TEV-BAND COSMIC RAY ANISOTROPY : ANISOTROPIC DIFFUSION

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Propagation of cosmic rays in the Galaxy

- Cosmic rays scatter in the turbulent Galactic magnetic field
- Propagation of Cosmic rays in the interstellar medium can be described by diffusion

$$\frac{\partial N}{\partial t} = \nabla D \nabla N + Q(E)\delta(t)\delta(\vec{r} - \vec{r}_s)$$

- Stochastic reacceleration, advection, and energy losses are neglected
- Escape from the Galaxy is encapsulated by introducing absorbing boundaries at $|z| = H$

Anisotropic Diffusion

- A partially ordered Galactic magnetic field (GMF) breaks the isotropy of diffusion
- Rate of diffusion across magnetic field lines is much less compared to diffusion rate along magnetic field
- $D_{\perp}/D_{\parallel} \gtrsim 10^{-2}$ for $\delta B/B \cong 1$
- The ratio is assumed to be independent of energy
- Regular component of the GMF (directed along the spiral arms) is assumed to be toroidal
- A general anisotropic diffusion of the CRs 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 from point-like sources

$$N(\rho, \phi, z) = G(z,t) N_0(\rho, \phi, t)$$

Mid plane density N_0 can be written as,

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

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

G , after summing over mirror images of Gaussian centered at z_s, can be approximated as

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

- Local CR flux is calculated after summing the contribution of relevant sources
- A Monte Carlo simulation is used to randomly place sources in the Galaxy with a given source distribution and source rate.

Anisotropy

- Anisotropy : $\frac{3D(E)}{c}\frac{\vec{\nabla}N}{N}$
- Anisotropy=Large scale anisotropy due to source inhomogeneity + discreteness anisotropy
- H/D_z is determined by B/C ratio
- In-plane diffusion rate is less constrained
- Trotta et al.(2011) reproduced B/C ratio in an isotropic diffusion model with

$$D_0 \simeq (1.2 + 1.3\,H) \times 10^{28}\ \mathrm{cm^2\ s^{-1}}$$

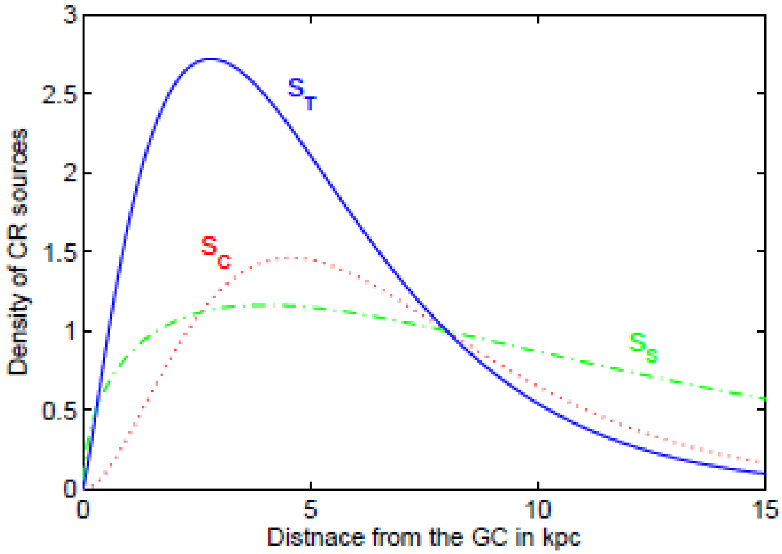
- $D(E) \sim D_0\,(E/4\ \mathrm{GeV})^{0.3}$
- D_z and D_φ are kept unchanged

Source Distribution

- CR source distribution is generally inferred from the distribution of various proxies, such as pulsars and SNRs
- Proposed distributions vary in their extent of steepness
- Distribution of CR sources along the direction perpendicular to the plane is

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

Radial Distribution



S_T: Pulsars (Trotta et al., 2011)
S_C: SNRs (Case & Bhattacharya, 1998)
S_s : Gamma ray Gradient (Strong et al., 2000)

