GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

Report for the passage of the year 2025

Particle acceleration and transport in the region surrounding the Cygnus star cluster

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Outline

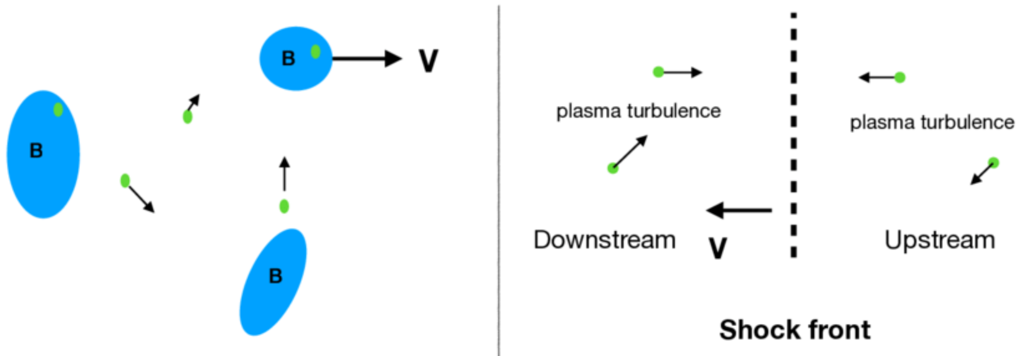
1. ***Introduction***
2. ***Modeling the gamma-ray emission from the Cygnus bubble***
3. ***Stochastic reacceleration of particles in the Superbubble***
4. ***Summary & future work***

1. Introduction

Origin of Galactic cosmic rays

- Cosmic rays (CRs):
  a) Mainly composed of protons
  b) Spectral features (cutoff, ankle, and knee, etc.)
  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) Star clusters (SCs)
  d) …

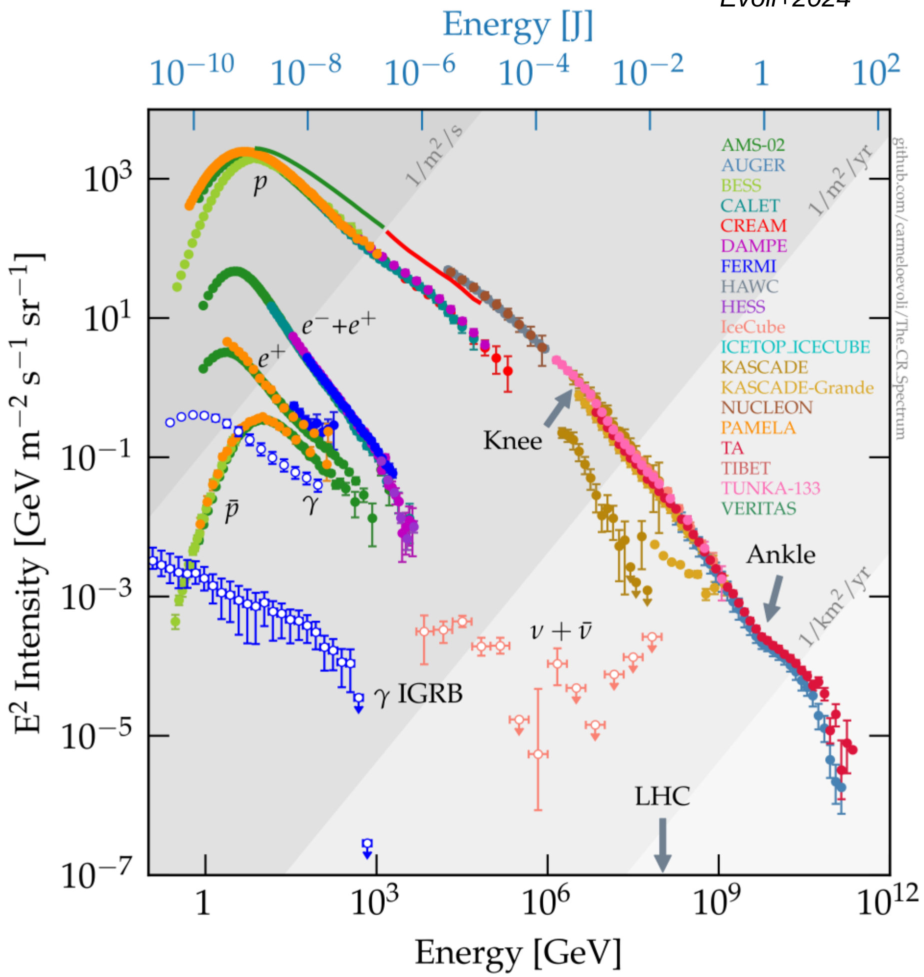
Che+2019



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

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

Evoli+2024

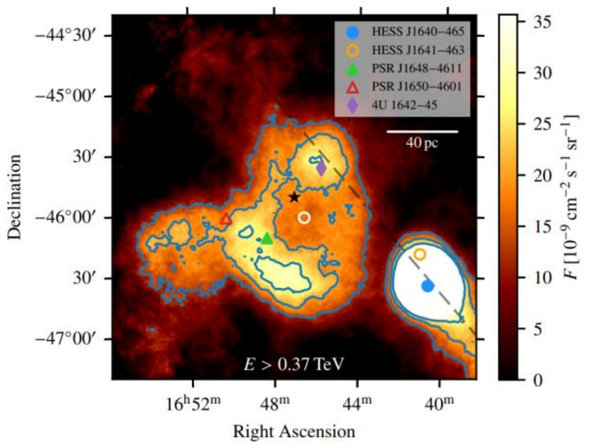


Star clusters as CR accelerators

- A star cluster is a gravitationally bound collection of stars, often hosting tens of massive stars, like OB, WR stars.
  a) Total wind power $\sim 10^{38} - 10^{39}$ erg s^{-1} *(Vieu+2022)*;
  b) γ-ray emission, e.g., Westerlund 1 *(Aharonian+2022)*, Cygnus OB2 *(LHAASO+2024)*, etc.;
  c) Anomalous $^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$ ratio in CRs *(Gupta+2020)*.

