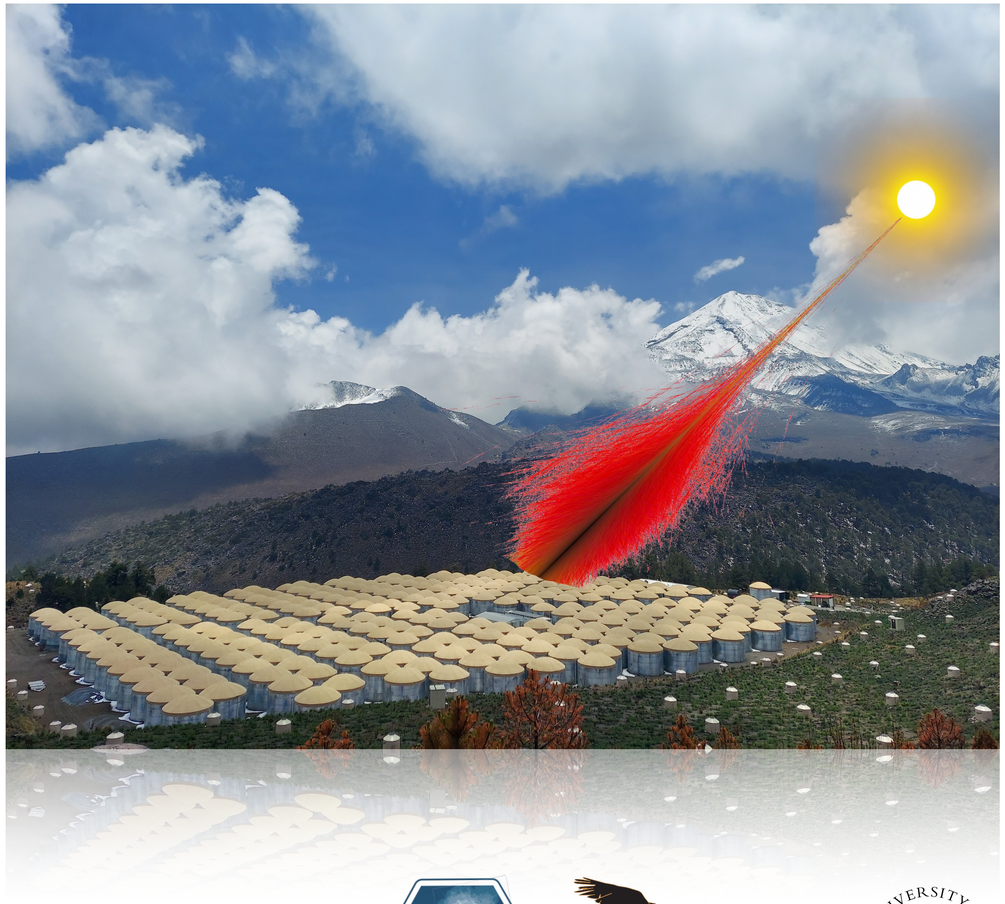
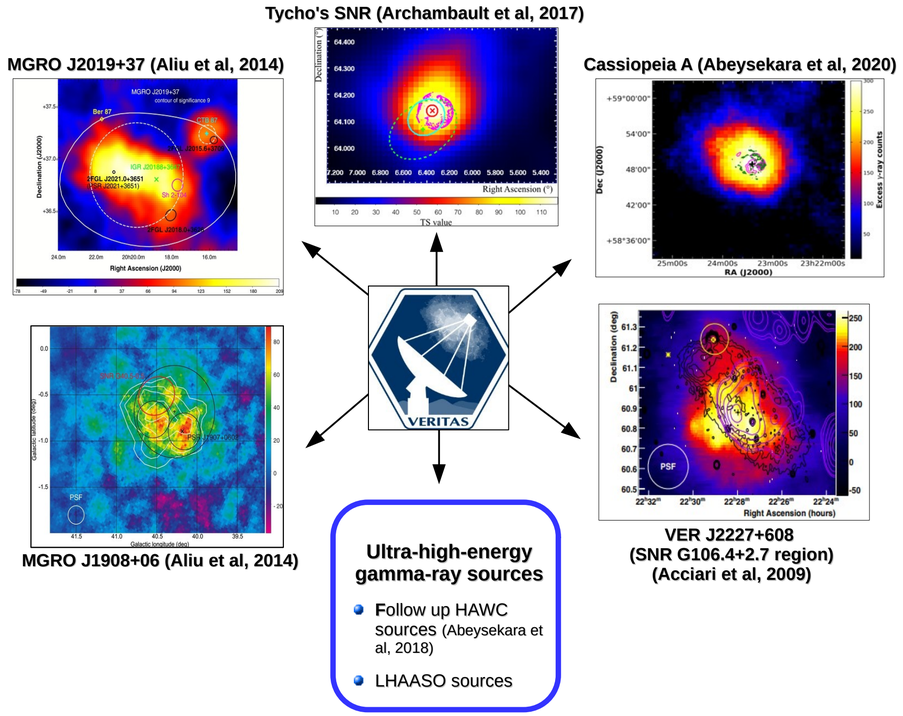
Investigating the origin of gamma-ray emission from the unidentified PeVatron LHAASO J2108+5157 using data from VERITAS, HAWC, Fermi-LAT and XMM-Newton



Sajan Kumar for the VERITAS & HAWC collaborations
University of Maryland, College Park
11th Fermi Symposium- September 10, 2024

