Modulation of the all-particle spectrum of cosmic rays in an anisotropic diffusion approach

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ICPPA, October 25, 2024

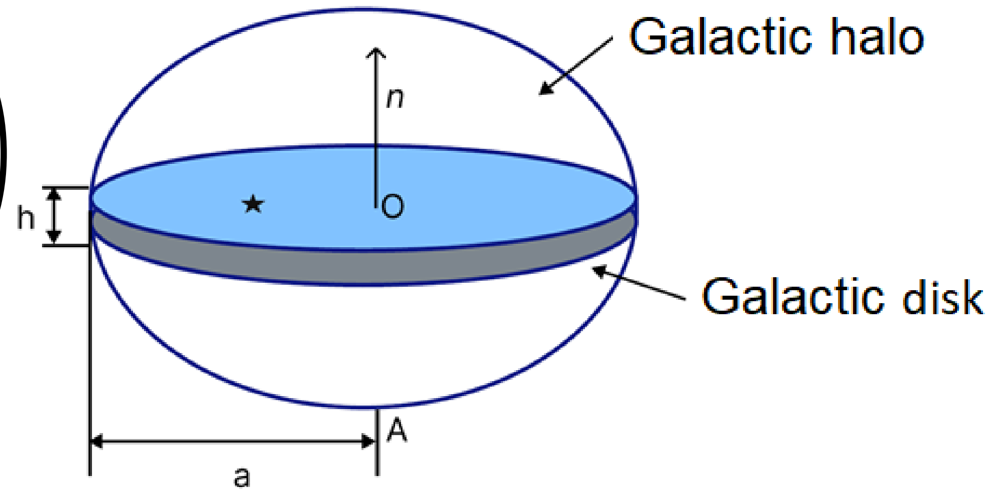
Problem Statement:

- Large inhomogeneities are observed in the spatial distribution of matter and the magnetic field of the Galaxy.
- There is no generally accepted interpretation of the cutoff around $4 \cdot 10^{15}\ eV$ (big knee).
- Recent numerical experiments indicate significant anisotropy of the diffusion tensor and a strong dependency of its components on the magnitude of the large-scale Galactic magnetic field.
- Recent comprehensive studies, including full-sky Faraday rotation measures of extragalactic sources and polarized synchrotron intensity, along with investigations into changes in the CR leakage mechanism from the Galaxy, support the use of an anisotropic diffusion model to describe CR's propagation.

Model. Diffusion equation:

$$\nabla(\widehat{D}\nabla f) = S(R, z)$$

Here, $\widehat{D} = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{pmatrix}$



∇ – Del operator, $S(R, z)$ – Source Distribution Function;

Model parameters:
h = 300 pc, a = 17 kpc — major semi-axis, OA = 9 kpc — Galactic halo height.

Partial differential equations:

$$\frac{\partial}{\partial x_i} D_{ij}(\vec{r}) \frac{\partial}{\partial x_j} f(\vec{r}) = S(\vec{r}),$$

here S (x_j) - concentration of sources at a point $\vec{r} = (x_1, x_2, x_3)$.

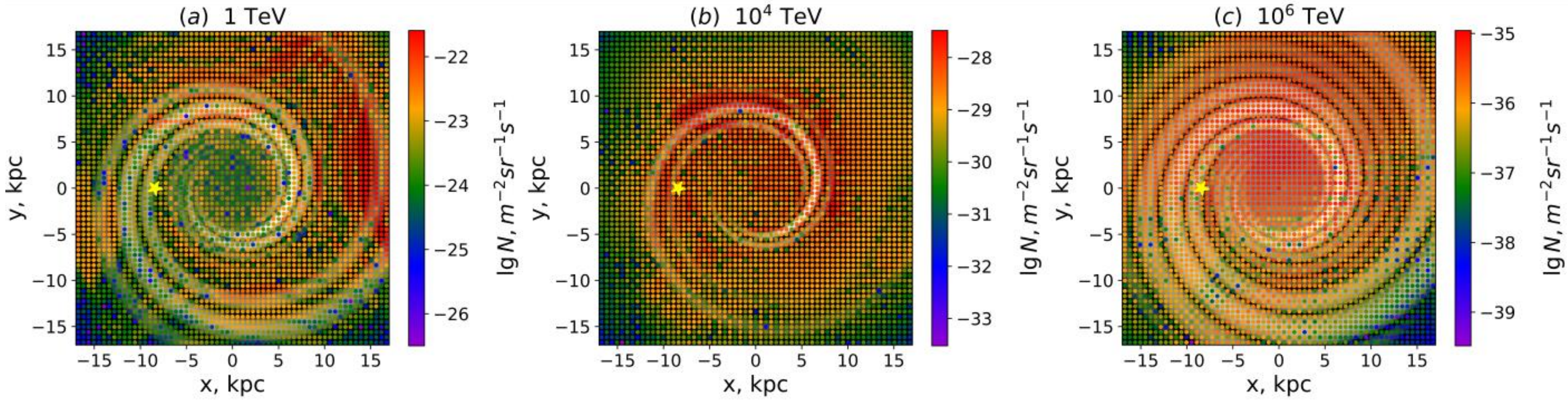
- Expansion of all derivatives to simple terms:

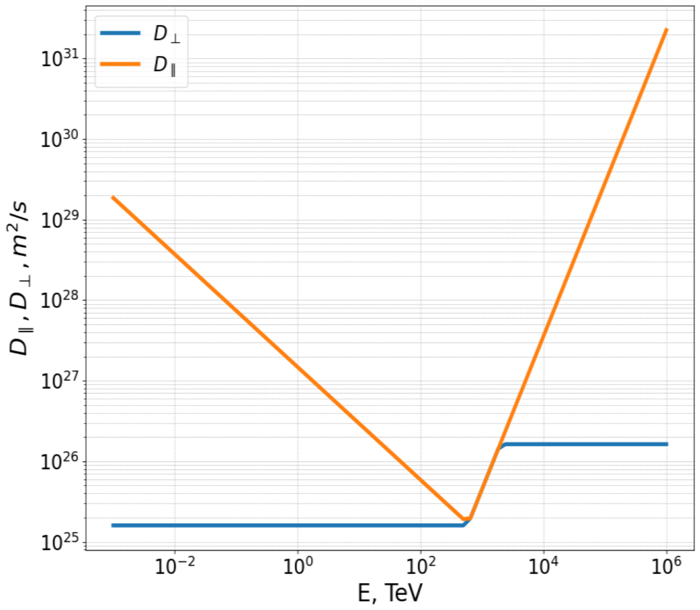
$$\frac{\partial D_{ij}(\vec{r})}{\partial x_i} \frac{\partial f(\vec{r})}{\partial x_j} \quad и \quad D_{ij}(\vec{r}) \frac{\partial^2 f(\vec{r})}{\partial x_i \partial x_j}$$

- Recursive replacement:

$$\frac{\partial g(\vec{r})}{\partial x_i} \to \frac{g(\vec{r} + \overrightarrow{x_i} h_i) - g(\vec{r} - \overrightarrow{x_i} h_i)}{2h_i}$$

Results. GCR concentrations:

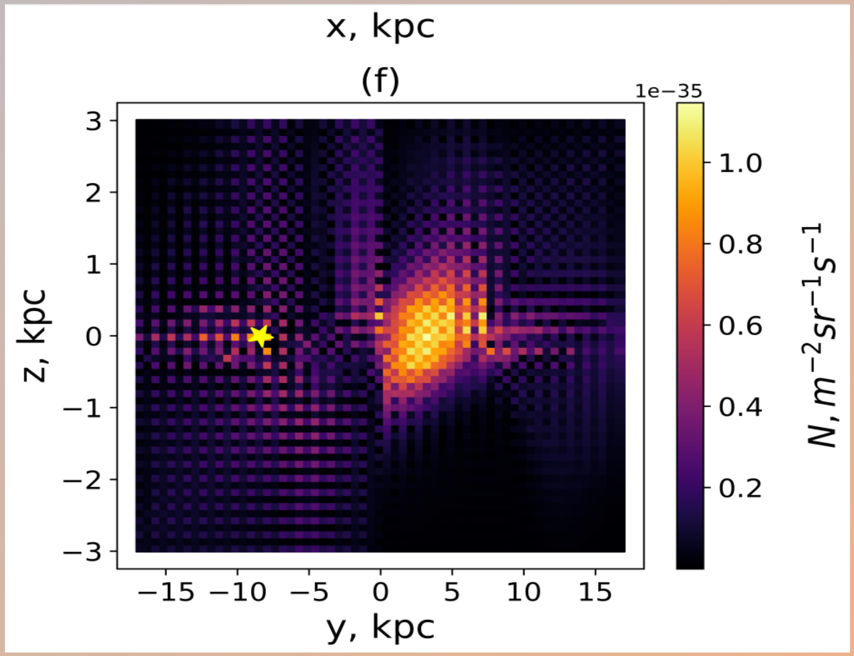


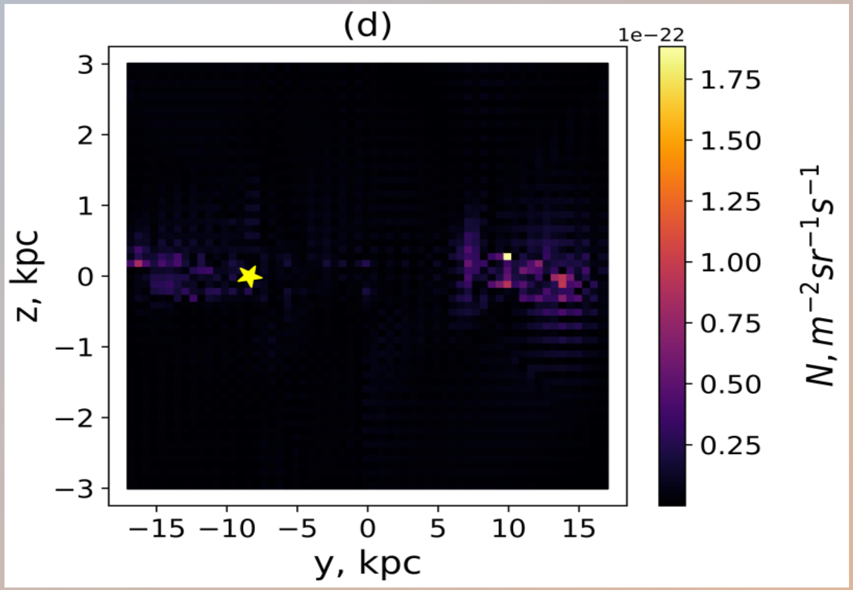


dependence of the GCR concentration on the coordinates in the disk plane z = 0 for different E, TeV. The star marks the position of the Sun.

