COSMIC-RAY ANISOTROPY AS A PROBE OF INTERSTELLAR TURBULENCE

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&

John G. Kirk (MPIK Heidelberg)

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
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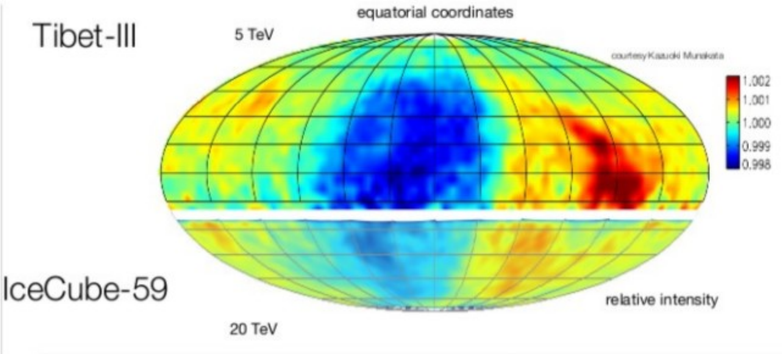
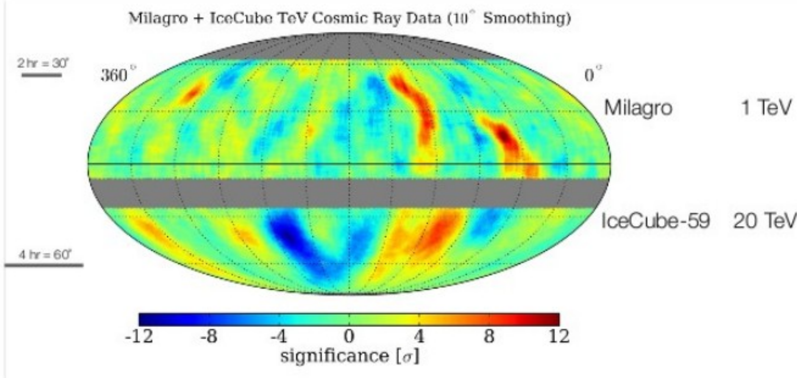
Large Scale Anisotropy ~0.1%



Small Scale Anisotropies ~0.01%



OUTLINE :

I – Why do we expect a large-scale anisotropy ?

II – The large-scale anisotropy as a new probe of turbulence & CR propagation properties

