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THE ISOTROPY PROBLEM OF TEV COSMIC RAYS

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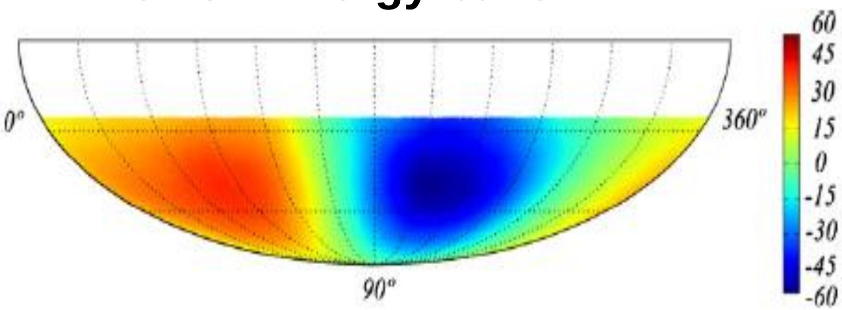
Texas Symposium, 2013

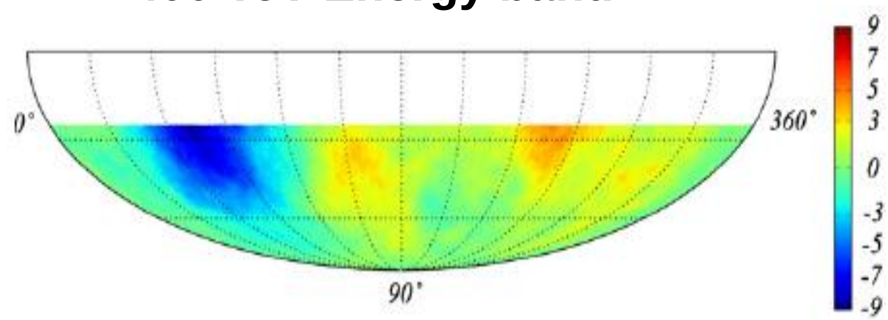
Anisotropy measurement by IceCube

IceCube reports the sidereal first harmonic in the CR intensity average over declination range -25^0 to -72^0

20 TeV Energy band



400 TeV Energy band



$$\delta_{obs} = (7.9 \pm 0.1_{\rm stat} \pm 0.3_{\rm sys}) \times 10^{-4}$$

$$\delta_{obs} = (3.7 \pm 0.7_{\rm stat} \pm 0.7_{\rm sys}) \times 10^{-4}$$

Abbasi et al., ApJ (2012)

Why is it a problem?

Propagation models constrain diffusion rate to fit B/C

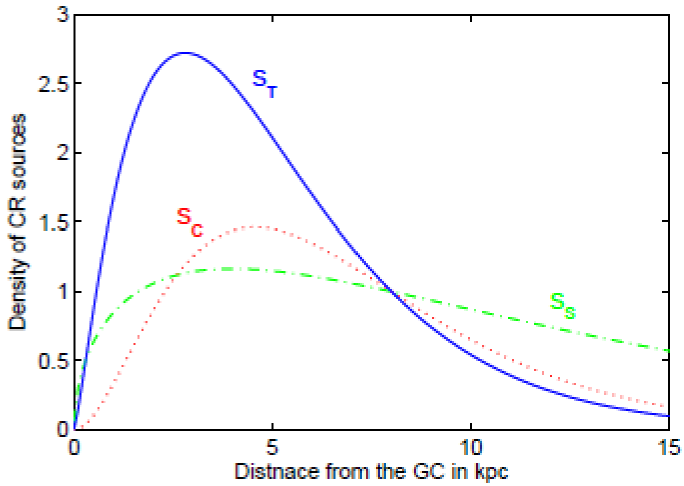
$$D(E) \simeq 10^{28}(E/GeV)^{1/3}cm^2s^{-1}D_{28}$$

The anisotropy in 1-1000TeV energy band predicted by Isotropic diffusion with a steep source distribution is more than an order of magnitude higher than the observations

Why Isotropic diffusion?