Directed flows of CR outflow from the disk into the Galactic halo

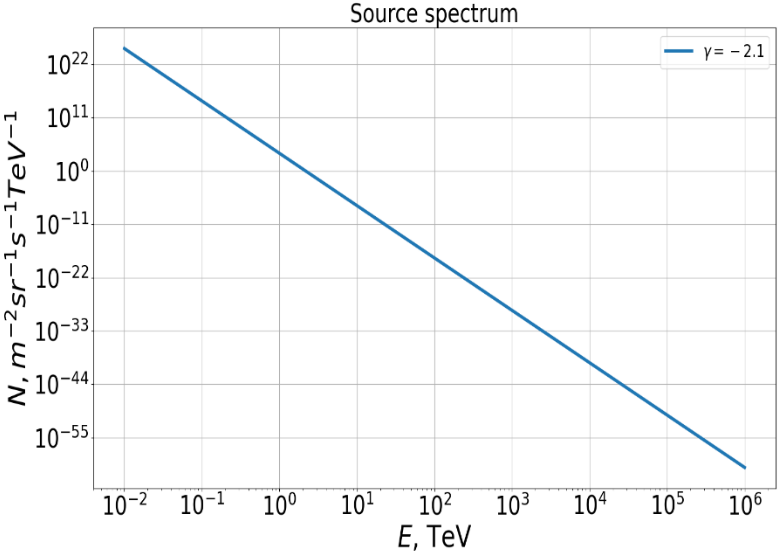
Position of
The Sun

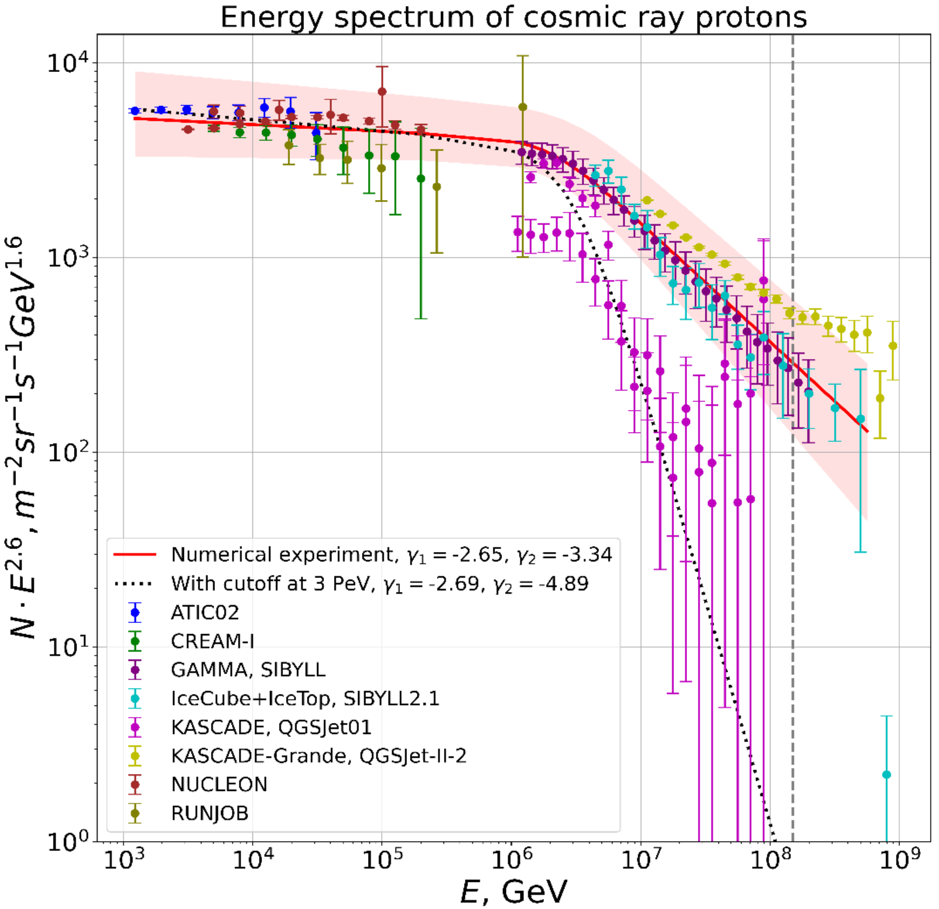




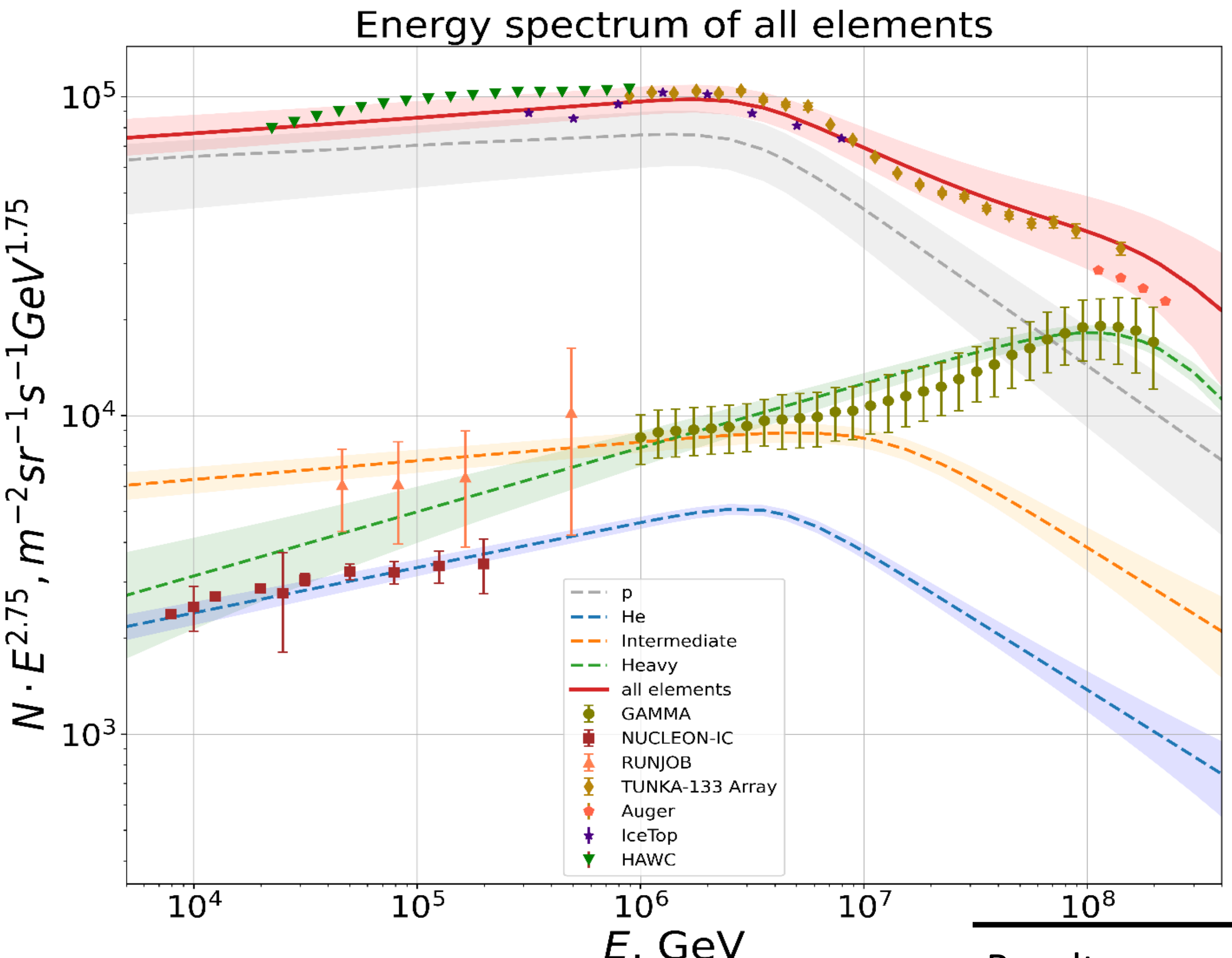
Energy spectrum of protons:

$$F_s(\gamma_1, \gamma_2, N_0, E_o, E) =$$
$$N_0 \left(\frac{E}{E_0}\right)^{-\frac{\gamma_1}{2}} \left(\frac{E}{E_0}\right)^{-\frac{\gamma_2}{2}} \left[\frac{(E_o/E)^{\frac{s}{2}} + (E/E_0)^{\frac{s}{2}}}{2}\right]^{\frac{\gamma_1 - \gamma_2}{s}}$$

