

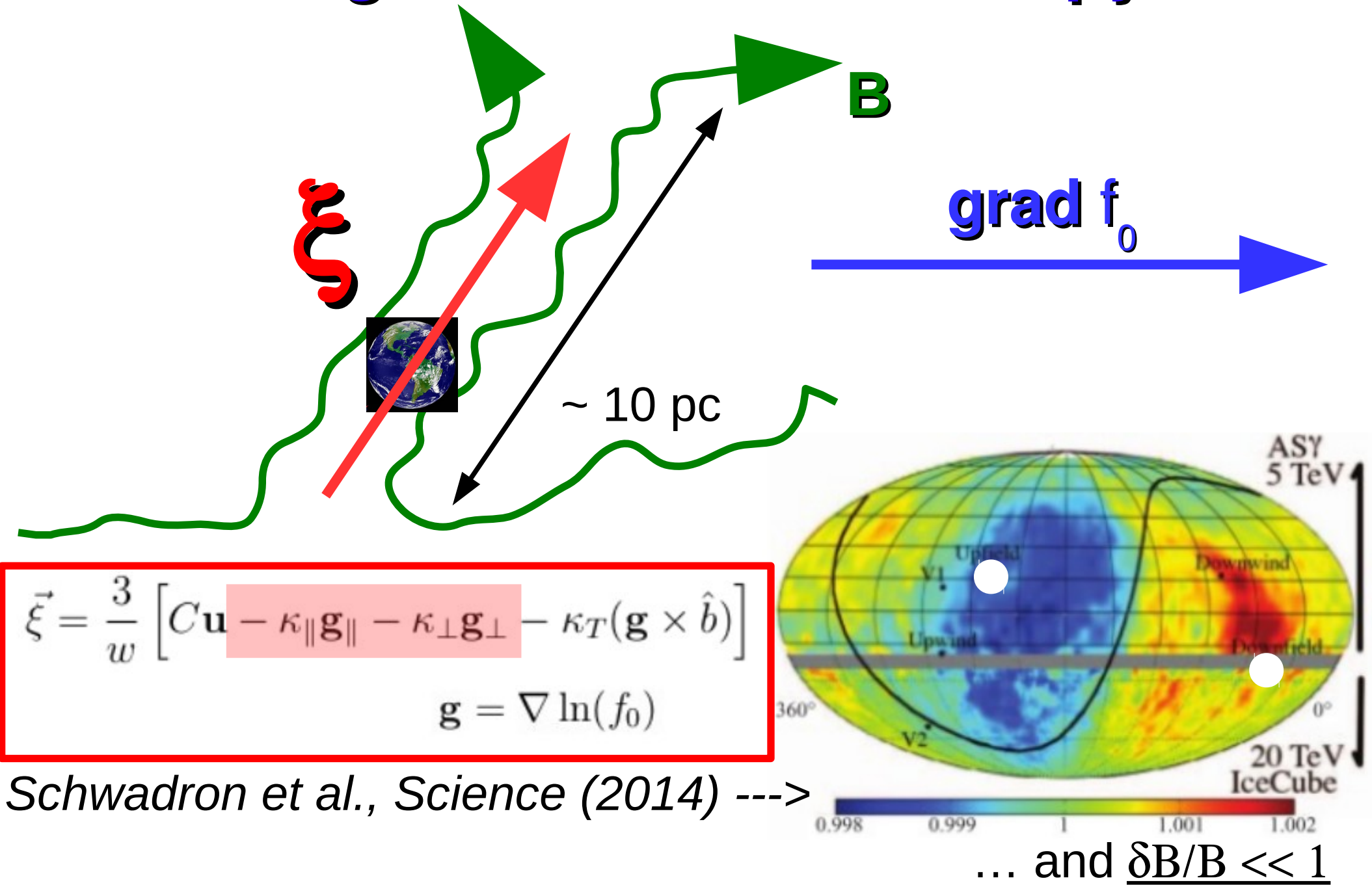
TeV-PeV CR ANISOTROPY AS A PROBE OF LOCAL INTERSTELLAR TURBULENCE

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& John G. Kirk (MPIK Heidelberg)

ApJ 835, 258 (2017) [arXiv:1610.06134]

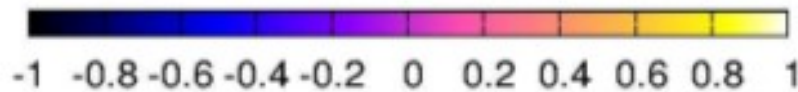
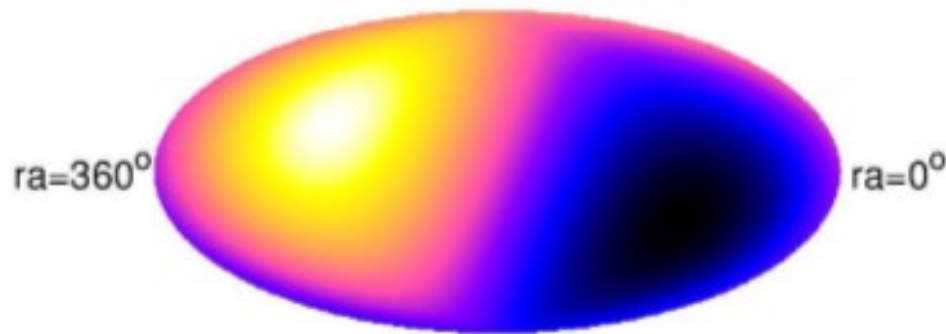
Summary: arXiv:1702.01001

Origin of the CR anisotropy



Cosmic-Ray Anisotropy

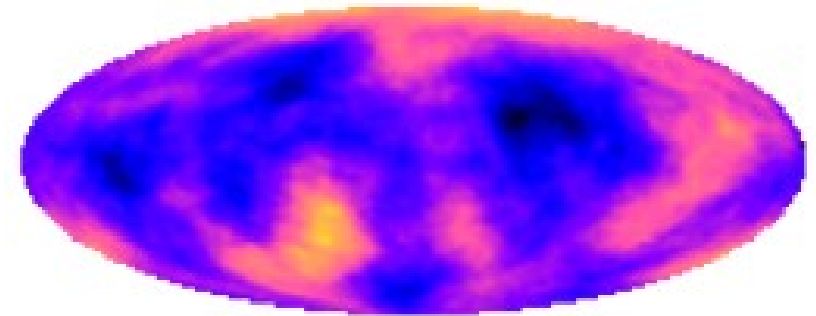
large-scale



- In the direction of field lines
- Amplitude
- **SHAPE**

small-scales

+



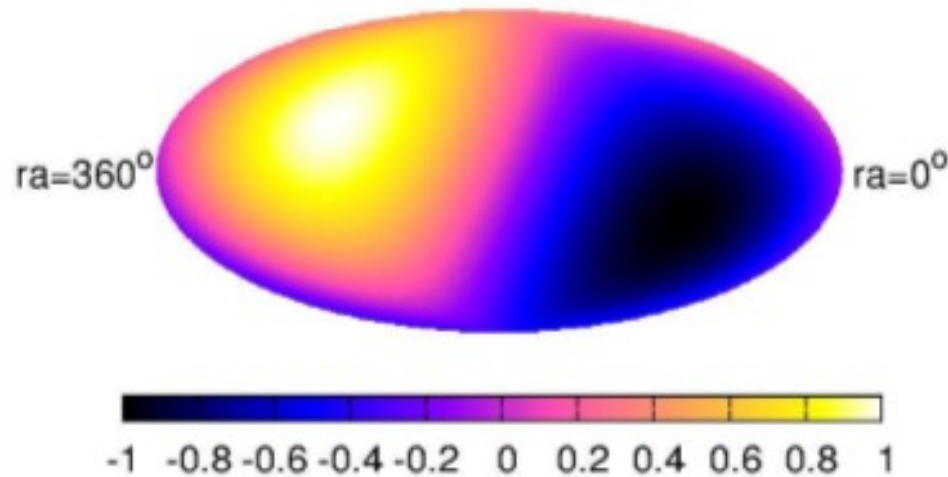
(« small » amplitude)



