Short Overview of Ground-based Gamma-ray Astrophysics

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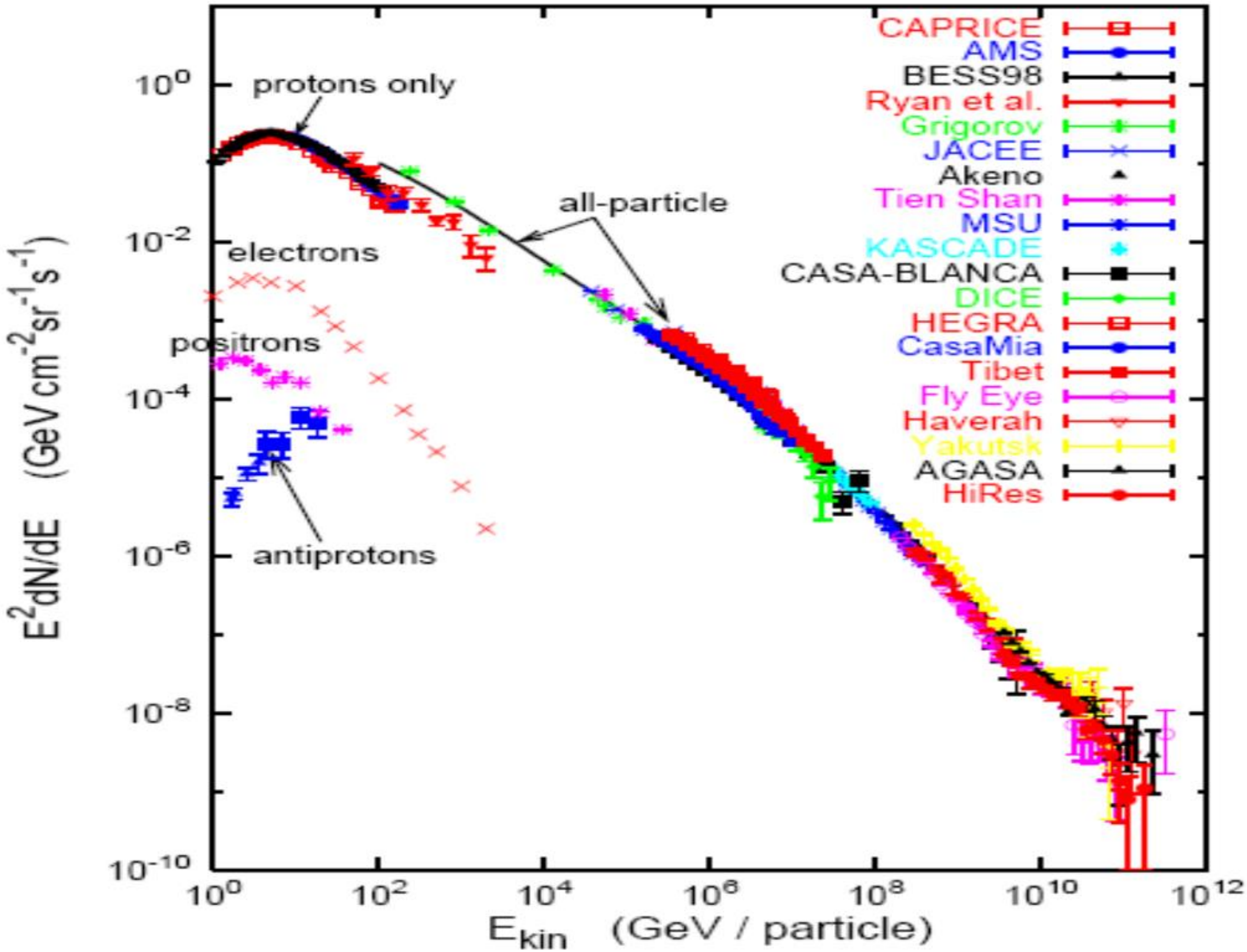
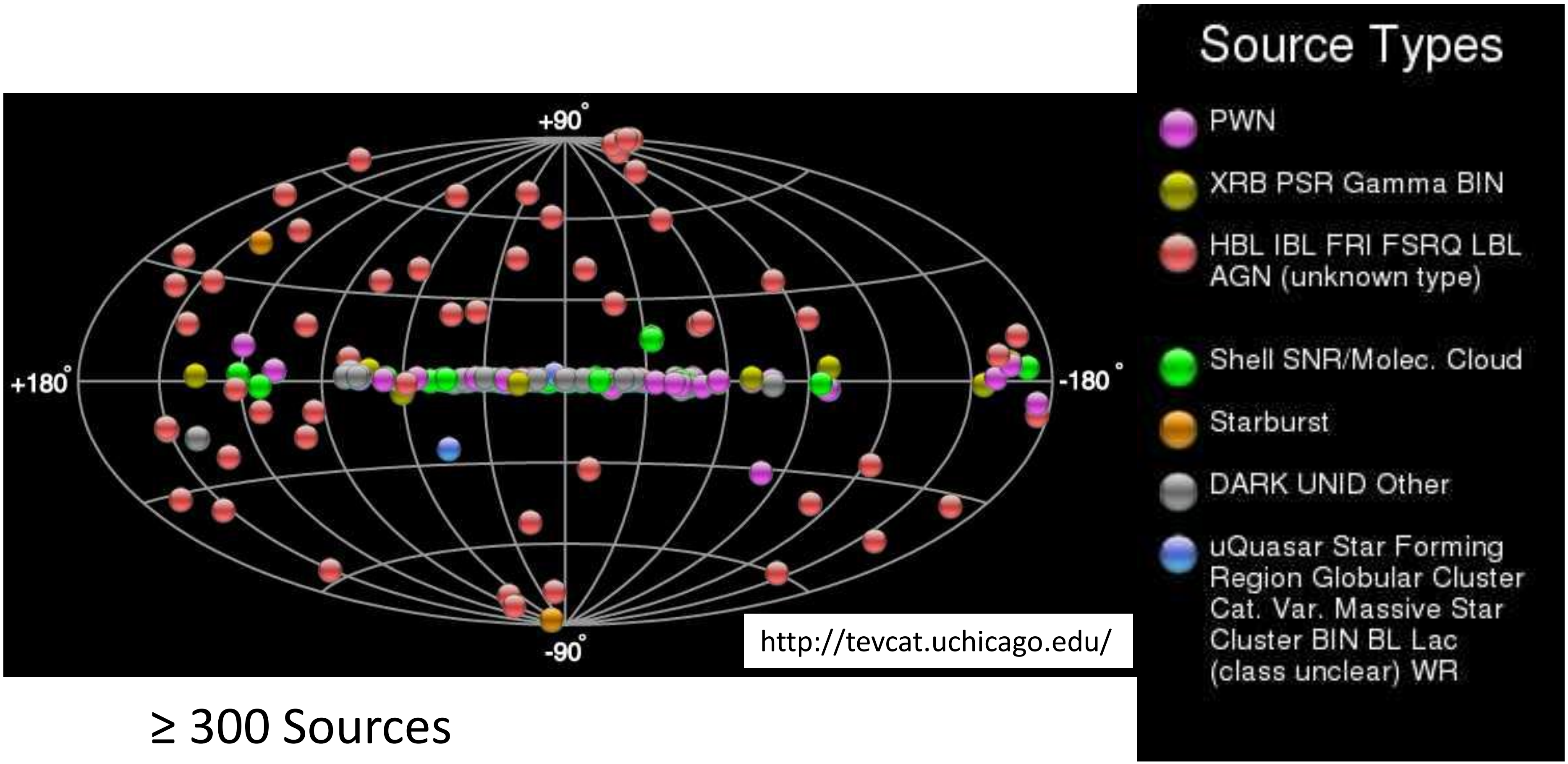
1912: Birthday of cosmic rays

