New Insights into the Acceleration and Transport of Cosmic Rays in the Galaxy

or

Some Simple Considerations

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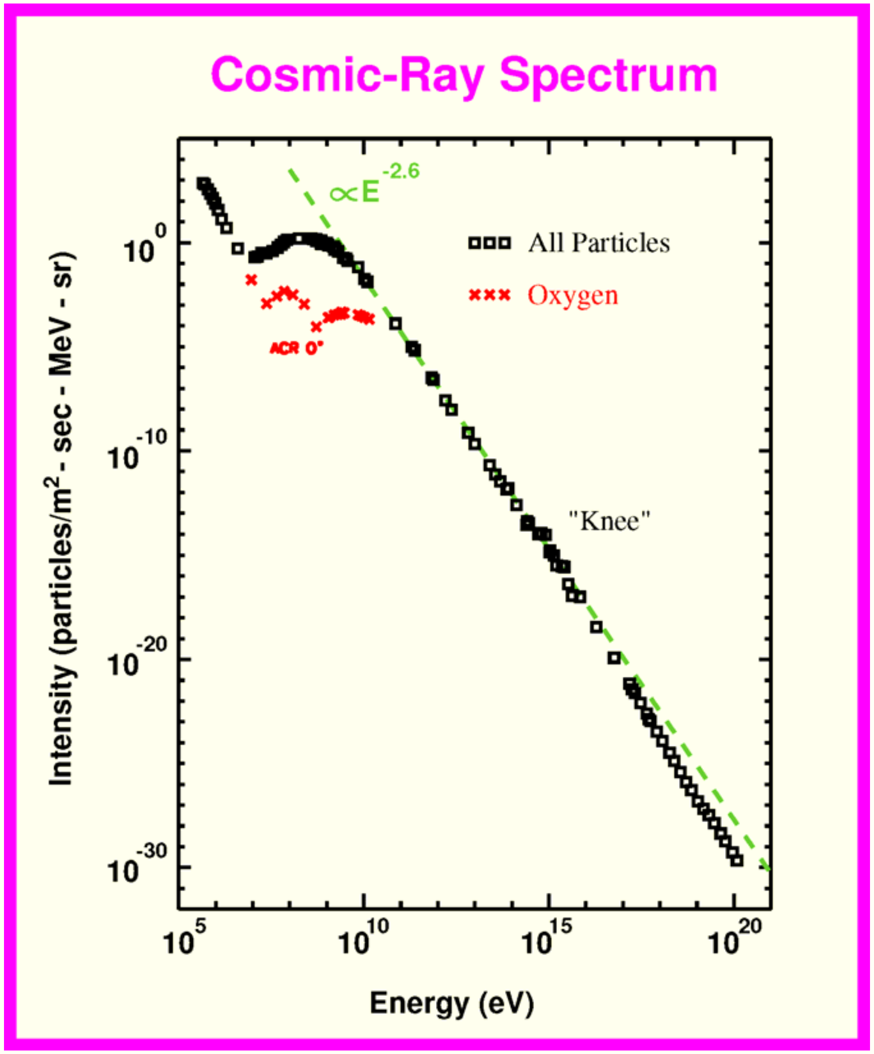
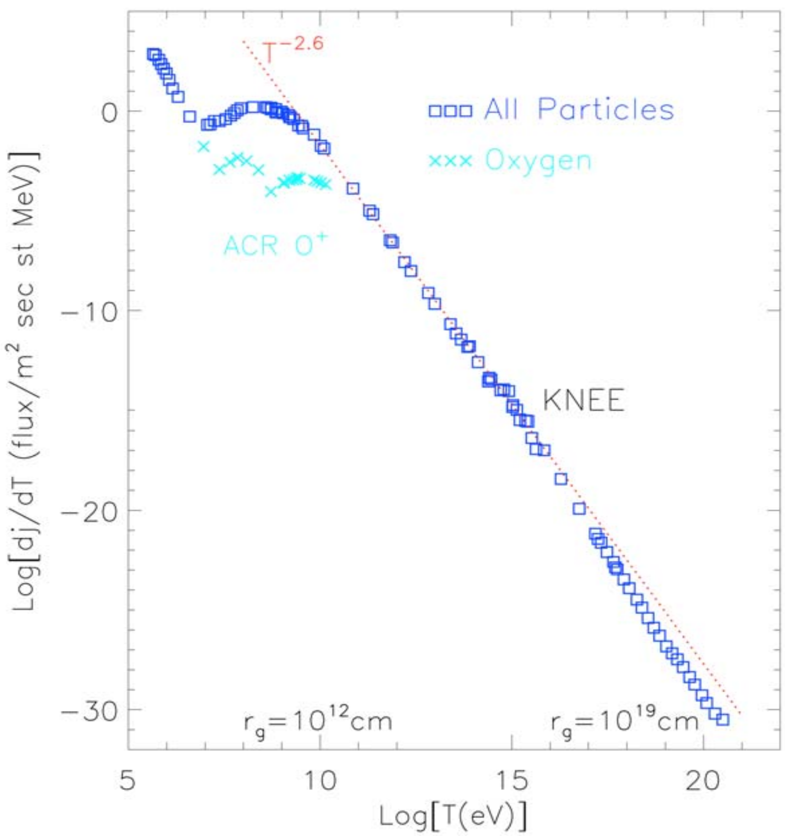
Outline

- Background/Introduction
- Simple Transport Approximations
- Observed Lifetimes and Anisotropies
$\Longrightarrow$ Problems
- One possible resolution?