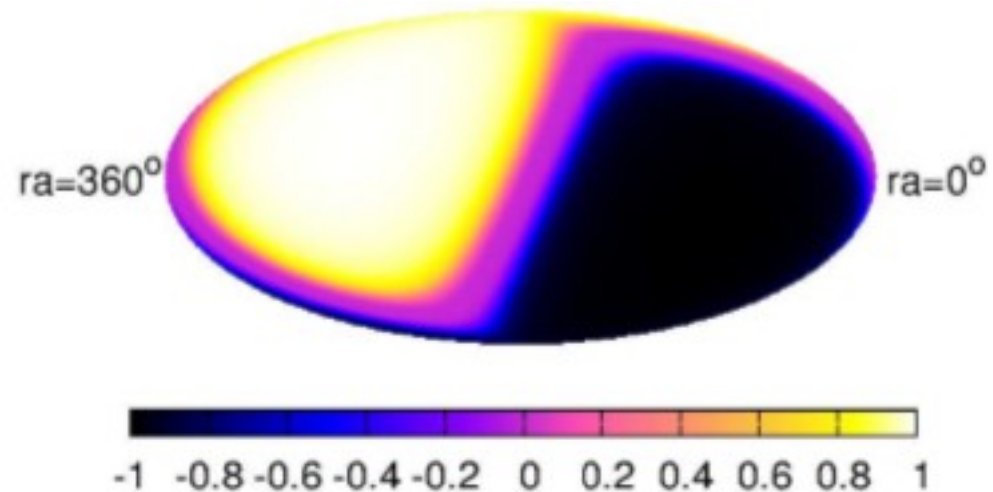
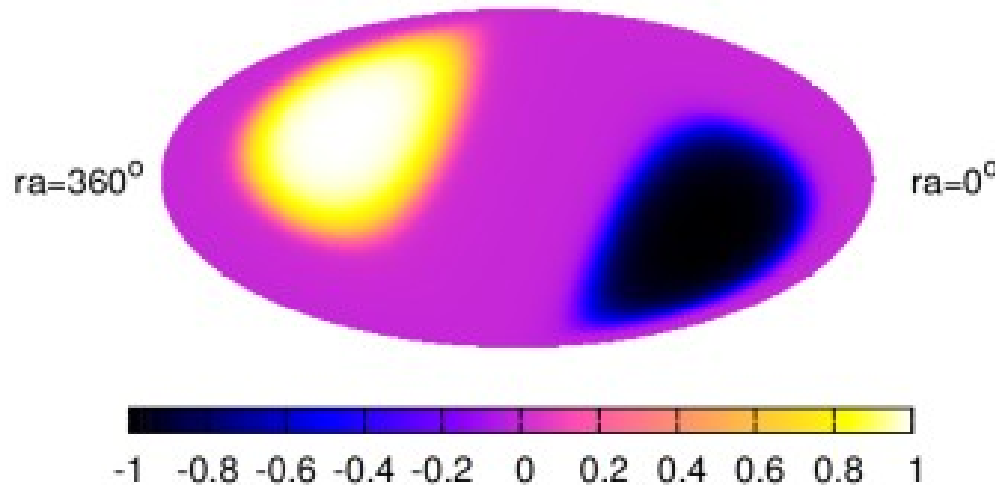
e.g. Malkov et al. (2010),
GG & Sigl (2012),
Drury (2013),
Desiati et al. (2013),
Ahlers (2014, ...),
Zhang et al. (2014), ...

LARGE-SCALE Cosmic-Ray Anisotropy

Dipole only ???

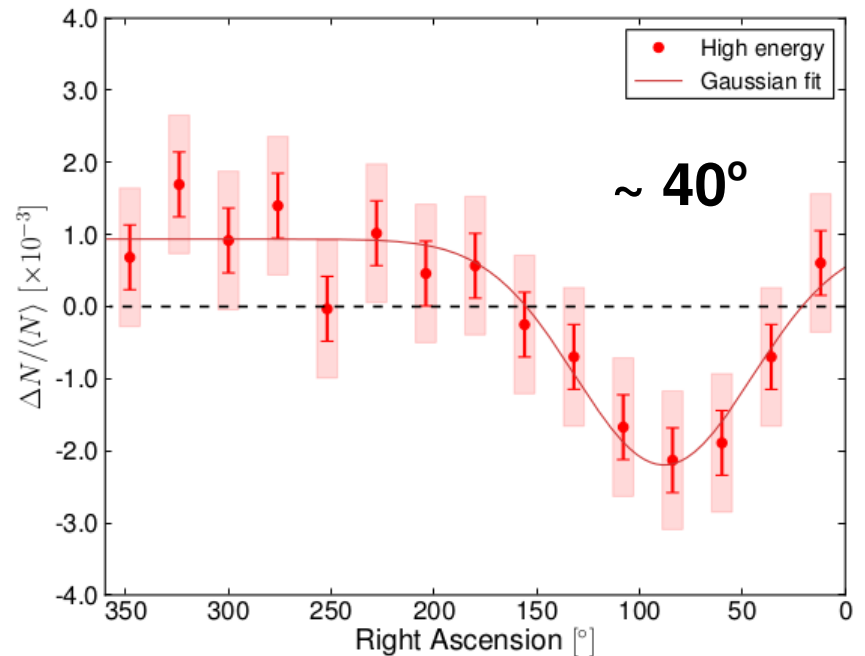
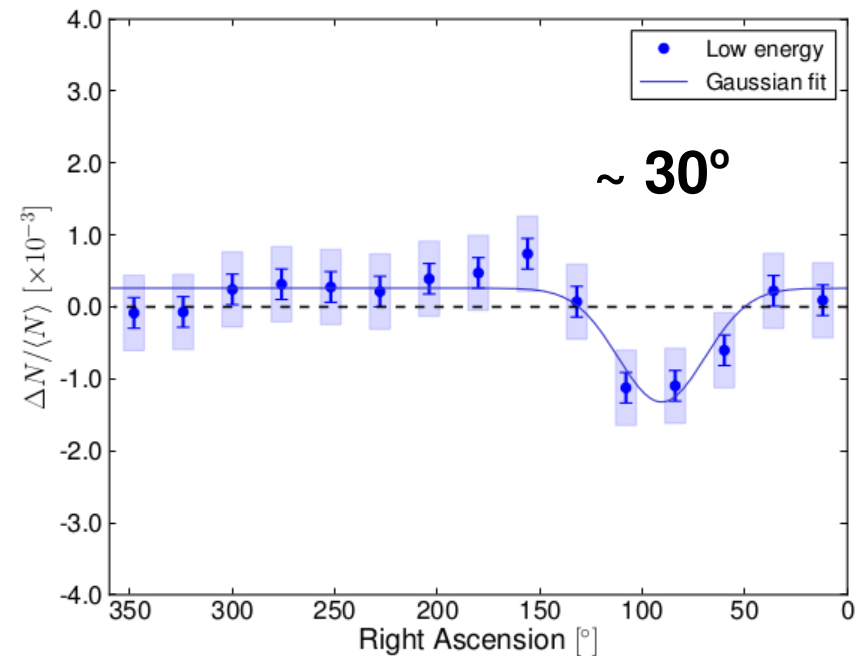
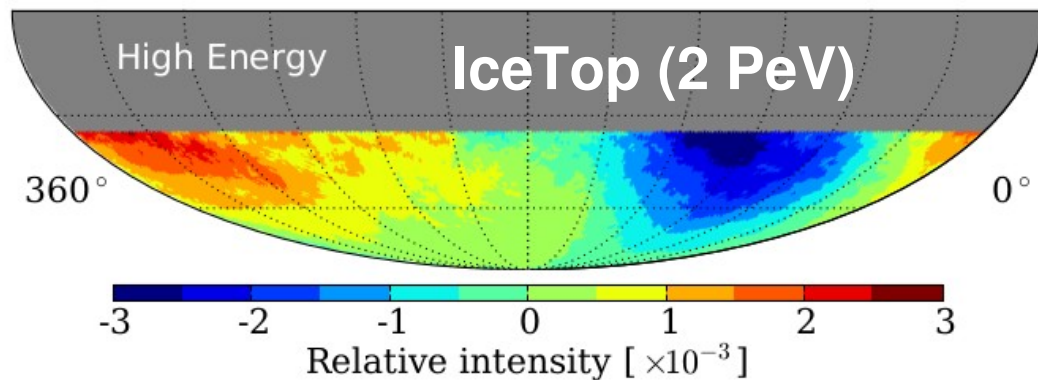
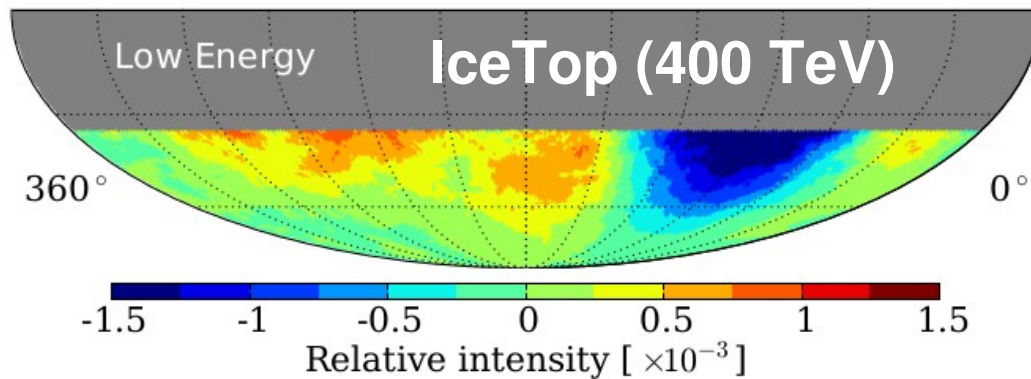