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

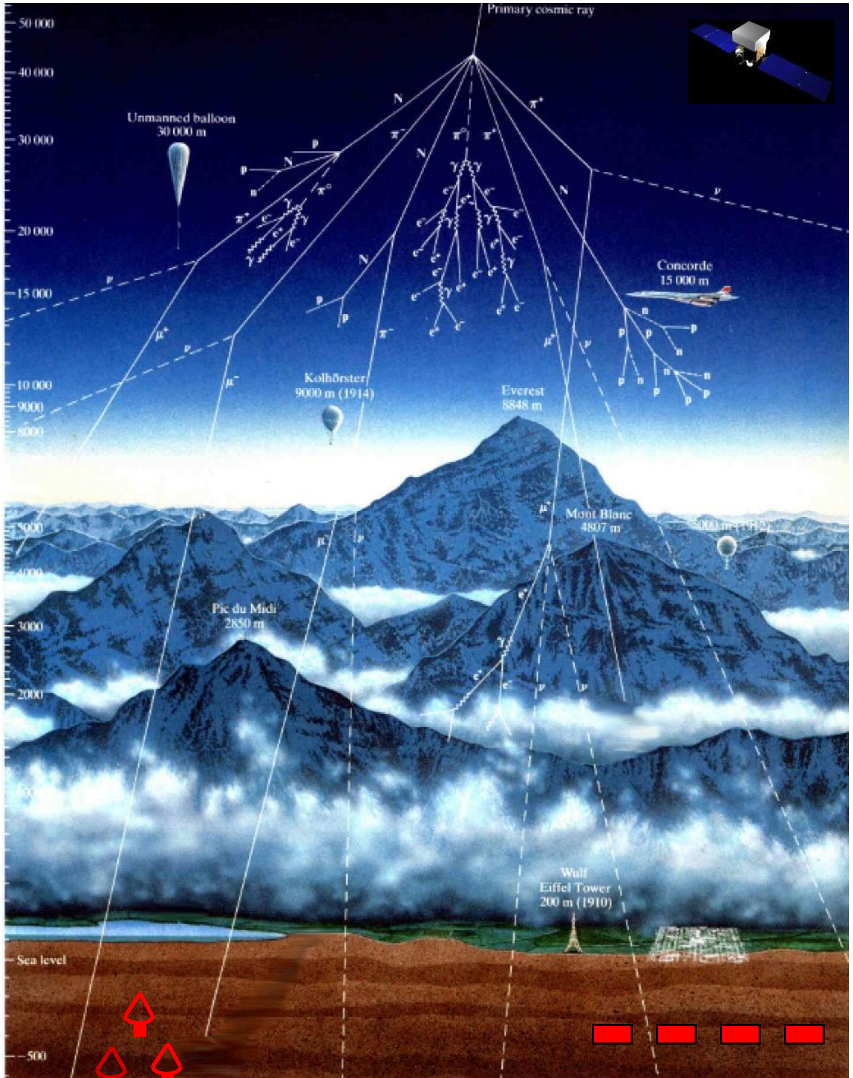


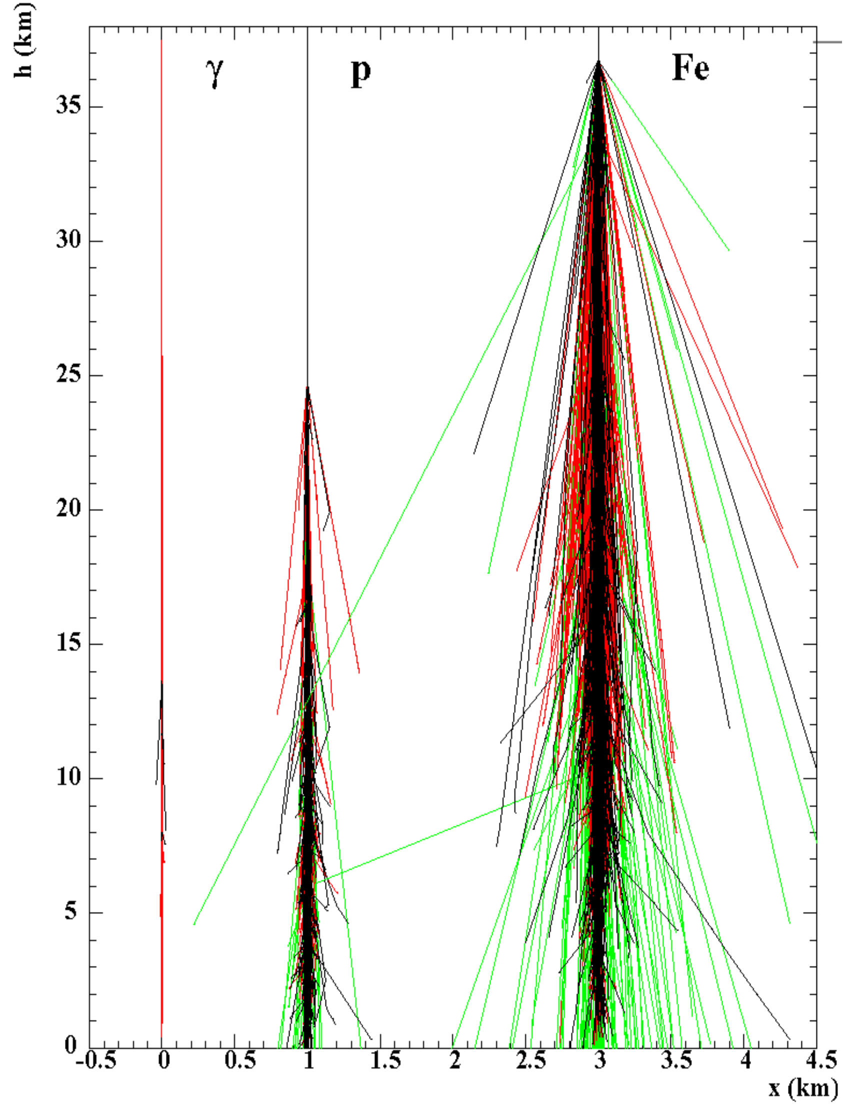
Today‘s VHE γ–ray Sources in the Sky



≥ 300 Sources

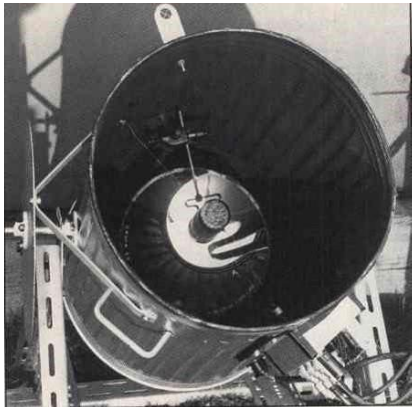
Extensive Air Showers





Important developments in ground-based γ-ray astronomy

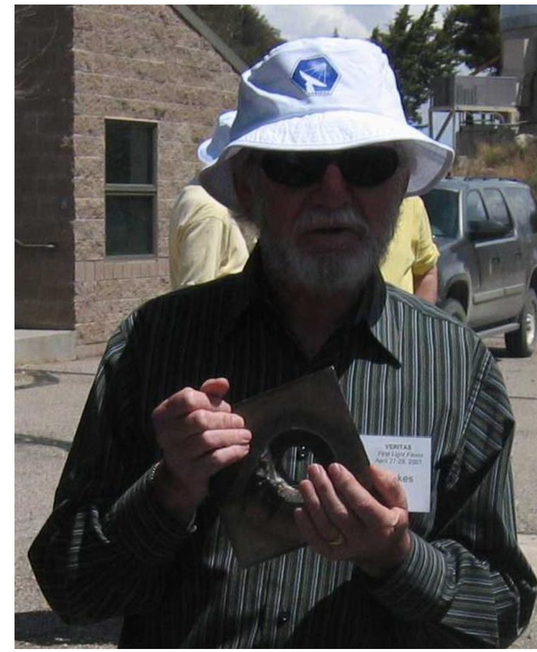
1952-1953 – discovery of Cherenkov pulses in atmosphere with a 0,25m ø mirror and a 2" PMT



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

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

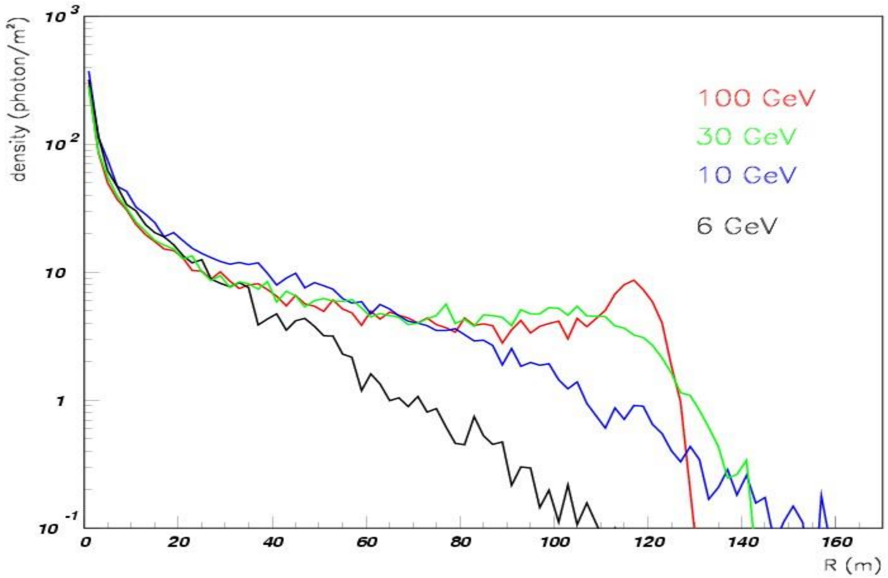
The Pioneer Trevor Weekes and his 10m Ø Whipple telescope gave birth to γ-ray astrophysics: 9σ from Crab Nebula in 1988 !

