

G**S****GRAN SASSO
SCIENCE INSTITUTE****S****I****SCHOOL OF ADVANCED STUDIES**
Scuola Universitaria Superiore*Report for the passage of the year 2026*

Particle acceleration and γ -ray emission in star clusters

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Date: 14 October 2026



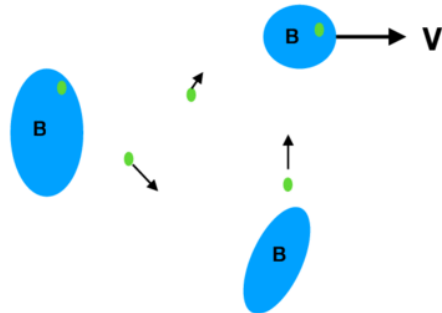
Outline

1. Introduction
2. Modeling the γ -ray emission from the Cygnus bubble
3. Understanding the origin of the γ -ray emission from Westerlund 1:
hadronic or leptonic?
4. Stochastic reacceleration of particles in the Superbubble
5. Summary & future work

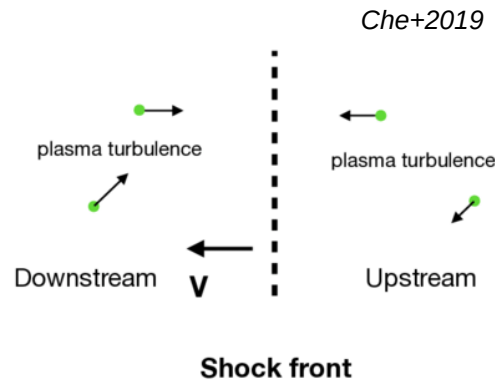
1. Introduction

Origin of Galactic cosmic rays

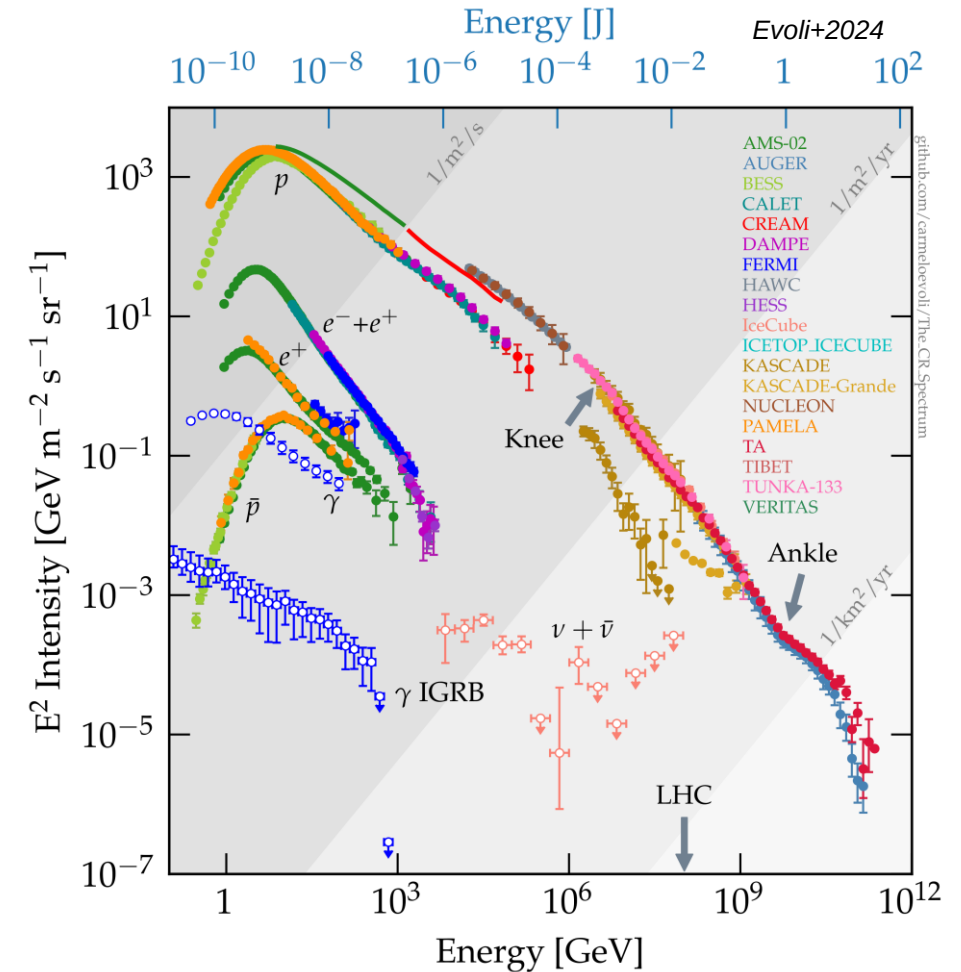
- Cosmic rays (CRs):
 - a) Mainly composed of protons
 - b) Spectral features (knee, 2nd knee, ankle, and cutoff...)
 - c) Galactic / extragalactic origin?
- How are CRs accelerated?
 - a) Diffusive shock acceleration (DSA, 1st order Fermi)
 - b) Stochastic acceleration (2nd order Fermi)
 - c) Magnetic reconnection
 - d) ...
- Accelerators of Galactic CRs?
 - a) Supernova remnant (SNRs)
 - b) Pulsar wind nebulae (PWNe)
 - c) Microquasars (MQs)
 - d) Star clusters (SCs)**
 - e) ...



2nd order Fermi-acceleration. Cosmic rays are accelerated by random moving magnetic clouds.

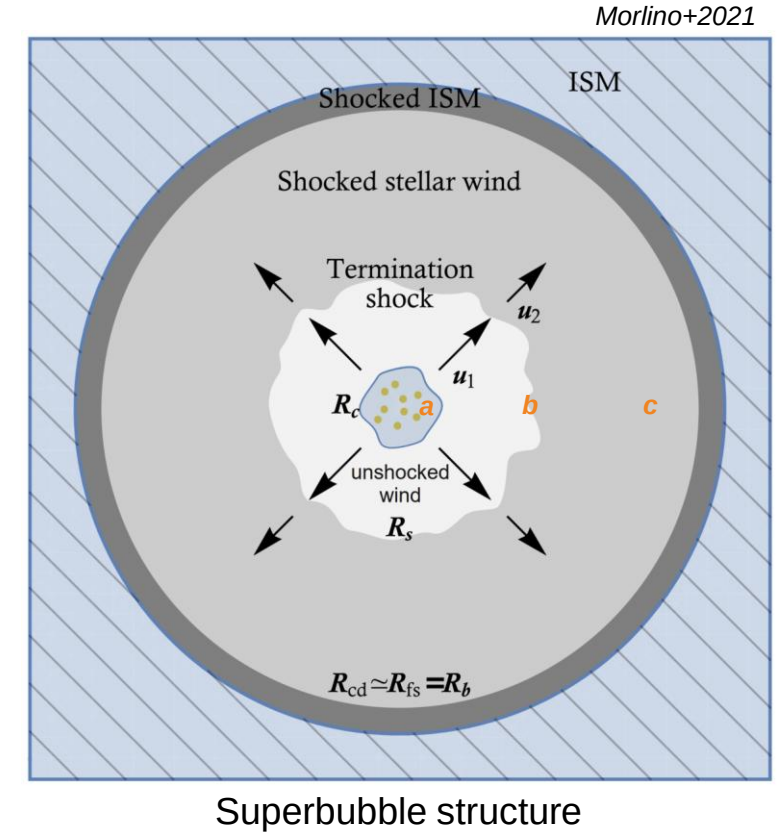
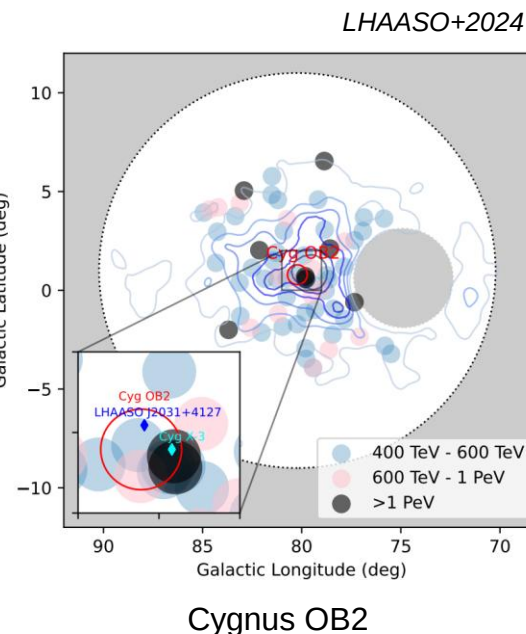
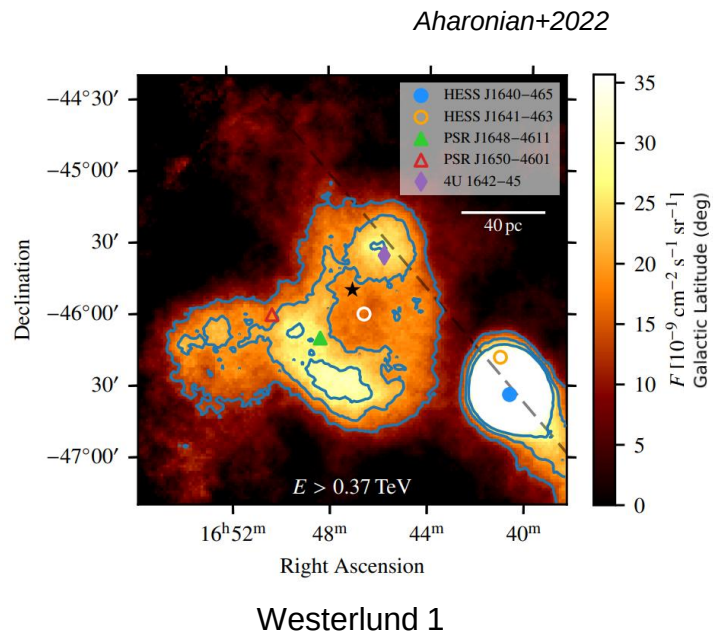


1st order Fermi-acceleration. Particles are accelerated by shock waves.



Star clusters as CR accelerators

- Star clusters are gravitationally bound stellar systems that typically contain dozens of massive stars (e.g., OB and WR stars).
 - Total wind power $\sim 10^{38} - 10^{39} \text{ erg s}^{-1}$ (Vieu+2022);
 - γ -ray emission, e.g., Westerlund 1 (Aharonian+2022), Cygnus OB2 (LHAASO+2024), leptonic or hadronic?
 - $^{22}\text{Ne}/^{20}\text{Ne}$ ratio anomaly (Gupta+2020).



- Possible acceleration mechanisms in SCs:
 - Acceleration by multiple stellar wind TSs (Klepach+2000);
 - Shock acceleration at the cluster wind TS (Morlino+2021);
$$\text{For } R_s \ll R_b, \quad \frac{u_2 R_s}{D_2(E)} = 1 \quad \Rightarrow \quad E_{\text{max}}$$
 - Stochastic acceleration by scattering with turbulence in the Superbubble (Bykov+2020).

