Astrophysics of Galactic PeVatrons

Andrii Neronov
APC Paris and EPFL Lausanne

Selected topics of **Astrophysics of Galactic PeVatrons**

Andrii Neronov
APC Paris and EPFL Lausanne

Origin of the Knee

LHAASO Collab. 2511.05013

What is the origin of the Knee of locally observed cosmic ray spectrum at 4 PV rigidity?

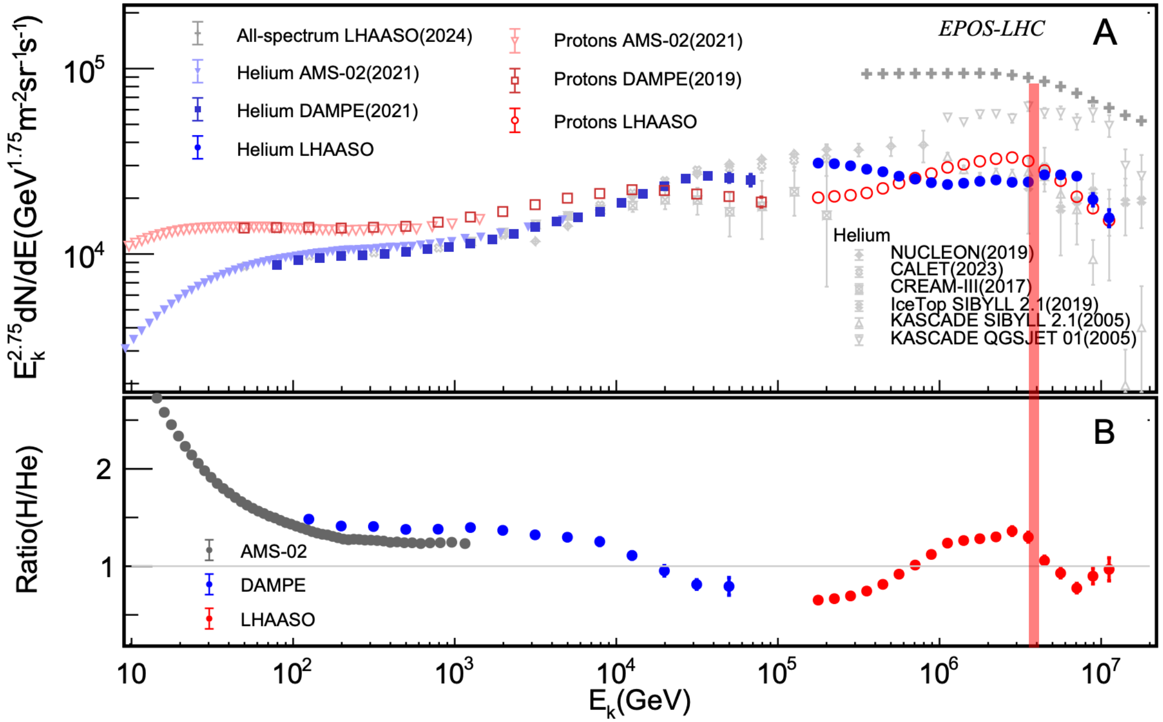
(A) CRs with rigidity above 4 PV are not efficienty retained by galactic magnetic field ?

or

(B) Galactic cosmic ray sources are typically not able to accelerate particles beyond 4 PV rigidity ?

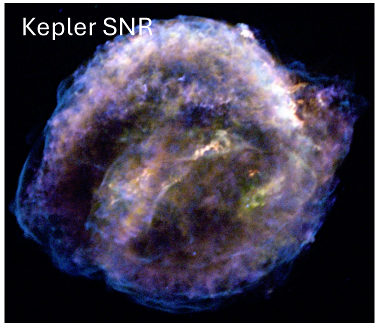
or

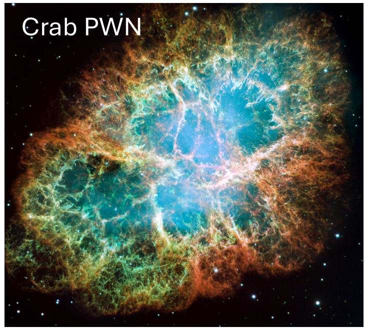
(C) PeV CR flux in the solar neighbourhood is influenced by single source that occasionally has 4 PeV cut-off ?

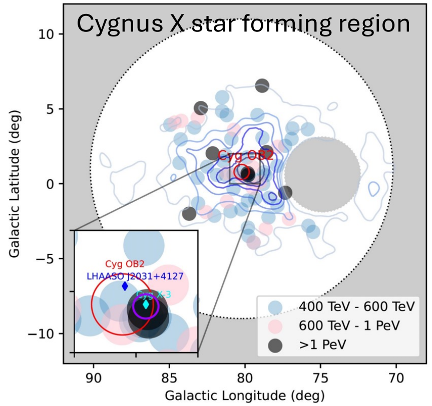


- Characterize population of galactic sources accelerating protons at least to the Knee energy.
- Characterize PeV particle injection and propagation in the interstellar medium.
- Identify (or rule out existence of) a “local source” that may provide $O(1)$ contribution to Knee CR flux.

Galactic PeVatron (candidate) overview

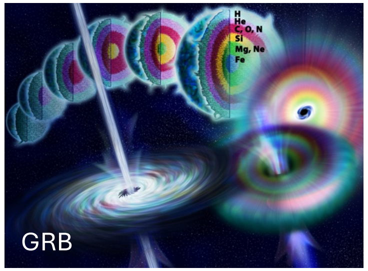


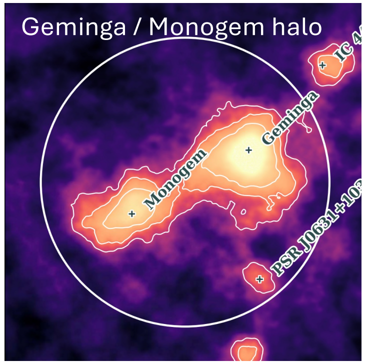


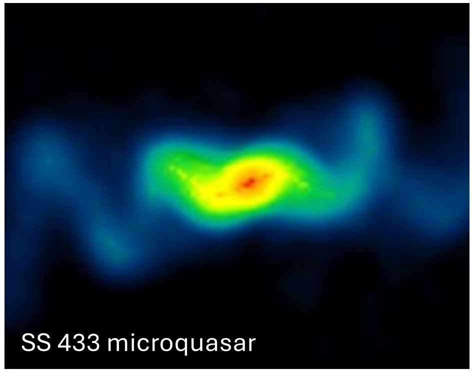


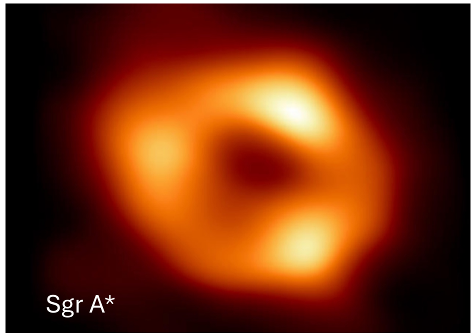
At least 6 types of astronomical sources to consider:

1. Supernova remnants (SNR)
2. Pulsar wind nebulae (PWN)
3. Pulsar halos (PH)
4. Gamma-ray bursts (GRB)
5. Young massive stellar clusters (YMSC)
6. Microquasars (MQ)
7. Galactic Center



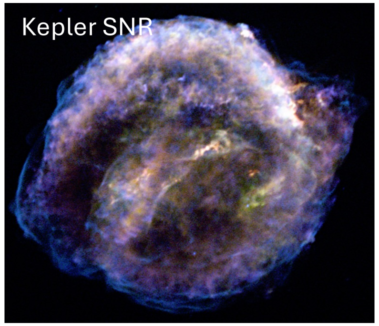




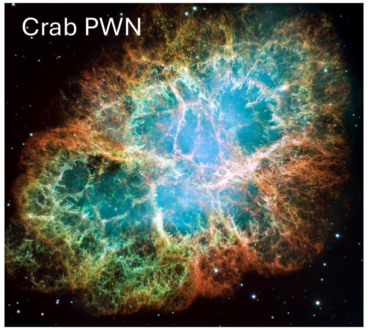


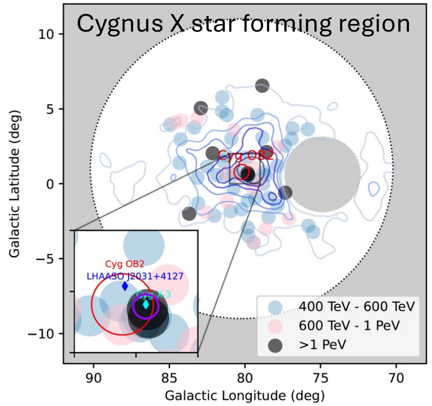
- **Characterize population of galactic sources accelerating protons at least to the Knee energy.**
- Characterize PeV particle injection and propagation in the interstellar medium.
- Identify (or rule out existence of) a “local source” that may provide $O(1)$ contribution to Knee CR flux.

Galactic PeVatron (candidate) overview



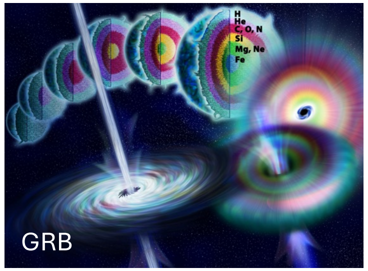
Talk by M.Lemoine

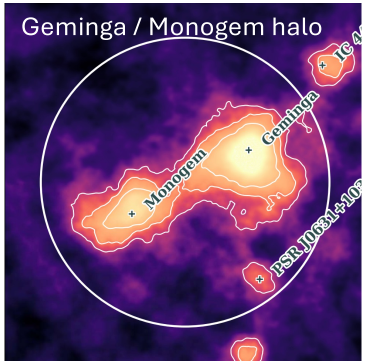


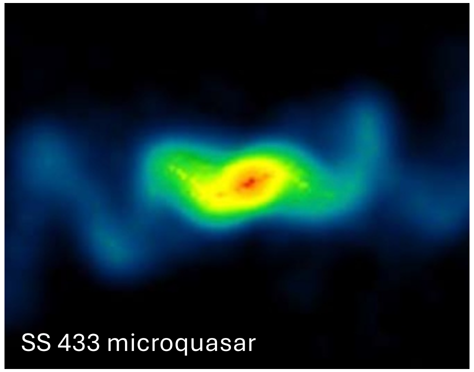


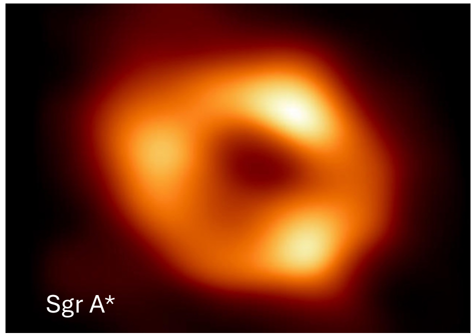
At least 6 types of astronomical sources to consider:

1. Supernova remnants (SNR)
2. Pulsar wind nebulae (PWN)
3. Pulsar halos (PH)
4. Gamma-ray bursts (GRB)
5. Young massive stellar clusters (YMSC)
6. Microquasars (MQ)
7. Galactic Center







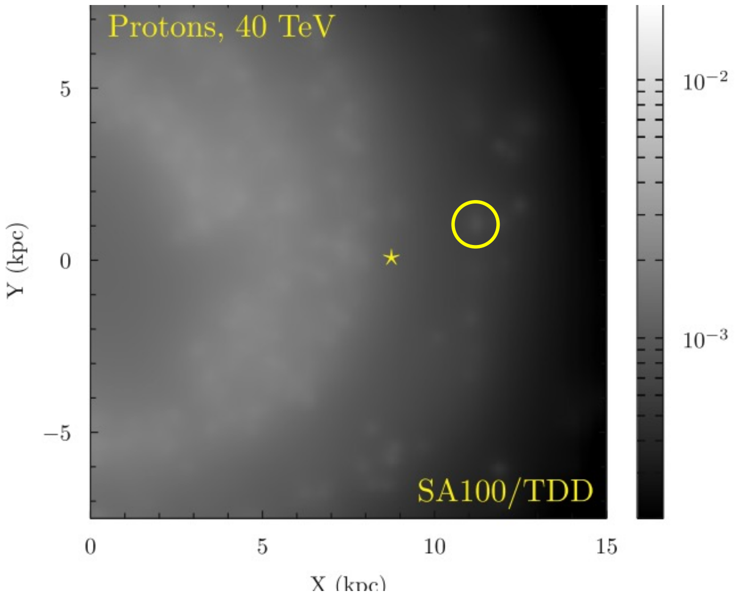


Talk by G.Giacinti and B.T.Zhang

- **Characterize population of galactic sources accelerating protons at least to the Knee energy.**
- Characterize PeV particle injection and propagation in the interstellar medium.
- Identify (or rule out existence of) a "local source" that may provide $O(1)$ contribution to Knee CR flux.

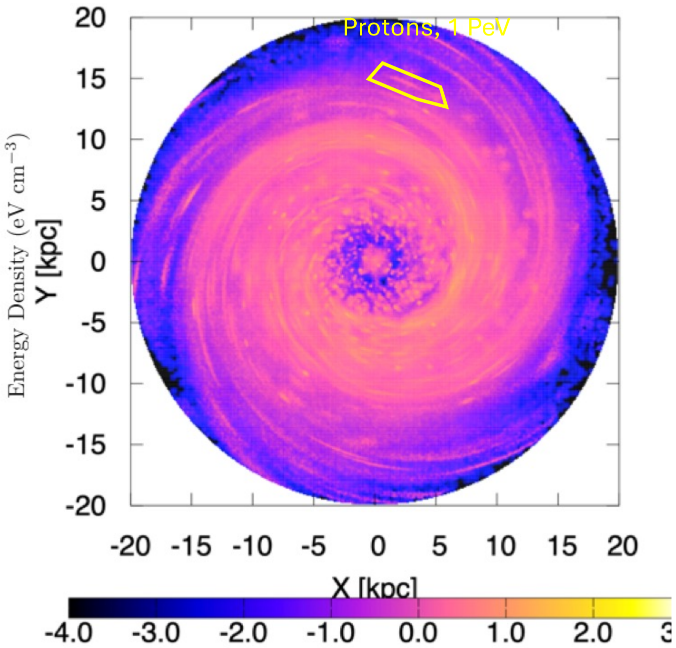
CR propagation models overview

isotropic



Porter et al. 2112.12745

anisotropic



Giacinti, Semikoz, 2305.10251

Uncertainty of propagation of sub-PeV CRs

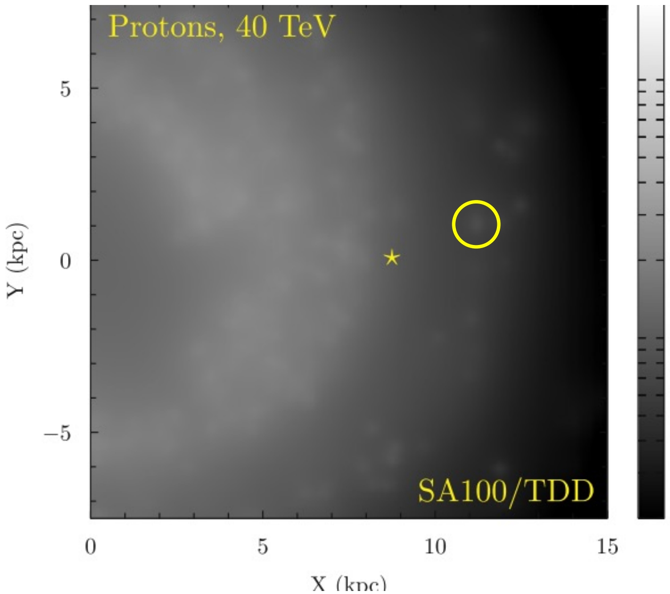
1. isotropic diffusion
2. anisotropic diffusion

In the energy range below PeV.

- Characterize population of galactic sources accelerating protons at least to the Knee energy.
- **Characterize PeV particle injection and propagation in the interstellar medium.**
- Identify (or rule out existence of) a "local source" that may provide $O(1)$ contribution to Knee CR flux.

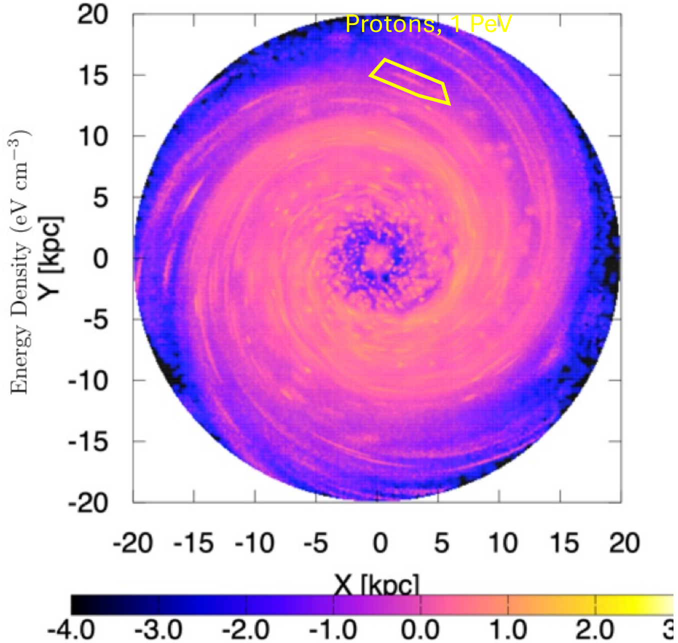
CR propagation models overview

isotropic



Porter et al. 2112.12745

anisotropic



Giacinti, Semikoz, 2305.10251

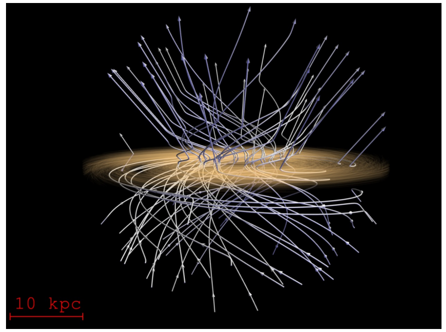
Uncertainty of propagation of sub-PeV CRs

1. isotropic diffusion
2. anisotropic diffusion

In the energy range below PeV.

Uncertainty of propagation of CRs with energies above PeV that can either diffuse or propagate via

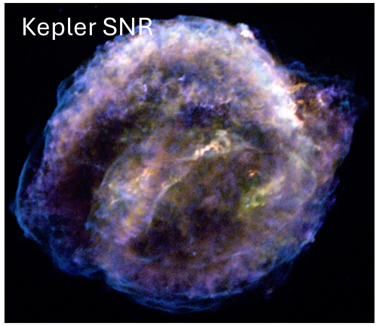
3. free streaming in uncertain Galactic field:

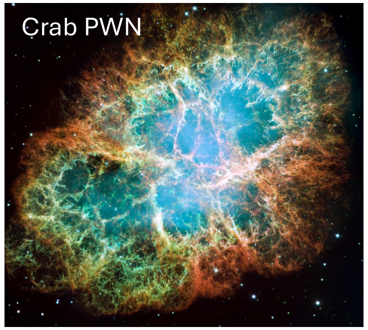


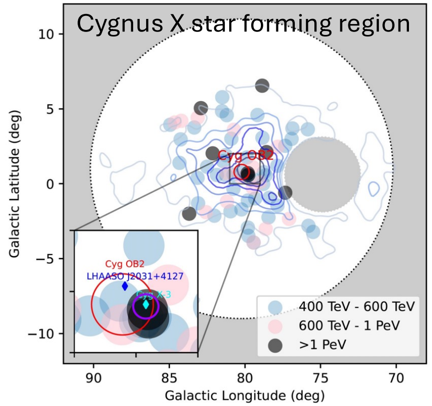
Jansson, Farrar 1204.3662

- Characterize population of galactic sources accelerating protons at least to the Knee energy.
- **Characterize PeV particle injection and propagation in the interstellar medium.**
- Identify (or rule out existence of) a “local source” that may provide $O(1)$ contribution to Knee CR flux.