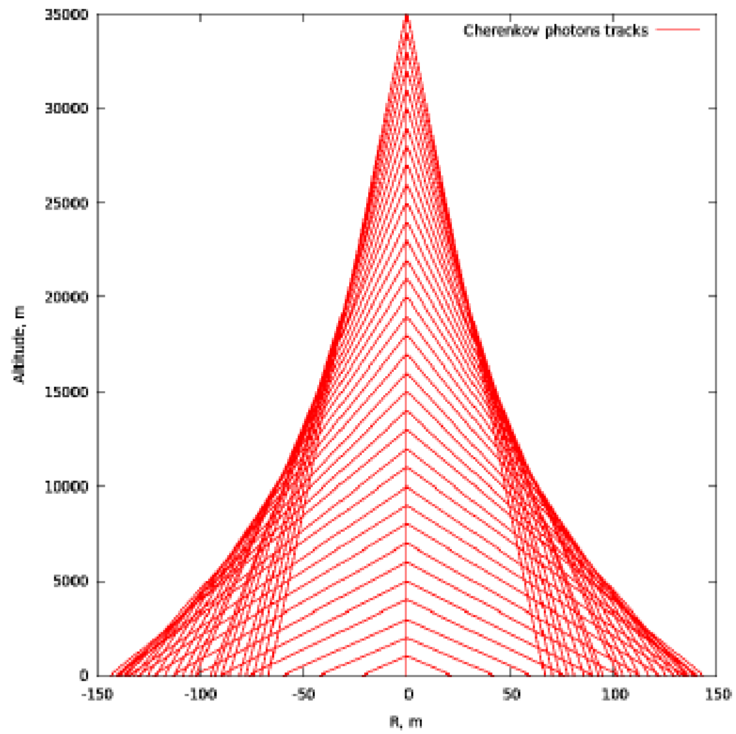


„If a telescope can within a few sec. evaporate a solid piece of steel, it can also measure gamma rays“
;-)

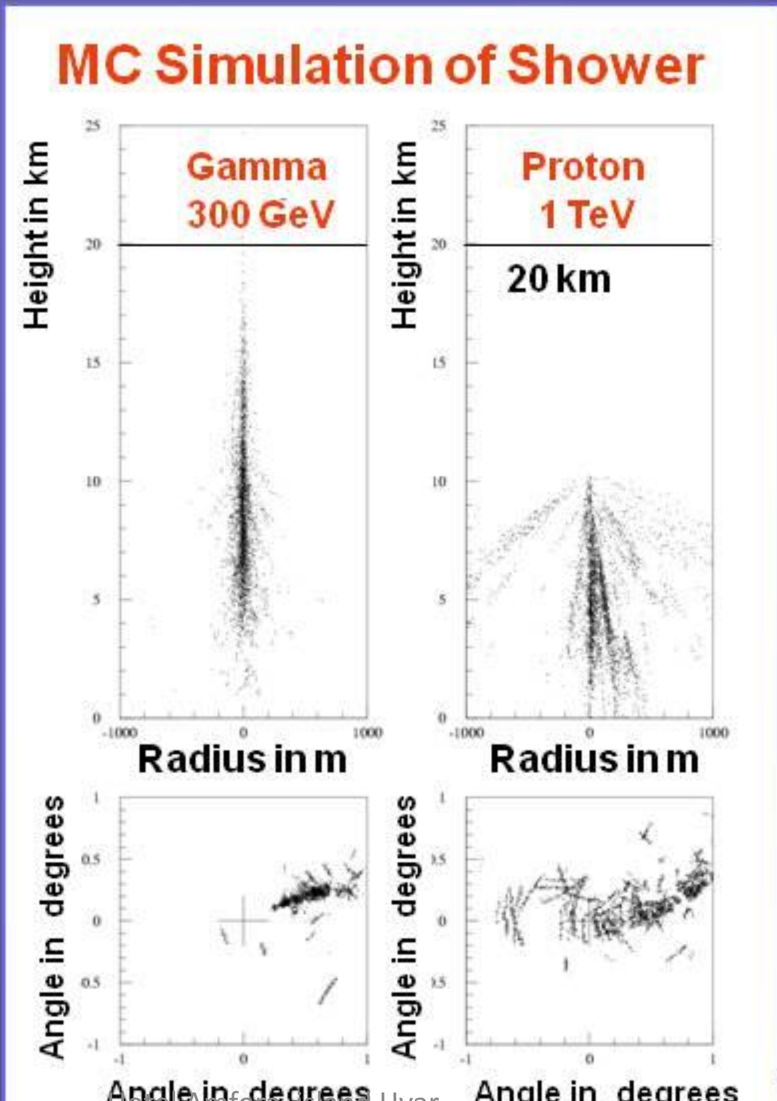
VERITAS, H.E.S.S., MAGIC and since recently, the 1st 23m Ø CTA/LST: at the frontier of VHE γ-astro-physics

