Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Journal Club - June 1 2022

https://www.nature.com/articles/s41586-021-03498-z

LHAASO

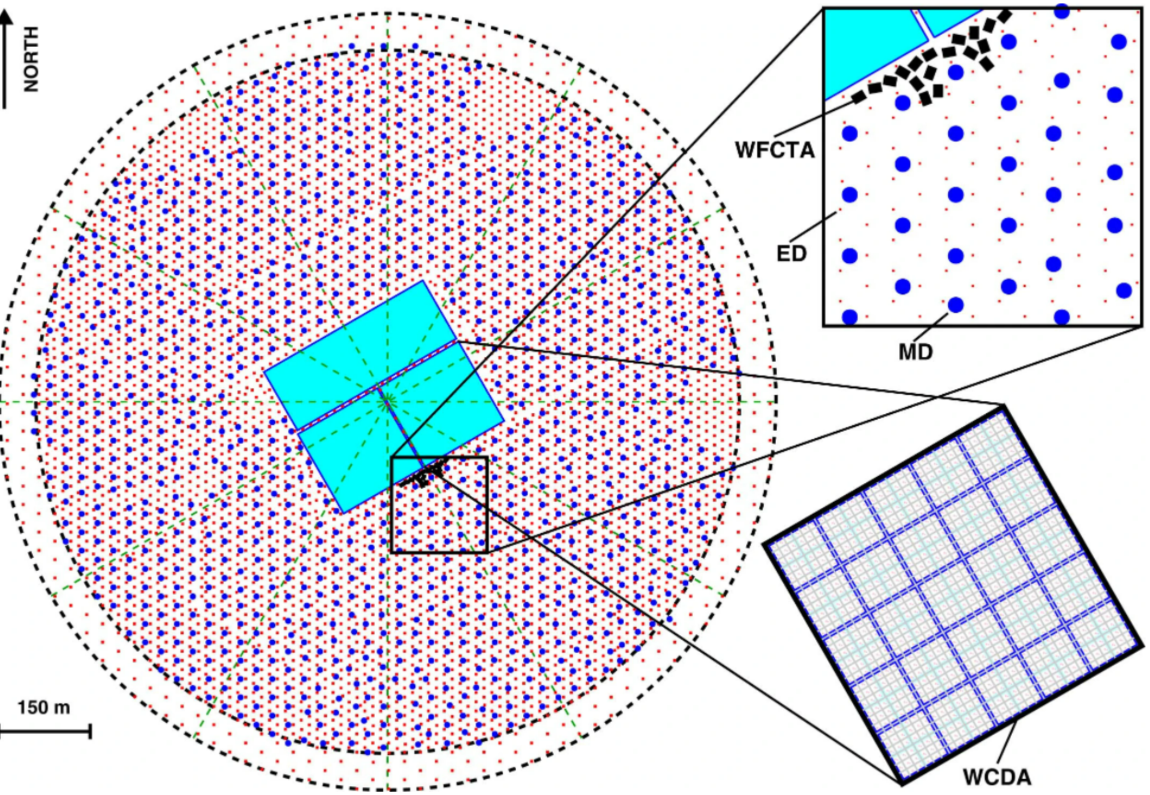


Fig. 1: Schematic drawing of the LHAASO layout

- The Large High Altitude Air Shower Observatory (LHAASO) is a dual-purpose complex of particle detectors designed for the study of cosmic rays (CRs) and γ-rays in the sub-TeV to 1000 PeV energy range.
- The vast area of the surface detectors, coupled with the high γ–proton separation efficiency, results in a sensitivity of the full array ($E2dN/dE$, where E is the particle energy and N is the number of particles), that approaches 10^{-14} erg cm^{-2} s^{-1}, which is substantially below the flux sensitivities of other current and planned space-borne and ground-based γ-ray detectors.

- LHAASO consists of three arrays:

The largest is the square kilometer array (KM2A), composed by surface counters and subsurface muon detectors. KM2A is designed to detect *CRs* from 10 TeV to 100 PeV and identify γ-ray photons among the *CRs* using the muon detector array. The muon content in an air shower event can be used to effectively reject hadronic showers initiated by *CRs*. Thus, KM2A serves as an Ultra High Energy (UHE, $E_\gamma > 0.1$ PeV) γ-ray telescope with energy resolution of $\leq 20\%$ and an angular resolution of $0.25°$.

The Water Cherenkov Detector Array (WCDA) consists of three ponds with total area of 0.08 km^2 , sensitive to γ-rays down to 0.1 TeV with an angular resolution ≈ 0.2 °. WCDA is designed to perform deep surveys of very high energy γ-ray sources for both pulsed and unpulsed signals. The sensitivity reaches the flux level of 10^{-12} erg cm^{-2} s^{-1} at energies above 2 TeV. At energies above 0.1 PeV, WCDA also serves as a large muon detector to enhance the capability of separation between electromagnetic and hadronic showers detected by

KM2A and WCDA are complemented by the Wide-Field-of-view Cherenkov Telescope Array (WFCTA), consisting of 18 telescopes designed for detection of the Cherenkov radiation emitted by air showers induced by *CRs* with energy ranging from 0.1 to 1000 PeV. Cherenkov light in showers initiated by γ-rays at energies above 0.1 PeV is recorded by the currently operating fourteen WFCTA telescopes which cover a 32° × 112°