III – Explanations for the small scale anisotropies

CR diffusion in the Milky Way

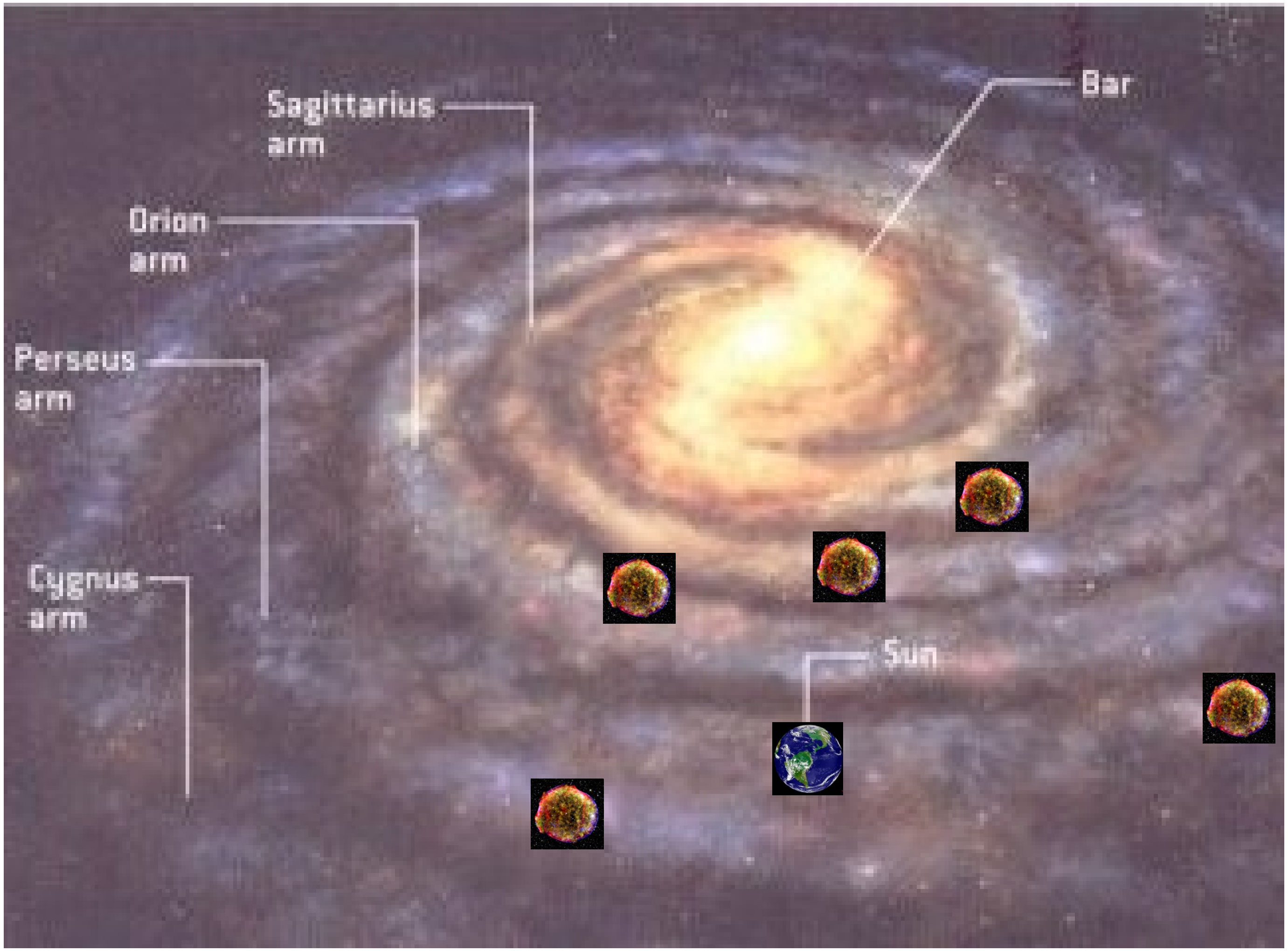
CR anisotropy

=

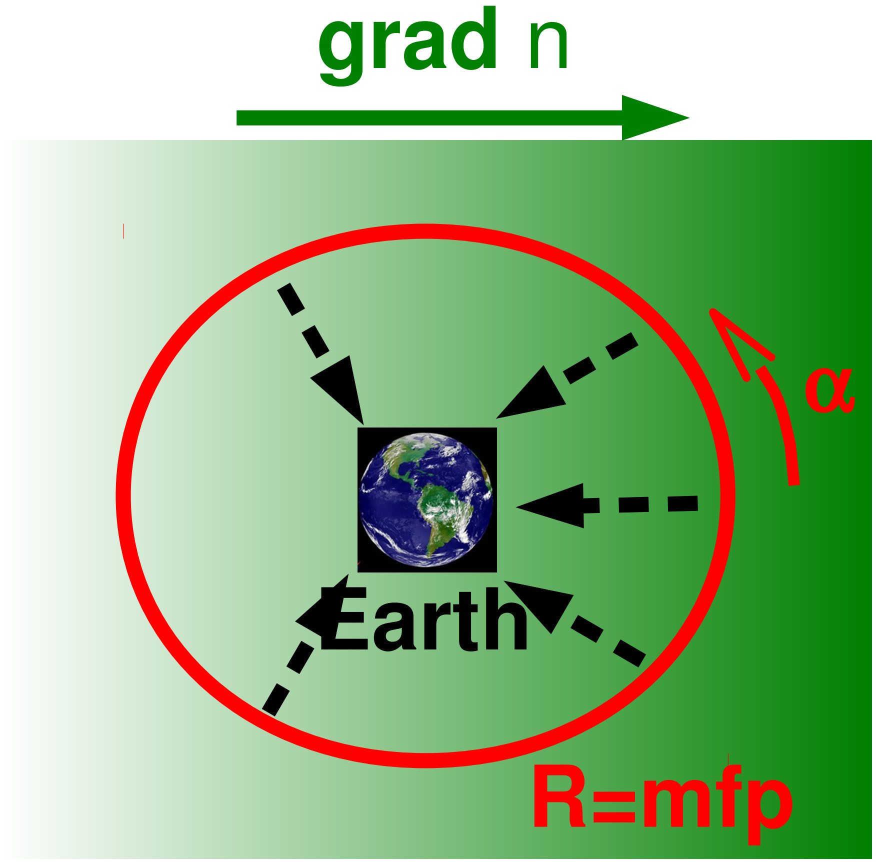
Compton-Getting effect

+

Grad (log(N_{CR})) from sources



Diffusion approximation - Dipole



$F = F_0\,(1+\delta \cos \alpha)$

$$\boldsymbol{\delta}(p) \simeq -\frac{3}{c_0}\frac{\mathbf{j}}{n} = \frac{3D(p)}{c_0}\frac{\boldsymbol{\nabla} n}{n}$$

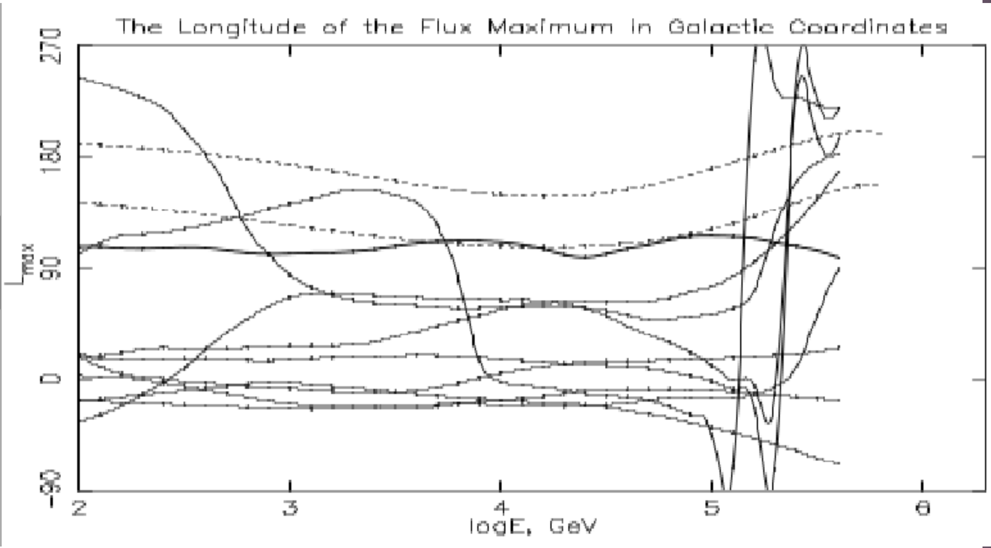
where $\mathbf{j}(\mathbf{r},p) = -D(p)\boldsymbol{\nabla} n$ is the CR current

