Multi-wavelength study of the galactic PeVatron candidate LHAASO J2108+5157

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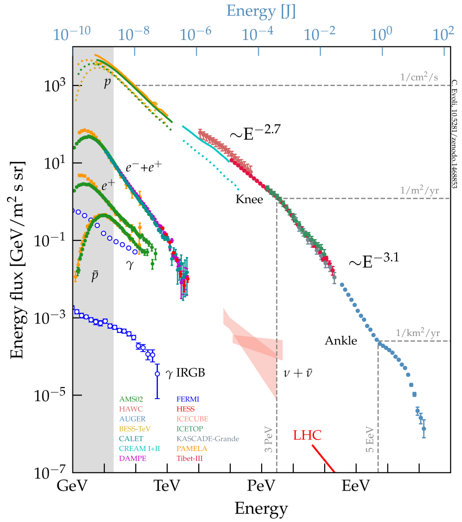
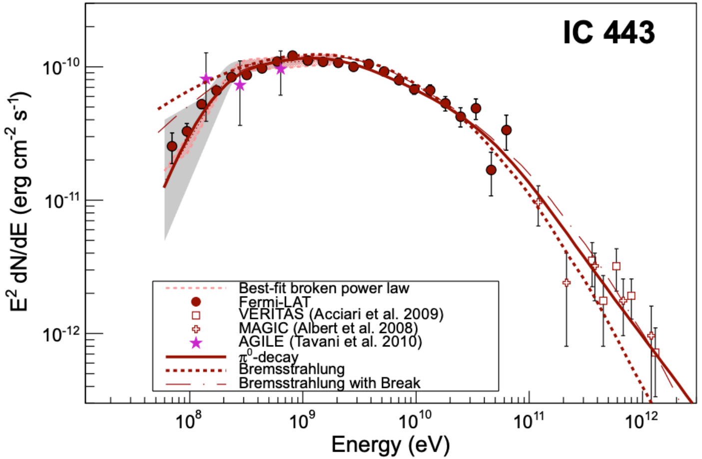
Galactic PeVatrons

- CR spectrum at least up to the knee is dominated by galactic sources of **unknown nature**
- Diffusive shock acceleration of protons in SNRs
- Interaction of relativistic protons with cooler gas leads to emission of gamma-ray photons with ~1/10 of energy of the incident protons via π^0 decay

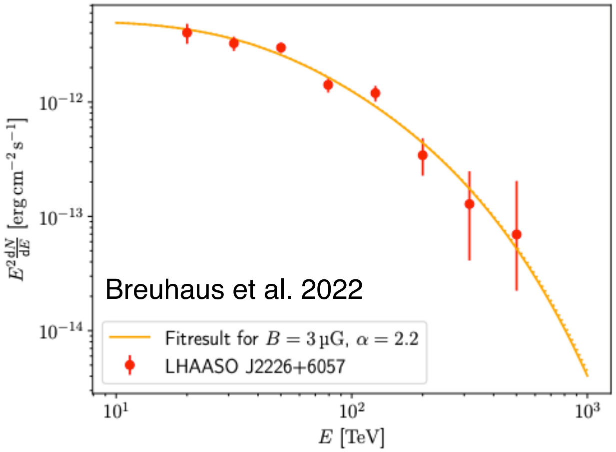


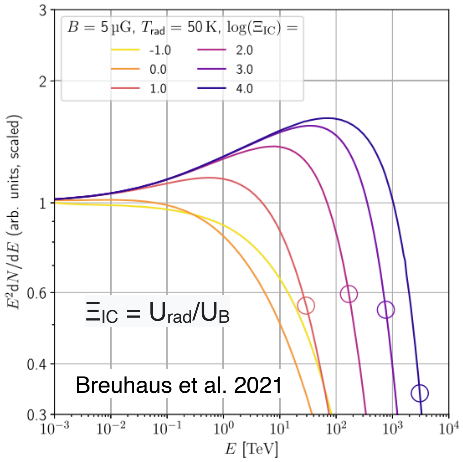


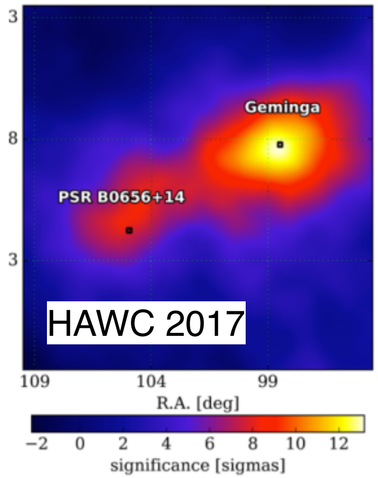
- "Pion bump" visible in gamma ray emission of several SNRs interacting with GMC -> evidence of **proton acceleration in SNRs**
- But **no firmly identified SNR show gamma ray emission beyond 100 TeV**

Galactic PeVatrons

- Many PeVatron candidates ($E_{\gamma,max}$ > 100 TeV) discovered in last years: Tibet-AS, HAWC, LHAASO experiments
- But **gamma ray emission above 100 TeV is not an evidence for proton accelerator -** IC scattering of electrons on bkg photon fields (Suppression at high-E due to Klein-Nishina effect is not that strong in radiation dominated environments* - vicinity of young pulsars, TeV halos with low B)



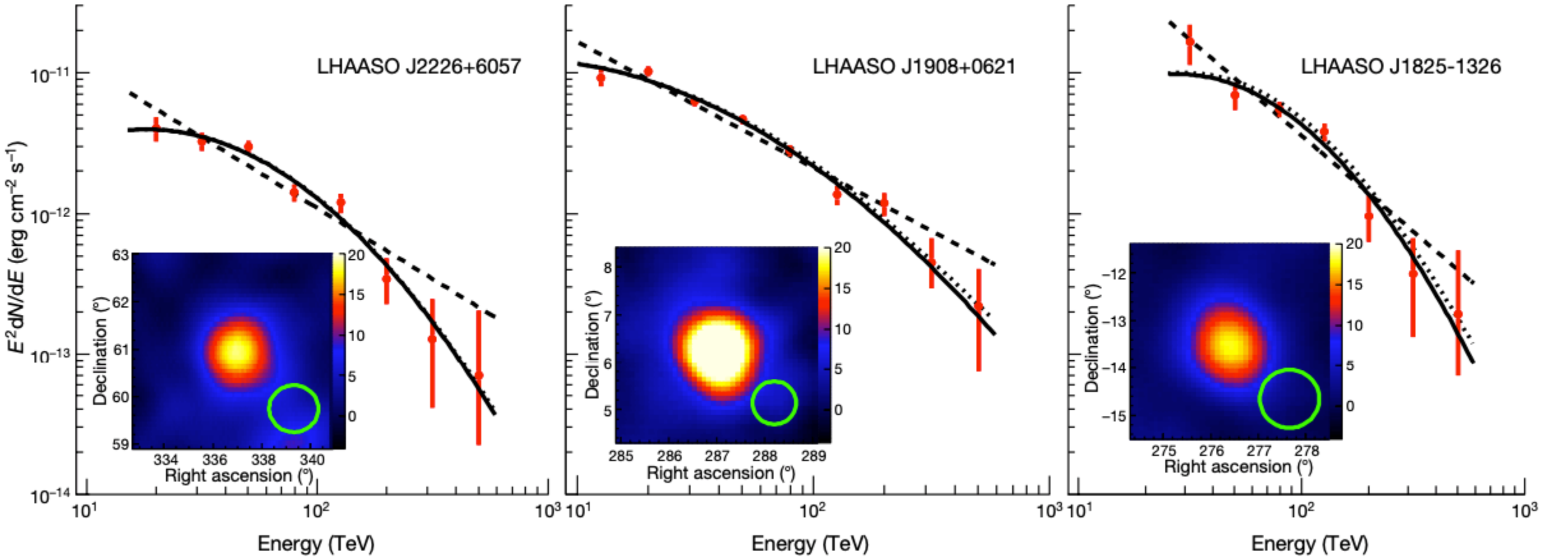




* That is due to increased cooling time for a certain interval of energies above E_{KN}, which compensates for the reduced IC cross section. For more details see (Breuhaus et al. 2021).