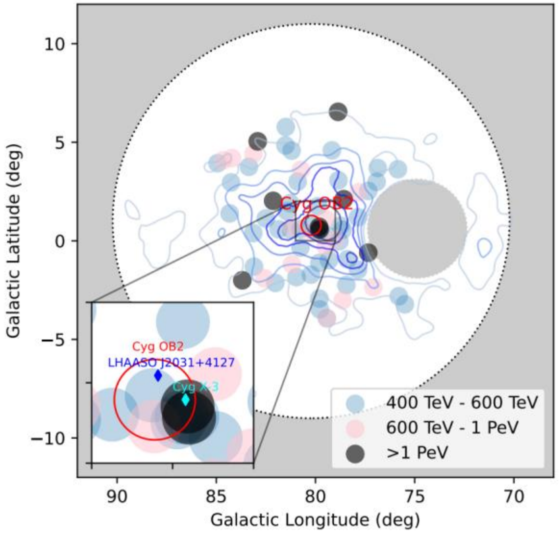
leptonic or hadronic?

Aharonian+2022



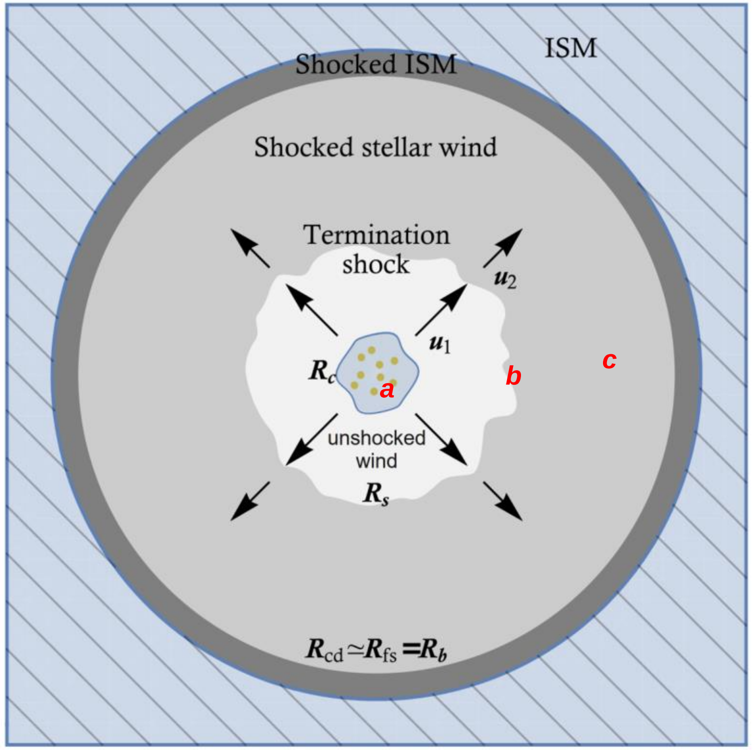
Westerlund 1

LHAASO+2024



Cygnus OB2

Morlino+2021



Superbubble structure

- Possible acceleration mechanisms in SCs:
  a) Acceleration by multiple stellar wind TSs *(Klepach+2000)*;
  b) Shock acceleration at the cluster wind TS *(Morlino+2021);*

$$\text{For } R_s \ll R_b, \quad \frac{u_2 R_s}{D_2(E)} = 1 \quad \Rightarrow \quad E_{max}$$

  c) Stochastic acceleration by scattering with the turbulence in the Superbubble *(Bykov+2020).*

2. Modeling the gamma-ray emission from the Cygnus Bubble

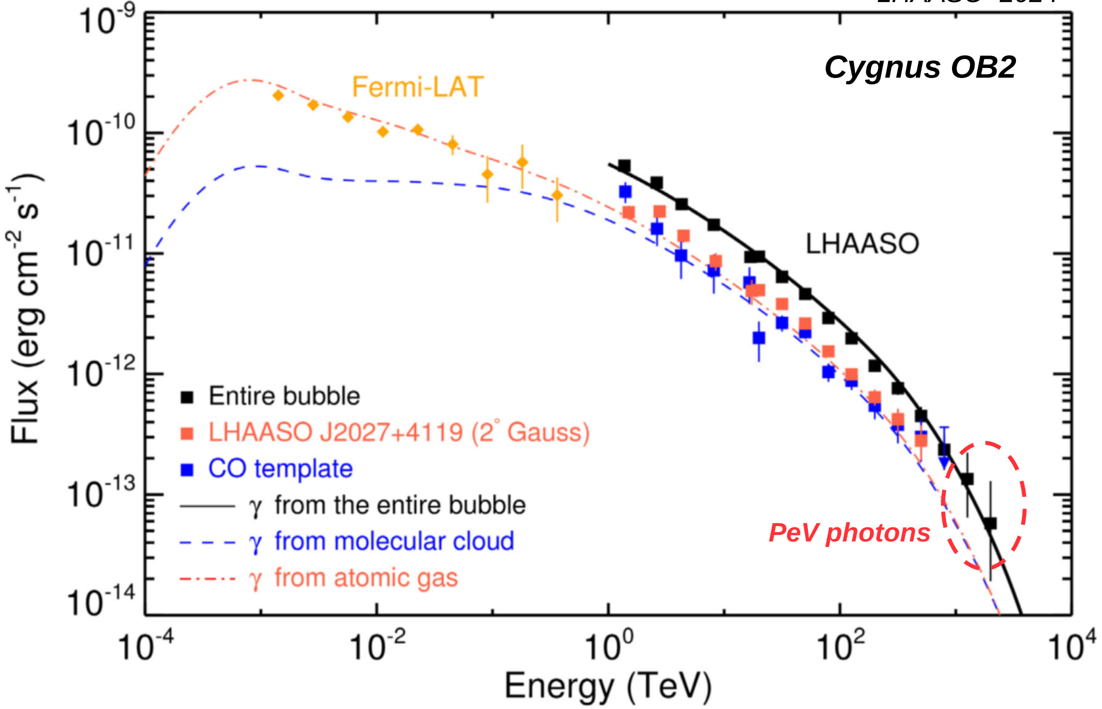
PeV γ-ray photons from the Cygnus bubble

- Cygnus OB2
  a) 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 $\sim 2-3\times 10^{38}\ \mathrm{erg\ s^{-1}}$ *(Harer+2025)*.