2. Modeling the γ -ray emission from the Cygnus bubble

PeV γ -ray photons toward the Cygnus bubble

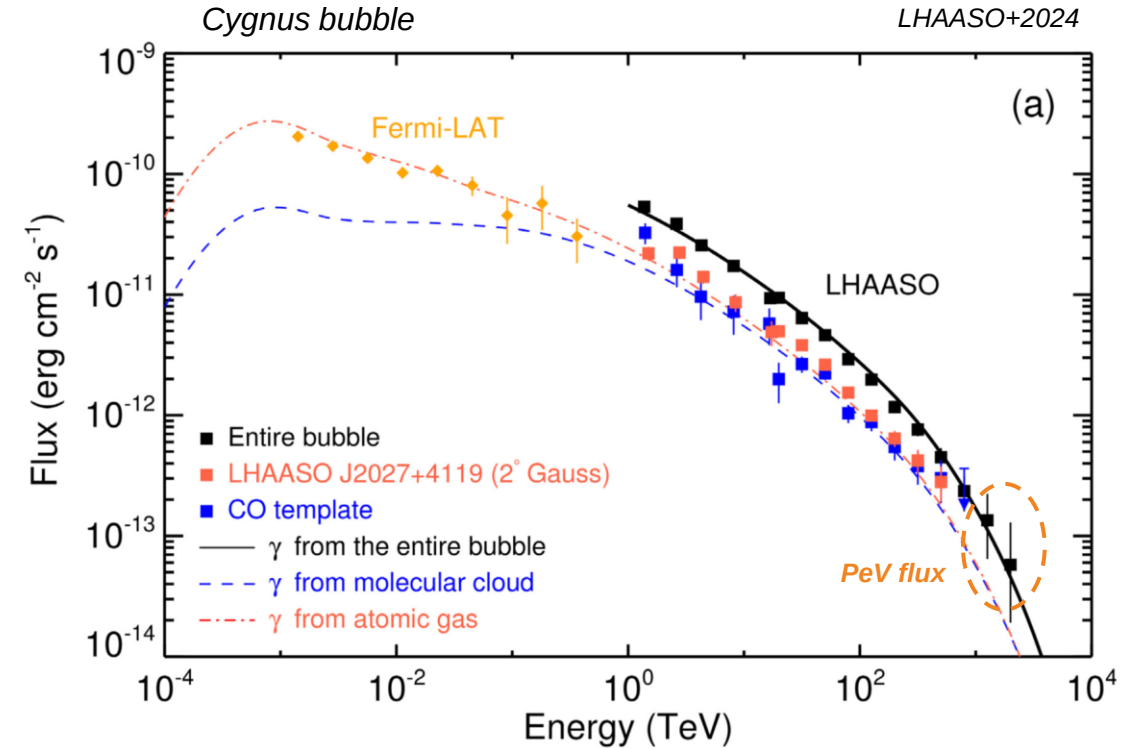
- Cygnus OB2

- a) Massive OB association in the Cygnus-X region;
- b) ~ 169 OB stars, including 3 WR stars (*Wright+2015*);
- c) ~ 1.4 kpc away, with an average age about 3 Myr;
- d) Total wind luminosity: a few $\times 10^{38}$ erg s $^{-1}$.

Cygnus OB2



Image credit: NASA

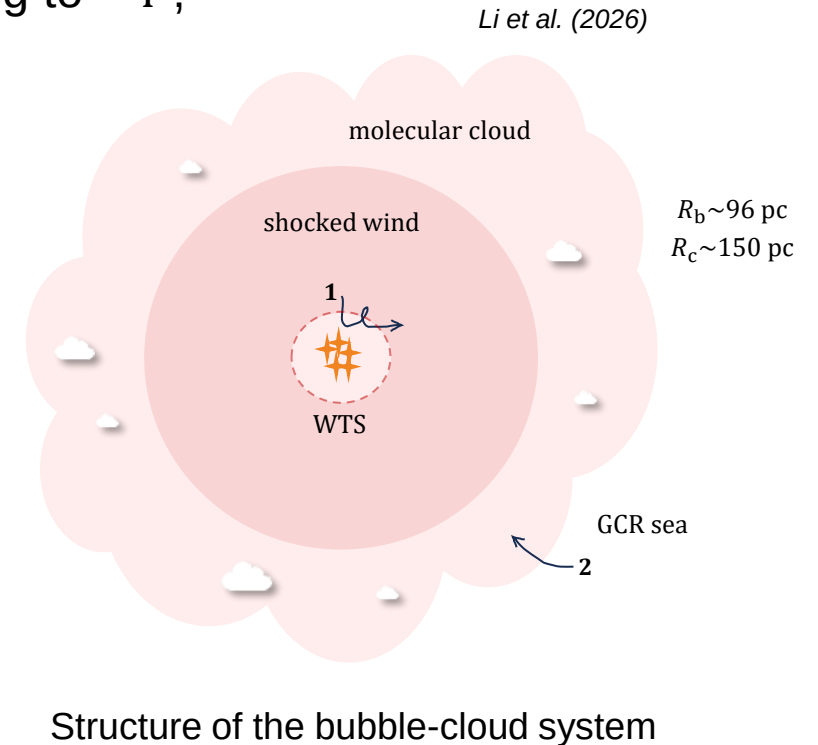
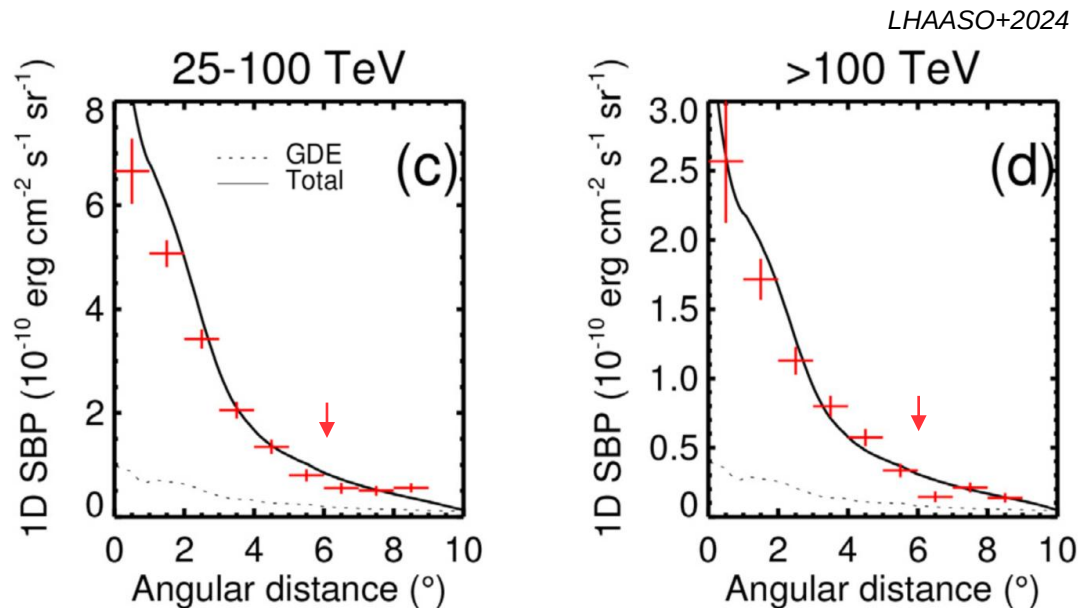


$$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$$

Energy of parent CRs exceeds 10 PeV!

Implication of the γ -ray morphologies

- LHAASO observation indicates that the emission extends to at least 6° , corresponding to ~ 150 pc at a distance of 1.4 kpc;
- However, the theory of bubble evolution predicts $R_b \sim 96$ pc, corresponding to $\sim 4^\circ$;
- The bubble is surrounded by a molecular cloud with $R_c \sim 150$ pc.



Particle transport equation

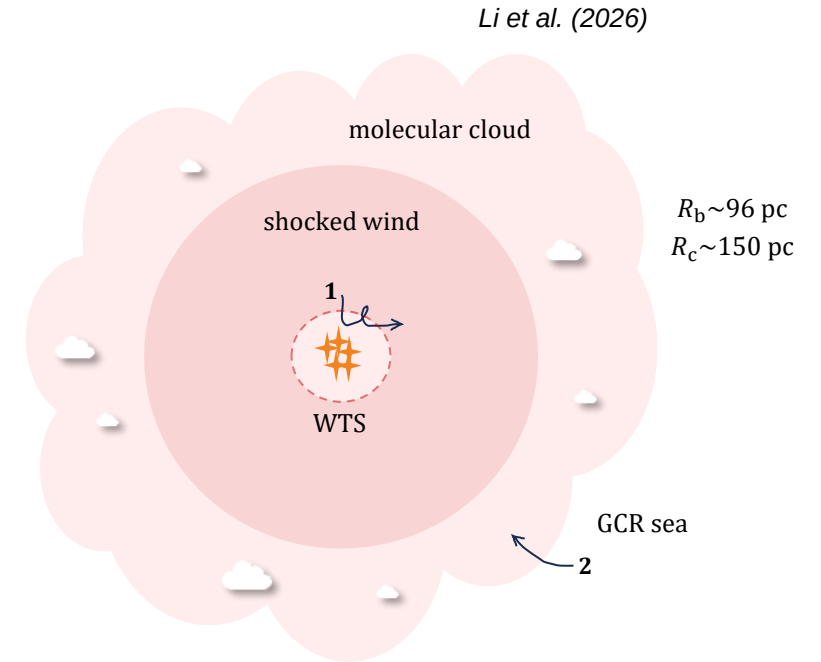
$$\frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 D(r, p) \frac{\partial f}{\partial r} \right] - \tilde{u}(r) \frac{\partial f}{\partial r} + \frac{1}{r^2} \frac{d}{dr} \left[r^2 \tilde{u}(r) \right] \frac{p}{3} \frac{\partial f}{\partial p} - \frac{1}{p^2} \frac{\partial}{\partial p} \left[p^2 \dot{p} f \right] + Q(r, p) = 0$$

- $D_{rr}(r, p)$: diffusion coefficient, $D_{rr} \simeq \frac{1}{3} v r_L \frac{1}{k_{\text{res}} W(k_{\text{res}})} \quad \frac{B_0^2}{4\pi} = \eta_B \rho u^2$

Two-zone diffusion in the downstream of the WTS:

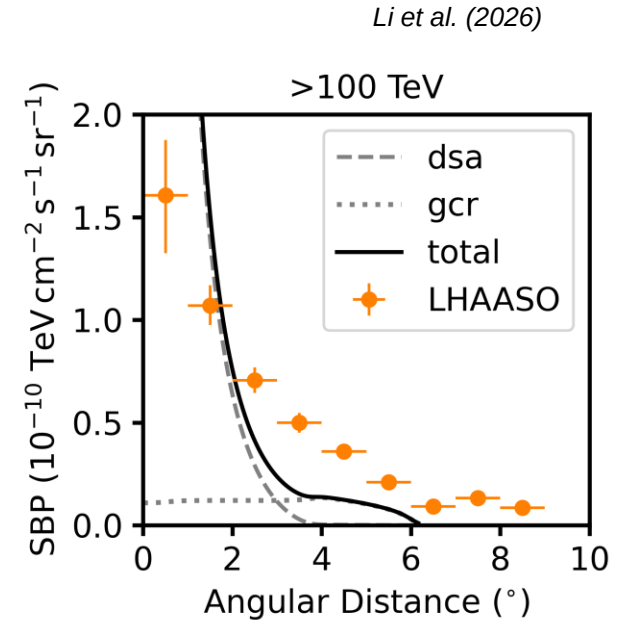
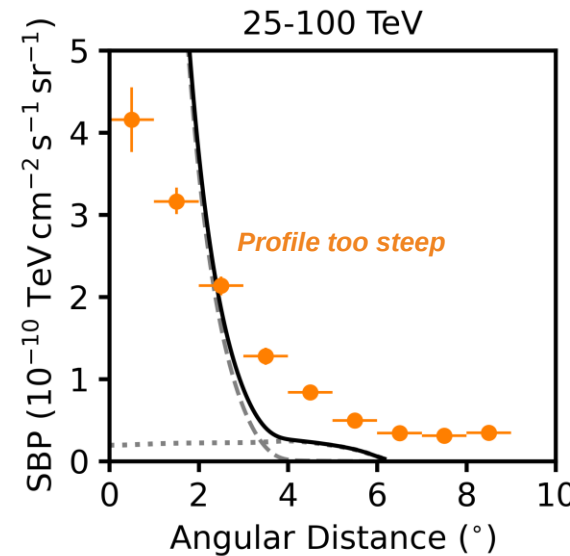
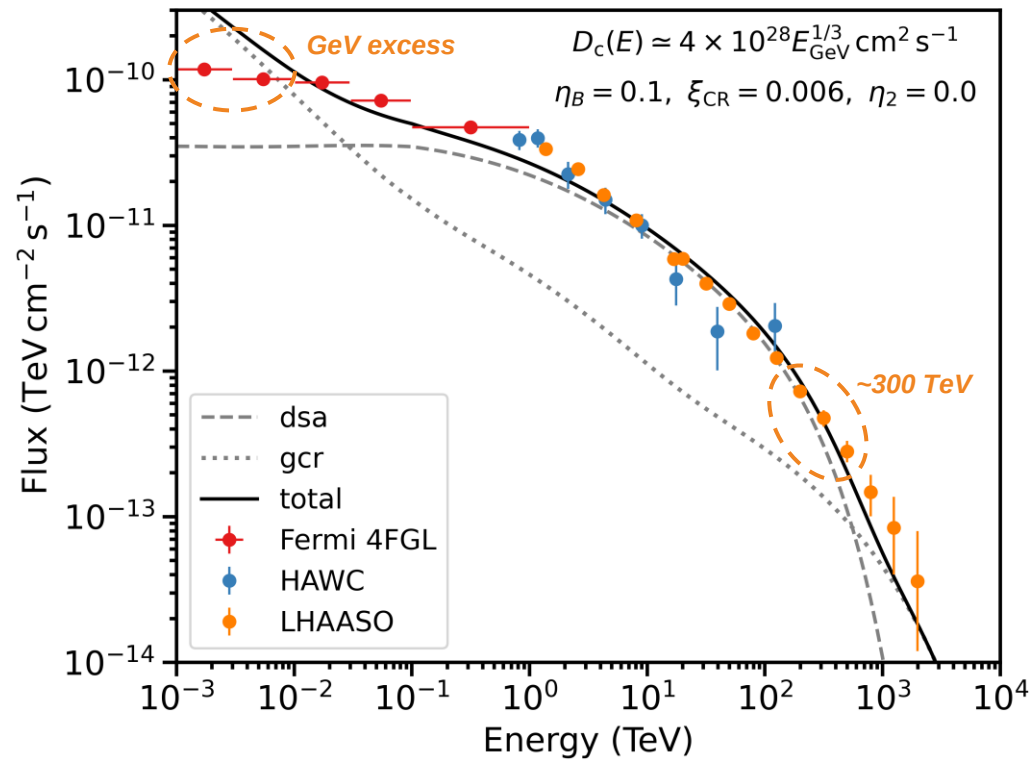
$$D_2(r, E) = \begin{cases} D_b(r, E), & R_s < r \leq R_b \\ D_c(E), & R_b < r \leq R_c \end{cases} \quad D_b(r, E): \text{Bohm diffusion coefficient}$$

