Supernova remnants as Galactic PeVatron candidates

Agnibha De Sarkar

Senior Research Fellow, Astronomy & Astrophysics group

Raman Research Institute

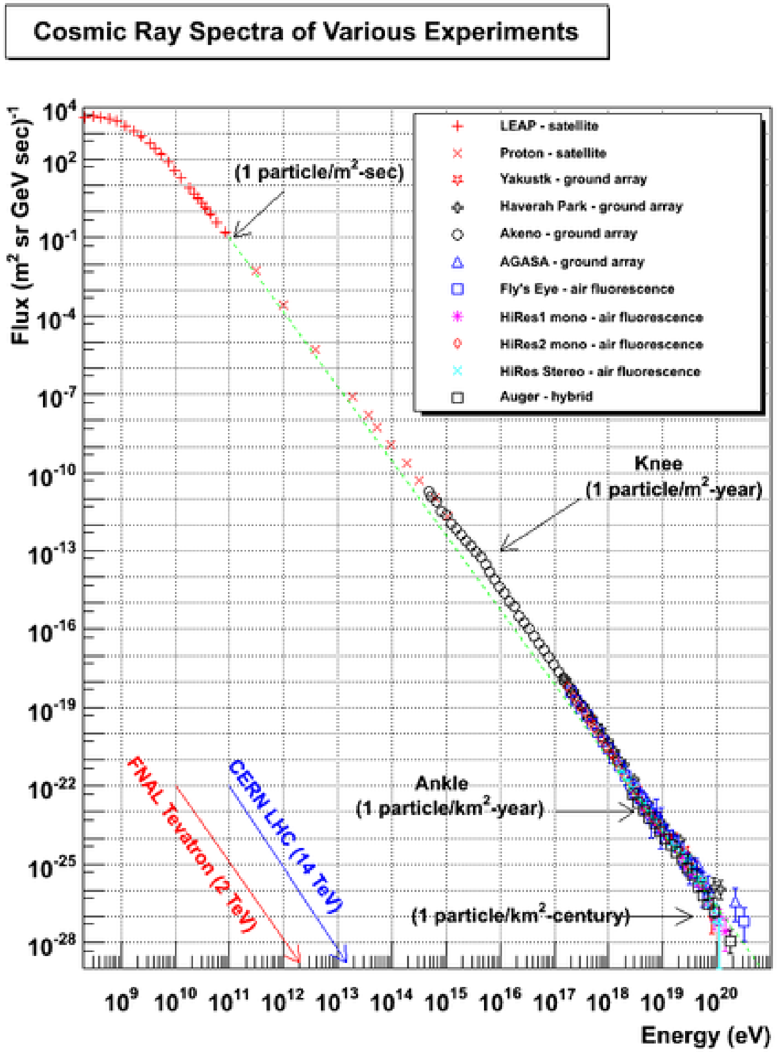
RRI

Advances in Astroparticle Physics and Cosmology

AAPCOS-2023

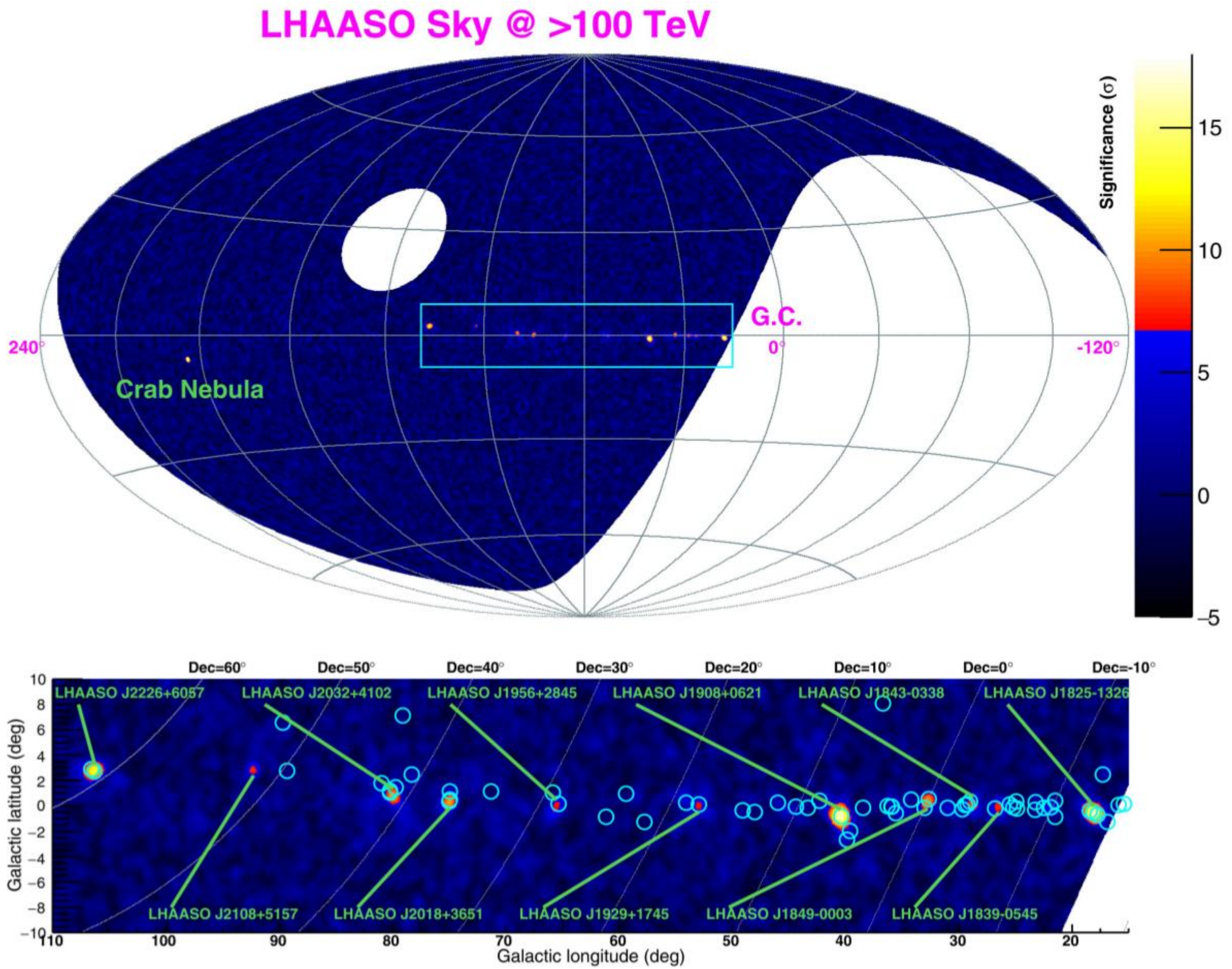
23rd – 27th January, 2023

Galactic PeVatrons and LHAASO:



- PeVatrons are Galactic sources accelerating particles to the knee energy (~ 3 PeV).
- Recent progress in air shower arrays (e.g. LHAASO) has enlarged the list of PeVatron candidates substantially.