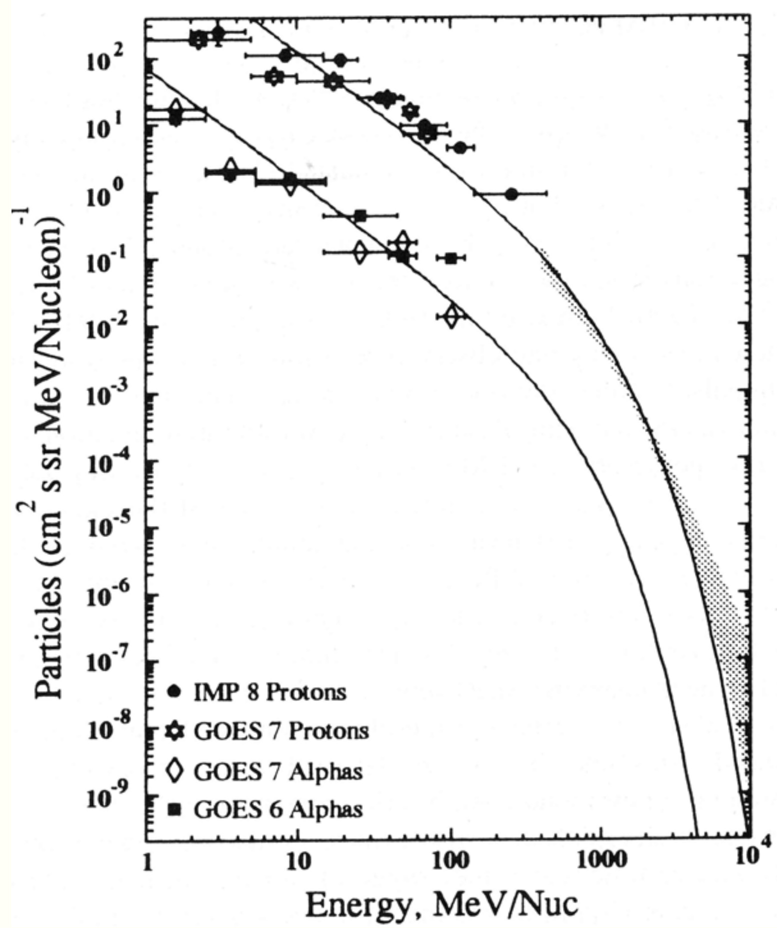
The observed quiet-time cosmic-ray spectrum



The observed energy spectra of cosmic rays are remarkably similar everywhere they are observed.

