COSMIC-RAY ANISOTROPY AS A PROBE OF INTERSTELLAR TURBULENCE

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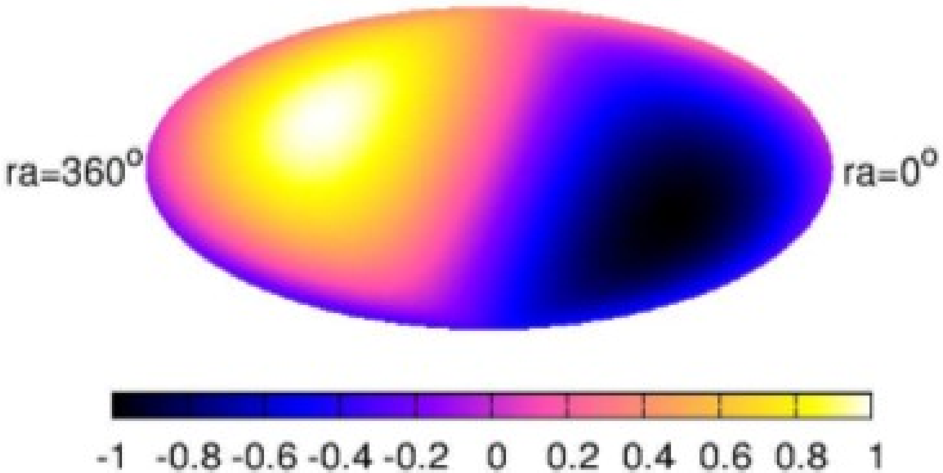
Cosmic-Ray Anisotropy

large-scale | **small-scales**



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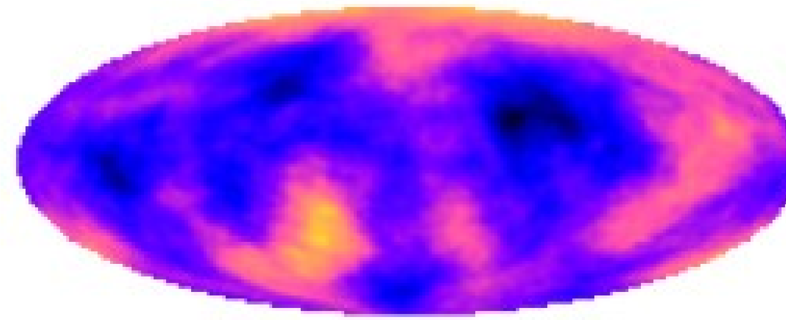


See Markus Ahlers' talk

→ In the direction of field lines
→ Amplitude

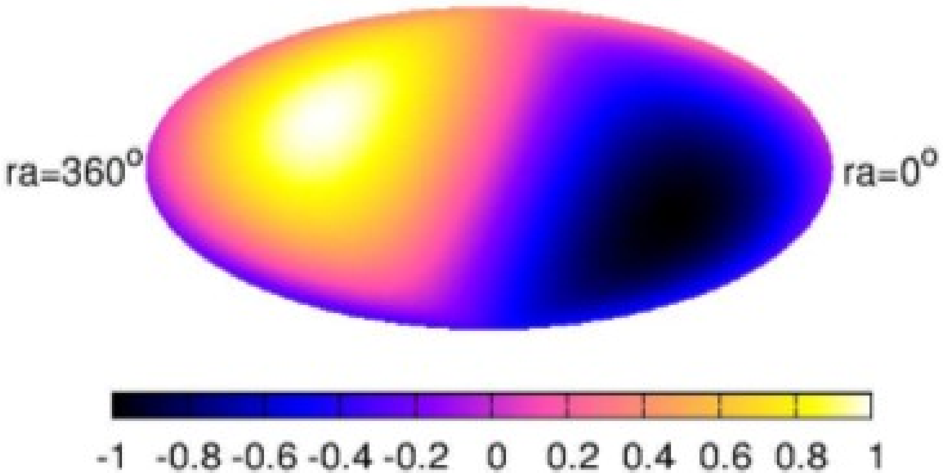
→ **<u>Shape</u>** **(… Dipole ?)**

See : Giacinti & Sigl (2012)
Drury (2013)
Ahlers (2014)
Ahlers & Mertsch (2015)

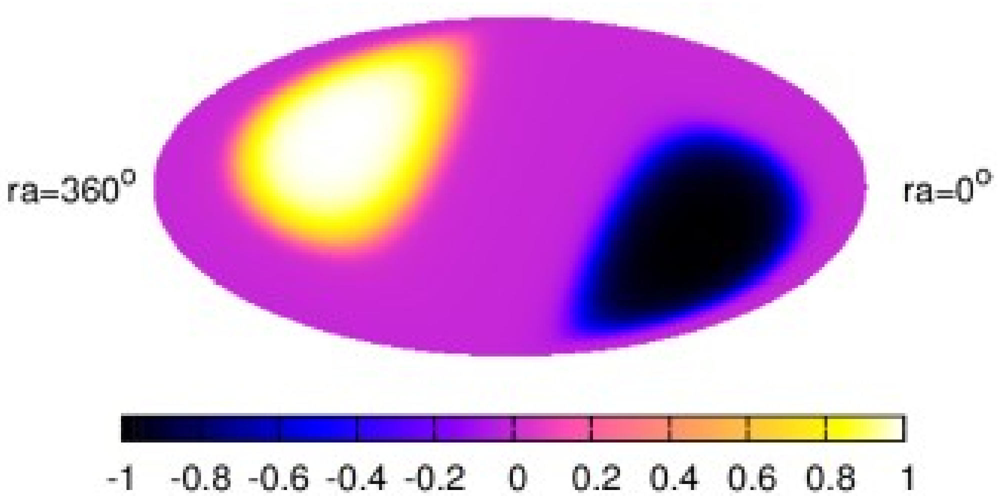
« small » amplitude

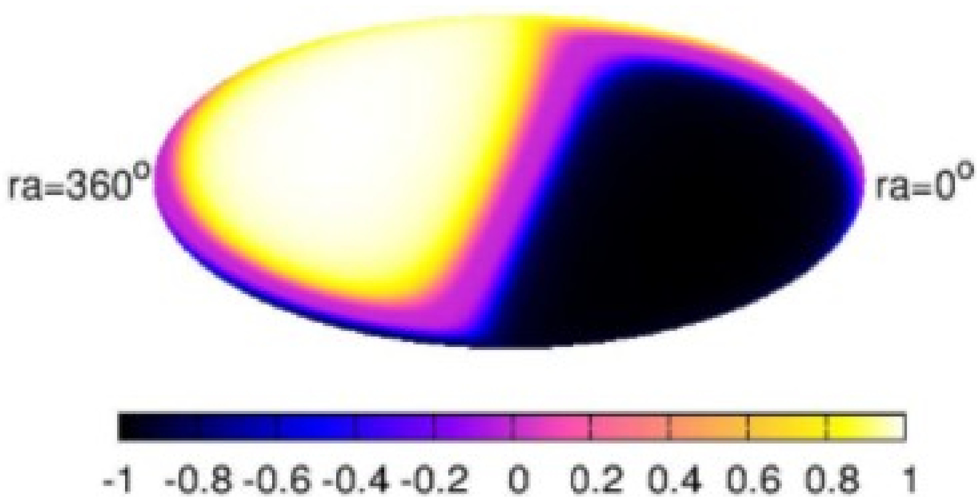
Cosmic-Ray Anisotropy

Dipole only

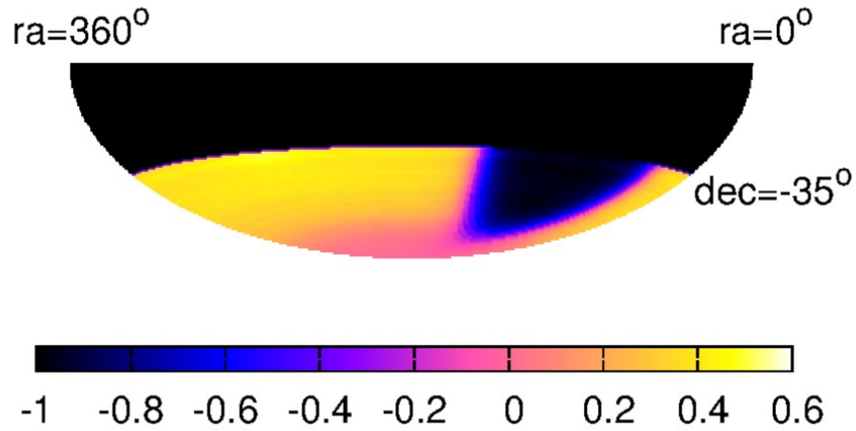


Or could the L-S CR anisotropy look like this ? :

