Historical Overview and Basic Details of the Ground-Based VHE γ-Astrophysics by Means of Imaging Air Cherenkov Telescopes

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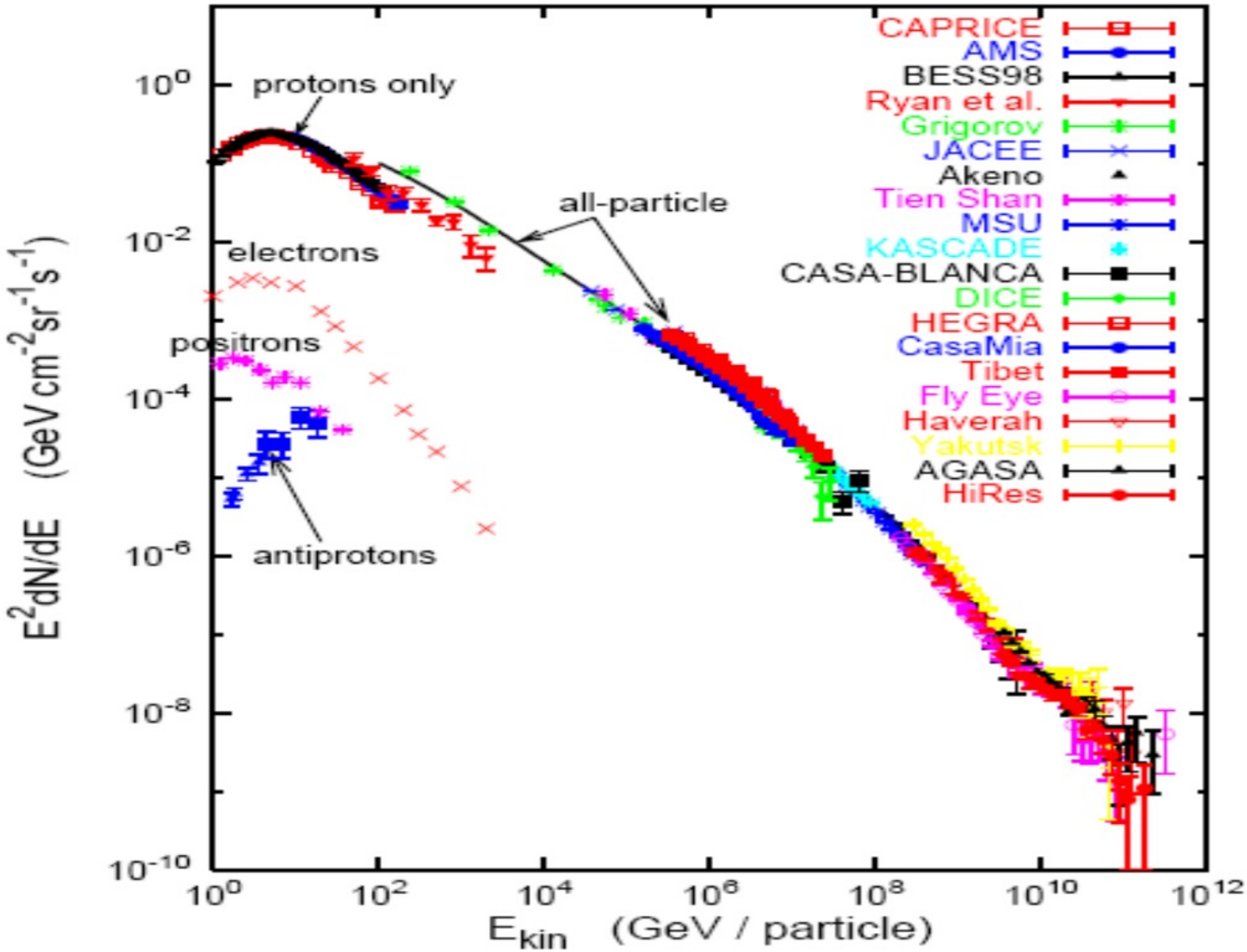
1912: Birthday of cosmic rays

In a series of balloon flights, up to an altitude of 5000 meters a.s.l., Victor Hess discovered "penetrating radiation" coming from outside, from space.

The non-thermal sky: energies and rates of CR

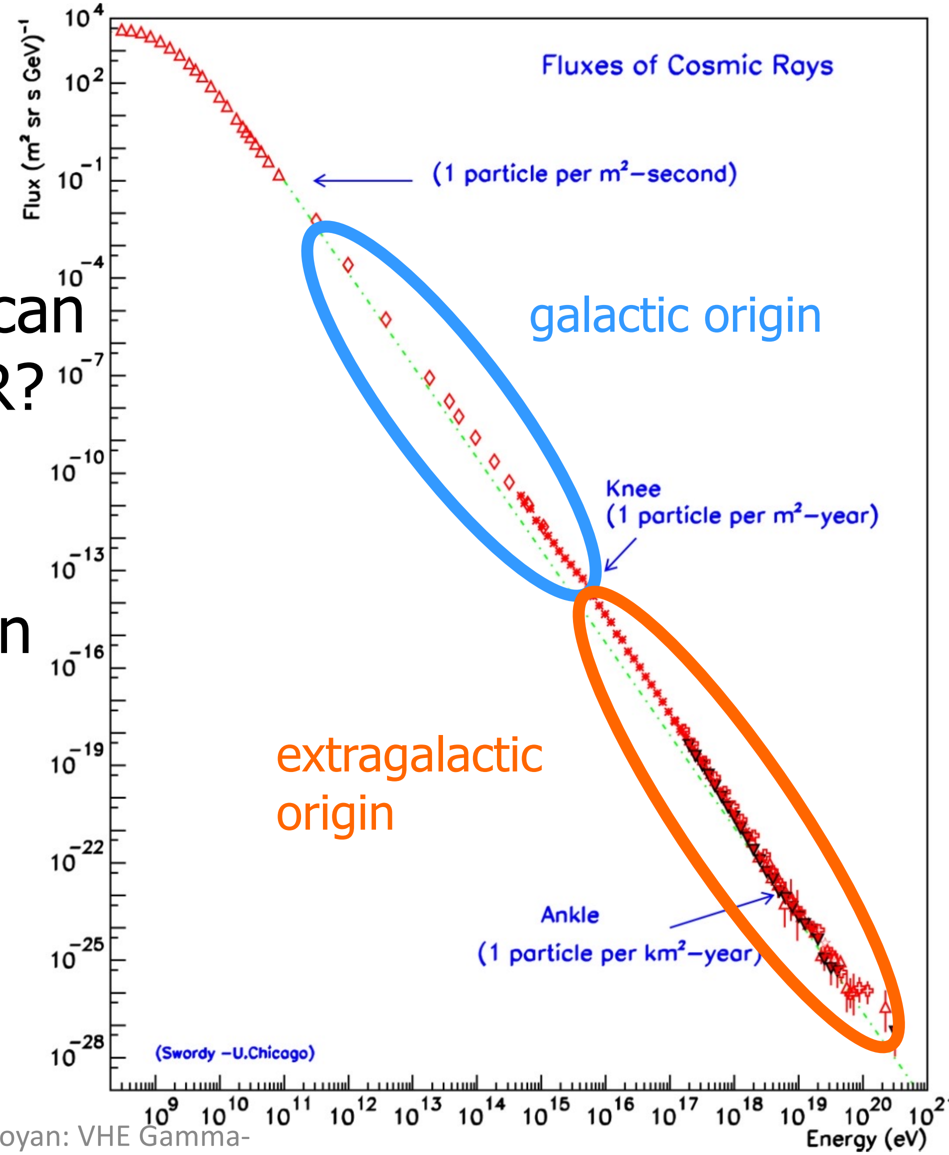


Origin of cosmic rays

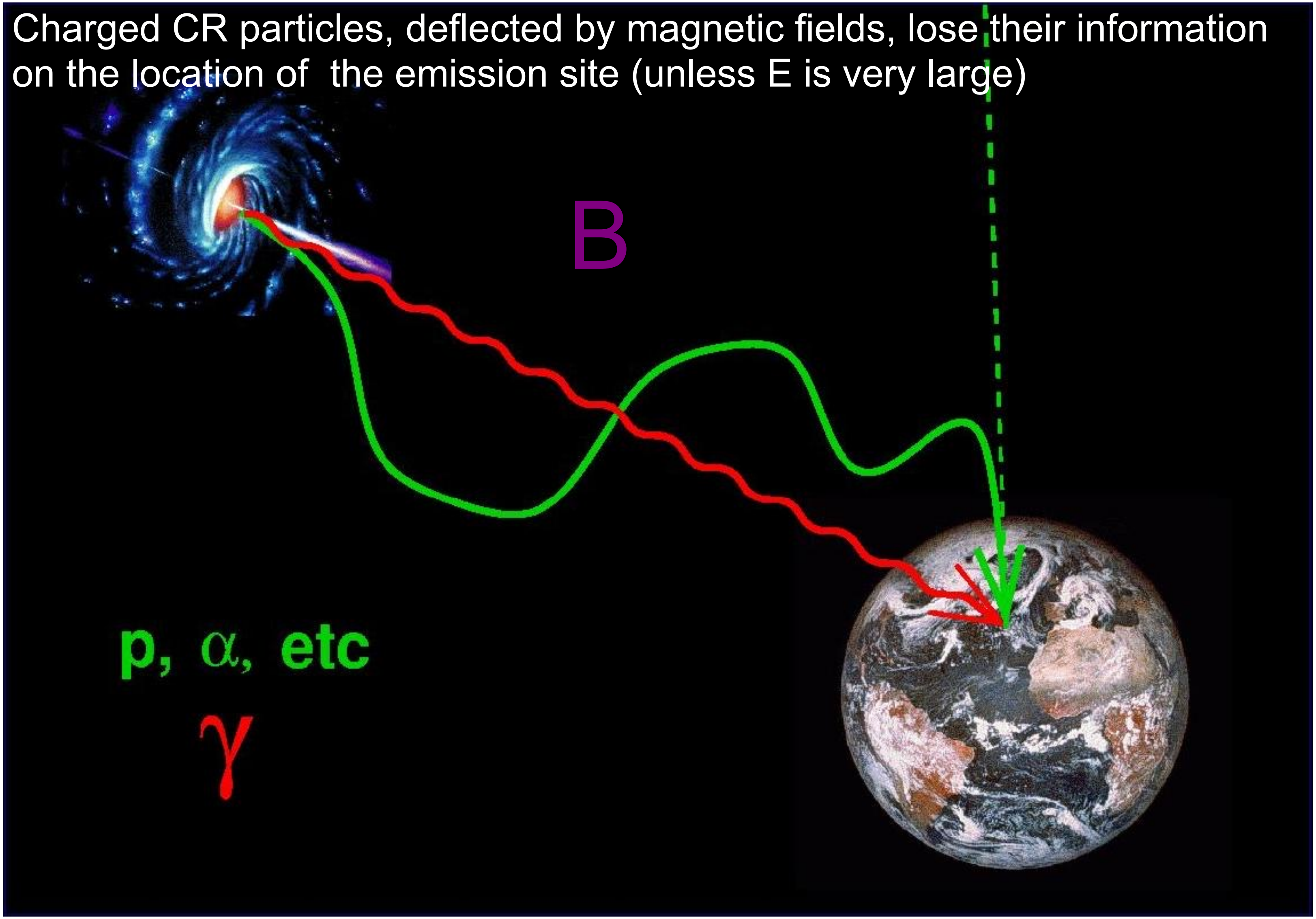
Discovered in 1912 but their sources are not yet identified!
Which object(s) in our galaxy can provide the right amount of CR?

Supernova remnants could accelerate swept-up particles in their magnetic shock waves

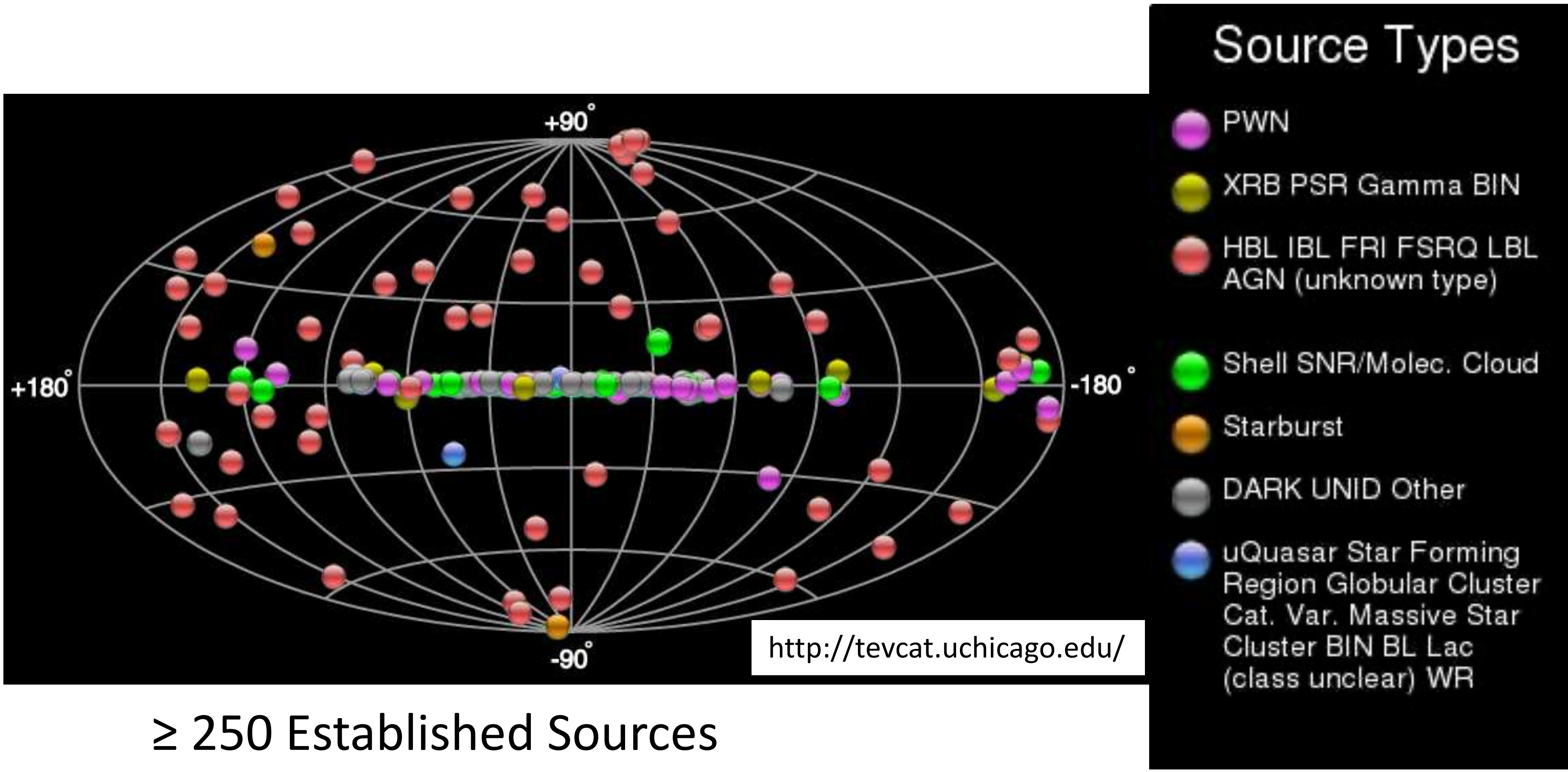
Signature: Hadronic generated Gamma-rays from SNRs



Astronomy with Charged Cosmic Rays ?



Today's VHE γ–ray Sources in the Sky



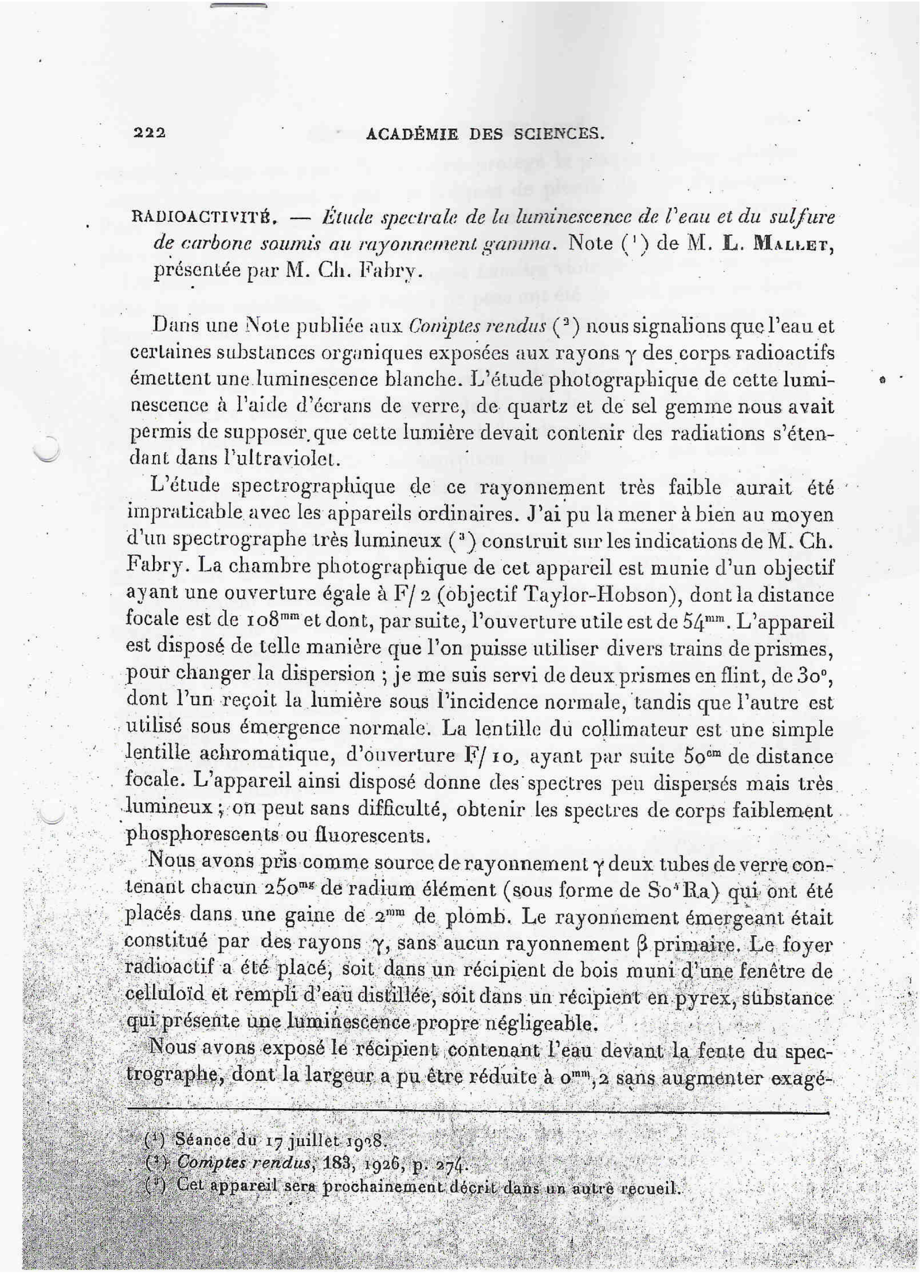
≥ 250 Established Sources

Cherenkov light: the beginnings

- In a series of publications Oliver Heaviside has calculated and predicted the main features of a special emission when an e- movs in a transparent medium with a speed higher than that of light.
- The work of the genius, who advanced his time by half a century, was not appreciated by contemporary scientists and was forgotten. In 1912 he calculated the geometry and the angle of emission relative to the axis of movement of the charge (1888, 1889, 1892, 1899, 1912a,b)
- Please note that during the end of 19th century scientists believed the space was feeled-in with Ether.

Cherenkov light: the beginnings

- It took almost 50 years until the effect was experimentally discovered and later on got the name Cherenkov
- Also Sommerfeld studied the problem of a charge moving in vacuum with a speed v > c (1904). The relativistic principles prohibit such a motion in vacuum but in a medium with given *n* then his equations give valid solution („sonic boom“).
- First observation of ghostly bluish glow of bottles in the dark cellar, containing radium salts dissolved in distilled water, by Marie Curie in 1910 (E. Curie, 1937). It was thought to be a type of fluorescence.



RADIOACTIVITÉ. — *Étude spectrale de la luminescence de l'eau et du sulfure de carbone soumis au rayonnement gamma.* Note [1] de M. L. MALLET, présentée par M. Ch. Fabry.

Dans une Note publiée aux *Comptes rendus* [2] nous signalions que l'eau et certaines substances organiques exposées aux rayons γ des corps radioactifs émettent une luminescence blanche. L'étude photographique de cette luminescence à l'aide d'écrans de verre, de quartz et de sel gemme nous avait permis de supposer que cette lumière devait contenir des radiations s'étendant dans l'ultraviolet.

L'étude spectrographique de ce rayonnement très faible aurait été impraticable avec les appareils ordinaires. J'ai pu la mener à bien au moyen d'un spectrographe très lumineux [3] construit sur les indications de M. Ch. Fabry. La chambre photographique de cet appareil est munie d'un objectif ayant une ouverture égale à F/2 (objectif Taylor-Hobson), dont la distance focale est de 108^{mm} et dont, par suite, l'ouverture utile est de 54^{mm}. L'appareil est disposé de telle manière que l'on puisse utiliser divers trains de prismes, pour changer la dispersion ; je me suis servi de deux prismes en flint, de 30°, dont l'un reçoit la lumière sous l'incidence normale, tandis que l'autre est utilisé sous émergence normale. La lentille du collimateur est une simple lentille achromatique, d'ouverture F/10, ayant par suite 50^{cm} de distance focale. L'appareil ainsi disposé donne des spectres peu dispersés mais très lumineux ; on peut sans difficulté, obtenir les spectres de corps faiblement phosphorescents ou fluorescents.

Nous avons pris comme source de rayonnement γ deux tubes de verre contenant chacun 250^{mg} de radium élément (sous forme de SO^4Ra) qui ont été placés dans une gaine de 2^{mm} de plomb. Le rayonnement émergeant était constitué par des rayons γ, sans aucun rayonnement β primaire. Le foyer radioactif a été placé, soit dans un récipient de bois muni d'une fenêtre de celluloïd et rempli d'eau distillée, soit dans un récipient en pyrex, substance qui présente une luminescence propre négligeable.

Nous avons exposé le récipient contenant l'eau devant la fente du spectrographe, dont la largeur a pu être réduite à 0^{mm},2 sans augmenter exagé-

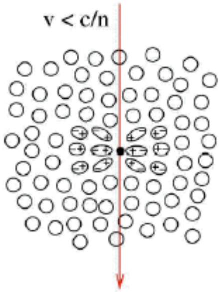
(1) Séance du 17 juillet 1928.
(2) *Comptes rendus*, 183, 1926, p. 274.
(3) Cet appareil sera prochainement décrit dans un autre recueil.