- $\tilde{u}(r)$: effective advection velocity
- $Q(r, p)$: injection term, $Q(r, p) = 4\pi R_s^2 \eta_{\text{inj}} n_1 u_1 \frac{\delta(p - p_{\text{inj}})}{4\pi p^2} \frac{\delta(r - R_s)}{4\pi r^2}$
- Two CR components:
 1. CRs that are injected and accelerated at the WTS;
 2. Penetrated Galactic CRs that are reaccelerated at the WTS.



Structure of the bubble-cloud system

Contribution of Galactic CRs to the γ -ray emission

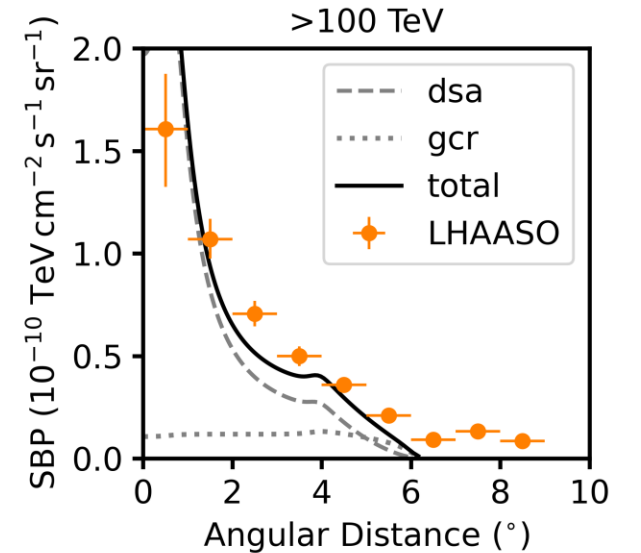
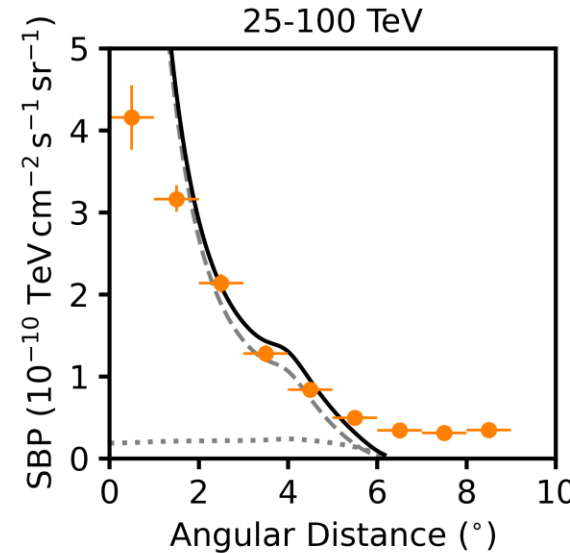
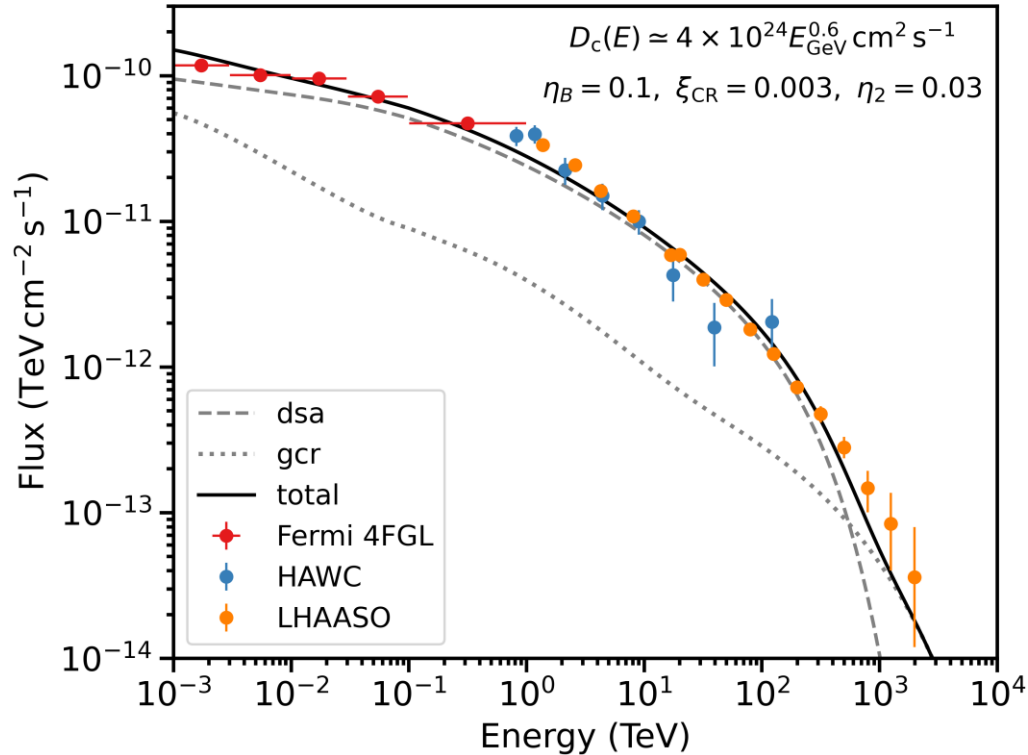


- Galactic CRs contribute significantly to the γ -ray flux above $\sim 300 \text{ TeV}$. However, the predicted flux exceeds the observations below $\sim 10 \text{ GeV}$.
- The predicted γ -ray morphology is too steep, suggesting that the emission should extend over a larger region.

Effect of slow diffusion in the cloud

Slow diffusion within the cloud can:

- a) Reduce the penetration of low-energy Galactic CRs from the ISM into the cloud;
- b) Suppress the escape of shock-accelerated particles from the cloud into the ISM.



Li et al. (2026)

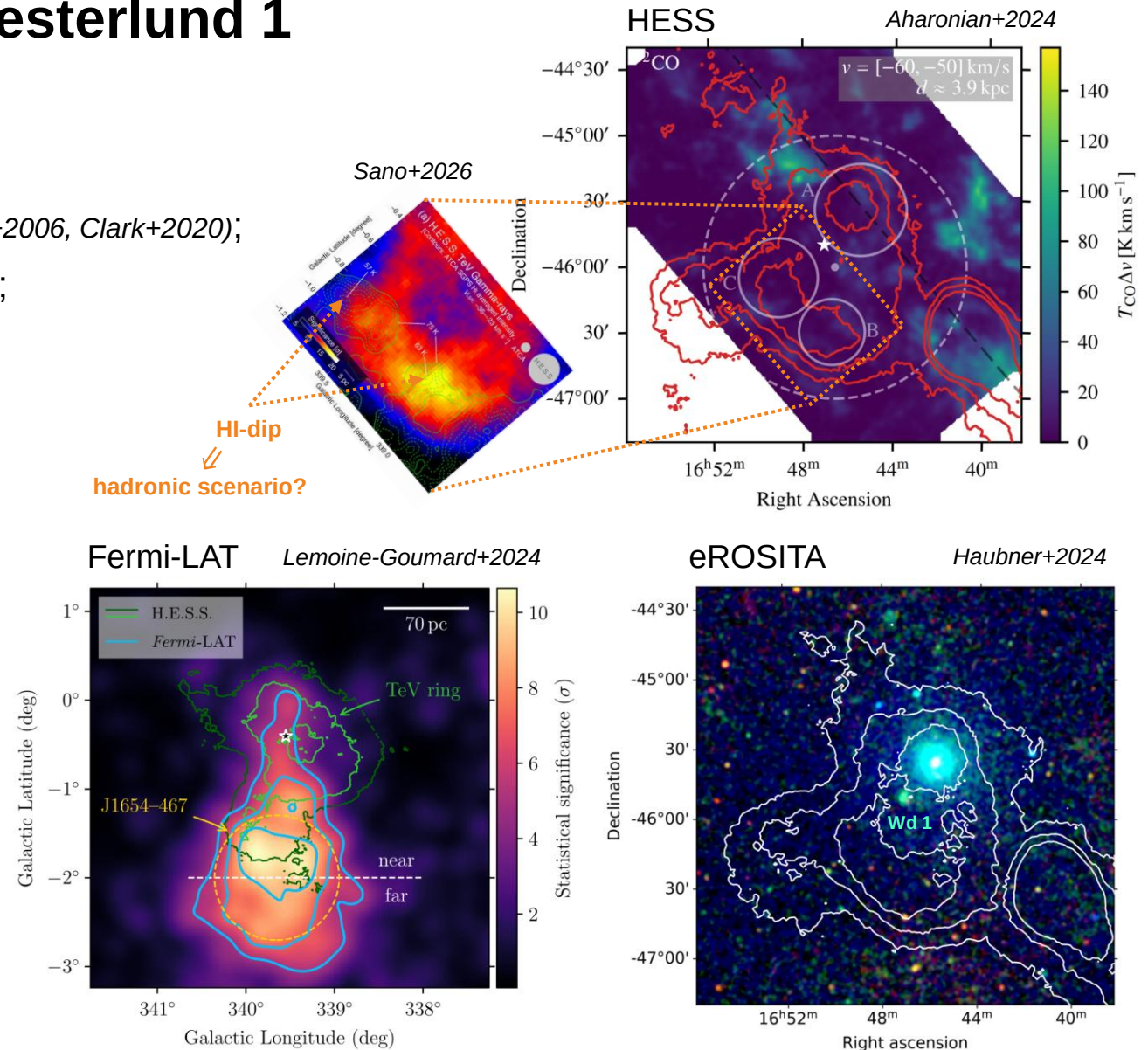
3. Understanding the origin of the γ -ray emission from Westerlund 1: hadronic or leptonic?

