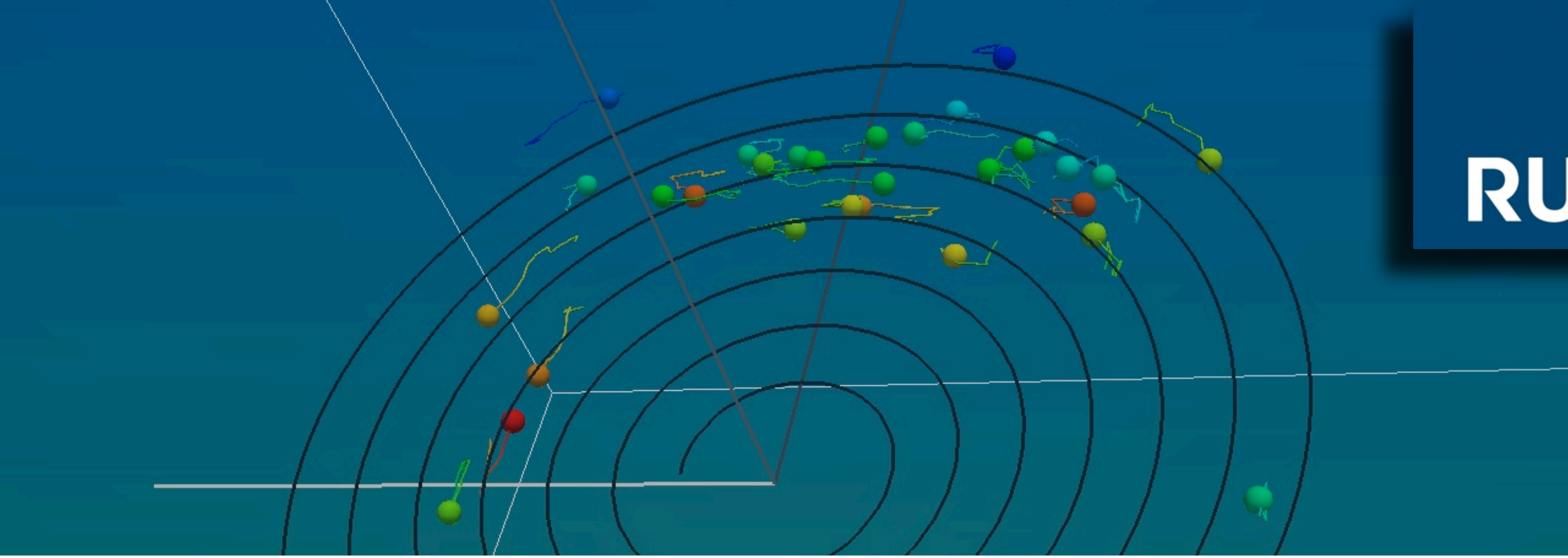

The Long-Term Azimuthal Structure of the Galactic Cosmic Ray Distribution due to Anisotropic Diffusion

Cosmic rays and their interstellar medium environment (CRISM-2011), Montpellier, 30.06.2011

Frederic Effenberger, **Horst Fichtner, Ingo Büsching and Klaus Scherer**

Ruhr-Universität Bochum, FAKULTÄT FÜR PHYSIK
Theoretische Physik IV - Weltraum und Astrophysik

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The Long-Term Azimuthal Structure of the Galactic Cosmic Ray Distribution due to Anisotropic Diffusion

Two faces of the same coin:

Cosmic Ray modulation in the Heliosphere

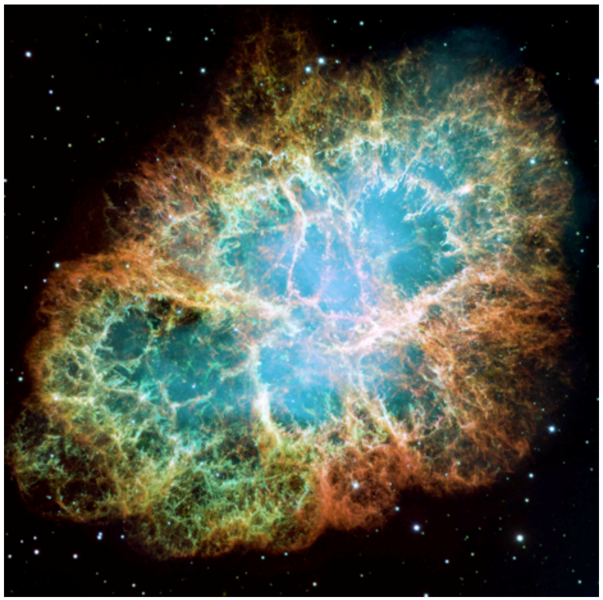
$\Updownarrow$

Cosmic Ray transport in the Galaxy

$$\frac{\partial f}{\partial t} = \nabla \cdot (\hat{\kappa} \nabla f) - \vec{v} \cdot \nabla f + p \left(\frac{1}{3} (\nabla \cdot \vec{v}) + a_\pi \right) \frac{\partial f}{\partial p} + 3 a_\pi f + \frac{q}{p^2}$$

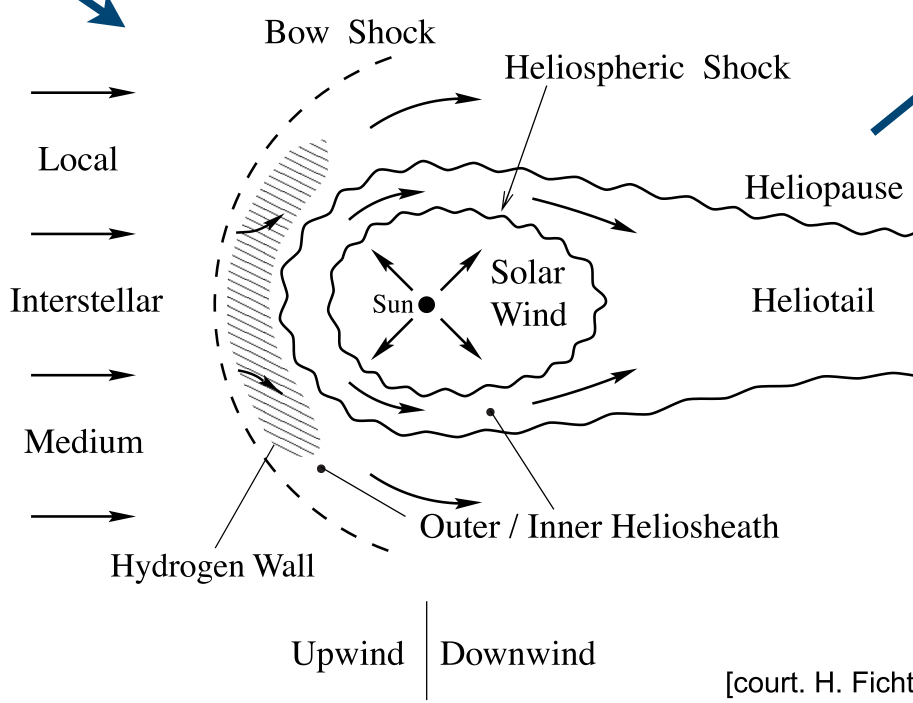
Tracing the Ways of the Cosmic Rays

From CR Sources to Heliospheric Modulation

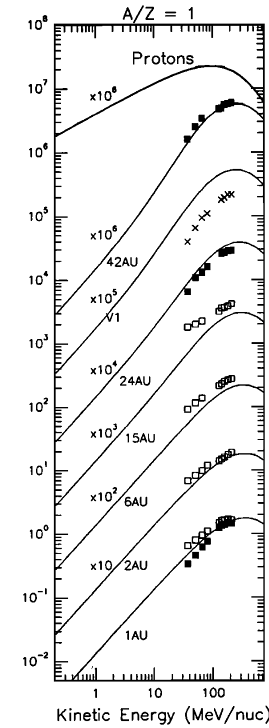


Crab Nebula

$$j = 12.14 \cdot \beta(E_k + 0.5E_0)^{-2.6}$$



[court. H. Fichtner]



[Reinecke et al., 1993, JGR]

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Galactic Propagation
Source Distribution