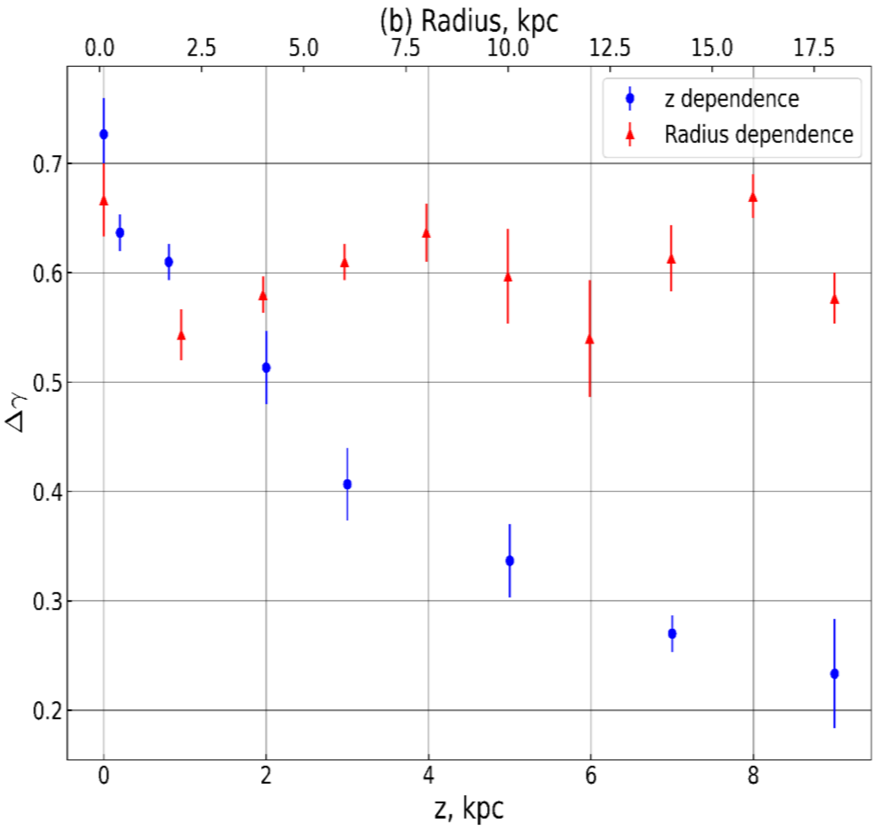


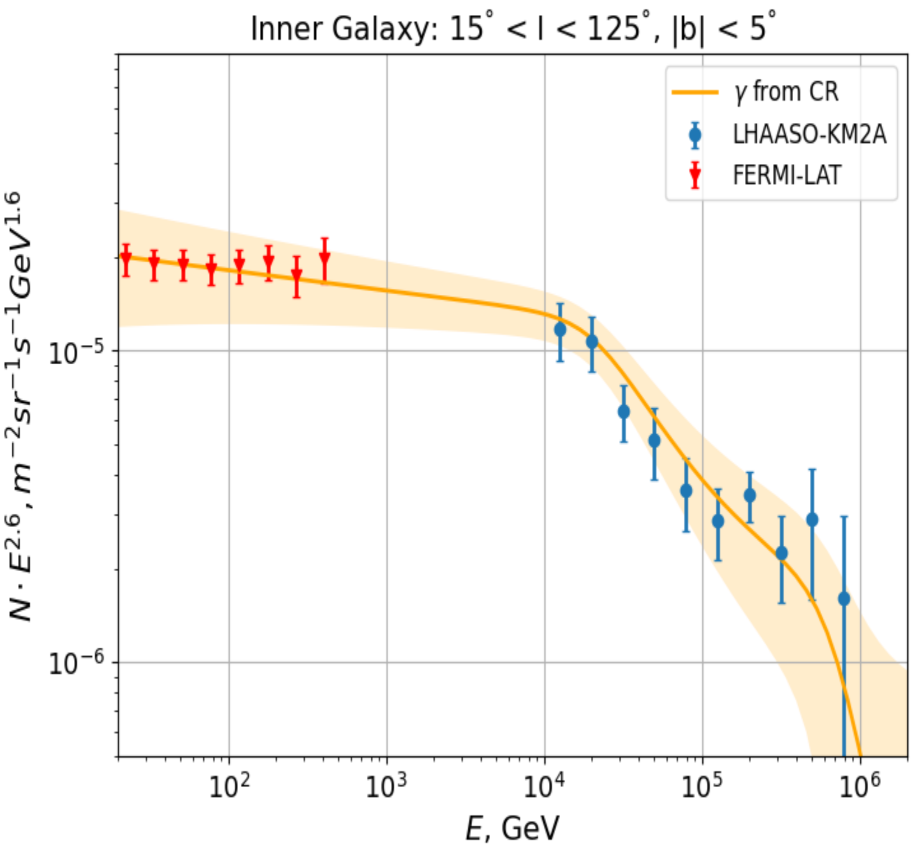


All-particle spectrum:



Spatial modulation:

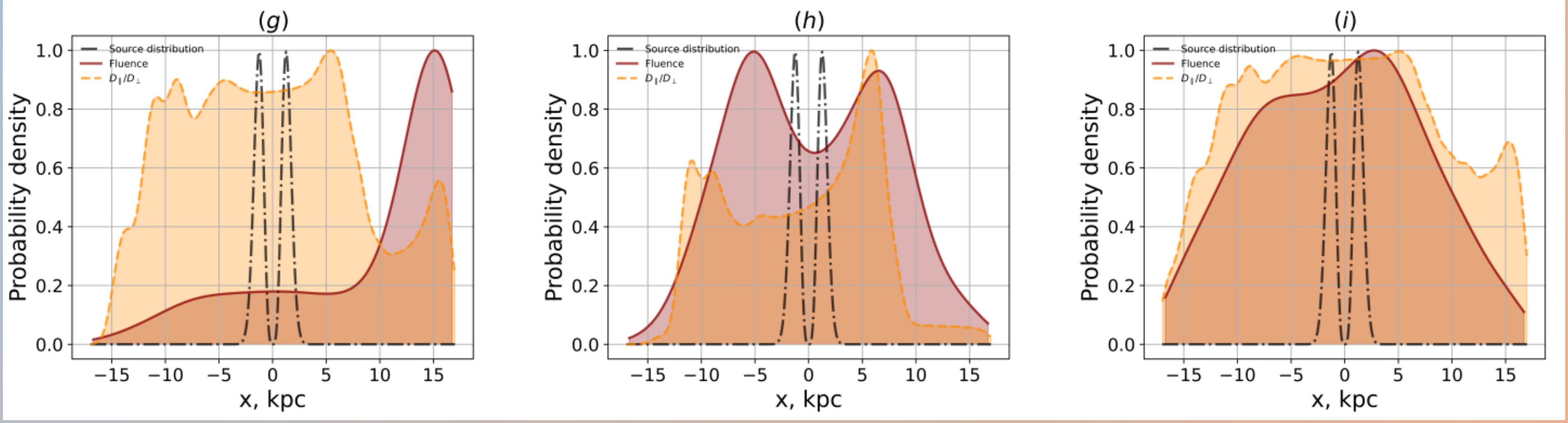




Conclusions:

1. A mathematical model was developed to describe the anisotropic transport of cosmic rays (CRs) with a general tensor form, and a software package was designed to simulate the CR proton concentrations throughout the galaxy;
2. This model describes the modulation effect on the energy spectrum of CR all-particle spectrum, with the break position aligning well with experimental data;
3. The characteristics of the break vary significantly depending on the spatial position within the galaxy, which is consistent with the latest experimental findings and underscores the significant influence of CR transport in interpreting experimental data.

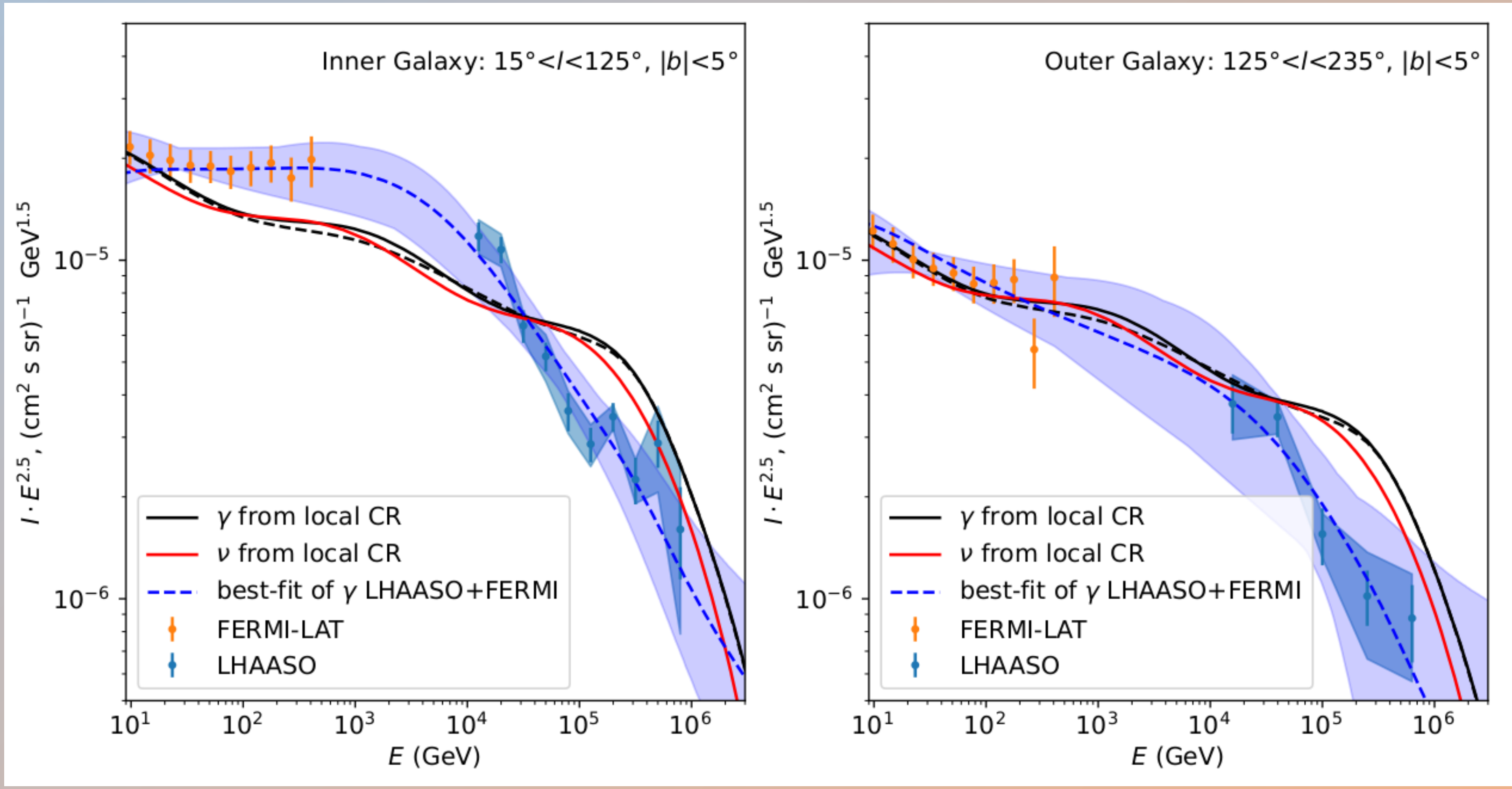
Backup: GCR concentrations:



We hypothesize that the mechanism of CRP leakage from the galactic disk into the halo is intricately linked to the anisotropic diffusion characteristics of CRPs and their complex energy-dependent behavior.