B/C does not constrain diffusion rate parallel to the Galactic plane

Radial Distribution



S_T: Pulsars (Trotta et al., 2011)

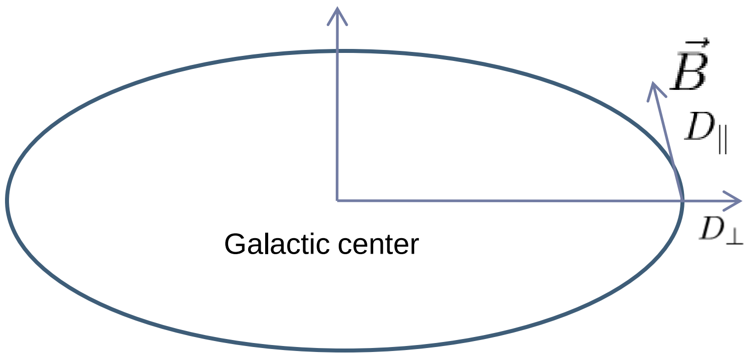
S_C: SNRs (Case & Bhattacharya, 1998)

S_s : Gamma ray Gradient (Strong et al., 2000)

Anisotropic Diffusion of Cosmic Rays

A partially ordered Galactic magnetic field breaks the isotropy of diffusion

$D_{\perp}/D_{\parallel} \gtrsim 10^{-2}$ for $\delta B/B \cong 1$



A general anisotropic diffusion of the cosmic rays is described by

$$\frac{\partial N}{\partial t} = \frac{\partial}{\rho \partial \rho} \rho D_{\rho} \frac{\partial N}{\partial \rho} + \frac{\partial}{\rho^2 \partial \phi} D_{\phi} \frac{\partial N}{\partial \phi} + \frac{\partial}{\partial z} D_z \frac{\partial N}{\partial z} + Q(E)\delta(t)\delta(\rho - \rho_0)\delta(\phi)\delta(z - z_s)/\rho.$$

Cosmic Ray Flux Anisotropy

- Flux from a source: $N(\rho,\phi,z) = G(z,t)N_0(\rho,\phi,t)$

$$G \simeq \frac{1}{\sqrt{2\pi Dt}} \exp\left(-\frac{(z-z_s)^2}{4Dt}\right)(1+\tilde{t})^{1.25}\exp(-(1.5\tilde{t})^{0.97} \qquad \tilde{t} = 2Dt/H^2$$

$$N_0(\rho,\phi,t) = \frac{\Theta(t)}{2\pi D_\perp t}\frac{Q(E)}{H}\exp\left(-\frac{\rho^2+\rho_0^2}{4D_\perp t}\right)\left[\frac{1}{2}I_0(\tilde{\rho}) + \sum_{n=1}^{\infty}\cos(n\phi)I_{\nu(n)}(\tilde{\rho})\right]$$

$$\tilde{\rho} = \rho\rho_0/2D_\perp t \qquad \nu(n) = n\sqrt{D_{\|}/D_\perp}$$

- Anisotropy: $\vec{\delta} = 3\left(D_\rho\frac{\partial N_{tot}}{\partial \rho}\hat{\boldsymbol{\rho}} + D_\phi\frac{\partial N_{tot}}{\rho\partial\phi}\hat{\boldsymbol{\phi}} + D_z\frac{\partial N_{tot}}{\partial z}\hat{\boldsymbol{z}}\right)/cN_{tot}$

Use the Monte Carlo method to randomly place sources in the Galaxy with a pulsar-like source distribution (a steep distribution) and source rate 1 in every 100 years.