The breakthrough of LHAASO

- In their Nature paper (LHAASO col., 2021a), they **identified 12 UHE gamma-ray sources emitting photons with energies > 100 TeV**, up to 1.4 PeV
- Most of them can be associated with nearby pulsar, which are believed to be electron accelerators -> **leptonic PeVatrons** -> nature of Gal. CR accelerators remains an open question



The breakthrough of LHAASO

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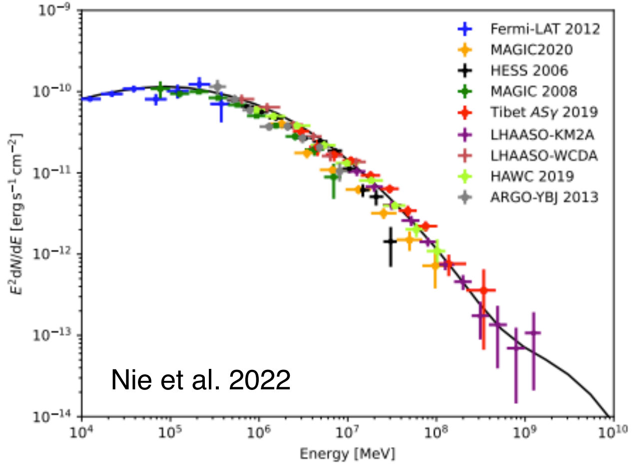
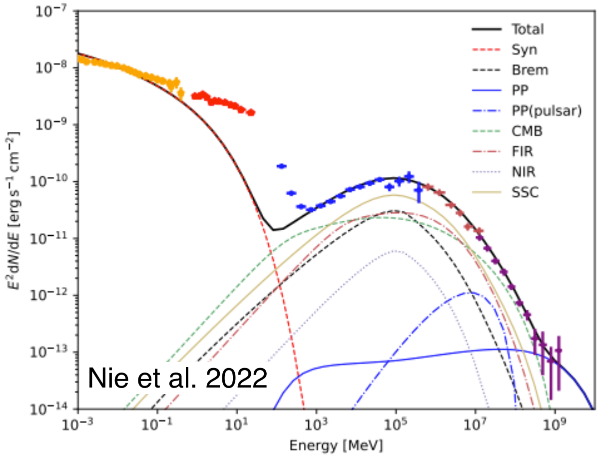
- Note that acceleration of hadrons in pulsars is not a priori excluded. Some hybrid models considering protons from photo disintegration of Fe nuclei were proposed for Crab recently.





E²dN/dE (erg cm⁻² s⁻¹)
Energy (TeV) Energy (TeV) Energy (TeV)

The breakthrough of LHAASO

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2[d]	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3[e]	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3[f]	< 2[f]	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7[g]	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5[h]	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4[i]	$\sim 10 - 20$[j]	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}$[d]	$1.8 - 3.3$[k]	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2[d]	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}$[l]	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	3.3 ± 0.3[m]/4.0 ± 0.5[n]	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08[o]	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08[o]	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8[p]	~ 10[p]	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8[p]	~ 10[p]	2.2×10^{37}	

The breakthrough of LHAASO

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						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
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LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
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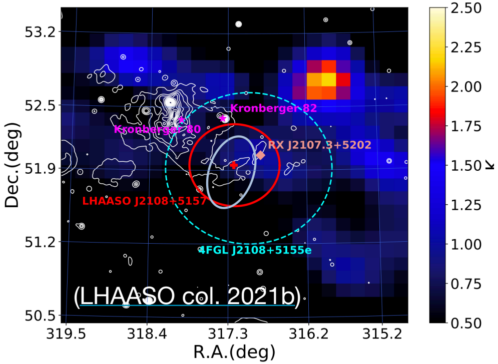
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

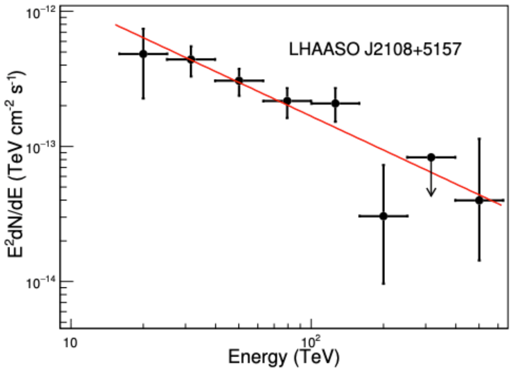
LHAASO J2108+5157

- Discovery and detailed analysis (LHAASO col., 2021a, b)
- **Unidentified** UHE gamma-ray source and Gal. PeVatron candidate
- 95% UL on extension: 0.26 deg
- **Possible counterparts:**
  - **X-ray**: No counterpart (Swift-XRT)
  - **HE**: 4FGL J2108.0+5155 (0.13 deg from the UHE source)
  - **VHE**: No counterpart -> **Ideal target for LST-1**
- No PWN/ATNF pulsar within 1 deg
- Two young stellar clusters in the region, two molecular clouds in the direction of the source.

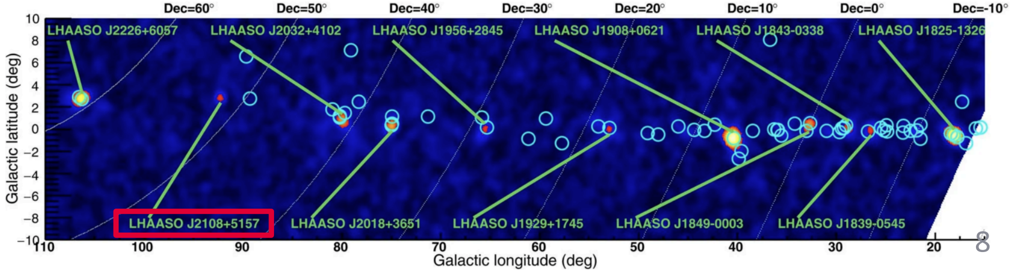
Brightness temperature distribution of 12CO(1–0) line survey



SED of the UHE source, Power-law photon index -2.83 (LHAASO col. 2021b)



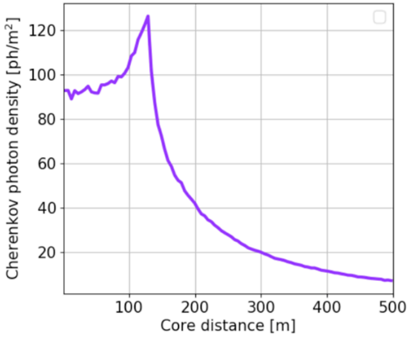
LHAASO skymap at energies above 100 TeV (LHAASO col. 2021a)

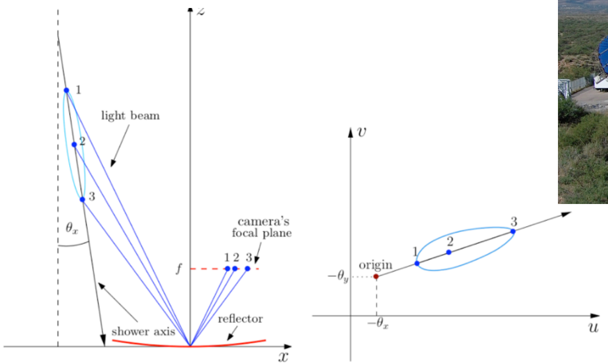


Imaging Atmospheric Cherenkov Technique

- Earth atmosphere highly opaque to gamma-rays
- Direct gamma-ray detection **up to ~100 GeV** by **space-borne satellite detectors**
- **E > 100 GeV**, low flux, large effective area is necessary – **ground detectors** (water Cherenkov detectors or Cherenkov telescopes)
- **Secondary particles** moving through the atmosphere with v > c/n emit **Cherenkov radiation**

Largest IACT observatories





(a) Mapping of an air shower.