Cygnus OB2

Image credit: NASA

LHAASO+2024



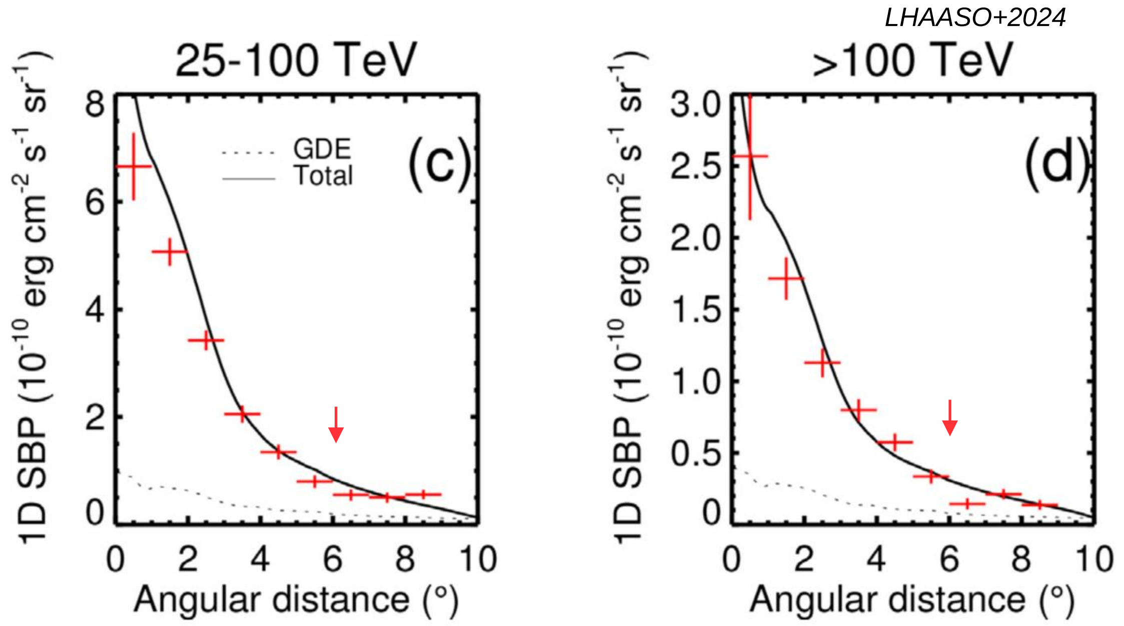
$$pp \to \pi^0 \to \gamma\gamma$$

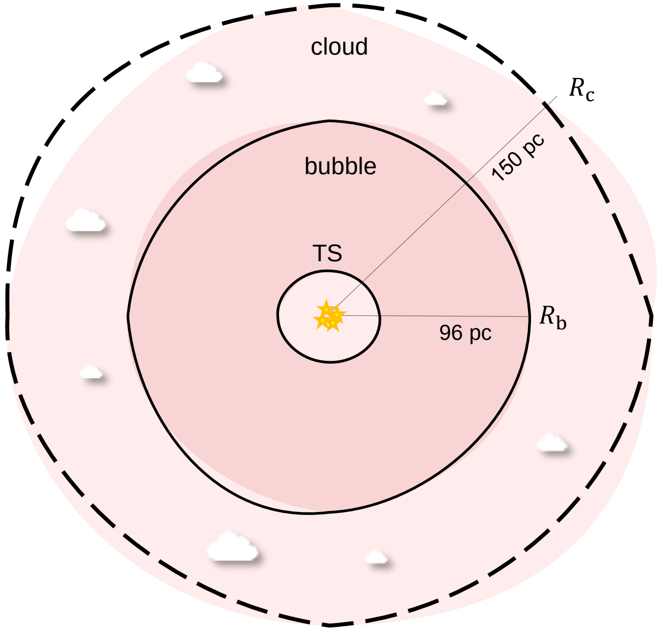
Energy of parent CRs exceeds 10 PeV!

Implication of the γ-ray morphologies

- LHAASO observations: emission extending to at least 6°, corresponding to ~ 150 pc at a distance of 1.4 kpc;
- Dynamical evolution of bubble: $R_b \sim 96$ pc.

The Cygnus bubble is surrounded by a molecular cloud with $R_c \sim 150$ pc, in which Cygnus OB2 was born.





bubble-cloud structure

Particle transport equation

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

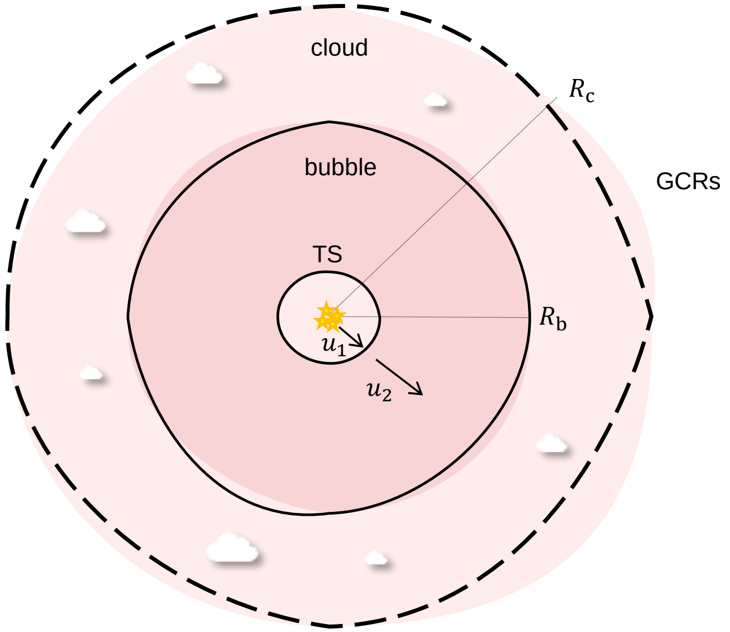
- $D_{rr}(r,p)$: diffusion coefficient, $D_{rr} \simeq \frac{1}{3} v r_{\rm L} \frac{1}{k_{\rm res} W(k_{\rm res})}$ $\quad \frac{B_0^2}{4\pi} = \eta_B \rho u^2$

  Diffusion coefficient downstream the TS:

  $$D_2(r,E) = \begin{cases} D_{\rm b}(r,E), & R_{\rm s} < r \le R_{\rm b} \\ D_{\rm c}(E), & R_{\rm b} < r \le R_{\rm c} \end{cases}$$