Lateral distribution of Cherenkov light from a single muon

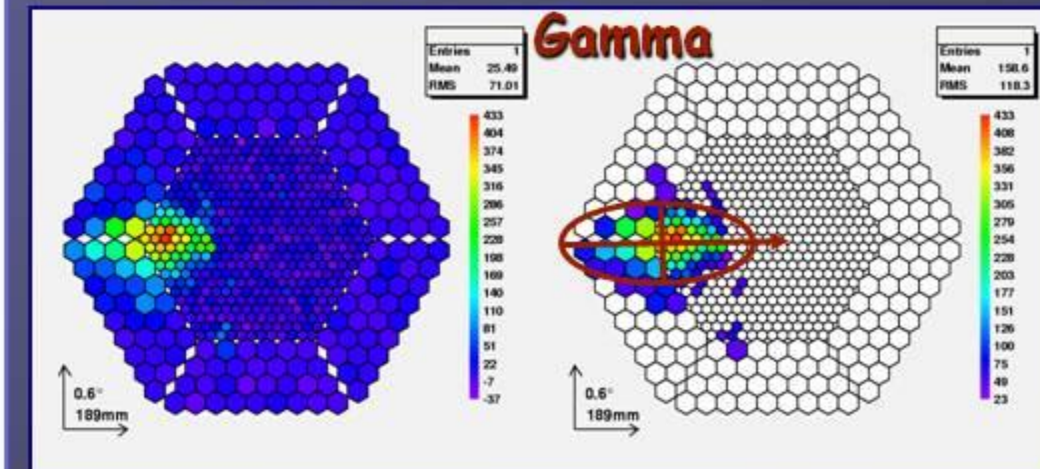


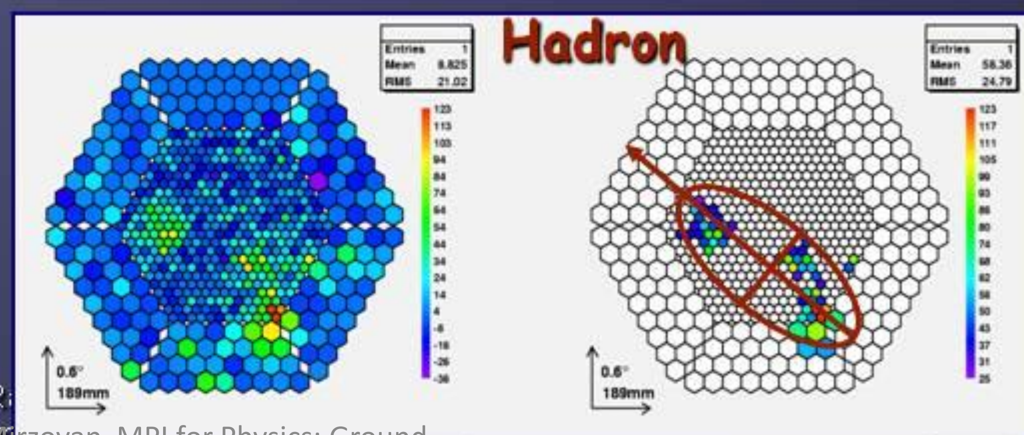


Gamma/Hadron separation

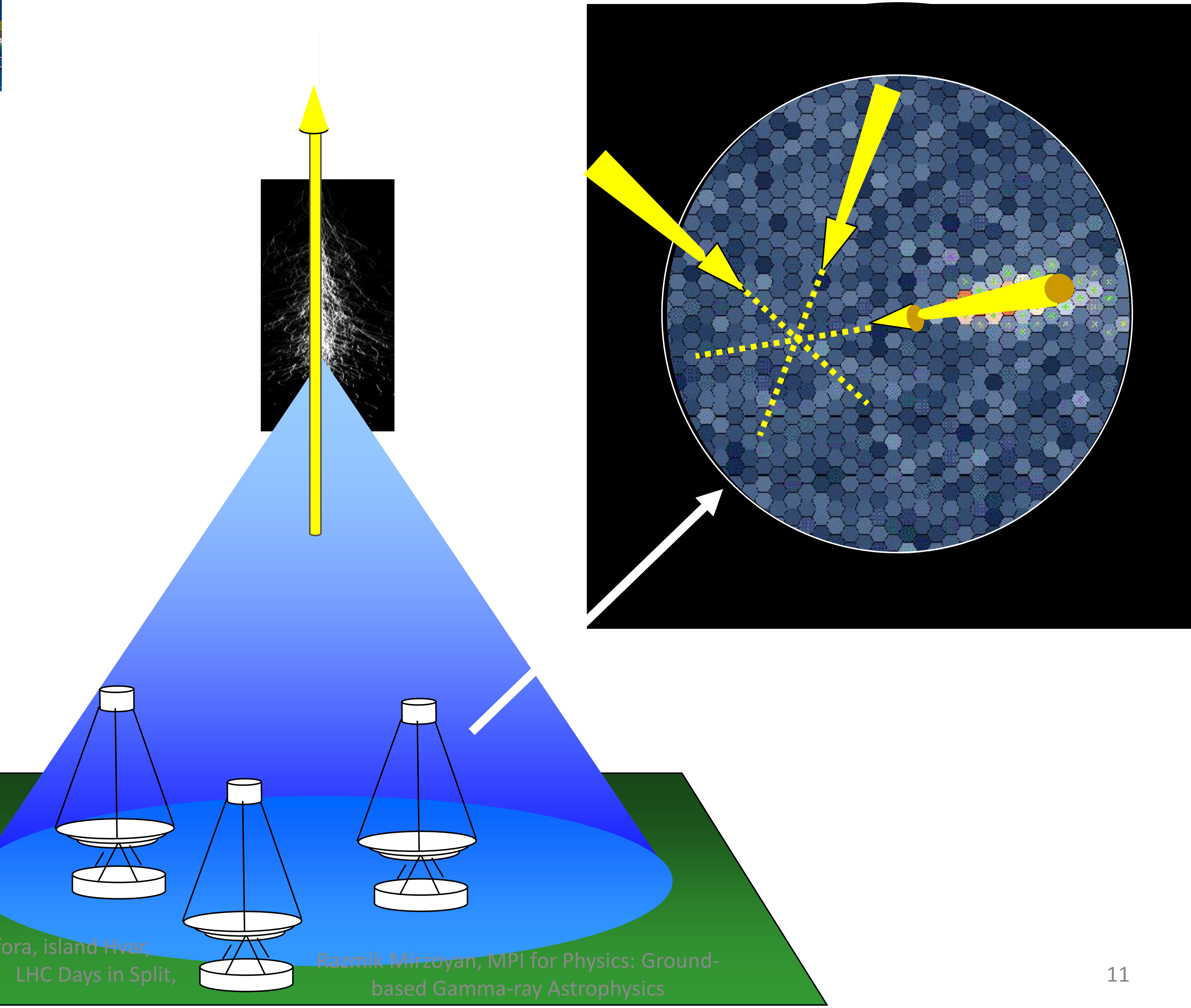


Hadron Rejection by Image Shape + Orientation ~ 99.9 %

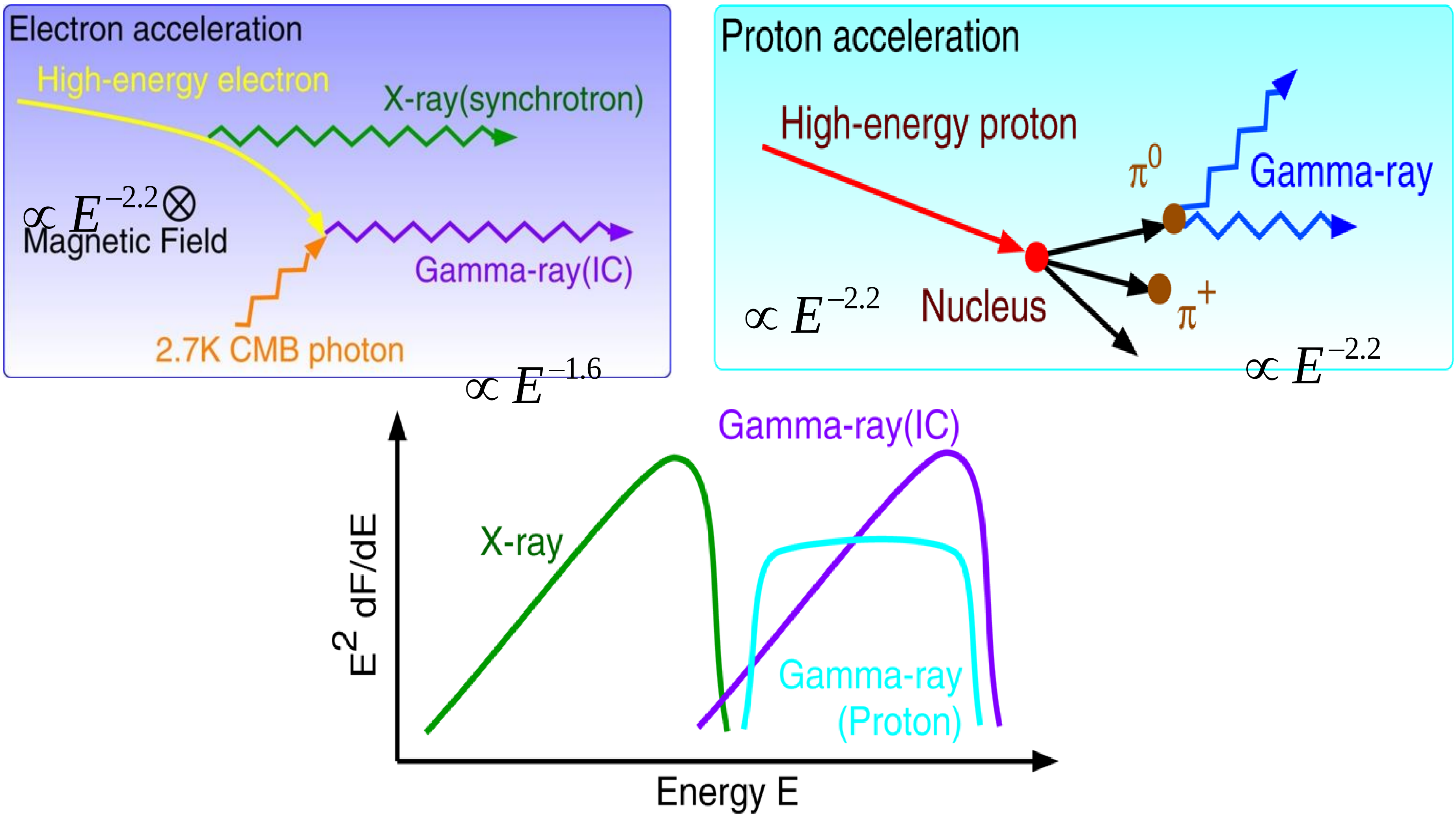




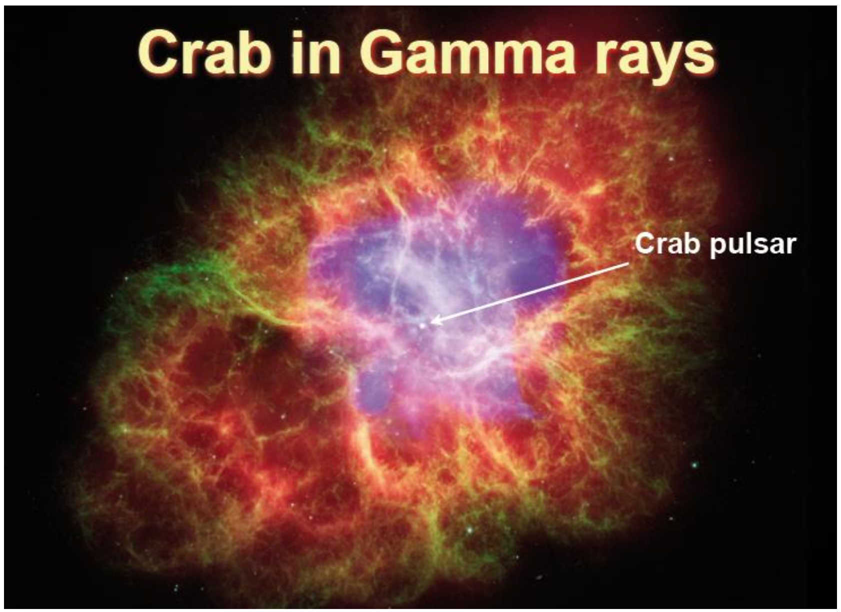

LHC Days in Split
30 September - 4 October 2024
Hotel Amfora, Hvar
Island of Hvar, Croatia



Gamma-Ray Emission Processes
Astrophysical process



Composite figure of the Crab Nebula



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

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

RESEARCH ARTICLE

Science **361, July 2018**

NEUTRINO ASTROPHYSICS

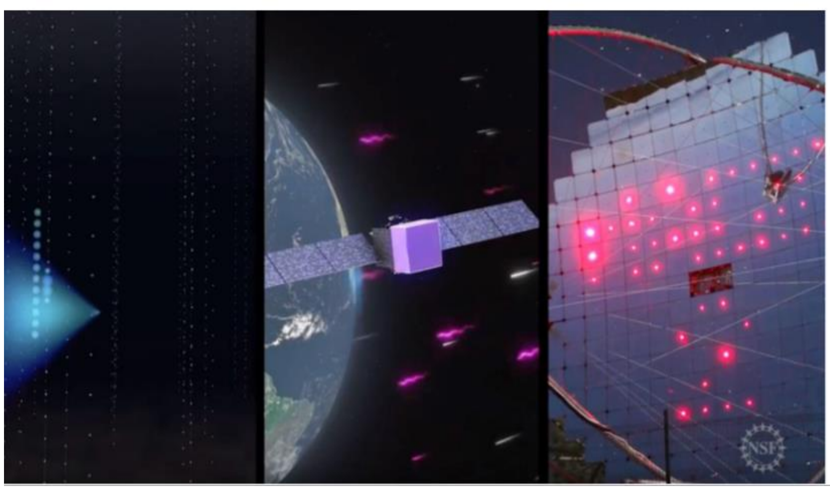
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