... or could it look like this :

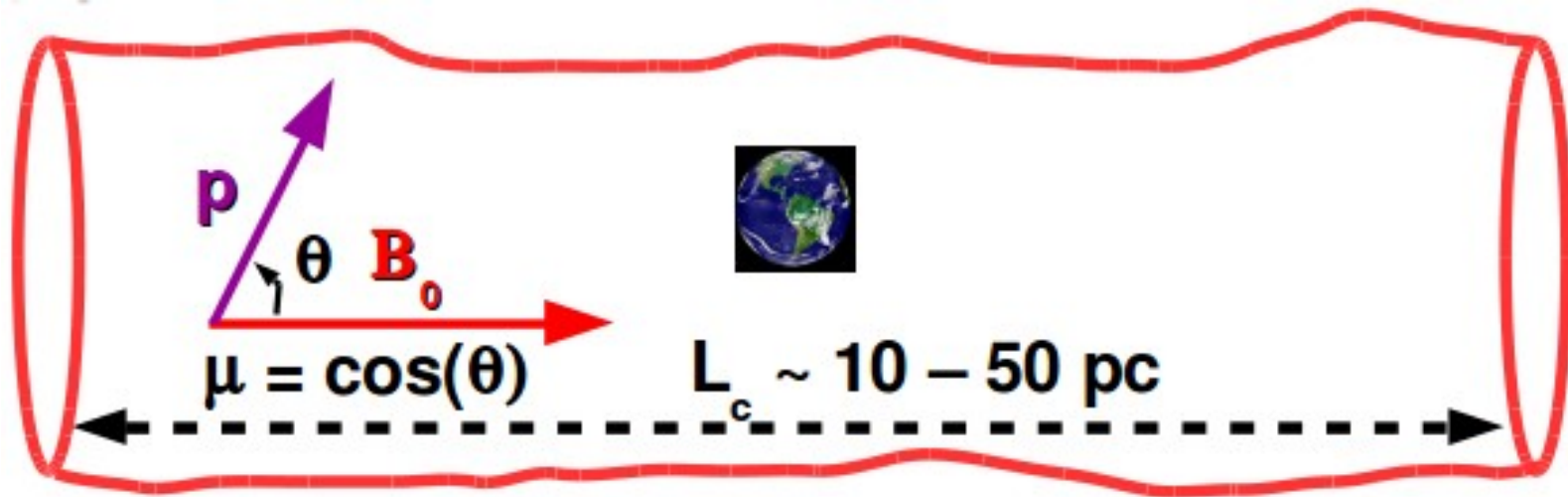


Observations (IceCube, IceTop)

Aartsen et al. (2013)



CR Anisotropy : Probe of turbulence

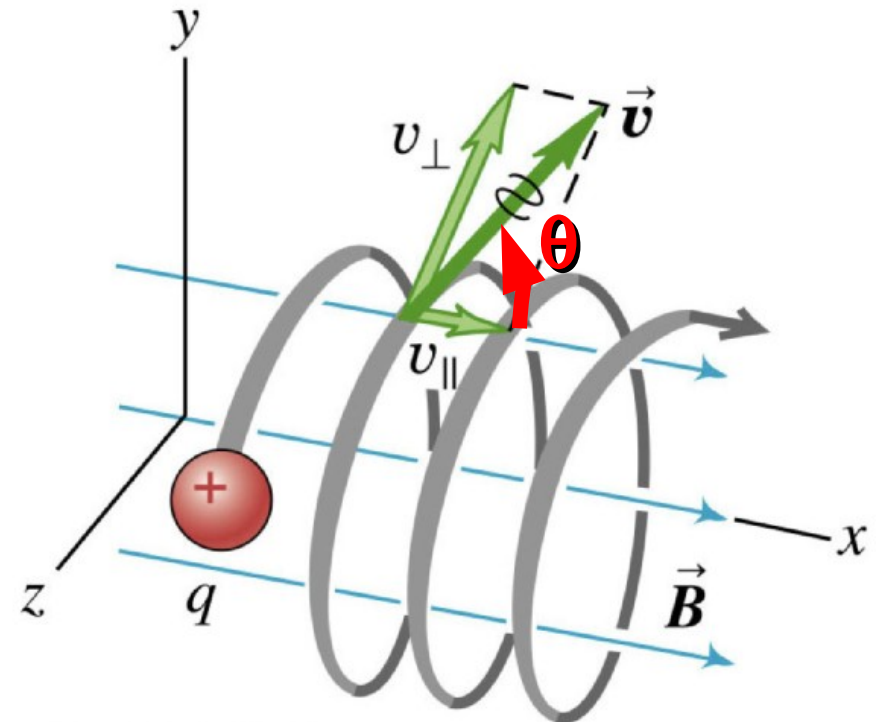


$$\mu v \frac{\partial f}{\partial x} = \frac{\partial}{\partial \mu} \left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right)$$

(gyrophase-averaged)

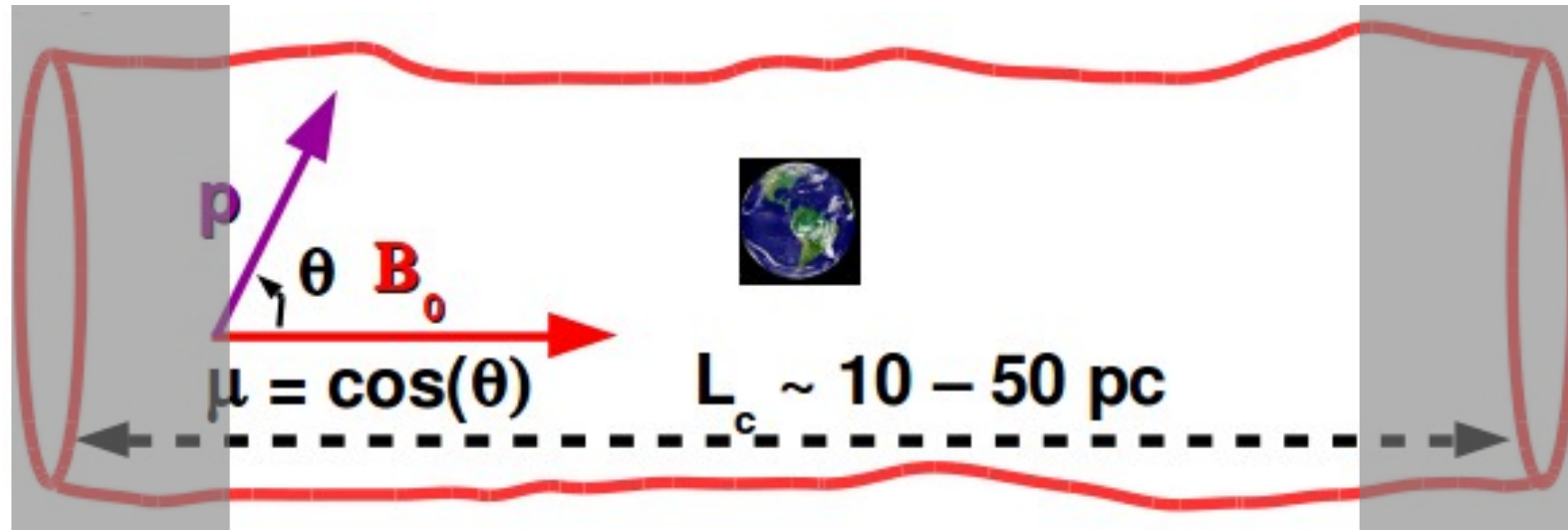
$$\delta \mathbf{B} / \mathbf{B}_0 \ll 1$$

Pitch-angle diffusion



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CR Anisotropy : Probe of turbulence



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

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

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

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

(« boundary layer »)

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

Pitch-angle diffusion coefficient

$$D_{\mu\mu} = \Omega^2 (1 - \mu^2) \int d^3k \int_0^\infty d\tau \sum_{n=-\infty}^{\infty} \left(\frac{n^2 J_n^2(z)}{z^2} M_A(\mathbf{k}, \tau) + \frac{k_{\parallel}^2 J_n'^2(z)}{k^2} M_{S,F}(\mathbf{k}, \tau) \right),$$