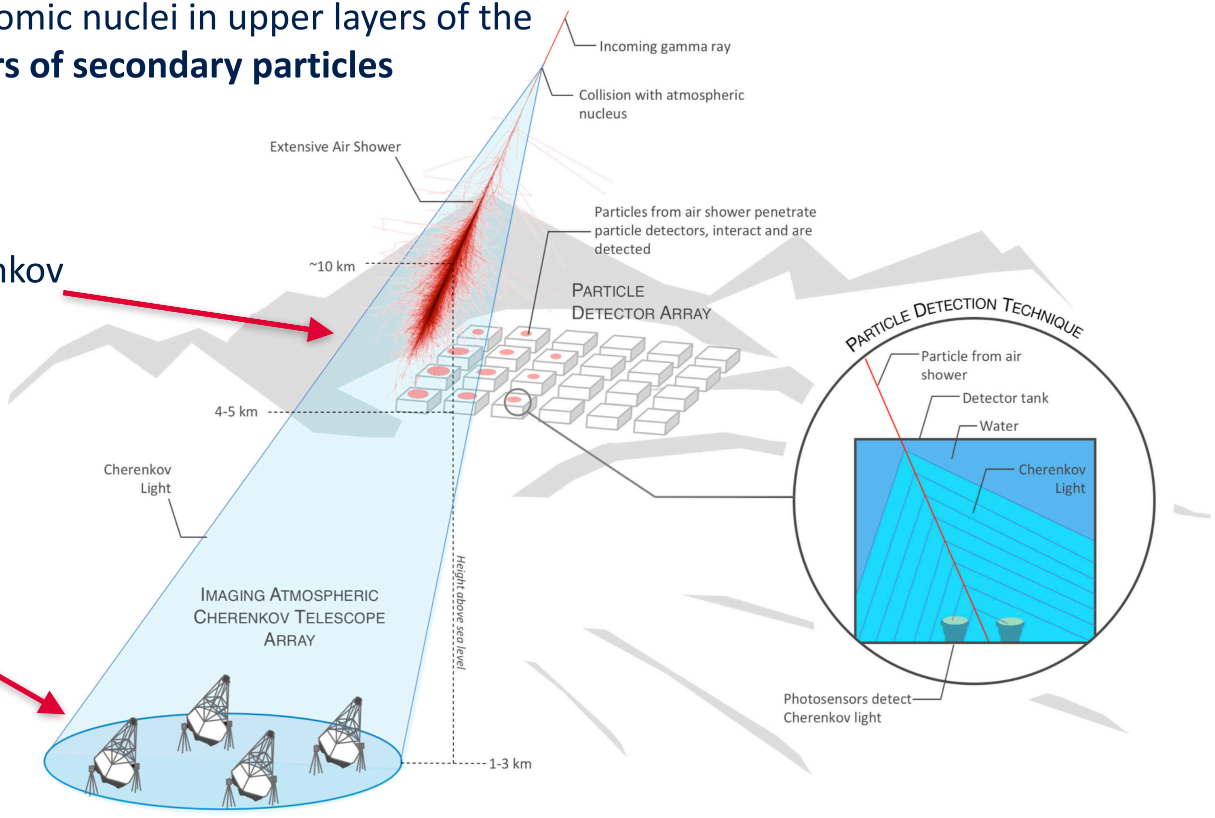
(b) Corresponding camera image.

Ground-based gamma-ray astronomy

VHE gamma-rays interact with atomic nuclei in upper layers of the atmosphere and produce **showers of secondary particles**

"Direct" detection of secondary shower particles → Water Cherenkov detectors at high altitude sites (LHAASO, HAWC, SWGO)

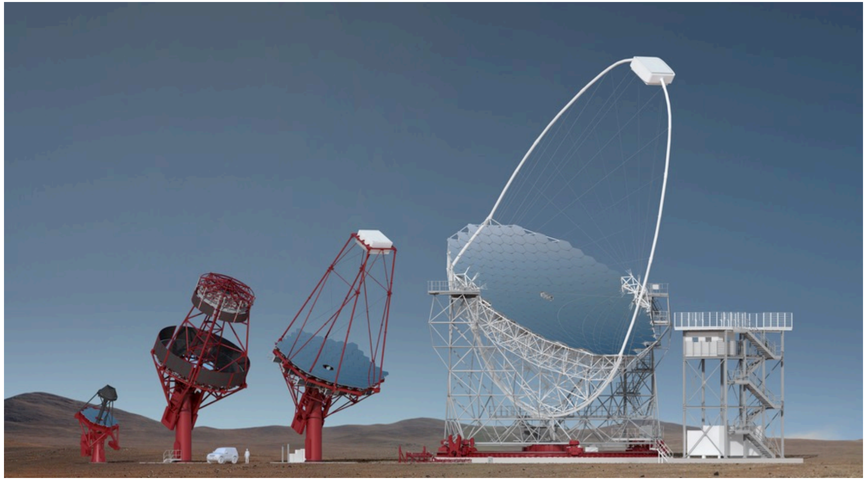
Detection of Cherenkov radiation emitted by the secondary shower particles in the atmosphere (H.E.S.S., MAGIC, VERITAS, CTA)

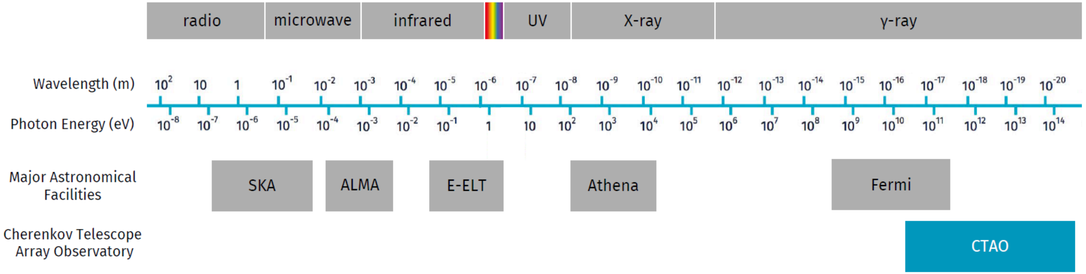


Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Cherenkov Telescope Array (CTA)

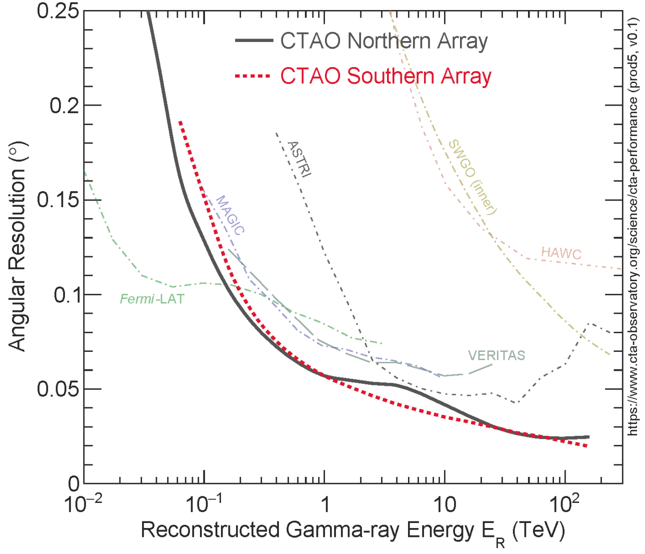
- The next generation ground-based VHE gamma-ray observatory
- **Two sites**: CTA-North (La Palma), CTA-South (Atacama desert)
- **Three different sizes of telescopes** to optimise sensitivity in a wide energy range of 20 GeV - 300 TeV
- CTA Consortium: **1500 scientists** and engineers from about **150 institutes** all around the world (4 from CR, **including FZU**)

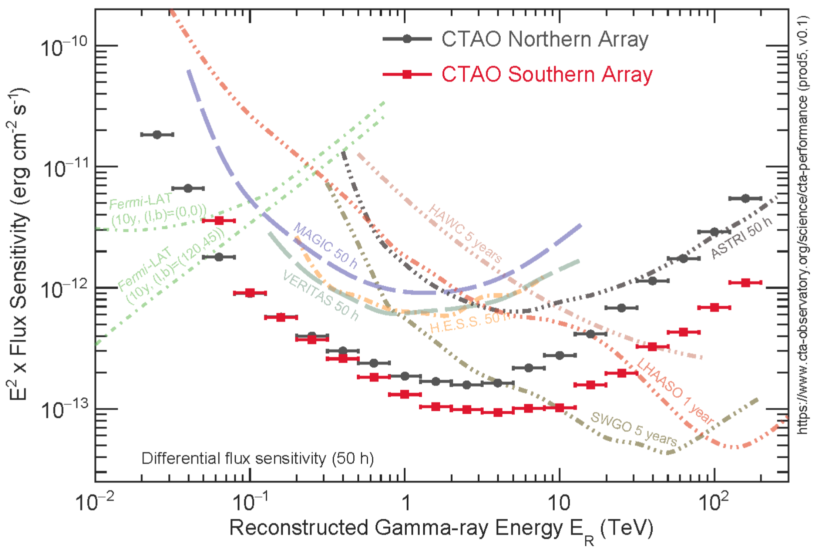




CTAO performance (Alpha conf.)