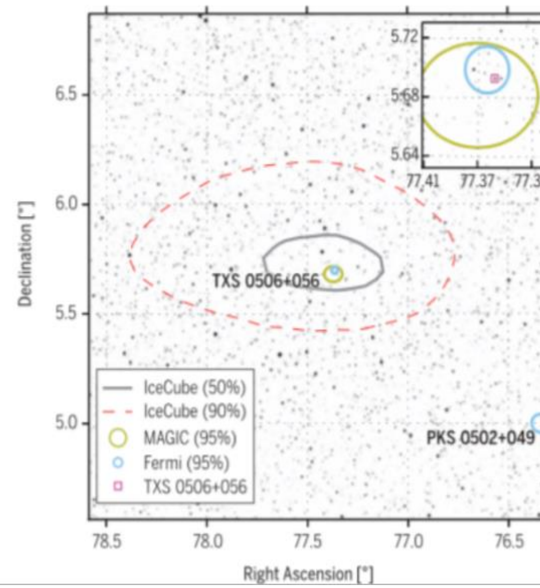
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

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 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



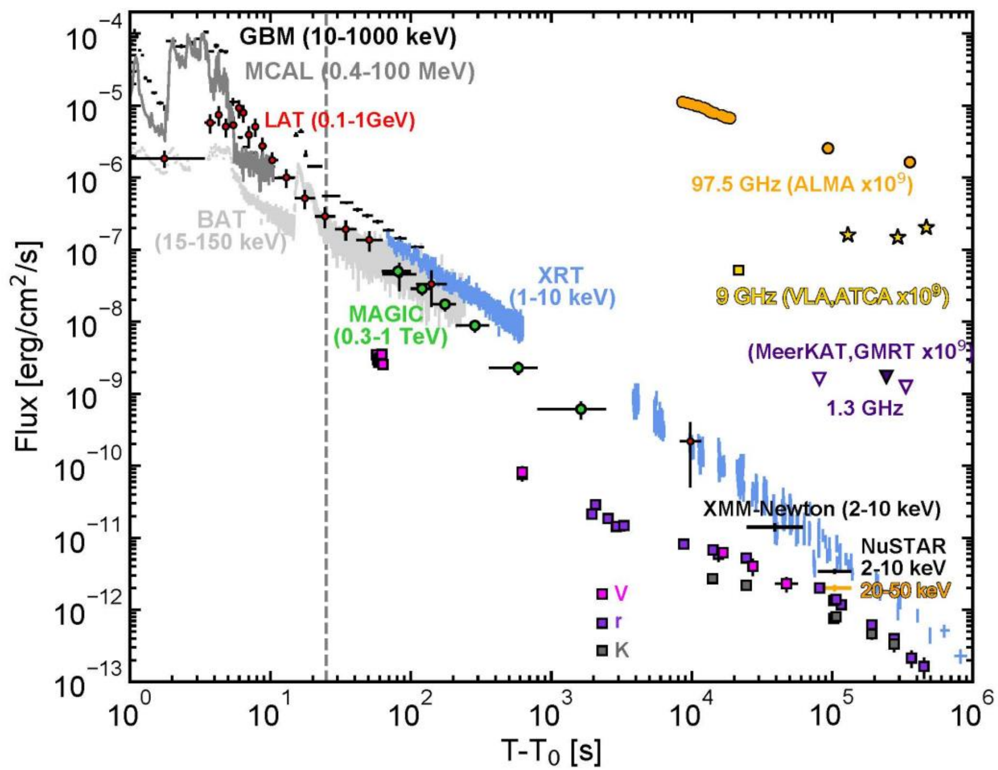


GRB190114C MWL light curves by 2 dozen space & ground-based instruments measured on 14.01.2019

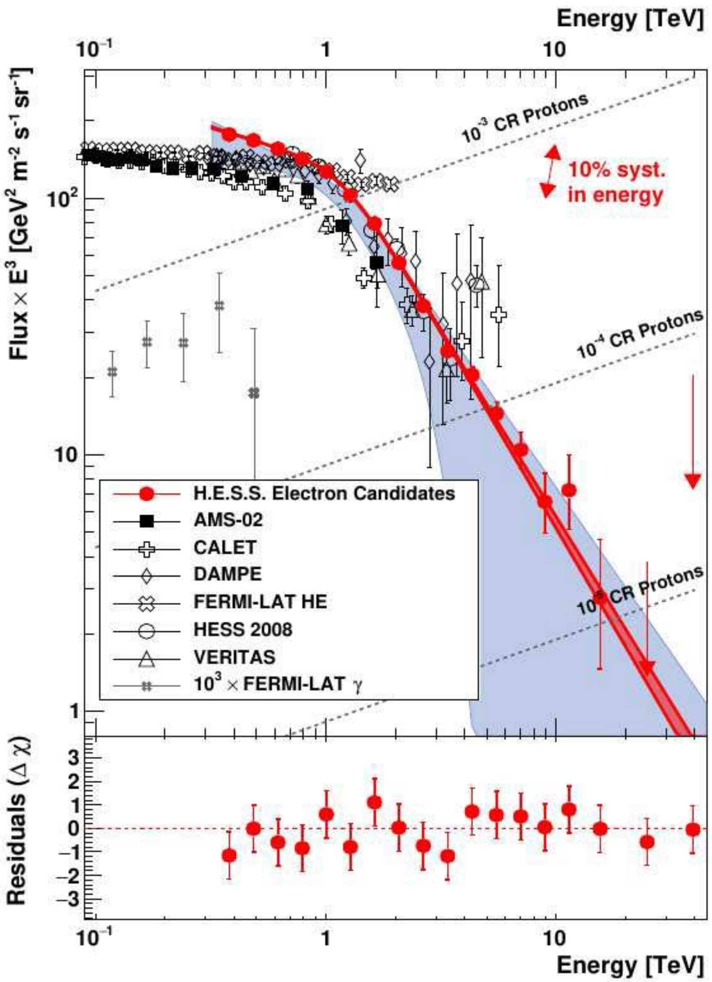
MAGIC published 2-papers in *Nature, in Nov. 2019*

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



e± 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.