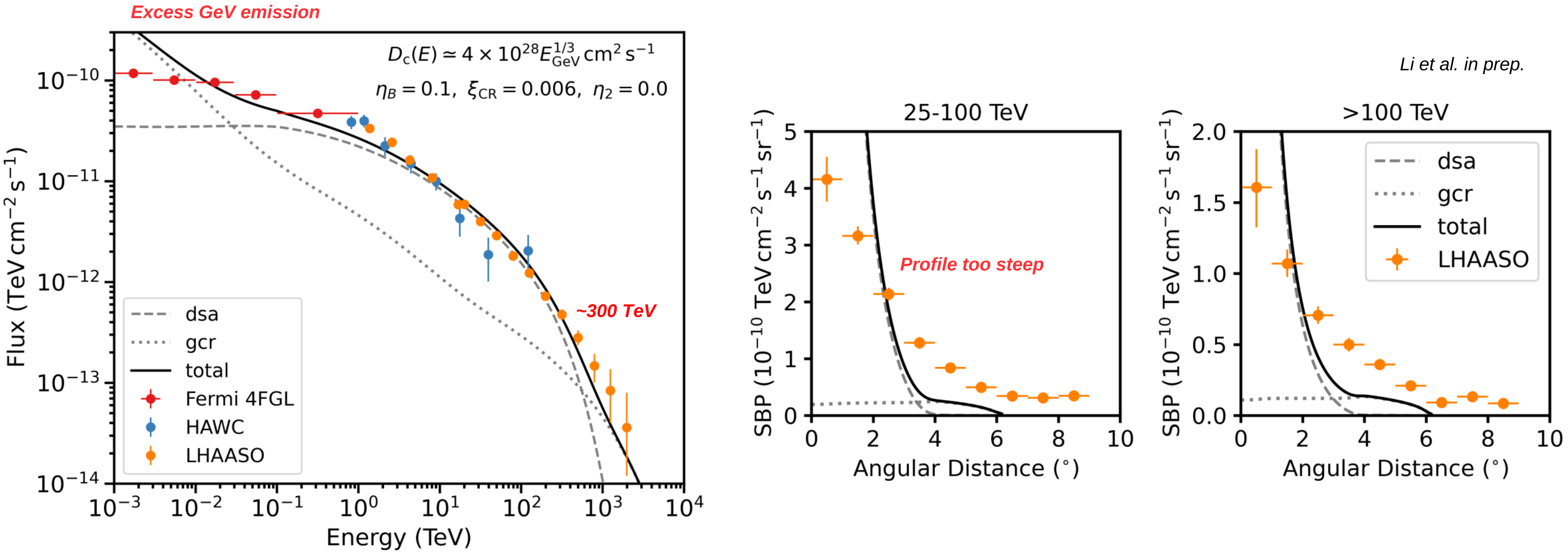
  $D_{\rm b}(r,E)$: Bohm diffusion coefficient

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



bubble-cloud structure

Contribution of GCRs to the γ-ray emission



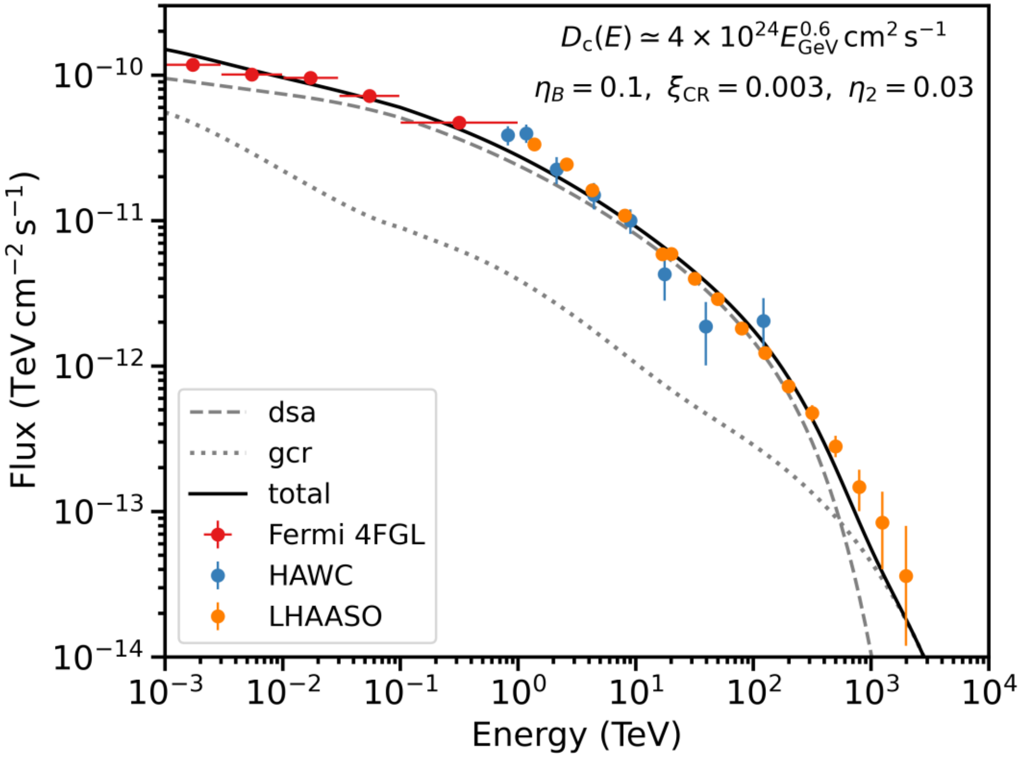
- GCRs contribute a significant fraction of γ-ray flux above ~300 TeV; However, predicted flux overshoots the data below ~10 GeV.
- The predicted morphologies are too steep, indicating that γ-ray photons should spread in a larger region.