Multi-wavelength observations of Westerlund 1

- Westerlund 1
 - a) Most massive star cluster in the Galaxy;
 - b) ~ 24 WR stars and > 100 OB-type stars (*Crowther+2006, Clark+2020*);
 - c) ~ 3.9 kpc away, with an average age about 4 Myr;
 - d) Total wind luminosity $\sim 10^{39} \text{ erg s}^{-1}$ (*Harer+2023*).
- Multi-wavelength observations
 - a) HESS
 1. Ring-like feature in TeV map;
 2. No association between γ -ray peak and molecular cloud $\Rightarrow$ leptonic origin?
 - b) Fermi-LAT

GeV outflow from the Galactic plane.
 - c) eROSITA
 1. No non-thermal X-ray emission detected;
 2. X-ray upper limit.
 - d) Planck

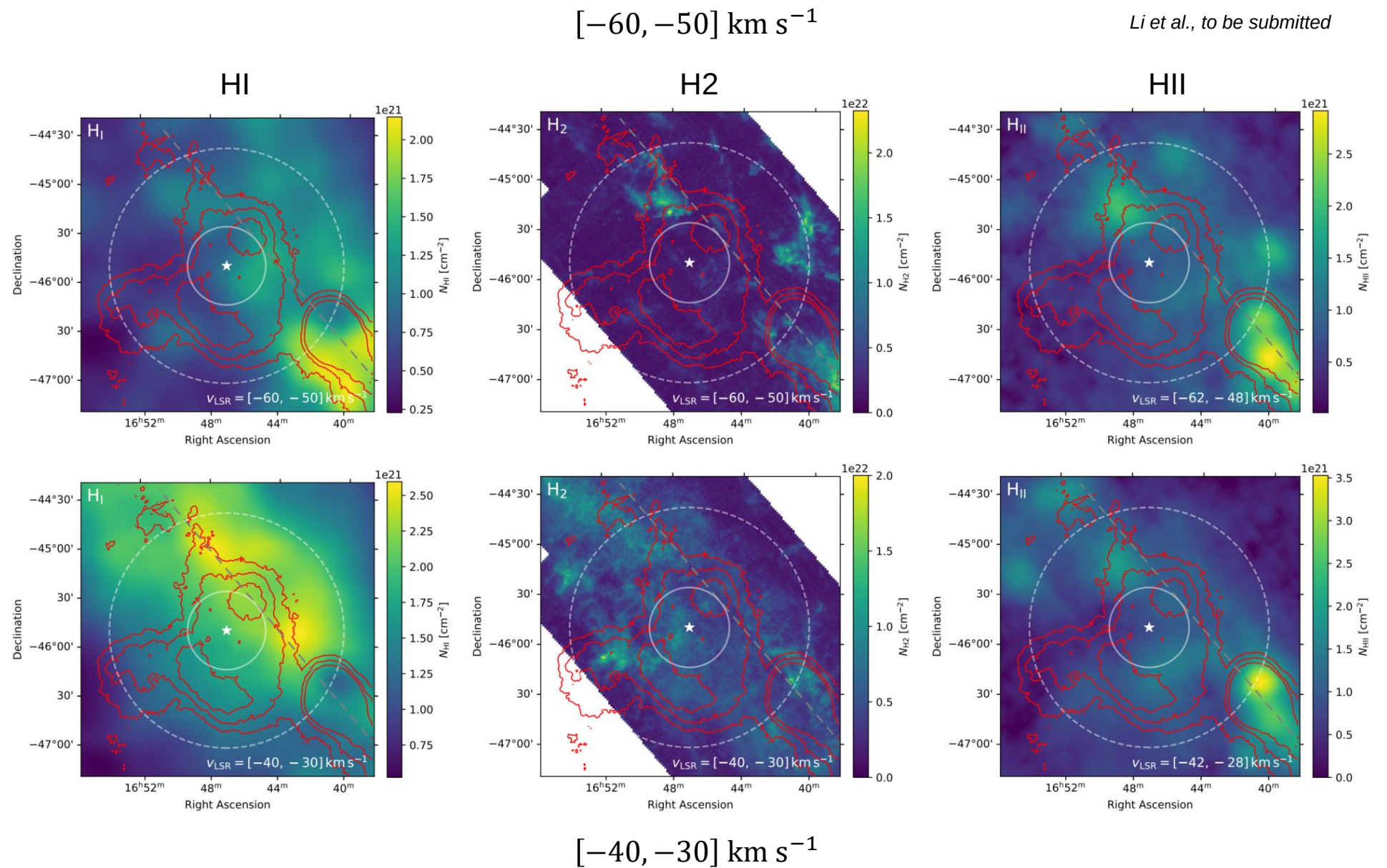
Radio upper limit.
- Origin of the γ -ray emission?



Gas analysis

- Data set
 - HI: GASS III
 - H₂: Mopra
 - HII: HIPASS

- $M_{\text{HI}} \approx 1.59 \times 10^5 M_{\odot}$
 $n_{\text{HI}} \approx 2.8 \text{ cm}^{-3}$
- $M_{\text{H}_2} \approx 8.44 \times 10^5 M_{\odot}$
 $n_{\text{H}_2} \approx 7.5 \text{ cm}^{-3}$
- $M_{\text{HII}} \approx 1.5 \times 10^5 M_{\odot}$
 $n_{\text{HII}} \approx 1.8 \text{ cm}^{-3}$



Leptonic model

Li et al., to be submitted

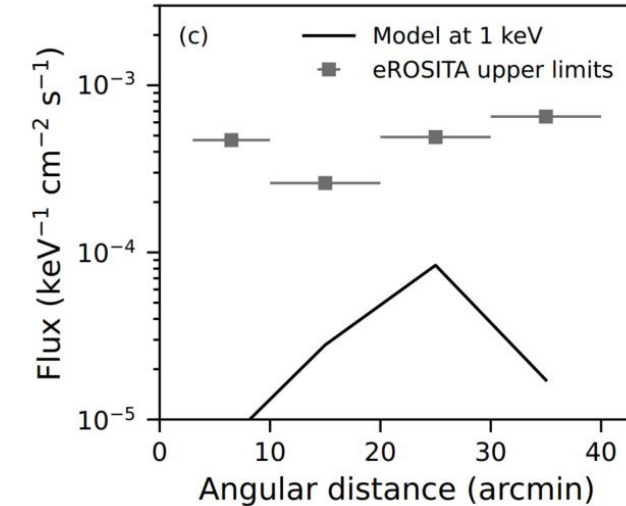
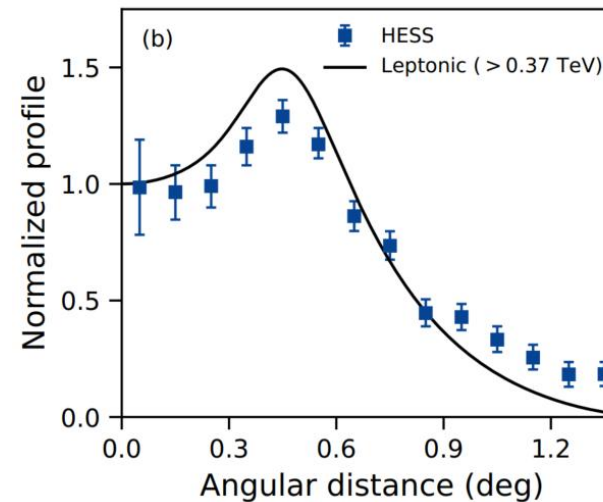
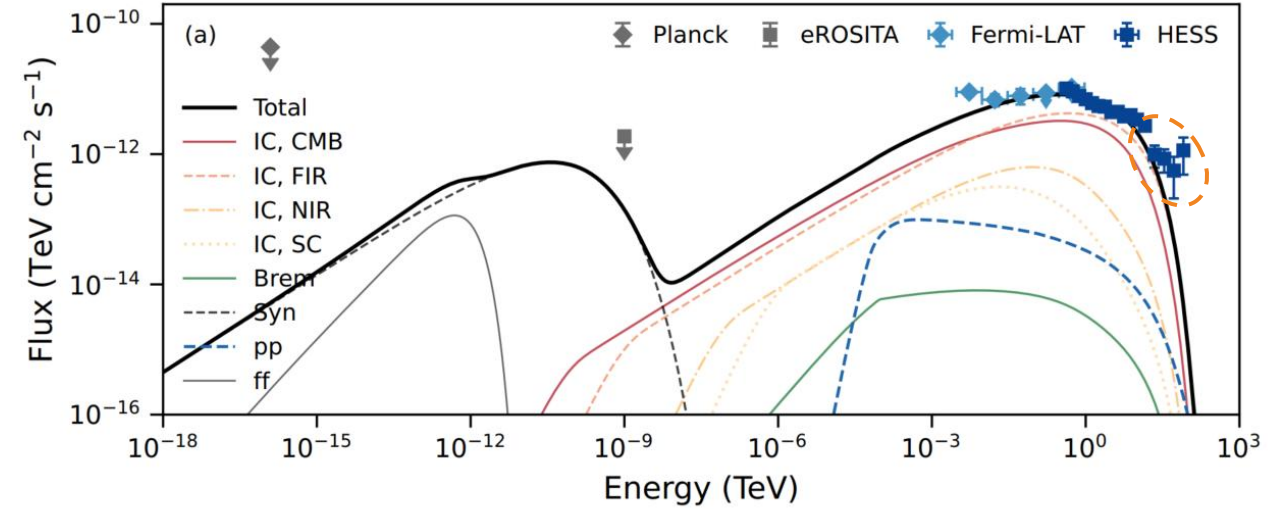
- Model setup

- Assume spatially dependent Kraichnan diffusion;
- Solve steady-state transport equation for electrons and protons;
- Calculate non-thermal emission from electrons and protons.

L_c (pc)	R_s (pc)	R_b (pc)	n_0 (cm ⁻³)	n_b (cm ⁻³)	η_B	B_2 (μG)	η_2	$\xi_{CR,e}$	$\xi_{CR,p}$	K_{ep}
0.2	30.8	98.2	25	0.02	1.0×10^{-3}	3.1	0	7.0×10^{-4}	0.07	0.01

- Results

- γ-ray flux is dominated by IC emission;
- Hadronic contribution is negligible in this case, due to the low target gas density;
- Unable to fit the highest-energy γ-ray data points above 10 TeV, due to severe energy loss of electrons.