METASTUDY OF THE SPIRAL STRUCTURE OF OUR HOME GALAXY

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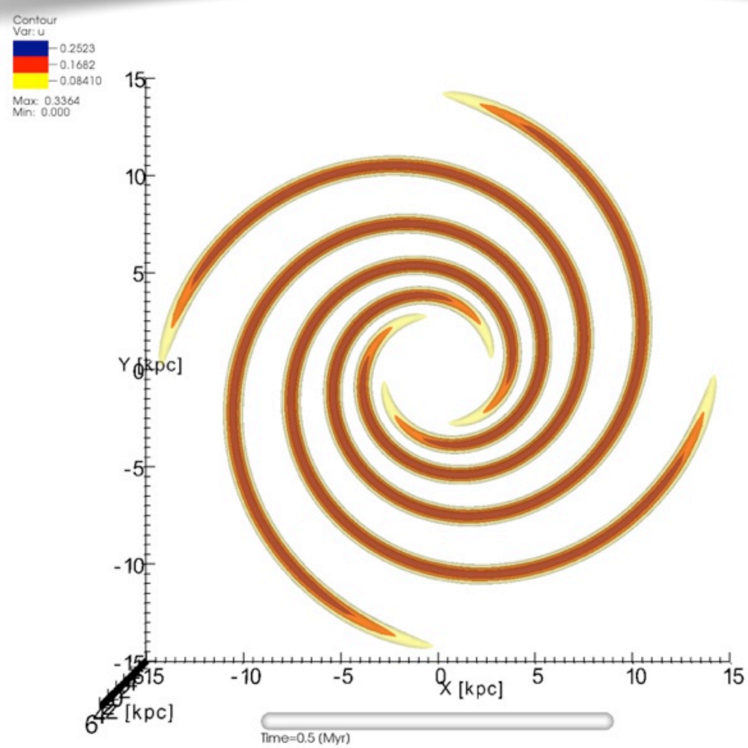
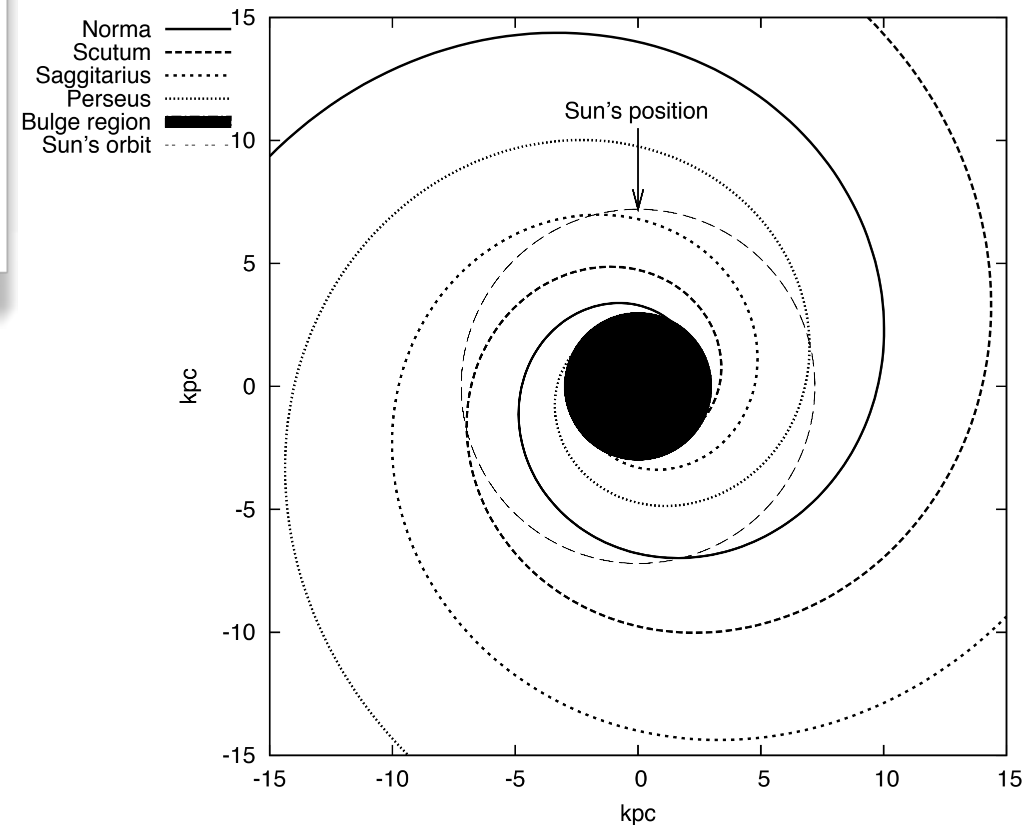
Received 2001 May 7; accepted 2001 October 10

ABSTRACT

The current maps of the Milky Way disk still have large differences, much like early maps of the Earth's continents made in the 16th century had sizeable differences in the locations of continents and many areas labeled "terra incognita." Exactly where are the spiral arms in our home Galaxy (in radius and longitude)? Here a meta-analysis is made of the recent (1995–2001) observational data on the pitch angle (p) and the number (m) of spiral arms in our home Galaxy. In order to clarify our image of the structure of the Milky Way, logarithmic model arms of the form $\ln(r/r_0) = k(\theta - \theta_0)$ are fitted to the observed tangents to the spiral arms and to the observed position angle (P.A.) of the Galaxy's central bar. The main results are that $p = 12°$ inward and $m = 4$, with logarithmic spiral arm parameters $r_0 =$ 2.3 kpc and $\theta_0 = 0°$ for the Norma arm. The value of θ_0 for the other three arms is modeled by rotating the Norma arm in steps of 90°. These values are similar to those found by Ortiz & Lépine using earlier

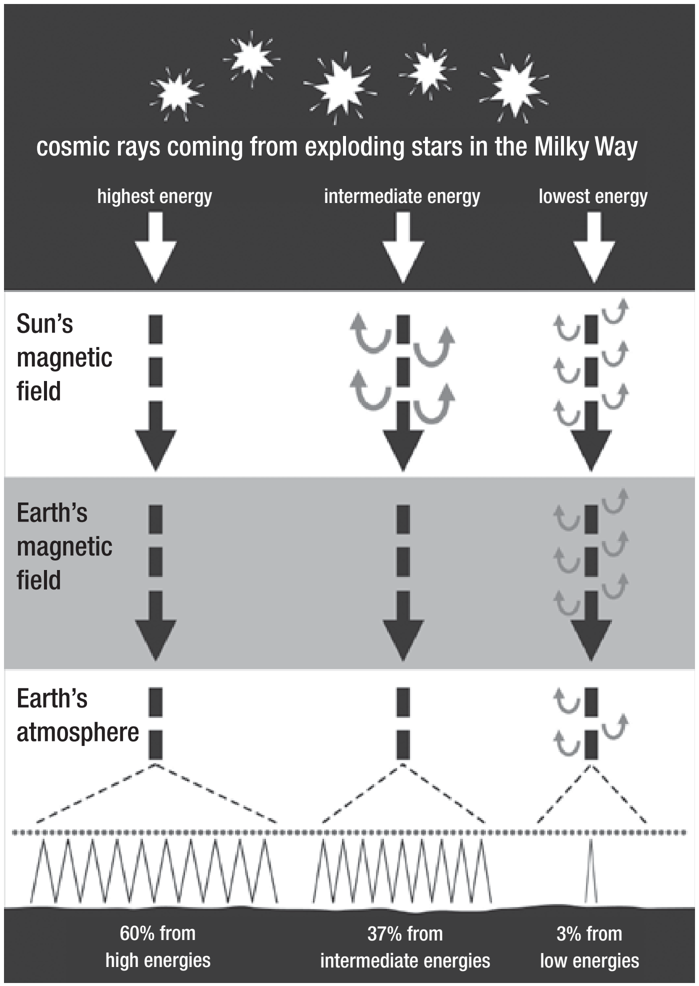
A logarithmic spiral-arm pattern
[Vallée, 2002, ApJ]



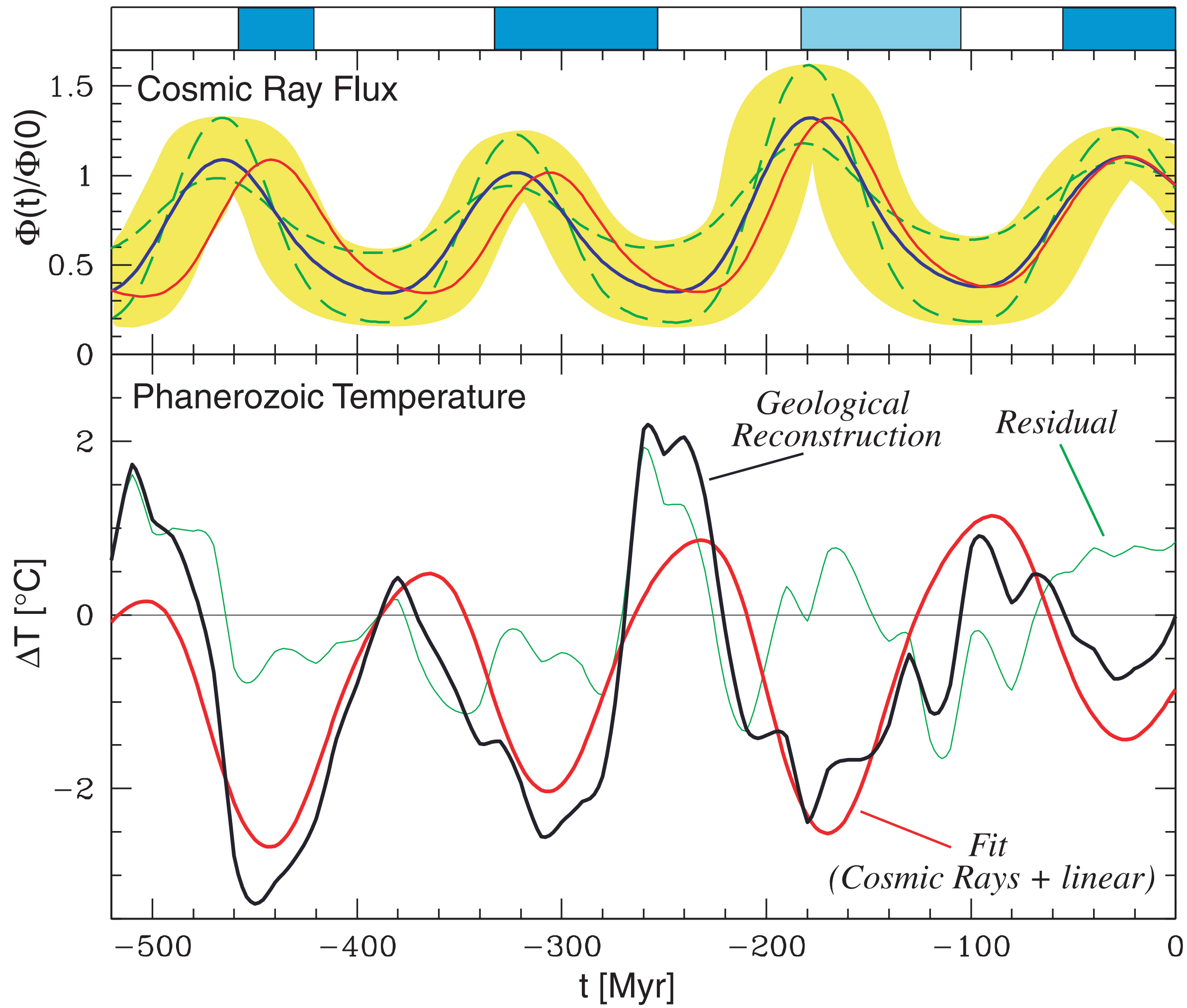


$$Q \propto p^{-s}$$

Galactic Propagation
A possible „Cosmic Ray - Climate“ Connection



[Svensmark, 2007, Astronomy & Geophysics]



[Shaviv & Veizer, 2003, GSA Today]

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Galactic Propagation
Galactic Magnetic Fields

M51 [Fletcher & Beck, MPIfR]