- The analysis of showers detected in less than one year of operation, has revealed many hot spots as clusters of γ-rays. The article reports 12 γ-ray sources with energies ≥ 100 TeV detected with statistical significance $\geq 7\sigma$. Out of all of them, the most energetic photon had an energy of 1.4 PeV.
- Above 100 TeV, the spectra of these sources are steep, characterized by a power-law photon index of $\Gamma \approx 3$. Between 10 TeV and 500 TeV, the spectra experience gradual steepening with energy. To explore this tendency, the spectra were fitted by the log-parabola function $dN/dE \propto E^{-\Gamma(E)}$, where the local photon index $\Gamma(E) = a + b \log E$ characterizes the slope of the tangent.
- The gradual steepening of γ-rays in the range of ~ 100 TeV is partly due to the γ-γ absorption that occurs during their interactions with the diffuse far-infrared and microwave radiation fields. However, for all sources, the effect of absorption appears to be small, even at the highest energies.

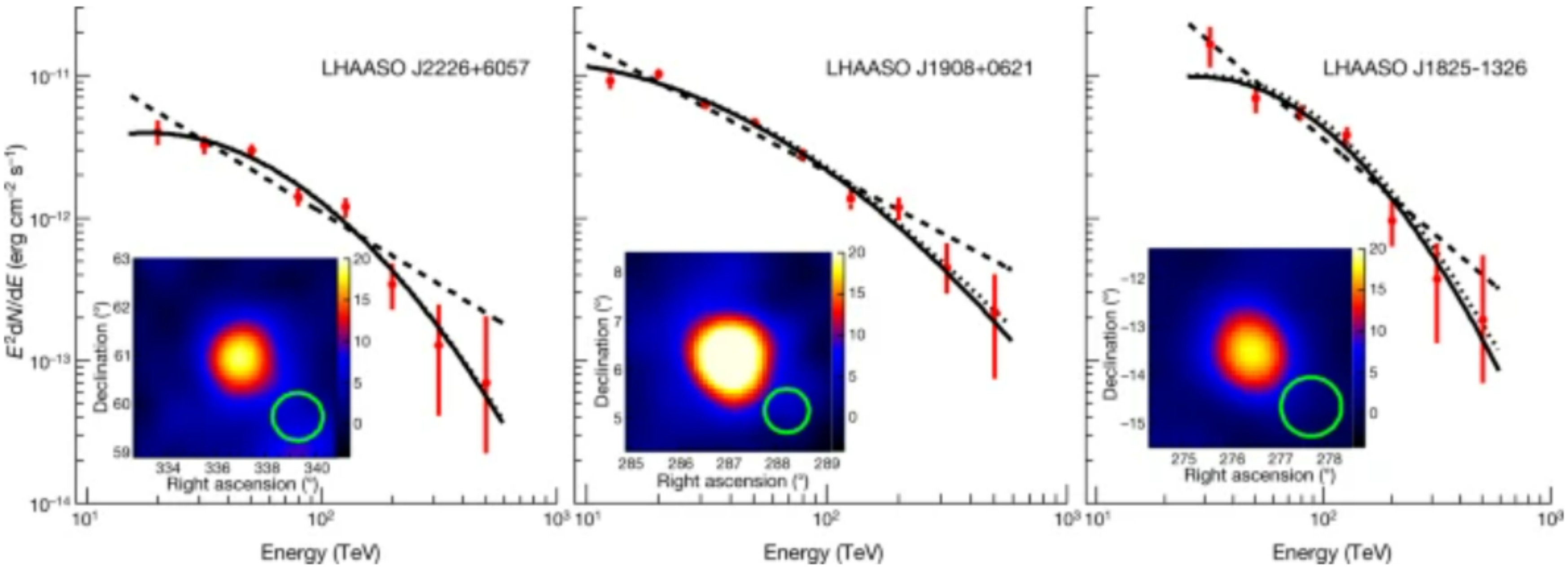


Fig. 2: Spectral energy distributions and significance maps.

- In the vicinity of the extended UHE sources, one can find potential counterparts for both the γ-ray production regions and the nearby particle accelerators
- The only firmly identified source out of the 12 is the Crab Nebula, a representative of pulsar wind nebulae
- The size of a pulsar wind nebula is determined by the region in which electrons advect with the nebular flow. Typically, it varies between a few to 10 parsecs. These hydrodynamical formations are enveloped by larger and more regular structures consisting of relativistic electrons and positrons that have already left the nebula and propagate diffusively in the interstellar medium. The spectrum of γ-rays depend on the character of propagation of electrons → it can be used to measure the diffusion coefficient in the interstellar medium.