- **CTAO Northern Array:** 4 Large-Sized Telescopes and 9 Medium-Sized Telescopes (area covered by the array of telescopes: ~0.25 km^2)
- **CTAO Southern Array:** 14 Medium-Sized Telescopes and 37 Small-Sized Telescopes (area covered by the array of telescopes: ~3 km^2)





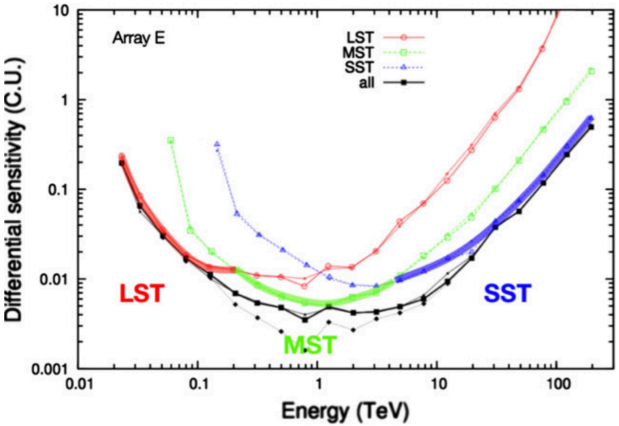
Why so many telescopes?

High energy gamma rays

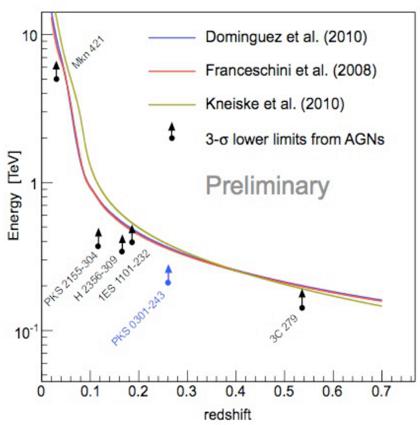
- Low rate of brights showers (a lot of secondary particles emitting Cherenkov radiation) → a large area covered by small telescopes

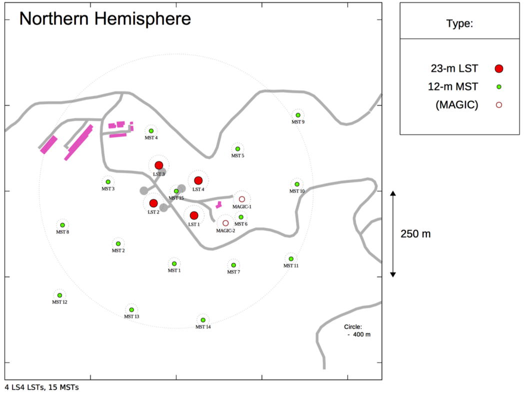
Low energy gamma rays

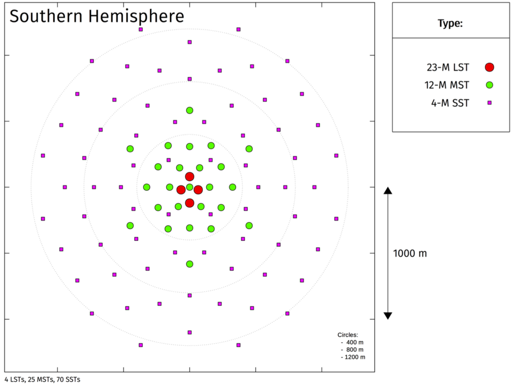
- High rate of faint showers → a few large telescopes needed



“Cosmic gamma-ray horizon” (optical depth=1) for different EBL models





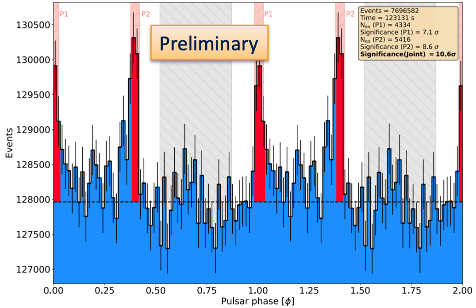


Large-Sized Telescope prototype (LST-1)

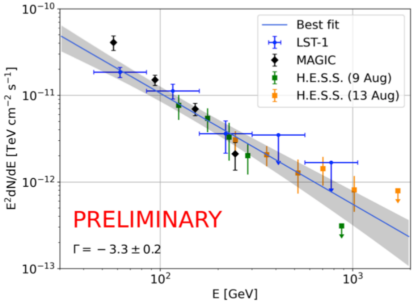
- The first CTA telescope on the site, installed on La Palma in 2018
- Currently in commissioning phase (but **ready for science**!)
- Mirror diameter - 23 m, pointing time 30 s (anywhere in the sky)
- In mono regime most sensitive between ~100 GeV - ~5 TeV (<10% C.U.), **energy threshold at ~20 GeV**
- More LSTs will come in following years

First science results

Crab pulsar detected at VHE



First nova ever detected at VHE

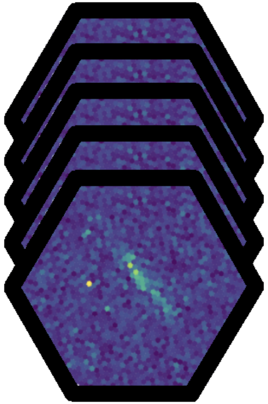


Exciting Galactic PeVatron candidate LHAASO J2108+5157 **(this talk)**

LST-1 data analysis in a (small) nutshell

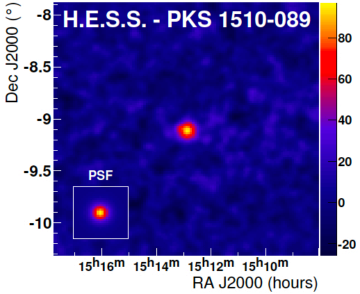
- Observation of Cherenkov light induced by secondary particles produced by VHE gamma rays interacting with atomic nuclei in upper layers of the atmosphere.
- The telescope sees images of the showers (not the source).
- The goal of reconstruction is to reconstruct position of the source and energy of primary photons by comparison with Monte Carlo events.

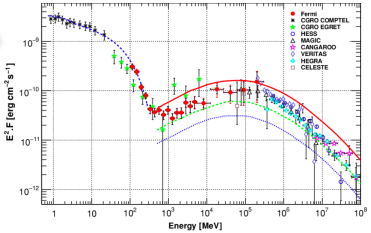
Data



MC

Reconstruction chain





Observation of LHAASO J2108+5157 with LST-1

- Wobble position between LHAASO and *Fermi*-LAT source, 0.5 deg offset
- Observed from June to September 2021 (interrupted by **volcano eruption**)
- **49.3 hours of effective time** after quality cuts
- Data calibration and reconstruction with lstchain v0.9.6
- Random Forests for energy and direction reconstruction, and gamma/hadron separation trained on Allsky MC with NSB tuned on the LHAASO source field

Wobble observation mode

- Telescope pointed in a direction offset wrt nominal source coordinates.
- No dedicated 'OFF source' runs needed to estimate background

