THE GALACTIC-EXTRAGALACTIC TRANSITION

PROPAGATION OF COSMIC RAYS IN GALACTIC TURBULENT MAGNETIC FIELDS AND MULTI-MESSENGER OBSERVATIONS

GRAN SASSO SCIENCE INSTITUTE

INFN

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Passage of the Year 2025

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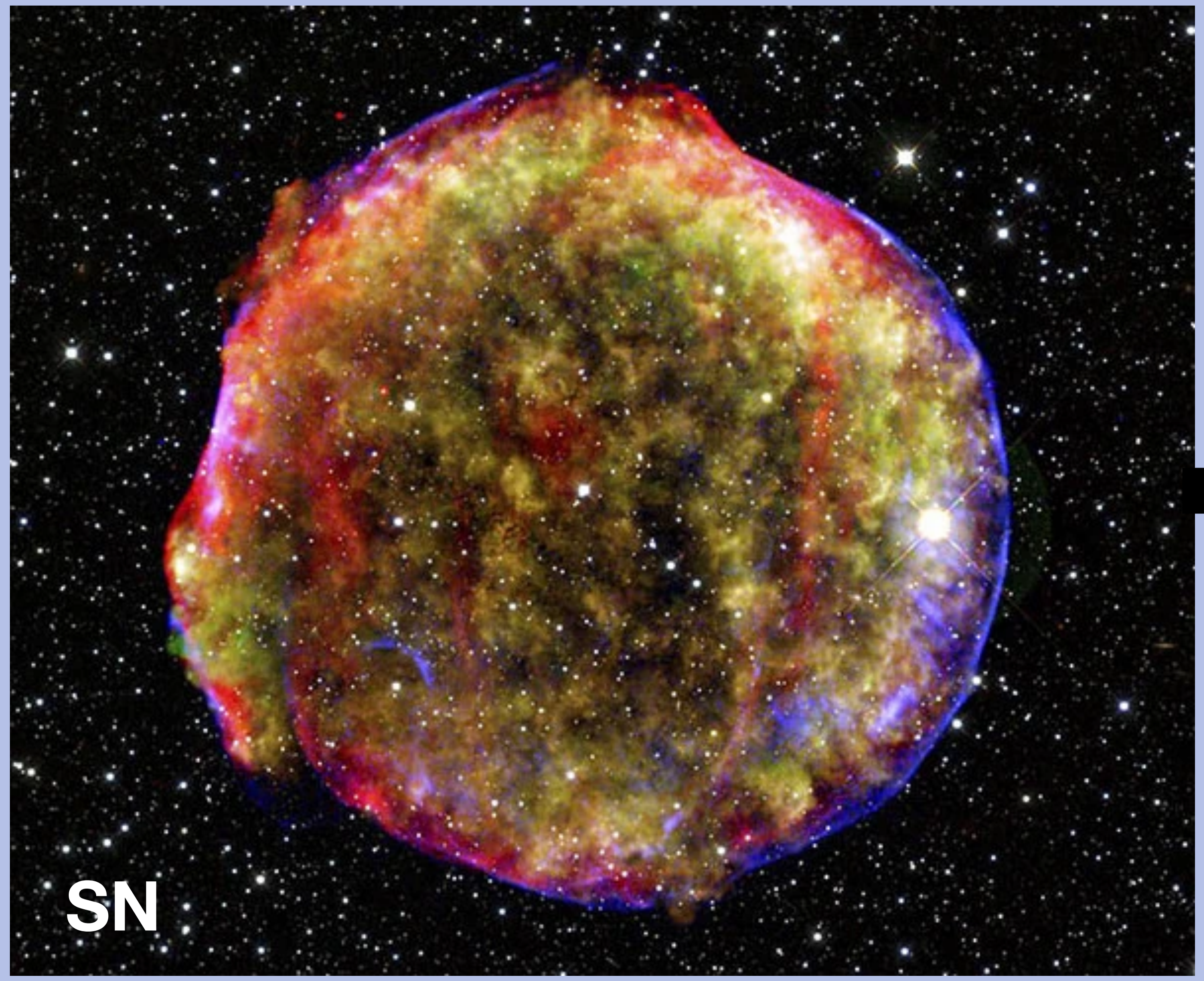
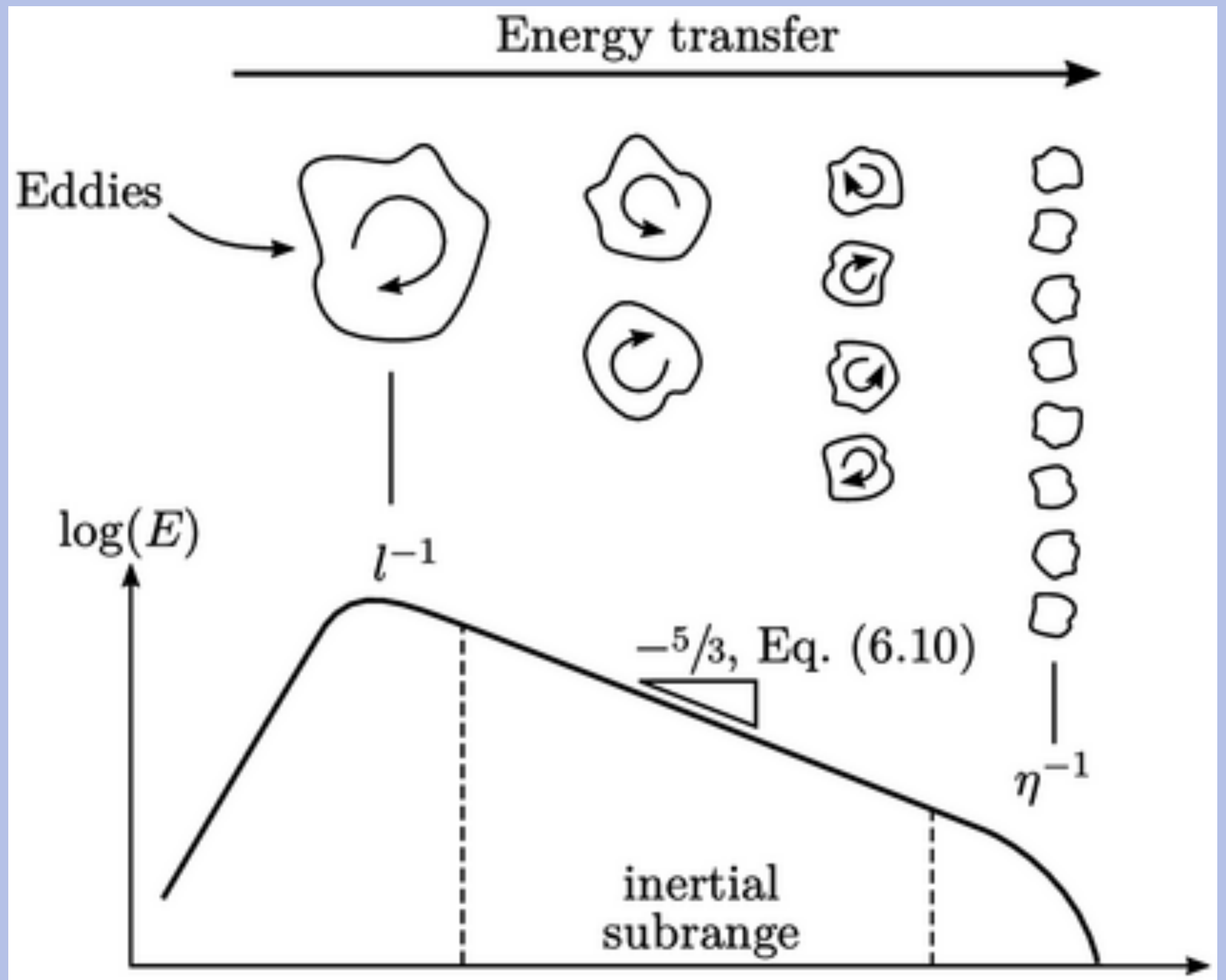
Simple paradigm of Galactic cosmic ray propagation



Turbulence cascade

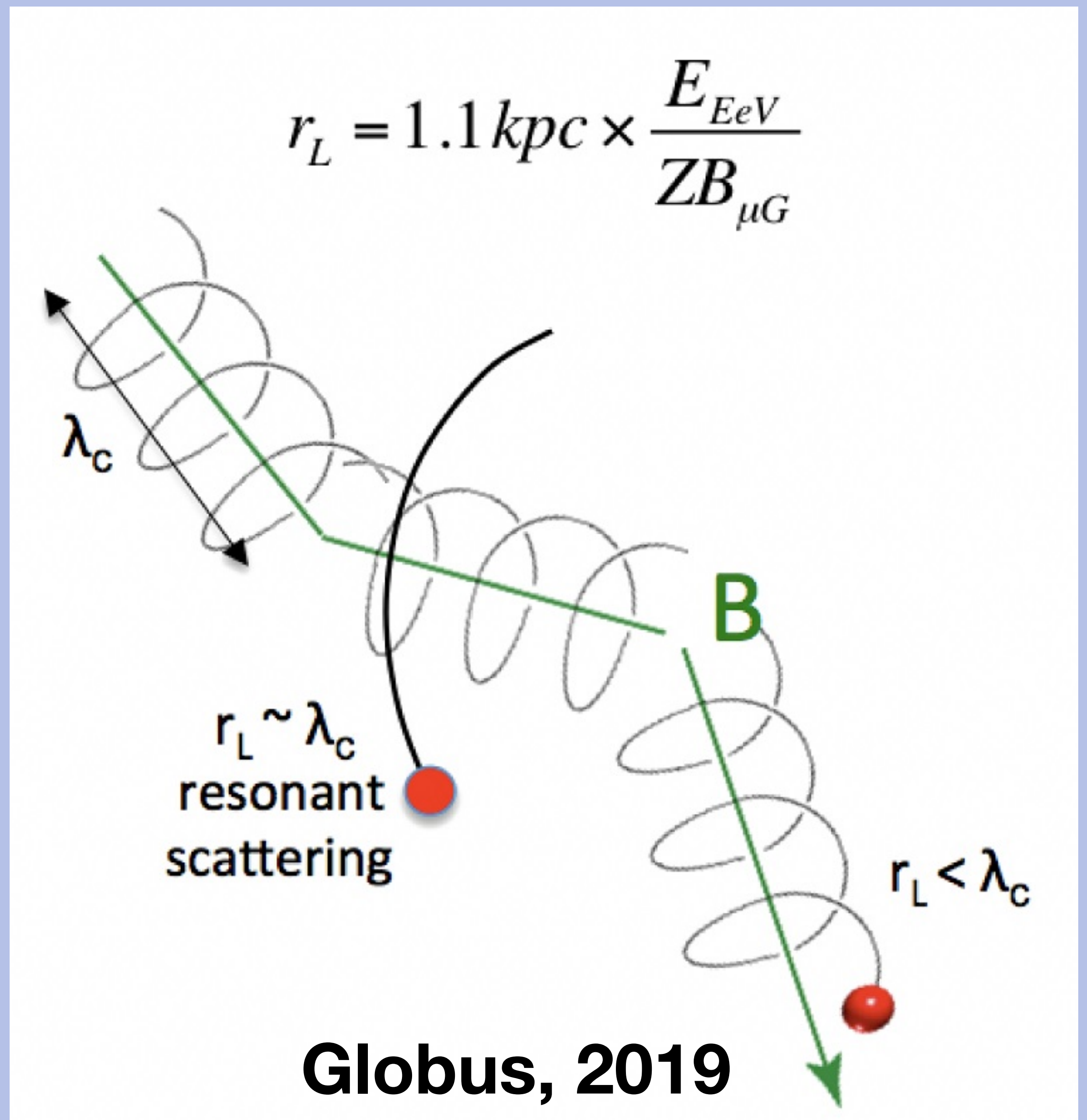


Globus, 2019

Kolmogorov spectrum $\propto k^{-5/3}$

Kraichnan spectrum $\propto k^{-3/2}$

Resonant scattering with Alfvèn waves ($k_{||}^{-1} \sim r_L$)



Globus, 2019

Simple description of magnetic turbulence.

More complete description of turbulence **requires MHD numerical treatment.**

Simple paradigm of Galactic cosmic ray propagation

Diffusion tensor: $D_{ij} = (D_\parallel - D_\perp) b_i b_j + D_\perp \delta_{ij} - D_A \epsilon_{ijk} b_k$

Cosmic ray transport: $-\nabla_i D_{ij}(\mathbf{r}) \nabla_j N(\mathbf{r}) = Q(\mathbf{r})$

Cylindrical coordinate system assuming azimuthal symmetry

$$\left(-\frac{1}{r}\frac{\partial}{\partial r}\left[rD_\perp \frac{\partial}{\partial r}\right] - \frac{\partial}{\partial z}\left[D_\perp \frac{\partial}{\partial z}\right] + u_r \frac{\partial}{\partial r} + u_z \frac{\partial}{\partial z}\right) N(\mathbf{r}) = Q(\mathbf{r})$$

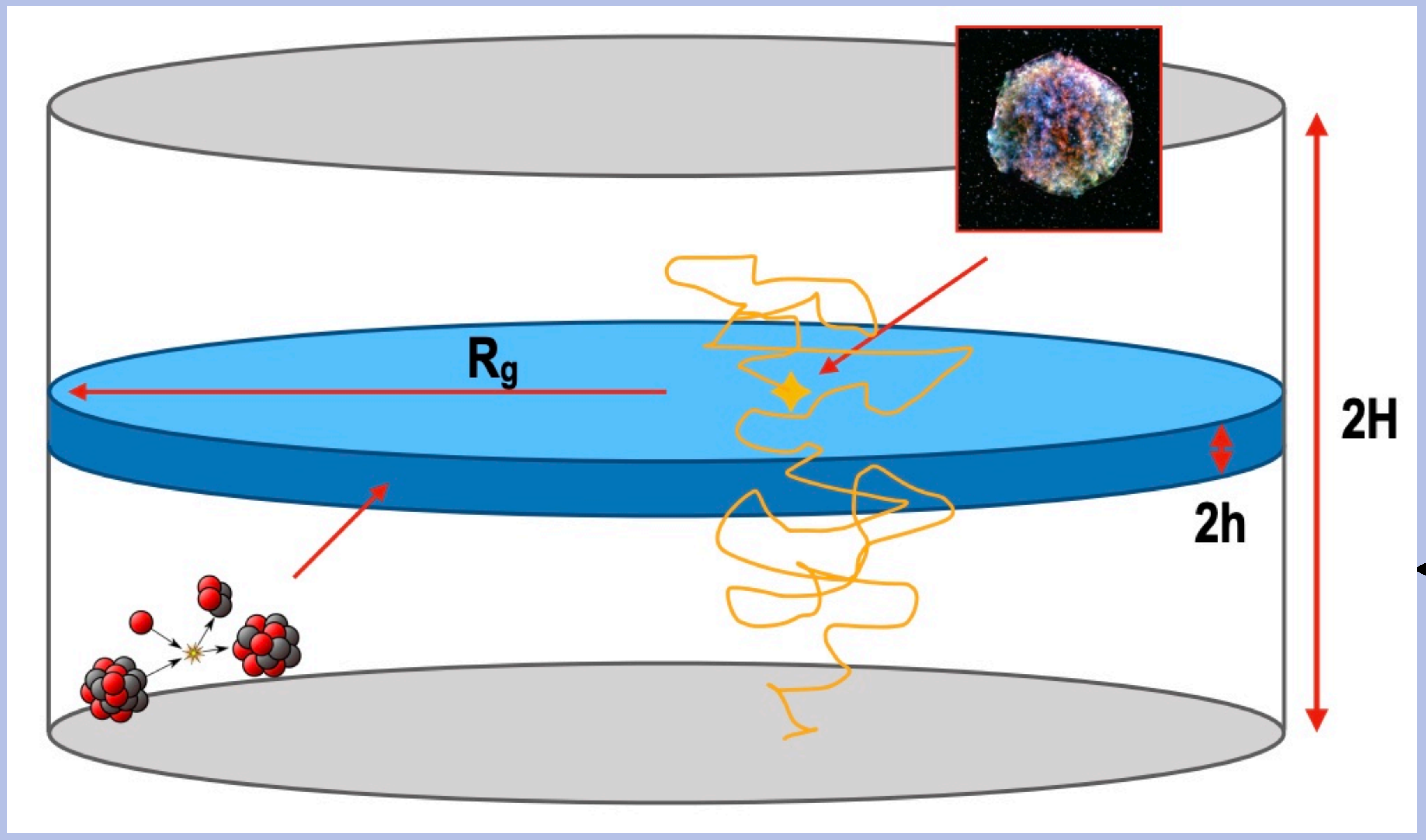
Drift velocities:

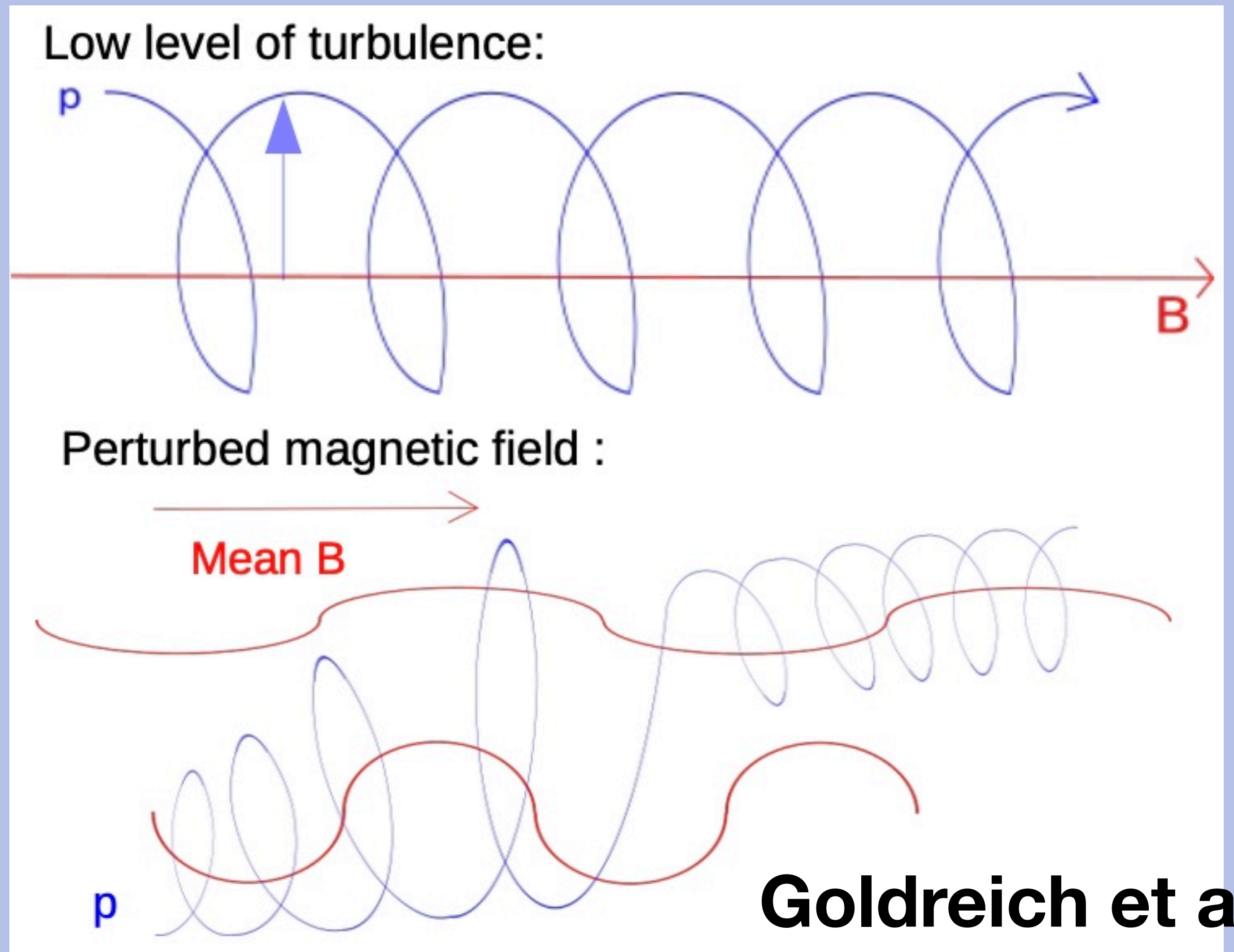
$$u_r = -\frac{\partial(D_A b_\phi)}{\partial z}$$

$$u_z = \frac{1}{r}\frac{\partial(r D_A b_\phi)}{\partial r}$$

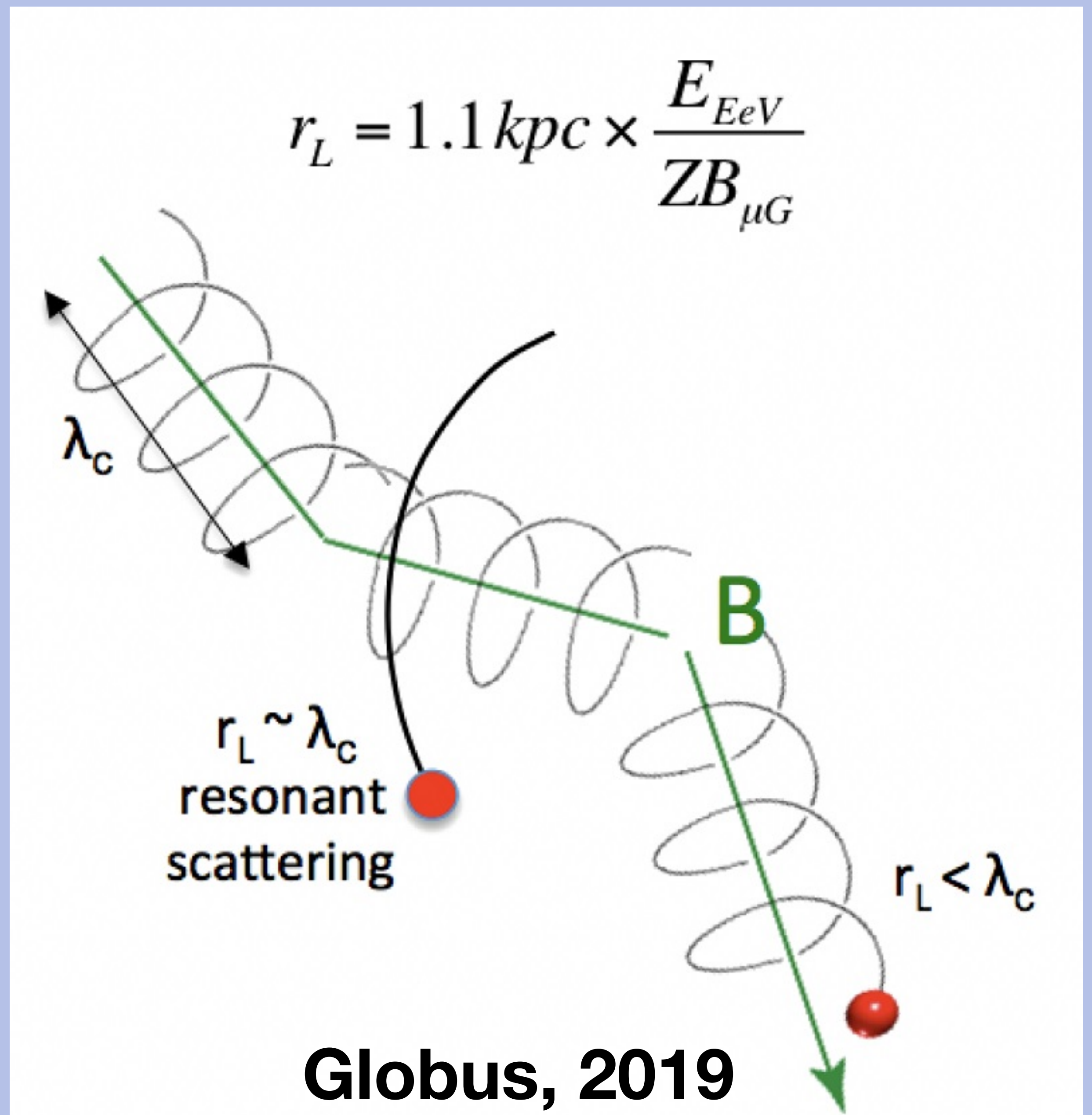
Resonant scattering with Alfvèn waves ($k_\parallel^{-1} \sim r_L$)

