TeV-PeV CR ANISOTROPY AND LOCAL INTERSTELLAR TURBULENCE

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Summary: arXiv:1702.01001

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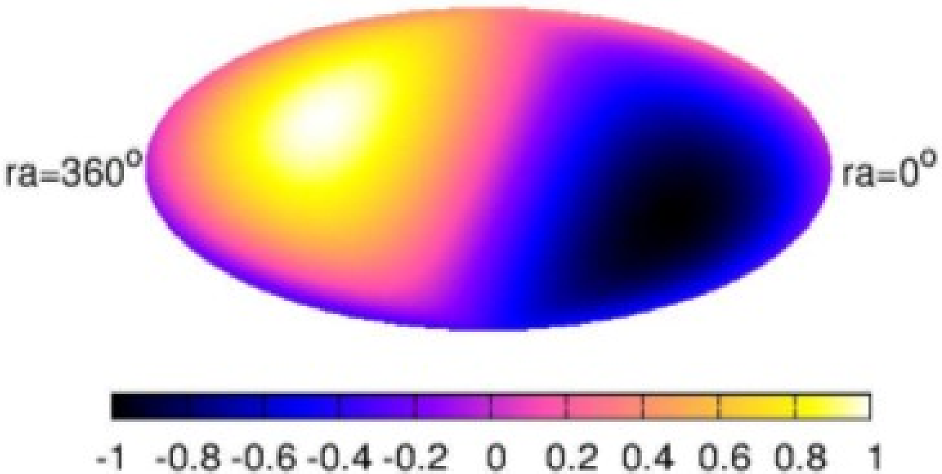
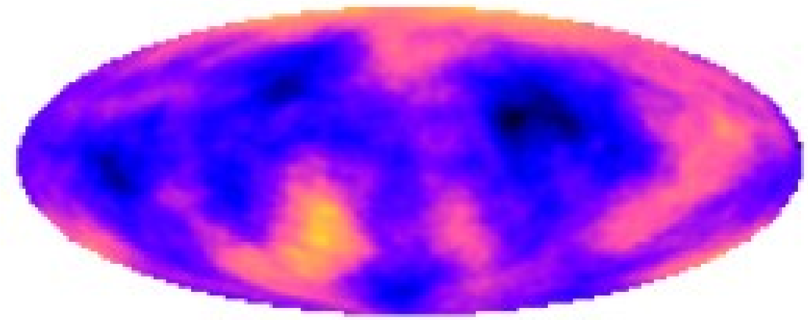
Cosmic-Ray Anisotropy

large-scale + **small-scales**





(« small » amplitude)

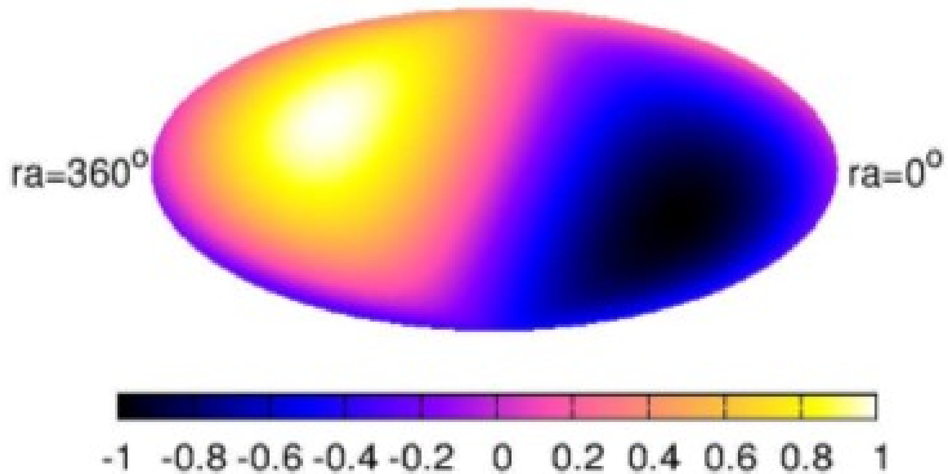
→ In the direction of field lines
→ Amplitude

→ **<u>SHAPE</u>**

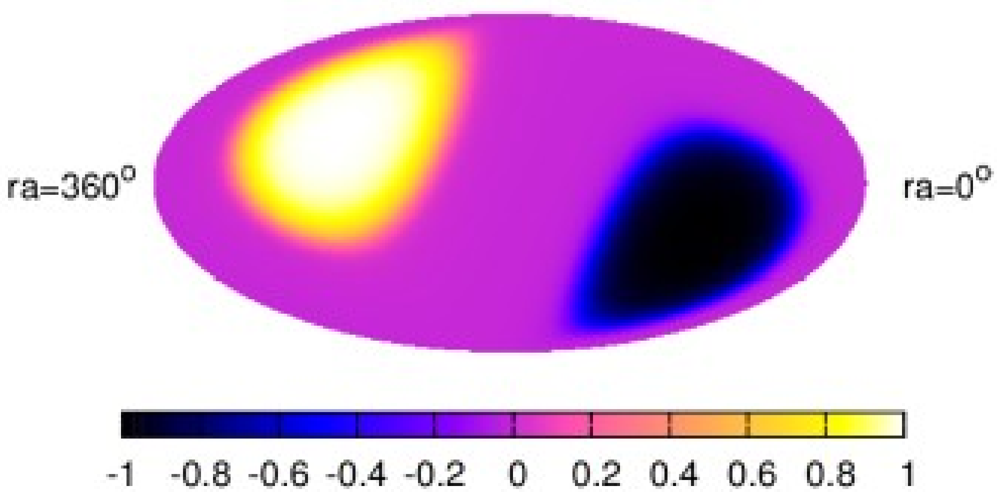
e.g. GG & Sigl (2012),
Ahlers (2014, …),
Malkov et al. (2010),
Drury (2013),
Desiati et al. (2013),
Zhang et al. (2014), …

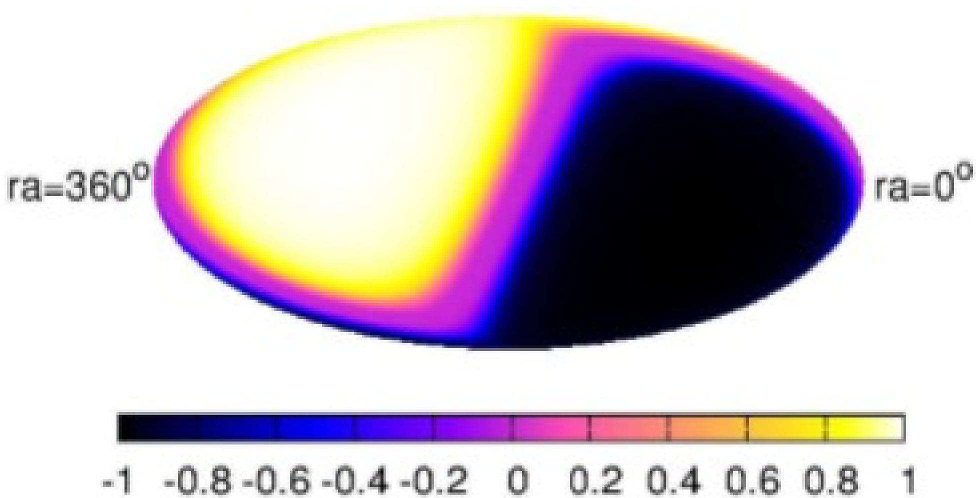
LARGE-SCALE Cosmic-Ray Anisotropy

Dipole only ?



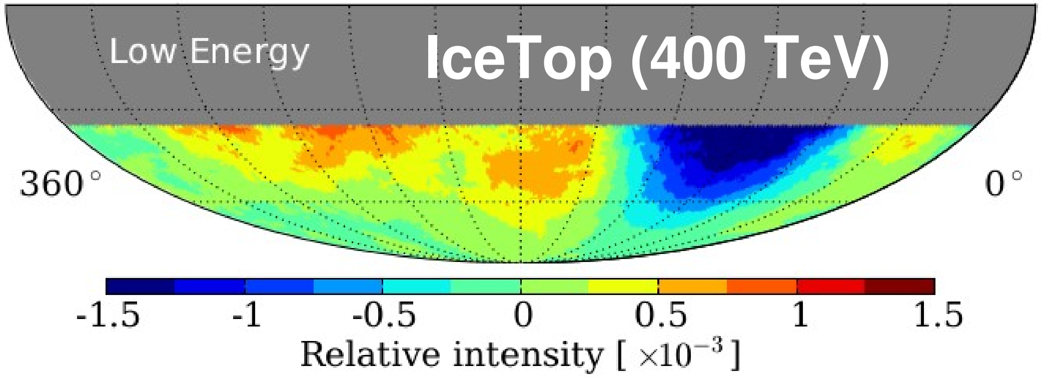
… or could it look like this :