- French scientists M.L. Mallet published 3 articles on the bluish glow in transparent liquids (1926-1929).
- On the left one can see a scan of one of those papers (1926)
- Mallet recongnised the continuous spectrum of emission that was contradicting the fluorescence theory, but failed to offer any deep explanation

Cherenkov light: the beginnings

- Pavel Cherenkov: born July 28th 1904 in a poor peasant family in village Novaya Chigla, Voronezh province.
- 1924-1928 studying in Voronezh sate university.
- 1930: postgraduate student of Sergej Vavilov at the Institute of Physics of Soviet Academy of Sciences in Sankt-Petersburg (later on FIAN).
- Had to find the fluorescence nature of solvents of uranium salts, emitting bluish light
- Big was his surprise that also pure solvents and even water were emitting the annoying background light

Cherenkov Effect

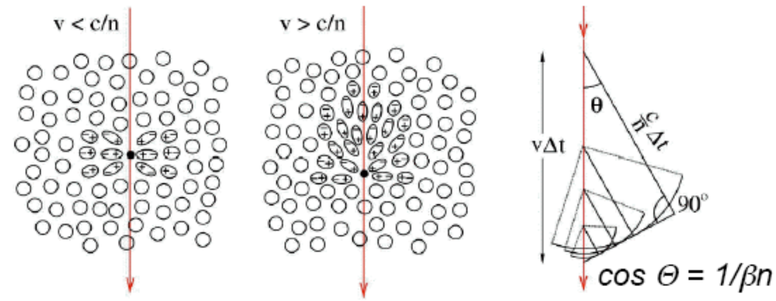


Medium, refractive index n

Charged particle with v < c/n traverses medium
==> local, shorttime polarization of medium

Reorientation of electric dipoles results in (very faint) isotropic radiation

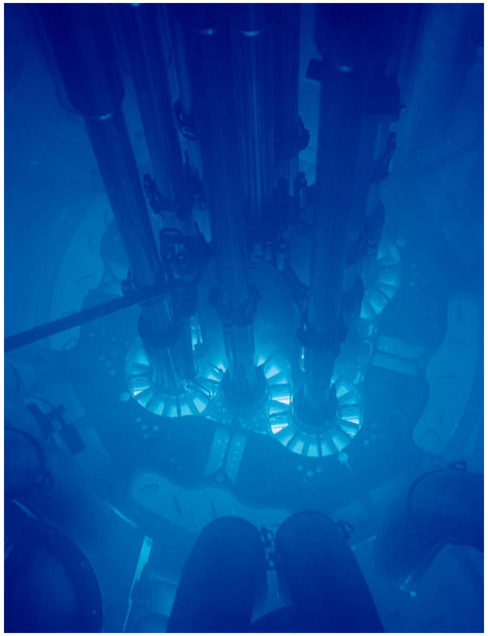
Cherenkov Effect



Similar to sonic boom if $v > c_{acoustic}$

v > c/n
==> radiation from different points along the trajectory arrive **in phase** within narrow light-cone at the observer ==> **bright light**

- Initially complaning about his boss: he had to spend >1-1,5 hours in a dark, cold cellar, for accomodating his eyes
- He noticed that the emission is not chaotic, but is related to the track of moving particle.
- 1934-1938 conducting a series of brilliant expeirments.
- Obtained doctorate in 1940



The Suspicious Emission

- In 1937 Cherenkov succeeded to measure the anisotropy of the emission and submitted it to the journal „Nature“
- „Nature“ declined his paper
- Fortunately „The Physical Review“ accepted it
- In that paper he has mentioned the possibility to measure fast e-

LETTERS TO THE EDITOR

Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the eighteenth of the preceding month, for the second issue, the third of the month. Because of the late closing dates for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.

Communications should not in general exceed 600 words in length.

P.A. Cerenkov
The Physical Institute of the Academy of Sciences U.S.S.R., Moscow
Received June 15, 1937

Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light

In a note published in 1934 [1] as well as in the subsequent publications [2] [3] [4] the present author reported his discovery of feeble visible radiation emitted by pure liquids under the action of fast electrons (β-particles of radioactive elements or Compton electrons liberated in liquids in the process of scattering of γ-rays). This radiation was a novel phenomenon, which could not be identified with any of the kinds of luminescence then known as the theory of luminescence failed to account for a number of unusual properties (insensitiveness to the action of quenching agents, anomalous polarization, marked spacial asymmetry, etc.) exhibited by the radiation in question. In 1934 the earliest results obtained in the experiments with γ-rays led S.I. Wawilow [5] to interpret the radiation observed as a result of the retardation of the Compton electrons liberated in liquids by γ-rays. A comprehensive quantitative theory subsequently advanced by I.M. Frank and I.E. Tamm

[6] afforded an exhaustive interpretation of all the peculiarities of the new phenomenon, including its most remarkable characteristic – the asymmetry.

According to their theory, an electron moving in a medium of refractive index n with a velocity exceeding that of light in the same medium ($\beta > 1/n$) is liable to emit light which must be propagated in a direction forming an angle θ with the path of the electron, this angle being determined by the equation:

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

where β is the ratio of the electron velocity to that of light in vacuum.

A successful experimental verification of formula (1) was only performed with water [4] for which, at the moment

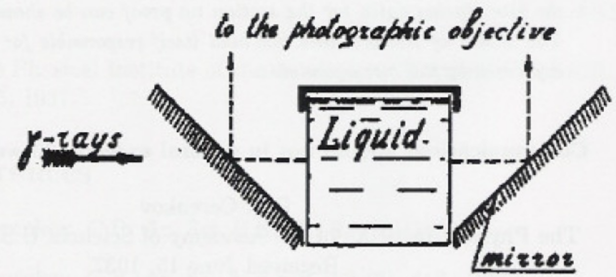


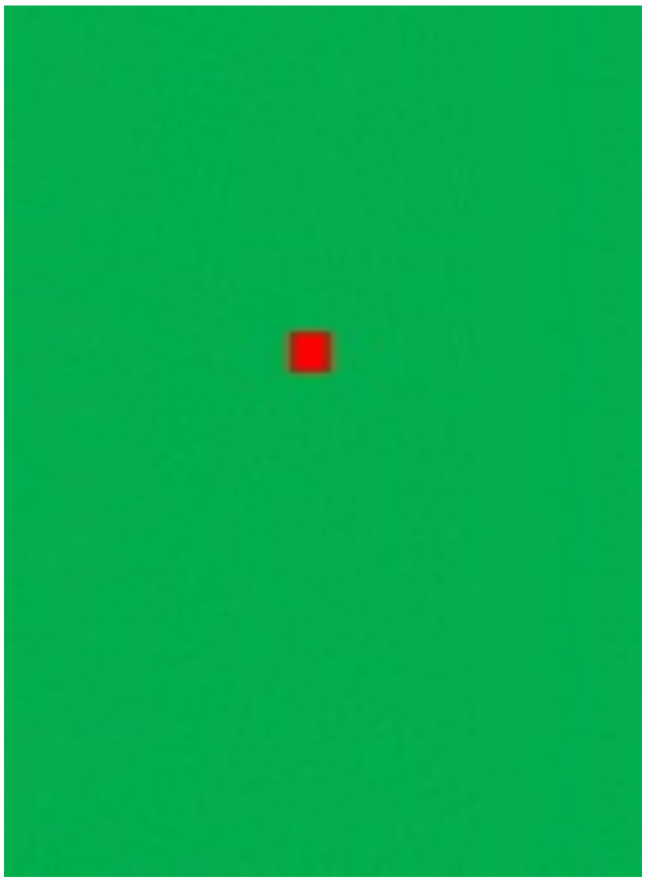
Figure 1: Arrangement of apparatus.

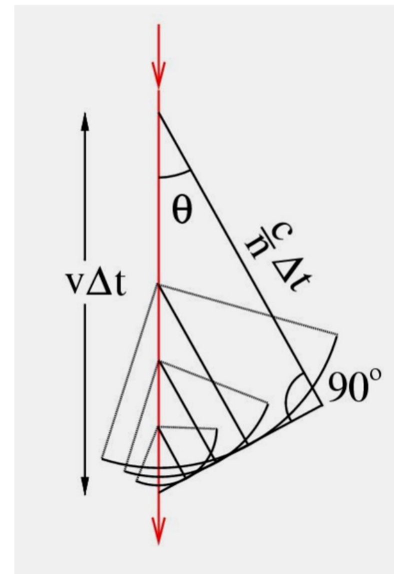
of publication of the above theory, data were already available which had been obtained by visual observations by the method of quenching [7] [8].

We recently performed additional experiments in which the intensity of radiation was recorded photographically, the records being taken simultaneously for all the angles θ lying in a plane passing through the primary electron beam. The liquid was placed in a cylindrical glass vessel with very thin walls, and the light emitted by the liquid was reflected by a conical mirror in an upward direction to the object glass of a photographic camera as indicated in Fig. 1. An approximately parallel beam of γ-rays, filtered through a 3-mm lead plate, fell on the liquid horizontally. The γ-radiation used was equivalent to that of 794 mg of radium. The considerable thickness of the lead screen, the large aperture of the object glass (f : 1.4) and the long exposure (72 hours) ensured sufficient distinctness of the photographs.

Cherenkov radiation

Analogous to “sonic boom”





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

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

Cherenkov, Tamm and Frank awarded Nobel Prize in 1958

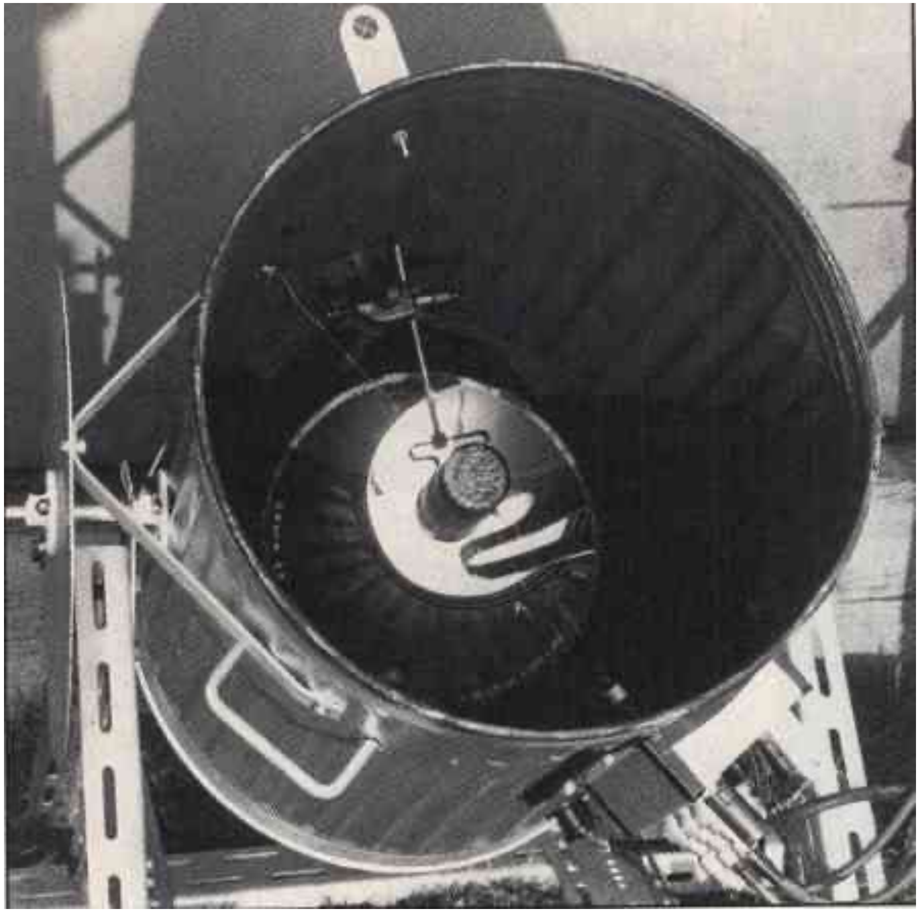
- S. I. Vavilov has passed away in 1951 (after ~10 heart attackes).
- Nobel prize is awarded only to scientists who are alive

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

The Experimental Beginning



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

Gamma-ray Astronomy, the beginning

AN AIR SHOWER TELESCOPE

AND THE DETECTION OF 10^{12} eV PHOTON SOURCES

Giuseppe Cocconi *

CERN - Geneva.

Seminal paper by Phillip Morrison, 1958

1) This paper discusses the possibility of detecting high energy photons produced by discrete astronomical objects. Sources of charged particles are not considered as the smearing produced by the magnetized plasmas filling the interstellar spaces probably obliterates the original directions of movement.

5). Here are some numerical estimates.

The Crab Nebula: Visual magnitude of polarized light m = 9.

Magnetic field in the gas shell $H \simeq 10^{-4}$ gauss.

Therefore: $U_\gamma = 10^{12}\,eV$ and $R(10^{12}\,eV) \approx 10^{-3.2}\ m^{-2}\,s^{-1}$.

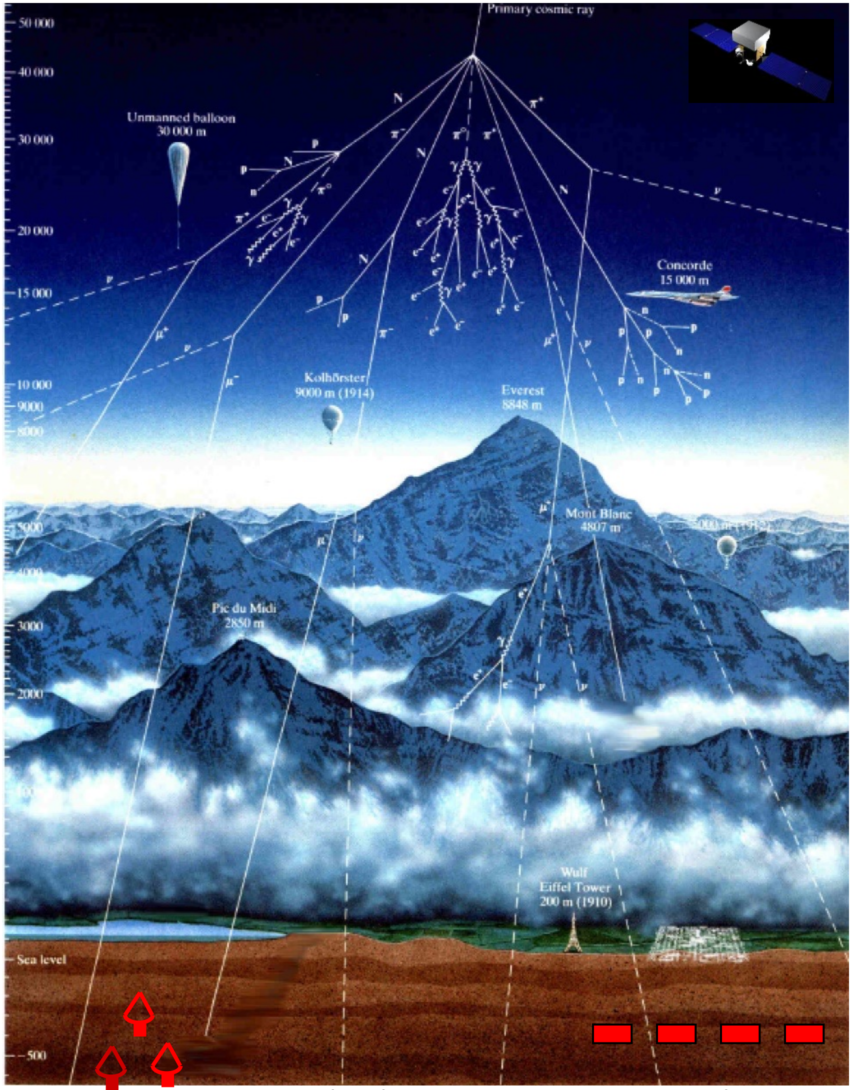
The signal is thus about 10^3 times larger than the background (2). Probably in the Crab Nebula the electrons are not in equilibrium with the trapped cosmic rays, and our estimate is over-optimistic. However, this source can probably be detected even if its efficiency in producing high energy photons is substantially smaller than postulated above.

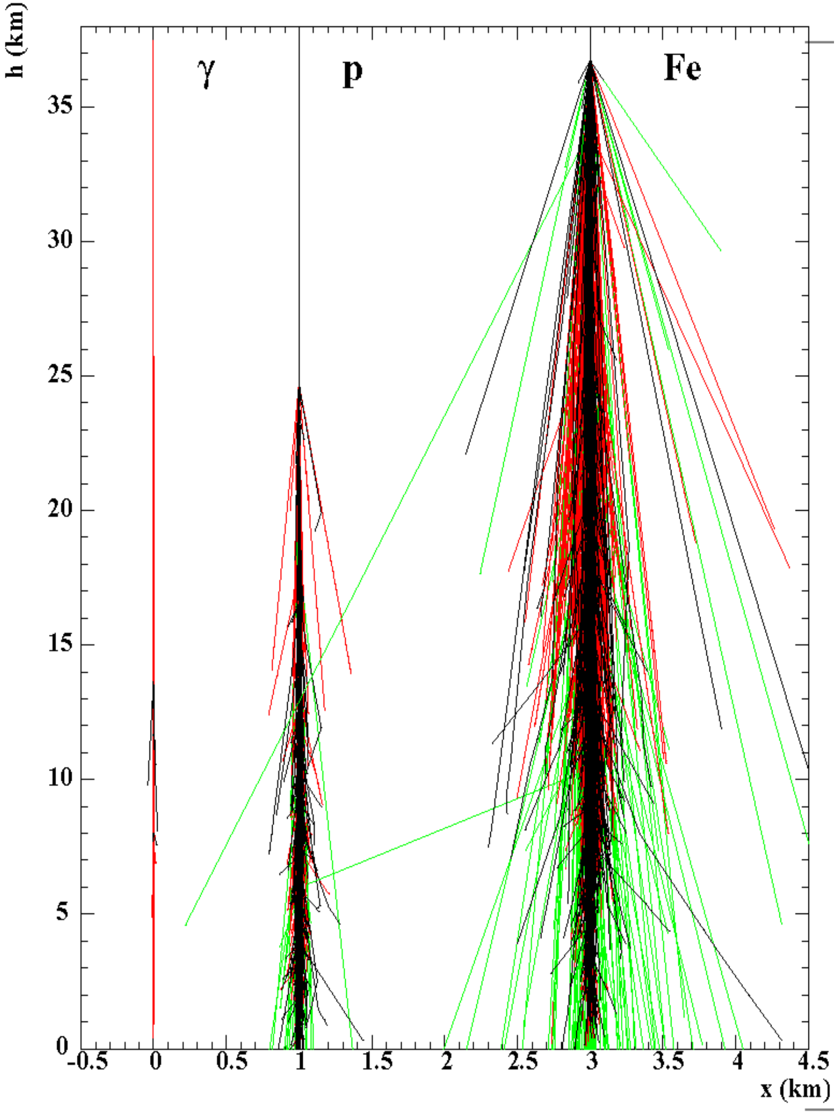
M87, the Jet Nebula: m = 13.5 $H \simeq 10^{-4}$ gauss.

$R(10^{12}\,eV) \simeq 10^{-5}\,m^{-2}\,s^{-1}$, still well above the background (2). For this object our evaluation is probably not fundamentally wrong.

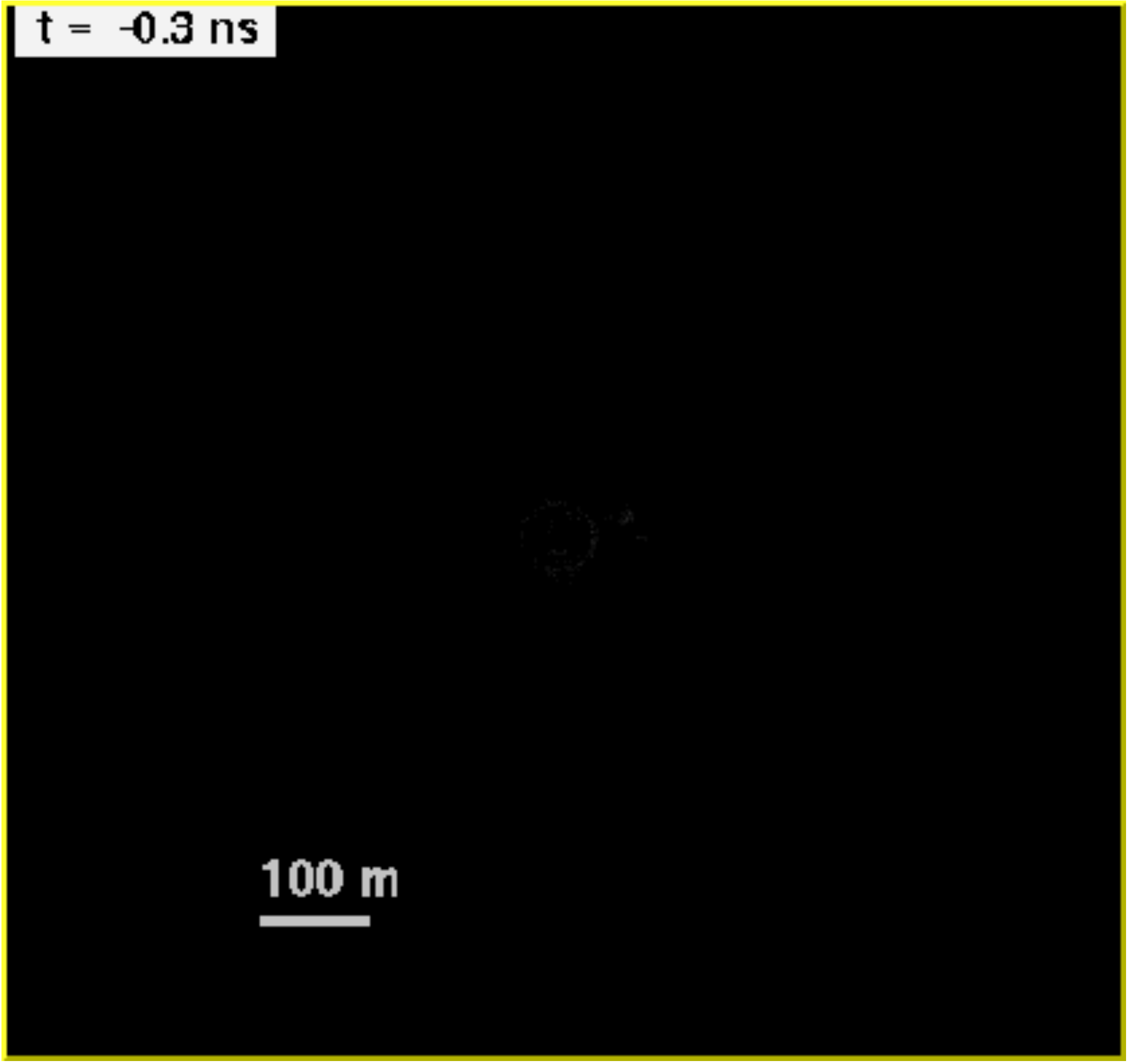
Also proposed at higher energies independently by Giuseppe Cocconi, 1959