- SNR+MCs, PWNe, young stellar clusters are some of the leading candidates for being the Galactic PeVatrons.

Galactic PeVatrons and LHAASO:



LHAASO J1908+0621: Source association

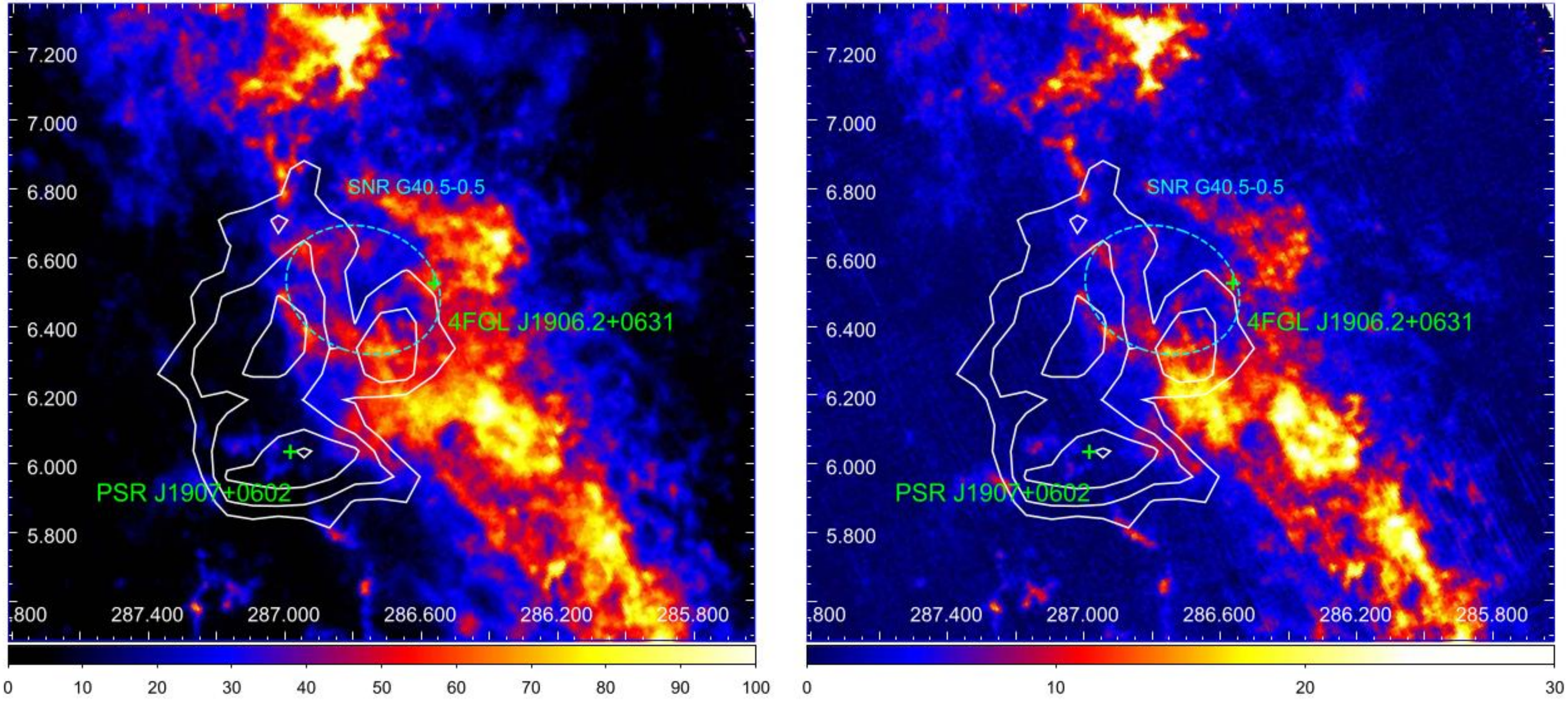
- Middle aged (20 – 40 kyr) radio SNR G40.5-0.5 (D ≈ 8 kpc).
  - a) D ≈ 3.5 kpc from CO observation
  - b) D ≈ 5.5 – 8.5 kpc from Σ-D relation.

- PSR J1906.2+0631, radio pulsar, D ≈ 7.9 kpc, likely associated with SNR G40.5-0.5.