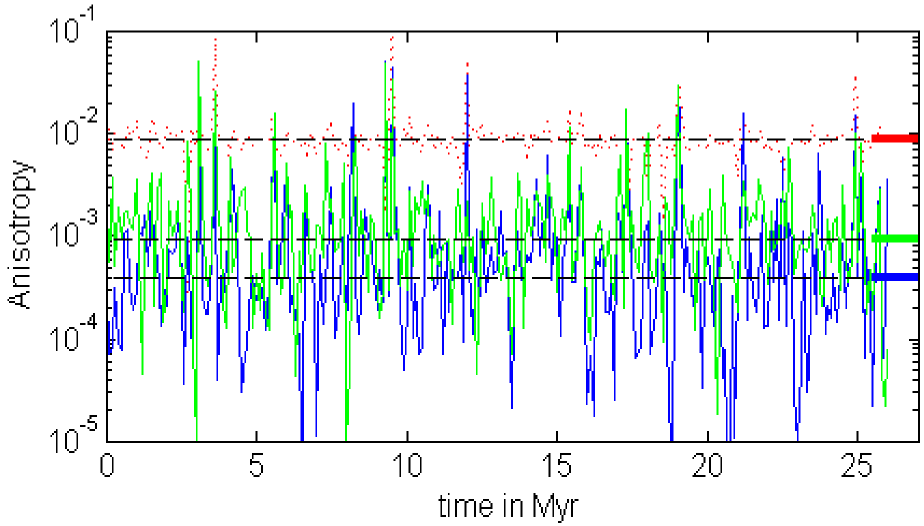
Anisotropy at 20 TeV

Source rate : 1 per 100 yr

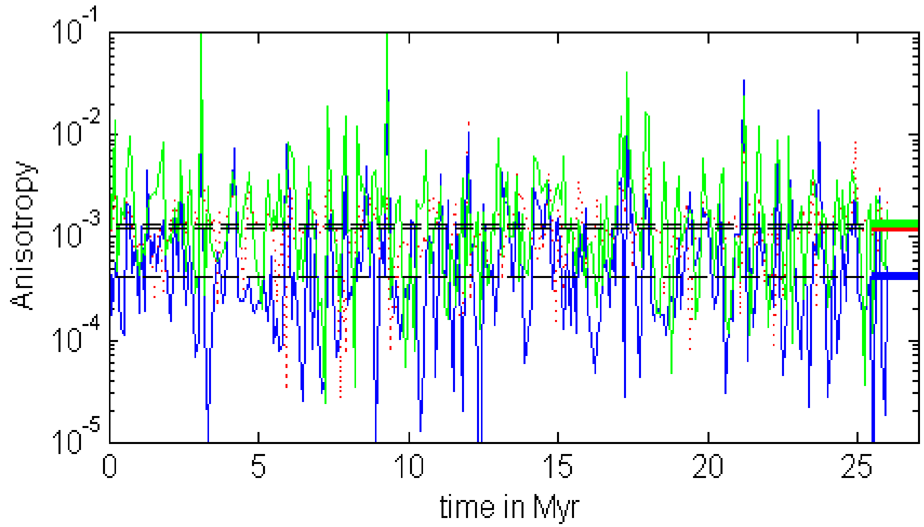
H=5 kpc

--δ_r --δ_z --δ_φ

Isotropic diffusion



Anisotropic Diffusion: $D_\rho = D_{iso}/10$

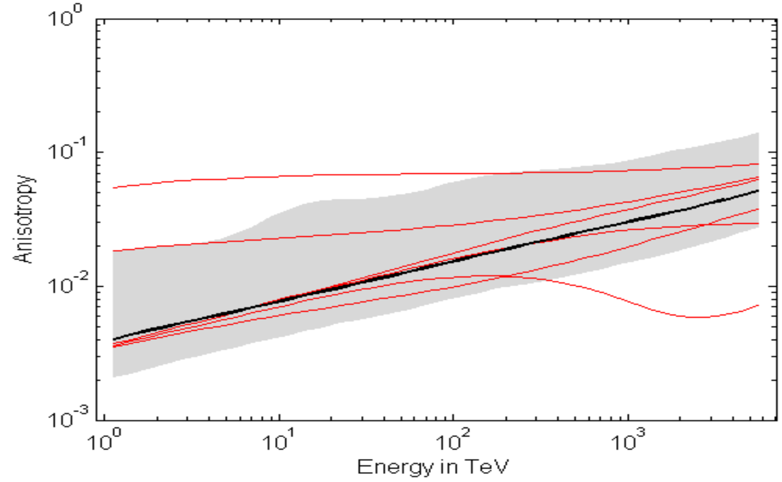


- Radial anisotropy is large and a dominant contributor to total anisotropy for a steep distribution
- Radial anisotropy decrease with decrease in radial diffusion rate
- For pulsar distribution, radial anisotropy becomes comparable to the azimuthal anisotropy for $D_\rho = D_{iso}/10$