Extensive Air Showers

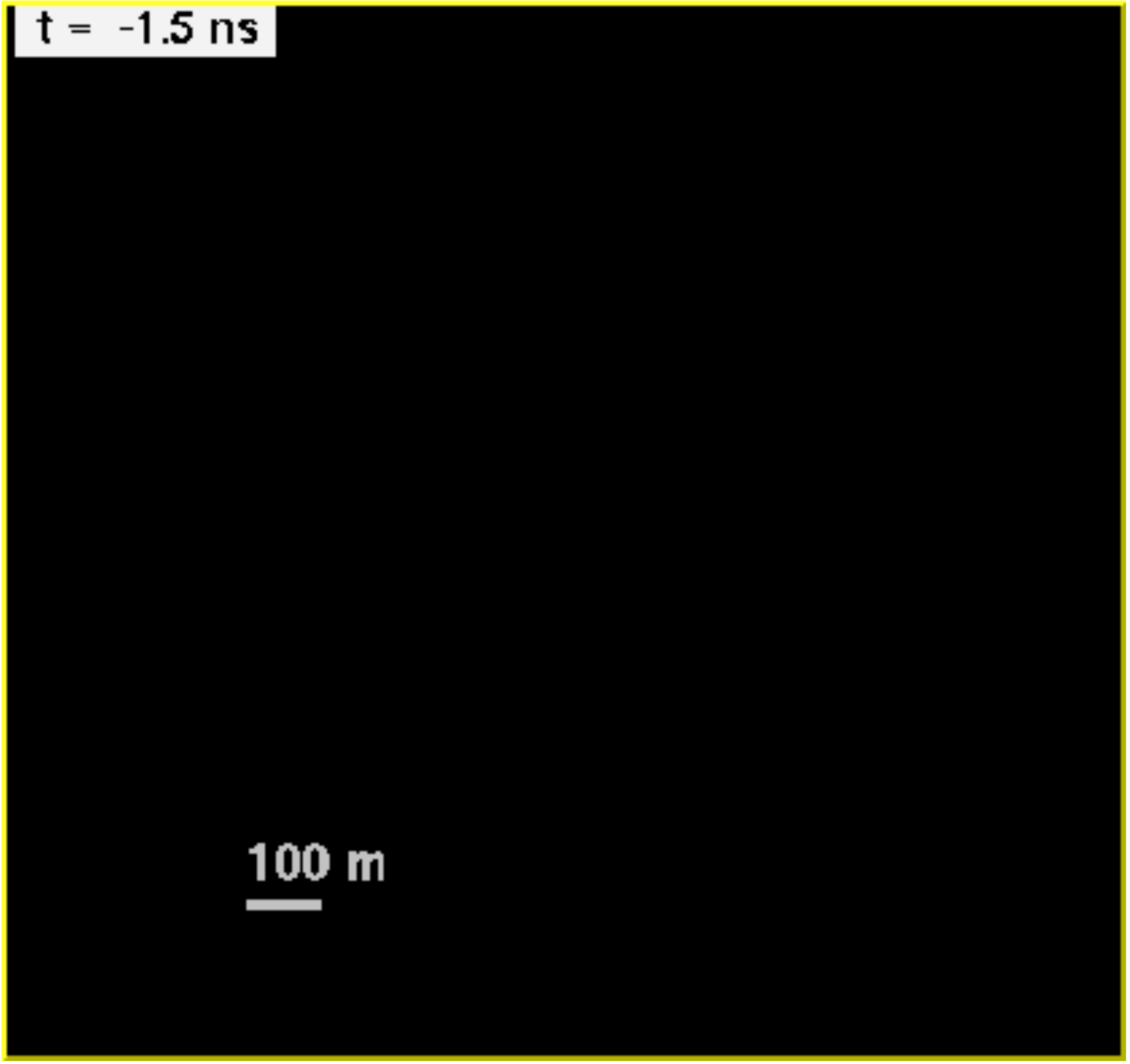




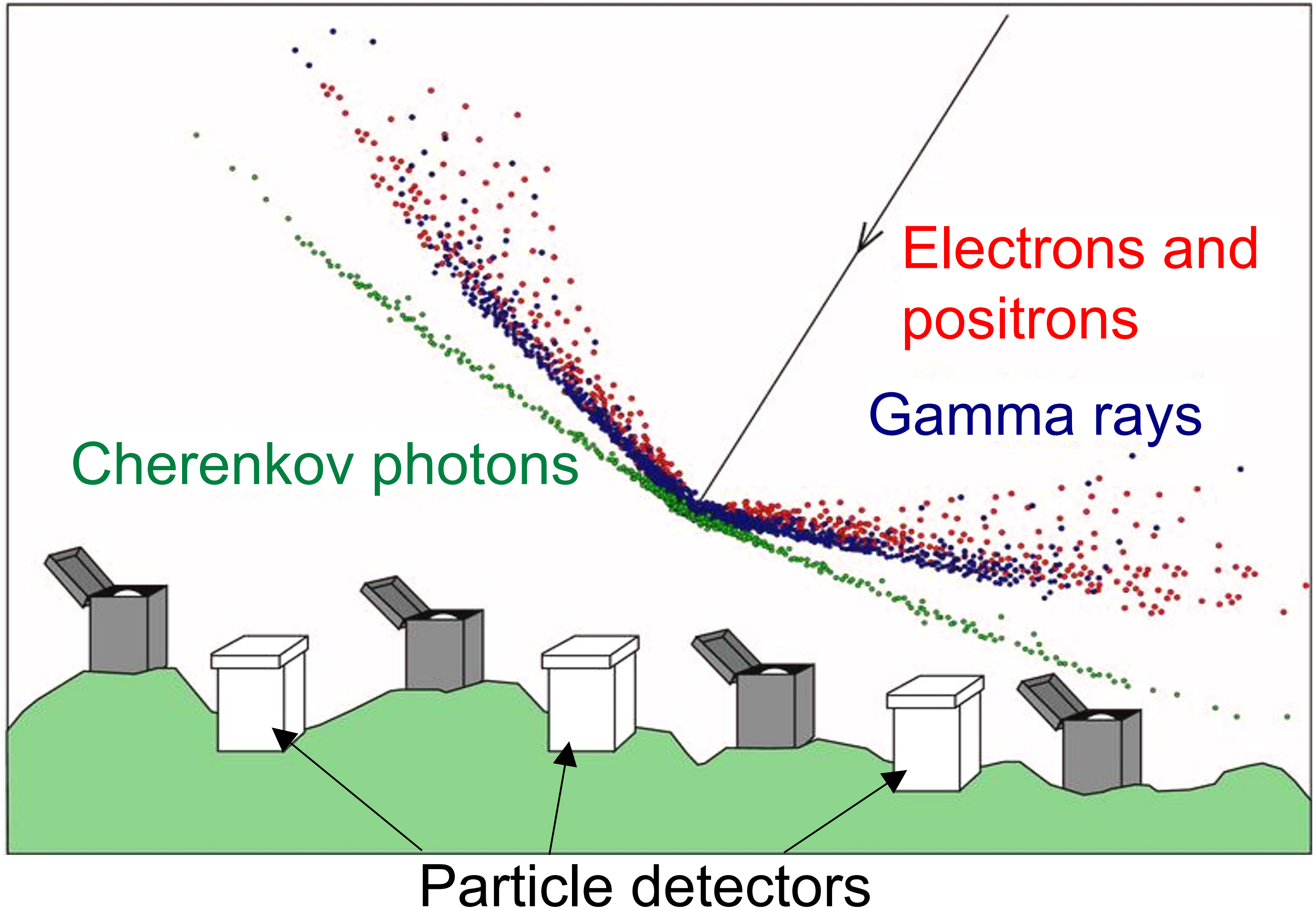
A 100 GeV γ-ray event on the ground



A 200 GeV proton on the ground

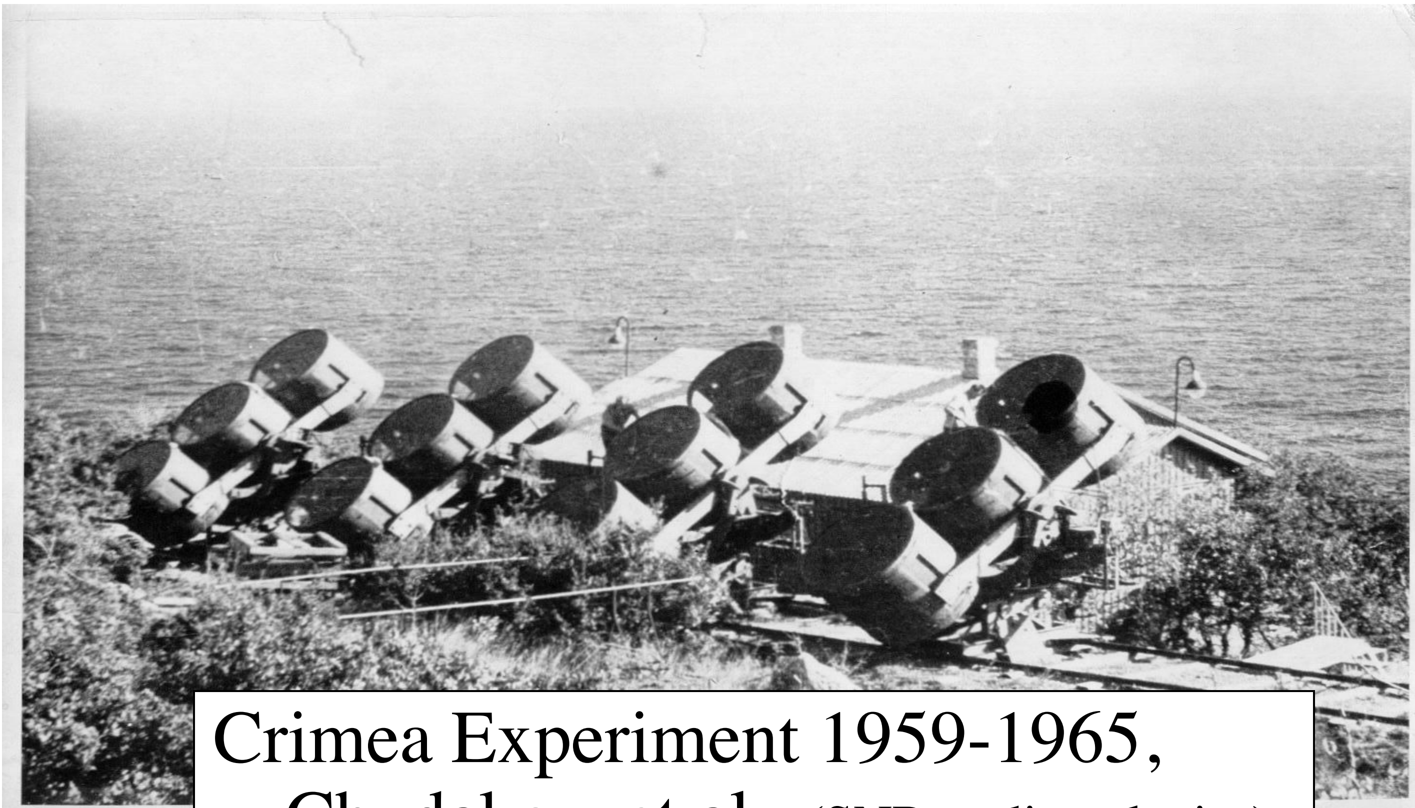


Air Showers measured on the ground



1921-2001

Alexander Chudakov and the Cherenkov Technique for Gamma Ray Astronomy



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

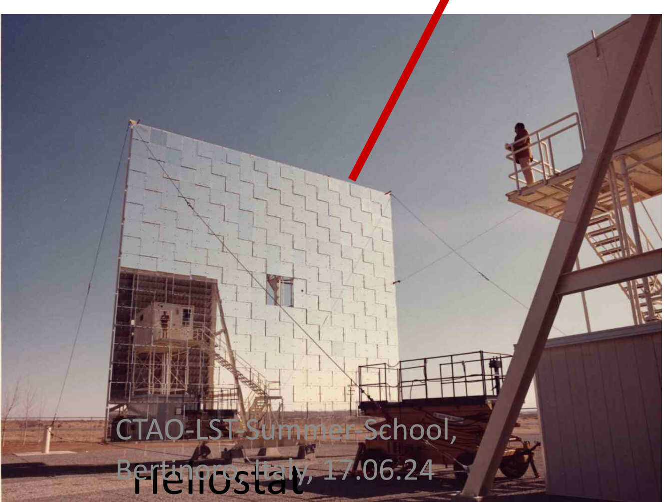
Таблица 1

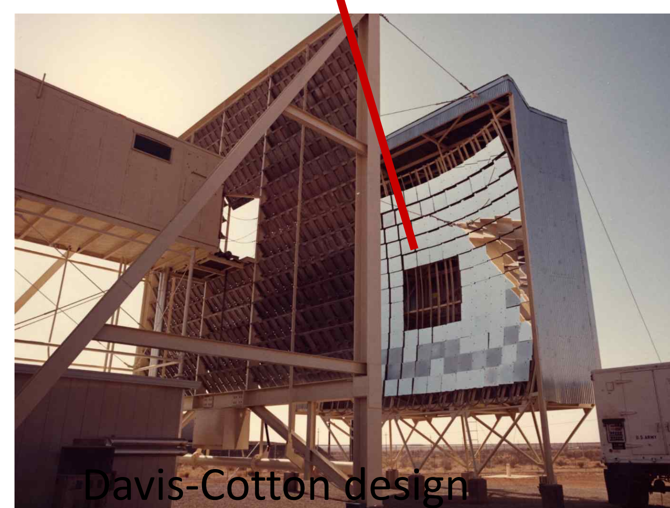
Астрономический объект и период наблюдений	Часовой угол	Склонение	Число сеансов	$\delta \pm \sigma$, %	
				$\vartheta_{эф} \approx \pm 1°$	$\vartheta_{эф} \approx \pm 3°$
Дискретные радиоисточники					
Телец А (Крабовидная туманность)					
1960			15	−0,15±1,32	+1,30±0,95
1961	5^h32^m	+22°00′	13	−0,70±1,20	−0,60±0,84
1962 *			19	−1,40±0,82	−0,45±0,54
Кассиопея А					
1962			8	+0,60±0,93	−0,47±0,56
1962 *	$23^h21^m,6$	+58°35′	12	−0,36±1,10	−0,77±0,66
Лебедь А					
1960			19	+1,60±0,92	+1,60±0,80
1961	$19^h58^m,4$	+40°32′	70	+0,22±0,35	+0,67±0,28
1962			62	+0,15±0,63	−0,65±0,52
1962 *			20	+0,50±0,76	+0,60±0,54
1963 *			20	+1,16±0,77	+0,97±0,53
Дева А					
1961			10	−0,23±3,0	−0,14±2,10
1962	$12^h28^m,9$	+12°38′	10	+0,37±1,0	+0,54±0,70
Персей А					
1962	3^h14^m	+42°24′	4	−1,80±2,30	−2,00±1,24
Стрелец А					
1963	$17^h43^m,3$	−28°58′	7	—	+10,5±20
Скопления галактик					
Большая Медведица II					
1962	10^h54^m	+56°30′	1	−5,0±2,9	−3,0±1,24
Северная корона					
1962	15^h22^m	+27°24′	2	+3,3±2,1	+1,9±1,4
Волосы Вероники					
1962	12^h55^m	+28°41′	1	+1,5±3,4	+1,7±2,4
Волопас					
1962	14^h33^m	+31°16′	1	+2,4±6,9	+6,6±4,7

* Звездочкой отмечены измерения с компенсацией тока от неба.

- A multitude of sources have been observed and serious statistical treatment of data has followed
- Except for some small fluctuations no significant flux has been observed ≥ 3.5-5 TeV, Flux upper limit: 5 x 10-11 ph/cm^2s
- They turned down the too optimistic prediction of Cocconi about 1000:1 S/N

1st Smithsonian venture into VHE gamma-ray used Solar Furnace at Natick, MA ~ 1965-6.
Gamma-ray Astronomy Group led by Giovanni Fazio





The Pioneer Trevor Weekes; life-long trying hard, until succeeding with Crab Nebula in 1988

THE ASTROPHYSICAL JOURNAL, Vol. 154, November 1968

A SEARCH FOR DISCRETE SOURCES OF COSMIC GAMMA RAYS OF ENERGIES NEAR 2×10^{12} eV

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Received September 3, 1968

ABSTRACT

By use of the atmospheric Čerenkov nightsky technique, a study has been made of the cosmic-ray air-shower distribution from the direction of thirteen astronomical objects. These include the Crab Nebula, M87, M82, quasi-stellar objects, X-ray sources, and recently exploded supernovae. An anisotropy in the direction of a source would indicate the emission of gamma rays of energy 2×10^{12} eV. No statistically significant effects were recorded. Upper limits of 3–30 $\times 10^{-11}$ gamma ray cm^{-2} sec^{-1} were deduced for the individual sources.

Cherenkov Shower Imaging using Image Intensifiers (1960-65) and Stereo Detectors (1972-76)

Image Intensifier Pictures of Cherenkov light Image from Cosmic Ray Air Shower.
On short time-scale images are brighter than bright star (Vega).
Work by David Hill (M.I.T.) and Neil Porter (U.C.D.) in 1960

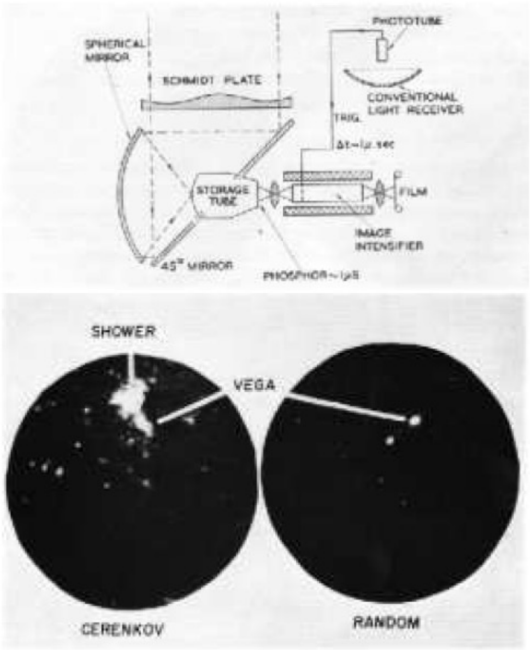
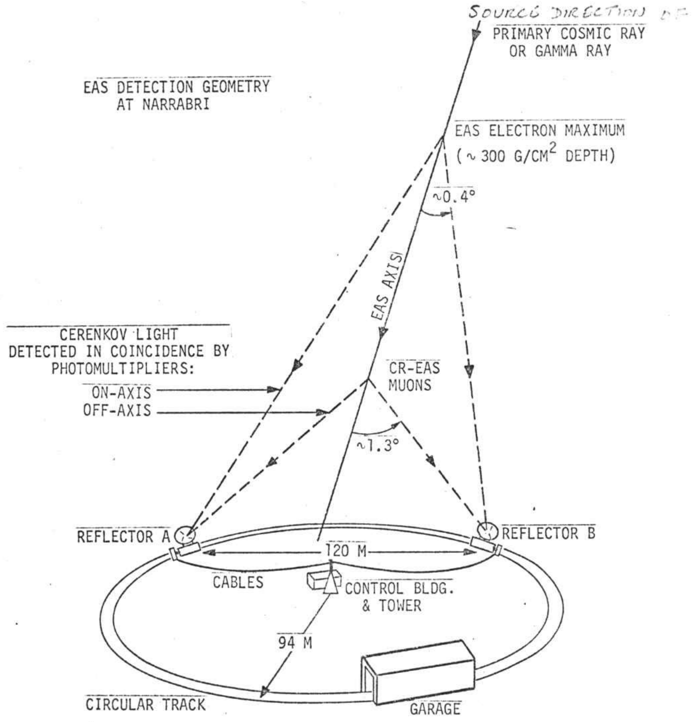


Figure 5. **Top:** Image Intensifier used by Hill and Porter to record the images of cosmic ray air showers [24]. **Bottom** Images of the night-sky triggered by an ACT (left) and triggered randomly (right). The field of view was ±12.5°.



Josh Grindlay demonstrates value of stereo imaging with two-pixel system (Double Beam Technique) at Mt. Hopkins and Narrabri (1972-76)

Victor Zatsepin, born in 1928

In 1960's Victor Zatsepin well-
-understood all the main features of the air Cherenkov technique.

I learned from him that in 1960 was long seriously considering a key question about how one could measure multiple images of showers (which kind of cameras can do it?).

He performed simulations of air showers in 1961-64 (were there computers available, really ?)

- „URAL" was the name of the russian computer that was operated by a specially trained staff.

The 1st S… on the Potential…

SOVIET PHYSICS JETP VOLUME 20, N

THE ANGULAR DISTRIBUTION OF INTENSITY OF C EXTENSIVE COSMIC-RAY AIR SHOWERS

V. I. ZATSEPIN

P. N. Lebedev Physics Institute, Academy of Sciences

Submitted to JETP editor March 2, 1964

J. Exptl. Theoret. Phys. (U.S.S.R.) 47, 689-696 (Augus

The angular distribution of intensity is calculated for terrestrial atmosphere by extensive air showers of co showers arriving from the zenith and for conditions of titude of 3860 m above sea level. Photographic observ against the celestial sphere, as obtained in [2,3] is evi the calculations.

1. INTRODUCTION

In the registration of extensive air showers (EAS) by means of Cerenkov counters,[1,2] a knowledge of the angular distribution of the Cerenkov radiation is important primarily from the methodological point of view (choice of the angle subtended by the Cerenkov counters to obtain optimal signal-to-noise ratio, estimates of the accuracy of the angular coordinates of high-energy primary particles, and so on). Besides this, the angular distribution of the light from showers is already itself the object of physical investigation,[3] and therefore it is important to ascertain what kind of information about a shower can be obtained from such data. The present calculation has been made for this purpose, and is based on the following ideas.

Cerenkov radiation is mainly caused by the electronic component, which makes up the bulk of the charged particles in a shower. Owing to multiple Coulomb scattering by the nuclei of atoms in the air, electrons of energy E at a depth p have a Gaussian distribution of distances r from the axis of the shower, and a Gaussian distribution of angles relative to a mean angle ϑ, which depends on r. The dispersions of the transverse and angular distributions depend on E. The energy spectrum of the electrons is an equilibrium one and does not depend on the degree of development of the shower in depth. For the case of primary photons the variation of the electrons with height is taken to be that given by the electromagnetic cascade theory,[4] and for the case of primary protons, that given by the calculations of Nikol'skiĭ and Pomanskiĭ.[5] The light emitted by the electrons is at the angle ϑ_{Cer} with the direction of their

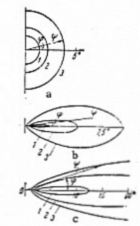
CONCLUSION

The calculations that have been made enable us to draw the following conclusions:

1. Since the maximum intensity of the light from a shower does not coincide with the direction of arrival of the primary particle, in researches in which the determination of the angular coordinates of the primary particle is made by photographing the light flash from the shower one should seek improved accuracy in this determination by photographing the shower simultaneously from several positions.

2. If the distance from the axis of the shower to the detector is determined from independent data, then an analysis of the shape of the light flash from the shower and its total intensity gives information both about the initial energy of the primary particle and about the position in the atmosphere of the maximum of the shower, and can thus be used for the analysis of fluctuations in the development of showers in the atmosphere.

In conclusion I regard it as my pleasant duty to express my gratitude to A. E. Chudakov for suggesting this topic and for helpful discussions.



…ours of equal intensity in the light flash at …s from the axis of a shower arising from a …ith $E_{0p} = 4.5 \times 10^6$ BeV (3860 m above sea …, 2, and 3 correspond to the intensities …$I_{max}(R)$, and $10^{-1} I_{max}(R)$, and diagrams …or distances 0, 100, and 400 m from the …er.

… 10^{15} eV is considerably larger than … a shower at sea level. This differ… due to the different distance of the …ice from the maximum of the …he shape of the spot of light is sen…ight of the maximum of the shower, … principle an analysis of the shape …o to determine the position of the … shower.

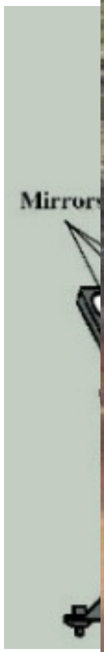
… calculations have been made on the …ons as the calculations of the spatial … the light made in [6], and therefore …cked directly by calculating the total …ensity

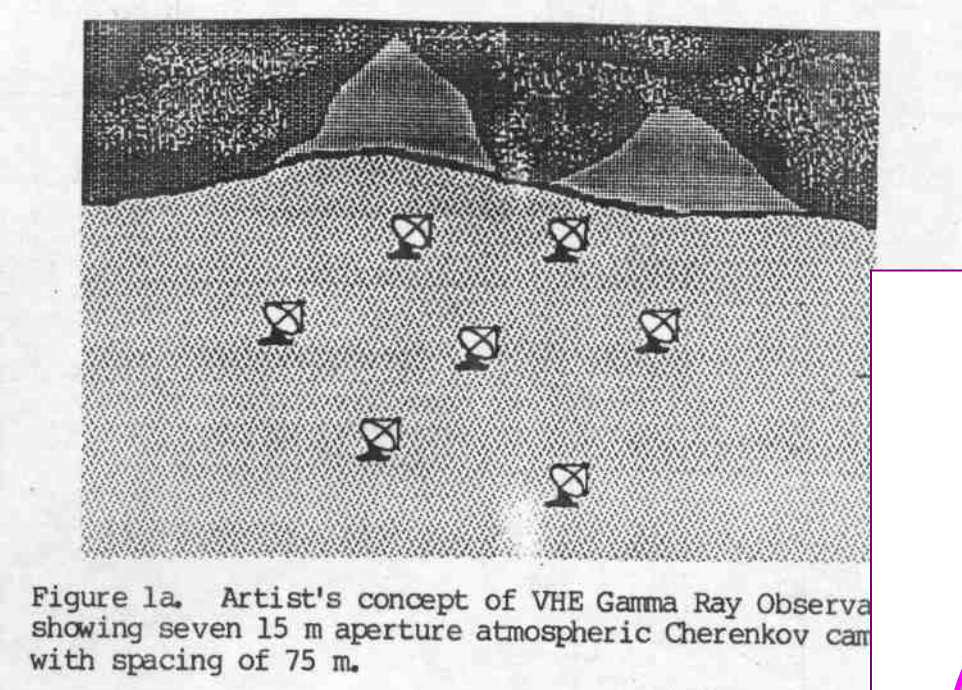
$$\int_0^{2\pi}\int_0^{10^\circ} I(E_0, R, \psi, \varphi)\sin\psi\, d\psi\, d\varphi \quad (11)$$

…nce from the axis of the shower and …ith the results obtained in [6]. Cal… (11) have been made for seal level …and R = 400 m. The results agreed … of [6] to an accuracy of several

…ions that have been made enable us …owing conclusions: … maximum intensity of the light from …ot coincide with the direction of …rimary particle, in researches in …mination of the angular coordinates …particle is made by photographing …rom the shower one should seek …acy in this determination by photo-

Arnold Stepanian's pioneering imaging "stereo "telescopes: GT-48 in Crimea

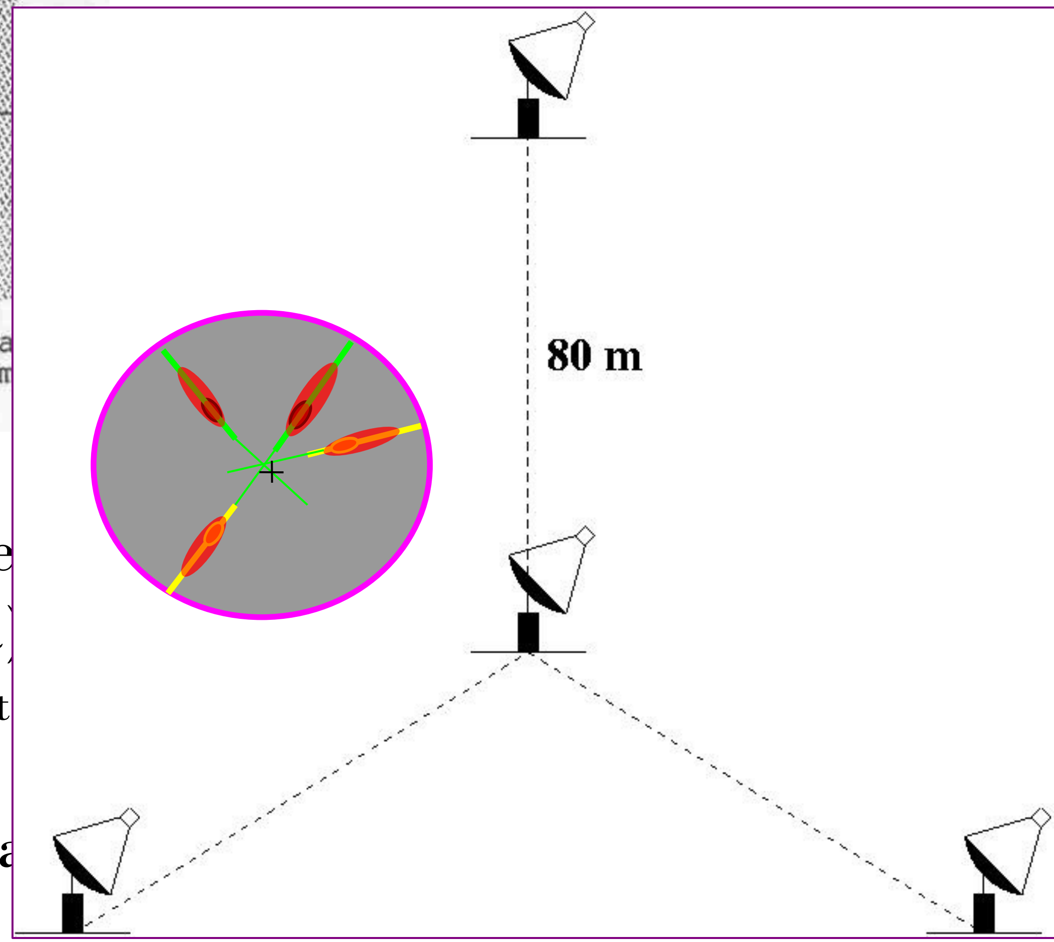




An array of ACIT's was first proposed in 1984 (prior to the detection of the Crab Nebula)

(NASA Workshop, Space Lab. Science, Bat Rouge, 1984)

This is the configuration that wa later adopted for VERITAS.