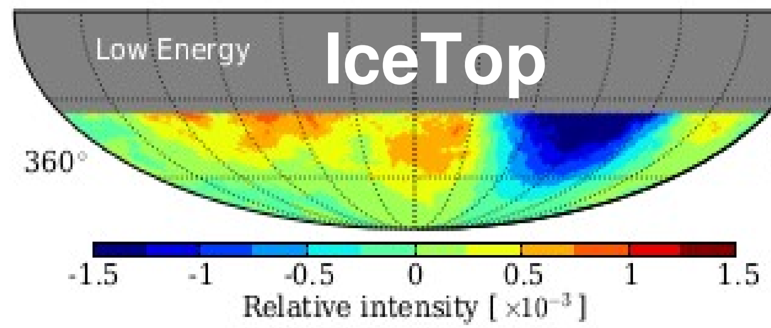


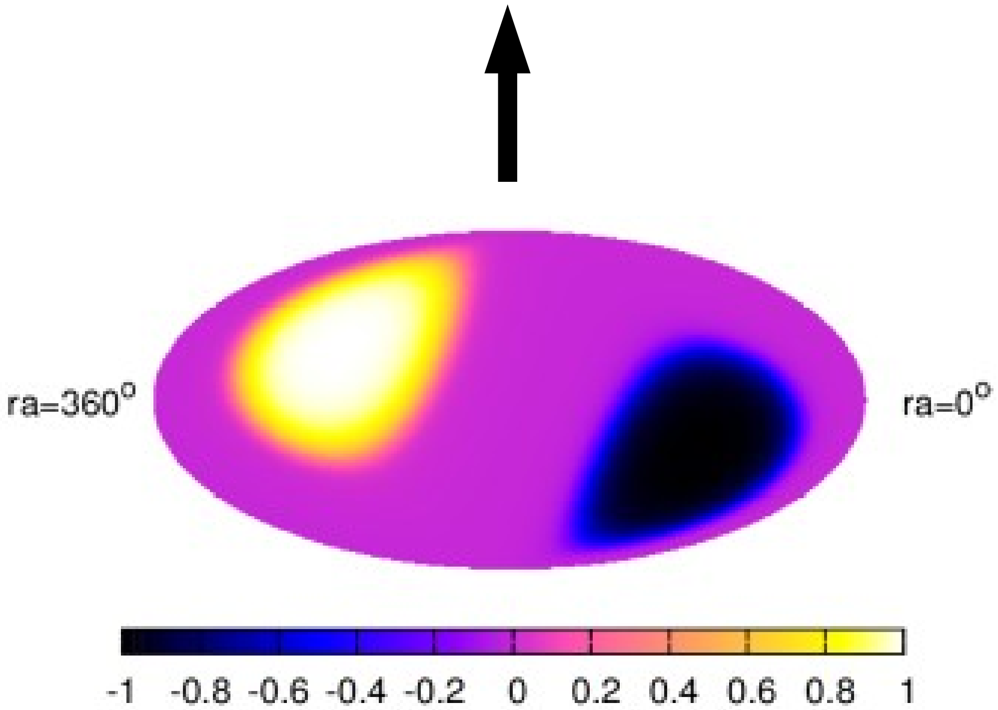


Cosmic-Ray Anisotropy



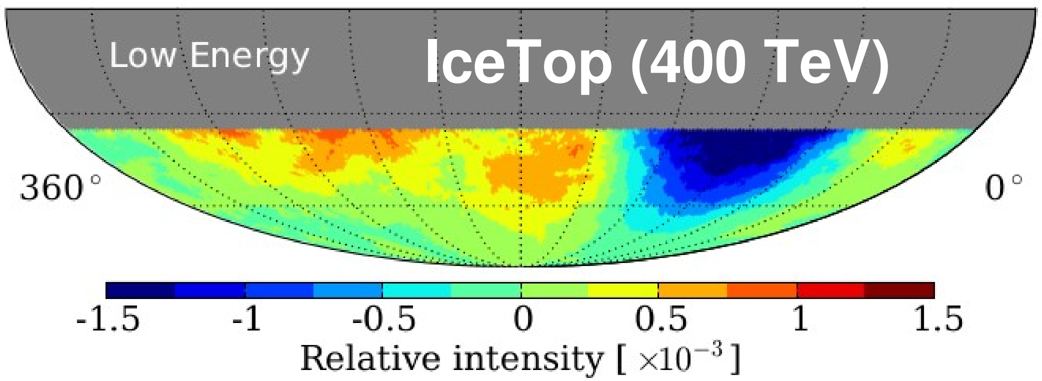
vs

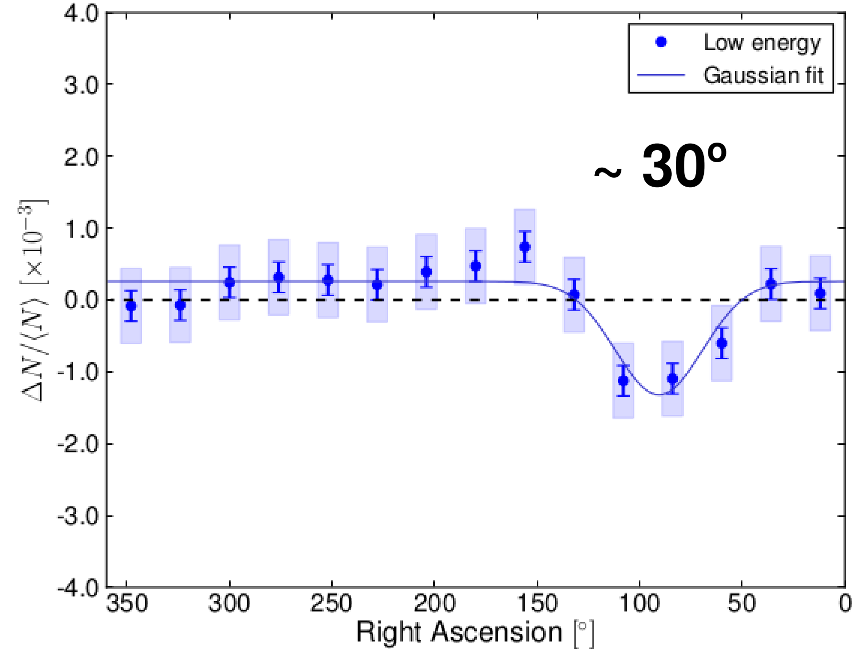


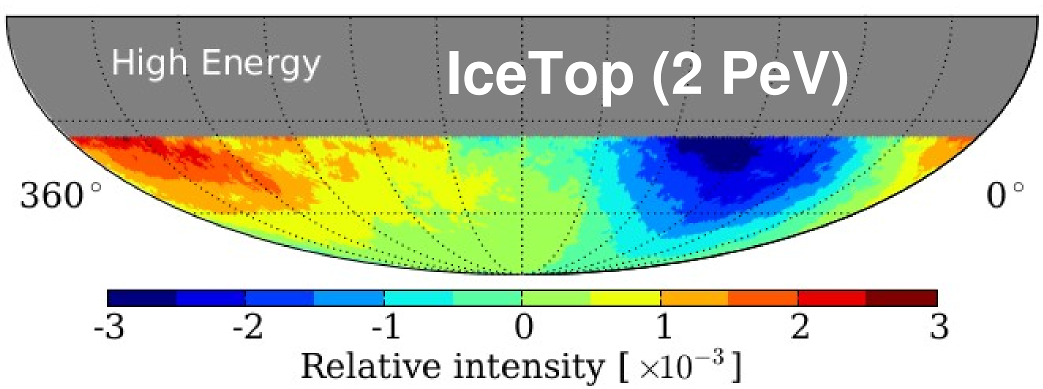


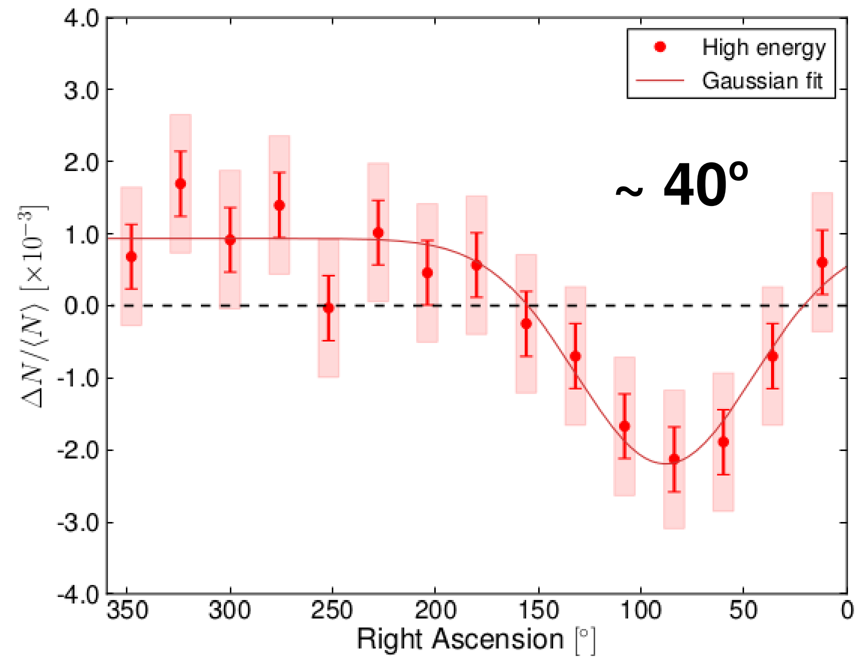
Observations (IceCube, IceTop)