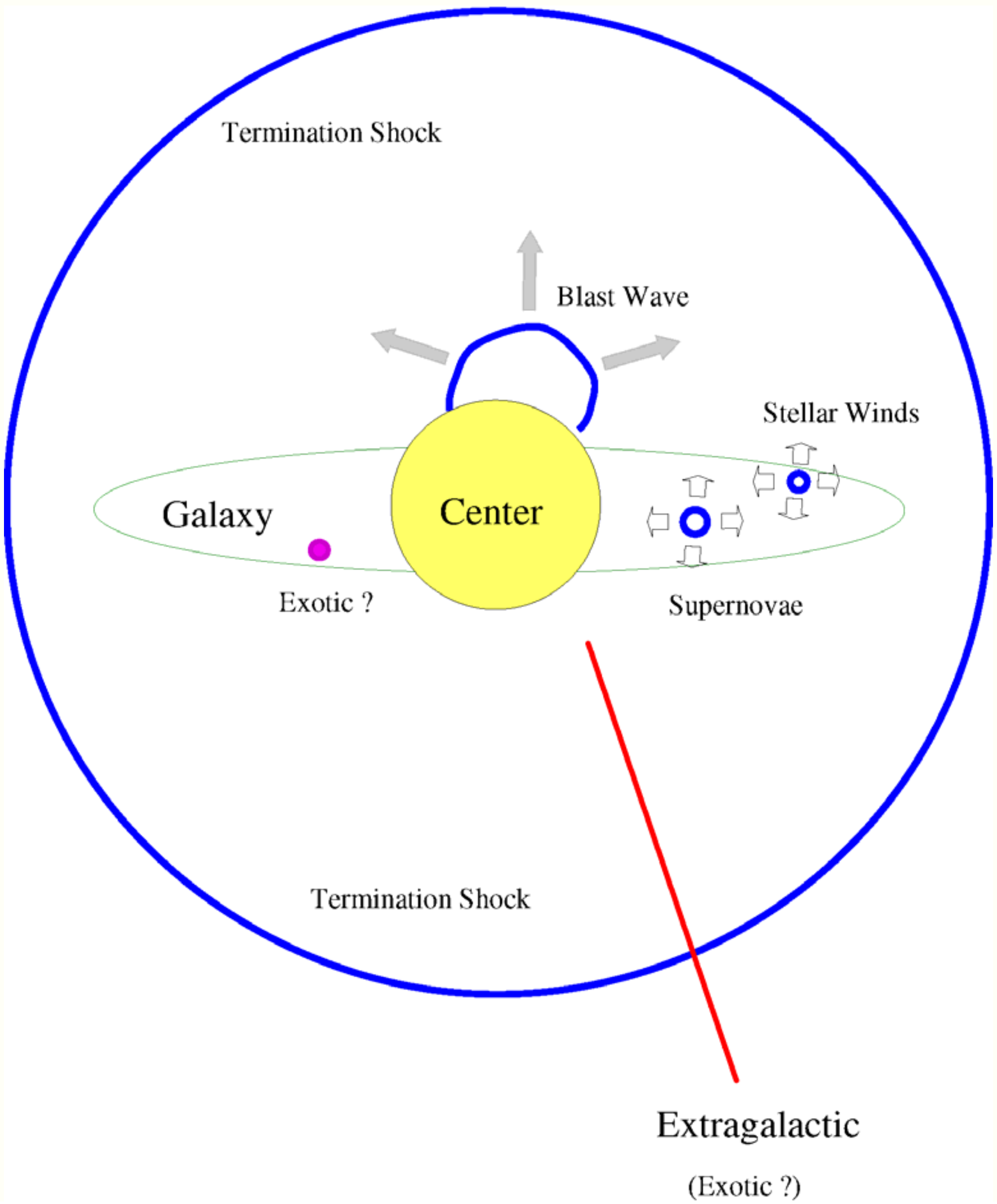


The Galaxy

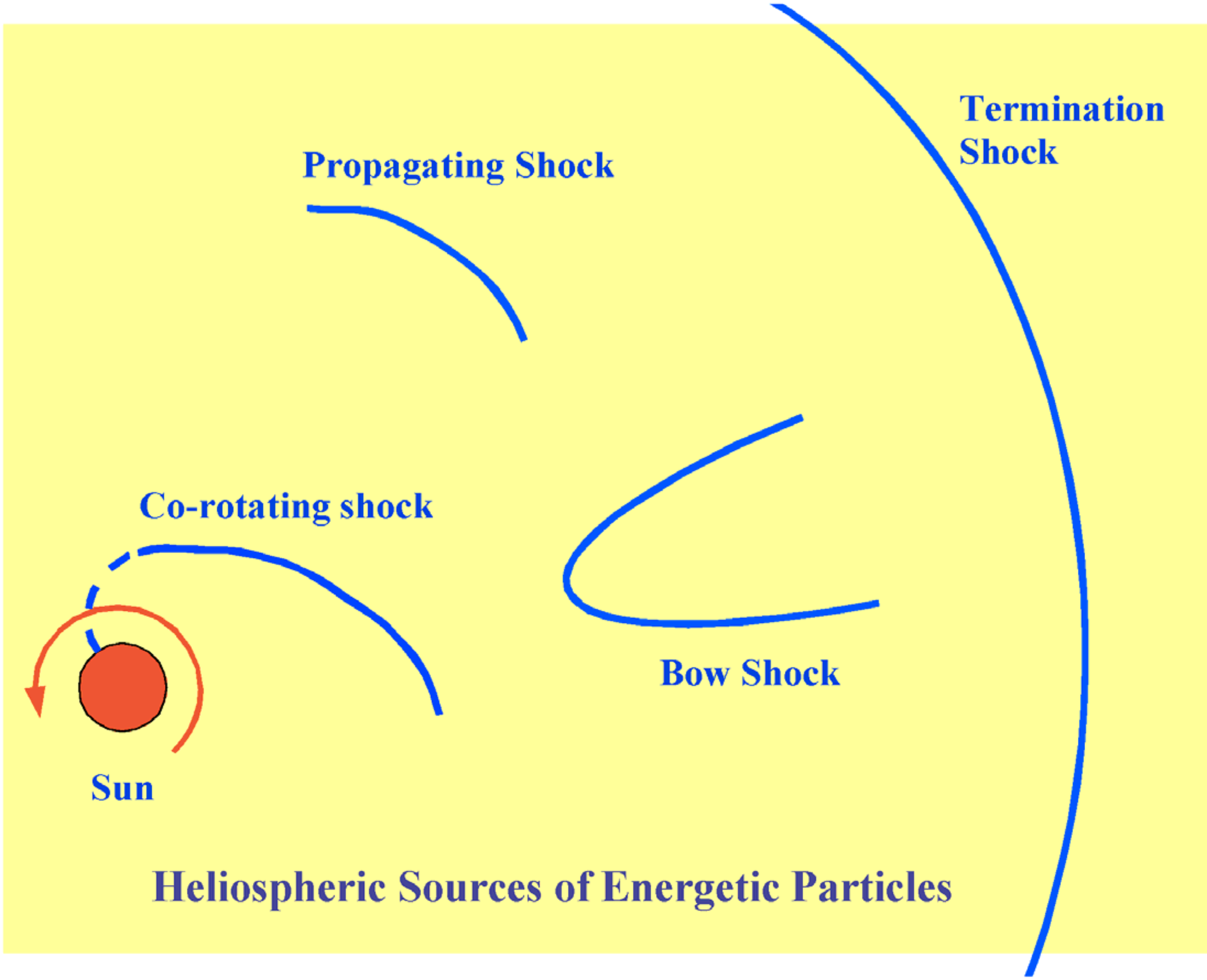


The Sun

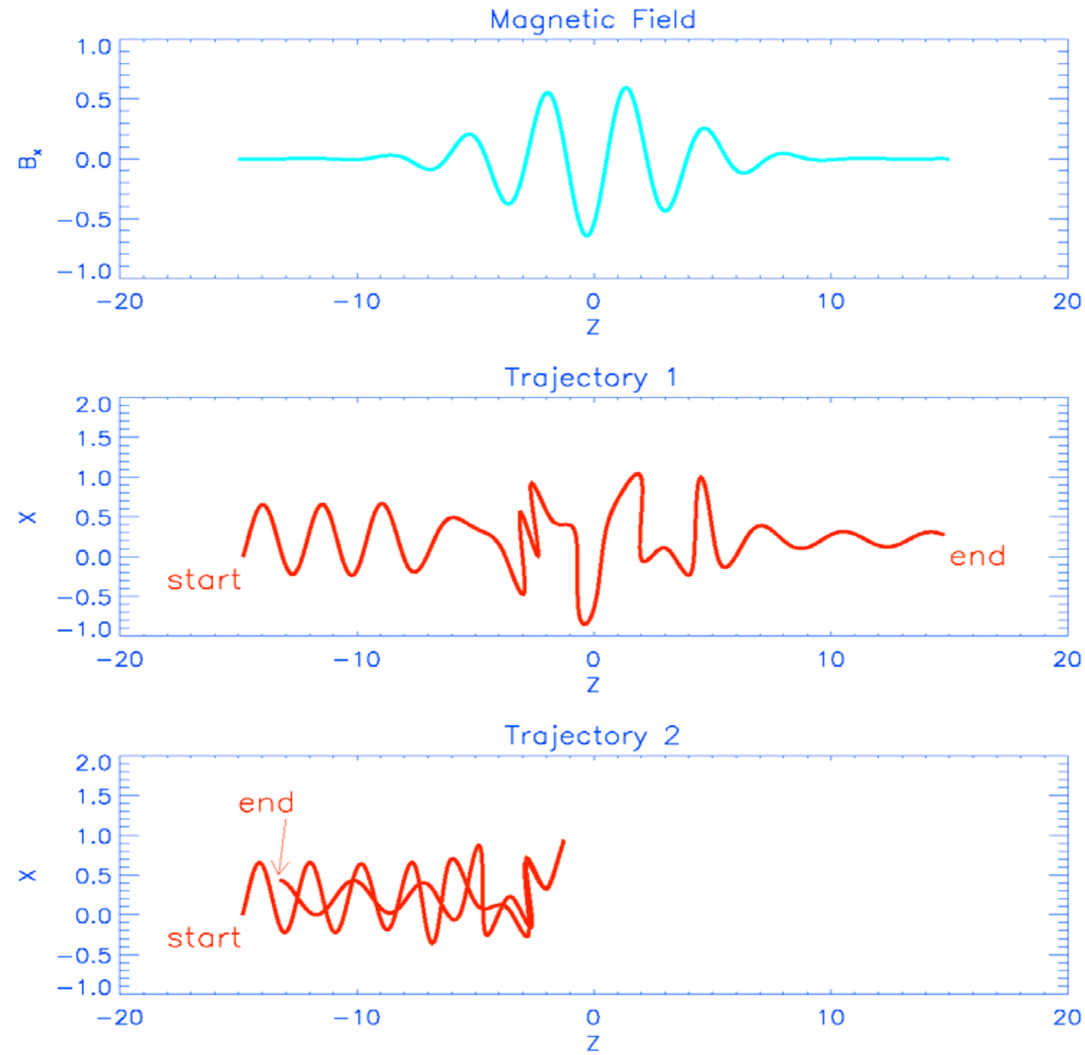
Probably nearly all cosmic rays are due to diffusive shock acceleration



Shocks in the heliosphere are also sources of energetic charged particles.