Some key developments

- 70-80‘s: plenty of „discoveries“ on 3-4 σ level
- M. Hillas: „A physicist‘s aparatus gradually learns what is expected of it (blame the apparatus for a dog-like desire to please)“
- La Jolla, 1985: Michel Hillas suggested to use the „Hillas“ parameters
- 1989: Whipple discovers 9σ signal from Crab

First Gamma-ray Experiment at Whipple Observatory, 1967-68

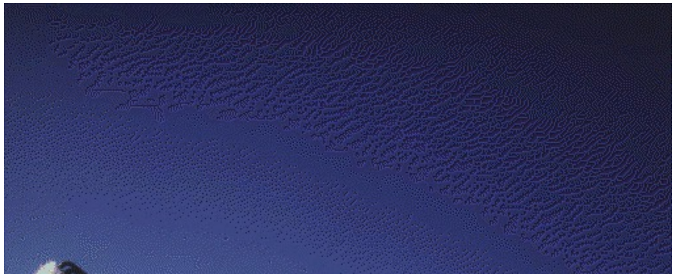
Work on the Mt. Hopkins Observatory proceeds at an astonishing pace. The laser and Baker-Nunn systems are now installed and operating and the large optical reflector is scheduled to arrive by the end of next month. In preparation for the LOR installation, Trevor Weekes (above, left) and George Rieke have conducted seeing tests with two movable searchlight reflectors. Look carefully – some outcroppings at the base of Mt. Hopkins are visible upside-down in the reflector.

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

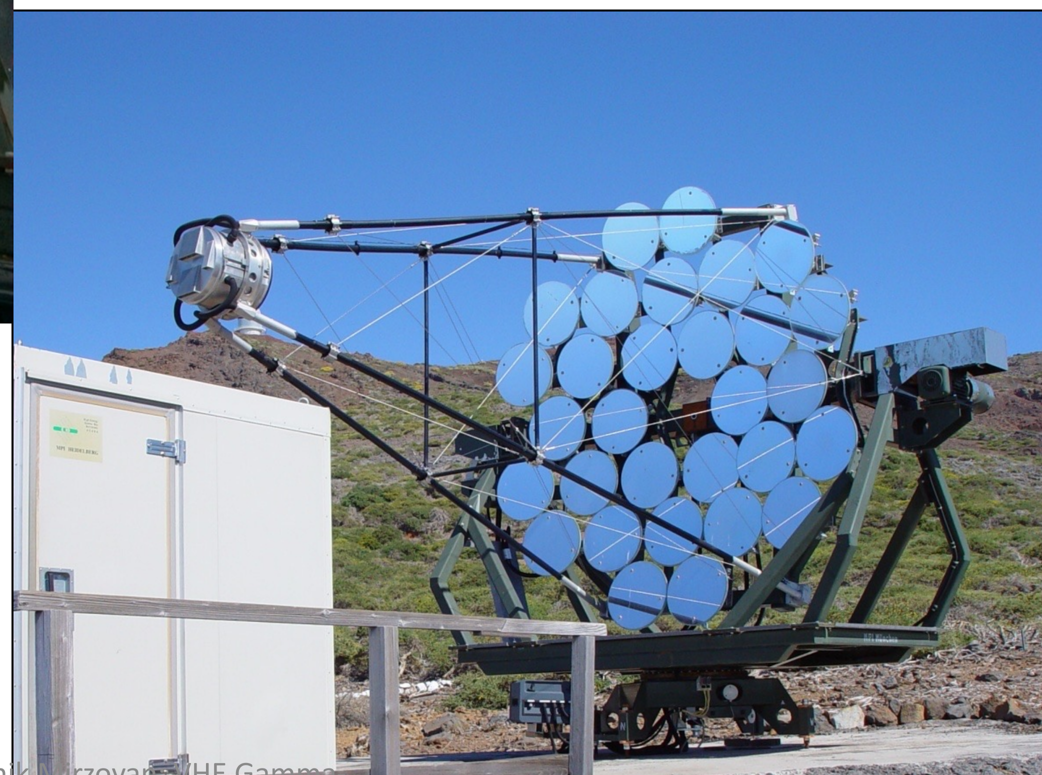
„If a telescope can within a few s evaporate a solid piece of steel, it can also measure gamma rays"
;-)

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

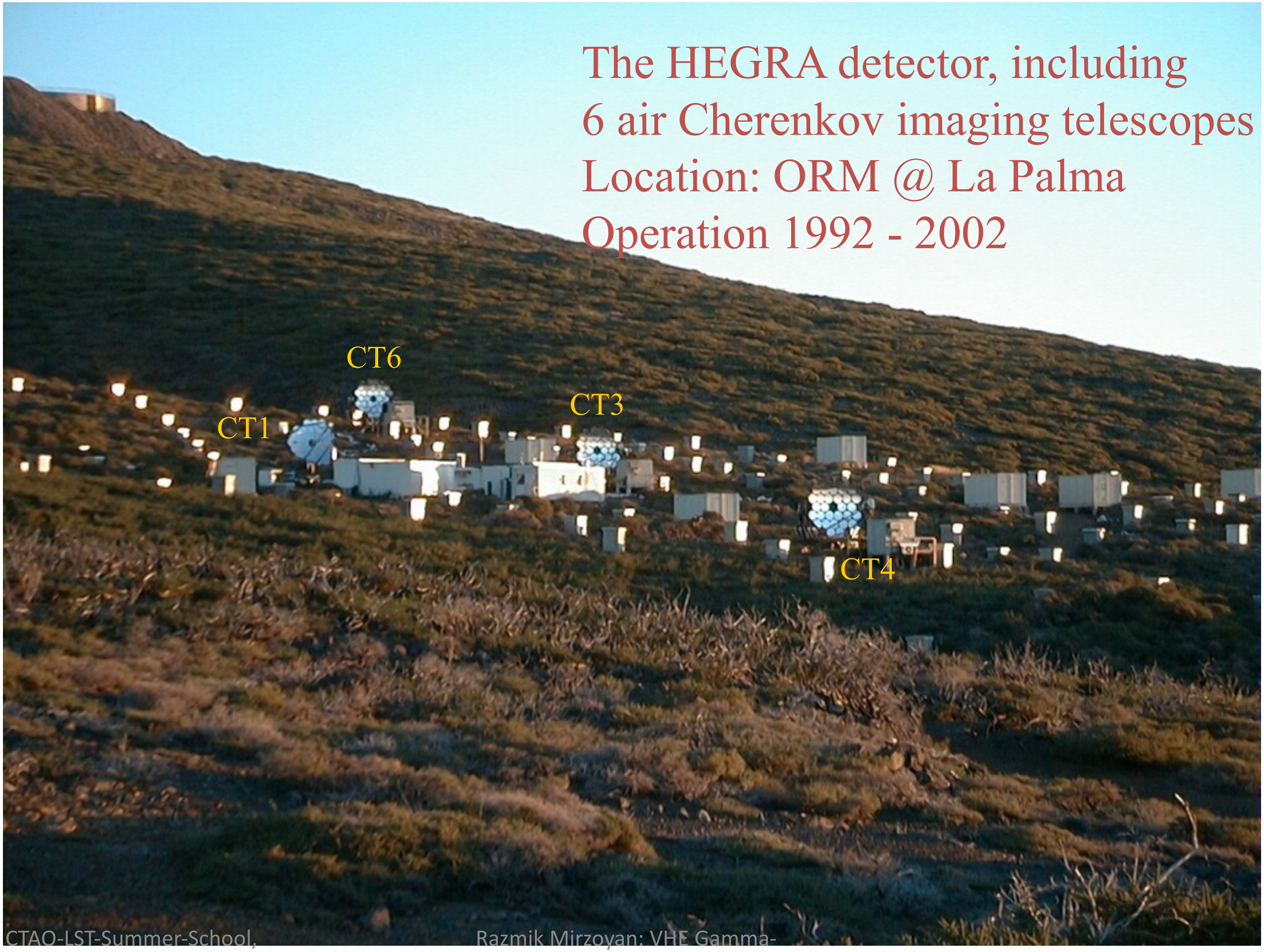
CT1 started to collect data in summer 1992
The 1st signal from Crab Nebula fall 1992



CT2 – CT6: 5 more telescopes were built until 1997.



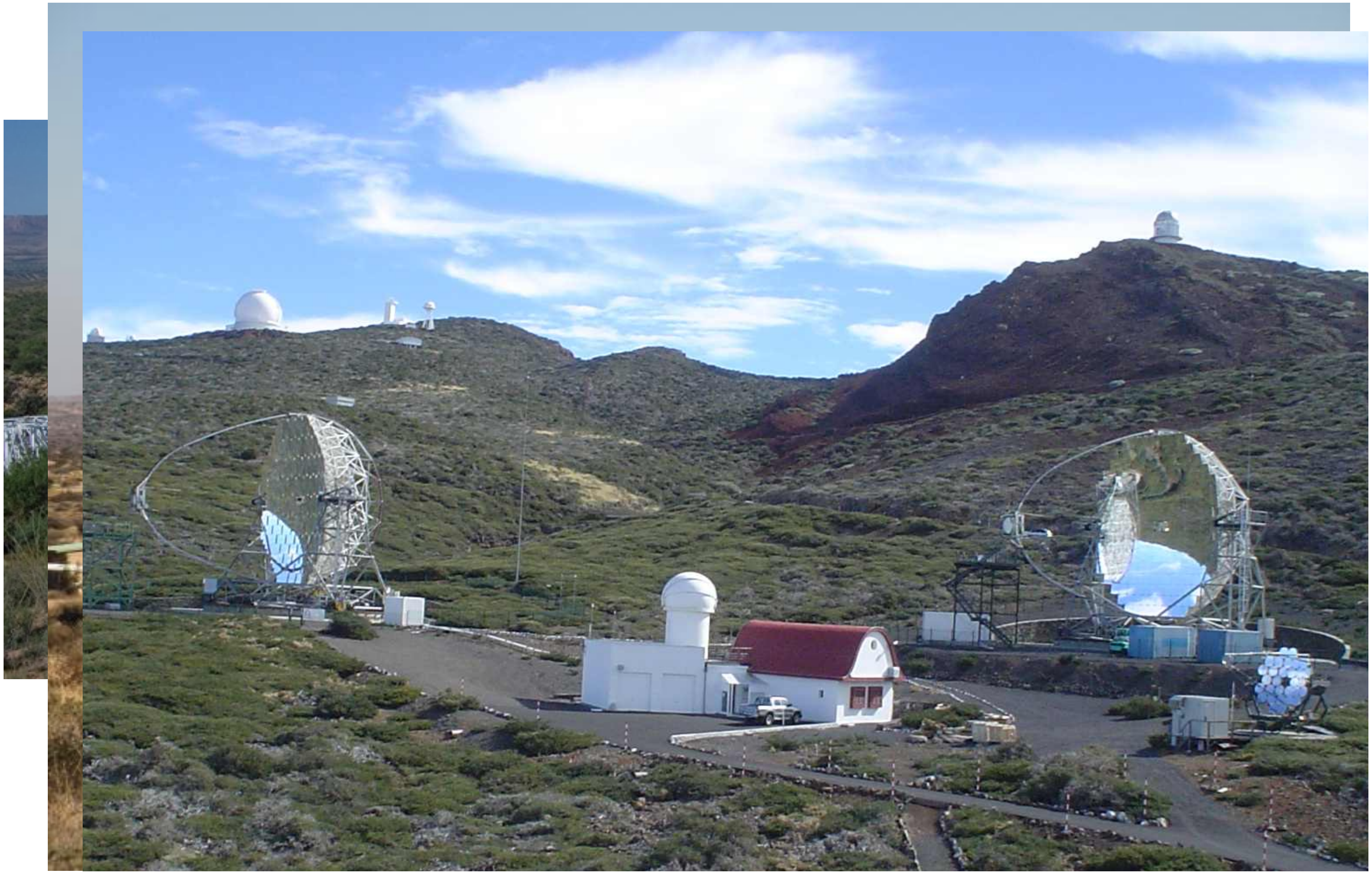
The 1st telescope of HEGRA, the CT1 (installed spring 1992)


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

Milestones in VHE γ astro-physics

- 2nd generation imaging telescopes, lead by the pioneering 10m Ø Whipple telescope, made the breakthrough, in the first time allowing to measure reliably γ sources at $E \geq 700$ GeV
- 2nd generation telescope arrays, put in proximity and set into coincidence (later on dubbed as „Stereo“), led by HEGRA, allowed increasing the sensitivity and precision of measurements
- 3rd generation telescope MAGIC was 1st to lower the operational energy range of an IACT by one order of magnitude, down to 25 GeV (discovery of γ pulses from Crab pulsar at $E \geq 25$ GeV, SCIENCE,2008)

VERITAS, H.E.S.S. & MAGIC: still exploring the limits of VHE γ-astro-physics

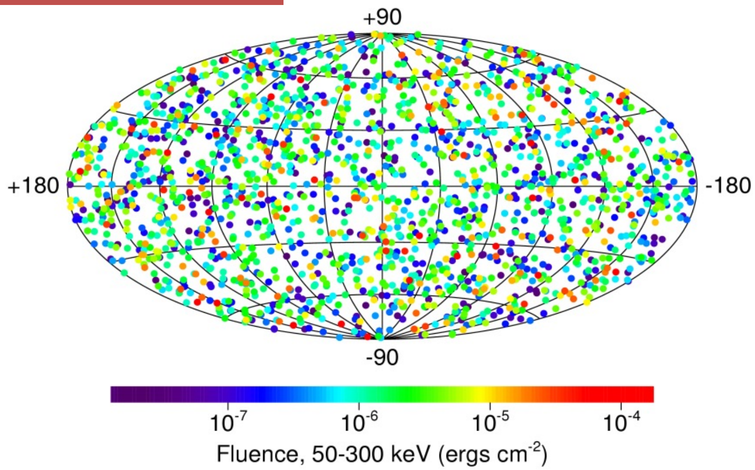


System of 2 MAGICs: the main parameters

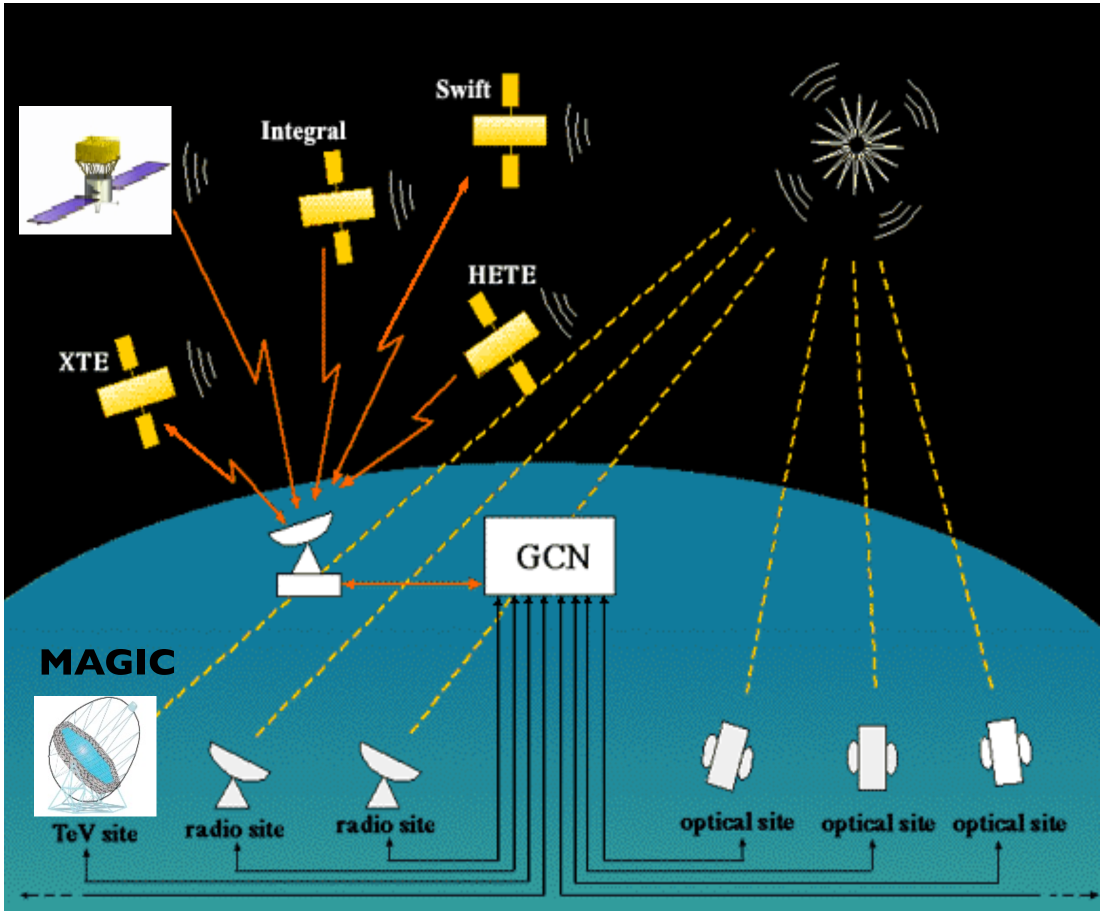
- Energy threshold (trigger): ~ 50 GeV
- Energy threshold in *"Sum-Trigger"* modus: 30 - 35 GeV
- Energy resolution: 15 % - 23 % for $E \leq 10$ TeV
- Angular resolution: 0.07° for $E \geq 300$ GeV; 0.05° @ 1 TeV
- Sensitivity: source with 6/1000 of Crab Nebula 5σ in 50h
- Light-weight construction, only ~ 70 T
- Fast re-positioning to any coordinates in the sky: 25s/180°
- Opto-electric design optimized to provide ~ 2.5ns FWHM pulses
- Data digitized by using DRS4 chips operated at 1.67 GigaSample/s
- Producing ~ 1 TB data per observation night per telescope

GRB observations

Uniformity



Duration of Burst



GRB trigger from a satellite to MAGIC: 13 sec

Capability: slew to any position in ≤ 50 sec

Fast Rotation of MAGIC to„catch“ GRB

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

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

$n = 1 + \eta_h$

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

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

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

(≈ 21 MeV at sea level)

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

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 λ_1 = 300 nm, λ_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/cm²

Cherenkov emission threshold in water and in glass

- Water: n = 1.33;
  θ_{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

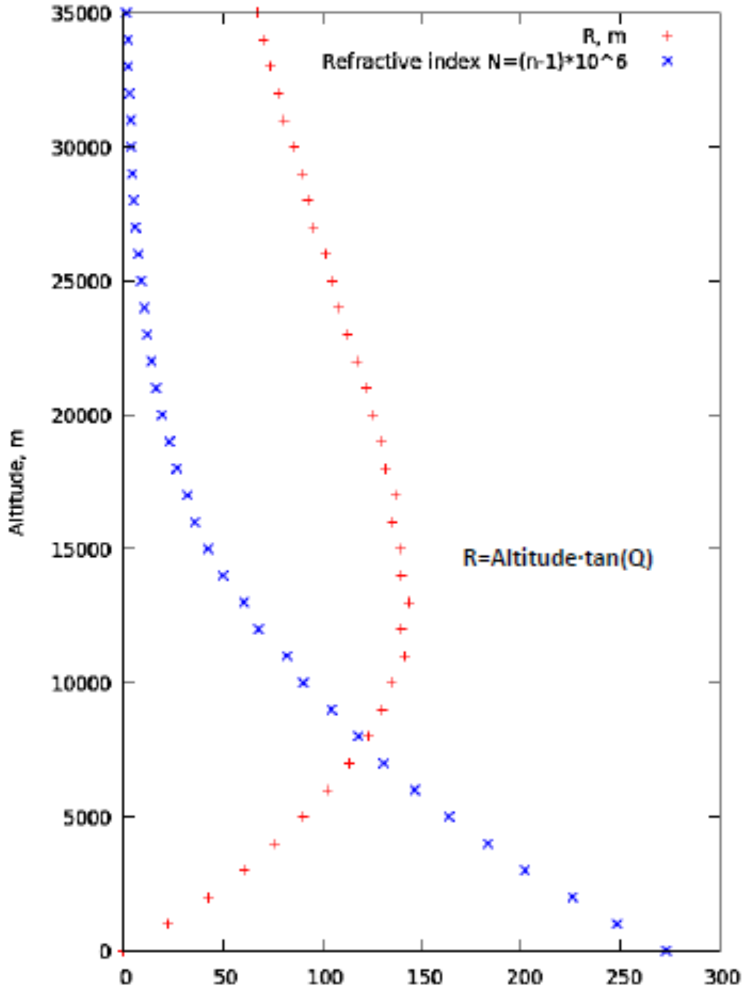
- Plexiglas: n = 1.50;
  θ_{max} = 48.2°
  for $e^{\pm}$ E_{thr} = 686 KeV
  for $\mu^{\pm}$ E_{thr} = 142 MeV
  $N_{photons/mm}$ = 46 for λ in (300 – 600) nm

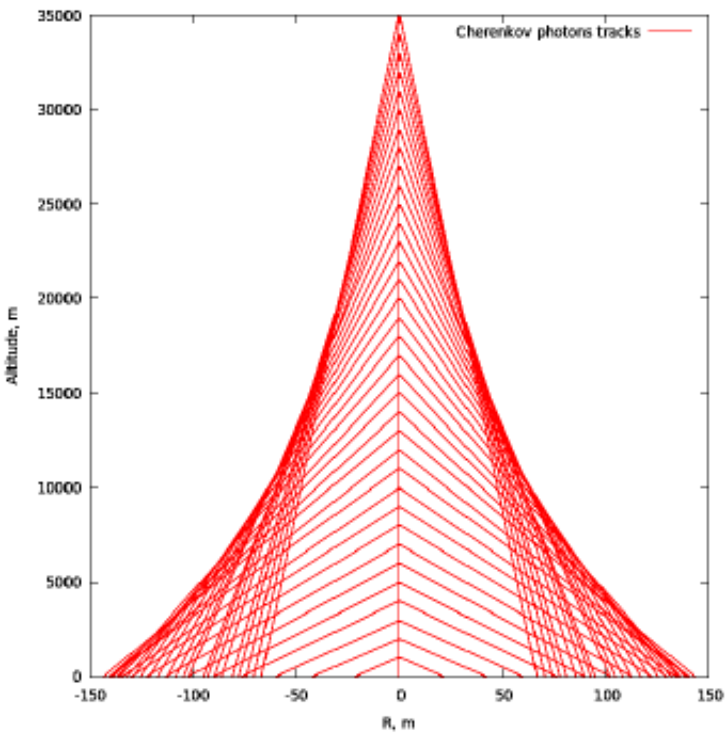
Number of emitted Cherenkov photons in the atmosphere