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



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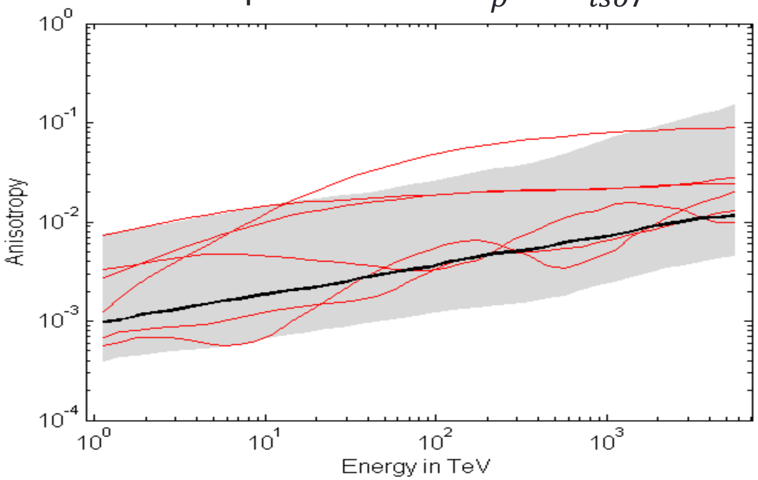
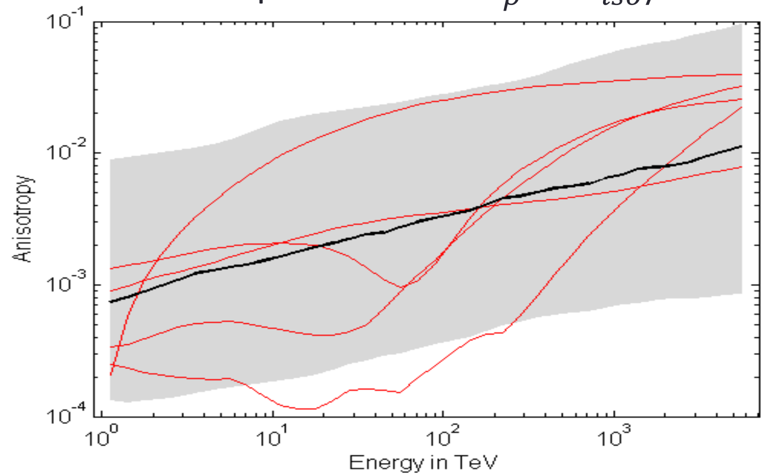
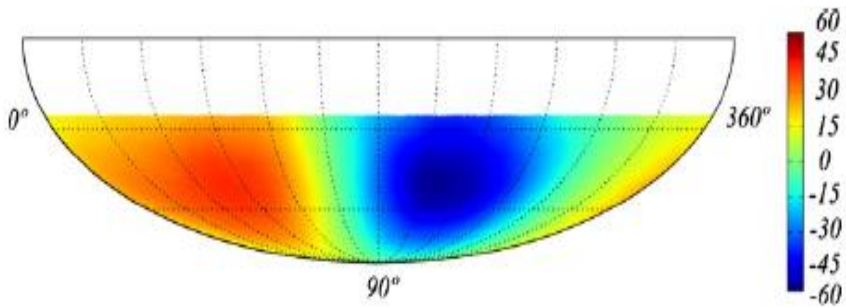


Anisotropic Diffusion: $D_\rho = D_{iso}/100$

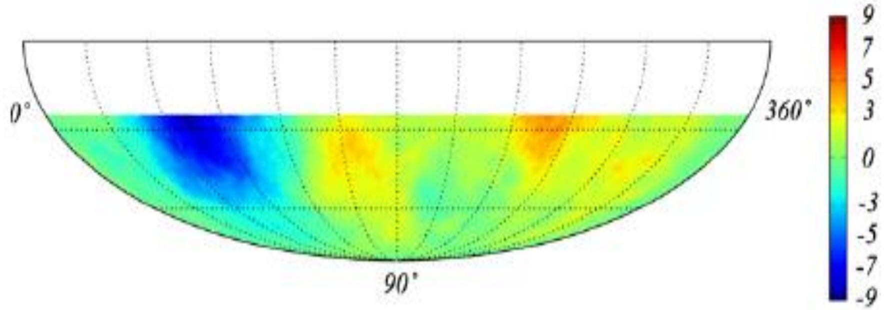


Anisotropy measurement by IceCube

20 TeV Energy band



400 TeV Energy band



Abbasi et al., ApJ (2012)

