cherenkov telescope array

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

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for the CTA LST project

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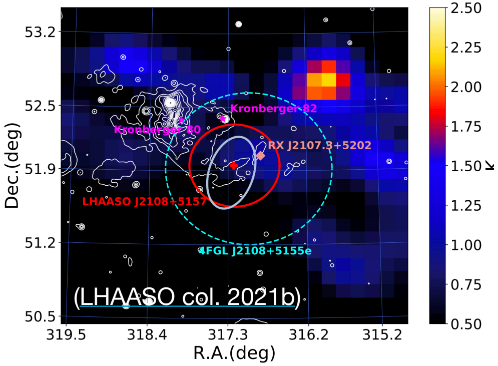
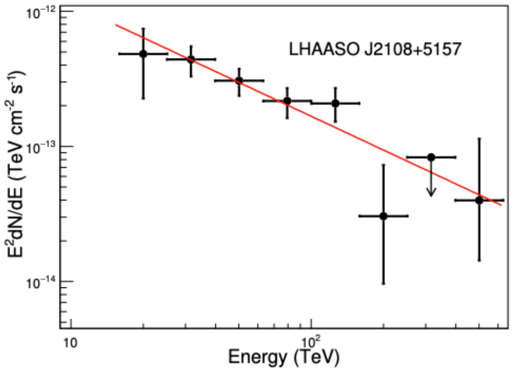
# LHAASO J2108+5157

- 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
- No PWN/ATNF pulsar within 1 deg
- Two young stellar clusters in the region. Presence of nearby molecular clouds.

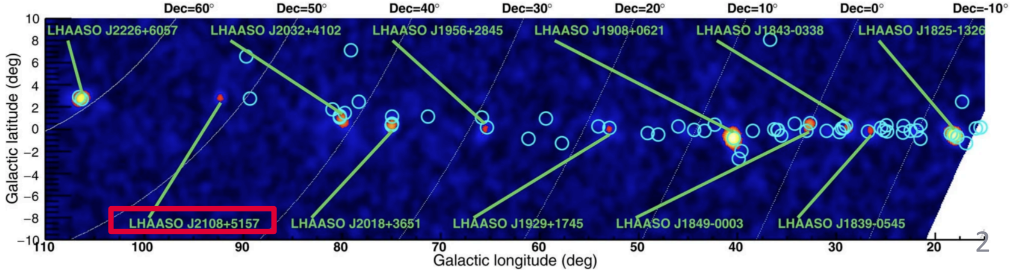
Brightness temperature distribution of 12CO(1–0) line survey




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




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



# Large-Sized Telescope prototype (LST-1)

- 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
- LST-1
  - The first CTA telescope on the site, installed in La Palma in 2018
  - Currently in commissioning phase
  - Mirror diameter of 23 m, in mono regime most sensitive between ~100 GeV - ~5 TeV (<10% C.U.), **energy threshold at ~20 GeV**.

## LST-1 talks at TeVPA 2022

- For **LST-1 performance** see: Daniel Kerszberg (Tue 16:30)
- For more **LST-1 science** results see: Y. Kobayashi (Thu 16:50), D. Green (Tue 15:50)

# Observations with LST-1

- Wobble position between LHAASO and *Fermi*-LAT source, 0.5 deg offset
- Observed from June to September 2021
- **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
- Source independent analysis