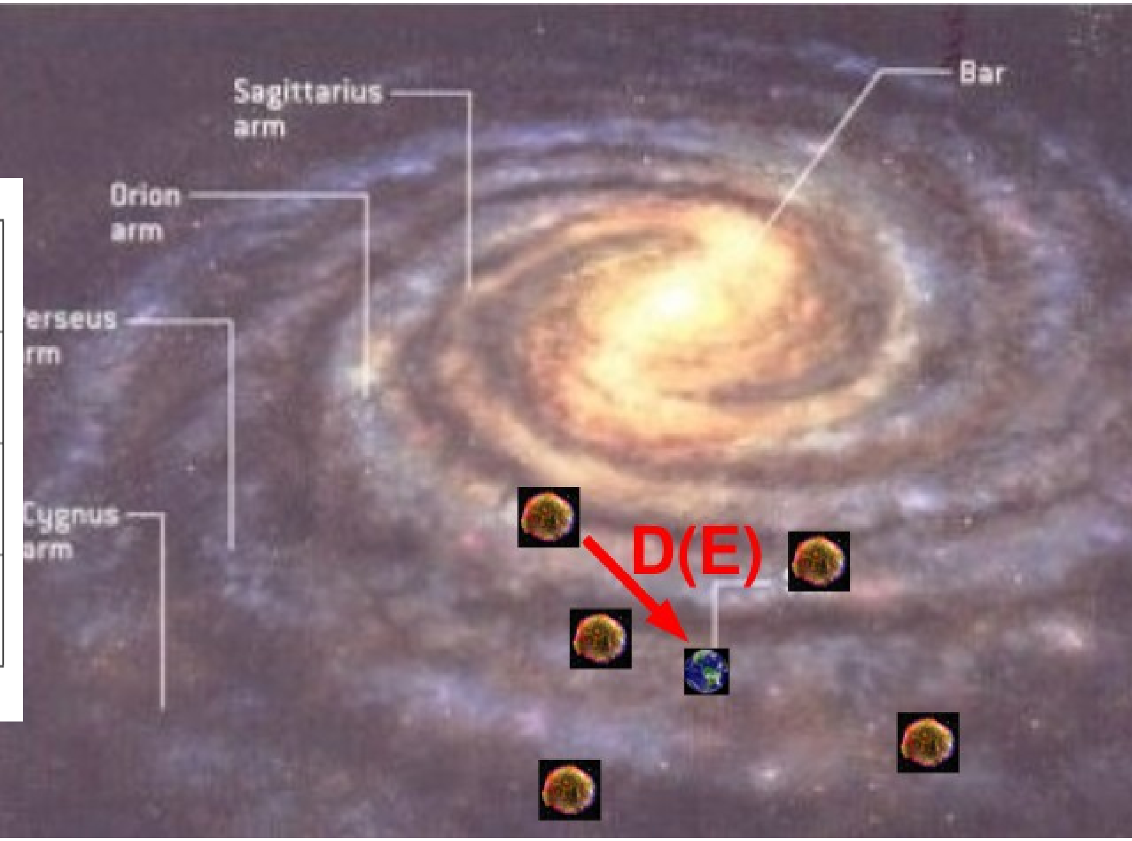
Fluctuations of δ (E)

The Anisotropy of Galactic Cosmic Rays as a Product of
Stochastic Supernova Explosions

A. D. Erlykin[1,2] and A. W. Wolfendale[2]
[1]PN Lebedev Physical Institute, Moscow, Russia
[2]Department of Physics, University of Durham, Durham, UK

Astropart. Phys. 25 (2006) 183





Anisotropy (Amplitude) Problem

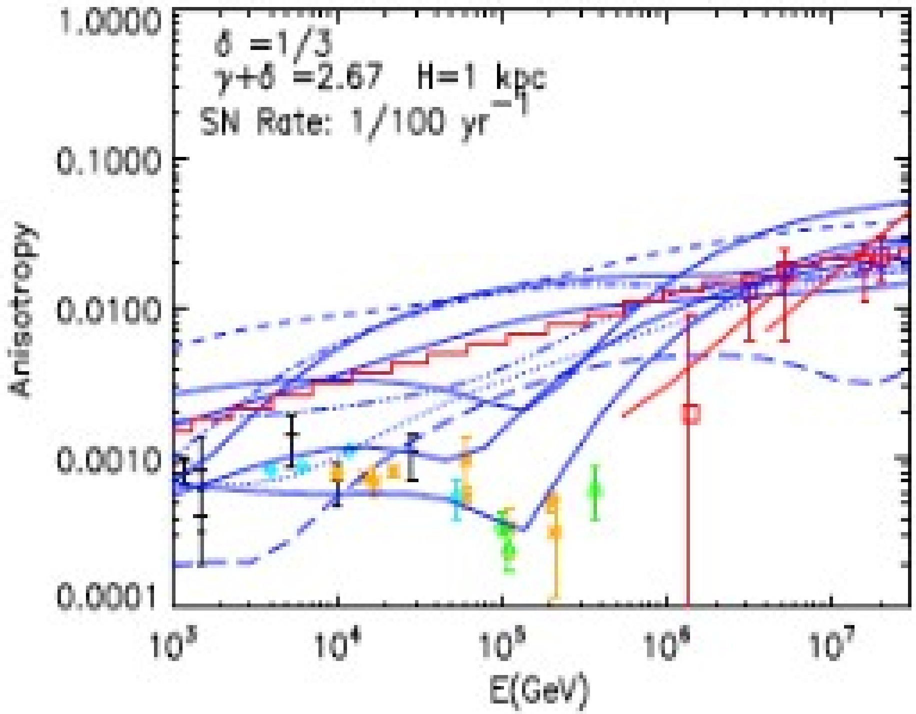
Diffusive propagation of cosmic rays from supernova remnants in the Galaxy. II: anisotropy

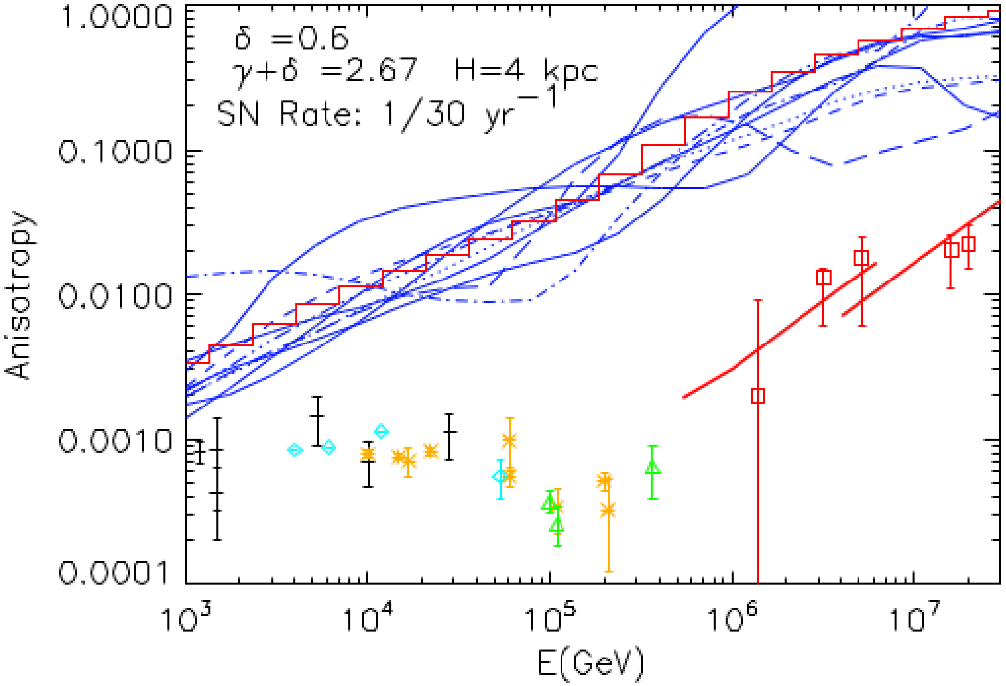
Pasquale Blasi and Elena Amato

INAF/Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5 - 50125 Firenze, ITALY