Motion in an irregular magnetic field is sensitive to initial conditions (chaotic): This demonstrates the importance of small-scale turbulence.



The Parker Transport Equation:

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}^{(S)}\frac{\partial f}{\partial x_j}\right]$$ ⇒ **Diffusion**

$$-\mathbf{U} \cdot \nabla f$$ ⇒ **Convection w. plasma**

$$-\mathbf{V_d} \cdot \nabla f$$ ⇒ **Grad & Curvature Drift**

$$+\frac{1}{3}\nabla \cdot \mathbf{U}\left[\frac{\partial f}{\partial \ell np}\right]$$ ⇒ **Energy change – electric field**

$$+Q$$ ⇒ **Source**

Where the drift velocity due to the large scale curvature and gradient of the average magnetic field is:

$$\mathbf{V_d} = \frac{pcw}{3q} \nabla \times \left[\frac{\mathbf{B}}{B^2}\right] = \nabla \cdot \kappa_{\mathbf{A}}$$

The associated anisotropy is obtained from the diffusive streaming flux

$$S_i = -\kappa_{ij} \partial f / \partial x_i + (U_i/3)\, p\, \partial f / \partial p$$

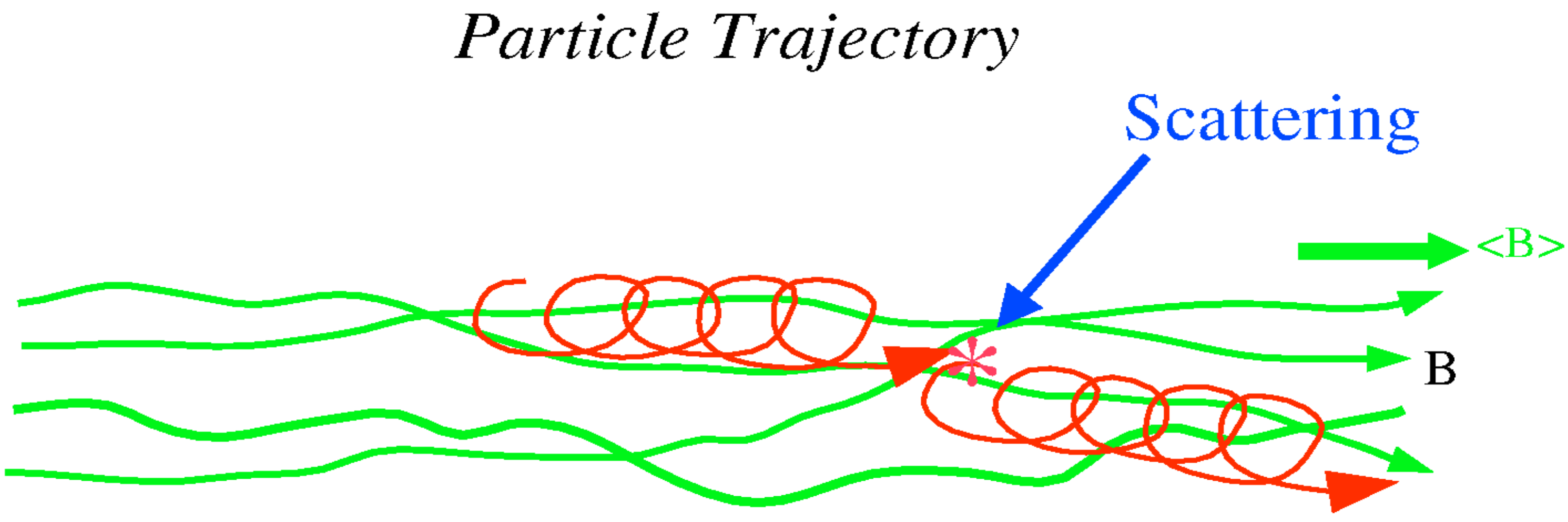
or bulk velocity S_i/w, which then gives the anisotropy

$$\delta_i = 3 S_i/w$$

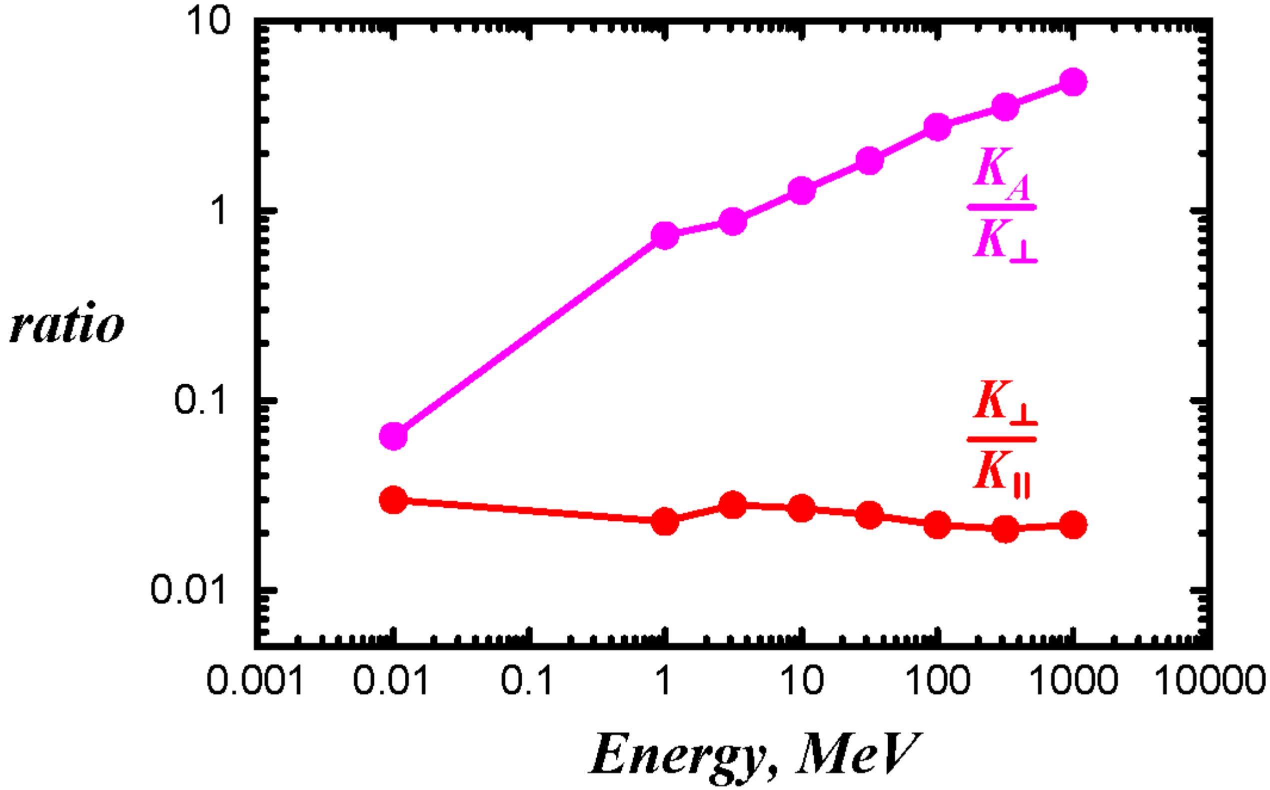
here w is the particle speed.