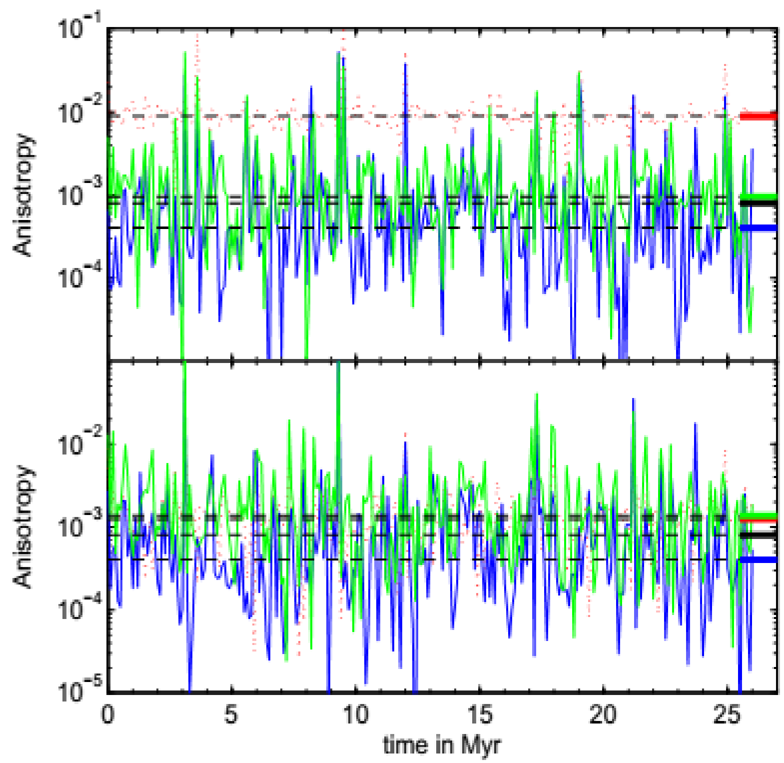
Anisotropy at 20 TeV

Source rate : 1 per 100 yr
H=5 kpc

- Radial anisotropy dominates for a steep source distribution
- Radial anisotropy decreases as the radial diffusion rate is reduced
- Azimuthal *discreteness* anisotropy becomes the dominant contributor to the total anisotropy for $D_\rho \gtrsim D^{iso}/10$

--δ_r --δ_z --δ_φ

Isotropic diffusion

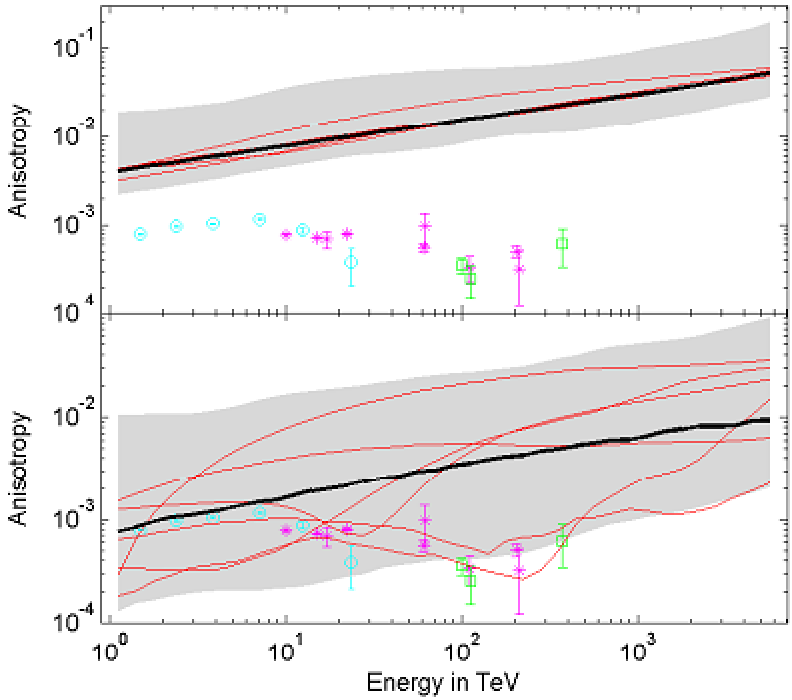


Anisotropic diffusion : $D_\rho = D^{iso}/10$

Anisotropy vs. Energy

- Total anisotropy at all energies goes down as the radial diffusion rate is reduced
- Fluctuation increases with decreasing radial diffusion rate since the total number of contributing sources becomes smaller
- Non-monotonic dependence of anisotropy on energy is due to discreteness of the sources