Aartsen et al. (2013)



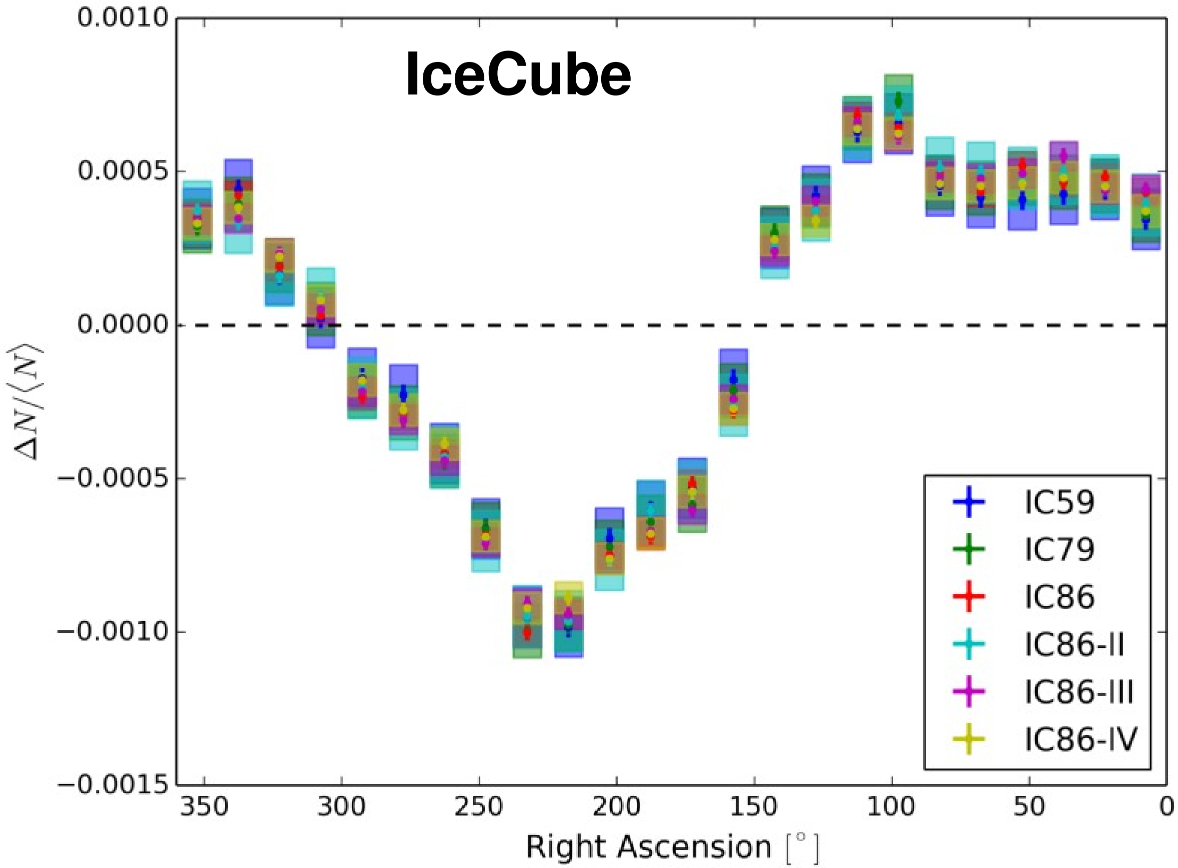


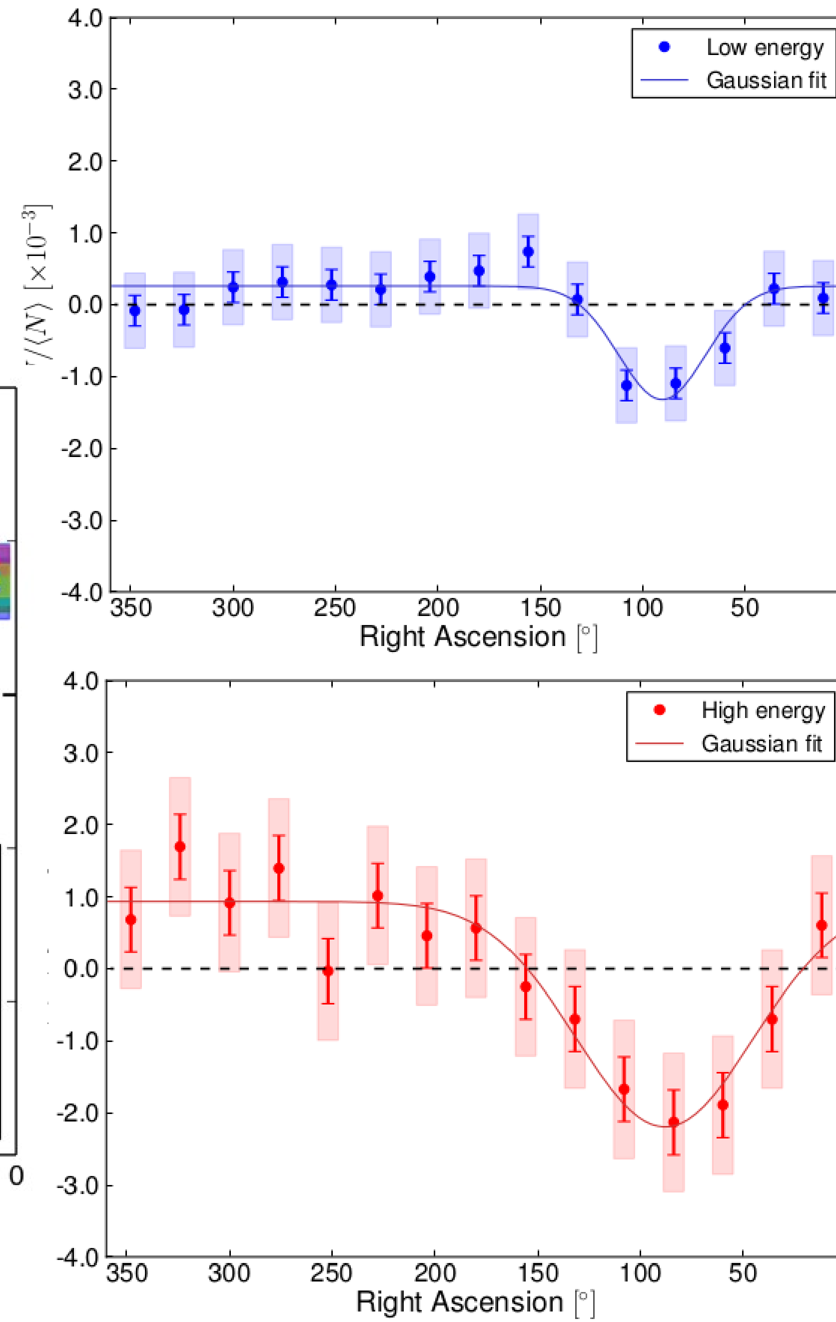




Observations (IceCube, IceTop)

Aartsen et al. (2016)





Direction of the local magnetic field

The Astrophysical Journal, 760:106 (18pp), 2012 December 1 Frisch et al.

Table 1
Various Directions

Source Coordinates	Longitude (deg)	Latitude (deg)	Notes (and References)
Direction of best-fitting magnetic field			
Polarization, Paper I, unweighted			
Ecliptic	263	37	Uncertainties ±35
Galactic	37	23	Uncertainties ±35
Polarization, this paper, unweighted			
Ecliptic	263^{+10}_{-5}	37 ± 15	
Galactic	37 ± 15	22 ± 15	
Polarization, this paper, weighted			
Ecliptic	263^{+15}_{-20}	47 ± 15	
Galactic	47 ± 20	25 ± 20	
ISMF from center of Ribbon arc			(2)
Ecliptic	221 ± 4	39 ± 4	(see the text)
Galactic	33 ± 4	55 ± 4	
Upwind direction of interstellar He° flow through heliosphere			$V = 23.2 \pm 0.3$ km s^{-1}, $T = 6300 \pm 390$ K (1)
Ecliptic	259.00 ± 0.47	4.98 ± 0.21	
Galactic	5.25 ± 0.24	12.03 ± 0.51	
Quadrant III pulsars			
Ecliptic	232	18	(6)
Galactic	5	42	(6)
Heliotail in globally distributed *IBEX* ENA flux			
Ecliptic	30 ± 30	0 ± 30	(5)
Galactic	146 ± 30	-49 ± 30	(5)
Direction of tail-in cosmic-ray asymmetries			
Sub-TeV anisotropies			
Ecliptic	90	−47	Cone half-width = 68 (3)
Galactic	230	−21	Cone half-width = 68 (3)
Ecliptic	66	−36	Center of Gaussian fit (4)
Galactic	211	−35	Center of Gaussian fit (4)

References. (1) McComas et al. 2012; (2) Funsten et al. 2009; (3) Nagashima et al. 1998; (4) Hall et al. 1999; (5) Schwadron et al. 2011; (6) Salvati 2010.