Galactic PeVatron (candidate) overview

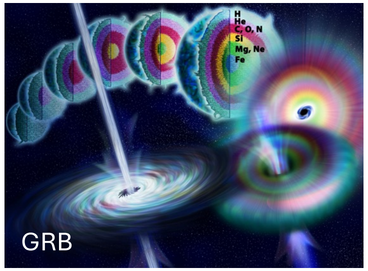


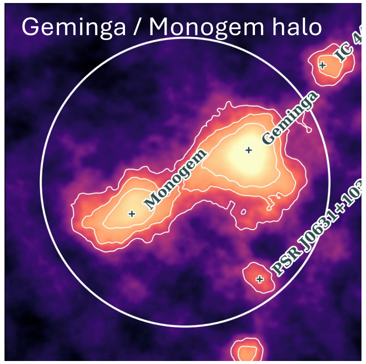


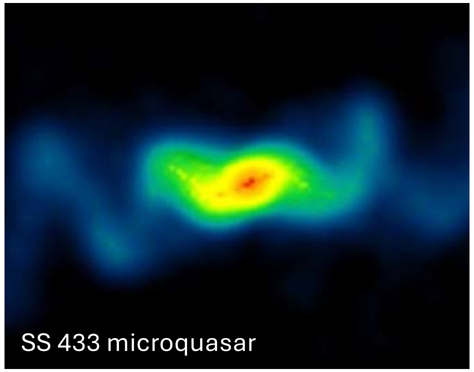


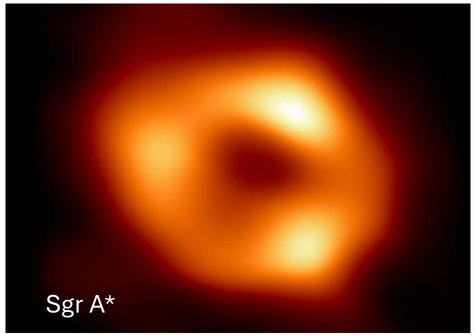
At least 6 types of astronomical sources to consider:

1. Supernova remnants (SNR)
2. Pulsar wind nebulae (PWN)
3. Pulsar halos (PH)
4. Gamma-ray bursts (GRB)
5. Young massive stellar clusters (YMSC)
6. Microquasars (MQ)
7. Galactic Center



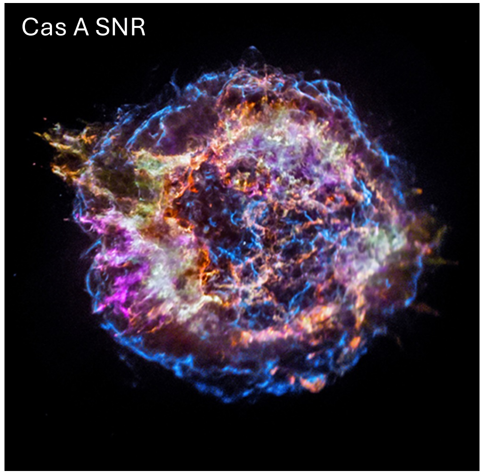






- **Characterize population of galactic sources accelerating protons at least to the Knee energy.**
- Characterize PeV particle injection and propagation in the interstellar medium.
- Identify (or rule out existence of) a "local source" that may provide $O(1)$ contribution to Knee CR flux.

PeV particles in historical supernova remnants ?



Maximal energy is reached at the end of free expansion phase. Three SNR are currently at this moment of evolution: Cas A, Kepler, Tycho.

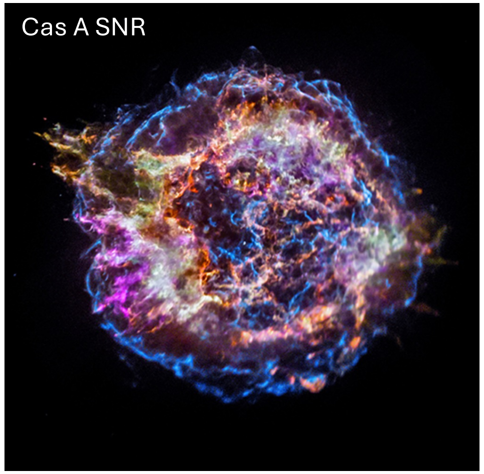
Acceleration time scale in Bohm diffusion limit $t_{acc} = R_L/v^2$. Maximal attainable energy within SNR lifetime t:

$$E = eBv^2t \simeq 10^{15} \left[\frac{B}{100\ \mu\text{G}}\right] \left[\frac{v}{10^{-2}}\right]^2 \left[\frac{t}{400\ \text{yr}}\right] \text{eV}$$

Measured parameters of historical supernova remnants confirm that acceleration up to 4 PeV is possible in these objects.

Name	d_s[kpc]	$B[\mu G]$	$v[c]$	t[yr]	E[PeV]
Cas A	3.4(Ap.J.440,706)	220 (astro-ph/0603723)	0.02 (2201.08911)	360 (astro-ph/0603371)	8
Kepler	5(2105.04235)	175 (astro-ph/0603723)	0.015 (0803.4011)	422	4
Tycho	3.8 (0810.5106)	215 (astro-ph/0603723)	0.013 (1009.6031)	454	4
SN 1006	2.2(astro-ph/0208415)	74 (astro-ph/0603723)	0.01-0.025(1312.3367)	1020	2-12
RCW 86	2.5(1306.3994)	100 (astro-ph/0409453)	0.003(1306.3994)	1841	0.4

PeV particles in historical supernova remnants ?



Maximal energy is reached at the end of free expansion phase. Three SNR are currently at this moment of evolution: Cas A, Kepler, Tycho.

Acceleration time scale in Bohm diffusion limit $t_{acc} = R_L/v^2$. Maximal attainable energy within SNR lifetime t:

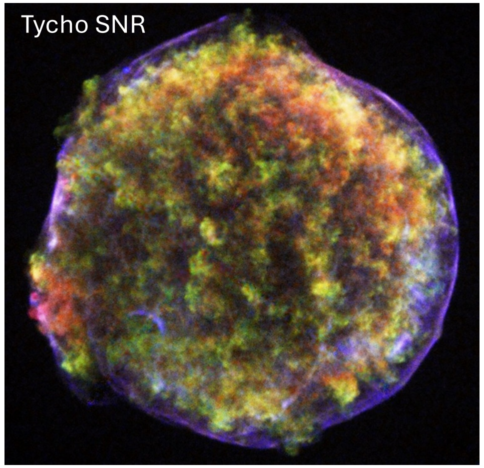
$$E = eBv^2t \simeq 10^{15} \left[\frac{B}{100\ \mu\text{G}}\right] \left[\frac{v}{10^{-2}}\right]^2 \left[\frac{t}{400\ \text{yr}}\right] \text{eV}$$

Measured parameters of historical supernova remnants confirm that acceleration up to 4 PeV is possible in these objects.

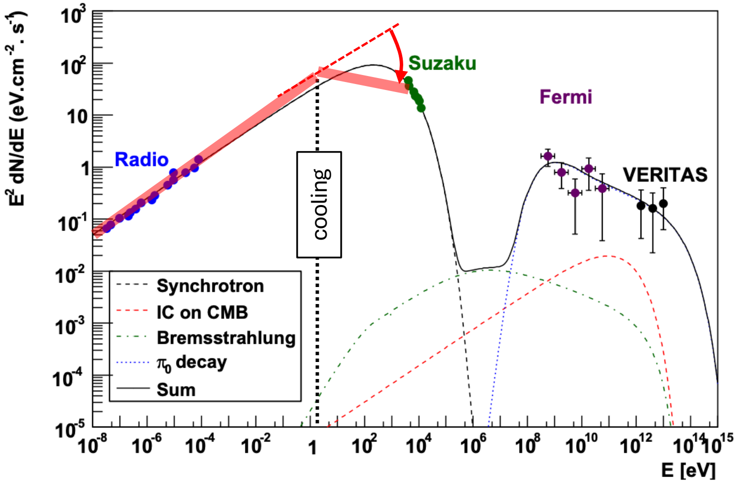
Name	d_s[kpc]	$B[\mu G]$	$v[c]$	t[yr]	E[PeV]
Cas A	3.4(Ap.J.440,706)	220 (astro-ph/0603723)	0.02 (2201.08911)	360 (astro-ph/0603371)	8
Kepler	5(2105.04235)	175 (astro-ph/0603723)	0.015 (0803.4011)	422	4
Tycho	3.8 (0810.5106)	215 (astro-ph/0603723)	0.013 (1009.6031)	454	4
SN 1006	2.2(astro-ph/0208415)	74 (astro-ph/0603723)	0.01-0.025(1312.3367)	1020	2-12
RCW 86	2.5(1306.3994)	100 (astro-ph/0409453)	0.003(1306.3994)	1841	0.4

Can observation data be used to validate the estimate of t_{acc}?

PeV particles in historical supernova remnants ?



Giordano et al. 1108.0265



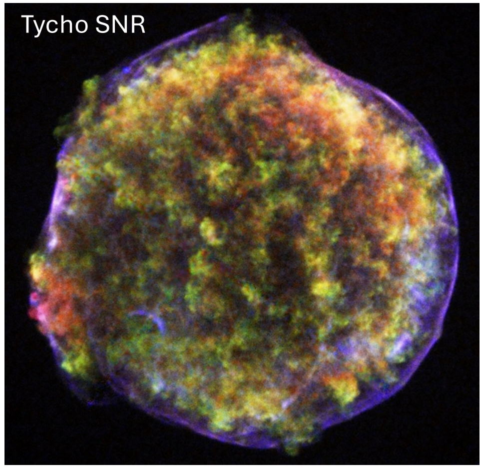
Electron synchrotron cooling time:

$$t_s = 413 \left[\frac{B}{200\ \mu\mathrm{G}}\right]^{-2} \left[\frac{E_e}{0.4\ \mathrm{TeV}}\right]^{-1} \mathrm{yr}$$

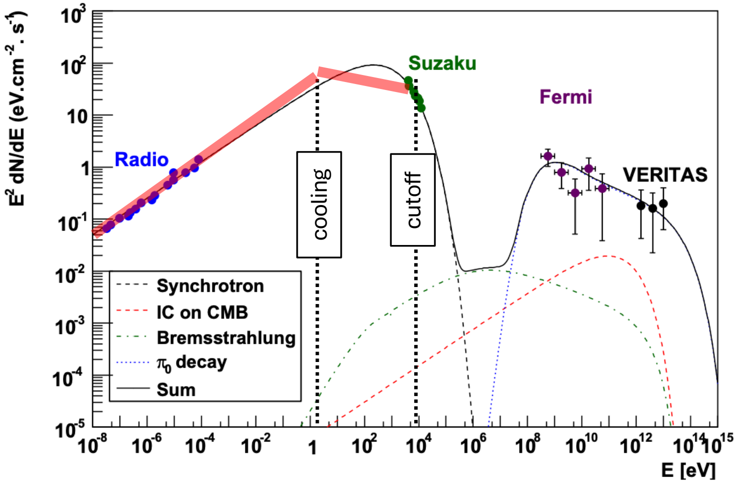
Expected cooling break in synchrotron spectrum:

$$E_{s,break} = 1.6 \left[\frac{B}{200\ \mu\mathrm{G}}\right] \left[\frac{E_e}{0.4\ \mathrm{TeV}}\right]^{2} \mathrm{eV}.$$

Synchrotron emission and acceleration time scale



Giordano et al. 1108.0265



Electron synchrotron cooling time:

$$t_s = 330 \left[\frac{B}{200\ \mu\text{G}}\right]^{-2} \left[\frac{E_e}{0.5\ \text{TeV}}\right]^{-1} \text{yr}$$

Expected cooling break in synchrotron spectrum:

$$E_{s,break} = 2.5 \left[\frac{B}{200\ \mu\text{G}}\right] \left[\frac{E_e}{0.5\ \text{TeV}}\right]^{2} \text{eV}.$$

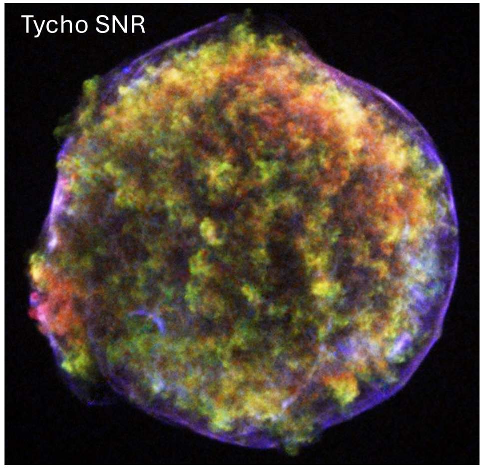
Acceleration time scale:

$$t_{acc} = 4.4 \left[\frac{E}{40\ \text{TeV}}\right] \left[\frac{B}{215\ \mu\text{G}}\right]^{-1} \left[\frac{v}{0.013}\right]^{-2} \text{yr}$$

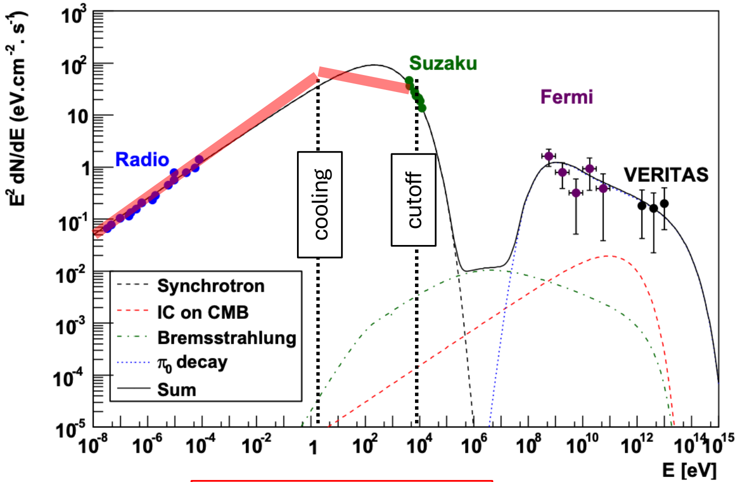
$t_{acc} \sim t_s$ for $E_e \simeq 40$ TeV. Expected synchrotron cut-off:

$$E_{s,cut} = 16 \left[\frac{B}{200\ \mu\text{G}}\right] \left[\frac{E_e}{40\ \text{TeV}}\right]^{2} \text{keV}.$$

Synchrotron emission and acceleration time scale



Giordano et al. 1108.0265



nonthermal visible/IR?

Electron synchrotron cooling time:

$$t_s = 330 \left[\frac{B}{200\ \mu\mathrm{G}}\right]^{-2} \left[\frac{E_e}{0.5\ \mathrm{TeV}}\right]^{-1} \mathrm{yr}$$

Expected cooling break in synchrotron spectrum:

$$E_{s,break} = 2.5 \left[\frac{B}{200\ \mu\mathrm{G}}\right] \left[\frac{E_e}{0.5\ \mathrm{TeV}}\right]^{2} \mathrm{eV}.$$

Acceleration time scale:

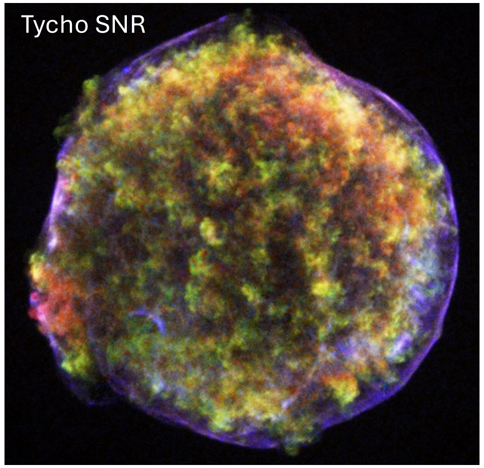
$$t_{acc} = 4.4 \left[\frac{E}{40\ \mathrm{TeV}}\right] \left[\frac{B}{215\ \mu\mathrm{G}}\right]^{-1} \left[\frac{v}{0.013}\right]^{-2} \mathrm{yr}$$

$t_{acc} \sim t_s$ for $E_e \simeq 40$ TeV. Expected synchrotron cut-off:

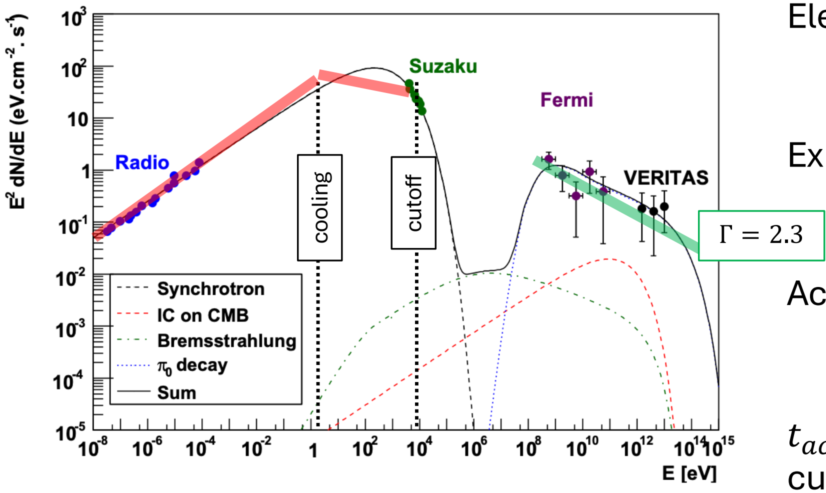
$$E_{s,cut} = 16 \left[\frac{B}{200\ \mu\mathrm{G}}\right] \left[\frac{E_e}{40\ \mathrm{TeV}}\right]^{2} \mathrm{keV}.$$

Measurement of synchrotron spectrum seems to provide validation of acceleration time scale estimate. They also provide measurement of injection spectrum $E^{-2.3}$, the acceleration time scale is consistent with theoretical estimate.