Hadronic model

Li et al., to be submitted

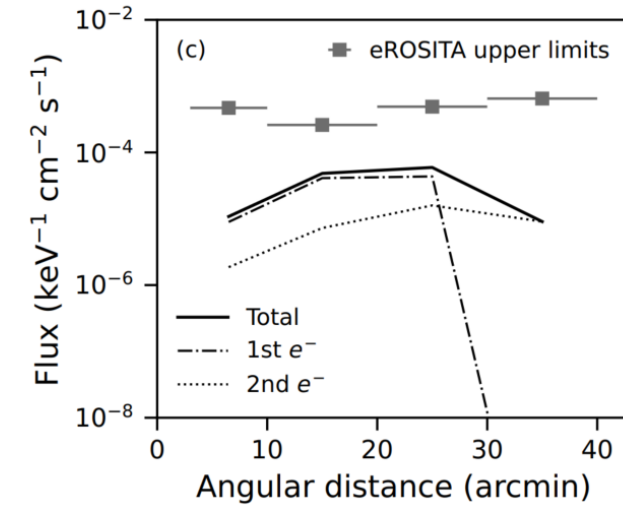
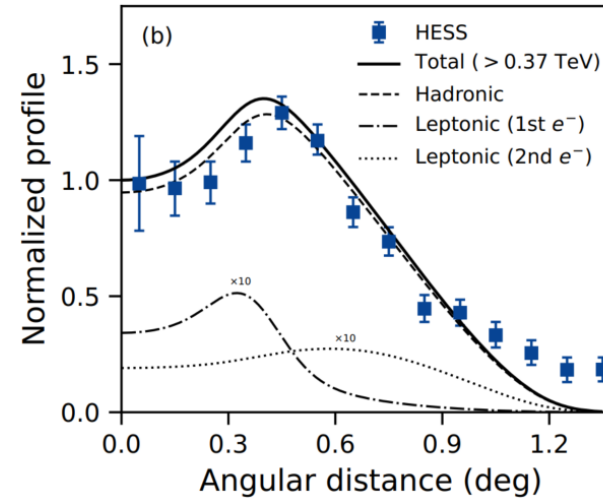
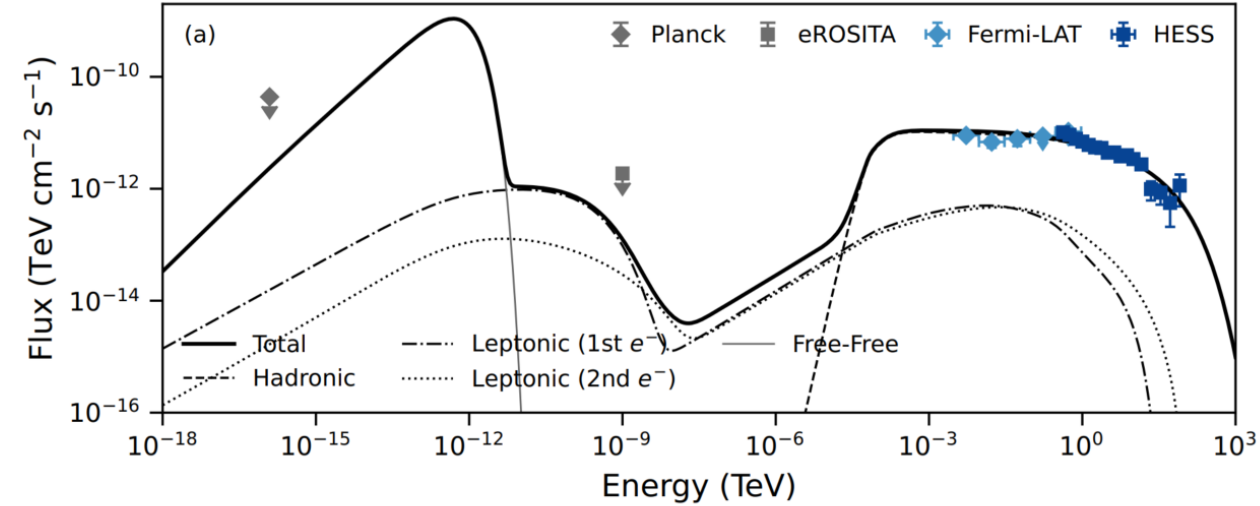
- Model setup

- Calculate hadronic emission from protons;
- Include contribution from both primary and secondary electrons.

L_c (pc)	R_s (pc)	R_b (pc)	n_0 (cm ⁻³)	n_b (cm ⁻³)	η_B	B_2 (μ G)	η_2	$\xi_{CR,e}$	$\xi_{CR,p}$	K_{ep}
0.2	25.0	85.5	50	2	0.04	24.2	0	8×10^{-5}	0.08	10^{-3}

- Results

- The model can reproduce both the multi-wavelength spectrum and γ -ray morphology;
- Spectral fitting favors the hadronic scenario.



4. Stochastic reacceleration of particles in the Superbubble

Stochastic acceleration

- Particle transport equation:

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 D_{rr} \frac{\partial f}{\partial r} \right] - \tilde{u} \frac{\partial f}{\partial r} + \frac{1}{r^2} \frac{d}{dr} [r^2 \tilde{u}] \frac{p}{3} \frac{\partial f}{\partial p} - \frac{1}{p^2} \frac{\partial}{\partial p} [p^2 \dot{p} f] + \frac{1}{p^2} \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial f}{\partial p} \right] + Q = 0$$

$D_{pp}(r, p)$: diffusion coefficient in momentum space, $D_{rr} D_{pp} = \frac{1}{9} v_A^2 p^2$ $D_{rr} \simeq \frac{1}{3} v r_L \frac{1}{k_{\text{res}} W(k_{\text{res}})}$

- Wave evolution (for Kolmogorov cascading):

Nonlinear coupling!

$$\frac{\partial W}{\partial t} + \frac{\partial}{\partial k} \left[\frac{a}{\sqrt{\rho}} k^{5/2} W^{3/2} \right] = -\Gamma(k) W + S \delta(k - k_0)$$

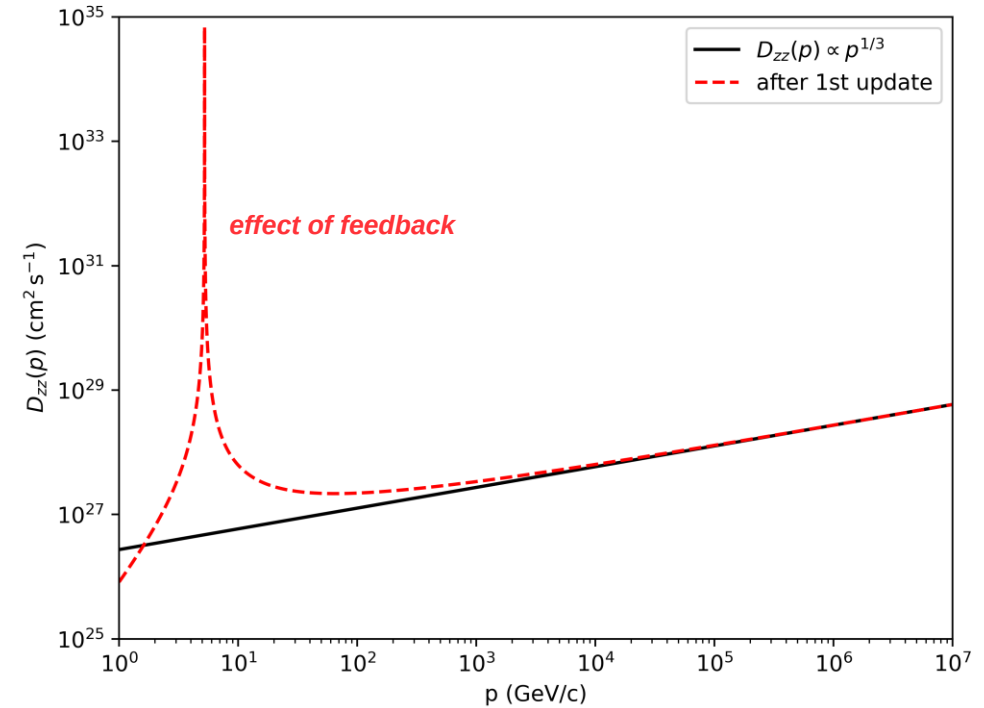
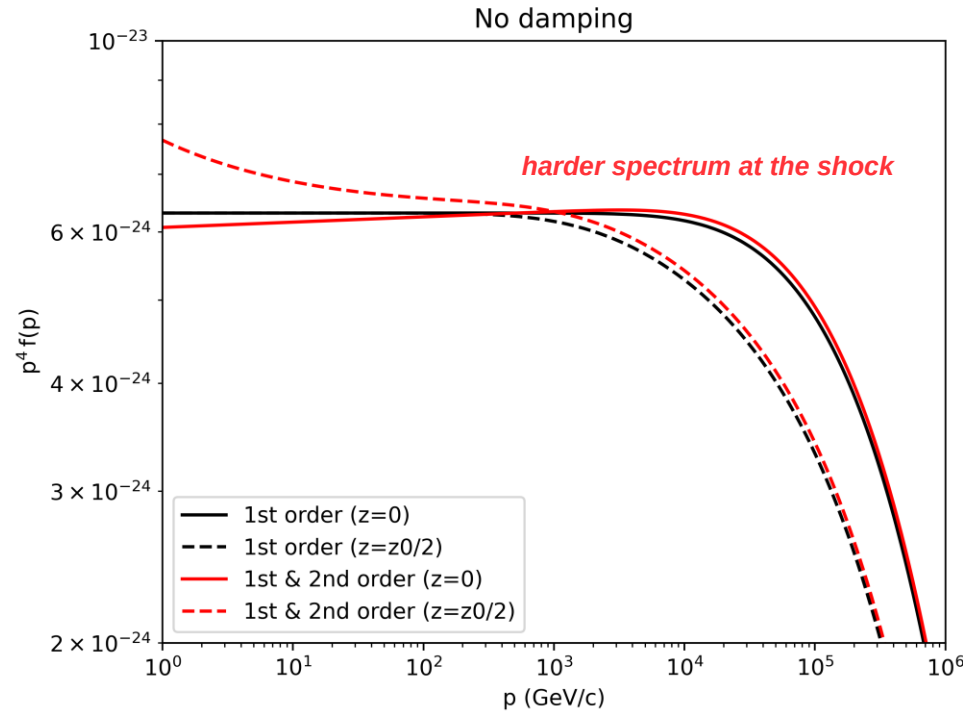
1. Cascading term

2. Damping term, $\Gamma(k) = \frac{8\pi^3 e^2 v_A^2}{k c^2} \int_{\frac{eB}{kc}} dp' p' f(p')$

3. Injection term

- Injected at the shock
- Injected locally in the bubble

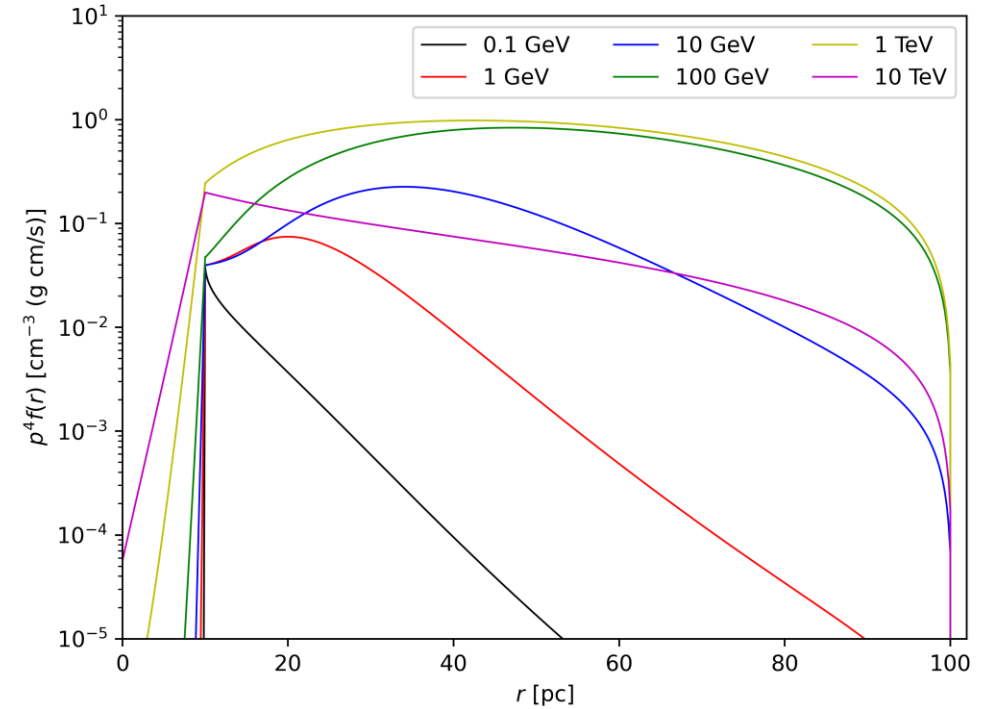
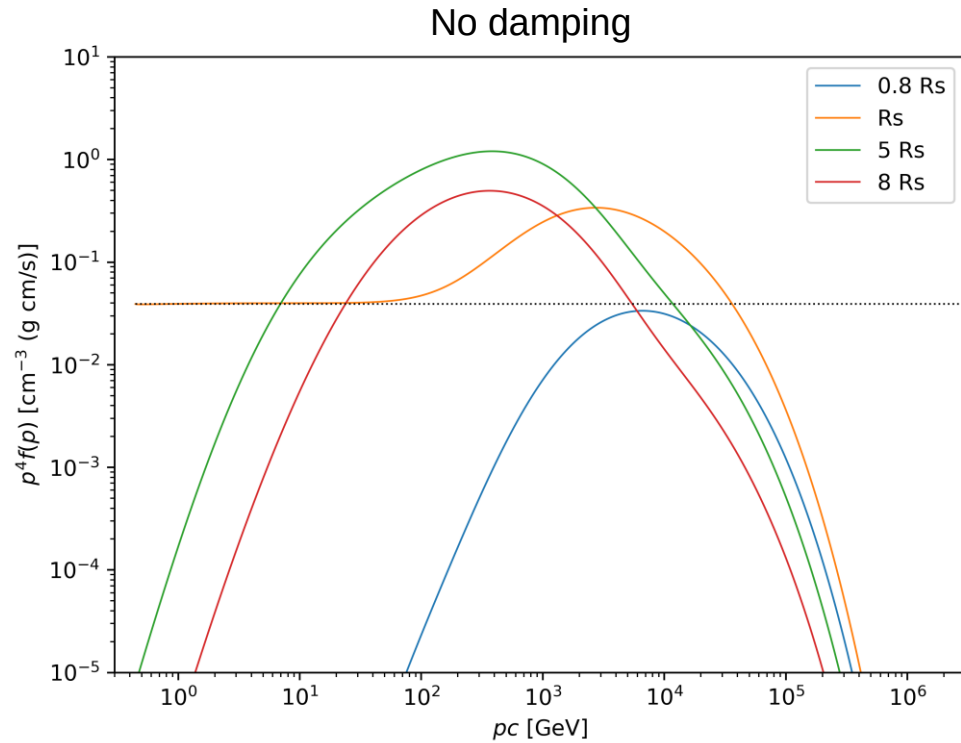
The case of 1D planar shock



- Simplifications: 1. Steady state; 2. No damping; 3. $\frac{1}{p^2} \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial f}{\partial p} \right] \sim \frac{f}{\tau_{\Pi}}$
- Analytical solution shows that stochastic acceleration has little effect on p_{max} , but it affects the spectrum of low-energy particles at large distances from the shock.

