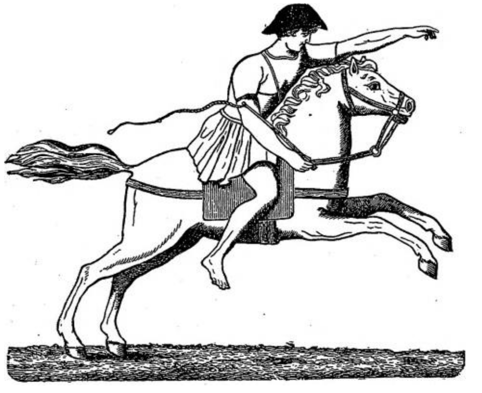
Գամմա Ճառագայթները Որպես Տիեզերքի Ամենաբարձր Էներգիաների Սուրհանդակներ



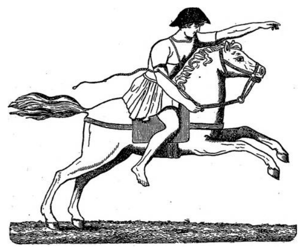
Exploring the Most Energetic Window to the Universe

Razmik Mirzoyan

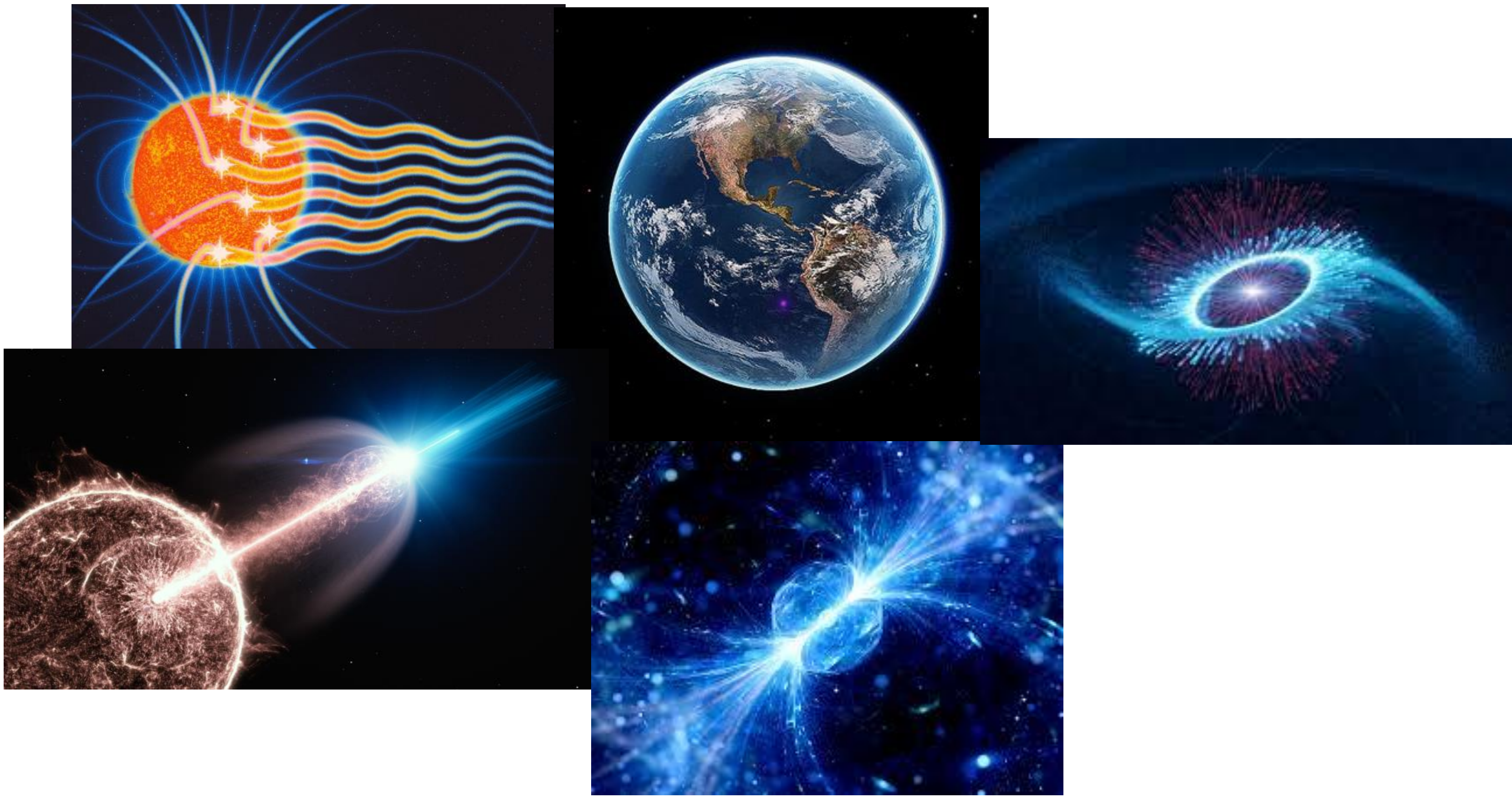
Max-Planck-Institute for Physics, Munich, Germany

National Academy of Sciences of Armenia

Գամմա Ճառագայթները Որպես Տիեզերքի Սուրհանդակներ



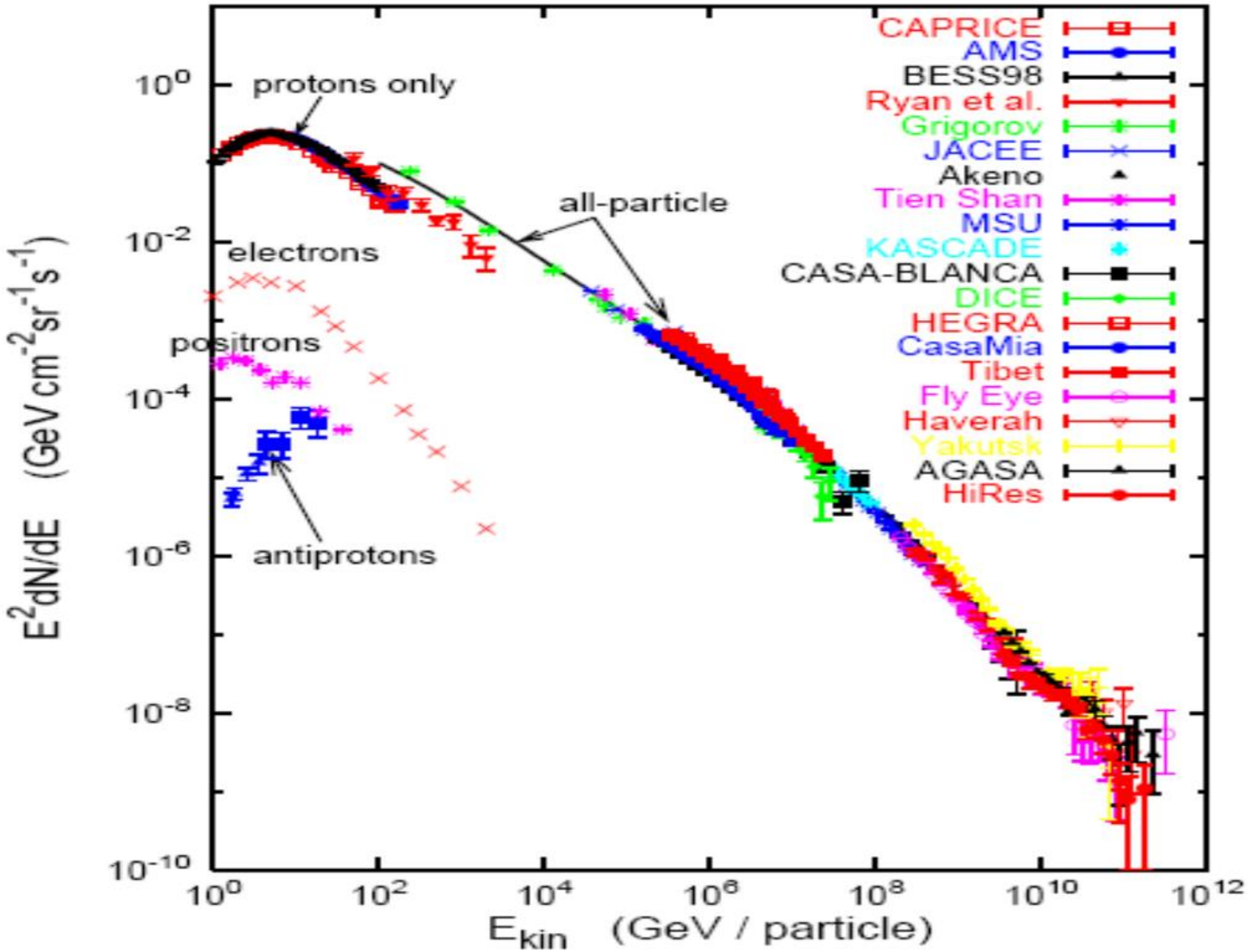
Gamma Ray of different origin constantly bombard the Earth



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



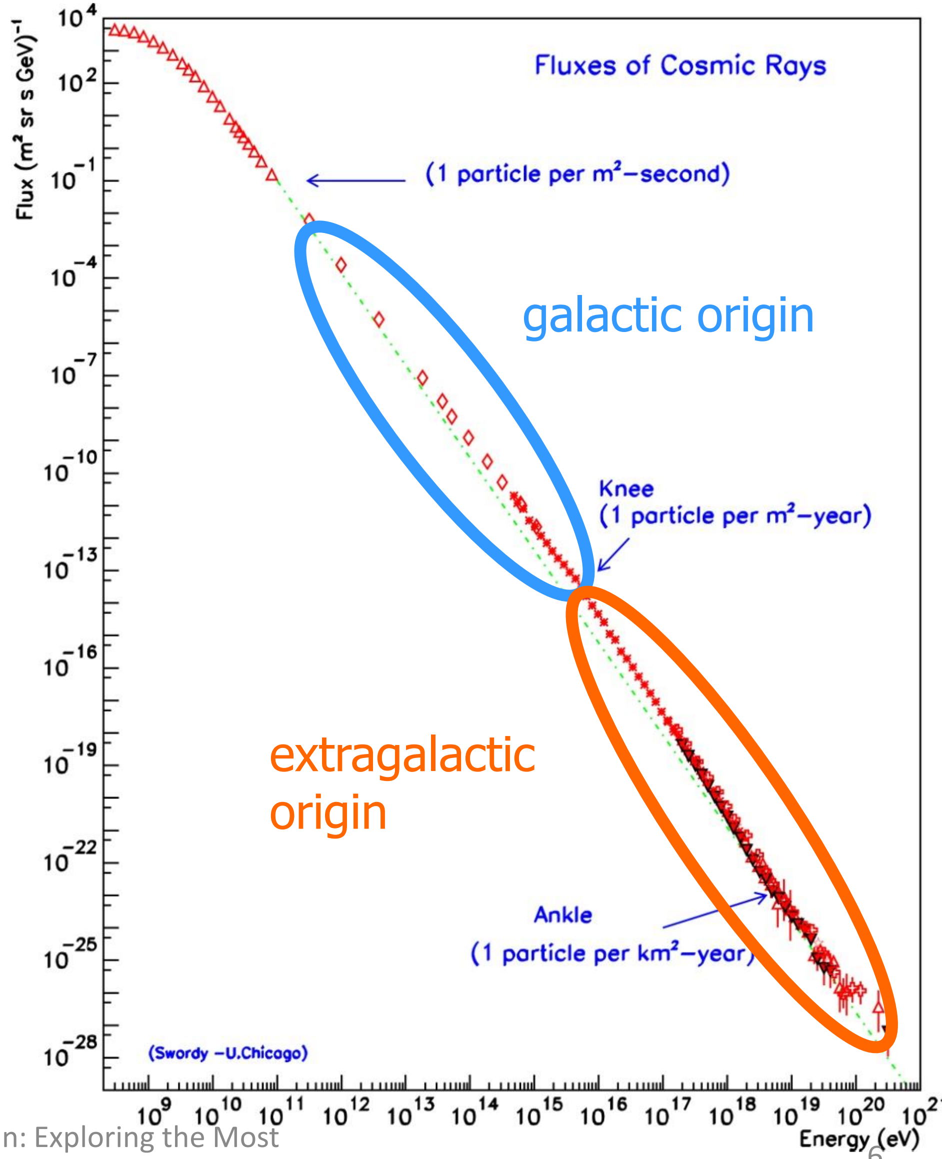
Origin of cosmic rays

Although many different types of sources have been discovered at GeV-TeV-PeV energies, it is not yet clear, which type of sources contribute to the cosmic rays measured at Earth

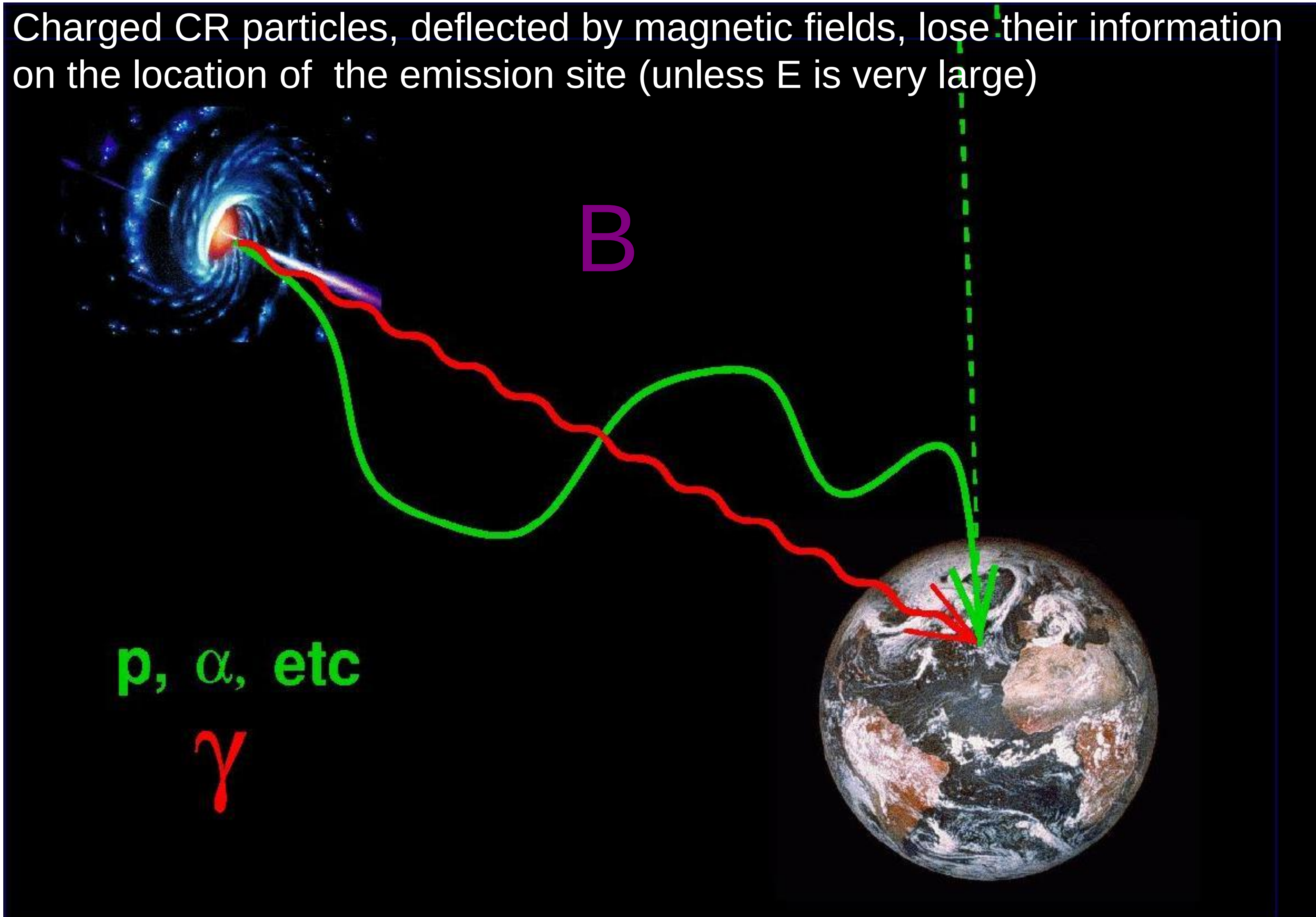
Which object(s) in our galaxy can provide the right amount of CR?

Supernova remnants, pulsars, PWN, … could accelerate swept-up particles

Signature: Hadronic generated Gamma-rays from SNRs, interactions with molecular clouds,…



Astronomy with Charged Cosmic Rays ?