Pion decay emission from protons



Giordano et al. 1108.0265



Electron synchrotron cooling time:

$$t_s = 330\left[\frac{B}{200\ \mu\mathrm{G}}\right]^{-2}\left[\frac{E_e}{0.5\ \mathrm{TeV}}\right]^{-1}\ \mathrm{yr}$$

Expected cooling break in synchrotron spectrum:

$$E_{s,break} = 2.5\left[\frac{B}{200\ \mu\mathrm{G}}\right]\left[\frac{E_e}{0.5\ \mathrm{TeV}}\right]^{2}\ \mathrm{eV}.$$

Acceleration time scale:

$$t_{acc} = 4.4\left[\frac{E}{40\ \mathrm{TeV}}\right]\left[\frac{B}{215\ \mu\mathrm{G}}\right]^{-1}\left[\frac{v}{0.013}\right]^{-2}\ \mathrm{yr}$$

$t_{acc} \sim t_s$ for $E_e \simeq 40$ TeV. Expected synchrotron cut-off:

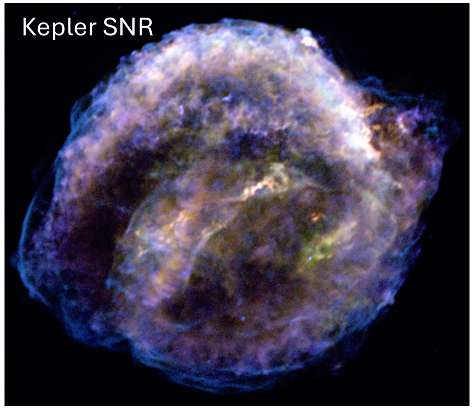
$$E_{s,cut} = 16\left[\frac{B}{200\ \mu\mathrm{G}}\right]\left[\frac{E_e}{40\ \mathrm{TeV}}\right]^{2}\ \mathrm{keV}.$$

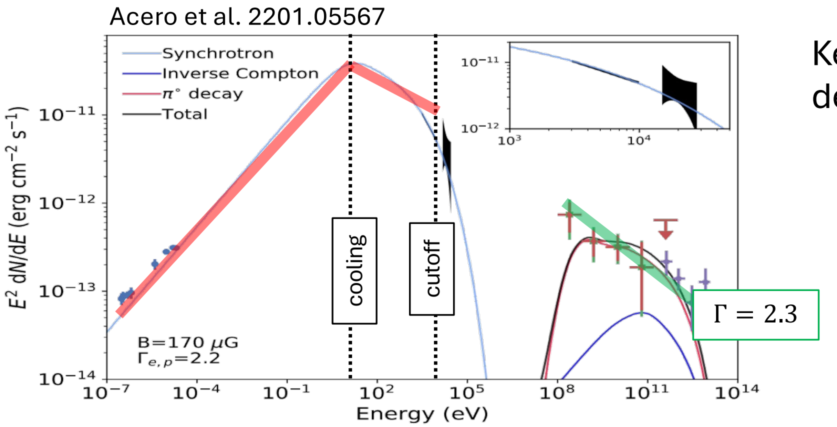
Measurement of synchrotron spectrum seems to provide validation of acceleration time scale estimate. They also provide measurement of injection spectrum $E^{-2.3}$, the acceleration time scale is consistent with theoretical estimate.

Protons are inevitably injected together with electrons, with the same spectrum. Pion decay emission from interactions of protons injected with spectrum $dN/dE \propto E^{-2.3}$ is consistent with GeV- 10 TeV band data. Pion decay spectrum is expected to reach $E_\gamma >$ 100 TeV band.

Injection with spectrum $E^{-2.3}$ can conveniently provide observed CR spectrum if galactic diffusion coefficient is $D \propto E^{1/3}$ (Kolmogorov).

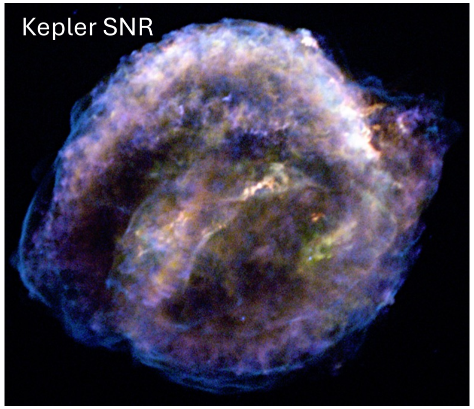
Pion decay emission from protons



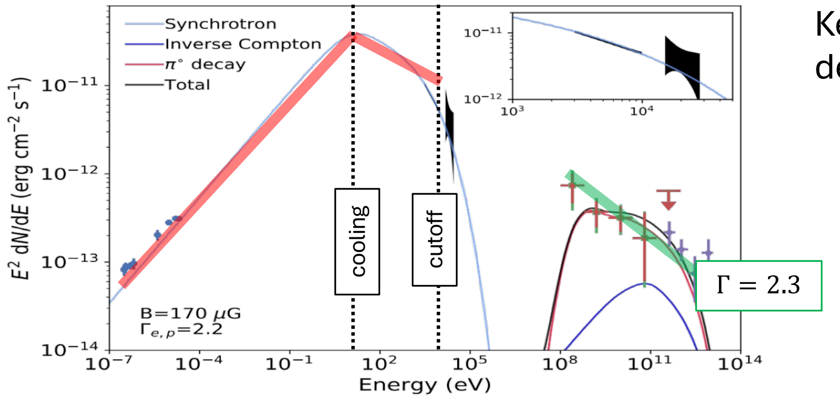


Kepler SNR data are consistent with the model derived from Tycho SNR.

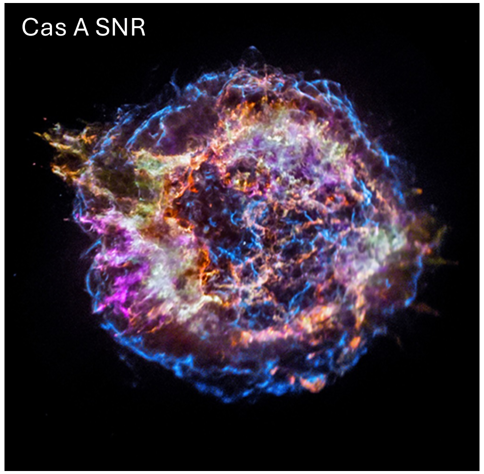
Pion decay emission from protons



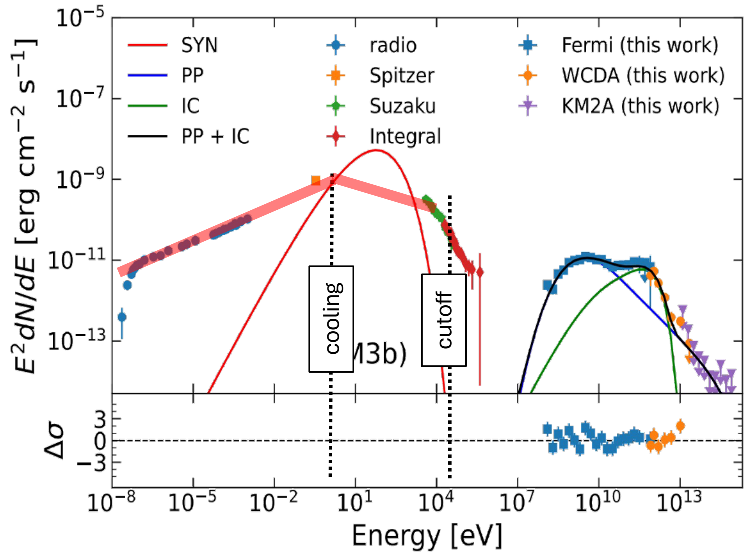
Acero et al. 2201.05567



Kepler SNR data are consistent with the model derived from Tycho SNR.

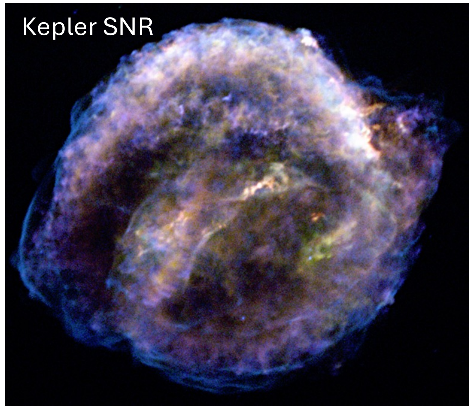


LHAASO Collab. 2502.04848

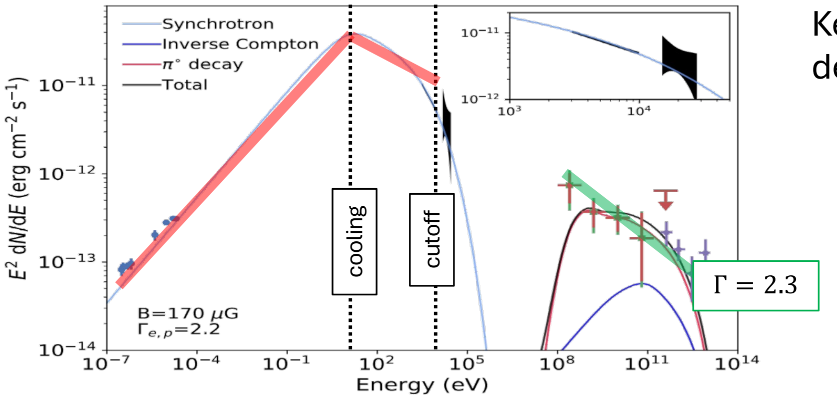


Cas A synchrotron emission is also consistent with emission from cooled electron population with somewhat softer spectrum, $\Gamma \simeq 2.5$

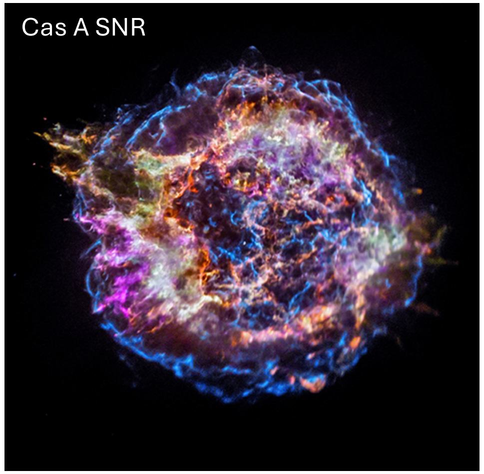
Pion decay emission from protons



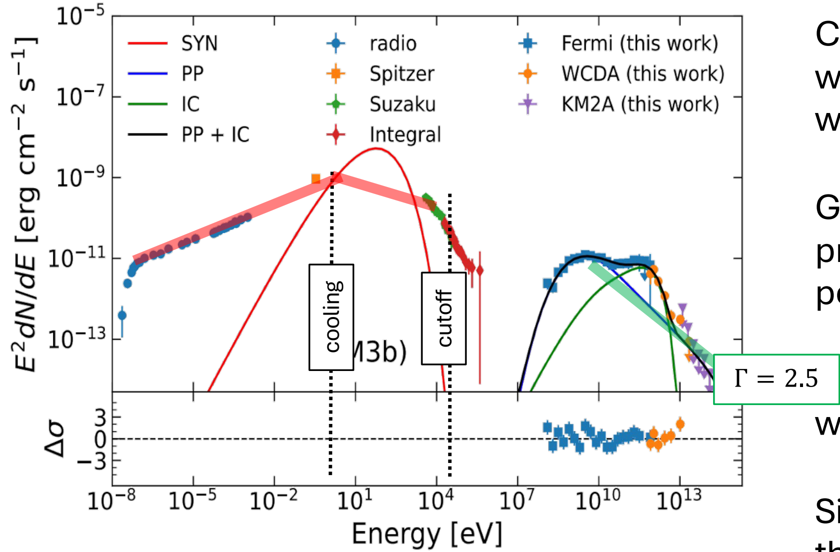
Acero et al. 2201.05567



Kepler SNR data are consistent with the model derived from Tycho SNR.



LHAASO Collab. 2502.04848



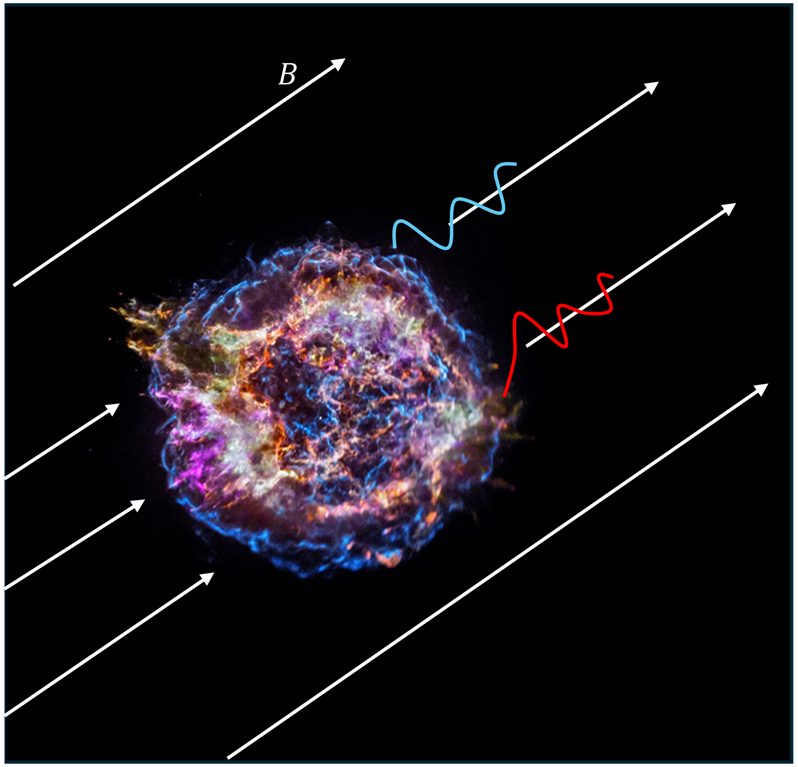
Cas A synchrotron emission is also consistent with emission from cooled electron population with somewhat softer spectrum, $\Gamma \simeq 2.5$

Gamma-ray spectrum consistent with $\Gamma \simeq 2.5$ proton injection spectrum. Extra structure, possibly from electron contribution.

Alternatively, harder proton injection spectrum, with suppression above 10 TeV ?

Signature of escape of $E > 10$ TeV particles from the source?

Particle escape from sources



Isotropic propagation model. Particles start diffusing in interstellar medium, with diffusion coefficient

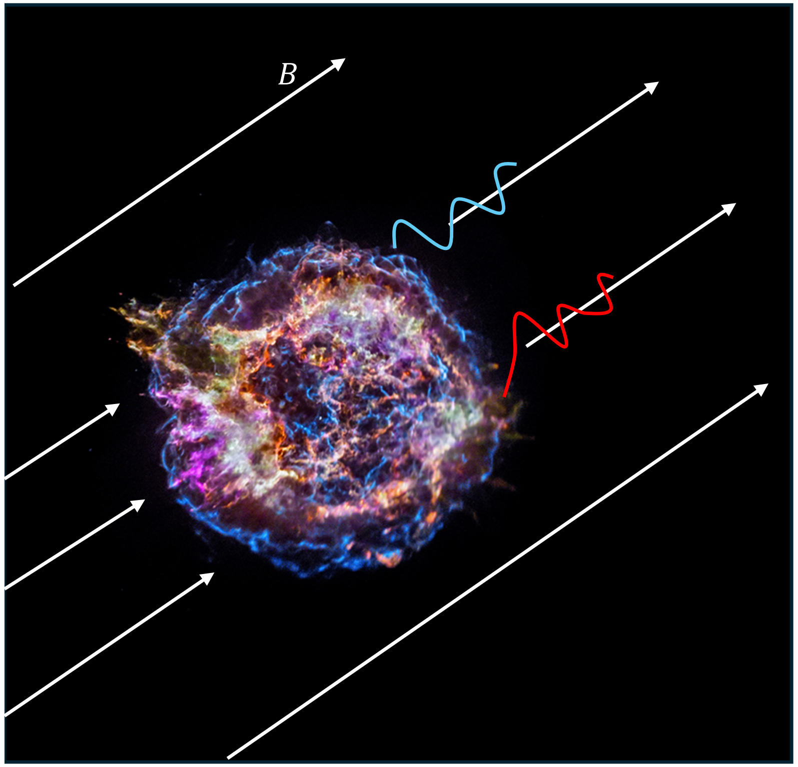
$$D = 10^{28} D_{28} \left[\frac{E}{4\ \mathrm{GeV}}\right]^{1/3} \frac{\mathrm{cm}^2}{\mathrm{s}} = 10^{30} D_{28} \left[\frac{E}{4\ \mathrm{PeV}}\right]^{1/3} \frac{\mathrm{cm}^2}{\mathrm{s}},$$

The diffusion regime starts on distance scales larger than mean free path

$$\lambda = 3D \simeq 33 \left[\frac{E}{4\ \mathrm{PeV}}\right]^{\frac{1}{3}} \mathrm{pc}$$

On smaller distance scales, particles spiral along magnetic field lines.

Particle escape from sources



Isotropic propagation model. Particles start diffusing in interstellar medium, with diffusion coefficient

$$D = 10^{28} D_{28} \left[\frac{E}{4\ \mathrm{GeV}}\right]^{1/3} \frac{\mathrm{cm}^2}{\mathrm{s}} = 10^{30} D_{28} \left[\frac{E}{4\ \mathrm{PeV}}\right]^{1/3} \frac{\mathrm{cm}^2}{\mathrm{s}},$$

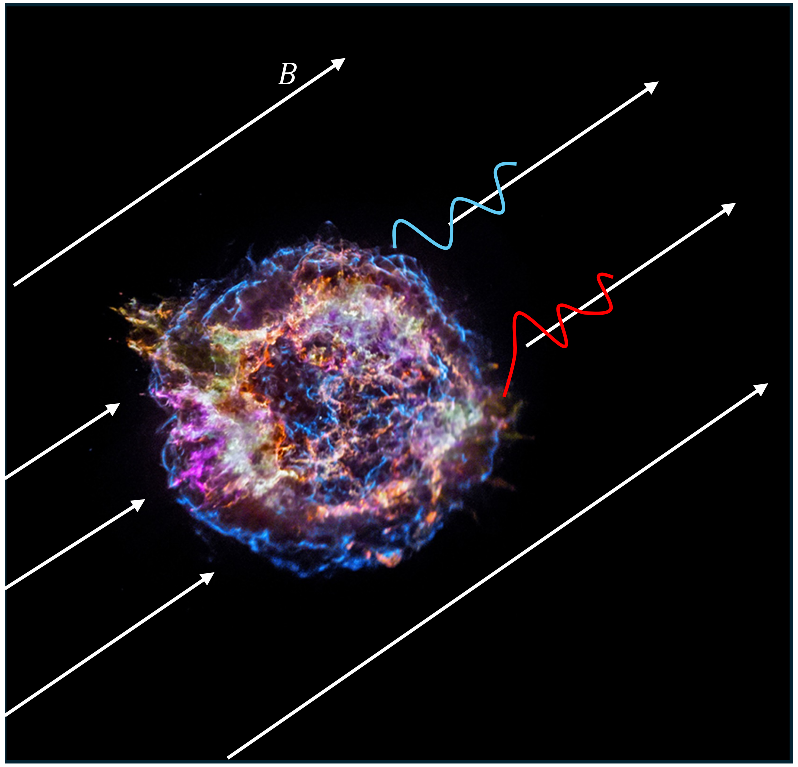
The diffusion regime starts on distance scales larger than mean free path

$$\lambda = 3D \simeq 33 \left[\frac{E}{4\ \mathrm{PeV}}\right]^{\frac{1}{3}} \mathrm{pc}$$

On smaller distance scales, particles spiral along magnetic field lines.

On occasion, λ is comparable to the correlation length of interstellar turbulence for particles with energies close to the Knee energy.