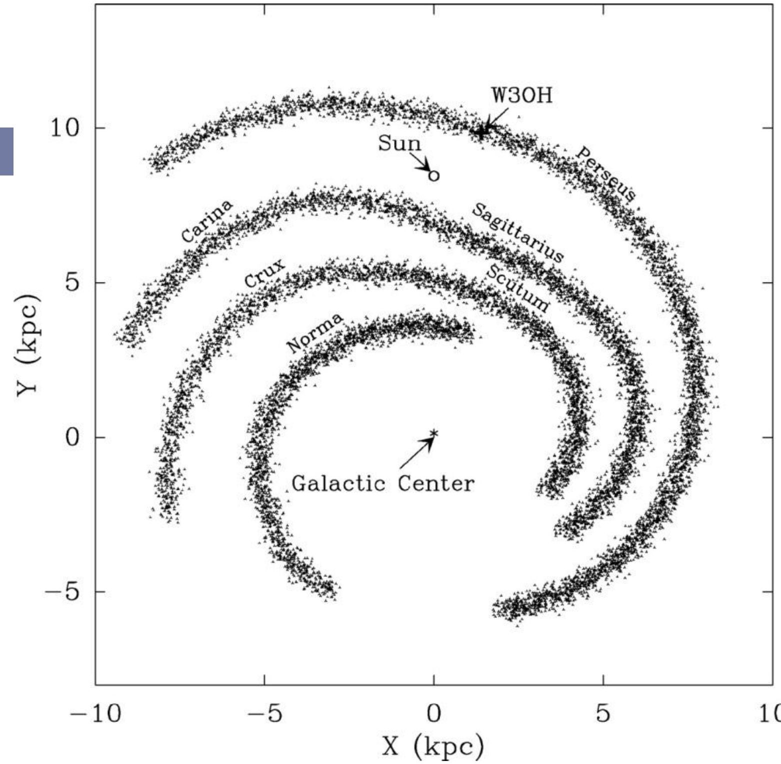
Isotropic diffusion



Anisotropic diffusion : $D_\rho = D^{iso}/50$

Spiral Arms

- Star formation in the Galaxy takes place in spiral arms
- We lie in Local spur, between two spiral arms Sagittarius and Perseus
- Sun completes one revolution in about 280 Myr relative to the spiral arms
- CRs are assumed to diffuse in the corotating frame of the Sun
- Four spiral arms, two major and two minor, are assumed



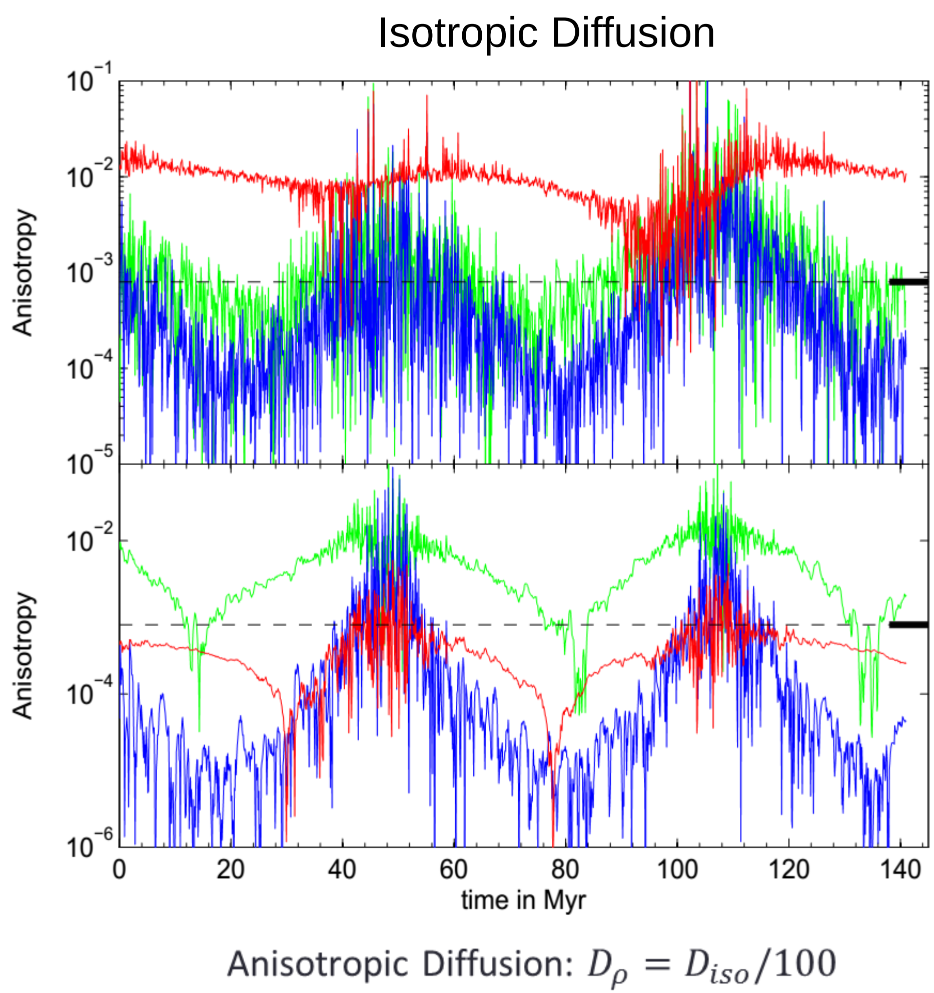
Xu *et al.*, Science (2006)