**Wobble observation mode**

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

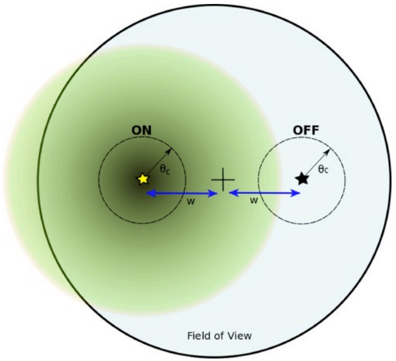


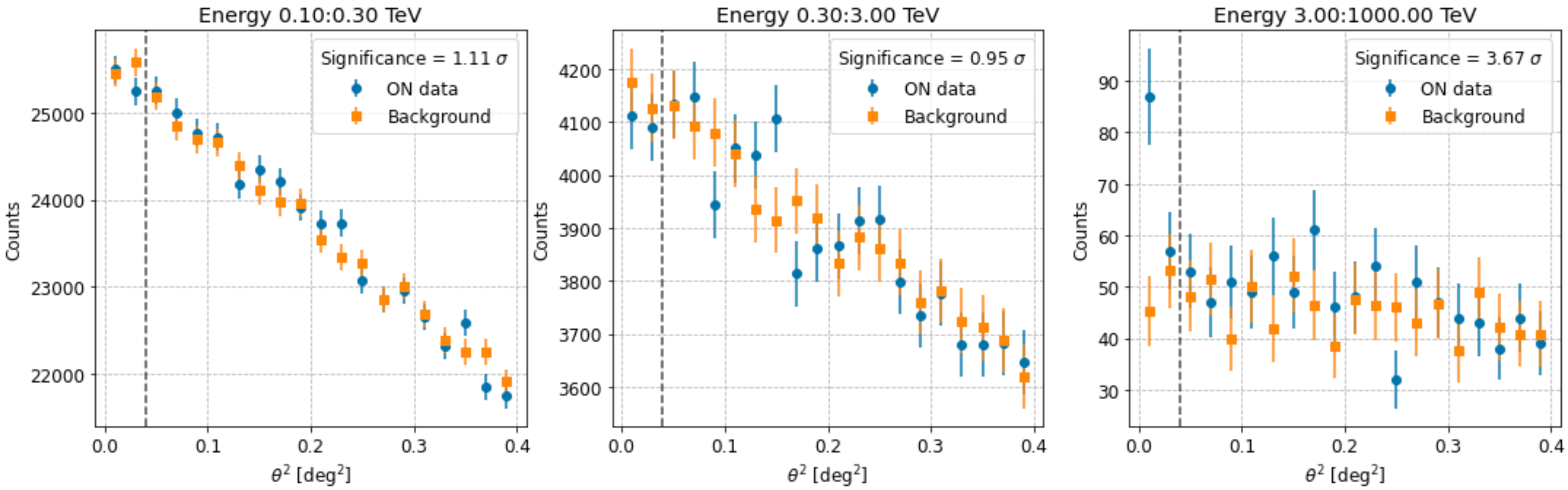

Figure from Palacio+(2019)

# LST-1 results: aiming for detection

- Theta² distribution in three blindly chosen energy bins
- Use of three reflected background positions (OFF regions) + the LHAASO reported coordinates (ON region)
- Gammaness and theta² 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%)**

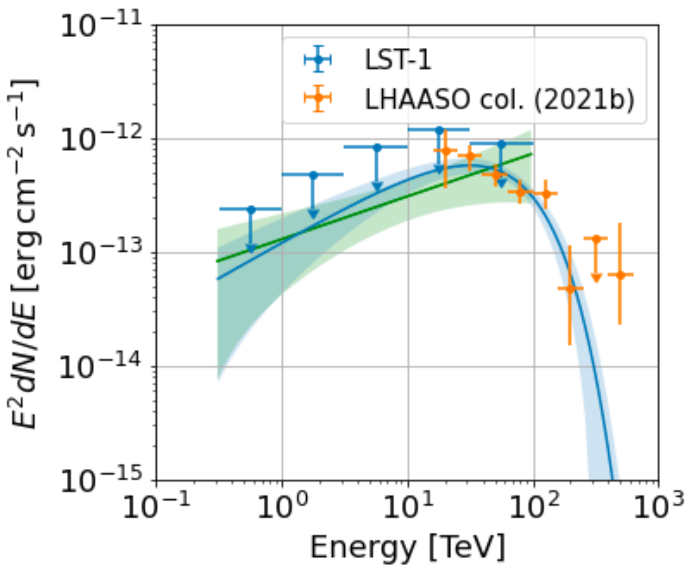
**Theta² distribution**

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
- 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**