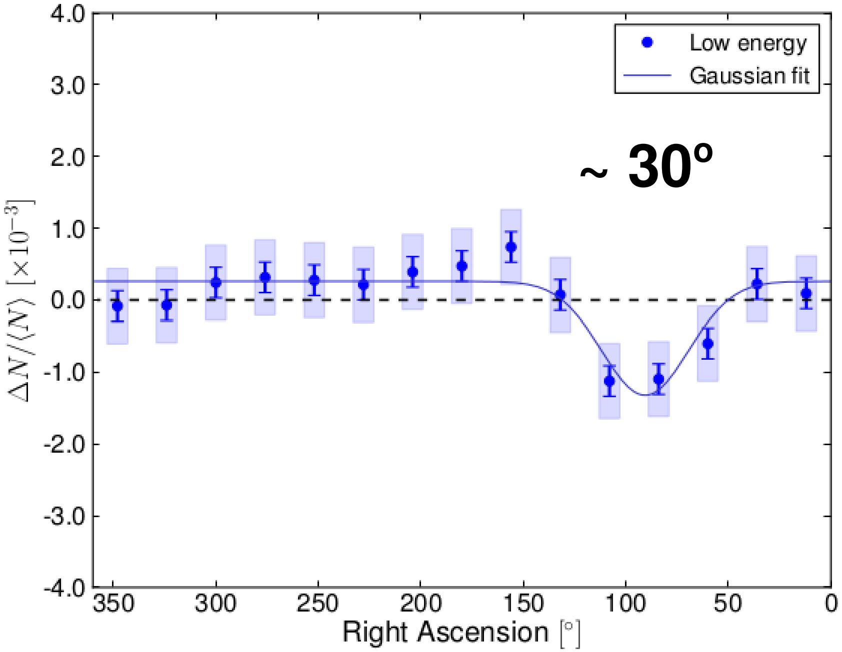


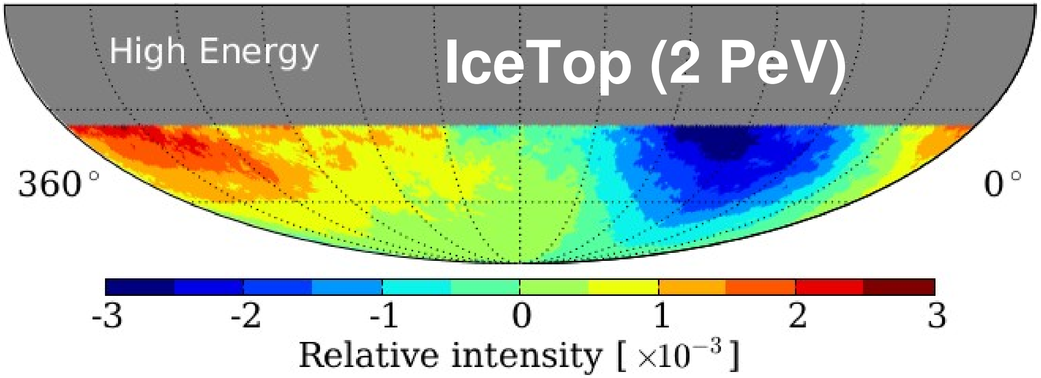


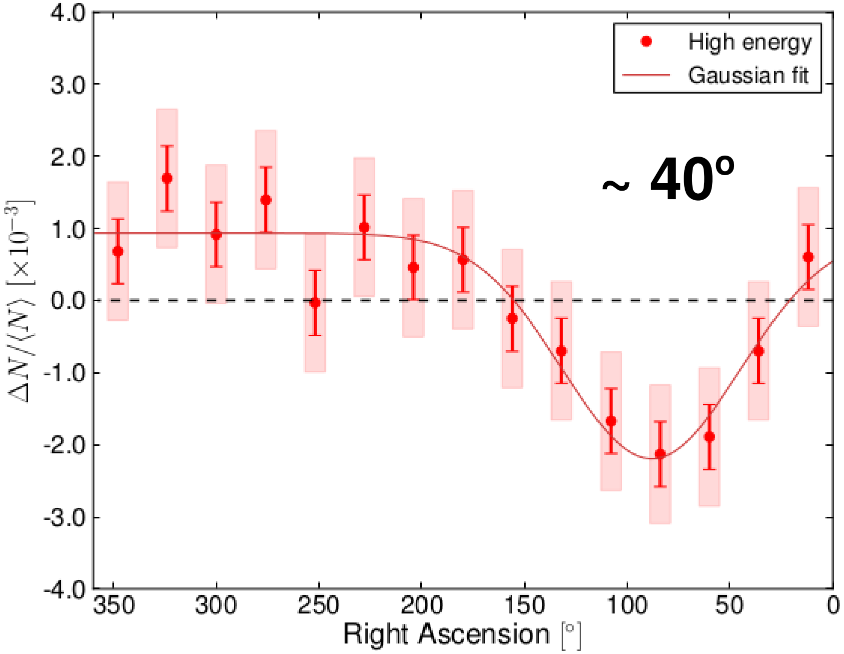
Observations (IceCube, IceTop)

Aartsen et al. (2013)

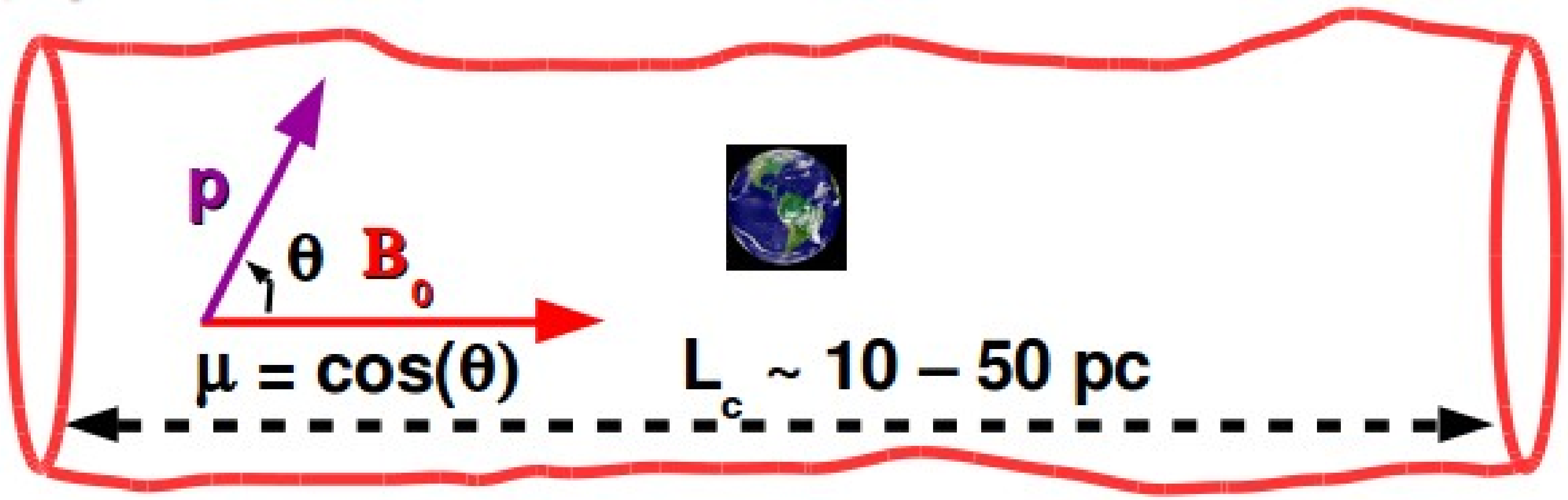








CR Anisotropy : Probe of turbulence

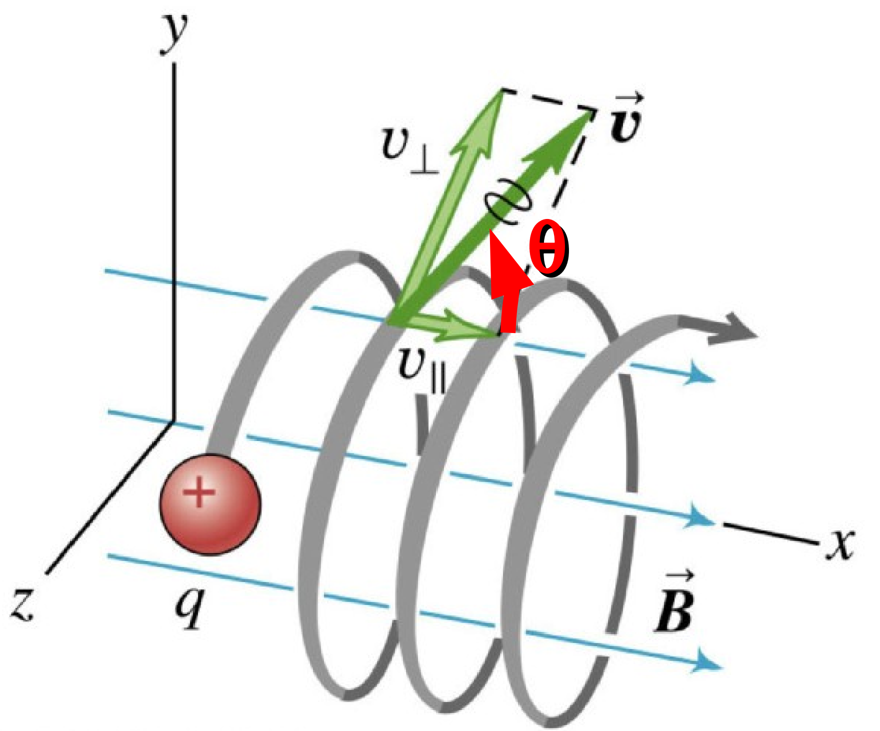


$$\mu v \frac{\partial f}{\partial x} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right)$$