Particle escape from sources



Isotropic propagation model. Particles start diffusing in interstellar medium, with diffusion coefficient

$$D = 10^{28} D_{28} \left[\frac{E}{4\ \mathrm{GeV}}\right]^{1/3} \frac{\mathrm{cm}^2}{\mathrm{s}} = 10^{30} D_{28} \left[\frac{E}{4\ \mathrm{PeV}}\right]^{1/3} \frac{\mathrm{cm}^2}{\mathrm{s}},$$

The diffusion regime starts on distance scales larger than mean free path

$$\lambda = 3D \simeq 33 \left[\frac{E}{4\ \mathrm{PeV}}\right]^{\frac{1}{3}} \mathrm{pc}$$

On smaller distance scales, particles spiral along magnetic field lines.

On occasion, λ is comparable to the correlation length of interstellar turbulence for particles with energies close to the Knee energy.

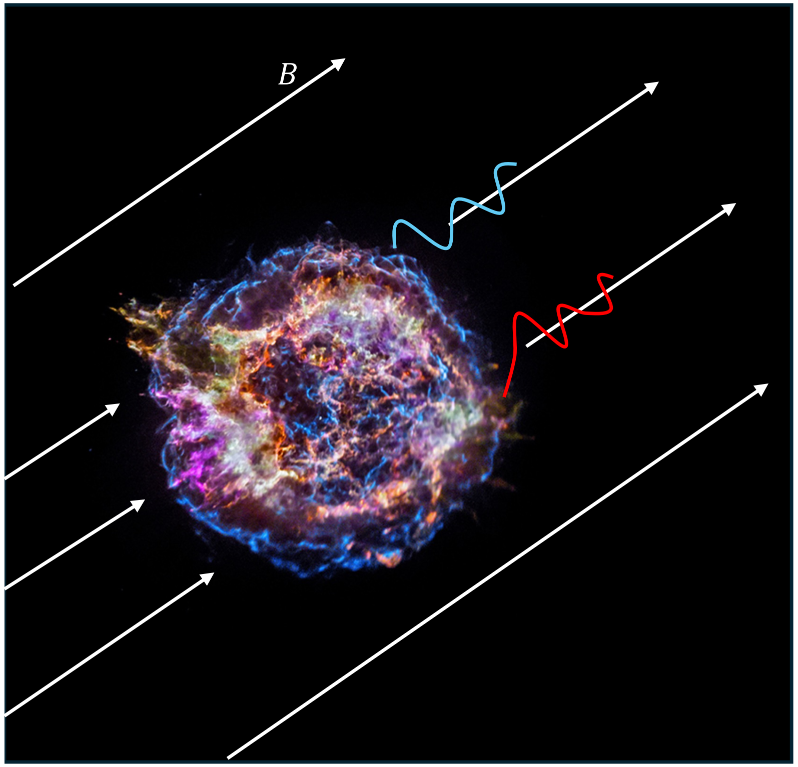
In diffusion regime particles spread up to distance

$$r_{diff} = 2\sqrt{Dt} \simeq 73\, D_{28}^{1/2} \left[\frac{t}{400\ \mathrm{yr}}\right]^{1/2} \left[\frac{E}{4\ \mathrm{PeV}}\right]^{1/6} \mathrm{pc}$$

Both λ and r_{diff} are resolvable for historical SNR:

$$\theta_\lambda = \frac{\lambda}{d_s} \simeq 0.5^\circ \left[\frac{d_s}{4\ \mathrm{kpc}}\right]^{-1} \left[\frac{E}{4\ \mathrm{PeV}}\right]^{\frac{1}{3}}; \quad \theta_{diff} = \frac{r_{diff}}{d_s} \simeq 1.1^\circ \left[\frac{d_s}{4\ \mathrm{kpc}}\right]^{-1} \left[\frac{E}{4\ \mathrm{PeV}}\right]^{\frac{1}{6}}$$

Particle escape from sources



Ansotropic propagation model. Particles start diffusing along Galactic magnetic field lines, with diffusion coefficients

$$D_{||} \gtrsim D, D_{\perp} \ll D$$

Diffusion distances in parallel and perpendicular directions are widely different,

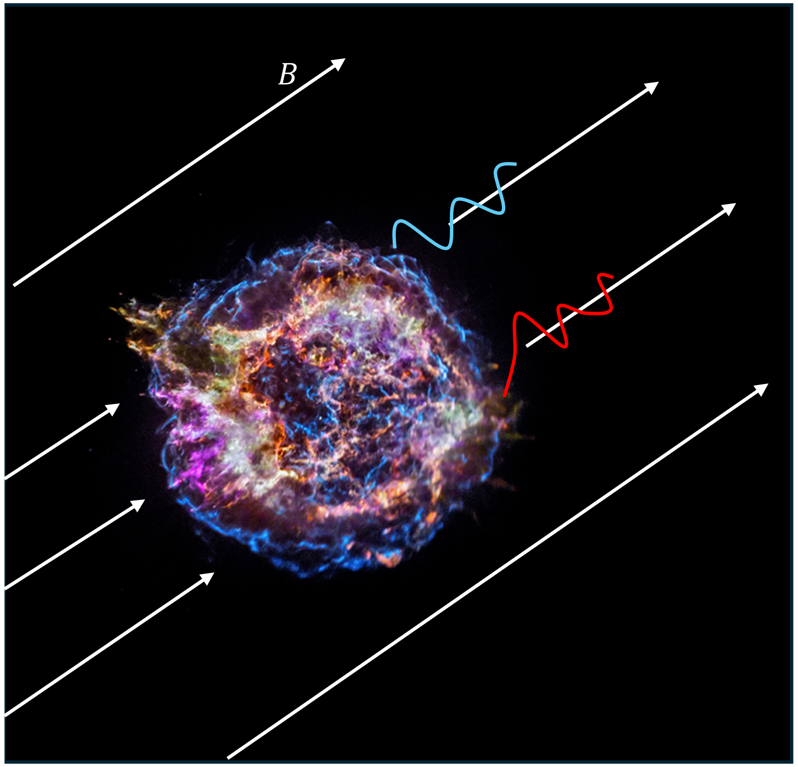
$$r_{diff} = 2\sqrt{Dt} \simeq 73\, D_{28}^{1/2} \left[\frac{t}{400\text{ yr}}\right]^{1/2} \left[\frac{E}{4\text{ PeV}}\right]^{1/6} \text{pc}$$

$$r_{||} \gtrsim r_{diff}, \qquad r_{\perp} \ll r_{diff}$$

Only diffusion in direction parallel to ordered magnetic field line is resolvable for historical SNR:

$$\theta_{||} \gtrsim \theta_{diff} = \frac{r_{diff}}{d_s} \simeq 1.1^{\circ} \left[\frac{d_s}{4\text{ kpc}}\right]^{-1} \left[\frac{E}{4\text{ PeV}}\right]^{\frac{1}{6}}$$

Tracing particle escape through into interstellar medium



Protons interact with interstellar medium protons (density n_{ISM}) via pion production and decay, with cross-section $\sigma_{pp} \simeq 3\times10^{-26}$ cm^2. Collision time scale

$$t_{pp} = (\sigma_{pp} n_{ISM})^{-1} \sim 37 \left[\frac{n_{ISM}}{1\ \mathrm{cm}^{-3}}\right]^{-1} \mathrm{Myr}$$

Proton looses a fraction $\kappa \sim 0.4$ of its energy in single collision, a fraction $\kappa_\gamma \sim 0.1$ is emitted as gamma-rays from neutral pion decays. Gamma-ray luminosity

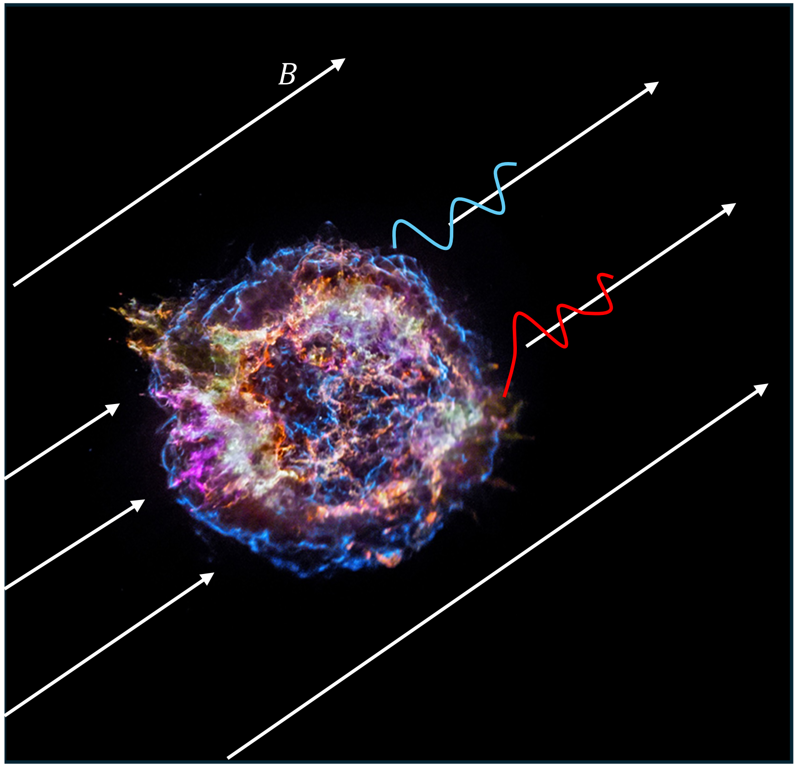
$$L_\gamma = \kappa_\gamma \frac{E_{CR}}{t_{pp}} \simeq 10^{34} \left[\frac{\kappa_\gamma}{0.1}\right] \left[\frac{E_{CR}}{10^{50}\mathrm{erg}}\right] \left[\frac{n_{ISM}}{1\ \mathrm{cm}^{-3}}\right] \frac{\mathrm{erg}}{\mathrm{s}}$$

A pocket of PeV protons that escaped from the source produces flux

$$F_\gamma = 5\times10^{-12} \left[\frac{d_s}{4\ \mathrm{kpc}}\right]^{-2} \left[\frac{\kappa_\gamma}{0.1}\right] \left[\frac{E_{CR}}{10^{50}\mathrm{erg}}\right] \left[\frac{n_{ISM}}{1\ \mathrm{cm}^{-3}}\right] \frac{\mathrm{erg}}{\mathrm{cm}^2\mathrm{s}}$$

For historical supernova remnants, injection spectrum $E^{-2.3} \ldots E^{-2.5}$ implies that the injected energy is $E_{CR} \sim 10^{48}$ erg in PeV energy range. $F_\gamma \lesssim 10^{-13}$ erg/(cm^{2}s).

Particle escape from sources

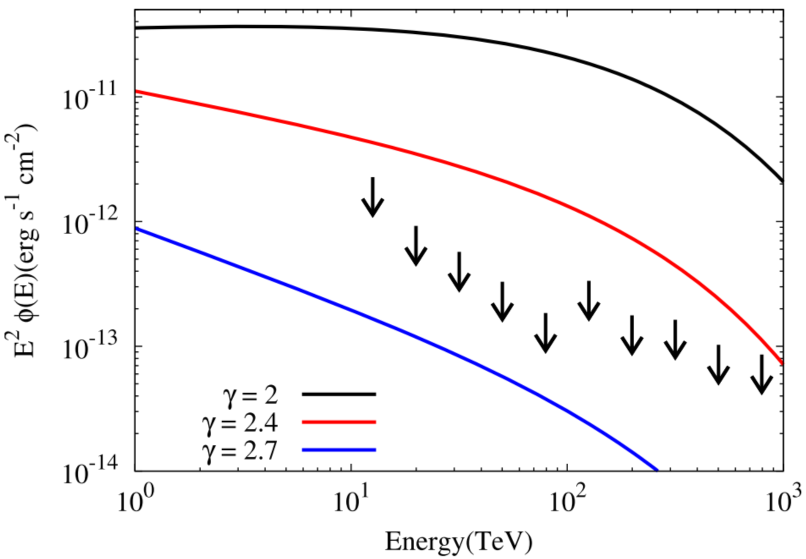


LHAASO has explored possibility that PeV particles have escaped the Cas A supernova, into medium with density $n \sim 10\ \mathrm{cm}^{-3}$.

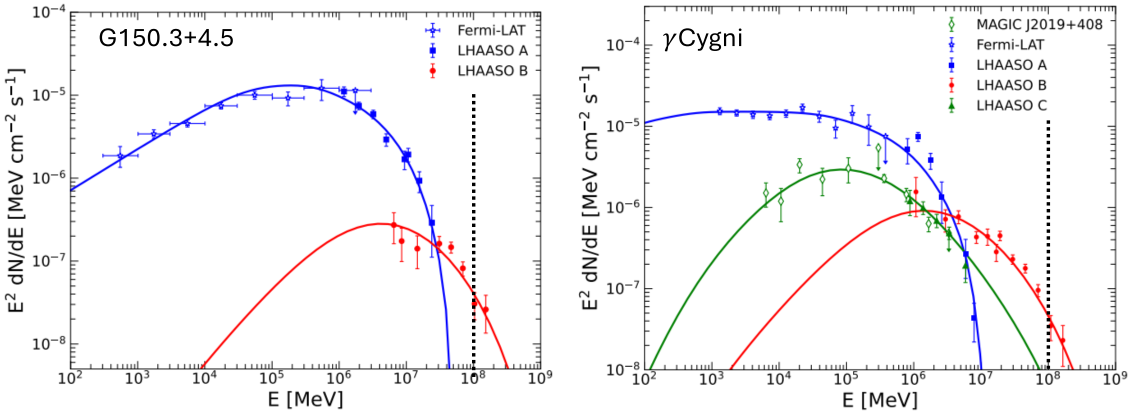
Harder than $\Gamma \simeq 2.5$ injection would possibly overshoot LHAASO upper bounds on emission from an extended reigon within 2° around Cas A.

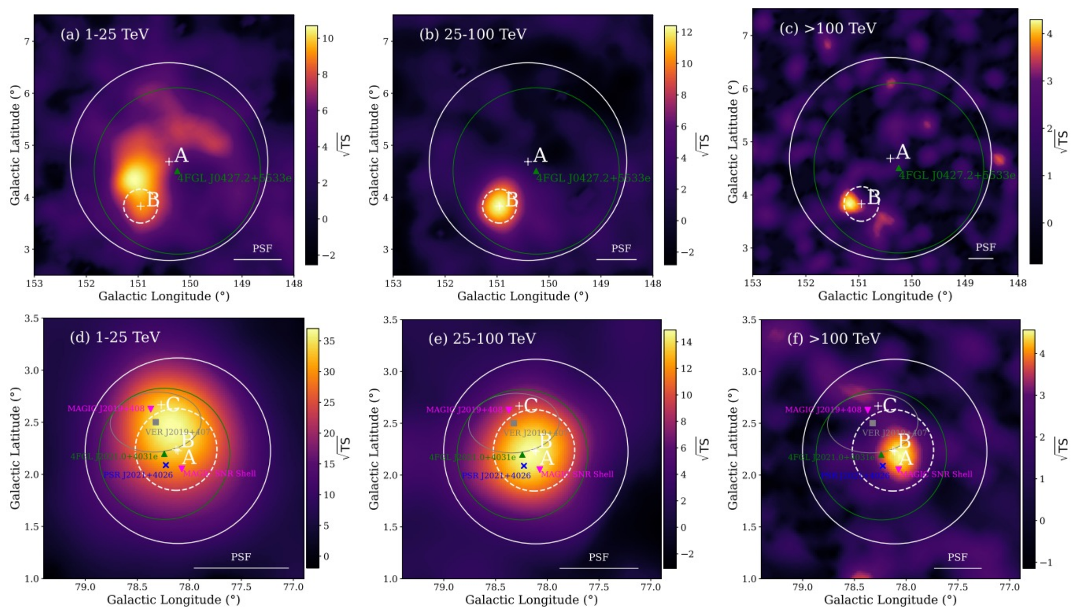
Need for account of uncertainties of ISM density before tension with the estimate of acceleration time scale from synchrotron data can be claimed....

LHAASO Collab. 2310.17082



PeV particles in middle age supernova remnants ?





Cas A, Kepler, Tycho are at distances 3.4-5 kpc.

More nearby SNR are easier to detect in 100 TeV range. However, they are past the maximal acceleration efficiency stage, PeV particles should have escaped.

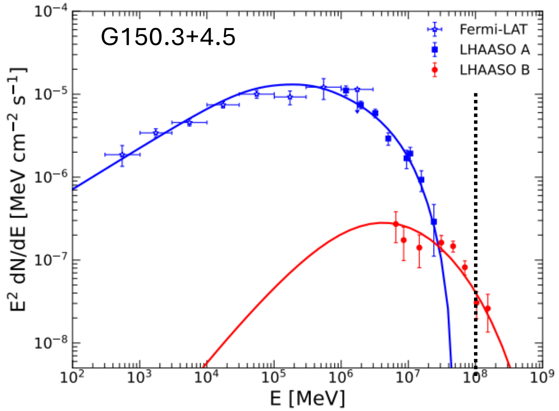
Emission above 100 TeV is detected from several SNR (e.g. G150.3+4.5 (40 kyr, 0.74 kpc), γCygni ($\sim$ 10 kyr, 1.7 kpc)).

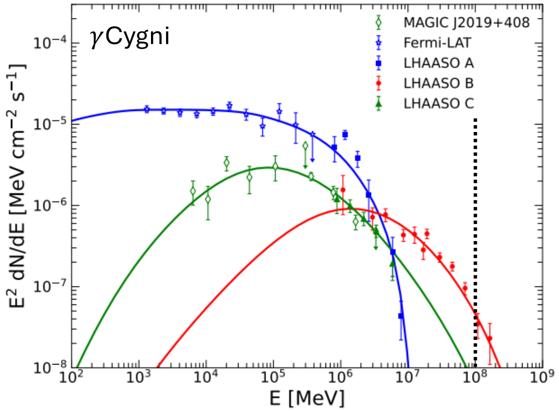
“Hadronic” origin favored (interaction with molecular clouds).

Sizeable contribution from electron Bremsstrahlung and inverse Compton scattering should be modeled in more details (based on synchrotron data?)

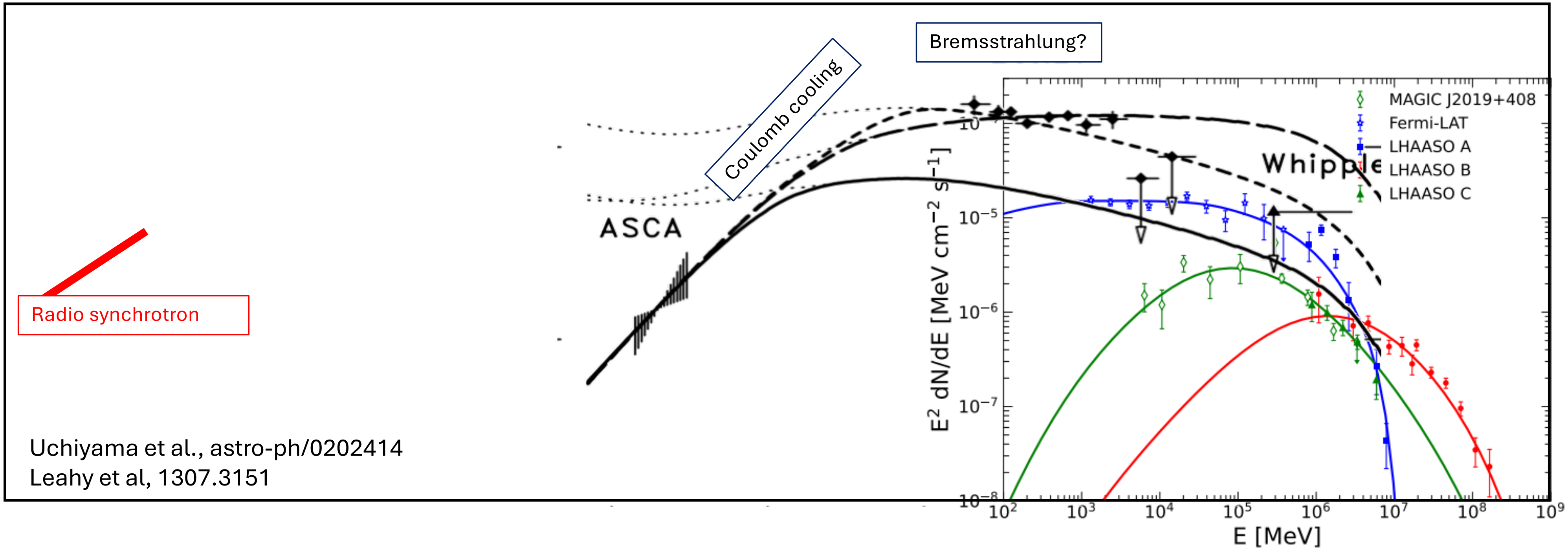
LHAASO Collab. 2604.22621

PeV particles in middle age supernova remnants ?