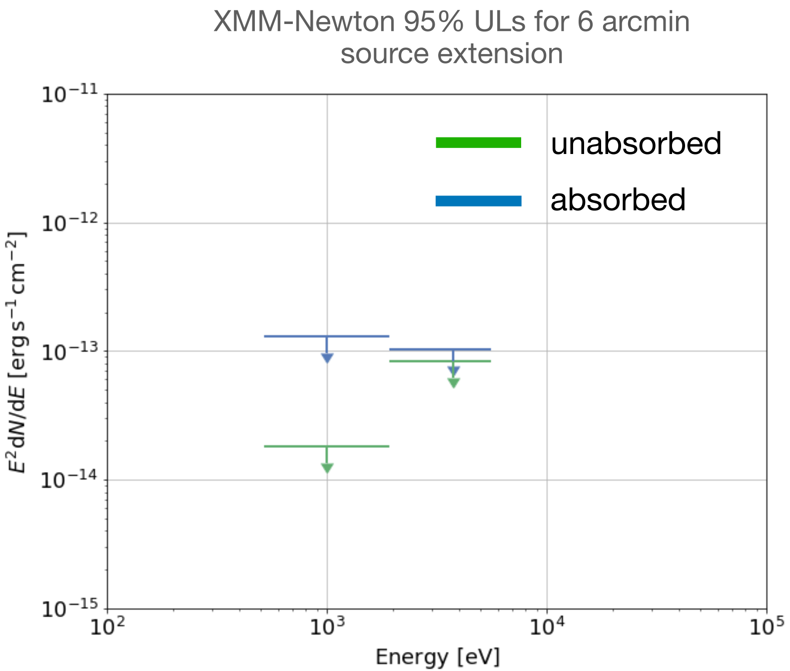



| Data | Spectral model | $N_0$ [$\times 10^{-14}$cm$^{-2}$s$^{-1}$TeV$^{-1}$] | $\Gamma$ | $E_{\text{cutoff}}$ [TeV] | $-2\log\mathcal{L}$ |
|---|---|---|---|---|---|
| LST-1 | PL | $8.02 \pm 5.42$ | $-1.62 \pm 0.23$ | - | 5.17 |
| LST-1 + LHAASO | ECPL | $7.57 \pm 4.82$ | $-1.37 \pm 0.22$ | $49.98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

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

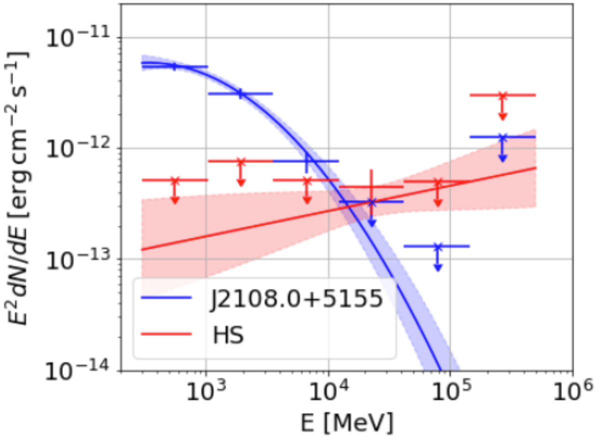
# XMM-Newton ToO observation

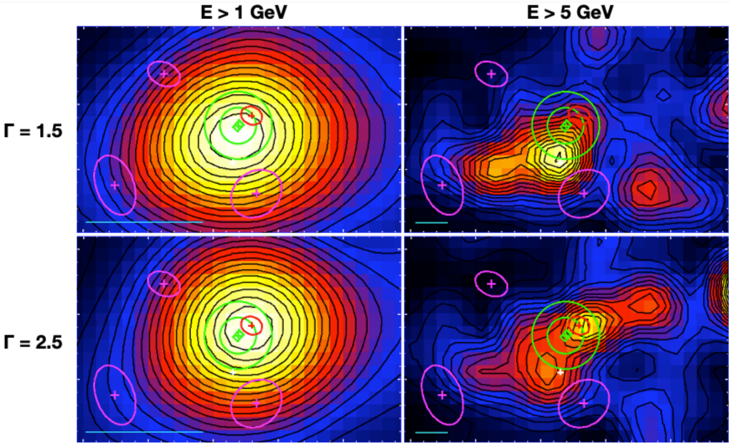
- Target of opportunity observation, **13.6 ks**, two energy bands: 0.5-2 keV, 2-7 keV
- **No detection**
- **Unknown source distance**: Two sets of ULs derived for different source distances
  - Absorbed (the source is distant)
  - Unabsorbed (the source is nearby)