E-mail: blasi@arcetri.astro.it, amato@arcetri.astro.it

JCAP **01**, 011 (2012)



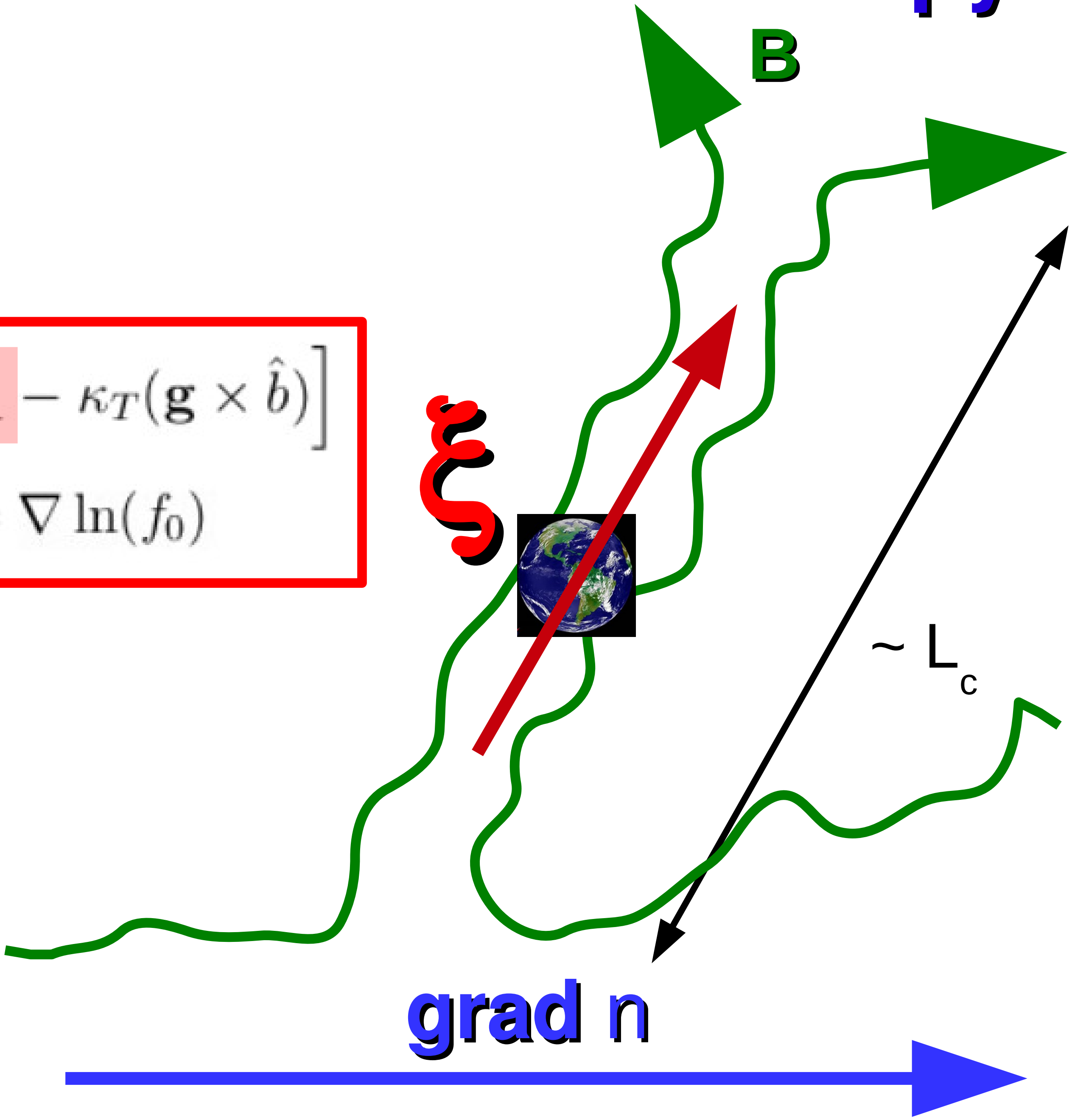


V. Zirakashvili : D smaller locally ? → Local bubble ?

Local MF lines and L-S CR Anisotropy

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

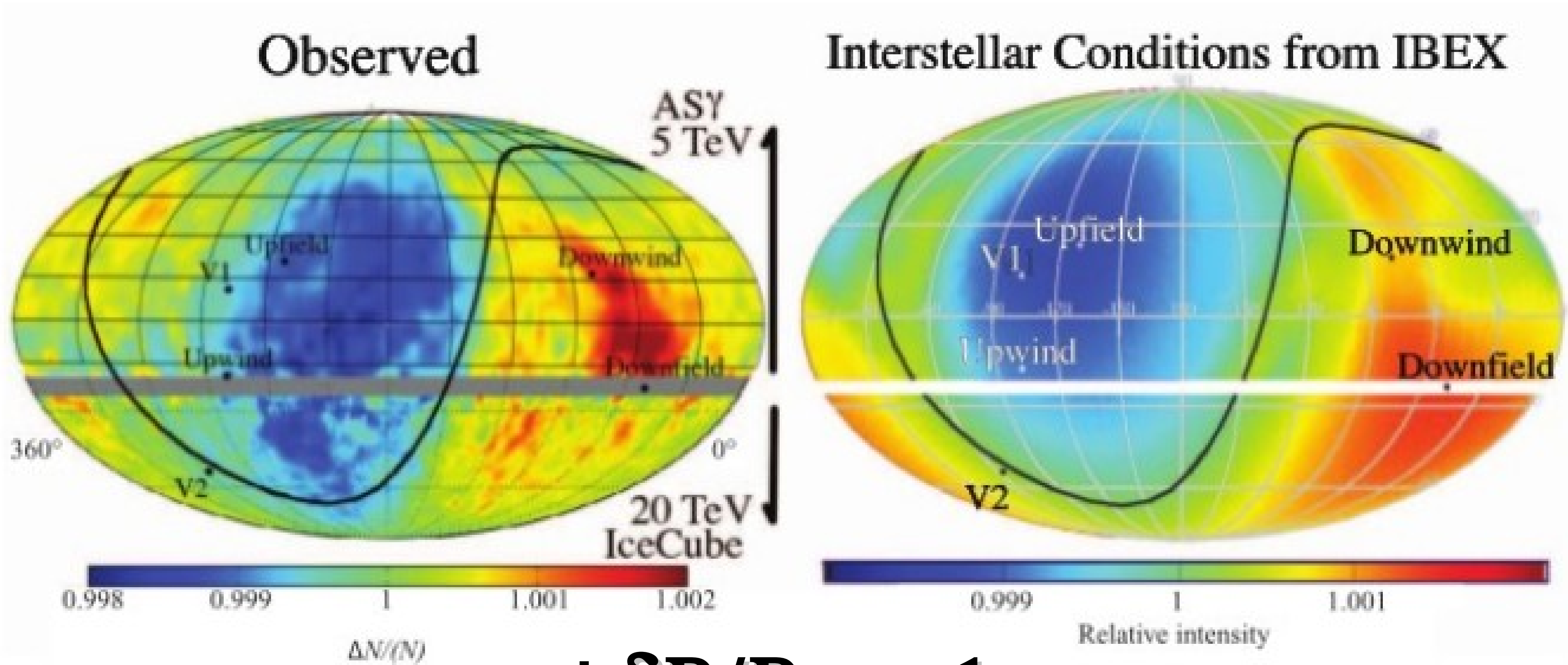
$$\mathbf{g} = \nabla\ln(f_0)$$