The case of 1D spherical shock

Li et al., in preparation



- Solve the particle transport equation using the finite volume scheme;
- Spectral bump at the shock is due to energy-dependent effective velocity felt by particles in the downstream.

$$u(r) = \begin{cases} u_1, & R_{sc} < r \leq R_s \\ u_2 \left(\frac{r}{R_s}\right)^{-2}, & R_s < r \leq R_b \end{cases}$$

Summary & future work

- We studied particle acceleration at the cluster WTS and their propagation in the Cygnus bubble:
 - a) Spatially dependent Bohm diffusion in the bubble and slow diffusion in the cloud are both required to reproduce the observed γ -ray spectrum and morphology.
 - b) Galactic CRs contribute significantly to the γ -ray emission above ~ 300 TeV.
 - We modeled the multi-wavelength spectrum and γ -ray morphology of Westerlund 1. For Kraichnan diffusion in the bubble, the hadronic scenario is favored against leptonic scenario.
 - We also studied stochastic reacceleration of particles in the Superbubble. We found that stochastic acceleration can influence the spectrum of low-energy particles at large distance from the shock.
-
- MHD simulation of the turbulence in the bubble can help us have a better understanding of particle transport and acceleration in this system, e.g. turbulence driven by shock-cloud interaction.
 - Hybrid/PIC simulations of the WTS can help us understand the microphysics of particle injection and acceleration.
 - Supernova explosion in the cluster core, acceleration by multiple shocks, penetration and ionization of CRs in molecular cloud...

Research activities

- Publications

- [1] B. Li, P. Blasi, E. Amato, “On the Role of Slow Diffusion in Modeling Gamma-Ray Emission from the Cygnus bubble,” *Proceedings of the 39th International Cosmic Ray Conference — PoS(ICRC2025)*, vol. 501, p. 067, 2025. doi:10.22323/1.501.0067
- [2] B. Li, P. Blasi, E. Amato, “Suppressed diffusion and gamma-ray emission from the Cygnus bubble,” *Astronomy & Astrophysics*, vol. 712, art. A41, 2026. doi:10.1051/0004-6361/202558034

- Conferences & Workshops

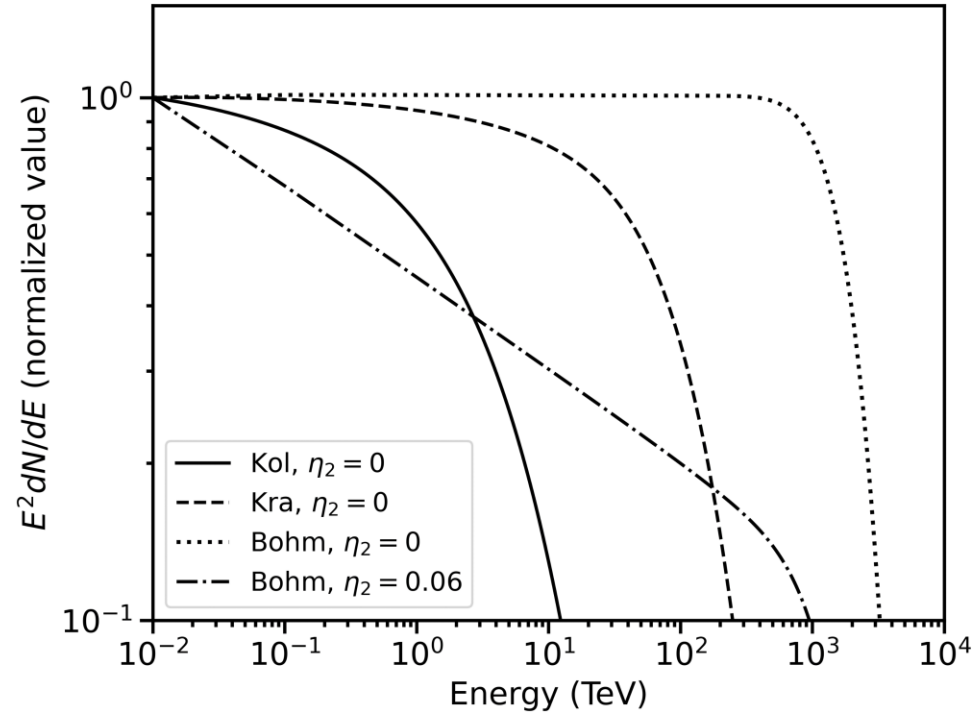
1. The 9th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy, Heidelberg, August 2026 — poster
2. The 46th COSPAR Scientific Assembly, Florence, August 2026 — talk
3. PLUTO/OpenGadget3 Symposium 2026, Heidelberg, June 2026 — online attendance
4. TAL Retreat, Florence, October 2025 — talk
5. 39th International Cosmic Ray Conference (ICRC 2025), Geneva, July 2025 — talk
6. Particle Acceleration and Transport: from the Sun to Extragalactic Sources, Rende, February 2025 — onsite attendance

- Schools

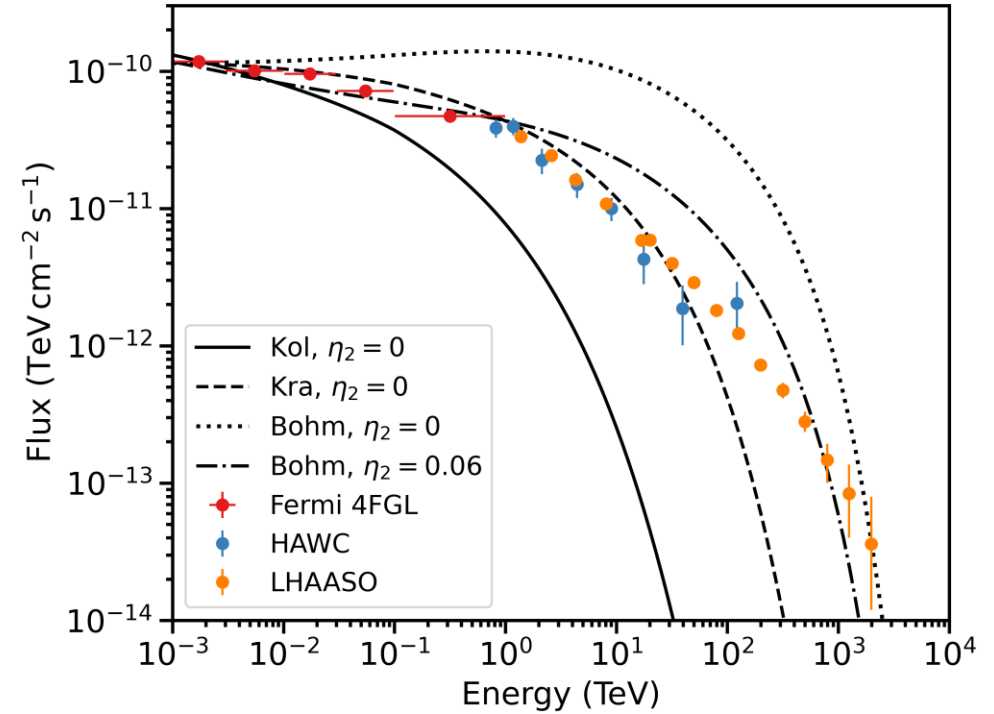
1. School on Computational Fluid Dynamics & Super Computing, Gran Sasso Science Institute, L'Aquila, July 2024.

Backup

Maximum particle energy (spatially uniform diffusion)