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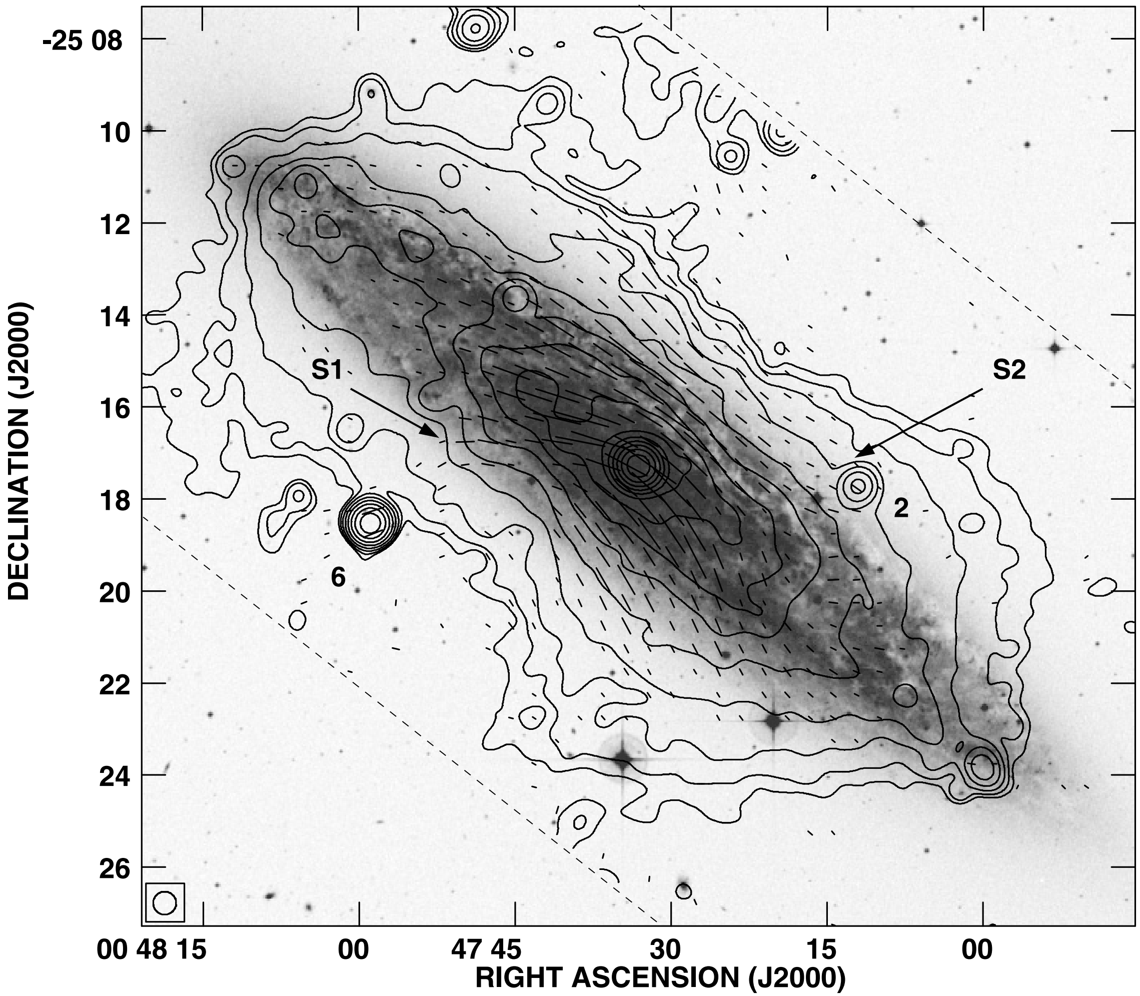
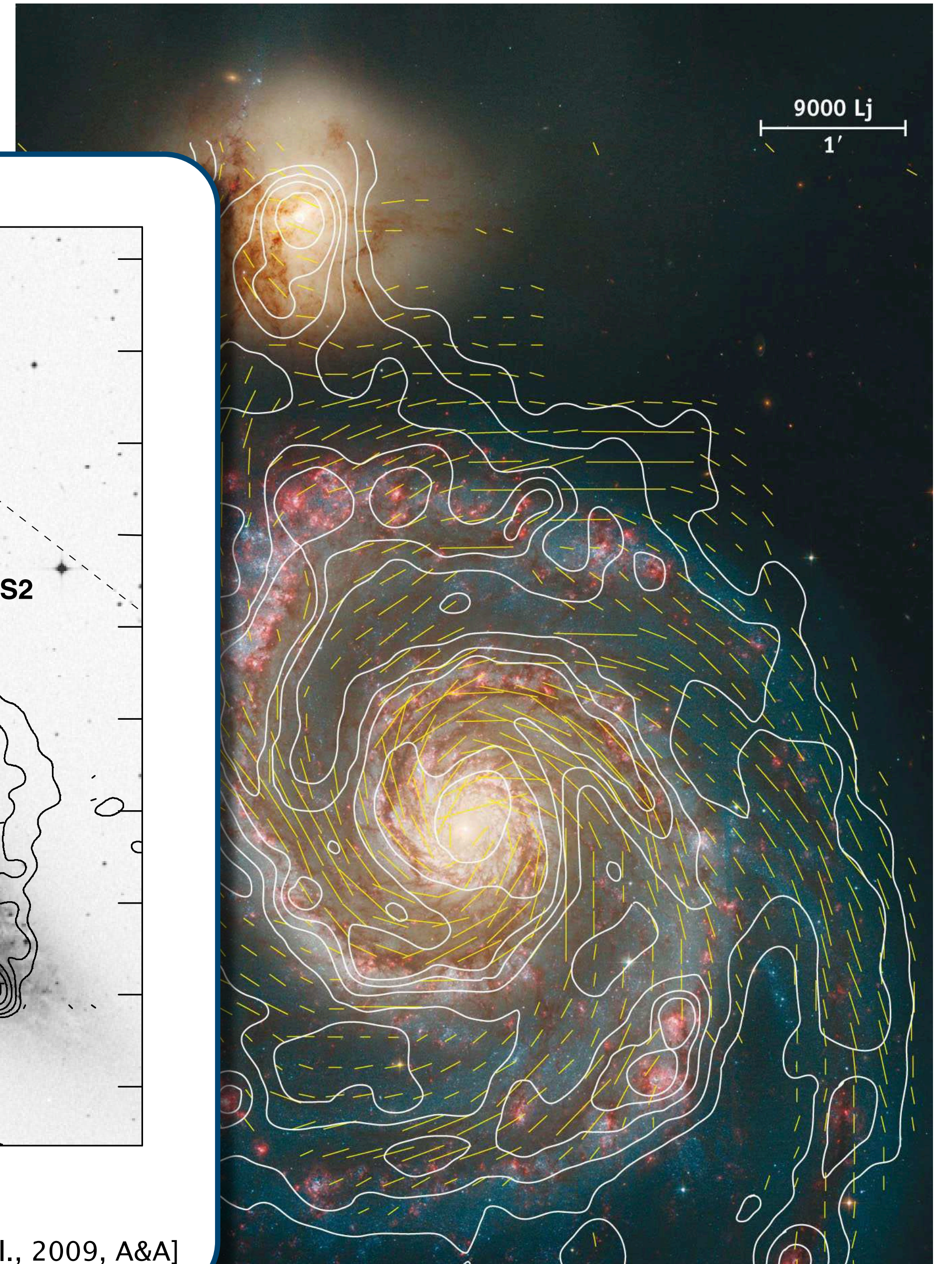
Galactic Propagation
Galactic Magnetic Fields



NGC 253 [Heesen et al., 2009, A&A]



M51 [Fletcher & Beck, MPIfR]

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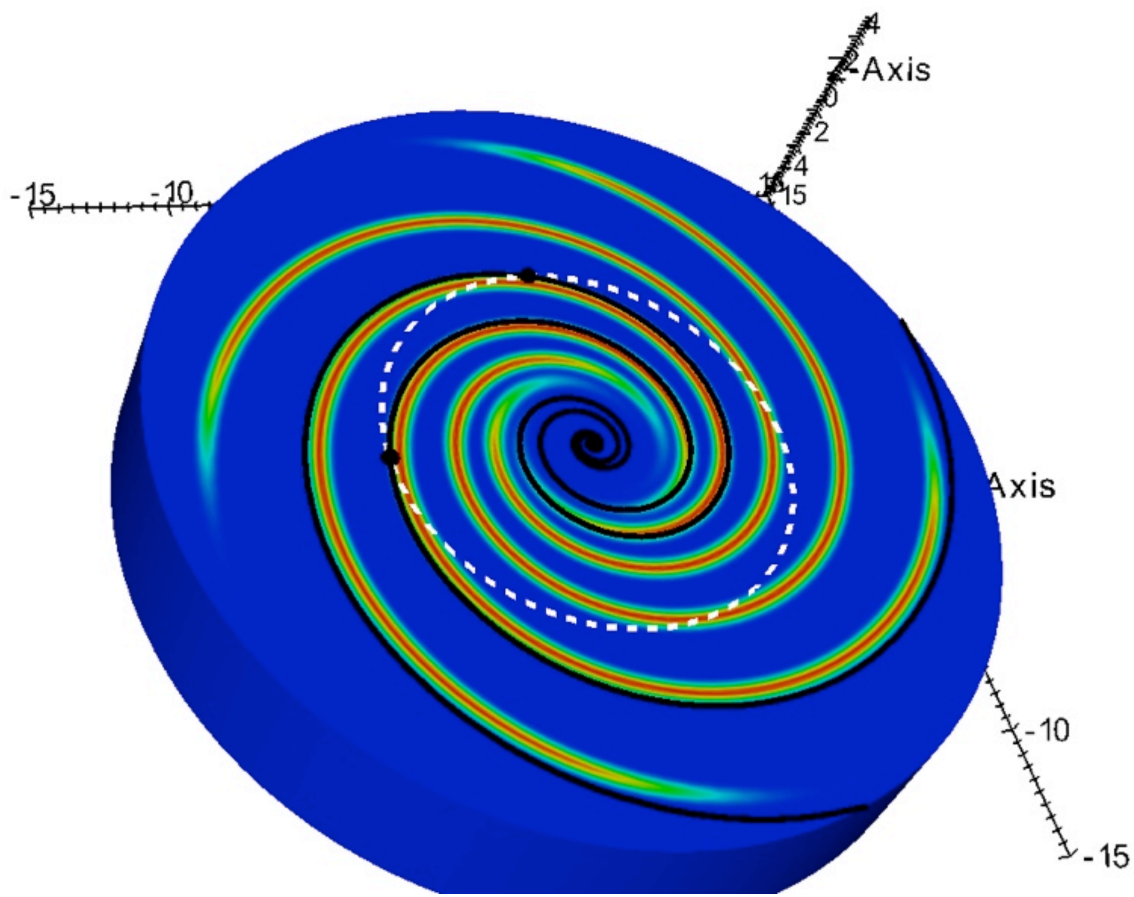
Galactic Propagation
Galactic Magnetic Fields

$$B_r^D = \gamma \frac{1}{r} \cdot exp(-|z|/z0)\, sin(p)$$
$$B_\varphi^D = \gamma \frac{1}{r} \cdot exp(-|z|/z0)\, cos(p)$$