One can generally estimate the anisotropy as $\delta \approx \lambda / L$, where λ is the mean free path and L is the macroscopic scale.

The turbulent electromagnetic field is described statistically. In the quasilinear approximation, the scattering rate $\nu \propto P_B[1/(r_c \cos \theta_{p)})]$. Notice also the large-scale field-line meandering.



Test-Particle Simulations using synthesized Kolmogorov turbulence (Gicalone and Jokipii, Ap. J. 1999 + 1 point)

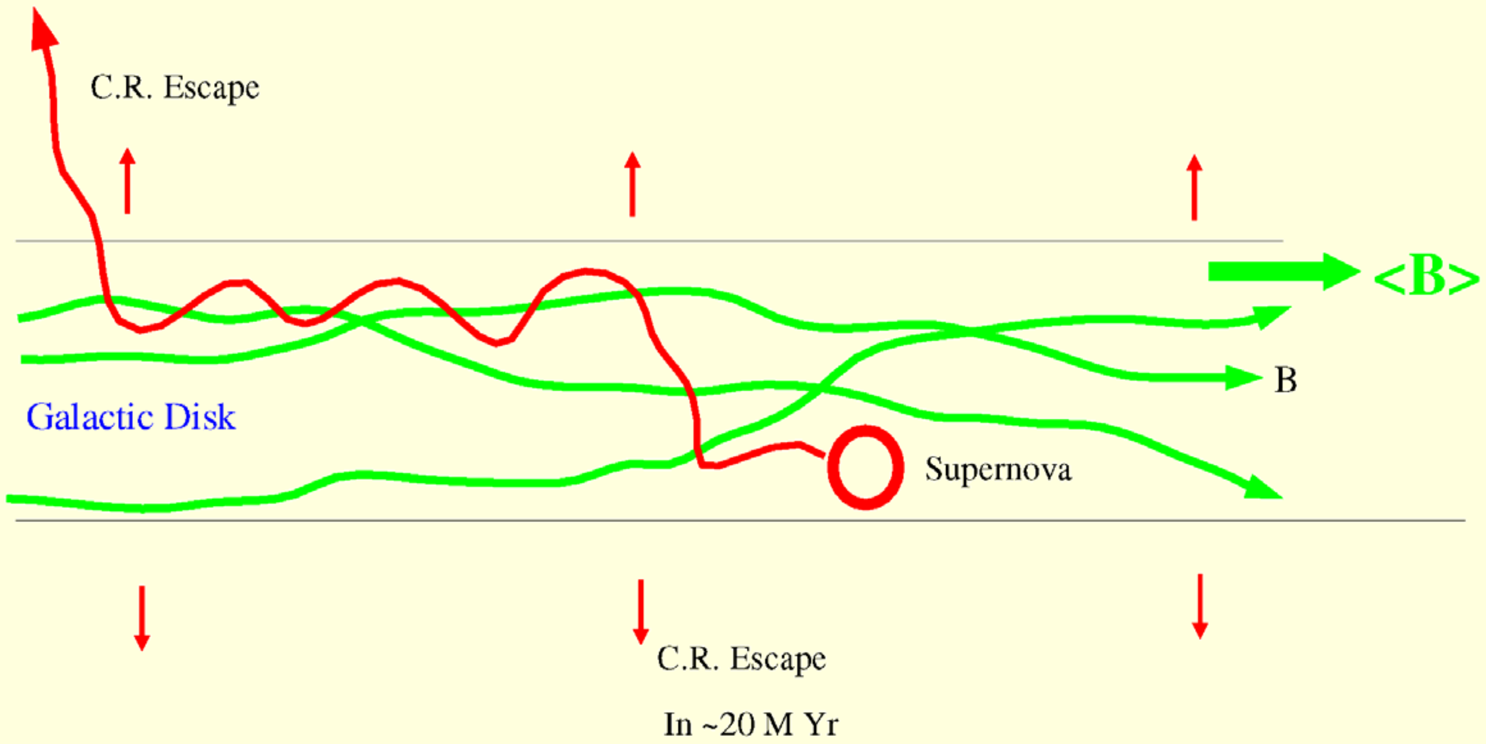


We *never* find the classical condition $\kappa_\perp = \kappa_\parallel / (1 + \omega^2 \tau^2)$ which would give a *much* smaller ratio.