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);

Frisch et al. 2012
→ local field

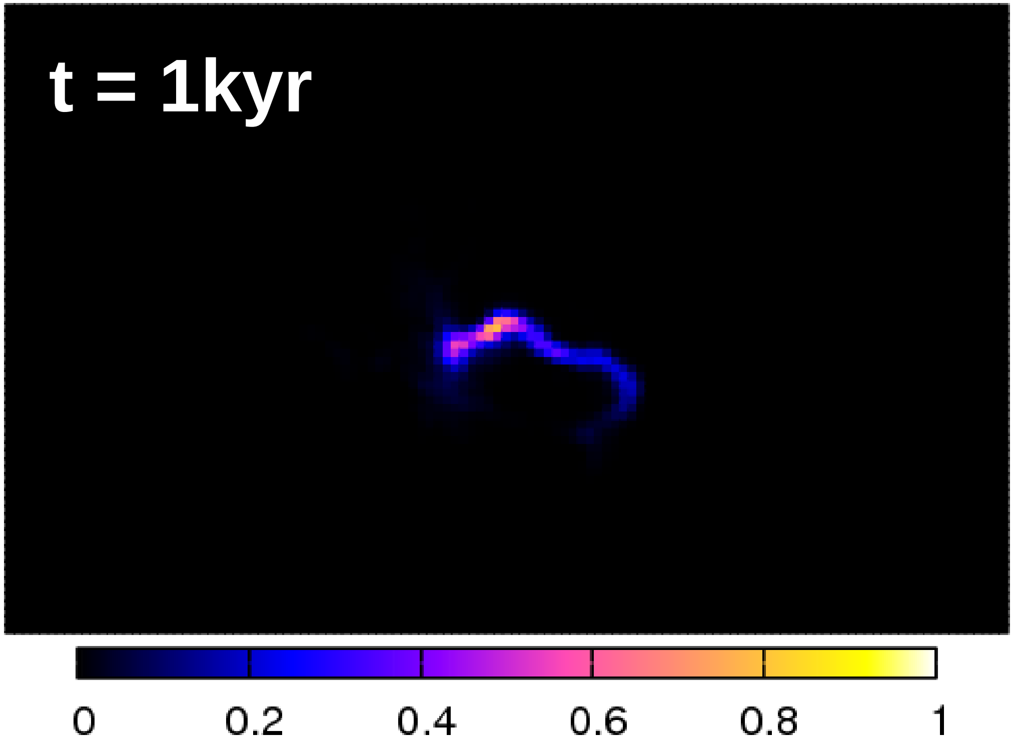


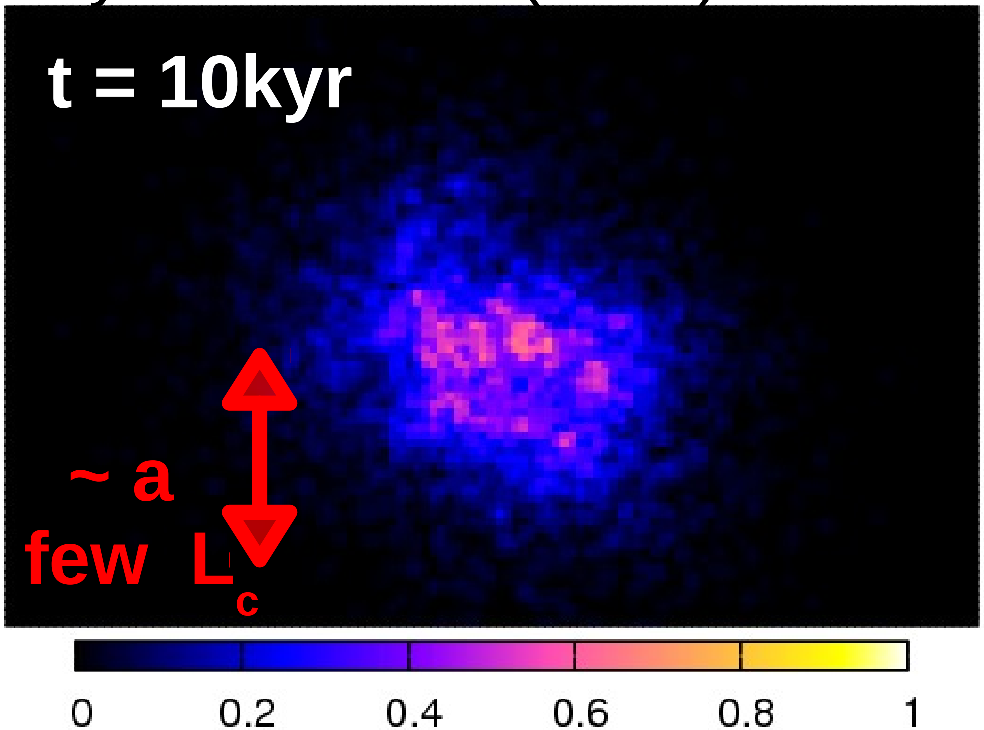
... and $\delta B/B_0 << 1$

Anisotropic diff. in *isotropic* turbulence

$r_L \ll$ m.f.p. $\ll L_c < L_{max}$

Giacinti, Kachelriess & Semikoz, Phys. Rev. Lett. (2012)
Phys. Rev. D (2013) :