# Fermi-LAT data analysis

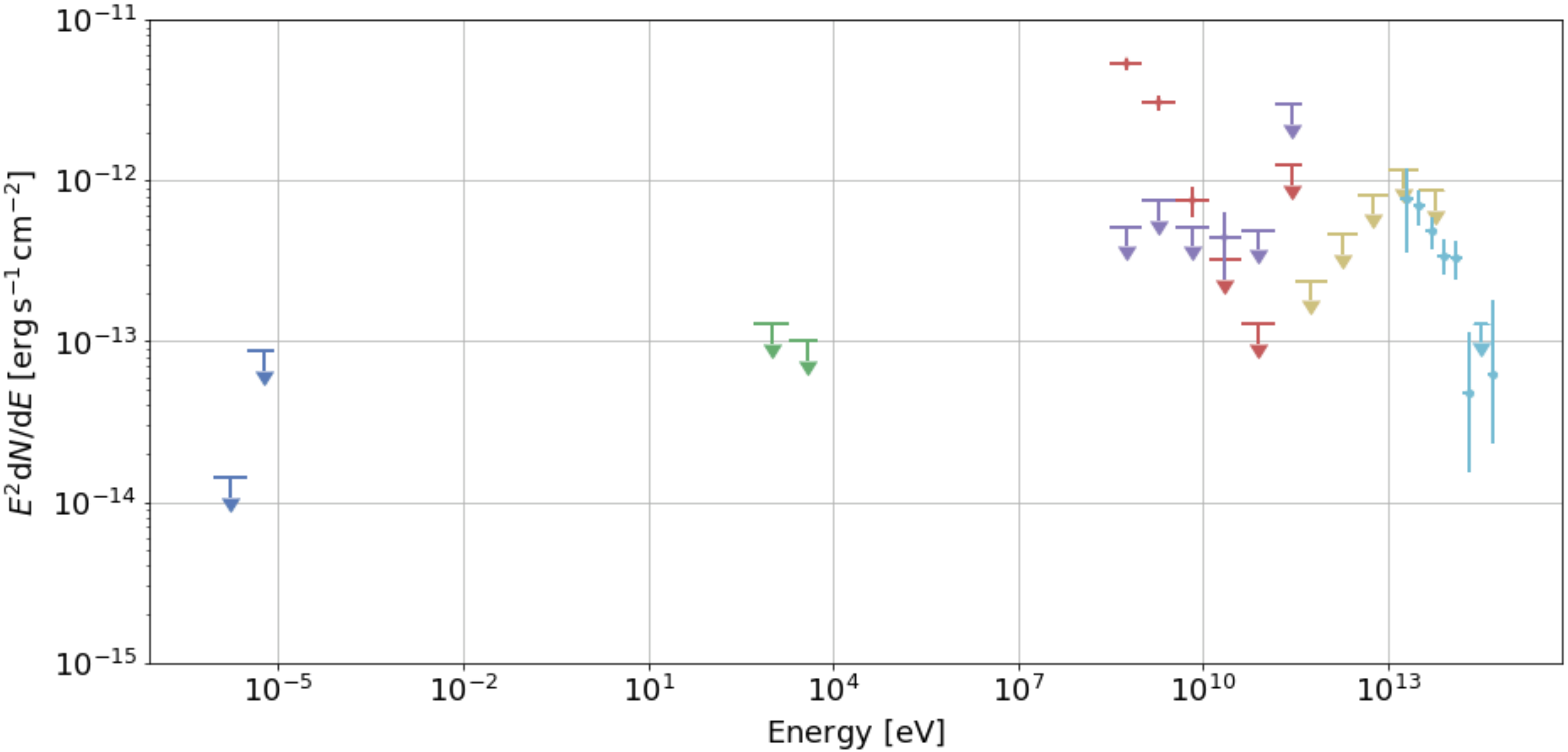
- Dedicated binned analysis of 12-year *Fermi*-LAT data
- Closest source 4FGL J2108.0+5155, a counterpart? - very soft spectrum
- **New hard spectrum source** (HS, 4sigma) dominating emission above ~4 GeV, located at the edge of the 95% extension limit of the UHE emission
- Likelihood fit adding HS in 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