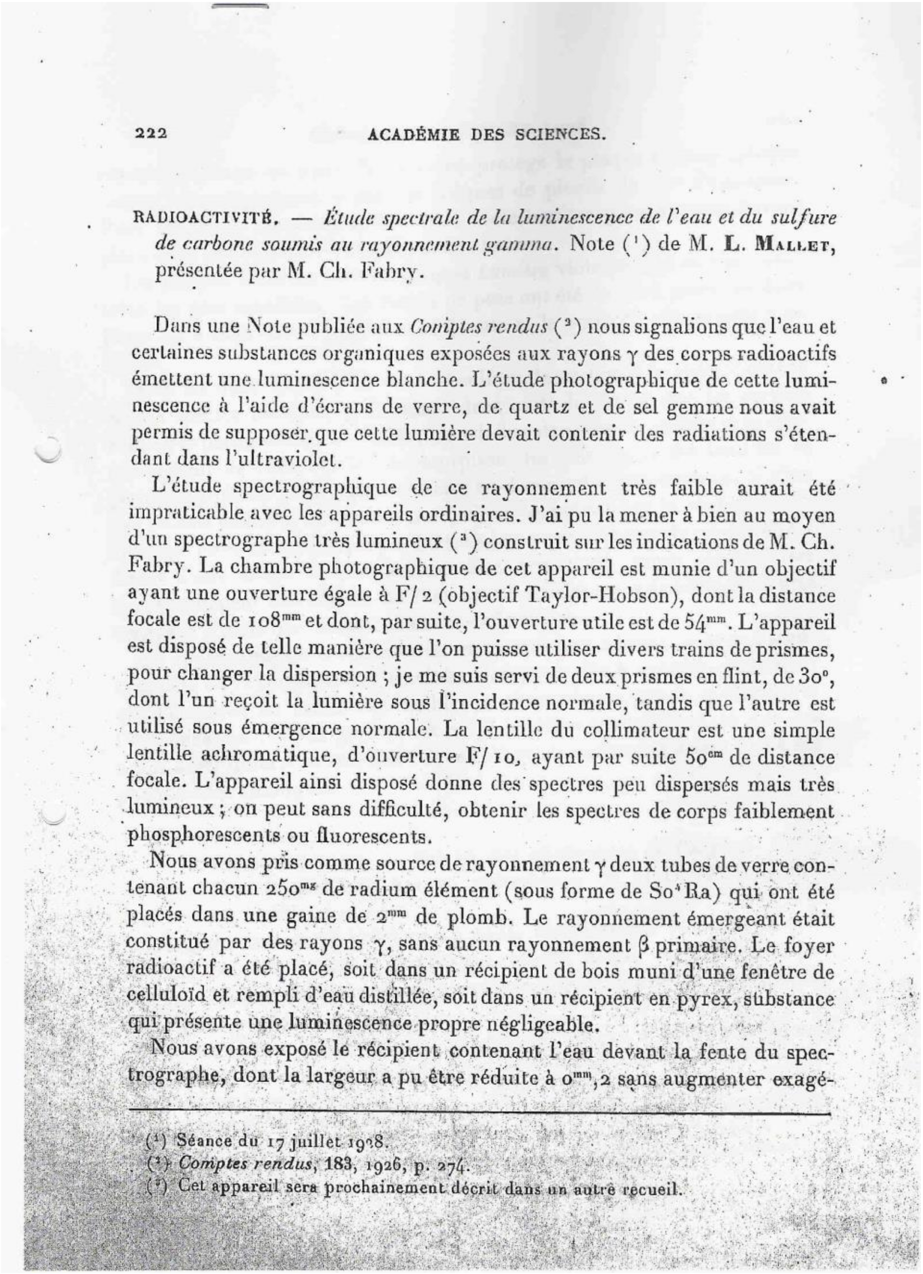


Cherenkov light: the beginnings

- 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

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

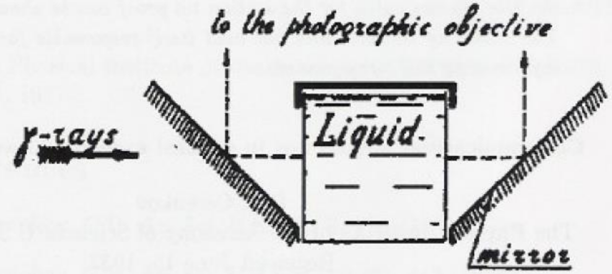


Figure 1: Arrangement of apparatus.

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

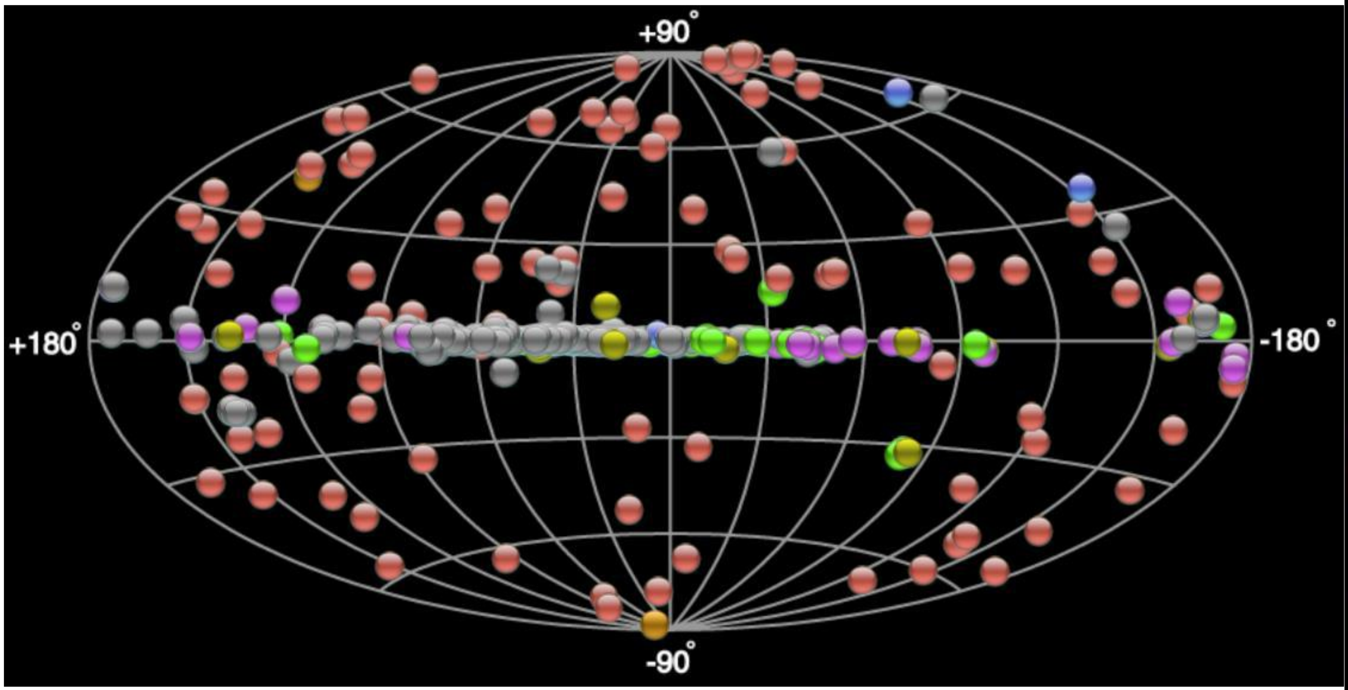
We recently performed additional experiments in which the intensity of radiation was recorded photographically, the records being taken simultaneously for all the angles θ lying in a plane passing through the primary electron

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, 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