- 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:

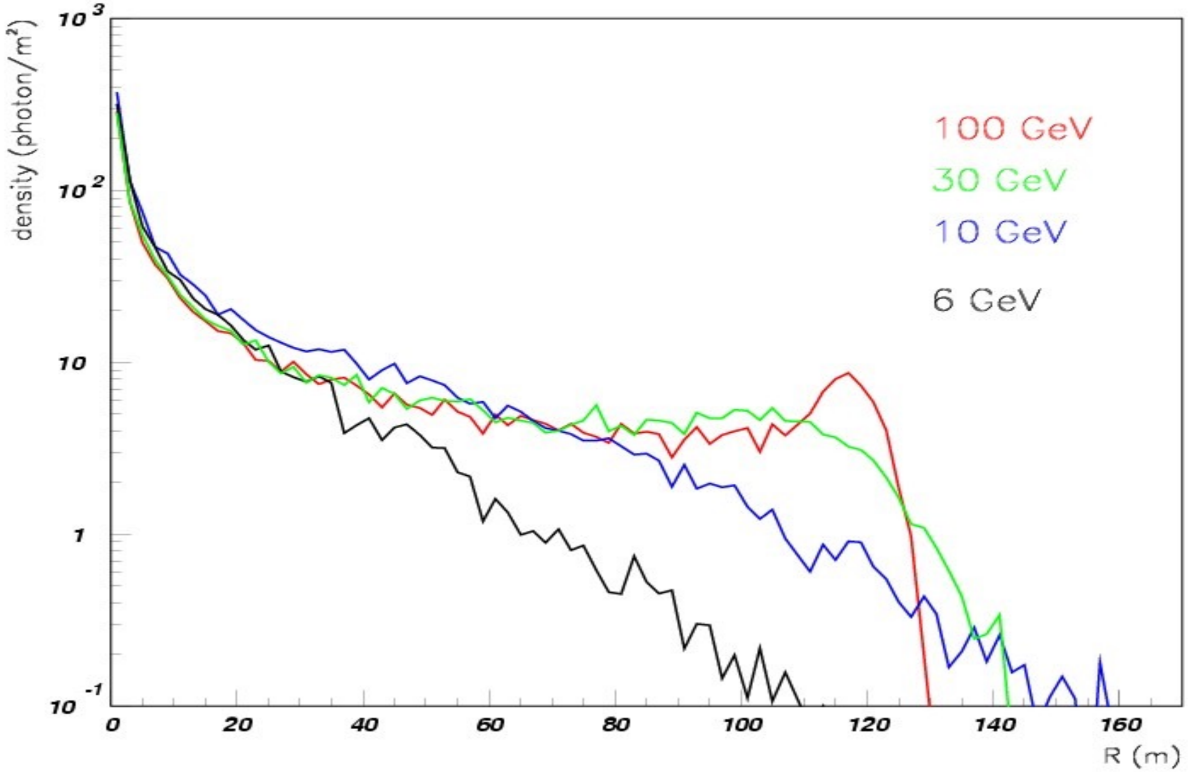
Slanth depth, g/cm²	100	300	800	1036
Height a.s.l., km	16	10	2.2	0
Number of emitted C-photons/m	4.5	13	35	45

Index of Refraction and Cherenkov Emission Angle versus Altitude





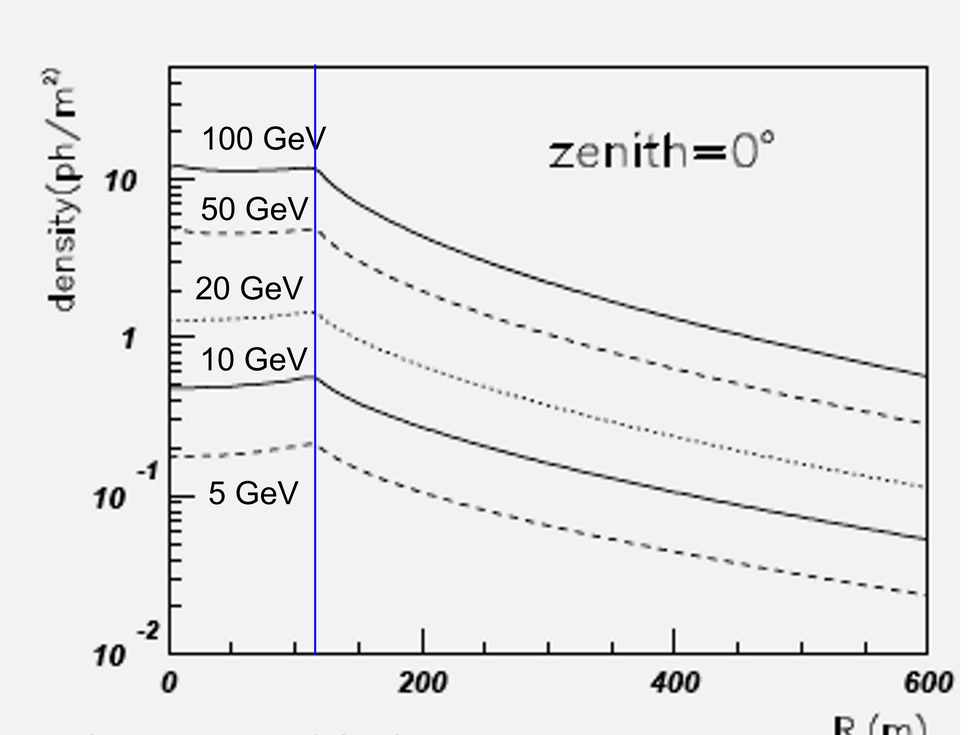
Lateral distribution of light from a single μ



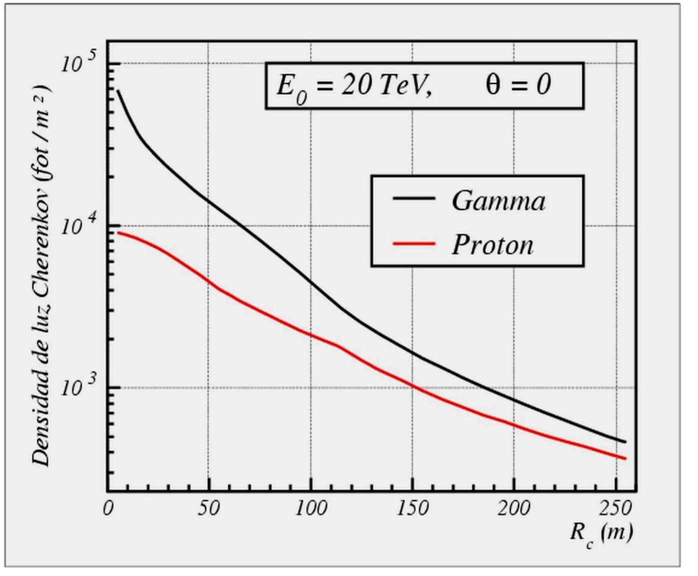
Lateral distribution of C-light

If e± shower extinguishes before reaching observation level (E< a few TeV) : Plateau up to the hump, then fast drop

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

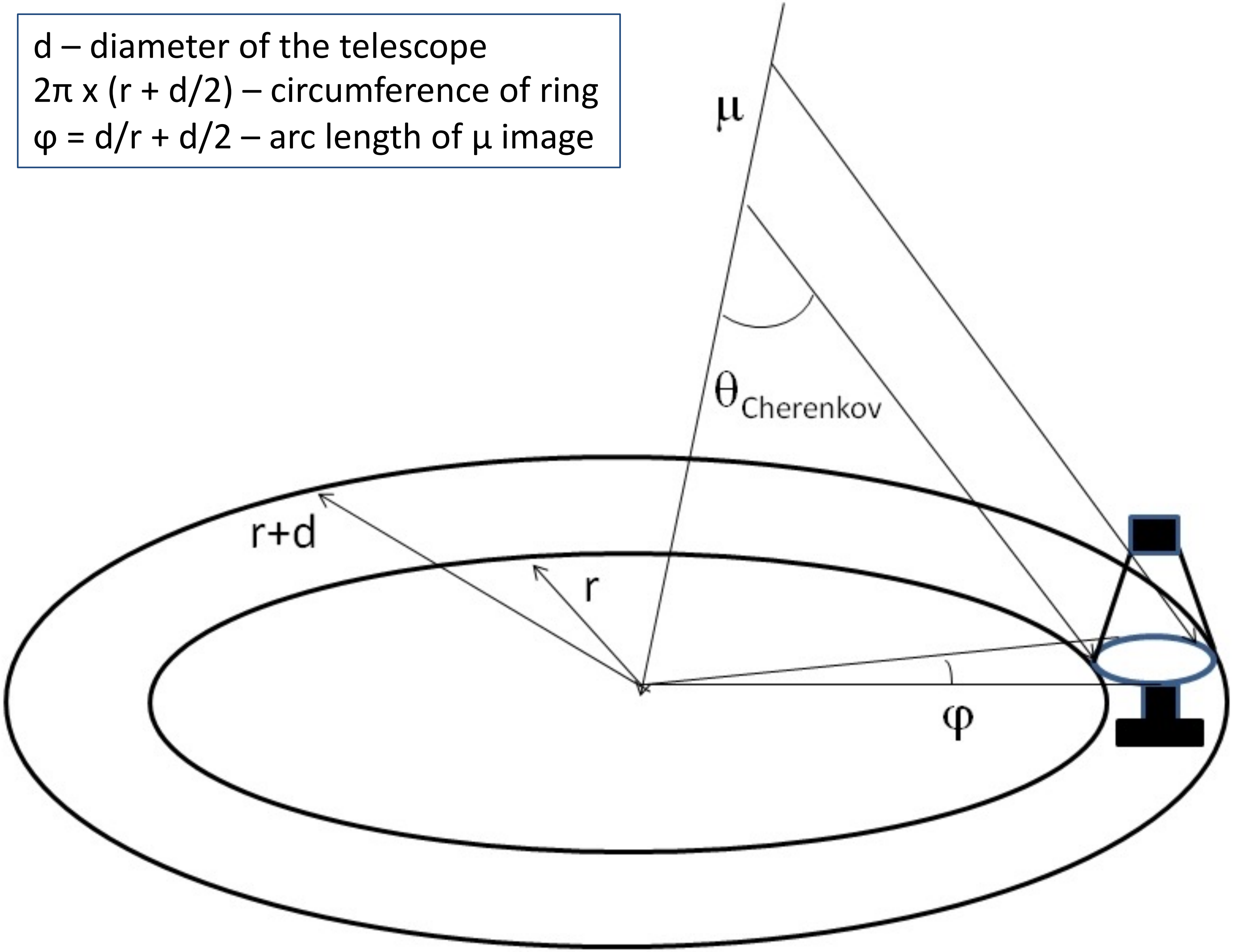


D. Sobczynska, CORSIKA simulations

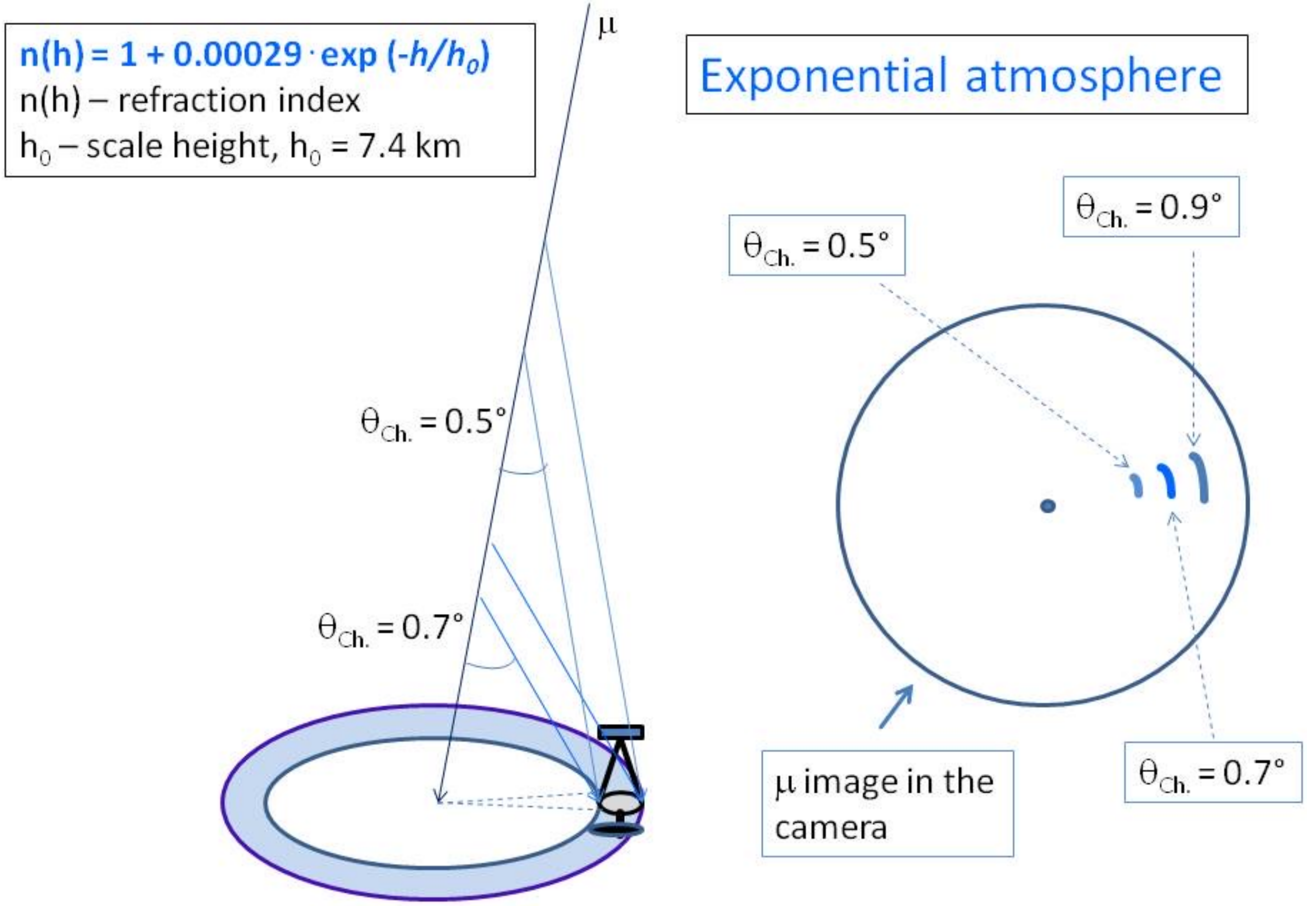


Note above: for a given E_0, a γ-ray produces far less light than a hadron!

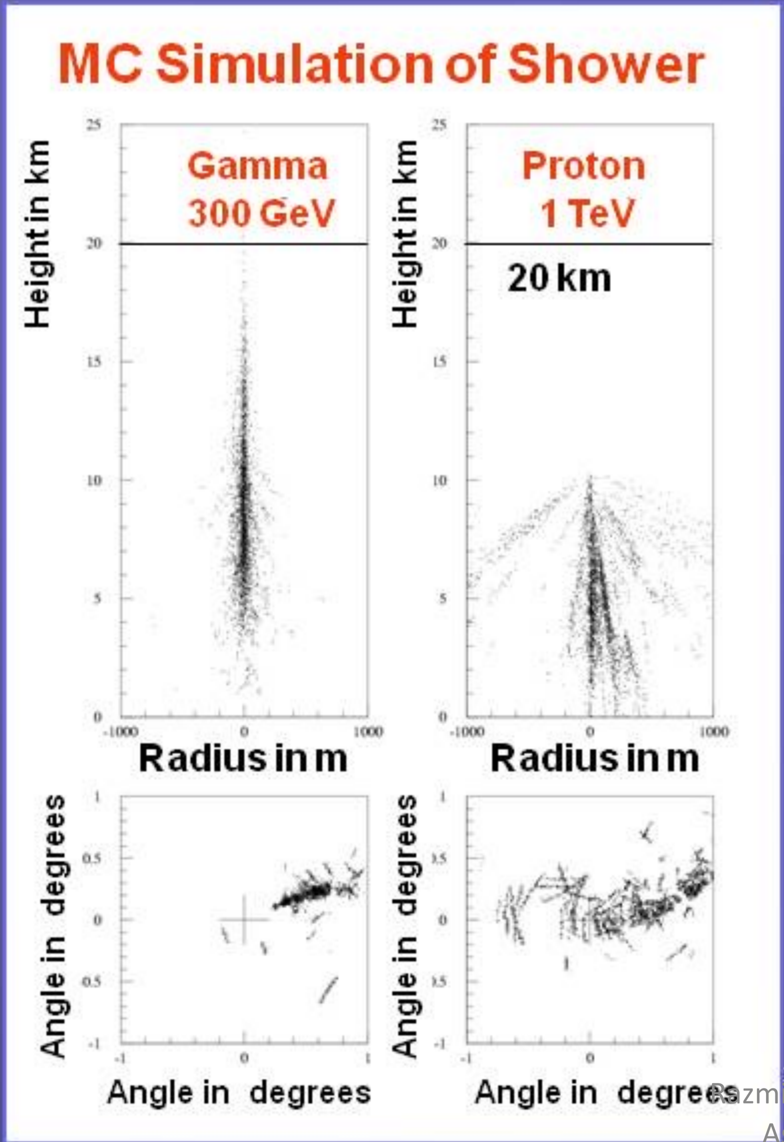
d – diameter of the telescope
2π x (r + d/2) – circumference of ring
φ = d/r + d/2 – arc length of μ image



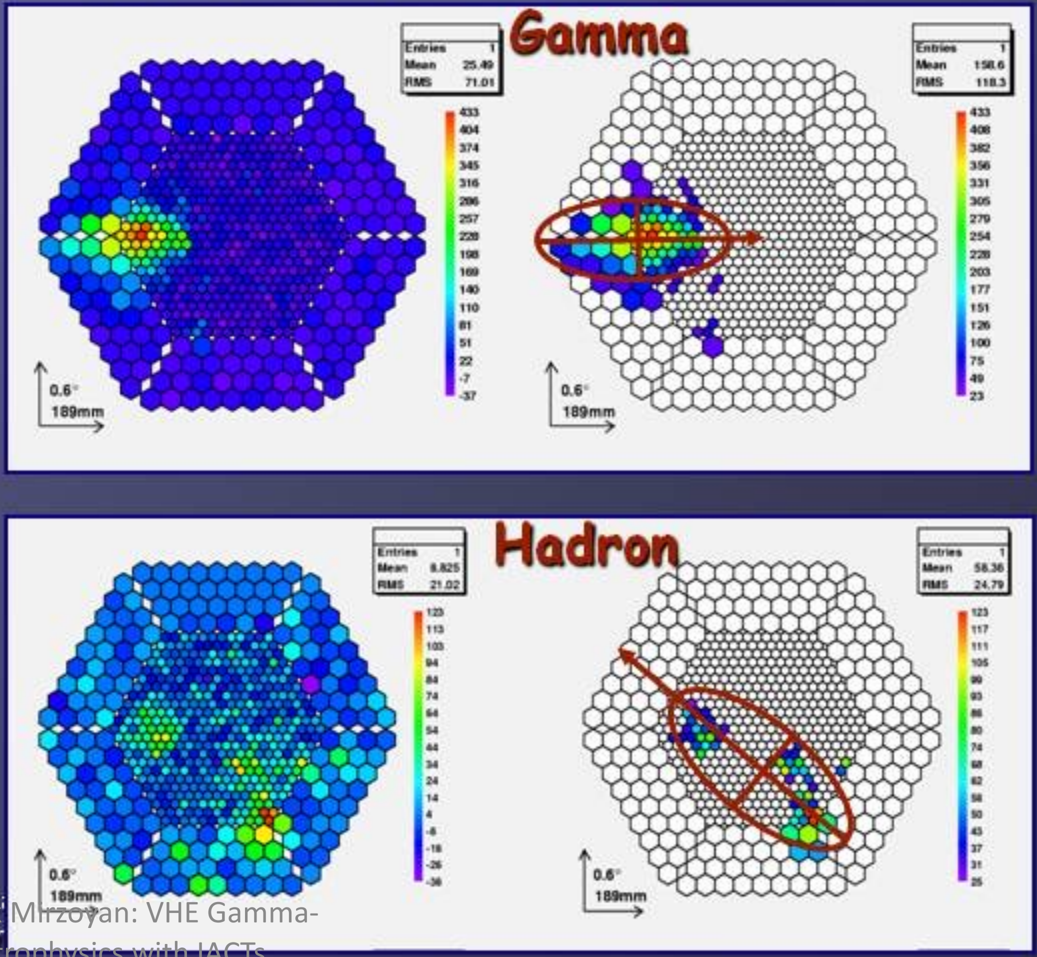
VHE γ-astrophysics with IACTs is possible thanks to exponential atmosphere