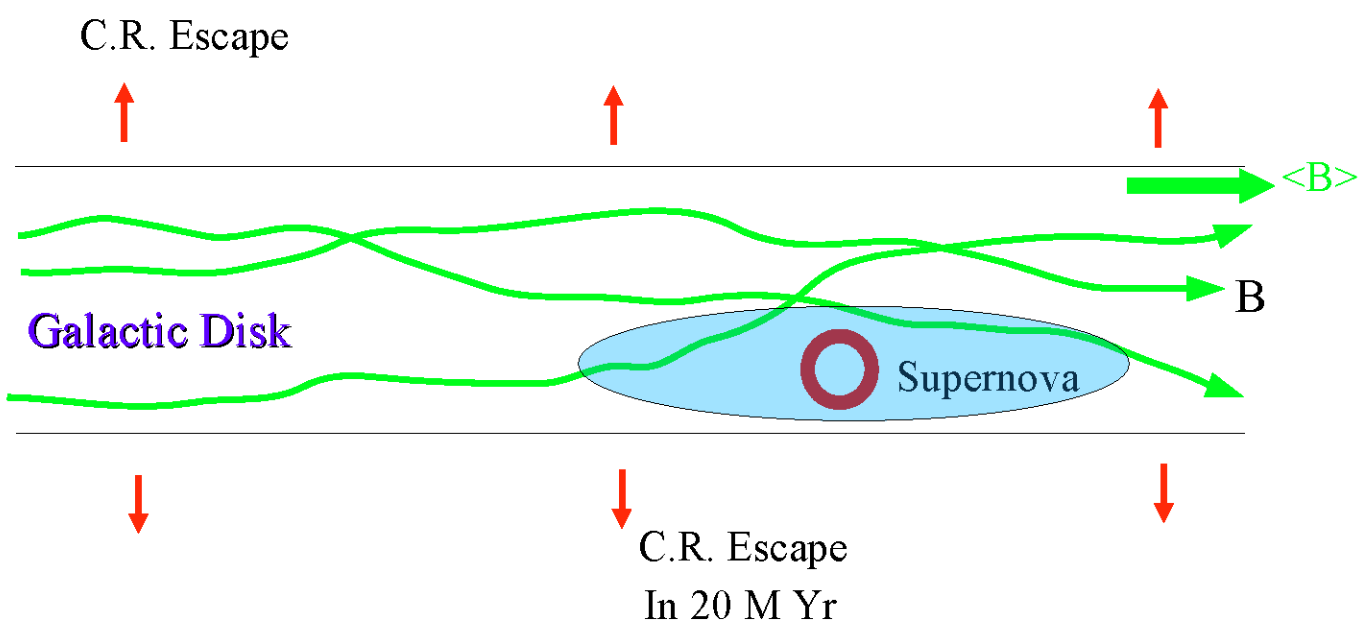
A very simple and reasonably successful picture of cosmic rays in the galaxy has evolved.

- Regard the galaxy as a box into which the cosmic rays are injected and from which they escape.

- Replace all of the diffusive transport and geometry complications by an effective loss rate which balances the acceleration and injection.



Note that the cosmic rays escape predominantly *across* the average magnetic field. For a more detailed discussion in terms of Loss across the galactic field, see Jokipii in “Interstellar Turbulence” ed by Franco, Cambridge, 1999.


C.R. Escape
<B>
B
Galactic Disk
Supernova
C.R. Escape
In 20 M Yr

Transport and Loss in the Galaxy

The transport equation is sometimes simplified to the very simple and basic equation

$$\partial f / \partial t \approx 0 \approx - f / \tau_L + Q$$

or

$$f = \tau_L Q$$

where f is the distribution function ($dj/dT = p^2 f$, where p is the momentum of the particle), $\tau \approx L^2 / \kappa_\perp$ and Q is the source of particles. For relativistic particles pc = T. Primary cosmic rays are accelerated from ambient material, presumably at supernova blast waves In this case Q_p is a power law: $Q_p(T) \propto T^{-(2-2.3)}$

The characteristic loss time τ_L can be determined from secondary nuclei, produced from collisions (spallation) with ambient gas.

Since, at high energies, the spallation approximately conserves energy per nucleon, we have the source of secondaries $Q_s \propto f_p$

Then we have

$f_s = \tau_L Q_s \propto \tau_L f_p$ or $f_s/f_p \propto \tau_L$

This ratio is observed to vary as $\approx T^{-.6}$ at $T \approx$ 1-10 GeV. Extrapolated to high Energies, this give problems. Observations show that $\tau_L \approx$ 20 Myr at GeV energies, or some 300 yr at 10^{18} eV!

We may inquire as to how large the perpendicular diffusion coefficient must be to yield .

$\tau_L \approx L^2 / \kappa_\perp$ to be $\approx 2 \times 10^7$ yrs

Setting L equal to a characteristic scale normal to the disk of some 500 pc yields $\kappa_\perp \approx 4 \times 10^{27}$ cm^2/sec, which is quite large.

A typically quoted value for $\kappa_\|$ of the order of or less than 10^{29} cm^2/sec, in which case the ratio of perpendicular to parallel diffusion is about 4%.

These all seem reasonable.

Anisotropies

- Strictly speaking we should not do anisotropies in the leaky box model.
- Nonetheless, simple considerable lead to reasonable anisotropies at GeV energies.
- In the diffusion approximation (the Parker equation), we can write for the anisotropy

  $c\,\delta \approx 3(L/\tau_L)$

  or

  $\delta \approx 3\,L/(\tau_L\,c) \approx 10^{-4}$ relative to the local plasma, which is not unreasonable.

At TeV energies. δ, relative to the local interstellar medium is < $\approx 3 \times 10^{-4}$