Evoli & Dupletsa, 2023



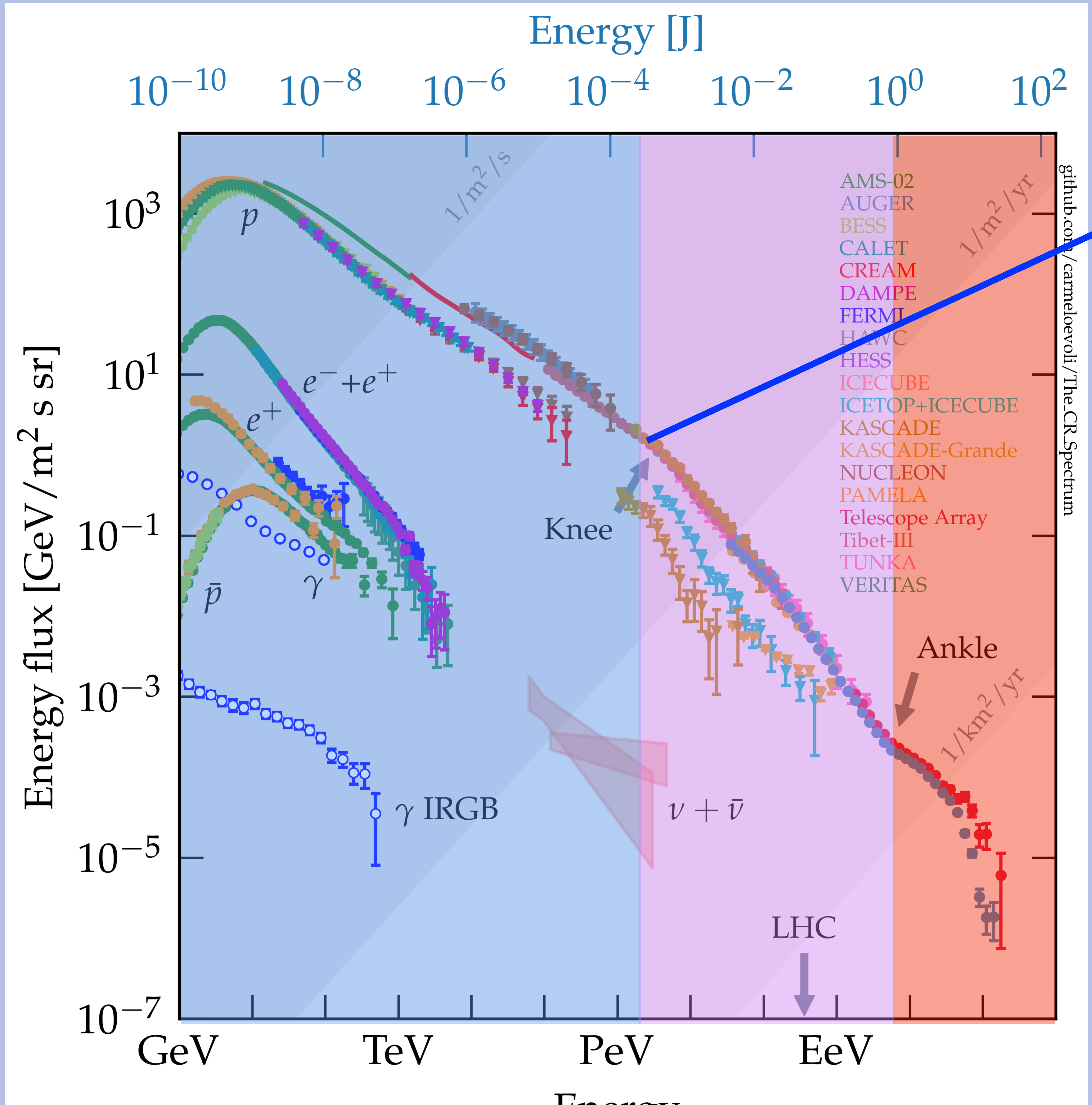


Goldreich et al., 2001



Globus, 2019

Cosmic ray galactic-extragalactic transition



Evoli, 2020

Maximum energy achieved by Galactic accelerators?

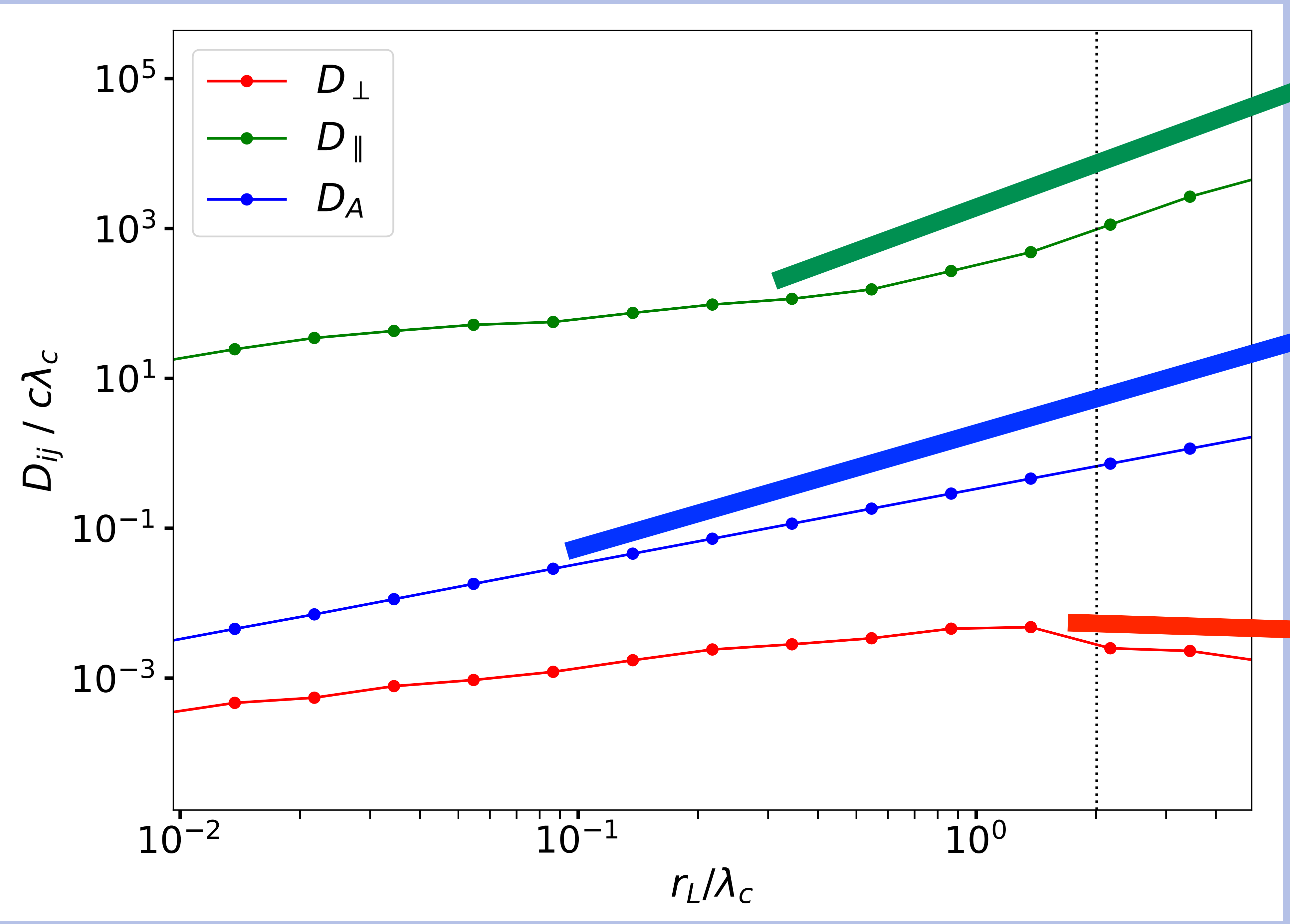
Escape of cosmic rays from the Galaxy?

Numerical simulations

CRPropa

- **Synthetic magnetic fields:** turbulent spectrum assumed to be Kolmogorov and isotropic, with random components Gaussian-distributed.

- **Test-particle simulations** of TeV-PeV particles. Diffusion coefficients measured as function of rigidity and turbulence level.