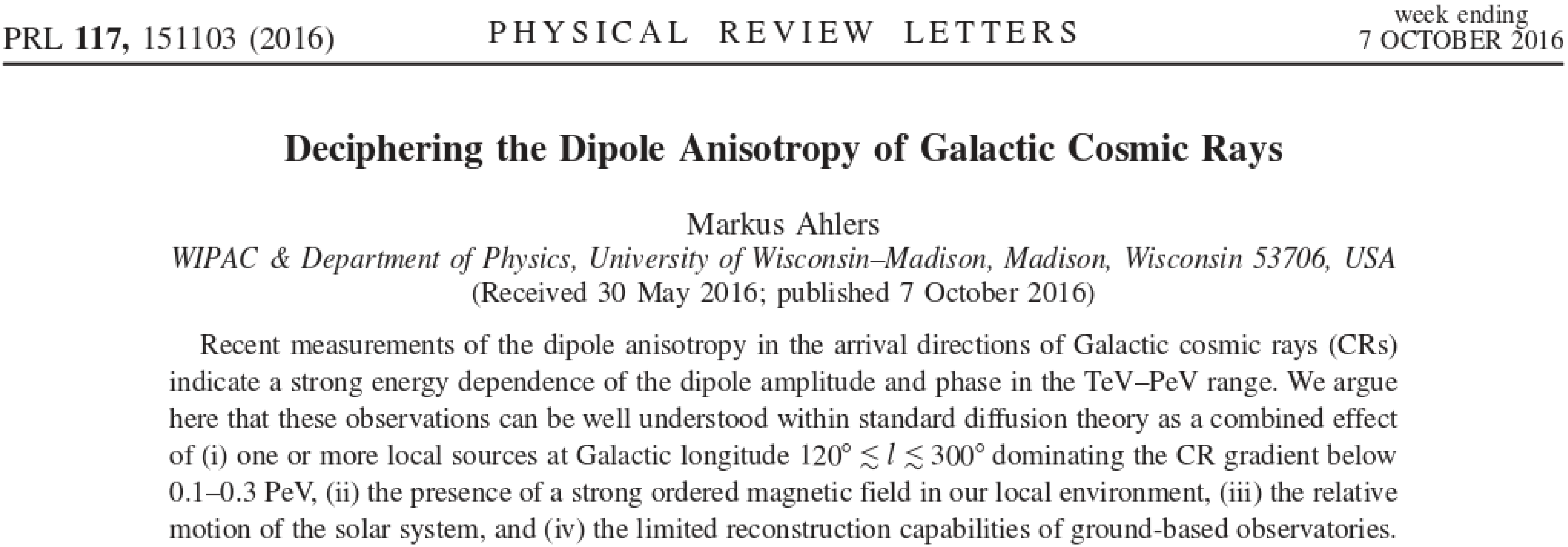




E/Z=1PeV, Kolmogorov spectrum,
L_{max}=150pc, box size : 400pc

... then starts to tend towards the $r \propto t^{1/2}$ behaviour

Modeling of Amplitude + Direction



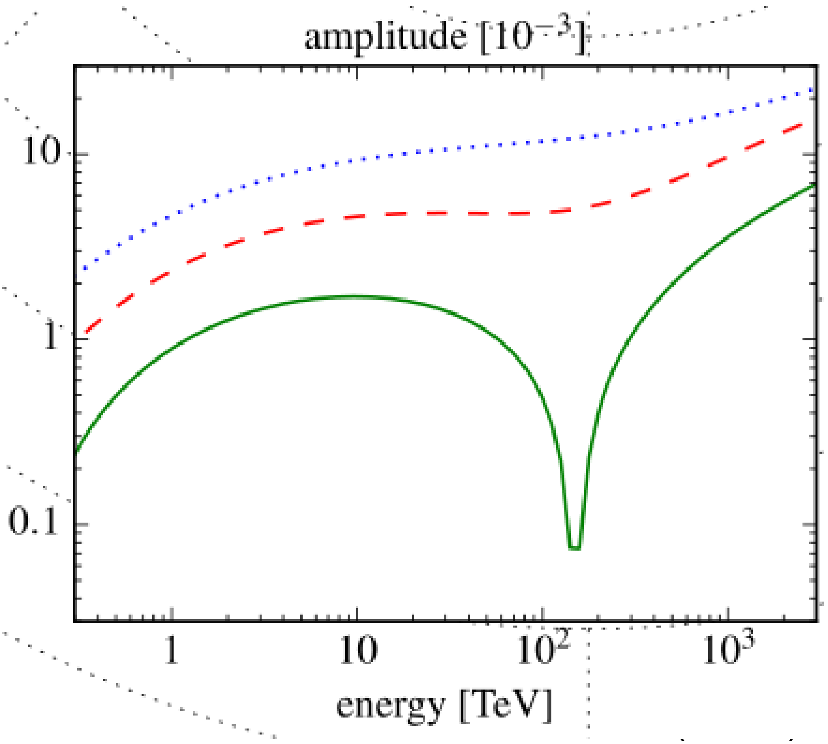
PRL **117,** 151103 (2016) PHYSICAL REVIEW LETTERS week ending
7 OCTOBER 2016

Deciphering the Dipole Anisotropy of Galactic Cosmic Rays

Markus Ahlers
WIPAC & Department of Physics, University of Wisconsin–Madison, Madison, Wisconsin 53706, USA

(Received 30 May 2016; published 7 October 2016)