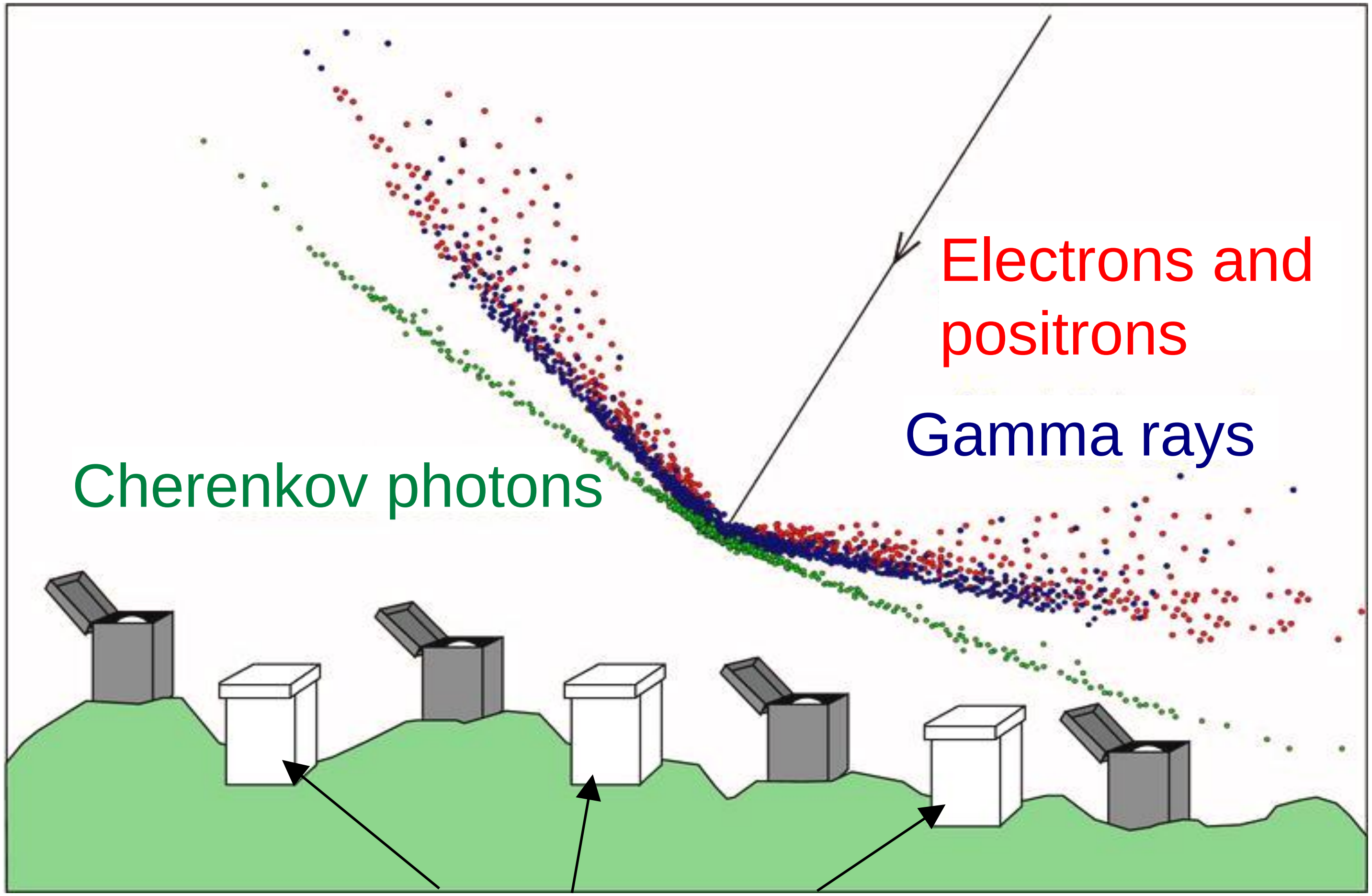
Today's VHE γ–ray Sources in the Sky



http://tevcat.uchicago.edu/

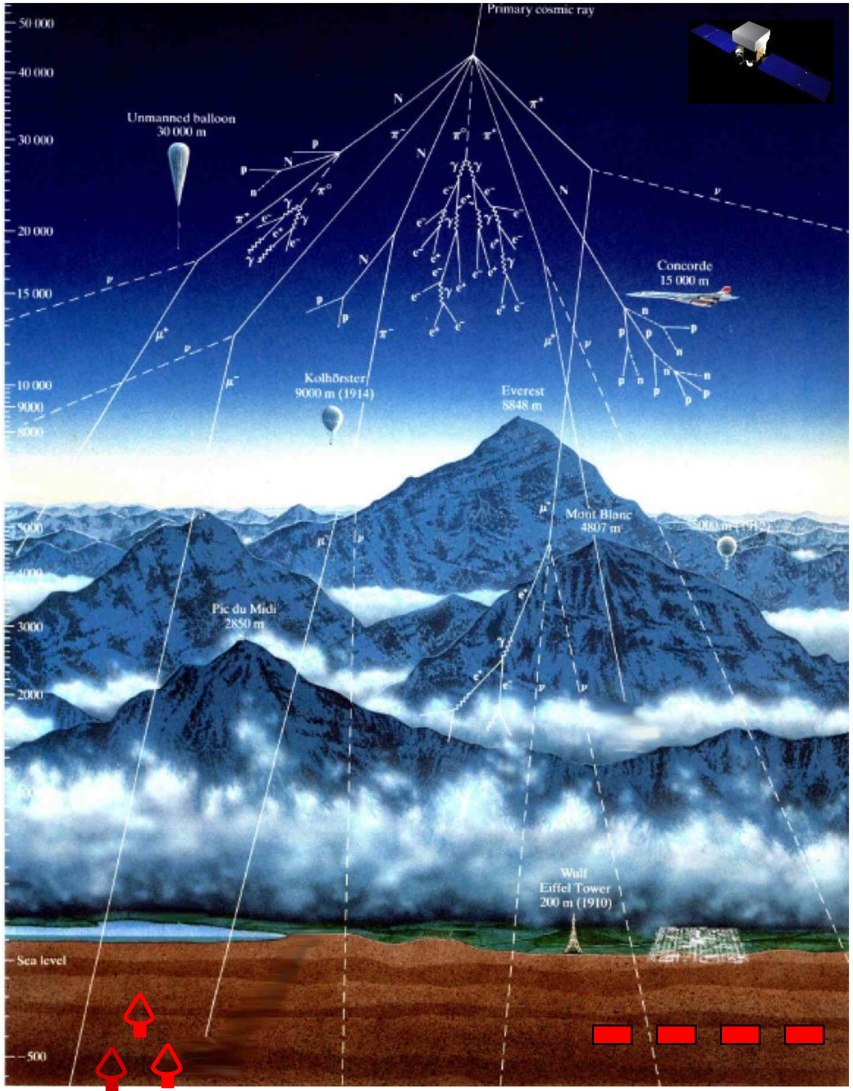
≥ 300 Sources

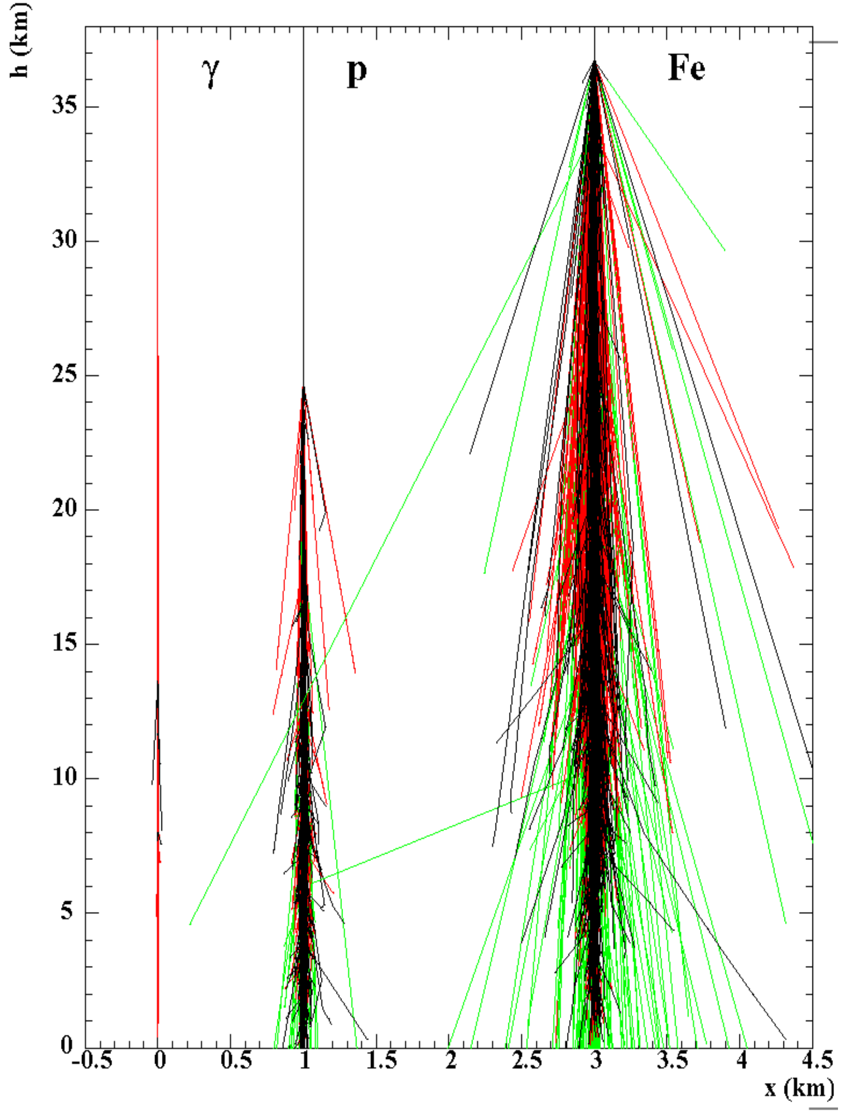
Air Showers measured on the ground



Particle detectors

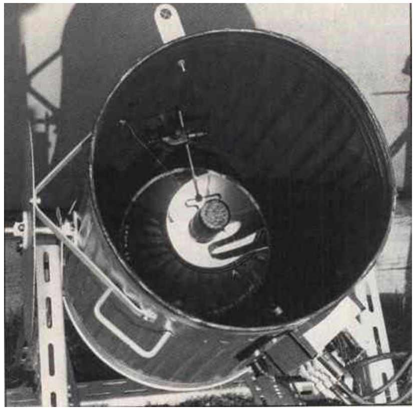
Extensive Air Showers





Important stages in ground-based γ-ray astronomy

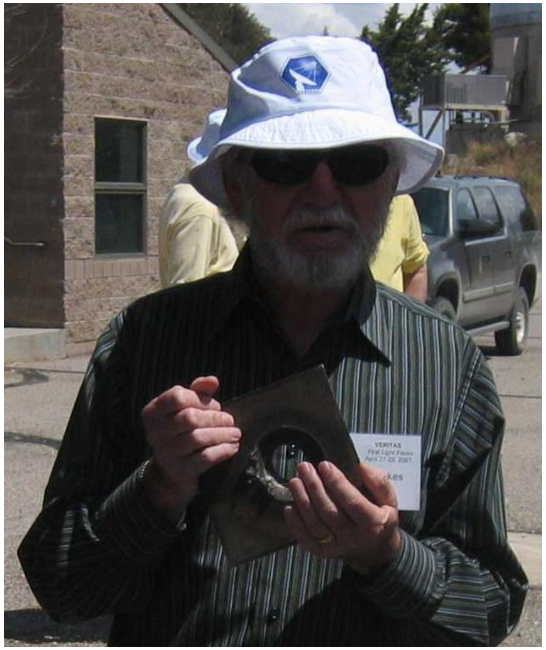
1952-1953 – discovery of Cherenkov pulses in atmosphere with a 0,25m ø mirror and a 2“ PMT



1959-1964 - Chudakovs experiment in Crimea
12 x 1,55m ø parabolic mirrors (total ~21 m²)

1968-2003 - 10m ø Whipple telescope AZ, USA

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



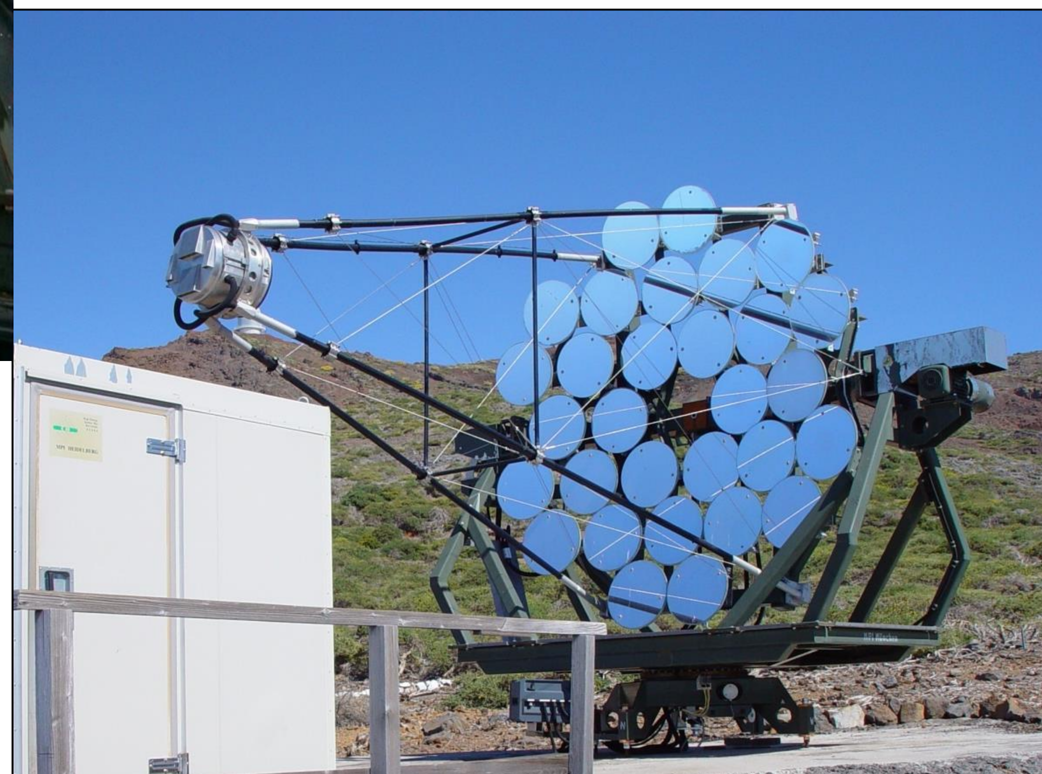
„If a telescope can within a few sec. evaporate a solid piece of steel, it can also measure gamma rays“
;-)

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

Nor Amberd cosmic ray Station, mount Aragats, 2000 m a.s.l., Armenia

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

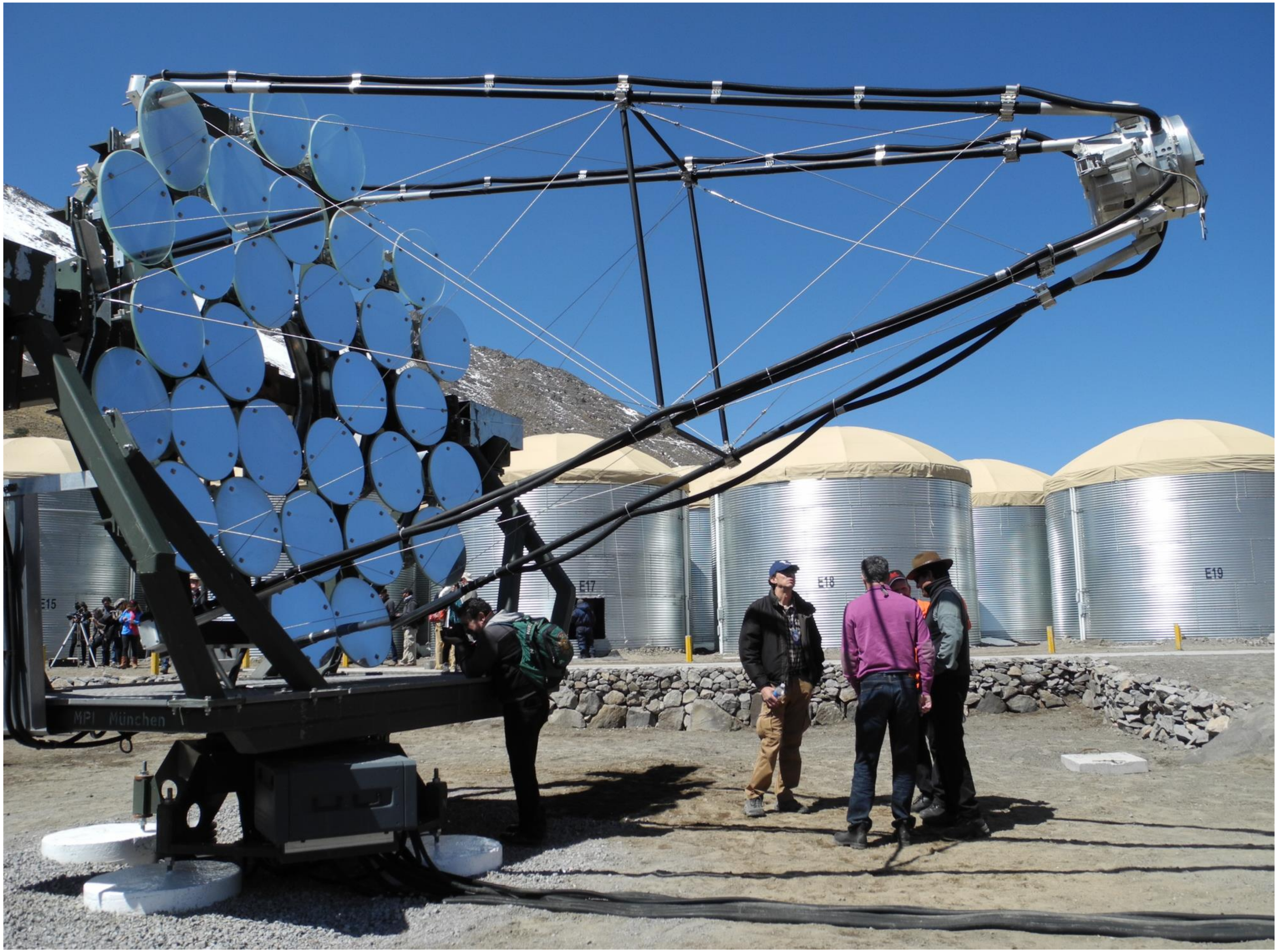
CT2 – CT6: 5 more telescopes were built until 1997.



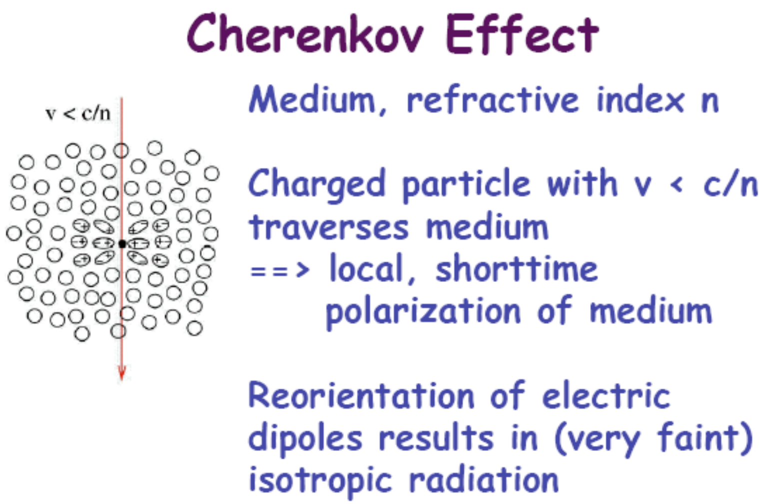
The 1st telescope of HEGRA, the CT1 (installed spring 1992)

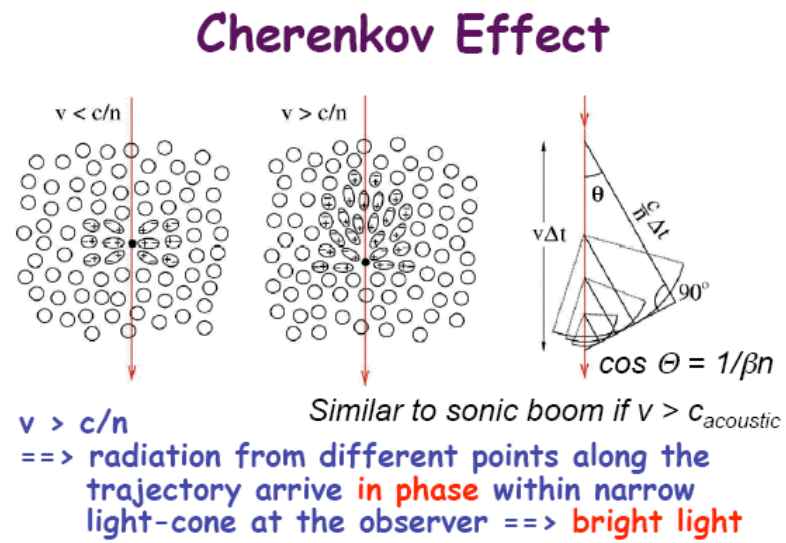

The HEGRA detector, including
6 air Cherenkov imaging telescopes
Location: ORM @ La Palma
Operation 1992 - 2002
CT6
CT1
CT3
CT4

One of the former HEGRA telescopes at the HAWC site

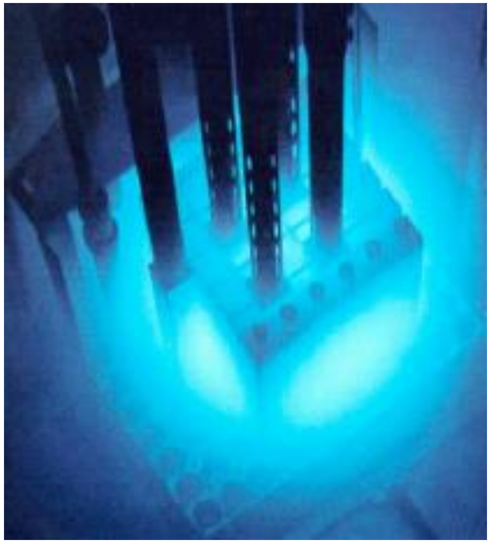


VERITAS, H.E.S.S., MAGIC and since a few years, the 1st 23m Ø CTA/LST: at the frontier of VHE γ-astro-physics



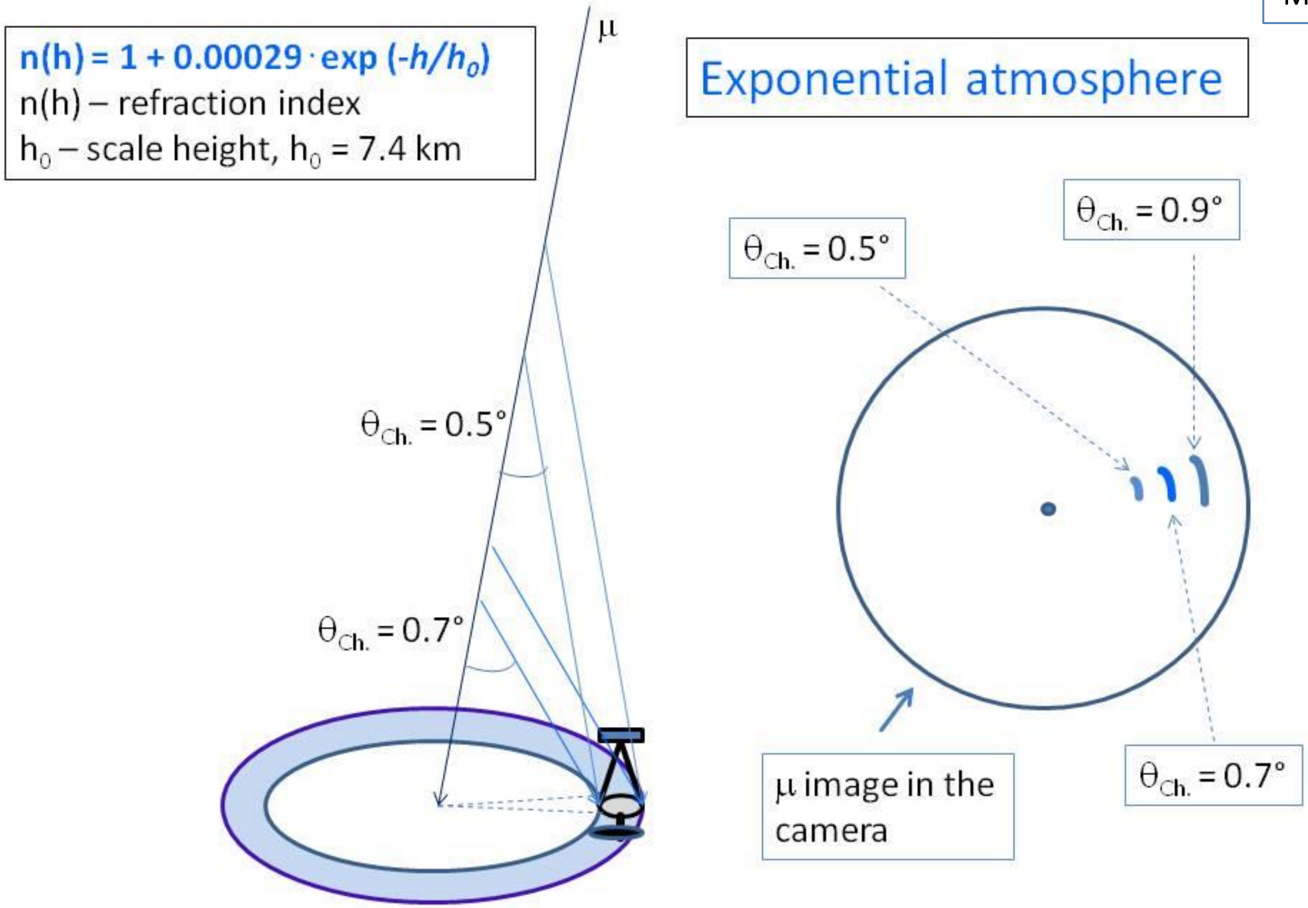


- In the beginning P. Cherenkov complained about his boss: he had to spend hours in a dark, cold cellar, for accomodating eyes
- He noticed that the emission is not chaotic, but is related to the track of moving particle
- In 1937 he succeeded to measure the anisotropy of the emission and submitted an article to the journal „Nature", who declined his paper
- „The Physical Review" accepted it