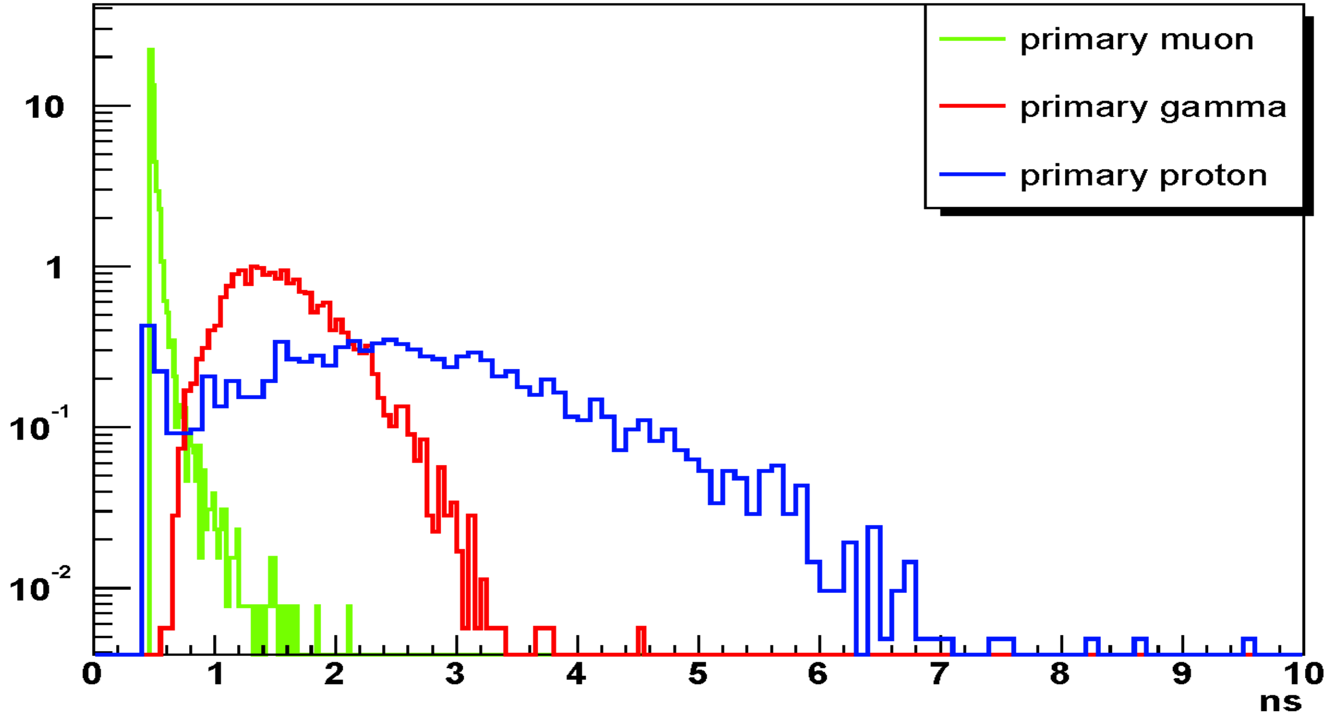
Gamma/Hadron separation

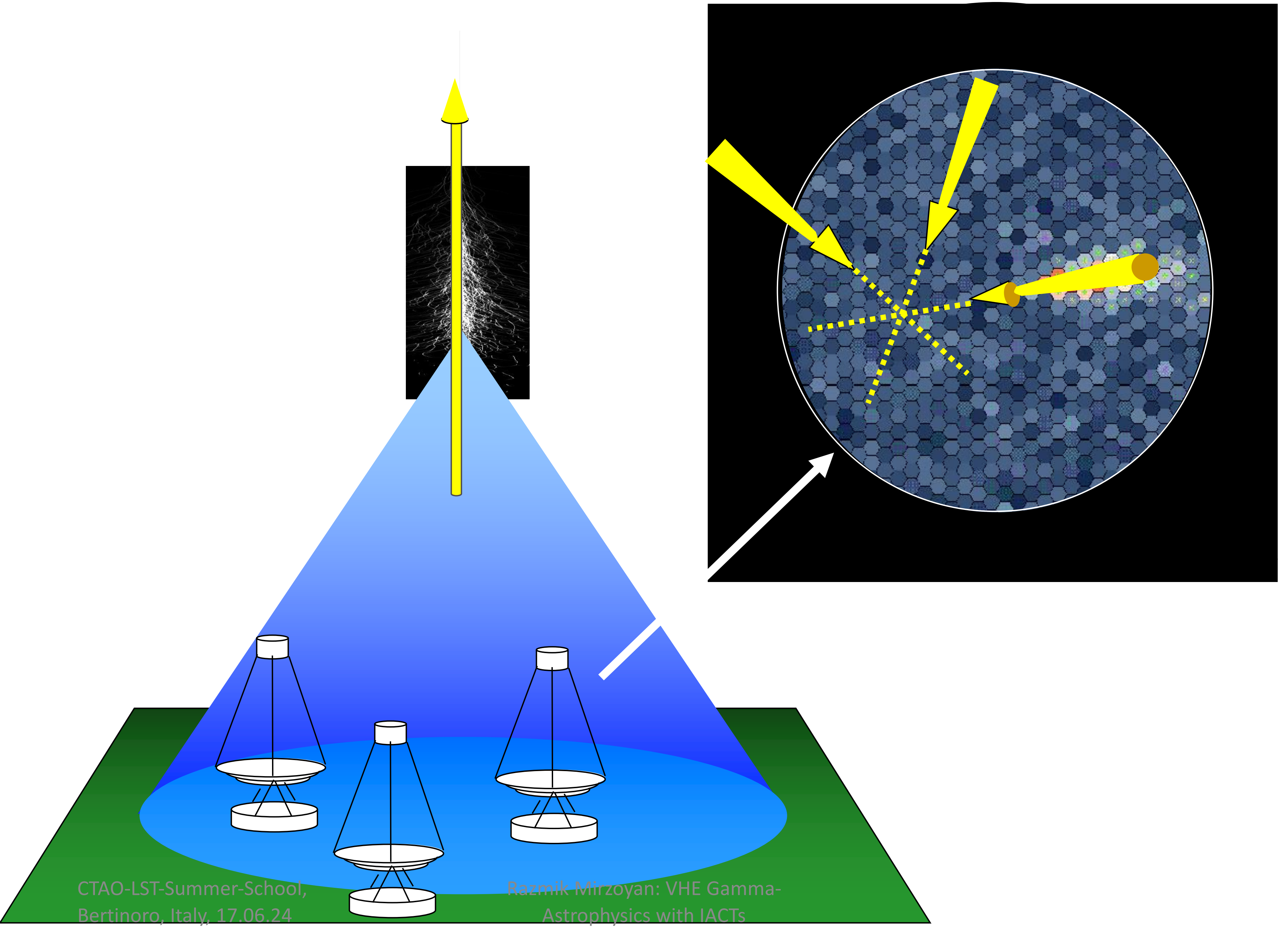


Hadron Rejection by Image Shape
+ Orientation ~ 99.9 %

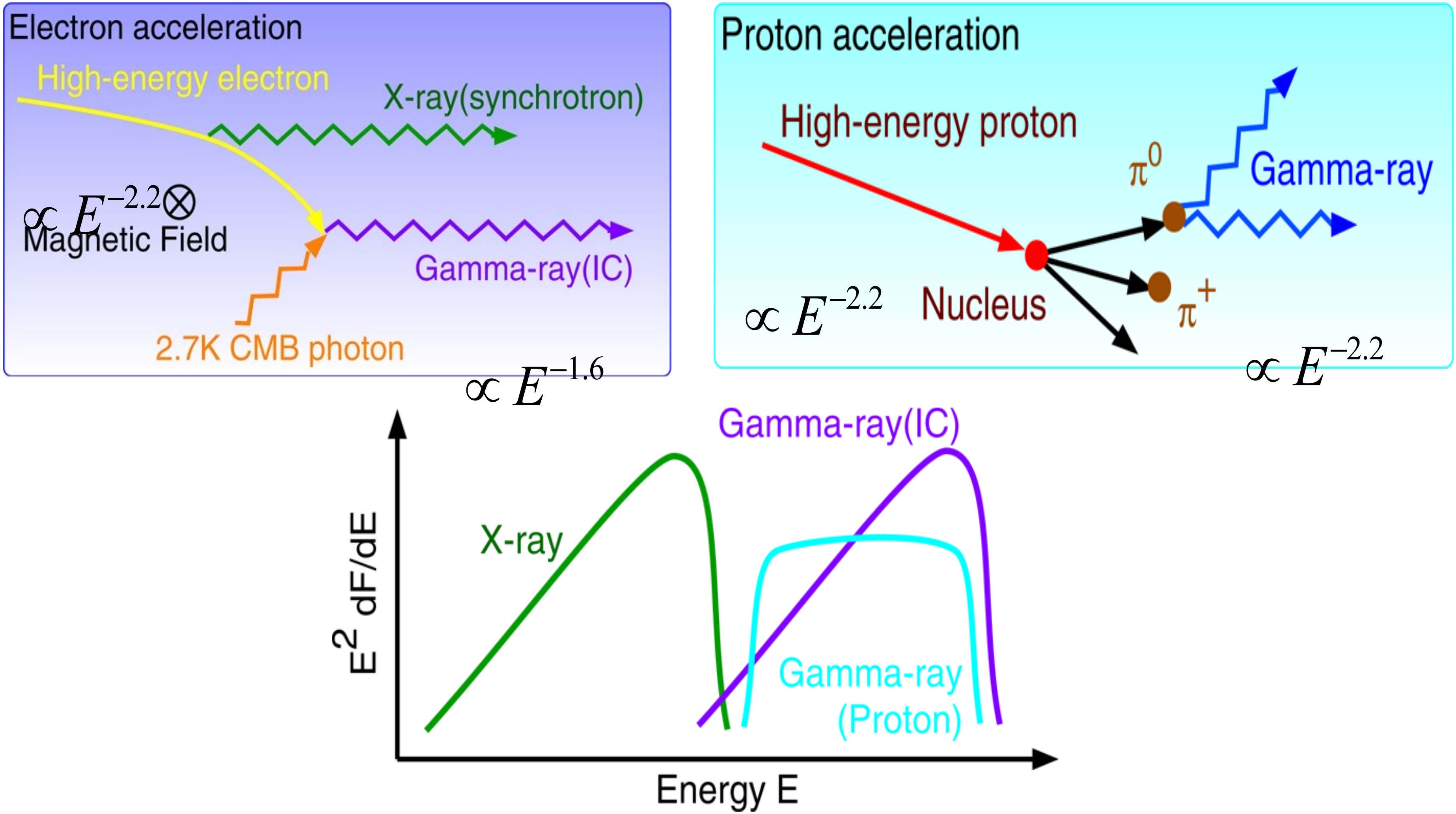


Arrival time distribution of Cherenkov photons



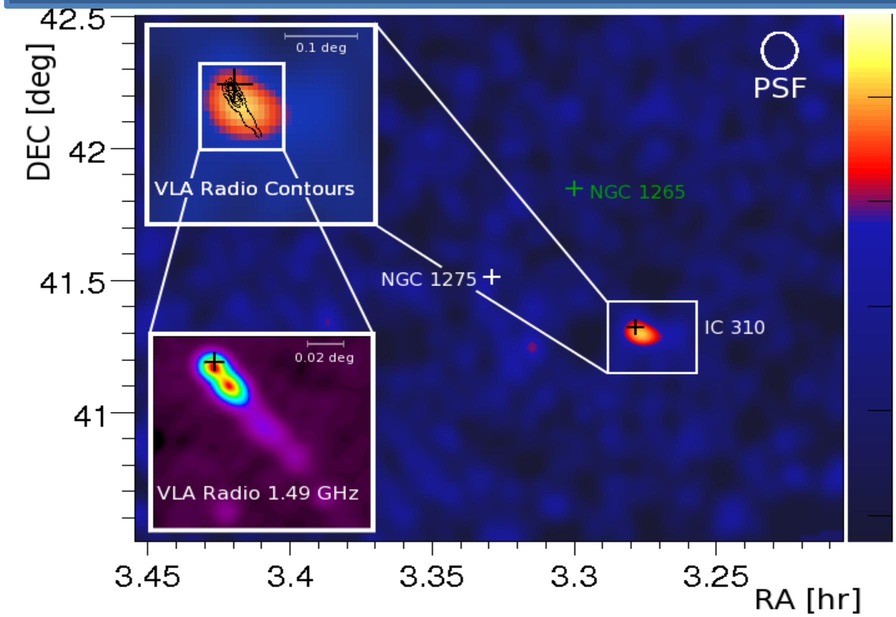


Gamma-Ray Emission Processes
Astrophysical process



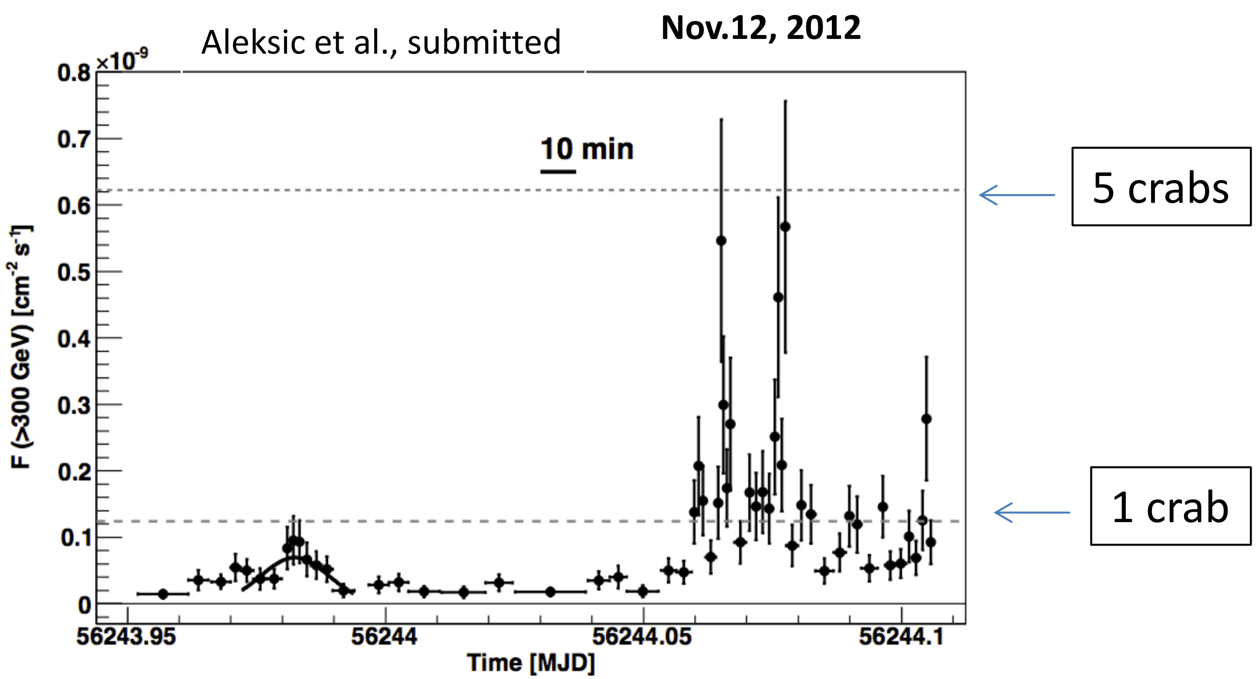
IC 310: Unexpected Discovery in the Perseus Cluster of Galaxies

IC 310: detected ≥ 30GeV by *Fermi*/LAT (Neronov et al. 2010) & ≥ 260GeV by MAGIC (Aleksic et al. 2010)



- Flux and spectral variability in X-ray
- Day-scale variability in VHE, no spectral variability
- Hard spectrum in HE and VHE → 2^{nd} hump ≥ 1TeV
- Original head-tail classification not supported
- VLBI reports parsec-scale blazar-like structures; $\theta \leq 38°$
- ➢ MWL campaign in Nov. 2012 to Feb 2013

Radiogalaxy IC 310



- Light curve with 1-minute bins shows extreme variability; unusual for a radio galaxy
- Still, spectral shape in the VHE remains constant
- No curvature in spectrum from 60 GeV – 10 TeV
- Difficult to explain with current (standard) theoretical scenarios !

Sciencexpress Research Articles

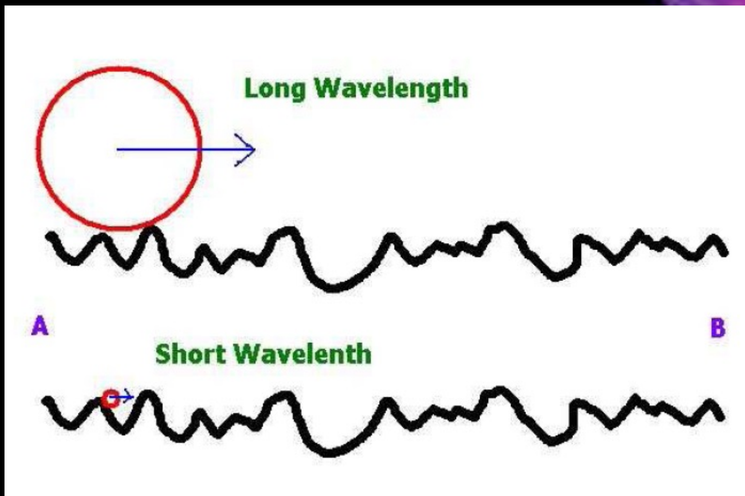
Black hole lightning due to particle acceleration at subhorizon scales

J. Aleksić,[1] S. Ansoldi,[2] L. A. Antonelli,[3] P. Antoranz,[4] A. Babic,[5] P. Bangale,[6] J. A. Barrio,[7] J. Becerra González,[8,25] W. Bednarek,[9] E. Bernardini,[10] B. Biasuzzi,[2] A. Biland,[11] O. Blanch,[1] S. Bonnefoy,[7] G. Bonnoli,[3] F. Borracci,[6] T. Bretz,[12,26] E. Carmona,[13] A. Carosi,[3] P. Colin,[6] E. Colombo,[8] J. L. Contreras,[7] J. Cortina,[1] S. Covino,[3] P. Da Vela,[4] F. Dazzi,[6] A. De Angelis,[2] G. De Caneva,[10] B. De Lotto,[2] E. de Oña Wilhelmi,[14] C. Delgado Mendez,[13] D. Dominis Prester,[5] D. Dorner,[12] M. Doro,[15] S. Einecke,[16] D. Eisenacher,[12] D. Elsaesser,[12] M. V. Fonseca,[7] L. Font,[17] K. Frantzen,[16] C. Fruck,[6] D. Galindo,[18] R. J. García López,[8] M. Garczarczyk,[10] D. Garrido Terrats,[17] M. Gaug,[17] N. Godinović,[5] A. González Muñoz,[1] S. R. Gozzini,[10] D. Hadasch,[14,27] Y. Hanabata,[19] M. Hayashida,[19] J. Herrera,[8] D. Hildebrand,[11] J. Hose,[6] D. Hrupec,[5] W. Idec,[9] V. Kadenius,[20] H. Kellermann,[6] K. Kodani,[19] Y. Konno,[19] J. Krause,[6] H. Kubo,[19] J. Kushida,[19] A. La Barbera,[3] D. Lelas,[5] N. Lewandowska,[12] E. Lindfors,[20,28] S. Lombardi,[3] F. Longo,[2] M. López,[7] R. López-Coto,[1] A. López-Oramas,[1] E. Lorenz,† I. Lozano,[7] M. Makariev,[21] K. Mallot,[10] G. Maneva,[21] N. Mankuzhiyil,[2,29] K. Mannheim,[12] L. Maraschi,[3] B. Marcote,[18] M. Mariotti,[15] M. Martínez,[1] D. Mazin,[6] U. Menzel,[6] J. M. Miranda,[4] R. Mirzoyan,[6] A. Moralejo,[1] P. Munar-Adrover,[18] D. Nakajima,[19] A. Niedzwiecki,[9] K. Nilsson,[20,28] K. Nishijima,[19] K. Noda,[6] R. Orito,[19] A. Overkemping,[16] S. Paiano,[15] M. Palatiello,[2] D. Paneque,[6] R. Paoletti,[4] J. M. Paredes,[18] X. Paredes-Fortuny,[18] M. Persic,[2,30] J. Poutanen,[20] P. G. Prada Moroni,[22] E. Prandini,[11] I. Puljak,[5] R. Reinthal,[20] W. Rhode,[16] M. Ribó,[18] J. Rico,[1] J. Rodriguez Garcia,[6] S. Rügamer,[12] T. Saito,[19] K. Saito,[19] K. Satalecka,[7] V. Scalzotto,[15] V. Scapin,[7] C. Schultz,[15] T. Schweizer,[6] S. N. Shore,[22] A. Sillanpää,[20] J. Sitarek,[1] I. Snidaric,[5] D. Sobczynska,[9] F. Spanier,[12] V. Stamatescu,[1,31] A. Stamerra,[3] T. Steinbring,[12] J. Storz,[12] M. Strzys,[6] L. Takalo,[20] H. Takami,[19] F. Tavecchio,[3] P. Temnikov,[21] T. Terzić,[5] D. Tescaro,[8] M. Teshima,[6] J. Thaele,[16] O. Tibolla,[12] D. F. Torres,[23] T. Toyama,[6] A. Treves,[24] M. Uellenbeck,[16] P. Vogler,[11] R. Zanin,[18] M. Kadler,[12] R. Schulz,[12,32] E. Ros,[33,34,35] U. Bach,[33] F. Krauß,[12,32] J. Wilms[32]

[1]IFAE, Campus UAB, E-08193 Bellaterra, Spain. [2]Università di Udine, and INFN Trieste, I-33100 Udine, Italy. [3]INAF National Institute for Astrophysics, I-00136 Rome, Italy. [4]Università di Siena, and INFN Pisa, I-53100 Siena, Italy. [5]Croatian MAGIC Consortium, Rudjer Boskovic Institute, University of Rijeka and University of Split, HR-10000 Zagreb, Croatia. [6]Max-Planck-Institut für Physik, D-80805 München, Germany. [7]Universidad Complutense, E-28040 Madrid, Spain. [8]Inst. de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain. [9]University of Łódź, PL-90236 Lodz, Poland. [10]Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany. [11]ETH Zurich, CH-8093 Zurich, Switzerland. [12]Universität Würzburg, D-97074 Würzburg, Germany. [13]Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain. [14]Institute of Space Sciences, E-08193 Barcelona, Spain. [15]Università di Padova and INFN, I-35131 Padova, Italy. [16]Technische Universität Dortmund, D-44221 Dortmund, Germany. [17]Unitat de Física de les Radiacions, Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain. [18]Universitat de Barcelona, ICC, IEEC-UB, E-08028 Barcelona, Spain. [19]Japanese MAGIC Consortium, Division of Physics and Astronomy, Kyoto University, Japan. [20]Finnish MAGIC Consortium, Tuorla Observatory, University of Turku and Department of Physics, University of Oulu, Finland. [21]Inst. for Nucl. Research and Nucl. Energy, BG-1784 Sofia, Bulgaria. [22]Università di Pisa, and INFN Pisa, I-56126 Pisa, Italy. [23]ICREA and Institute of Space Sciences, E-08193 Barcelona, Spain. [24]Università dell'Insubria and INFN Milano Bicocca, Como, I-22100 Como, Italy. [25]Now at NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA and Department of Physics and Department of Astronomy, University of Maryland, College Park, MD 20742, USA. [26]Now at Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland. [27]Now at Institut für Astro- und Teilchenphysik, Leopold-Franzens- Universität Innsbruck, A-6020 Innsbruck, Austria. [28]Now at Finnish Centre for Astronomy with ESO (FINCA), Turku, Finland. [29]Now at Astrophysics Science Division, Bhabha Atomic Research Centre, Mumbai 400085, India. [30]Also at INAF-Trieste. [31]Now at School of Chemistry and Physics, University of Adelaide, Adelaide 5005, Australia. [32]Dr. Remeis-Sternwarte Bamberg, Astronomisches Institut der Universität Erlangen-Nürnberg, ECAP, D-96049 Bamberg, Germany. [33]Max-Planck-Institut für Radioastronomie, D-53121 Bonn, Germany. [34]Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain. [35]Departament d'Astronomia i Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain.

†Deceased.

Exotic Physics: Test of Lorentz Invariance Violation with VHE γ



$$E_{Pl} = \sqrt{\frac{\hbar c^5}{G}} \approx 1.22 \times 10^{19}\, GeV$$

If Gravity is a Quantum theory,
at a very short distance it may show a very complex "foamy" structure due to quantum fluctuation.