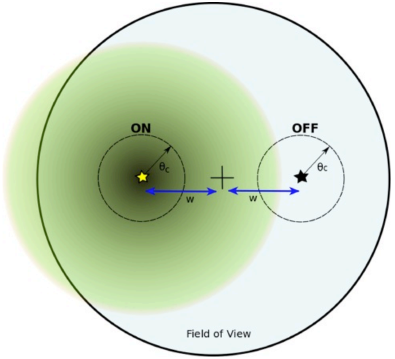


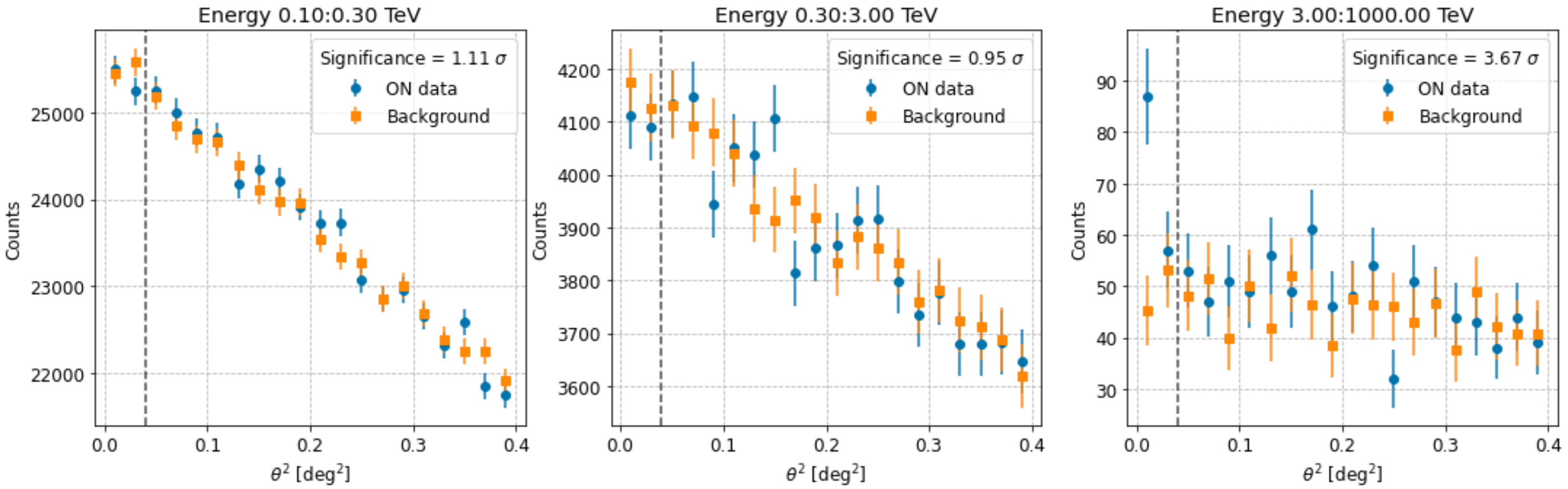
Figure from Palacio+(2019)

LST-1 results: aiming for detection

- Theta^2 distribution in three energy bins
- Use of three reflected background positions (OFF regions) + the LHAASO reported coordinates (ON region)
- Gammaness and theta^2 cuts optimised on Crab detection significance
- A hint of VHE emission at E>3 TeV with **3.7 sigma Li&Ma significance (S/B 46%)**

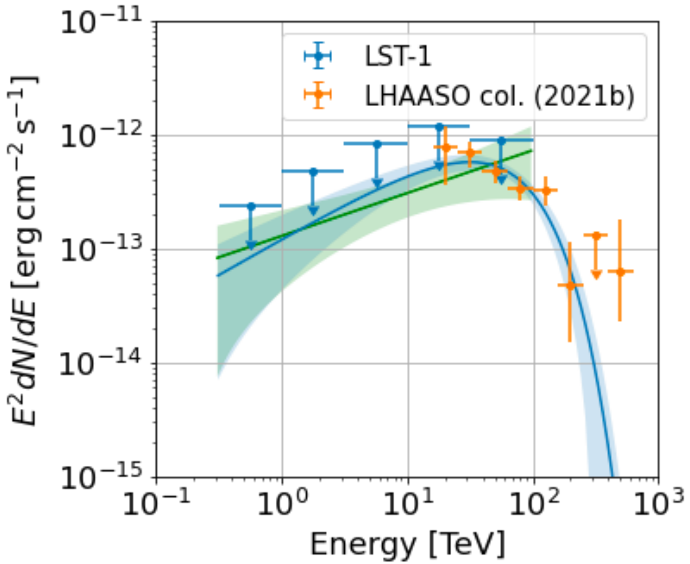
Theta^2 distribution

The squared angular distance between the reconstructed event directions and the source



LST-1 results: 1D spectral analysis

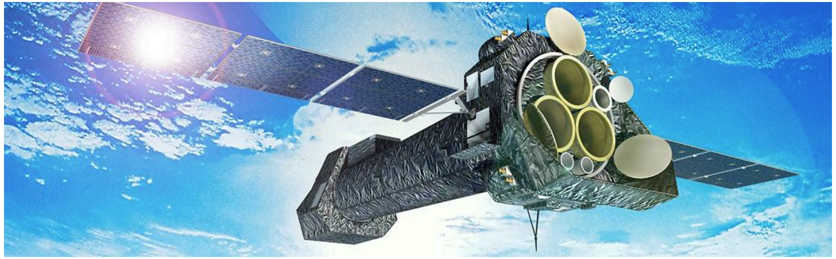
- 1D spectral analysis in Gammapy v0.19, point-like source assumption
- Power-law spectral model of LST-1 data between 100 GeV - 100 TeV (2.2 sigma)
- Joint likelihood fit of the LST-1 data and LHAASO flux-points using Power-law with Exponential Cutoff (ECPL) spectral model
- **Hard spectrum in the TeV range**



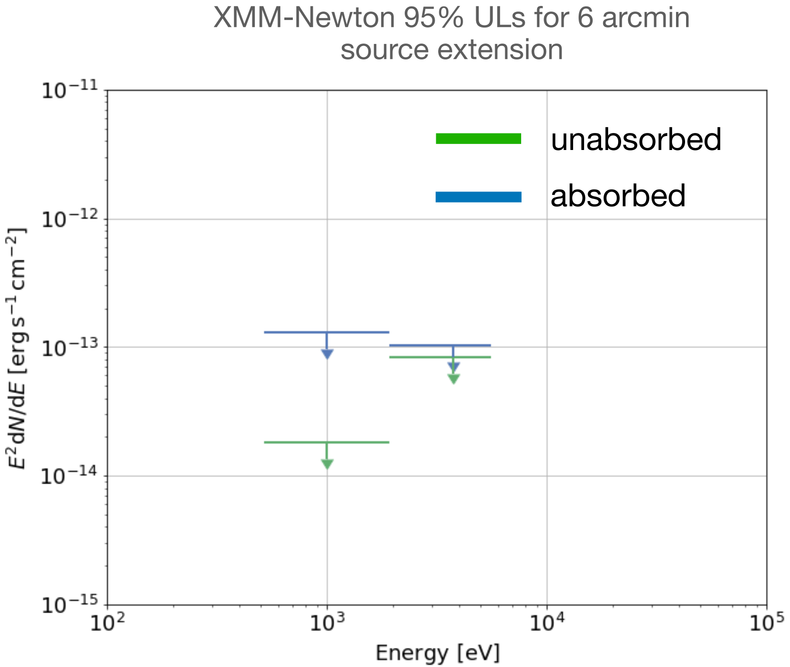
Data	Spectral model	N_0 [$\times 10^{-14}$cm^{-2}s^{-1}TeV^{-1}]	Γ	E_{cutoff} [TeV]	$-2\log\mathcal{L}$
LST-1	PL	8.02 ± 5.42	-1.62 ± 0.23	-	5.17
LST-1 + LHAASO	ECPL	7.57 ± 4.82	-1.37 ± 0.22	49.98 ± 13.49	7.30