1/r logarithmic spiral field aligned to the source distribution



Galactic Propagation
Adiabatic Losses

$$-\left(\frac{d\gamma}{dt}\right)_\pi (1 \ll \gamma \leq 3000) = 1.4 \times 10^{-16}[n_{HI}(\mathbf{r}) + 2n_{H_2}(\mathbf{r})] \times A^{-0.47}\gamma^{1.28}s^{-1}$$

Pion losses [Schlickeiser, 2002, p. 128]

$$\left(\frac{1}{3}(\nabla \cdot \vec{v}) + a_\pi\right)\frac{\partial f}{\partial p}$$

$$a_\pi \approx 4.5 \cdot 10^{-3}\,1/\mathrm{Myr}$$

$$\nabla \cdot \mathbf{v} \approx 100\,\mathrm{km/s}/10\,\mathrm{kpc}$$

$$\approx 10^{-2}\,1/\mathrm{Myr}$$

$$\Rightarrow a_\pi \approx \frac{1}{3}(\nabla \cdot \mathbf{v})$$

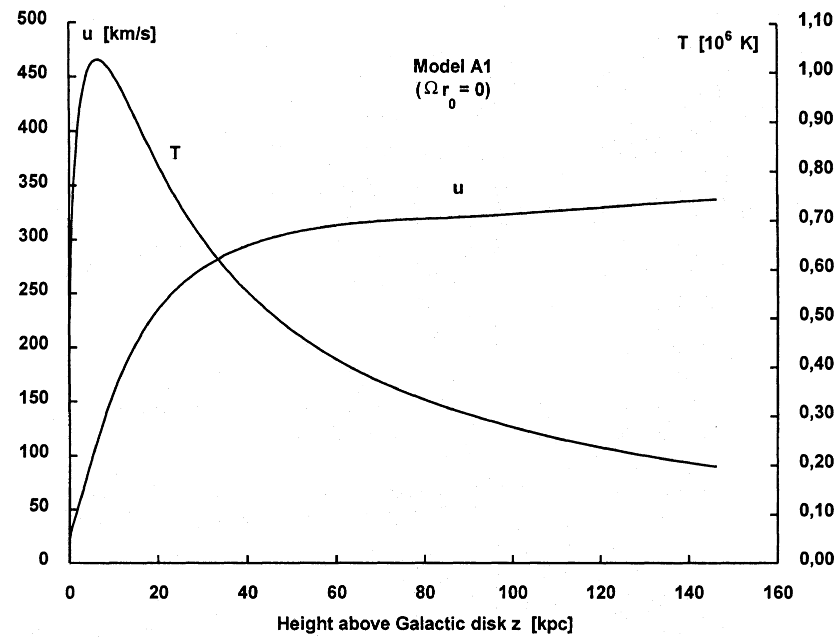


Fig. 4. Variation of the wind velocity and the gas temperature with distance z from the disk for the reference model but without rotation (model A1). The initial cosmic ray pressure, mass density, and meridional magnetic field strength are $P_{c0} = 2.0\,10^{-13}$ erg/cm^3, $\rho_0 = 1.27\,10^{-27}$ g/cm^3, $B_0 = 1.0\,10^{-6}$ G, respectively. The calculated value of the initial velocity is $u_0 = 23.29$ km/s, and the critical points are at $z_a = 8.58$ kpc, $z_f = 14.4$ kpc. The terminal velocity is $u_f = 484$ km/s

1d galactic wind model
[V N Zirakashvili, D Breitschwerdt, Vladimir S Ptuskin, and H J Voelk, 1996, A&A]

Two Questions,
Two Complementary Numerical Tools

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Two Questions, Two Complementary Numerical Tools

- Astrophysical Question:

What is the spatial distribution (and temporal dependence) of the cosmic ray intensity in the galaxy?

- Heliophysical Question:

How are the cosmic rays modulated on their way from the heliospheric boundary to earth?

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Two Questions, Two Complementary Numerical Tools

- Astrophysical Question:

What is the spatial distribution (and temporal dependence) of the cosmic ray intensity in the galaxy?

- Heliophysical Question:

How are the cosmic rays modulated on their way from the heliospheric boundary to earth?

- Grid-Based Numerics: DuFort-Frankel, VLUGR3 ...

Solving the CR-Transport Equation directly on a numerical grid via finite differences

- Stochastic Differential Equations (SDE)

Solve a SDE equivalent to the Transport Equation by tracing pseudo-particles

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Anisotropic Diffusion

How to construct a Diffusion Tensor

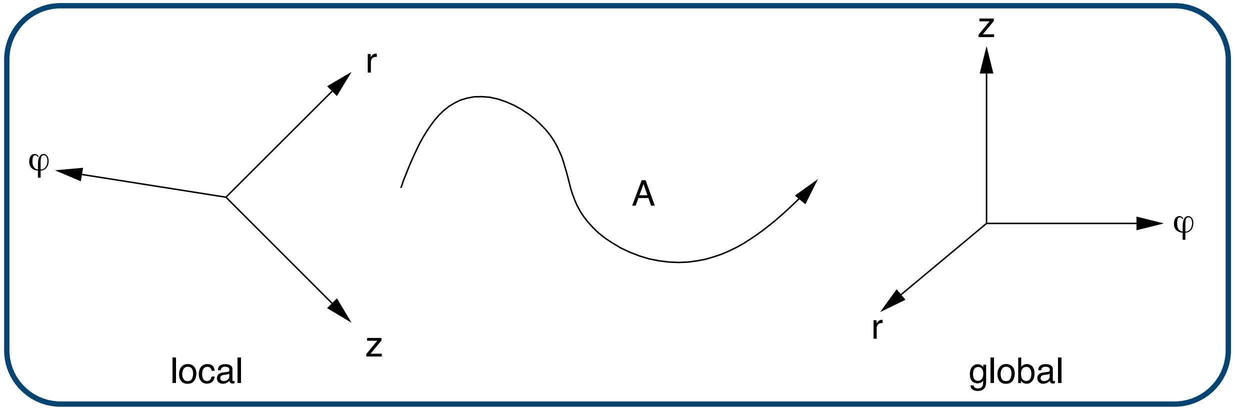
$$\frac{\partial f}{\partial t} = \nabla \cdot (\hat{\kappa}\, \nabla f)$$

local Tensor

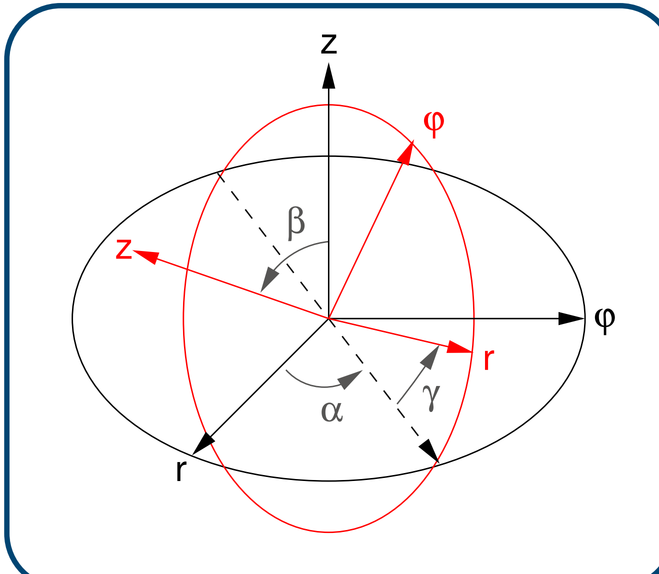
$$\hat{\kappa}_L = \begin{pmatrix} \kappa_{\perp 1} & 0 & 0 \\ 0 & \kappa_{\perp 2} & 0 \\ 0 & 0 & \kappa_{||} \end{pmatrix}$$

$$\begin{tikzcd} \text{local RF} \arrow[r, "\hat{\kappa}_L"] & \text{local RF} \arrow[d, "A"] \\ \text{global RF} \arrow[u, "A^T"] \arrow[r, "\hat{\kappa}_G"'] & \text{global RF} \end{tikzcd}$$

$$\hat{\kappa}_G = A^{-1}\hat{\kappa}_L A = A^T \hat{\kappa}_L A$$



Euler-Angle Transformation:



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Anisotropic Diffusion

The General Transformation

The symmetric global diffusion tensor:

$$
\begin{aligned}
\hat{\kappa}_{11} &= \kappa_{\perp 1} n_1^2 + \kappa_{\perp 2} b_1^2 + \kappa_{\|} t_1^2 \\
\hat{\kappa}_{12} &= \kappa_{\perp 1} n_1 n_2 + \kappa_{\perp 2} b_1 b_2 + \kappa_{\|} t_1 t_2 \\
\hat{\kappa}_{13} &= \kappa_{\perp 1} n_1 n_3 + \kappa_{\perp 2} b_1 b_3 + \kappa_{\|} t_1 t_3 \\
\hat{\kappa}_{22} &= \kappa_{\perp 1} n_2^2 + \kappa_{\perp 2} b_2^2 + \kappa_{\|} t_2^2 \\
\hat{\kappa}_{23} &= \kappa_{\perp 1} n_2 n_3 + \kappa_{\perp 2} b_2 b_3 + \kappa_{\|} t_2 t_3 \\
\hat{\kappa}_{33} &= \kappa_{\perp 1} n_3^2 + \kappa_{\perp 2} b_3^2 + \kappa_{\|} t_3^2
\end{aligned}
$$

General magnetic field & local diffusion coefficients

↓

Calculate local trihedron

↓

Include in transformation to global reference frame

↓

General, fully anisotropic, global diffusion tensor

In any case: The simple structure of the diffusion tensor in the local frame may lead to complicated tensor elements in the global frame, depending on the magnetic field.