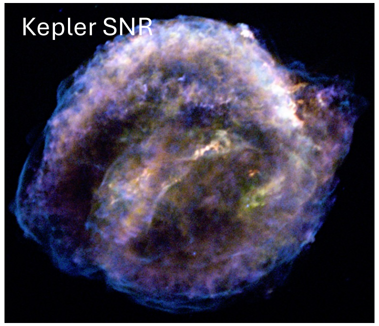


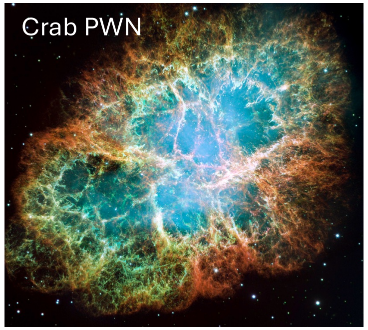


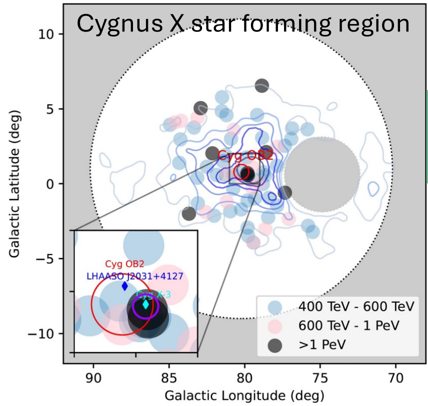
γ-Cygni 7 kyr, 1.7 kpc



Galactic PeVatron (candidate) overview

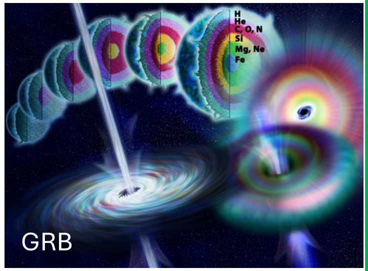


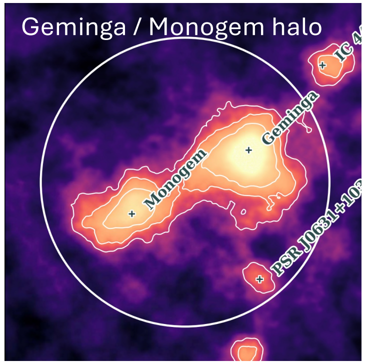


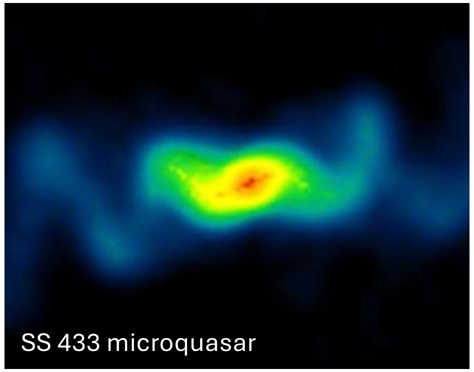


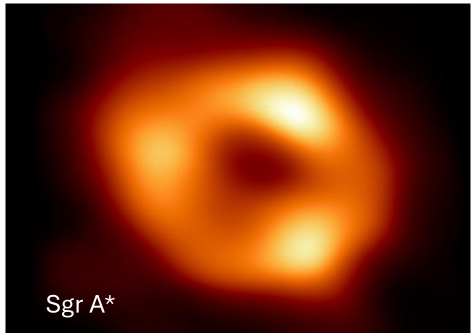
At least 6 types of astronomical sources to consider:

1. Supernova remnants (SNR)
2. Pulsar wind nebulae (PWN)
3. Pulsar halos (PH)
4. Gamma-ray bursts (GRB)
5. Young massive stellar clusters (YMSC)
6. Microquasars (MQ)
7. Galactic Center



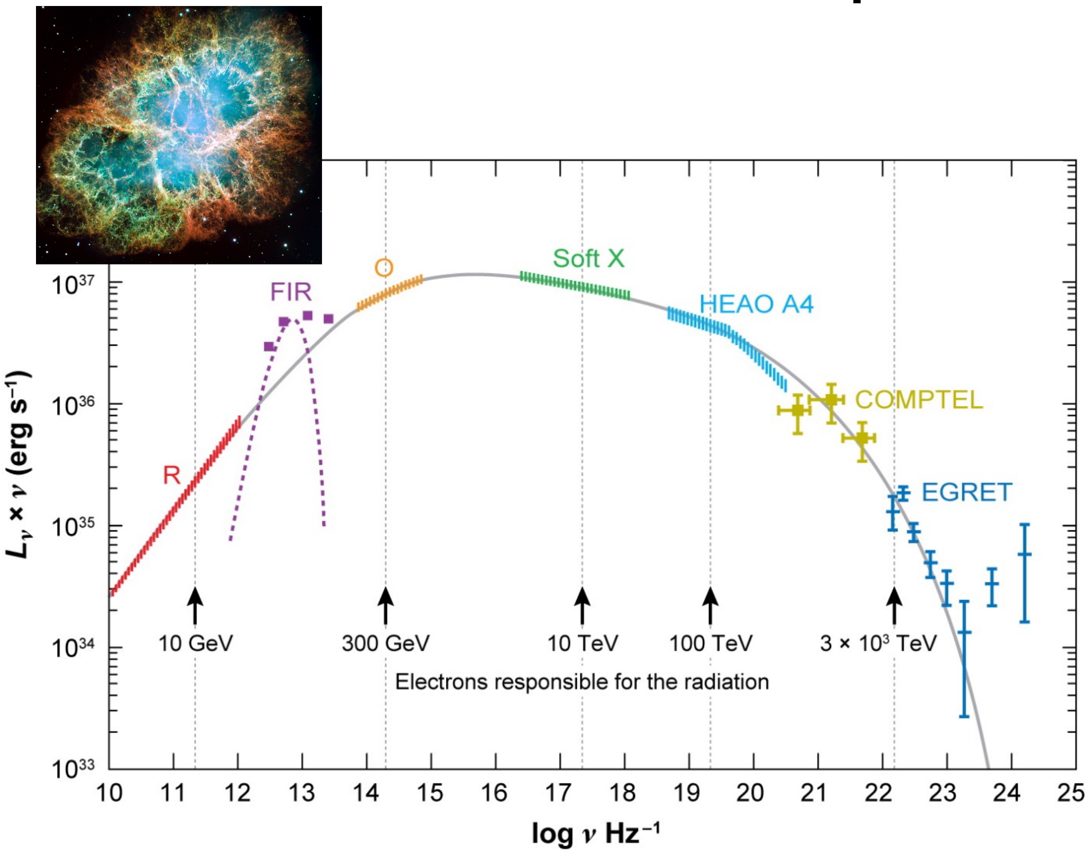






- **Characterize population of galactic sources accelerating protons at least to the Knee energy.**
- Characterize PeV particle injection and propagation in the interstellar medium.
- Identify (or rule out existence of) a “local source” that may provide $O(1)$ contribution to Knee CR flux.

PeV pulsar wind nebulae



Particles are accelerated at the termination shock of pulsar wind. Distance to the shock is determined by pressure balance between pulsar wind an surrounding medium:

$$\rho c^2 = \frac{\dot{E}}{4\pi c R^2} = n_m T_m$$

$$R \simeq 0.05 \left[\frac{\dot{E}}{10^{38}\frac{\text{erg}}{\text{s}}}\right]^{\frac{1}{2}} \left[\frac{n_m}{10\ \text{cm}^{-3}}\right]^{-\frac{1}{2}} \left[\frac{T_m}{10^7\ \text{K}}\right]^{-\frac{1}{2}} \text{pc}$$

Magnetic field at the termination shock is determined by magnetisation $B^2/8\pi = \sigma_B \rho$.

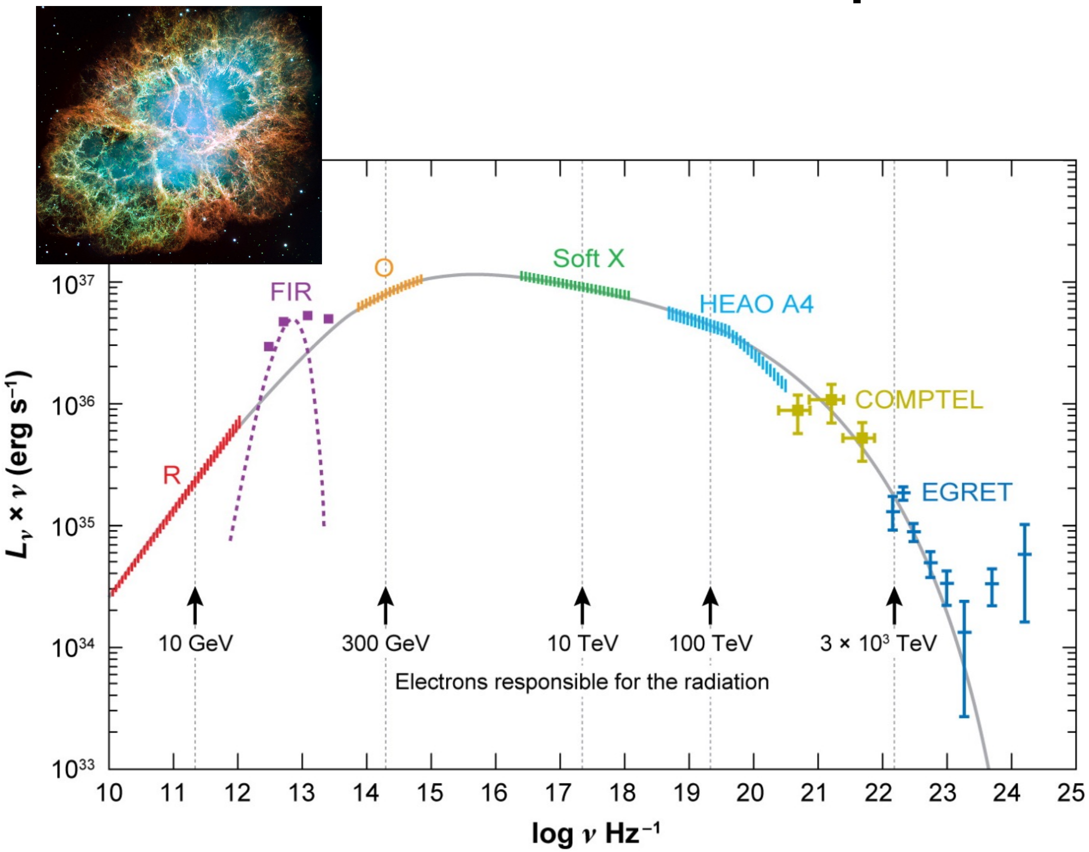
$$B \simeq 1.3\times10^{-4} \left[\frac{\sigma_B}{0.1}\right]^{\frac{1}{2}} \left[\frac{n_{ISM}}{10\ \text{cm}^{-3}}\right]^{\frac{1}{2}} \left[\frac{T_{ISM}}{10^7\ \text{K}}\right]^{\frac{1}{2}} \text{G}$$

Maximal energies attainable for an acceleraiton process at the shock:

$$E_{max} = eBR \simeq 6 \left[\frac{\sigma_B}{0.1}\right]^{\frac{1}{2}} \left[\frac{\dot{E}}{10^{38}\frac{\text{erg}}{\text{s}}}\right]^{\frac{1}{2}} \text{PeV}$$

... independent of the properties of external medium!

PeV pulsar wind nebulae



Particles are accelerated at the termination shock of pulsar wind. Distance to the shock is determined by pressure balance between pulsar wind an surrounding medium:

$$\rho c^2 = \frac{\dot{E}}{4\pi c R^2} = n_m T_m$$

$$R \simeq 0.05 \left[\frac{\dot{E}}{10^{38}\frac{\text{erg}}{\text{s}}}\right]^{\frac{1}{2}} \left[\frac{n_m}{10\ \text{cm}^{-3}}\right]^{-\frac{1}{2}} \left[\frac{T_m}{10^7\ \text{K}}\right]^{-\frac{1}{2}} \text{pc}$$

Magnetic field at the termination shock is determined by magnetisation $B^2/8\pi = \sigma_B \rho$.

$$B \simeq 1.3{\times}10^{-4} \left[\frac{\sigma_B}{0.1}\right]^{\frac{1}{2}} \left[\frac{n_{ISM}}{10\ \text{cm}^{-3}}\right]^{\frac{1}{2}} \left[\frac{T_{ISM}}{10^7\ \text{K}}\right]^{\frac{1}{2}} \text{G}$$

Maximal energies attainable for an acceleraiton process at the shock:

$$E_{max} = eBR \simeq 6 \left[\frac{\sigma_B}{0.1}\right]^{\frac{1}{2}} \left[\frac{\dot{E}}{10^{38}\frac{\text{erg}}{\text{s}}}\right]^{\frac{1}{2}} \text{PeV}$$

... independent of the properties of external medium!

Relevance to the Knee origin:

It is not clear a-priori, if protons are accelerated: pulsar wind is loaded with e^+, e^-. Protons can be

- lifted from neutron star or
- penetrate as neutral particles from outside
- diffuse from shocked surrounding medium toward termination shock.

PeV pulsar wind nebulae

LHAASO PWN, E>100 TeV

Name	Age[kyr]	F_{50}	D[kpc]	$\dot{E}$ [10^{35}erg/s]	E_{max} [σ_B/0.1] PeV	Association
J0007+7303u	14	3.41	1.4	4.5	0.36	PSR J0007+7303
J0206+4302u J0212+4254u J0216+4237u	MSP	0.54	3.2	2.4	0.26	PSR J0218+4232*
J0534+2200u	0.97	6.23	2	4.6×10^3	11.7	Crab
J1740+0948u	114	0.41	1.4	2.3	0.26	PSR J1740+1000*
J1809−1918u	51	9.46	3.4	18	0.73	PSR J1809-1917
J1814−1719u	5	4.20	5	560	4	PSR J1813-1749
J1825−1256u	14	5.08	3.5	36	1	PSR J1826−1256
J1825−1337u	21	10.10	3.9	28	0.9	PSR J1826-1334
J1831−1007u	128	2.56	4.3	11	0.6	PSR J1831−0952
J1837−0654u	23	3.06	6.6	55	1.3	PSR J1838-0655
J1848−0001u	43	1.64	7	98	1.7	PSR J1849−0001
J1908+0615u	20	6.86	3.2	28	0.9	PSR J1907+0602
J1928+1813u J1928+1746u	83	3.2	4.3	16	0.7	PSR J1928+1746
J1929+1846u	2.9	0.64	6.5	120	1.9	PSR J1930+1852
1954+2836u	69	0.42	-	10	0.6	PSR J1954+2836
J1959+2846u	22	0.84	2	3.4	0.3	PSR J1959+2846
J2018+3643u J2020+3649u	7	6.22	1.8	34	1	PSR J2021+3651

PWN and pulsar halos are the dominant source class in 1st LHAASO catalog above 100 TeV.

Only very young, high spin-down power PWN can accelerate particles to the Knee energy.

Total energy injected into high-energy particles by young PWN can be signigicant:

$$E_{tot} \sim E_{rot,0} \sim \frac{M\Omega_0^2 R^2}{5} \sim 1.8\times10^{51}\left[\frac{T_0}{3\ \text{ms}}\right]^{-2} \text{erg}$$

... comparable to kinetic energy of supernova shell if initial neutron star rotation period is $T_0 \lesssim 3$ ms.

PeV electrons are certainly cooled inside the PWN. Protons would escape.