* Reference energy for PL and ECPL: E_0 = 1 TeV

XMM-Newton ToO observation

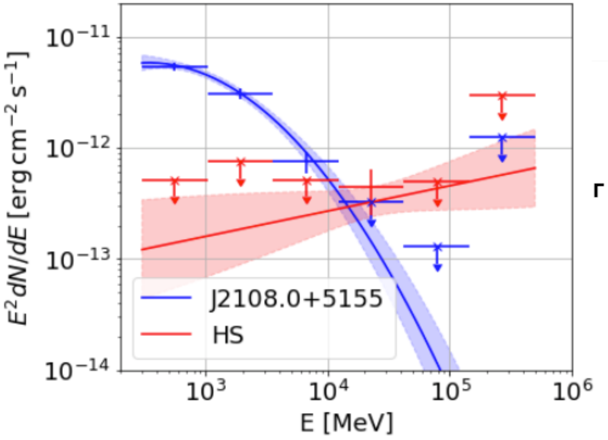


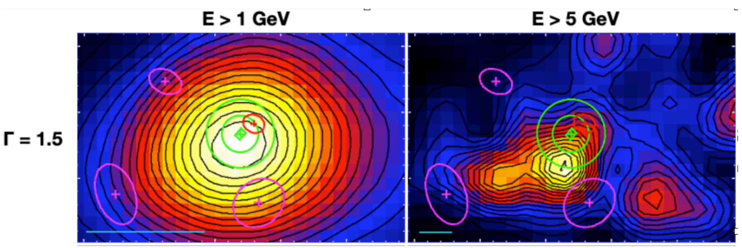
- Target of opportunity observation, **13.6 ks**, two energy bands: 0.5-2 keV, 2-7 keV
- **No detection**
- **Unknown source distance**: Two sets of ULs derived for different source distances
  - Absorbed (the source is distant)
  - Unabsorbed (the source is nearby)



Fermi-LAT data analysis

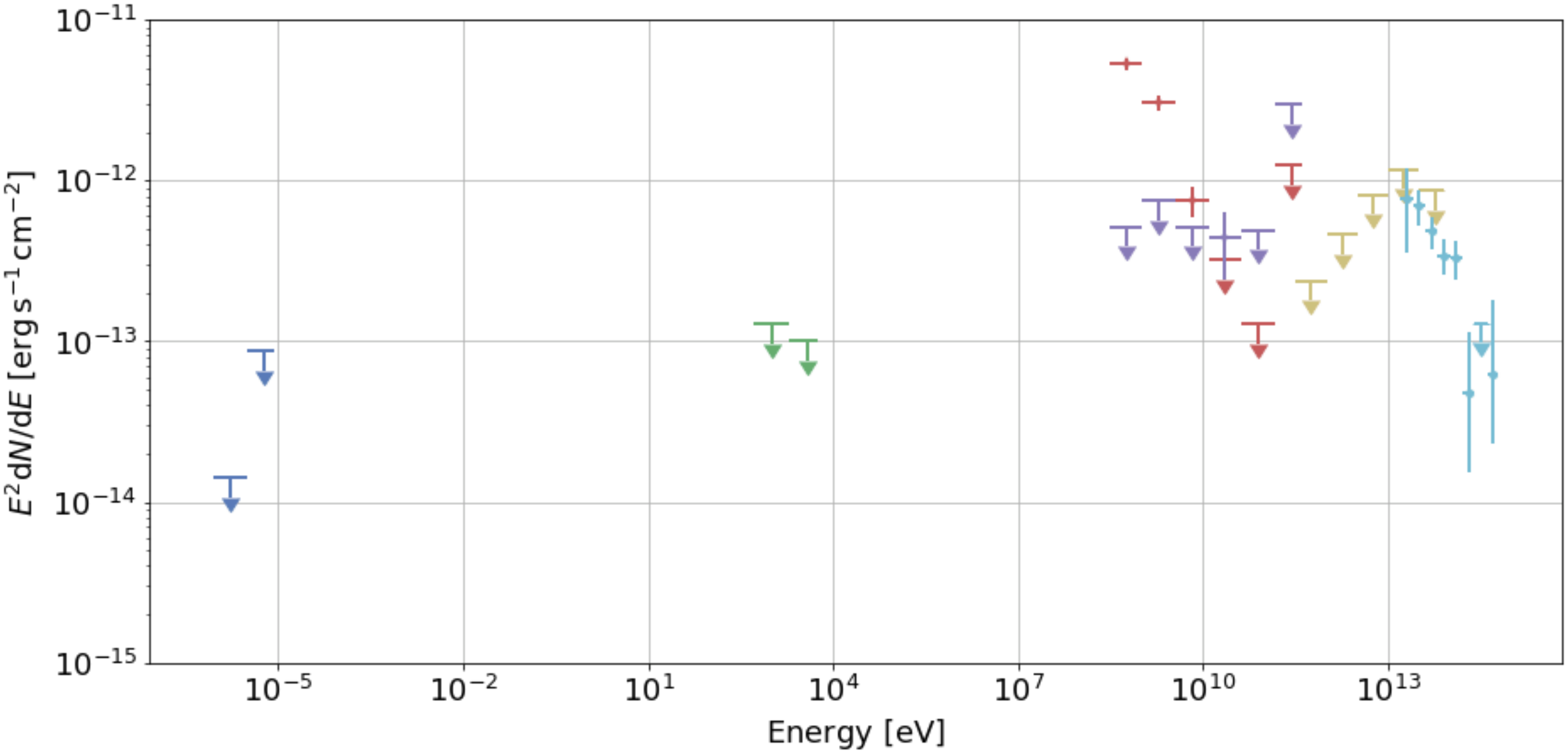
- Dedicated binned analysis of 12-year *Fermi*-LAT data
- Closest source 4FGL J2108.0+5155, a counterpart? - very soft spectrum
- **New hard spectrum source** (HS, 4sigma) dominating emission above ~4 GeV, located at the edge of the 95% extension limit of the UHE emission
- Likelihood fit adding HS in the model -> new spectral shape for 4FGL J2108.0+5155
- **Superposition of two point-like sources**: one brighter and softer, the other fainter but harder



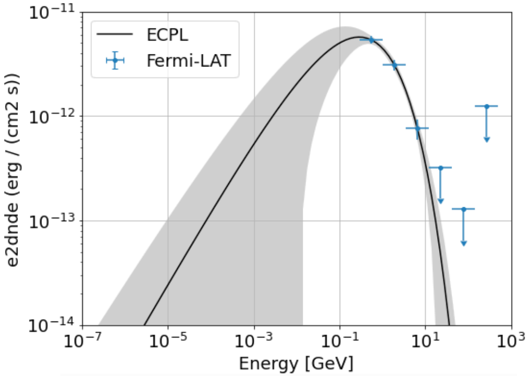


- Small green circle: 95% position uncertainty of the UHE source
- Larger green circle: 95% UL on the UHE source extension
- Known 4FGL-DR3 sources are shown in magenta

Multi-wavelength SED



4FGL J2108.0+5155 - a pulsar hypothesis

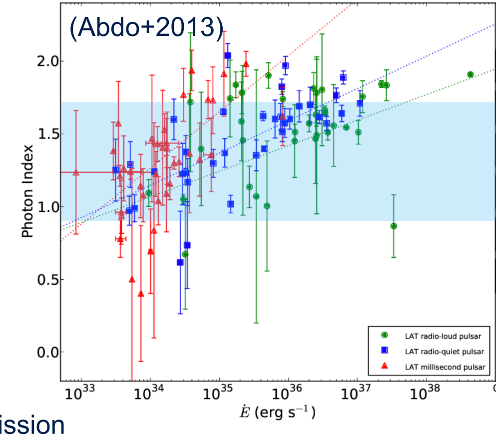


$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma} \exp(-(\lambda E)^{\alpha})$$

name	value	unit	error
index	1.29E+00		4.13E-01
amplitude	7.85E-09	cm-2 s-1 TeV-1	3.81E-08
reference	1E+00	TeV	0E+00
lambda	1.89E+01	GeV-1	6.30E+01
alpha	3.76E-01		1.71E-01

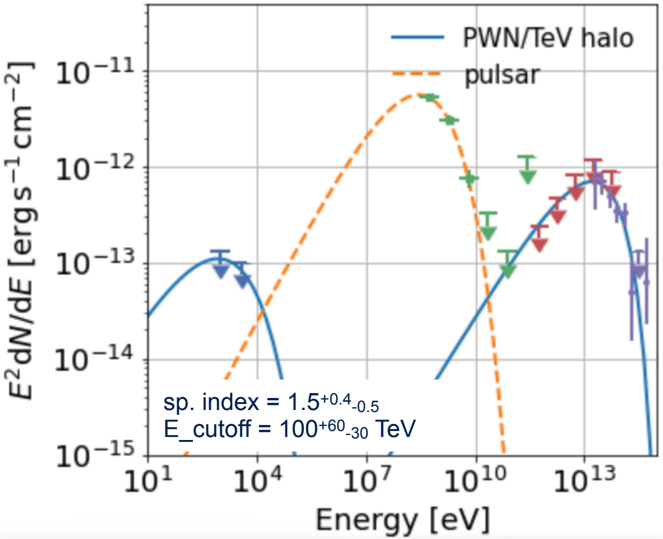
Sub-exponential cutoff - typical for a pulsar HE emission

- Parkinson (2016) **classified** the 3rd Fermi catalog counterpart 3FGL J2108.1+5202 **as a pulsar**
- There is a population of pulsars with SED dominated by HE/VHE emission (e.g. Geminga)



- Sub-exponential cutoff power-law phenomenological model compared with 2nd Fermi PSR catalog (Abdo+2013) -> **spin-down power of tentative pulsar constrained (Ė = 10^{34-37} erg/s)**

TeV emission - PWN/TeV halo object?