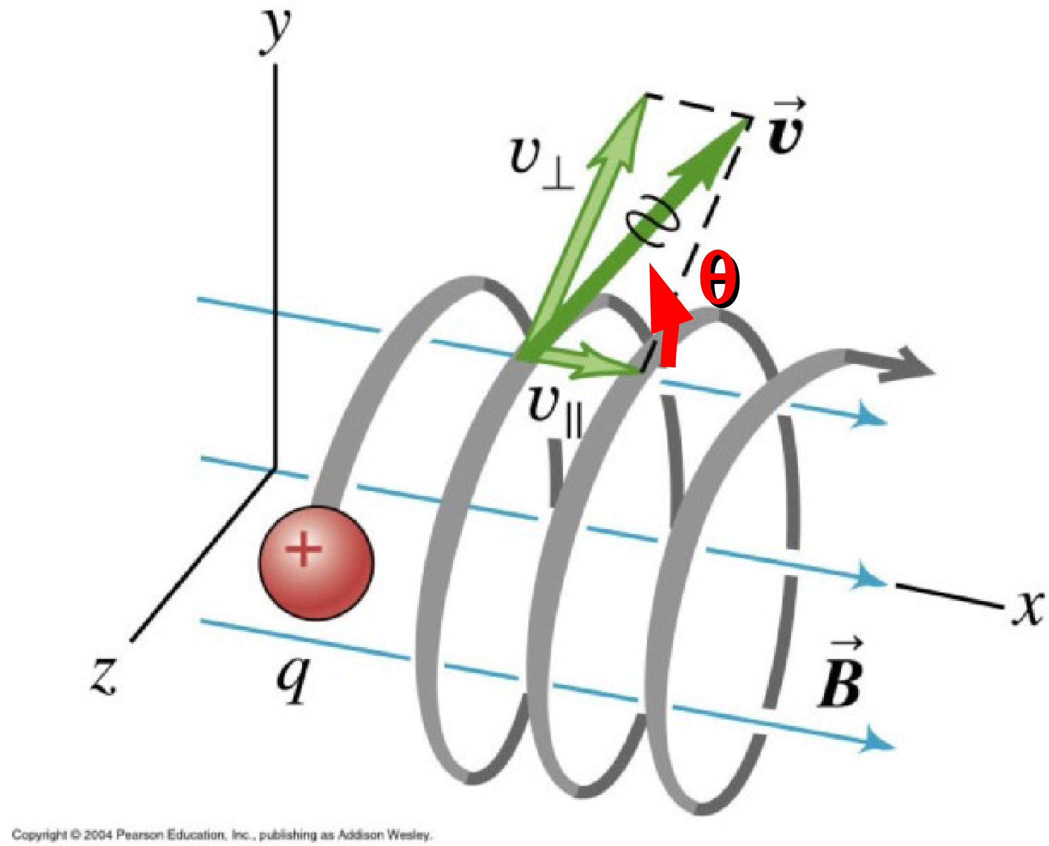
Frisch et al. 2012

Schwadron et al. 2014

$\delta B/B \ll 1$

CR trajectories

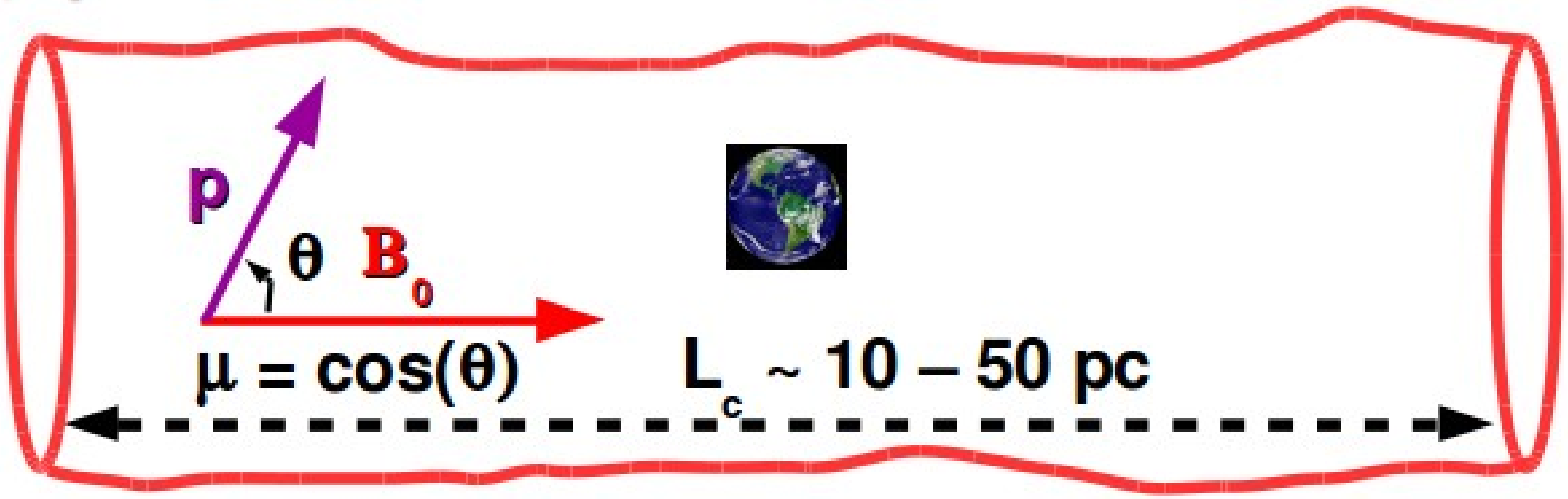
$\delta B = 0$



$\delta B / B_0 << 1$

Pitch-angle diffusion

CR Anisotropy : Probe of turbulence



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

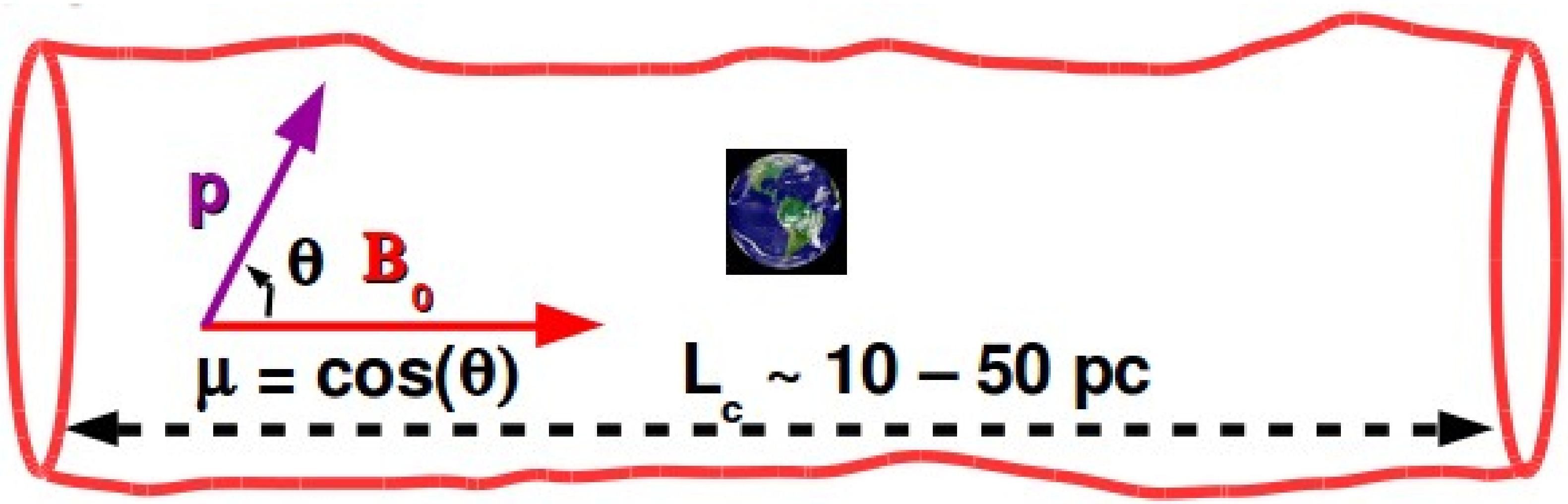
(gyrophase-averaged)