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

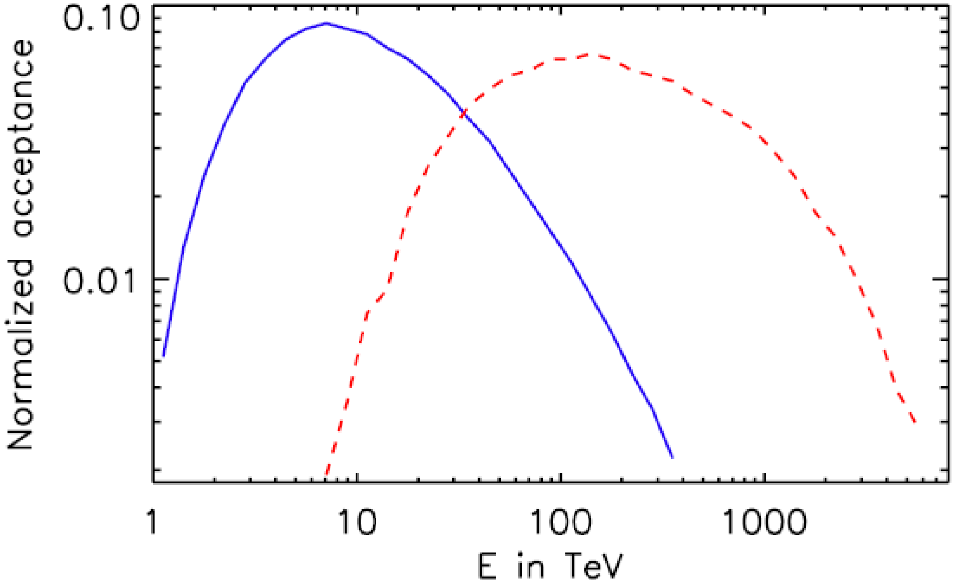
$$\delta_{obs} = (3.7 \pm 0.7_{\text{stat}} \pm 0.7_{\text{sys}}) \times 10^{-4}$$

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

Comparison with IceCube measurements

- Airshowers caused by heavy primaries behave approximately behave like superposition of airshowers produced by individual nucleons
- Heavy nuclei of nuclear change Z and energy E behaves like protons of energy E/Z
- Primaries are assumed to be protons
- Dipole anisotropy is projected at the characteristic declination -45^0

$$\delta_{\rm proj}(\theta_c) = \frac{\delta \cos\theta_d \cos\theta_c}{1 + \delta \sin\theta_d \sin\theta_c}$$