QLT coefficient

$$D_\parallel \propto r_L^{1/3}$$

Bohm-like coefficient

$$D_A \propto r_L$$

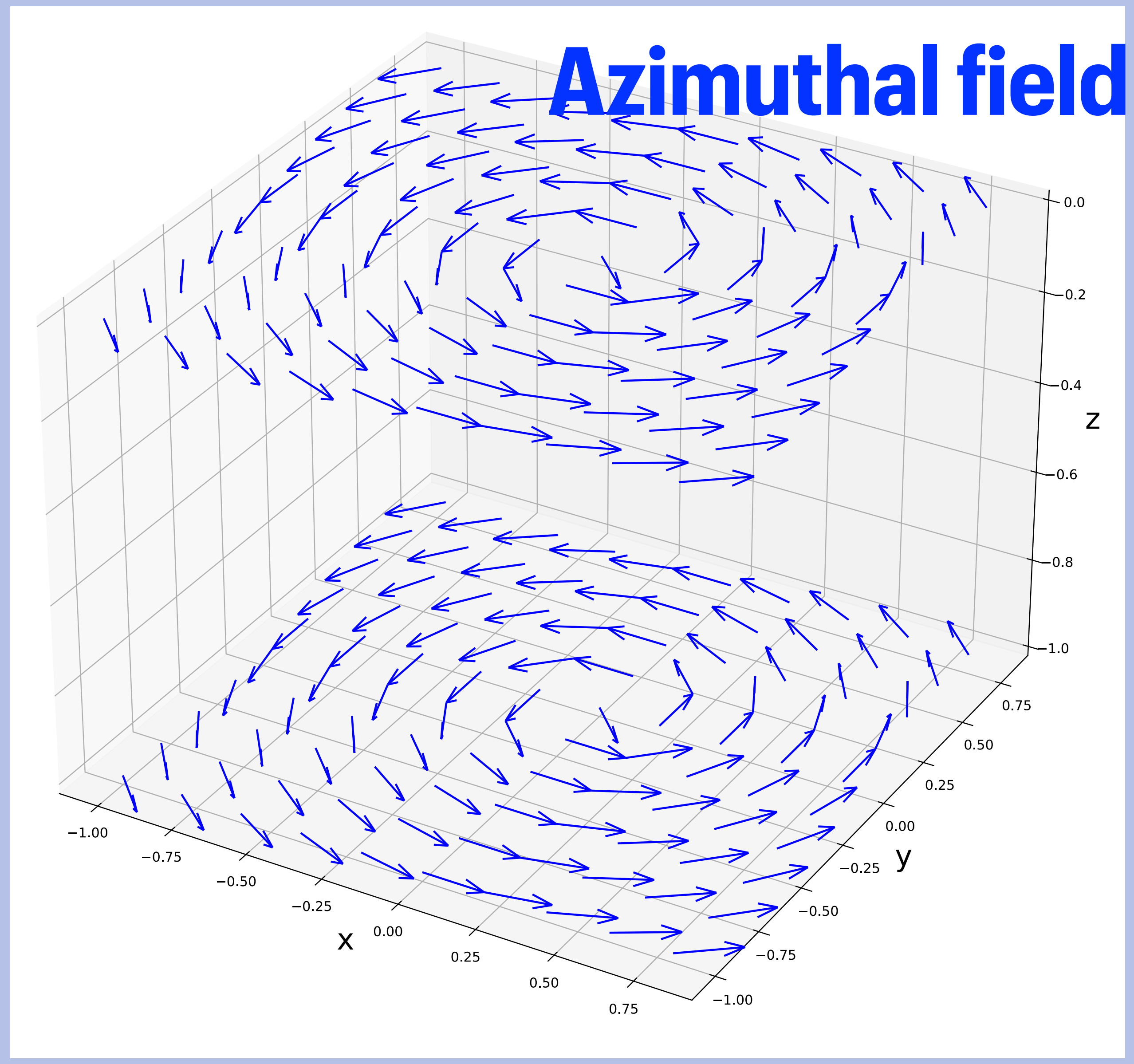
$$v_D \sim \frac{r_L c}{3L}$$

Corroboration of anomalous perpendicular behaviour

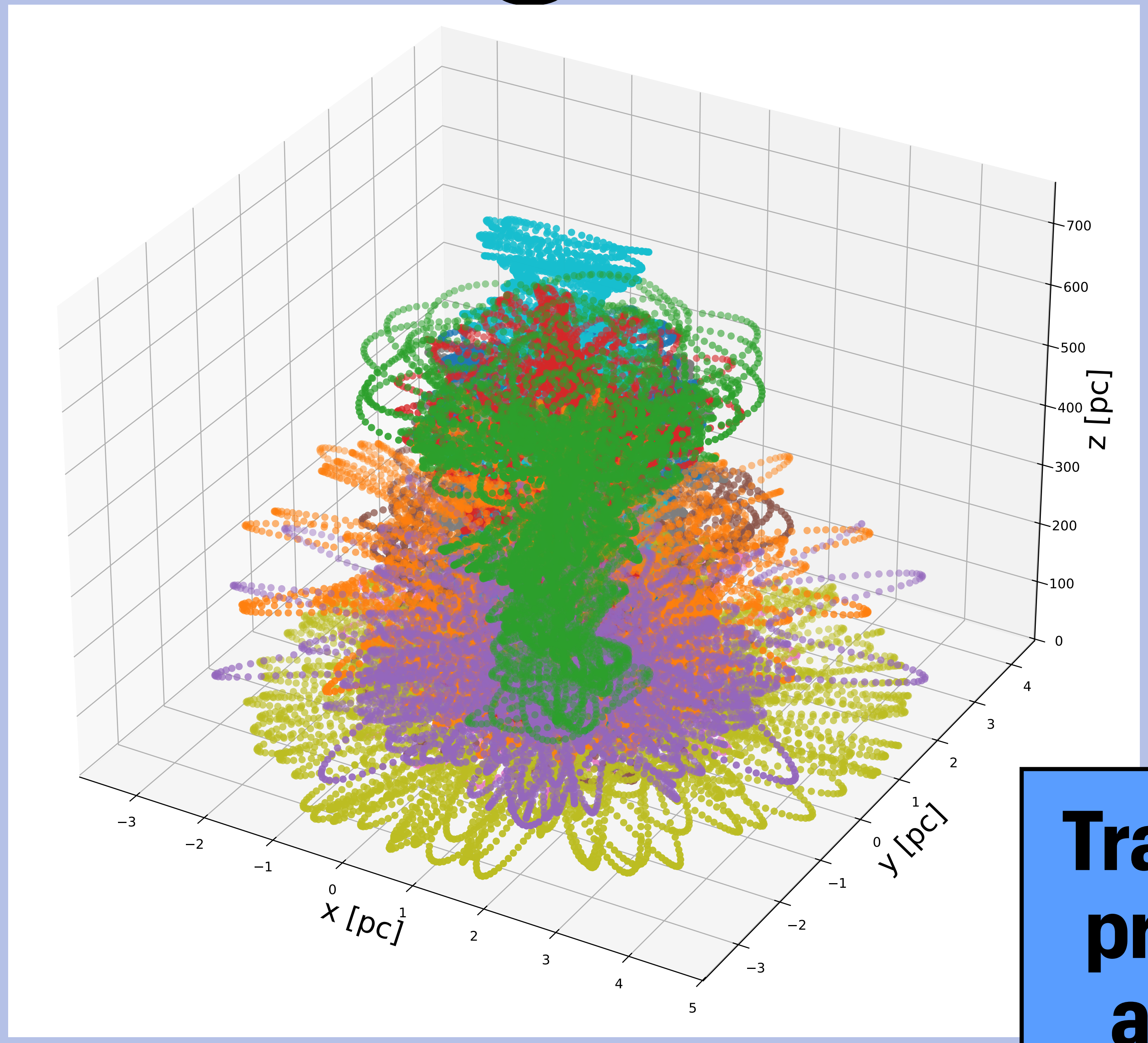
$$D_\perp \propto r_L^{1/2}$$

Cosmic ray escape time in Galactic magnetic fields

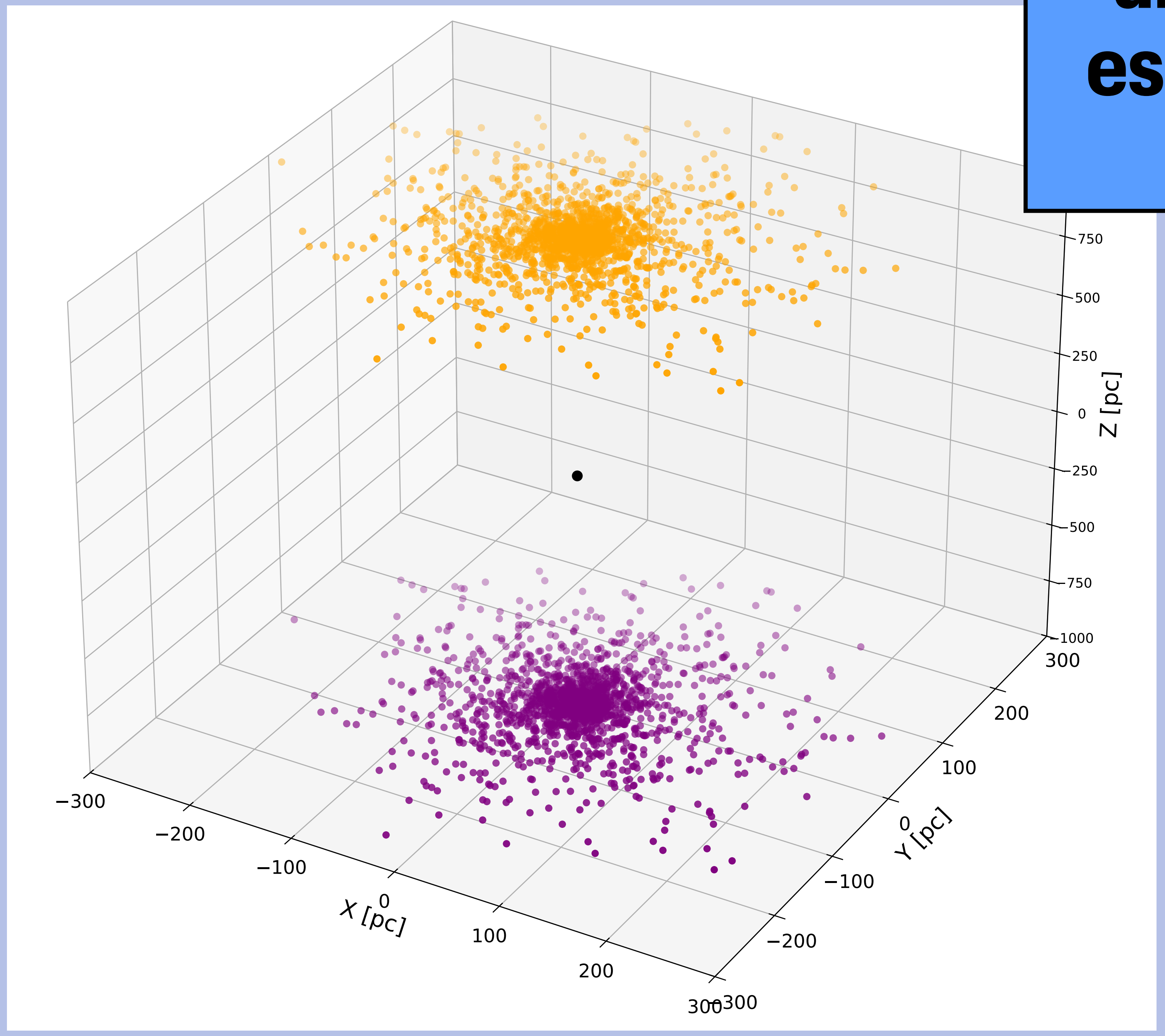
Galaxy-like magnetic field + turbulence



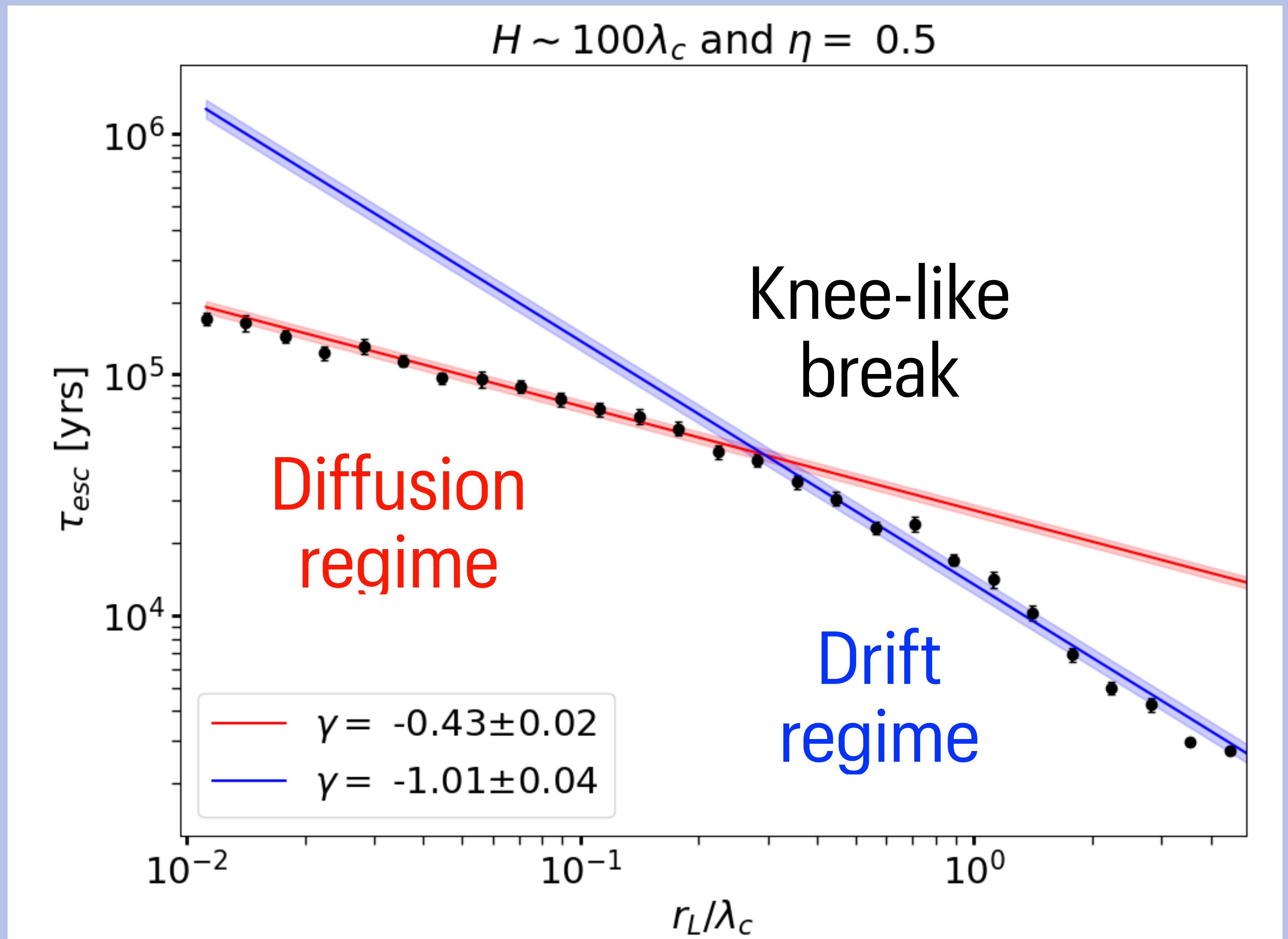
Particle injection



Track particle propagation and record escape from halo

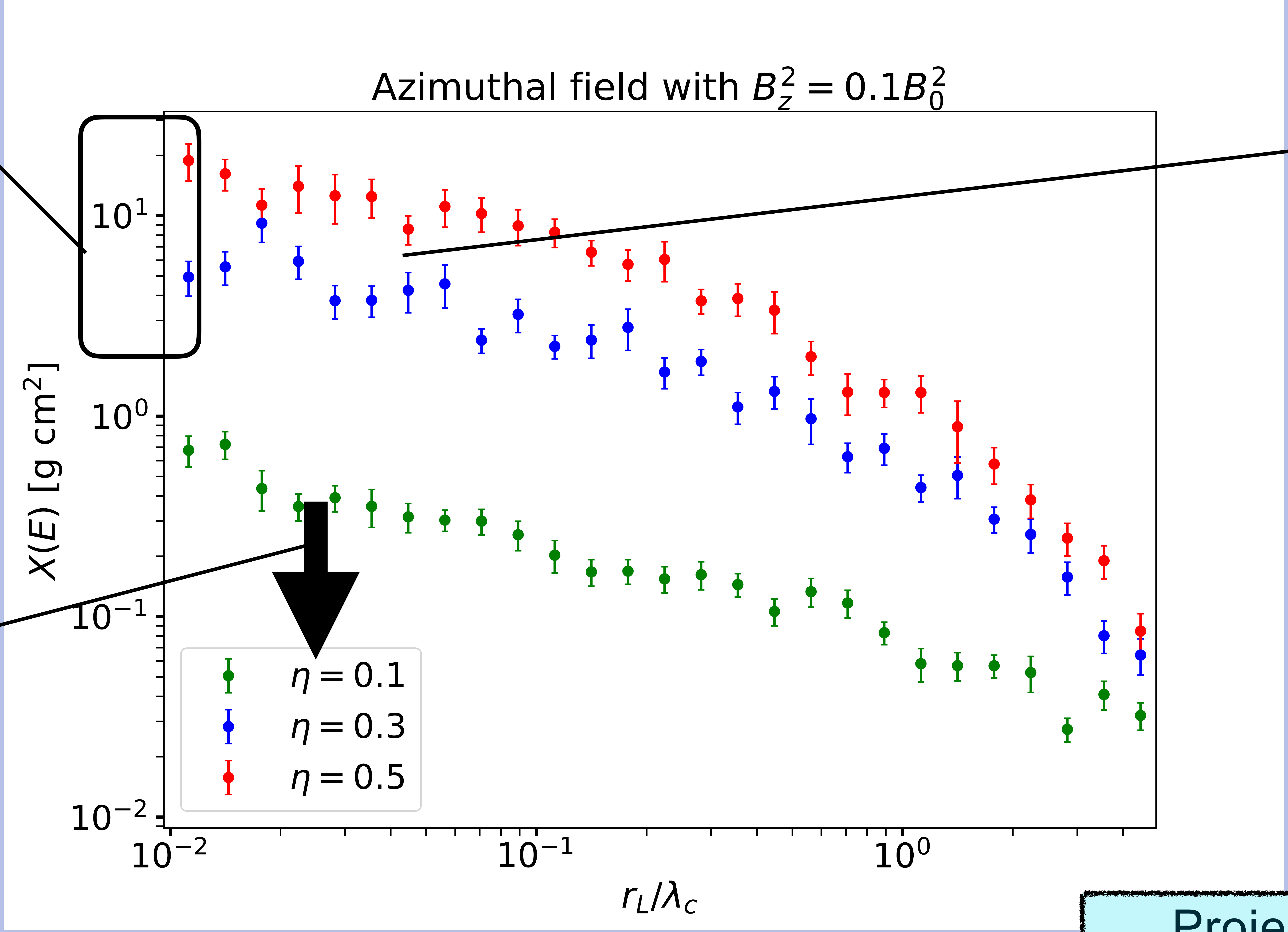


Compute escape times and grammage



Cosmic ray grammage in Galactic magnetic fields

Grammage higher than estimates from B/C measurements



Parallel diffusion dominates and makes escape faster

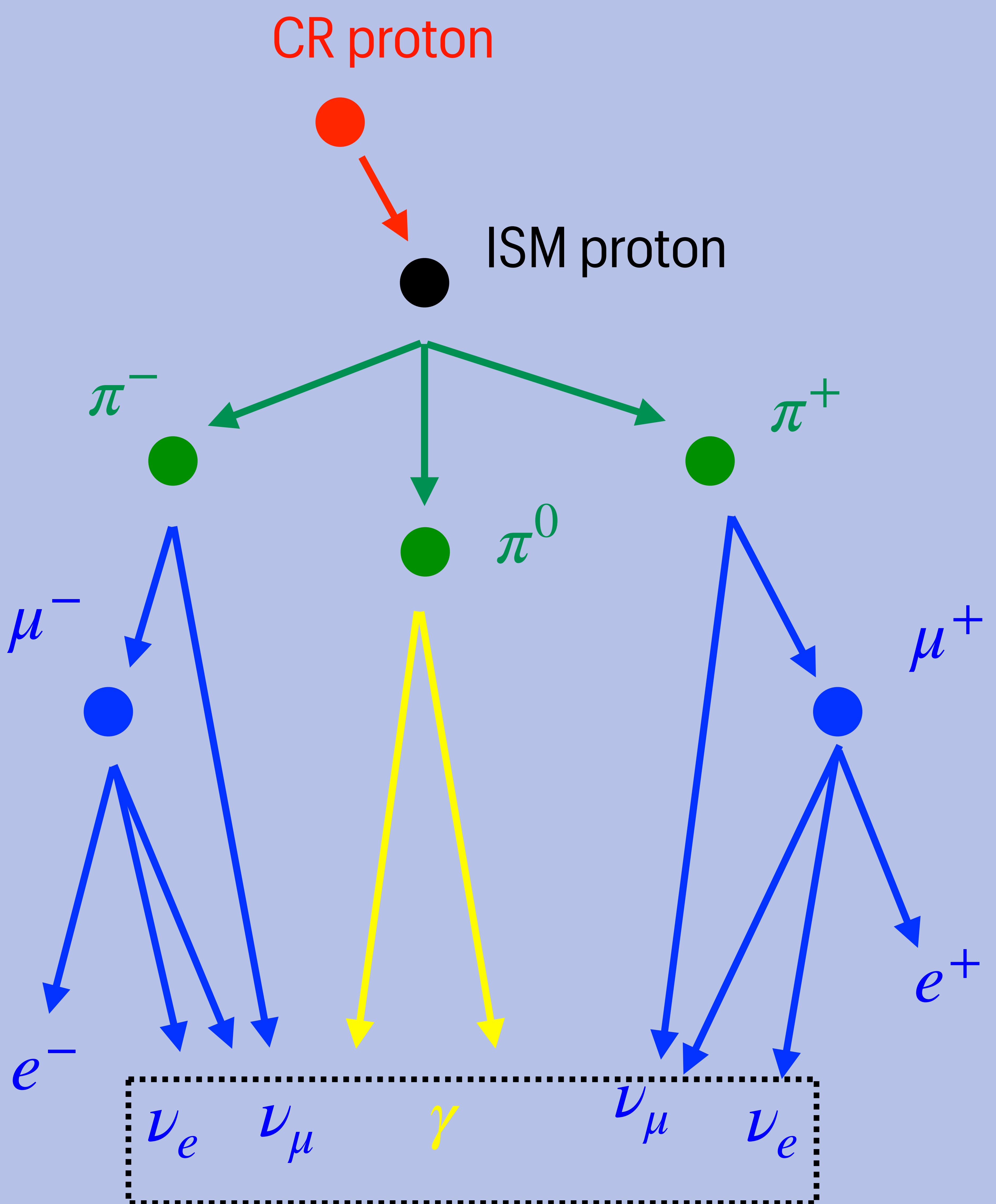
Lowering turbulence could further decrease grammage