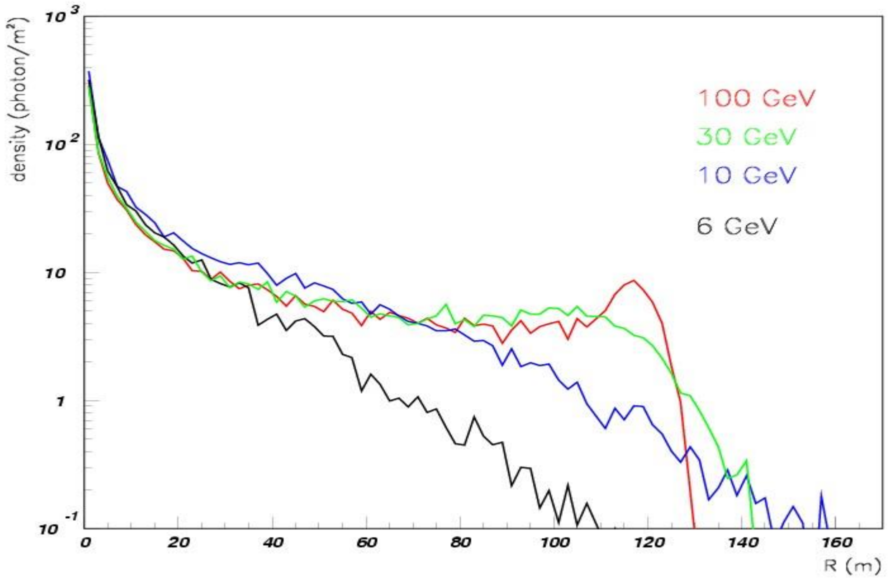


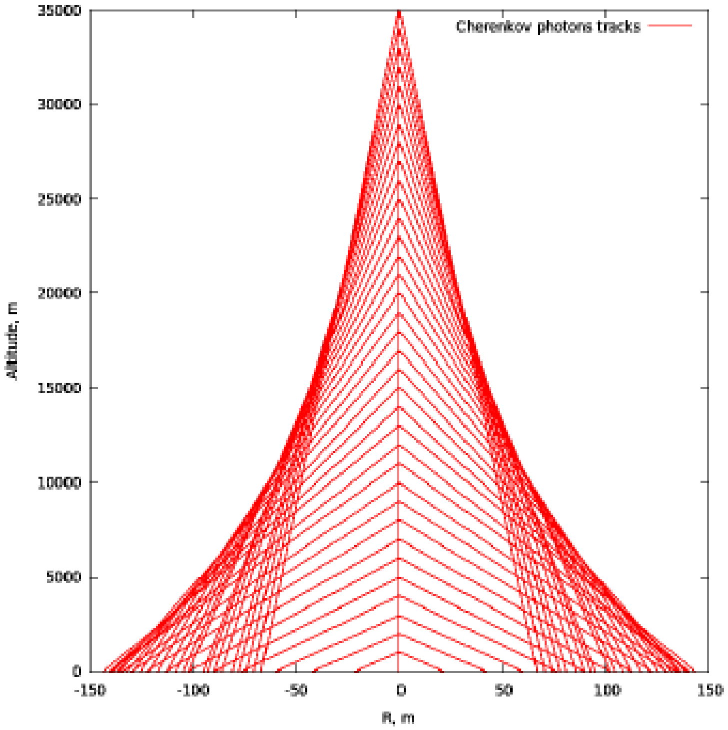
VHE γ-astrophysics with IACTs is possible thanks to exponential atmosphere

Mirzoyan, 2014

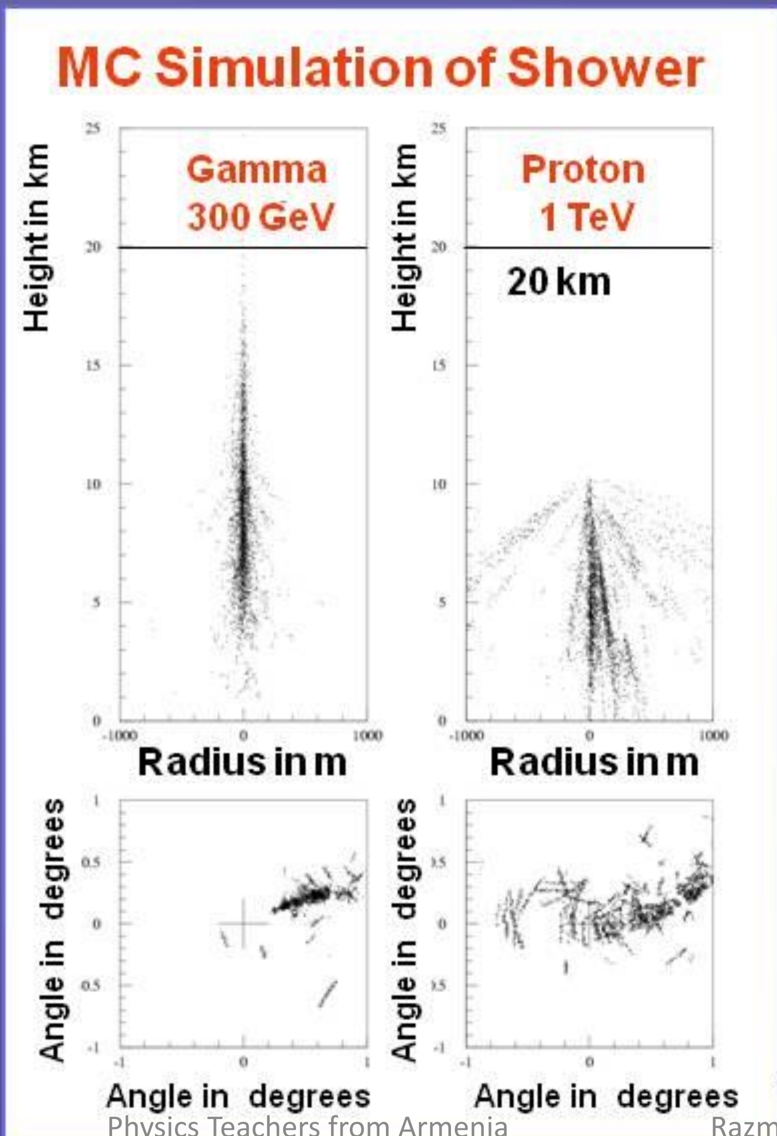


Lateral distribution of Cherenkov light from a single muon

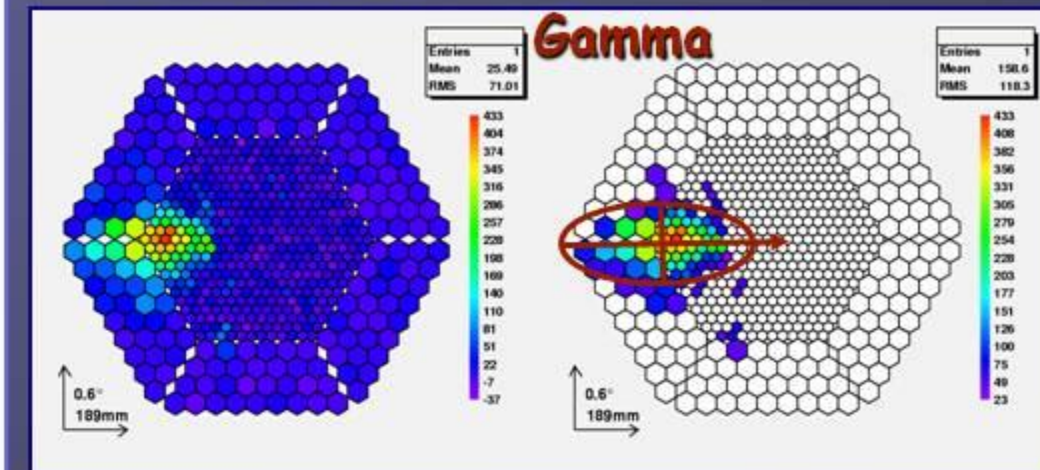


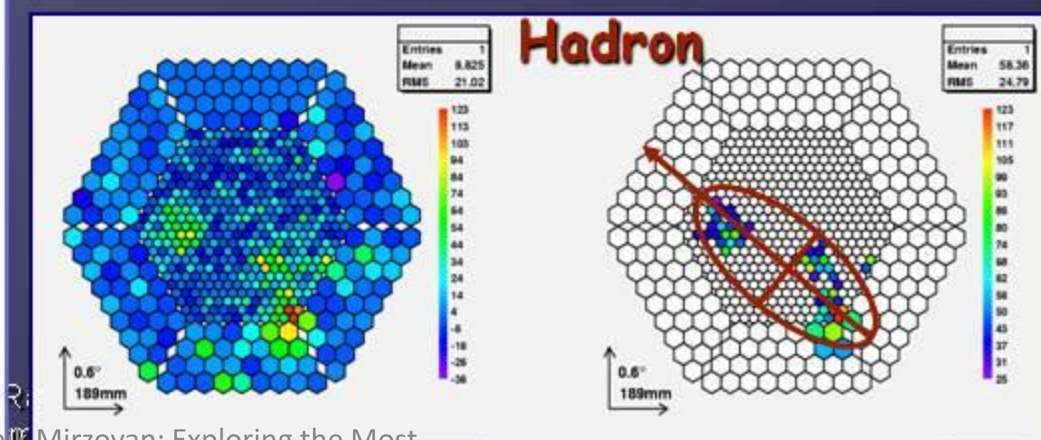


Gamma/Hadron separation



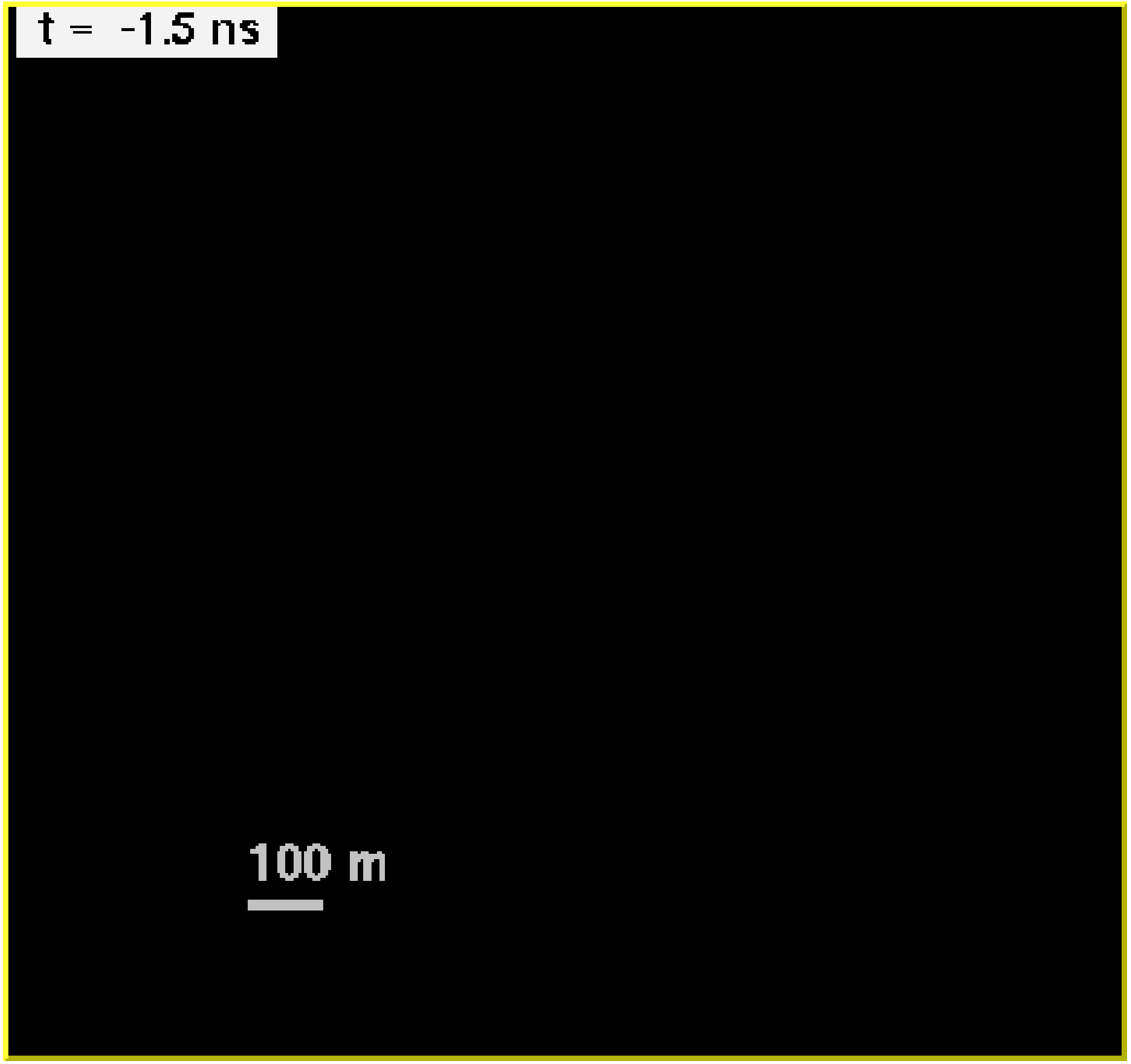
Hadron Rejection by Image Shape
+ Orientation ~ 99.9 %