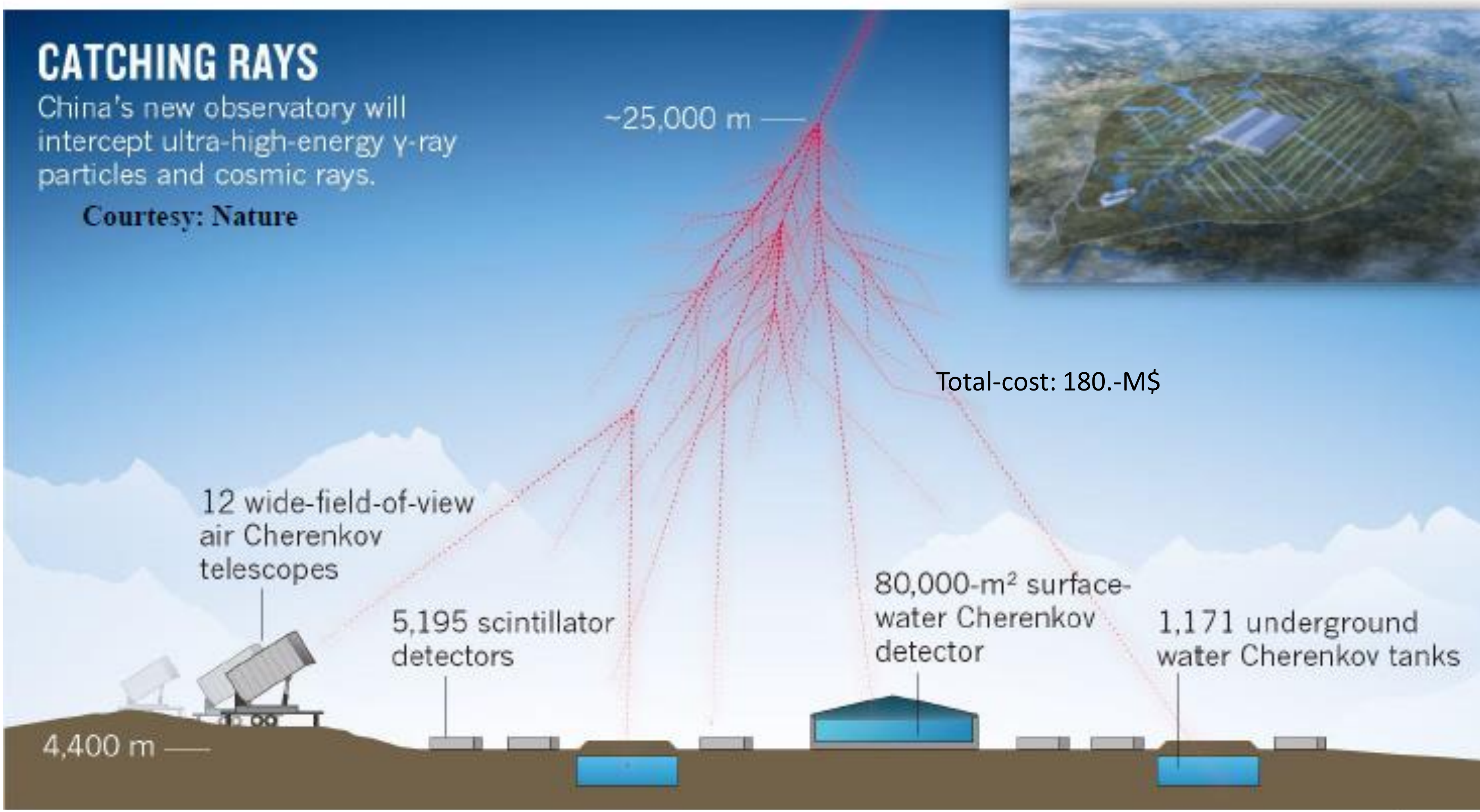
30% higher than other measurements

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

HAWC

Gamma-Ray signal from the Sun @ few TeV

Hybrid Detection of EASs by LHAASO

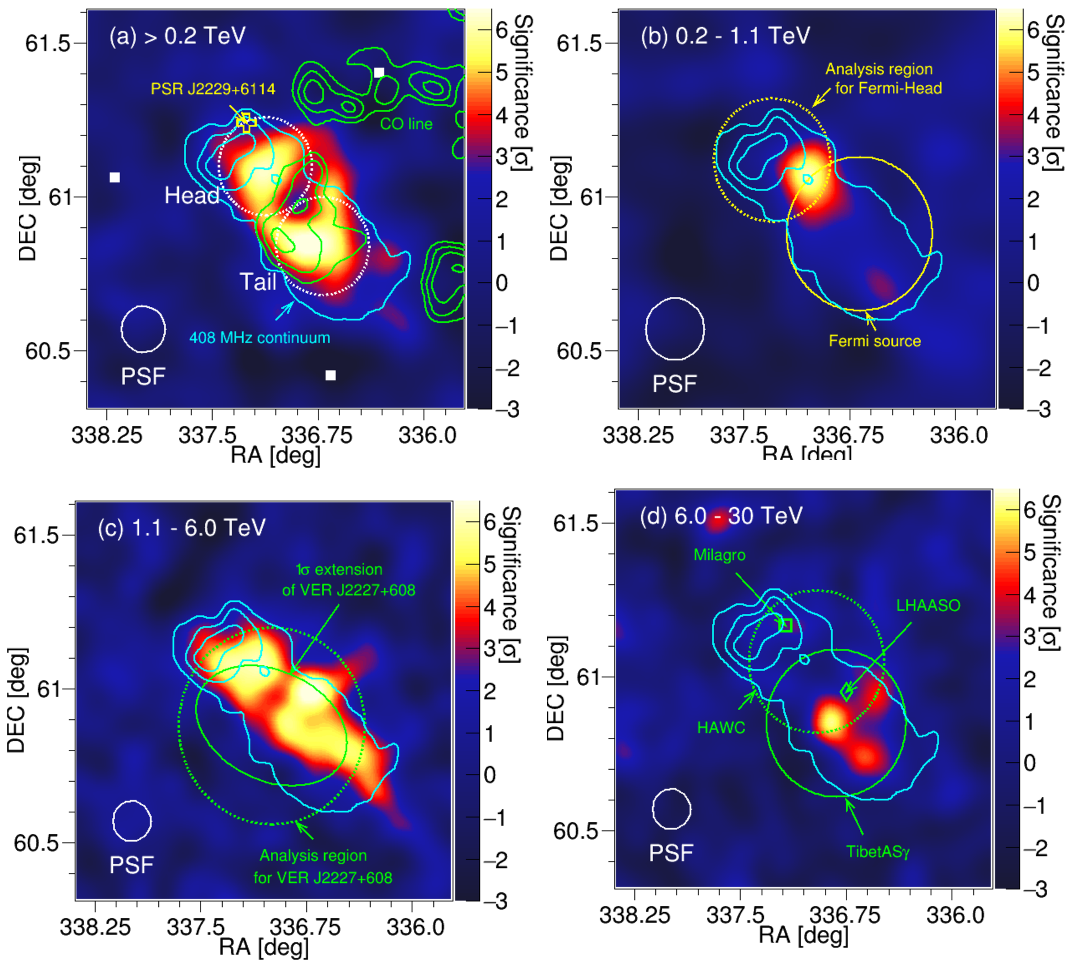


Total-cost: 180.-M$

LHAASO in China

Last couple of years LHAASO discovered several tens of PeVatrons

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.

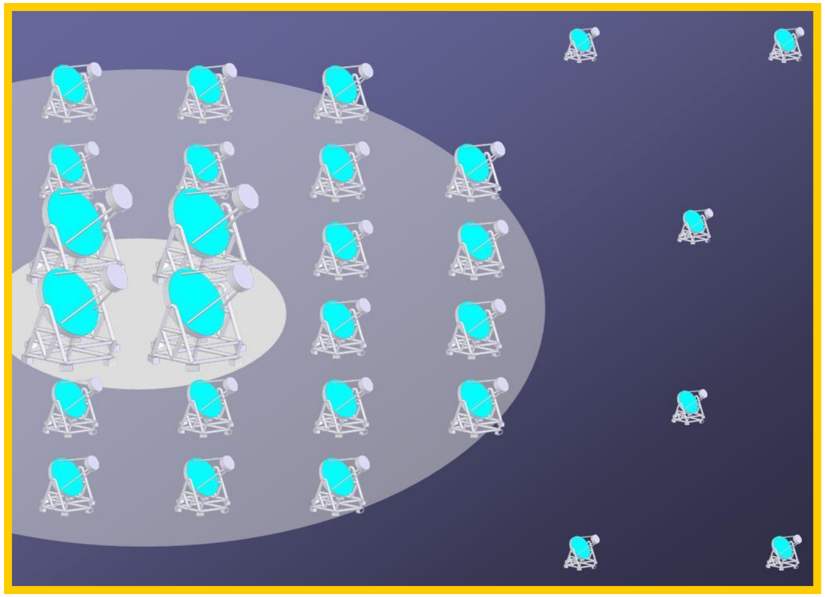
Next generation VHE γ ray Observatory CTA

MAGIC

HESS

>1500 scientists
>130 institutions

CTA



Astro-physicists from EU

JAPAN, US, India, Brazil, Mexico,….