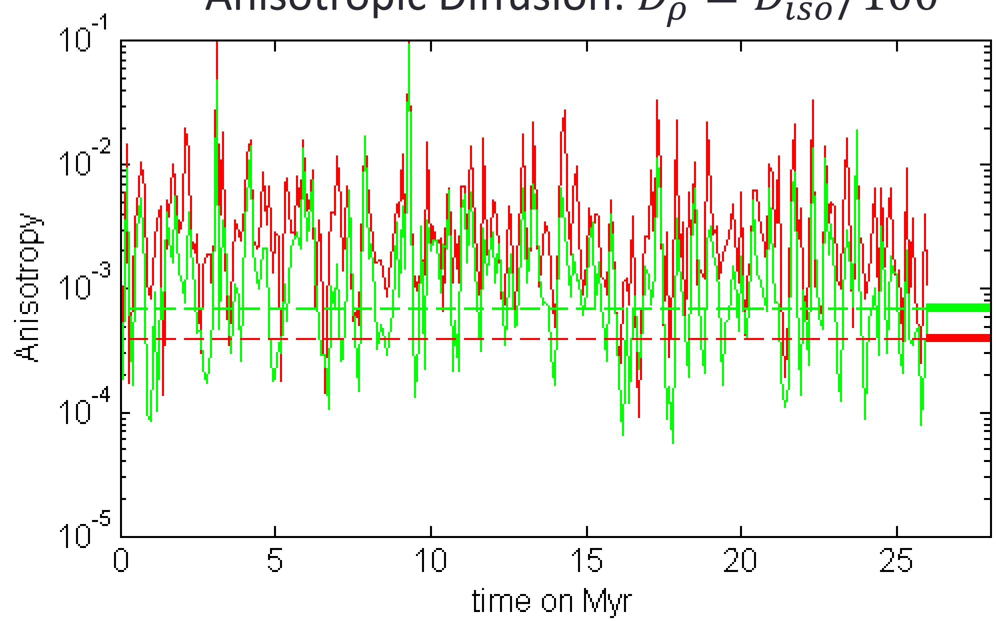


Distribution of the primaries in energy, assuming all primaries are protons

Anisotropy in 20 TeV and 400 TeV energy band

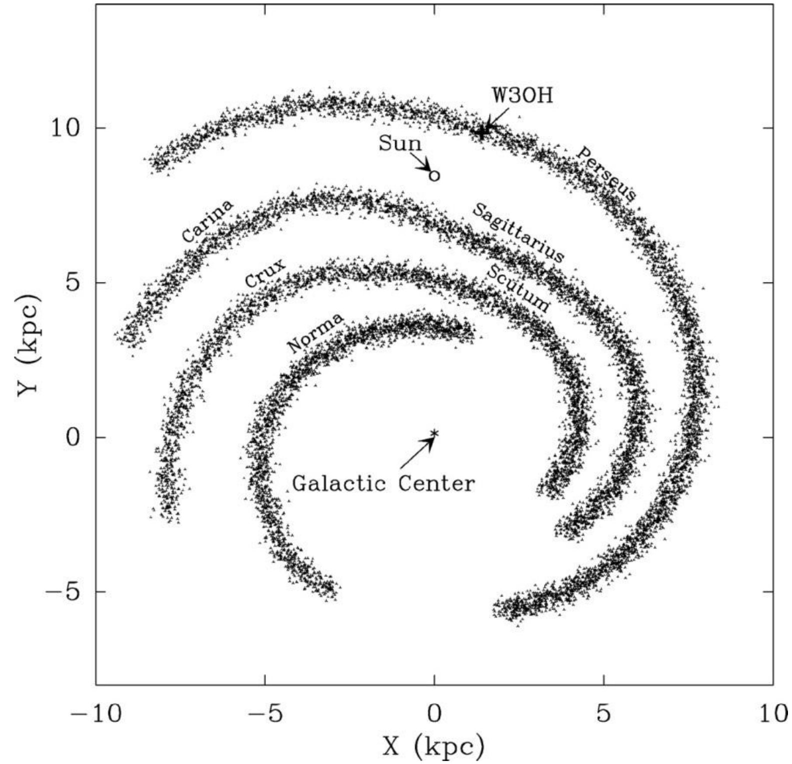
- Anisotropy is below the observed value in 20 and 400 TeV band for about 5 % of time
- Pohl & Eichler (2013) model the propagation with isotropic diffusion, conclude a need for a flat distribution and get to meet the observation about 5-10% of time

