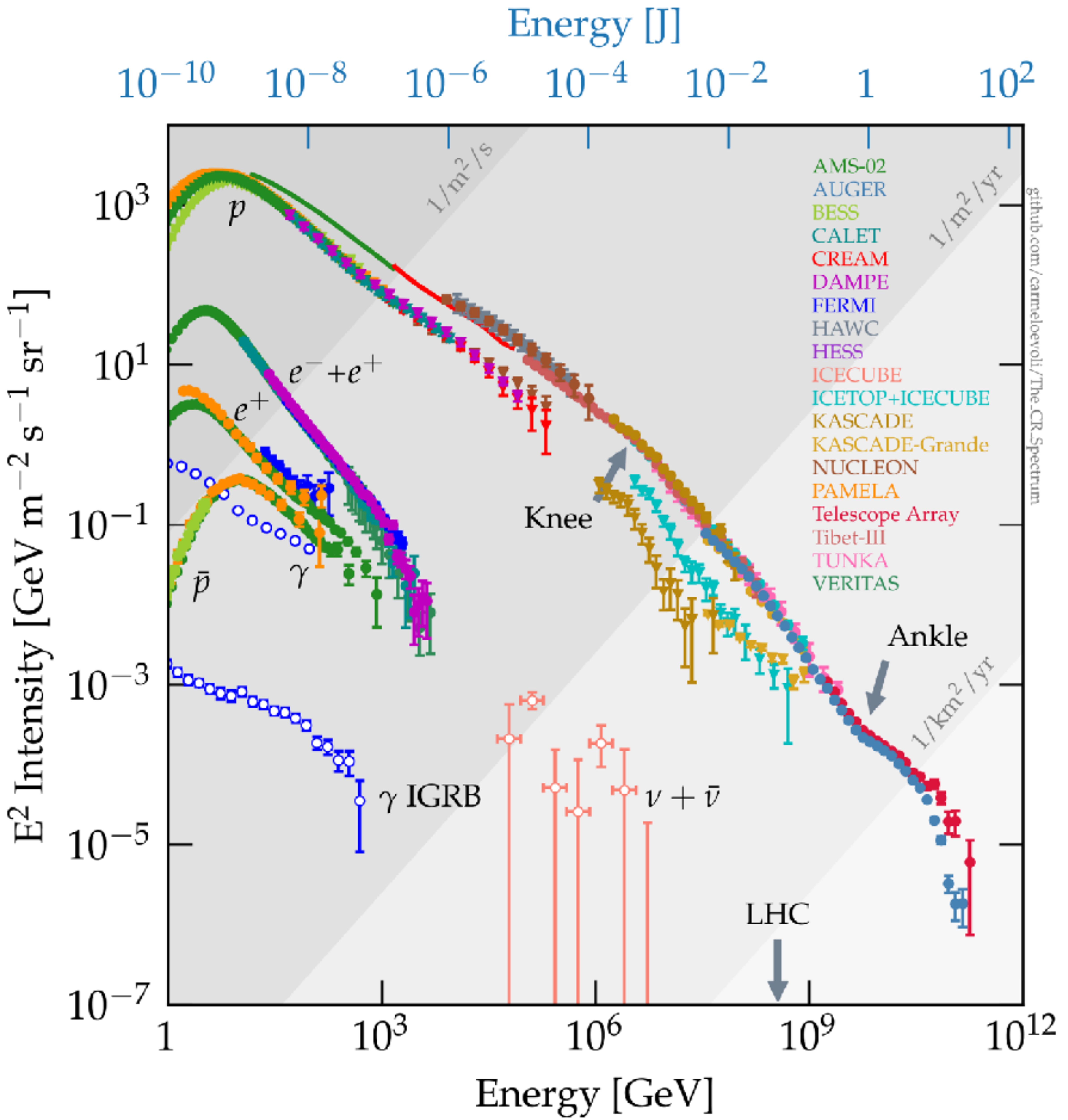
cherenkov telescope array

# Recent observation of LHAASO J2108+5157 with LST

SWISS CTA DAY 14-15 December 2022, Zurich

**BALBO MATTEO (on behalf of Jakub Jurysek et al.)**

# Where are the Galactic PeVatrons?




magnetic field

radius

shock speed

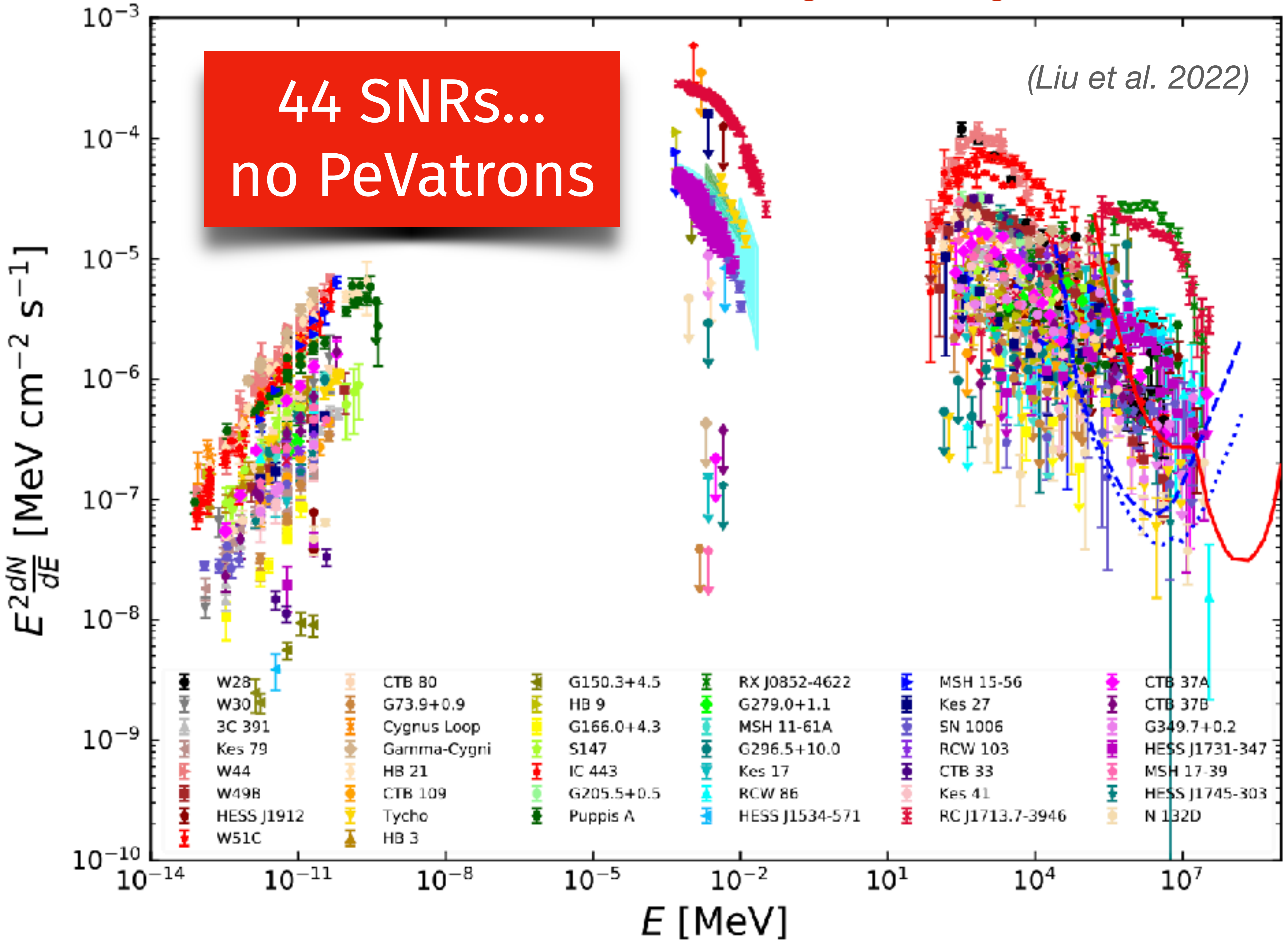
$$E_{max} \simeq v_s R B$$

**Hillas criterium:**

$$E_{max} \simeq 1 \left(\frac{v_s}{10^3 Km/s}\right)\left(\frac{R}{pc}\right)\left(\frac{B}{\mu G}\right) TeV$$