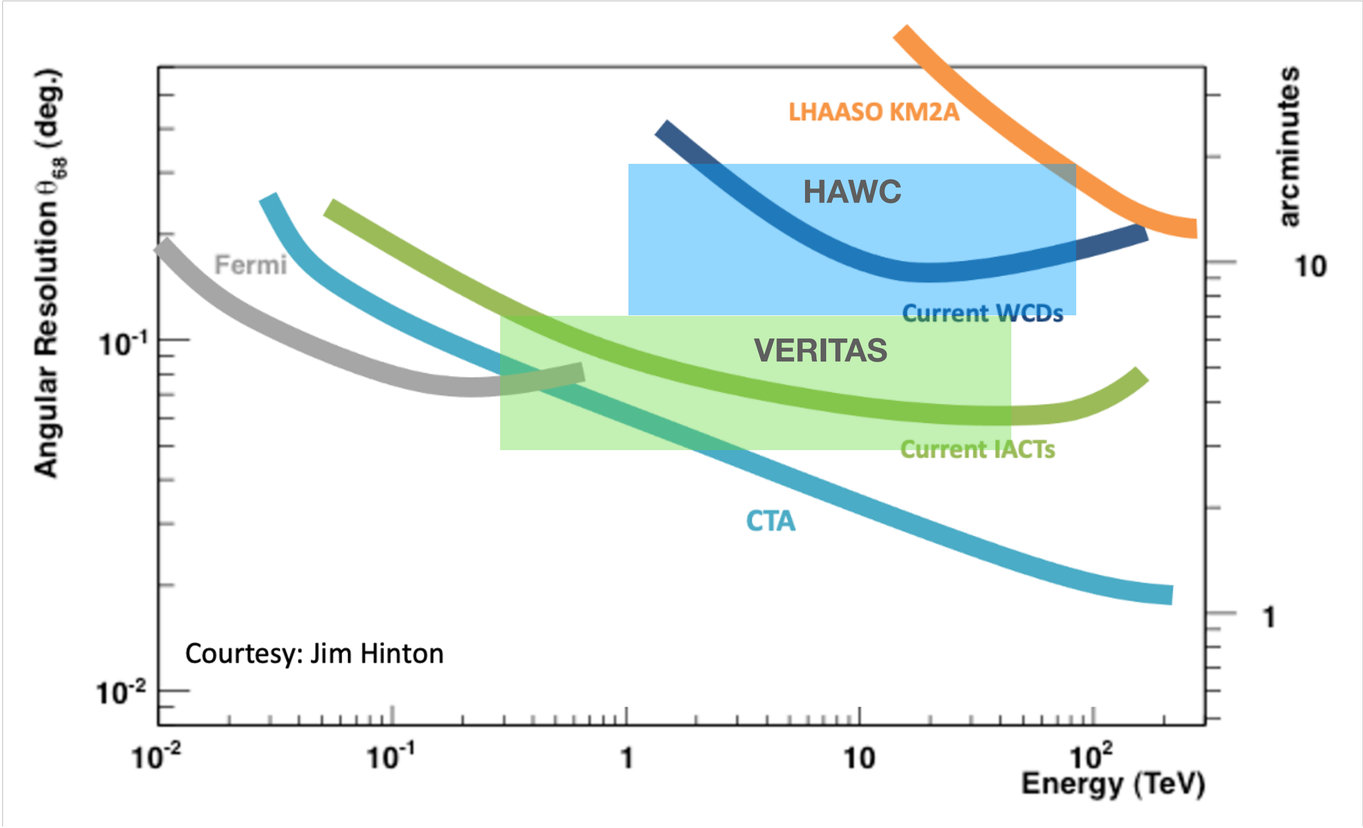
Motivation

- The Galactic PeVatron search is one of the key science project of ground based gamma-ray observatories
- LHAASO unveiled 43 PeVatron candidates. 8 out of 43 sources are not detected in 1-25 TeV energies **(“dark sources”**)
- 24 sources are listed as unidentified
- **Multi-wavelength observations are essential to understand the nature of these exotic sources**

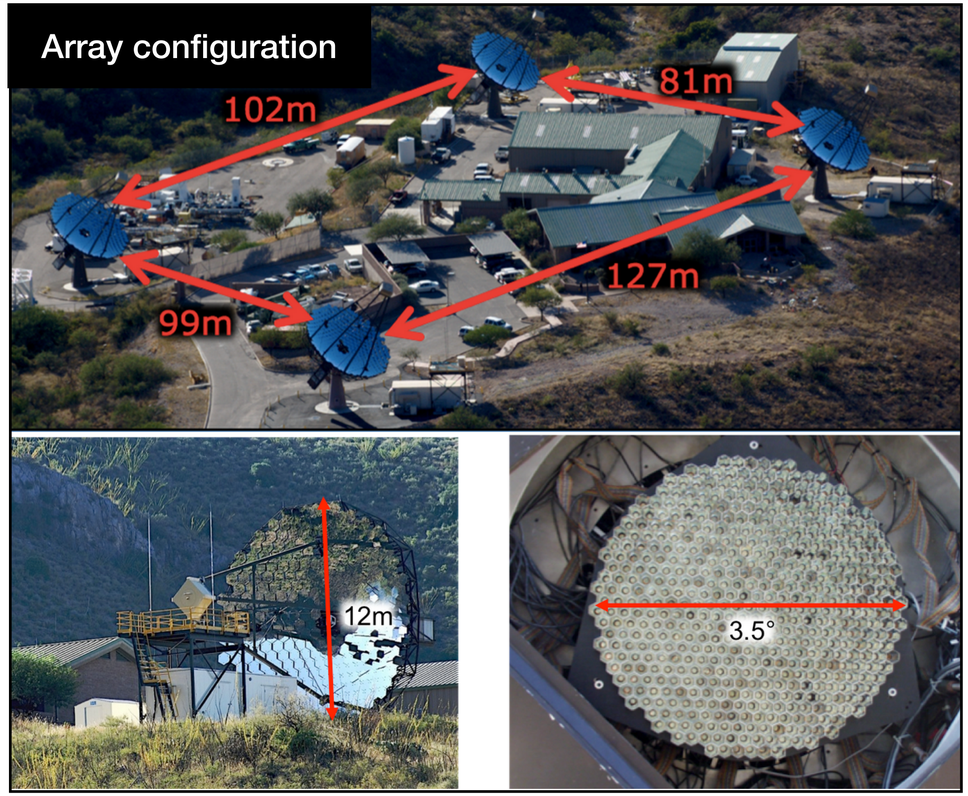


What do IACTs add to PeVatron Searches?

- Angular resolution
  - Identification of MWL counterparts
  - Disentangling of components/confused sources
- Extension of Spectra
  - Help distinguish emission models (hadronic vs leptonic)
- High(er) Statistics
  - Steeply falling power laws