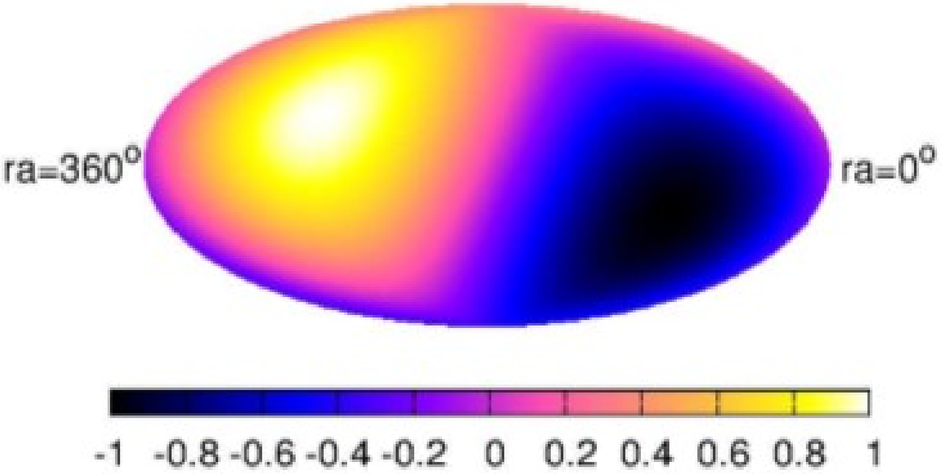
Recent measurements of the dipole anisotropy in the arrival directions of Galactic cosmic rays (CRs) indicate a strong energy dependence of the dipole amplitude and phase in the TeV–PeV range. We argue here that these observations can be well understood within standard diffusion theory as a combined effect of (i) one or more local sources at Galactic longitude $120° \lesssim l \lesssim 300°$ dominating the CR gradient below 0.1–0.3 PeV, (ii) the presence of a strong ordered magnetic field in our local environment, (iii) the relative motion of the solar system, and (iv) the limited reconstruction capabilities of ground-based observatories. We show that an excellent candidate of the local CR source respon
1–100 TeV is the Vela supernova remnant.

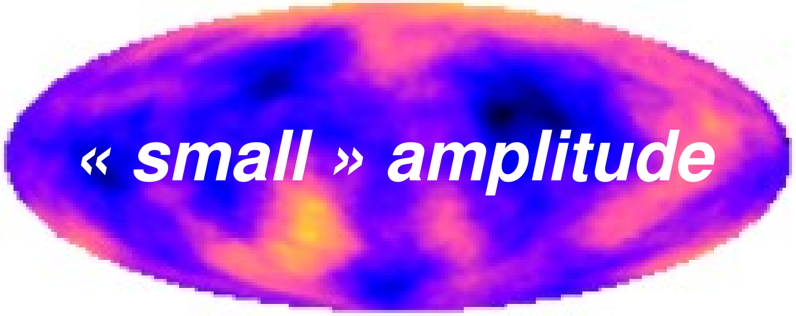


M. Ahlers (2016) : 1–100 TeV
anisotropy may be due to Vela.

Cosmic-Ray Anisotropy

large-scale + **small-scales**





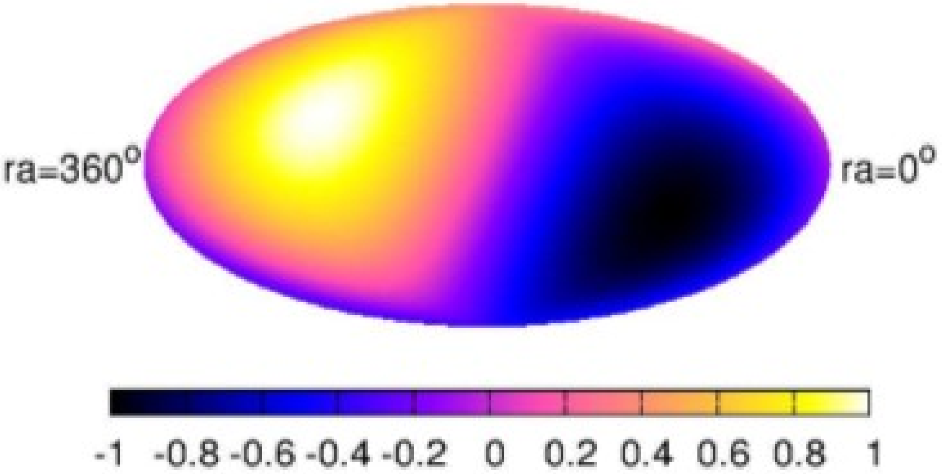
- → <u>Amplitude</u>
- → <u>Direction</u>

- → **<u>Shape</u> (… Dipole ?)**

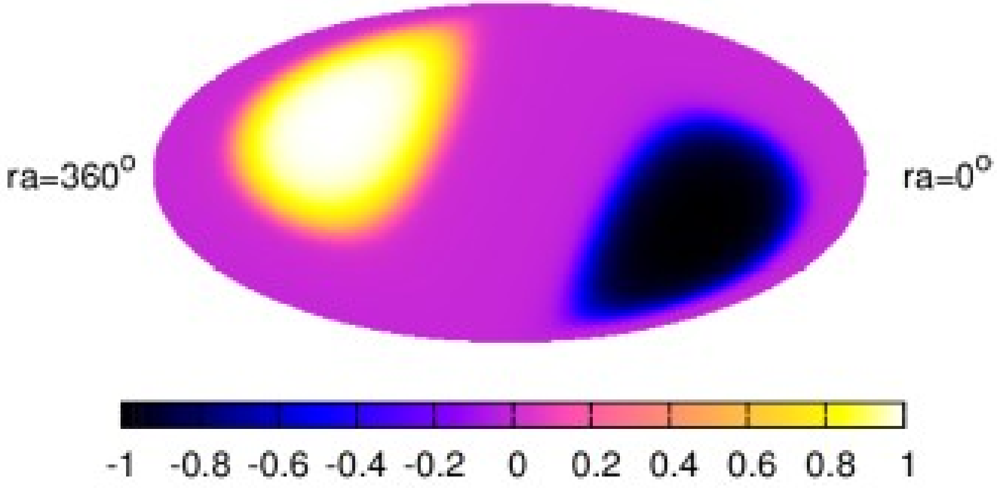
(See end of the talk)