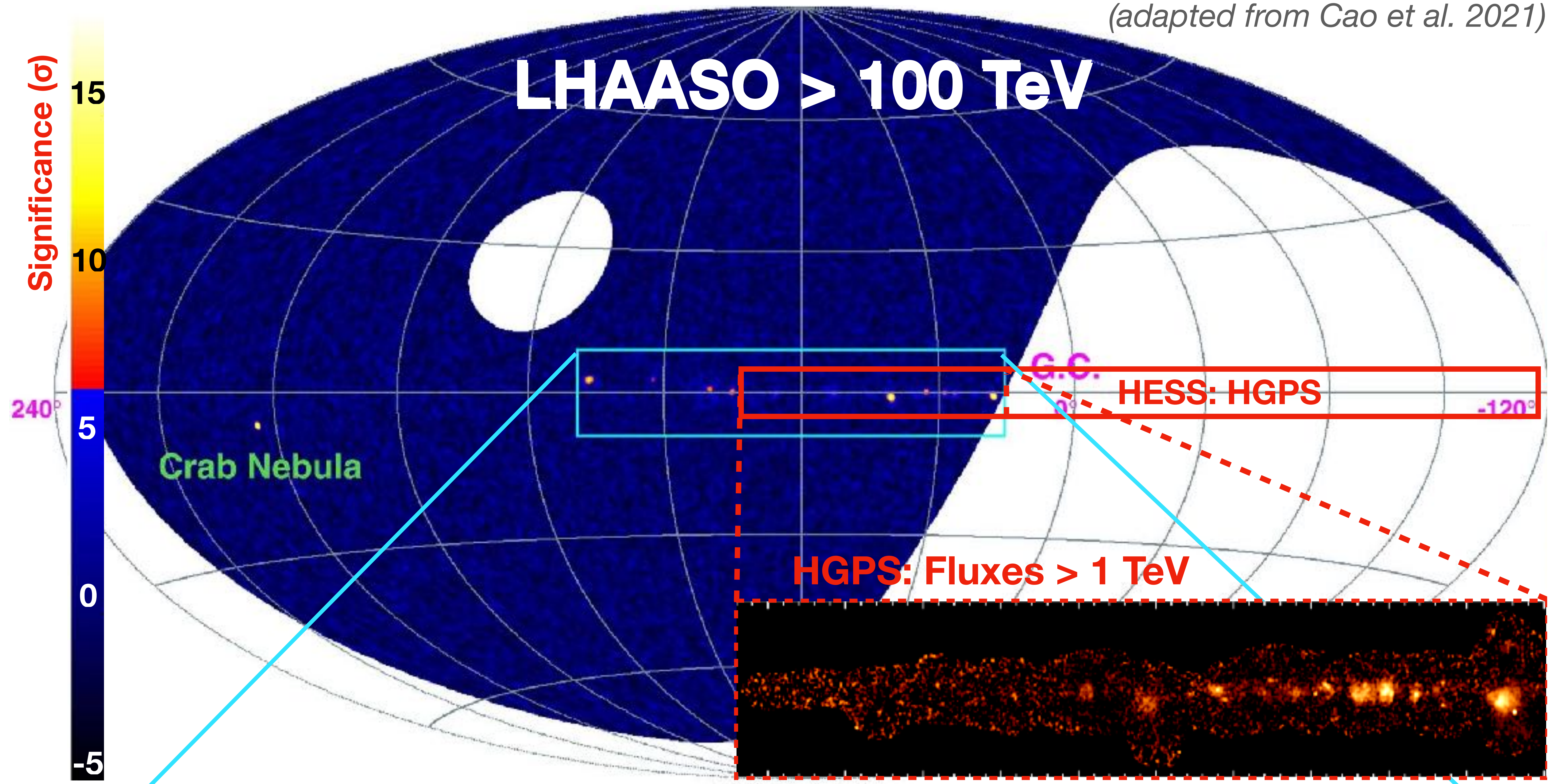
3 3 10

**44 SNRs... no PeVatrons**

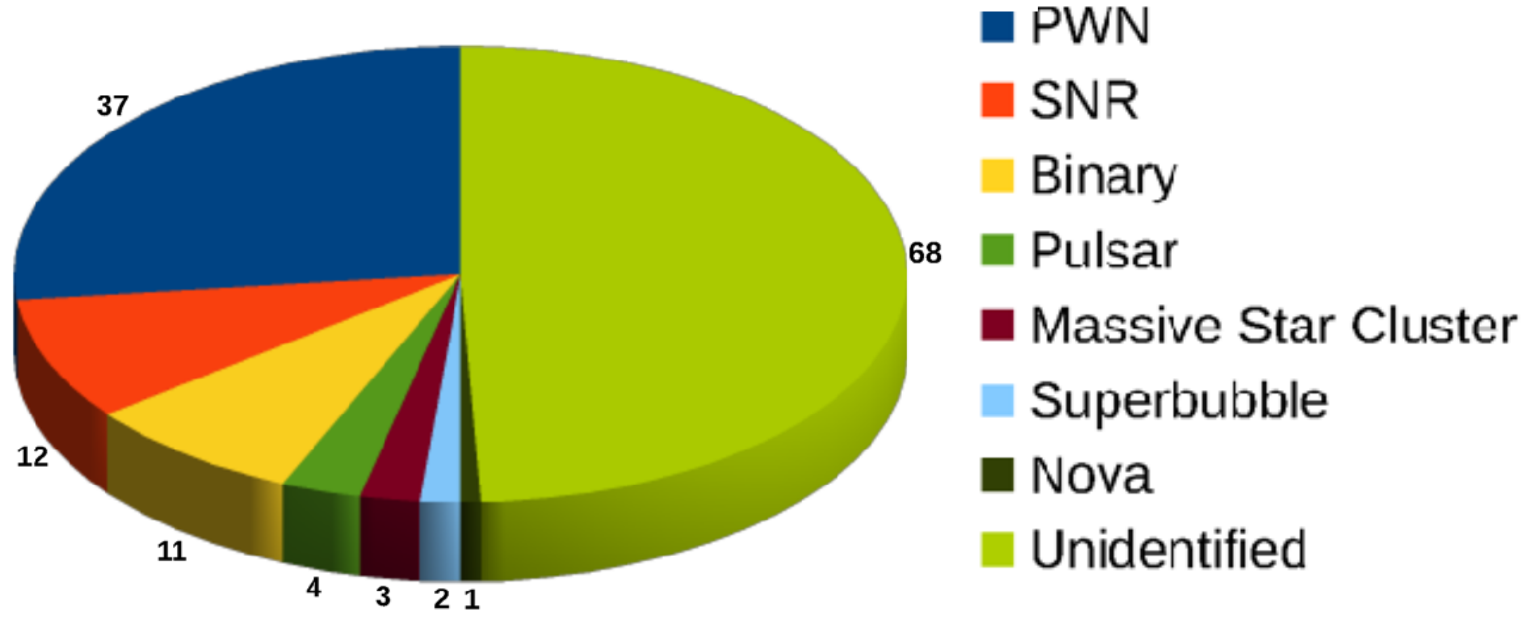


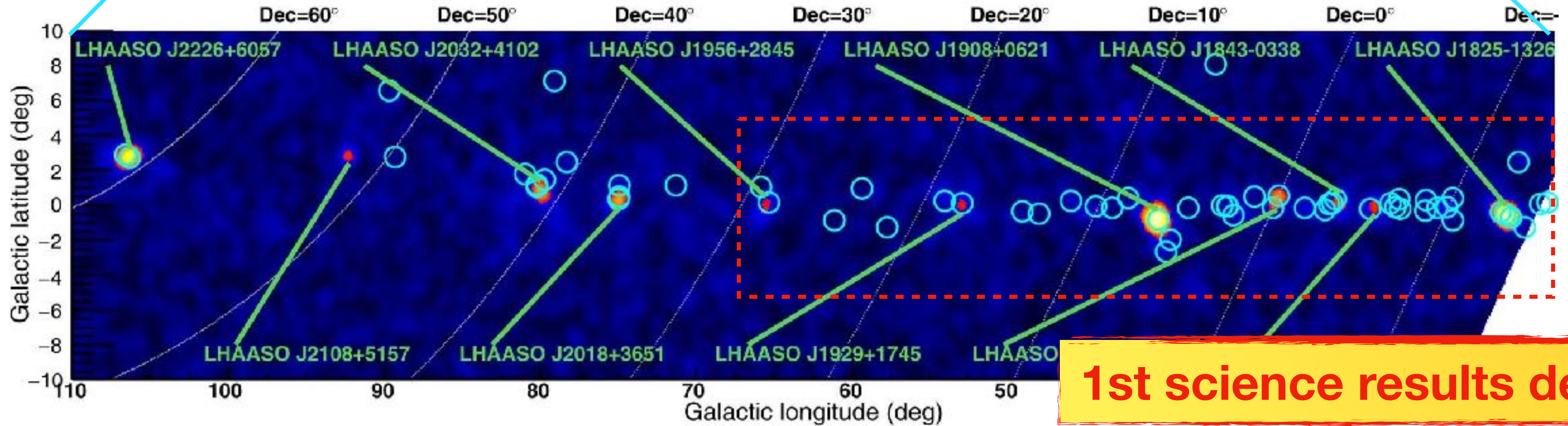
# Where are the Galactic PeVatrons?

(adapted from Cao et al. 2021)




TeVCat: Galactic sources




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

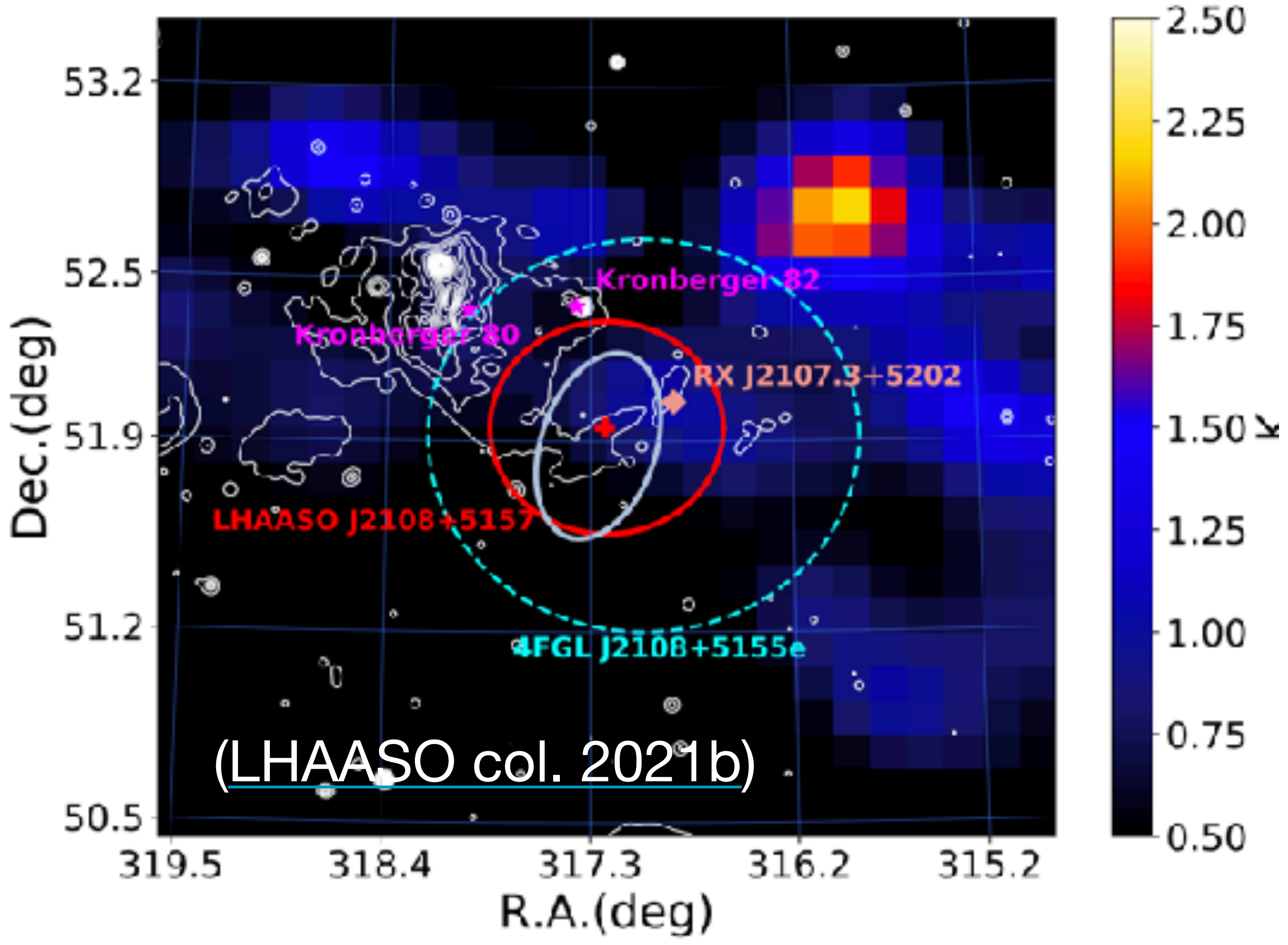
| LHAASO Source | Possible Origin | Type | Distance (kpc) | Age (kyr)[a] | $L_s$ (erg/s)[b] |
|---|---|---|---|---|---|
| LHAASO J0534+2202 | PSR J0534+2200 | PSR | 2.0 | 1.26 | $4.5 \times 10^{38}$ |
| LHAASO J1825-1326 | PSR J1826-1334 | PSR | $3.1 \pm 0.2^d$ | 21.4 | $2.8 \times 10^{36}$ |
| | PSR J1826-1256 | PSR | 1.6 | 14.4 | $3.6 \times 10^{36}$ |
| LHAASO J1839-0545 | PSR J1837-0604 | PSR | 4.8 | 33.8 | $2.0 \times 10^{36}$ |
| | PSR J1838-0537 | PSR | $1.3^e$ | 4.9 | $6.0 \times 10^{36}$ |
| LHAASO J1843-0338 | SNR G28.6-0.1 | SNR | $9.6 \pm 0.3^f$ | $< 2^f$ | — |
| LHAASO J1849-0003 | PSR J1849-0001 | PSR | $7^g$ | 43.1 | $9.8 \times 10^{36}$ |
| | W43 | YMC | $5.5^h$ | — | — |
| LHAASO J1908+0621 | SNR G40.5-0.5 | SNR | $3.4^i$ | $\sim 10 - 20^j$ | — |
| | PSR 1907+0602 | PSR | 2.4 | 19.5 | $2.8 \times 10^{36}$ |
| | PSR 1907+0631 | PSR | 3.4 | 11.3 | $5.3 \times 10^{35}$ |
| LHAASO J1929+1745 | PSR J1928+1746 | PSR | 4.6 | 82.6 | $1.6 \times 10^{36}$ |
| | PSR J1930+1852 | PSR | 6.2 | 2.9 | $1.2 \times 10^{37}$ |
| | SNR G54.1+0.3 | SNR | $6.3^{+0.8\ d}_{-0.7}$ | $1.8 - 3.3^k$ | — |
| LHAASO J1956+2845 | PSR J1958+2846 | PSR | 2.0 | 21.7 | $3.4 \times 10^{35}$ |
| | SNR G66.0-0.0 | SNR | $2.3 \pm 0.2^d$ | — | — |
| LHAASO J2018+3651 | PSR J2021+3651 | PSR | $1.8^{+1.7\ l}_{-1.4}$ | 17.2 | $3.4 \times 10^{36}$ |
| | Sh 2-104 | H II/YMC | $3.3 \pm 0.3^m/4.0 \pm 0.5^n$ | — | — |
| LHAASO J2032+4102 | Cygnus OB2 | YMC | $1.40 \pm 0.08^o$ | — | — |
| | PSR 2032+4127 | PSR | $1.40 \pm 0.08^o$ | 201 | $1.5 \times 10^{35}$ |
| | SNR G79.8+1.2 | SNR candidate | — | — | — |
| LHAASO J2108+5157 | — | — | — | — | — |
| LHAASO J2226+6057 | SNR G106.3+2.7 | SNR | $0.8^p$ | $\sim 10^p$ | — |
| | PSR J2229+6114 | PSR | $0.8^p$ | $\sim 10^p$ | $2.2 \times 10^{37}$ |