- PSR J1907+602, GeV & radio pulsar,
  - a) spin period ≈ 107 ms
  - b) spin-down luminosity ≈ 2.8 $\times 10^{36}$ erg s^{-1}
  - c) Characteristic age 19.5 kyr
  - d) D ≈ 3.2 $\pm$ 0.6 kpc from dispersion measures

- 4FGL J1906.2+0631, unidentified GeV source, distance unknown.

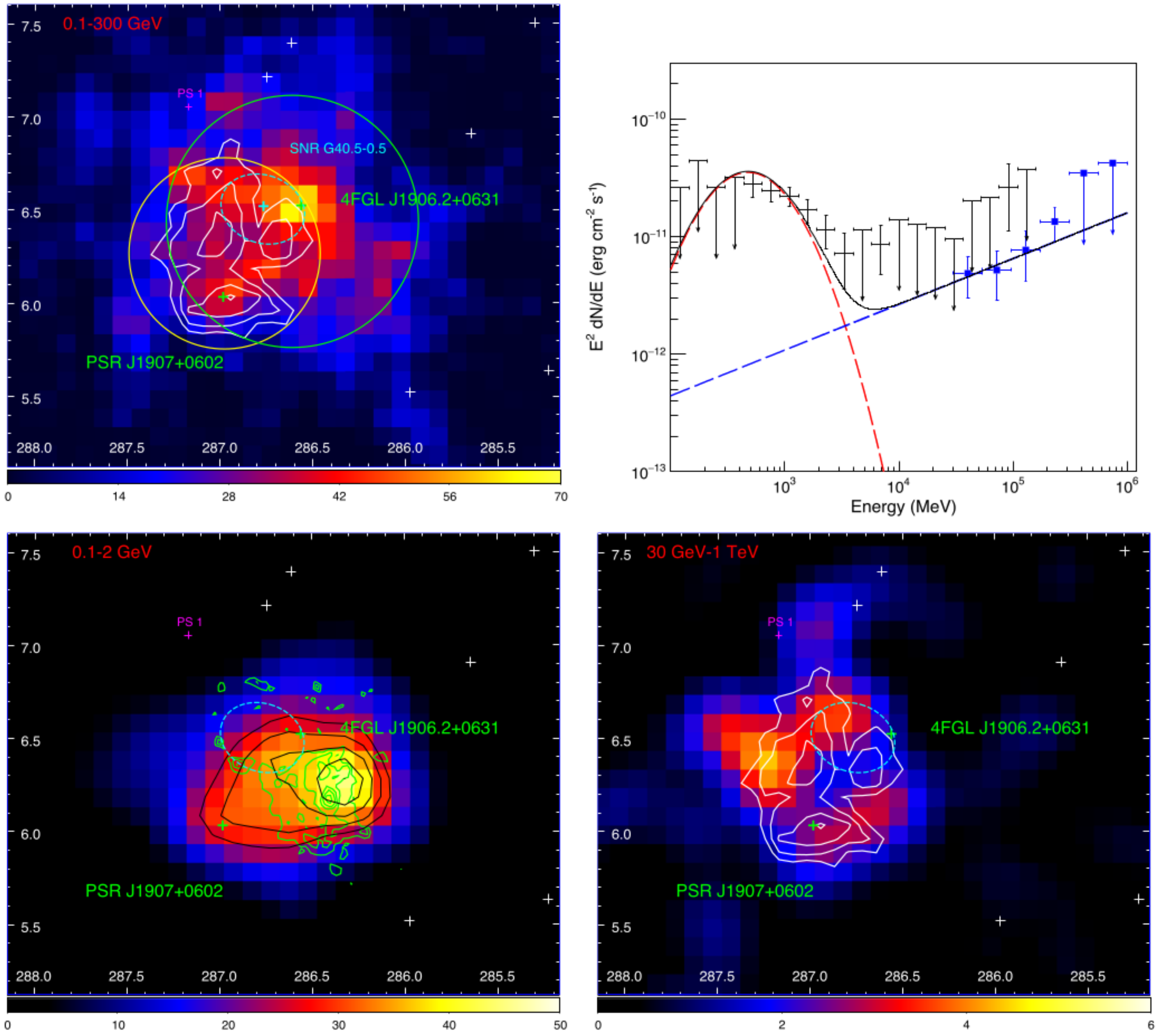
LHAASO J1908+0621: Source morphology

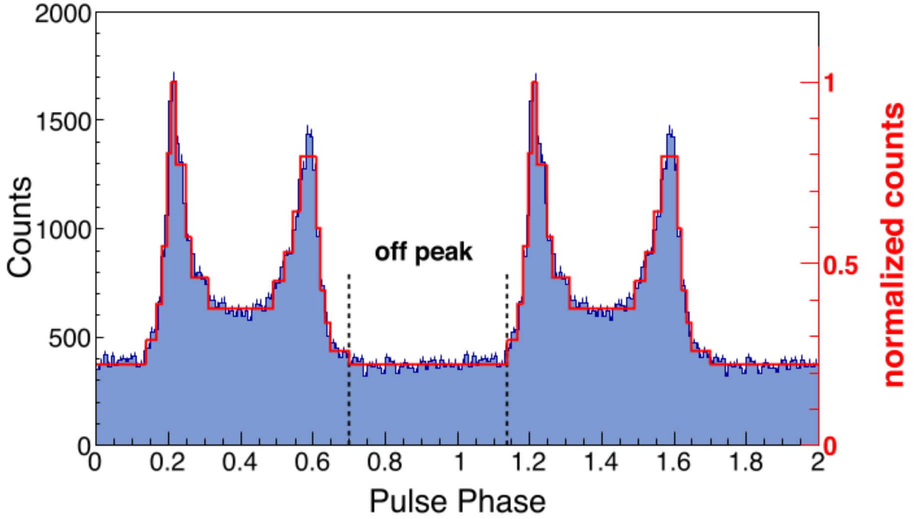


- 12_{CO} (J = 1 - 0) (left) & 13_{CO} (J = 1 - 0) (right) intensity maps, integrated in the velocity range 46-66 km s^{-1}.