Diffusion-drift interplay and enhancement

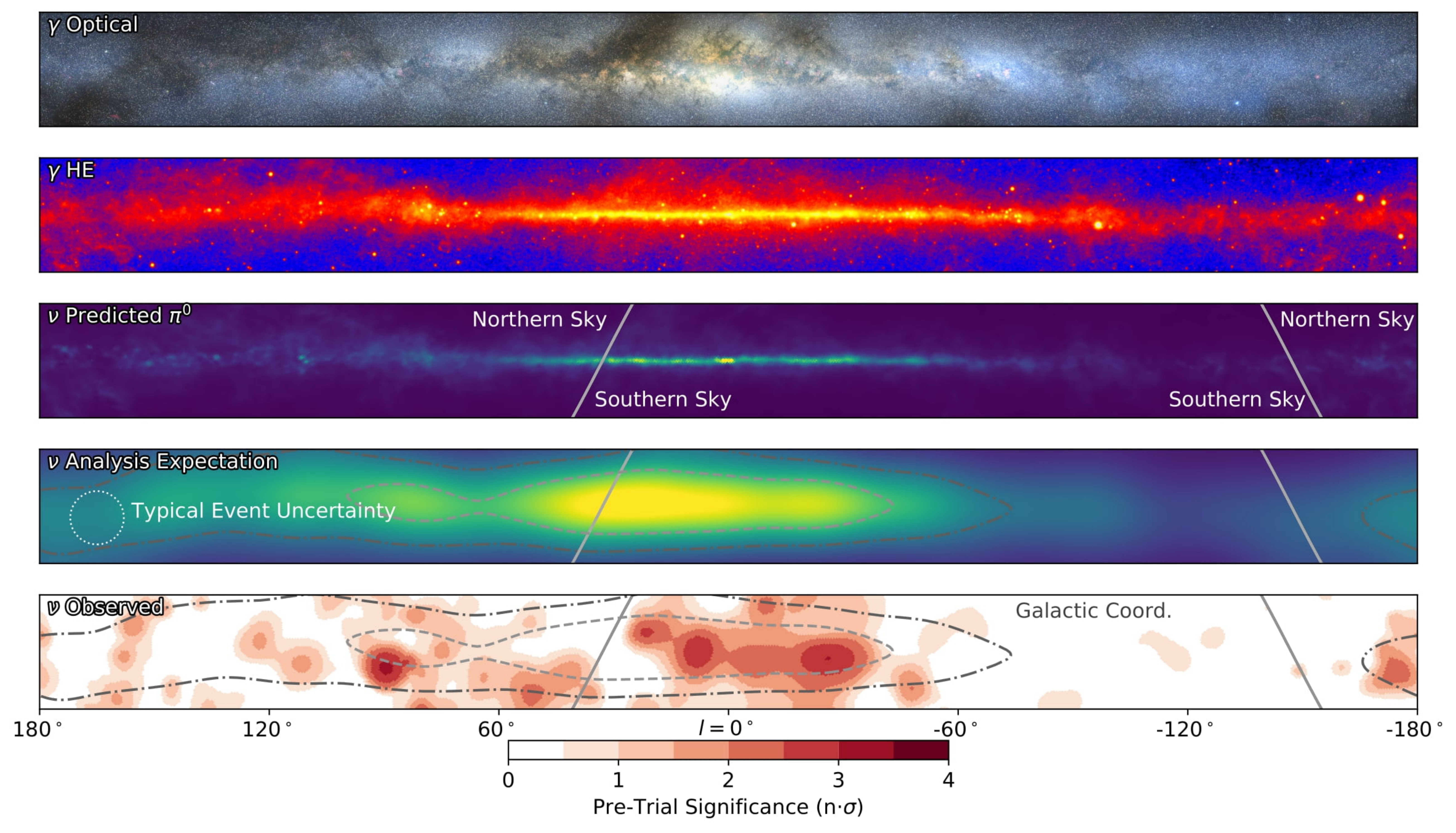
Project being finalised

Future: consider cosmic ray propagation in MHD turbulence

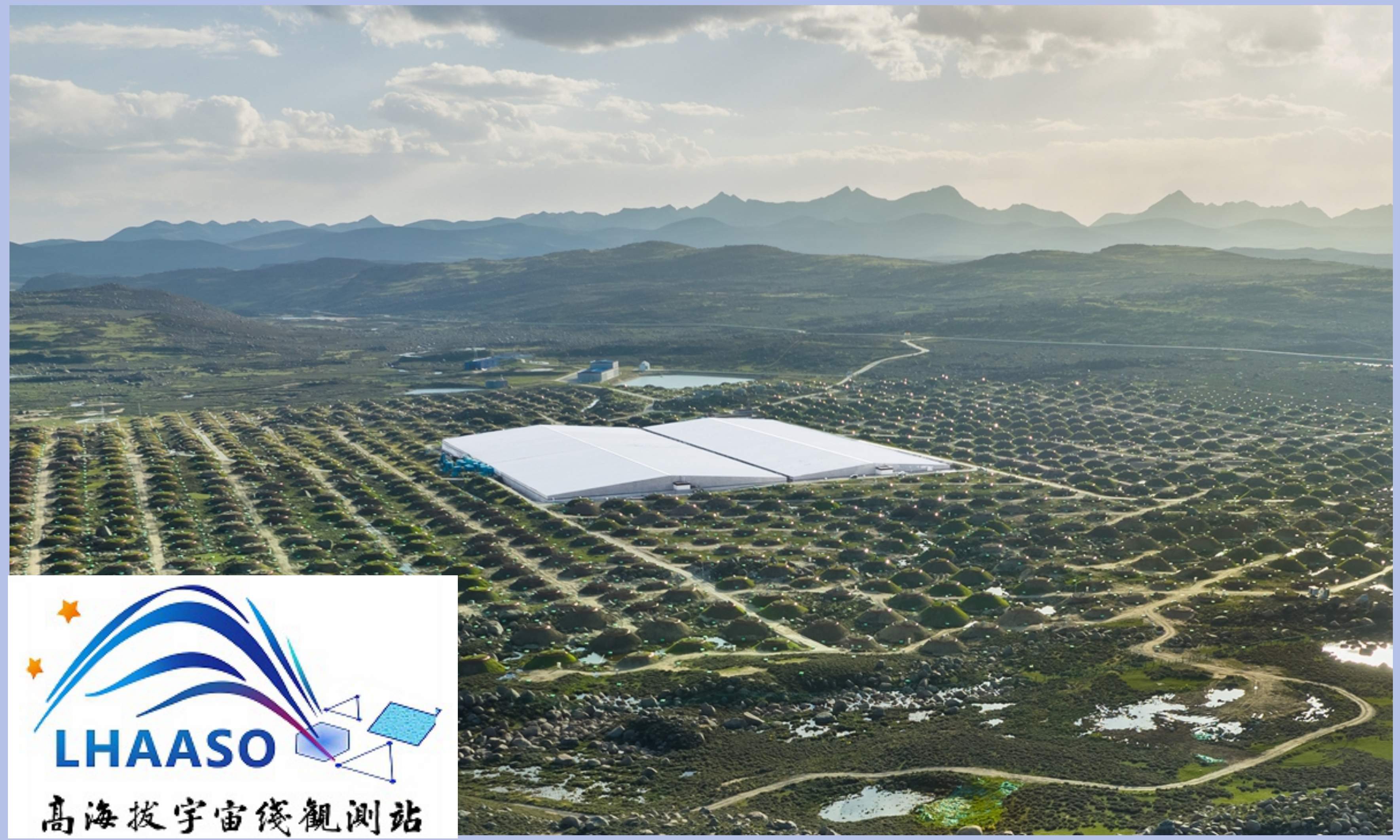
Secondary particles and diffuse fluxes

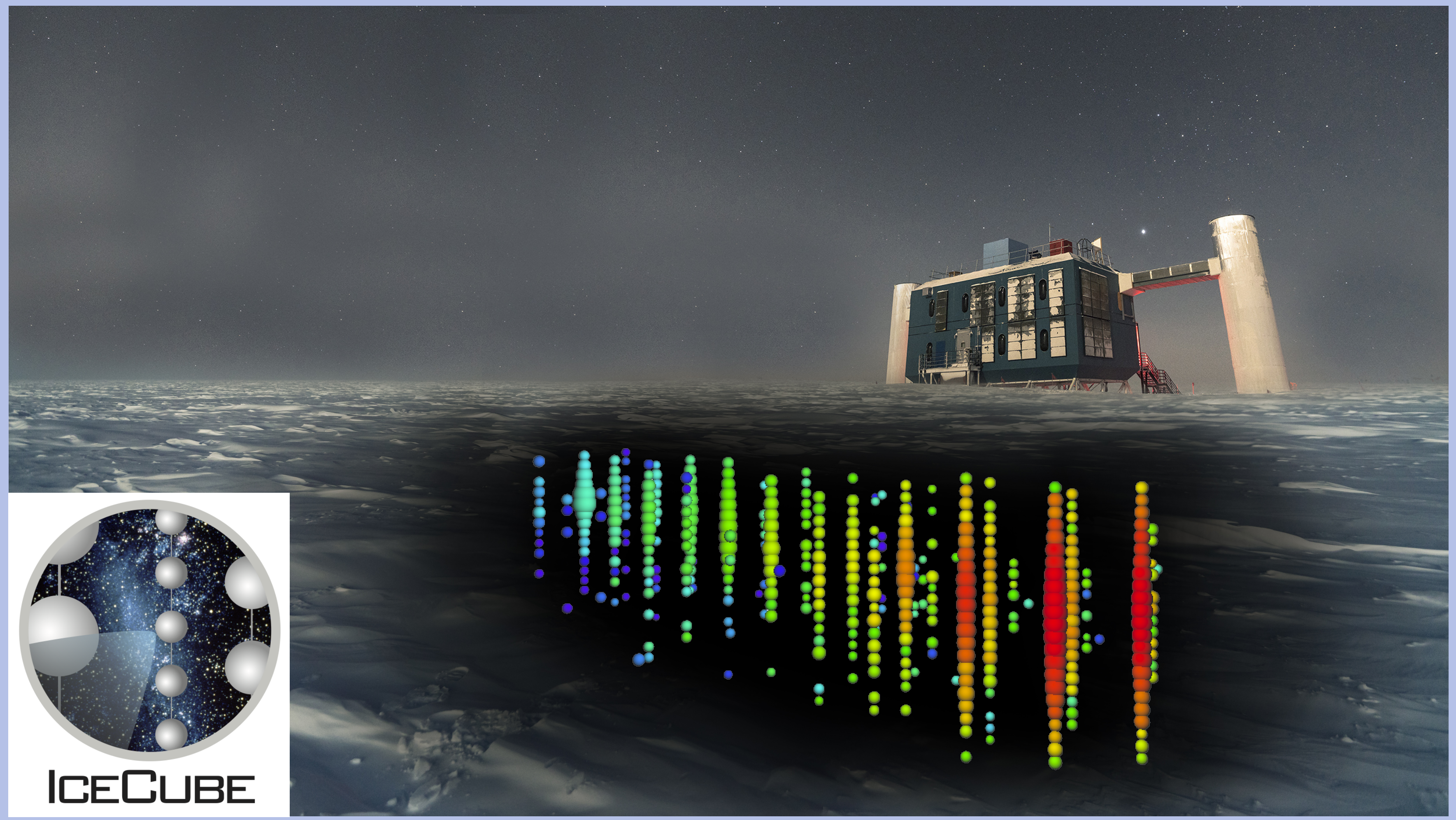


IceCube Coll., 2023

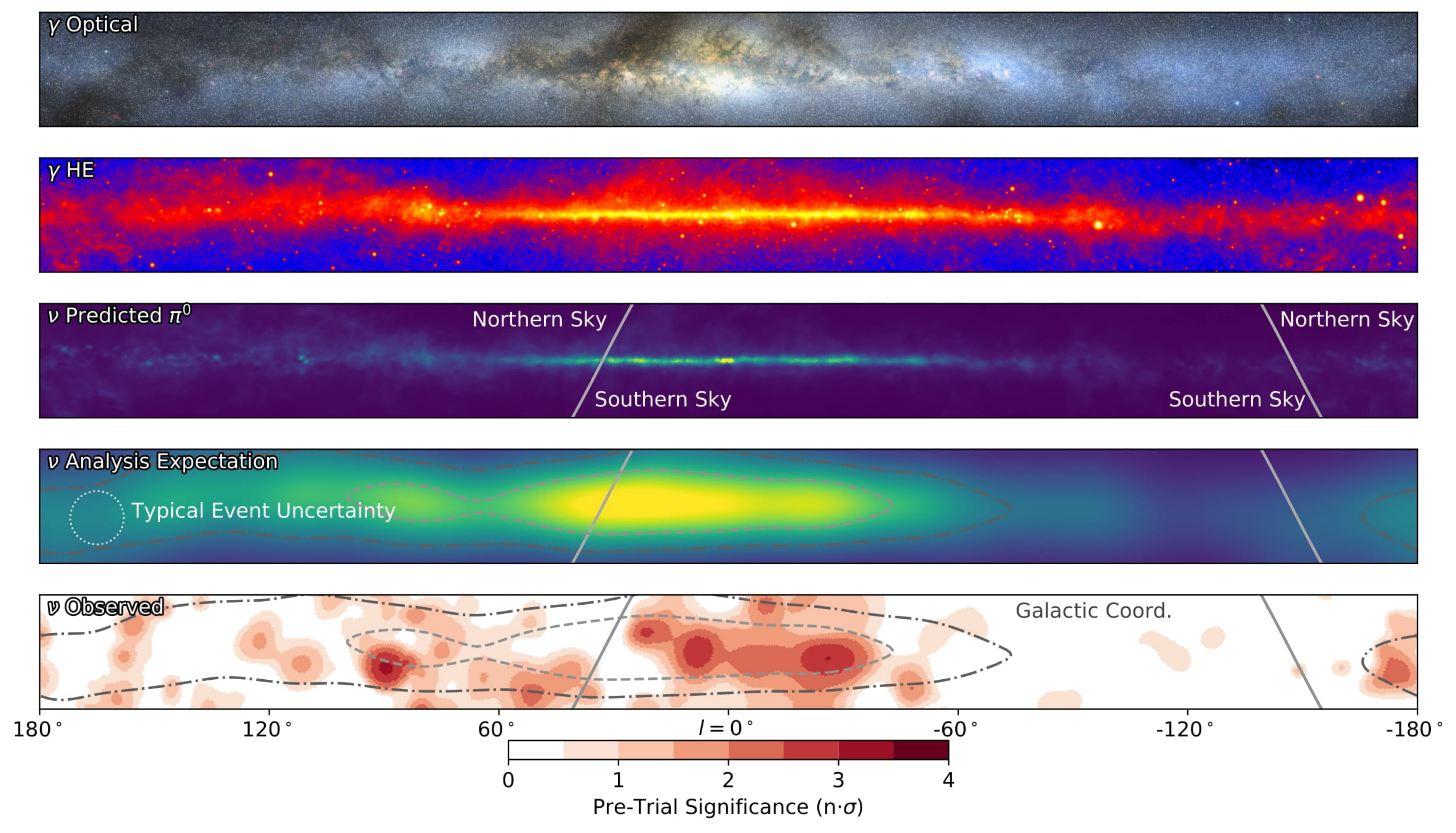


Secondary particles and diffuse fluxes

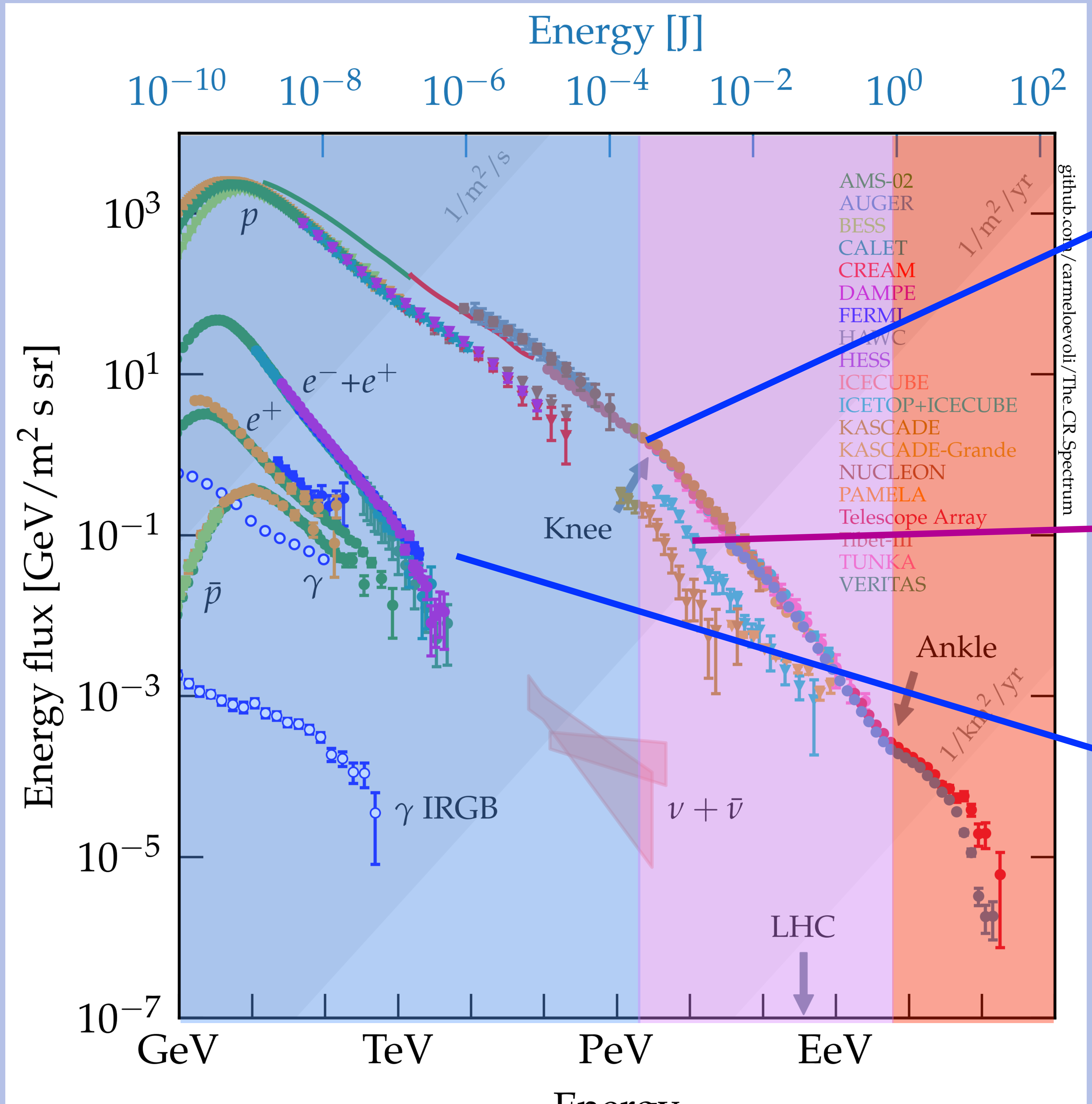




IceCube Coll., 2023



Cosmic ray galactic-extragalactic transition



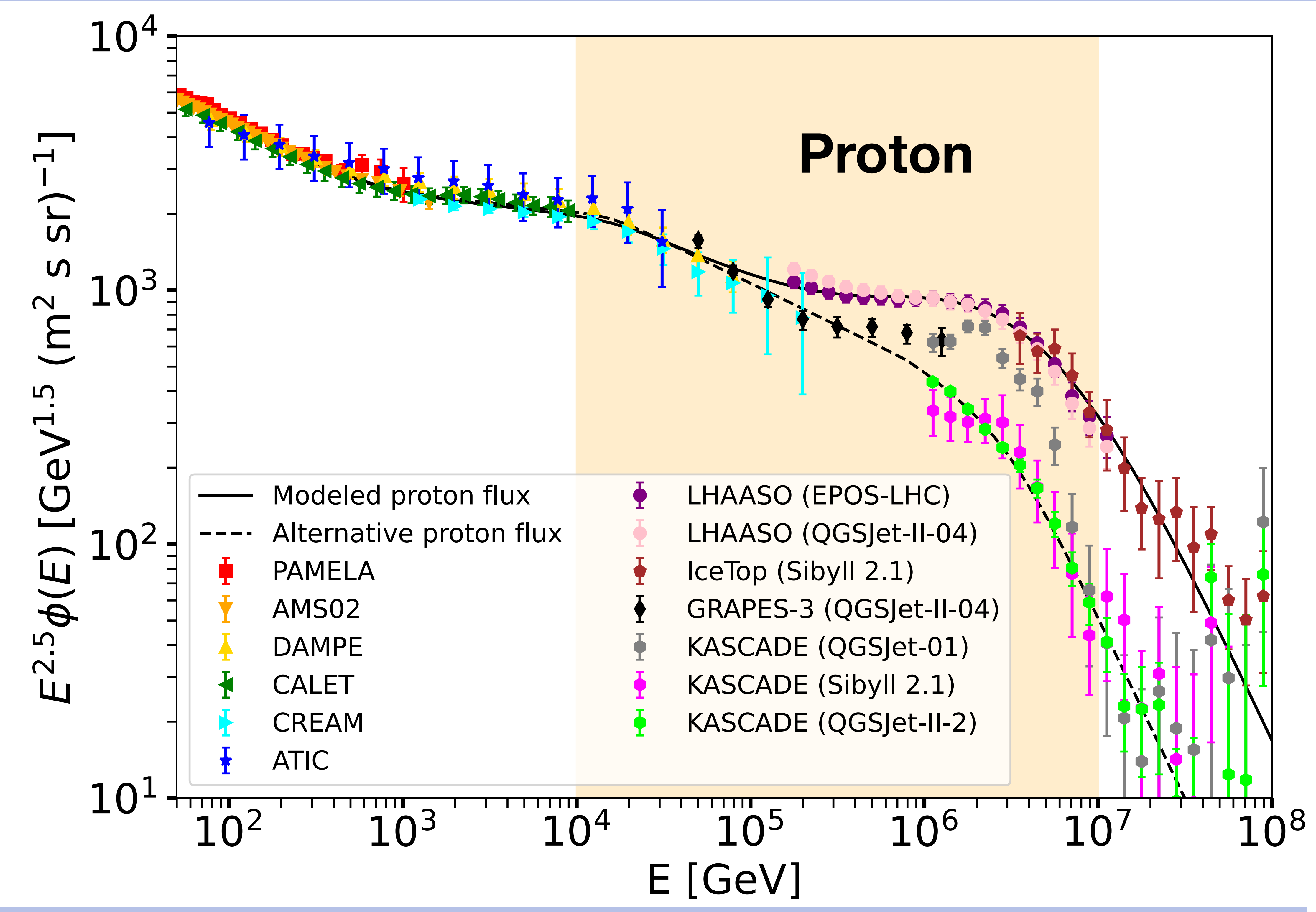
Evoli, 2020

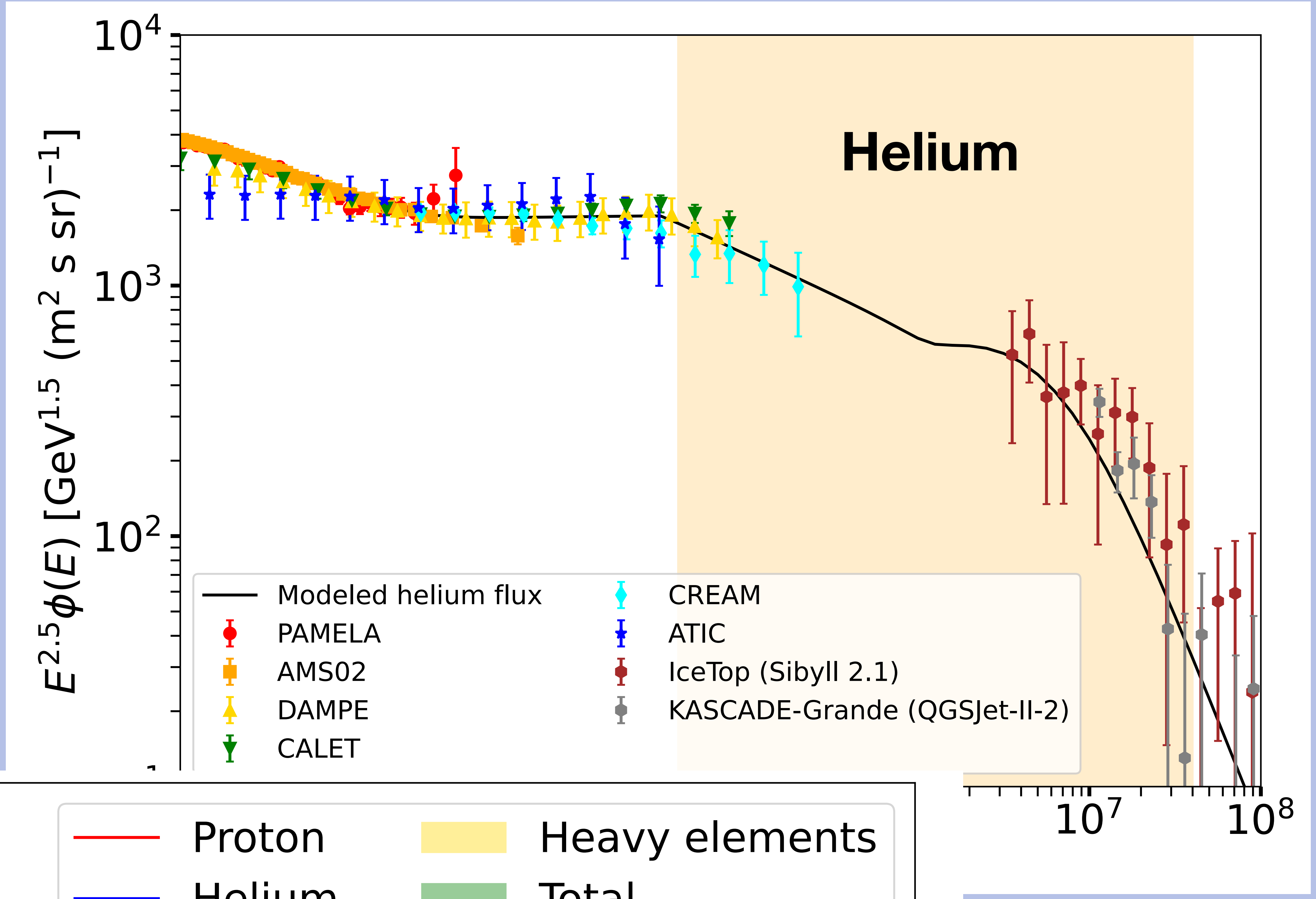
Maximum energy achieved by Galactic accelerators?

Escape of cosmic rays from the Galaxy?

Additional population in transition regime?

Spatial dependence of cosmic ray density and spectrum?



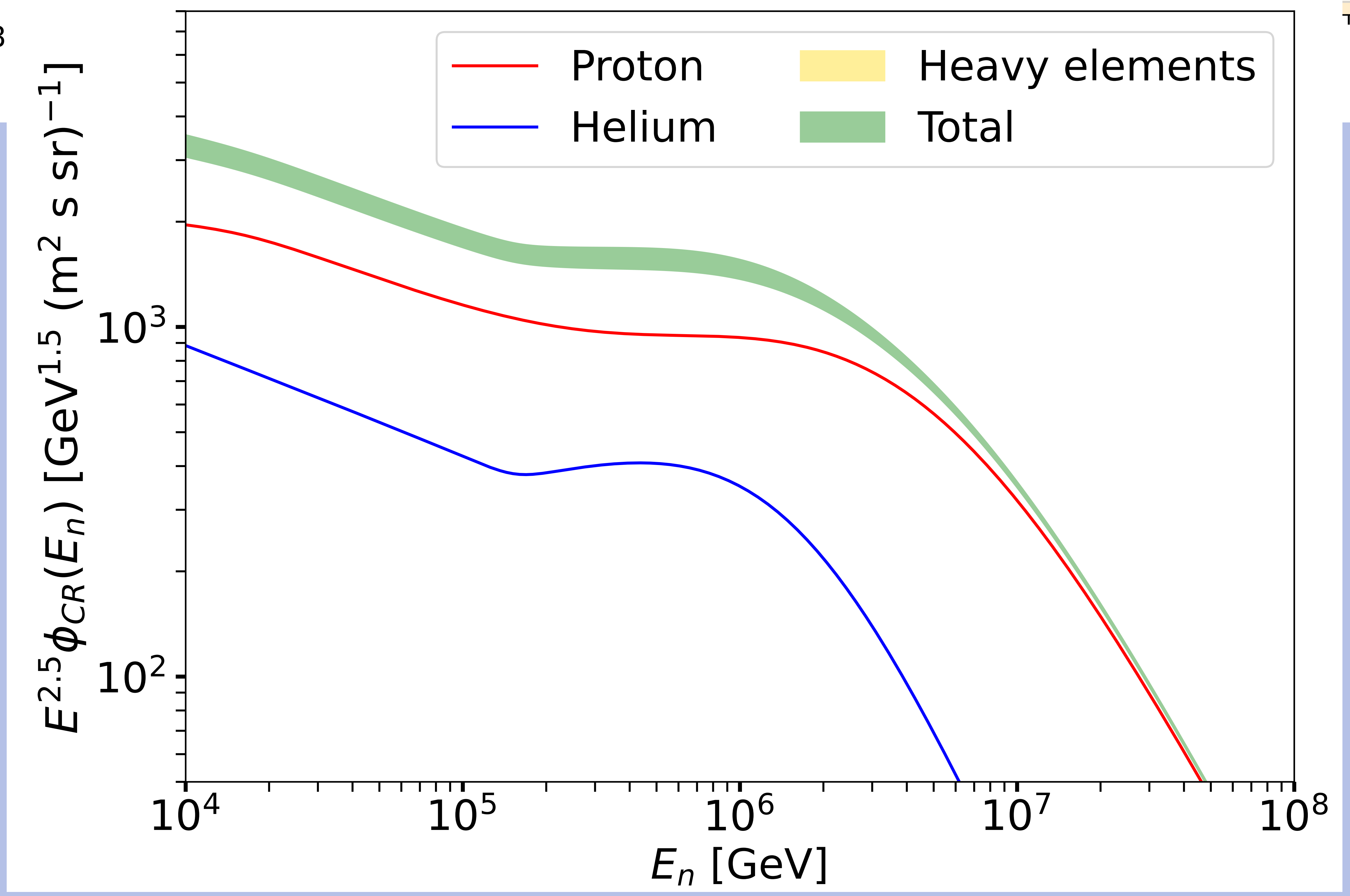


$$\phi(E) = K\left(\frac{E}{E_0}\right)^{-\alpha_1}\Pi_{i=1}^{i=4}\left[1+\left(\frac{E}{E_{b,i}}\right)^{1/\omega_i}\right]^{-(\alpha_{i+1}-\alpha_i)\,\omega_i}$$

$$\phi_{\rm CR}(E_n) = \sum_A A^2\,\phi_A(AE_n)$$

Nucleon flux

Nuclei flux



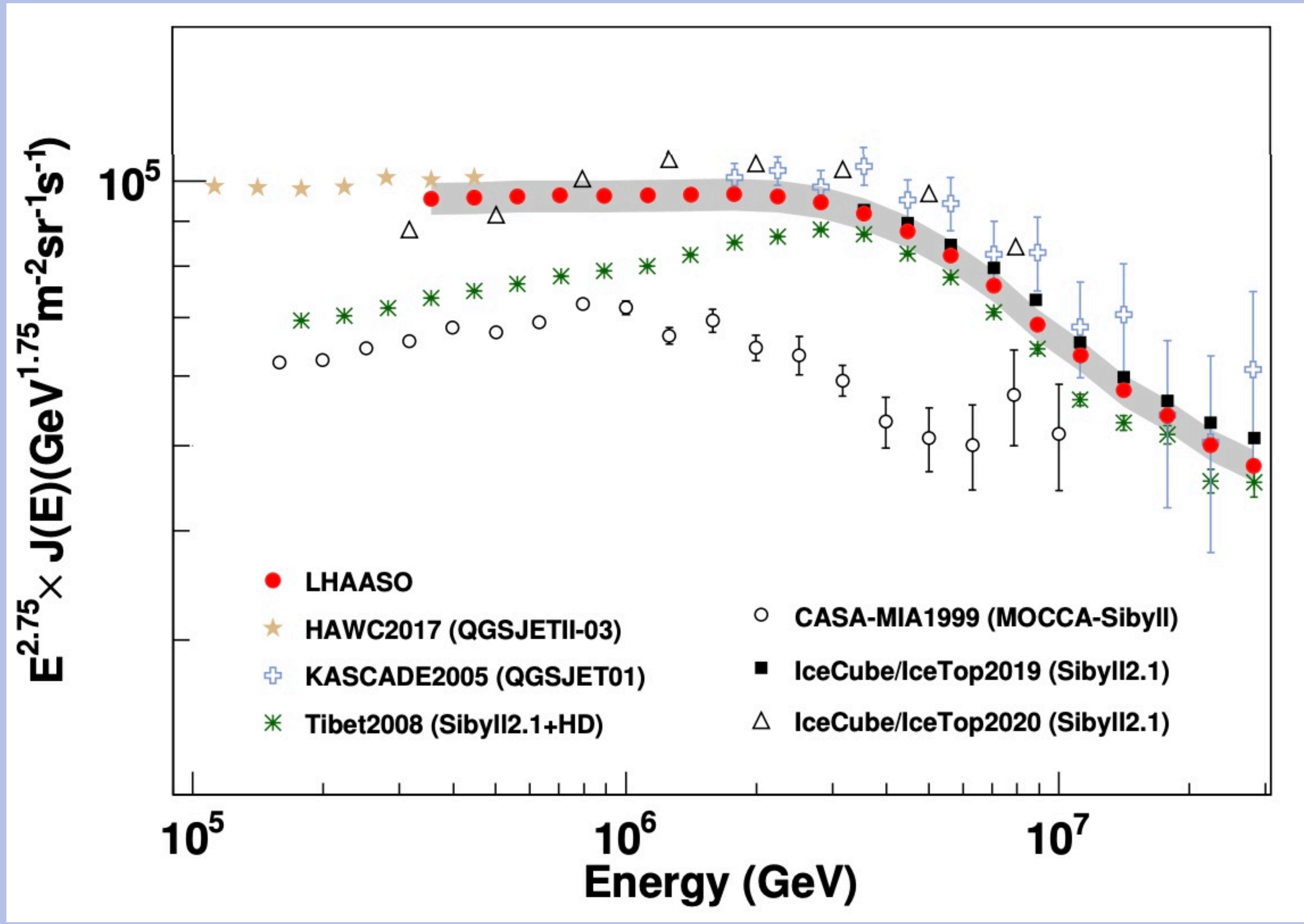
Additional project: Galactic cosmic ray flux and composition

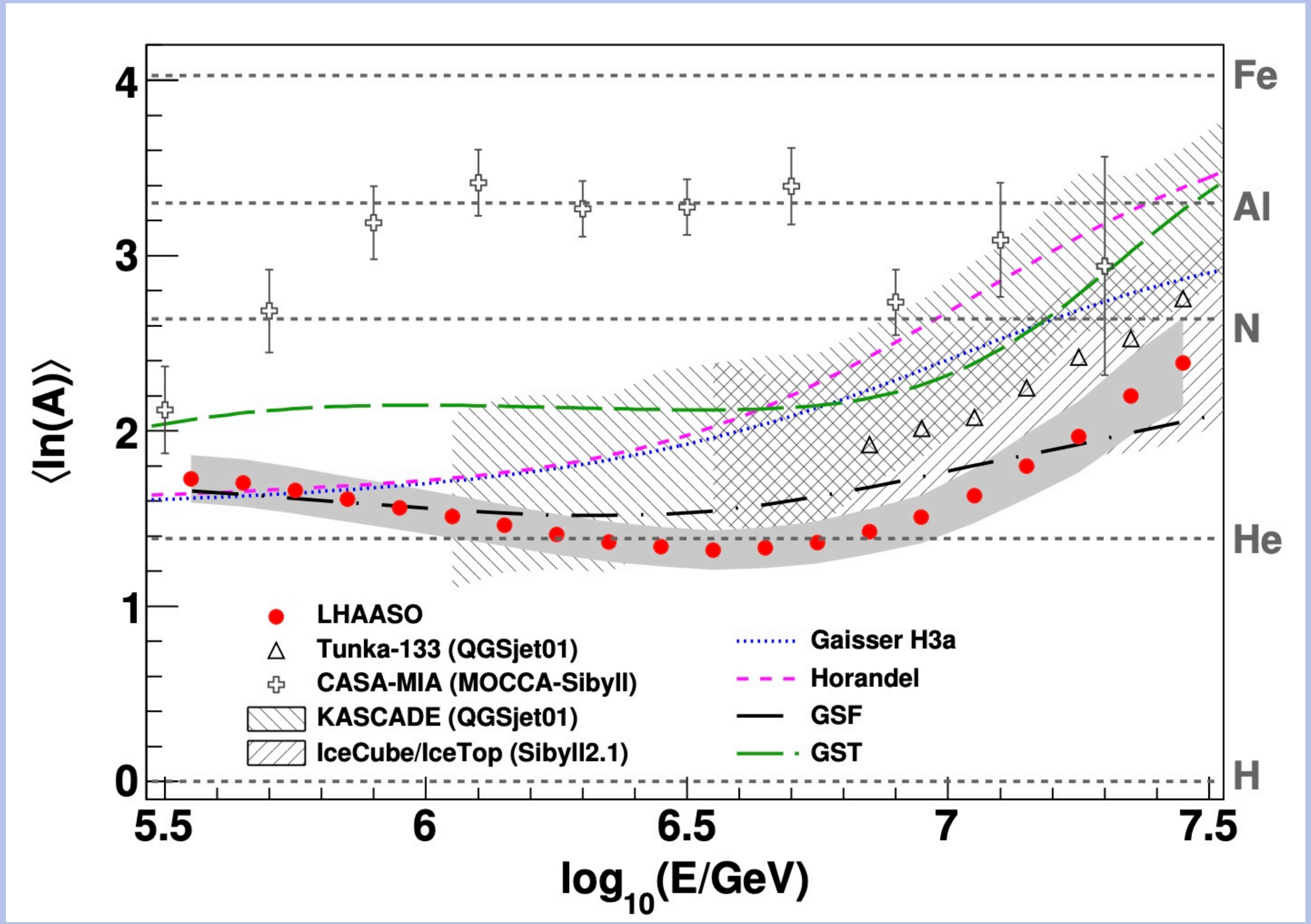
See Igor's presentation

Project being finalised

Currently, also measurements of the **all-particle flux** and **mean logarithmic mass** by LHAASO available across the cosmic ray knee.

