Understanding The Anisotropy Of Cosmic Rays In The TeV-PeV Energy Range

Robert Rettig

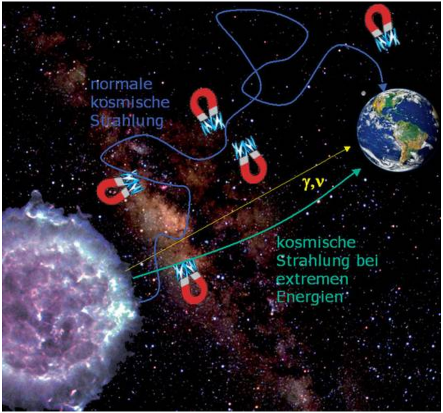
University of Potsdam/DESY Zeuthen
Theoretical Astroparticle Physics

ECRS 2014 Kiel
September 2^{nd} 2014

HELMHOLTZ
ASSOCIATION

Alliance for Astroparticle Physics

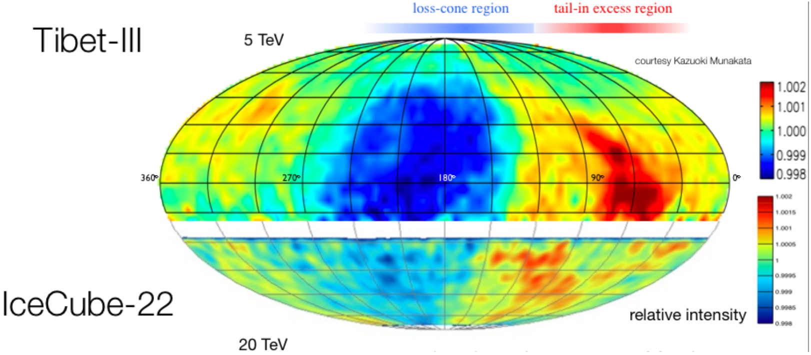
Cosmic-Ray Propagation



$\Longrightarrow$ deflections due to the interstellar/intergalactic magnetic field

$\Longrightarrow$ expectation at low energies: isotropic distribution of cosmic-ray arrival directions

Anisotropy At TeV-Energies



$\Longrightarrow$ large and small-scale anisotropies

Explanation Of The Anisotropy

Dipole Anisotropy $\Leftrightarrow$ Diffusion Approximation (e.g. Schlickeiser 1989)

$$\delta(E) \simeq -\frac{3}{c}\frac{\mathbf{j}}{n} = \frac{3D(E)}{c}\frac{\nabla n}{n}$$

Anomalous Anisotropy (small-scale structures): Ahlers (2014)

- turbulent magnetic field itself generates the small-scale structures
- existence of a global CR dipole necessarily generates a spectrum of higher multipole moments

$\Longrightarrow$ want to test this hypothesis by using numerical test-particle simulations

Set-Up: Tracking Particle Trajectories

- equation of motion

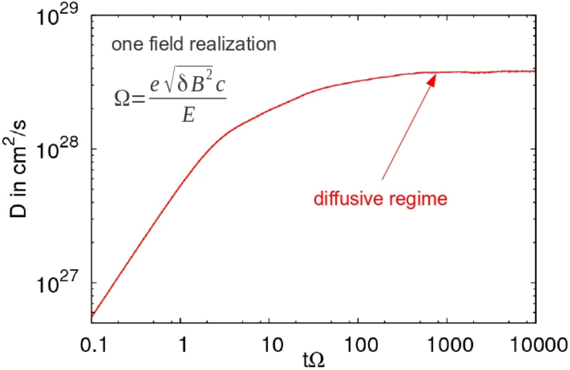
$$\frac{\mathrm{d}}{\mathrm{dt}}(\gamma m \mathbf{v}) = \frac{q}{c}\mathbf{v} \times \delta\mathbf{B}(\mathbf{r})$$

- turbulence generator from the literature (e.g. Giacalone & Jokipii, Tautz)

$$\delta\mathbf{B}(\mathbf{x},\mathbf{y},\mathbf{z}) = \Re \sum_{n=1}^{N} \widehat{\xi}_n A(k_n, L_c) e^{i(k_n z'_n + \beta_n)}$$

- transport parameter

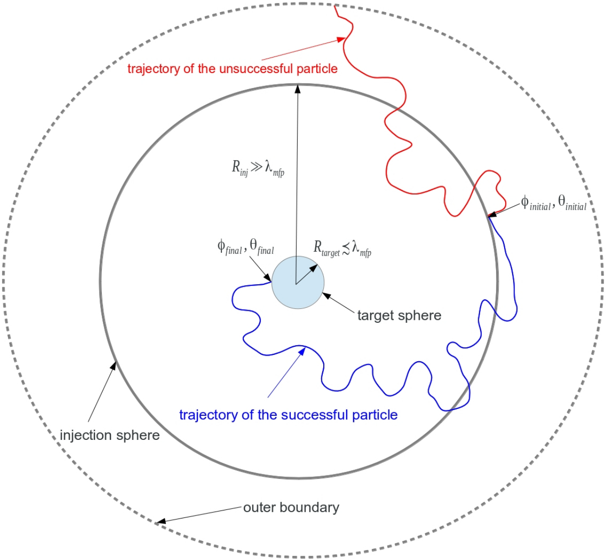
$$D = \frac{<(\Delta r)^2>}{6t} = \frac{1}{3}\lambda_{mfp} c$$