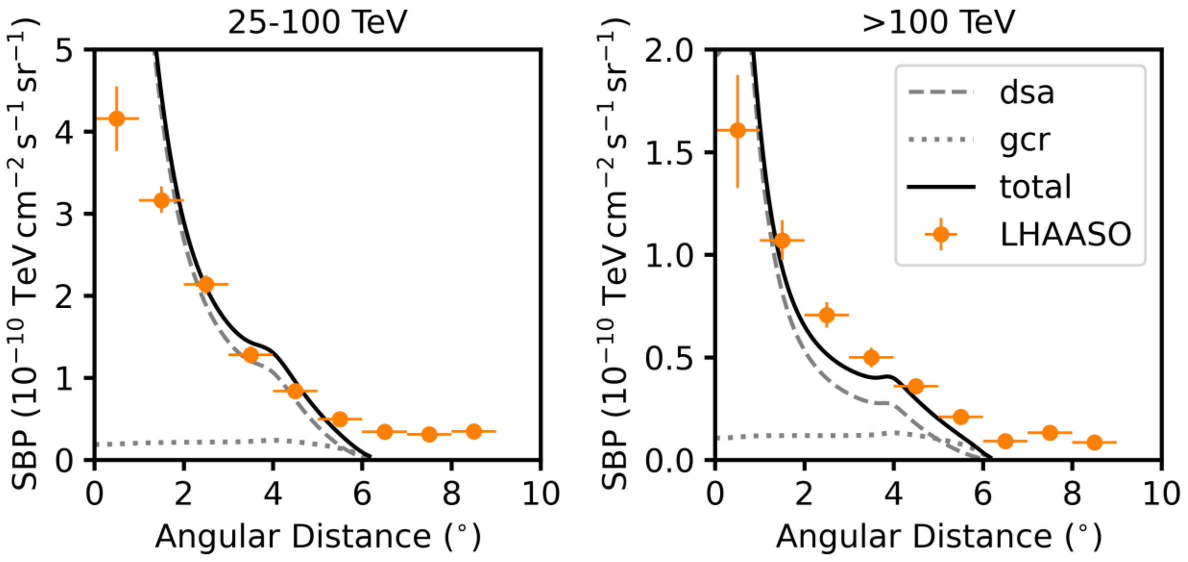
Effect of slow diffusion in the cloud

A slow diffusion in the cloud can:

a) Suppress the penetration of low-energy GCRs into the cloud;

b) Inhibit the escape of shock-accelerated particles from the cloud.





3. Stochastic reacceleration of particles in the Superbubble

Stochastic acceleration

- Particle transport equation

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

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

- Wave evolution (for Kolmogorov cascading)

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

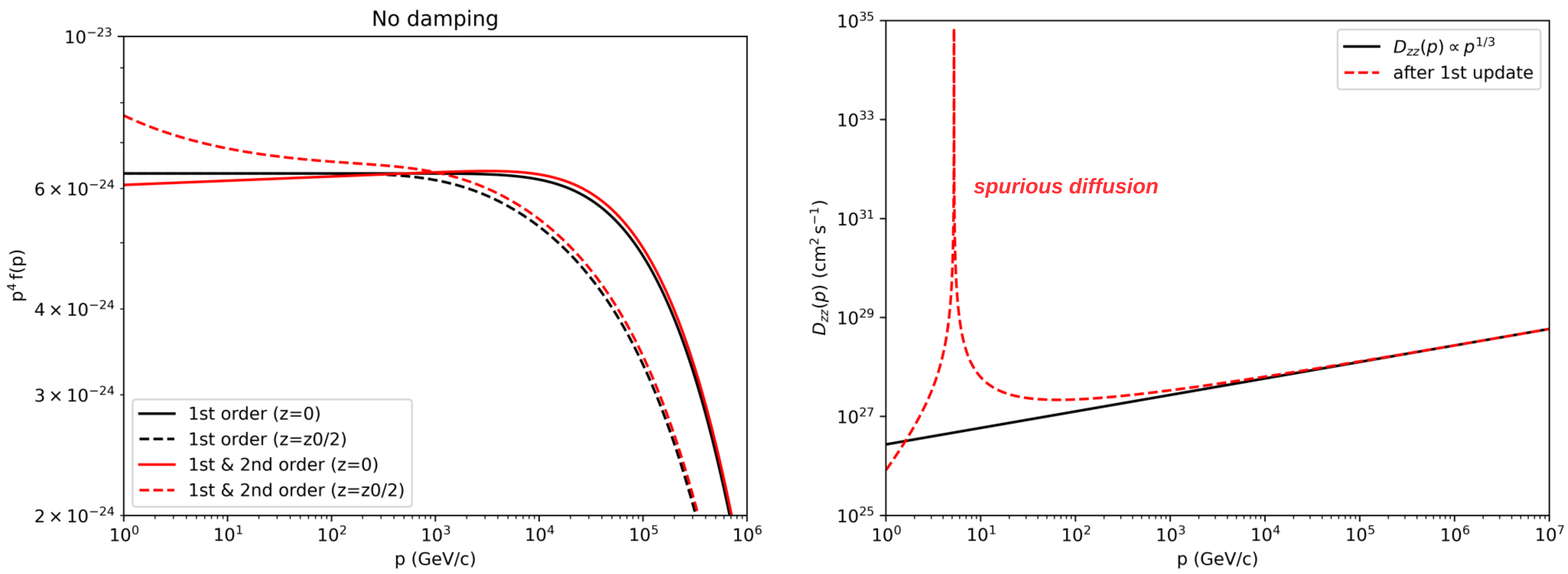
$$\frac{\partial W}{\partial t}+\boxed{\frac{\partial}{\partial k}\left[\frac{a}{\sqrt{\rho}}k^{5/2}W^{3/2}\right]}=\boxed{-\Gamma(k)W}+S\,\delta(k-k_0)$$

1. Cascading term

Nonlinear equations

The case of 1D planar shock

- Simplifications: 1. Steady state; 2. No damping; 3. $\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial f}{\partial p}\right] \sim \frac{f}{\tau_{\rm II}}$



- Stochastic acceleration has little effect on $p_{\rm max}$, but it affects the spectrum of low-energy particles at large distances from the shock.

Summary & future work

- We studied particle acceleration at the WTS of Cygnus OB2 and their propagation in the Cygnus bubble by numerically solving the transport equations, and found that:
  a) Nonuniform Bohm diffusion in the bubble and slow diffusion in the cloud are both necessary to explain the observed gamma-ray spectrum and spatial morphologies;
  b) GCRs play a significant role in producing gamma-ray emission above ∼300 TeV.

- We also studied stochastic reacceleration of particles in the downstream of the WTS. For the simplified case of 1D planar shock, we found that stochastic acceleration has huge influence on the spectrum of low-energy particles at large distance from the shock.