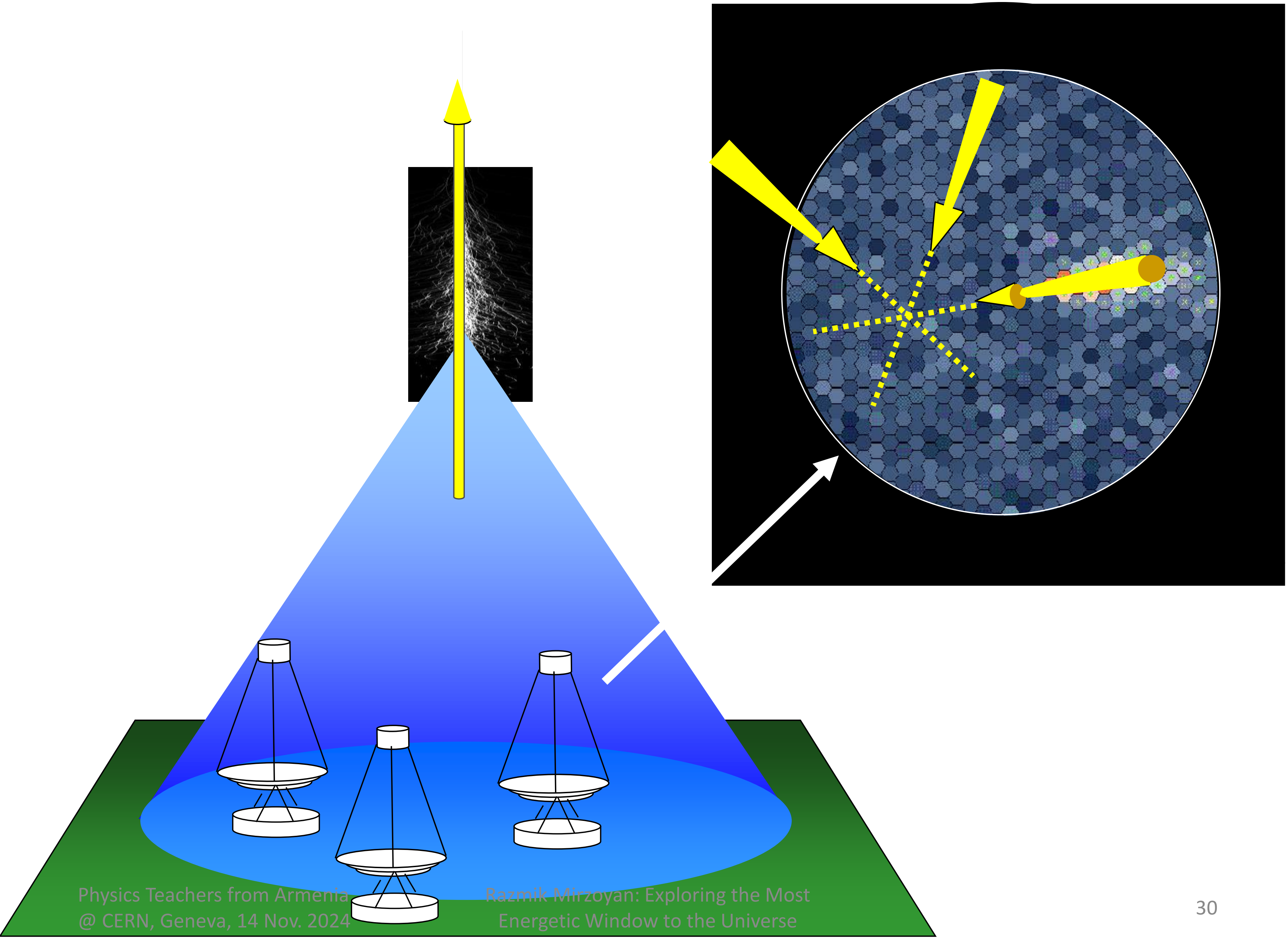




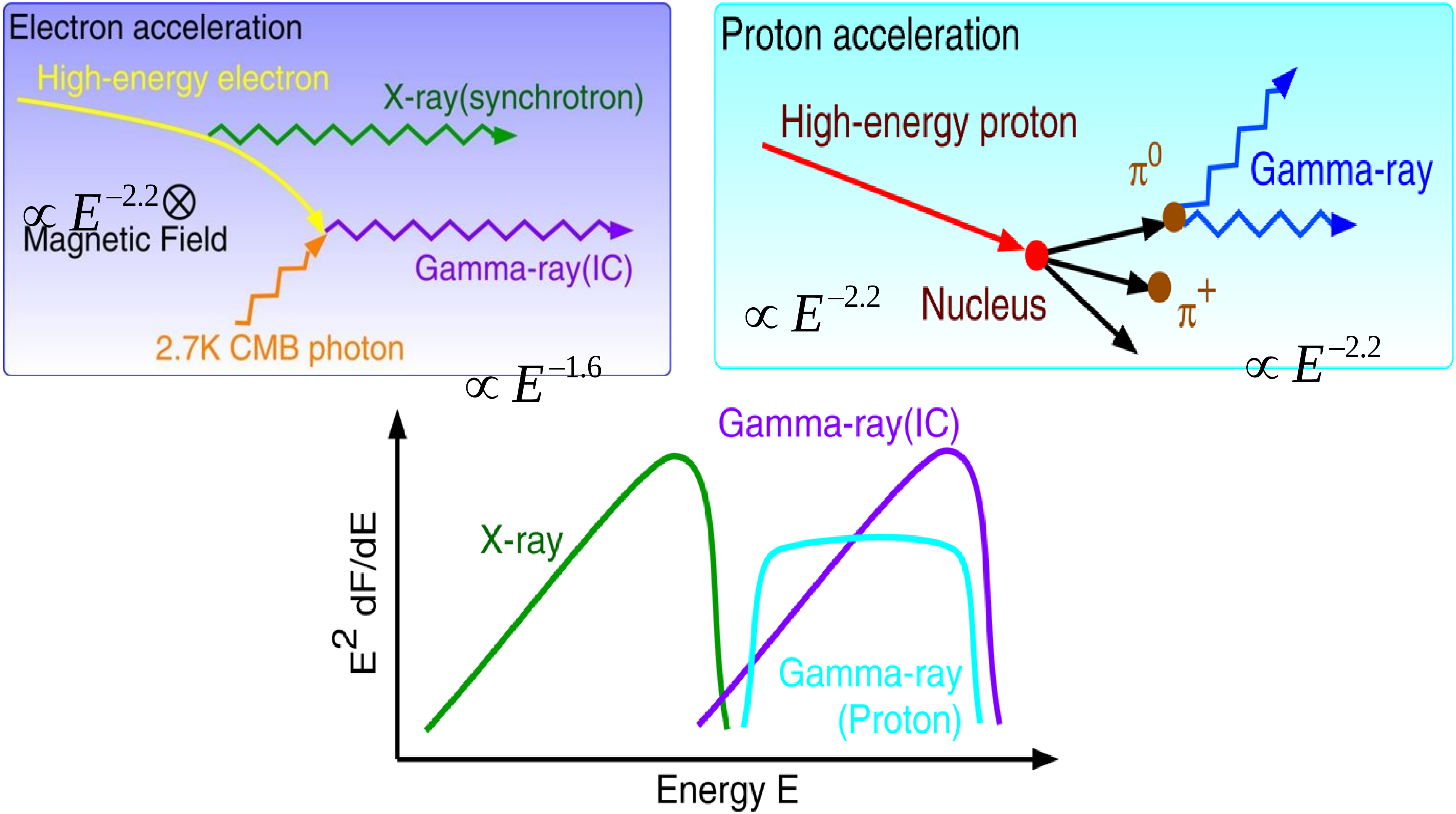
A 100 GeV γ-ray event on the ground

A 200 GeV proton on the ground



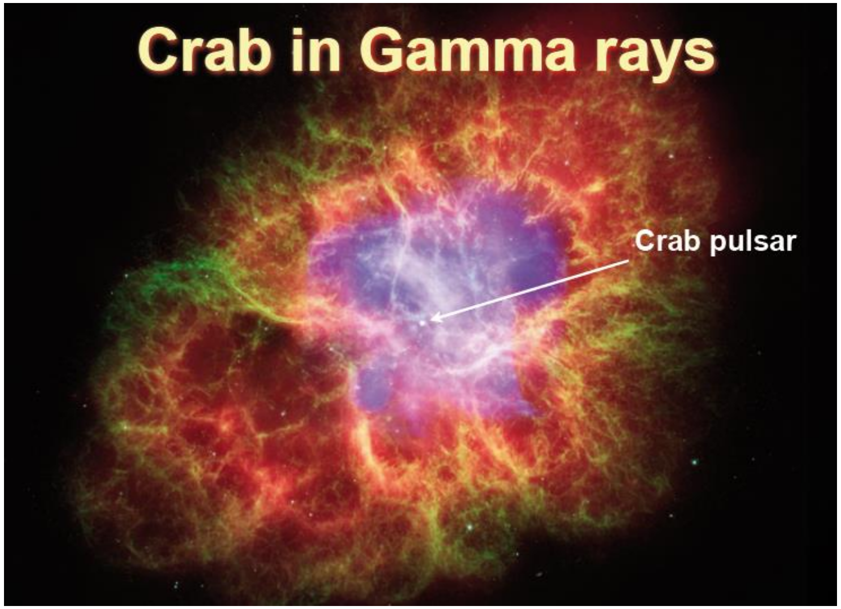


Gamma-Ray Emission Processes
Astrophysical process



Composite figure of the Crab Nebula

Nebula emission measured for $E \geq 1.1$ PeV

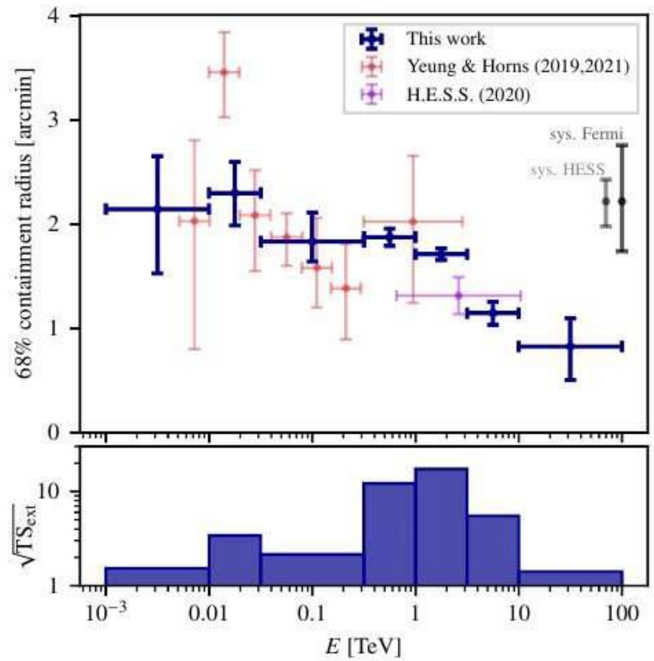


Pulsar emission measured up to 2 TeV

X-ray in blue (Chandra), optical in green and dark blue (HST), infrared in red (Spitzer Space Telescope).

Size of the Crab Nebula by H.E.S.S.

H.E.S.S., A&A; 2024



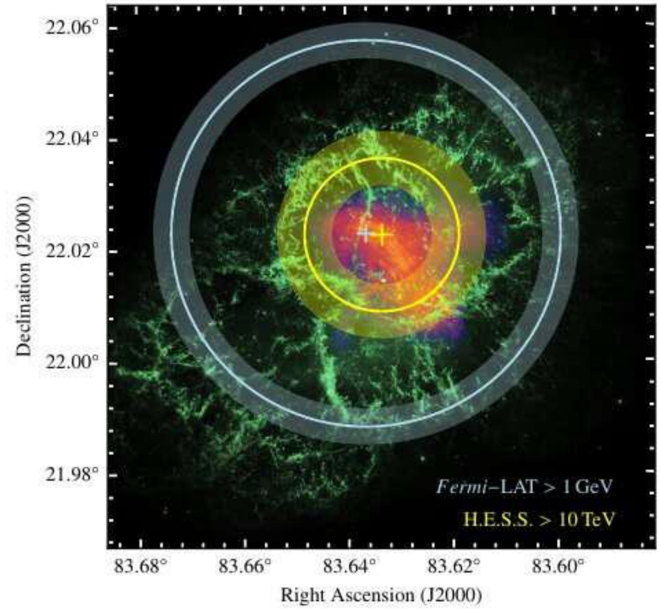


Fig. 7. Optical image of the Crab Nebula in green (credit: NAS

1st association of a ~300 TeV neutrino to a γ-ray source

RESEARCH ARTICLE

Science **361, July 2018**

NEUTRINO ASTROPHYSICS

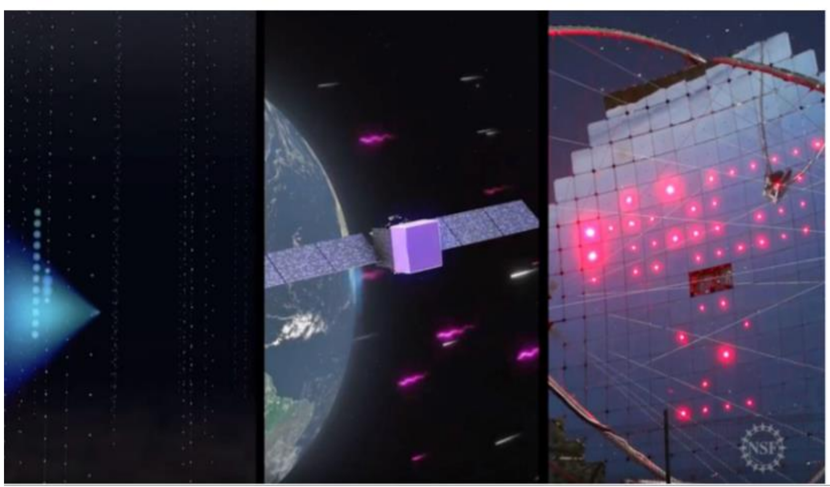
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

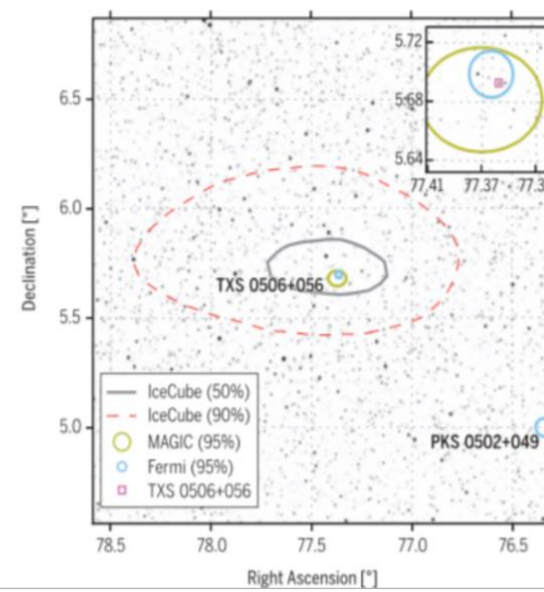
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

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 km³ 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





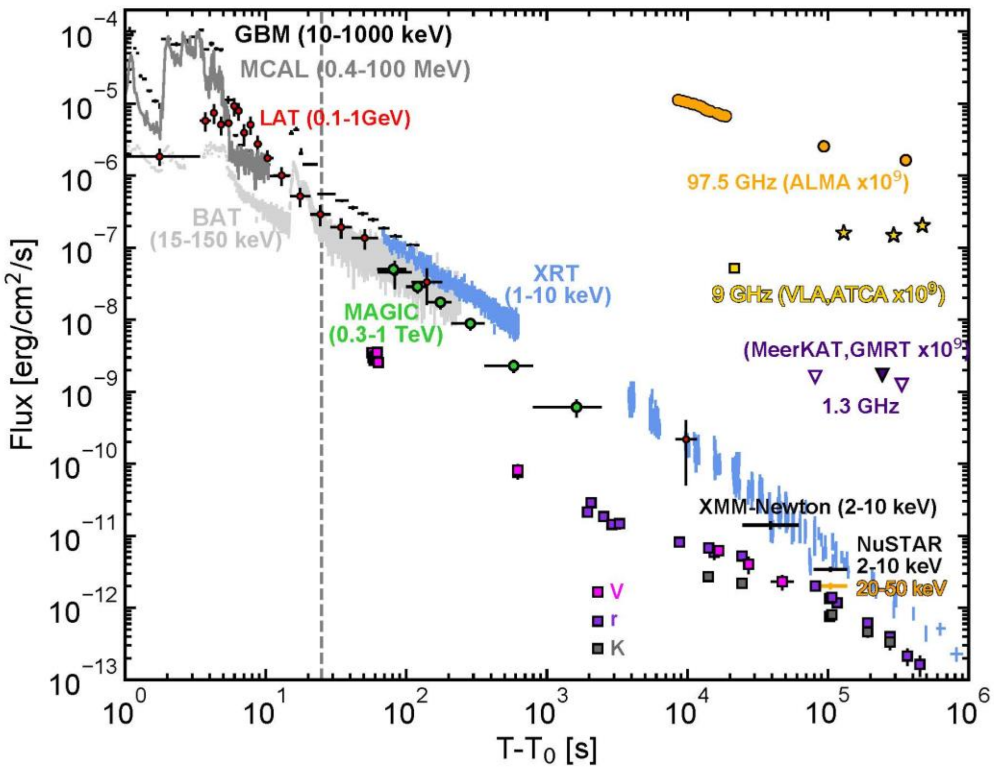
Press-conference at NSF in Alexandria, Washington, VA, USA, 12 July 2018

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

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

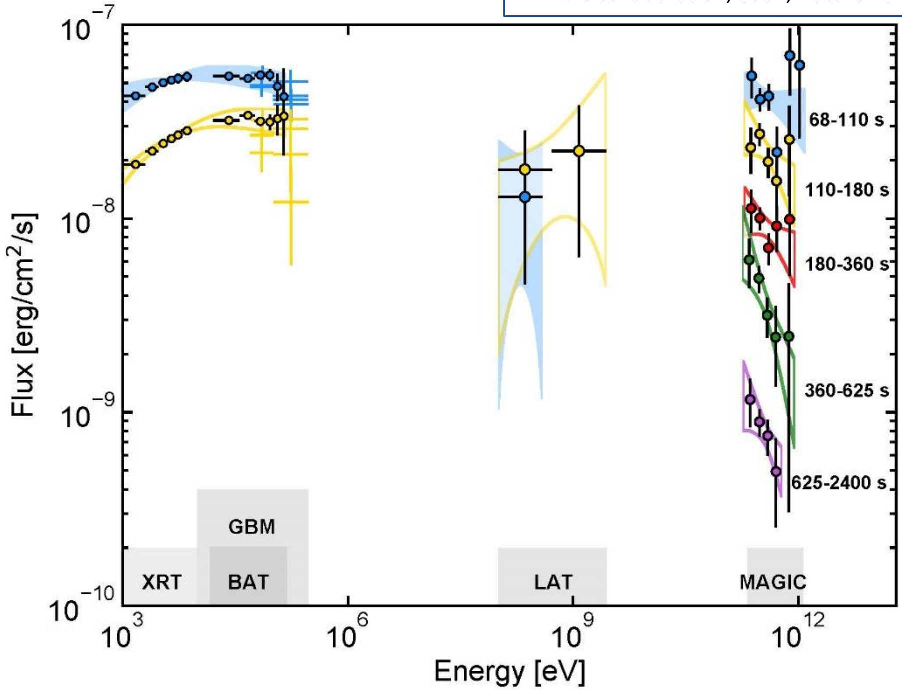
Nature 575, 455-458 (2019) & Nature 575, 459-463 (2019)