**1st science results derived from LST data! (Submitted to A&A)**

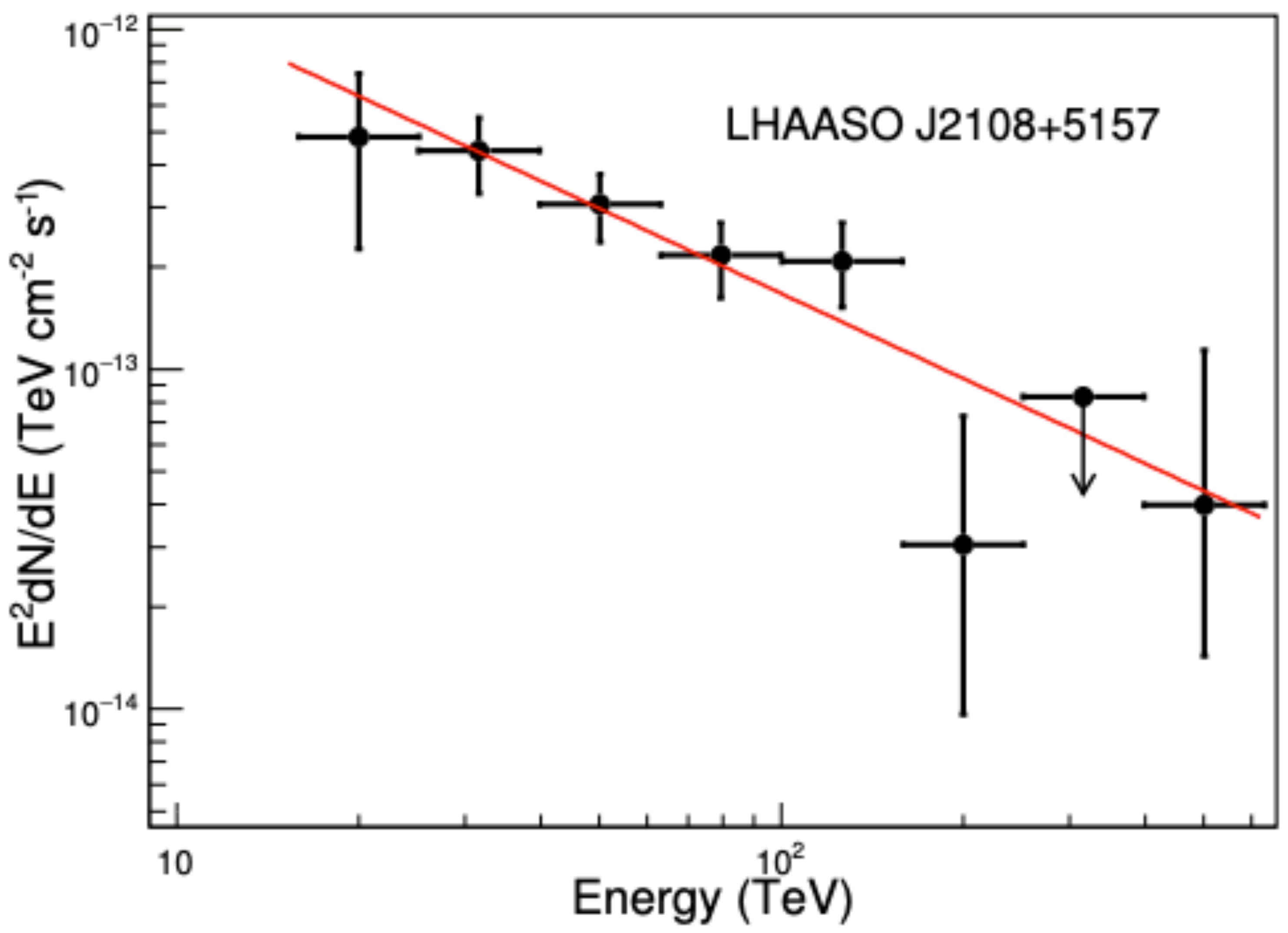
# LHAASO J2108+5157

- 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.

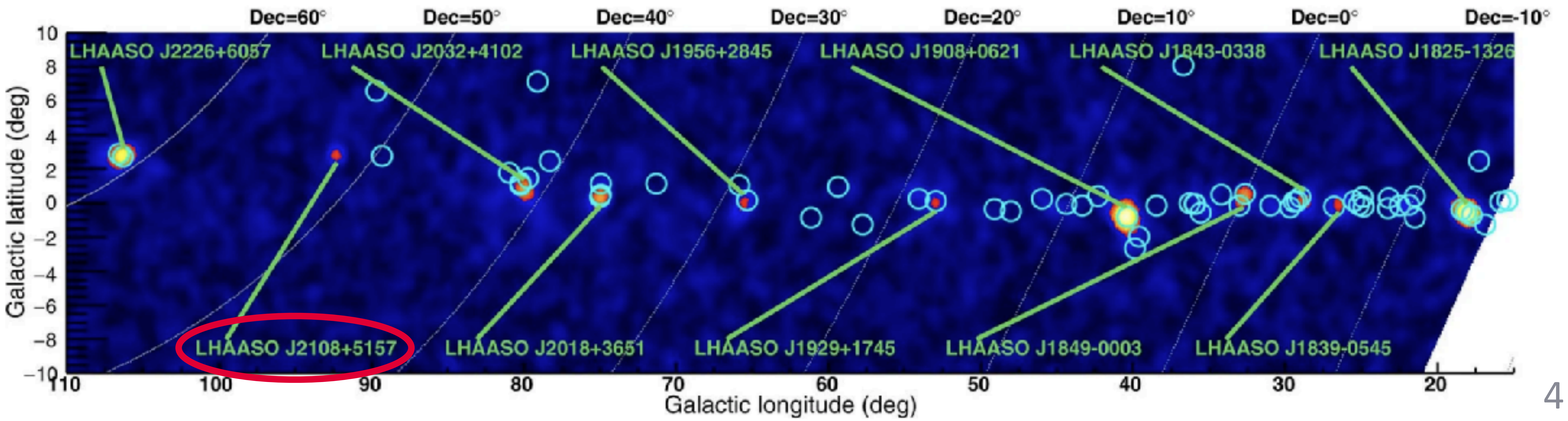
Brightness temperature distribution of 12CO(1–0) line survey