- IC emission from the electrons accelerated at the shock;

- Numerical simulations of the plasma and the turbulence in the environment of star cluster can help us have a better understanding of the microphysics in particle acceleration and transport.

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

- Conferences & Workshops

  1. 39th International Cosmic Ray Conference (ICRC 2025), Geneva, July 2025 — talk.
  2. Particle Acceleration and Transport: from the Sun to Extragalactic Sources, Rende, February 2025 — attendance.
  3. TAL Retreat, Florence, October 2025 — talk.

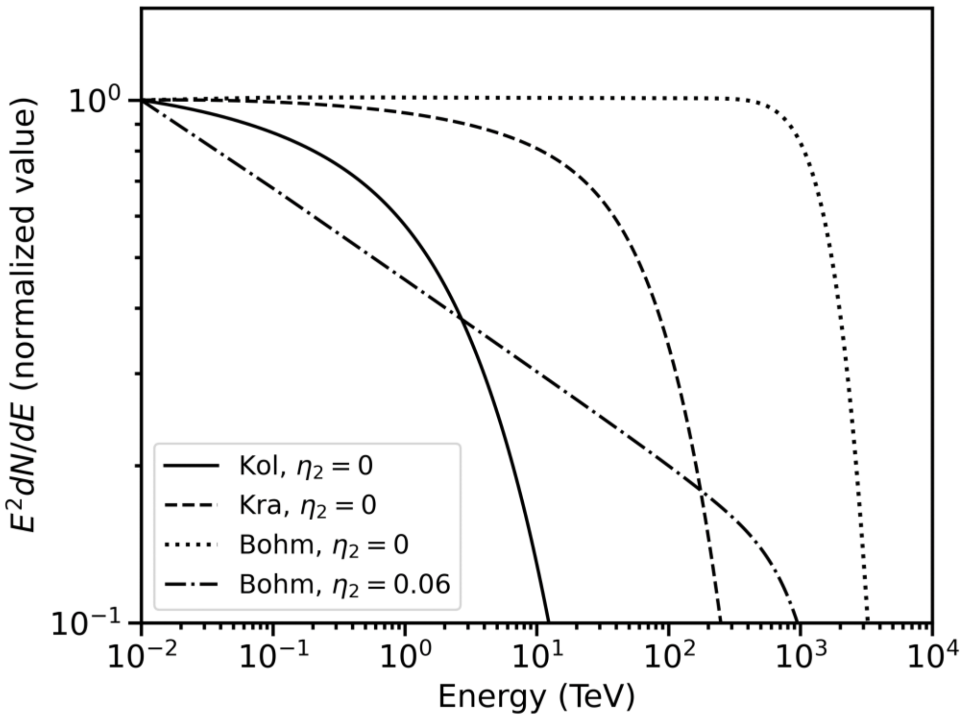
- Schools

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

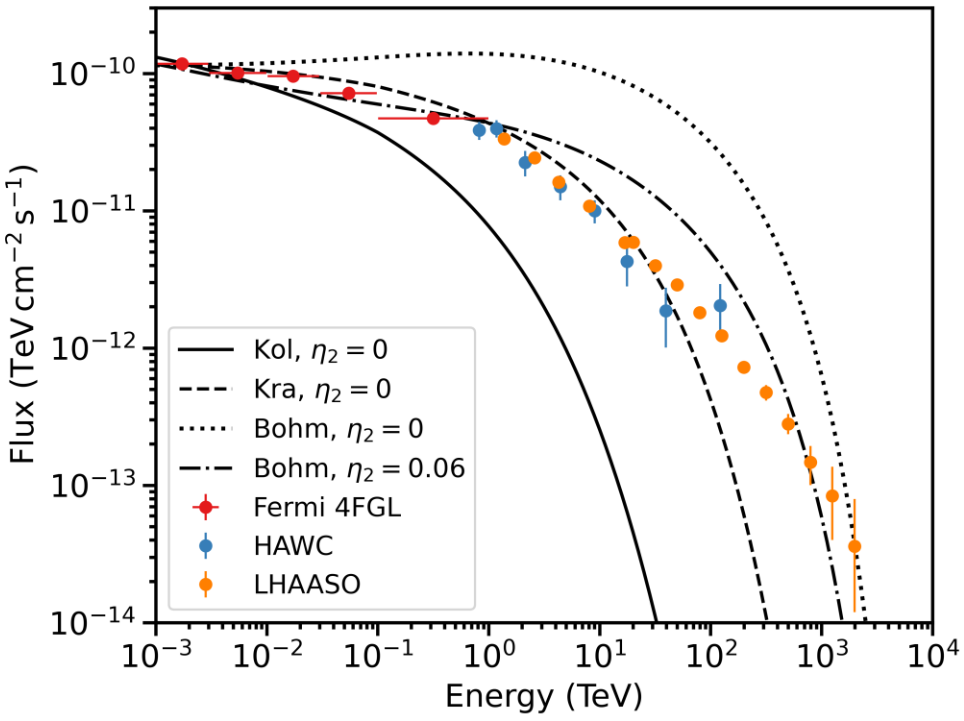
Backup

Maximum particle energy (uniform diffusion)

Li et al. in prep.