The spectrum

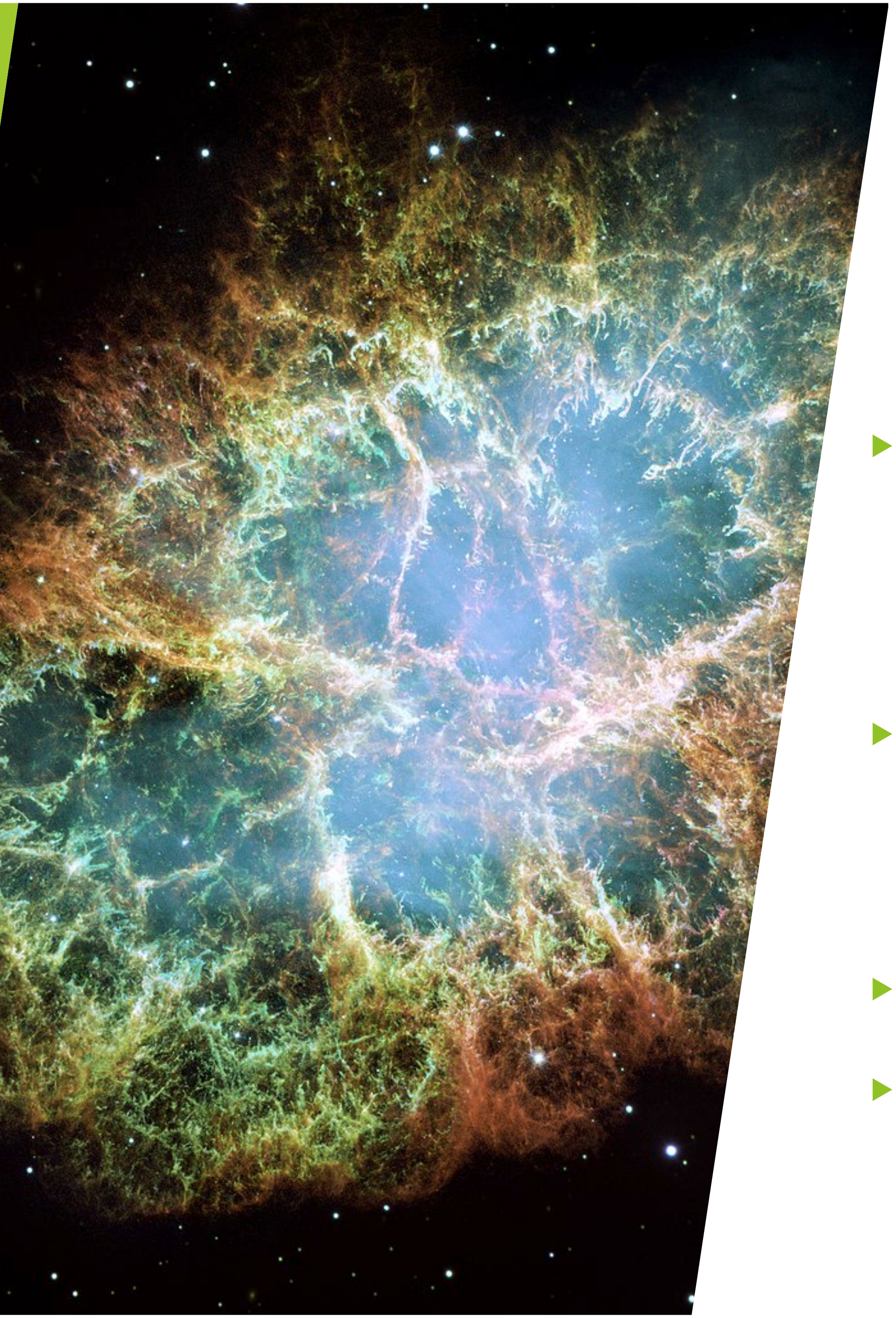
- The γ-ray spectral points with energies from GeV to several hundred TeV could be explained by a power-law spectrum of accelerated electrons. Although acceleration at the wind termination shock could, in principle, boost the energy of electrons to 1 PeV, their escape from the acceleration site and further propagation over distances of tens of parsecs is a challenge.
- Alternatively, UHE γ-rays can be explained by interactions of protons with the ambient gas through the production and decay of $\pi 0$. If the reported fluxes at GeV and TeV energies are linked to the UHE source, it is difficult to fit the spectral points in the entire GeV–PeV energy range of γ-rays using a simple power law with an exponential cutoff. The production of hadronic UHE γ-rays can be realized in a scenario in which the accelerated particles have left their acceleration site and have entered nearby high-density clouds.
- The energy spectrum of protons approaching the clouds depends not only on the initial spectrum but also on the propagation timescales of *CRs* and on the distances to the clouds. Therefore, one may expect unusual energy distributions of *CRs* inside the clouds. In this scenario, a supernova remnant could play the role of the particle accelerator

PeVatron candidates

- Although supernova remnants remain prime candidates as suppliers of Galactic CRs, massive stars with powerful winds have been proposed as a viable alternative.
- A preference for young massive star clusters as proton PeVatrons over supernova remnants has recently been argued in the context of the $1/r$-type spatial distributions of parent protons, derived from the observations of extended TeV γ-ray sources associated with luminous stellar clusters.
- The positional coincidence of LHAASO J2032+4102 with the Cygnus Cocoon that surrounds Cygnus OB2, and with photons exceeding 1 PeV emitted from it, can be treated as evidence of the operation of massive stars as hadronic PeVatrons.
- Regardless of the nature of objects associated with the UHE sources, the photons detected by LHAASO far beyond 100 TeV prove the existence of Galactic PeVatrons.