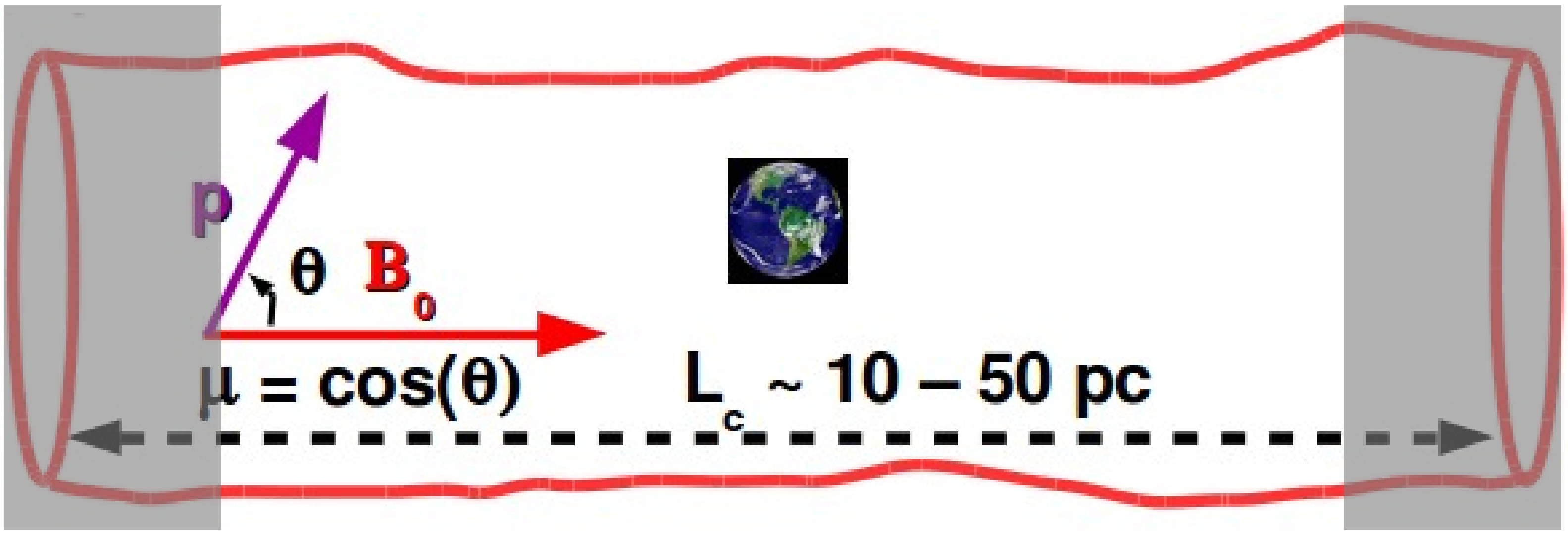
(gyrophase-averaged)

$\delta B/B_0 << 1$

Pitch-angle diffusion



CR Anisotropy : Probe of turbulence



$$\mu v \frac{\partial f}{\partial x} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right)$$

$$\int_0^{\mu} \mathrm{d}\mu' \, \frac{1 - \mu'^2}{D_{\mu'\mu'}}$$

α

=> $f(x,\mu) = \sum_i a_i e^{\Lambda_i x/v} Q_i(\mu) + a_{\text{diff}}\left[x + g(\mu)\right] + f_0$

NOT **$1 - \mu^2$**
in general !

if $\exp\left(-\Lambda_1 d/v\right) \ll 1$

(« boundary layer »)

Pitch-angle diffusion coefficient

$$D_{\mu\mu} = \Omega^2 \left(1 - \mu^2\right) \int \mathrm{d}^3 k \int_0^\infty \mathrm{d}\tau$$

$$\sum_{n=-\infty}^{\infty} \left(\frac{n^2 J_{\rm n}^2(z)}{z^2} M_{\rm A}(\mathbf{k}, \tau) + \frac{k_\parallel^2 J_{\rm n}'^2(z)}{k^2} M_{\rm S,F}(\mathbf{k}, \tau) \right) ,$$

where $z = k_\perp l \varepsilon \sqrt{1-\mu^2}$, and Ω is the Larmor frequency. $M_{\rm A,S,F}$ respectively represent the normalized power spectra of Alfvén, slow and fast modes:

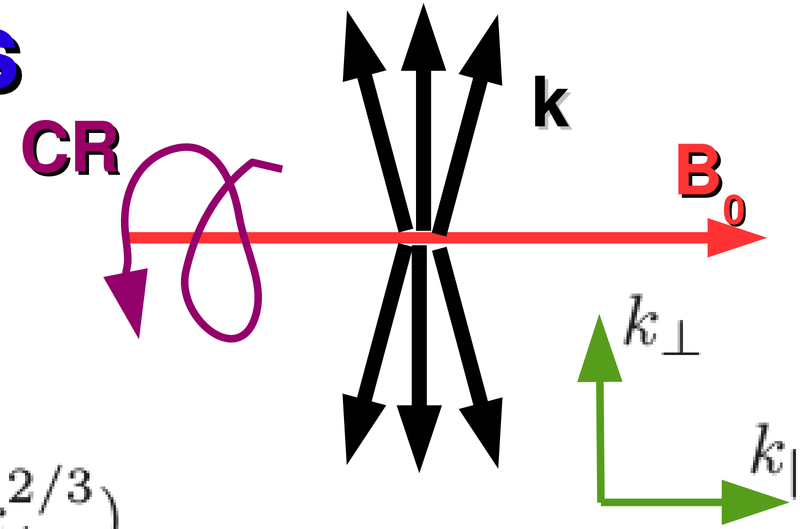
$$M_{\rm w}(\mathbf{k}, \tau) = \langle \mathbf{B}_{1,\rm w}(\mathbf{k}, t) \cdot \mathbf{B}^*_{1,\rm w}(\mathbf{k}, t+\tau) \rangle / B_0^2 \ ,$$

=>

$$D_{\mu\mu} = \Omega^2 \left(1 - \mu^2\right) \int \mathrm{d}^3 k \sum_{n=-\infty}^{\infty} \left(\frac{n^2 J_{\rm n}^2(z)}{z^2} \mathcal{I}_{\rm A}(\mathbf{k}) + \frac{k_\parallel^2 J_{\rm n}'^2(z)}{k^2} \mathcal{I}_{\rm S,F}(\mathbf{k}) \right) \times R_{\rm n}(k_\parallel v_\parallel - \omega + n\Omega) \ ,$$

where $\mathcal{I}_{\rm A,S,F}$ respectively correspond to the normalized energy spectra of the Alfvén, slow and fast modes.

Alfven (and Slow) modes



Goldreich & Sridhar (1995)

$$|k_{||}| \lesssim |k_\perp|^{2/3} l^{-1/3}$$

(1) $\mathcal{I}_{\rm A,S} = \mathcal{I}_{\rm 1,A,S} \propto k_\perp^{-10/3} h(k_{||} l^{1/3}/k_\perp^{2/3})$

where $h(y) = 1$ if $|y| < 1$, and $h = 0$ otherwise (see Chandran (2000))

(2) MHD simulations of Cho & Lazarian (2002) :

$$\mathcal{I}_{\rm A,S} = \mathcal{I}_{\rm 2,A,S} \propto k_\perp^{-10/3} \exp(-k_{||} l^{1/3}/k_\perp^{2/3})$$

Fast magnetosonic modes

MHD simulations of Cho & Lazarian (2002) :

Isotropic with $\mathcal{I}_{\rm M}(\mathbf{k}) \propto k^{-3/2}$

Resonance functions (RF)

(1) NARROW : RF dominated by Lagrangian correlation time :

$$R_{\mathrm{n},1}(k_\parallel v_\parallel - \omega + n\Omega) = \mathcal{R}e\left(\int_0^\infty \mathrm{d}\tau\, \mathrm{e}^{-i(k_\parallel v_\parallel - \omega + n\Omega)\tau - \tau/\tau_\mathrm{w}}\right) = \frac{\tau_\mathrm{w}^{-1}}{(k_\parallel v_\parallel - \omega + n\Omega)^2 + \tau_\mathrm{w}^{-2}}$$