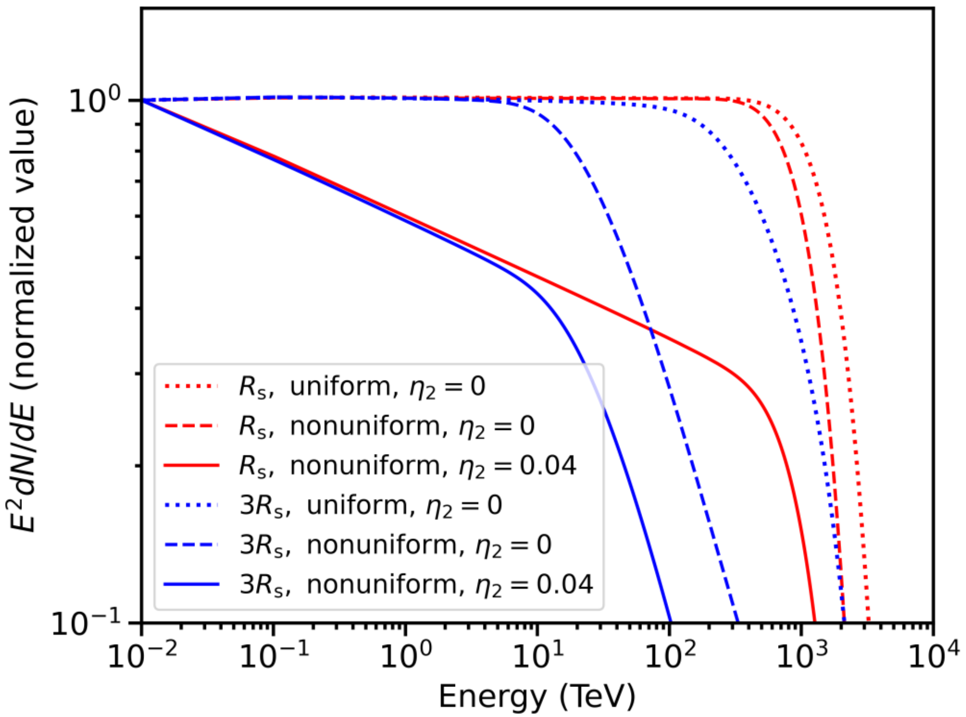


Particle spectrum at TS

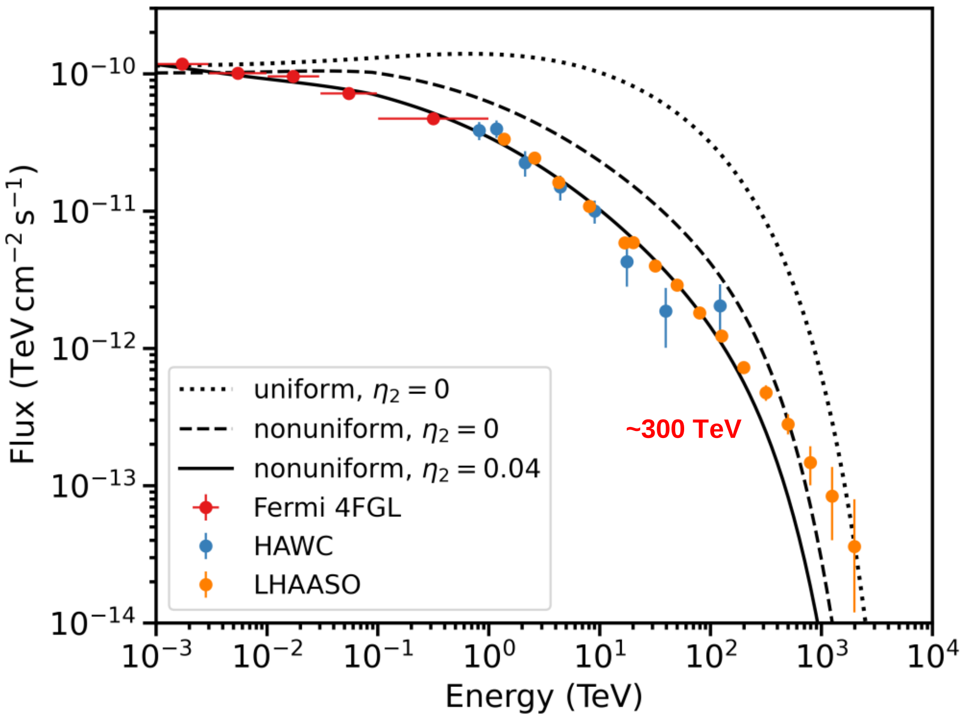


Predicted γ-ray spectrum

Effect of nonuniform diffusion

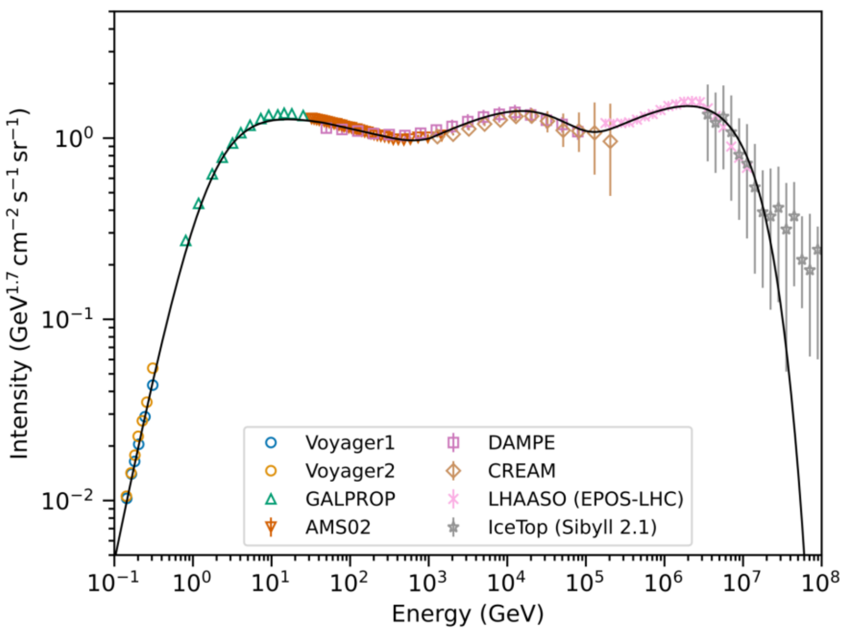


Particle spectra at R_s and $3R_s$

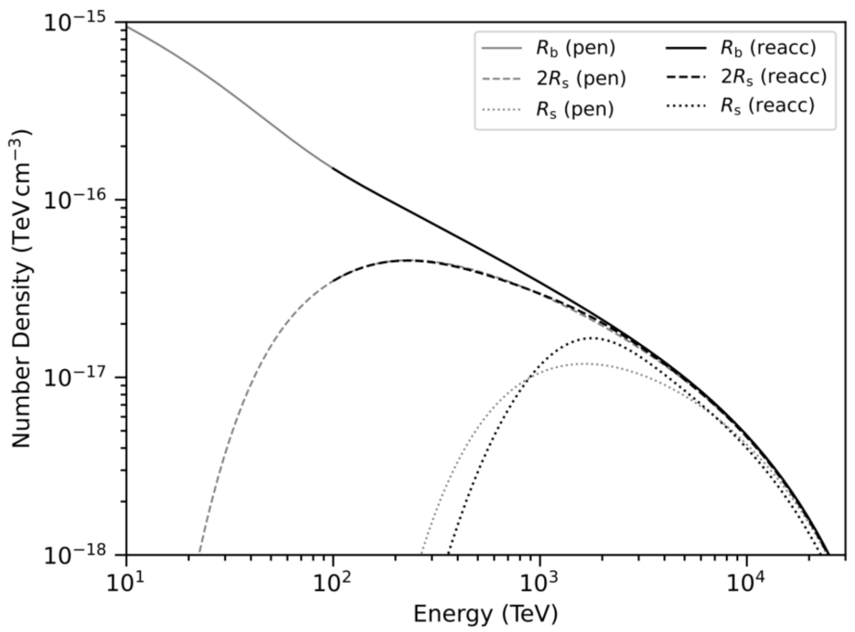


Predicted γ-ray spectrum

Penetration and re-acceleration of GCRs



Locally measured spectrum of GCR proton

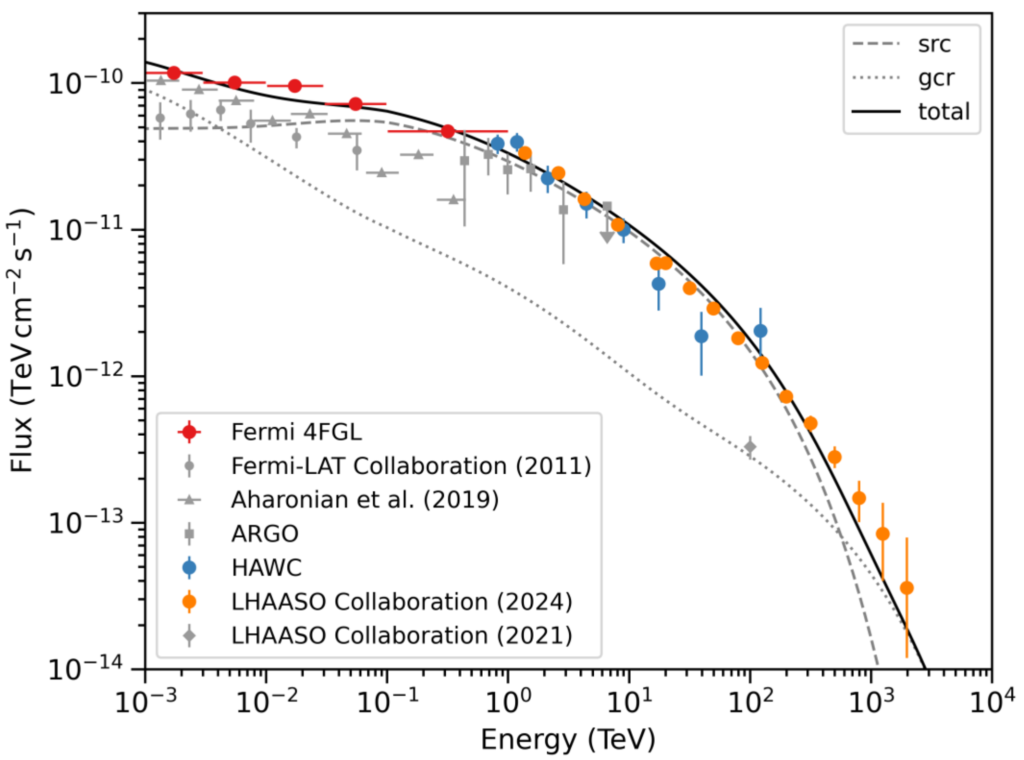


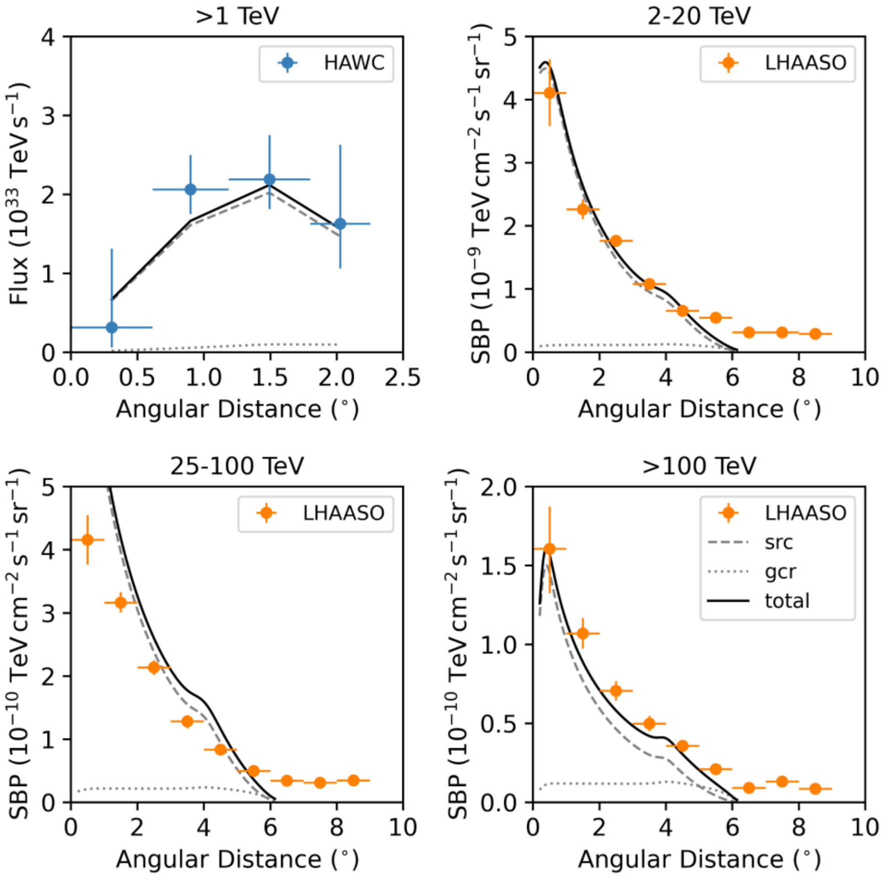
Spectra of penetrated and re-accelerated GCRs

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

Point source with constant injection in the center of the star cluster

Li et al. in prep.





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

$$Q \sim E^{-2} \exp(-\frac{E}{1\ \mathrm{PeV}})$$

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

- For a central continuous injection source, it provides good fits to both the SED and morphologies, with reasonable model parameters.