LHAASO Coll., 2024





$$\phi_\gamma(E_\gamma; s, l, b) = \int_0^\infty ds\, n_{gas}(s, l, b)\, e^{-\tau(s, E_\gamma)} \int_{E_\gamma}^\infty dE_n \frac{d\sigma}{dE_\gamma}(E_n, E_\gamma)\, \phi_{\mathrm{CR},\odot}(E_\mathrm{n})$$

Absorption

- CMB — Vernetto & Lipari, 2016

Cross-section

- AAFrag — Kachelriess et al., 2023

Galactic gas

- Emission lines — Porter et al., 2021, Dundovic et al., 2021
- Dust opacity — Aghanim et al., 2016, Ade et al., 2011

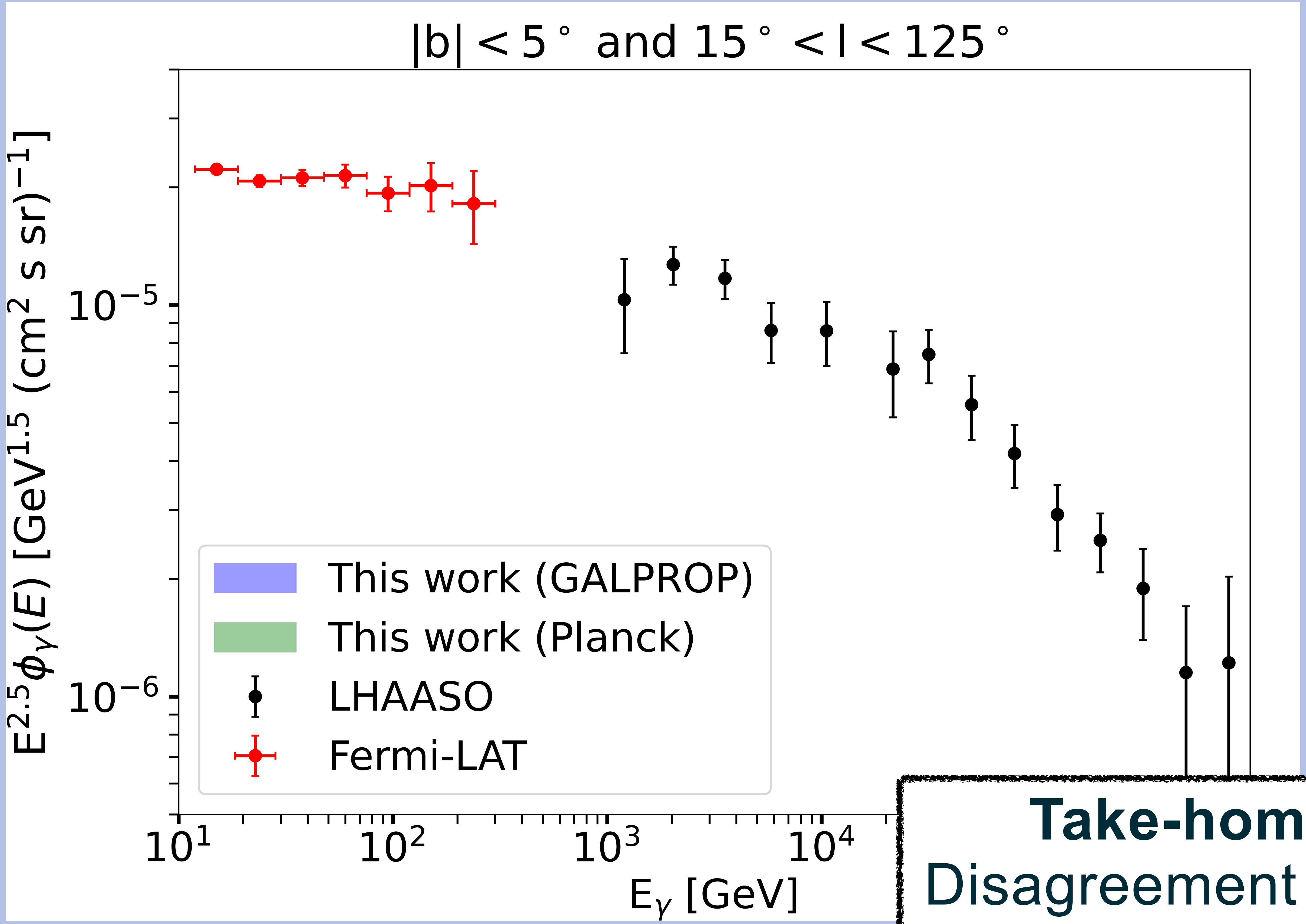
Cosmic ray nucleon flux

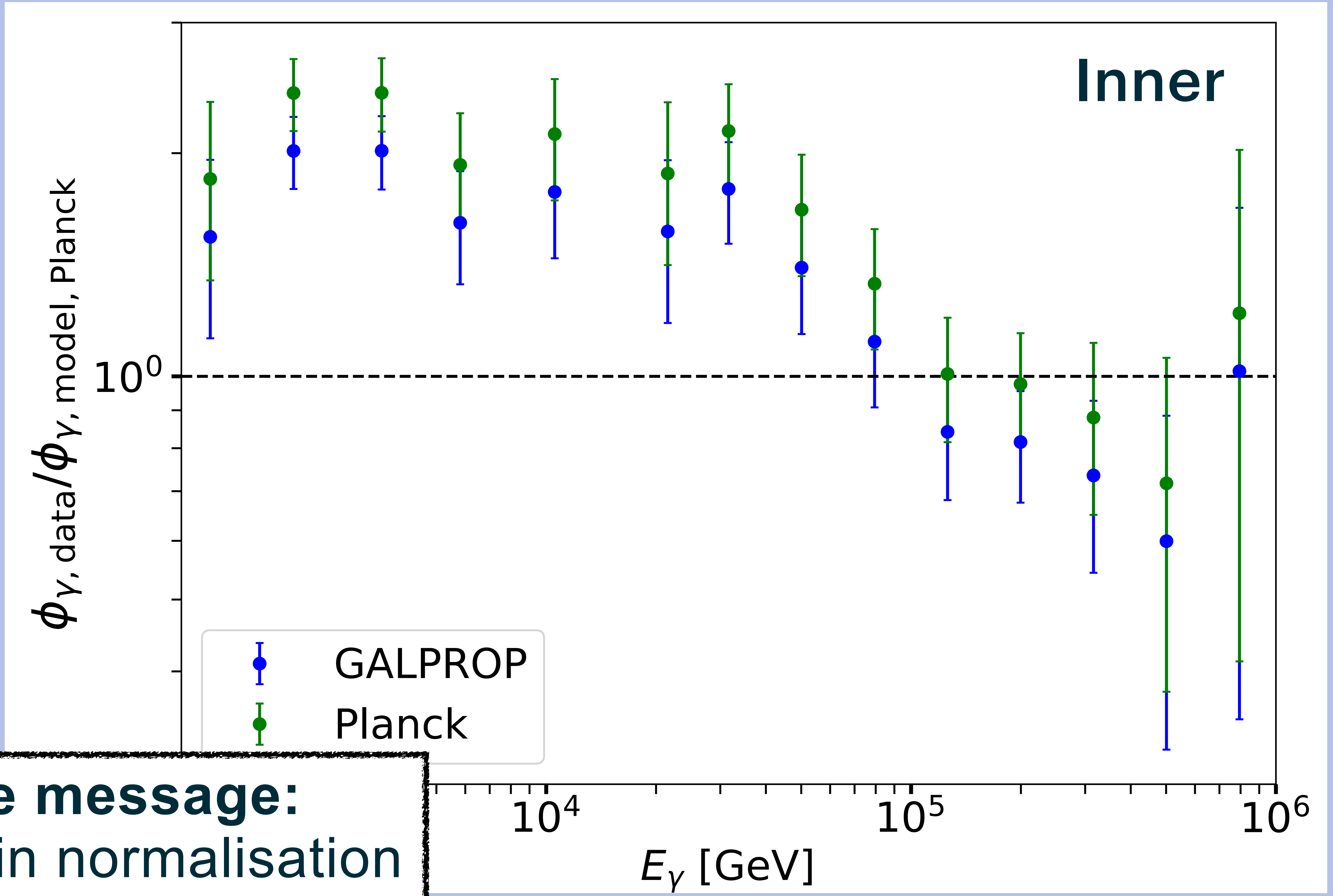
- Phenomenological model
- Uniform distribution
- Space-independent spectrum

Gamma-ray Diffuse Emission: Comparison with LHAASO

- Excess in LHAASO observations found only in the inner region at low energies.
- No distinction from space-dependent to space-independent spectrum in LHAASO regions

Espinosa Castro et al., MNRAS Lett, 2025





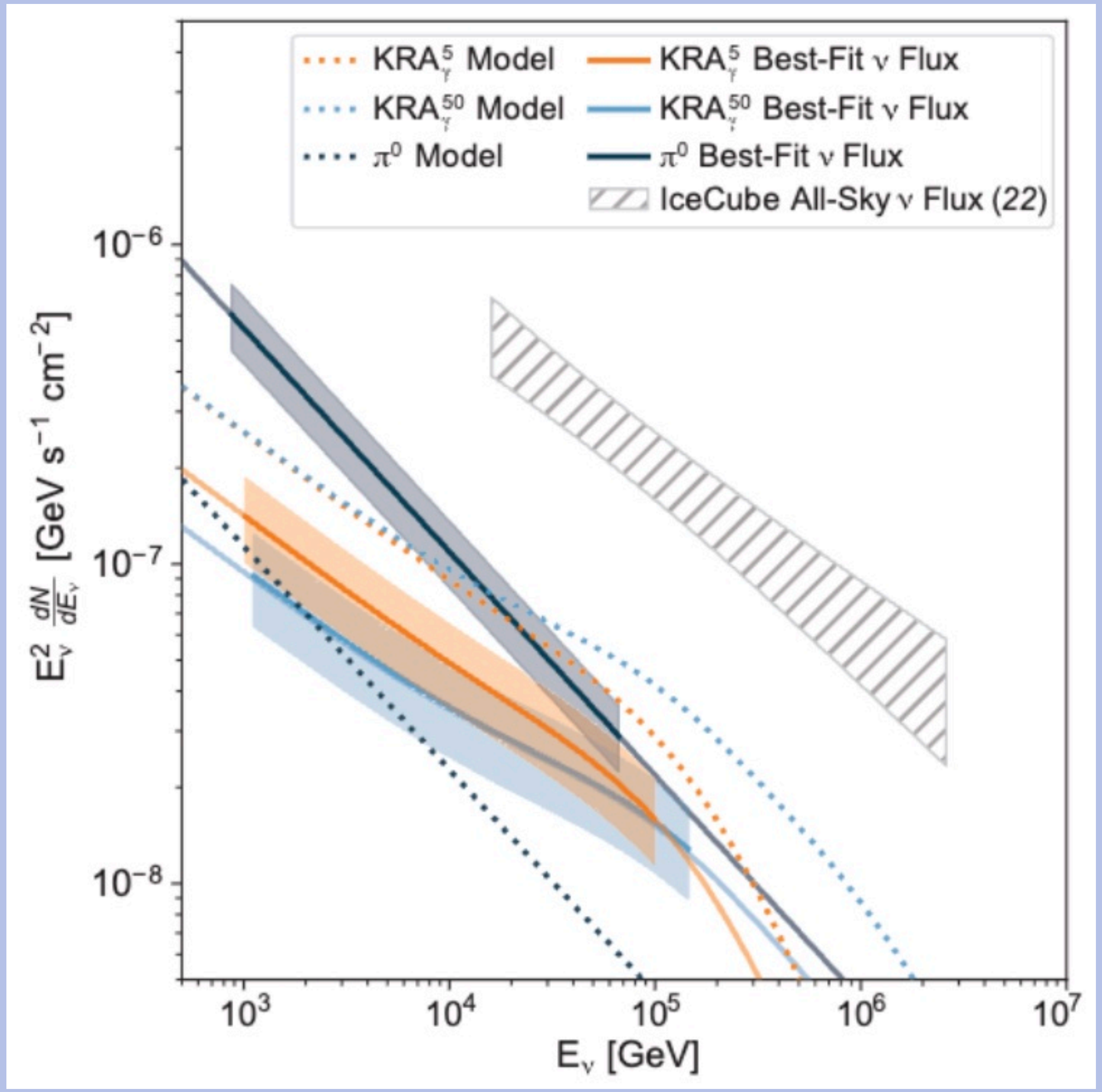
Take-home message:
Disagreement in normalisation and spectral shape.

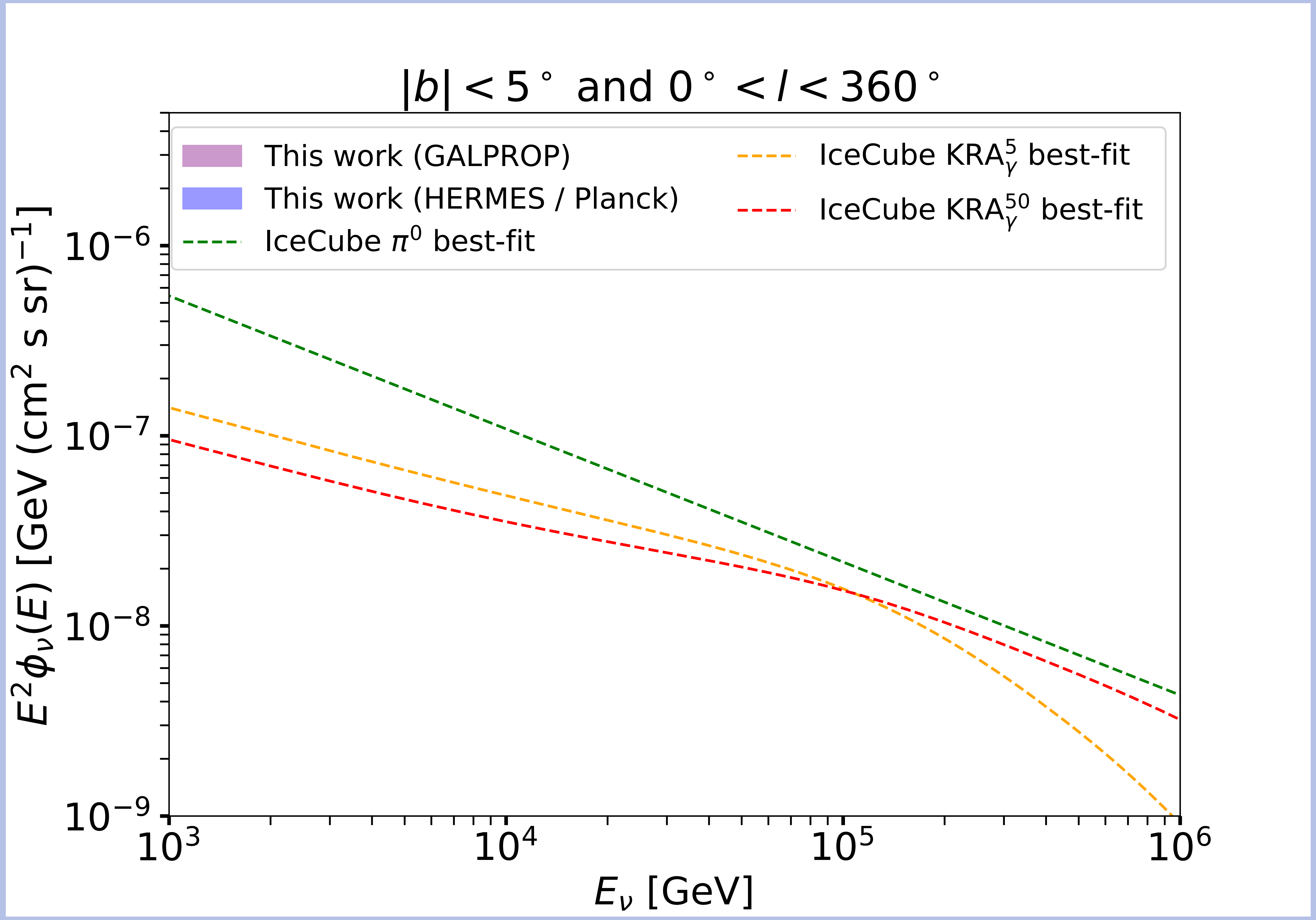
Neutrino Diffuse Emission: Comparison with IceCube

- Overall normalisation can be reproduced but different spectral shape.
- Strong constraints on contribution from Galactic sources.

Paper in prep.

IceCube Coll., 2023





SUMMARY

- Perpendicular diffusion has an **anomalous rigidity dependence** in synthetic field simulations.
- Propagation explanation of cosmic ray knee may be inadequate and predict **higher confinement times** in Galactic magnetic fields.
- Galactic cosmic rays at the knee seem to be **incompatible** with observations of VHE gamma-rays.
- All-particle flux and composition analysis suggests **second population** required at the knee to explain data.

- $\Longrightarrow$ **Is the cosmic ray knee explained by the maximum acceleration energy of a second population of Galactic sources peaking at PeV energies?**

PUBLICATIONS

- L. E. Espinosa Castro, F. L. Villante, V. Vecchiotti, C. Evoli and G. Pagliaroli, MNRAS Lett., Vol. 543, 1, 2025, p. L20–L26
- L. E. Espinosa Castro, F. L. Villante, V. Vecchiotti, C. Evoli, and G. Pagliaroli, PoS ICRC2025, 640 (2025)
- L. E. Espinosa Castro, C. Evoli, and P. Blasi, PoS ICRC2025, 037 (2025)
- I. Vaiman, C. Evoli, and L. E. Espinosa Castro, PoS ICRC2025, 148 (2025)

CONFERENCES AND SEMINARS

- Contributed talk in 39th International Cosmic Ray Conference - July 2025; Geneva, Switzerland
- Poster in 39th International Cosmic Ray Conference - July 2025; Geneva, Switzerland
- Contributed talk in Toulouse, Arcetri, and L'Aquila Retreat - October 2025; Arcetri, Italy

OUTREACH ACTIVITIES

- SHARPER (European Research Night September) / Street Science - September 2024; L'Aquila, Italy
- SHARPER (European Research Night September) / Street Science - September 2025; L'Aquila, Italy

BACKUP SLIDES

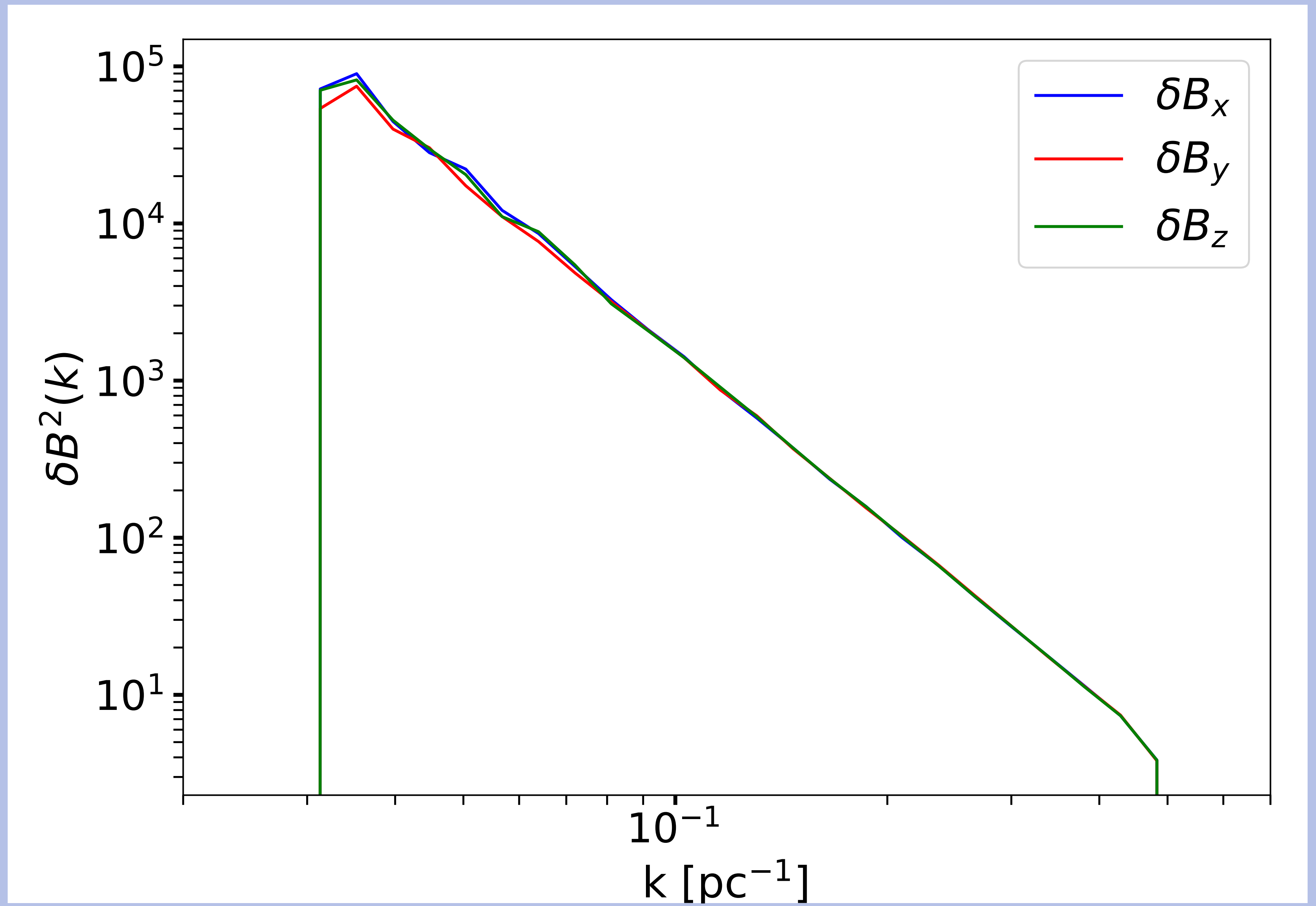
Numerical simulations

CRPropa

- **Synthetic magnetic fields:** turbulent spectrum assumed to be Kolmogorov and isotropic, with random components Gaussian-distributed.