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

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

(« boundary layer »)

CR Anisotropy : Probe of turbulence



NOT $1 - \mu^2$ in general => <u>NOT a dipole !</u>

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

α

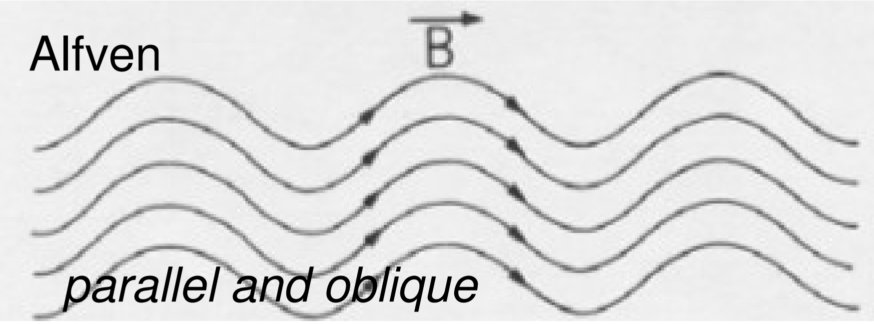
=> $f(x,\mu) = \sum_i a_i e^{\Lambda_i x/v} Q_i(\mu) + a_{\mathrm{diff}}\,[x + g(\mu)]$

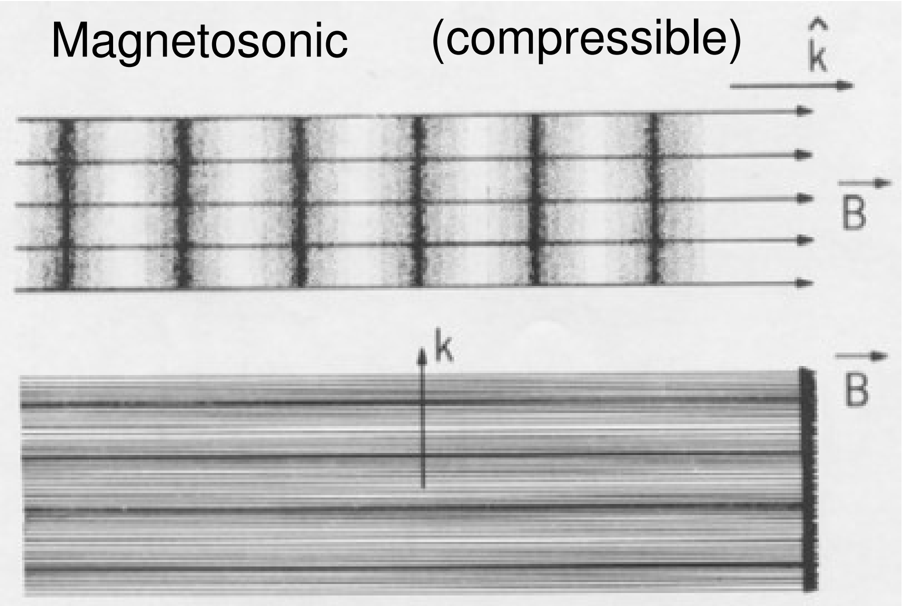
if $\exp(-\Lambda_1 d/v) \ll 1$

(« boundary layer »)

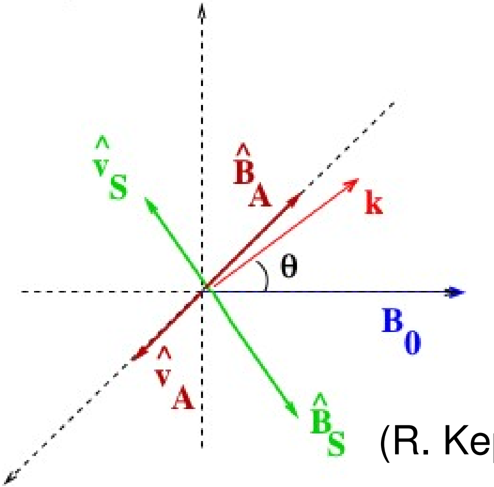
Magnetohydrodynamic waves

Alfven, Slow and Fast modes (compressible)





Alfven and pseudo-Alfven modes (incompressible)



(R. Keppens)

Pitch-angle diffusion coefficient

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

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

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

$$\varepsilon = v/(l\Omega) = r_{\mathrm{L}}/l$$

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

=>

$$D_{\mu\mu} = \Omega^2\left(1-\mu^2\right)\int \mathrm{d}^3k \sum_{n=-\infty}^{\infty}\left(\frac{n^2 J_{\mathrm{n}}^2(z)}{z^2}\mathcal{I}_{\mathrm{A}}(\mathbf{k})\right.$$

$$\left. + \frac{k_{\|}^2 J_{\mathrm{n}}'^2(z)}{k^2}\mathcal{I}_{\mathrm{S,F}}(\mathbf{k})\right) \times R_{\mathrm{n}}(k_{\|}v_{\|} - \omega + n\Omega) ,$$

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

Resonance functions

RF dominated by Lagrangian correlation time : **« NARROW »**

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

see Chandran (2000)

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

$$\tau_F = l/(v_A \tilde{k}^{1/2}) \qquad \tilde{k} = kl$$

Conservation of the adiabatic invariant $v_\perp^2/B$ **« BROAD »**

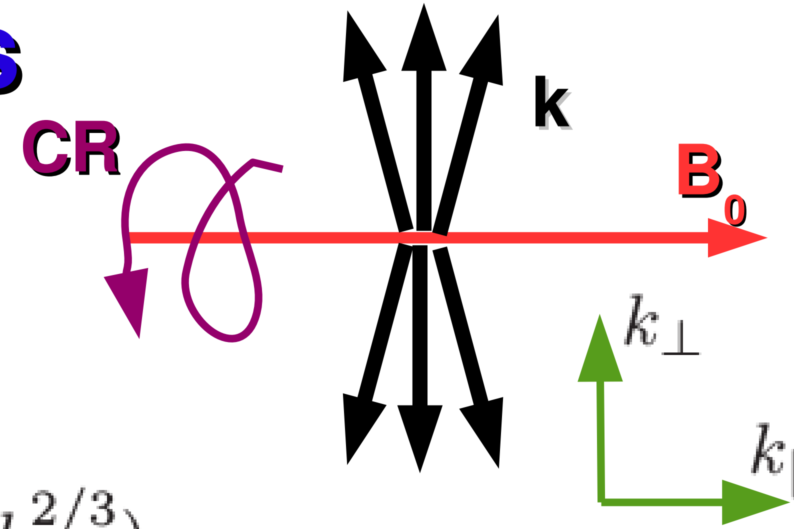
The variations of $v_\parallel$ are dominated by the variations $\delta B_\parallel$

see Yan & Lazarian (2008)

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

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

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

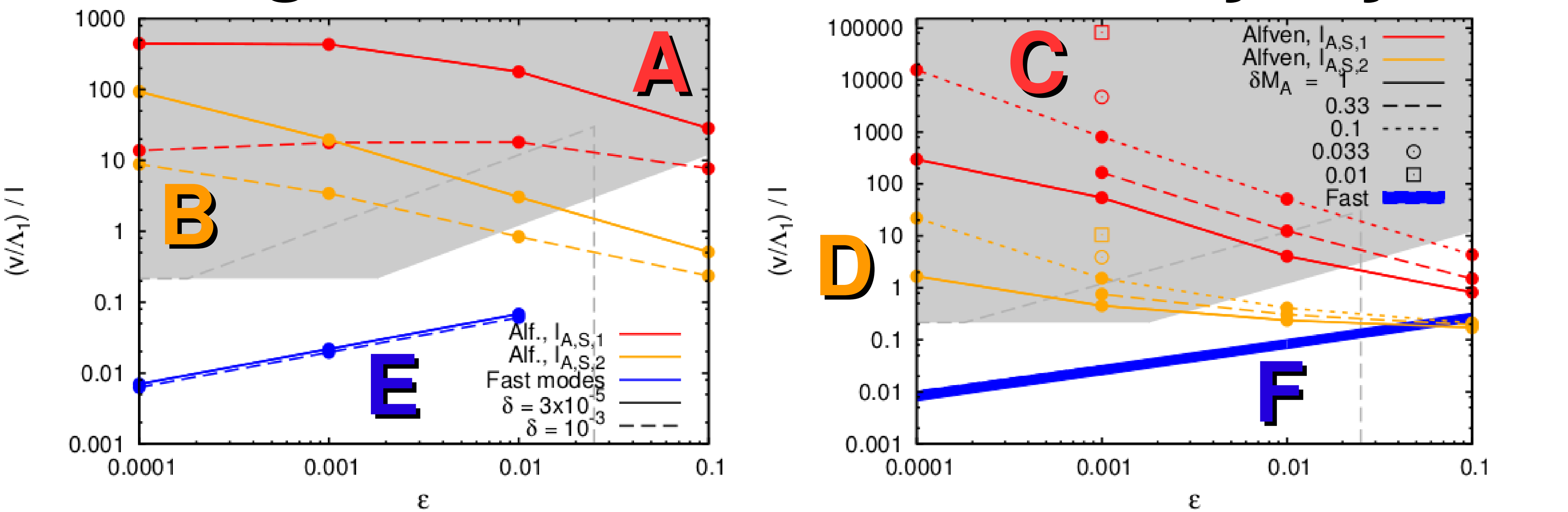
MHD simulations of Cho & Lazarian (2002) :