PeV pulsar wind nebulae

Electrons can be readily traced, because they produce inverse Compton emission on (at least) interstellar radiaiton field (ISRF) and Cosmic Microwave Backgorund (CMB):

$$E_\gamma \simeq \gamma^2 \epsilon_{CMB} \simeq 160 \left[\frac{E_e}{200\ \mathrm{TeV}}\right]^2 \left[\frac{\epsilon_{CMB}}{10^{-3}\ \mathrm{eV}}\right] \mathrm{TeV}$$

Name	Age[kyr]	F_{50}	D[kpc]	$\dot{E}$ [10^{35}erg/s]	E_{max} [σ_B/0.1] PeV	Association
J0007+7303u	14	3.41	1.4	4.5	0.36	PSR J0007+7303
J0206+4302u J0212+4254u J0216+4237u	MSP	0.54	3.2	2.4	0.26	PSR J0218+4232*
J0534+2200u	0.97	6.23	2	4.6×10^3	11.7	Crab
J1740+0948u	114	0.41	1.4	2.3	0.26	PSR J1740+1000*
J1809−1918u	51	9.46	3.4	18	0.73	PSR J1809-1917
J1814−1719u	5	4.20	5	560	4	PSR J1813-1749
J1825−1256u	14	5.08	3.5	36	1	PSR J1826−1256
J1825−1337u	21	10.10	3.9	28	0.9	PSR J1826-1334
J1831−1007u	128	2.56	4.3	11	0.6	PSR J1831−0952
J1837−0654u	23	3.06	6.6	55	1.3	PSR J1838-0655
J1848−0001u	43	1.64	7	98	1.7	PSR J1849−0001
J1908+0615u	20	6.86	3.2	28	0.9	PSR J1907+0602
J1928+1813u J1928+1746u	83	3.2	4.3	16	0.7	PSR J1928+1746
J1929+1846u	2.9	0.64	6.5	120	1.9	PSR J1930+1852
1954+2836u	69	0.42	-	10	0.6	PSR J1954+2836
J1959+2846u	22	0.84	2	3.4	0.3	PSR J1959+2846
J2018+3643u J2020+3649u	7	6.22	1.8	34	1	PSR J2021+3651

PeV pulsar wind nebulae

Electrons can be readily traced, because they produce inverse Compton emission on (at least) interstellar radiaiton field (ISRF) and Cosmic Microwave Backgorund (CMB):

$$E_\gamma \simeq \gamma^2 \epsilon_{CMB} \simeq 160 \left[\frac{E_e}{200\ \mathrm{TeV}}\right]^2 \left[\frac{\epsilon_{CMB}}{10^{-3}\ \mathrm{eV}}\right]\ \mathrm{TeV}$$

Cooling time due to inverse Compton scattering of CMB is

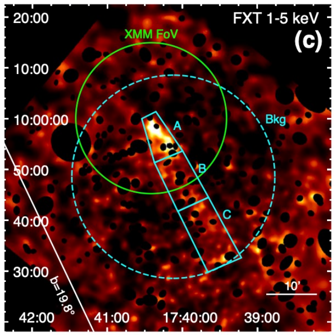
$$t_{IC} \simeq 7.4 \left[\frac{U_{CMB}}{0.25\,\frac{\mathrm{eV}}{\mathrm{cm}^3}}\right]^{-1} \left[\frac{E_e}{100\ \mathrm{TeV}}\right]\ \mathrm{kyr}$$

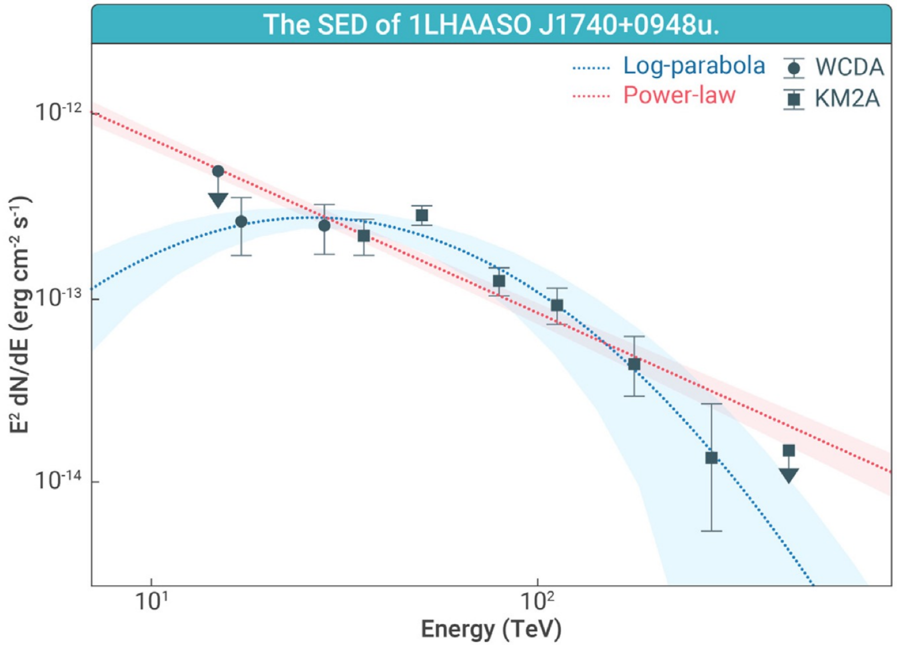
Magnetic field $B \simeq 3\ \mu\mathrm{G}$ has energy density $U_B \simeq U_{CMB}$. Combined synchrotron and inverse Compton cooling time is $t_{IC+S} \simeq 0.5 t_{IC}$.

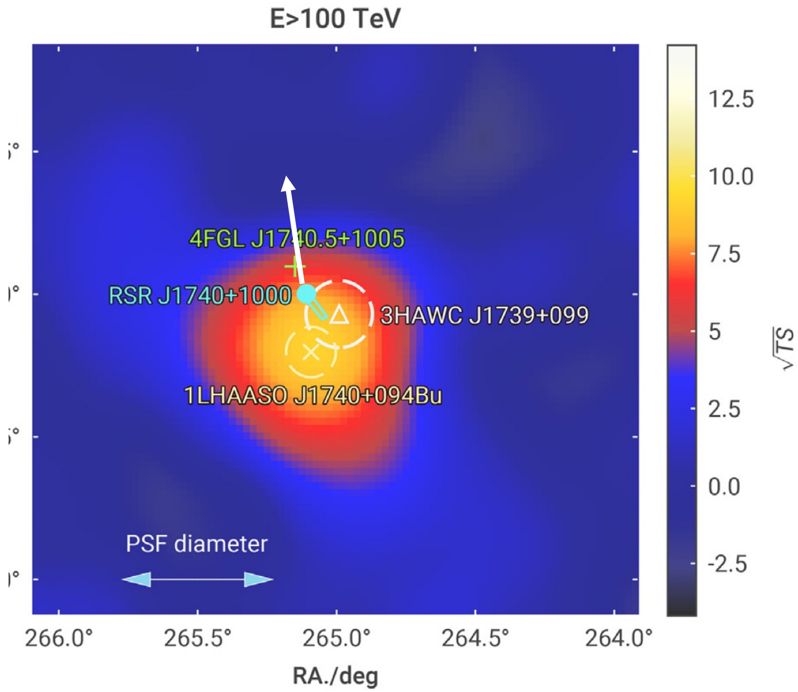
Name	Age[kyr]	F_{50}	D[kpc]	$\dot{E}$ [10^{35}erg/s]	E_{max} [σ_B/0.1] PeV	Association
J0007+7303u	14	3.41	1.4	4.5	0.36	PSR J0007+7303
J0206+4302u J0212+4254u J0216+4237u	MSP	0.54	3.2	2.4	0.26	PSR J0218+4232*
J0534+2200u	0.97	6.23	2	4.6×10^3	11.7	Crab
J1740+0948u	114	0.41	1.4	2.3	0.26	PSR J1740+1000*
J1809−1918u	51	9.46	3.4	18	0.73	PSR J1809-1917
J1814−1719u	5	4.20	5	560	4	PSR J1813-1749
J1825−1256u	14	5.08	3.5	36	1	PSR J1826−1256
J1825−1337u	21	10.10	3.9	28	0.9	PSR J1826-1334
J1831−1007u	128	2.56	4.3	11	0.6	PSR J1831−0952
J1837−0654u	23	3.06	6.6	55	1.3	PSR J1838-0655
J1848−0001u	43	1.64	7	98	1.7	PSR J1849−0001
J1908+0615u	20	6.86	3.2	28	0.9	PSR J1907+0602
J1928+1813u J1928+1746u	83	3.2	4.3	16	0.7	PSR J1928+1746
J1929+1846u	2.9	0.64	6.5	120	1.9	PSR J1930+1852
1954+2836u	69	0.42	-	10	0.6	PSR J1954+2836
J1959+2846u	22	0.84	2	3.4	0.3	PSR J1959+2846
J2018+3643u J2020+3649u	7	6.22	1.8	34	1	PSR J2021+3651

No escape of 100 TeV particles from PWN

PSR J1740+1000 PWN







Highest energy particles efficiently cool in PWN, without escaping into ISM. A clean test is e.g. PSR J1740+1000, a high Galactic latitude source ($b \simeq 20°$) at $d_s \simeq 1.3$ kpc, spin-down age $t \simeq 114$ kyr.

Source is point-like above 100 TeV. Isotropic diffusion of $E > 100$ TeV electrons would have produced a source of the size

$$r_{diff} = 2\sqrt{Dt_{IC+S}} \simeq 120\, D_{28}^{\frac{1}{2}} \left[\frac{E_e}{100\ \mathrm{TeV}}\right]^{-\frac{1}{3}} \mathrm{pc}, \qquad \theta_{diff} = \frac{r_{diff}}{d_s} \simeq 5^\circ D_{28}^{\frac{1}{2}} \left[\frac{E_e}{100\ \mathrm{TeV}}\right]^{-\frac{1}{3}} \left[\frac{d_s}{1.5\ \mathrm{kpc}}\right]^{-1}$$

LHAASO Collab. 2502.15447

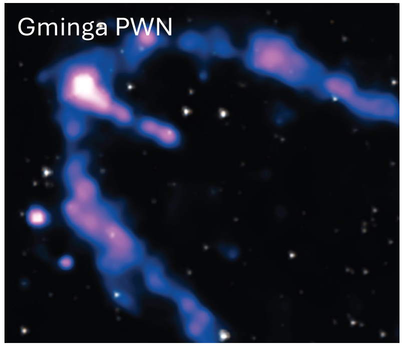
PeV pulsar wind nebulae

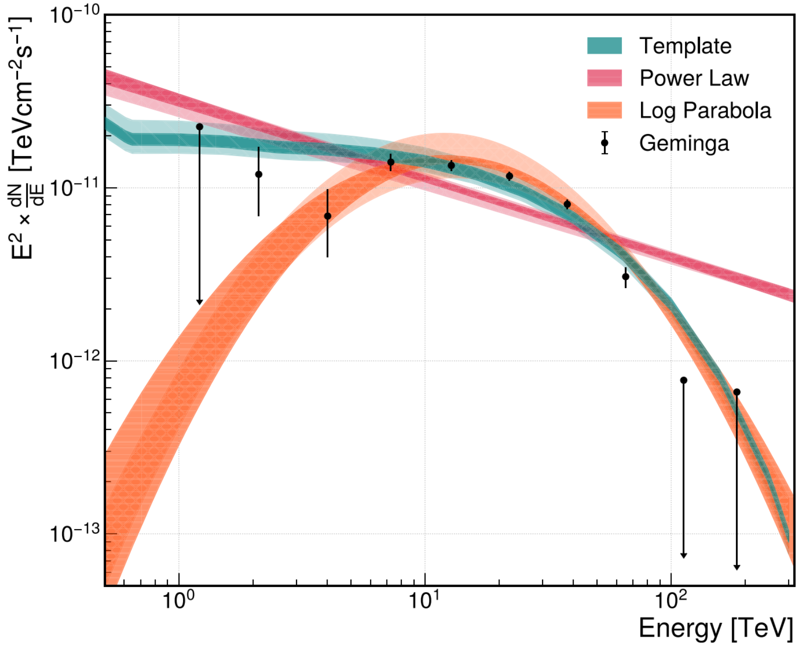
PWN are typically found inside SNR. Even if particles would escape from the PWN, they would propagate in environment created by expanding SNR (turbulence?). This further slows down escape into ISM.

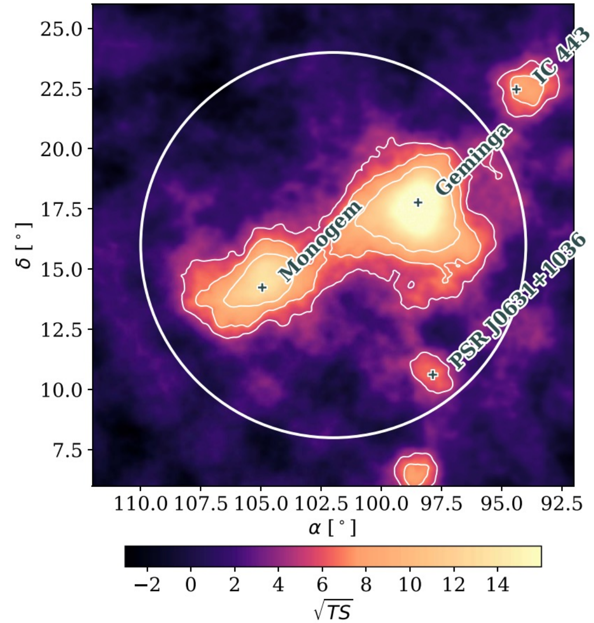
This situation is possibly found in pulsar halos.

Name	Age[kyr]	F_{50}	D[kpc]	$\dot{E}$ $[10^{35}$erg/s$]$	E_{max} $[\sigma_B/0.1]$ PeV	Association
J0007+7303u	14	3.41	1.4	4.5	0.36	PSR J0007+7303
J0206+4302u J0212+4254u J0216+4237u	MSP	0.54	3.2	2.4	0.26	PSR J0218+4232*
J0534+2200u	0.97	6.23	2	4.6×10^3	11.7	Crab
J1740+0948u	114	0.41	1.4	2.3	0.26	PSR J1740+1000*
J1809−1918u	51	9.46	3.4	18	0.73	PSR J1809-1917
J1814−1719u	5	4.20	5	560	4	PSR J1813-1749
J1825−1256u	14	5.08	3.5	36	1	PSR J1826−1256
J1825−1337u	21	10.10	3.9	28	0.9	PSR J1826-1334
J1831−1007u	128	2.56	4.3	11	0.6	PSR J1831−0952
J1837−0654u	23	3.06	6.6	55	1.3	PSR J1838-0655
J1848−0001u	43	1.64	7	98	1.7	PSR J1849−0001
J1908+0615u	20	6.86	3.2	28	0.9	PSR J1907+0602
J1928+1813u J1928+1746u	83	3.2	4.3	16	0.7	PSR J1928+1746
J1929+1846u	2.9	0.64	6.5	120	1.9	PSR J1930+1852
1954+2836u	69	0.42	-	10	0.6	PSR J1954+2836
J1959+2846u	22	0.84	2	3.4	0.3	PSR J1959+2846
J2018+3643u J2020+3649u	7	6.22	1.8	34	1	PSR J2021+3651

Slow escape of 100 TeV particles from pulsar halos







Geminga halo is the prototypical PH around pulsar of spin-down age $t \simeq 340$ kyr, $d_s \simeq 0.25$ kpc,. Source is point-like above 100 TeV. Isotropic diffusion of $E > 100$ TeV electrons would have produce a source of the size

$$r_{diff} = 2\sqrt{D t_{IC+S}} \simeq 38\, D_{27}^{\frac{1}{2}} \left[\frac{E_e}{100\text{ TeV}}\right]^{-\frac{1}{3}} \text{pc}, \qquad \theta_{diff} = \frac{r_{diff}}{d_s} \simeq 9^\circ D_{27}^{\frac{1}{2}} \left[\frac{E_e}{100\text{ TeV}}\right]^{-\frac{1}{3}} \left[\frac{d_s}{0.25\text{ kpc}}\right]^{-1}$$

which is much larger than size of PWN observed in X-rays, comparable to extent of SNR at the end of its expansion. Diffusion coefficient in the region (formerly) occupied by SNR is suppressed, compared to isotropic diffusion coefficient in the ISM.

HAWC Collab. Ap.J. 974, 246 (2024)

PeV pulsar wind nebulae

PWN are typically found inside SNR. Even if particles would escape from the PWN, they would propagate in environment created by expanding SNR (turbulence?). This further slows down escape into ISM.

No SNR is present around PWN in the case of millisecond pulsars: “recycled” pulsars previously spun-up by accresion from companion star.

MSP are typically not in the Galactic Plane, in “quiet” ISM.

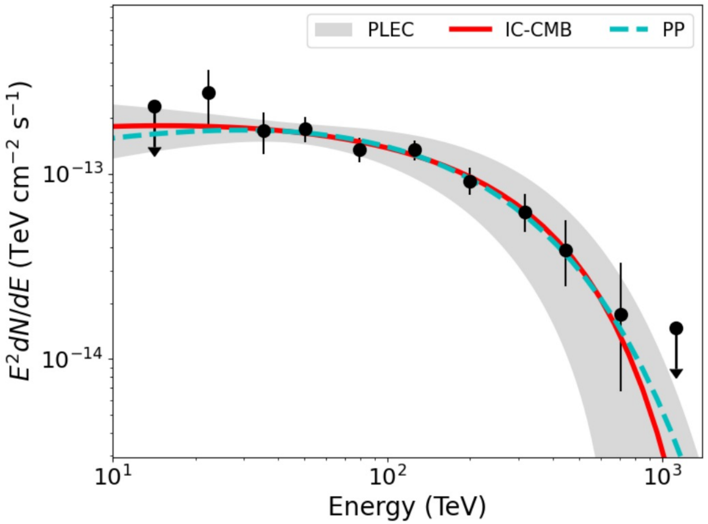
Escape of particles from PWN of MSP can be used to study diffusion in ISM!

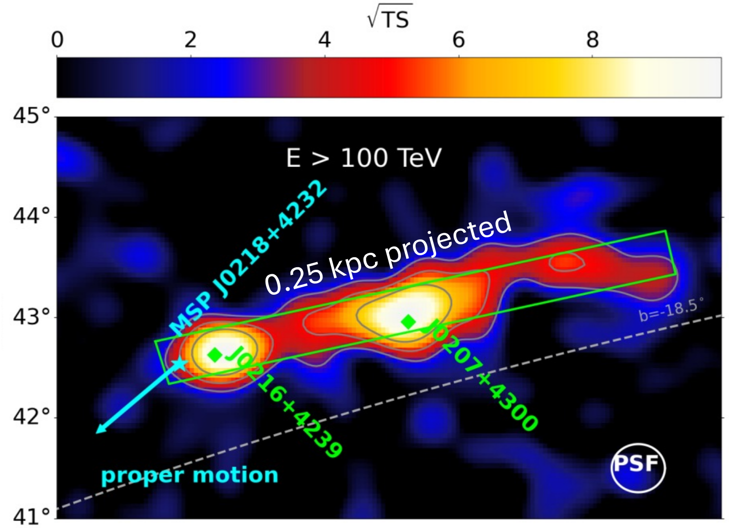
Name	Age[kyr]	F_{50}	D[kpc]	$\dot{E}$ $[10^{35}$erg/s $]$	E_{max} $[\sigma_B/0.1]$ PeV	Association
J0007+7303u	14	3.41	1.4	4.5	0.36	PSR J0007+7303
J0206+4302u J0212+4254u J0216+4237u	MSP	0.54	3.2	2.4	0.26	PSR J0218+4232*
J0534+2200u	0.97	6.23	2	4.6×10^{3}	11.7	Crab
J1740+0948u	114	0.41	1.4	2.3	0.26	PSR J1740+1000*
J1809−1918u	51	9.46	3.4	18	0.73	PSR J1809-1917
J1814−1719u	5	4.20	5	560	4	PSR J1813-1749
J1825−1256u	14	5.08	3.5	36	1	PSR J1826−1256
J1825−1337u	21	10.10	3.9	28	0.9	PSR J1826-1334
J1831−1007u	128	2.56	4.3	11	0.6	PSR J1831−0952
J1837−0654u	23	3.06	6.6	55	1.3	PSR J1838-0655
J1848−0001u	43	1.64	7	98	1.7	PSR J1849−0001
J1908+0615u	20	6.86	3.2	28	0.9	PSR J1907+0602
J1928+1813u J1928+1746u	83	3.2	4.3	16	0.7	PSR J1928+1746
J1929+1846u	2.9	0.64	6.5	120	1.9	PSR J1930+1852
1954+2836u	69	0.42	-	10	0.6	PSR J1954+2836
J1959+2846u	22	0.84	2	3.4	0.3	PSR J1959+2846
J2018+3643u J2020+3649u	7	6.22	1.8	34	1	PSR J2021+3651

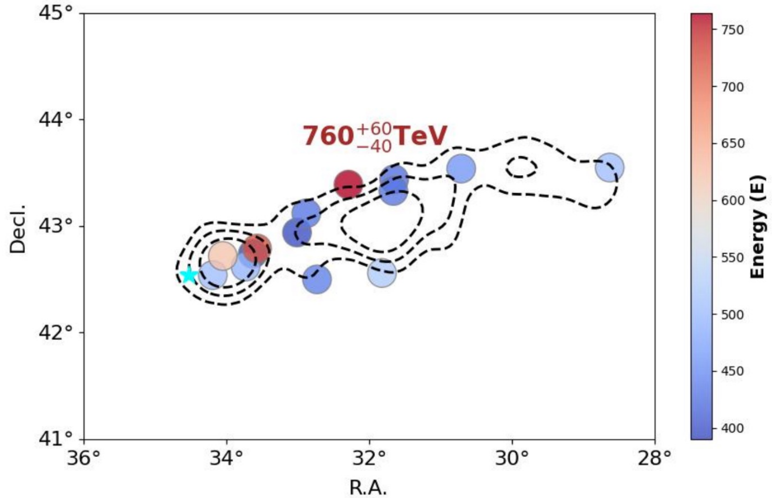
Free escape of 100 TeV particles from millisecond pulsar

1LHAASO J0206+4302u, J0212+4254u and J0216+4237u form collectively a “Peanut” source associated to high Galactic latitude PSR J2018+4232.