IFFT in grid $\delta B(\vec{x}) = \int d^3k \, \delta\tilde{B}(\vec{k}) \, e^{-i\vec{x}\cdot\vec{k}}$

$$W(k) \propto \frac{\delta B^2 l_b}{\pi k^2} \frac{(k l_b)^q}{[1 + (k l_b)^2]^{(s+q)/2}}$$



Inputs:

- δB_{rms} given by turbulence level $\eta = \dfrac{\delta B_{rms}}{B_0}$
- Spacing of grid $\Delta x \sim 10^{-2}$ pc
- Number of grid points $N_{grid} = 2048$
- Kolmogorov turbulent spectrum $s = 5/3$, $q = 4$
- Bend-over scale $l_b \sim$ few pc

Additional quantities:

- Size of grid $L = \Delta \cdot N_{grid}$
- Minimum turbulent scale $L_{min} = 2 \cdot \Delta$
- Maximum turbulent scale $L_{max} = L/2$
- Correlation length $\lambda_c = \dfrac{4\pi}{\delta B^2} \int_0^\infty dr \int_0^\infty dk \dfrac{\sin(kr)}{kr} k^2 W(k)$

Simulation parameters

- Uniform field with $B_0 = 1\mu G$
- Turbulence levels $\eta = \dfrac{\delta B_{rms}}{B_0} = 0.1, 0.3, 0.5$
- $\Delta = 0.15$ pc $\sim 10 \cdot r_L \left(E = 10^{15}\,\text{eV}\right)$
- $N_{grid} = 2048$
- Kolmogorov spectrum, i.e. $\gamma = 5/3$
- $L = 102.4$ pc, $L_{min} = 0.2$ pc, $L_{max} = 12.8$ pc and $\lambda_c = 2.73$ pc

$\Longrightarrow$ Scattering resonance around PeV energy

- Number of particles $N_p = 10^3$
- Number of position/velocity measurements $N_t = 10^5$
    - Step for position/velocity measurements $\Delta t = 0.1\, r_L/c$
    - Maximum distance travelled by particles $D = 10^4\, r_L$
- Minimum and maximum integrations steps $l_{min} = 0.1$ pc and $l_{max} = 100$ Mpc

Numerical simulations

CRPropa

Ansatz (Bieber & Matthaeus, 1997):

$$R_{\parallel}(t) = \frac{c^2}{3} e^{-t/\tau_{\parallel}}$$

$$R_{\perp}(t) = \frac{c^2}{3} \cos \omega t \, e^{-t/\tau_{\perp}}$$

$$R_{A}(t) = -\frac{c^2}{3} \sin \omega t \, e^{-t/\tau_{A}}$$

Mean displacements method

$$D_{ij} = \frac{\left\langle \Delta x_i \Delta x_j \right\rangle}{2\tau}$$

TGK method

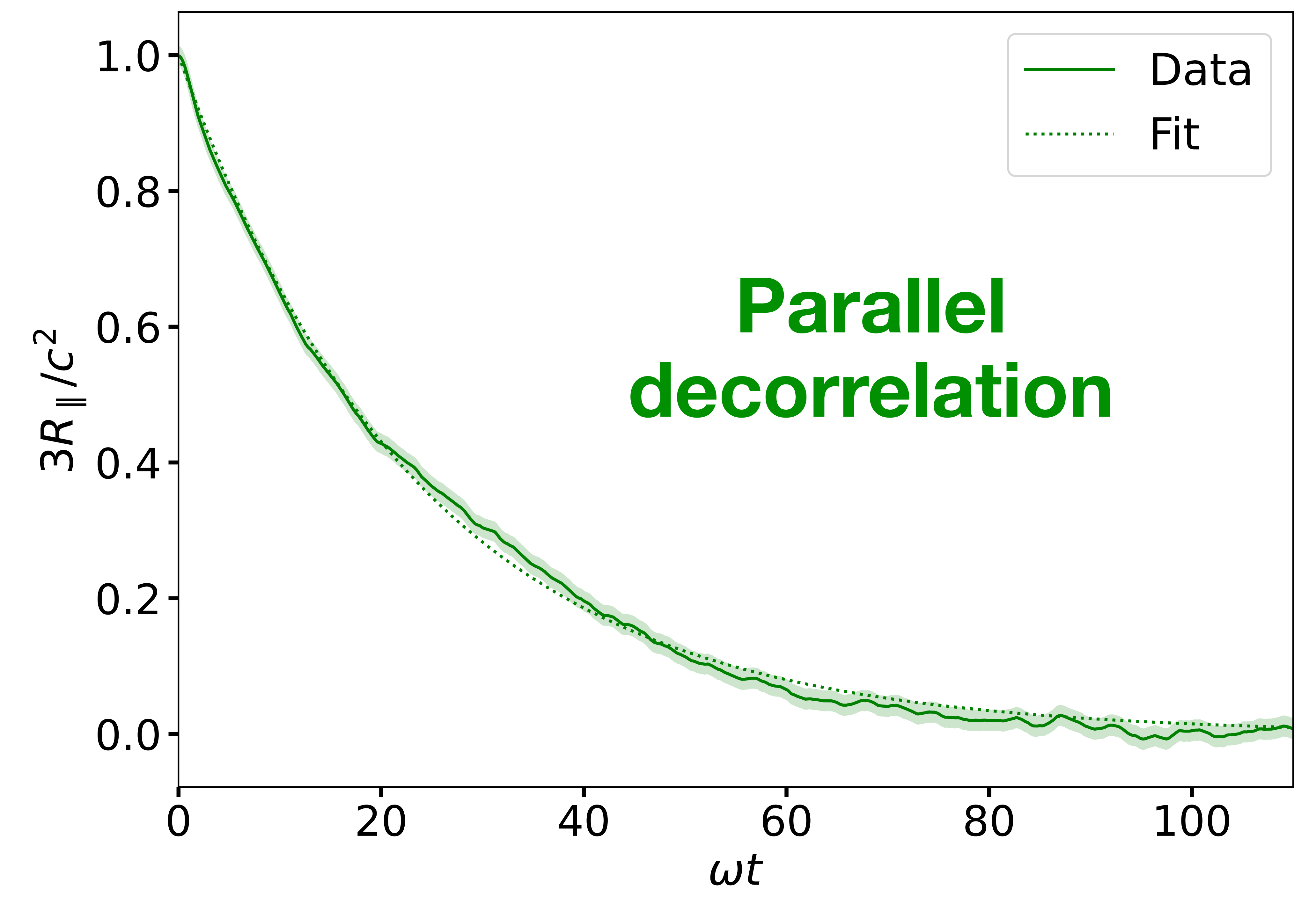
$$D_{ij} = \int_0^\infty dt \left\langle v_i(0) v_j(t) \right\rangle = \int_0^\infty dt \, R_{ij}(t)$$

If $\omega^{-1} \ll \tau_{\perp}$, $\quad D_{\perp} \propto \frac{R^{\alpha_{\perp}}}{(R^{-1}R^{\alpha_{\perp}})^2} = R^{2-\alpha_{\perp}}$

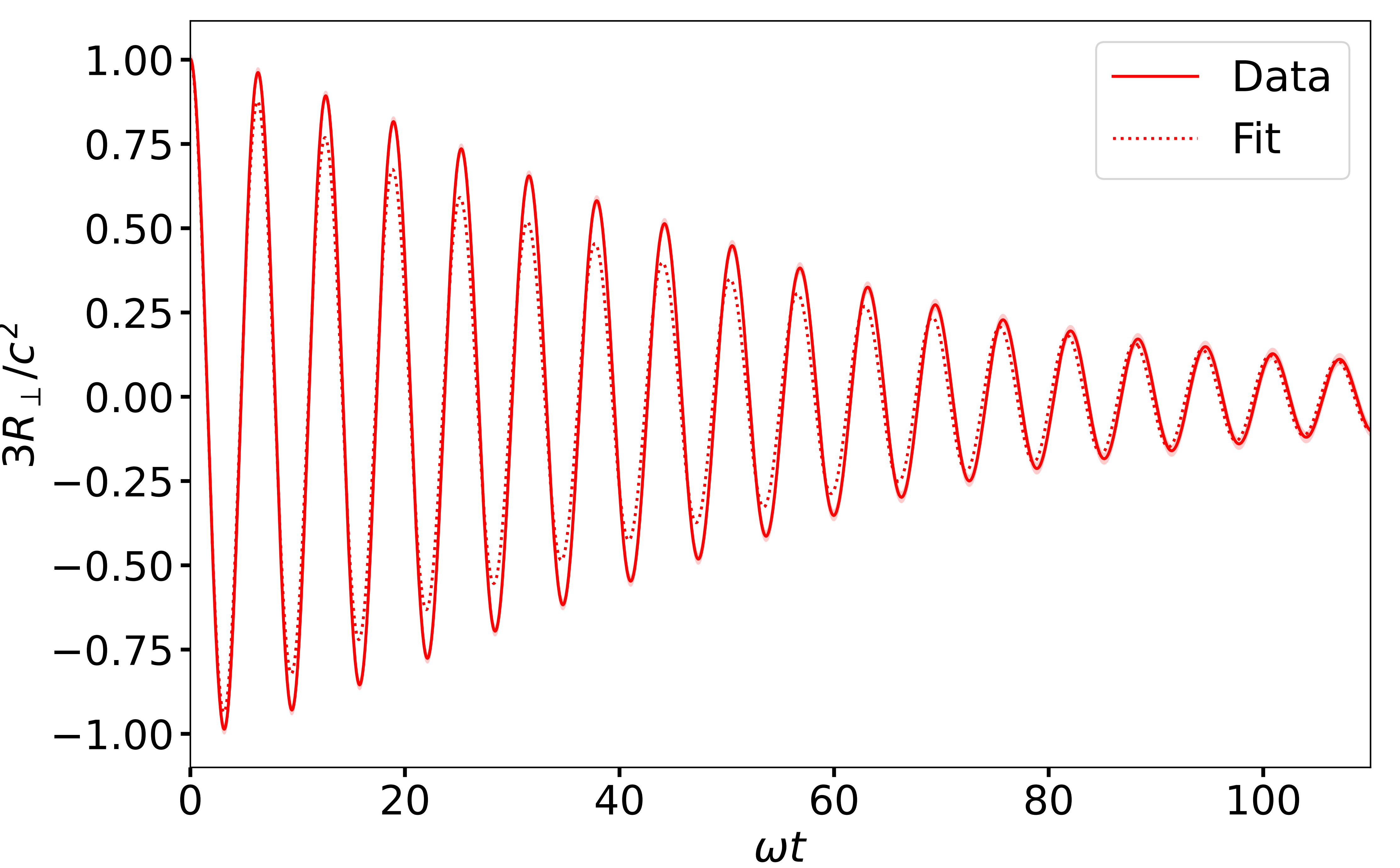
If $\omega^{-1} \gg \tau_{\perp}$, $\quad D_{\perp} \propto R^{\alpha_{\perp}}$

If $\omega^{-1} \ll \tau_{A}$, $\quad D_{A} \propto \frac{R^{-1}R^{2\alpha_{A}}}{(R^{-1}R^{\alpha_{A}})^2} = R$

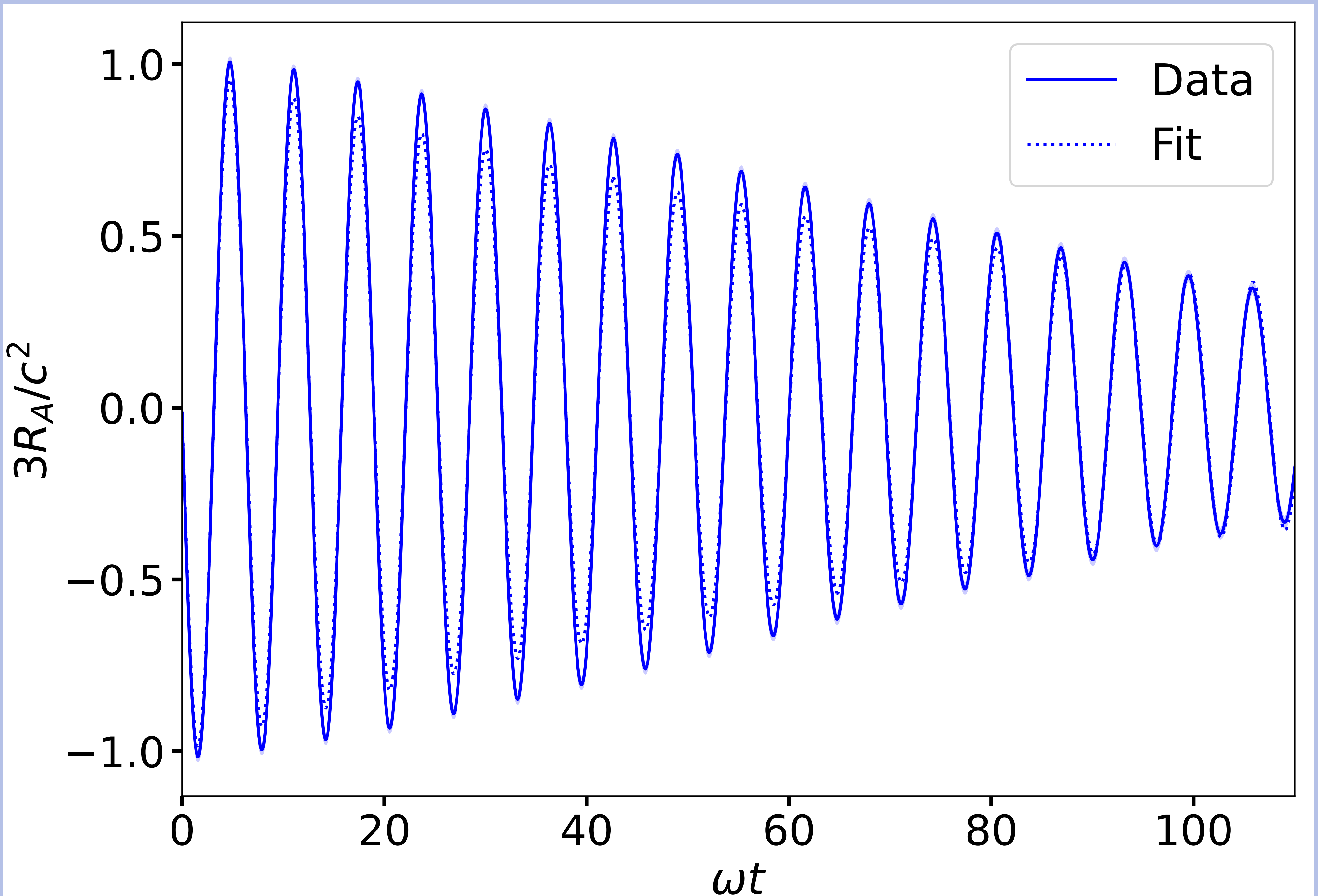
If $\omega^{-1} \gg \tau_{A}$, $\quad D_{A} \propto R^{2\alpha_{A}-1}$



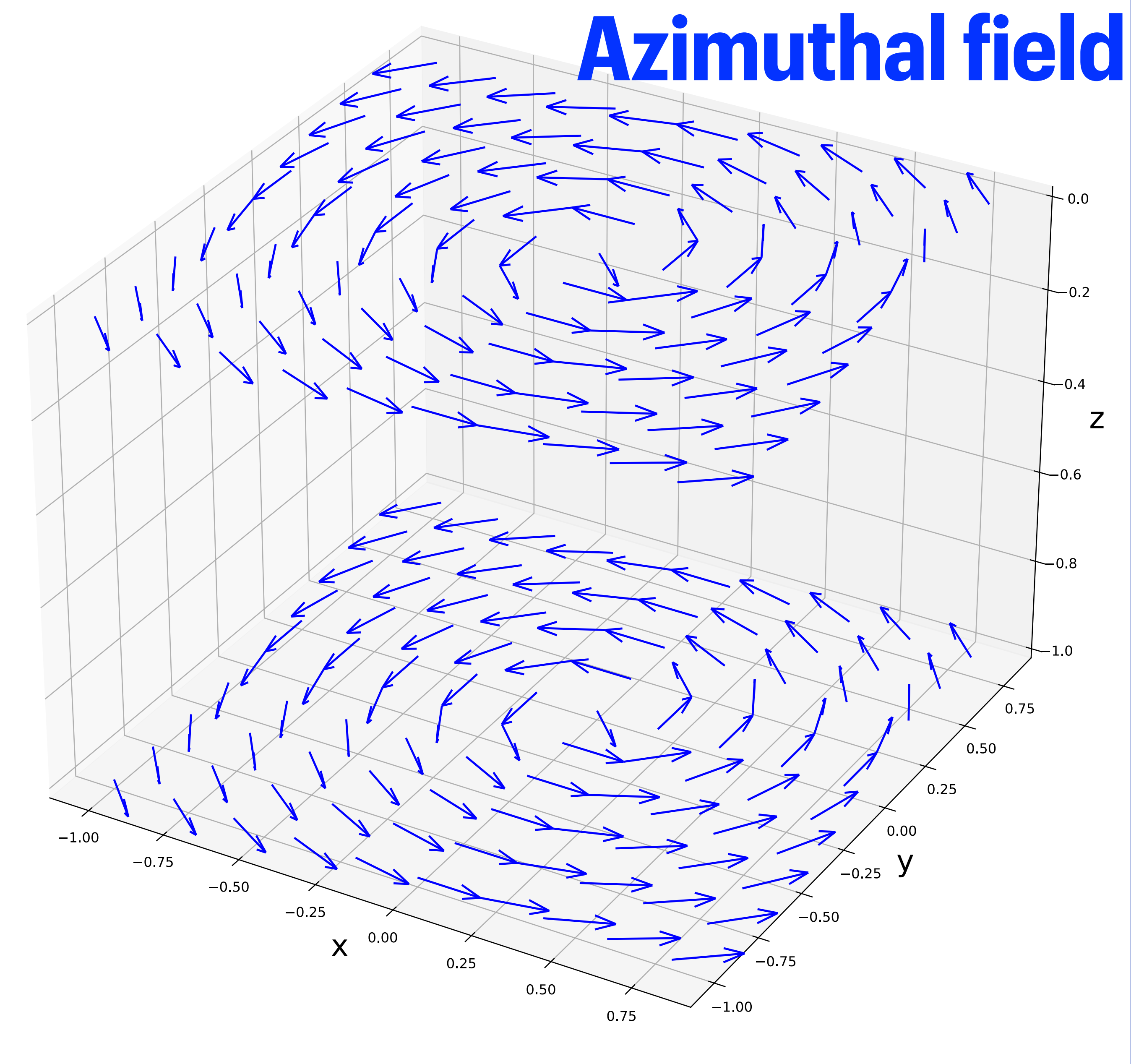
Perpendicular decorrelation



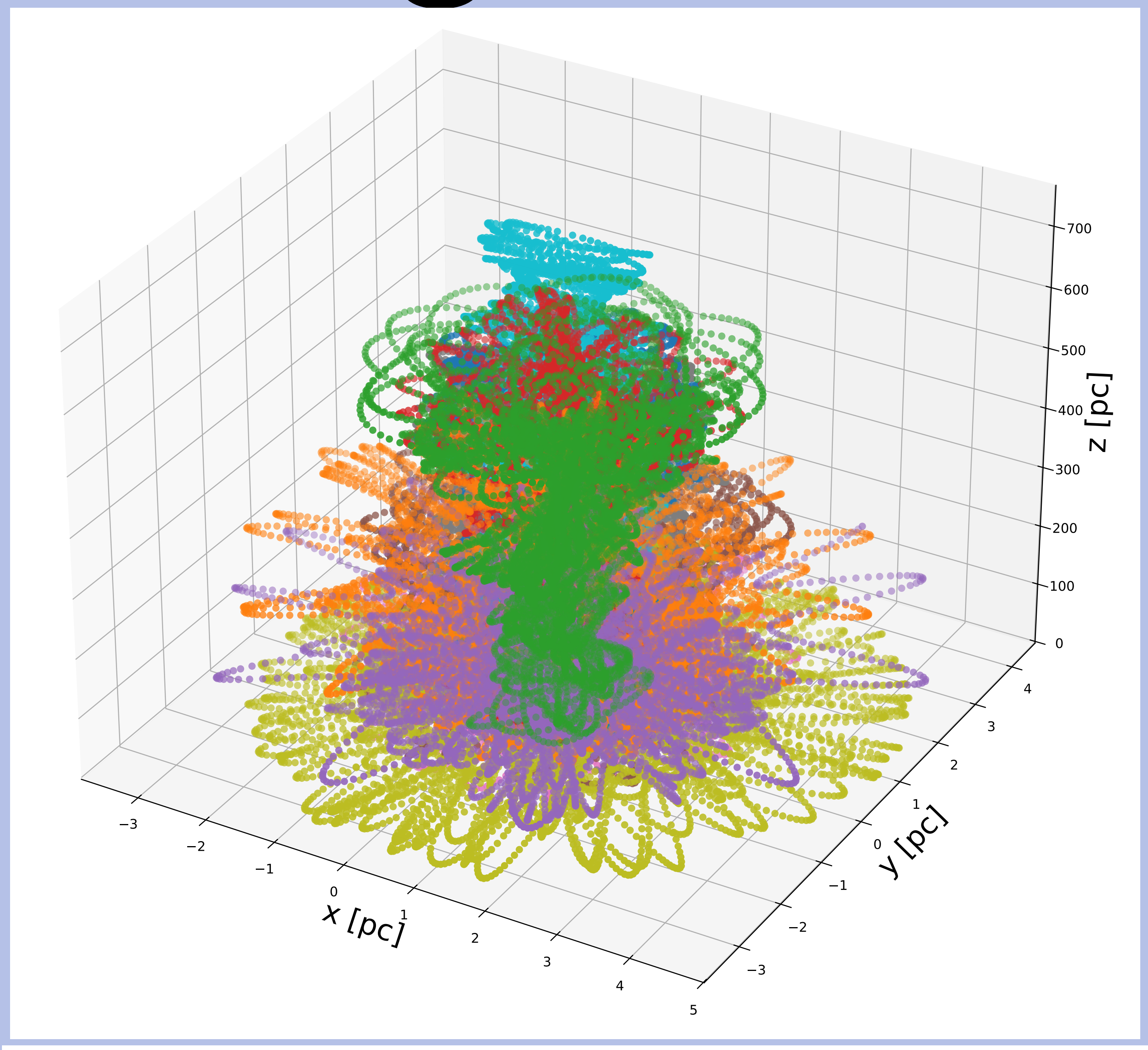
Antisymmetric decorrelation



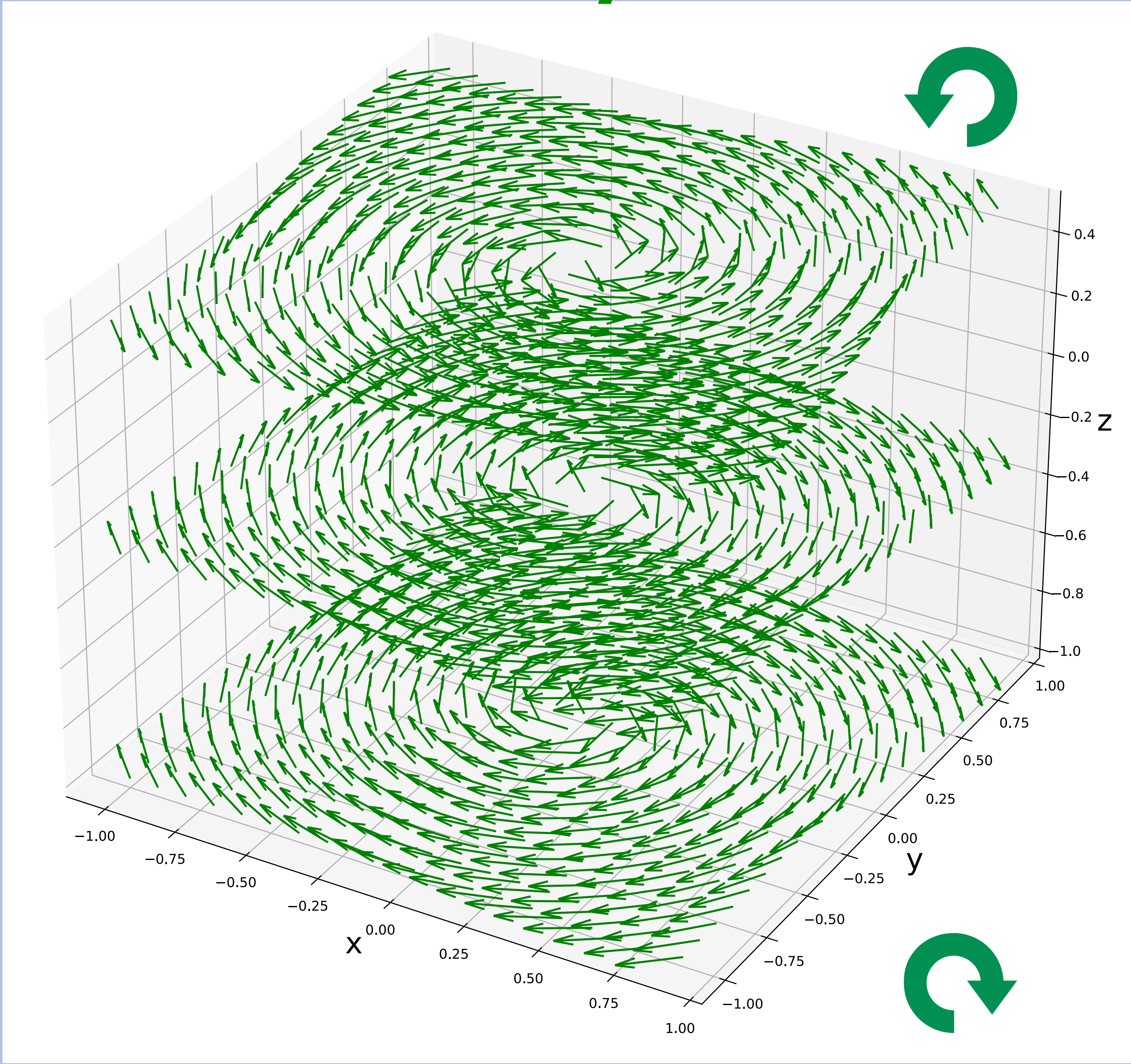
Cosmic ray escape time in Galactic magnetic fields