PeV γ-rays from Crab Nebula

https://arxiv.org/abs/2111.06545



Crab Nebula

- The Crab Nebula is a remnant of the explosion of a massive star, formed on Aug 24, 1054 A.D. It is the brightest pulsar wind nebula, an extended nonthermal structure powered by the ultrarelativistic electron-positron wind from the central neutron star (the Crab Pulsar).
- The Crab Nebula is one of the brightest γ-ray sources in the sky, which has been observed for decades at TeV energies. At the transition from GeV to TeV energies, the spectral energy distribution (SED) achieves a maximum around 100 GeV.
- The angular size of the γ-ray source at TeV energies has been reported $\approx$ 50 arcsec.
- The Crab Nebula was among the first sources detected at energies well beyond 100 TeV using LHAASO.

Observations of the Crab

▶On 2020 January 11 at 17:59:18 Coordinated Universal Time (UTC), a giant air shower was recorded by all three LHAASO detectors. The shower arrived from the direction of Crab.

▶The event was identified as a γ-ray induced shower. The chance probability of this event to be misidentified is estimated as 0.1%. Two independent estimates of the shower energy from the KM2A and WFCTA data gave 0.88 ± 0.11 PeV and $0.92_{-0.20}^{+0.28}$ PeV, respectively.

▶On 2021 January 4 at 16:45:06, another shower at even higher energy, i.e. 1.12 ± 0.09 PeV, was registered by KM2A at zenith angle $12.9°$:

- ▶more vertically arrived and better measured by KM2A.
- ▶but the primary photon arrived one hour before the Crab entered the FoV of the WFCTA telescopes.

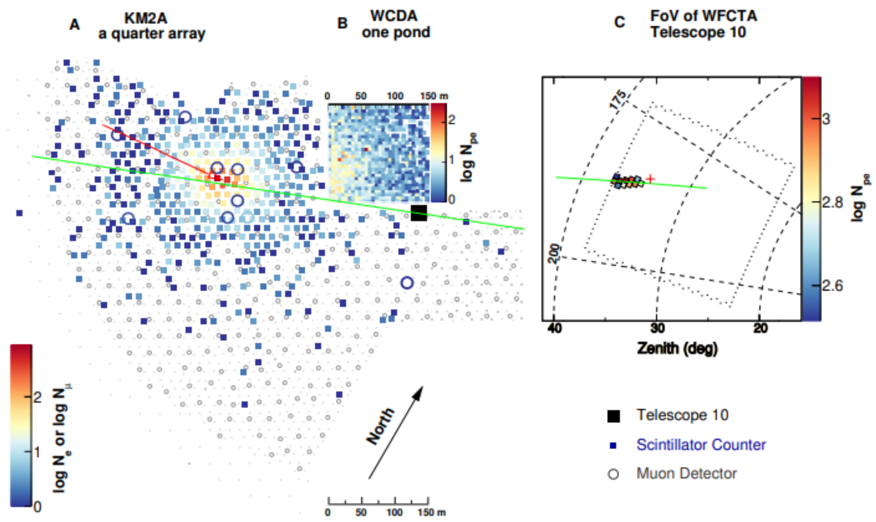


Fig. 3: The 0.88 PeV γ-ray event from the Crab recorded by the LHAASO detectors

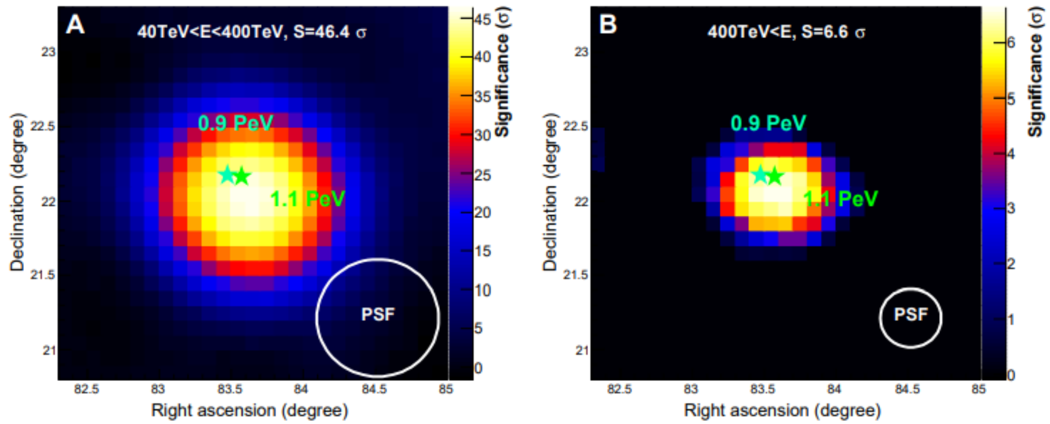


Fig. 4: Significance maps of the Crab Nebula

During the 401 days KM2A operated, a total of 89 UHE γ-rays with energy exceeding 0.1 PeV were detected from the Crab.

Above 0.1 PeV, about 0.05 events per hour, equivalent to 135 events per year.