Spatial modulation in the isotropic approach:

C. Prevotat, M. Kachelrieß, S. Koldobskiy, A. Neronov and D. Semikoz, 2024



Magnetic field model:

MICHAEL UNGER & GLENNYS R. FARRAR. 2024

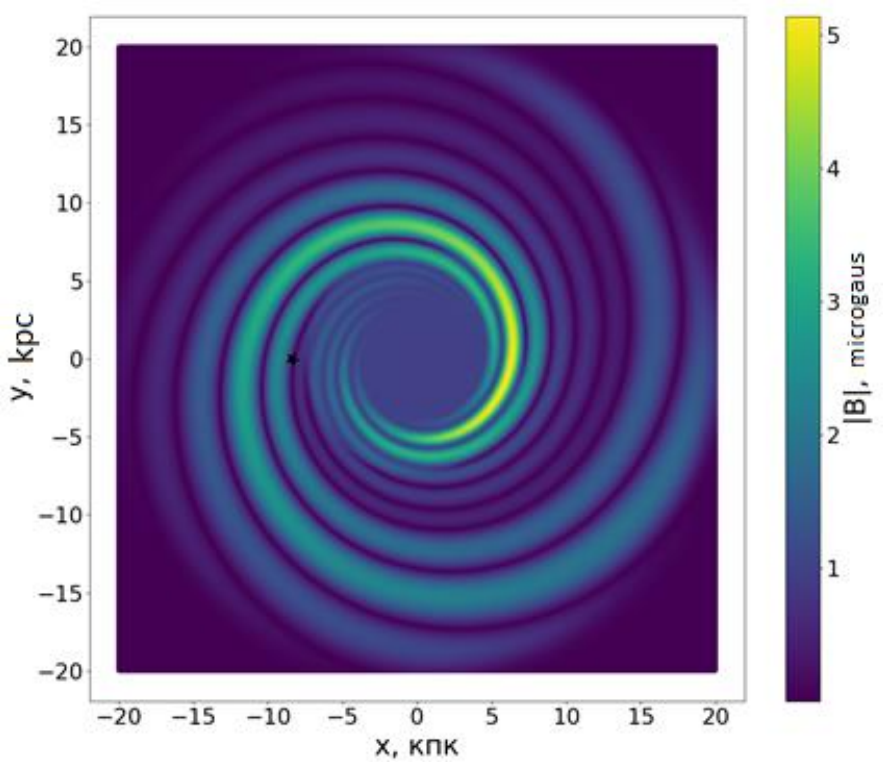
$$B(r_0, \phi_0) = \sum_{m=1}^{n} B_m \cos\left(m(\phi_0 - \phi_m)\right)$$

$$\mathbf{B}_{\mathrm{d}} = (\sin\alpha, \cos\alpha, 0)\,\frac{r_0}{r}\,B(r_0, \phi_0)\,h_{\mathrm{d}}(z)\,g_{\mathrm{d}}(r),$$

