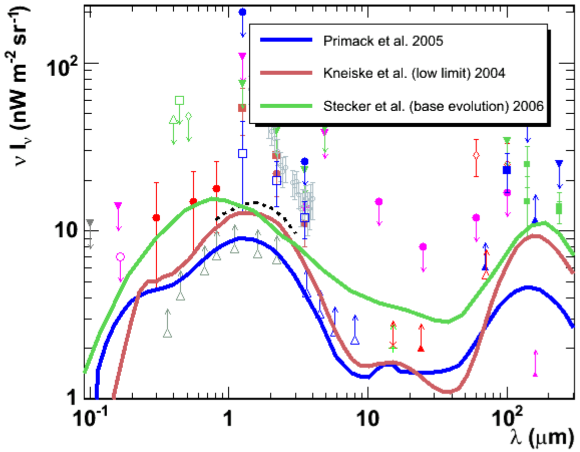
Cherenkov Telescope Array

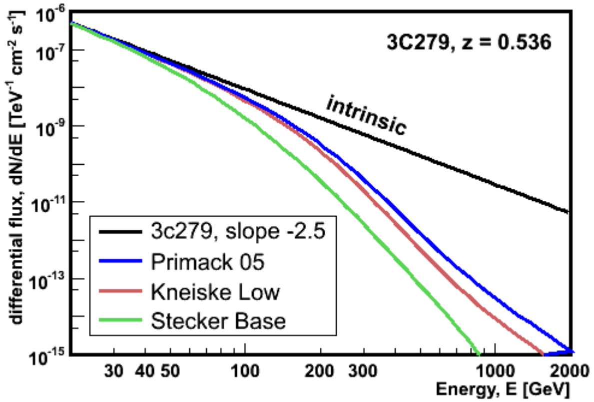


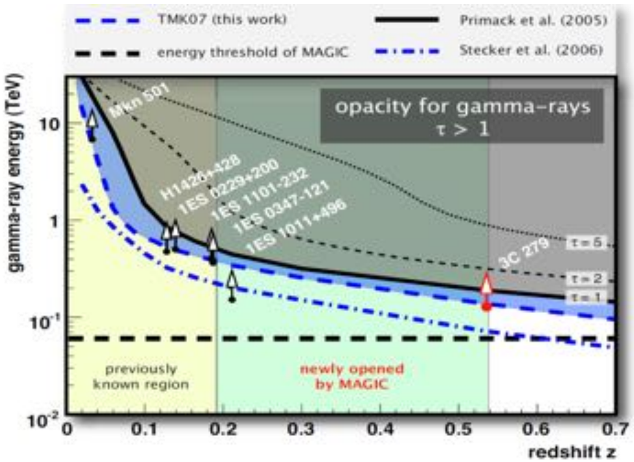
The 1st 23m diameter LST (between 2 MAGICs) of CTA is in the end phase of commissioning

Gamma Ray Absorption by EBL









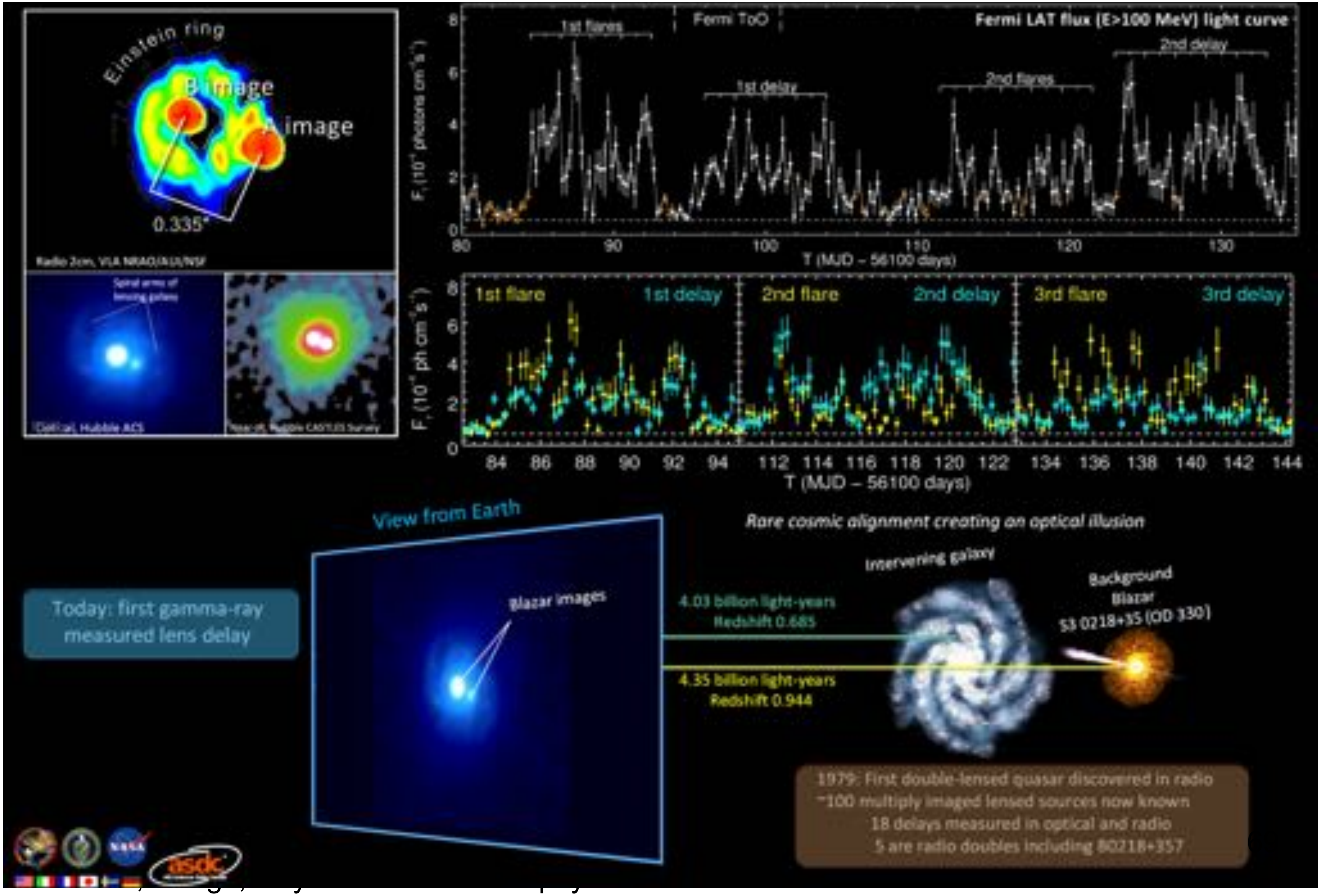
Oldest VHE γ-rays in Universe from a source at red shift of $z = 0.944$

Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 With the MAGIC Telescopes

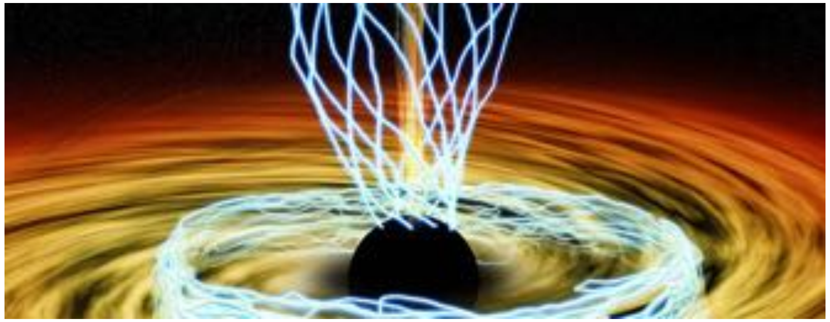
ATel #6349; *Razmik Mirzoyan (Max-Planck-Institute for Physics) On Behalf of the MAGIC Collaboration*
on 28 Jul 2014; 14:20 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

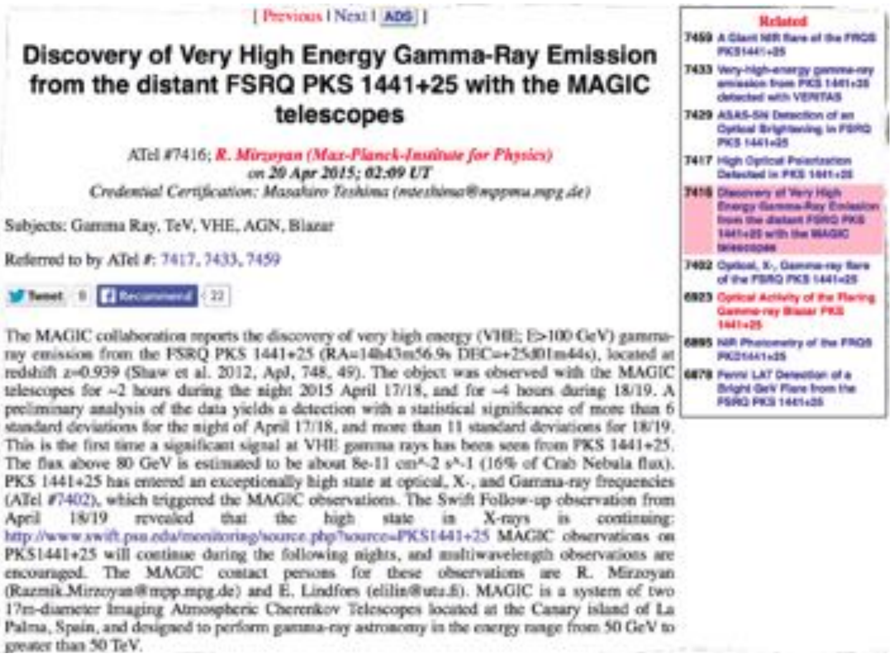
- On a few occasions Fermi mission measured flares of the blazar S3 0218+357 *with a time lag of 11.5 days*.
- This was interpreted as due to the gravitational lensing effect
- 2 weeks ago MAGIC detected a flare with $> 5\ \sigma$ at the anticipated time of the arrival of Fermi gravitational lense echo
- The most distant source discovered @ VHE !

Gravitational lense system S3 0218 (also known as B0218+357)



Discovery of FSRQ PKS-1441 +25





[Previous | Next | ADS]

Discovery of Very High Energy Gamma-Ray Emission from the distant FSRQ PKS 1441+25 with the MAGIC telescopes

ATel #7416; *R. Mirzoyan (Max-Planck-Institute for Physics)*
on 20 Apr 2015; 02:09 UT
Credential Certification: Masahiro Teshima (mteshima@mppmu.mpg.de)