Use gamma ray beam from AGNs/GRBs
to study the space-time structure

Energy 1000GeV ~ $10^{-16} E_{Pl}$
Distance 100~1000Mpc ($10^{16\text{-}17}$sec)

Visible time delay ~ 1 - 10 sec

Linear deviation:

$$\xi_1 < 0; \quad v = c\left(1 - \frac{E}{M_{QG1}}\right); \quad n(E) = 1 + \frac{E}{M_{QG1}}$$

Quadratic deviation:

$$\xi_1 = 0; \quad \xi_2 < 0; \quad v = c\left(1 - \frac{E^2}{M_{QG2}^2}\right); \quad n(E) = 1 + \frac{E^2}{M_{QG2}^2}$$

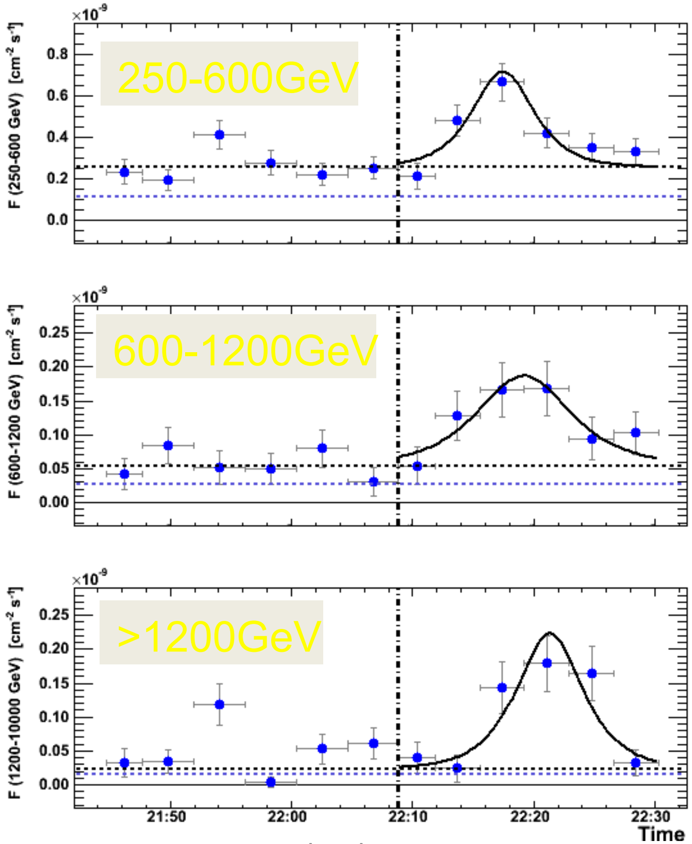
Fast time variation of VHE γ from AGN Mrk-501 by MAGIC, PKS 2155 by HESS

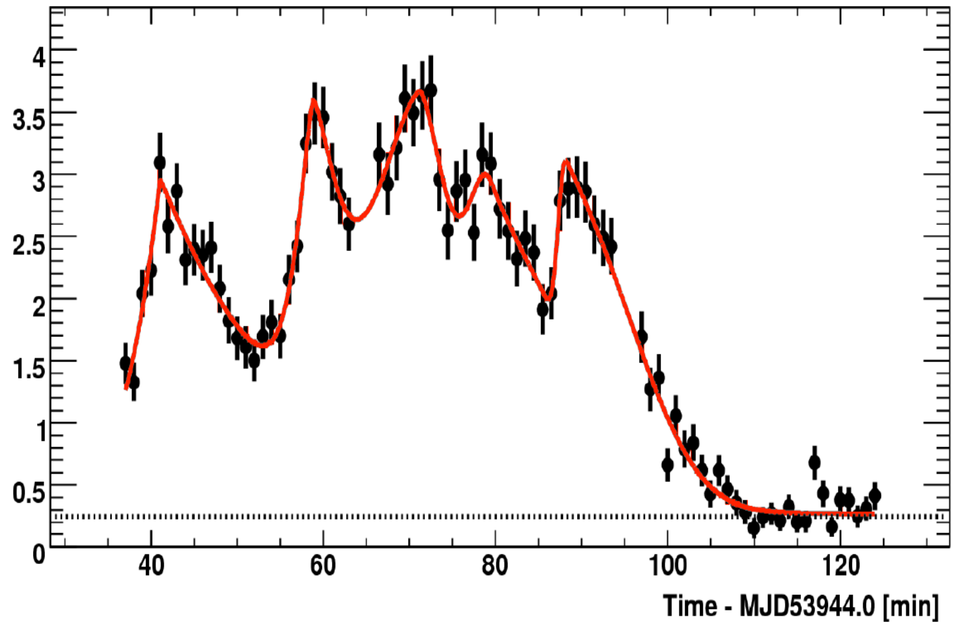
Mrk501(z=0.03) MAGIC observation

$M_{QG1} > 0.26 \times 10^{18}$GeV

PKS2155(z=0.116) HESS observation

$M_{QG1} > 0.72 \times 10^{18}$GeV

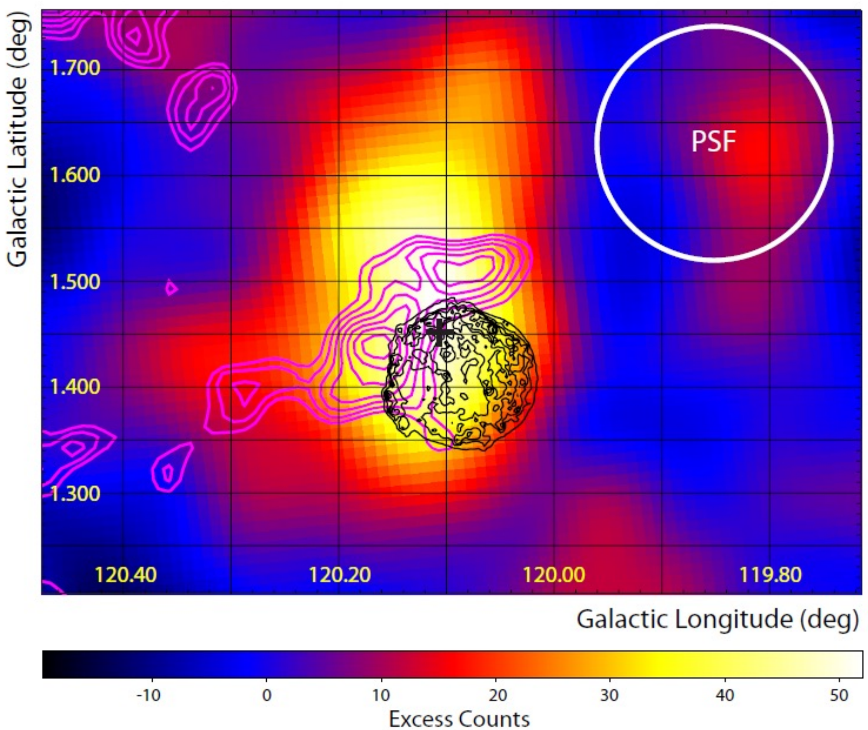




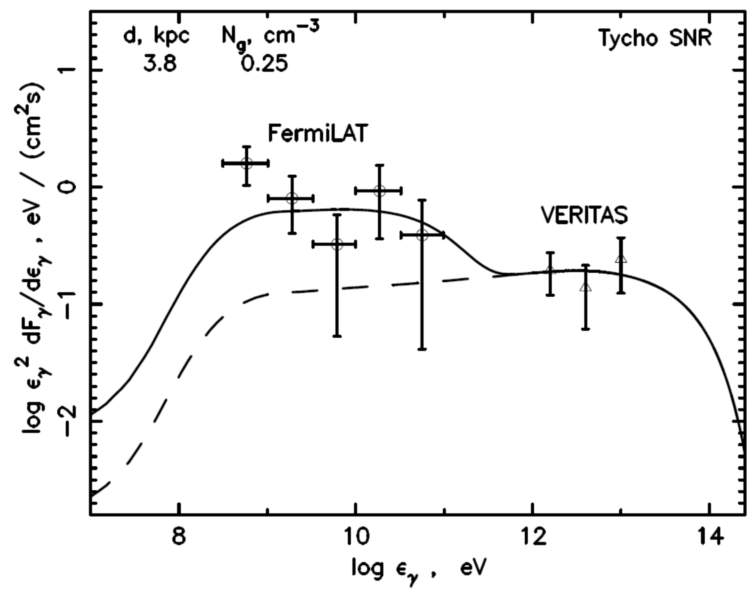
CTA can provide ~10sec time resolution for the fast variation

VERITAS discovery of Tycho SNR

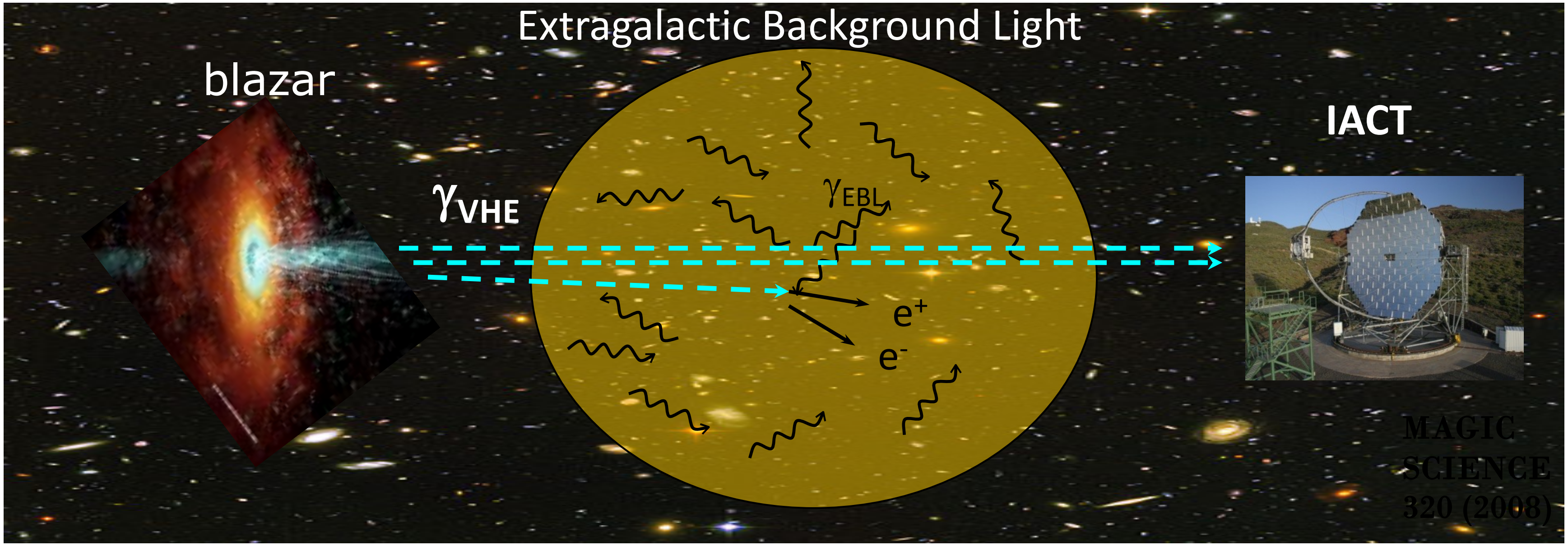
Historical SNR first observed in 1572
Type Ia; estimated distance: 3.8 kpc
0.9 % crab units

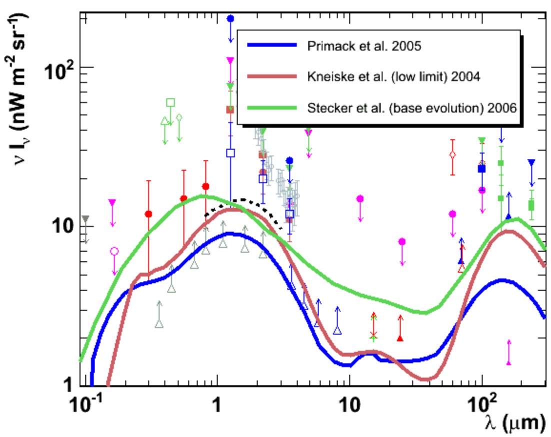


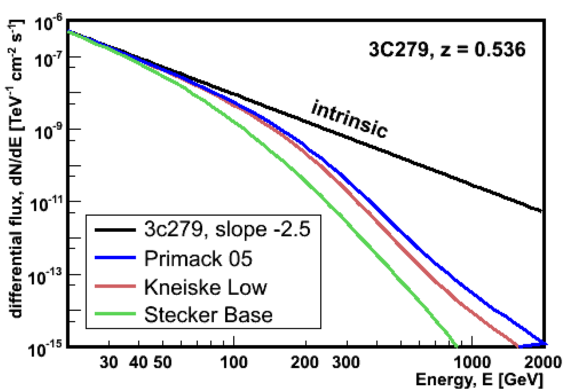
Berezhko, et al., 2012

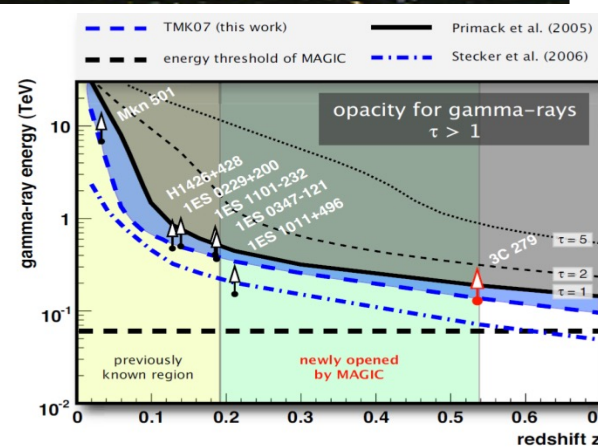


Gamma Ray Absorption by EBL

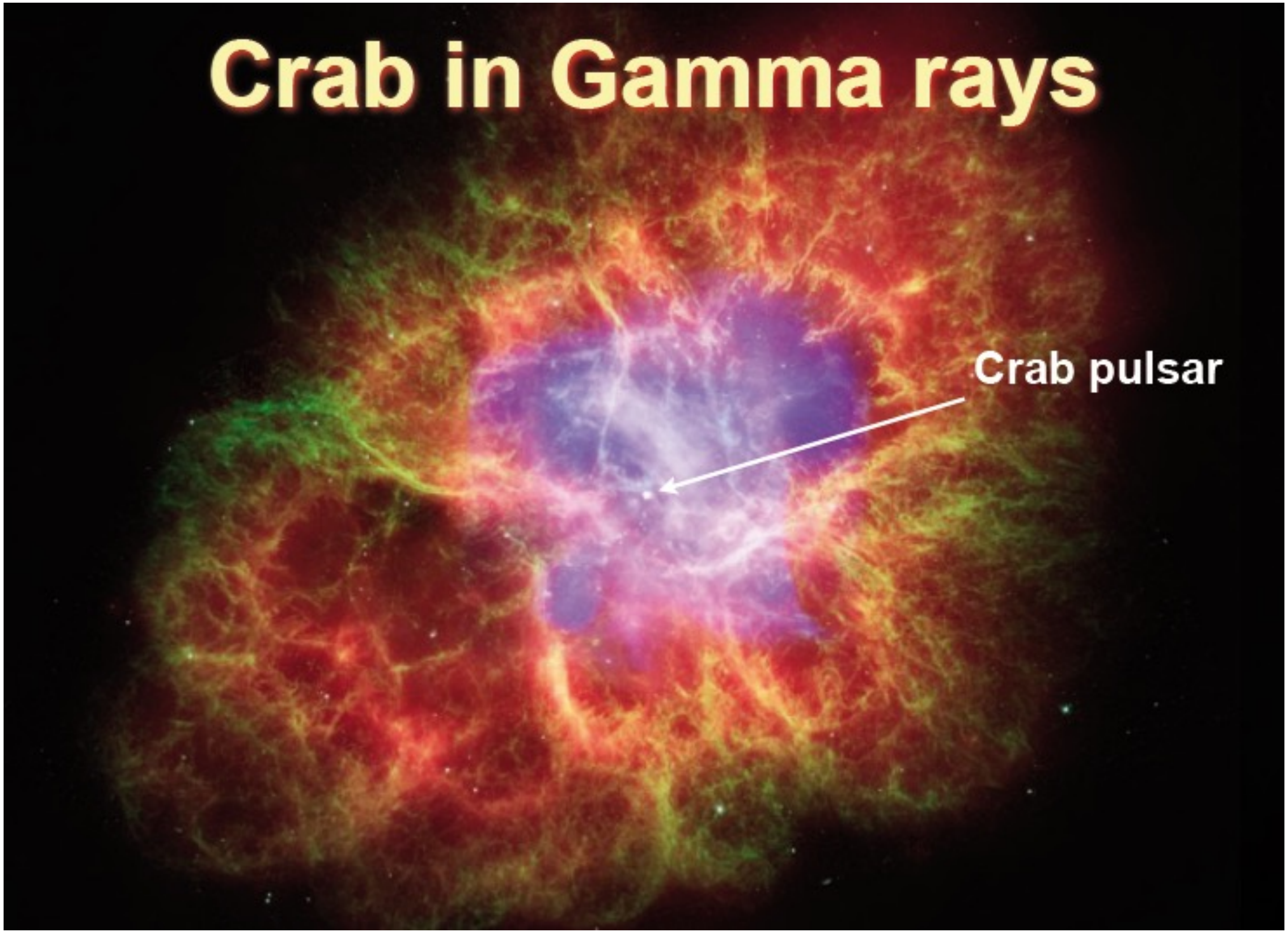




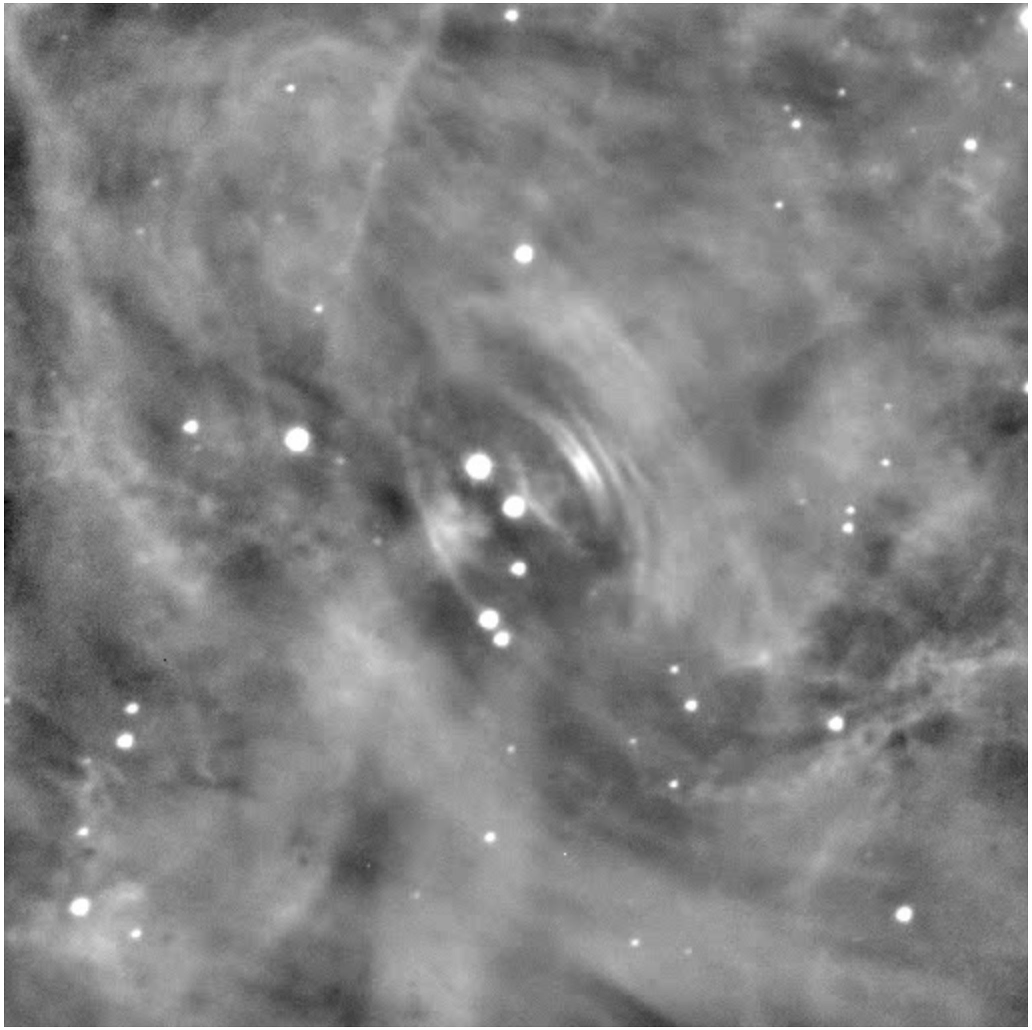




Composite figure of Crab Nebula



Crab pulsar



Aliu et al. (MAGIC collab.)
Science 322 (2008) 1221
First detection of emission above 25GeV for a pulsar

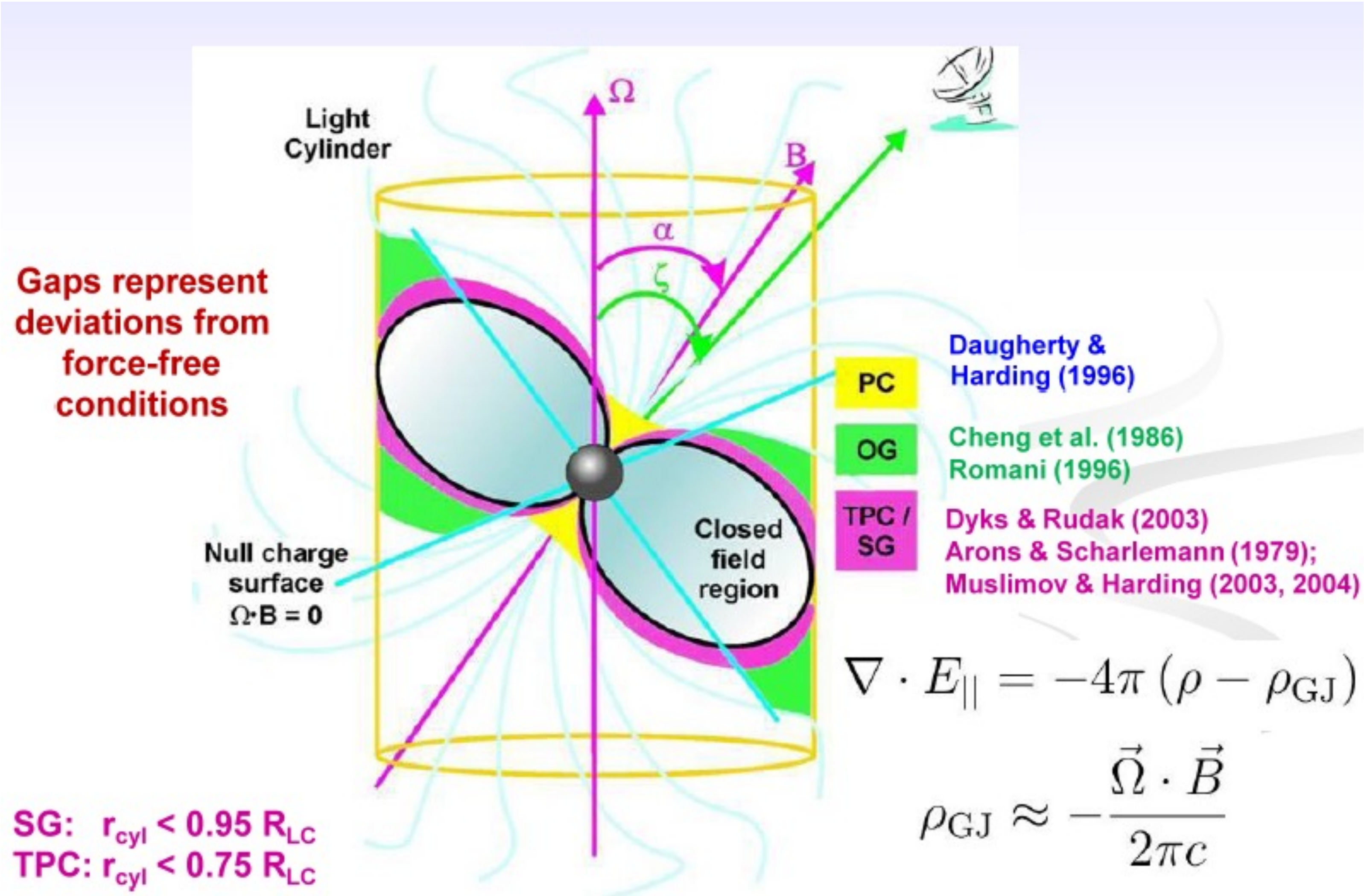
Aliu et al. (VERITAS collab.)
Science 334 (2011) 69-72
First detection of emission above 100GeV

Aleksic et al (MAGIC collab.), ApJ, 742 (2011) 43,
First spectrum 25-100GeV

Aleksic et al (MAGIC collab.), A&A, 540 (2012) A69
First spectrum 50-400GeV

Aleksic et al (MAGIC collab.), A&A, accepted for publication
Discovery of Bridge Emission