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




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

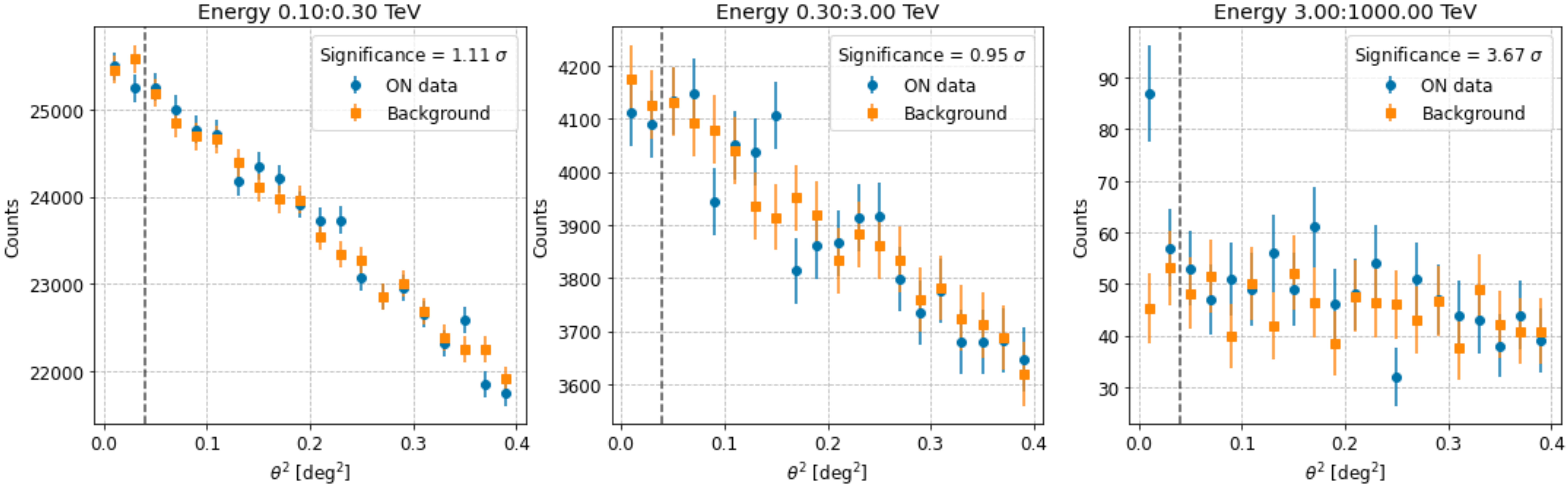


# LST-1 results: aiming for detection

- 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%)**

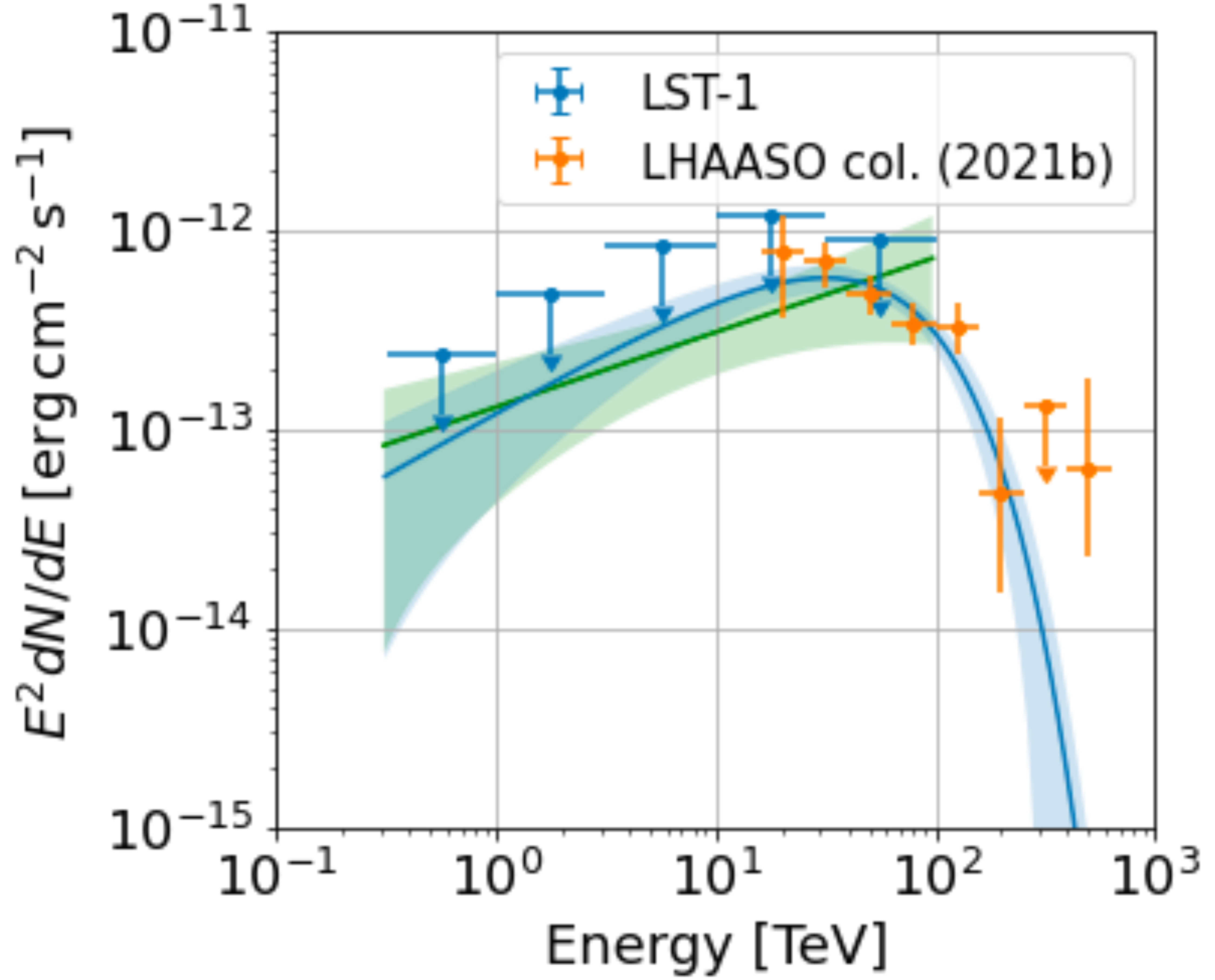
**Theta² distribution**

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**



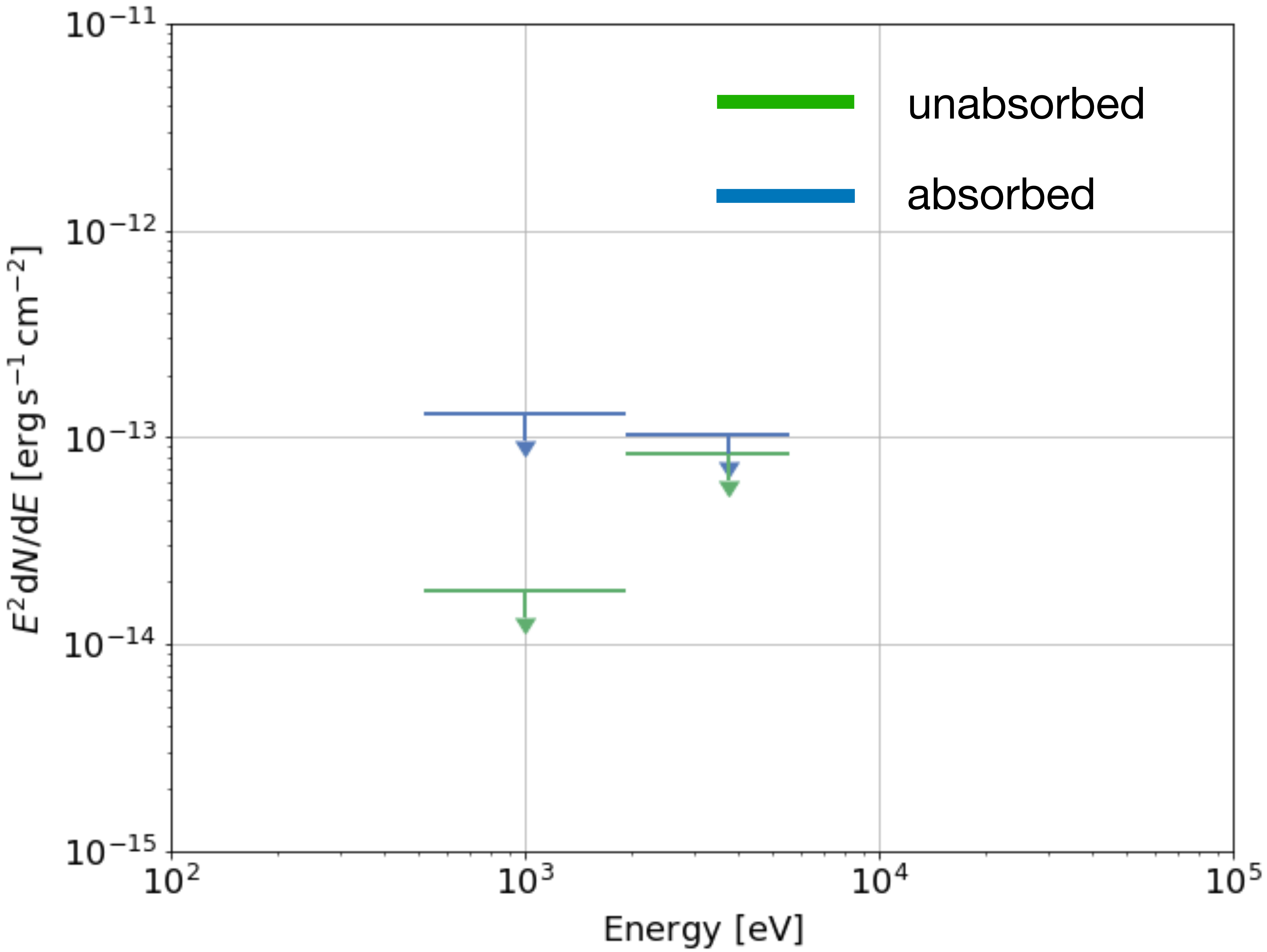

| Data | Spectral model | $N_0$ [$\times 10^{-14}$cm$^{-2}$s$^{-1}$TeV$^{-1}$] | $\Gamma$ | $E_{cutoff}$ [TeV] | $-2\log\mathcal{L}$ |
|---|---|---|---|---|---|
| LST-1 | PL | $8.02 \pm 5.42$ | $-1.62 \pm 0.23$ | - | 5.17 |
| LST-1 + LHAASO | ECPL | $7.57 \pm 4.82$ | $-1.37 \pm 0.22$ | $49.98 \pm 13.49$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