Subjects: Gamma Ray, TeV, VHE, AGN, Blazar

Referred to by ATel #: 7417, 7433, 7459

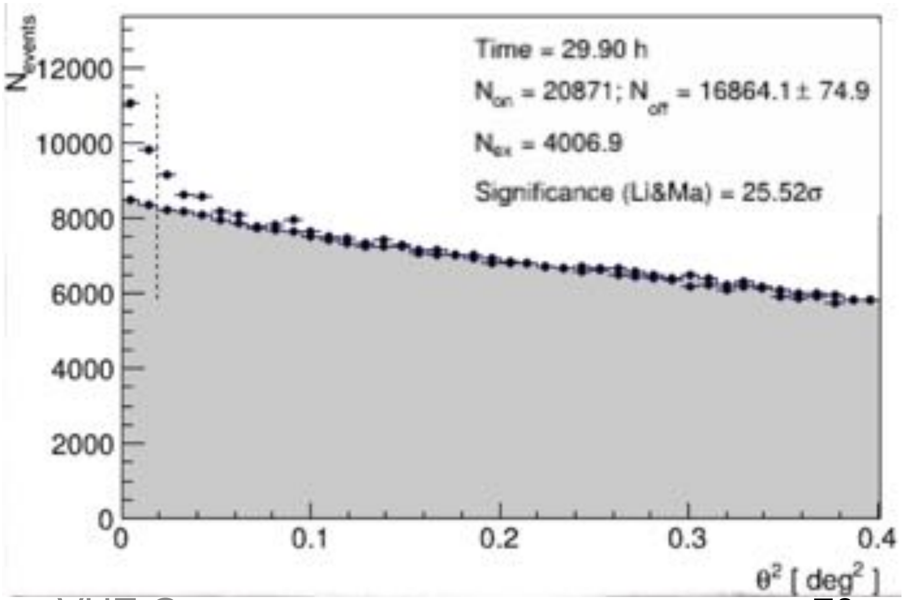
Tweet 0 Recommend 22

The MAGIC collaboration reports the discovery of very high energy (VHE; E>100 GeV) gamma-ray emission from the FSRQ PKS 1441+25 (RA=14h43m56.9s DEC=+25d01m44s), located at redshift z=0.939 (Shaw et al. 2012, ApJ, 748, 49). The object was observed with the MAGIC telescopes for ~2 hours during the night 2015 April 17/18, and for ~4 hours during 18/19. A preliminary analysis of the data yields a detection with a statistical significance of more than 6 standard deviations for the night of April 17/18, and more than 11 standard deviations for 18/19. This is the first time a significant signal at VHE gamma rays has been seen from PKS 1441+25. The flux above 80 GeV is estimated to be about 8e-11 cm^-2 s^-1 (16% of Crab Nebula flux). PKS 1441+25 has entered an exceptionally high state at optical, X-, and Gamma-ray frequencies (ATel #7402), which triggered the MAGIC observations. The Swift Follow-up observation from April 18/19 revealed that the high state in X-rays is continuing: http://www.swift.psu.edu/monitoring/source.php?source=PKS1441+25 MAGIC observations on PKS1441+25 will continue during the following nights, and multiwavelength observations are encouraged. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and E. Lindfors (elilin@utu.fi). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Canary island of La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

Related

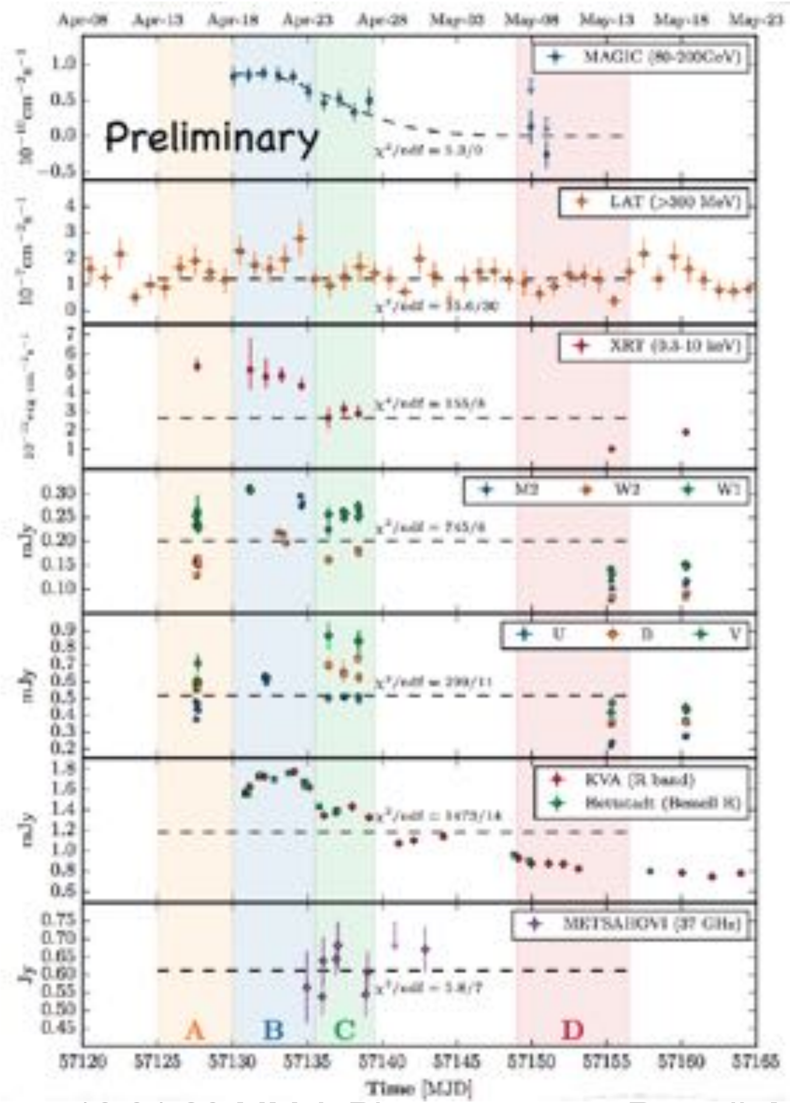
- 7459 A Giant NIR flare of the FRQS PKS1441+25
- 7433 Very-high-energy gamma-ray emission from PKS 1441+25 detected with VERITAS
- 7429 ASAS-SN Detection of an Optical Brightening in FSRQ PKS 1441+25
- 7417 High Optical Polarization Detected in PKS 1441+25
- 7416 Discovery of Very High Energy Gamma-Ray Emission from the distant FSRQ PKS 1441+25 with the MAGIC telescopes
- 7402 Optical, X-, Gamma-ray flare of the FSRQ PKS 1441+25
- 6923 Optical Activity of the Flaring Gamma-ray Blazar PKS 1441+25
- 6895 NIR Photometry of the FRQS PKS1441+25
- 6878 Fermi LAT Detection of a Bright GeV Flare from the FSRQ PKS 1441+25