A tail-like distribution of sources from spiral front is assumed to model spiral arms:

$$P(d)=\exp(-d/300\ \text{pc})$$

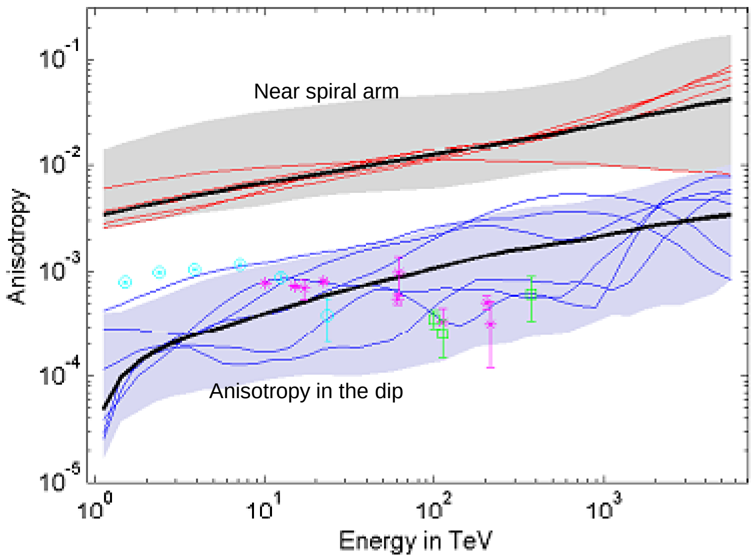
Anisotropy at 20 TeV

- Anisotropy is dependent on our location with respect to the spiral arms
- Even for isotropic diffusion, near the inner edge of the spiral arm flux cancellation causes a dip in the radial anisotropy
- Anisotropy is smaller in the inter-arm regions due to distantness of the sources and flux cancellation



Anisotropy vs. Energy

- Near a spiral arm anisotropy is higher due to proximity of sources and the fluctuation is smaller due to larger number of contributing sources
- Fluctuation in the dip period is comparatively large



Anisotropic diffusion : $D_\rho = D^{iso}/50$

Nearby Supernovae

SNR	Distance (kpc)	Age (Myr)	Anisotropy at 1 TeV
Geminga	0.25	0.3	0
Monogem	0.3	0.08	0.0004
Vela	0.25	0.01	0.025
Cygnus loop	0.8	0.015	0.0001
Vela Jr.	0.21	0.001	0.034

Under the assumption of **Isotropic** diffusion anisotropy due to Vela and Vela Jr. is inconsistent with the measurement

Conclusions

- Large scale radial anisotropy in case of a steep distribution is marginalized by a smaller radial diffusion rate and makes the case of a steep distribution nearly as good as flat distributions.
- Using the diffusion rate that reproduces B/C ratio, the observed anisotropy can be reproduced, but only with a small probability(~5%)
- The surprisingly low large scale anisotropy in TeV band could be due to our location in the Galaxy with respect to the spiral arms and small radial diffusion rate
- Isotropic diffusion implies a large anisotropy from Vela SNR, strengthening the case of anisotropic diffusion