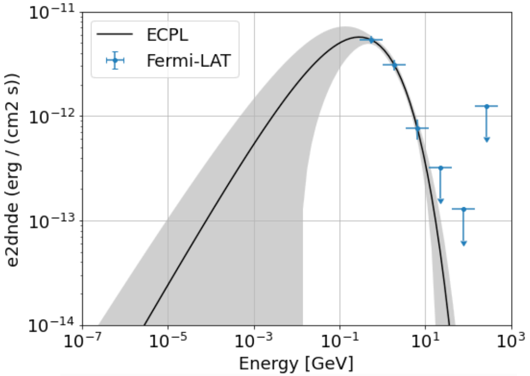




- Small green circle: 95% position uncertainty of the UHE source
- Larger green circle: 95% UL on the UHE source extension
- Known 4FGL-DR3 sources are shown in magenta

# Multi-wavelength SED



# 4FGL J2108.0+5155 - a pulsar hypothesis

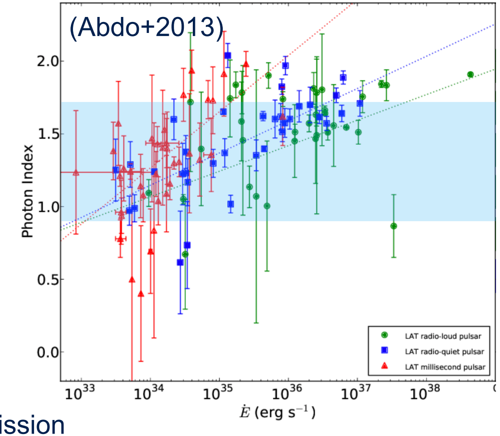



$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma} \exp(-(\lambda E)^{\alpha})$$

| 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 |

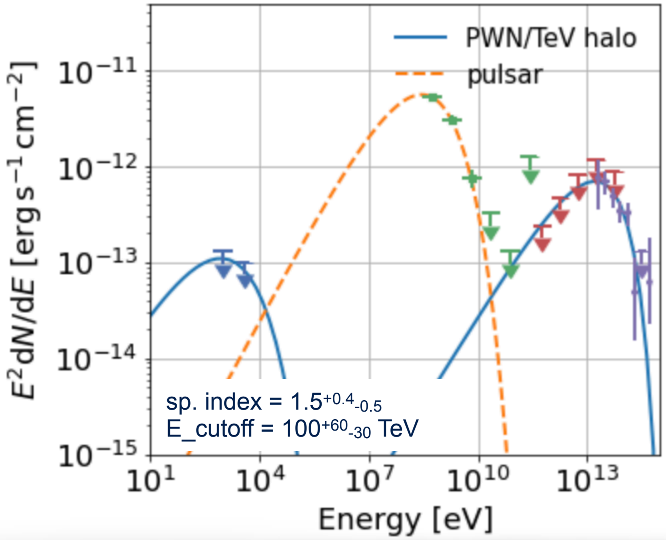
Sub-exponential cutoff - typical for a pulsar HE emission

- Parkinson (2016) **classified** the 3rd Fermi catalog counterpart 3FGL J2108.1+5202 **as a pulsar**
- **Problem: the source is not detected in radio/X-ray**
  - There is a population of radio quiet 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 ($\dot{E}$ = $10^{34-37}$ 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 (< 1 uG)**
  - Too low for a typical 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