Anisotropic Diffusion: $D_\rho = D_{iso}/100$



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

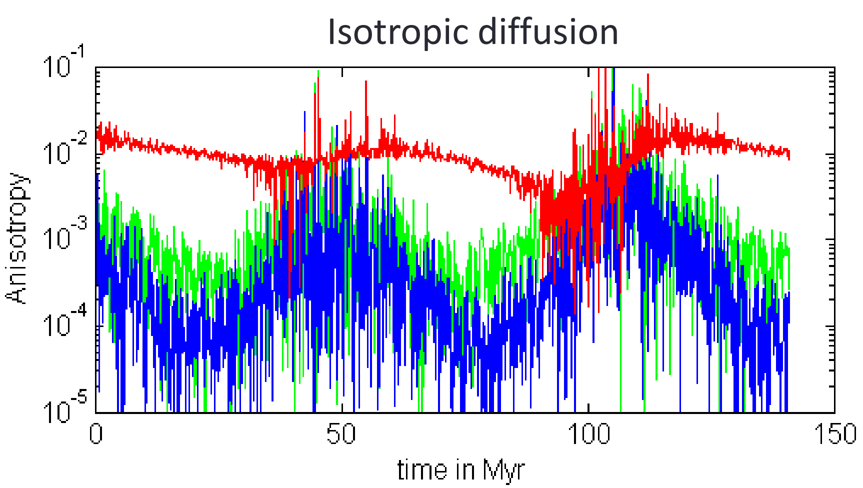


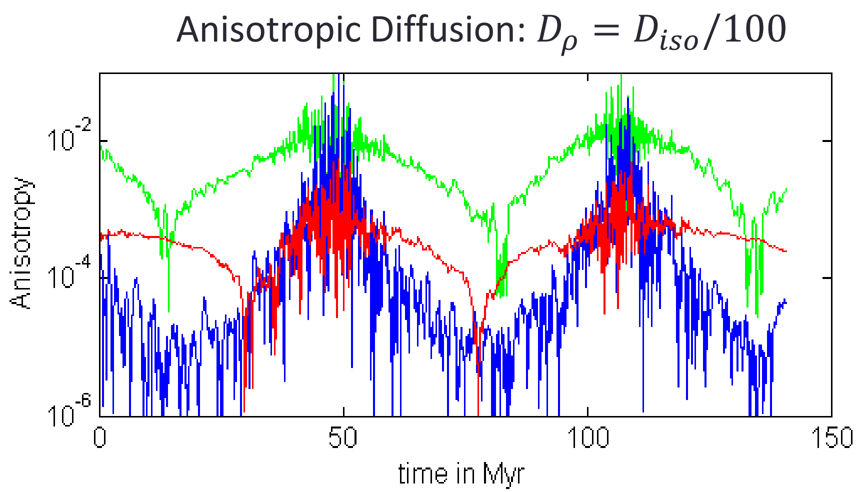
Xu *et al.*, Science (2006)

A tail-like distribution of sources from spiral front is assumed to model spiral arms: P(d)=exp(-d/300 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