The 'muon cut' filter: number of muons detected by KM2A in the shower < 1/230 of the number of particles detected by the KM2A surface counters → the cosmic ray background is cutted by the factors of 1,000 and 500,000 at 50 TeV and 1 PeV, respectively.

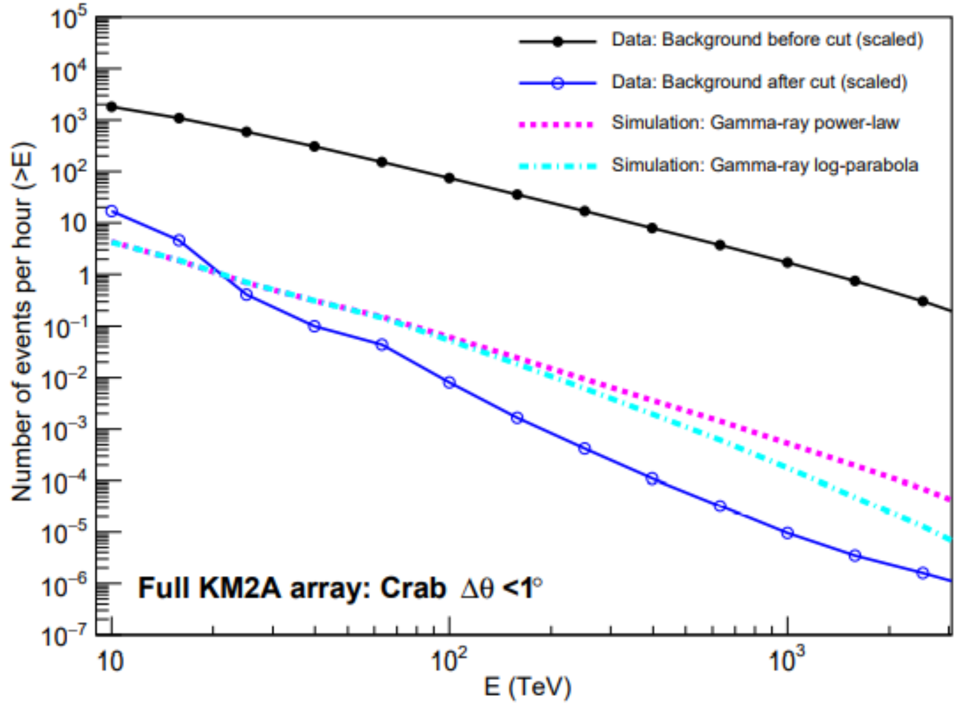


Fig. 5: The rates of detection of γ-rays from the Crab and the cosmic ray background events above the shower energy E by the 1 km^2 array in a cone of 1◦ centered at the Crab direction

The Spectral Energy Distribution Measurement

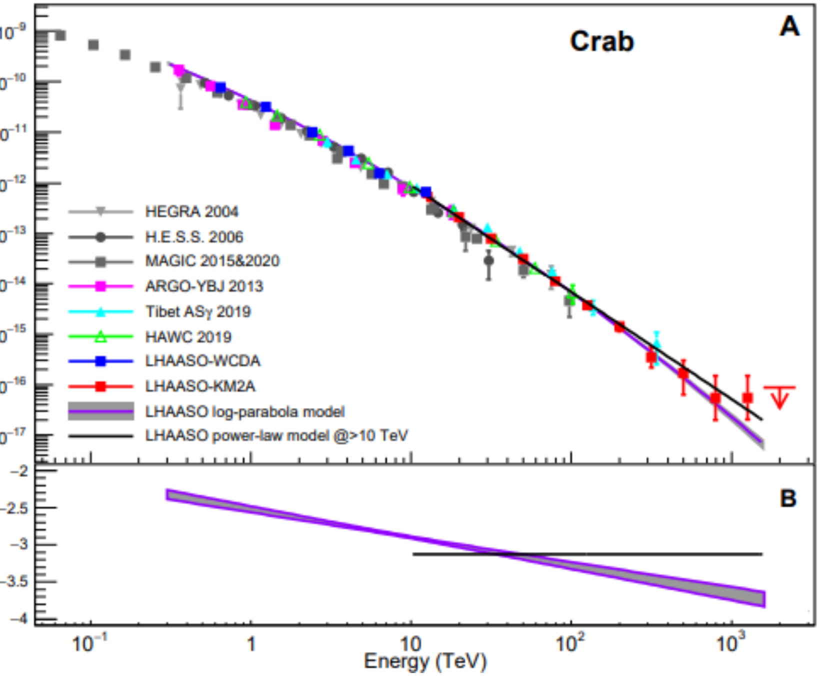


Fig. 6: γ-ray flux of the Crab measured by LHAASO and spectral fitting

- The γ-ray fluxes in the energy range from 0.5 to 13 TeV are measured using the WCDA. The measurement using KM2A covers the higher energy range from 10 TeV to 1.6 PeV.
- From September 2019 to October 2020, the t exposure was 343.5 transits of the Crab. The t independent measurements of γ-ray flux fit a S functional form:
- $dN/dE = (8.2\pm0.2)\times10^{-14}\,(E/TeV)^{-\Gamma}$ cm^{-2} s^{-1} TeV^{-1}
- The two measurements are smoothly connec in the region around 12.5 TeV.
- Function $\Gamma = (2.90 \pm 0.01) + (0.19\pm0.02)\log_{10}(E/TeV)$ → a gradual steepening of the spectrum, $\Gamma \approx 2.5$ at 1 TeV to 3.7 at 1 PeV.