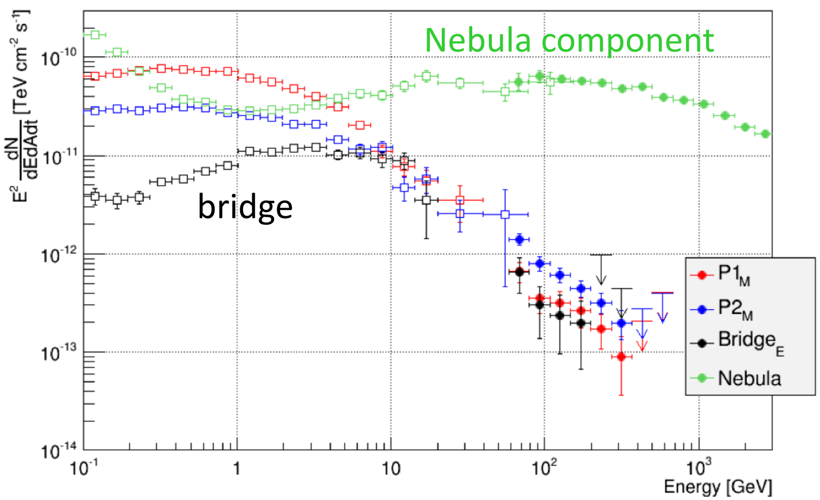
Cartoon of a pulsar

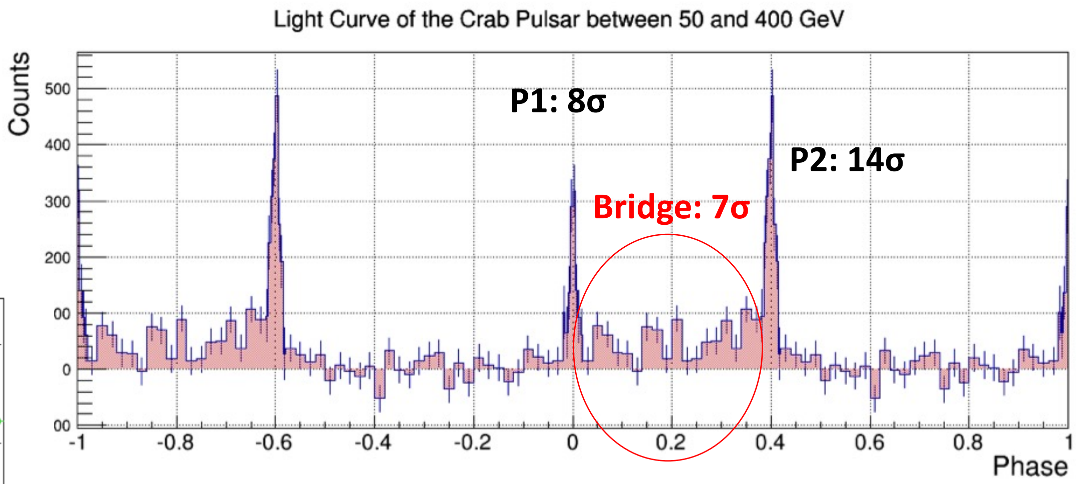


MAGIC bridge emission & very narrow pulses

J. Aleksic, et al., arXiv:1402.4219

Fermi bridge emission becomes strong above few GeV

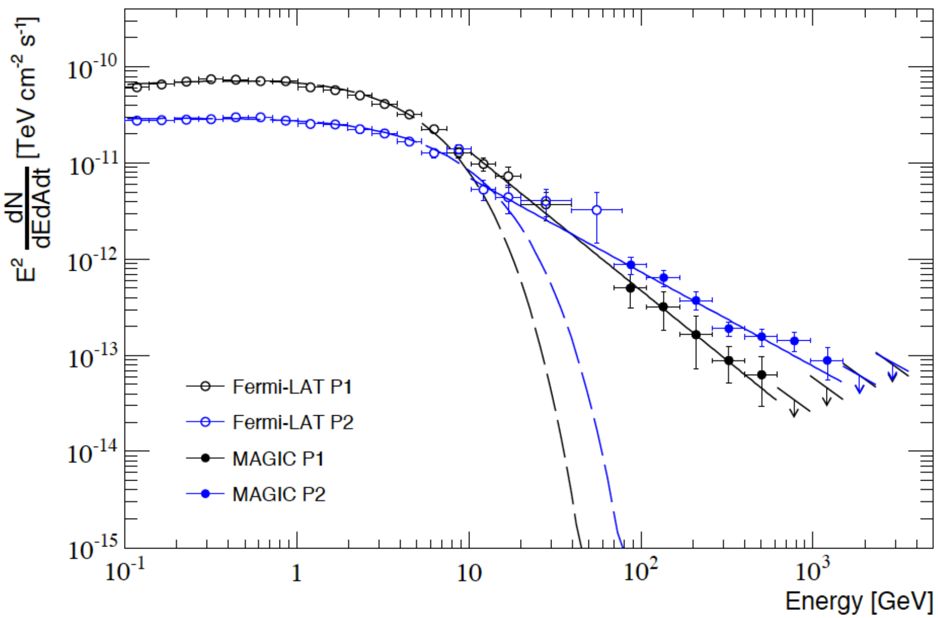




- bridge hints on toroidal bending of magnetic lines near LC
- This result set a quest for precision Crab pulsar theories

The last word is not yet said: soon new results, new insights…

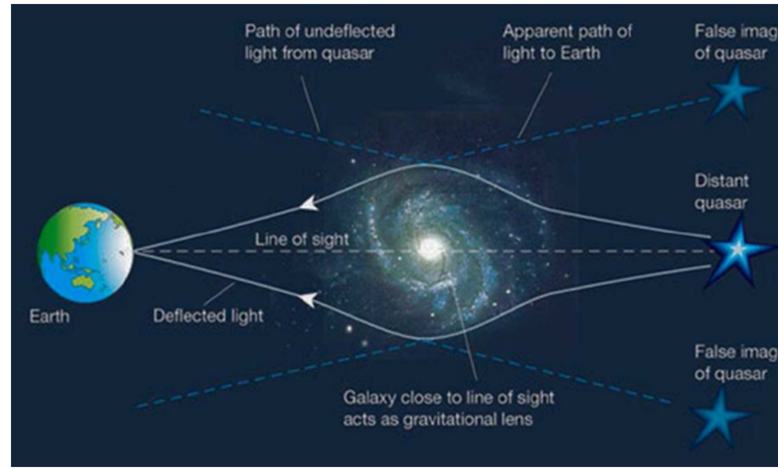
the Crab pulsar as a very compact accelerator of TeV γ rays

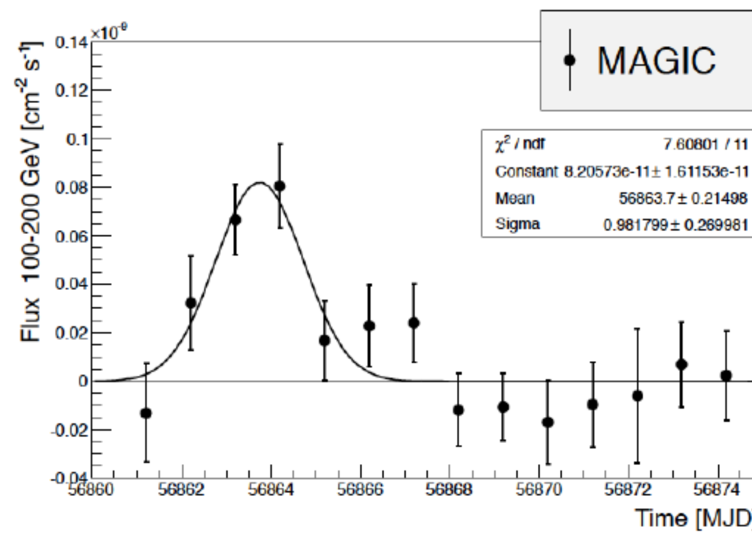


- Discovered pulsed emission from Crab, spectrum extending ≥ 1.2 TeV
- Challenging the emission models
- MAGIC-Fermi fit shows IC emission from ~10 GeV to ≥ 1 TeV
- Emission from the neighborhood of Light Cylinder (r ~1600km)
- TeV pulsation is used to put quadratic limits for Lorentz Invariance Violation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

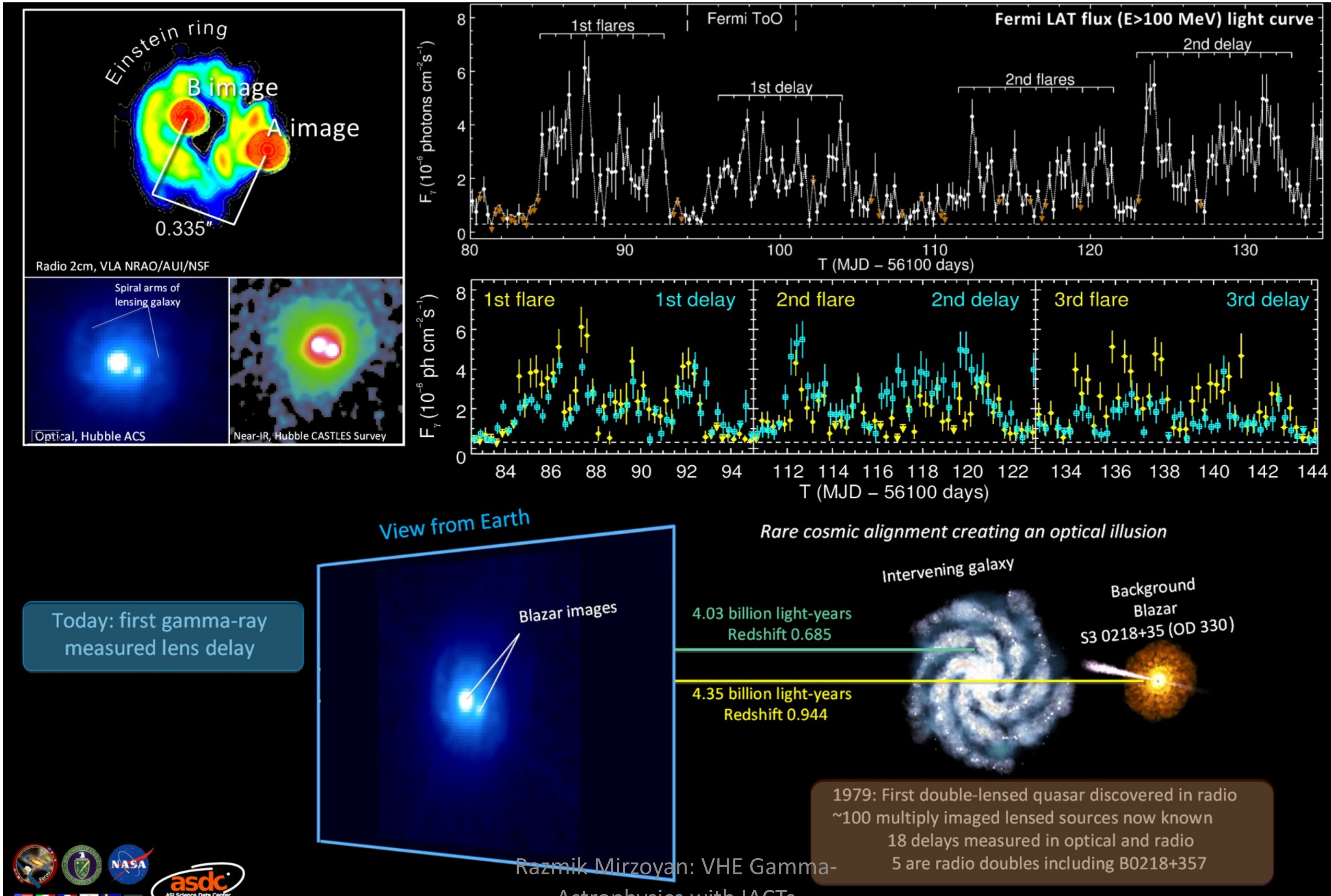
Discovery of Gravitationally Lensed Blazar S3 0218+357 residing at the red shift 0.944

- In 2012 Fermi observed high state, with many overlapping flares
- Fermi claimed 11.46 ± 0.16 days delay for the lensed component
- On July 13/14 2014 Fermi again observed a high state
- Magic started observing 2 days before the predicted delayed signal and kept on-going till 5th of August

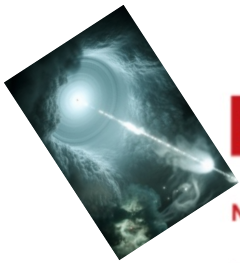




Gravitational lense system S3 0218 (also known as B0218+357)



First association of a ~300 TeV neutrino to a γ-ray source



Science 361, July 2018

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

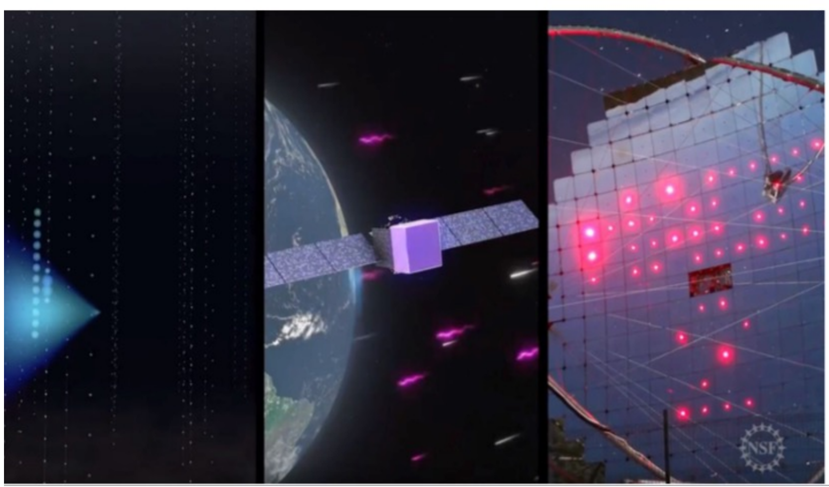
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

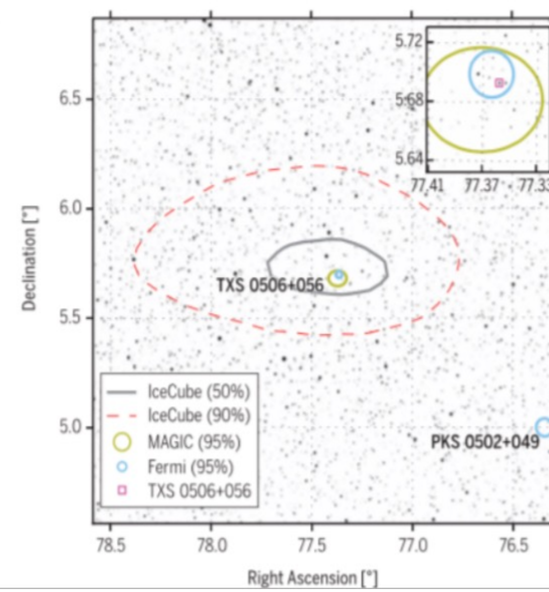
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

evaluated below, associating neutrino and γ-ray production.

The neutrino alert

IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detector array, a muon is produced moving through



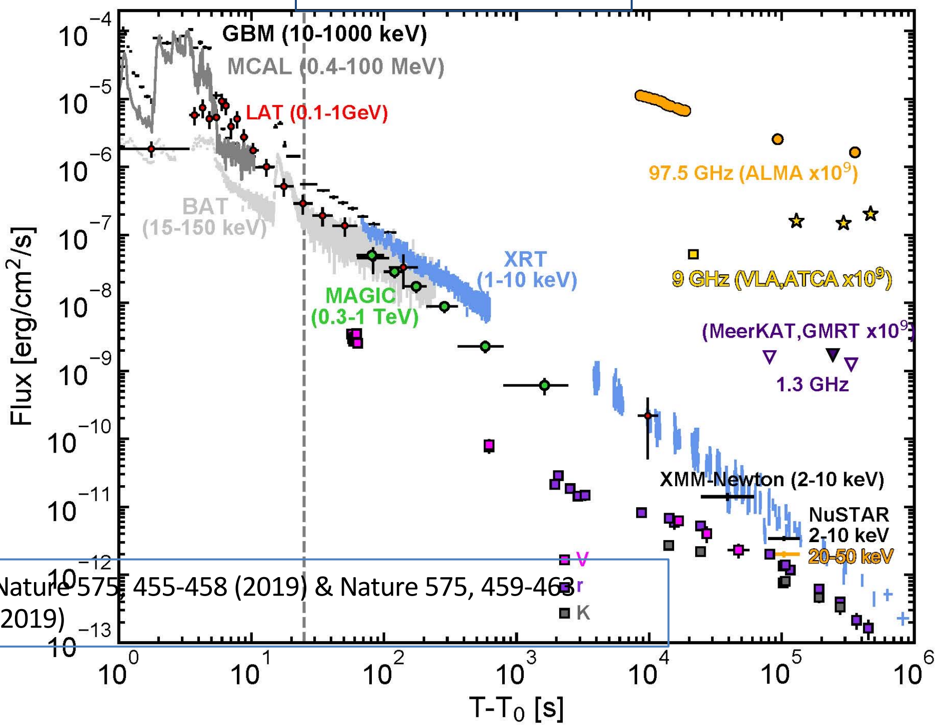


GRB190114C MWL light curves by MAGIC & 2 dozen space- and ground-based instruments measured on 14.01.2019

MAGIC published 2-papers in *Nature, 575 Nov. 2019*

- For the first time GRB measured @ TeV
- Measurements started 57 s after onset
- T_{90}~ 360 s, bright, long GRB
- E_{iso}~ 3 x 10^{53} (1keV - 10 MeV)
- Red shift z = 0.4245
- Detected ~ 60σ in afterglow, the energy range 200 GeV – 2 TeV
- TeV flux similar to that in X-rays
- Intensity > 130 Crab in the first minute
- Purest ever gamma-ray sample

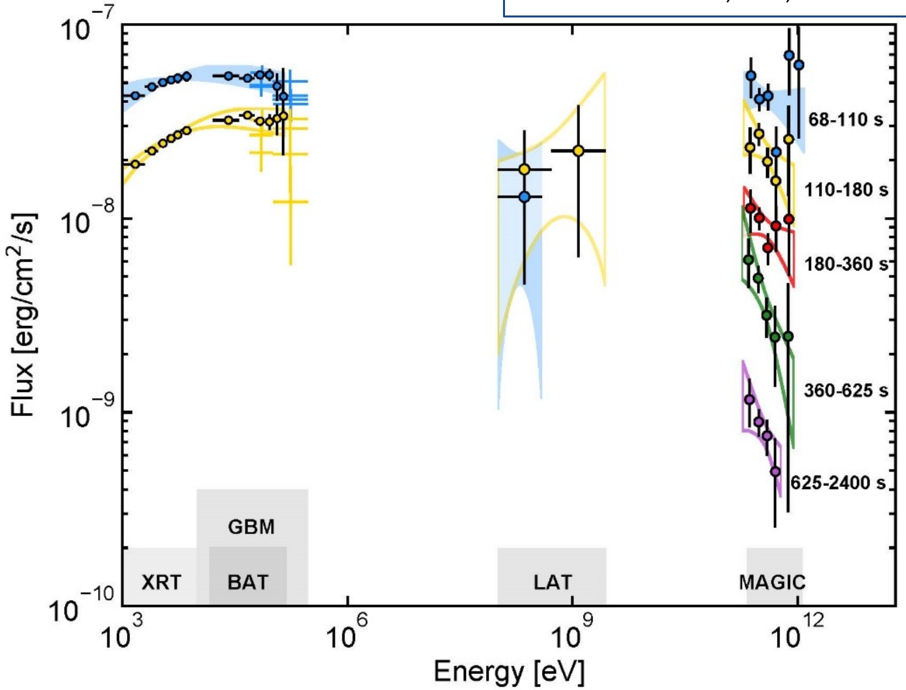
Acciari, et al., Nature 2019



Nature 575, 455-458 (2019) & Nature 575, 459-463 (2019)

Evolution of GRB 190114C could be followed with ultra-short time resolution

MAGIC collaboration, et al., Nature 2019



Nature, 575
November 2019

- The incredible intensity @ TeV allowed us to follow the spectral evolution in extremely short time intervals
  - 42s (1st bin)
  - 70s (2nd bin)
  - 180s (3rd bin)
- The SSC process with two-bump structure could successfully explain the TeV emission
- GRBs even more powerful than assumed before the discovery of the TeV emission

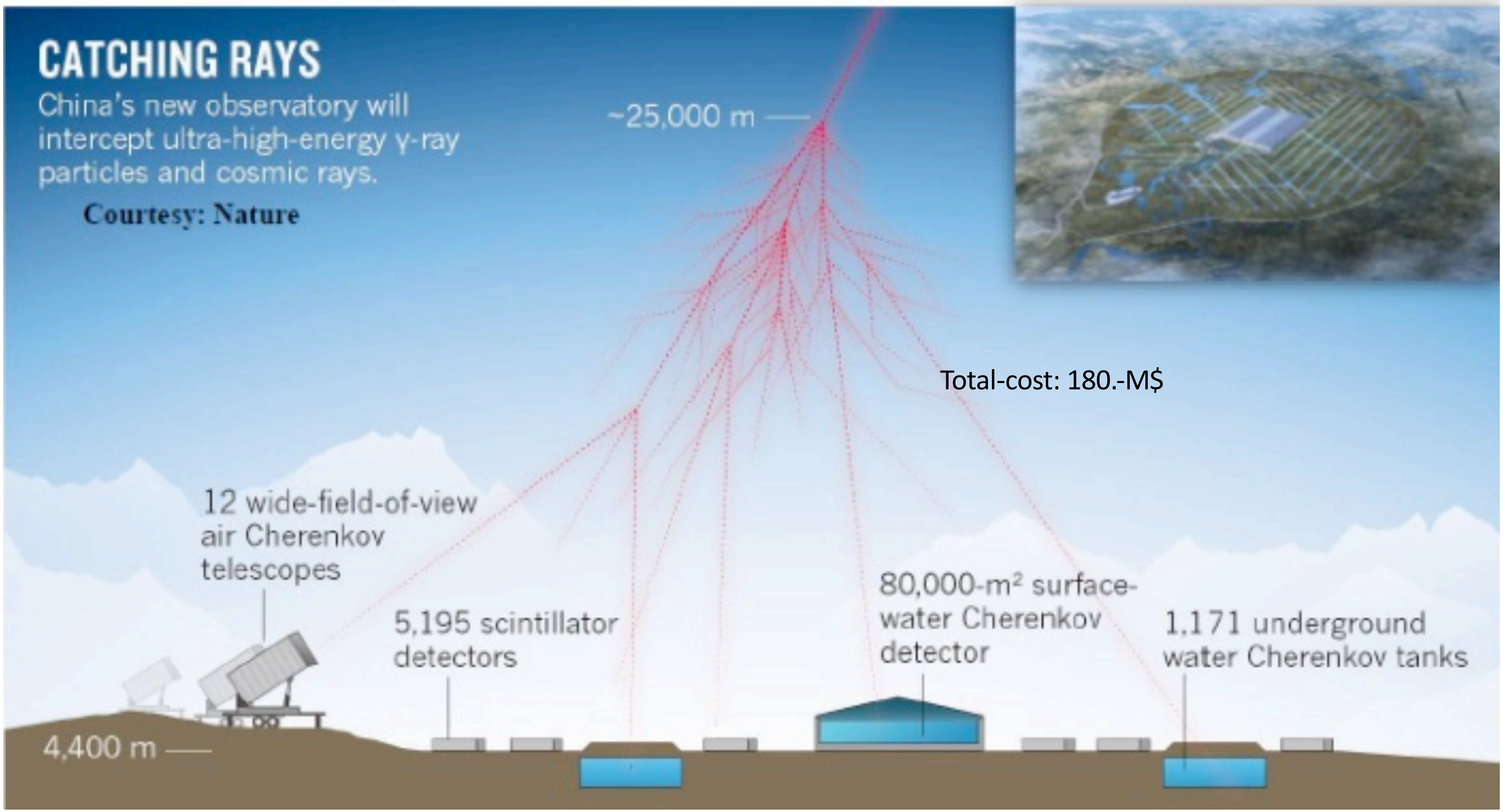
HAWC

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

Hybrid Detection of EASs by LHAASO

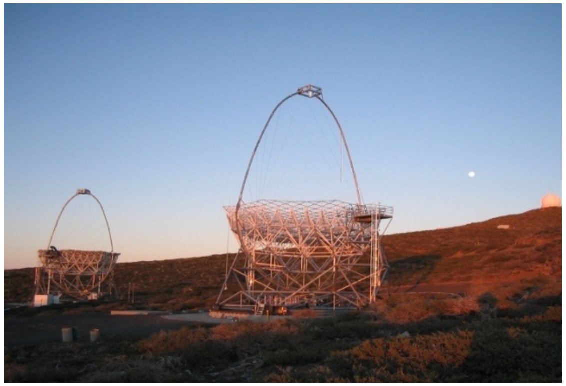


LHAASO in China

Last couple of years LHAASO discovered several tens of PeVatrons

Next generation VHE γ ray Observatory CTA

MAGIC



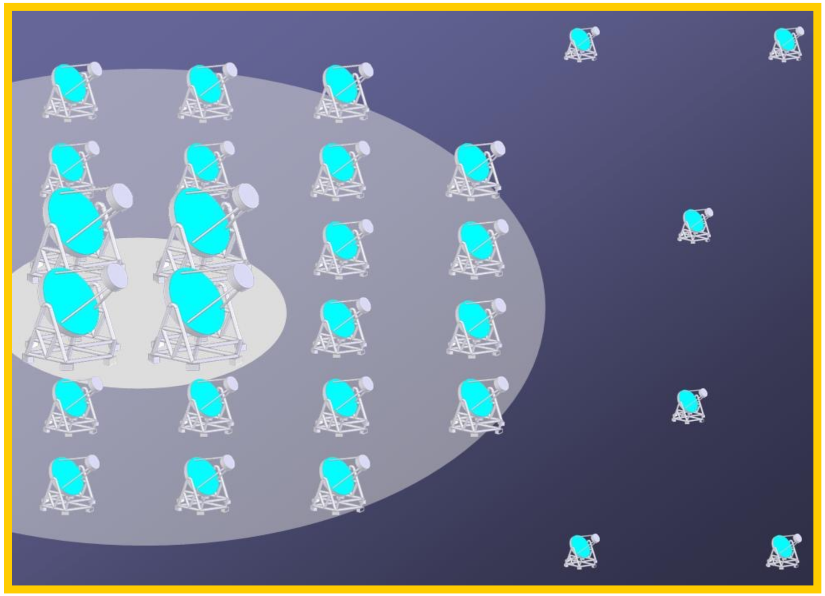
HESS Phase II

Astro-physicists from EU

JAPAN, US, India, Brazil, Mexico, …

>1500 scientists
>130 institutions

CTA



LST1 taking data

Reflector frame of LST-4 installed recently

Photo of the LST-construction site in La Palma taken several weeks ago

Slide shown at the recent LST/CTAO Collab. Meeting in Prague; construction of 4 LSTS will be ready in coming 2 years