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

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

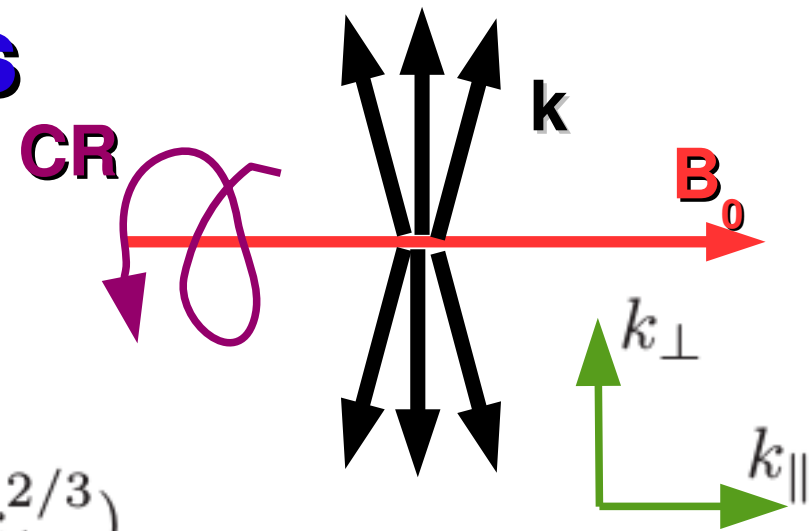
$$\Rightarrow D_{\mu\mu} = \Omega^2 (1 - \mu^2) \int d^3k \sum_{n=-\infty}^{\infty} \left(\frac{n^2 J_n^2(z)}{z^2} \mathcal{I}_A(\mathbf{k}) + \frac{k_{\parallel}^2 J_n'^2(z)}{k^2} \mathcal{I}_{S,F}(\mathbf{k}) \right) \times R_n(k_{\parallel} v_{\parallel} - \omega + n\Omega),$$

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

Alfven (and Slow) modes

Goldreich & Sridhar (1995)

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



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

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

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

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

Fast magnetosonic modes

MHD simulations of Cho & Lazarian (2002) :

$$\text{Isotropic with } \mathcal{I}_M(\mathbf{k}) \propto k^{-3/2}$$

Resonance functions (RF)

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

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

Chandran (2000)

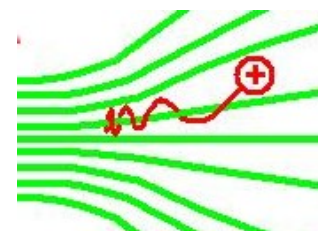
$$\begin{aligned}
 \tau_{A,S} &= l^{1/3} / (v_A k_{\perp}^{2/3}) \\
 \tau_F &= l / (v_A \tilde{k}^{1/2}) \quad \tilde{k} = kl
 \end{aligned}$$

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

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

Yan & Lazarian

(2008)



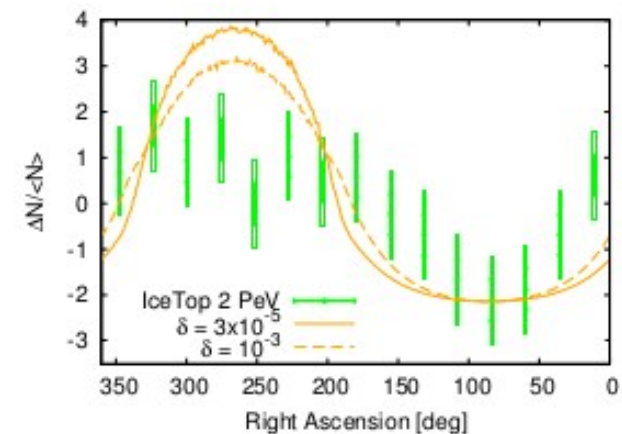
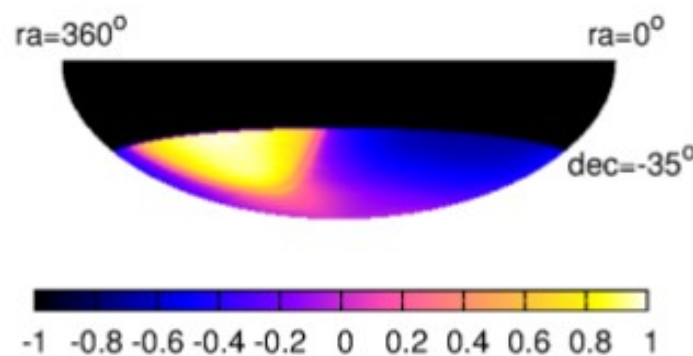
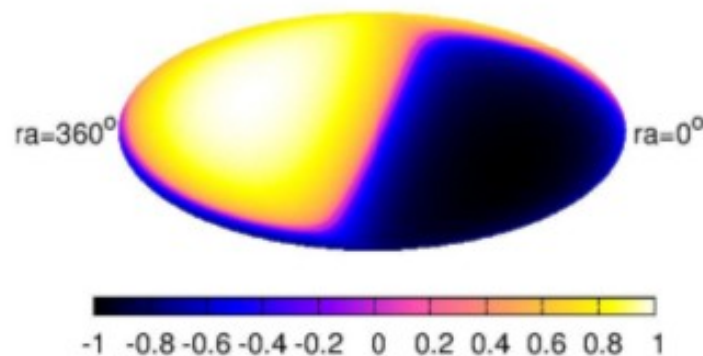
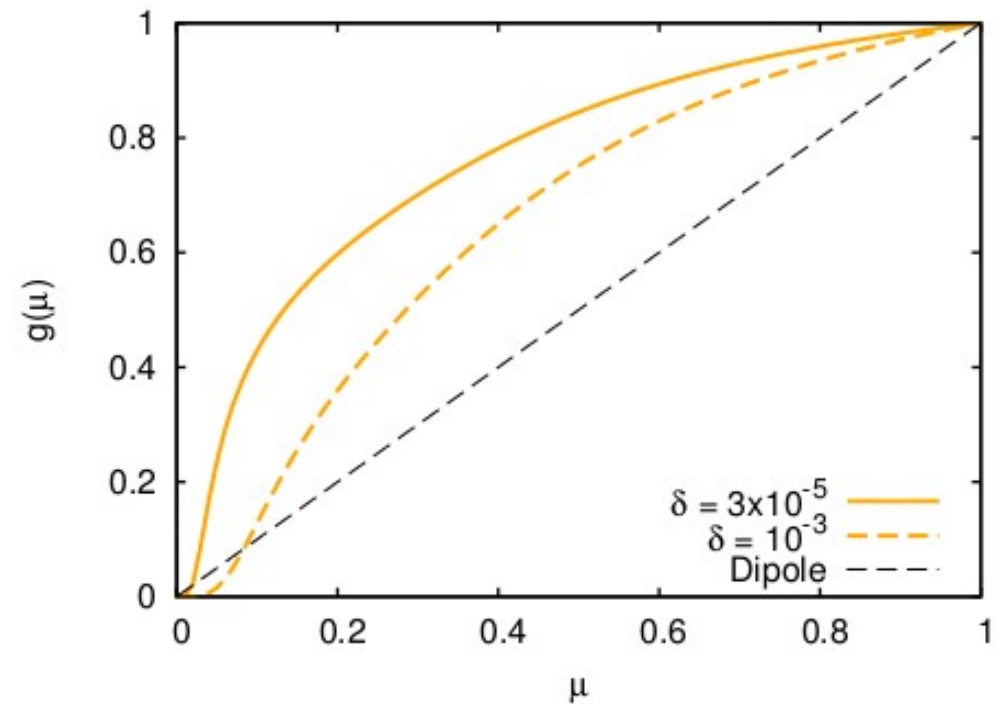
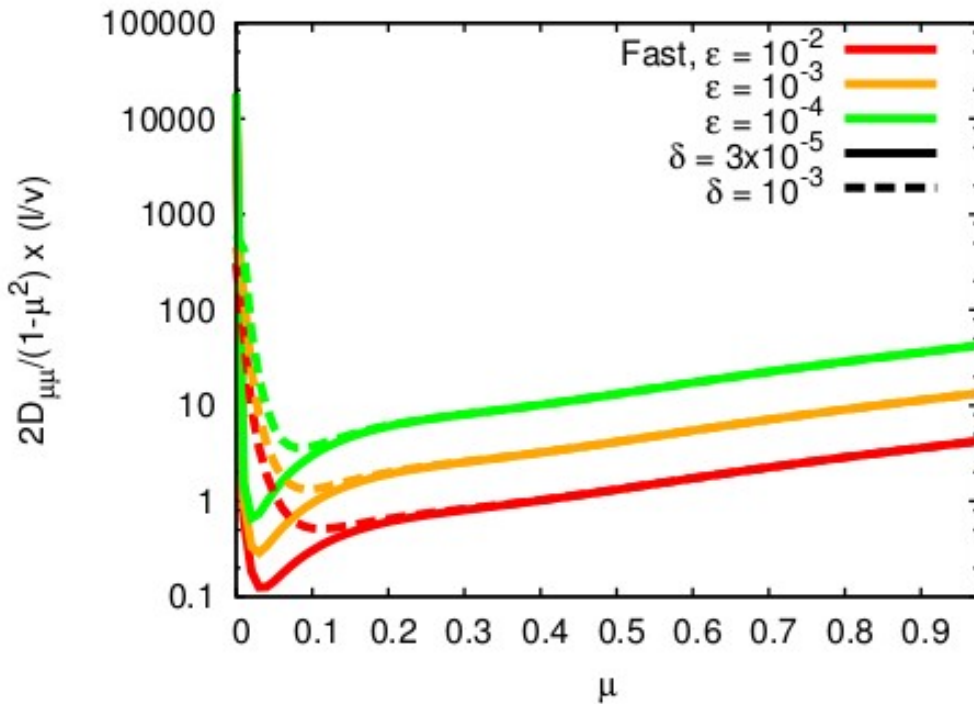
B_0