Chandran (2000)

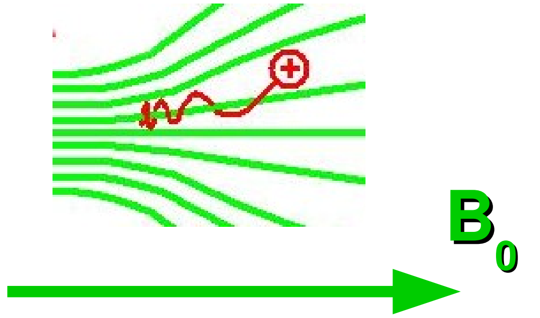
$$\tau_{\mathrm{A,S}} = l^{1/3}/(v_\mathrm{A} k_\perp^{2/3})$$

$$\tau_\mathrm{F} = l/(v_\mathrm{A}\tilde{k}^{1/2}) \qquad \tilde{k} = kl$$

(2) BROAD : Conservation of the adiabatic invariant $v_\perp^2/B$

$$R_{\mathrm{n},2}(k_\parallel v_\parallel - \omega + n\Omega) = \mathcal{R}e\left(\int_0^\infty \mathrm{d}\tau\, \mathrm{e}^{-i(k_\parallel v_\parallel - \omega + n\Omega)\tau - k_\parallel^2 v_\perp^2 \delta\mathcal{M}_\mathrm{A}\tau^2/2}\right) = \frac{\sqrt{\pi}}{k_\parallel v_\perp \delta\mathcal{M}_\mathrm{A}^{1/2}} \exp\left(-\frac{(k_\parallel v_\parallel - \omega + n\Omega)^2}{k_\parallel^2 v_\perp^2 \delta\mathcal{M}_\mathrm{A}}\right)$$

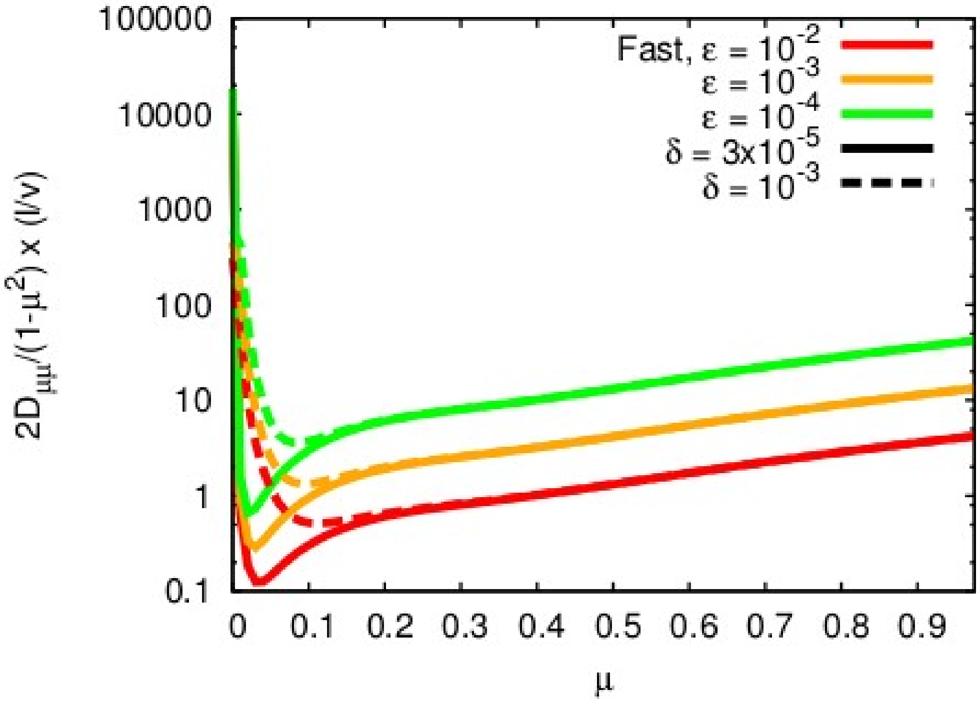
Yan & Lazarian (2008)

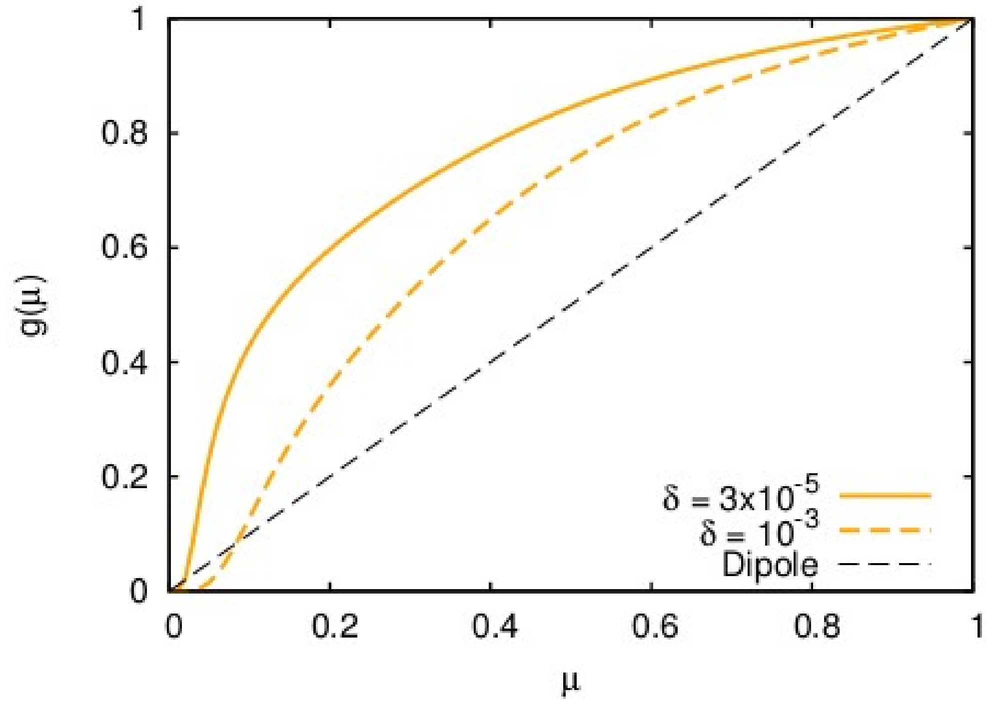


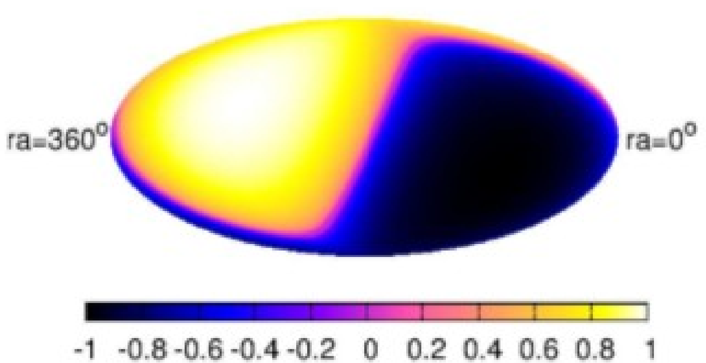
$$\delta\mathcal{M}_\mathrm{A} = \sqrt{\langle\delta B_\parallel^2\rangle/B_0^2}$$

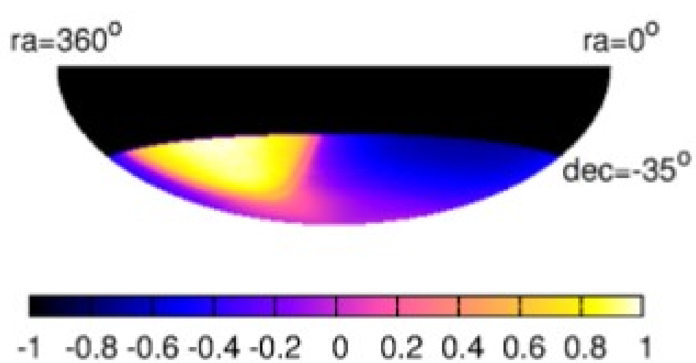
Case 1 : Fast modes & Narrow RF

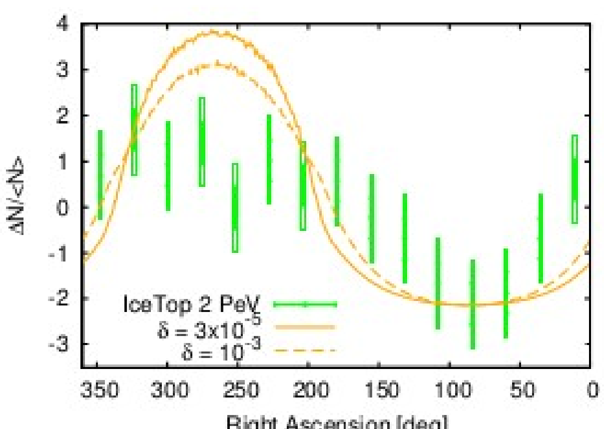
No visible dependence of the *shape* on CR energy $\varepsilon = v/(l\Omega) = r_{\mathrm{L}}/l$