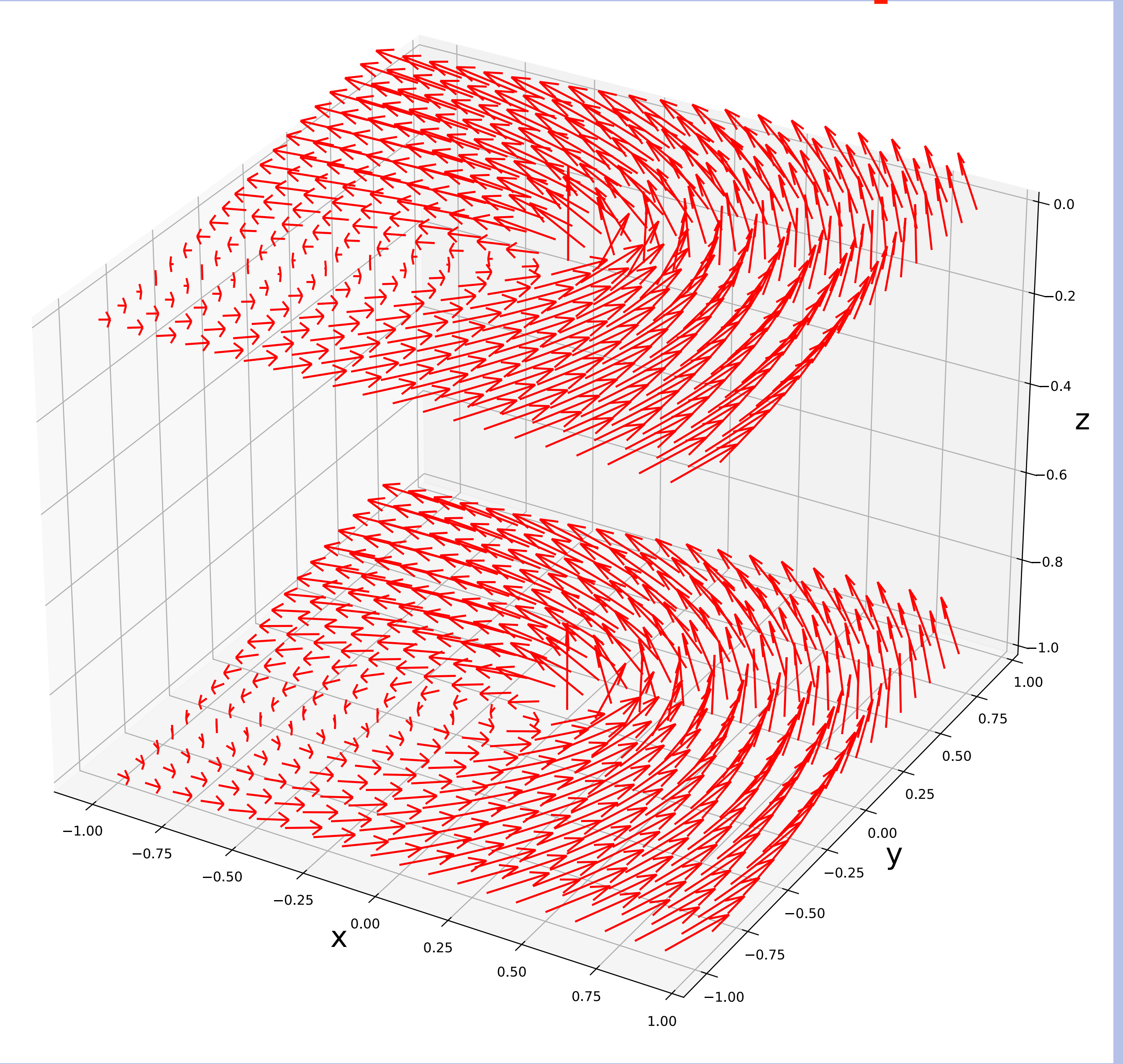
Particle injection

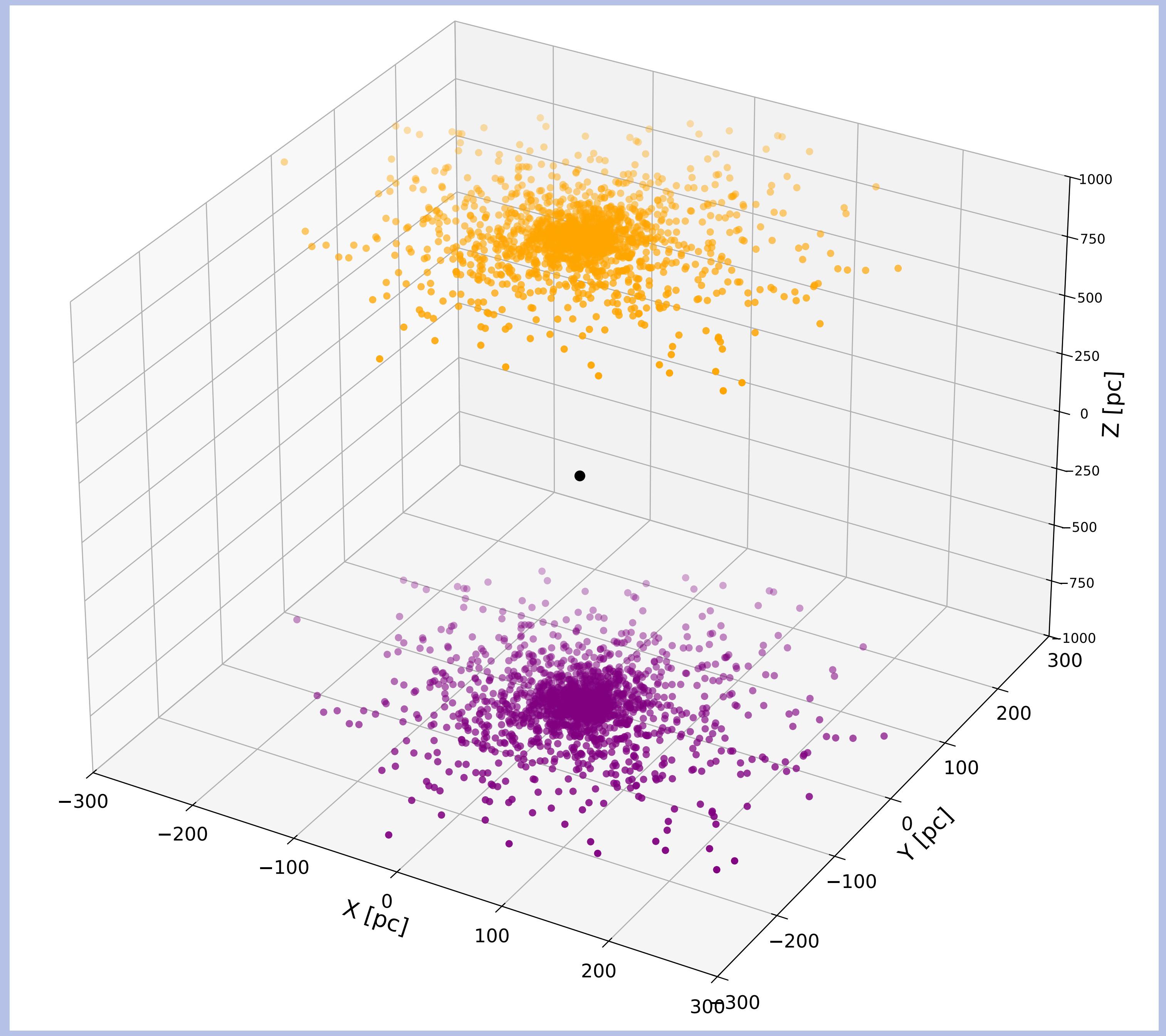


Azimuthal antisymmetric field

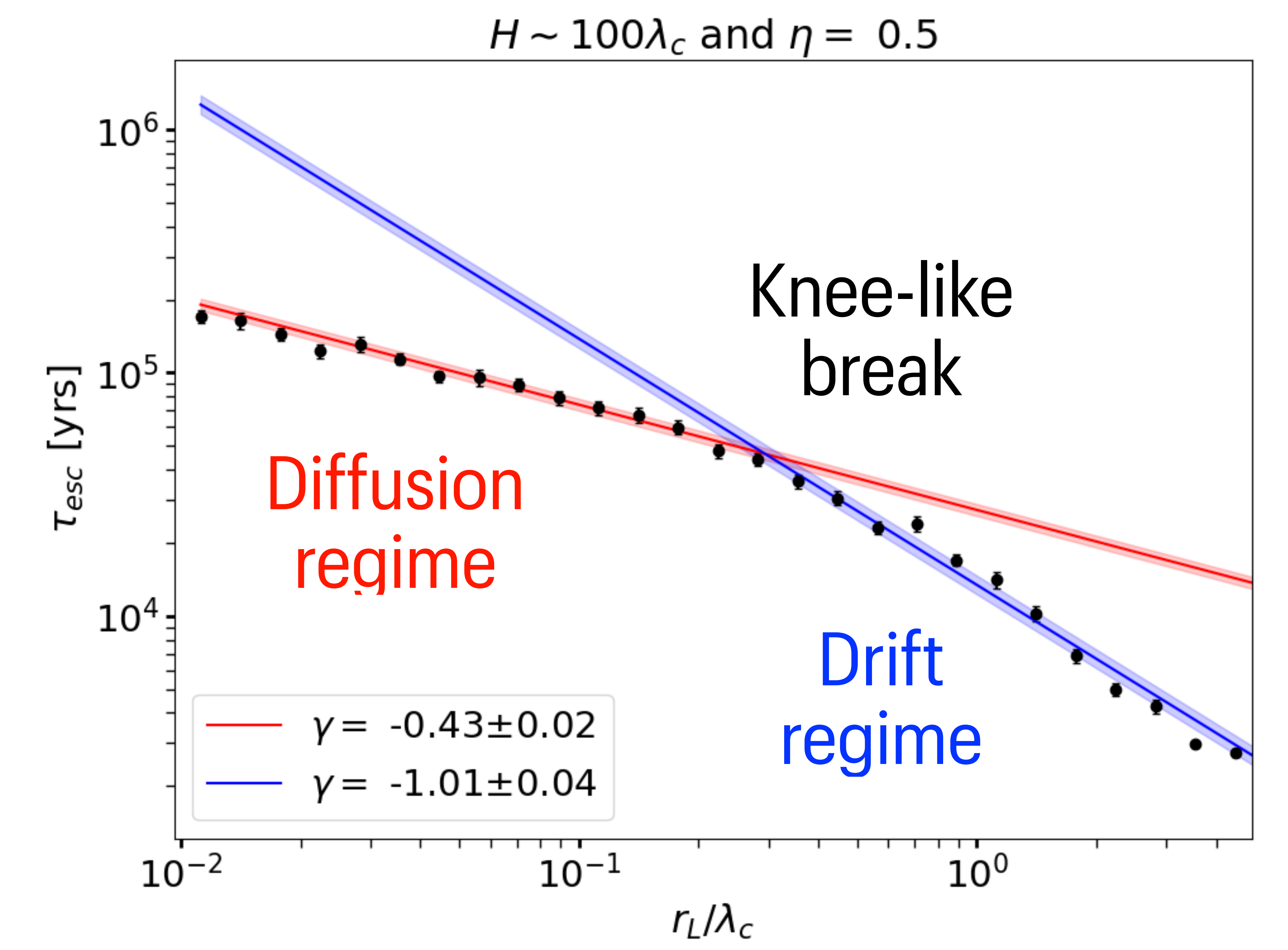


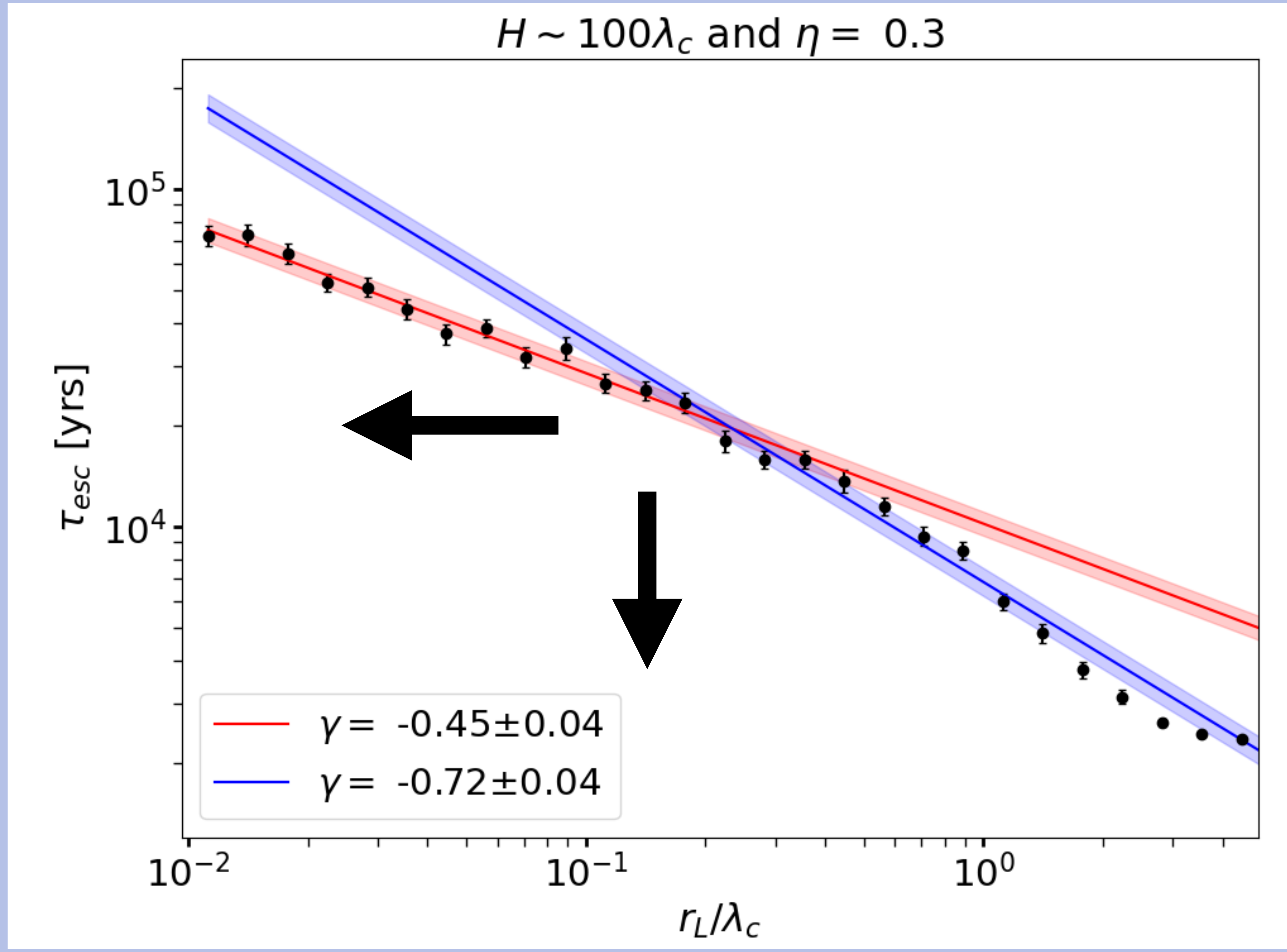
Field with vertical component



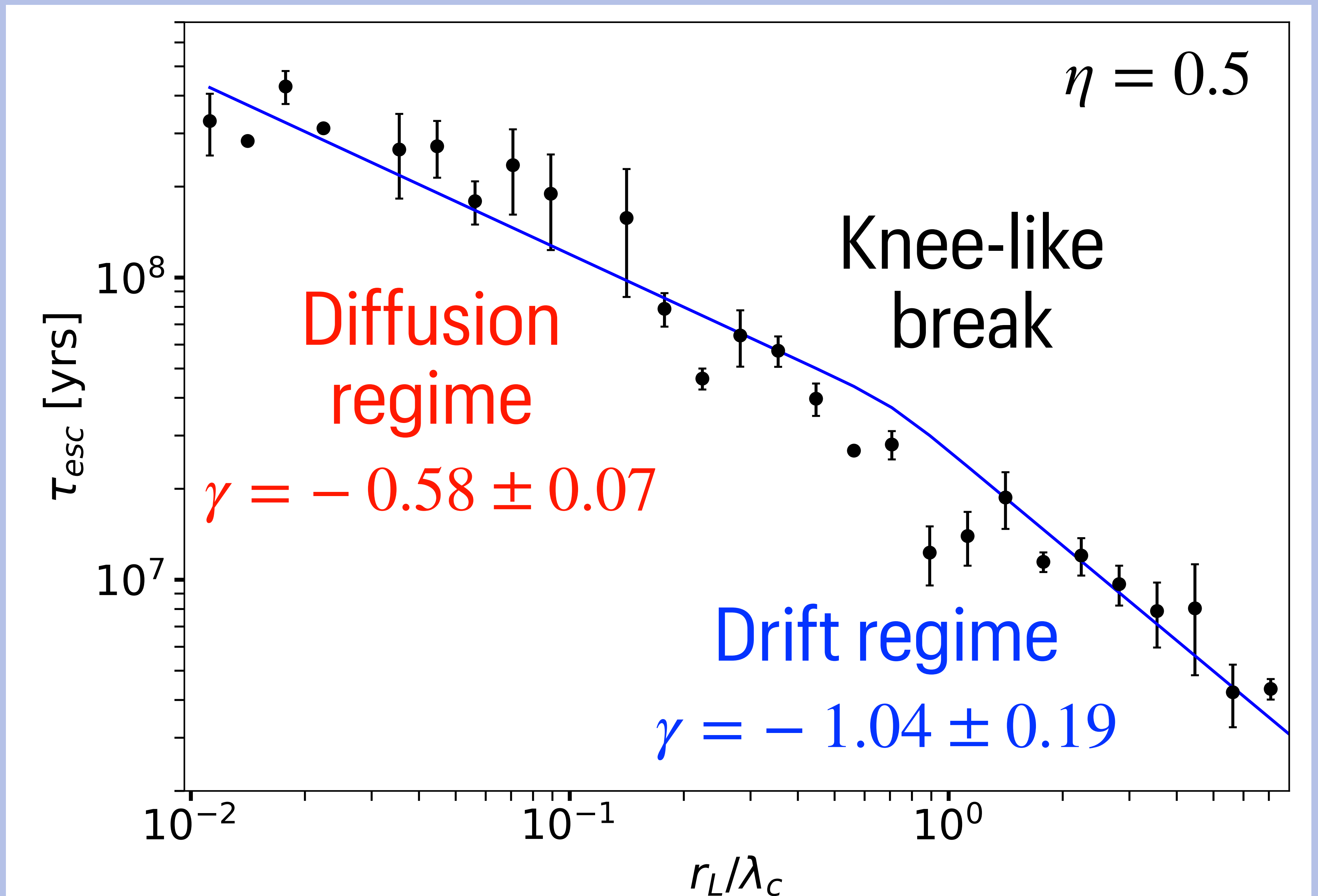


Azimuthal field

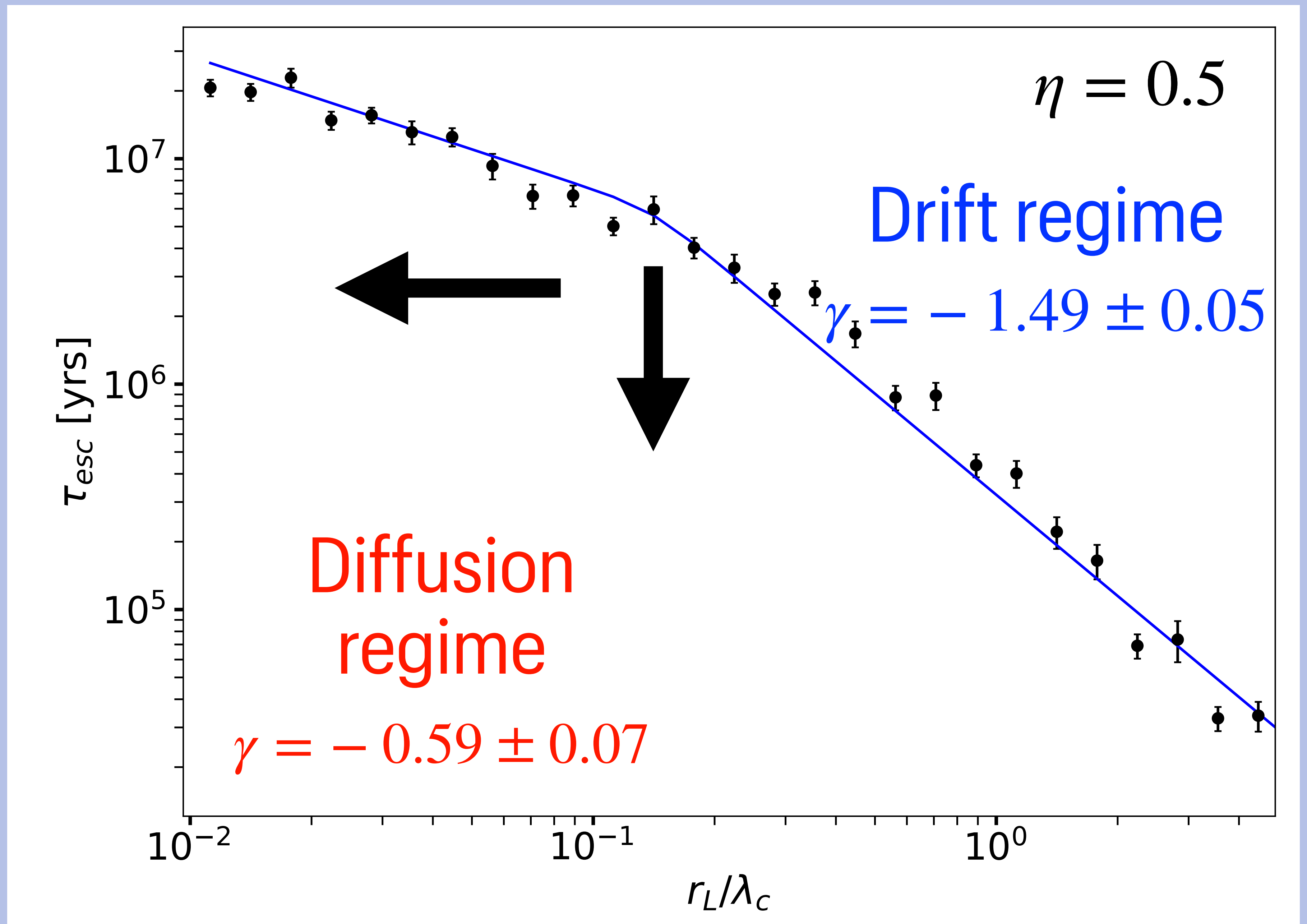




Azimuthal antisymmetric field



Field with vertical component

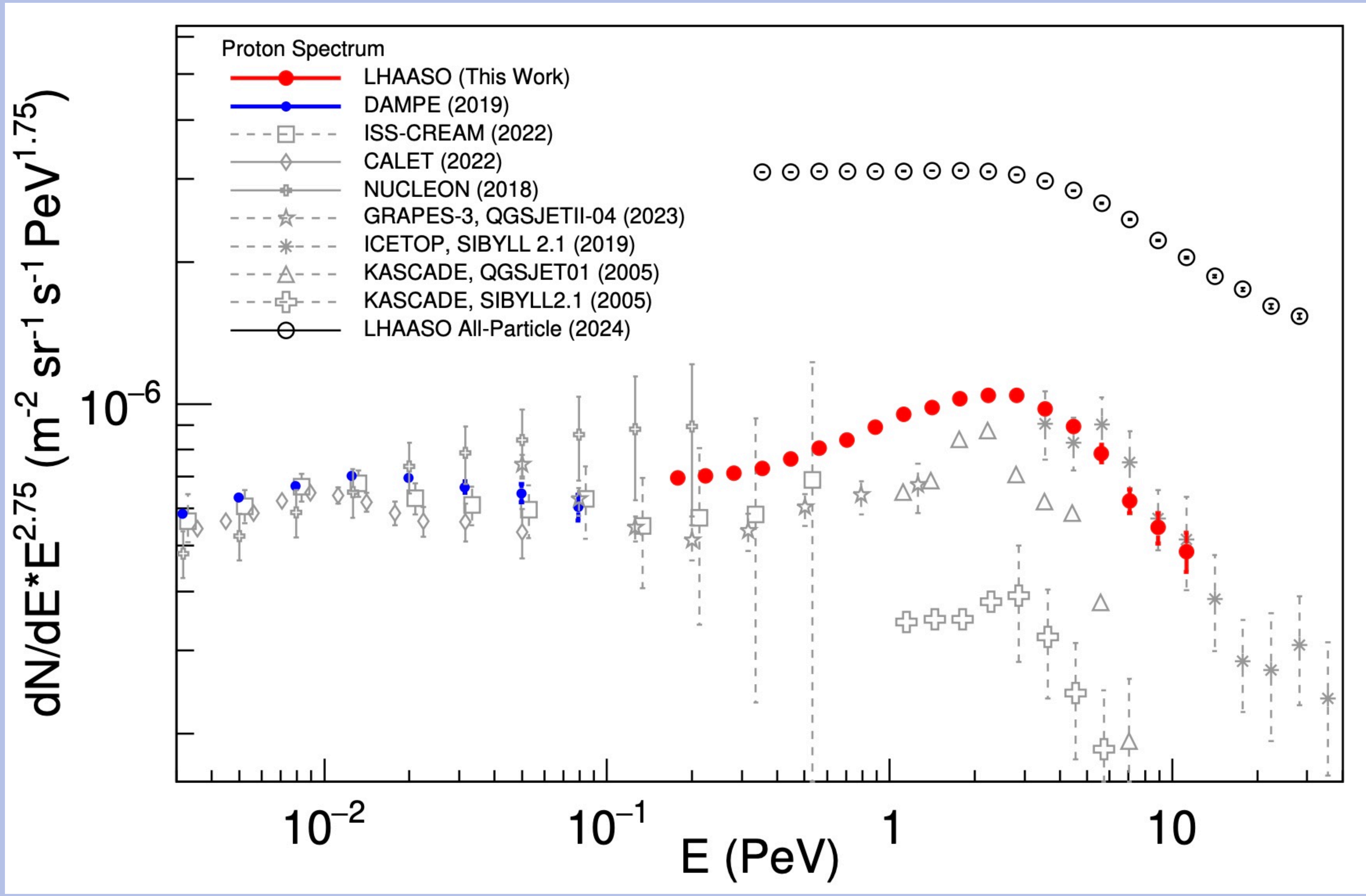


Motivation: LHAASO proton knee

- LHAASO connecting low- (< 100 TeV) and high-energy (> 1 PeV) proton measurements.
- Spectral breaks at $R \sim 300$ GV, $R \sim 10$ TV and $R \sim 10^2$ TV (GRAPES-3).
- Discrepancy of proton flux measurements between ground-based experiments.