Li et al., ApJL, (2021)

LHAASO J1908+0621: Source morphology



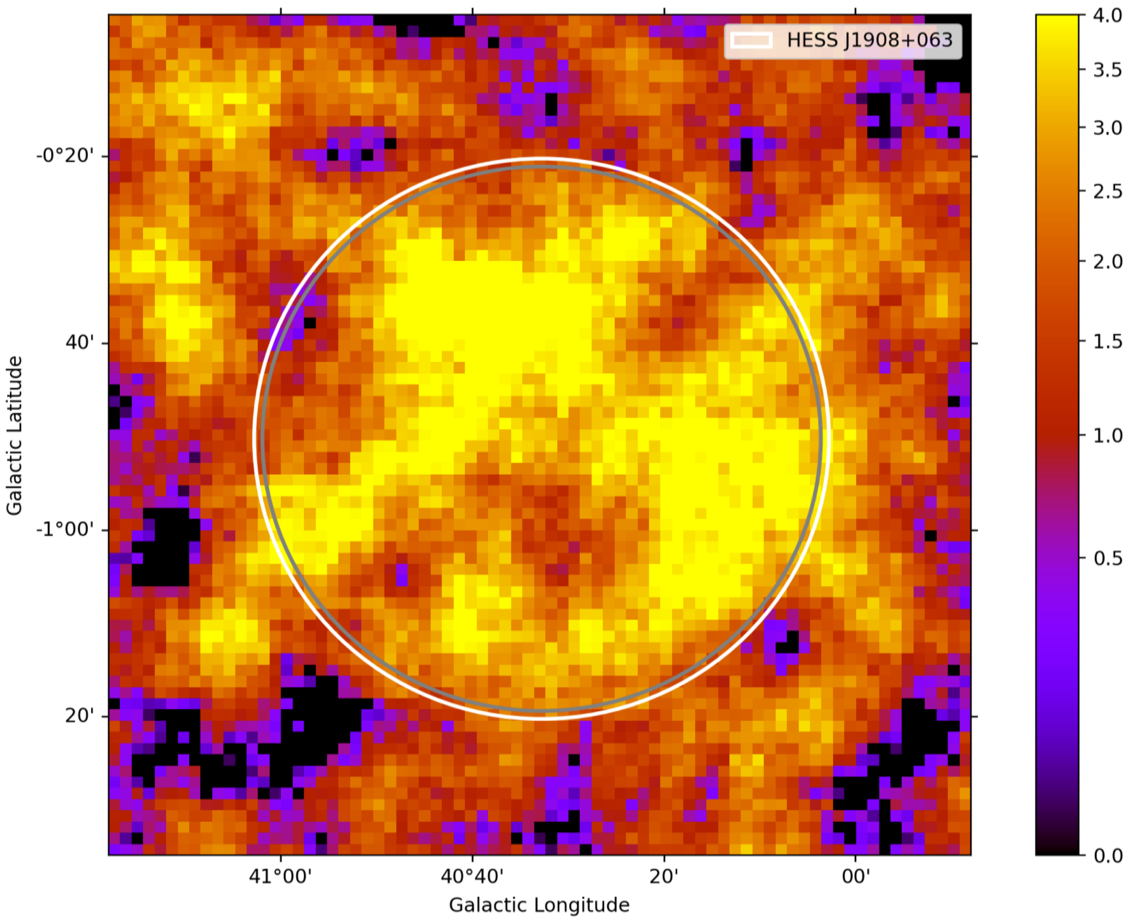


- Pulse profile of PSR J1907+0602 above 300 MeV with an ROI of 0.6^o. Two rotational pulse periods with a resolution of 100 phase bins per period are shown. Off-peak intervals are 0.0 – 0.136 and 0.697 – 1.0 (Li et al. 2021).

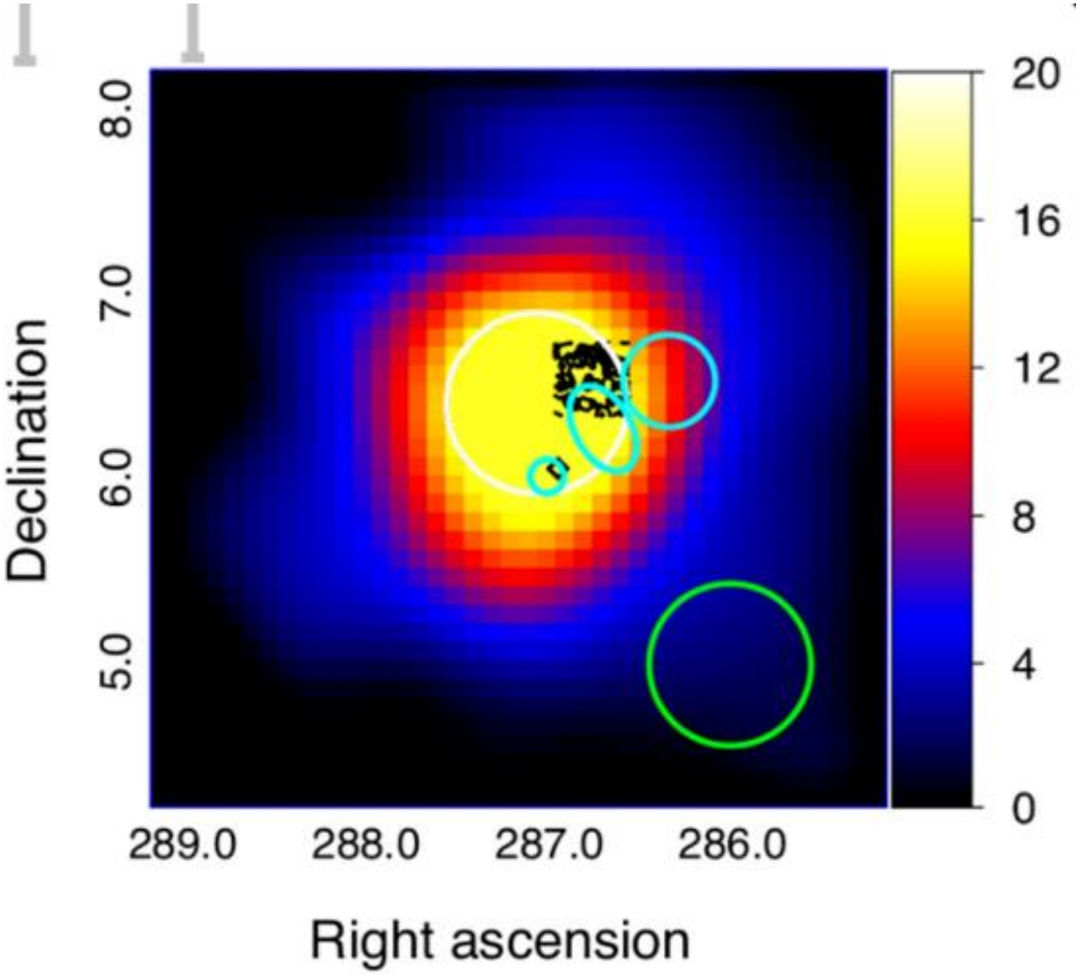
- An extended source, dubbed as Fermi J1906+0626 was found, associated with LHAASO J1908+0621 (Li et al. 2021).