Anisotropic Diffusion
Model Parameters

INFLUENCE OF TURBULENCE DISSIPATION EFFECTS ON THE PROPAGATION OF LOW-ENERGY COSMIC RAYS IN THE GALAXY

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Received 2010 May 28; accepted 2010 October 24; published 2010 December 3

Galactic diffusion coefficients:

$$\kappa_\parallel = \begin{cases} \kappa_0 \left(\frac{\zeta}{\zeta_0}\right)^{0.6} & \text{for } \zeta \geqslant \zeta_0 \\ \kappa_0 \left(\frac{\zeta}{\zeta_0}\right)^{-a} & \text{for } \zeta < \zeta_0. \end{cases}$$

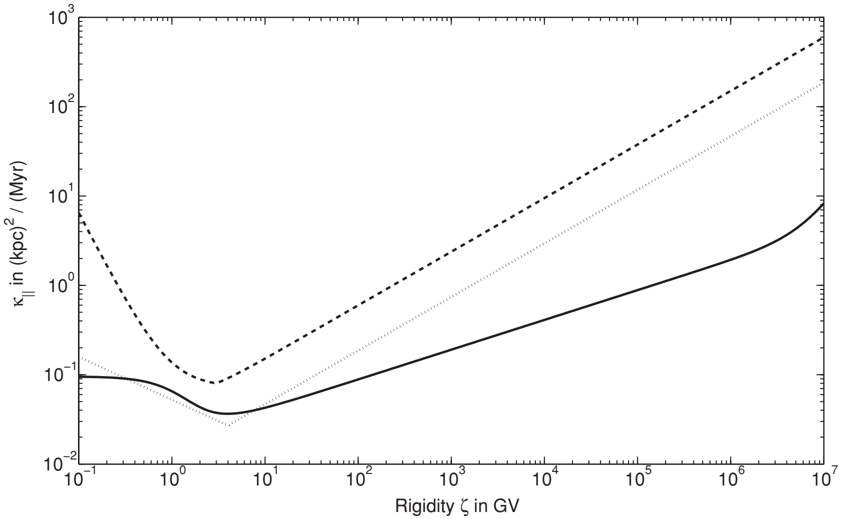

Figure 2. Theoretical results for the parallel diffusion coefficient of galactic protons vs. their magnetic rigidity (solid line). The first change (break-point) in the rigidity dependence can be found at $\zeta_0 \approx 3$–4 GV and the second one at $\zeta \approx 10^6$ GV. Our new results are compared with the phenomenological results of Ptuskin et al. (2006, dashed line) and those obtained by Büsching & Potgieter (2008, dotted line).

$$\kappa_\parallel = 0.073\,(\mathrm{kpc})^2(\mathrm{Myr})^{-1} \approx 2.3\cdot 10^{28}(\mathrm{cm})^2(\mathrm{s})^{-1}$$

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Anisotropic Diffusion
Model Parameters

Perpendicular and parallel diffusion coefficients:

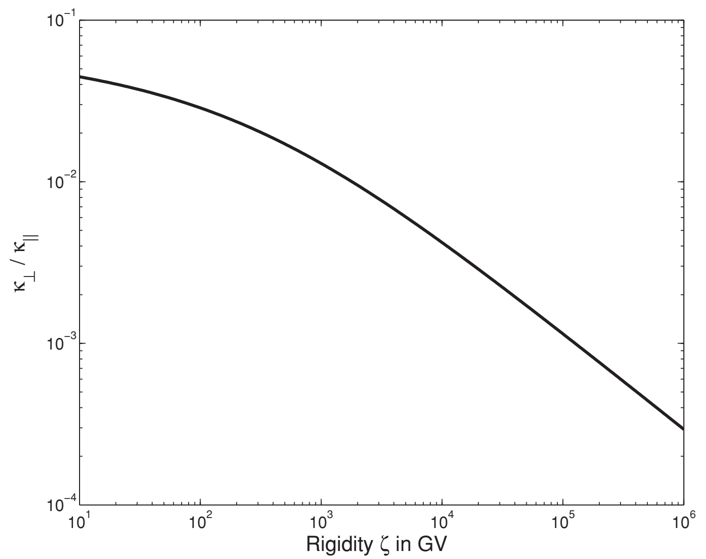

Figure 7. Transport of protons in the ISM: the ratio $\kappa_\perp/\kappa_\|$ vs. the magnetic rigidity in physical units (solid line). To obtain these results we have employed the correlation tensor of CLV02. For the parallel diffusion coefficient we have used the phenomenological model.

[A. Shalchi, I. Büsching, A. Lazarian, and R. Schlickeiser, 2010, ApJ]

Cosmic-ray-driven dynamo in galactic disks

A parameter study

M. Hanasz[1], K. Otmianowska-Mazur[2], G. Kowal[2,3], and H. Lesch[4]

⋮

initial growth only until $t = 450$ Myr and decay thereafter. The present results indicate that magnetic-field amplification is possible only for $K_\perp \leq 3\times10^3$ pc^2 Myr^{-1} $\simeq 10^{27}$ cm^2 s^{-1}. *Therefore, the anisotropy in the CR diffusion seems to be a crucial condition for magnetic-field amplification in the process of the CR-driven dynamo.*

$$\kappa_{\perp 1} \approx \kappa_{\perp 2} \approx (0.1 - 0.01) \cdot \kappa_{\|}$$

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Numerical Model

Stochastic Differential Equations

Transport Equation:

- Time-forward equation:

$$\begin{aligned} \frac{\partial f}{\partial t} = & \quad \vec{\nabla} \cdot \left(\vec{\nabla} \cdot \left[{}^{t}\mathcal{K} f \right] \right) - \vec{\nabla} \cdot \left(\left[(\vec{\nabla} \cdot {}^{t}\mathcal{K}) + \vec{U} \right] f \right) \\ & + \quad \frac{\partial^2}{\partial q^2} \left(D_{qq} f \right) - \frac{\partial}{\partial q} \left(\left[\frac{\partial D_{qq}}{\partial q} - \hat{\Omega} \right] f \right) - L_F f + S \end{aligned}$$

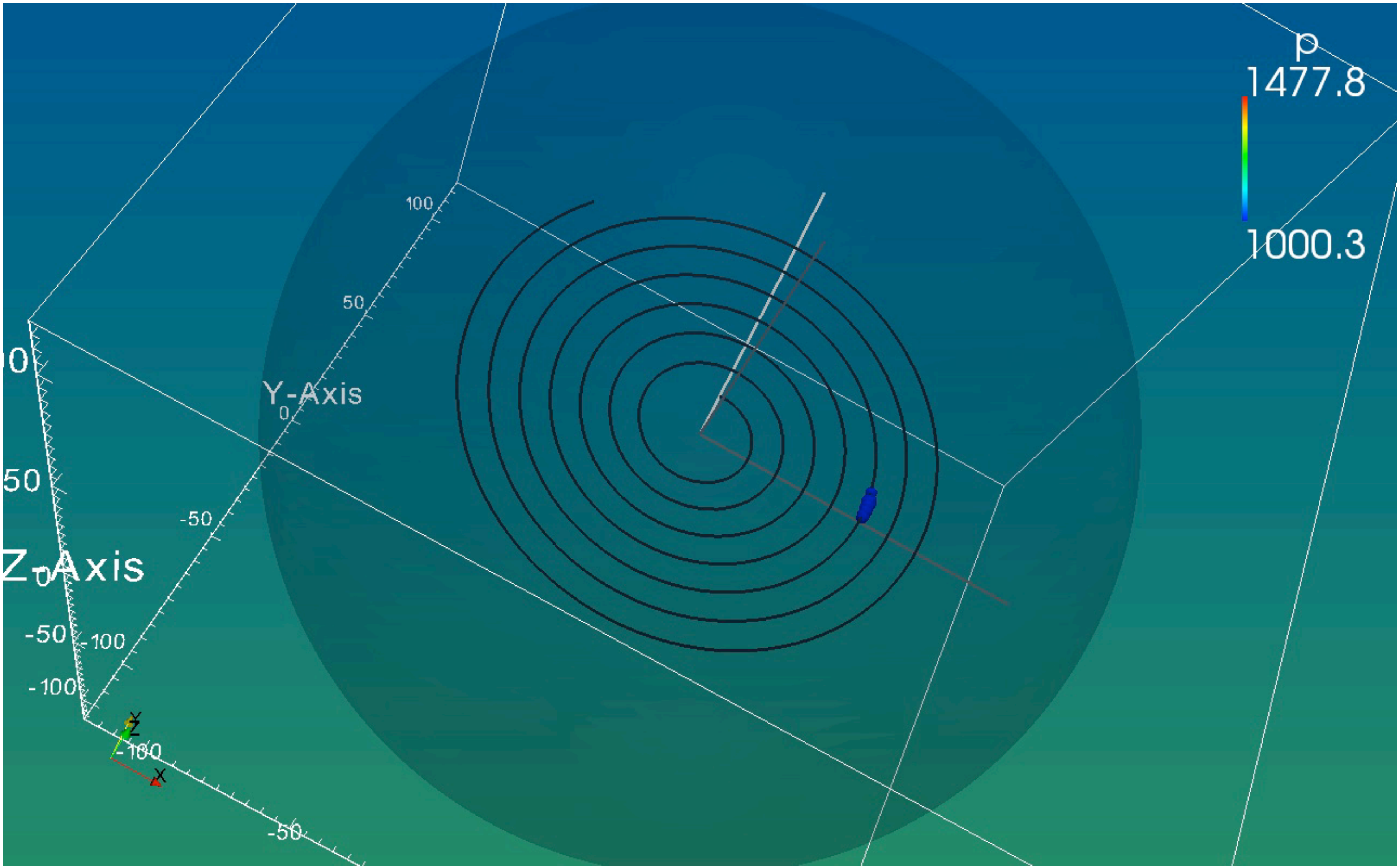
- Time-backward equation:

$$\begin{aligned} \frac{\partial f}{\partial t} = & \quad \mathcal{K} : (\vec{\nabla} \otimes \vec{\nabla} f) + \left((\vec{\nabla} \cdot \mathcal{K}) - \vec{U} \right) \cdot \vec{\nabla} f \\ & + \quad D_{qq} \frac{\partial^2 f}{\partial q^2} + \left(\frac{\partial D_{qq}}{\partial q} + \hat{\Omega} \right) \frac{\partial f}{\partial q} - L_B f + S \end{aligned}$$

SDE (backward):

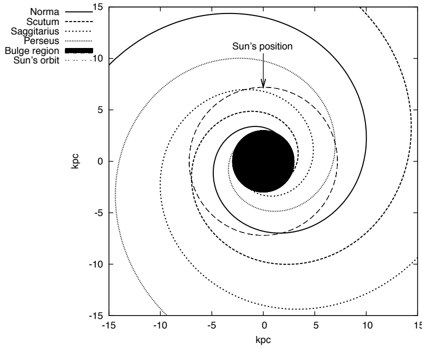
$$\begin{aligned} d\vec{r} &= \left((\vec{\nabla} \cdot \mathcal{K}) - \vec{U} \right) dt + \mathcal{B} \cdot d\vec{\omega}_r \\ dq &= \left(\frac{\partial D_{qq}}{\partial q} + \hat{\Omega} \right) dt + \sqrt{2 D_{qq}} d\omega_q \end{aligned}$$