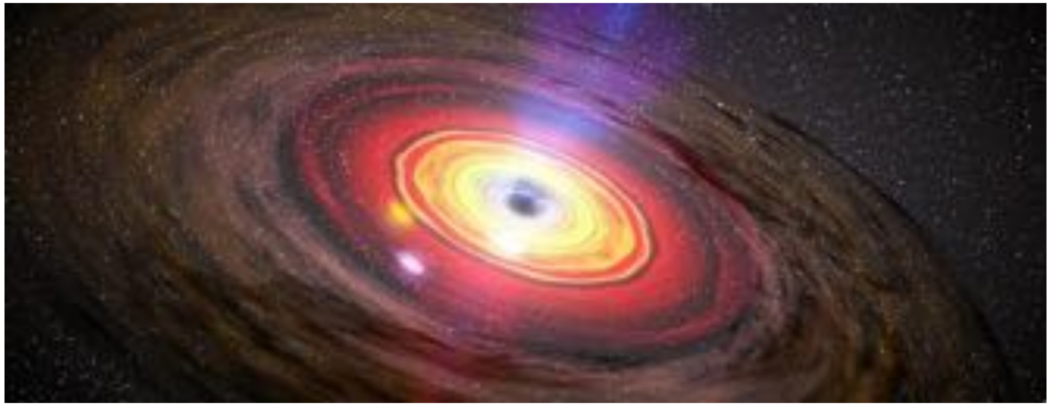
- Along with S3 0218 +357, z = 0.944, this is the most distant VHE source: **z = 0.939**
- Started observing on April 17[th] after alert from Fermi, for 10 days