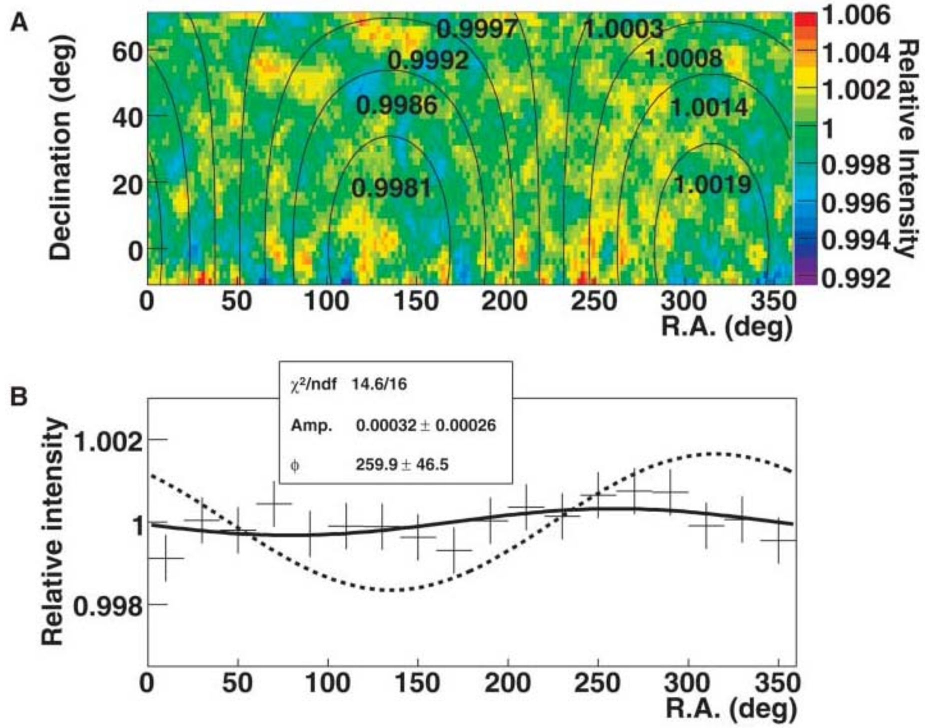


Fig. 4. Celestial or 2D local sidereal time CR intensity map and its 1D projection in the R.A. direction for 300 TeV CRs of all data. (**A**) The colored map is the same as Fig. 3E. The contours are the "apparent" 2D anisotropy expected from the Galactic CG effect. The width of the vertical color bin is 7.25×10^{-4} for the relative intensity in (A). The 1D projection is in map (**B**) for Dec between 25° and 70°, where the dashed line is the expected Galactic CG response and the solid line is the best fit to this observation using a first-order harmonic function. The fitting function is in the form of Amp $\times$ cos(R.A. $-$ ϕ) where ϕ is in degrees and Amp is the amplitude. The χ^2 fit involves the ndf given by the number of bins minus two for the two fitting parameters Amp and ϕ. The data shows no Galactic CG effect with a confidence level of ~5 SD.

From Amenomori, et al, Science, 2006

BUT, what happens at high energies?

- We must remember that observations mandate that τ_L scale as $T^{.6}$.

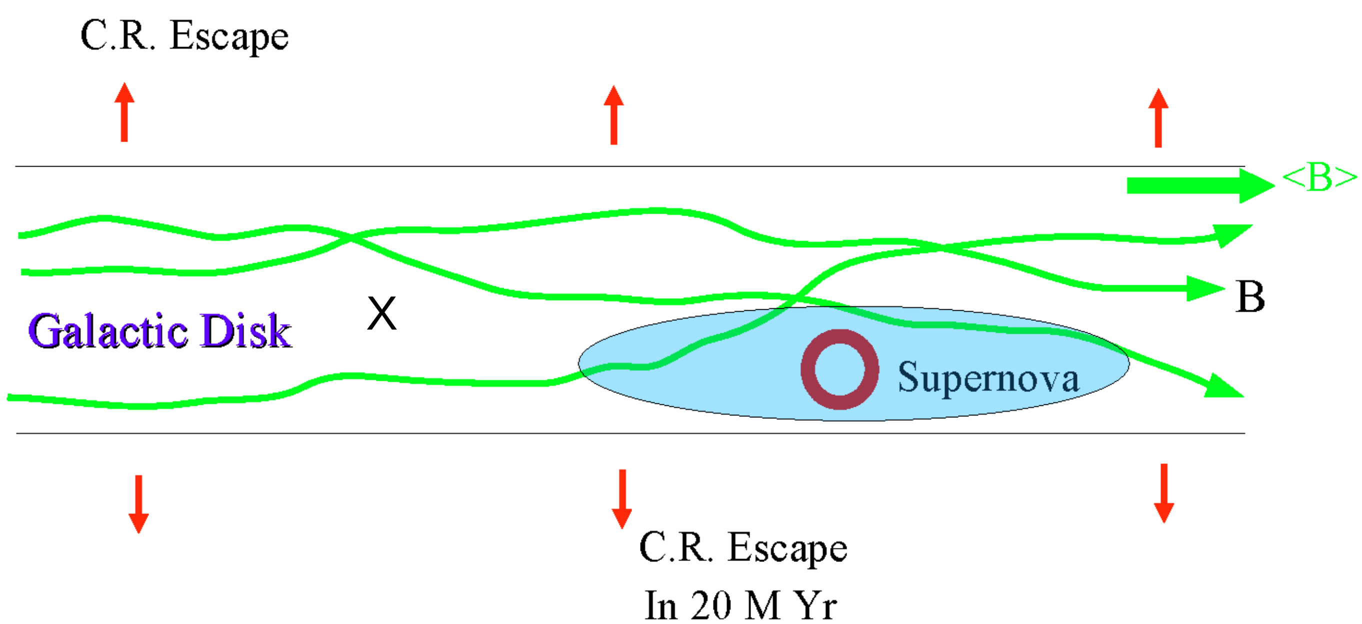
- This gives $\delta \approx 1$ at 10^{18} eV

- Observations give $\delta < \approx 5\%$ (Sokolsky, private communication, 2007.

- The theoretical scaling of τ_L as $T^{.33}$ for Kolmogorov turbulence is barely acceptable at about 5%.

What can we do?

- The above arguments are quite basic.
- Perhaps the answer is to consider more-realistic geometries.
- We are observing near the center of the galactic disk. In this case, the gradients and hence the anisotropies can be much smaller.