- 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



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

MAGIC collaboration, et al., Nature 2019



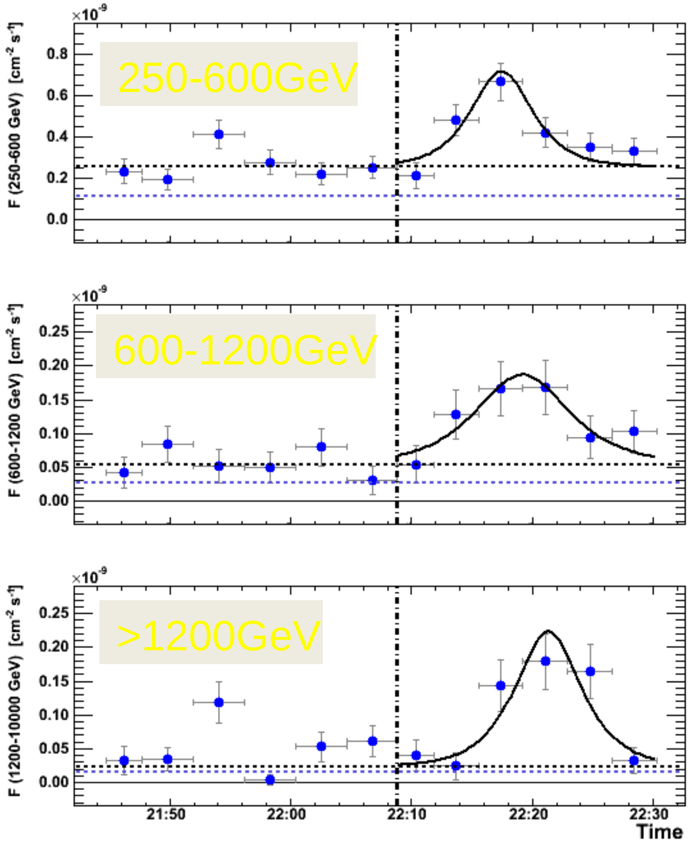
Nature, 575
November 2019

- 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

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

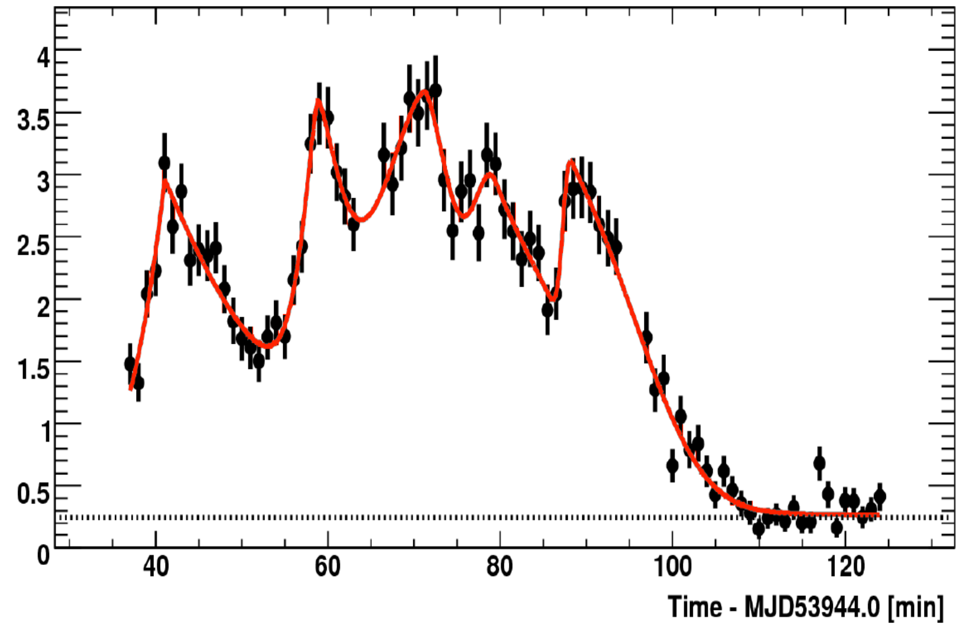
Mrk501(z=0.03) MAGIC observation

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



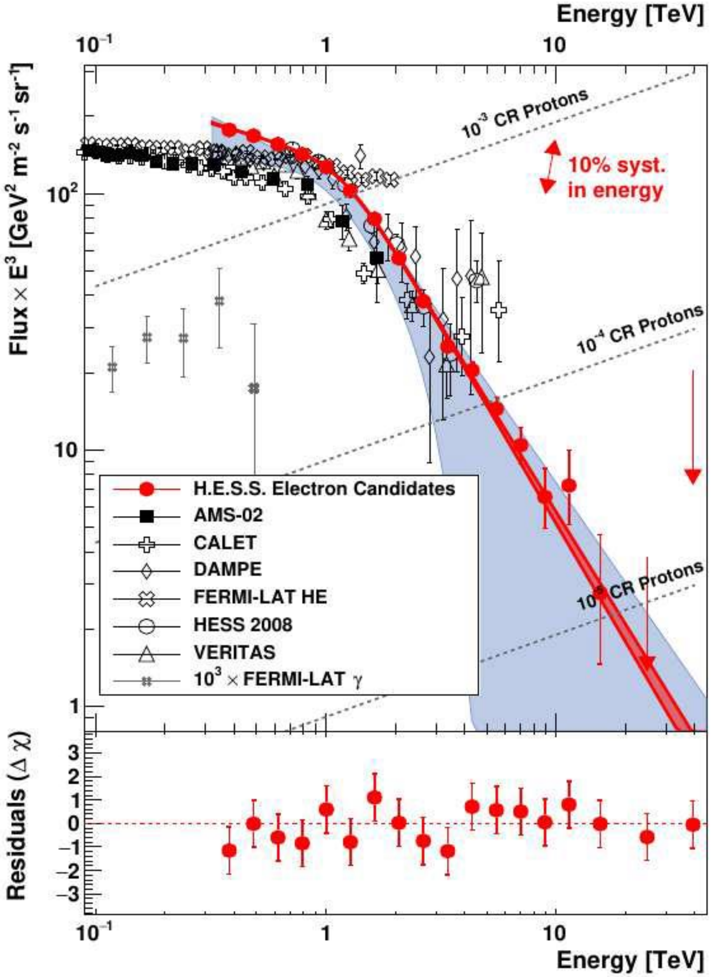
PKS2155(z=0.116) HESS observation

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



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

e$^{\pm}$ spectrum from H.E.S.S.



No significant deviations from broken PL

$$F(E) = F_0 \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\Gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right)^{-(\Gamma_2-\Gamma_1)\alpha}$$

No confirmation of 1.4 TeV break (potential DM signal), Yuan et al.

No rise (hardening) above 5 TeV

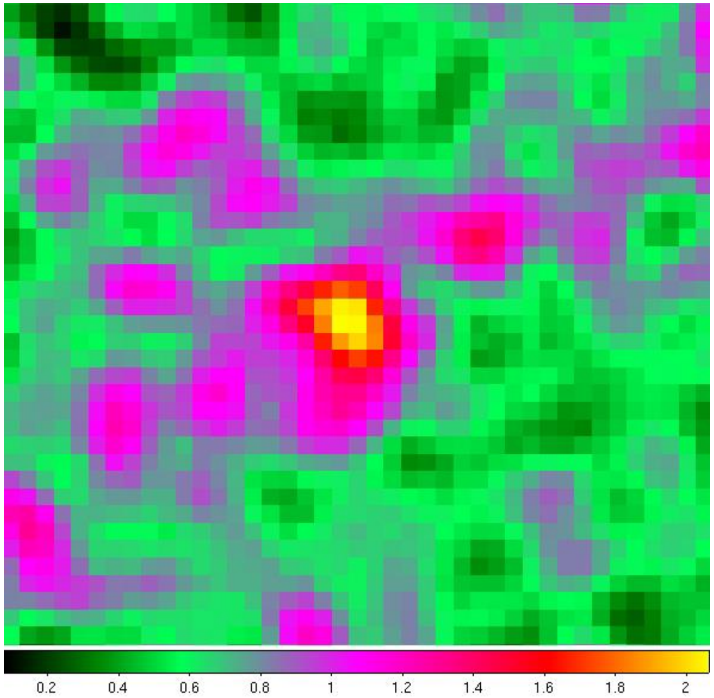
No confirmation of 1.4 TeV break (potential DM signal), Yuan et al.

30% higher than other measurements

marginally compatible with DAMPE
significantly higher than VERITAS
incompatible with 95% lower limit (LAT)
α→ 0, Eb → 1.09 TeV

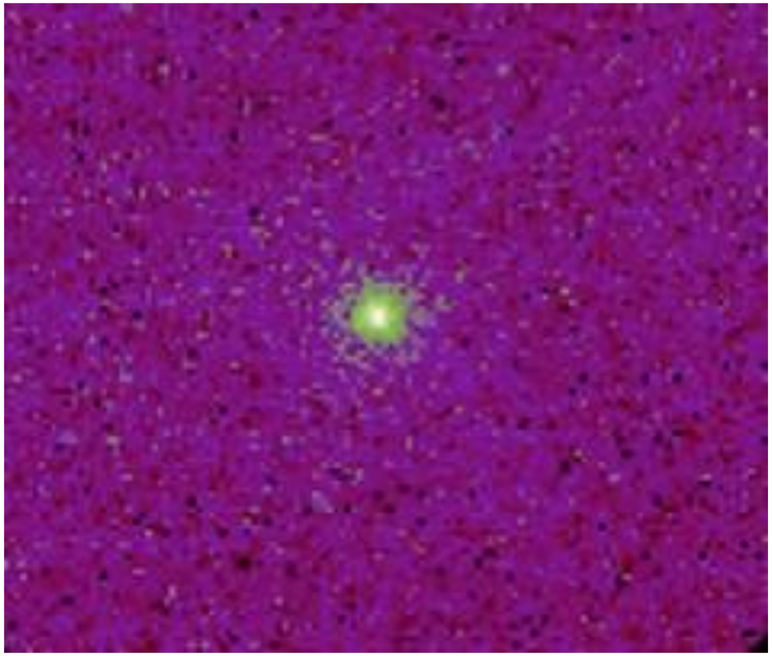
1st Detections of the Quiet Sun in γ Rays

Orlando & Strong (2008) A&A 480, 847



EGRET

Fermi LAT Coll. ApJ. (2011) 734, 116

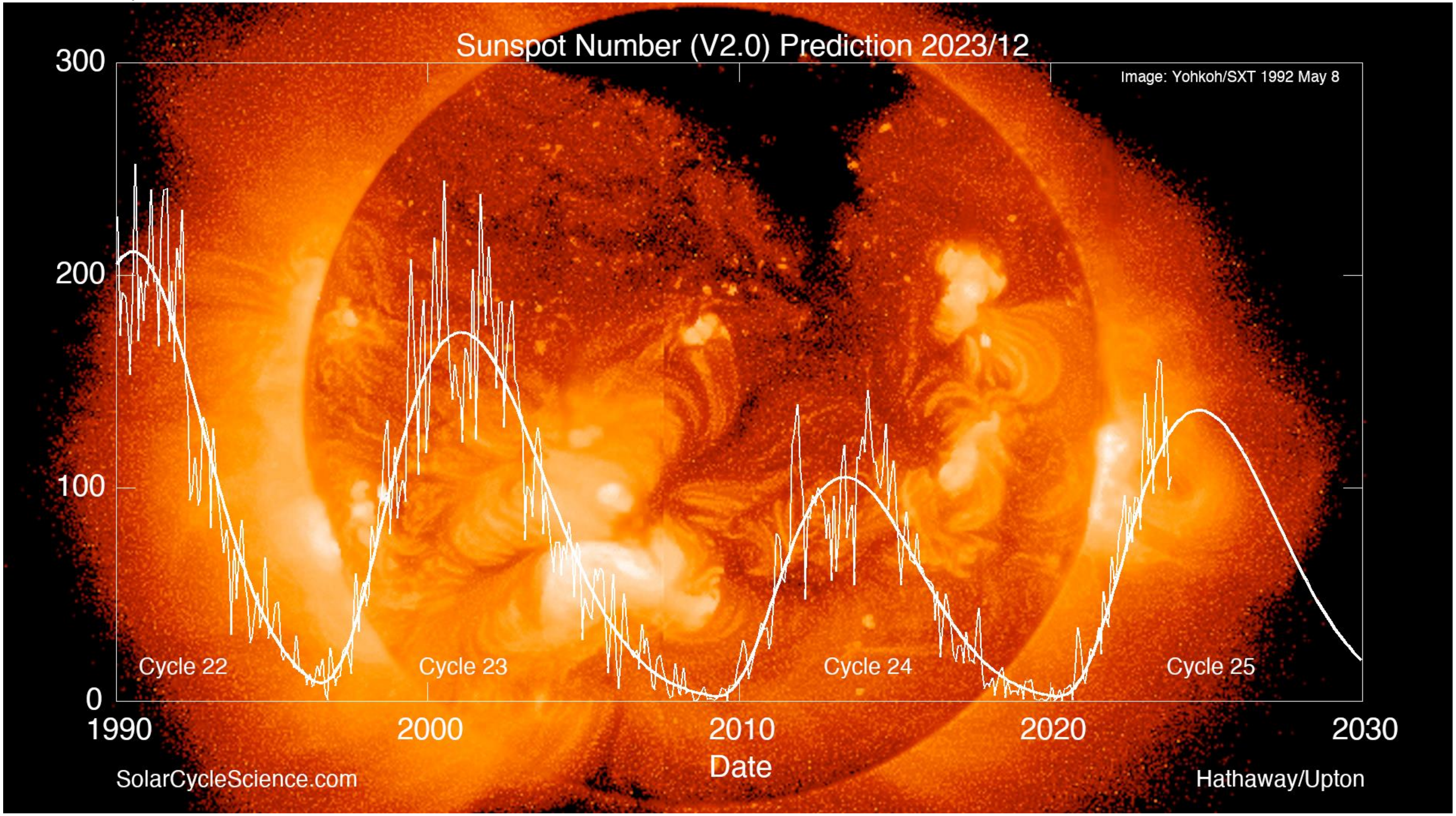


FERMI

The Astrophysical Journal, 962:52 (16pp), 2024 February 10 https://doi.org/10.3847/1538-4357/ad1bd2

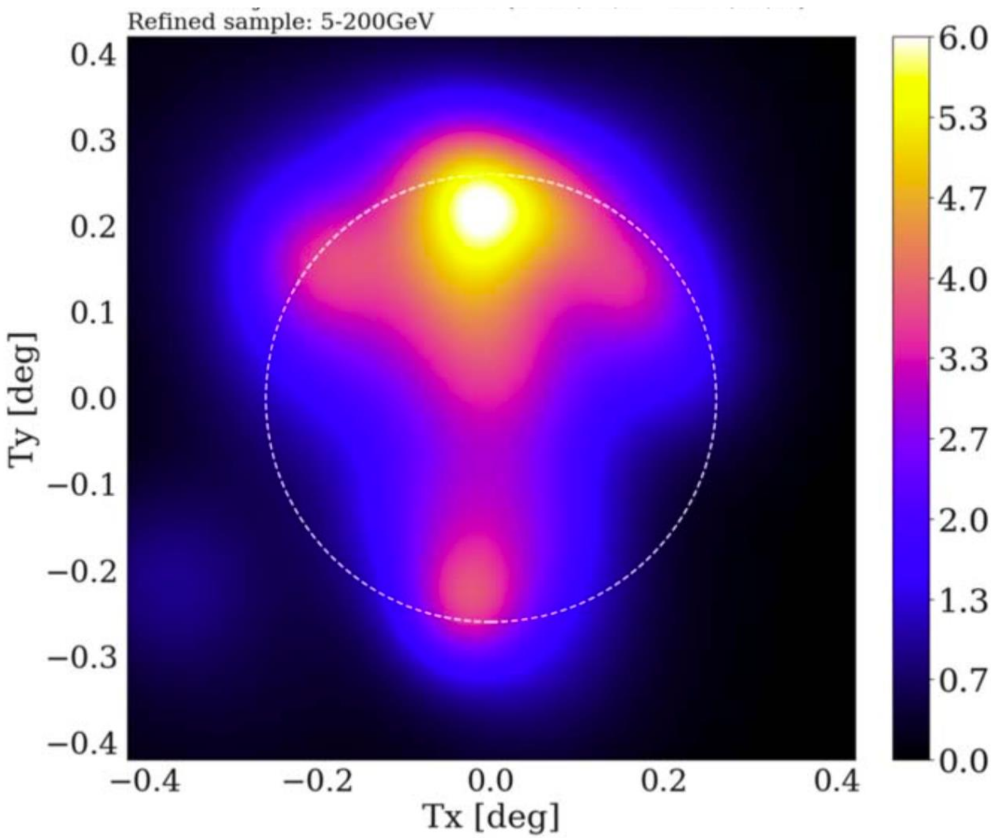
Yet Another Sunshine Mystery: Unexpected Asymmetry in GeV Emission from the Solar Disk