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

# XMM-Newton ToO observation

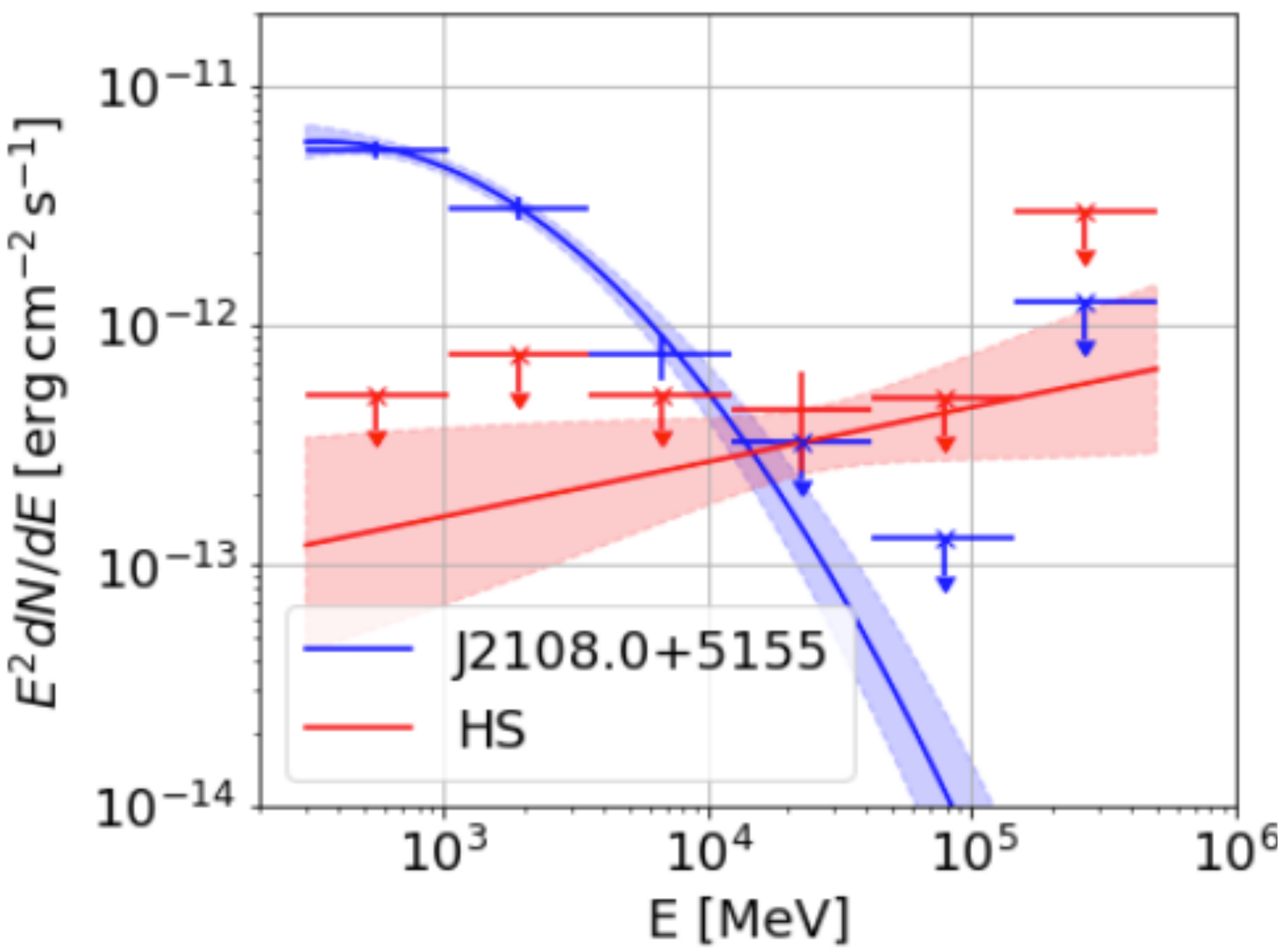
- Target of opportunity observation, **13.6 ks**, two energy bands: 0.5-2 keV, 2-7 keV
- **No detection**
- **Unknown source distance**: Two sets of ULs derived for different source distances
  - Absorbed (the source is distant)
  - Unabsorbed (the source is nearby)

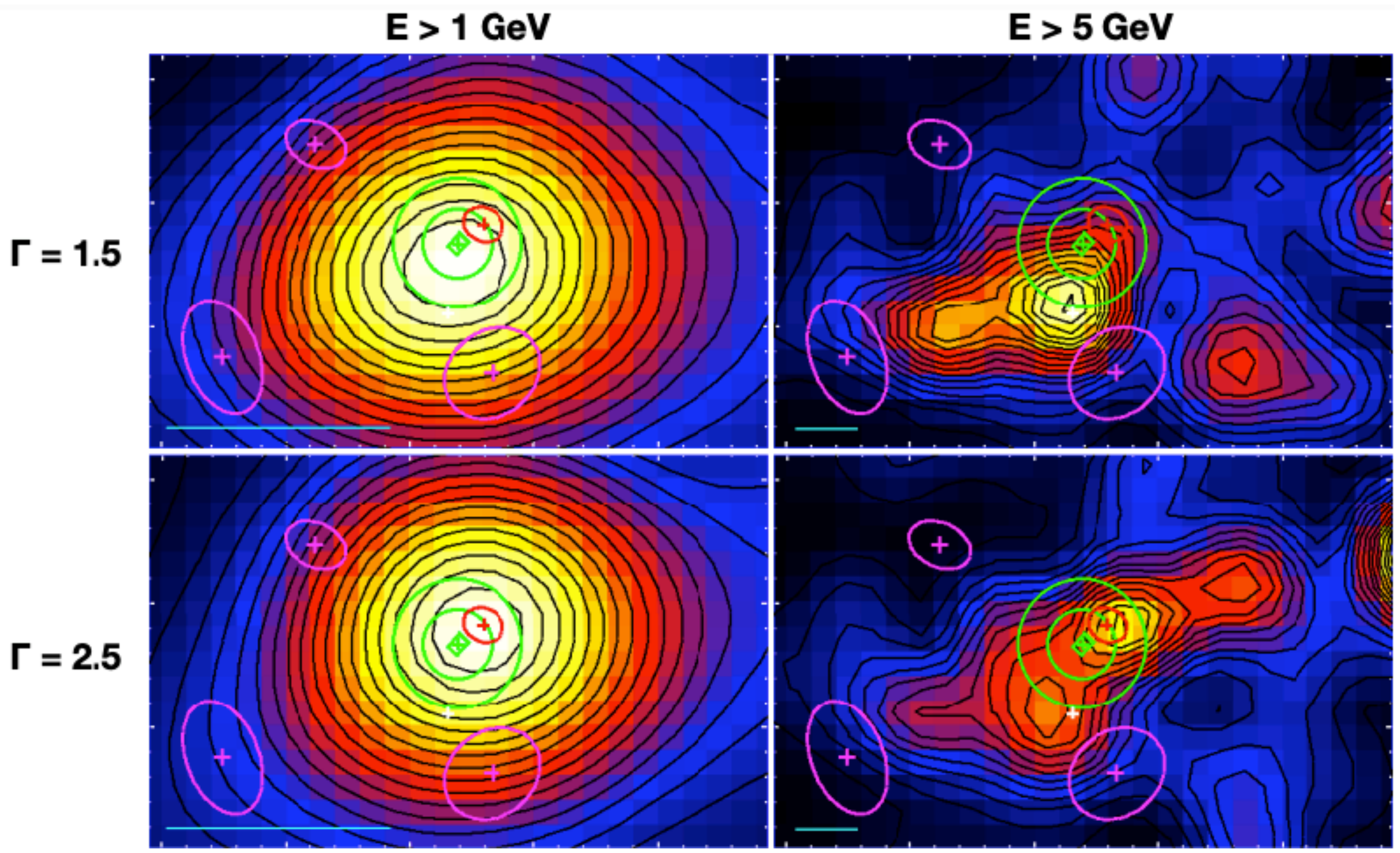
XMM-Newton 95% ULs for 6 arcmin source extension



# 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

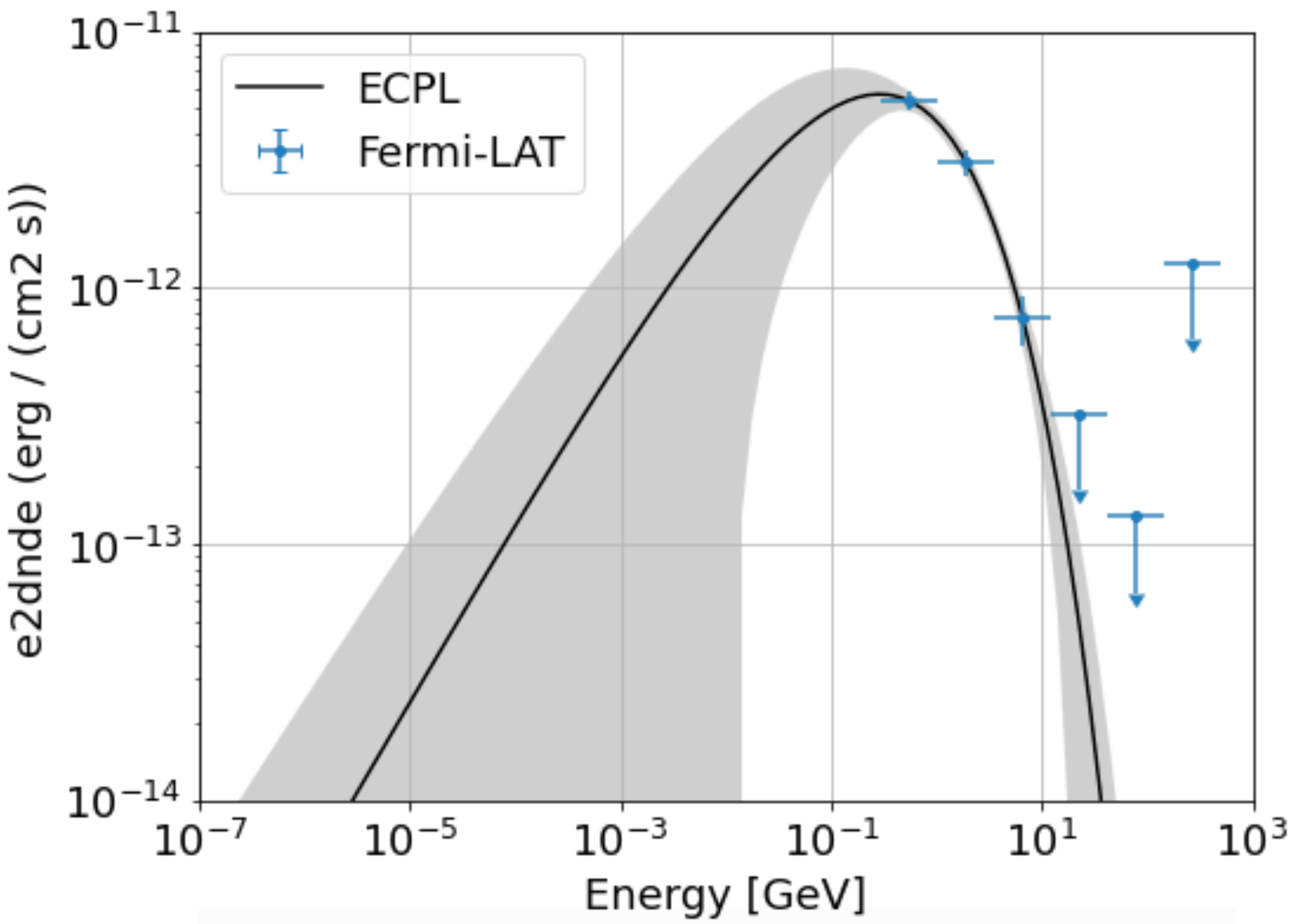



- Small green circle: 95% position uncertainty of the UHE source
- Large green circle: 95% UL on the UHE source extension
- Known 4FGL-DR3 sources are shown in magenta
- 4FGL J2108.0+5155 is shown in red
- new HS source is white