Li et al., ApJL, (2021)

LHAASO J1908+0621: Source morphology



H.E.S.S. morph., 100 GeV – 100 TeV



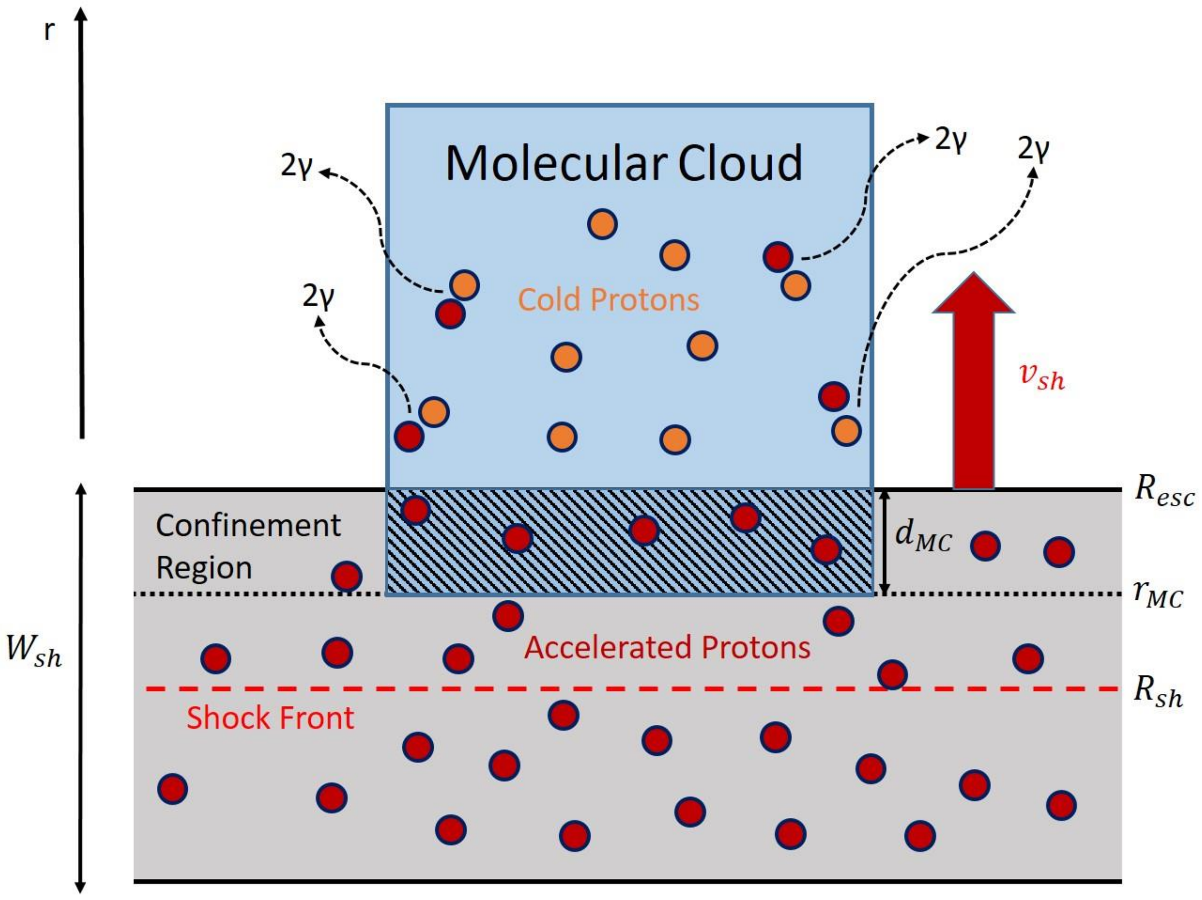
LHAASO morph., E > 100 TeV

Cao et al., Nature, (2021)

LHAASO J1908+0621: SNR G40.5-0.5 + MCs (Hadronic)

- Explosion inside a tenuous spherical cavity, surrounded by dense MCs.
- Free expansion for $\sim$ 200 years, SNR enters Sedov phase.
- Shock front expands radially while particles accelerate through DSA at the shock front.
- Confinement region around shock front due to strong magnetic turbulence.
- Outermost boundary of containment region collides with surrounding MC surface, SN enters momentum conserving phase, the particles accelerations stops.
- Comparatively higher energy protons escape confinement region and enter the dense MC region, while lower energy protons are still confined around SNR.
- Consequently, a suppression in the proton injection spectral shape at lower energies is expected.
- Escaped protons interact with cold protons inside MCs, producing gamma-rays and neutrinos.
- The total gamma-ray and neutrino flux is calculated at the time of collision, assuming that the particles lose energy rapidly before escaping due to slow diffusion inside the MCs.