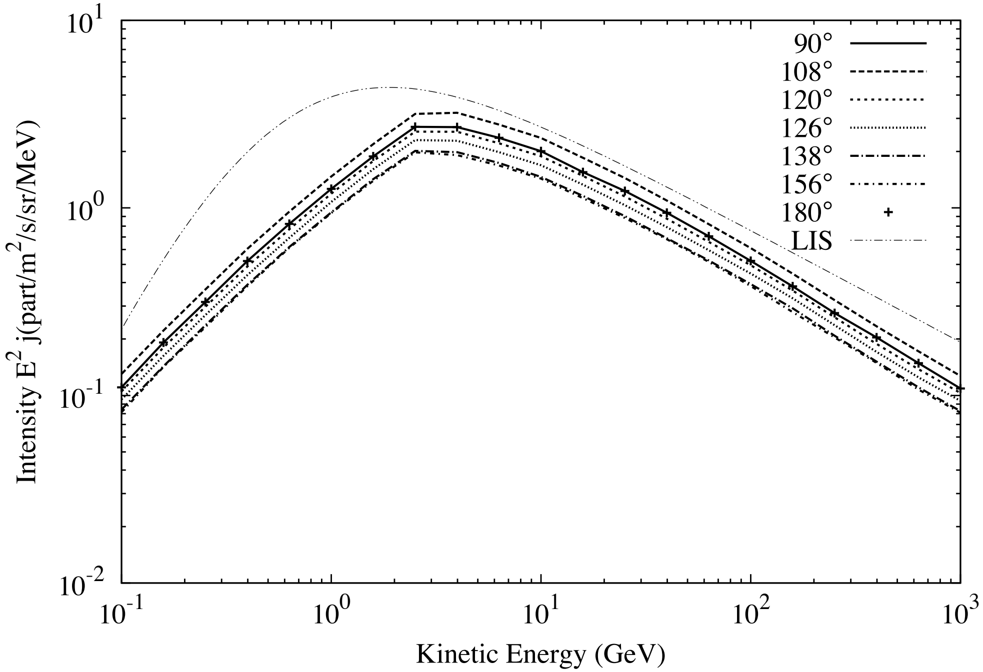
Numerical Model
Illustration



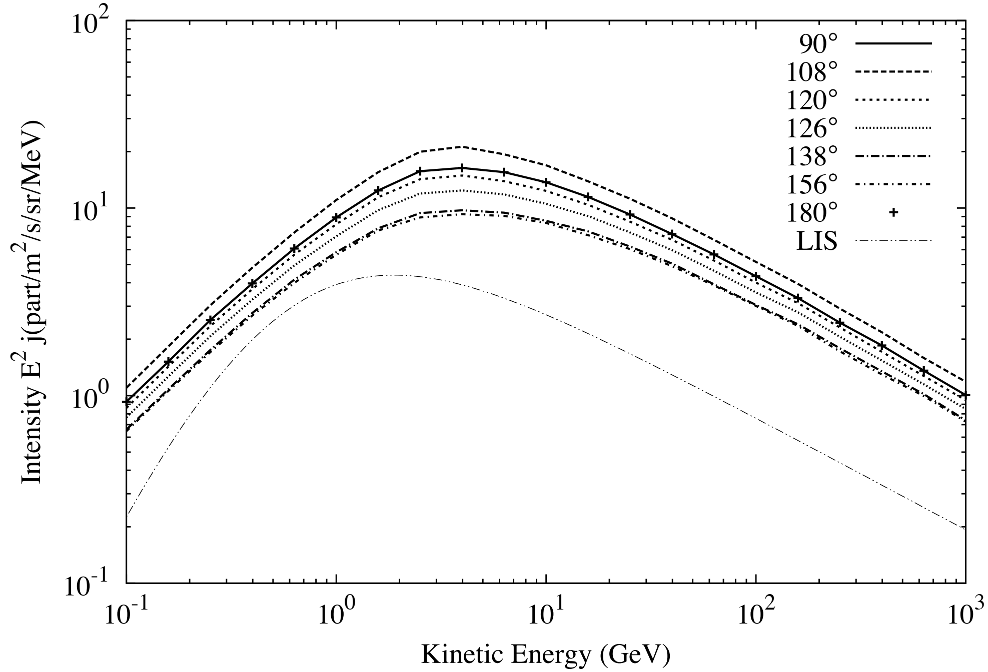
Results

Spectra Isotropic vs Anisotropic





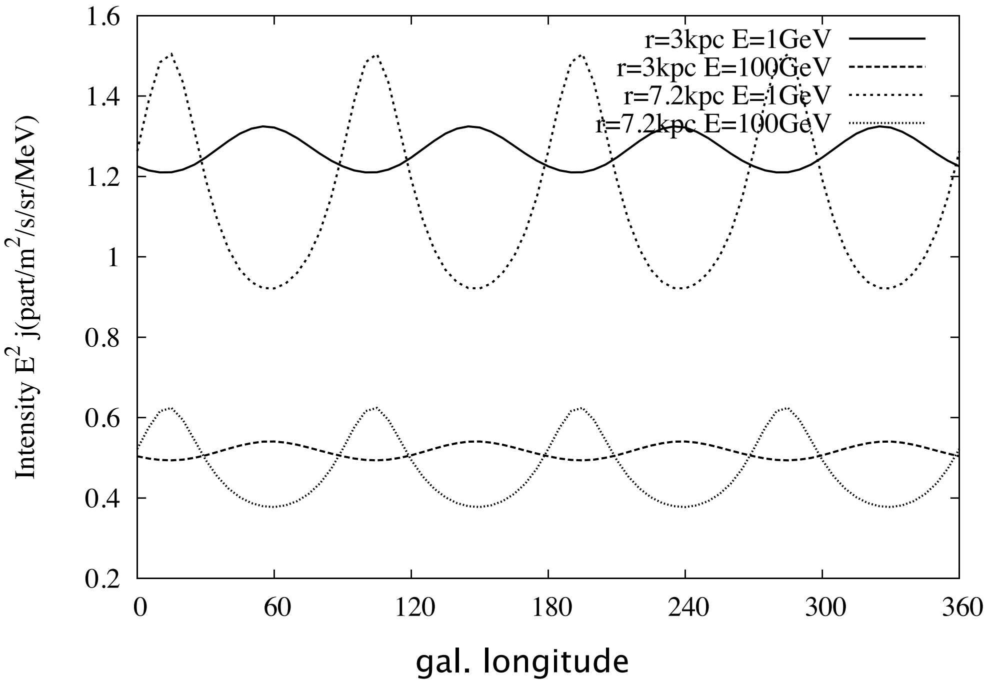
Isotropic Diffusion



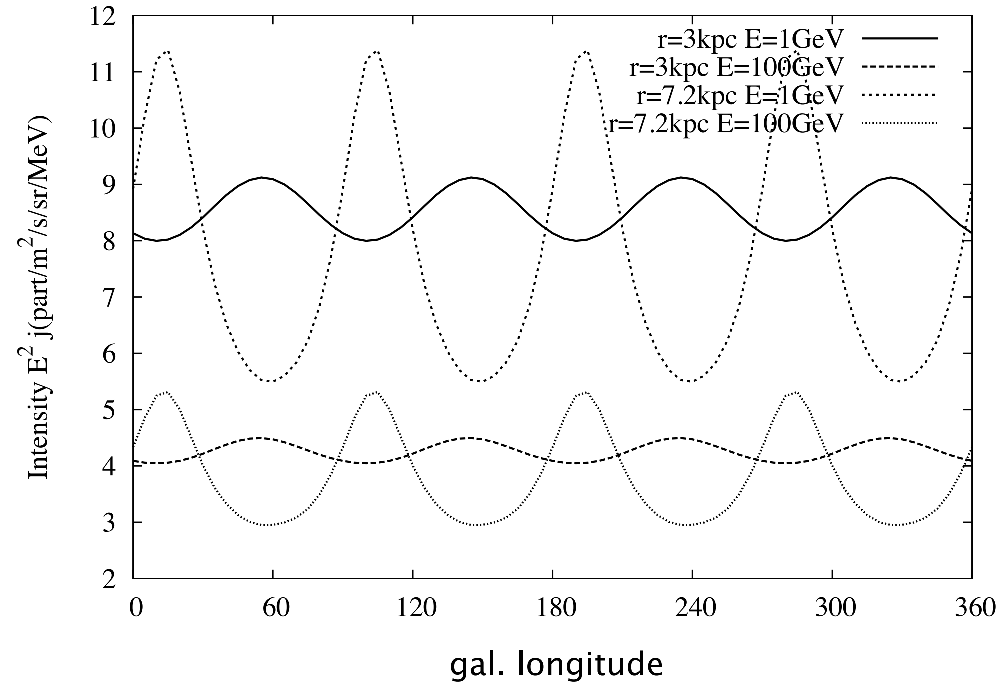
Anisotropic Diffusion

Results

Orbital Variation Isotropic vs Anisotropic



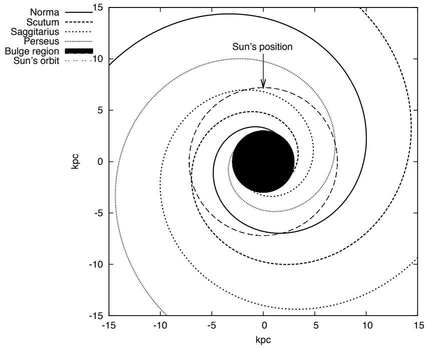
Isotropic Diffusion

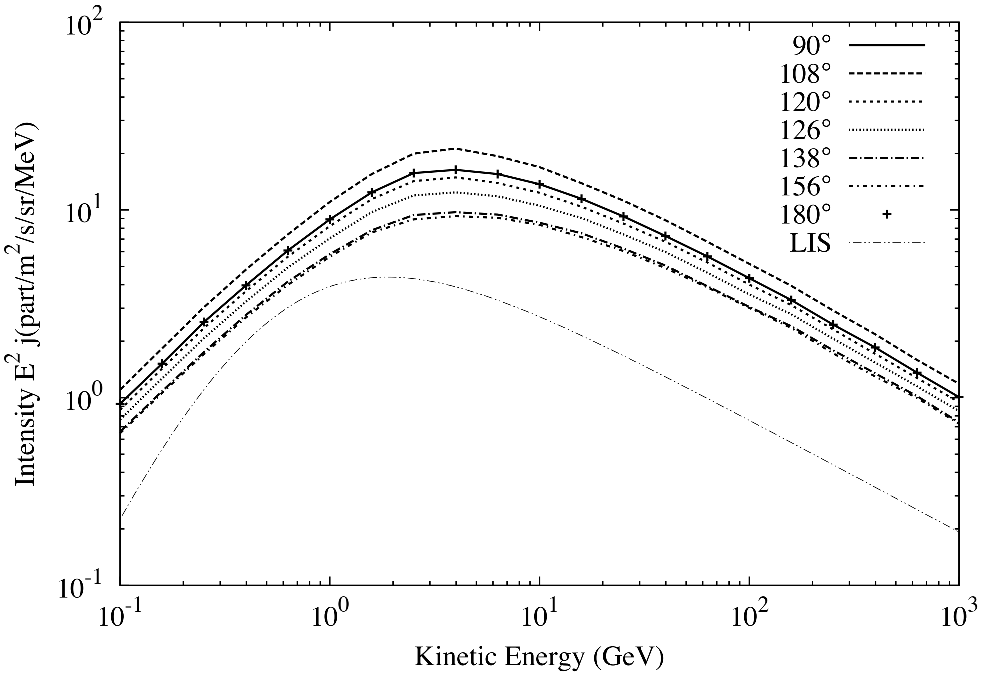


Anisotropic Diffusion

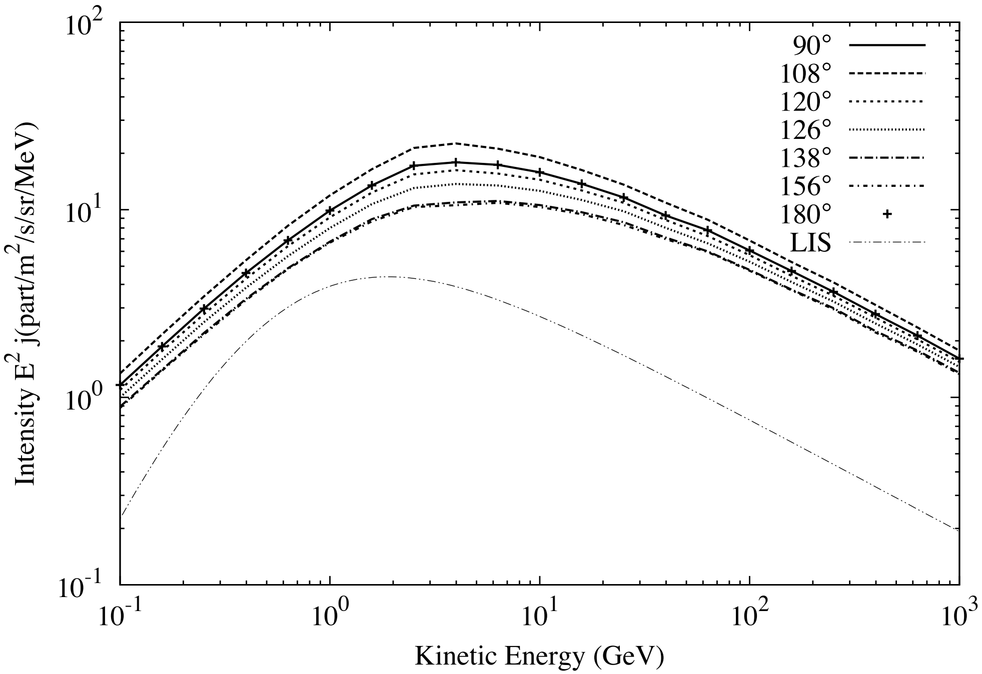