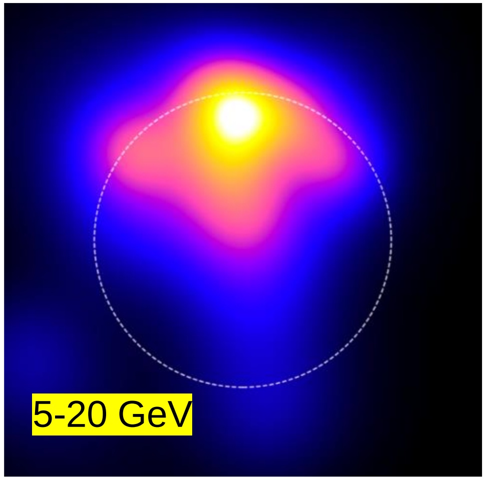
Bruno Arsioli[1,2,3,4] and Elena Orlando[3,4,5]

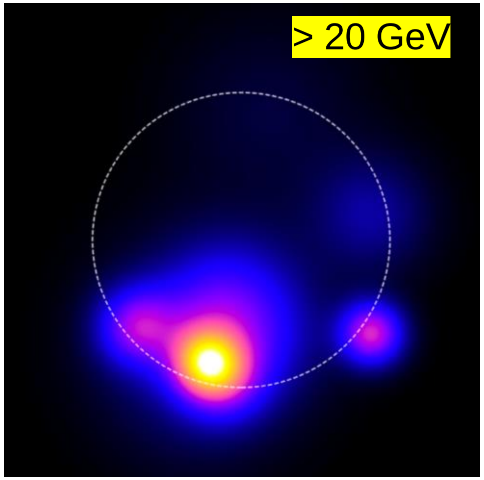


Non-uniformity of the solar disk in ~2014

Elena Orlando, RICAP-24

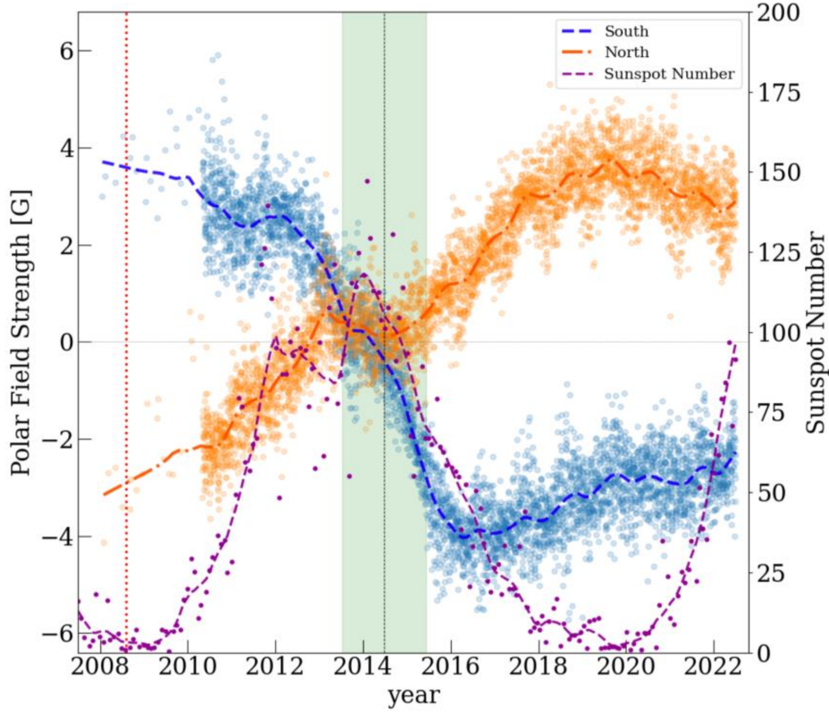




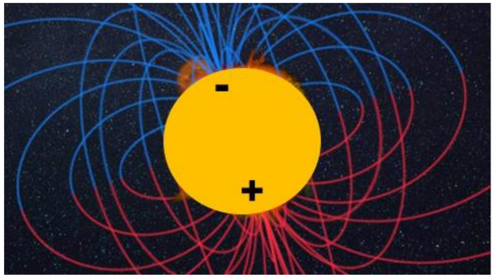


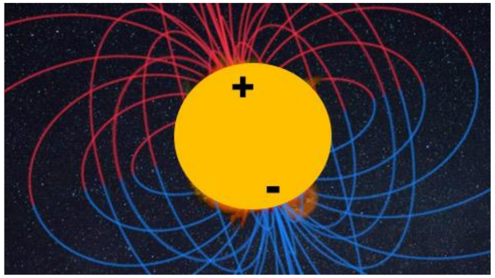
~2014: Sun’s Polar Magnetic Field Flip

Elena Orlando, RICAP-24

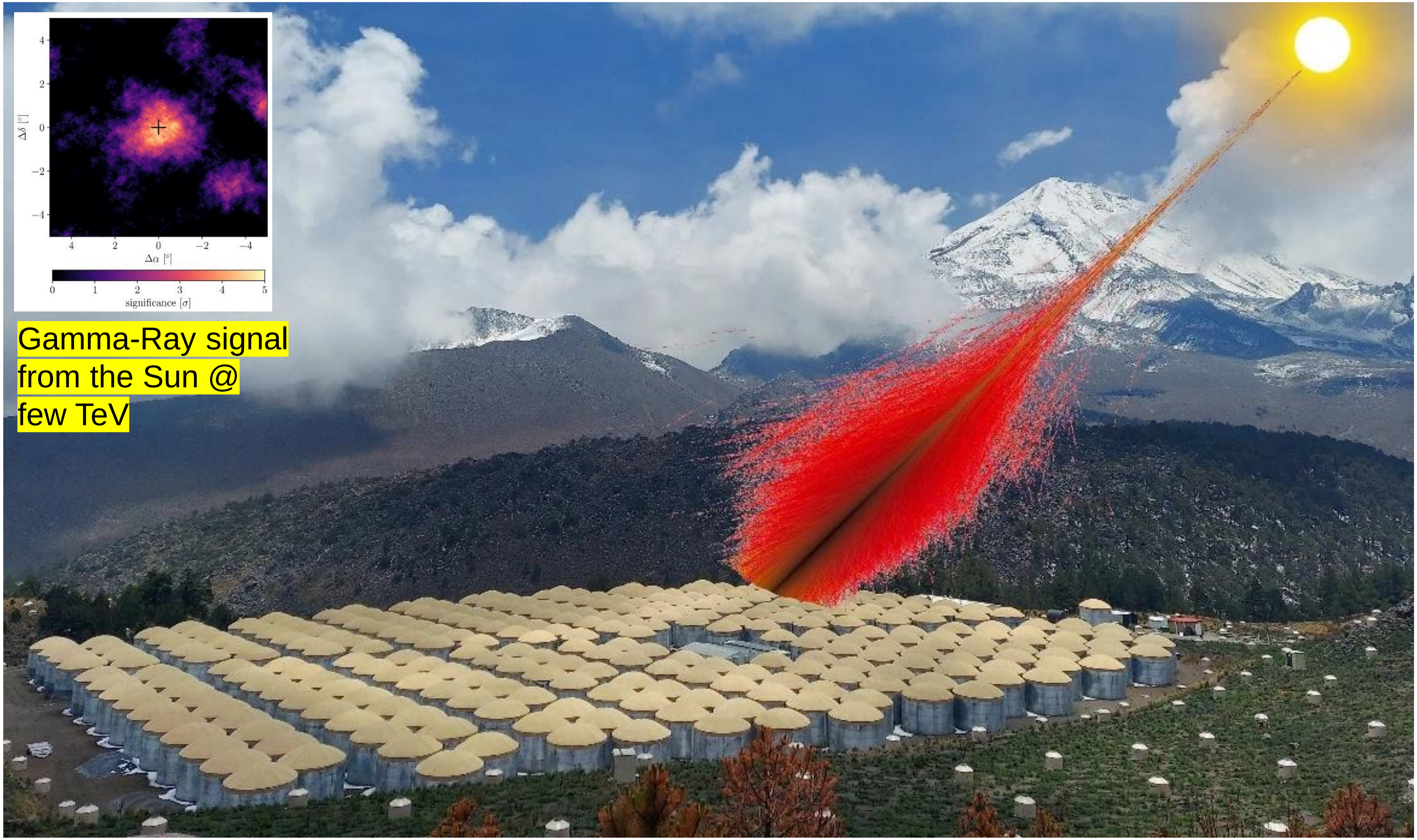


Data from the Wilcox Solar Observatory (WSO)





HAWC



$\Delta\delta$ [°]
$\Delta\alpha$ [°]
significance [σ]
Gamma-Ray signal from the Sun @ few TeV

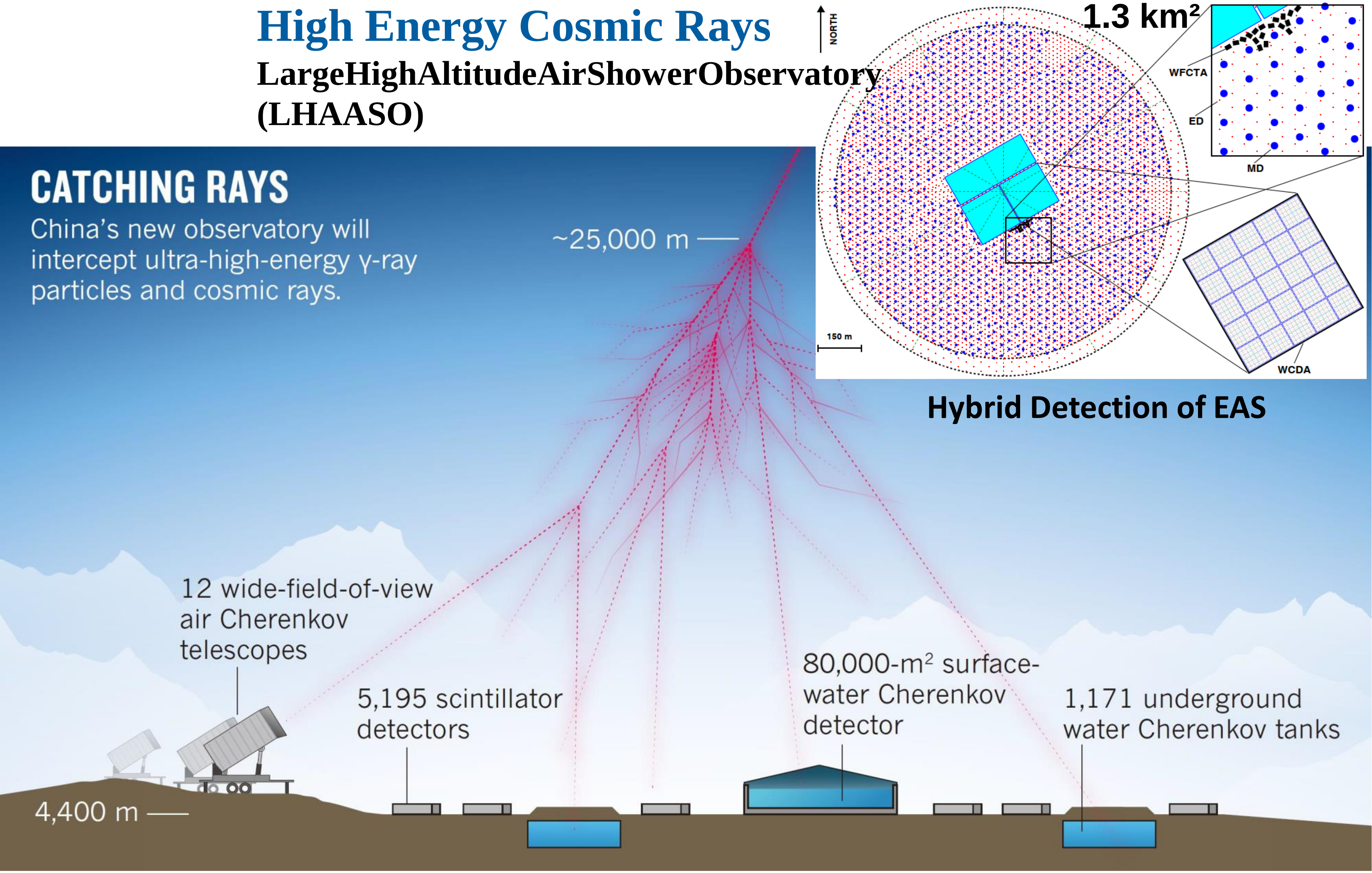
HAWC

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

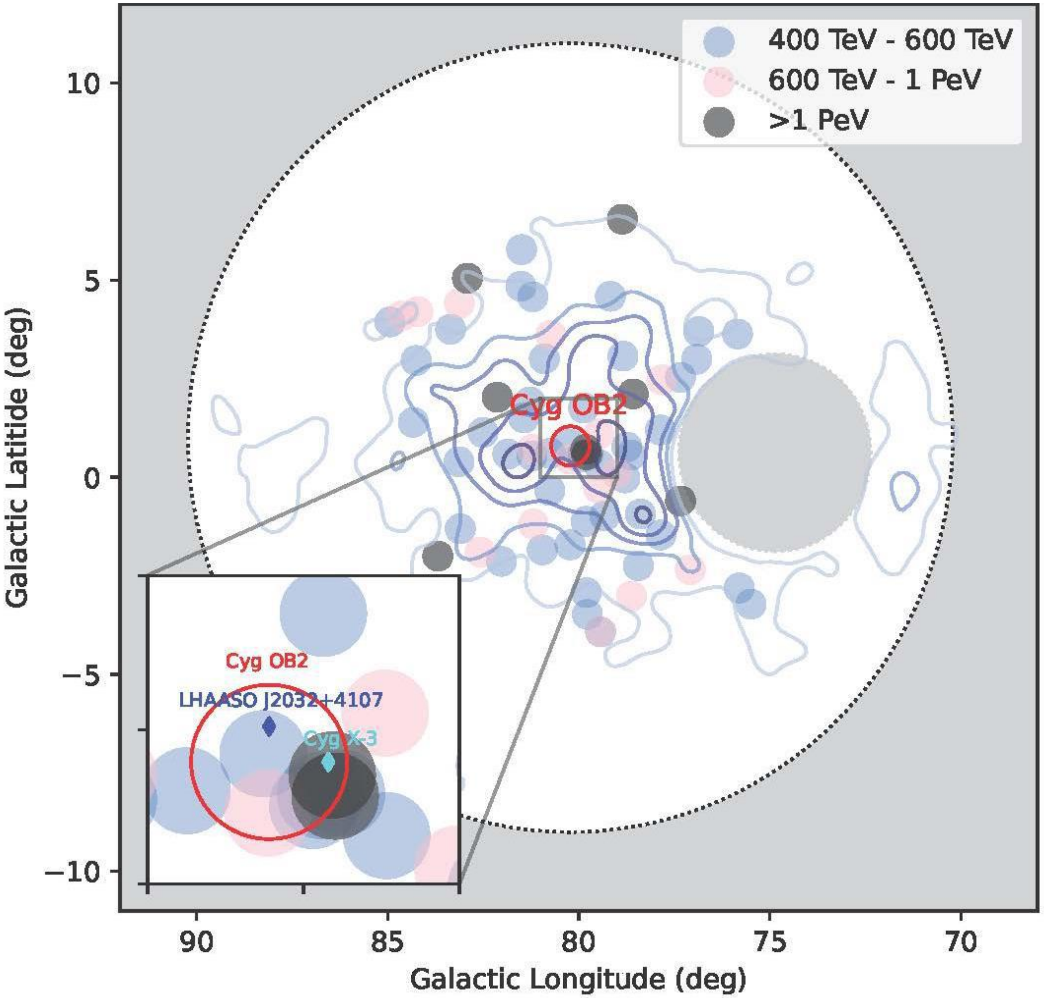
High Energy Cosmic Rays

LargeHighAltitudeAirShowerObservatory (LHAASO)



Hybrid Detection of EAS

A Bubble of UHE γ's centered at a complex core Cygnus OB2, binary J2032+4107, MQ X-3