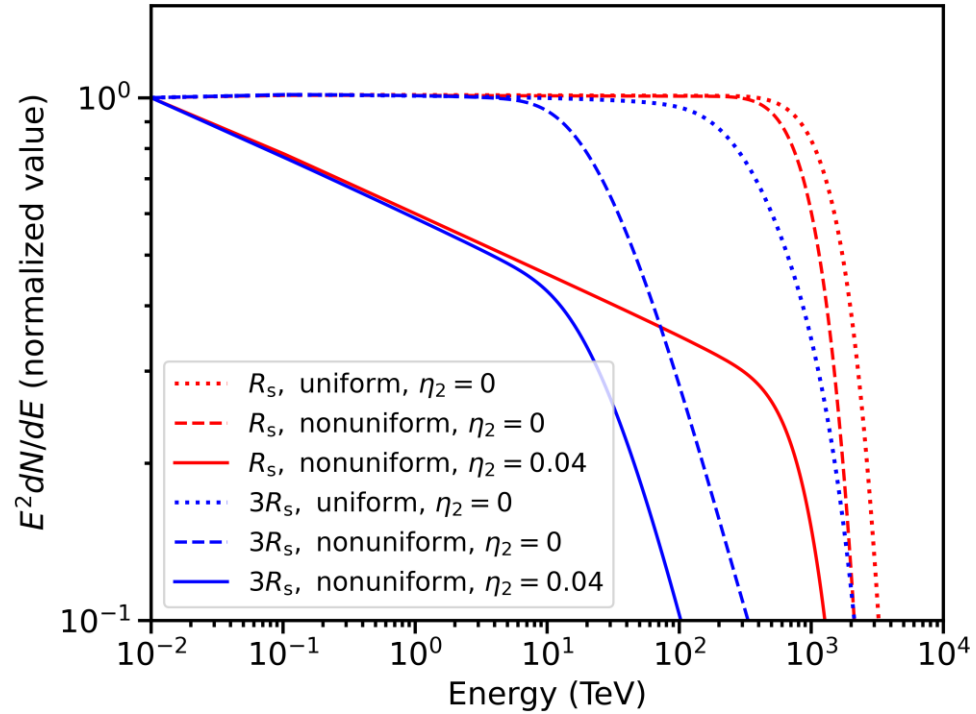


Particle spectrum at TS

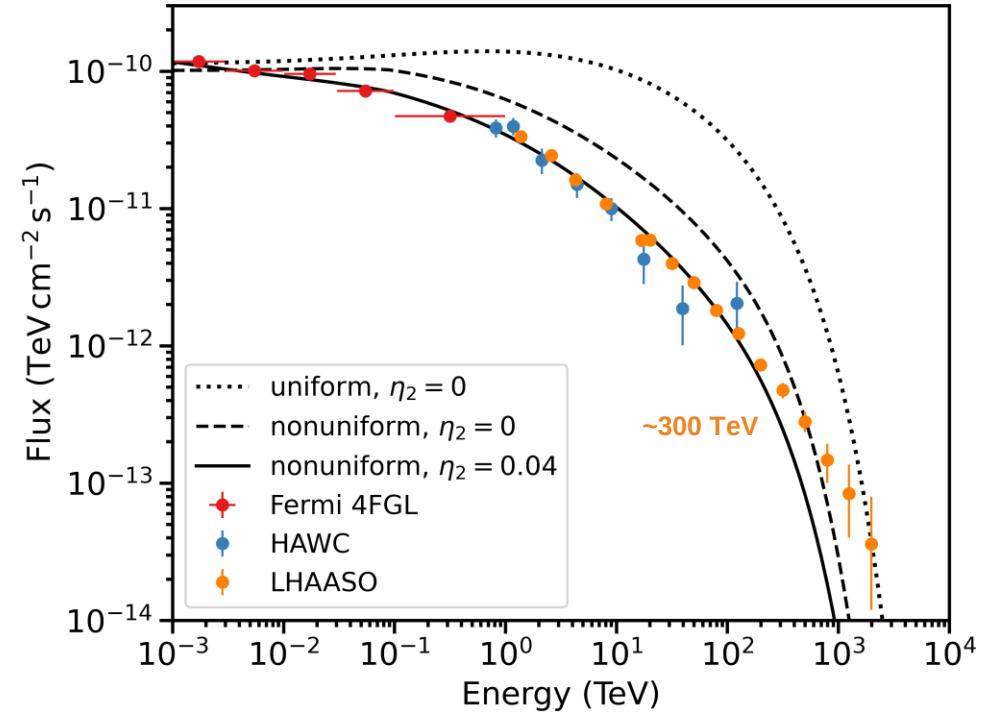


Predicted γ -ray spectrum

Effect of spatially dependent diffusion

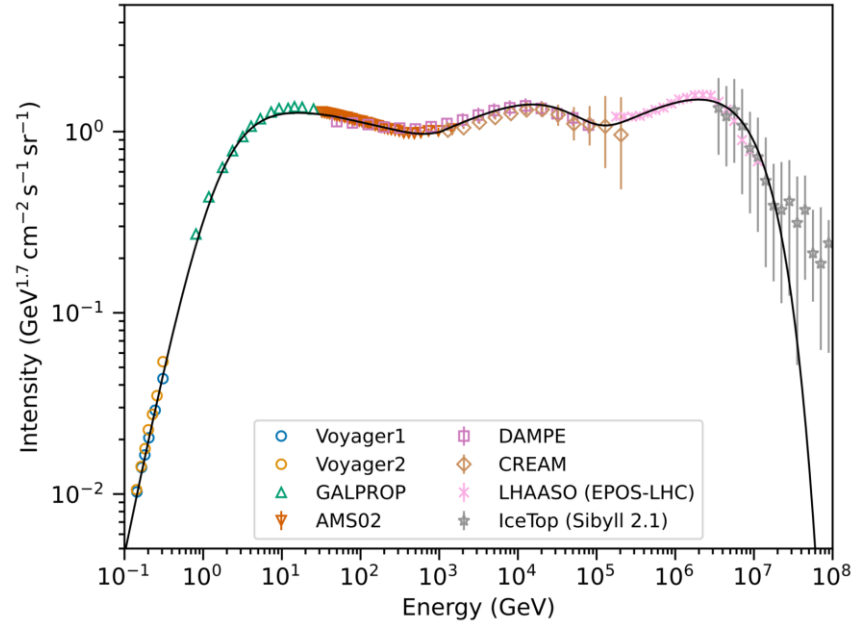


Particle spectra at R_s and $3R_s$

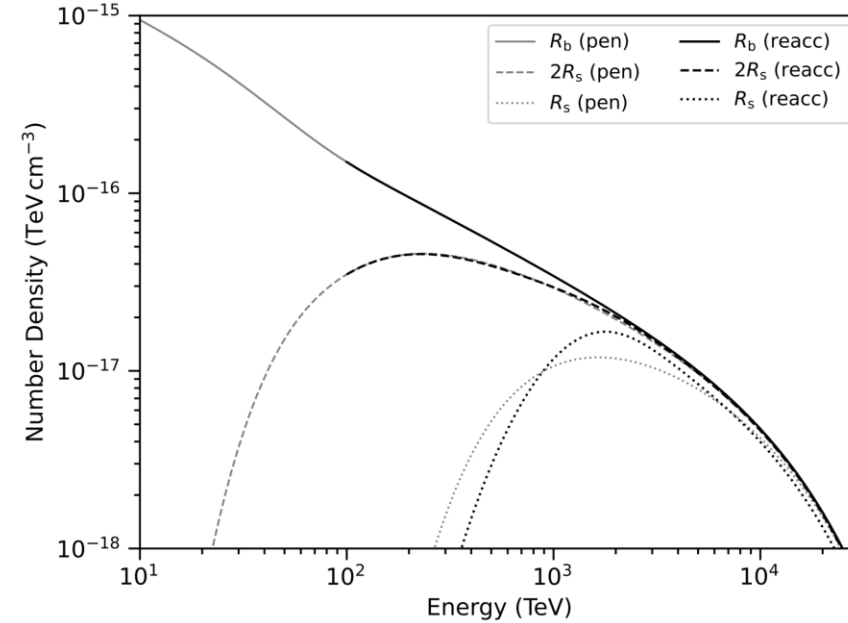


Predicted γ -ray spectrum

Penetration and reacceleration of Galactic CRs



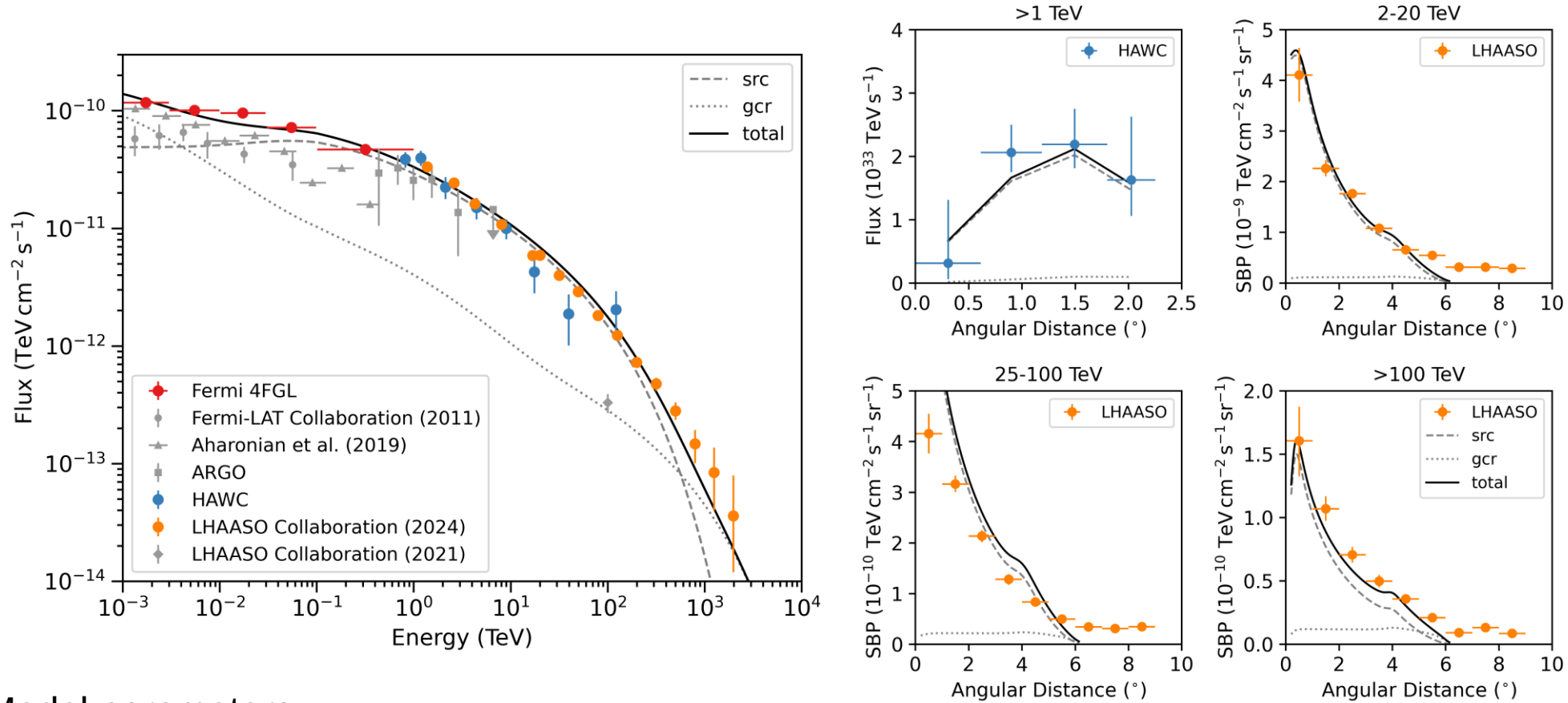
Locally measured spectrum of GCR proton



Spectra of penetrated and re-accelerated GCRs

- Galactic CRs that have penetrated the bubble may contribute to the measured γ -ray flux.
- Reacceleration is only important at the WTS.
- Effect of reacceleration on the volume integrated spectrum is negligible.

Central point source with continuous injection



- Model parameters:

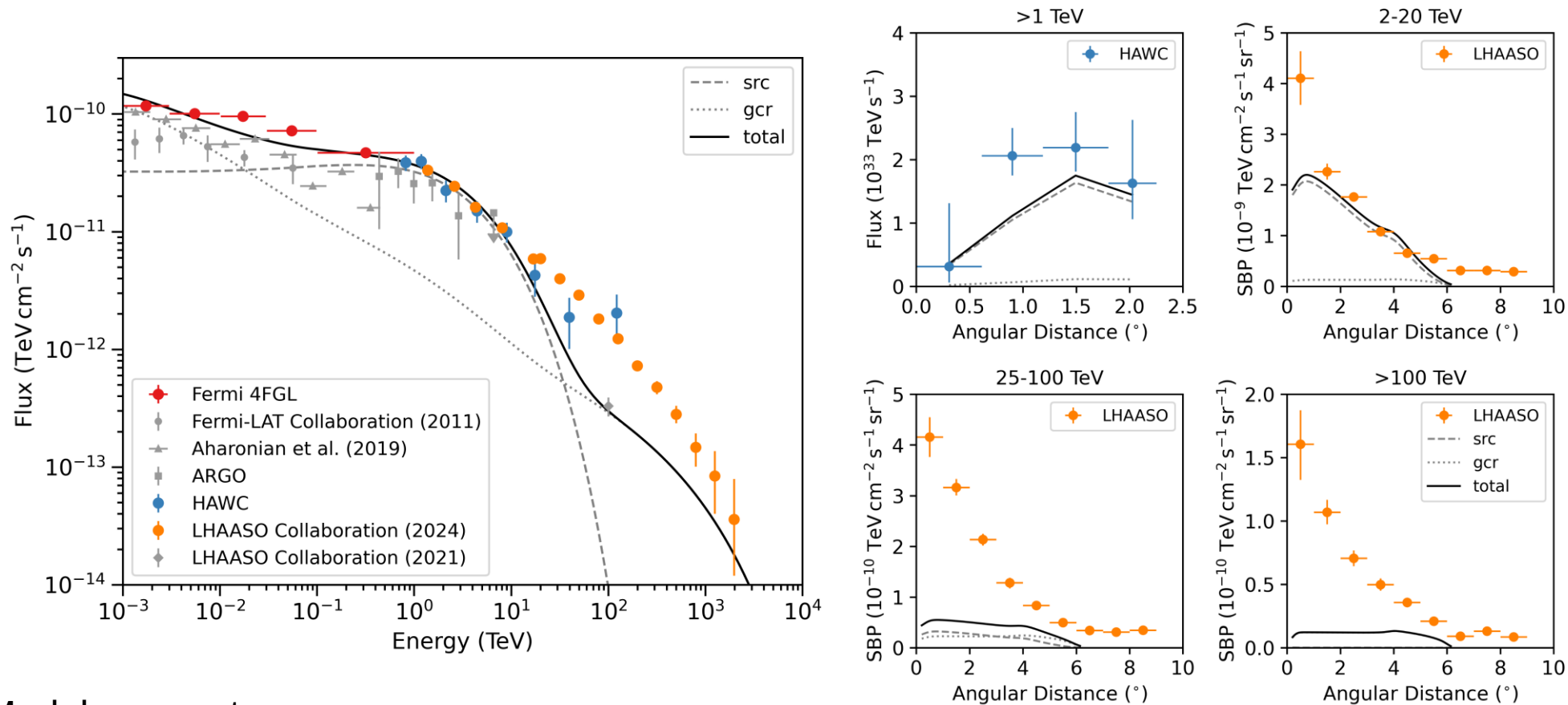
$$L_p = 2.5 \times 10^{36} \text{ erg s}^{-1}$$

$$Q(E) \sim E^{-2} \exp\left(-\frac{E}{E_{\text{max}}}\right), E_{\text{max}} = 1 \text{ PeV}$$

$$D(E) = 4 \times 10^{24} E_{\text{GeV}}^{0.6} \text{ cm}^2 \text{ s}^{-1}$$

- A central continuous injection source reproduces both the observed spectrum and morphology with the adopted model parameters.
- Suppressed diffusion is also required.