- Photons from the Crab Nebula have been detected from MHz radio to UHE γ-rays, and consists of several pulsed and unpulsed components.
- γ-rays can be produced in three physically distinct sites:
  - pulsar's magnetosphere
  - ultrarelativistic electron-positron wind
  - nebula
- UHE γ-rays are absorbed in the strong magnetic field of the pulsar → a pulsed component expected only from the magnetosphere in the form of MeV-to-GeV γ-rays.
- The detection of pulsed TeV γ-rays from the Crab initiated a new concept allowing the location of the pulsed γ-ray production in the wind.
- In the analysis, the entire flux is assumed to be consisted only by an unpulsed component and is produced in the nebula.

Parameters estimation

- Broad-band nonthermal emission dominated by two mechanisms:
  - synchrotron radiation
  - inverse Compton (IC) scattering of relativistic electrons interacting with the ambient magnetic and radiation fields
- In the standard paradigm, the acceleration of electrons is initiated by the termination of the wind by a standing reverse shock at a distance R ≈ 0.1 pc from the pulsar.
- Detection of PeV photons → estimate the accelerator size l, the magnetic field strength B, and the minimum acceleration rate η.
- In the Crab Nebula, several radiation fields supply target photons for the IC scattering of electrons. At energies above 100 TeV, the 2.7 K Cosmic Microwave Background radiation (CMBR) dominates the γ-ray production. CMBR is well quantified → γ-ray data provides direct information about the parent electrons.
- $E_e \simeq 2.15 (E_\gamma / 1 PeV)^{0.77}\ PeV$ → 1.1 PeV photon derives from an electron of energy 2.3 PeV
- Simultaneous modelling of the synchrotron and IC components → constrains on the magnetic field strength: $B \simeq 112_{-13}^{+15}\ \mu G$
  - Upper limit: synchrotron radiation ≤ measured MeV flux
  - Lower limit: electron gyroradius $R_g = E_e / eB \leq l$

- Magnetohydrodynamic (MHD) models of the Crab Nebula → electrons are accelerated at the termination of an electron wind, then advected into the nebula through the MHD outflow
- X-ray imaging of the inner parts of the nebula → location of the acceleration site: close to the termination shock, at R ≈ 0.1 − 0.14 pc from the pulsar
- The lower limit on the magnetic field gives B ≥ 20 μG. The standard one-zone model, which assumes that both the synchrotron and IC components of radiation are produced in the same region by the same electron population, gives $B \simeq 112\ \mu G \rightarrow l \geq 0.02\ pc$.
- Constraints inconsistent with estimates of the characteristic size and magnetic field in the region where the flares of the MeV/GeV γ-ray emission originate. Variation of γ-ray fluxes on timescales of days interpreted by fast acceleration and synchrotron cooling of PeV electrons in compact (R ≤ 0.01 pc) highly magnetized (B ≥ 1 mG) regions. Large magnetic field → IC γ-ray component suppressed; an indirect link between the PeV electrons responsible for the UHE γ-ray emission and the synchrotron MeV/GeV flares is not exluded.
- Detection of ~ 1 PeV photons → the acceleration rate overcomes the synchrotron losses of the parent electrons up to PeV energies. The acceleration rate of electrons is $\dot{E} = e\varepsilon c = \eta e B c$, where
  - η : ratio of the projection of the electric field ε, averaged over the particle trajectory, to the magnetic field, $\eta = \varepsilon / B$.
- For the detected $E_\gamma = 1.1$ PeV and B derived from the one-zone model, $\eta \approx 0.16$. For comparison, at the diffusive shock acceleration in young supernova remnants, η is smaller by at least 3 orders of magnitude

Discussion

- Agreement between detection of PeV photons and predictions for the standard MHD paradigm of the Crab Nebula?
  - The latter assumes that nonthermal emission from X-rays to multi-TeV γ-rays is produced by electrons accelerated at the termination of the pulsar wind
- Modelization of the Crab's multi-wavelength radiation within the idealized Synchrotron-IC one-zone model, assuming a homogeneous spatial distribution of the magnetic field and electrons.
- For $E_\gamma \geq 100$ TeV γ-rays, the dominant target for IC scattering is the 2.7 K CMBR, with properties that are known very precisely. For a steady-state electron energy distribution, above 1 TeV, assunction of a power-law function terminated by a super-exponential cutoff $E^{-\alpha} \exp[-(E/E_0)^2]$ at the high-energy end.
- Using three free parameters:

Power-law slope $\alpha = 3.42$	Cutoff energy $E_0 = 2.15$ PeV	Magnetic field $B = 112$ μG

- Reproduction of the SED fit of reasonable accuracy from the X-rays to multi-MeV γ−rays with synchrotron radiation, and the TeV to PeV γ-rays with IC radiation. Below 1 TeV, the electron spectrum must undergo a break to avoid a conflict with the synchrotron radiation at optical to radio frequencies, and to provide a smooth transition of the IC radiation from TeV to GeV energies. The magnetic field $B \simeq 112\ G$ derived for the production region of multi-TeV to PeV γ-rays, is a factor of 2-3 smaller than the average nebular magnetic field, consistent with the MHD flow model.