VERITAS Overview



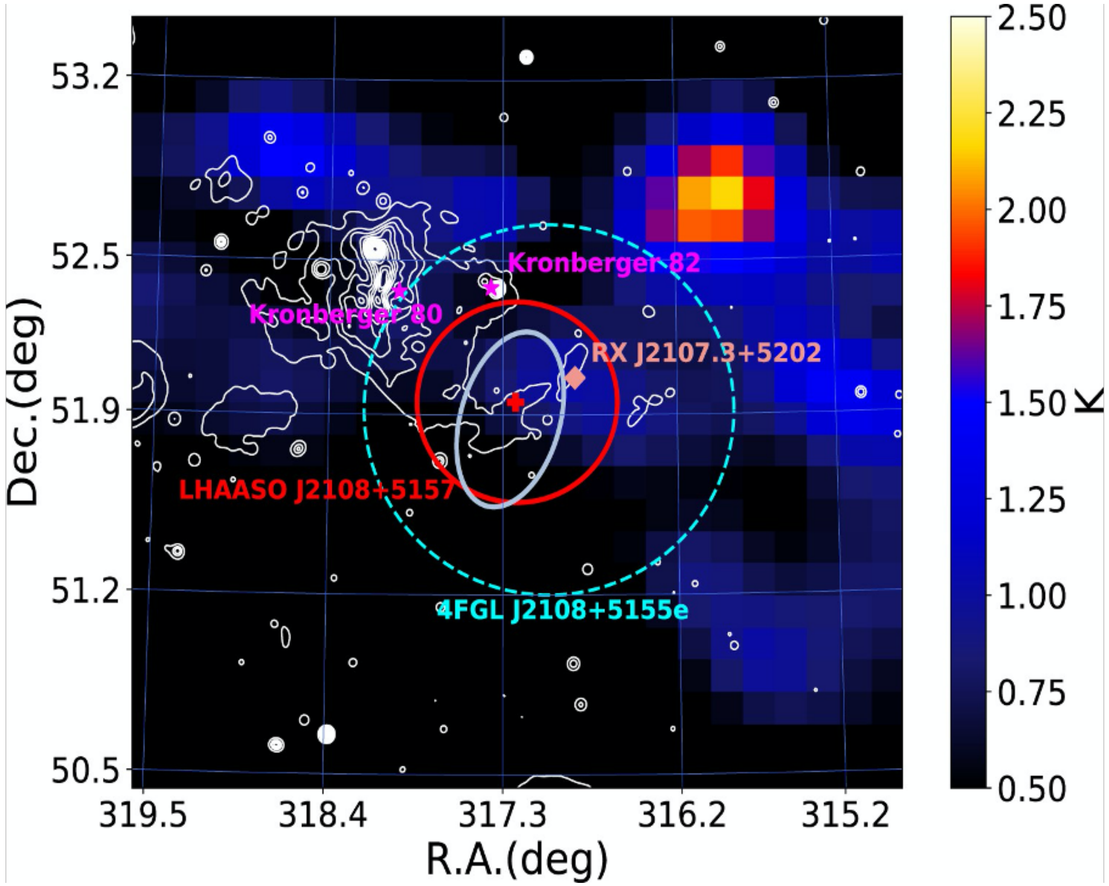
- Four telescopes each with a diameter of 12m, FOV = 3.5 deg
- Energy range : 85 GeV to > 30 TeV
- Angular resolution: 0.08 deg @ 1 TeV
- 1% Crab in < 25 hours

HAWC Overview

- Operating at 4100 m elevation on Sierra Negra, Mexico
- 300 water Cherenkov detectors, area = $22000\ \mathrm{m}^2$
- Sensitive to gamma rays above 1 TeV
- Instantaneous field of view = 2 sr, 95% duty cycle

LHAASO J2108+5157

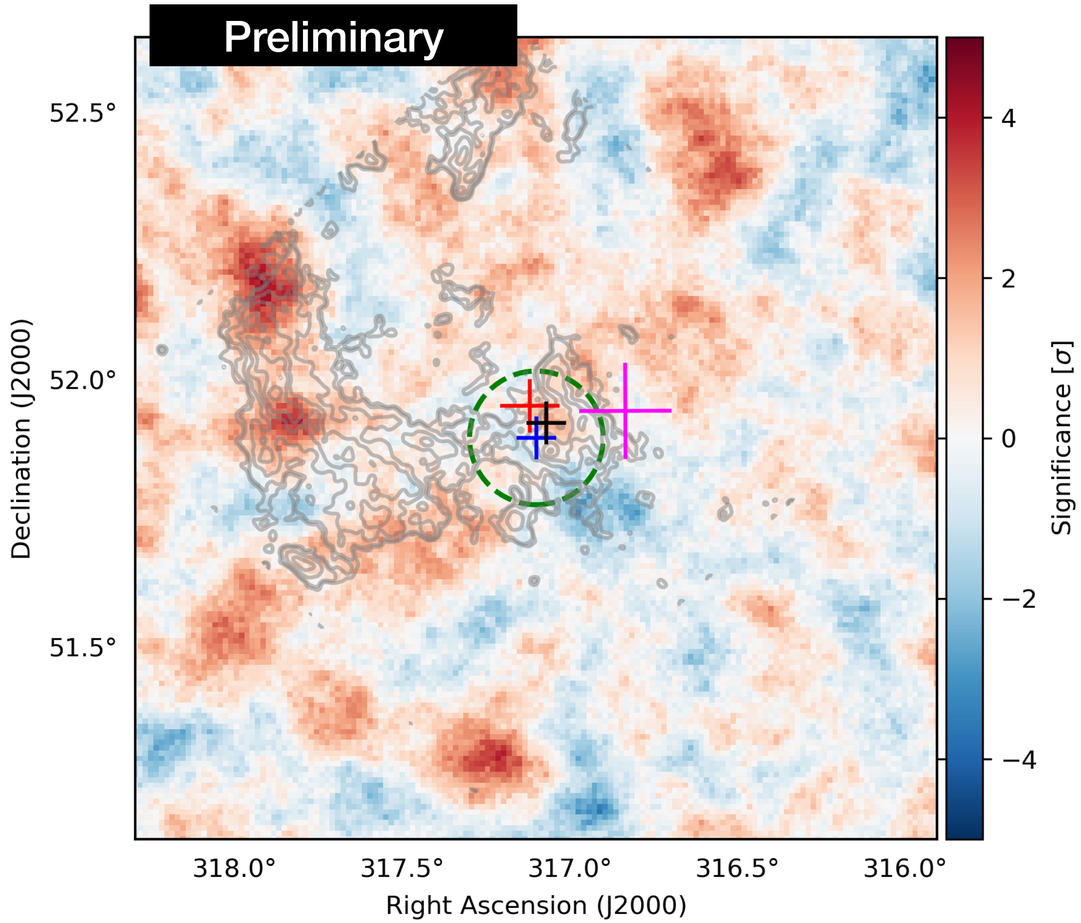
- **Cao et al. 2021 paper**
  - 9.6 $\sigma >$ 25 TeV, 8.5 $\sigma >$ 100 TeV
  - Spectrum is defined by power-law fit ($\Gamma = -2.83 \pm 0.18_{stat}$)
  - Point like source, extension $< 0.26^{\circ}$
  - Spatially coincident with molecular cloud, 4FGL J2108+5155, star clusters
- **Cao et al. 2023 Catalog Paper**
  - Detected in WCDA and KM2A
  - WCDA, $\Gamma = -1.56 \pm 0.34_{stat}$
  - KM2A, $\Gamma = -2.97 \pm 0.07_{stat}$
  - Marginally extended @ 0.14 deg, 0.19 deg in WCDA and KM2A respectively