25 σ, > 4000 γ events
Spectrum measured in
40 – 250 GeV energy range

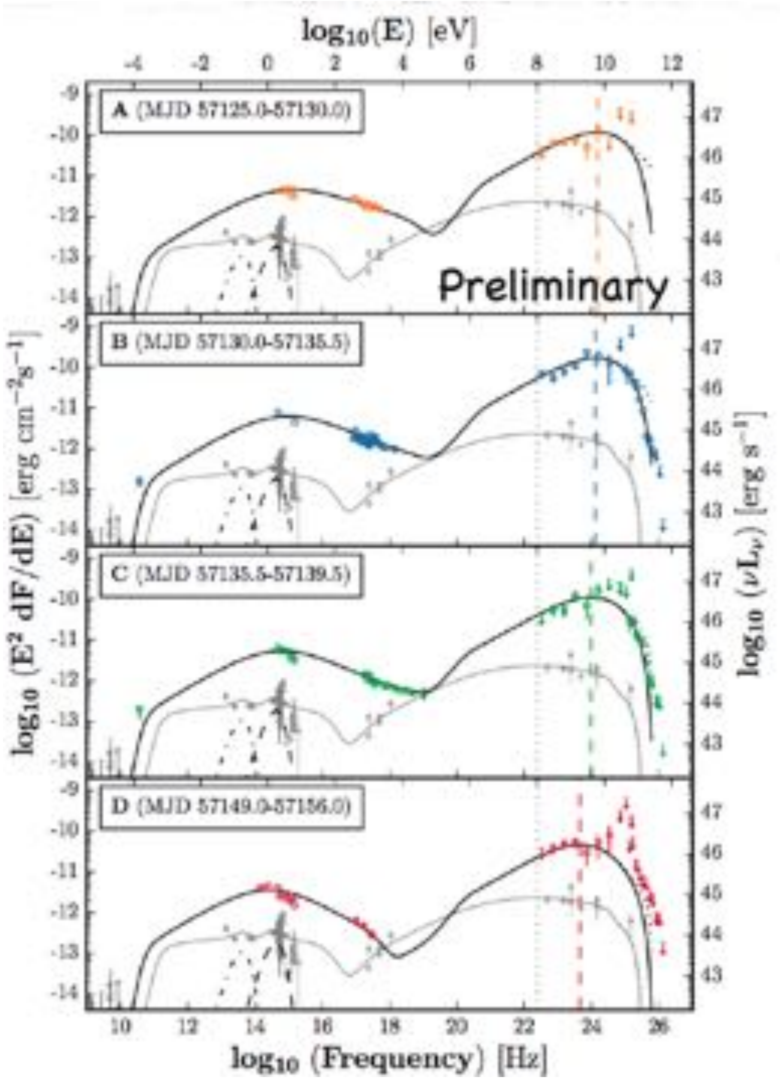
PKS-1441 +25



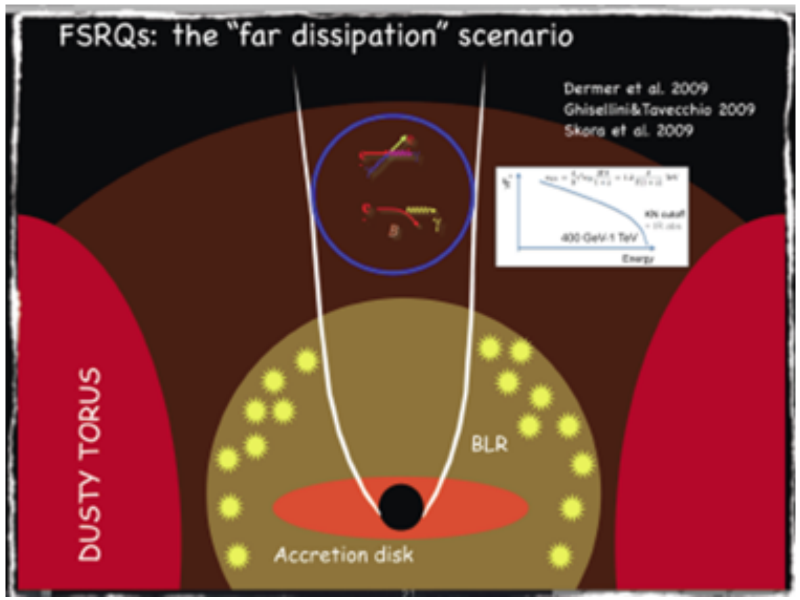


- Two flux states can be distinguised during the flare
- Flux halving time is ~ 6 days
- No signal after the moon-break period

SED PKS-1441 +25

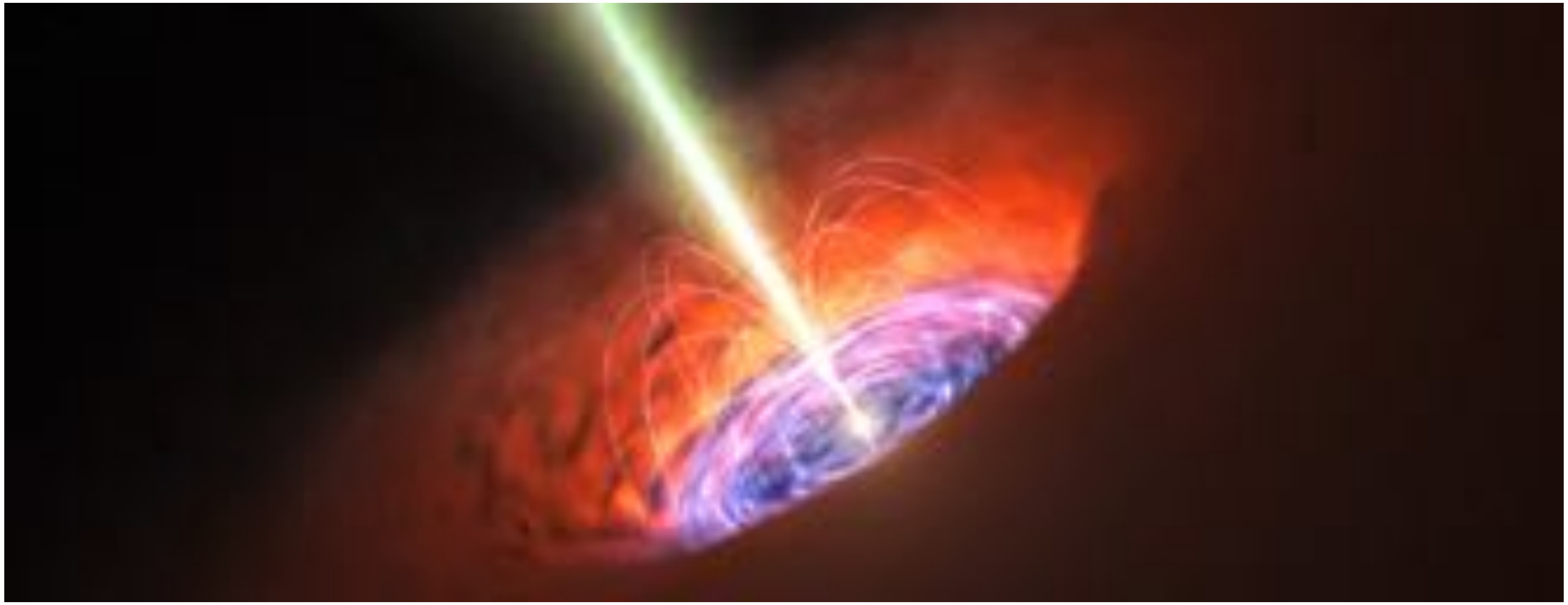


Lack of absorption features in the measured HE - VHE γ-ray spectra allows one to constrain the location of emitting region to be far from the center