# Multi-wavelength SED

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

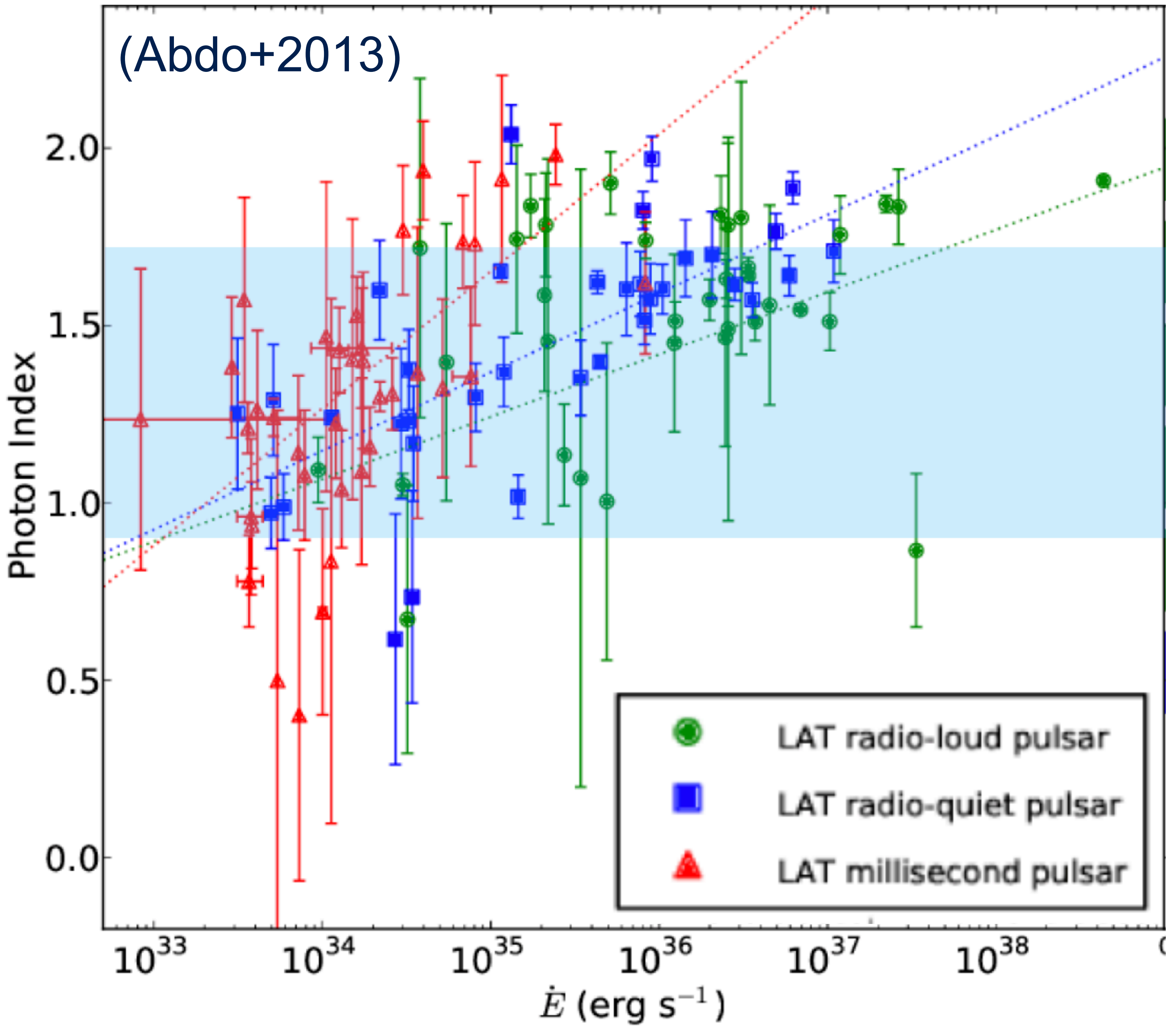



$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma} \exp(-(\lambda E)^{\alpha})$$

| parameter | value | error | unit |
|---|---|---|---|
| index | 1.29E+00 | 4.1E-01 | |
| amplitude | 7.85E-09 | 3.8E-08 | $cm^{-2}\ s^{-1}\ TeV^{-1}$ |
| reference | 1E+00 | —— | TeV |
| lambda | 1.89E+01 | 6.3E+01 | $GeV^{-1}$ |
| alpha | 3.76E-01 | 1.7E-01 | |

Sub-exponential cutoff - typical for a pulsar HE emission

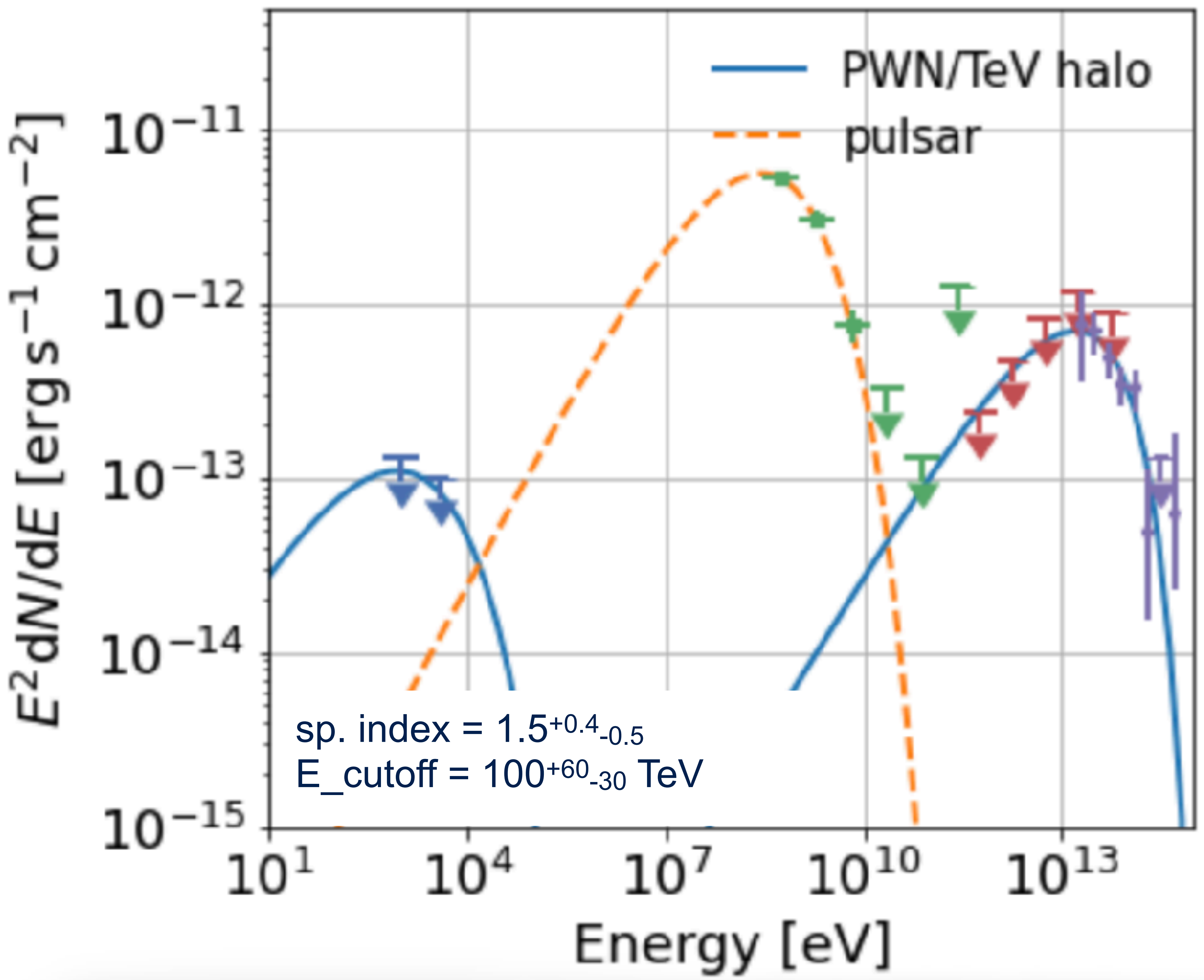
- Parkinson (2016) **classified** the 3rd Fermi catalog counterpart 3FGL J2108.1+5202 **as a pulsar**
- **Problem: the source is not detected in radio/X-ray**
  - There is a population of radio quiet pulsars with SED dominated by HE/VHE emission (e.g. Geminga)




Sub-exponential cutoff power-law phenomenological model compared with 2nd Fermi PSR catalog (Abdo+2013) -> **spin-down power of tentative pulsar constrained**

**($\dot{E}$ = $10^{34\text{-}37}$ 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 μG)**
  - Too low for a typical PWN (~1 - 100 μG)
  - 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