[Image credit: Cao et al. 2021a]

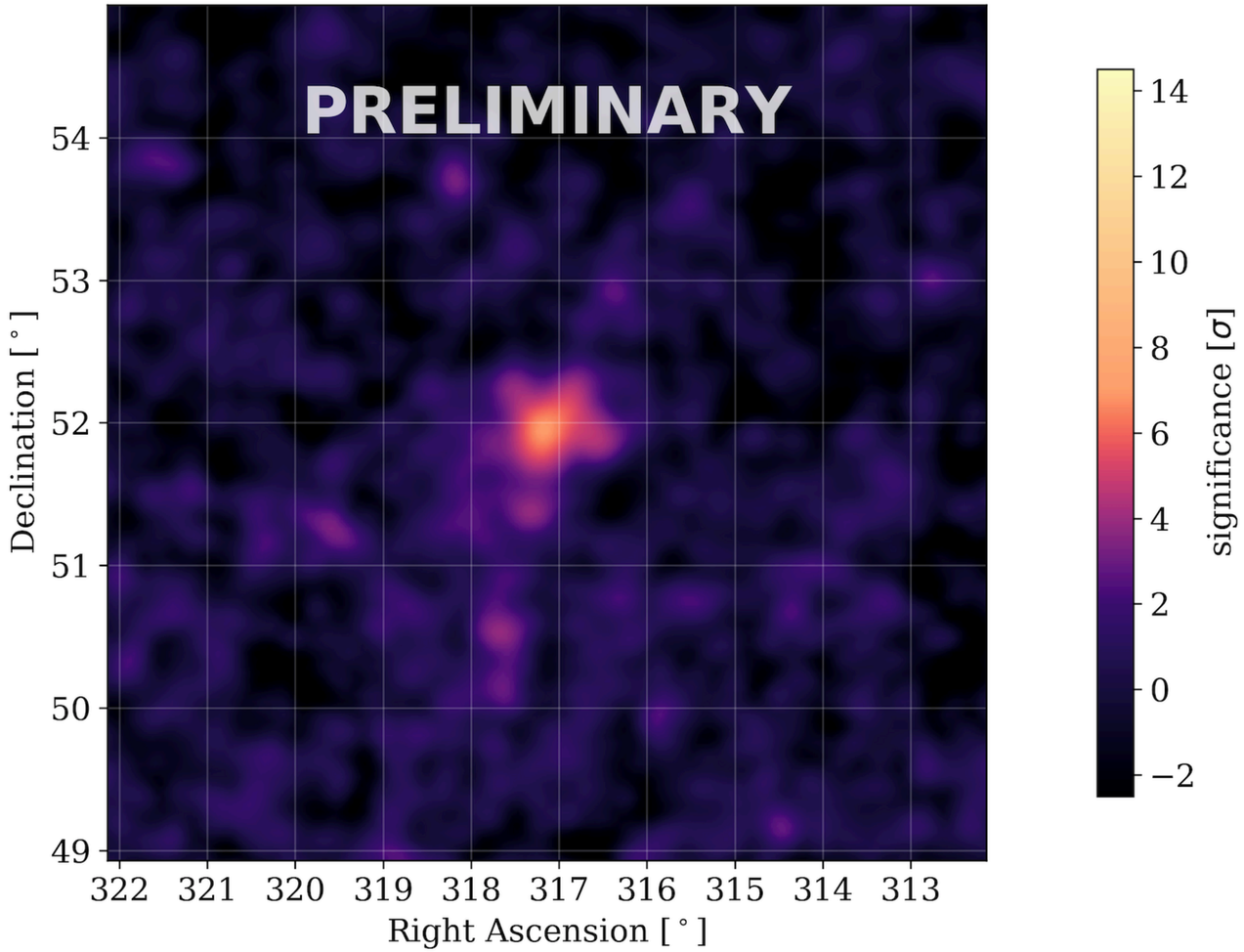
VERITAS Analysis

- VERITAS followed this source in 2021
- Total exposure 35 hours
- Both point source ($\theta = 0.1^{\circ}$) and extended source ($\theta = 0.25^{\circ}$) analysis result in **null detection**