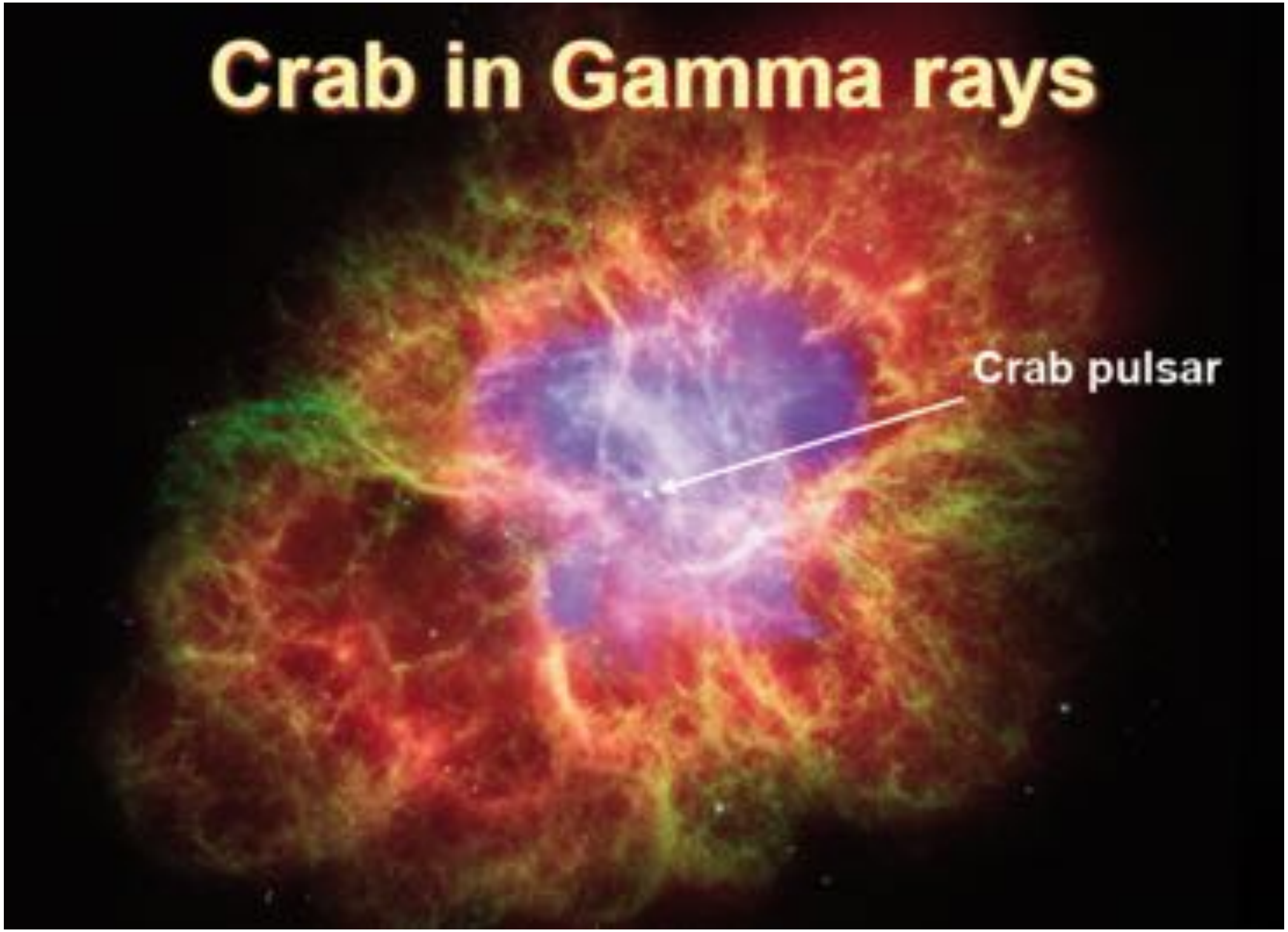
External Compton scenario

Joint NASA-MAGIC-VERITAS press-release on PKS-1441 +25 on 15th Dec. 2015

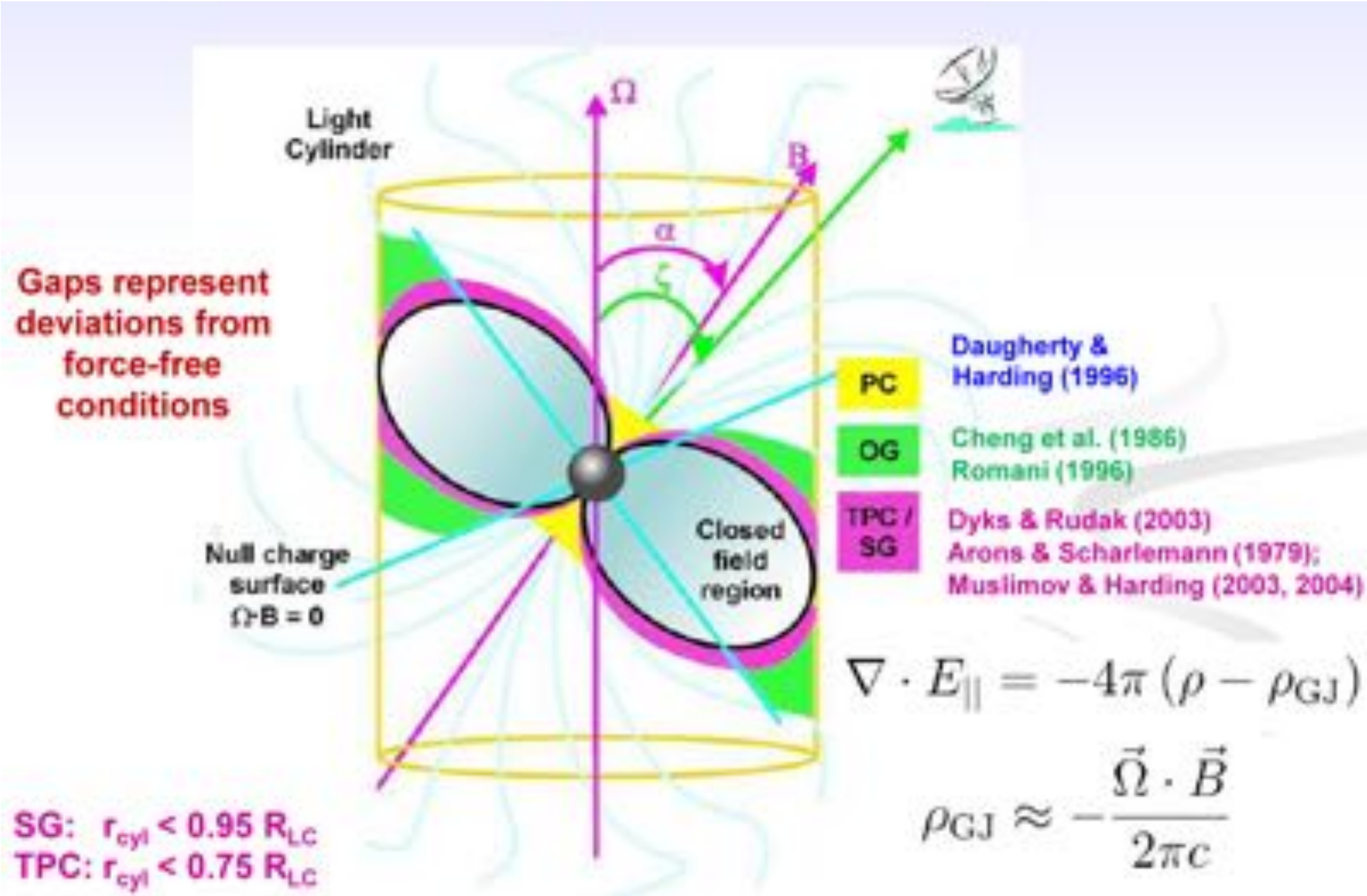


FineCut4-NASA-8PM-11-Dec-15.mp4

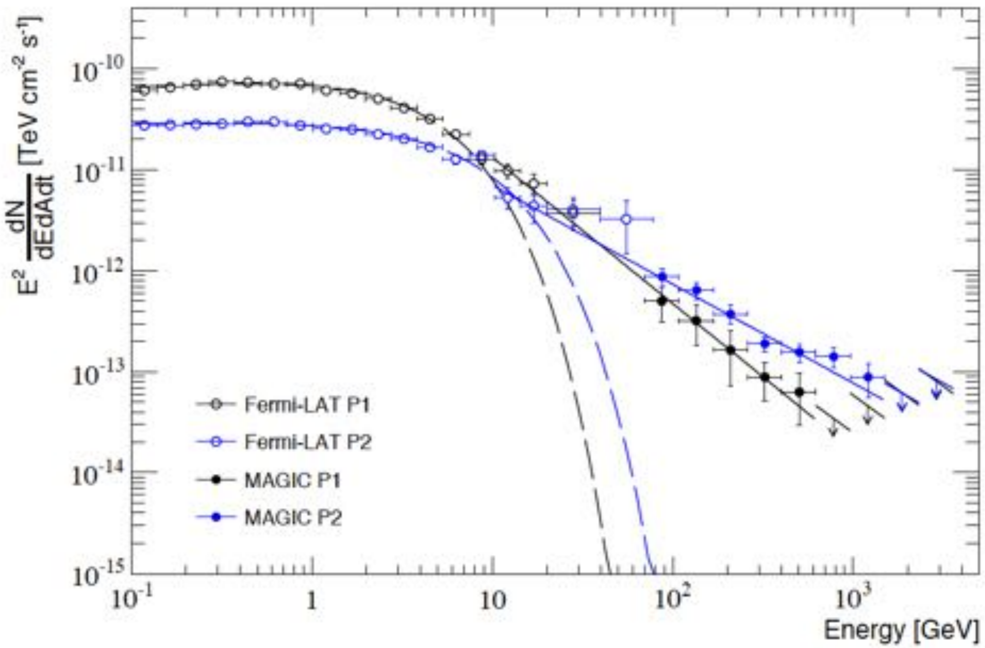
Composite figure of Crab Nebula



Cartoon of a pulsar

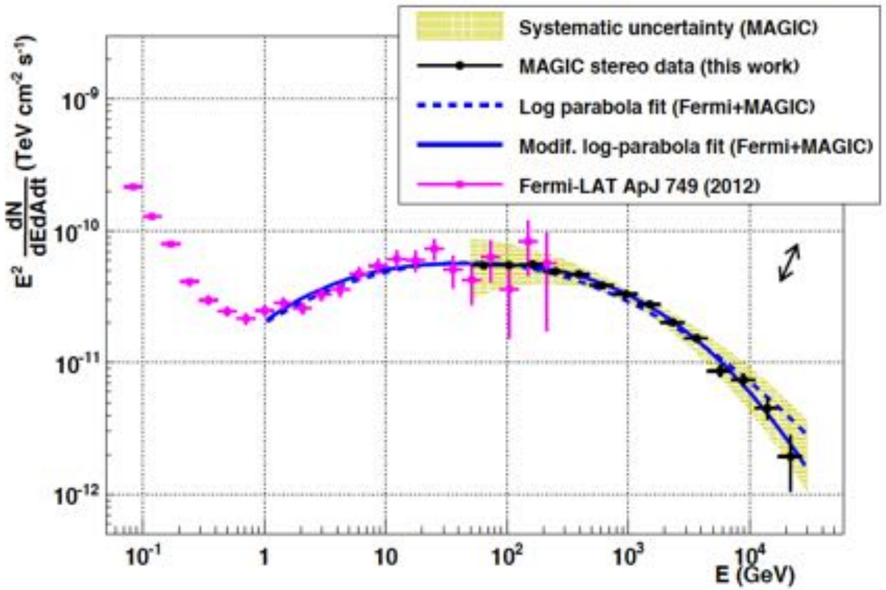


MAGIC established the Crab pulsar as the most compact accelerator of TeV γ rays



- Discovered pulsed emission from Crab, spectrum extending ≥ 1.2 TeV
- Challenging the emission models
- MAGIC-Fermi fit shows IC emission from ~10 GeV to ≥ 1 TeV
- Emission from the neighborhood of Light Cylinder (r ~1600km)
- TeV pulsation is used to put quadratic limits for Lorentz Invariance Violation (LIV): EQG2 > 4.4 x 10^{10} GeV: this is only factor 3 below current best limit from Fermi