Results

Spectra, Halosize





Anisotropic Diffusion,
H = 2kpc



Anisotropic Diffusion,
H = 4kpc

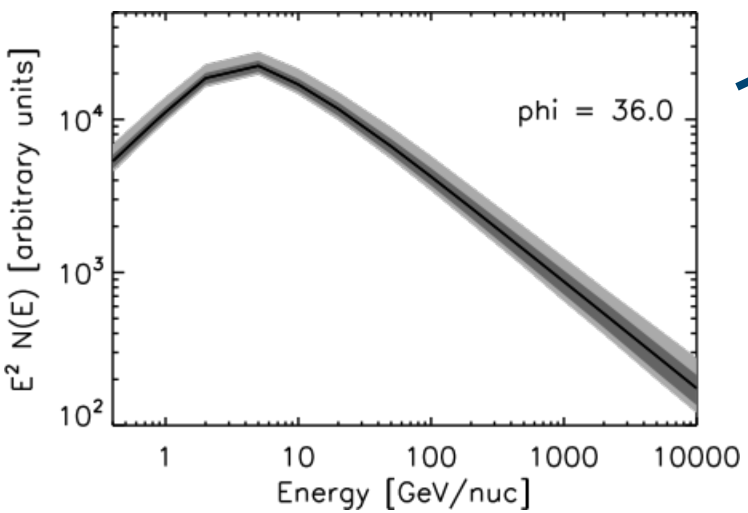
Results

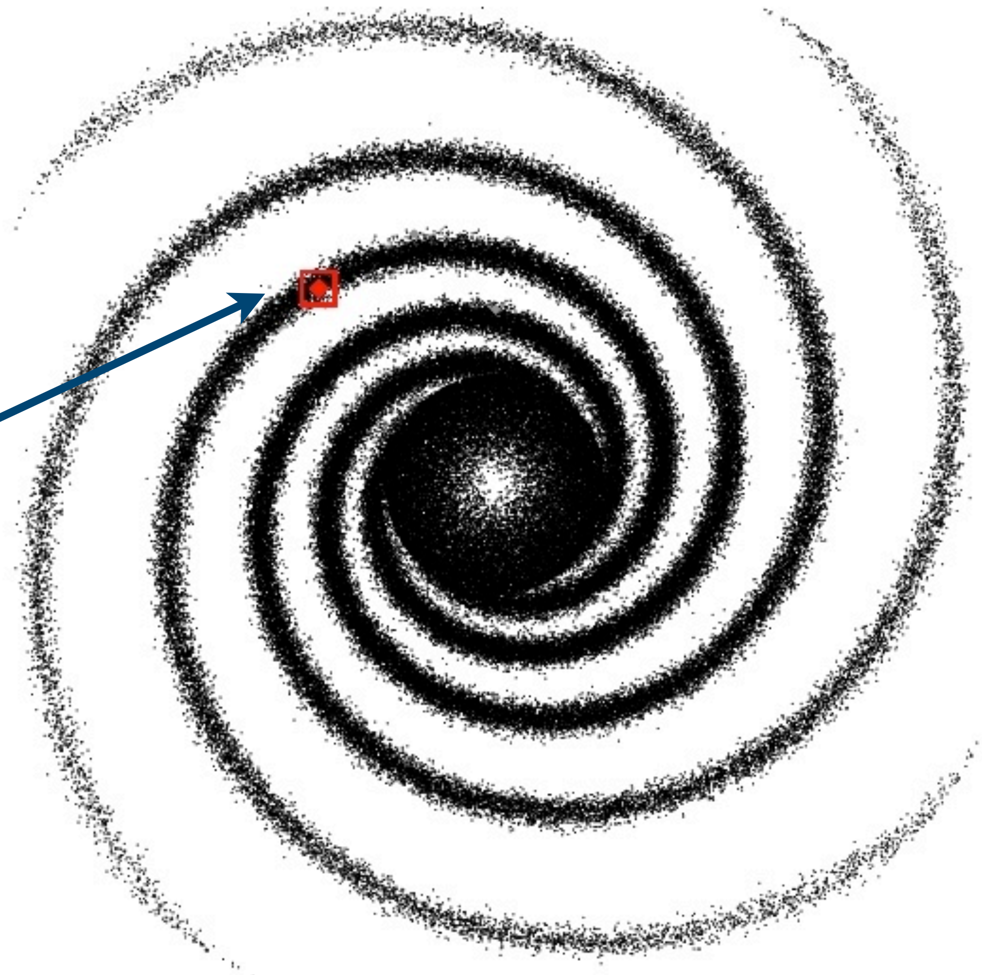
Stochastically distributed sources

[Büsching and Potgieter, 2008, Adv. in Space Res.]

Simplified equation:

$$\frac{\partial N}{\partial t} - S = \nabla(k(p)\nabla N) - \frac{\partial}{\partial p}(BN) - \frac{N}{T}$$





Results

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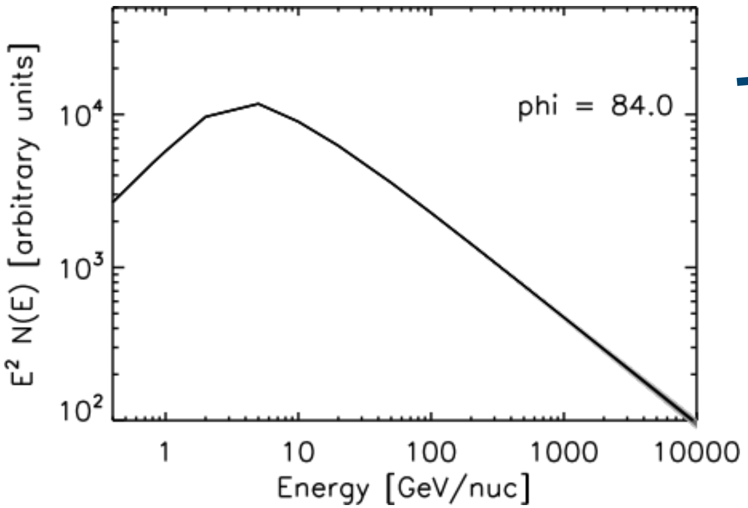