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

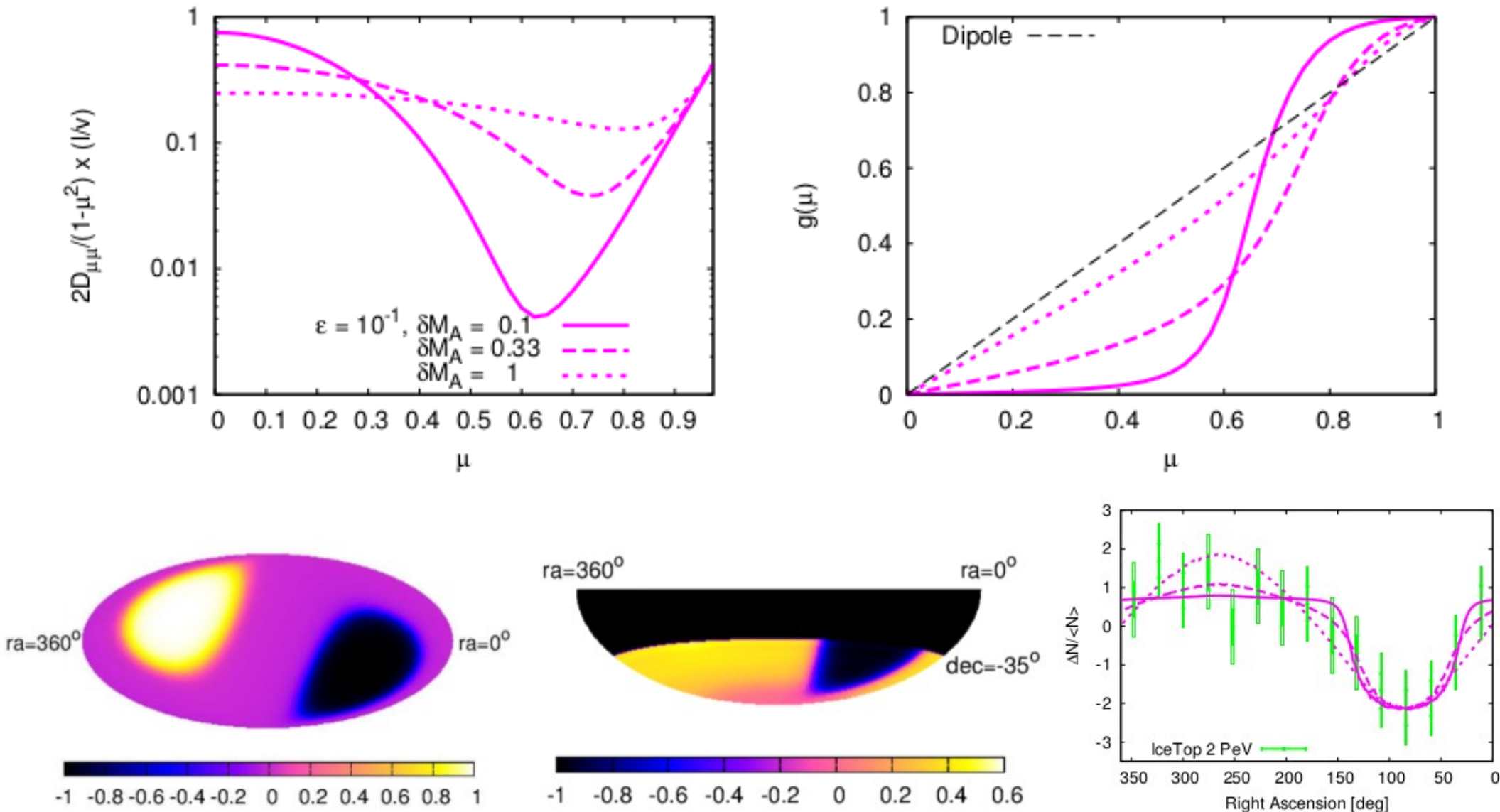
Case 1 : Fast modes & Narrow RF

No visible dependence of the *shape* on CR energy $\varepsilon = v/(l\Omega) = r_L/l$

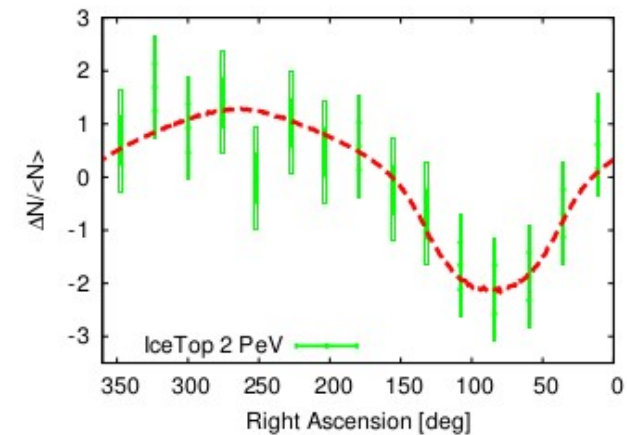
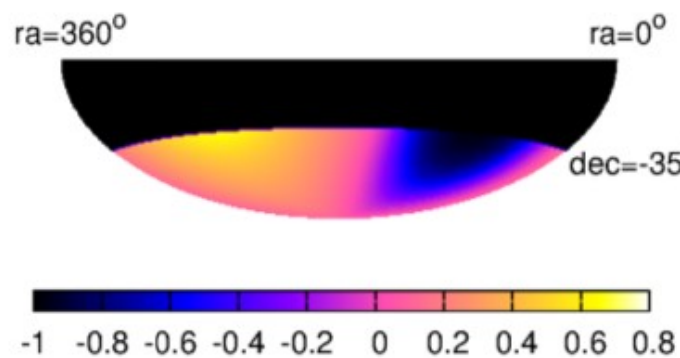
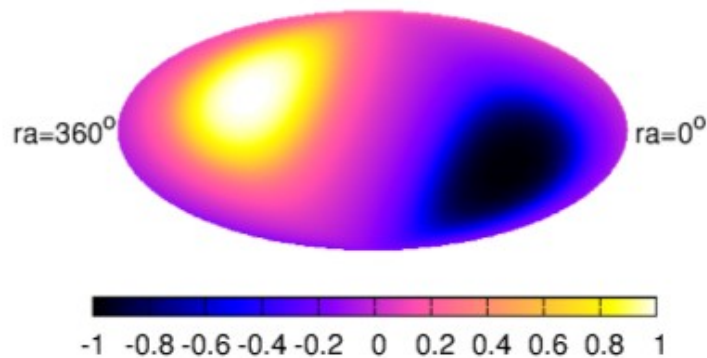
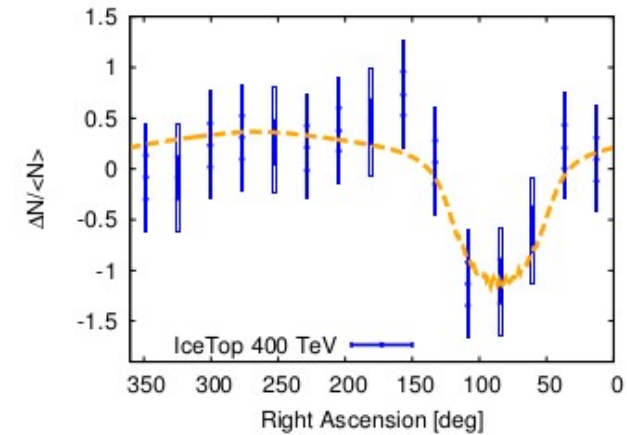
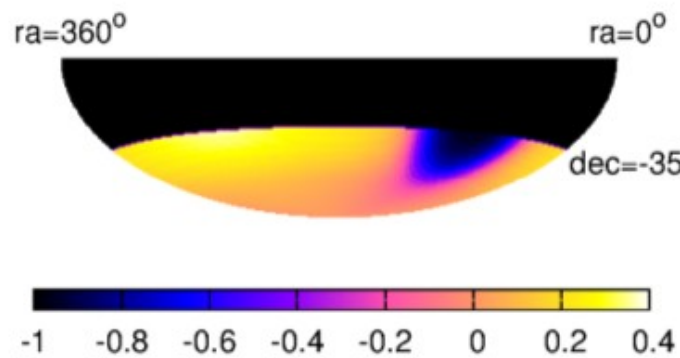
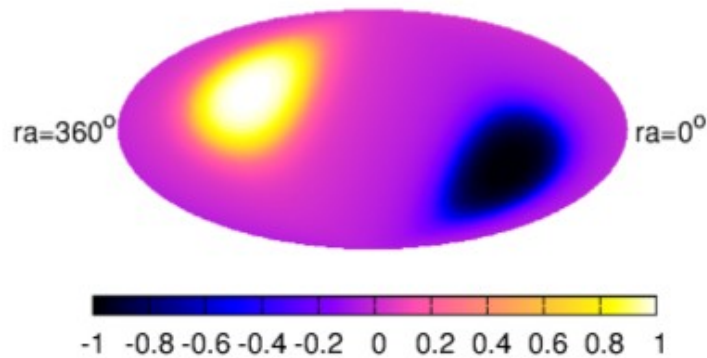


RULED OUT !