This is a millisecond pulsar in a binary with a white dwarf, an old system not surrounded by a SNR environment. Particles escaping from the source diffuse in genuine ISM.





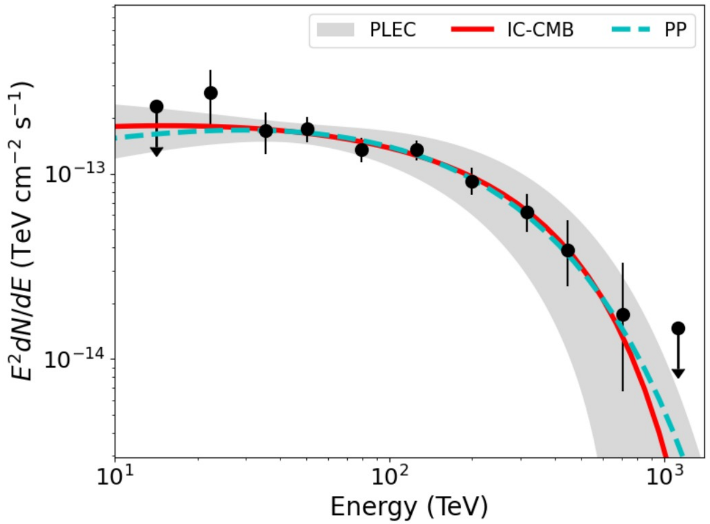


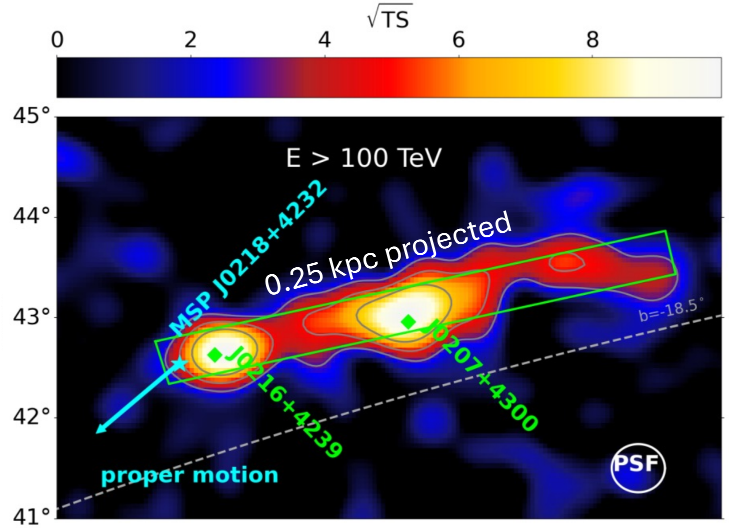
LHAAO Collab. 2510.06786

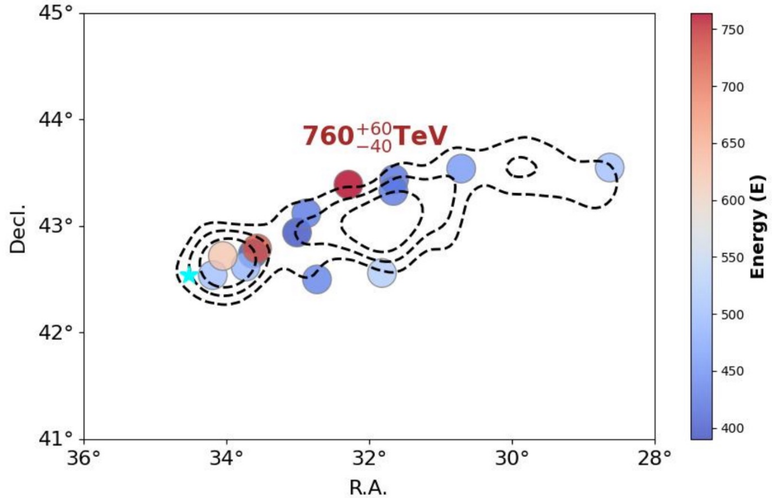
Evidence for anisotropic diffusion at high Galactic latitude

1LHAASO J0206+4302u, J0212+4254u and J0216+4237u form collectively a “Peanut” source associated to high Galactic latitude PSR J2018+4232.

This is a millisecond pulsar in a binary with a white dwarf, an old system not surrounded by a SNR environment. Particles escaping from the source diffuse in genuine ISM.







PP model fit assumes that emission is from neutral pion decays.

Pulsar moves over the source length in 2.6 Myr. Protons injected along the pulsar path would have spread spread on

$$r_{diff} = 2\sqrt{Dt} \simeq 6\, D_{28}^{1/2} \left[\frac{t}{2.6\ \mathrm{Myr}}\right]^{1/2} \left[\frac{E}{4\ \mathrm{PeV}}\right]^{1/6} \mathrm{kpc}$$

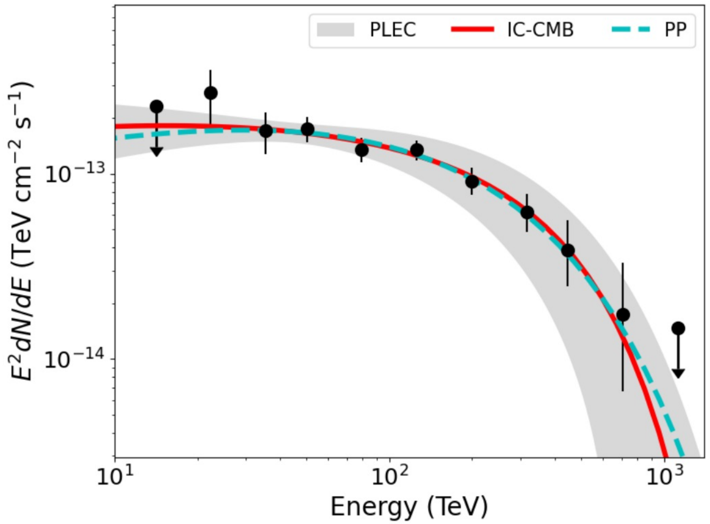
in isotropic diffusion model. In anisotropic diffusion model, spread along magnetic field line is even longer. Impossible to explain source morphology.

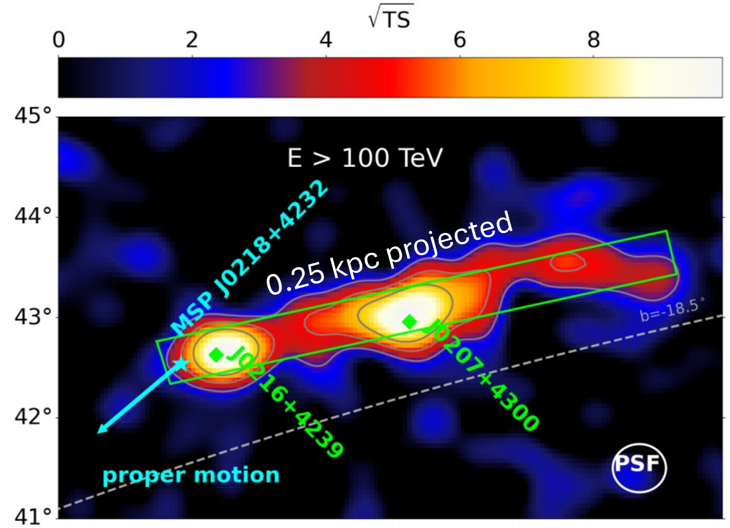
LHAAO Collab. 2510.06786

Evidence for anisotropic diffusion at high Galactic latitude

1LHAASO J0206+4302u, J0212+4254u and J0216+4237u form collectively a "Peanut" source associated to high Galactic latitude PSR J2018+4232.

This is a millisecond pulsar in a binary with a white dwarf, an old system not surrounded by a SNR environment. Particles escaping from the source diffuse in genuine ISM.





IC-CMB model is for emission from electrons. Cooling time

$$t_{IC+S} \simeq 1 \left[\frac{U_{CMB+B}}{0.5\frac{\mathrm{eV}}{\mathrm{cm}^3}}\right]^{-1} \left[\frac{E_e}{400\ \mathrm{TeV}}\right]^{-1} \mathrm{kyr}$$

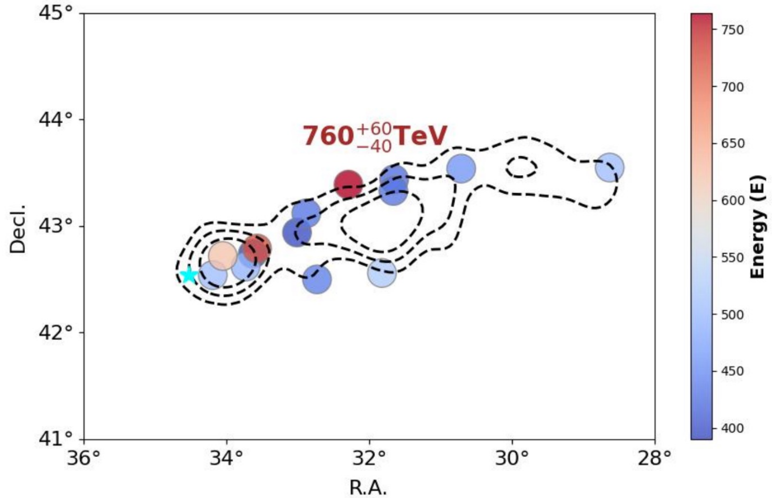
Cooling distance $d_{IC+S} = ct_{IC+S} \simeq 0.3$ kpc $\simeq$ source length. Electrons can only spiral along ordered magnetic field, without being scattered. This suggests

$$\lambda_{||} > 0.3\ \mathrm{kpc}, D_{||} > 10^{31}\ \mathrm{cm^2 s^{-1}} \quad \text{at 400 TeV}$$

Source half-width: $r_\perp \simeq 12\ \mathrm{pc} = 2\sqrt{D_\perp t_{IC+S}}$; $D_\perp \simeq 10^{28}\ \mathrm{cm}^2/s$ at 400 TeV.

$$\frac{D_{||}}{D_\perp} \gtrsim 10^3$$

Well above the Galactic Plane ($H \simeq 1$ kpc).



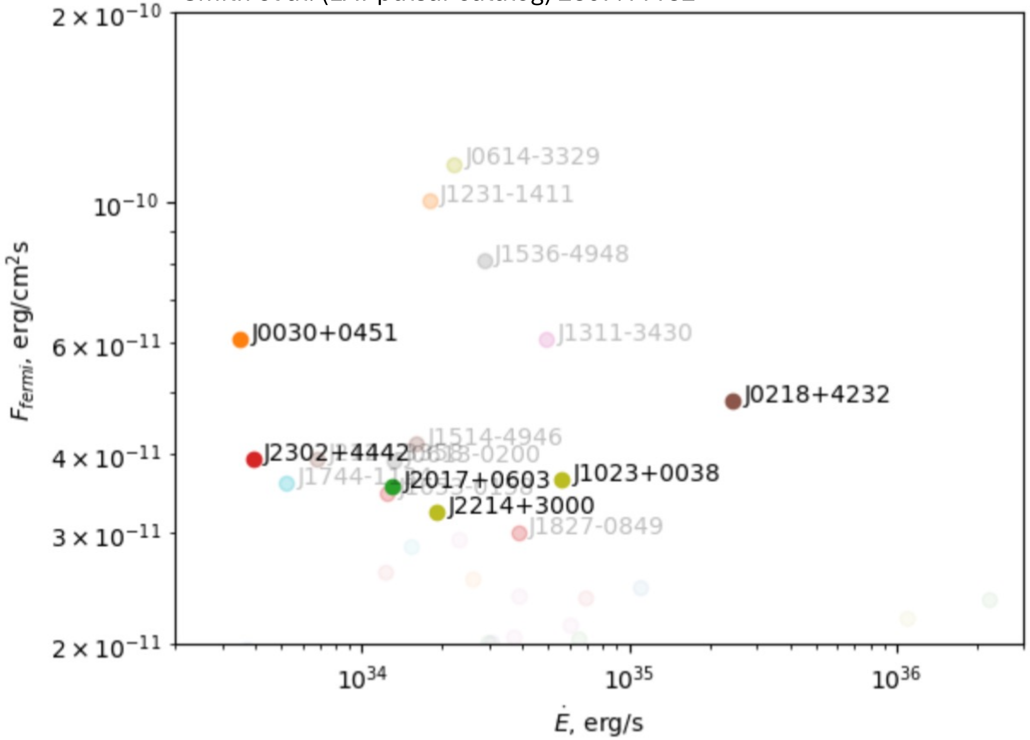
LHAAO Collab. 2510.06786

More millisecond pulsars for study of CR diffusion in ISM?

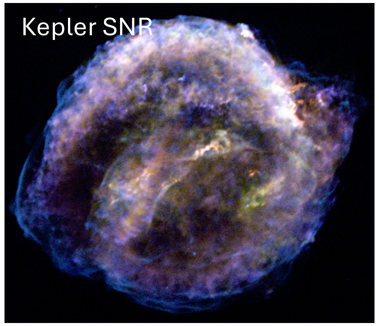
Millisecond pulsar are useful to probe diffusion of cosmic rays in ISM. Detecting mode of them in 100 TeV band would help.

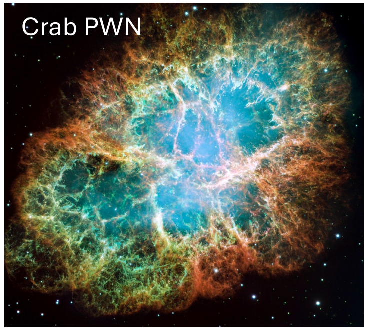
PSR J0218+4232 is the highest spin-down power, but not the highest (pulsed) flux in Fermi/LAT. If 100 TeV flux scales with pulsed flux, other MSP may be detectable in the Northern hemisphere with LHAASO. Even brighter sources are available in Southern hemisphere for SWGO.

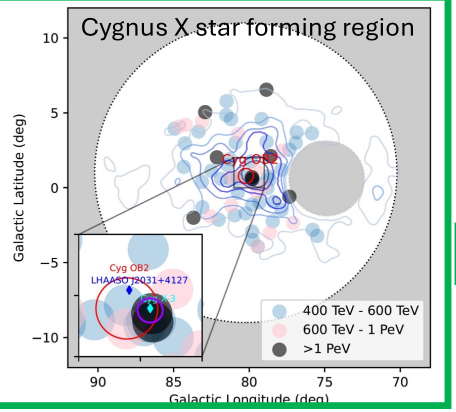
Smith et al. (LAT pulsar catalog) 2307.11132



Galactic PeVatron (candidate) overview

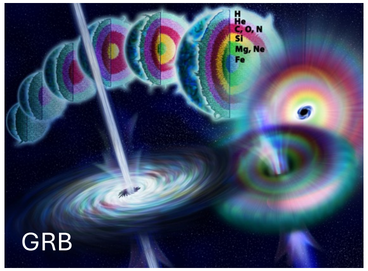


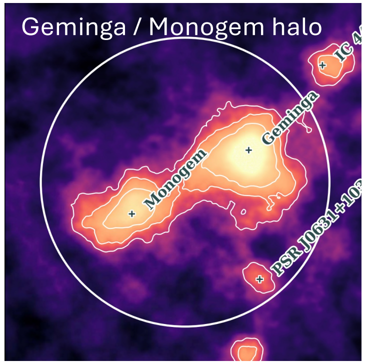


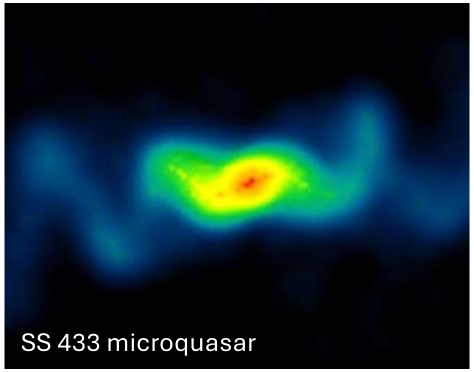


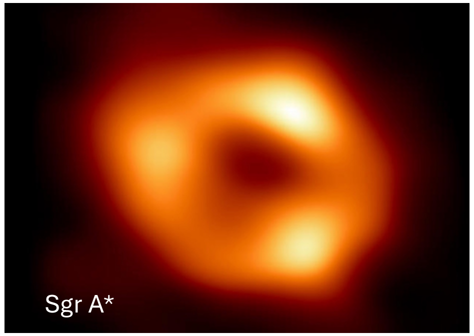
At least 6 types of astronomical sources to consider:

1. Supernova remnants (SNR)
2. Pulsar wind nebulae (PWN)
3. Pulsar halos (PH)
4. Gamma-ray bursts (GRB)
5. Young massive stellar clusters (YMSC)
6. Microquasars (MQ)
7. Galactic Center



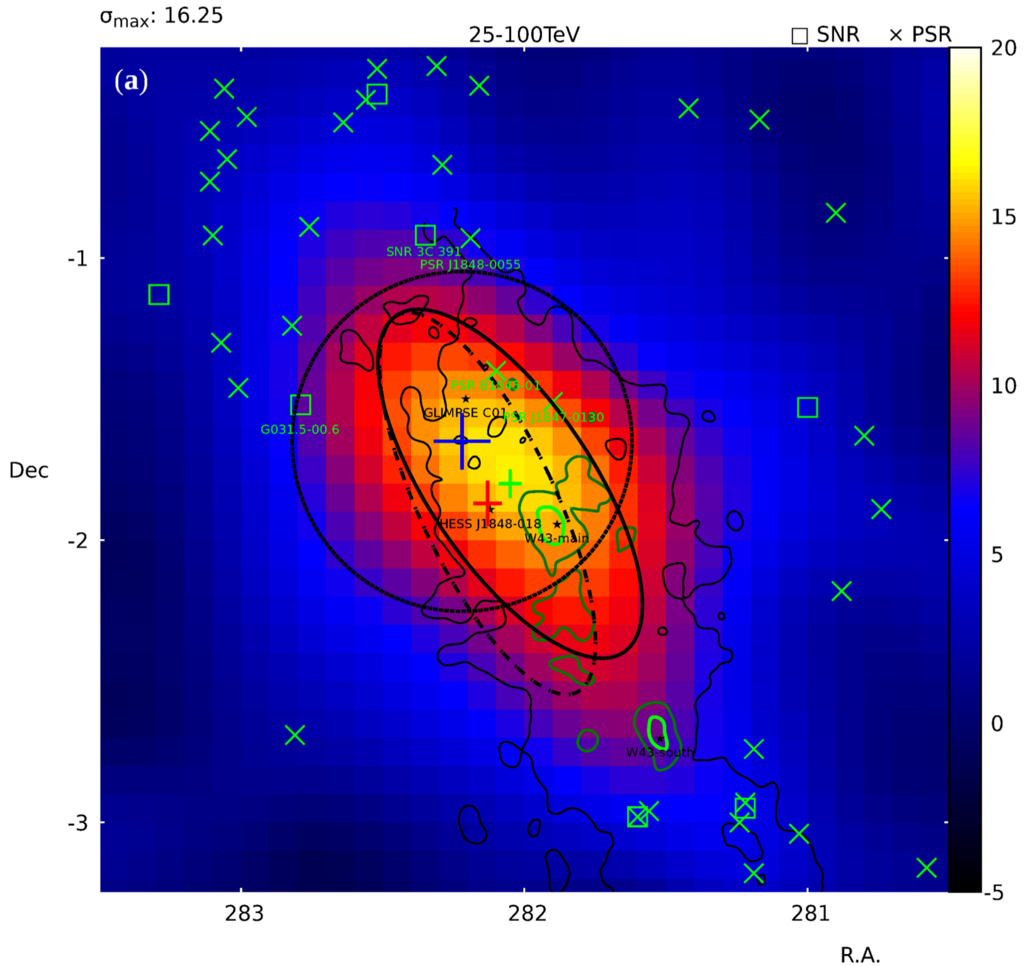






- **Characterize population of galactic sources accelerating protons at least to the Knee energy.**
- Characterize PeV particle injection and propagation in the interstellar medium.
- Identify (or rule out existence of) a “local source” that may provide $O(1)$ contribution to Knee CR flux.