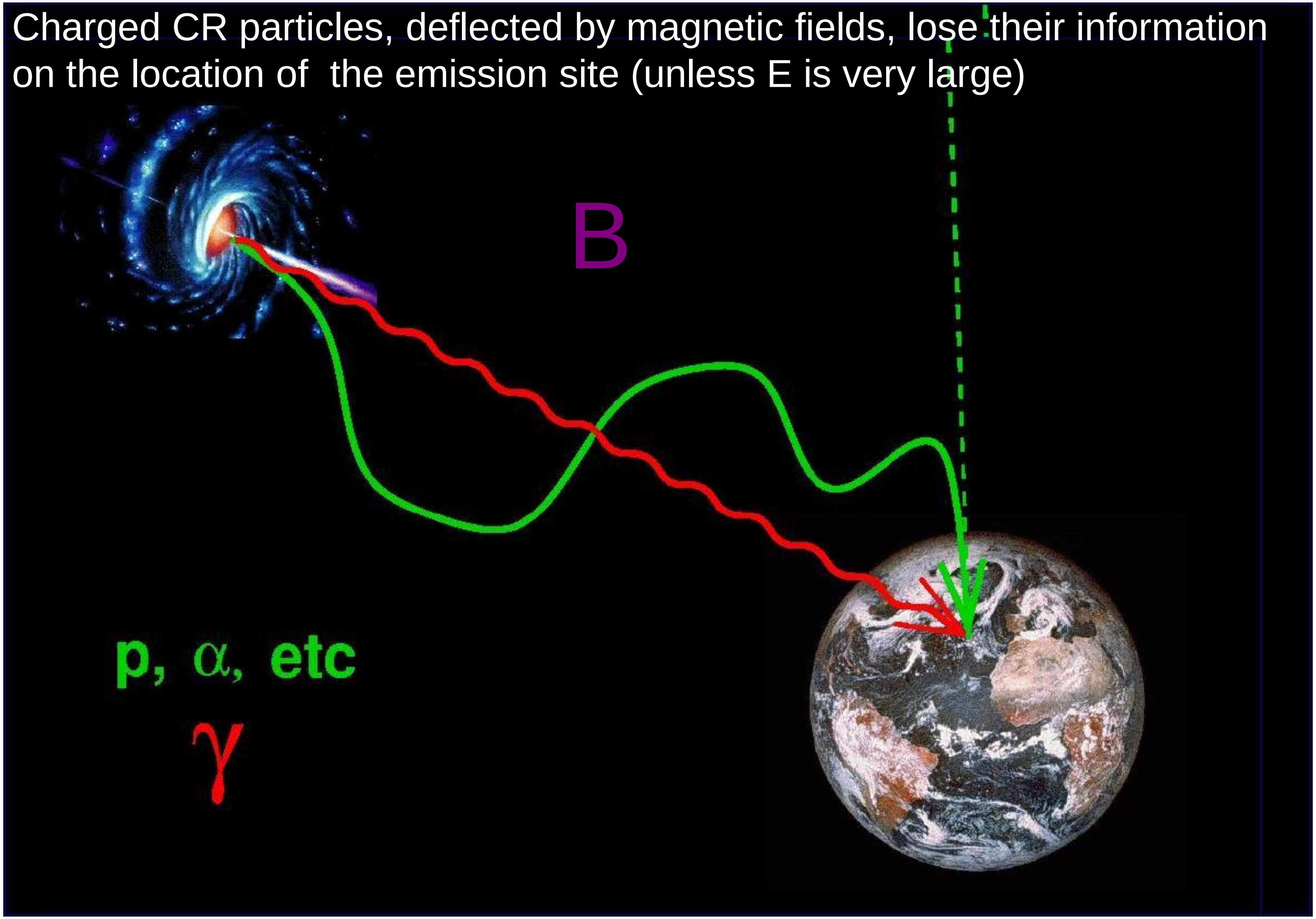
The 23m ø LST1 is taking data

Construction of 4 LSTS should be ready within 2 years

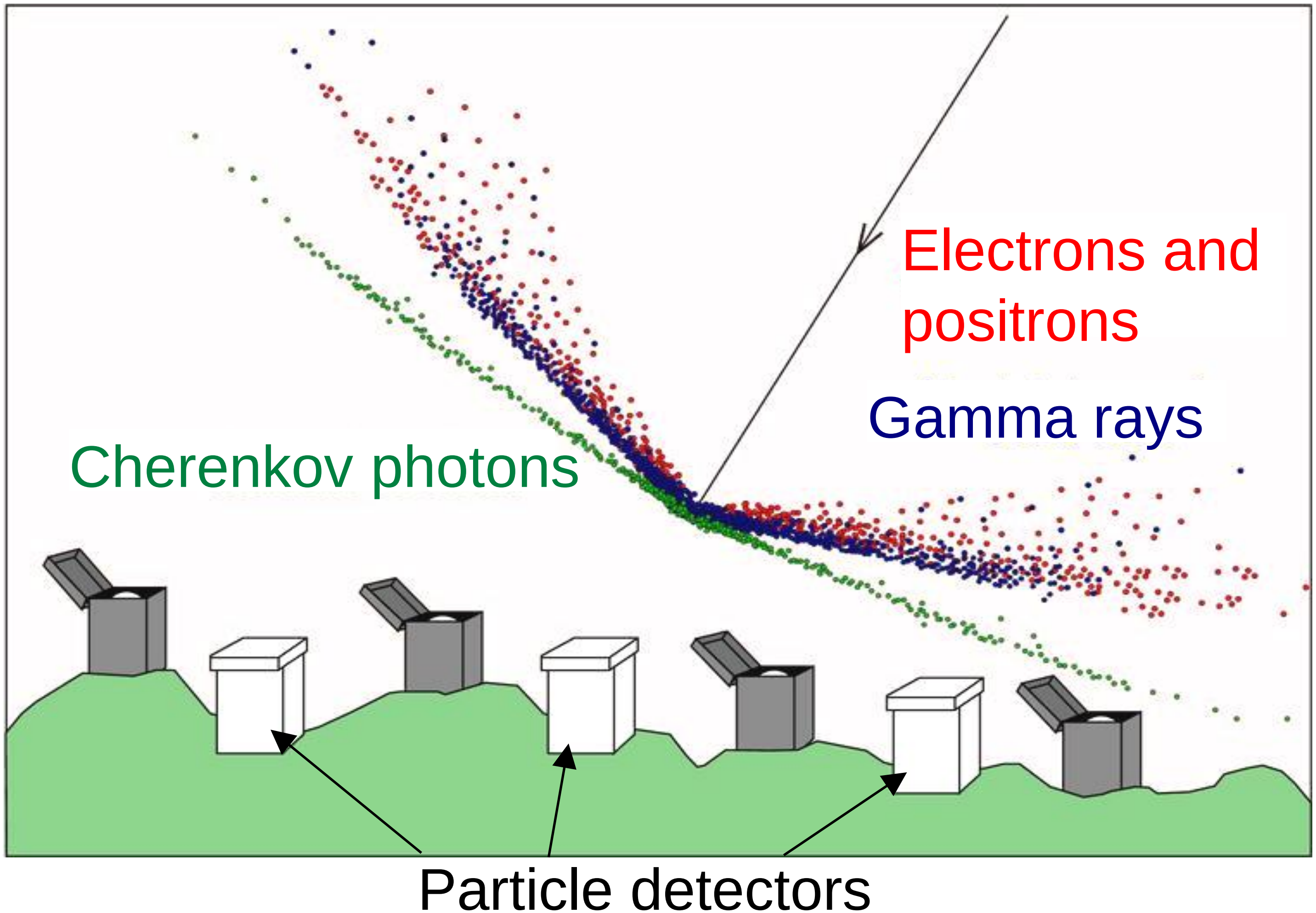
Conclusions

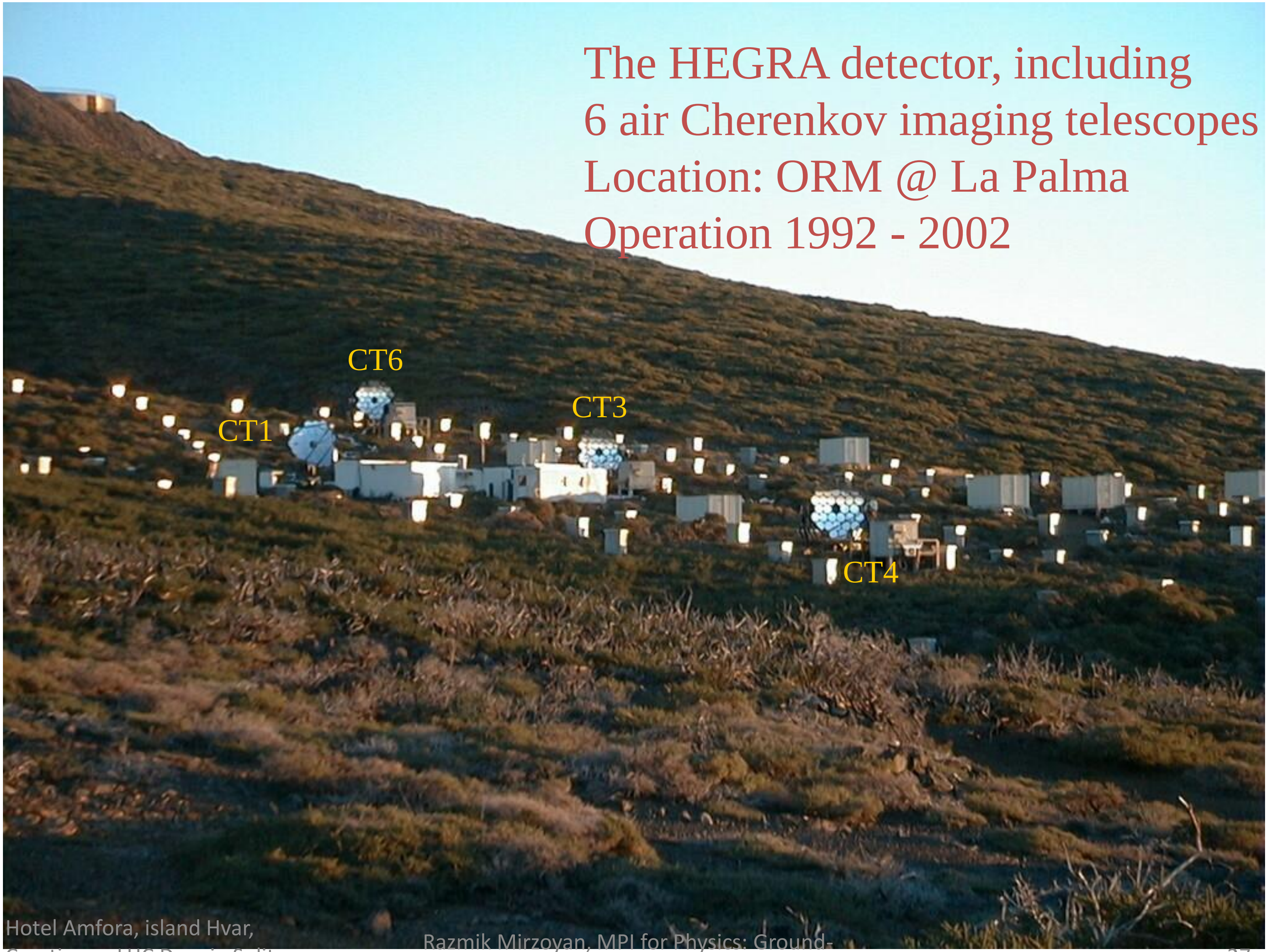
- Gamma-ray astrophysics provides the unique window to study the highest energy phenomena in the Universe
- The relatively recent addition of particle arrays such as HAWC, LHAASO (and in the near future SWGO) will allow to combine their very high sensitivity (~2000 hours of observation of a source in 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-IACT 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

Astronomy with Charged Cosmic Rays ?