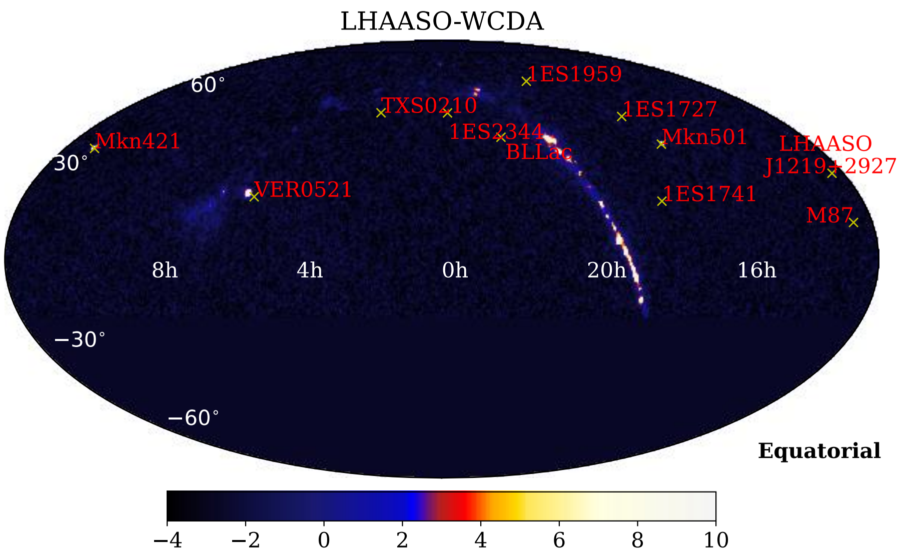


8 γ's above 1 PeV

PeV Photons are scattered in the Bubble, and seem not to associate with any small scale sources

LHAASO AGNs

1. A Survey of extra-galactic sources with full-WCDA data (508 days)



Credit: Min Zha &Zhen Cao

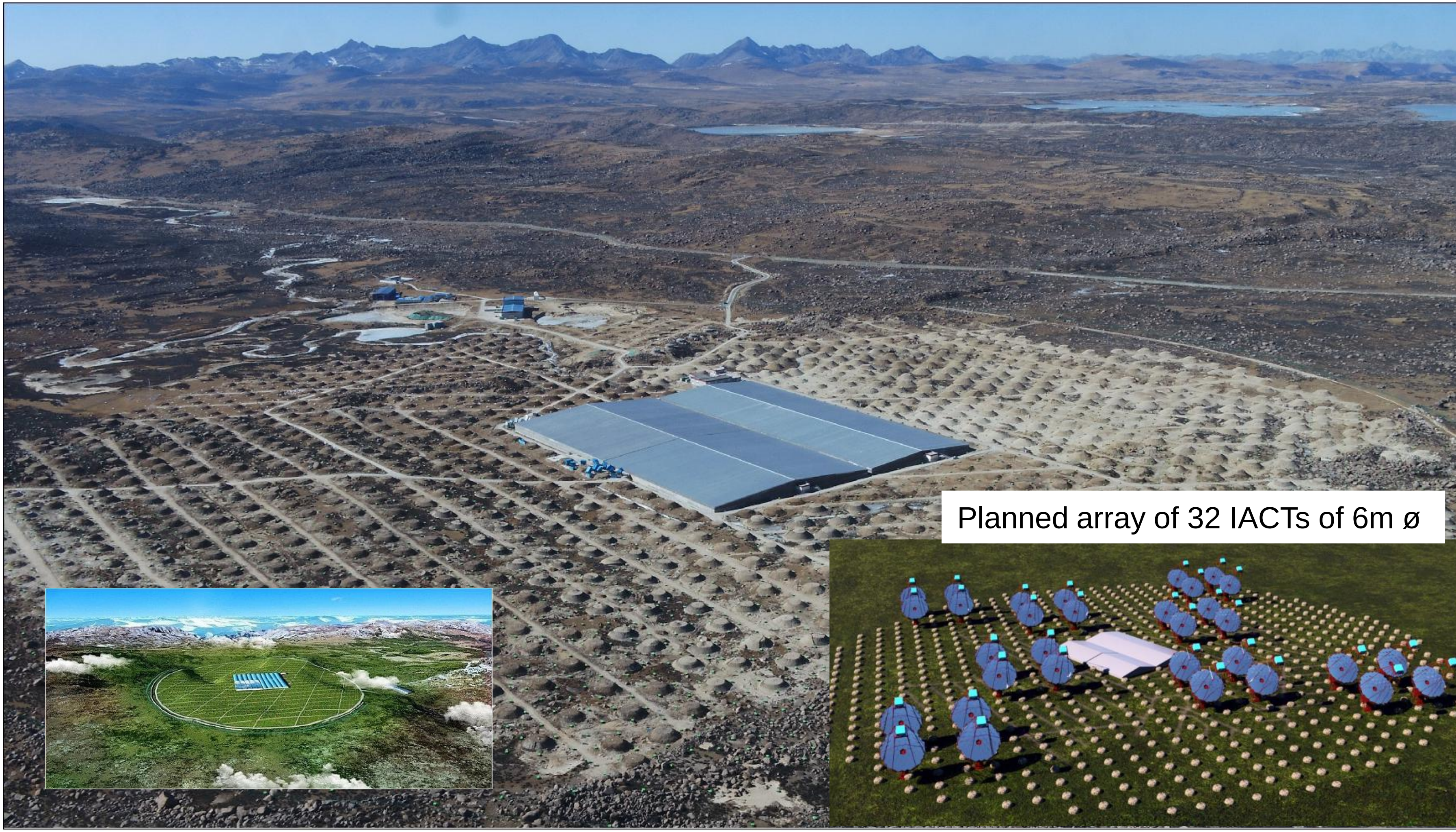
5 sources above 6σ are detected.

Name	RA[°]	Dec[°]	Significance[s.d]	Separation[°]
Mkn421	166.05	38.15	70.84	0.05
Mkn501	253.45	39.75	63.97	0.02
1ES2344+514	356.75	51.65	6.76	0.06
LHAASO J1219+2916	**184.95**	**29.25**	**6.71**	**x**
1ES1727+502	261.95	50.25	6.52	0.09
RXJ0648.7+1516	102.15	15.35	5.10	0.09
M87	**187.75**	**12.45**	**5.07**	**0.07**
TXS0210+515	33.65	51.75	4.95	0.05
1ES1741+196	265.85	19.55	4.41	0.15
BLLacertae	330.67	42.27	4.38	0.18
VER0521+211	80.55	21.05	4.23	0.19
1ES1959+650	299.65	65.05	4.18	0.18
W Comae	185.35	28.45	4.10	0.22

Comparison of the IACT technique (CTA) with LHAASO-type particle detector

Parameter	LHAASO	IACT	Comment
Area, km^2	1.3	Similar	for $N_{tel} \geq 25$
Angular acceptance	~2 sr	3° - 10°	Depend on IACT type
Angular resolution	0.2° - 0.3°	~0.05°	On average
Background rejection/tagging	10^4 (~100 TeV) 10^5 (≥ 600 TeV)	10^4 (~1 TeV)	
Threshold	Surface array ~20TeV (N_μ >>10) SWCD ≥ 500 GeV	20 GeV (LST) 80 GeV (MST) ~1 TeV (SST)	Different for different instruments
Observing selected source in FoV /y	2000 h	200 h	IACT can measure total ≤ 1000 h/y
Need to track	No	Yes	
Location height	~(4 - 5) km a.s.l.	~2 km a.s.l.	
Maintenance	Low	High	

Near Future Plans of LHAASO



CASA-MIA (and LHAASO)

- The **CASA-MIA** array (1992-1997) was located at Dugway, Utah, USA, at 1450m a.s.l.
- It consisted of 2 major components:
  - the Chicago Air Shower Array (**CASA**), 1089 scintillation detectors placed on a 15 m square grid and **covering an area of 0.23 km²**, and
  - the Michigan Array (**MIA**), a buried at a depth of ~ 3.5 m array of 1024 scintillation counters **for the muon component of air showers with an active area of 2400 m²**

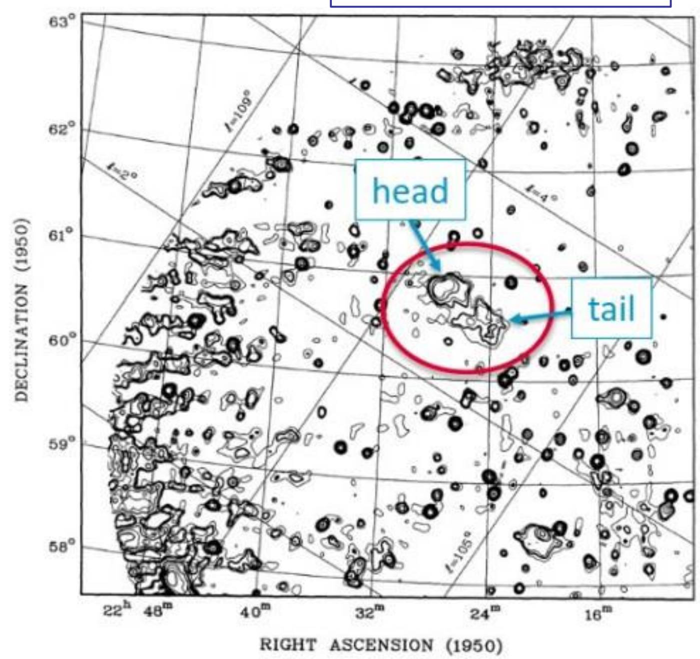
The underground muon detectors covered only ~1% of the total area. And it is a great pity, but this prevented them to discover the PeVatrons already ~30 years ago.

LHAASO increased the total area 4-times, to ~1km² and increased the coverage of muon detectors to 4%. And that had a magnificent effect; **LHAASO** discovered **dozens of PeVatrons**

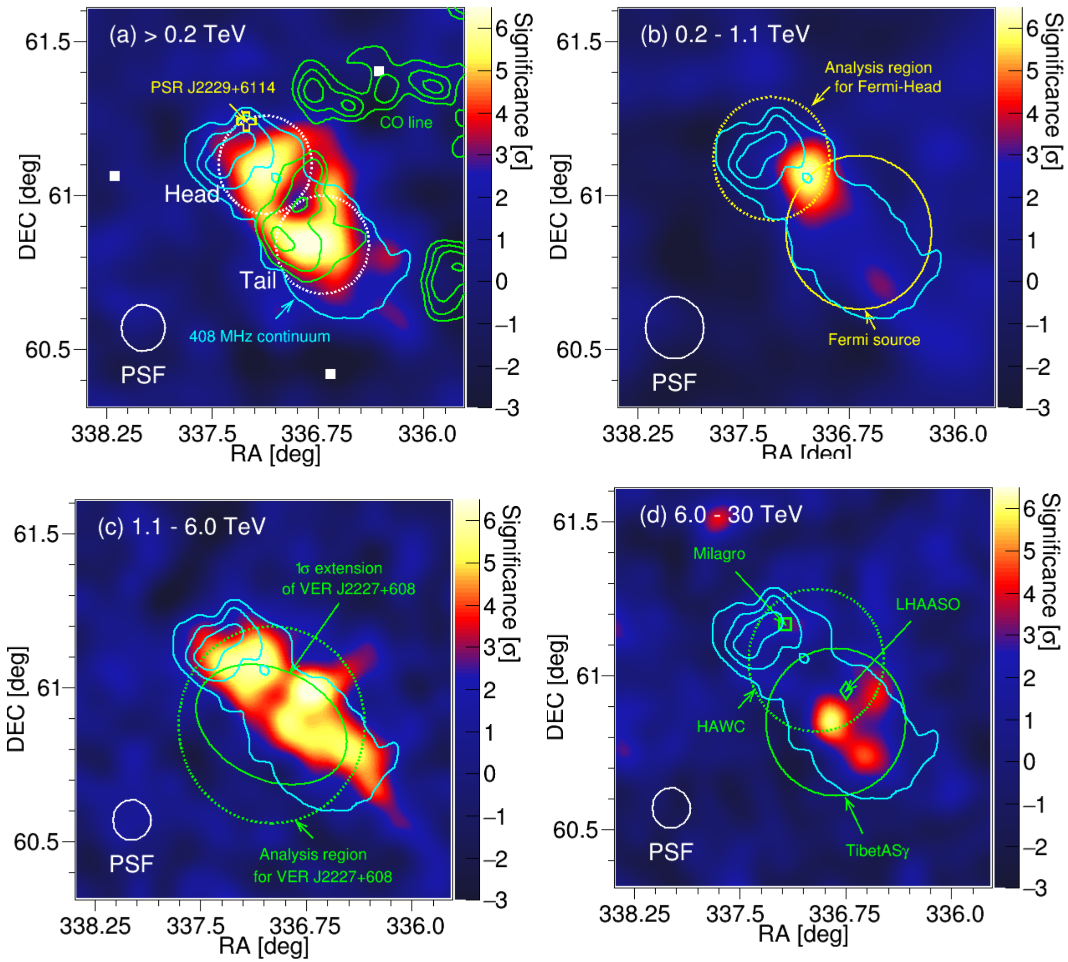
The Super Nova Remnant SNR G106.3+2.7
SNR, Pulsar and PWN

- SNR G106.3+2.6 first detected in radio
- Boomerang Pulsar Wind Nebula (PWN) identified in the head
- Pulsar detected close to the PWN
- Connected to molecular clouds (HI and CO):
  - Head: pulsar and its PWN colliding in dense HI cloud
  - Tail : expanding in low density HI cavity
  - CO cloud possibly around the tail or in foreground
- Distance : 0.8 – 10 kpc, Age < 10 400 y

Joncas & Higgs (1990)



SNR G106.3+2.7



MAGIC, A&A 2023

MAGIC observations provide compelling evidence of hadronic multi-TeV emission from the putative PeVatron

- The γ-ray emission region detected with the MAGIC telescopes in the SNR G106.3+2.7 is extended and spatially coincident with the radio continuum morphology.
- The multi-wavelength spectrum of the emission from the tail region suggests proton acceleration up to ~PeV, while the emission mechanism of the head region could either be hadronic or leptonic.

Next generation VHE γ ray Observatory CTA

MAGIC

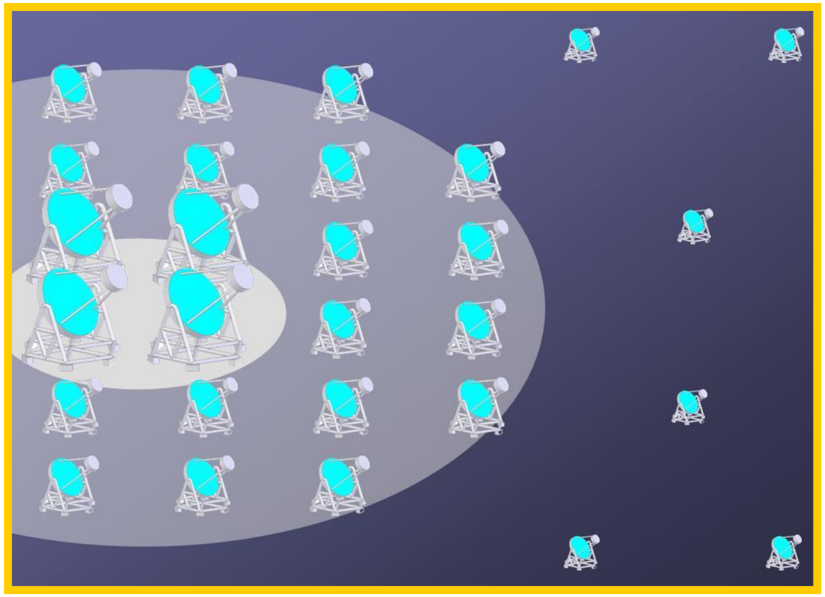
HESS

Astro-physicists from EU

JAPAN, US, India, Brazil, Mexico,.....

>1500 scientists
>130 institutions

CTA



The 23m ø LST1 is taking data & publishing papers

Assembly of the LST2, LST3, LST4 will be assembled by early 2026, commissioned by 2028

Photo of the Roque de los Muchachos observatory taken in August 2024

LST-2 LST-3 LST-1 LST-4 MAGIC-2 MAGIC-I

Conclusions

- Gamma-ray astrophysics provides the unique window to study the highest energy phenomena in the Universe
- The relatively recent addition of particle arrays such as HAWC, LHAASO (and in the near future SWGO) will allow one to combine their very high sensitivity (~2000 hours of observation of a source in the field of view) and their very high level of background tagging with the 4-5 times higher angular resolution and very high sensitivity of the IACT technique (CTAO North and South, ASTRII, 32-LACT Array in China)
- Such a combination will be of utmost importance for observing the Universe in the energy range from 10 GeV to 10 PeV
- These will become the indispensable part of multi-wavelength and multi-messenger observations of the Universe for at least the next ~30 years

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)