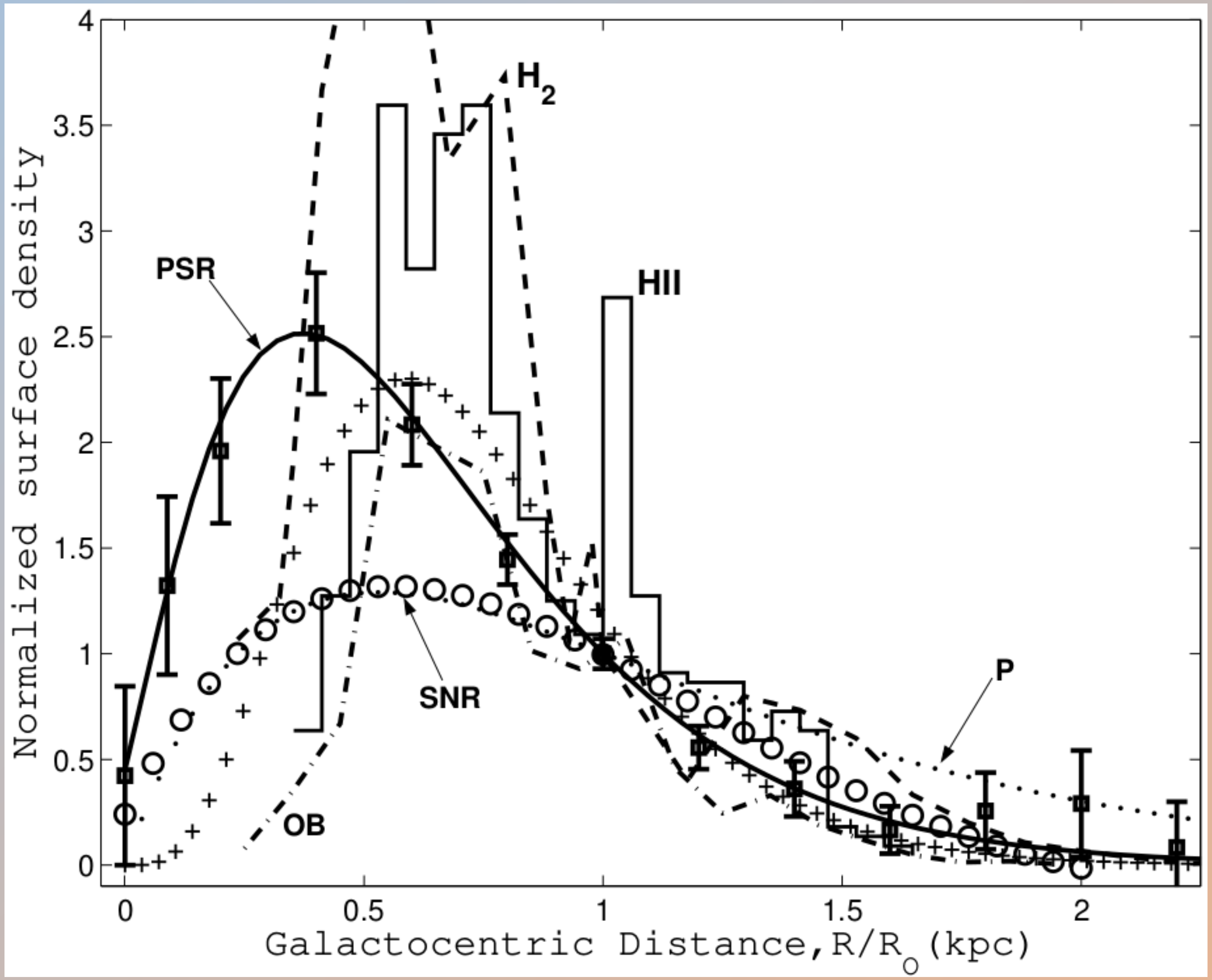
Where,

$$\phi_0 = \phi - \ln(r/r_0)/\operatorname{tg}\alpha.$$

The magnetic field in a cylindrical coordinate system at a point (r, φ, z) is given by the expression:

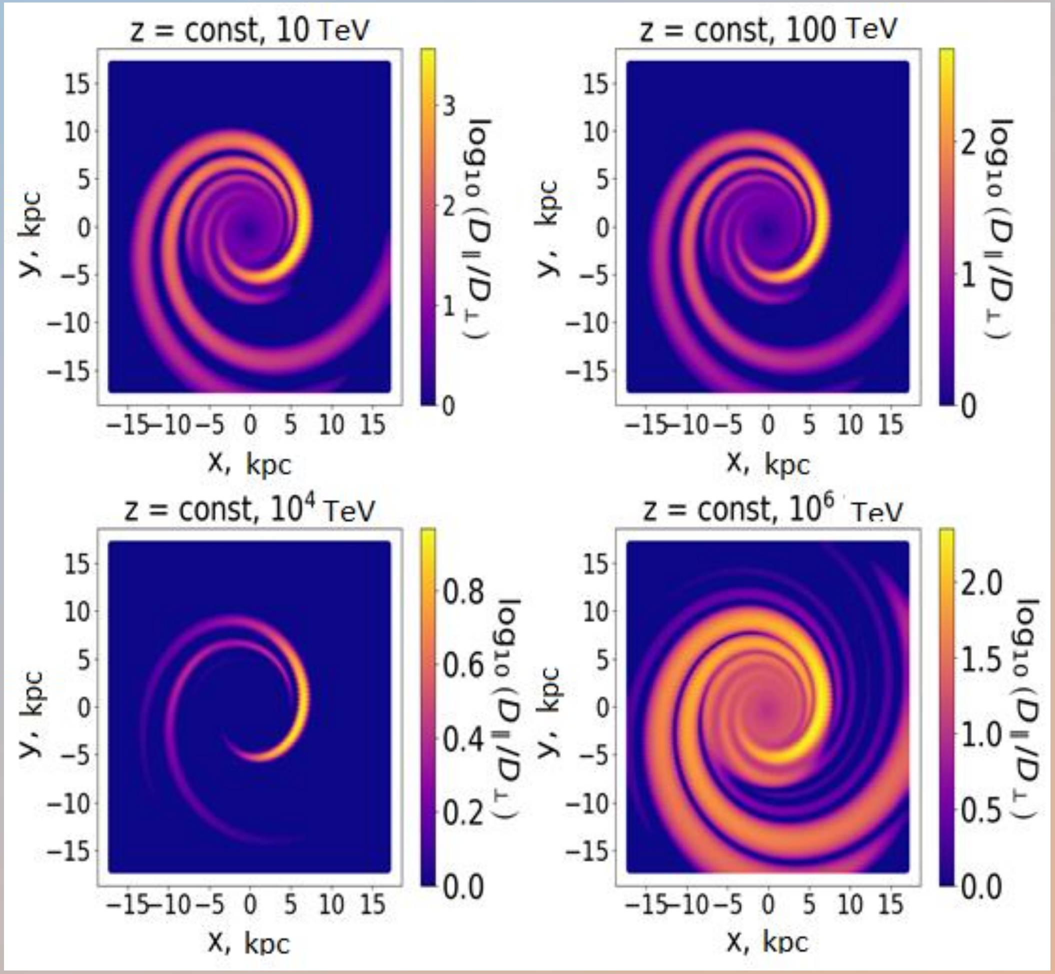


Distribution of sources:



Yusifov I. & Kucuk I. 2004

Energy dependence of the ratio of the diffusion tensor components:



Graphs of the dependence of $log_{10}\left(\frac{D_\parallel}{D_\perp}\right)$ on the coordinates in the disk plane for different E, TeV.