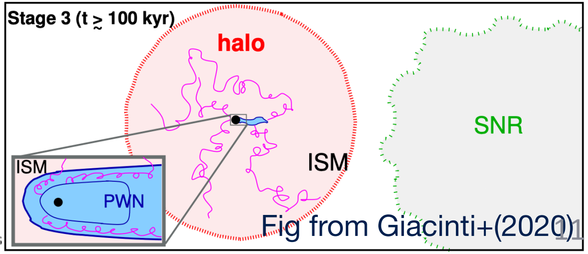
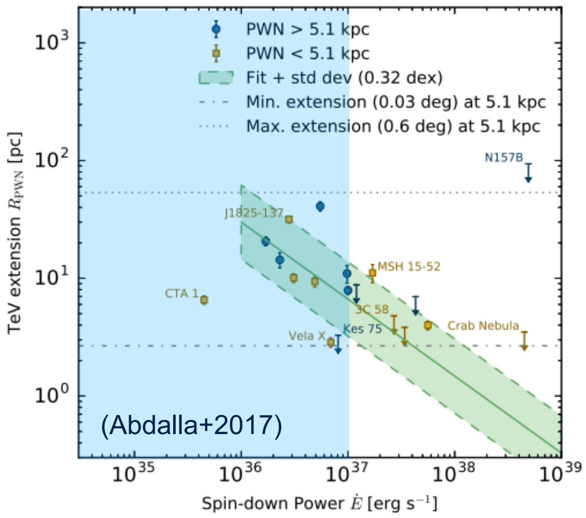
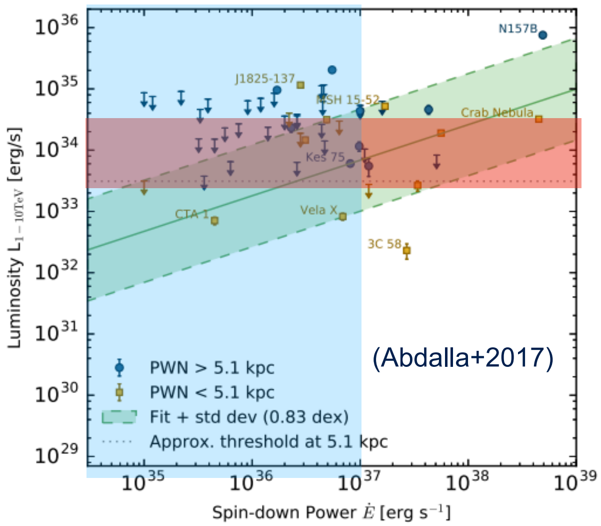



Fig from Giacinti+(2020)

# 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?

- Ce... 7,
  Li...
- TeV...
- LHA...
  dist...

## Energetics

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

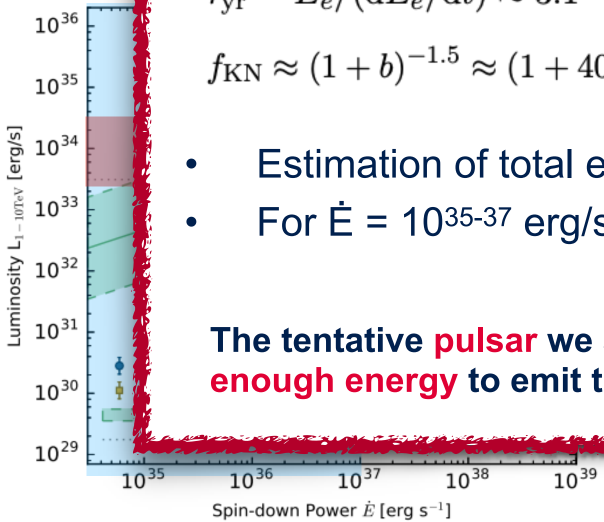
$$\tau_{yr} = E_e/(\mathrm{d}E_e/\mathrm{d}t) \approx 3.1 \cdot 10^5 U^{-1}_{\mathrm{rad,eV\,cm^{-3}}} E^{-1}_{e,\mathrm{TeV}} f^{-1}_{\mathrm{KN}}$$

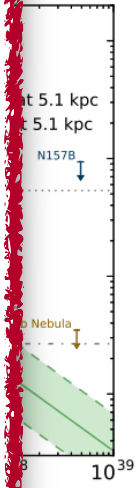
$$f_{\mathrm{KN}} \approx (1+b)^{-1.5} \approx (1 + 40 E_{e,\mathrm{TeV}} kT_{\mathrm{eV}})^{-1.5}$$