- Model of relativistic electrons emission calculated in Naima package (Zabalza 2015)
- Inverse Compton scattering on CMB and FIR photon fields
- **Problem: Strong X-ray ULs require low magnetic field (< 2 uG)**
  - Lower end of a typical B_{PWN} (~1 - 100 uG)
  - Comparable with B in **TeV halo** around Geminga (Liu et al. 2019)

TeV halos (see Lopez-Coto+2021 for a review)

- Forming at t>~10 kyr after SN, when the pulsar starts leaving SNR and accelerated electrons are no longer confined in PWN
- Extended bright emission
- TeV emitting region far from the pulsar
- Hard electron spectrum

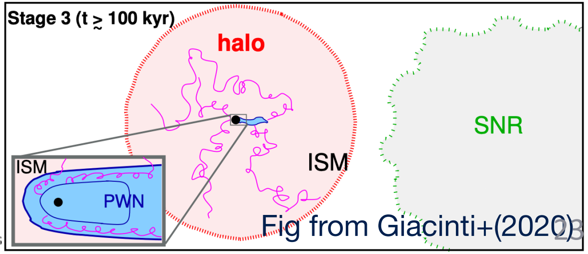
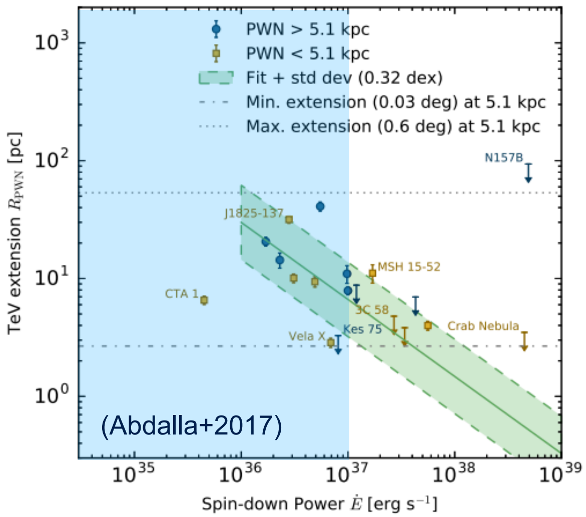
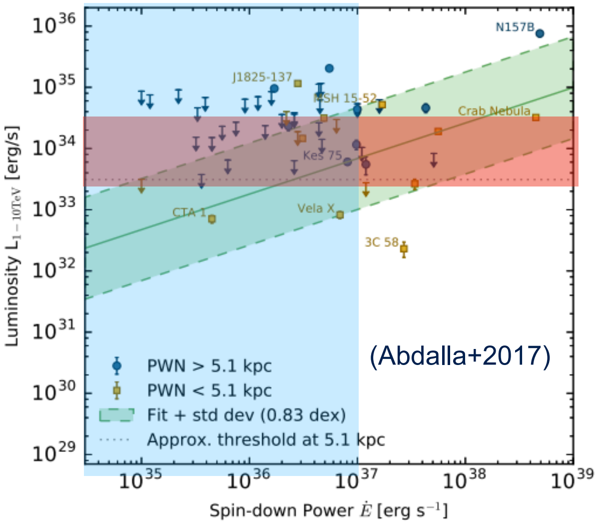


Fig from Giacinti+(2020)

TeV emission - PWN/TeV halo object?

- Comparison of TeV emission with population of TeV PWNe/TeV halos (Abdalla+2017, Linden+2017) following the pulsar hypothesis
- TeV extension for PSR of given Ė > ~10 pc
- LHAASO ULs on extension 0.26 deg => distance > ~2 kpc

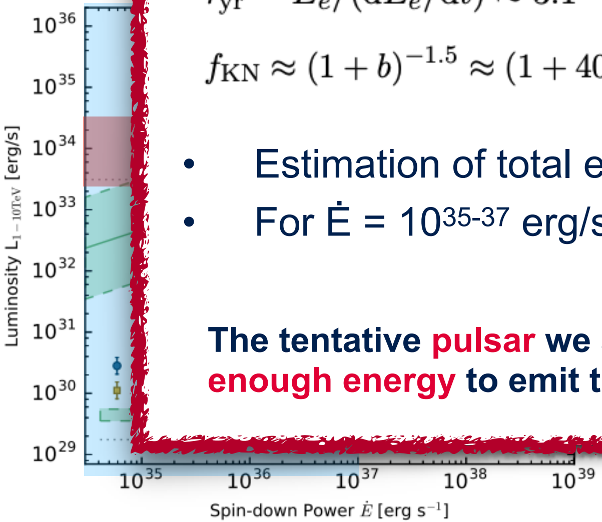


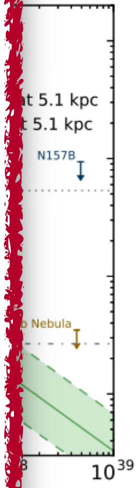


- TeV luminosity constrained by geometrical reasons and possible source extension consistent with limits on spin-down power from Fermi-LAT, further constraints on Ė = 10^{35-37} erg/s

TeV emission - PWN/TeV halo object?

- Co… 7,
  Li…
- TeV…
- LHA…
  dista…





Energetics

- Total energy in electrons $E_{tot} = 10^{45}$ (d/kpc)^2 erg
- IC electron cooling ([Moderski+2005])

$$\tau_{yr} = E_e/(\mathrm{d}E_e/\mathrm{d}t) \approx 3.1 \cdot 10^5 U^{-1}_{\mathrm{rad,eV\,cm^{-3}}} E^{-1}_{e,\mathrm{TeV}} f^{-1}_{\mathrm{KN}}$$

$$f_{\mathrm{KN}} \approx (1+b)^{-1.5} \approx (1 + 40 E_{e,\mathrm{TeV}} kT_{\mathrm{eV}})^{-1.5}$$

Cooling time of 100 TeV electrons: 30 kyr

- Estimation of total energy released by a pulsar: $E_{psr} = \dot{E}\, t_{cool}$
- For $\dot{E} = 10^{35\text{-}37}$ erg/s => $\mathbf{E_{psr} = 10^{47\text{-}49}}$ **erg.**

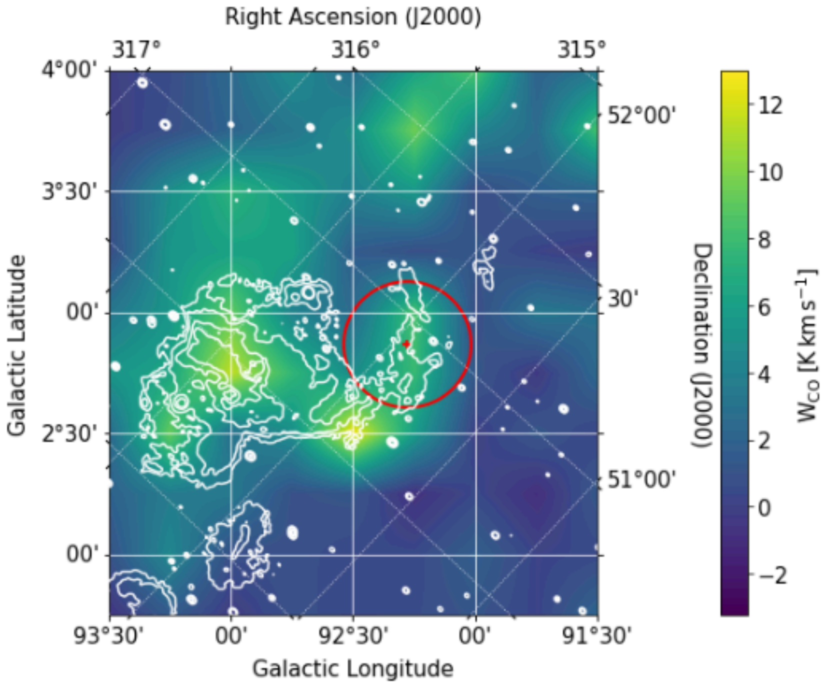
The tentative pulsar we see in the GeV range could provide the electrons with enough energy to emit the observed IC if closer than ~10 kpc.