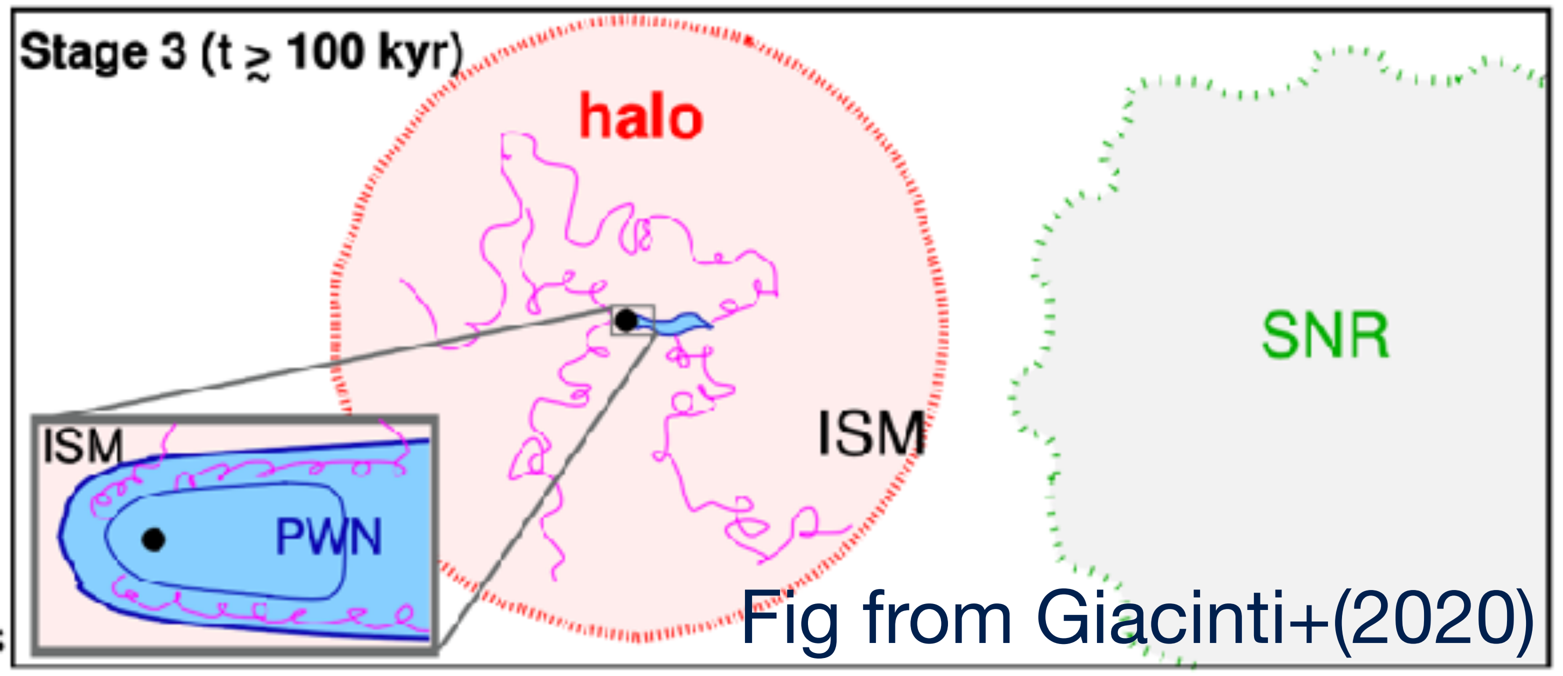
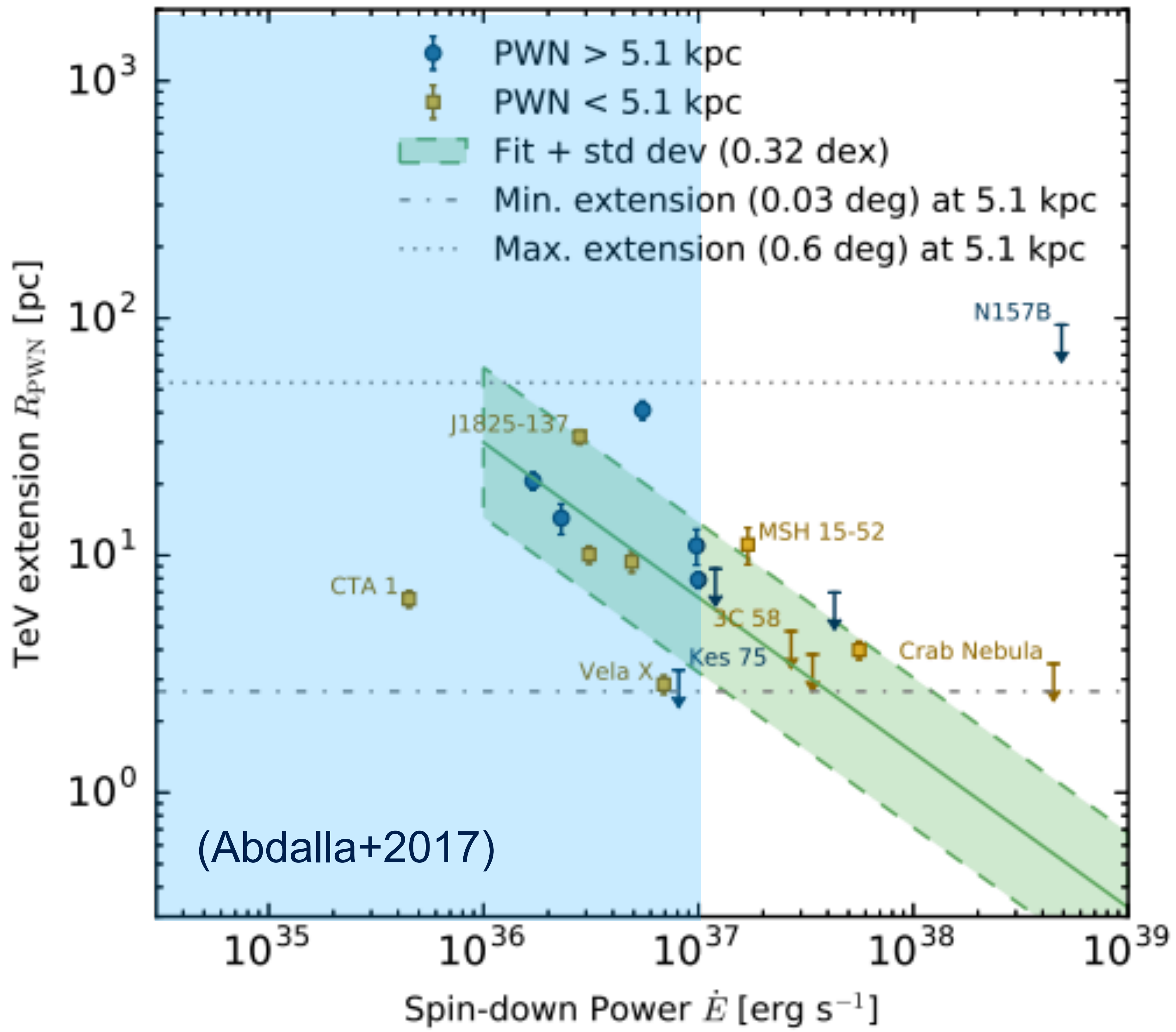
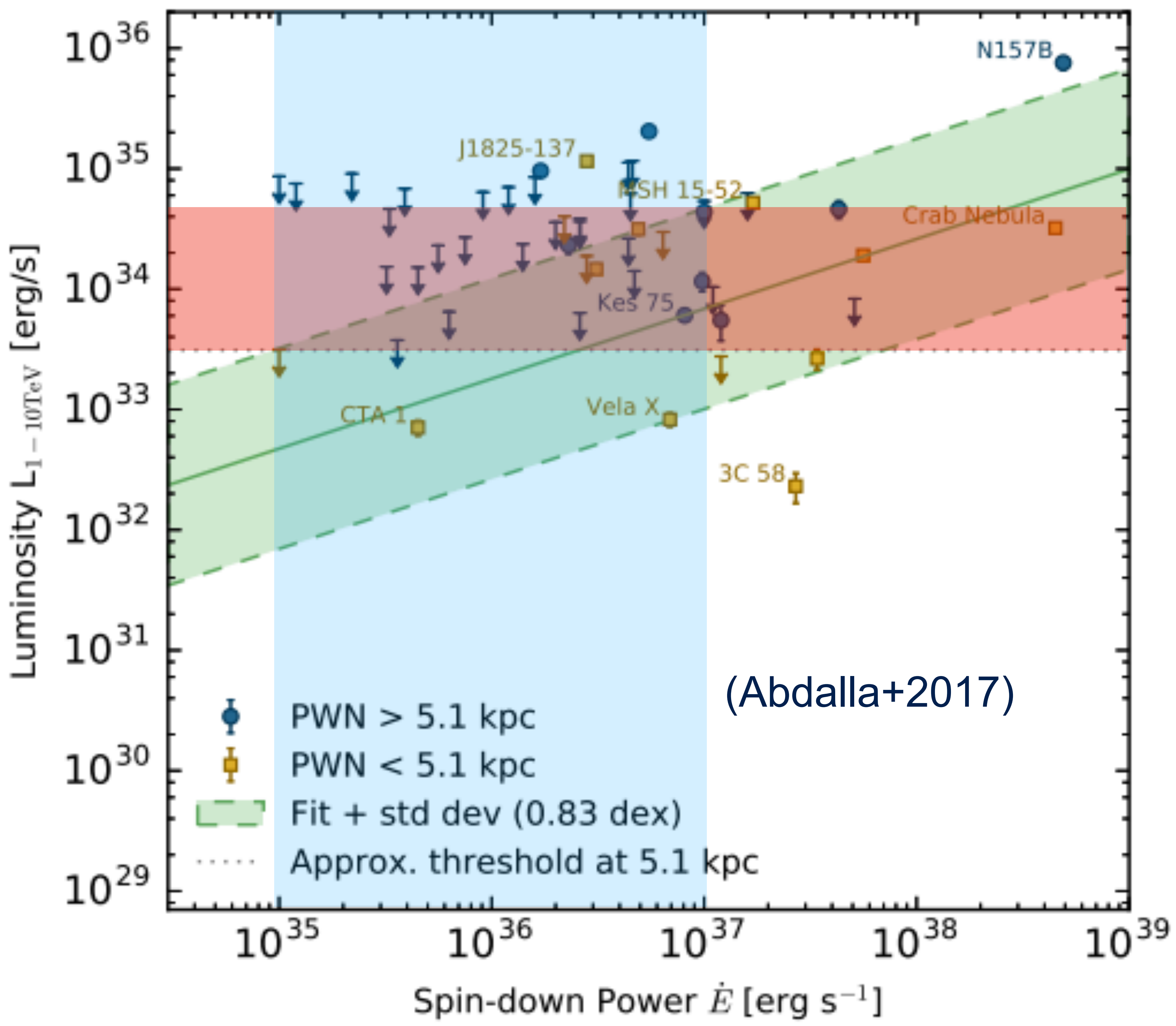


Fig from Giacinti+(2020)

# TeV emission - PWN/TeV halo object?

- Comparison of TeV emission with population of TeV PWNe/TeV halos (Abdalla+2017, 00) following the pulsar hypothesis
- TeV extension for PSR of given Ė ≳ 10 pc
- LHAASO ULs on extension 0.26 deg => distance ≳2