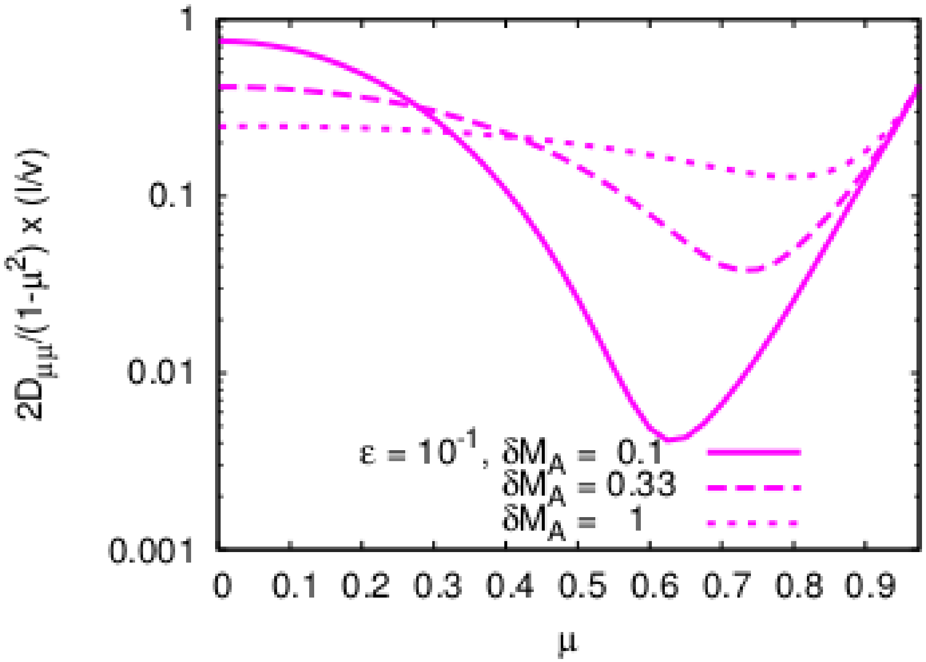


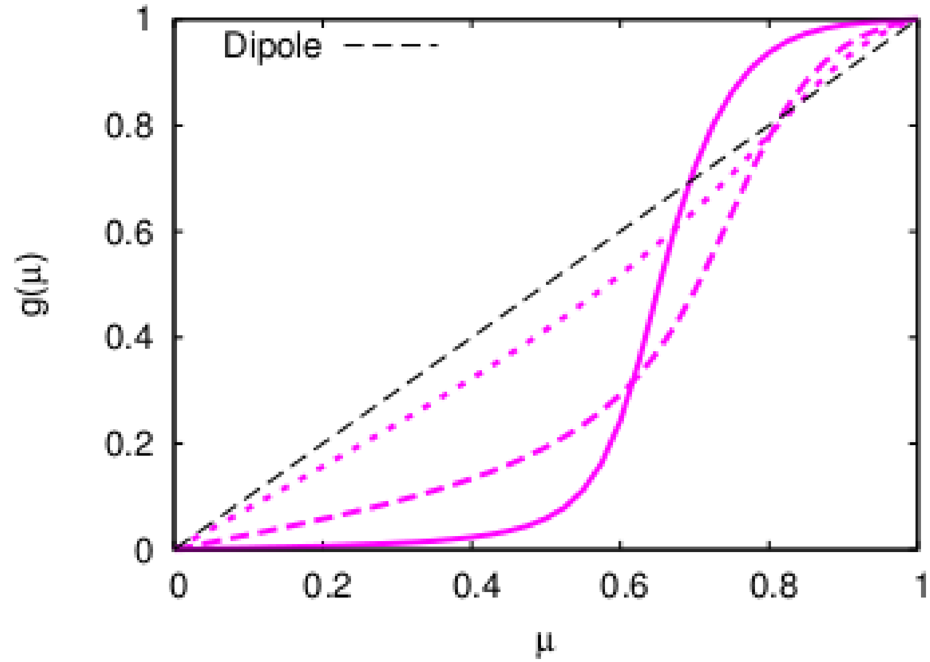


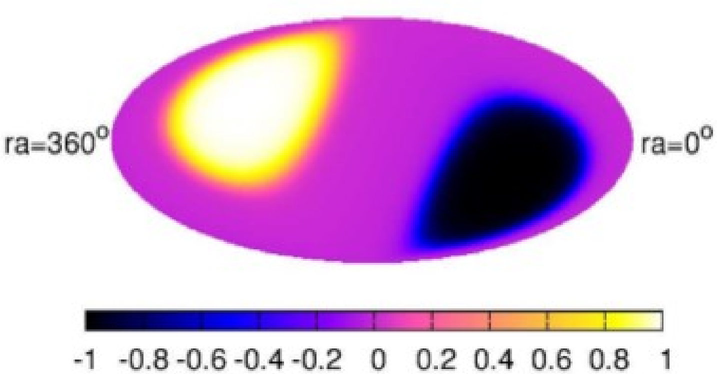


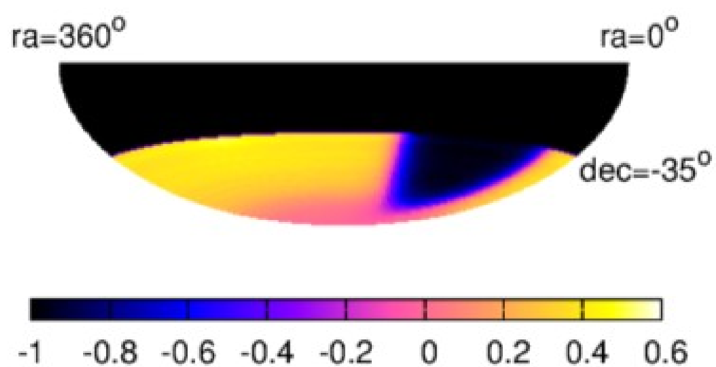
RULED OUT !