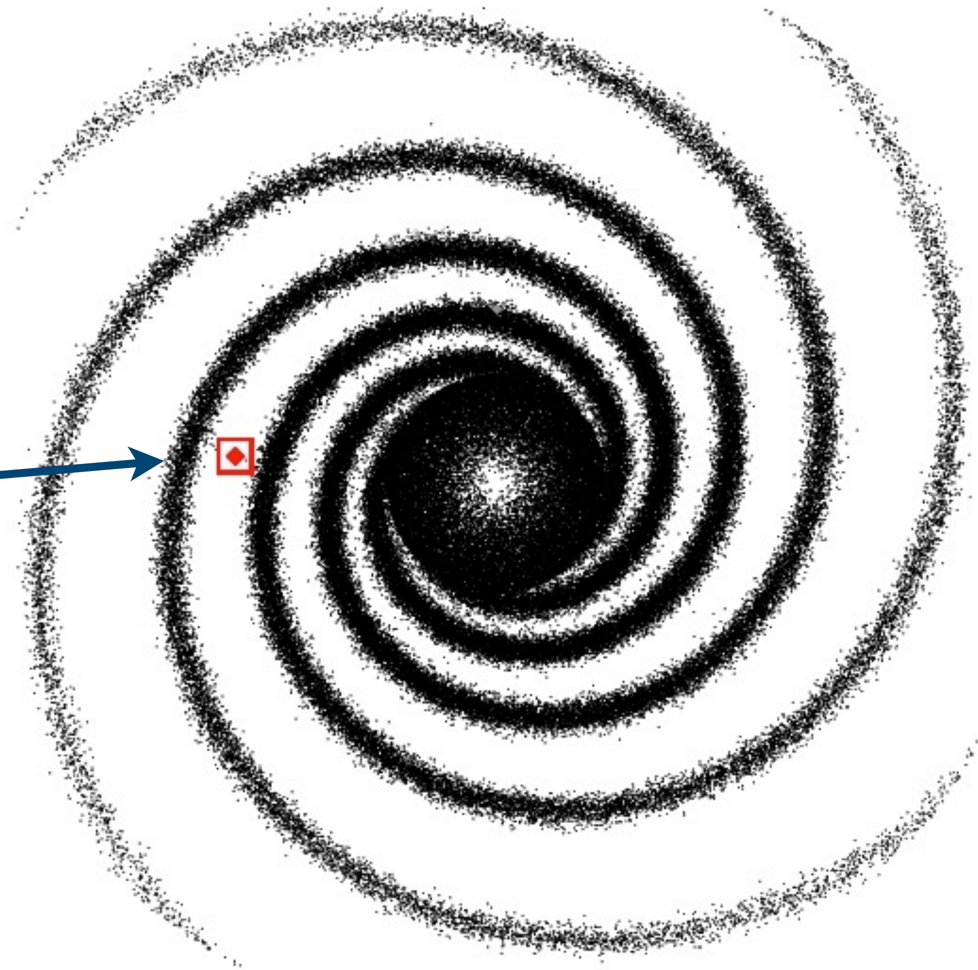

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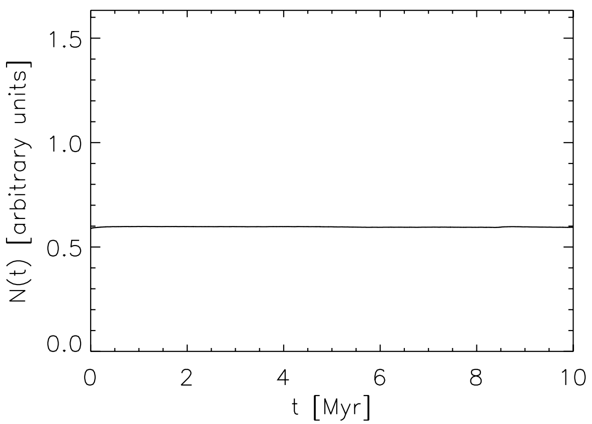
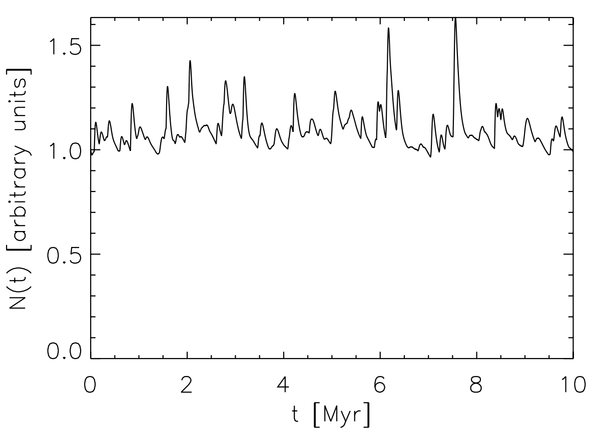
Results

Stochastically distributed sources

[Büsching and Potgieter, 2008, Adv. in Space Res.]

Variation on Intermediate Timescales:





Time-dependent source function:

$$S = \sum_i q_{0_i} p^{-s} (t - t_i) \exp\left(\frac{t - t_i}{\tau}\right) \times \Theta(t - t_i) \delta(\vec{r} - \vec{r}_i)$$

Inter-arm region

Inside of a spiral arm

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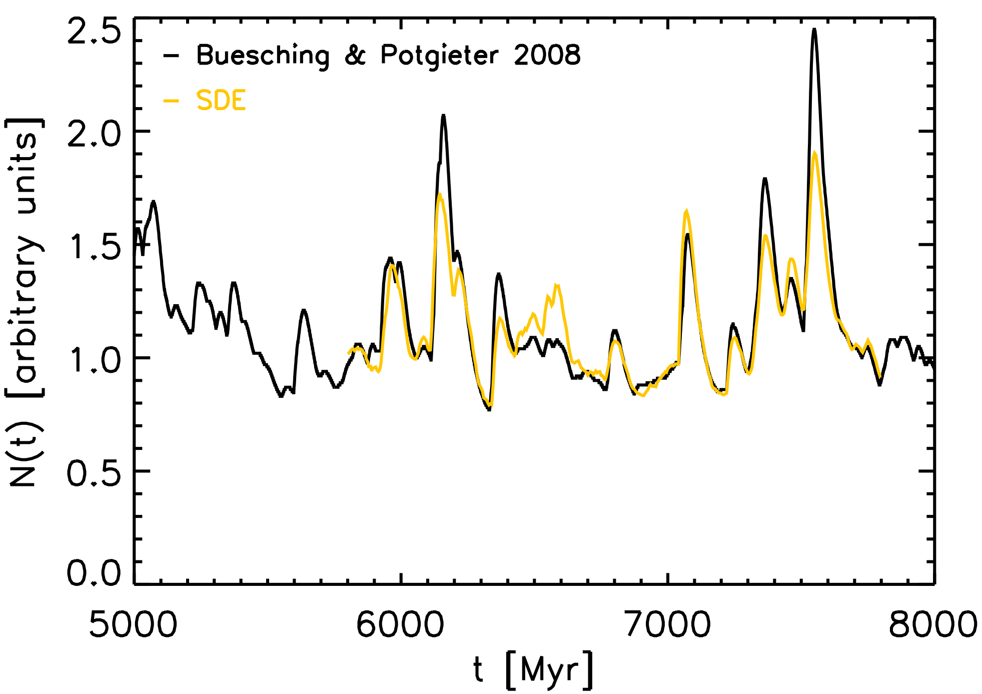
Results

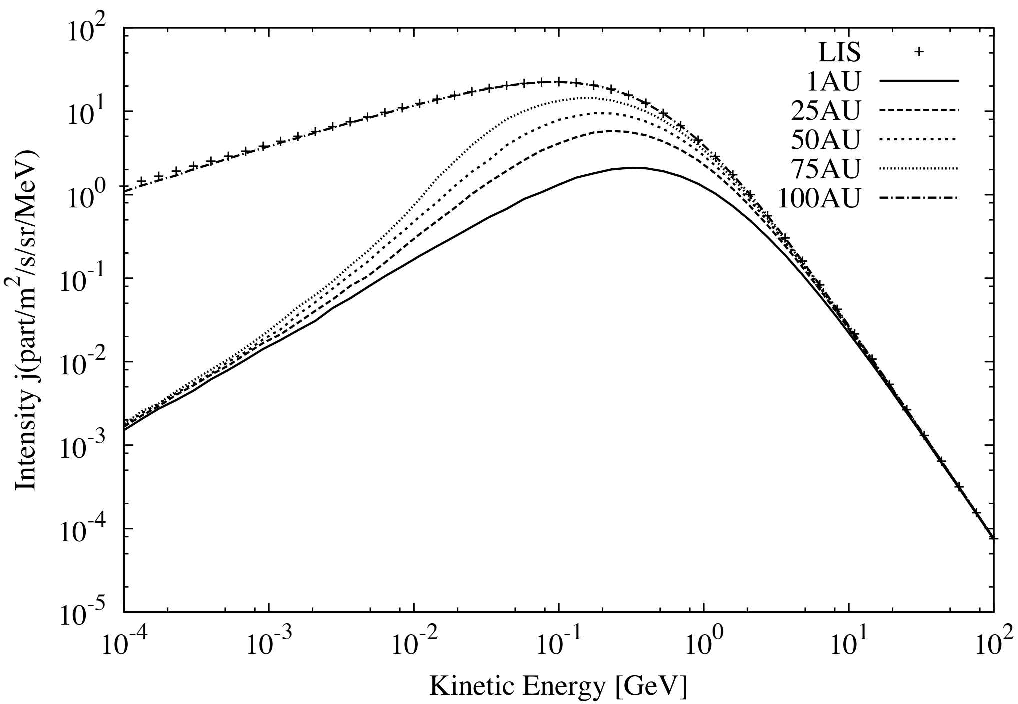
Code Tests

Galactic Time-Variation: SDE vs Green's Function Method



Isotropic Heliospheric Modulation: SDE vs Parker Propagator

[Stawicki et al., 2000, A&A]



Outlook

- Parameter study to estimate the influence of e.g. the strength of the perpendicular diffusion and the galactic scale height.
- More realistic galactic magnetic field models with parallel transport perpendicular to the disk.
- Time dependent sources and simulations.
- Connection with the heliospheric modulation model.
- Estimations of the climatic impact.

Conclusions

- Anisotropic Diffusion is important for Cosmic Ray transport on different scales and its proper treatment is needed to determine their actual distribution in the Galaxy and the modulation effects in the Heliosphere.
- Complementary numerical tools exist and are under development to investigate the properties of solutions to the Parker transport equation for various coordinate systems, setups and boundary conditions.
- The introduction of anisotropic diffusion shows some significant enhancement of cosmic ray flux variation along the suns orbit, especially in the 10 GeV range.
- Our model is principally capable of treating time dependent effects (in all four dimensions) and modeling a wide range of possible CR sources.