… from
Fermi-LAT, further constraints on Ė = 10…-37
erg/s

Molecular clouds

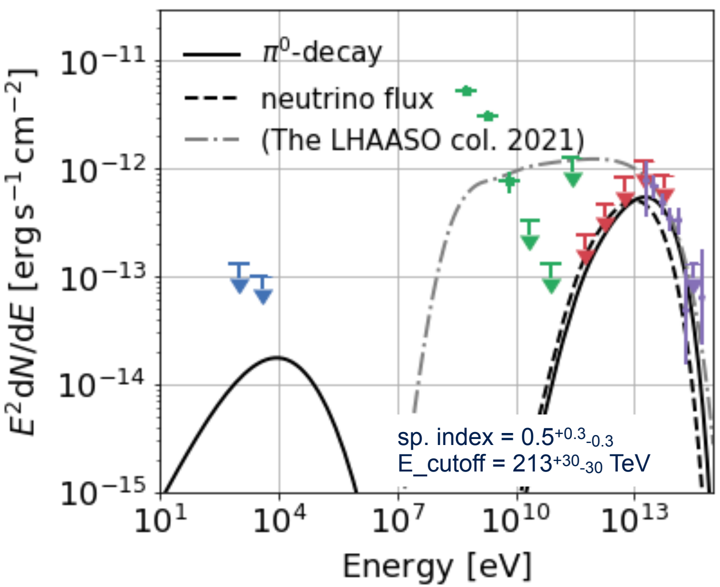
- Two molecular clouds spatially coincident with the source (d_1 = 3.1 kpc, d_2 = 2.0 kpc)
- Dedicated analysis to estimate total HI+H_2 density in the direction to the source
- **H_2**: Two peaks with v<0 km/s in CO(1-0) line spectrum radial velocity map
  - $n_1(H_2)$ = 51 cm^{-3}, $n_2(H_2)$ = 170 cm^{-3}
- **HI**: Estimated from brightness temperature velocity spectrum (optical thin limit assumption)
  - $n_1(HI)$ = 64 cm^{-3}, $n_2(HI)$ = 70 cm^{-3}

Velocity integrated CO density (W_{CO}) around v = -11.8 km/s



- Red circle: 95% UL on the UHE source extension
- White contours: 1420 MHz continuum emission

Hadronic scenario of emission



- **Two molecular clouds** spatially coincident with the source (d_1 = 3.1 kpc, d_2 = 2.0 kpc)
- **Two stellar clusters** in the direction to the source: Kronberger 80 (d = 7.9-13.7 kpc) and Kronberger 82 (unknown distance)

- Interaction of protons accelerated in old SNR/ stellar cluster with one of the molecular clouds
- Total energy in accelerated protons for both clouds < 10^{47} erg
- **Problem: very hard proton spectrum with sp. index 0.5±0.3 is inconsistent with diffusive shock acceleration**
  - Can be explained if only VHE protons can escape the acceleration region (Gabici&Aharonian 2007), or if gas clumps are present within the shell of SNR (Gabici&Aharonian 2014)

Problem: origin of HE gamma-ray emission

- An old SNR?
  - Photon index -3.2 too soft compared to old SNRs (Yuan+2012)

Summary and conclusions

- Data from LST-1, LHAASO, XMM-*Newton* and *Fermi*-LAT combined to provide a multi-wavelength information about unidentified source LHAASO J2108+5157

- **Gamma-ray pulsar + PWN/TeV halo:**
  - Self-consistent leptonic scenario of emission explaining both prominent peaks in the SED
  - Low magnetic field required by X-ray ULs - seems to be consistent with PWN or TeV halo

- **Interaction of relativistic protons with molecular clouds:**
  - Acceleration site unknown
  - Hard proton spectral index 0.5±0.3 needed to explain the emission - can be explained if only the most energetic protons can escape the acceleration region

First ever CTA-LST scientific paper

https://doi.org/10.48550/arXiv.2210.00775

Multiwavelength study of the galactic PeVatron candidate LHAASO J2108+5157

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Received ... / Accepted ...

ABSTRACT

Context. Several new ultrahigh-energy (UHE) gamma-ray sources have recently been discovered by the Large High Altitude Air Shower Observatory (LHAASO) collaboration. These represent a step forward in the search for the so-called Galactic PeVatrons, the enigmatic sources of the Galactic cosmic rays up to PeV energies. However, it has been shown that multi-TeV gamma-ray emission does not necessarily prove the existence of a hadronic accelerator in the source; indeed this emission could also be explained as inverse Compton scattering from electrons in a radiation-dominated environment. A clear distinction between the two major emission mechanisms would only be made possible by taking into account multi-wavelength data and detailed morphology of the source.
Aims. We aim to understand the nature of the unidentified source LHAASO J2108+5157, which is one of the few known UHE sources with no very high-energy (VHE) counterpart.
Methods. We observed LHAASO J2108+5157 in the X-ray band with *XMM-Newton* in 2021 for a total of 3.8 hours and at TeV energies with the Large-Sized Telescope prototype (LST-1), yielding 49 hours of good-quality data. In addition, we analyzed 12 years of *Fermi*-LAT data, to better constrain emission of its high-energy (HE) counterpart 4FGL J2108.0+5155. We used `naima` and `jetset` software packages to examine the leptonic and hadronic scenario of the multi-wavelength emission of the source.
Results. We found an excess (3.7σ) in the LST-1 data at energies $E > 3$ TeV. Further analysis of the whole LST-1 energy range, assuming a point-like source, resulted in a hint (2.2σ) of hard emission, which can be described with a single power law with a photon index of $\Gamma = 1.6 \pm 0.2$ the range of 0.3 – 100 TeV. We did not find any significant extended emission that could be related to a supernova remnant (SNR) or pulsar wind nebula (PWN) in the *XMM-Newton* data, which puts strong constraints on possible synchrotron emission of relativistic electrons. We revealed a new potential hard source in *Fermi*-LAT data with a significance of 4σ and a photon index of $\Gamma = 1.9 \pm 0.2$, which is not spatially correlated with LHAASO J2108+5157, but including it in the source model we were able to improve spectral representation of the HE counterpart 4FGL J2108.0+5155.

Announcement

2023-March-16

The LST Collaboration Publishes its first Scientific Paper with Data from the LST-1

On March 6, the LST Collaboration published its first scientific paper in the Astronomy & Astrophysics journal. The paper focuses on a multi-wavelength study of the unidentified ultra-high-energy gamma-ray source known as LHAASO J2108+5157. For the analysis, the LST Collaboration used 49 hours of data obtained with the LST-1, the prototype of the Large-Sized Telescope (LST) currently under commissioning at CTAO-North on La Palma (Spain). While the analysis did not result in any significant detection, the multi-wavelength approach, combining data from the LST-1 and other instruments, allowed the team to set strict upper limits on the source's emission that help shed light on its nature.

"Multiwavelength study of the galactic PeVatron candidate LHAASO J2108+5157" on A&A Journal.

The prototype of the Large-Sized Telescope, the LST-1, operating at the CTAO-North. Credit: Tomohiro Inada.

Backup slides

LST-1 results: Preliminary skymap

- Acceptance model from real data using [a tool](#) (M. De Bony).
- Ring-background technique adopted for determination of background, three known gamma-ray sources excluded not to contaminate the acceptance

- Slightly asymmetric significance distribution -> bkg model only preliminary
- Size of the excess consistent with point-like assumption (PSF@10TeV ~ 0.15 deg)