C.R. Escape
<B>
B
Galactic Disk
X
Supernova
C.R. Escape
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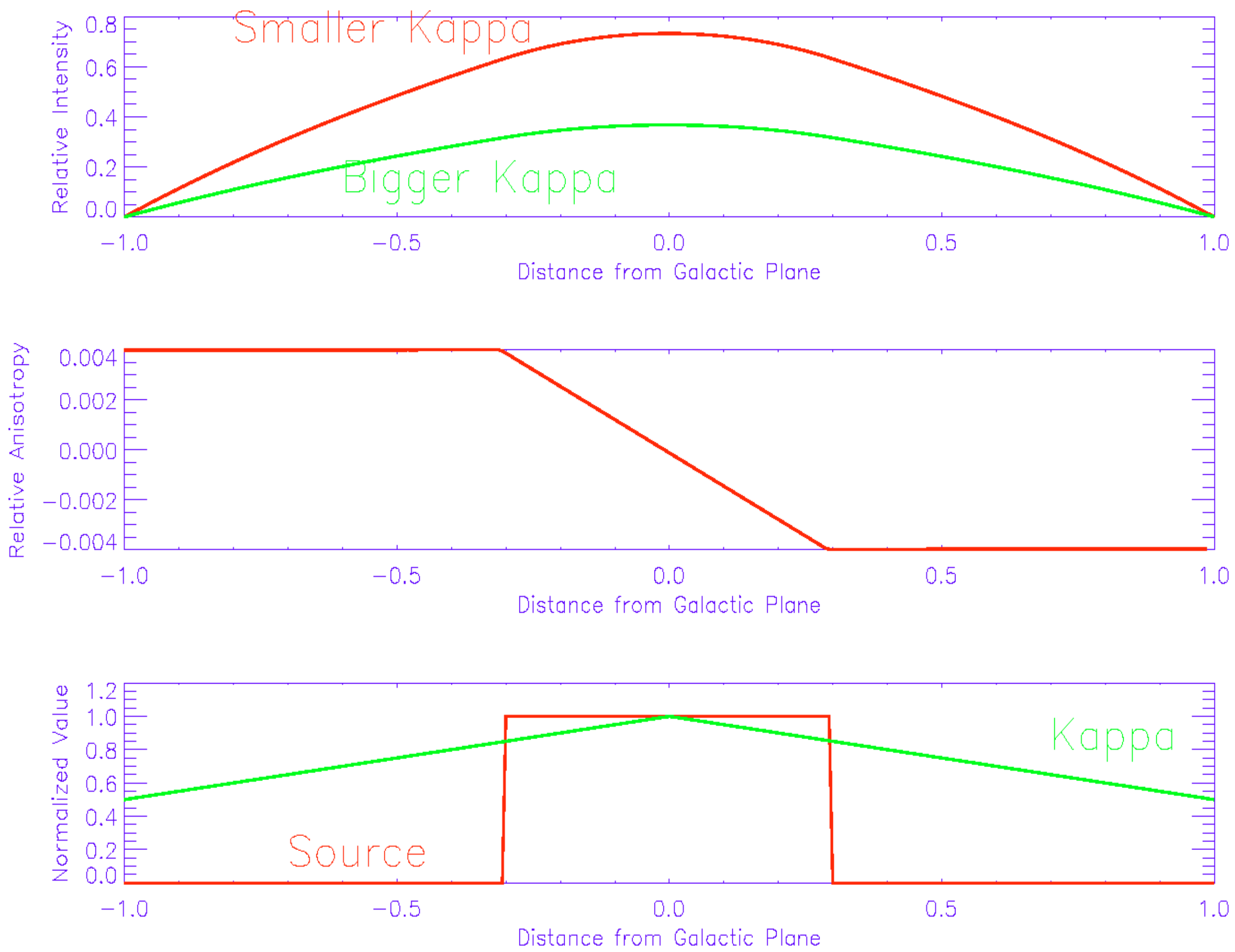
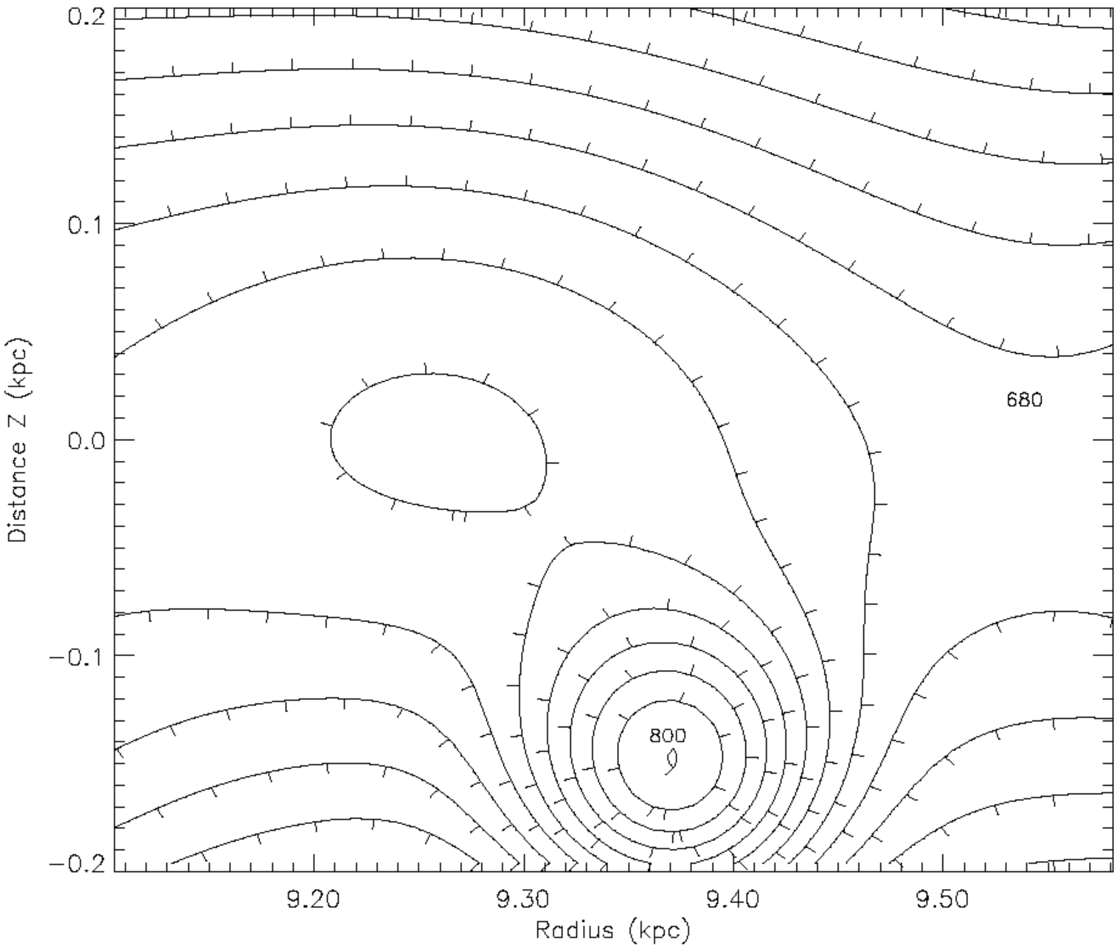
Results of a simple 1-dimensional model which illustrates the point



Even more-complicated scenarios are possible.

Results of a model calculation with multiple sources.



Conclusions

- Simple considerations based on observations lead to untenable conclusions regarding the anisotropy high-energy cosmic rays.

- Perhaps we must go to more-complicated models such as that illustrated here or those of Strong and Moskalenko.

- Can we find observational tests for these ideas?