LHAASO J1908+0621: SNR G40.5-0.5 + MCs (Hadronic)



Equations governing SNR evolution :

<u>Velocity evolution equations:</u>

1) $v_{sh}(t) = v_i$ (t < t_{Sedov})

$= v_i \, (t/t_{Sedov})^{-3/5}$ (t > t_{Sedov})

<u>Radius evolution equations:</u>

2) $R_{sh}(t) \propto (t/t_{Sedov})$ (t < t_{Sedov})

$\propto (t/t_{Sedov})^{2/5}$ (t > t_{Sedov})

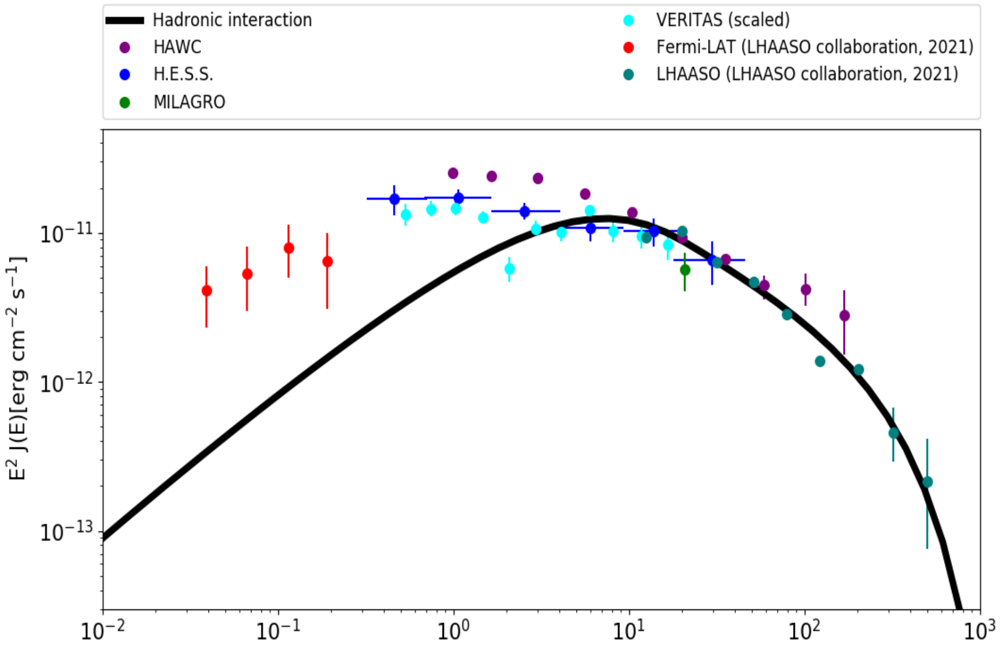
<u>Minimum energy needed by protons to escape:</u>

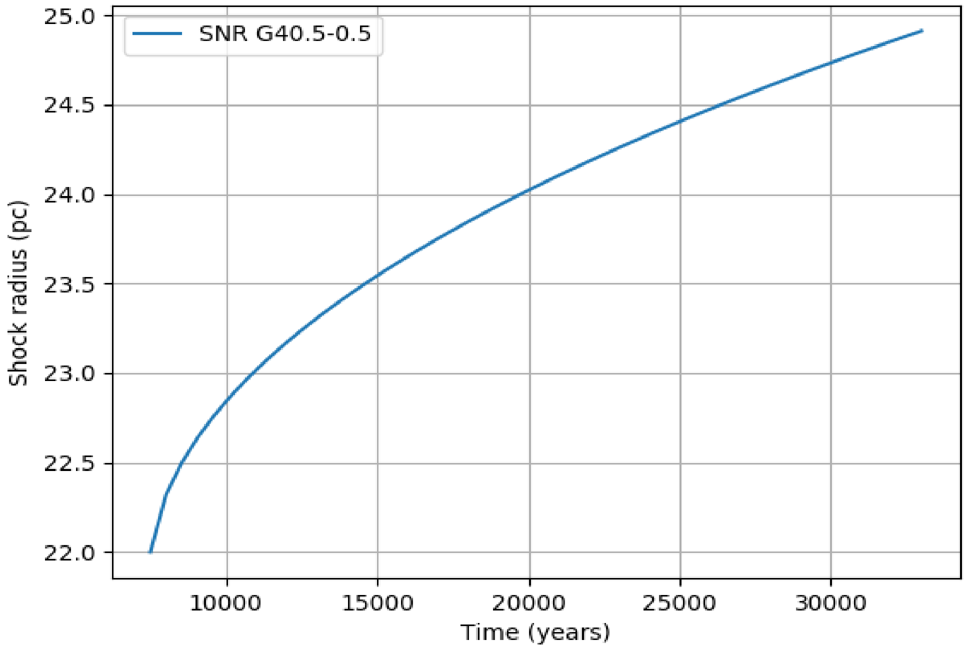
3) $E_{esc} = E_{max} \left(\frac{R_{sh}}{R_{Sedov}}\right)^{-\alpha}$