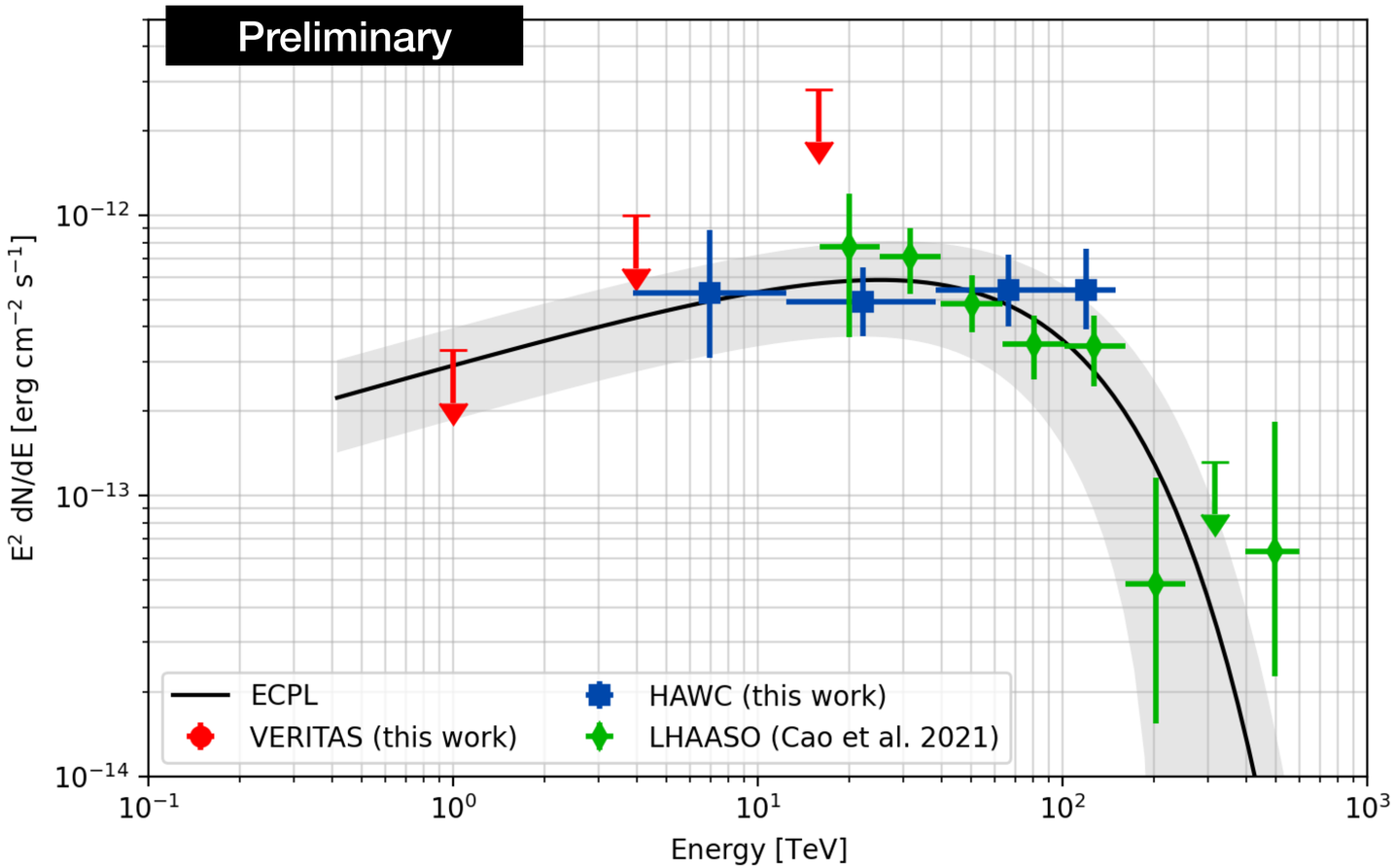
HAWC Analysis

- 2400 days of data
- Pass 5 reconstruction
- Detected @ 7.5 sigma
- Extended source model is preferred ($0.21^\circ \pm 0.04^\circ$)
- Power-law index = -2.45



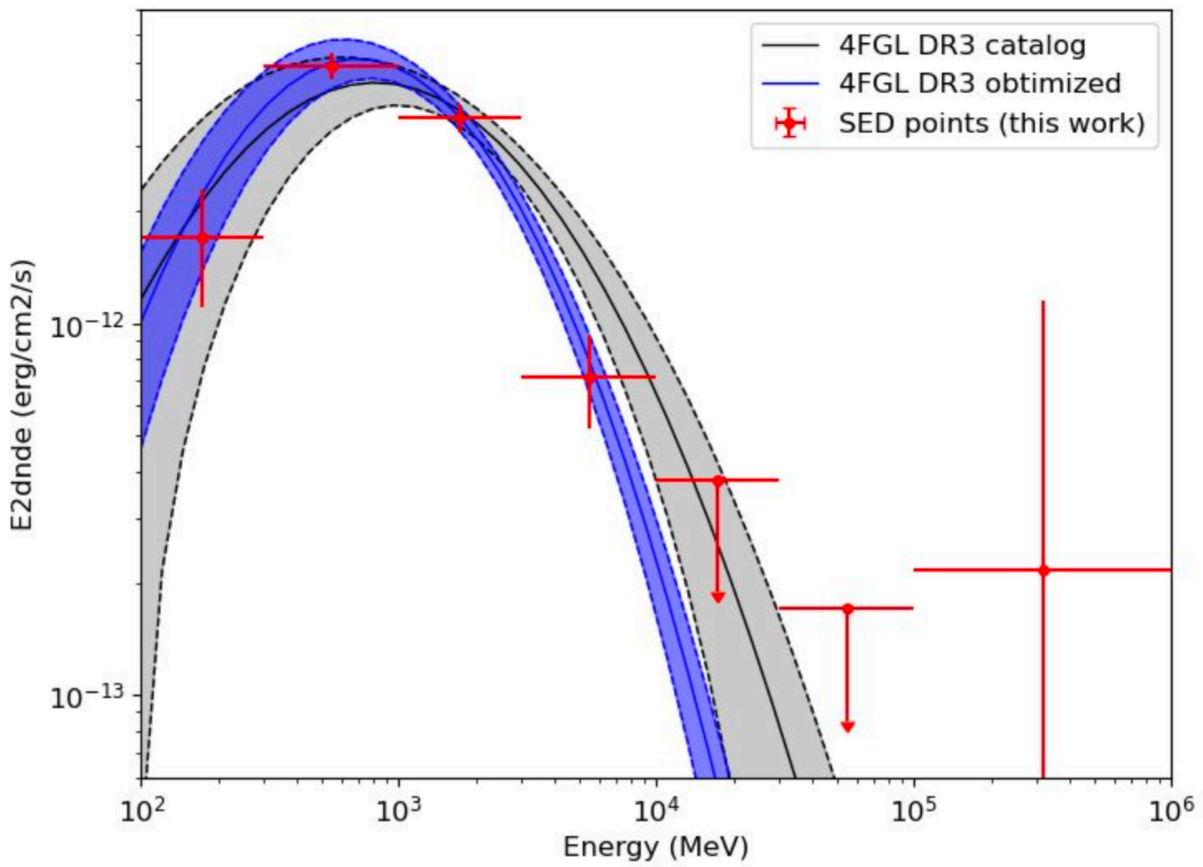
Joint-Fitting of TeV data

- Joint-fitting of VERITAS+HAWC+LHAASO data
- Exponential cutoff PL fit
  - *Index is fixed to a value of 1.7*
  - *Fixing index constraint the cutoff energy better*
  - *Cutoff energy = **82+/-30 TeV***
- VERITAS limits are already constraining the spectral index below 1.7