Aartsen et al., 2019 (IceTop),
Antoni et al., 2005 (KASCADE),
Finger, 2011 (KASCADE)

LHAASO Coll., 2025



- **Heavy component** $(A > 4)$ added by comparison between all-particle spectrum and sum of proton and helium spectra, assuming spectral shape conserved in rigidity.

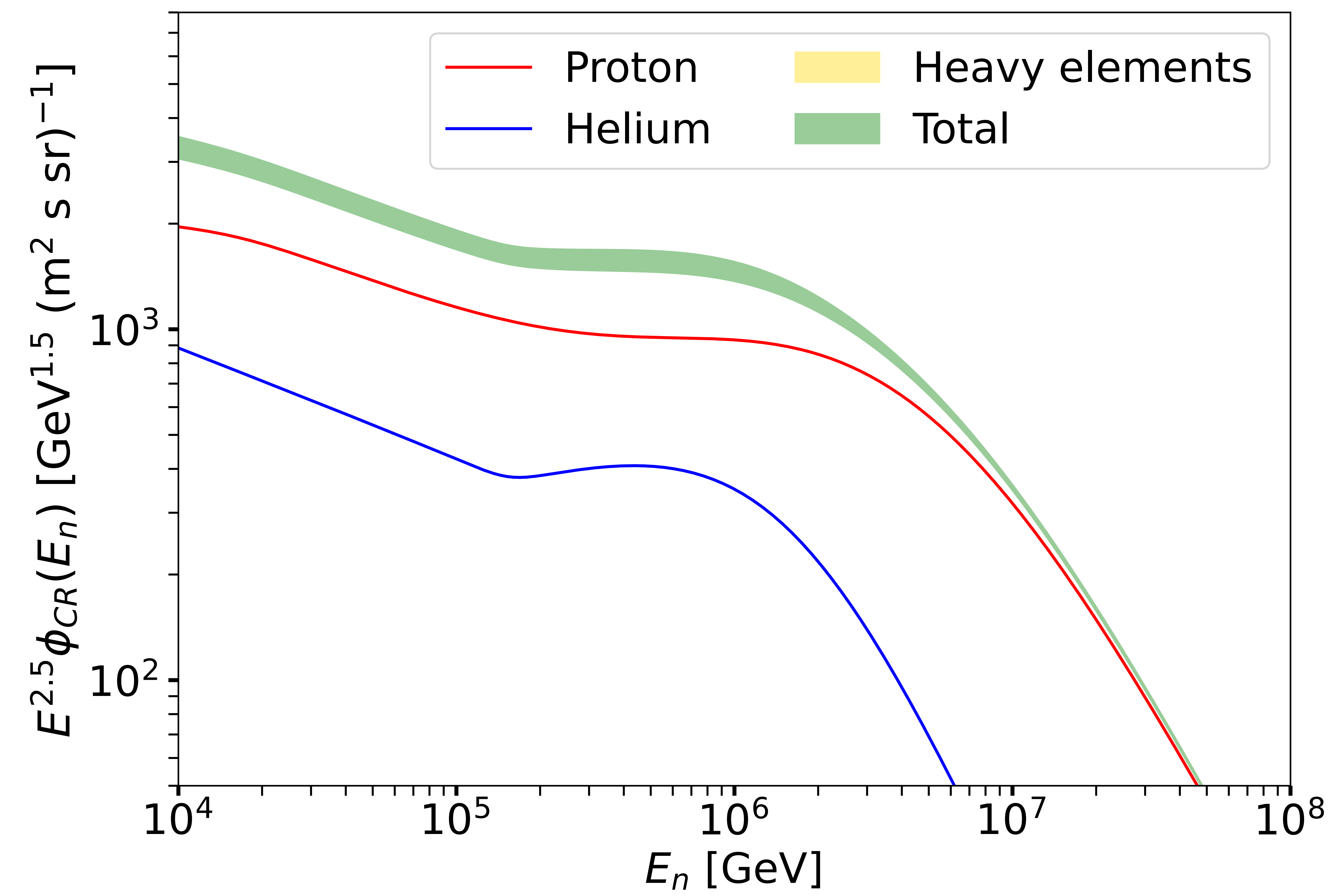
Take-home message:
Diffuse gamma-rays probe the proton flux at the knee

Relevant flux is in energy per nucleon, for which **proton component is dominant**

$$\phi_{\rm CR}(E_n) = \sum_A A^2\, \phi_A(AE_n)$$

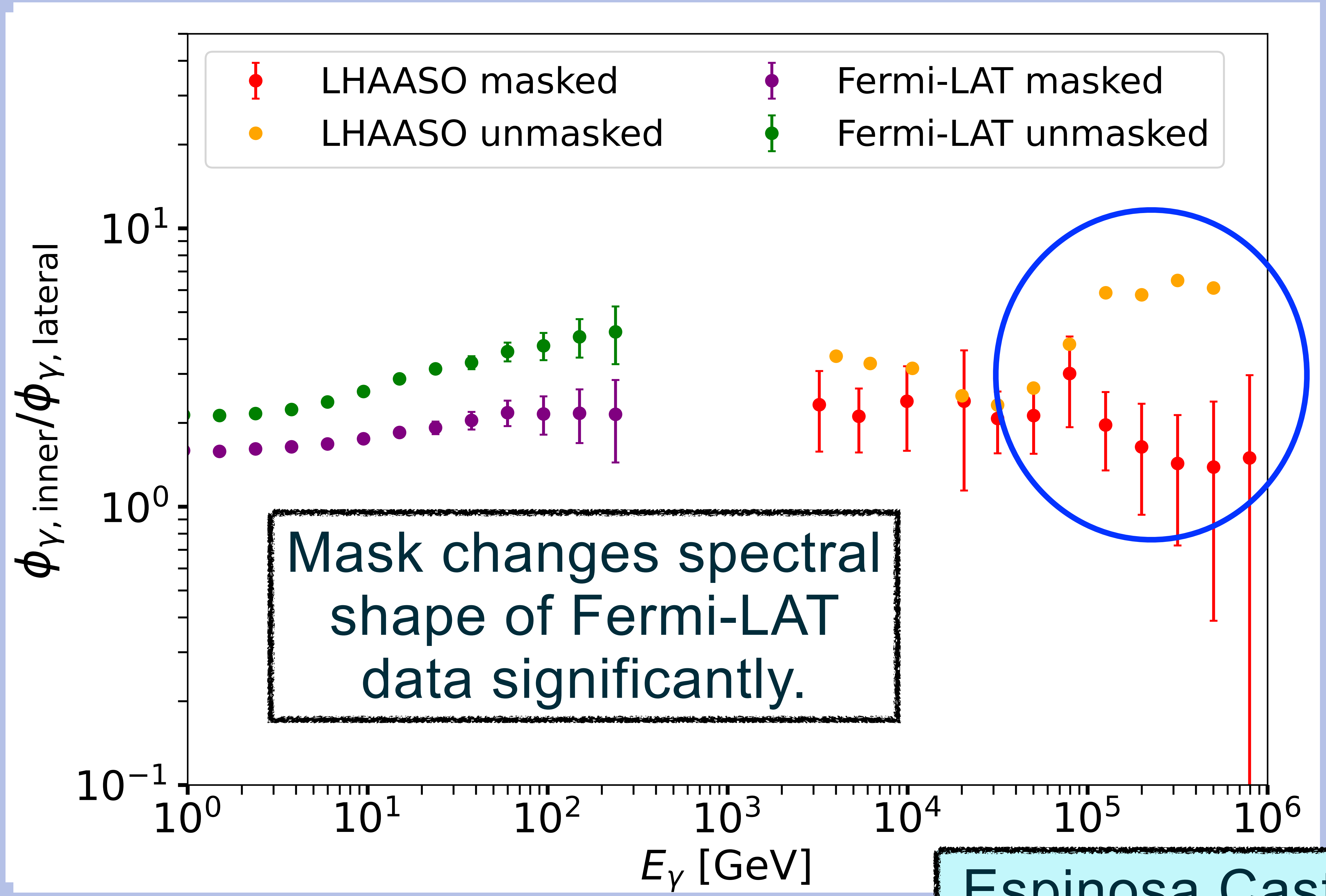
$$\phi_{{\rm CR},\odot}(E_{\rm n}) = \phi_{\rm p}(E_{\rm n}) + (1+k)\,\phi_{\rm He,\,CR}(E_{\rm n})$$

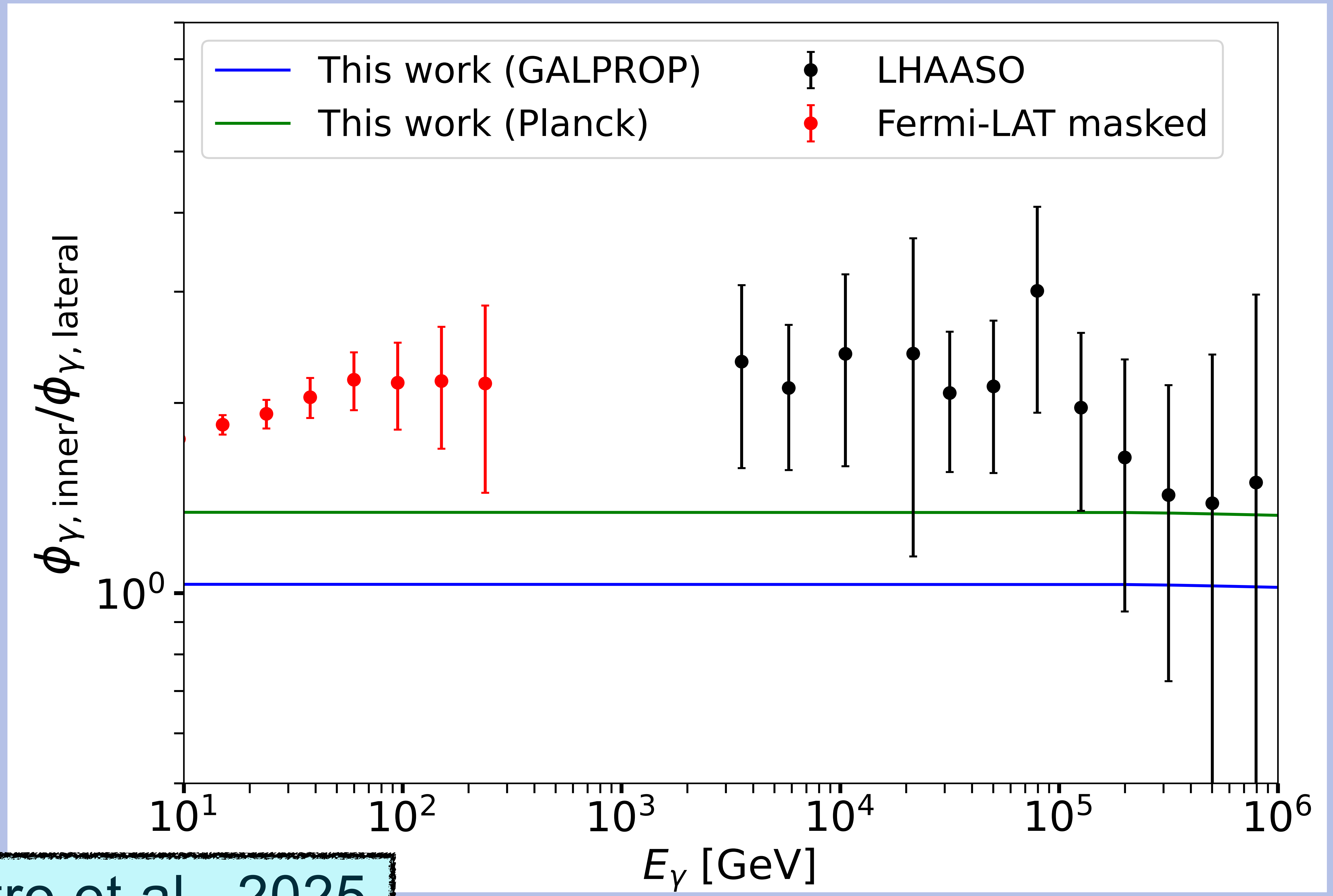
with $$k = \frac{\phi_{\rm heavy}(E)}{\phi_{\rm He}(E)}\left(\frac{A}{A_{\rm He}}\right)^{2-\alpha_1(He)}$$



Approximately energy independent ratio, determined by **number of targets** and **cosmic ray density distribution.**

- Hardening expected from Fermi-LAT data extrapolated to higher energies is incompatible with VHE measurements.
- No distinction from space-dependent to space-independent spectrum in LHAASO regions, possibly due to mask.



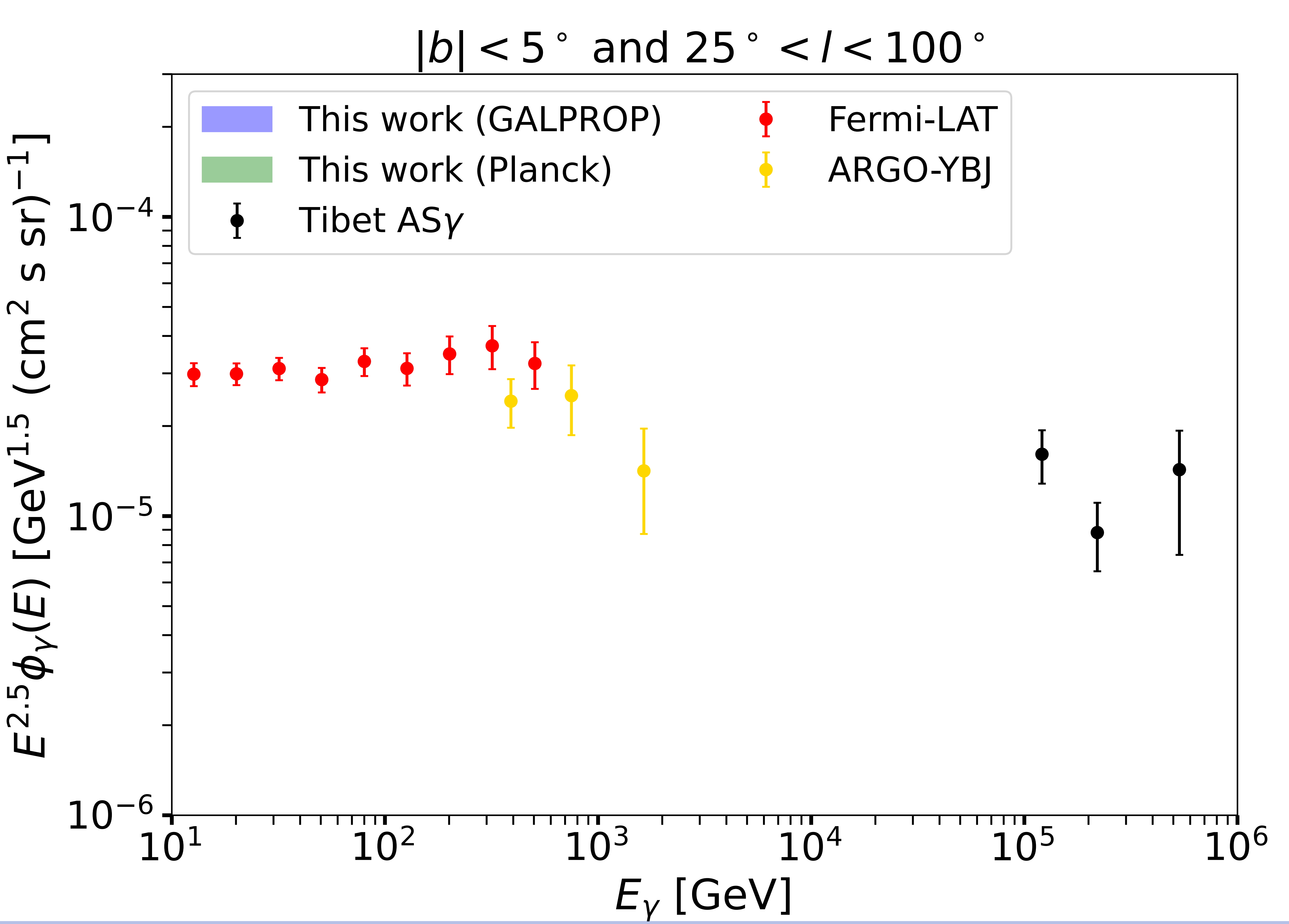


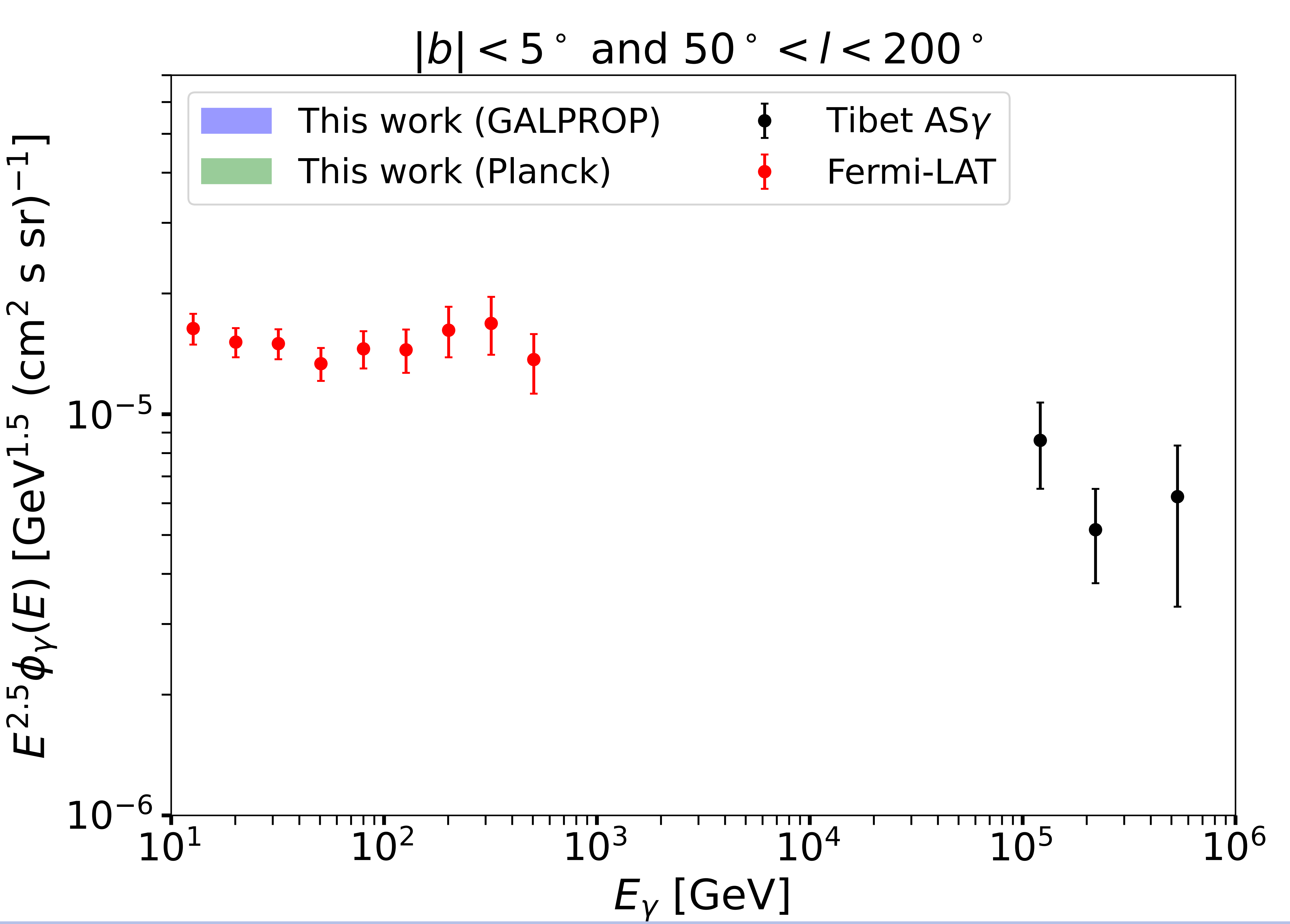
Espinosa Castro et al., 2025

Gamma-ray Diffuse Emission: Comparison with Tibet ASγ

- Underestimation of flux in both regions. Possible contribution of unresolved component.
- Planck column density template $\sim 20\,\%$ lower in inner region and $\sim 25\,\%$ lower in lateral region.

(See also Vecchiotti et al., 2022)





Espinosa Castro et al., 2025

Approximately energy independent ratio, determined by **number of targets** and **cosmic ray density distribution.**

- Hardening expected from Fermi-LAT data extrapolated to higher energies is incompatible with VHE measurements.
- No distinction from space-dependent to space-independent spectrum in LHAASO regions, possibly due to mask.