<u>Spectrum of the escaped protons ($E > E_{esc}$):</u>

4) N(E > E_{esc}) $\propto E^{-[s+(\beta/\alpha)]}$

Ohira et al., A&A, (2010)





Parameter Values :

- Distance, d = 8 kpc
- Sedov radius, R_{Sedov} = 2.1 pc
- Sedov time, t_{Sedov} = 210 years
- Initial shock velocity, v_i = 10^9 cm/s
- Maximum energy, E_{max} = $10^{15.5}$ eV
- Distance to MC surface, r_{MC} = 22 pc
- DSA acceleration index, s = 2.0
- Suppression index, α = 2.0
- Thermal leakage index, β = 1.5
- Collision time, $t_{coll} = 7.5 \times 10^3$ years
- Velocity at collision, $v_{sh}(t_{coll}) = 1.2 \text{ x } 10^8 \frac{cm}{s}$.
- Diffusion inside a molecular cloud D(E) ≈ 10^{28} χ $(E/10\ GeV)^{\delta}\ cm^2 s^{-1}$, where δ = 0.3-0.6 and χ ≤ 0.01.

- $\alpha_p = 2.75$
- E_{min} ≈ 30 TeV
- E_{max} ≈ 3.2 PeV
- $W_p \approx 2.5 \times 10^{49}$ erg
- $B_{MC} = 60\ \mu G$
- $n_{MC} = 45\ cm^{-3}$.

RRI

LHAASO J1908+0621: SNR G40.5-0.5 + MCs (Leptonic)

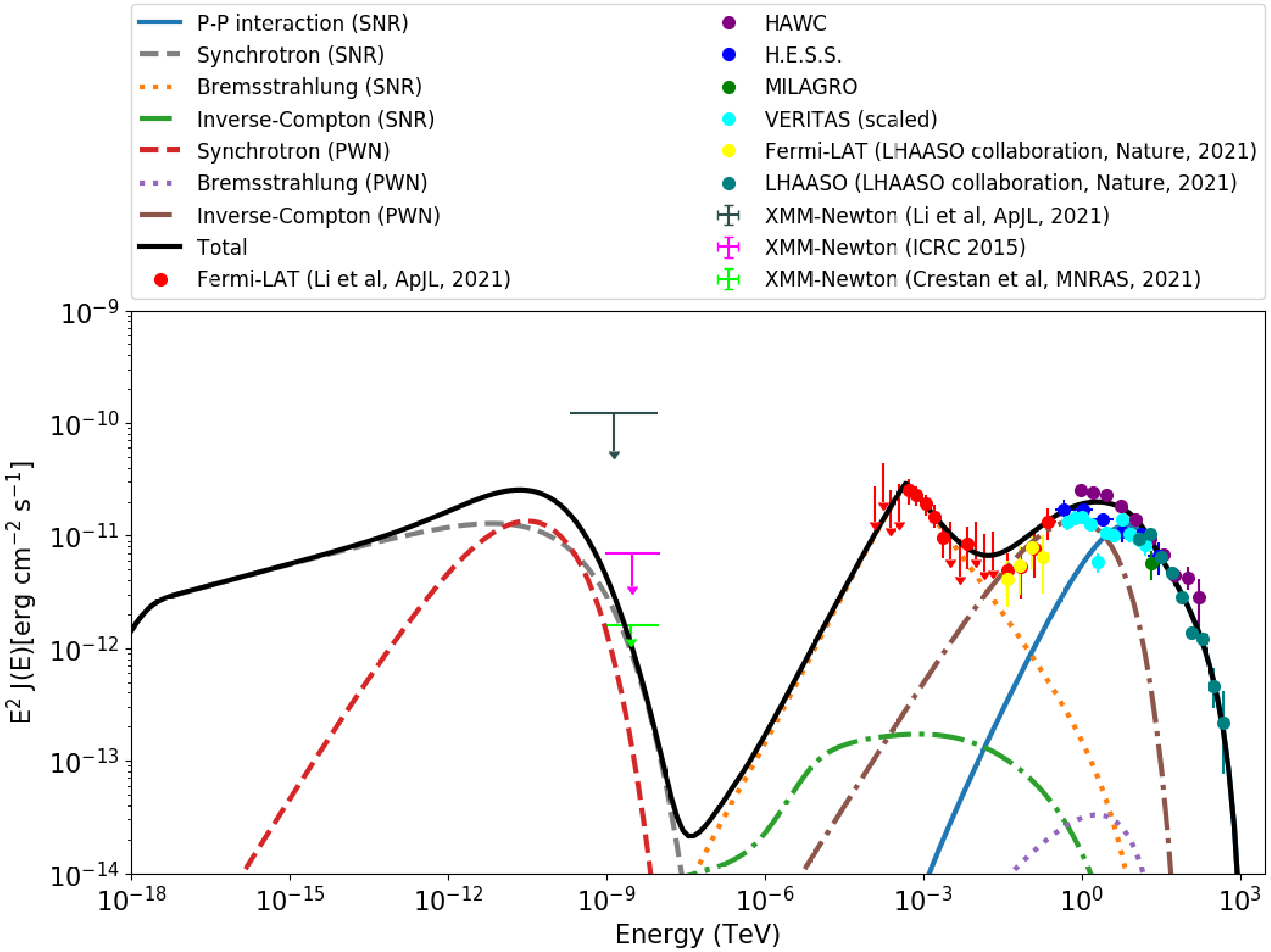
- Electrons also get accelerated at the SN shock front.
- The escaped electron spectrum is assumed to resemble that of proton, i.e. $\alpha_e^{SNR} \approx 2.75$.
- Power law with exponential cut-off as the spectrum of escaped electron population.
- $E_{max}^{e,SNR} \approx 14\,(v_{sh}(t_{coll})/10^8\ cm/s)(B_{MC}/10\ \mu G)^{-1/2}$ TeV; $E_{min}^{e,SNR} \approx 500$ MeV.
- Inverse-Compton, Bremsstrahlung & Synchrotron considered. Bremsstrahlung is dominant.
- Total energy budget, $W_e^{SNR} \approx 1 \times 10^{49}$ erg.