Case 2 : GS – Heaviside & Broad RF



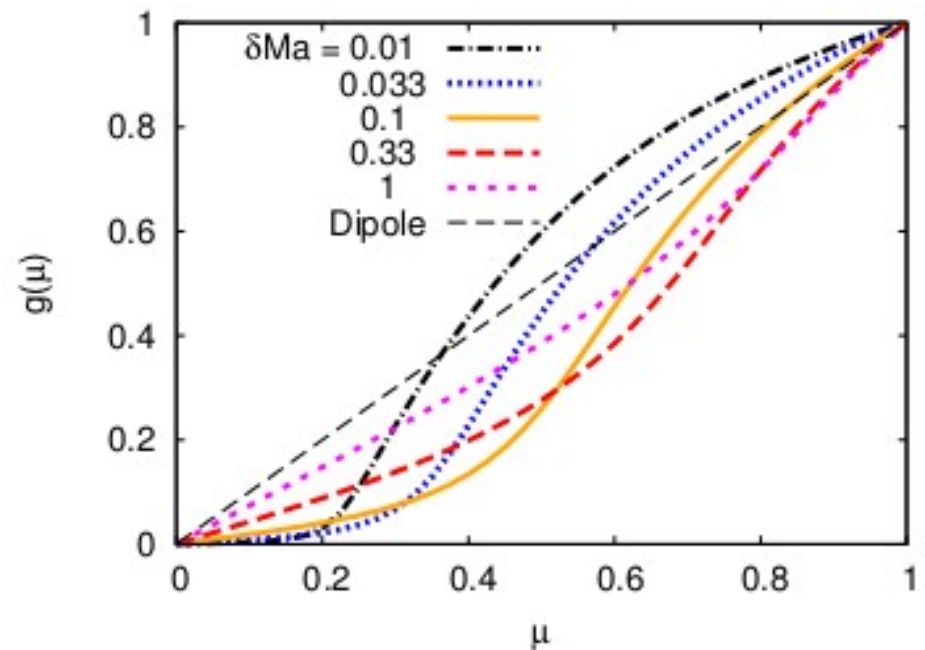
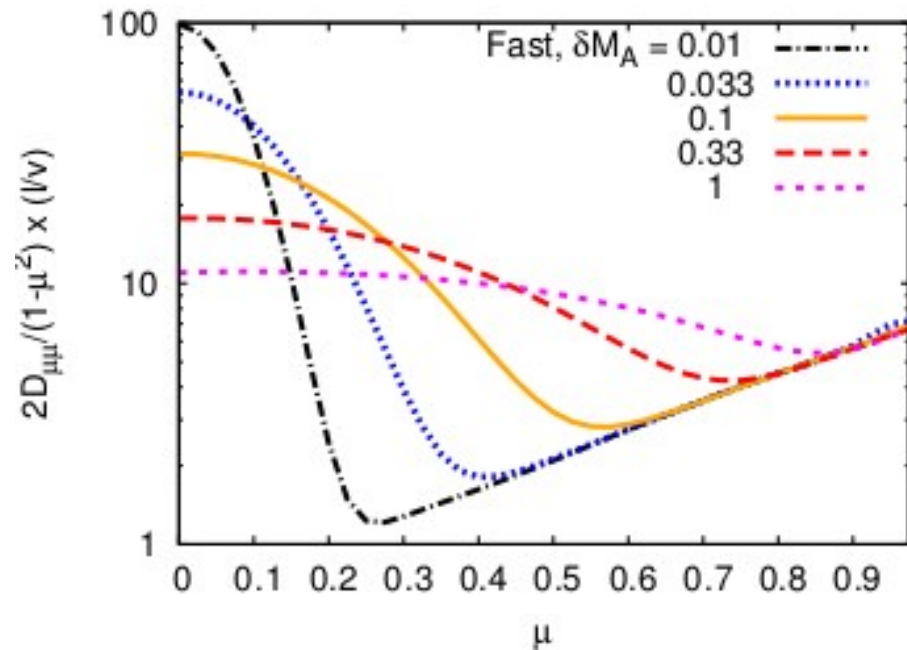
Case 3 : GS – Exponential & Broad RF



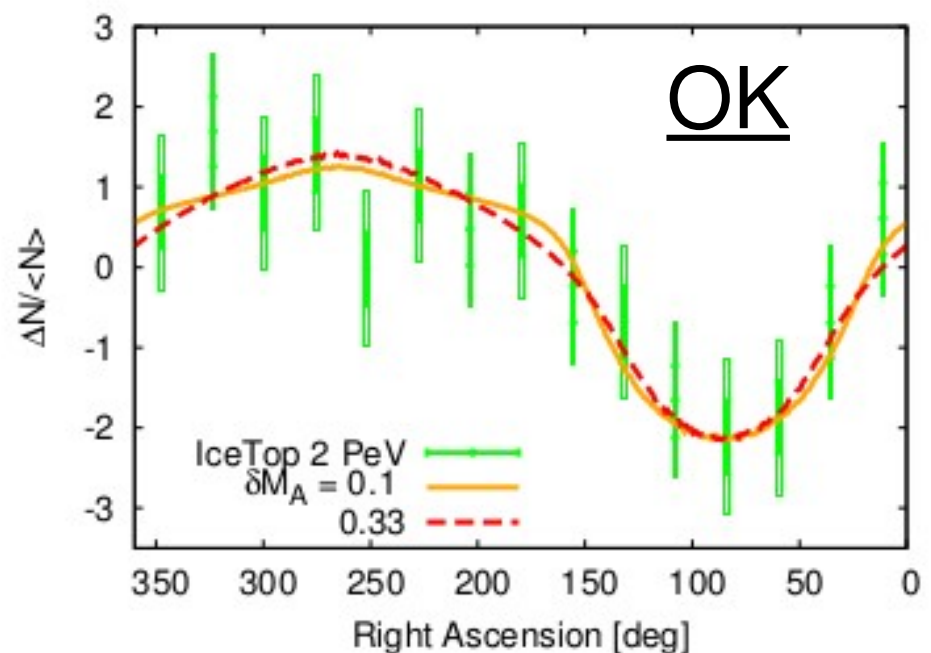
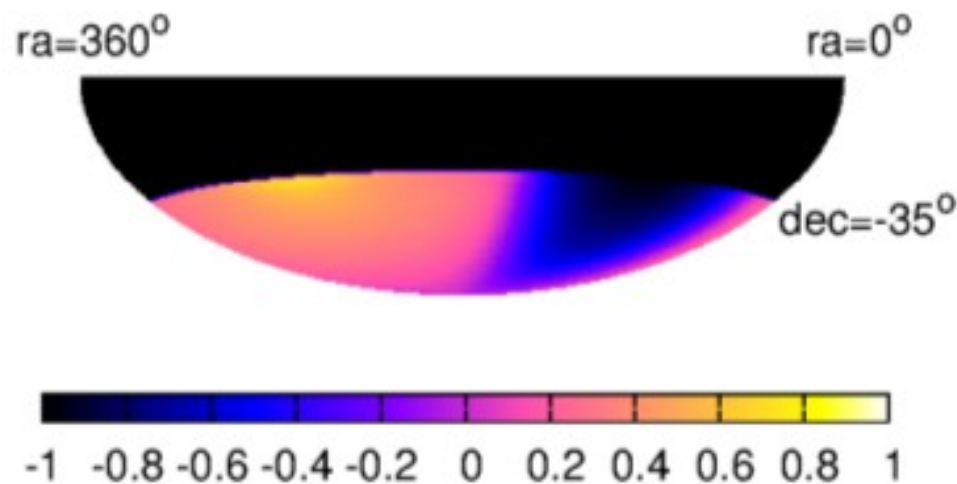
Can fit well the 400 TeV and the 2 PeV data !