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

Properties of the 6 turbulence models

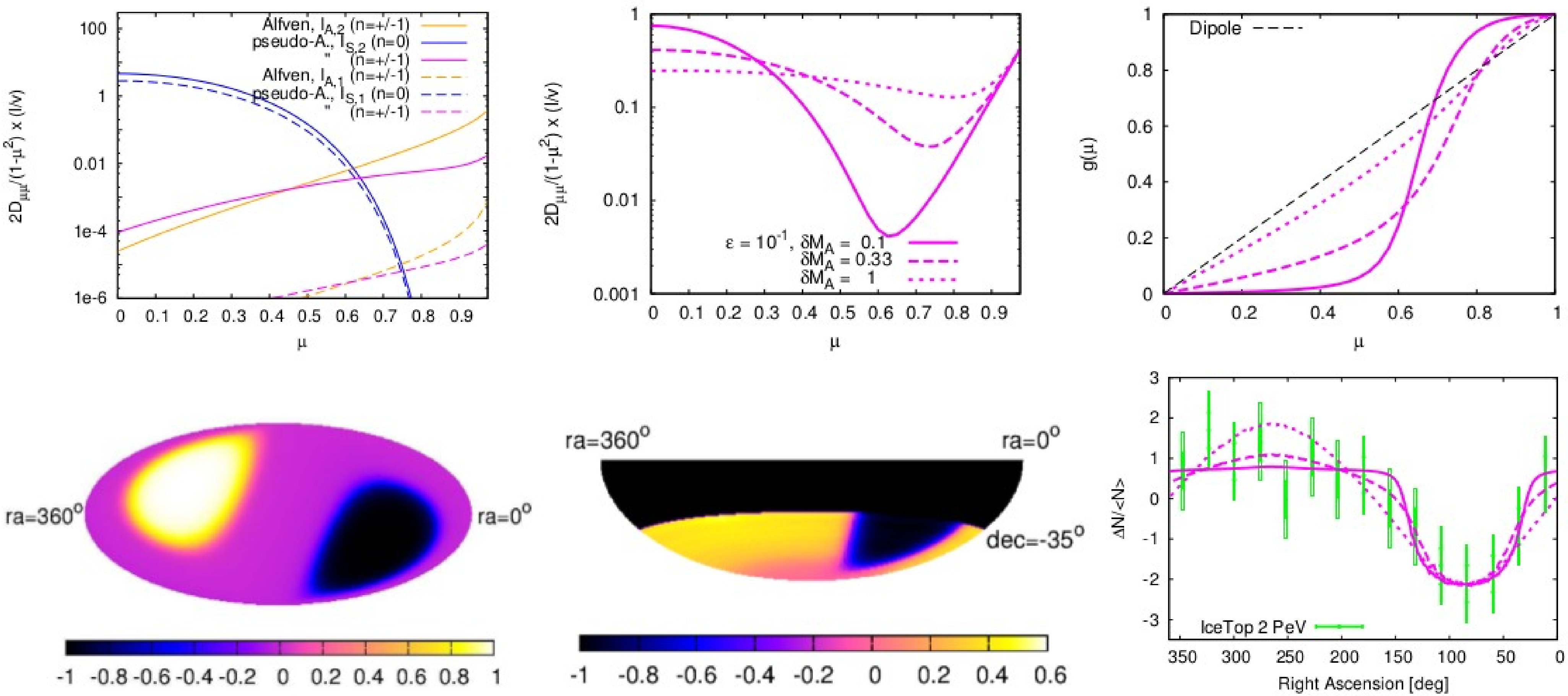
Case	Type	Spectrum		Resonance function
A	GS (incompressible)	Anisotropic	Heaviside ($\mathcal{I}_{A,S,1}$)	Narrow – $R_{n,1}(\delta = v_A/v)$
B	GS (incompressible)	Anisotropic	Exponential ($\mathcal{I}_{A,S,2}$)	Narrow – $R_{n,1}(\delta = v_A/v)$
C	GS (incompressible)	Anisotropic	Heaviside ($\mathcal{I}_{A,S,1}$)	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 – $R_{n,2}(\delta\mathcal{M}_A)$

First Eigenvalue and « Boundary layer »



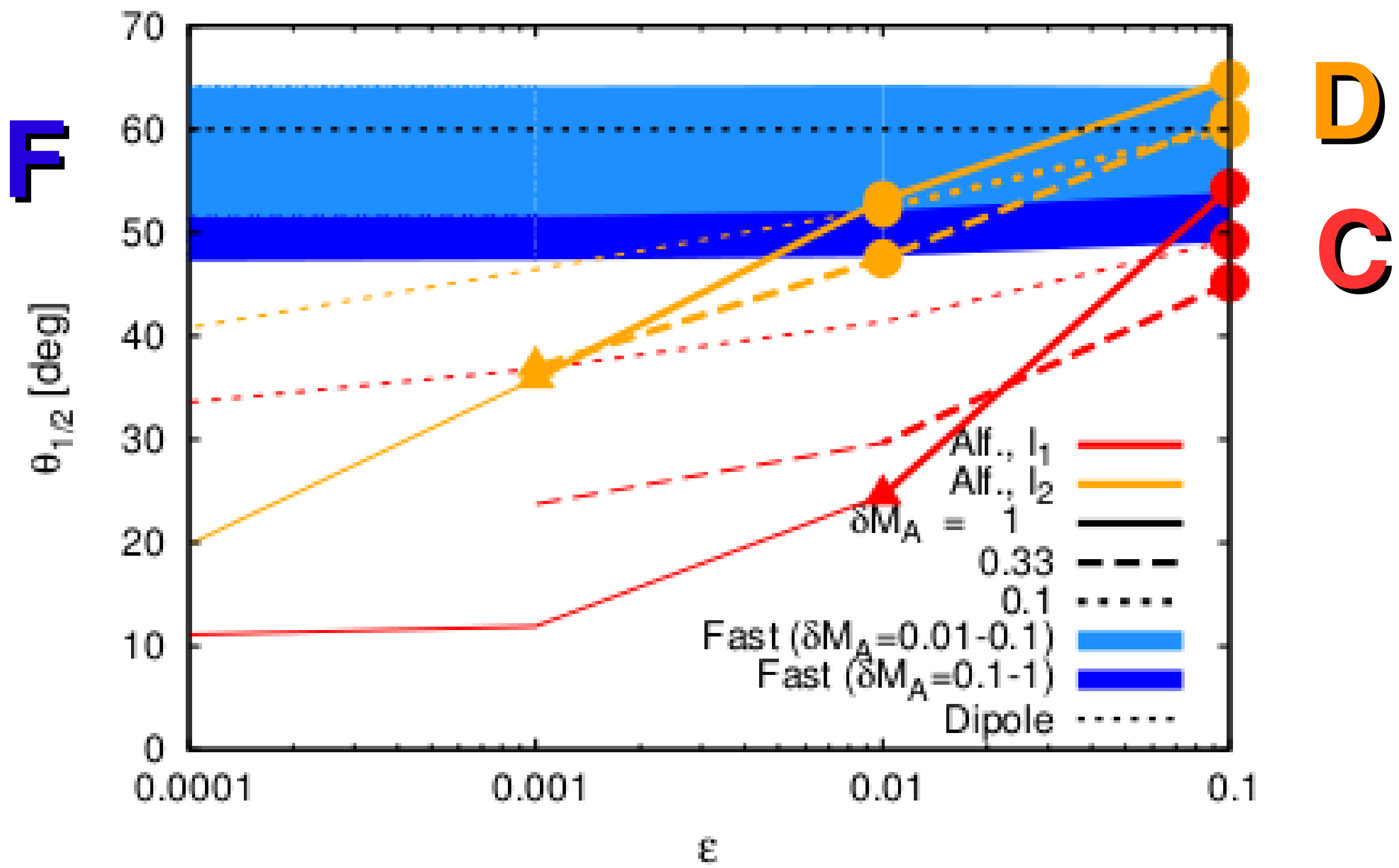
'Allowed' parameter-space : **Anisotropy too wide with the narrow RF**.