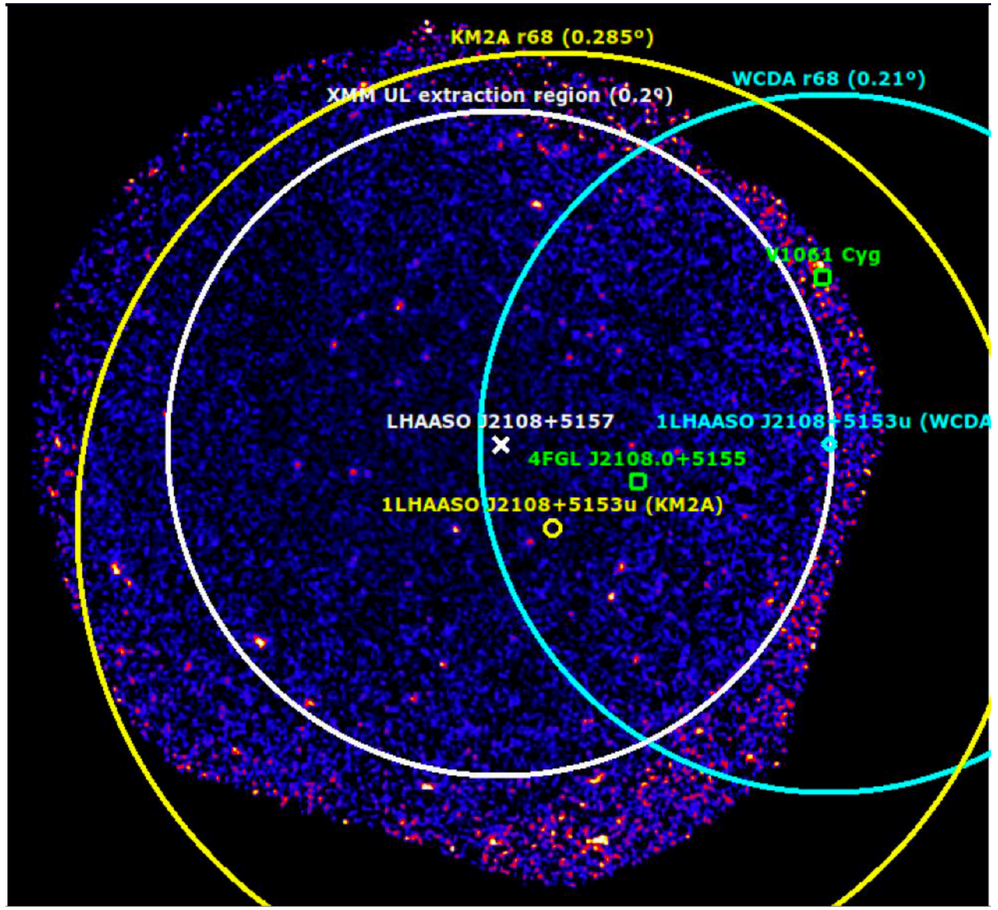
Fermi-LAT analysis details

- 14.2 yrs of pass 8 data in 0.1 GeV - 1 TeV
- Best-fit model is consistent with the 4FGL-DR3 catalog values
- Detected as point source
  - *Different from Cao et al. 2021) paper which claim extended source*
  - *No additional point source with hard spectral index is detected as reported by Abe et al. 2023*
  - *Discrepancy is due to optimization of model in different energy range*
- Sharp cutoff around 1 GeV and no detection above 10 GeV
  - *Unlikely to be associated with LHAASO J2108+5157*



XMM analysis details

- Total exposure 96 ks, after filtering net exposure 62 ks
- No significant emission is detected
- Spectral analysis
  - *Integration radius 0.2 degree*
  - *UL is calculated in 2-10 keV*