Principle

1. determine λ_{mfp}
2. determine outer boundary so that $\langle T_{successful} \rangle \approx \langle T_{unsuccessful} \rangle$
3. calculate Φ_{final}, Θ_{final} for many particles

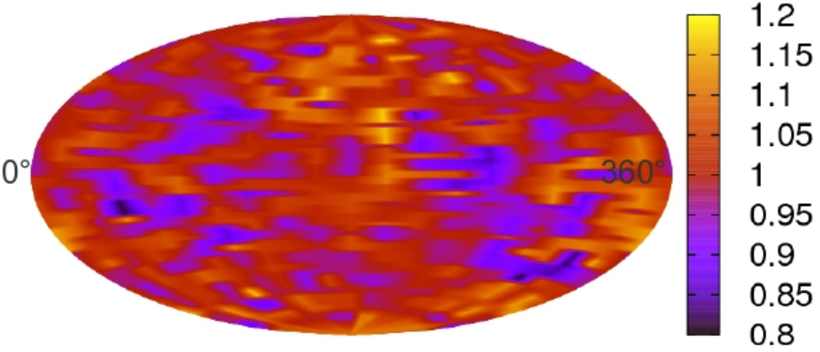
note: isotropic injection



Arrival Directions for $N_{successful} = 1.0 \times 10^6$, $\frac{2\pi r_L}{L_c} = 11.3$

$$E = 1\mathrm{PeV},\ \delta B = 3\mu\mathrm{G},\ L_c = 0.2\mathrm{pc}$$
$$R_{\mathrm{inj}} \approx 7\lambda_{mfp},\ R_{\mathrm{target}} \approx 0.7\lambda_{mfp}$$

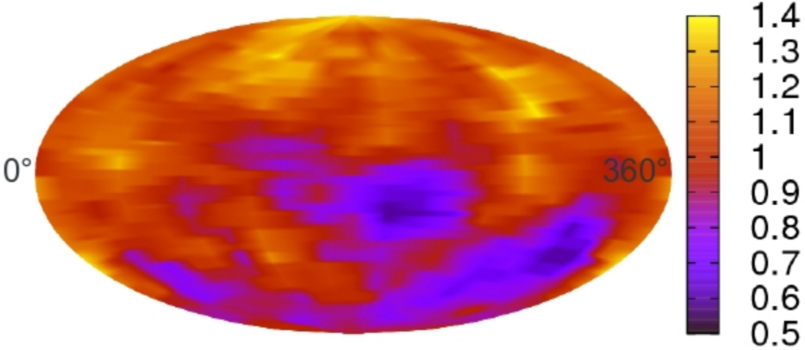
relative intensity $\frac{N_{\Phi,\Theta}}{\langle N \rangle}$ with statistical fluctuations $\simeq 3\%$



Arrival Directions for $N_{successful} = 1.0 \times 10^6$, $\frac{2\pi r_L}{L_c} = 1.1$

$$E = 1\text{PeV},\ \delta B = 3\mu\text{G},\ L_c = 2\text{pc}$$
$$R_{\text{inj}} \approx 21\lambda_{mfp},\ R_{\text{target}} \approx 0.8\lambda_{mfp}$$

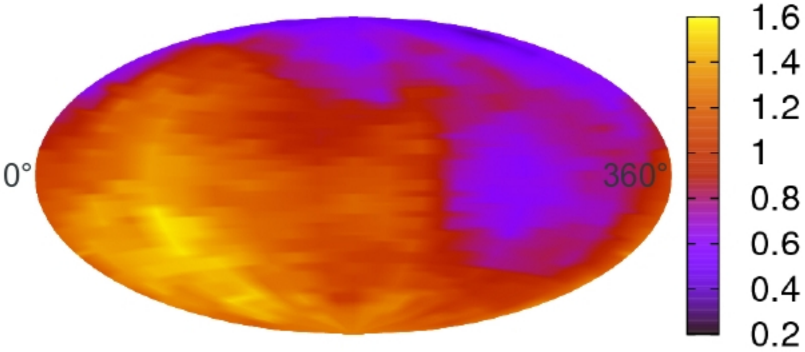
relative intensity $\frac{N_{\Phi,\Theta}}{\langle N \rangle}$ with statistical fluctuations $\simeq 3\%$



Arrival Directions for $N_{successful} = 1.0 \times 10^6$, $\frac{2\pi r_L}{L_c} = 0.1$

$$E = 1\text{PeV},\ \delta B = 3\mu\text{G},\ L_c = 20\text{pc}$$
$$R_{\text{inj}} \approx 13\lambda_{mfp},\ R_{\text{target}} \approx 0.5\lambda_{mfp}$$

relative intensity $\frac{N_{\Phi,\Theta}}{\langle N \rangle}$ with statistical fluctuations $\simeq 3\%$



Summary

- The anisotropy in the distribution of cosmic-ray arrival directions shows both large and small-scale structures.
- The turbulent magnetic field has been proposed to explain the small-scale structures. This can be tested by numerical test-particle simulations.
- Magnetic turbulence can indeed induce small-scale anisotropies in the arrival directions of cosmic rays. The structure of the anisotropy depends on the specific realization of the turbulent field as well as on the coherence length and particle energy, respectively. Under specific circumstances, i.e. larger coherence length, it is possible that the turbulent magnetic field induces also a large-scale dipole structure.
- It is not necessary to assume a global CR dipole moment to obtain higher multipole moments in the local CR distribution. However, it is difficult to reproduce the observed amplitudes of the anisotropy ($\Longrightarrow$ requires further investigations).