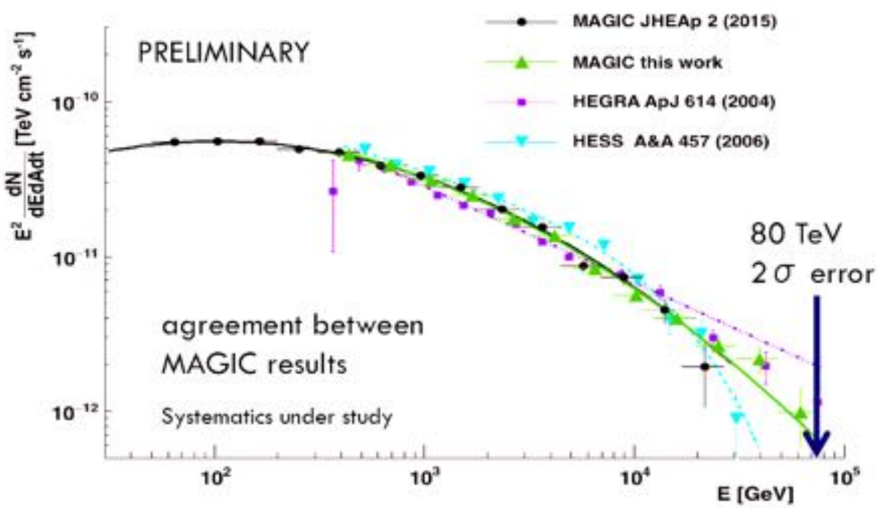
MAGIC & Crab Nebula



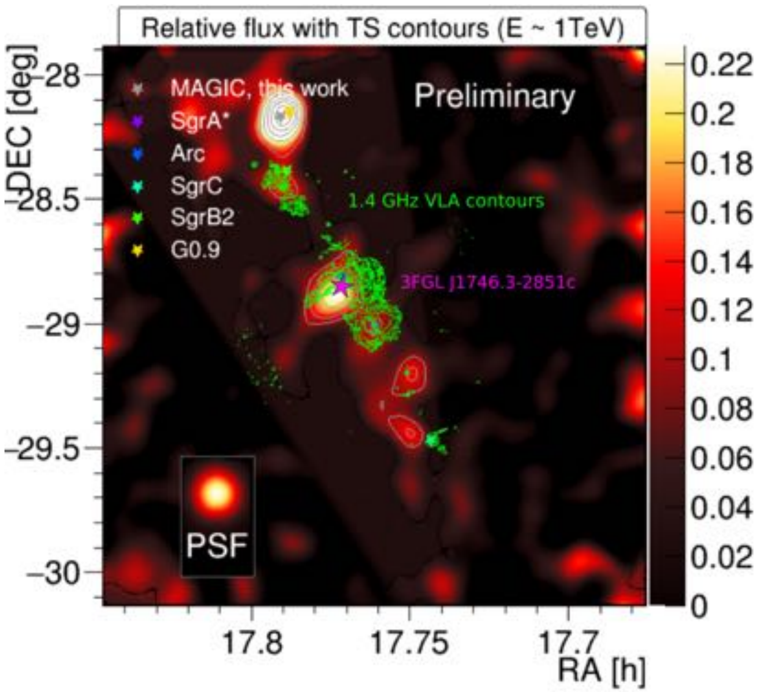
Aleksic et al. (MAGIC) JHEAP, 5, 2015

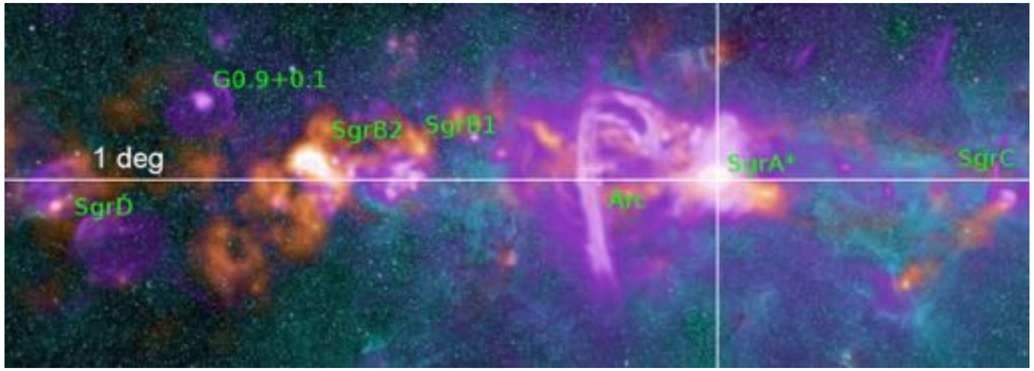
- Crab Nebula spectrum from 60 GeV till 30 TeV
- Together with Fermi LAT precision definition of the IC peak

Large zenith angle observations
$\theta \leq 70°$
for exploring the E range ~80 TeV



Discovery of the Arc @ Galactic Center





By using the very large zenith angle observation technique: $\theta_{obs.} \sim 58^\circ - 70^\circ$, MAGIC collected very significant statistics at the high energy end

- Good correlation: 90 cm radio image and TeV skymap (E ≥ 1TeV)
- Detected significant TeV gamma-ray excess apparently coincident with the radio Arc
- MAGIC source is coincident with the Fermi 3FGL J1746.3-2851c

Next ~ 5 - 10 years

- Successful source hunting and deep observation of diverse source types is in its best phase with current telescopes
- Better sensitivity and larger-size installations are under construction, commissioning and entering into operation phase