**Cooling time of 100 TeV electrons: 30 kyr**

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

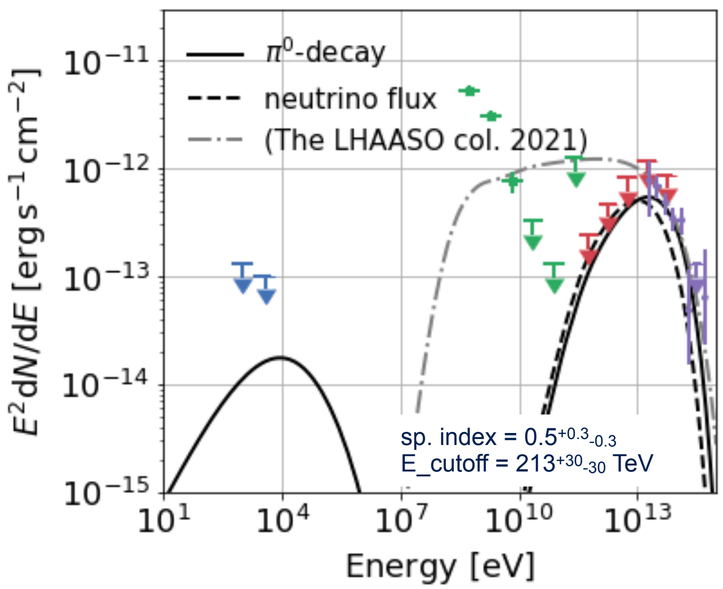
**The tentative pulsar we see in the GeV range could provide the electrons with enough energy to emit the observed IC if closer than ~10 kpc.**




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

# 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 TeV halo hypothesis

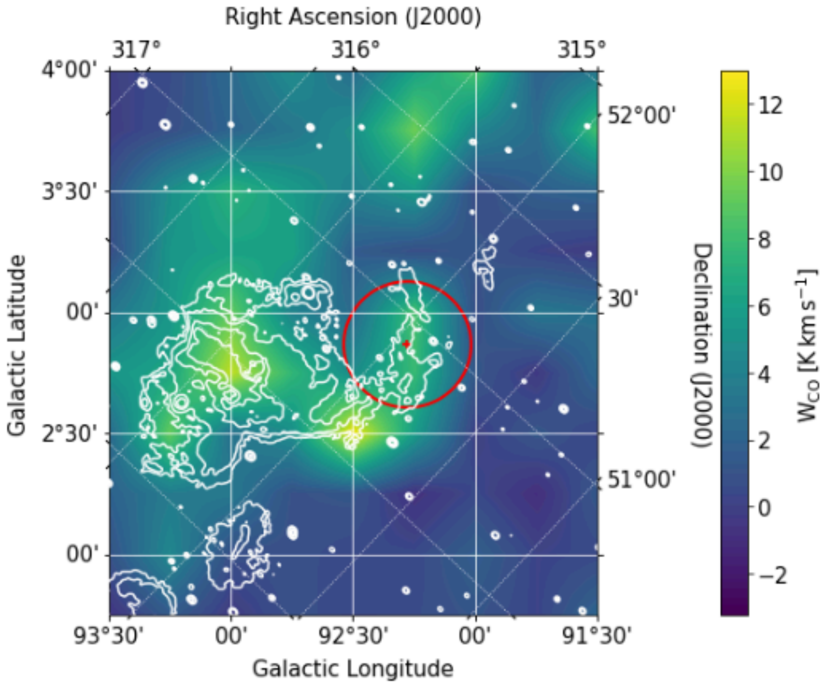
- **Interaction of relativistic protons with molecular clouds:**
  - Acceleration site unknown
  - Hard proton spectral index 0.5±0.3 needed to explain the emission - can be explained if gas clumps are present in a SNR shell, or if only the most energetic protons can escape the acceleration region