Case C : GS ('Heaviside, Broad')

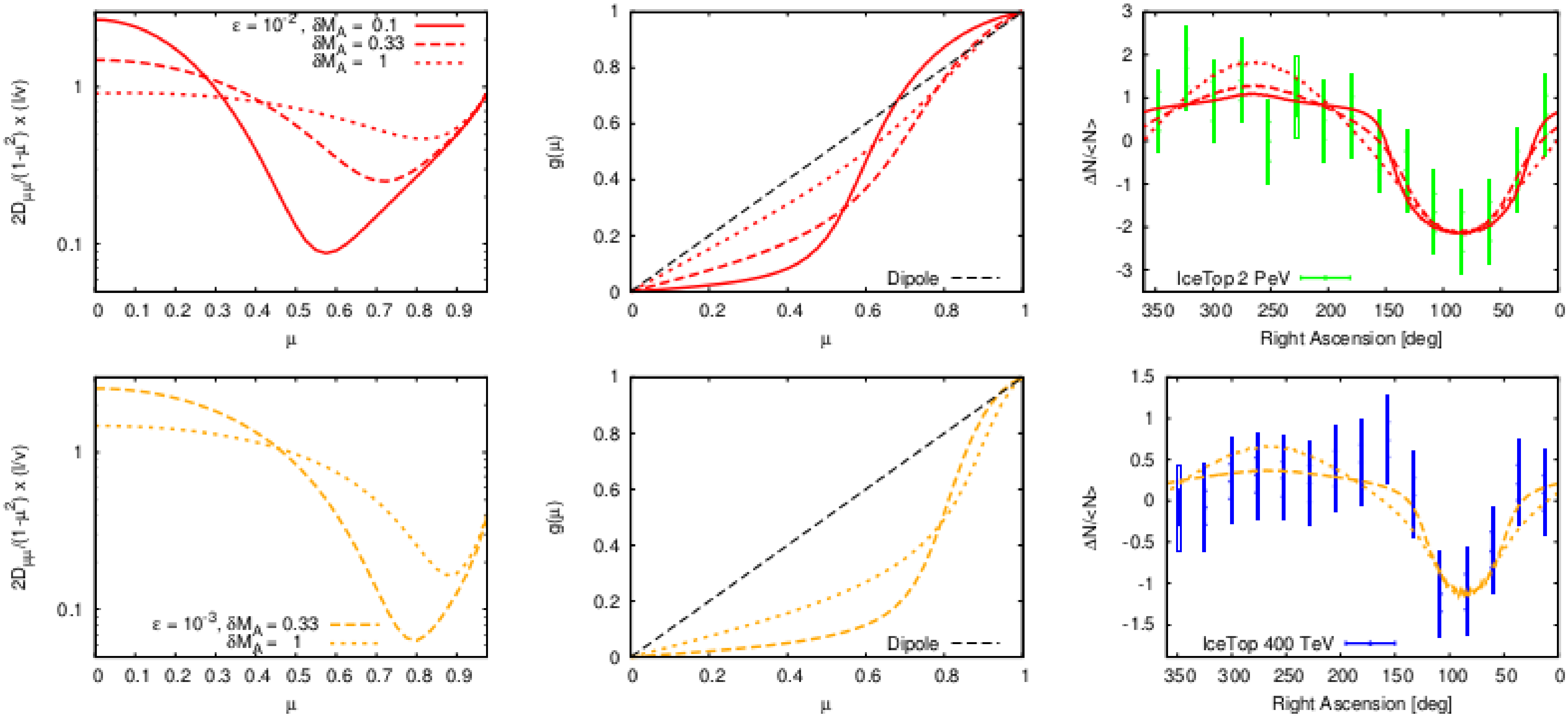


Half-width of the anisotropy

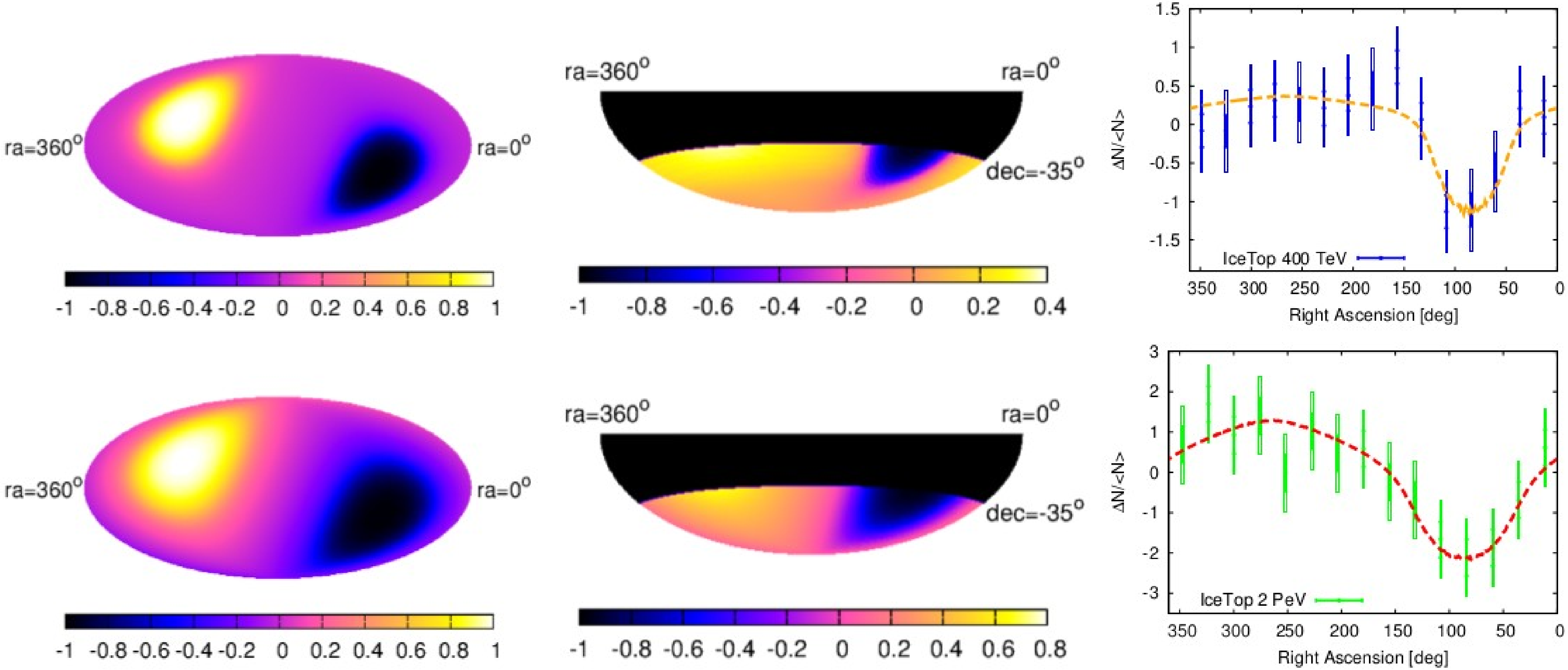
$$g\left(\cos\vartheta_{1/2}\right) = \frac{1}{2}$$



Case D : GS ('Exponential, Broad')



Case D : GS ('Exponential, Broad')



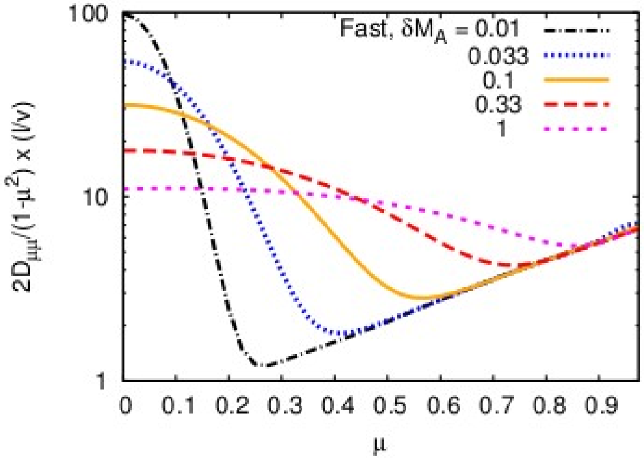
Can fit well the 400 TeV and the 2 PeV data !