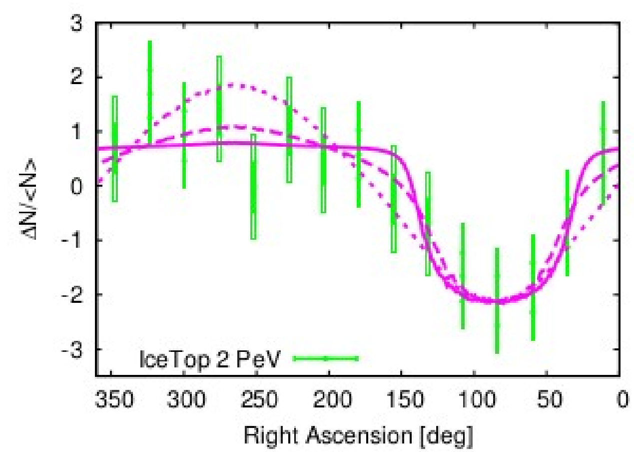
Case 2 : GS – Heaviside & Broad RF



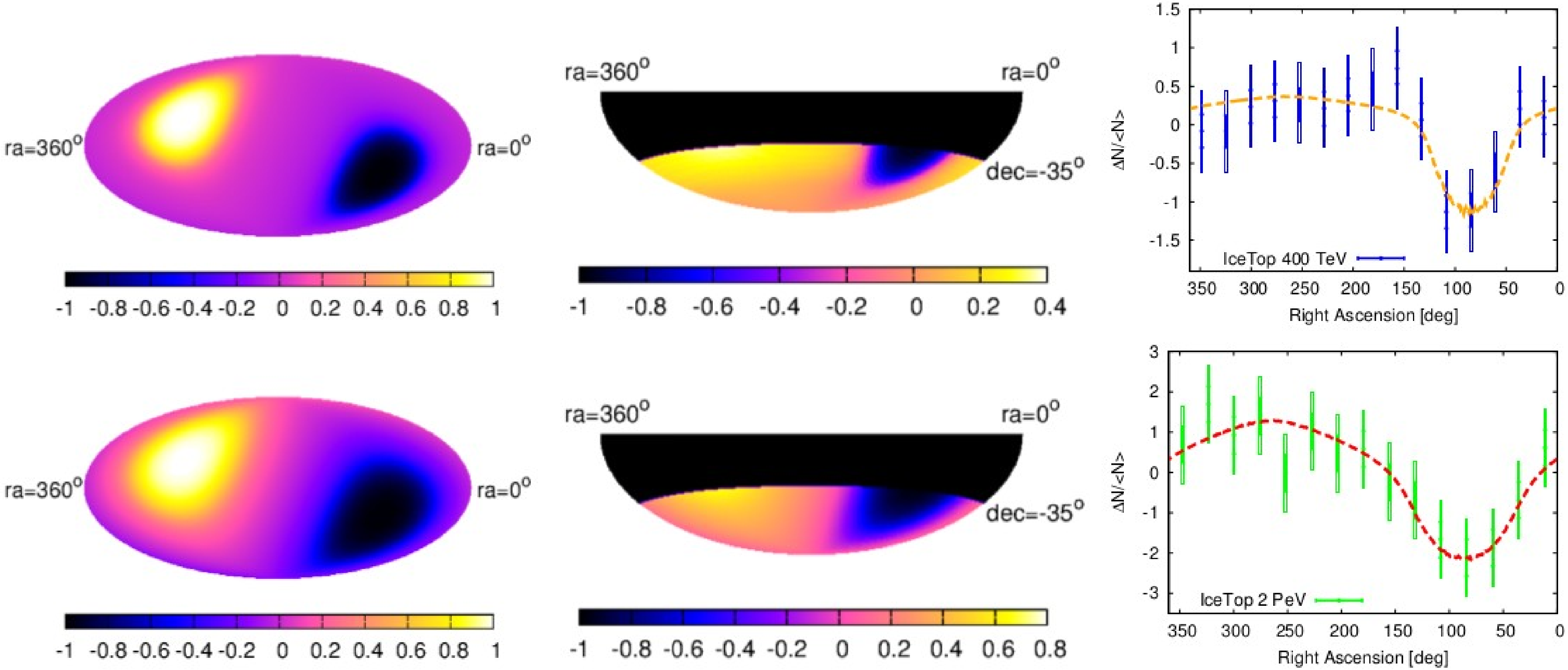








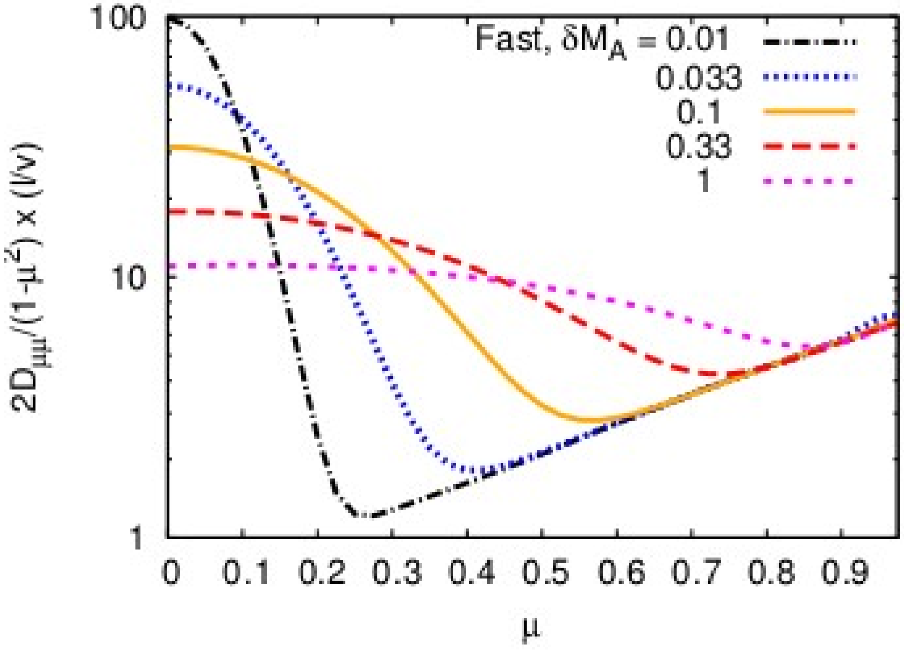
Case 3 : GS – Exponential & Broad RF

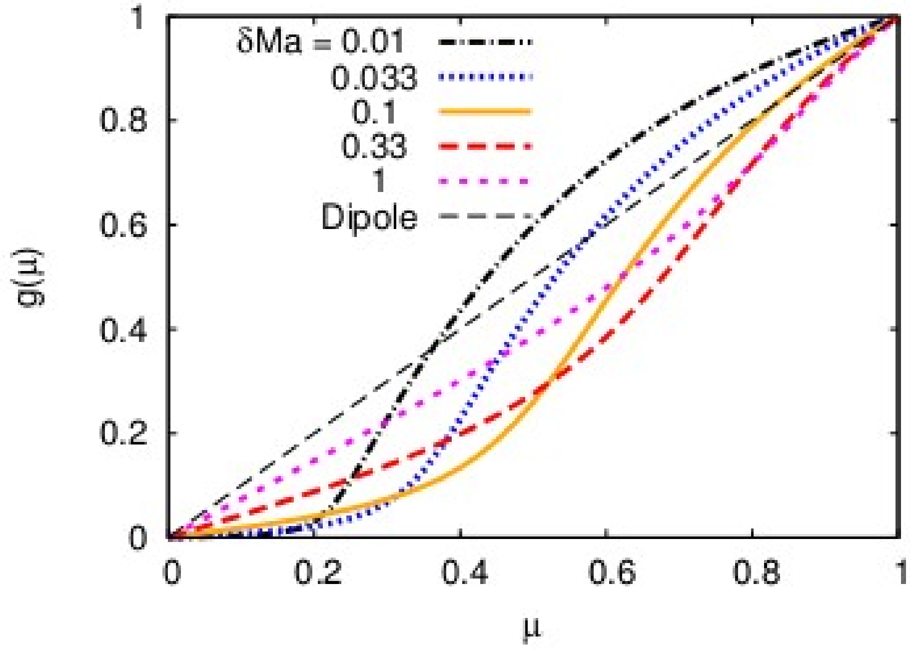


Can fit well the 400 TeV and the 2 PeV data !

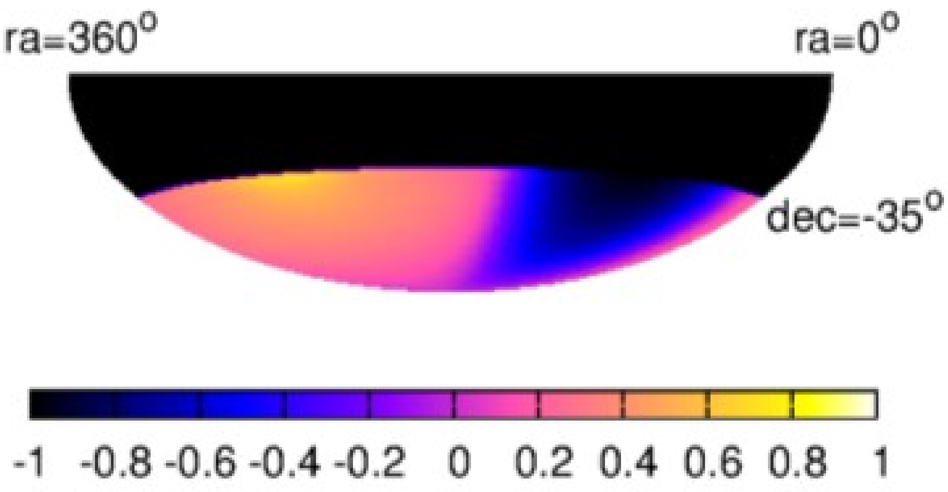
Energy-dependence reproduced for fixed turbulence parameters

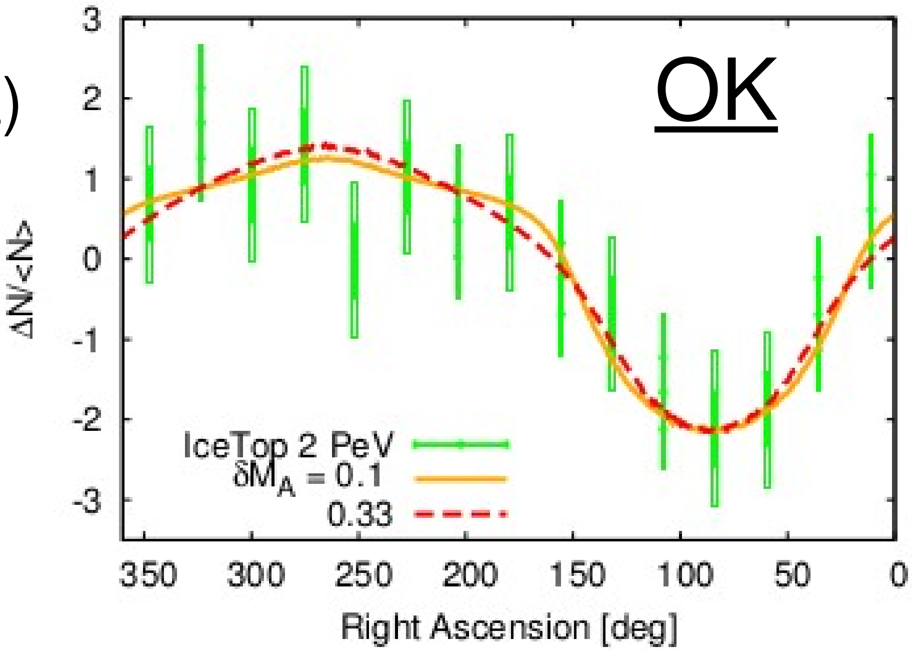
Case 4 : Fast modes & Broad RF





Can **fit the 2 PeV data** ! →
(But cannot fit well the 400 TeV data)