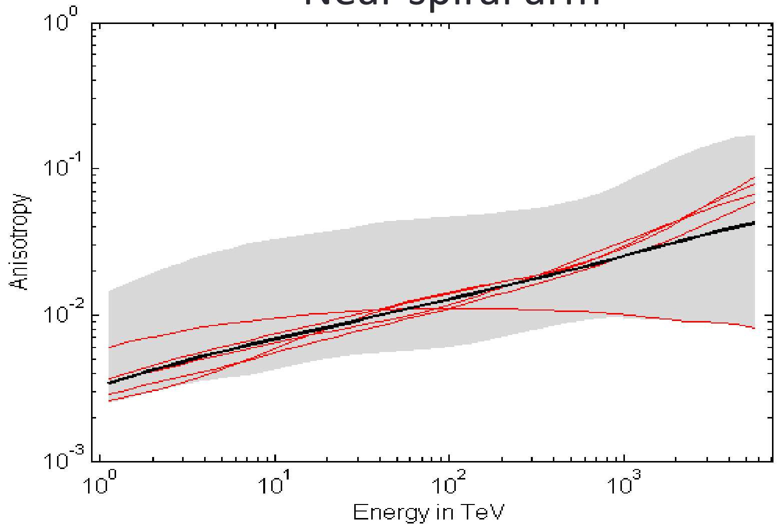




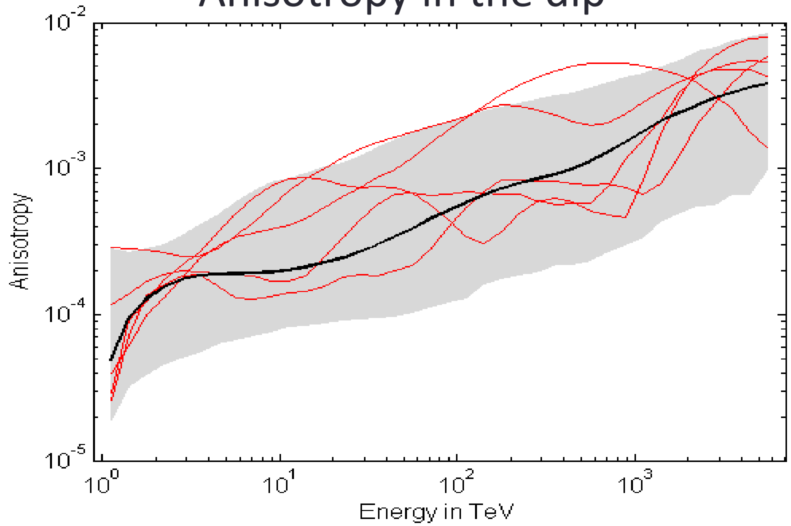
Anisotropy vs. Energy

- 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

Near spiral arm



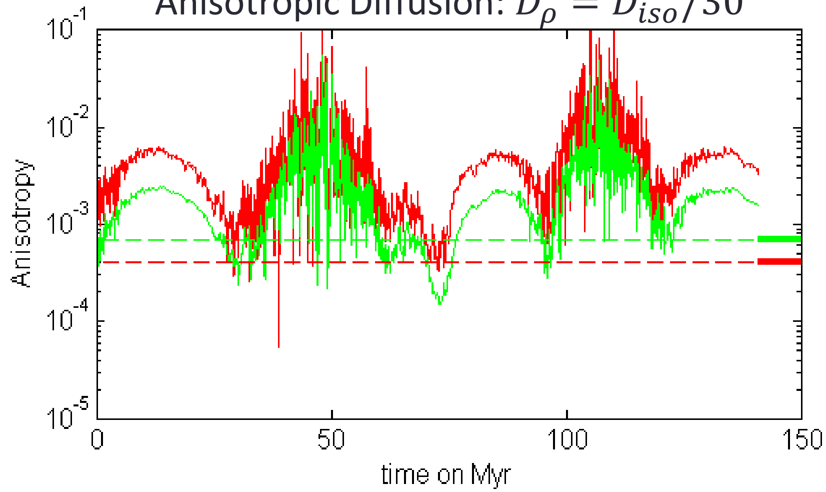
Anisotropy in the dip



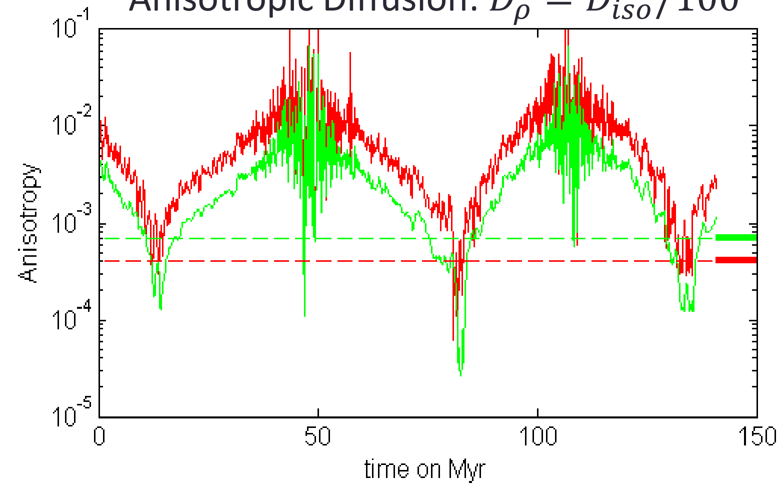
Anisotropy in 20 TeV and 400 TeV energy band

- During the Inter-arm dip, anisotropy is below the measured value in 20 and 400 TeV band for about 30 % of time for $D_\rho = D_{iso}/30$ and 20% of time for $D_\rho = D_{iso}/100$
- Location of the dip is parameter dependent
- The dip period last for about 5 Myr

Anisotropic Diffusion: $D_\rho = D_{iso}/30$



Anisotropic Diffusion: $D_\rho = D_{iso}/100$



Nearby SNRs

- Anisotropy due to a single source: 3r/2ct $\approx \frac{10^{-2}}{2}\left(\frac{r}{kpc}\right)\left(\frac{t}{Myr}\right)^{-1}$
- An anisotropy smaller than 10^{-3} requires that source be within 100 pc

$$d = \sqrt{2D(1TeV) \times Age}$$

SNR	Distance(kpc)	Age(Myr)	Anisotropy	d(kpc)
Geminga	0.25	0.3	0.004	1
Monogem	0.3	0.08	0.017	0.52
Vela	0.25	0.01	0.1	0.19
Cygnus loop	0.8	0.015	0.26	0.2
Vela Jr.	0.21	0.001	0.87	0.06

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 as par with flat distributions.
- Using the diffusion rate that fits B/C ratio, the observed anisotropy can be reproduced for axisymmetric source distribution for about 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
- Anisotropy due to known nearby supernovas is large as compared to the observation, which implies a relatively small TeV CR production in them or their special alignment relative to us.