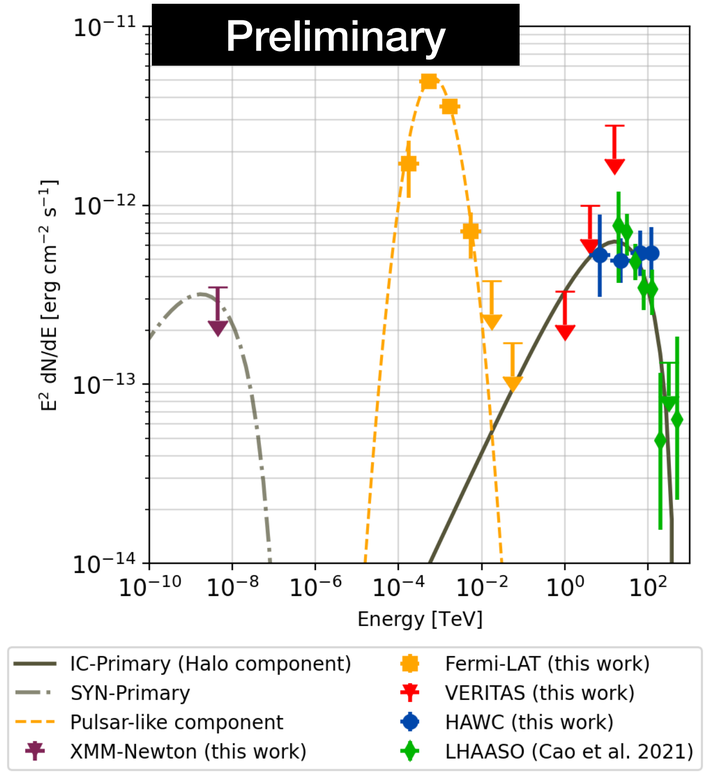


Modeling gamma-ray emission

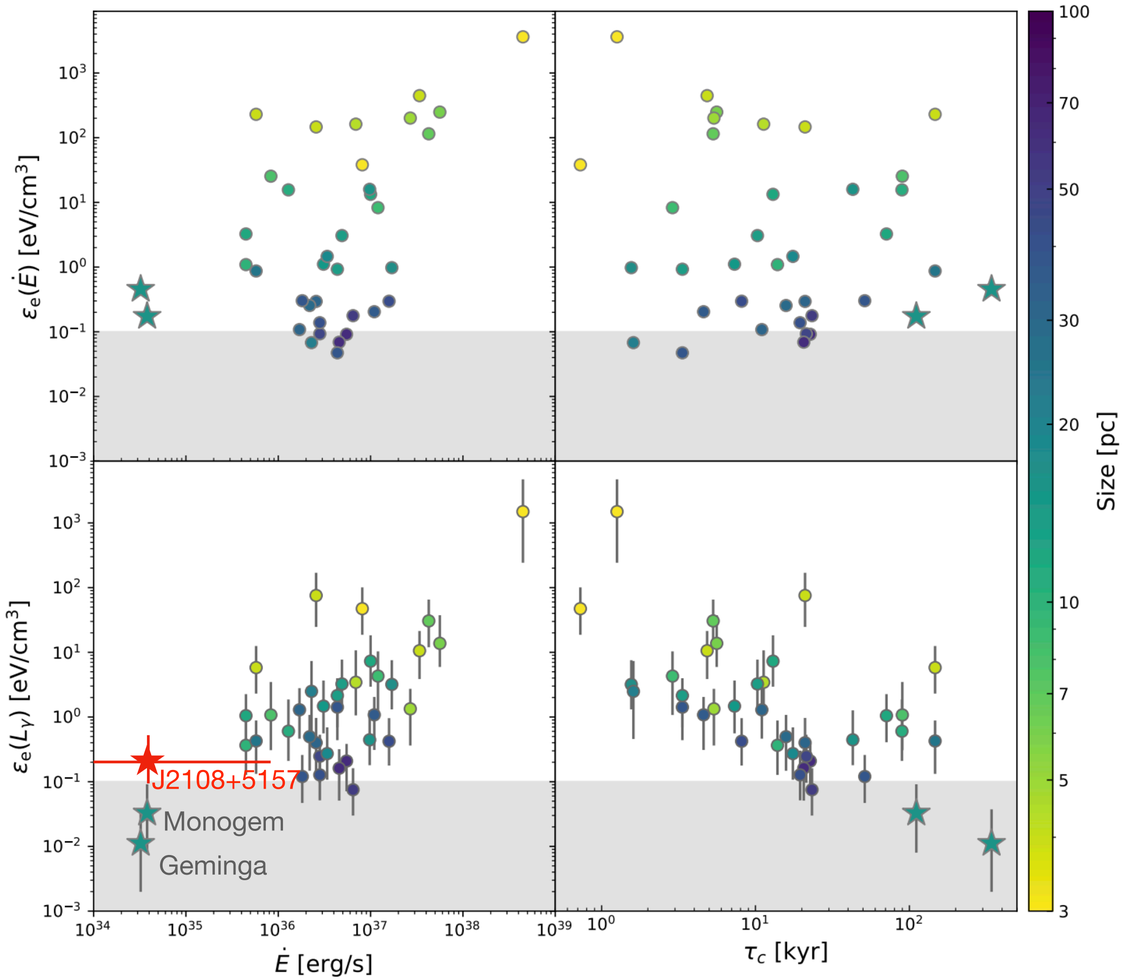
Leptonic Emission

Steady state electron population

$$\frac{dN}{dE} = N_0 (E/E_0)^{-\Gamma} \exp(-E/E_{cut})$$



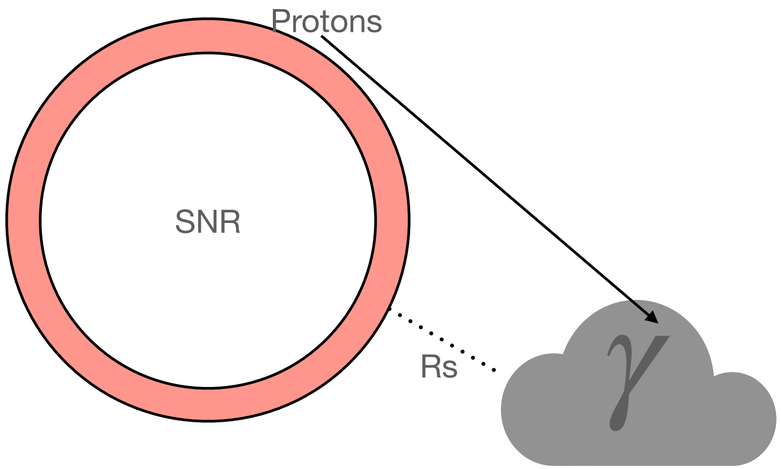
Fix index = 2
Source distance = 1 kpc
Physical size = 4.4 pc
$E_{cut} = 165^{+69}_{-48}$ TeV
Magnetic field < 1.5 uG



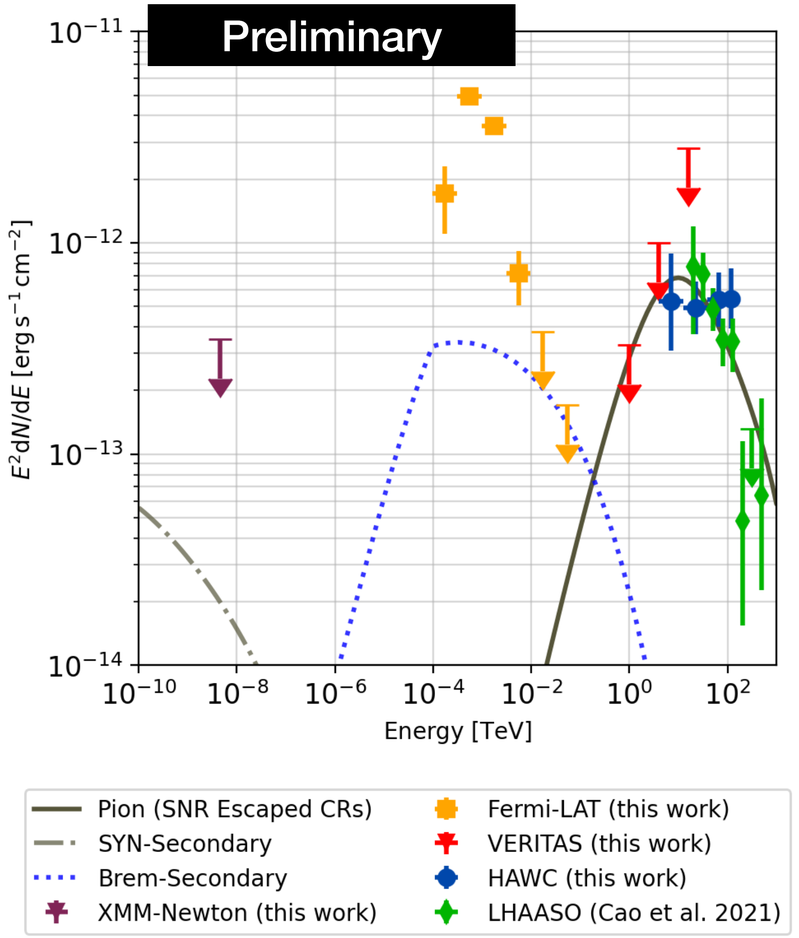
Giacinti et al. 2019

Modeling gamma-ray emission

Hadronic Emission



- Emission originates from escaped CRs accelerated in SNR (Type II)
- Distance between SNR and MC (R_s) = 100 pc
- Density in cloud = 133 cm-3, distance (d) = 1.6 kpc
- $Q(E) = N_0(E/E_0)^{-\Gamma}, \Gamma = 2$ (Injected proton spectrum)



Parameters	Best-fit value	Fixed
Spectral Index (Γ)	2.0	True
E_{max}	3 PeV	True
B	≥ 20 μG	True
n_H	133 cm^{-3}	True
Distance	1.6 kpc	True
R	100 pc	True
Age	$25.4^{+13.2}_{-8.7}$ kyr	False

Table 2. Parameters of Hadronic Model

Conclusions

- We report **non-detection** of LHAASO J2108+5157 with 35 hours of VERITAS and 62 ks of XMM
- We report **detection** of LHAASO J2108+5157 with 2400 days of HAWC and 14 yrs of LAT (if associated)
  - No accelerator has been firmly identified in the vicinity of J2108
  - Emission from pulsar halo is plausible based on energy density estimation in the emission region although no pulsar has been detected in the vicinity
  - Nearby molecular cloud potentially indicating hadronic nature of emission
  - Hadronic emission explain the TeV data, however Fermi-points below 10 GeV can not be explained under the hadronic model
  - New class of “passive” gamma-ray sources?