Conclusions and perspectives

(A) Explanation for the data (IceCube/Top)

(B) Large-scale CR Anisotropy = NEW Probe of

(i) local ISMFs (Modes and their anisotropy in k-space)

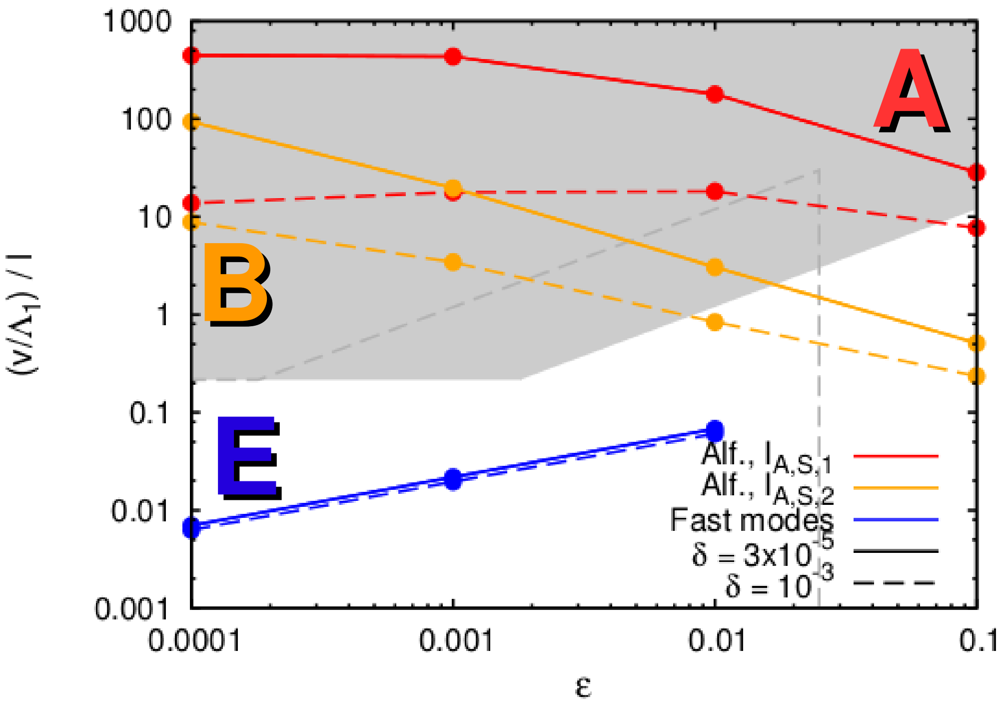
(ii) local CR transport properties

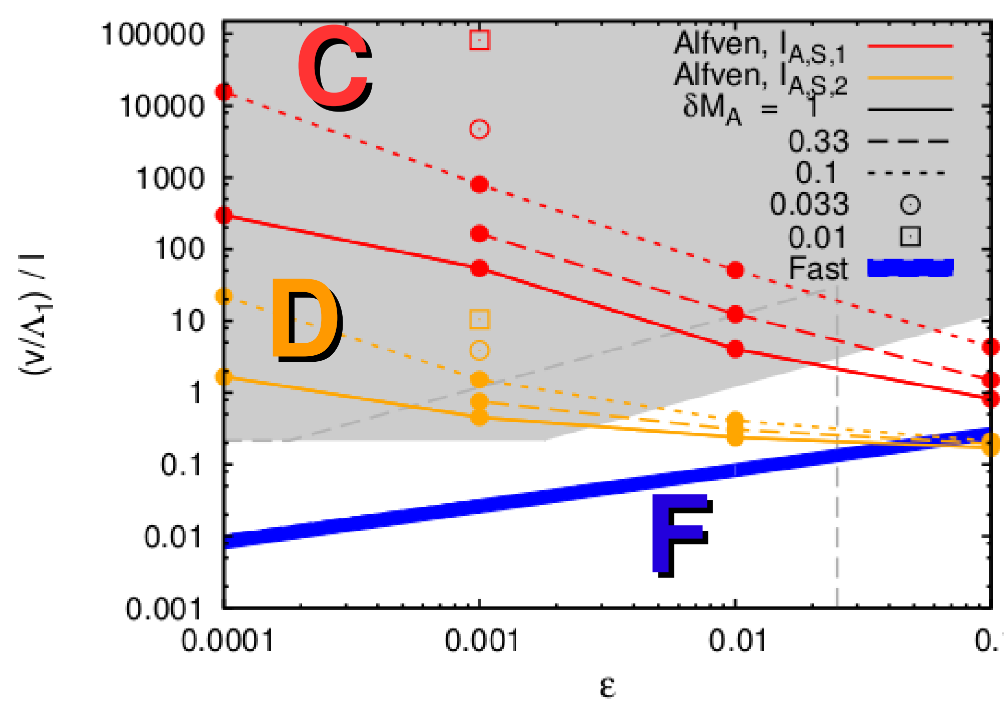
The existing data already places constraints !

→ Flattening in directions perpendicular to field lines,
→ Can fit the 2 PeV data with GS turbulence or fast modes with a moderately broad RF,
→ Constraints on RF : Narrow ones disfavoured,
→ Change in anisotropy shape with CR energy ?
- - -> |**k**|-dependent anisotropy in power spectrum ??

First Eigenvalue and « Boundary layer »

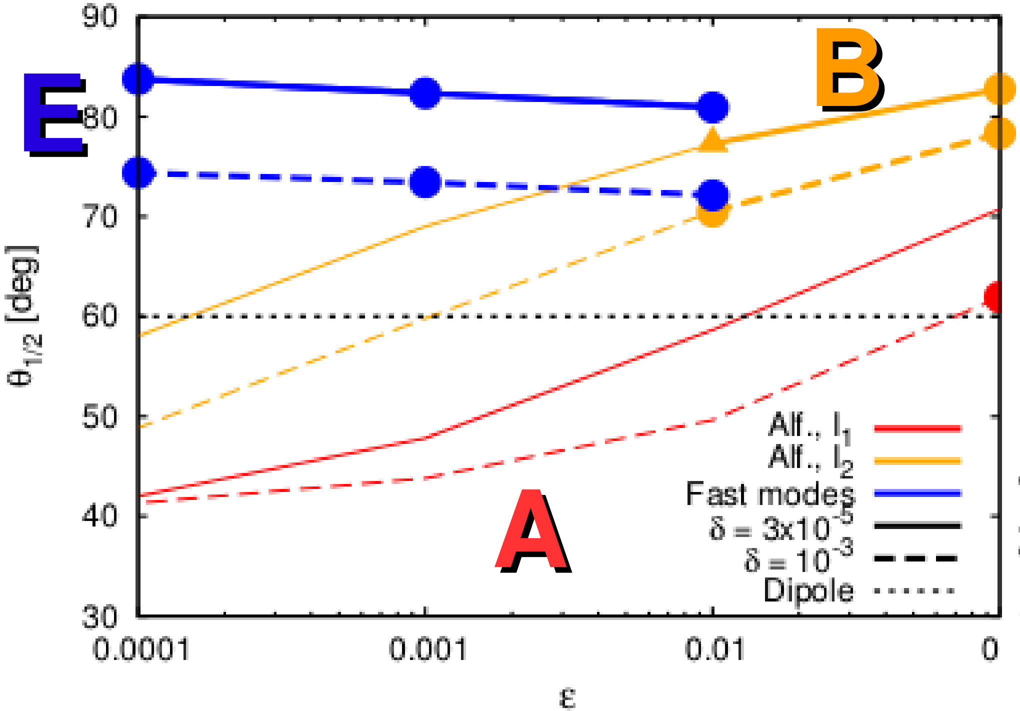
Case	Type	Spectrum		Resonance function
A	GS (incompressible)	Anisotropic	Heaviside ($\mathcal{I}_{A,S,1}$)	Narrow – $R_{n,1}(\delta = v_A/v)$
B	GS (incompressible)	Anisotropic	Exponential ($\mathcal{I}_{A,S,2}$)	Narrow – $R_{n,1}(\delta = v_A/v)$
C	GS (incompressible)	Anisotropic	Heaviside ($\mathcal{I}_{A,S,1}$)	Broad – $R_{n,2}(\delta\mathcal{M}_A)$
D	GS (incompressible)	Anisotropic	Exponential ($\mathcal{I}_{A,S,2}$)	Broad – $R_{n,2}(\delta\mathcal{M}_A)$
E	Fast modes (compressible)	Isotropic	$\mathcal{I}_M \propto k^{-3/2}$	Narrow – $R_{n,1}(\delta = v_A/v)$
F	Fast modes (compressible)	Isotropic	$\mathcal{I}_M \propto k^{-3/2}$	Broad – $R_{n,2}(\delta\mathcal{M}_A)$