# Backup slides

# Molecular clouds

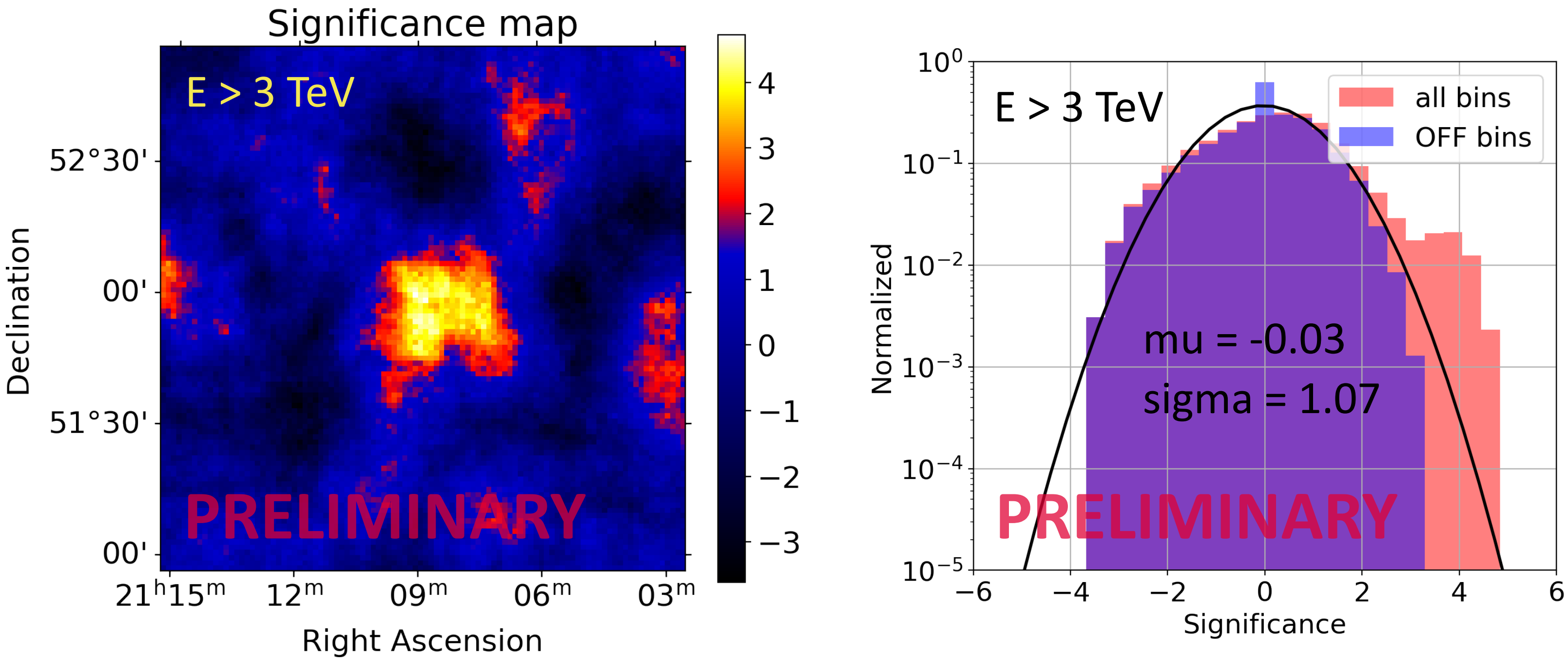
- Two molecular clouds spatially coincident with the source ($d_1$ = 3.1 kpc, $d_2$ = 2.0 kpc)
- Dedicated analysis to estimate total HI+$H_2$ density in the direction to the source
- **$H_2$**: Two peaks with v<0 km/s in CO(1-0) line spectrum radial velocity map
  - $n_1(H_2) = 51\ cm^{-3}$, $n_2(H_2)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

# Skymap


Significance map
E > 3 TeV
PRELIMINARY
52°30'
00'
51°30'
00'
Declination
21h15m
12m
09m
06m
03m
Right Ascension
4
3
2
1
0
−1
−2
−3
E > 3 TeV
all bins
OFF bins
mu = -0.03
sigma = 1.07
PRELIMINARY
Normalized
Significance