Air Showers measured on the ground

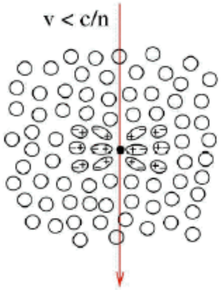



The HEGRA detector, including
6 air Cherenkov imaging telescopes
Location: ORM @ La Palma
Operation 1992 - 2002
CT6
CT3
CT1
CT4

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 ≥ 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 ≥ 25 GeV, SCIENCE,2008)

Cherenkov Effect

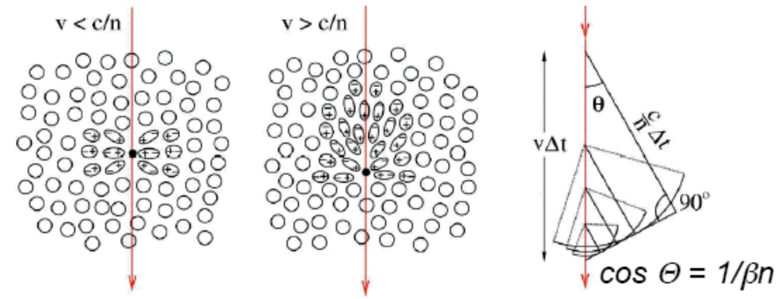


Medium, refractive index n

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

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

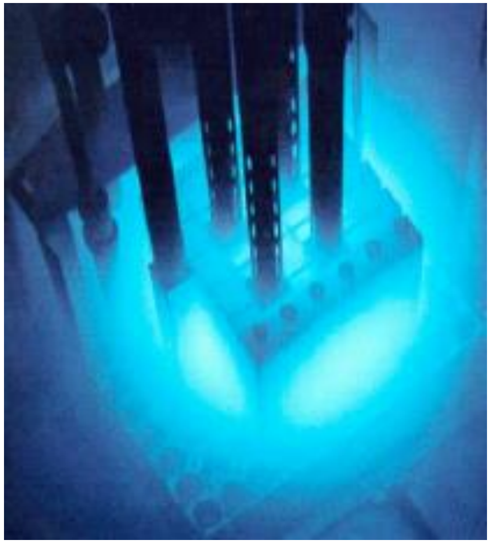
Cherenkov Effect



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

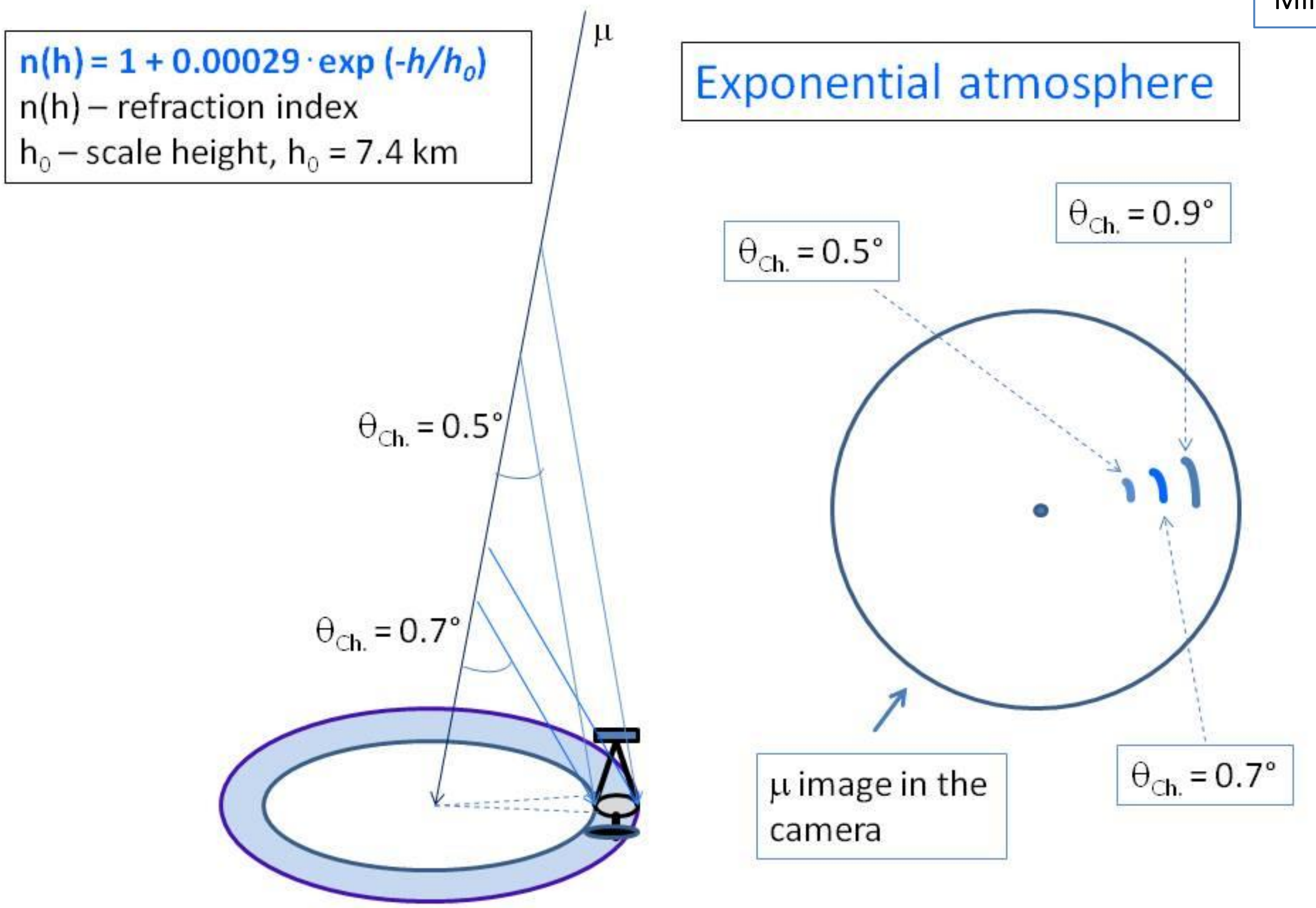
v > c/n
==> radiation from different points along the trajectory arrive in phase within narrow light-cone at the observer ==> bright light

- 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



CASA-MIA (and link to LHAASO)

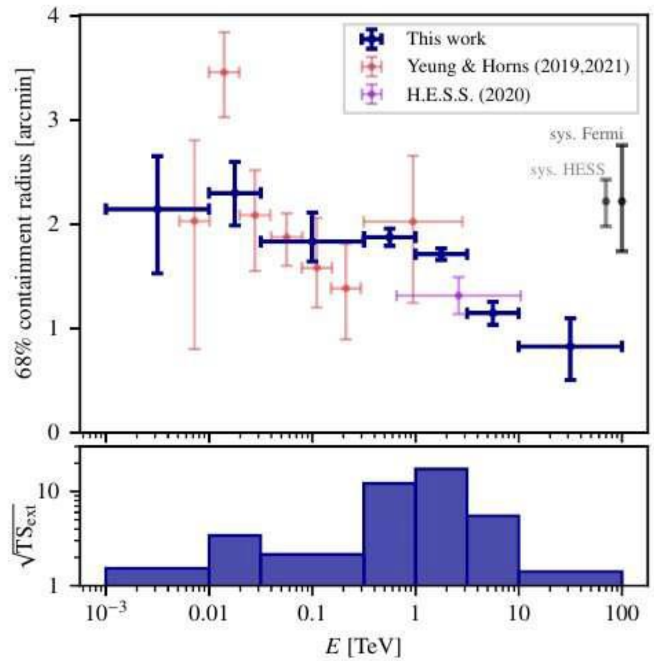
- The **CASA-MIA** array was located at Dugway, Utah, USA, at 1450m a.s.l.
- It consisted of 2 major components:
  - the Chicago Air Shower Array (**CASA**), 1089 scintillation detectors placed on a 15 m square grid and **covering an area of 0.23 km²**, and
  - the Michigan Array (**MIA**), a buried 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, which prevented them to discover PeVatrons already ~30 years ago.

LHAASO increased the total area 4-fold and increased the relative share of muon detectors to 4%. And that had a magnificent effect; **LHAASO** discovered several **dozens of PeVatrons**

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

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



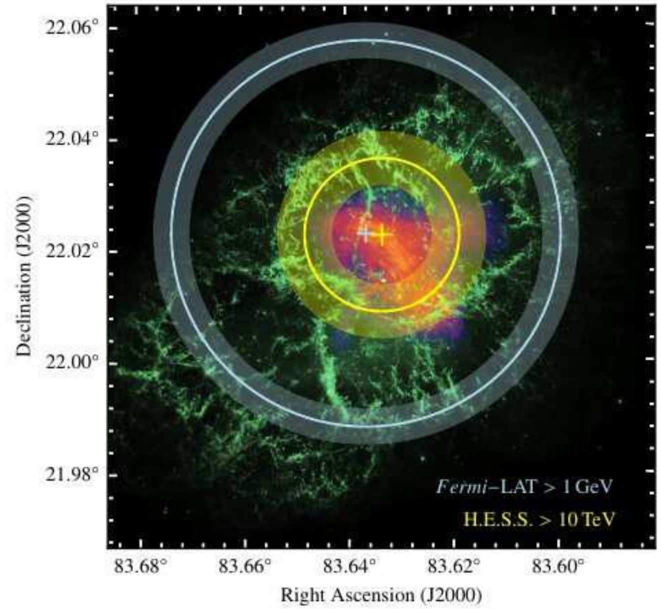


Fig. 7. Optical image of the Crab Nebula in green (credit: NAS