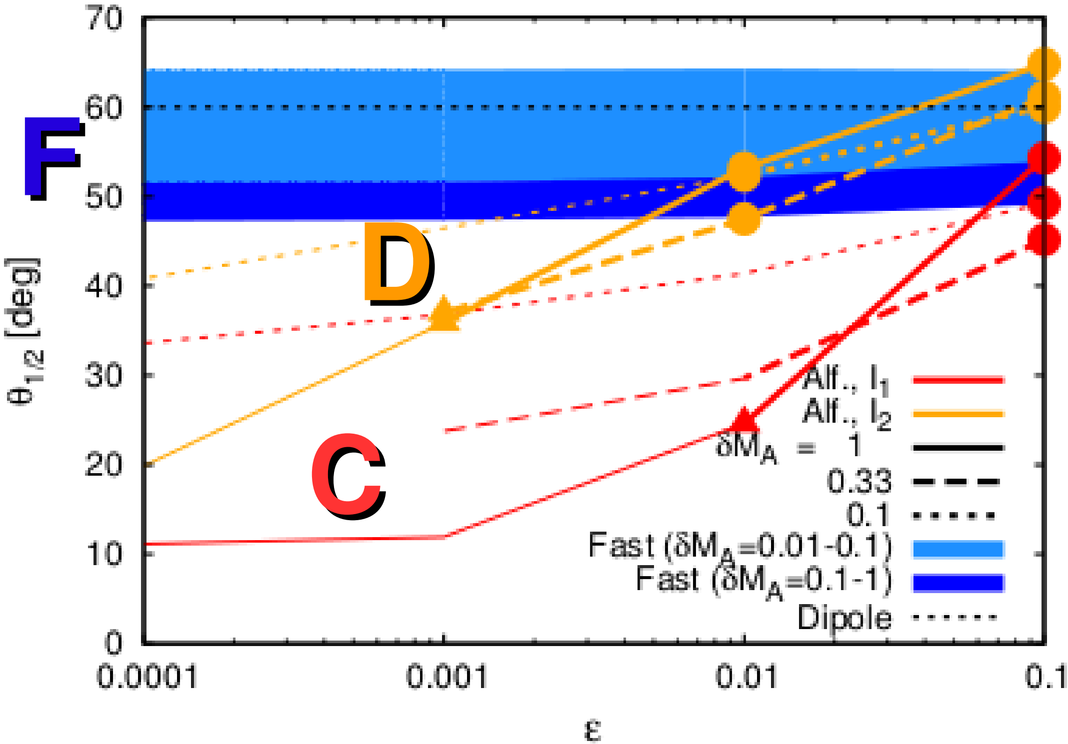




Half-width of the anisotropy

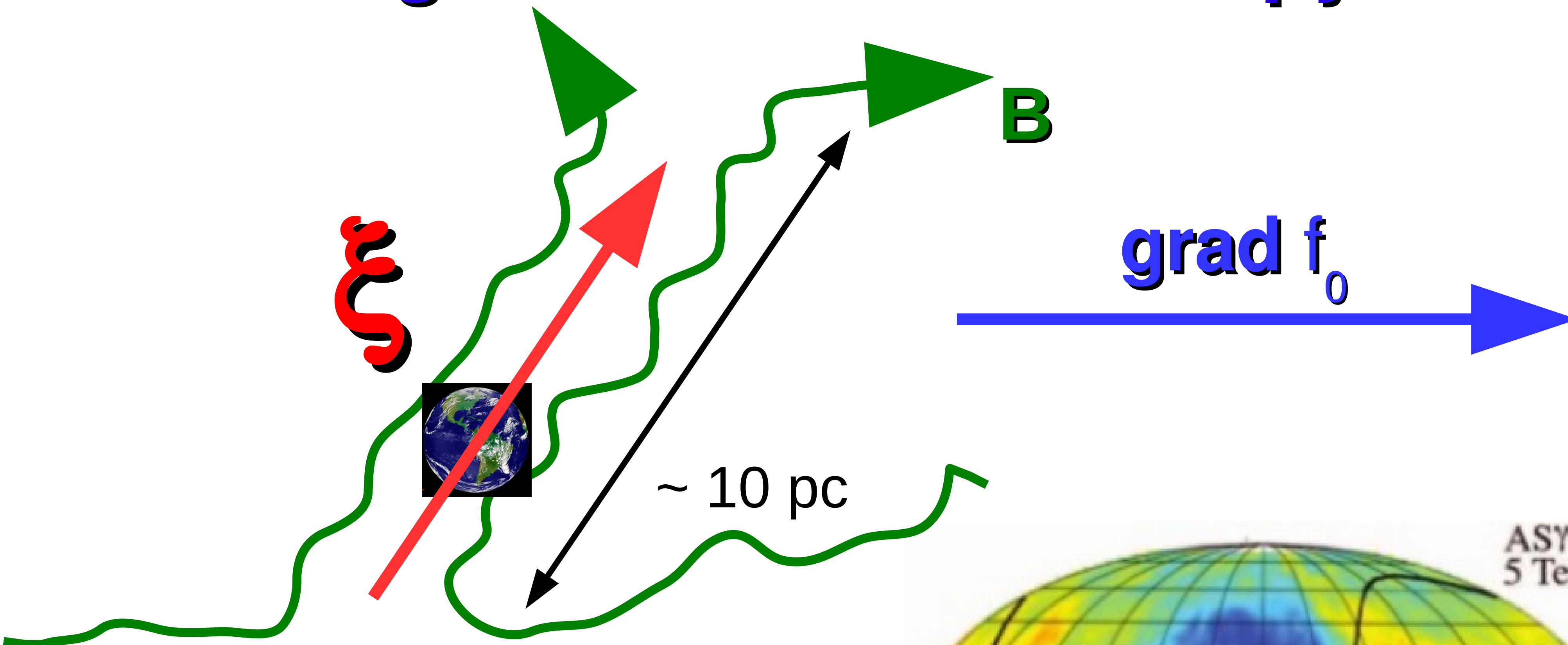
$$g\left(\cos\vartheta_{1/2}\right) = \frac{1}{2}$$





Within the allowed parameter-space, the **anisotropy is too wide with the narrow RF**.

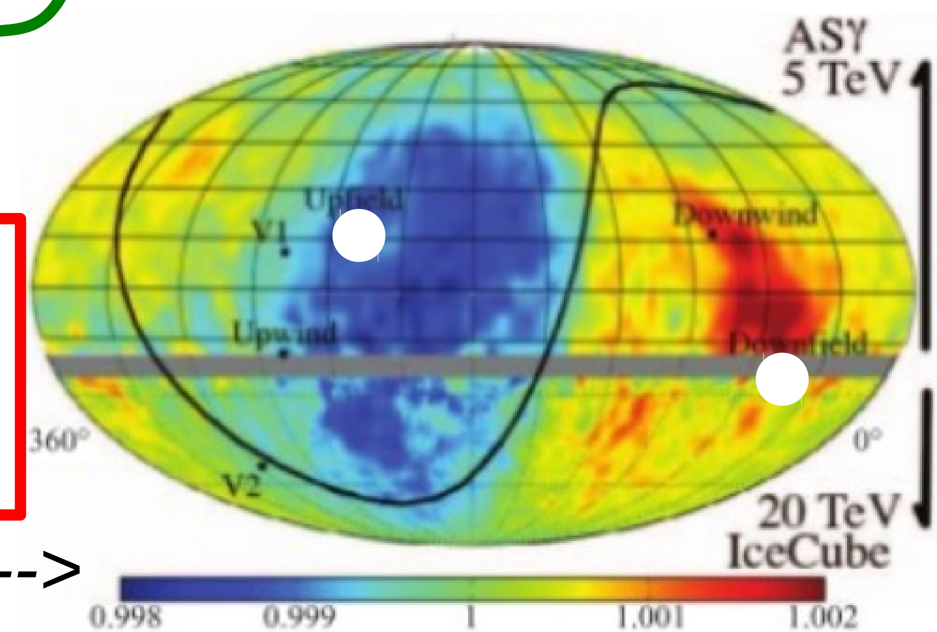
Origin of the CR anisotropy



$$\vec{\xi} = \frac{3}{w}\left[C\mathbf{u} - \kappa_{\parallel}\mathbf{g}_{\parallel} - \kappa_{\perp}\mathbf{g}_{\perp} - \kappa_T(\mathbf{g}\times\hat{b})\right]$$

$$\mathbf{g} = \nabla \ln(f_0)$$

Schwadron et al., Science (2014) --->



… and δB/B << 1