Central point source with burst-like injection



- Model parameters:

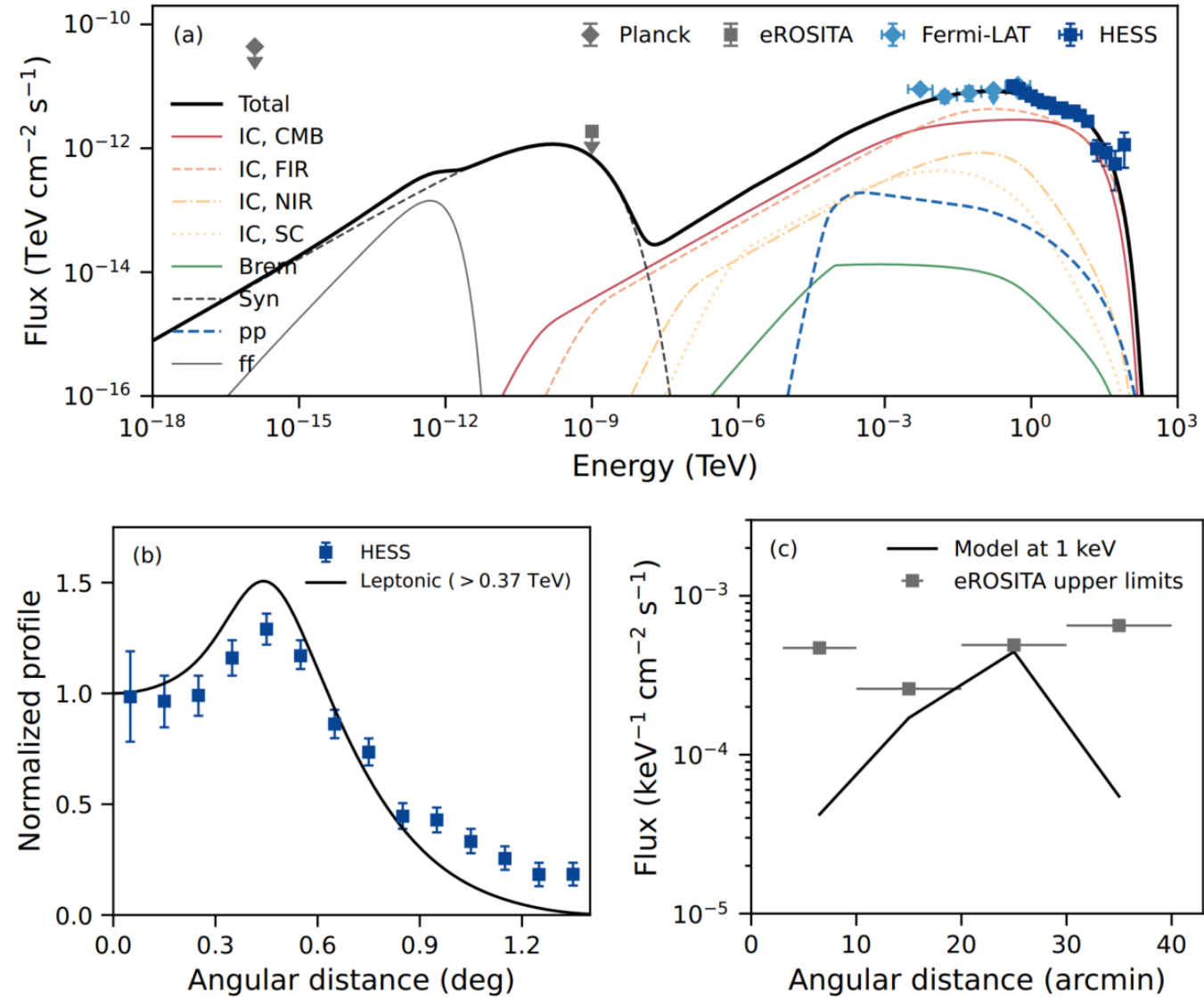
$$T_{\text{SN}} = 60 \text{ kyr}, \quad E_{\text{SN}} = 10^{51} \text{ erg}, \quad \xi_{\text{CR}} = 0.1$$

$$Q(E) \sim E^{-2} \exp\left(-\frac{E}{E_{\text{max}}}\right), \quad E_{\text{max}} = 1 \text{ PeV}$$

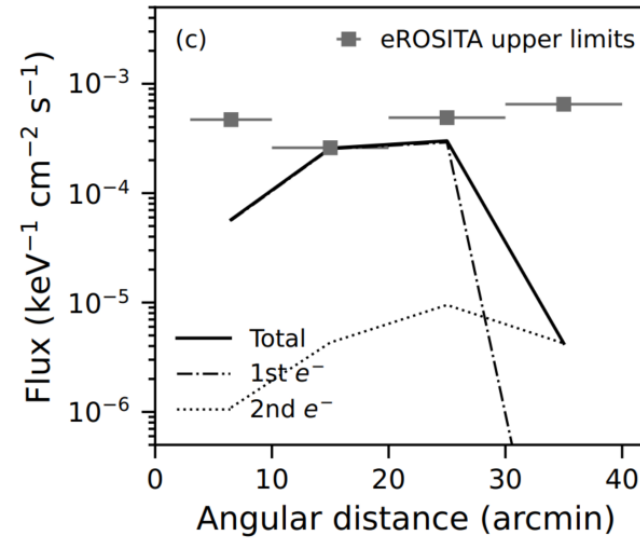
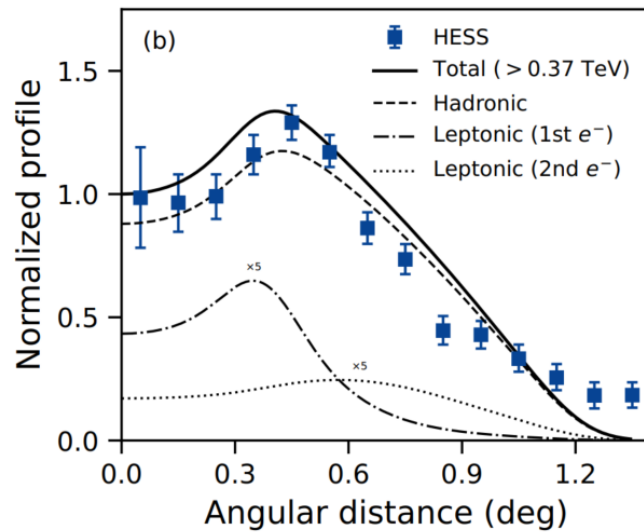
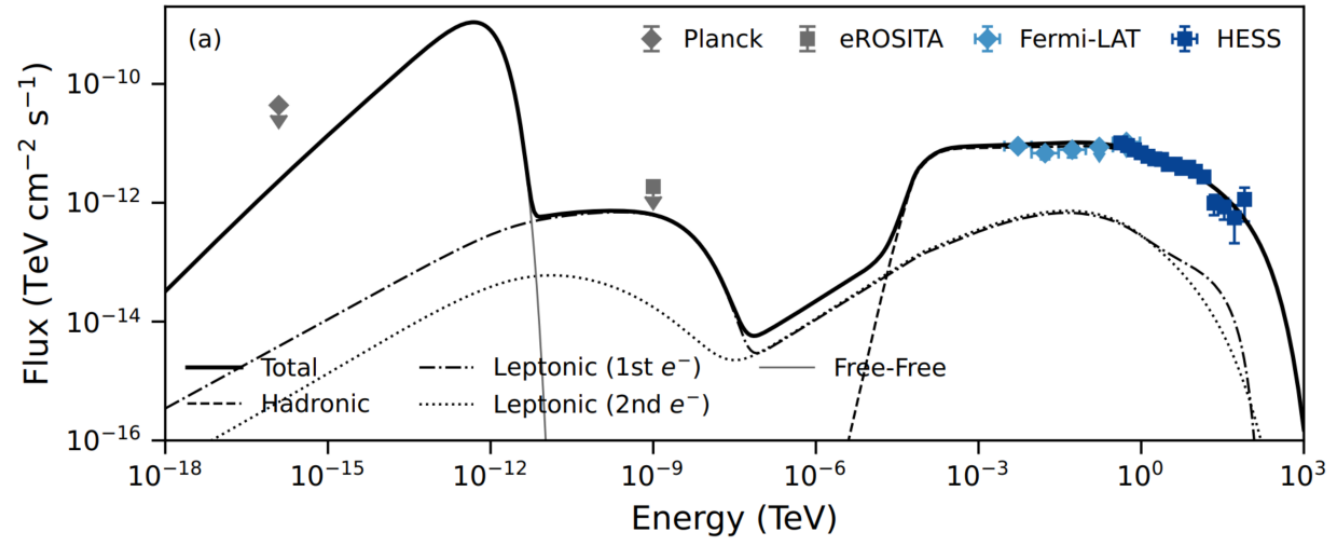
$$D(E) = 4 \times 10^{24} E_{\text{GeV}}^{0.8} \text{ cm}^2 \text{ s}^{-1}$$

- A central impulsive source alone (e.g., an SNR) cannot explain the observed γ -ray emission.
- This may indicate the presence of an additional emission component, e.g., IC emission from electrons.

Leptonic model with Bohm diffusion



Hadronic model with Bohm diffusion



Model parameters

Table 1: Model parameters.

	L_c (pc)	R_s (pc)	R_b (pc)	n_0 (cm ⁻³)	n_b (cm ⁻³)	η_B	B_2 (μ G)	η_2	$\xi_{\text{CR,e}}$	$\xi_{\text{CR,p}}$	K_{ep}
Nonuniform Bohm											
Leptonic model	1.0	29.1	94.7	30	0.02	1.0×10^{-3}	3.3	0.4	1.0×10^{-3}	0.1	0.01
Hadronic model	1.0	25.0	85.5	50	2	0.01	12.1	0	6.2×10^{-5}	0.062	10^{-3}
Nonuniform Kraichnan											
Leptonic model	0.2	30.8	98.2	25	0.02	1.0×10^{-3}	3.1	0	7.0×10^{-4}	0.07	0.01
Hadronic model	0.2	25.0	85.5	50	2	0.04	24.2	0	8×10^{-5}	0.08	10^{-3}

Solution at the shock

$$N_0(E) = K \left(\frac{E}{E_{\text{inj}}} \right)^{-\frac{\mathcal{R}+2}{\mathcal{R}-1}} \times \exp \left\{ \int_{E_{\text{inj}}}^E \frac{dE'}{E'} \left[\frac{3\mathcal{R}(\mathcal{D}_1 - 1)}{1 - \mathcal{R}} - \frac{3\mathcal{D}_2}{1 - \mathcal{R}} \right] \right\}$$

$$\mathcal{D}_{1,2}(E) = \frac{D_{1,2} \left. \frac{\partial N}{\partial r} \right|_{1,2}}{\tilde{u}_{1,2} N_0(E)}$$