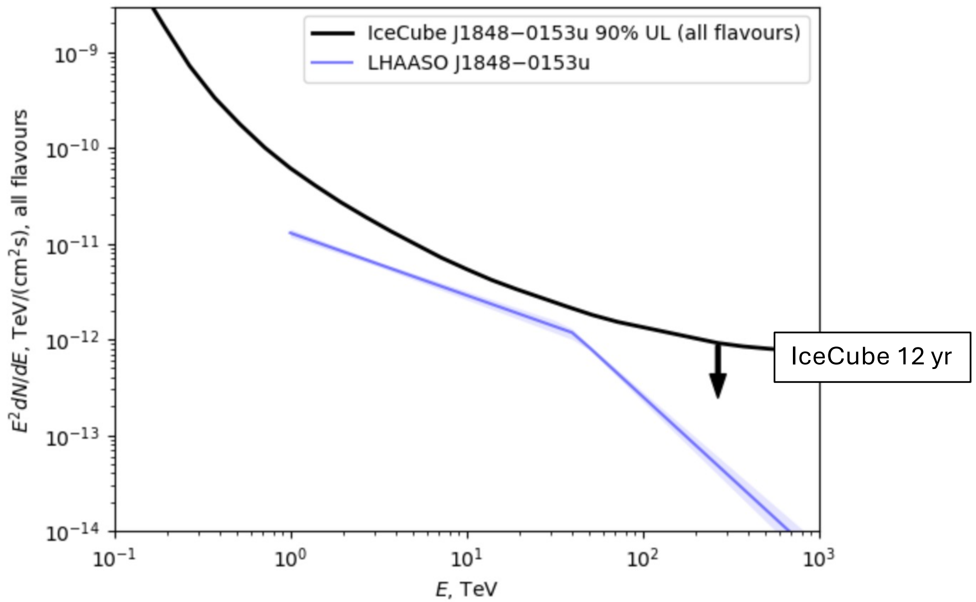
PeV particles in young massive stellar clusters?



A claim of "young stellar cluster" W43 in LHAASO paper.

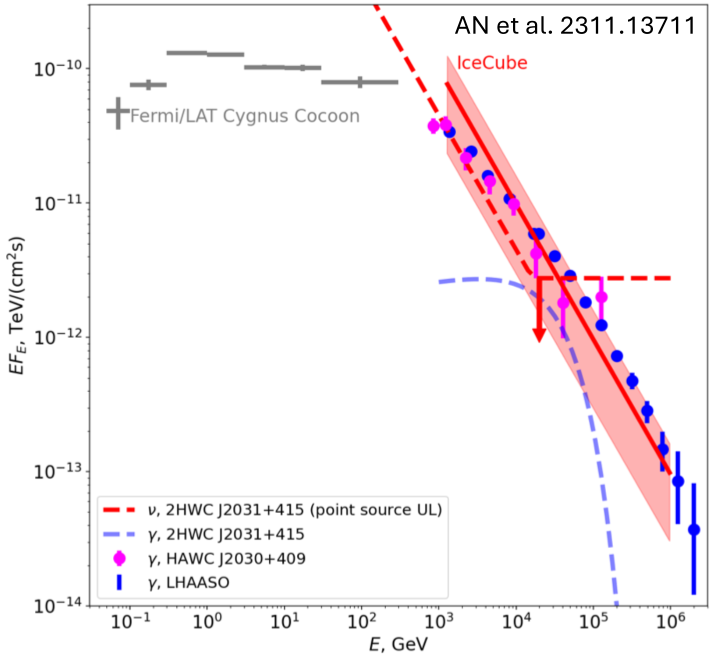
Nevertheless, two pulsars: J1847-0130 (10^{32} erg/s spin-down power) and 1845-01 (7×10^{32} erg/s). A bit further away is PSR J1848-0055 (3×10^{33} erg/s). Potentially contributing to γ-ray flux. Source spectrum is very consistent with PWN.

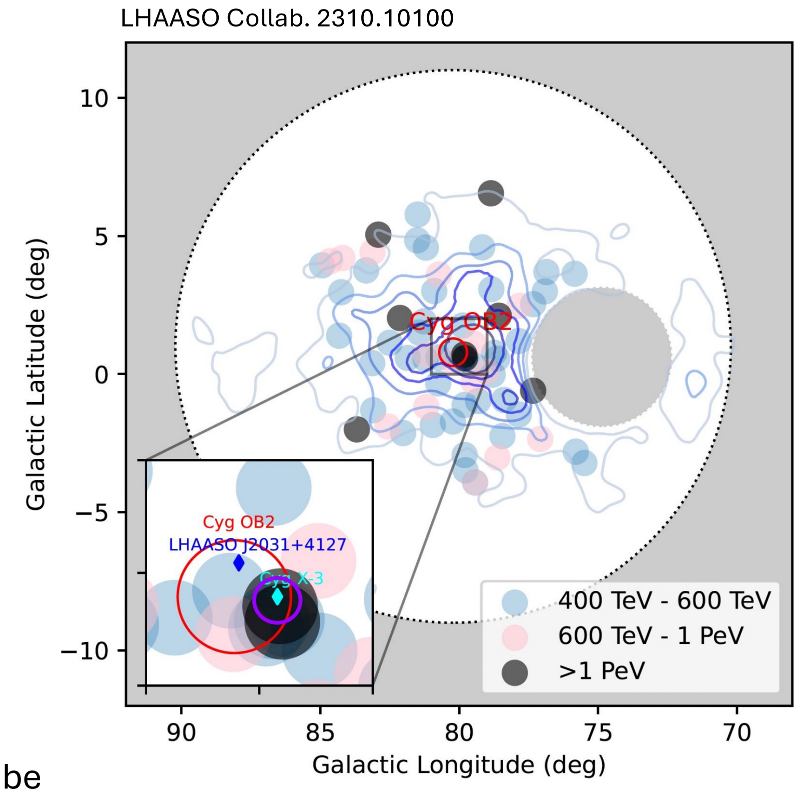
Emission from YMSC is expected to be hadronic. Neutrinos would distinguish PWN from YMSC model. However, neutrino telescopes lack sensitivity:



LHAASO Collab. 2408.09905

PeV particles in young massive stellar clusters?



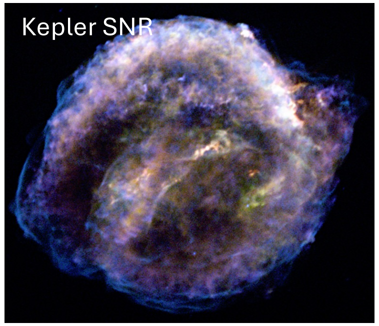


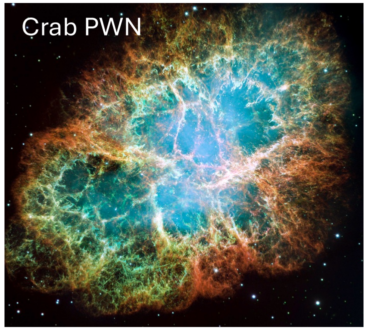
Cygnus X region is a notable exception: its flux is within sensitivity reach of IceCube and KM3NeT.

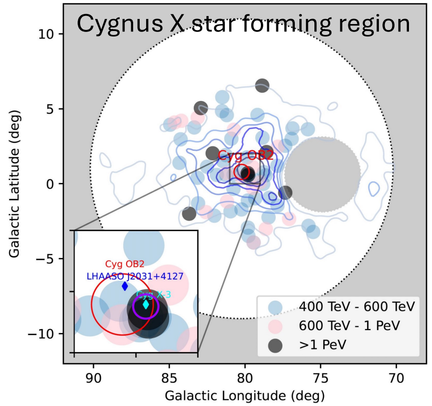
However, it is not clear if YMSC (Cyg OB2 association) is THE source of emission. Several other sources contribute:

- Cyg X-3 microquasar
- PSR J2032+4127 (binary with young pulsar)

Galactic PeVatron (candidate) overview

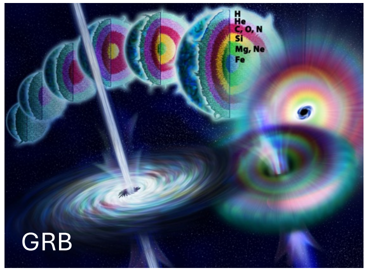


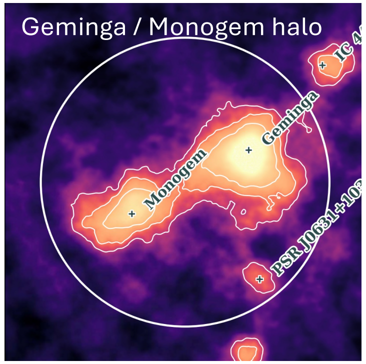


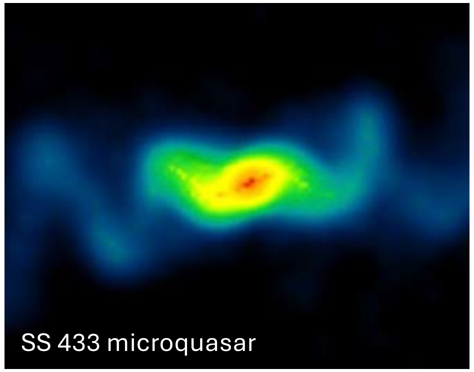


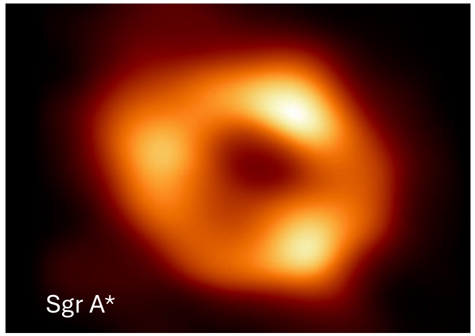
At least 6 types of astronomical sources to consider:

1. Supernova remnants (SNR)
2. Pulsar wind nebulae (PWN)
3. Pulsar halos (PH)
4. Gamma-ray bursts (GRB)
5. Young massive stellar clusters (YMSC)
6. Microquasars (MQ)
7. Galactic Center





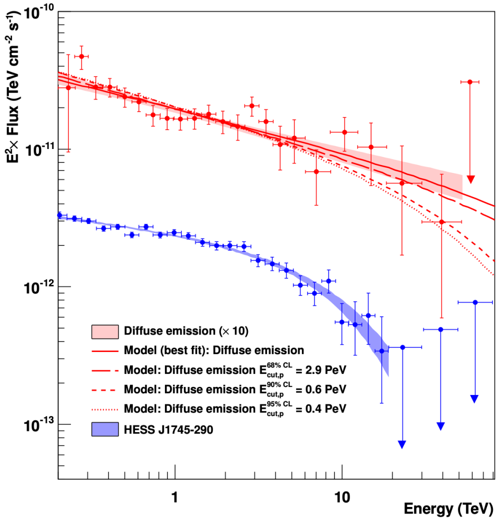


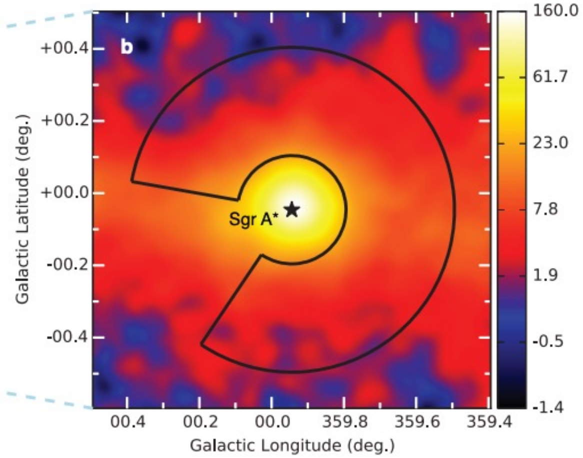


- **Characterize population of galactic sources accelerating protons at least to the Knee energy.**
- Characterize PeV particle injection and propagation in the interstellar medium.
- Identify (or rule out existence of) a “local source” that may provide $O(1)$ contribution to Knee CR flux.

PeV particles in Galactic Center region?

HESS Collab. 1603.07730



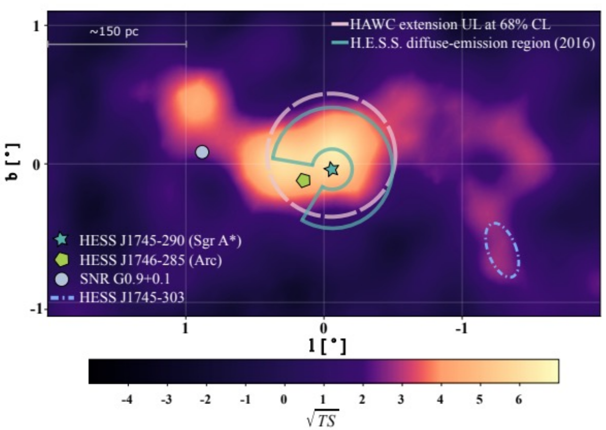


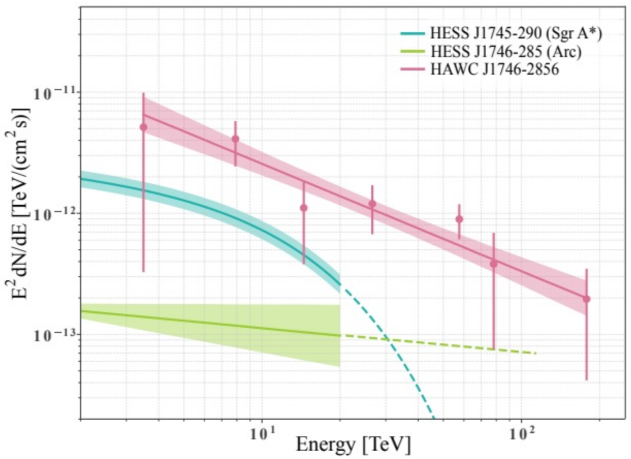
Still one more source with (the most) complex content:

- Supermassive black hole Sgr A*
- Dark matter spike (?)
- Sgr A bubble (and SNR or PWN?)
- Galactic Bulge (including MSPs?)
- The Great Annihilator (1E 1740.7-2942)
- ...

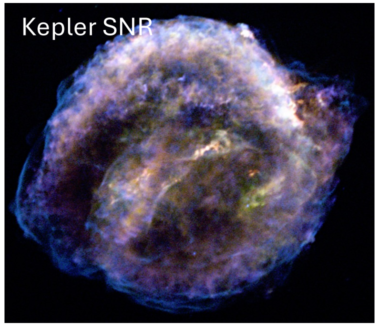
Neutrino emission is detectable with IceCube and KM3Net. Most significant excess in IceCube Galactic neutrino signal. Excess found in ANTARES.

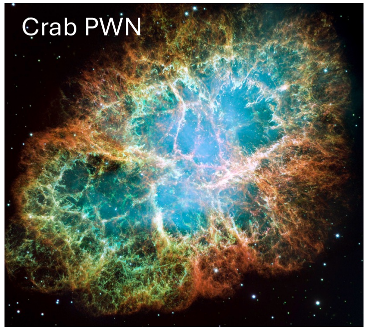
HAWC Collab. 2407.03682

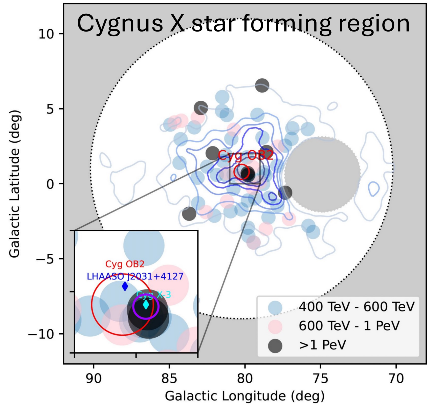




Summary

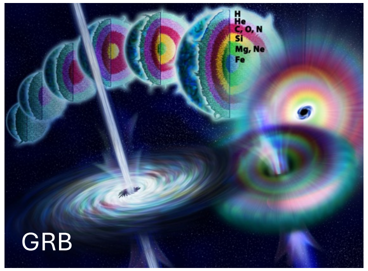


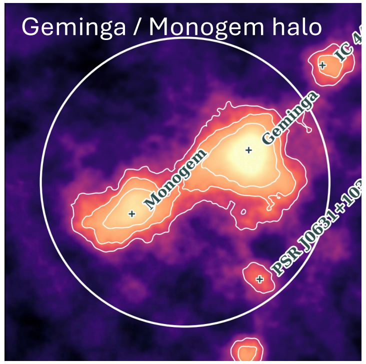


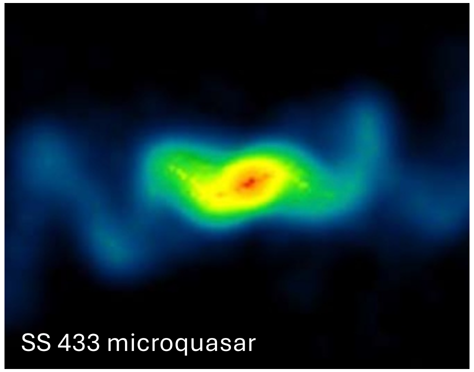


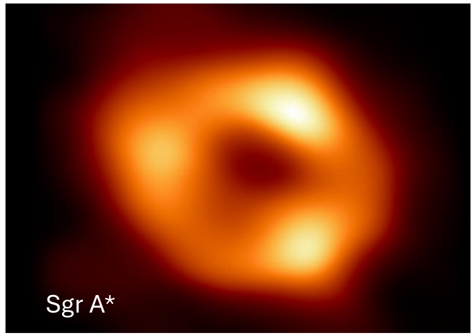
At least 6 types of astronomical sources to consider:

1. Supernova remnants (SNR)
2. Pulsar wind nebulae (PWN)
3. Pulsar halos (PH)
4. Gamma-ray bursts (GRB)
5. Young massive stellar clusters (YMSC)
6. Microquasars (MQ)
7. Galactic Center









- Characterize population of galactic sources accelerating protons at least to the Knee energy.
- Characterize PeV particle injection and propagation in the interstellar medium.
- Identify (or rule out existence of) a "local source" that may provide $O(1)$ contribution to Knee CR flux.