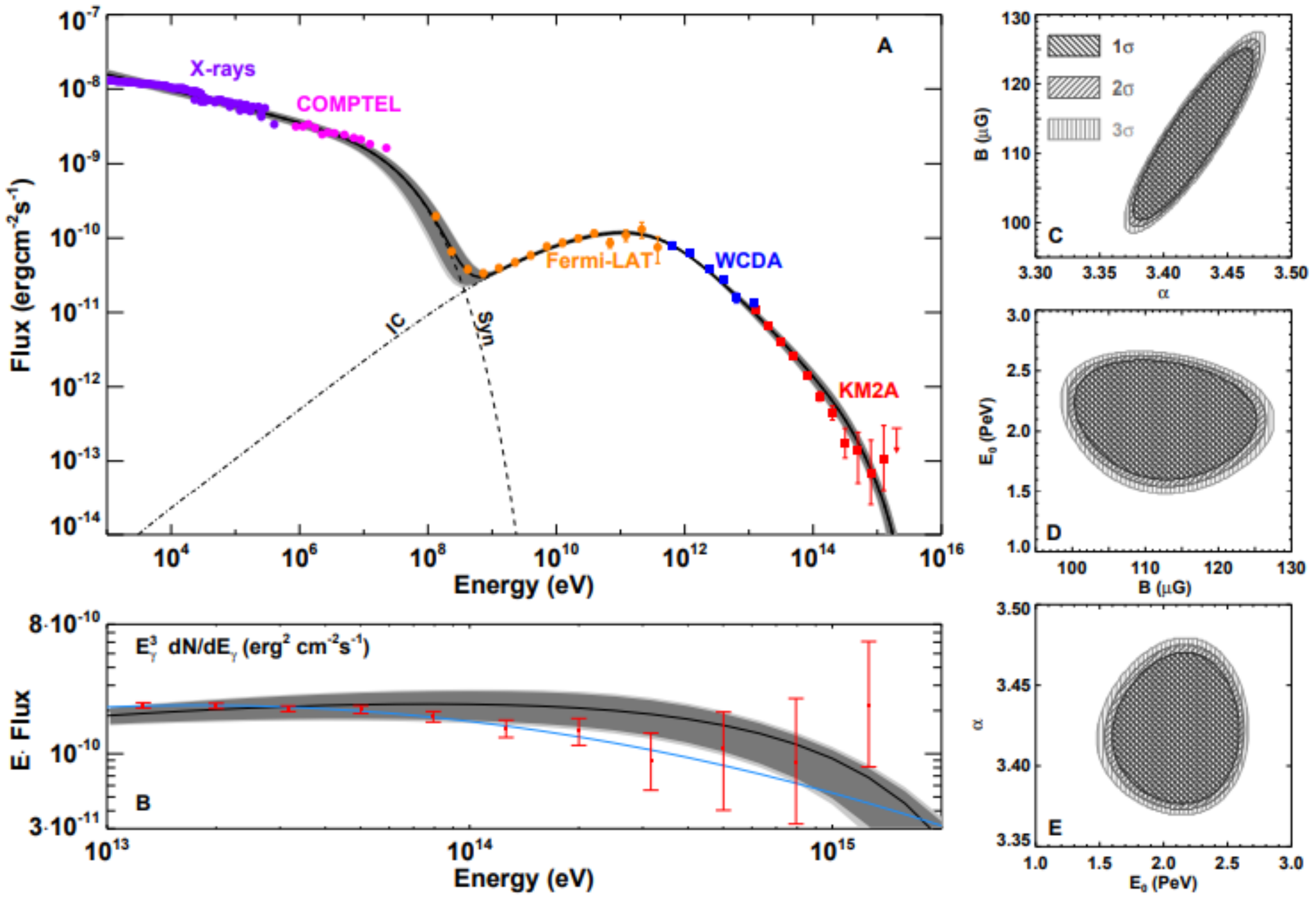


Fig. 7: The Spectral Energy
Distribution of the Crab Nebula
Panel A: The black curves repre
the fluxes of the Synchrotron ar
components of radiation of an
electron population calculated w
the one-zone model.

One zone-model

- Within the one-zone model, the IC γ-ray spectrum is precisely predicted.
- The KM2A spectral points from 10 TeV to 1 PeV do agree, within the statistical uncertainties, with the one-zone fit, but there are possible deviations from its predictions: between 60 TeV and 500 TeV, two differ with a significance of 4σ indicating a steeper spectrum than the one-zone model predictions.
- The possible excess around 1 PeV indicates an opposite tendency - a hardening of the spectrum. A hardening of the electron spectrum is difficult to accommodate with plausible assumptions. The problem of suppression of the one-zone spectrum at 1 PeV can be circumvented by introducing a second population of PeV electrons.
- A second electron component could extend the SED to a few PeV but not much further. Any detection of γ-rays well beyond 1 PeV would require non-leptonic origin of the extra component of radiation, i.e. the presence of multi-PeV protons and nuclei in the nebula
- Because of the limited energy budget available for acceleration of protons, hadronic interactions cannot be responsible for the overall broad-band γ-ray luminosity.