Energy-dependence reproduced for fixed turbulence parameters

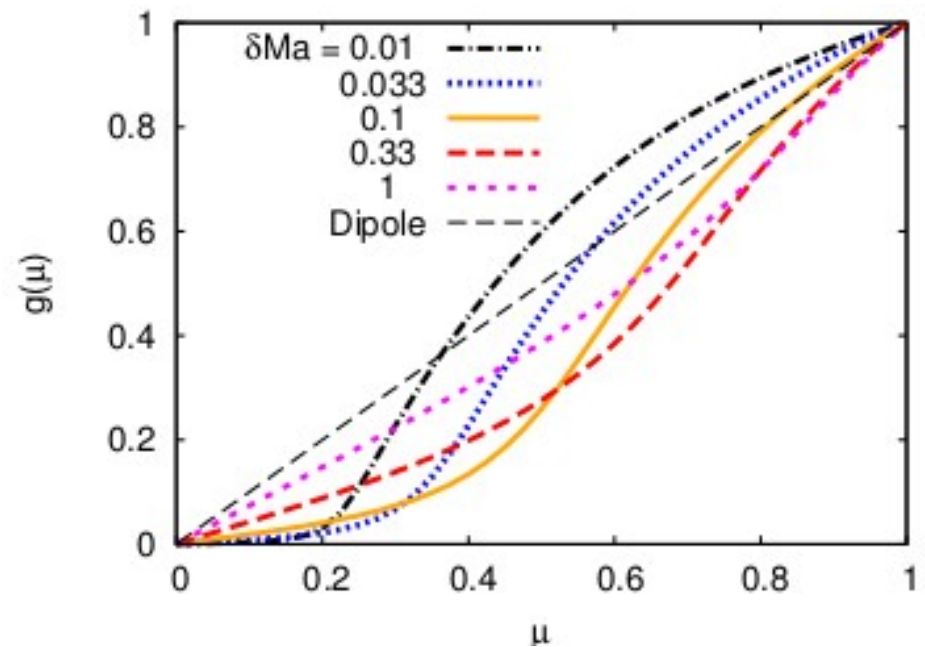
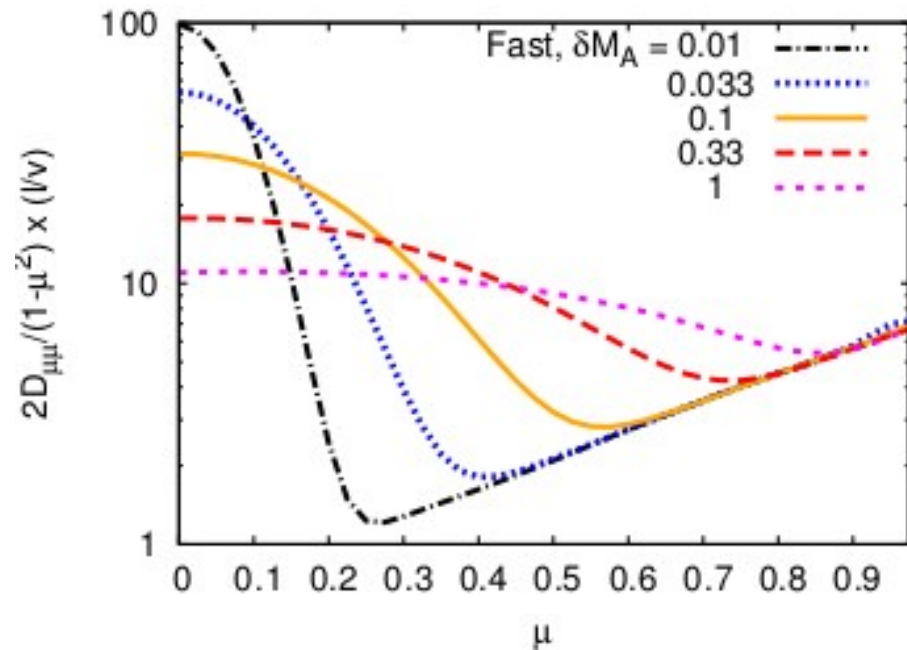
Case 4 : Fast modes & Broad RF



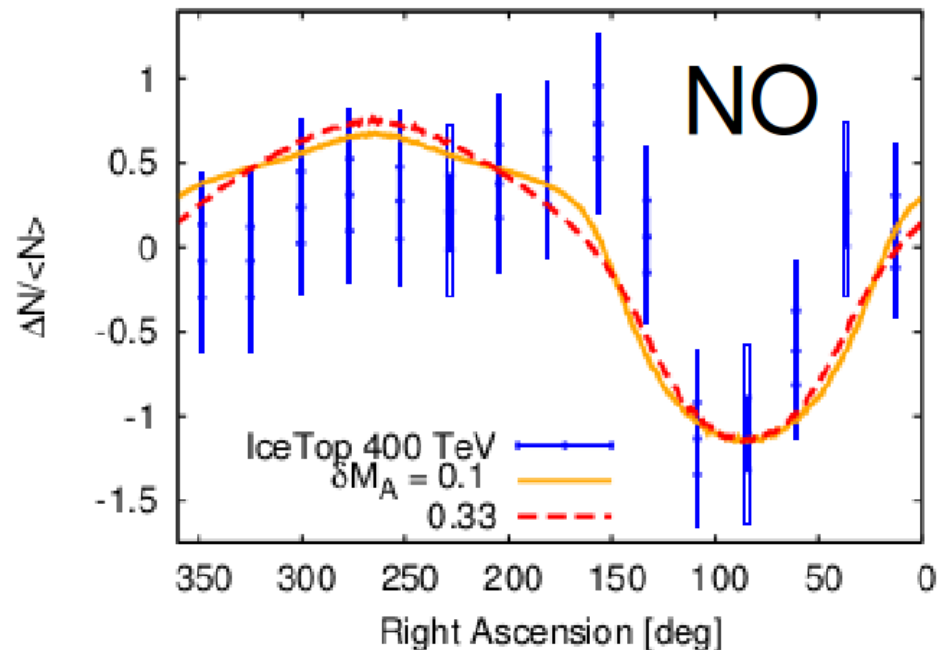
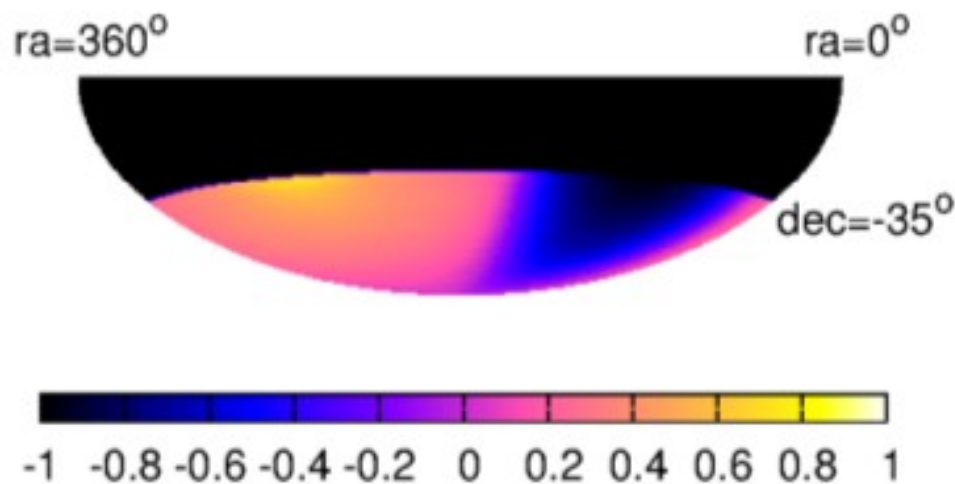
Can fit the 2 PeV data ! $\rightarrow$



Case 4 : Fast modes & Broad RF



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)