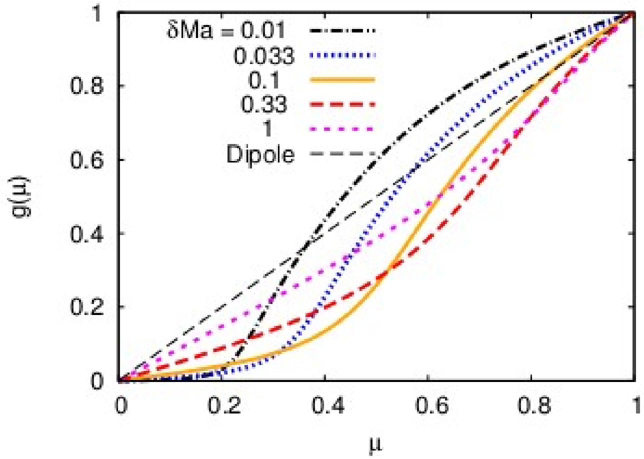
Energy-dependence reproduced for fixed turbulence parameters

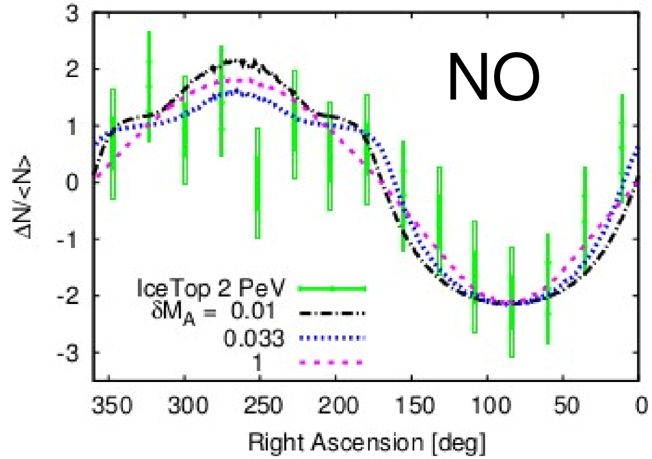
Case F : Fast modes ('Broad')

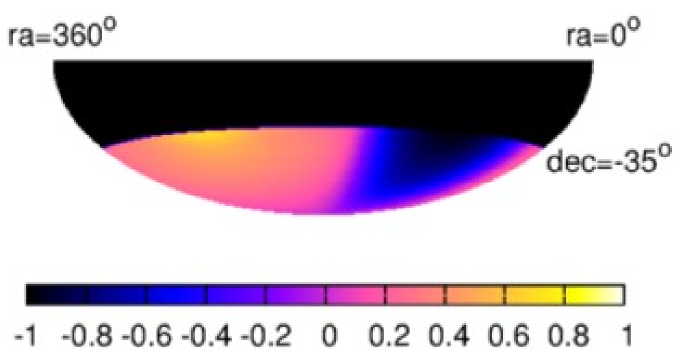
No visible dependence of the *shape* on CR energy

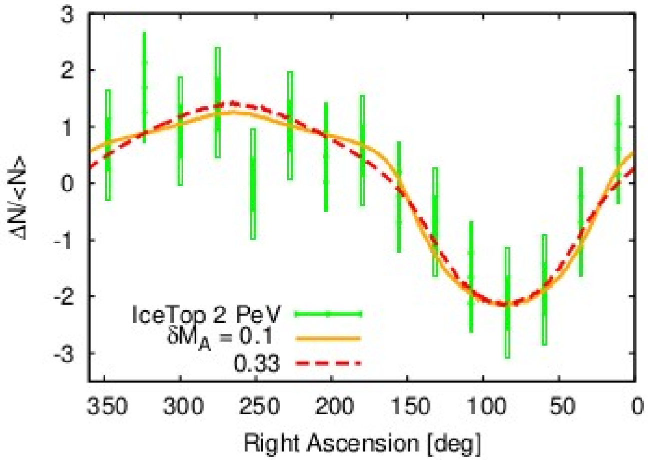
If present, iso. fast modes dominate CR scattering (→ Lazarian et al.)

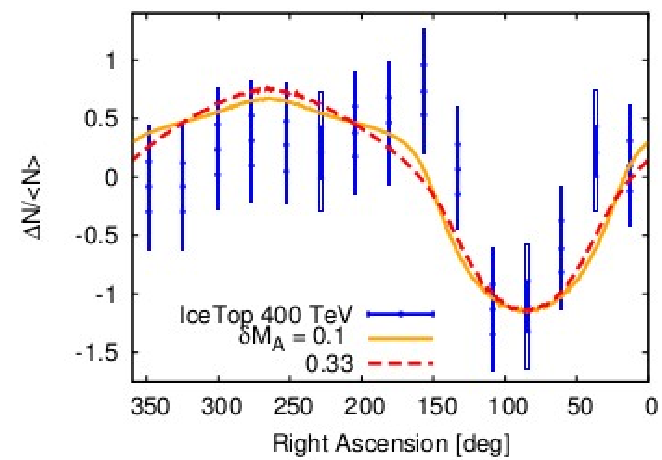












NO

Can fit well the 2 PeV data !

Not a (perfect) dipole, even if turbulence is *isotropic*

Conclusions and perspectives

- Flattening in directions perpendicular to field lines
- Can fit the 2 PeV data with GS turbulence or fast modes
- Change in anisotropy shape with CR energy ?
- Constraints on resonance functions

Large-scale CR Anisotropy = Probe of ISMFs :

Modes present and their anisotropy (in k-space)

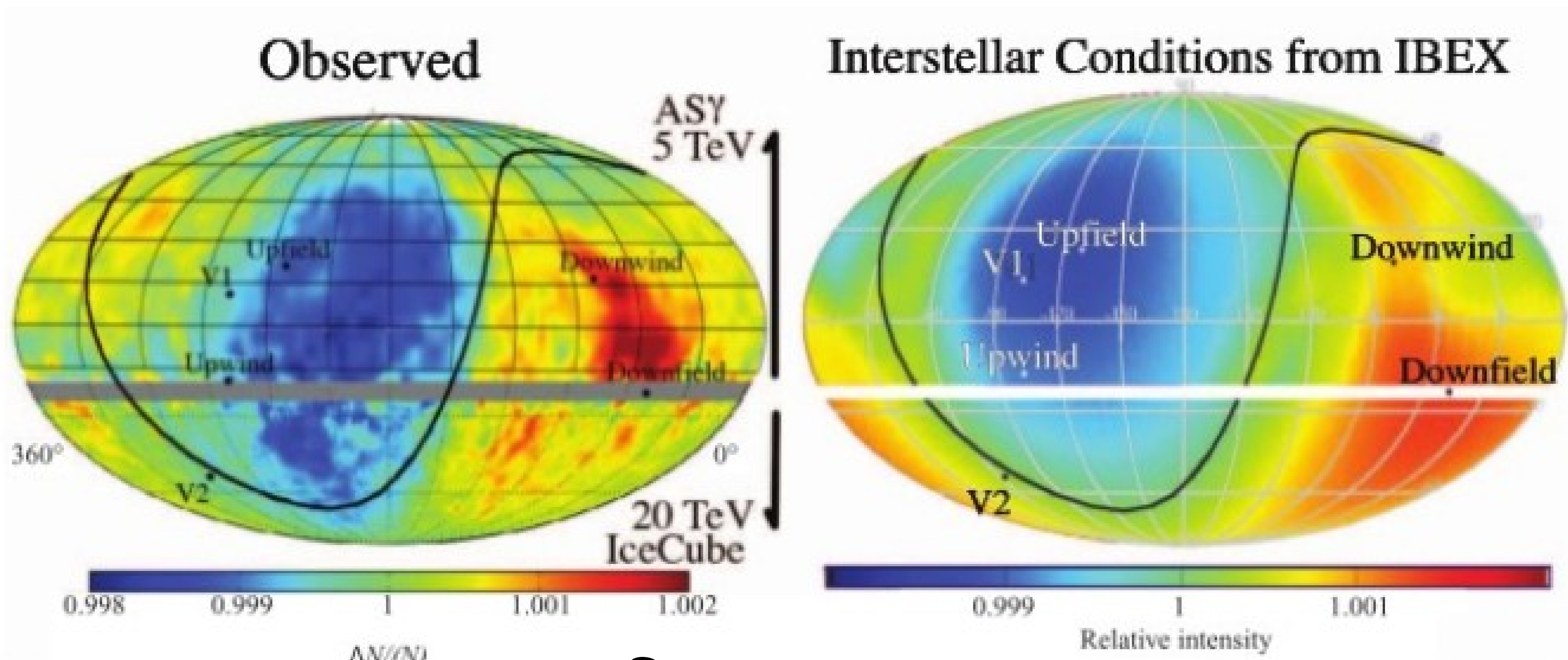
---> Explanation for the data

---> Probe of turbulence in collisionless magnetized fluids !

Data can already put constrains

Local MF lines and L-S CR Anisotropy

Global Anisotropies in TeV Cosmic Rays Related to the Sun's Local Galactic Environment from IBEX
N. A. Schwadron *et al.*
Science **343**, 988 (2014);



... and $\delta B/B_0 << 1$