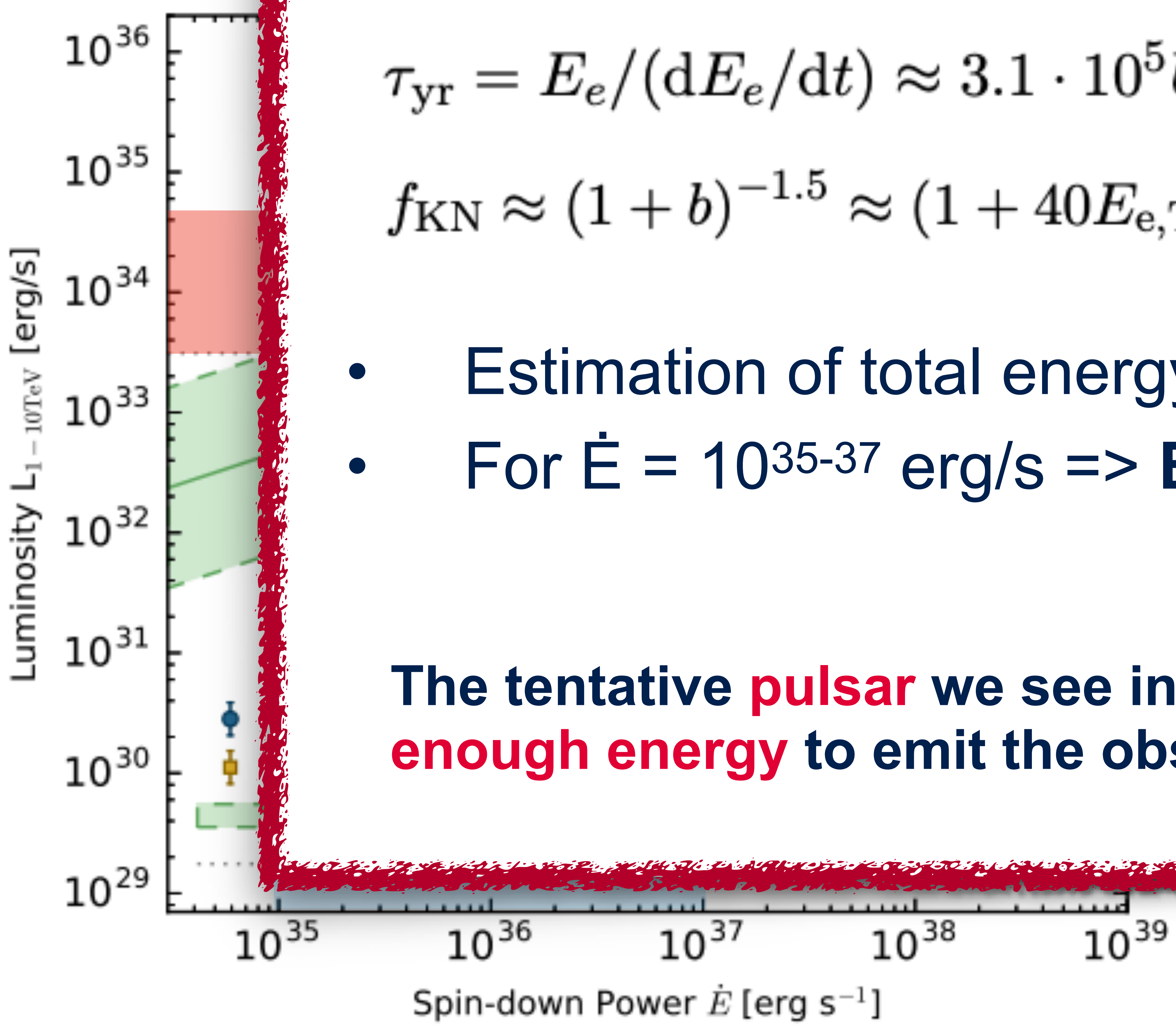



- TeV luminosity constrained by Galactic geometrical reasons and possible source extension consistent with limits on spin-down power from Fermi-LAT, further constraints on Ė = $10^{35-37}$ erg/s

# TeV emission - PWN/TeV halo object?

- Comparison of TeV emission with population of TeV PWN … puls…
- TeV…
- LHA…




## Energetics

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

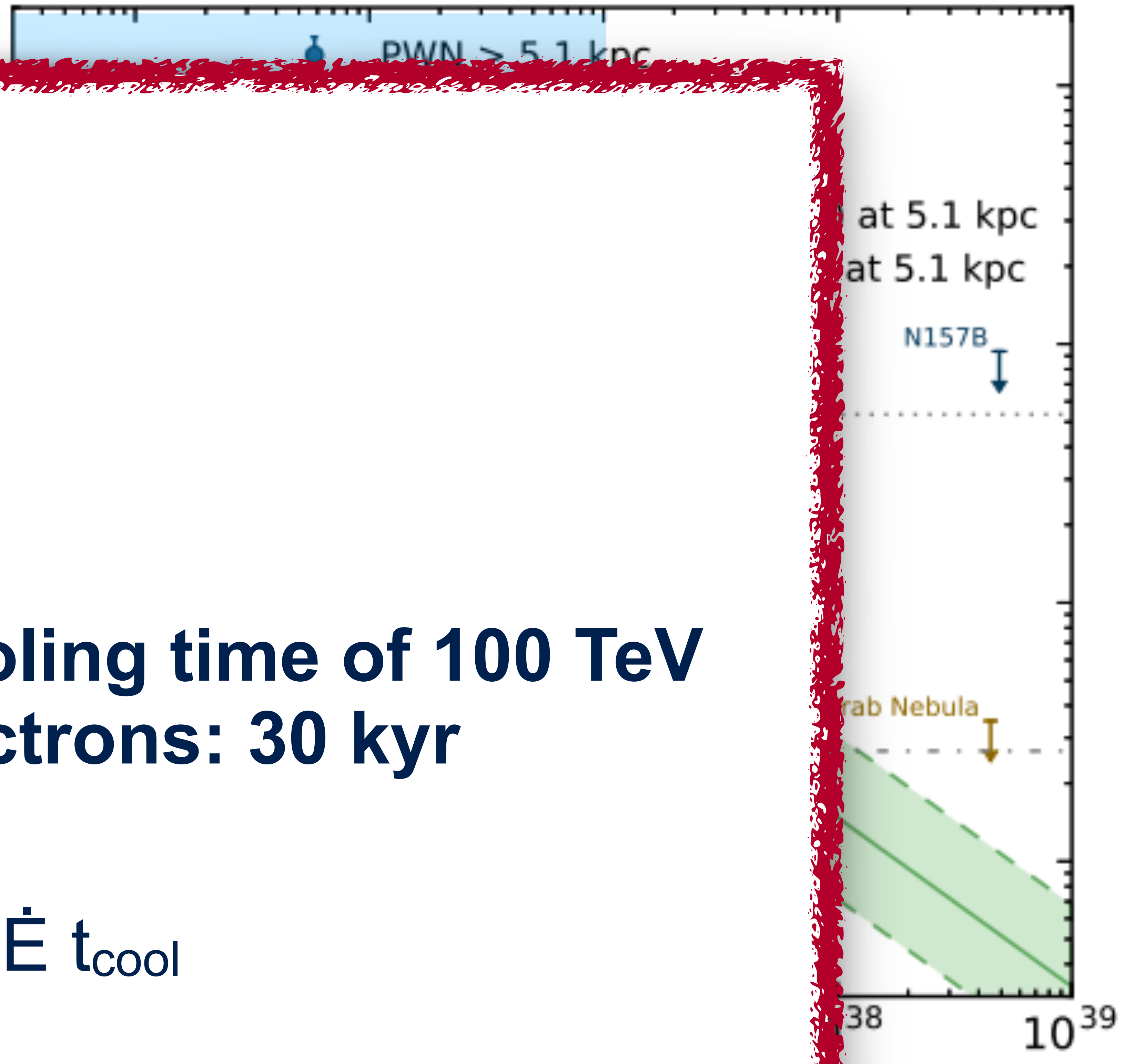
$$\tau_{yr} = E_e/(\mathrm{d}E_e/\mathrm{d}t) \approx 3.1 \cdot 10^5 U^{-1}_{\mathrm{rad,eV\,cm^{-3}}} E^{-1}_{e,\mathrm{TeV}} f^{-1}_{\mathrm{KN}}$$

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

**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 => **$E_{psr} = 10^{47\text{-}49}$ 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.**

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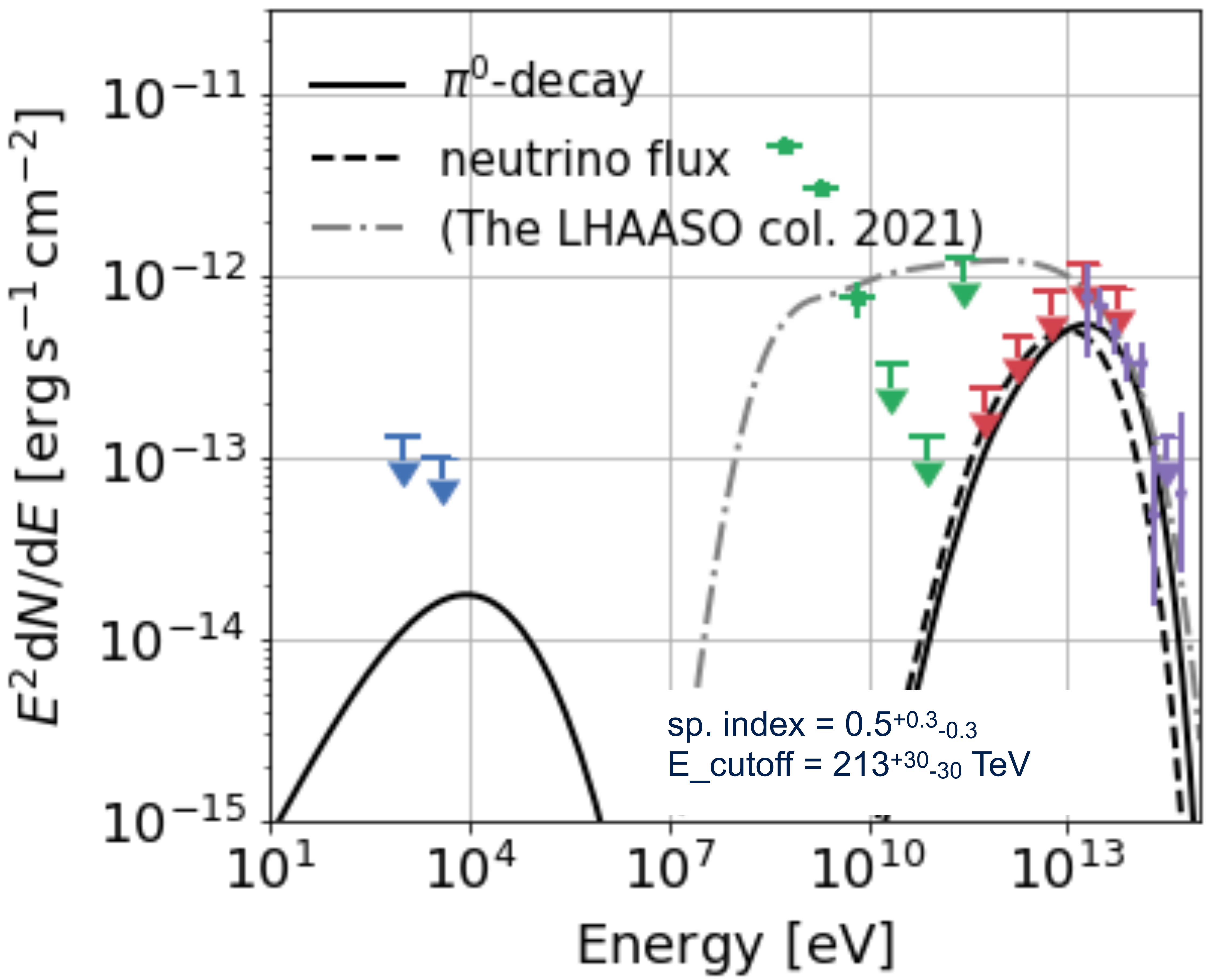
…-down
power from Fermi-LAT, further constraints on $\dot{E}$ = $10^{35\text{-}37}$ erg/s

# 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