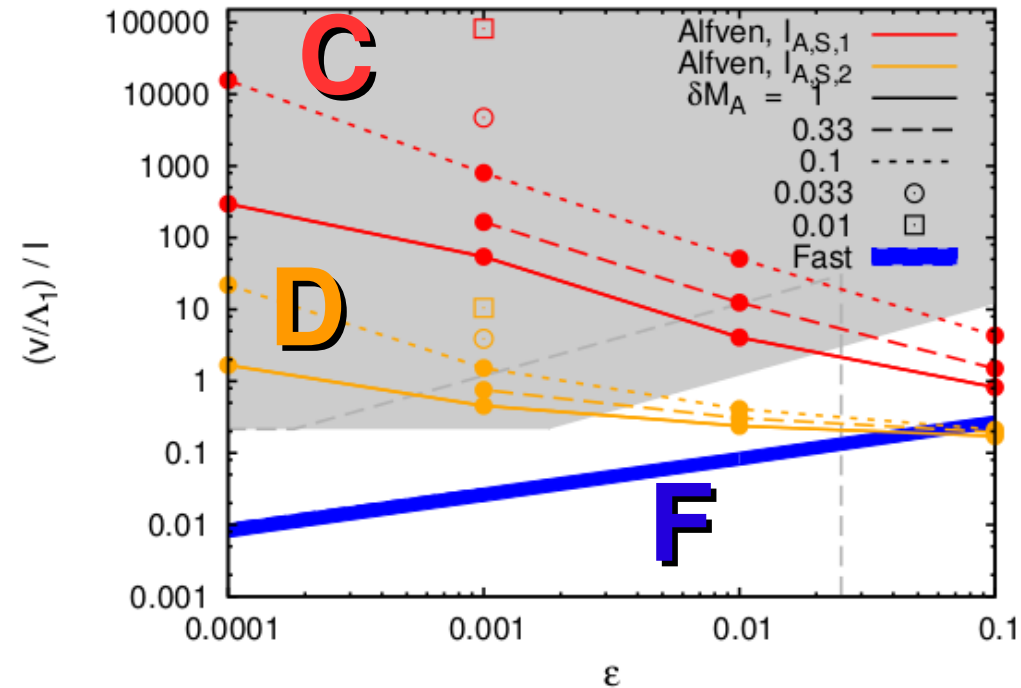
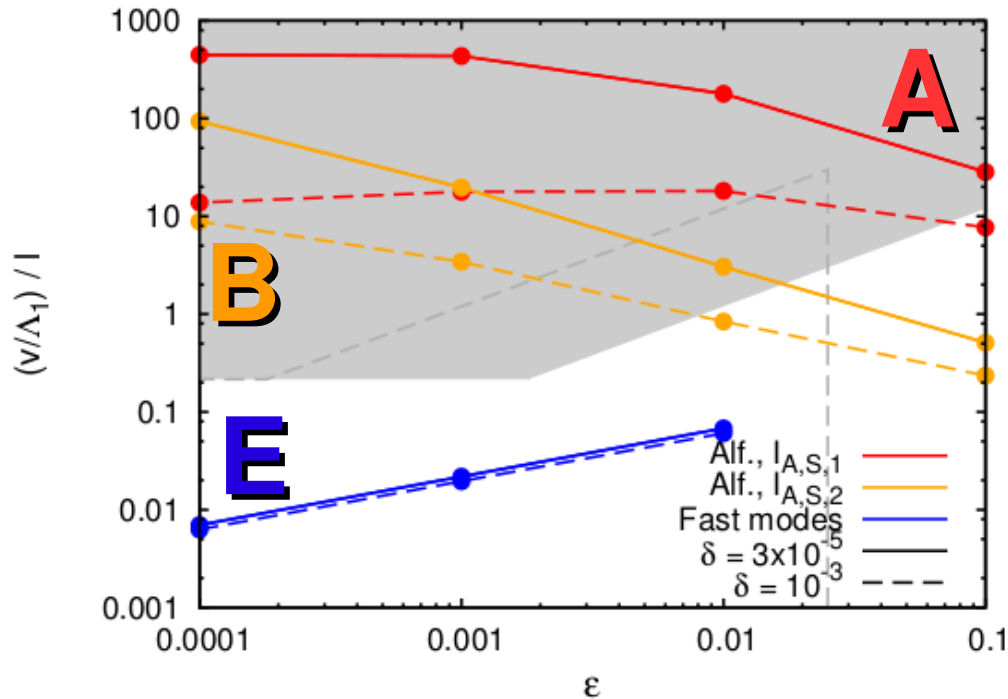
(ii) local CR transport properties

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 ?
 - - -> $|\mathbf{k}|$ -dependent anisotropy in power spectrum ??

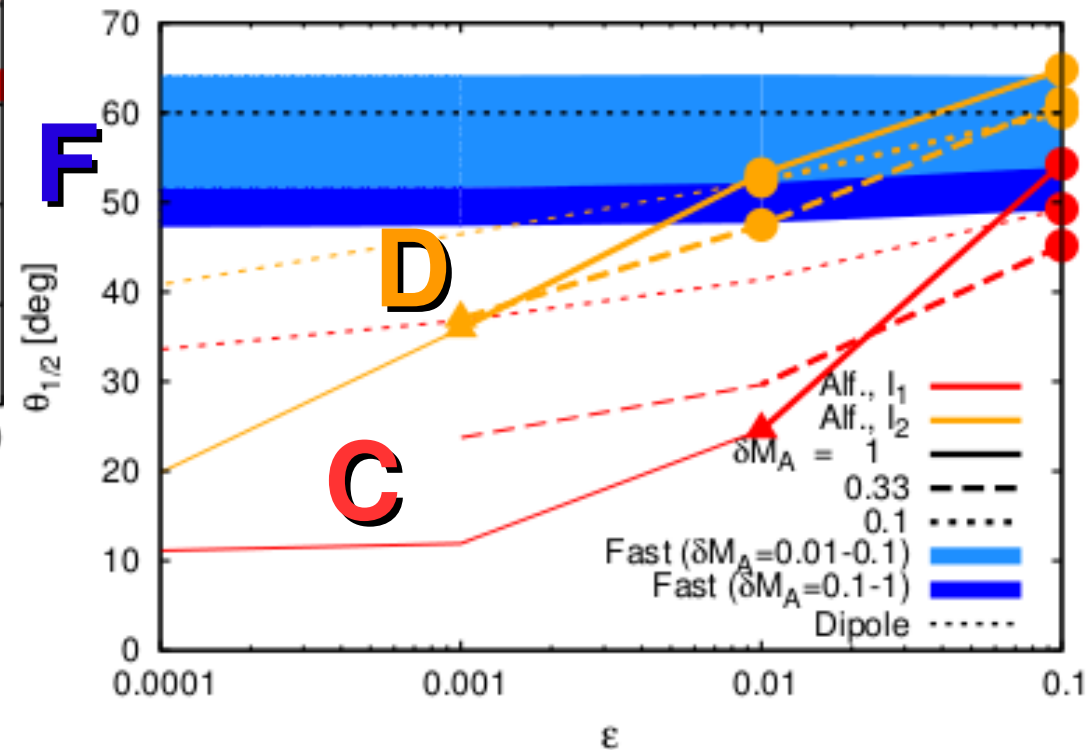
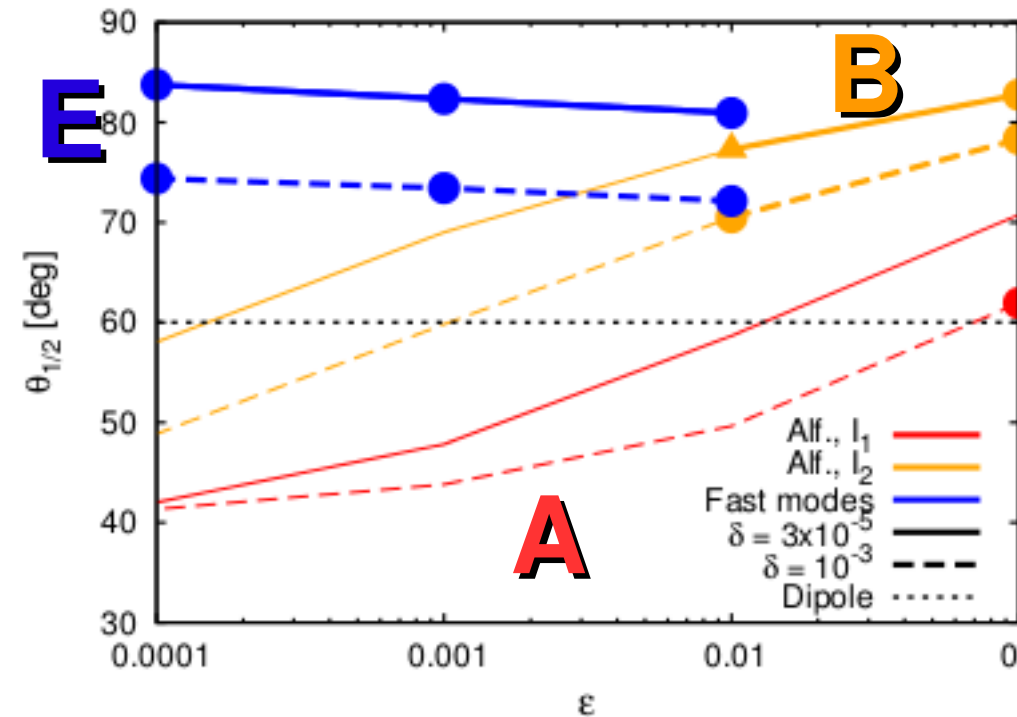
First Eigenvalue and « Boundary layer »

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

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



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