LHAASO J1908+0621: PWN J1907+0602

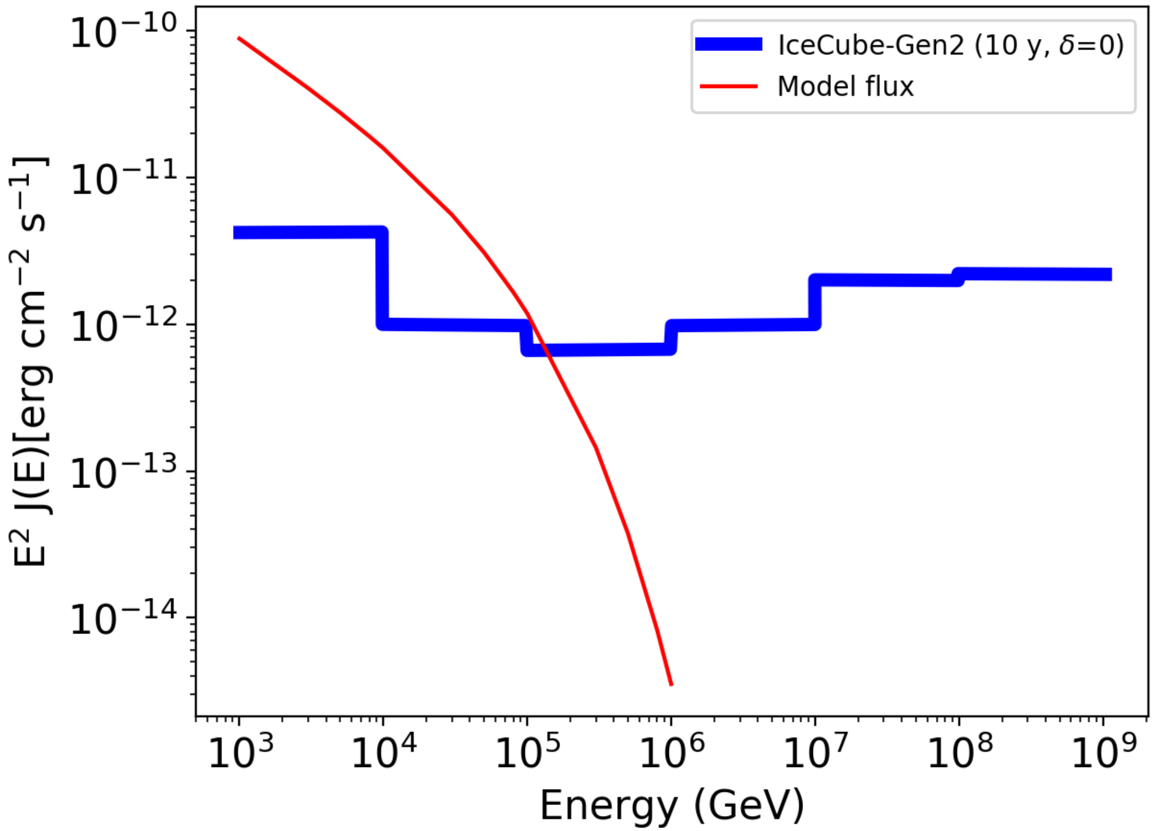
RRI

- Distance & age are considered to be 3.2 kpc and 19.5 kyr.
- IC, synchrotron and bremsstrahlung are considered. IC & synchrotron are dominant.
- Magnetic field of the order of $\sim$ μG; $B_{PWN} \approx 3$ μG considered for synchrotron.
- Galactic ISRF and CMB considered as target photon for IC.
- Power law with exponential cut-off as electron spectrum.
- Injection spectral index, $\alpha_e^{PWN} \approx$ 1.5; minimum energy, $E_{min}^{e,PWN} \approx 0.511$ MeV (electron rest mass energy).
- Maximum energy, $E_{max}^{e,PWN} \approx 10$ TeV, constrained by X-ray upper limits.

LHAASO J1908+0621 : Multi-wavelength SED



LHAASO J1908+0621 : Neutrino flux



- Although not significant yet, a neutrino hotspot has been observed coincident with LHAASO J1908+0621.

- Neutrinos are also produced in hadronic p-p interaction, along with gamma-rays.

- Muonic neutrino flux calculated through two channels.
  1) Direct decay of charged pions ($\pi \rightarrow \mu\, \nu_\mu$).
  2) Decay of muons ($\mu \longrightarrow e\, \nu_\mu\, \nu_e$).

- Total estimated muon neutrino flux exceeds ICECUBE-Gen2 sensitivity limit to detect the neutrino flux from a point source at the celestial equator with an average significance of 5σ after 10 years of observations.

Summary:

- A candidate PeVatron source, LHAASO J1908+0621, was studied.
- Observed LHAASO data, as well as data observed by H.E.S.S., VERITAS were explained by hadronic interaction between SNR G40.5-0.5 and associated MCs.
- Leptonic contributions from SNR+MC system and PWN J1907+0602 were also considered to explain the Fermi-LAT, H.E.S.S., VERITAS data.
- The multi-wavelength SED was explained by the model. The model is also consistent with the observed morphology. The total synchrotron emission does not violate the observed X-ray upper limits.
- With the model, the neutrino hotspot can be consistently explained.
- Further observations at UHE energy are needed to confirm the source contribution.