Thank you
Any questions?

- Background slides

Modeling gamma-ray emission

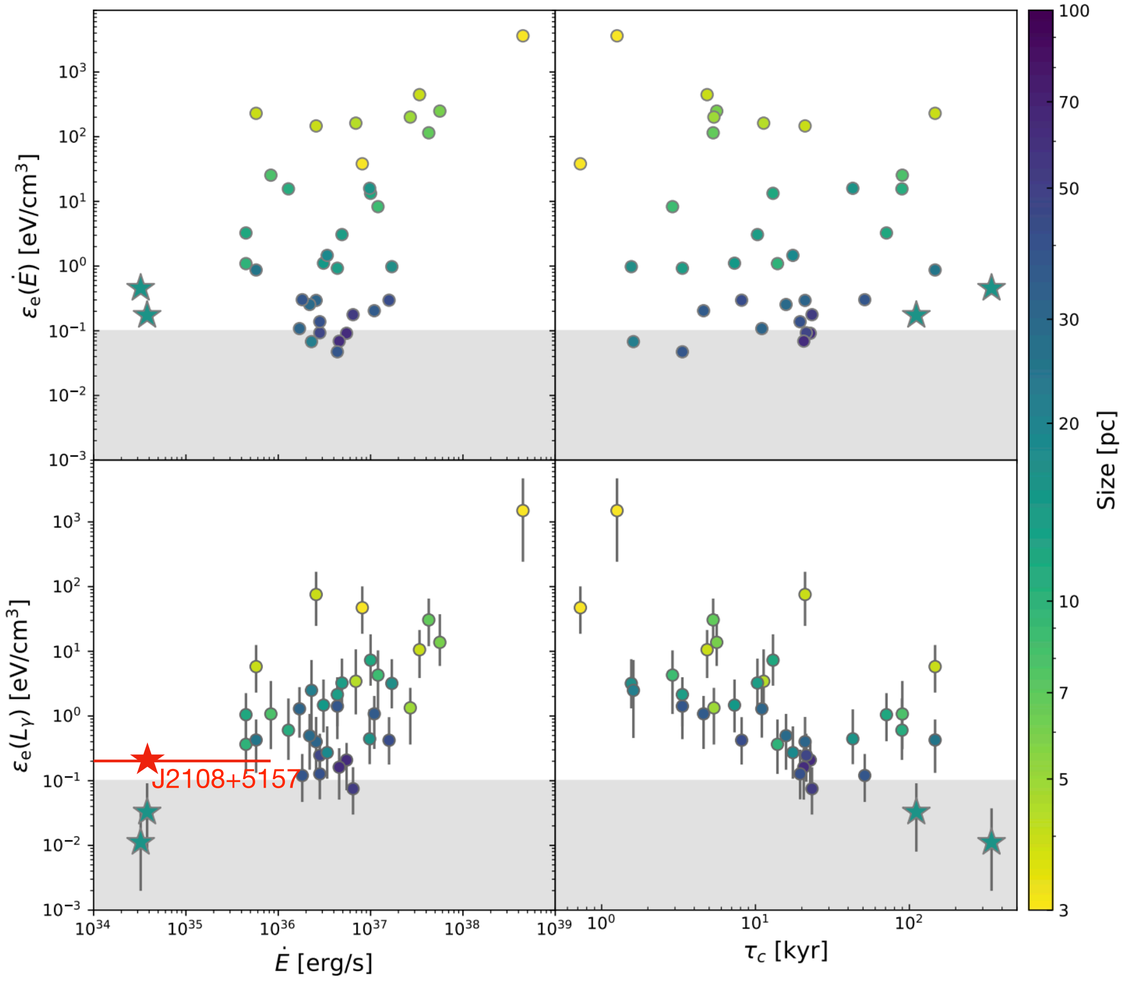
Hadronic Emission

- Emission originates from escaped CRs accelerated in SNR (Type II)
- Distance between SNR and MC (r) = 100 pc
- Density in cloud = 133 cm-3, distance (d) = 1.6 kpc
- $Q(E) = N_0(E/E_0)^{-\Gamma}$ (Injected proton spectrum)
- $N_p(E,R,T) = \frac{Q(E)}{\pi^{3/2}R_{diff}^3}\exp\left(\frac{-R^2}{R_{diff}^2}\right)$
- $R_{diff} = 2\sqrt{D(E)(T-\chi(E))}$
- $D(E) = \chi\ 3\times10^{28}\left(\frac{E}{10GeV}\right)^{0.5}\left(\frac{B}{3\mu G}\right)^{-0.5}\ \mathrm{cm^2 s^{-1}}, Where\ \chi = 0.01$
- $\chi(E) = t_{sedov}\left(\frac{E}{E_{max}}\right)^{-1/2.5}, t_{sedov} = 1.6kyr$
- $E_{max} = 3\ \mathrm{PeV}$
- $\frac{dN_\gamma}{dE_\gamma} = \frac{n_{gas}c}{4\pi d^2}\left(\frac{4}{3}\pi R_s^3\right)\int \frac{d\sigma_{pp}}{dE_\gamma}(E_\gamma,E)N_p(E,R,T)dE$

Modeling gamma-ray emission

Leptonic Emission

- Size in deg (radius) = 0.25 (68% radius from LHAASO measurement)
- For 1 kpc distance, physical size = 4.3 pc
- Total energy in electrons = 3 x 10^45 erg
  - *Energy density = (0.2+/-0.1) eV/cm3*
    - ***0.06 eV/cm3 for 3 kpc distance***
  - *ISM energy density = 0.1 eV/cm3*
  - *Implies that relativistic electrons are not contained in a region energetically and dynamically dominated by pulsar*
  - *Implies electrons are outside the PWN region*
  - *Emission is from halo*
  - *UL on magnetic field is consistent with magnetic field around halos*
  - *Red star on the image lies close to Gaminga and monogem*



Giacinti 2019 et al.