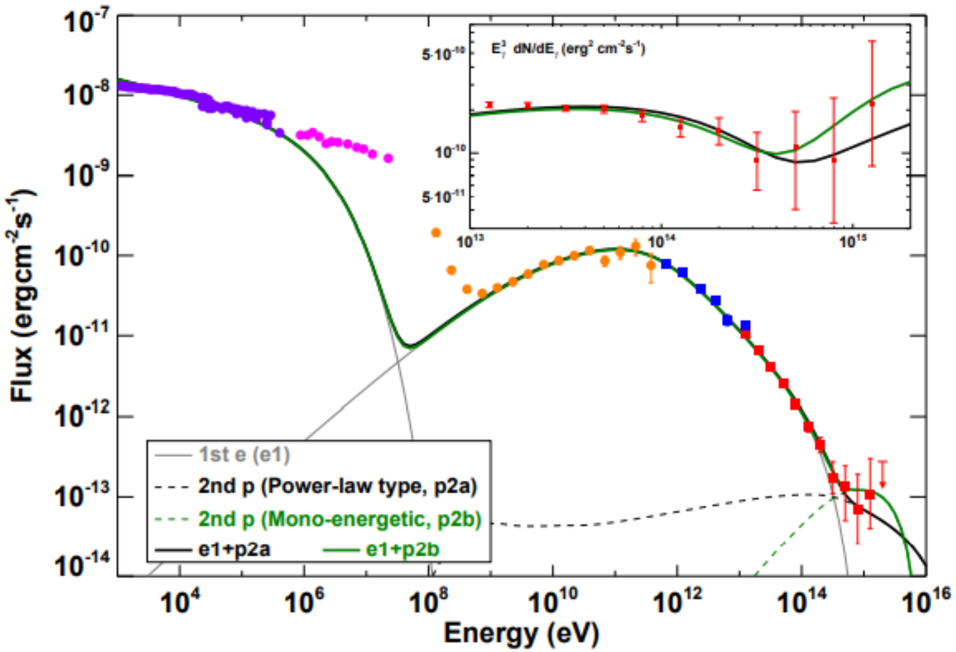


Fig. 8: A two-zone scenario with two electron populations

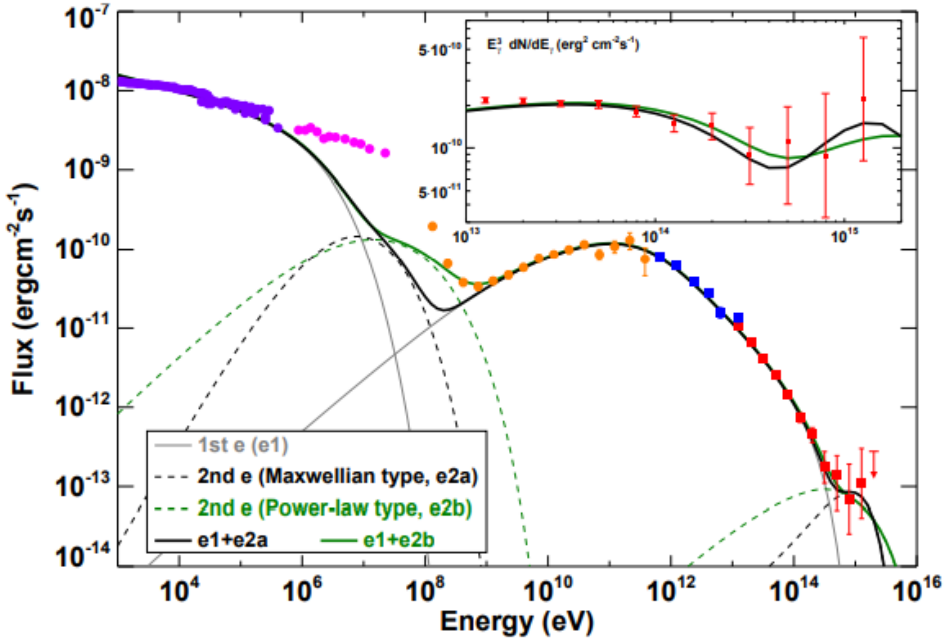


Fig. 9: A two-zone scenario with the the main (electron) and second (proton) relativistic particle populations

The future

- The acceleration of protons to PeV energies requires extreme physical conditions, representing a challenge for any Galactic source population, including supernova remnants and young massive star clusters.
- Pulsar wind nebulae as potential electron PeVatron in our Galaxy require even more extreme theoretica speculations.
- In the coming years, observations with LHAASO wi reduce the flux detection threshold by at least an order of magnitude. This will increase the number o UHE sources and provide high-quality energy spectra and the morphology of UHE sources. Extension of the spectra without an indication of a cutoff beyond several PeV would not only robustly identify the hadronic origin of the UHE γ radiation but would reveal the sites of super-PeVatrons

THANK YOU FOR THE ATTENTION!