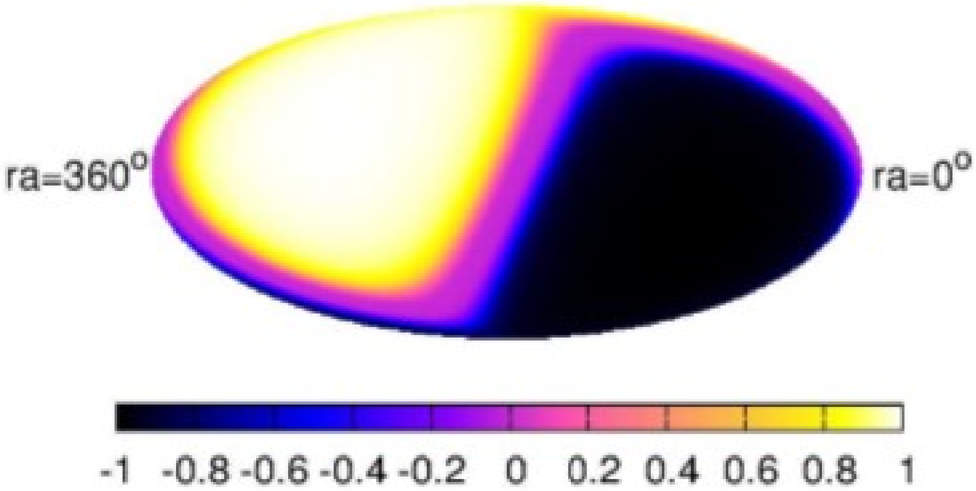
Cosmic-Ray Anisotropy

Dipole only



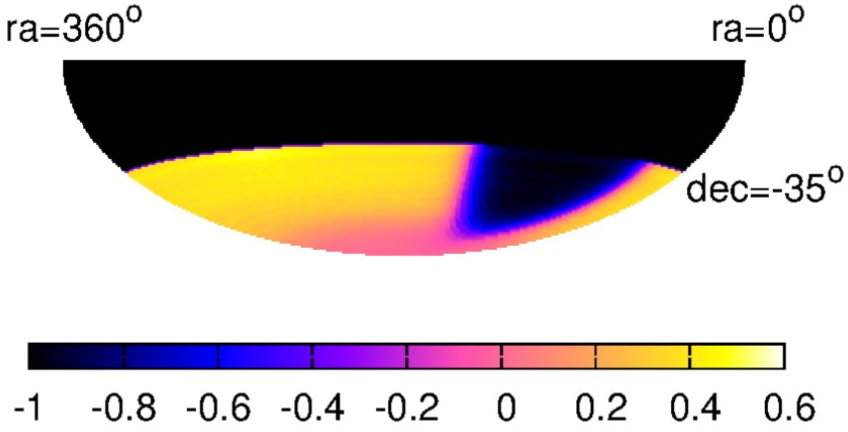
Or could the L-S CR anisotropy look like this ? :



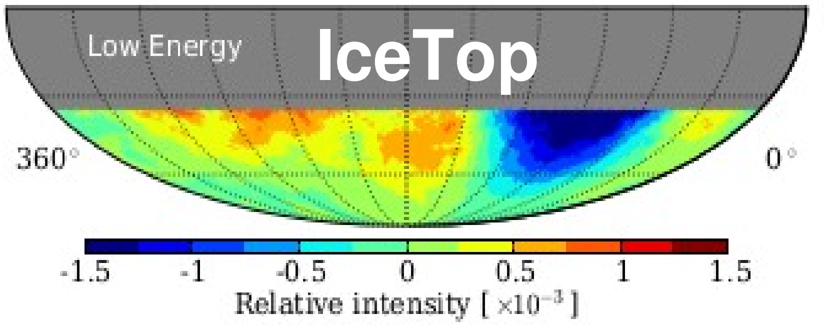


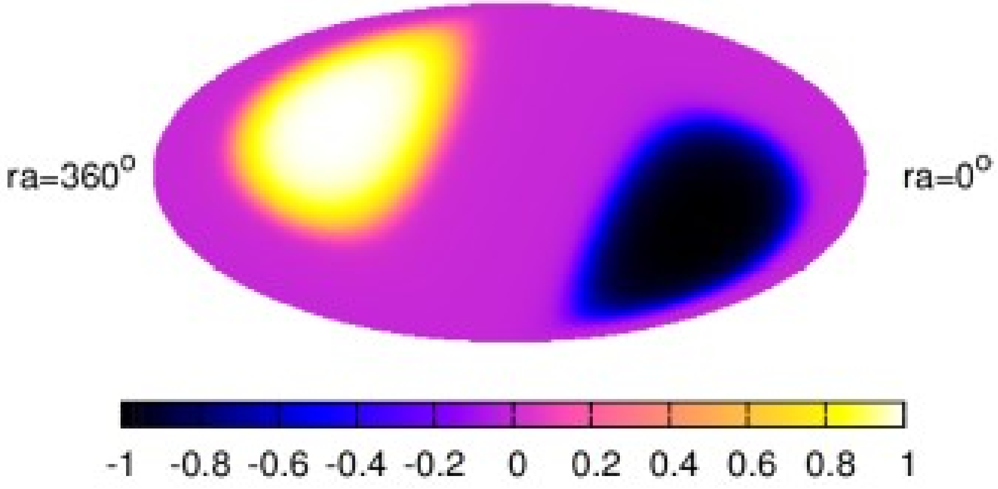
Not a (perfect) dipole, even if turbulence is *isotropic* !

Cosmic-Ray Anisotropy



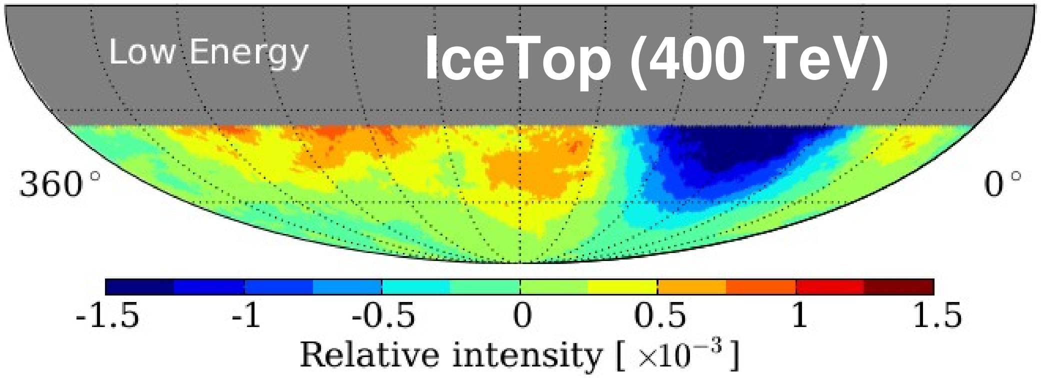
vs



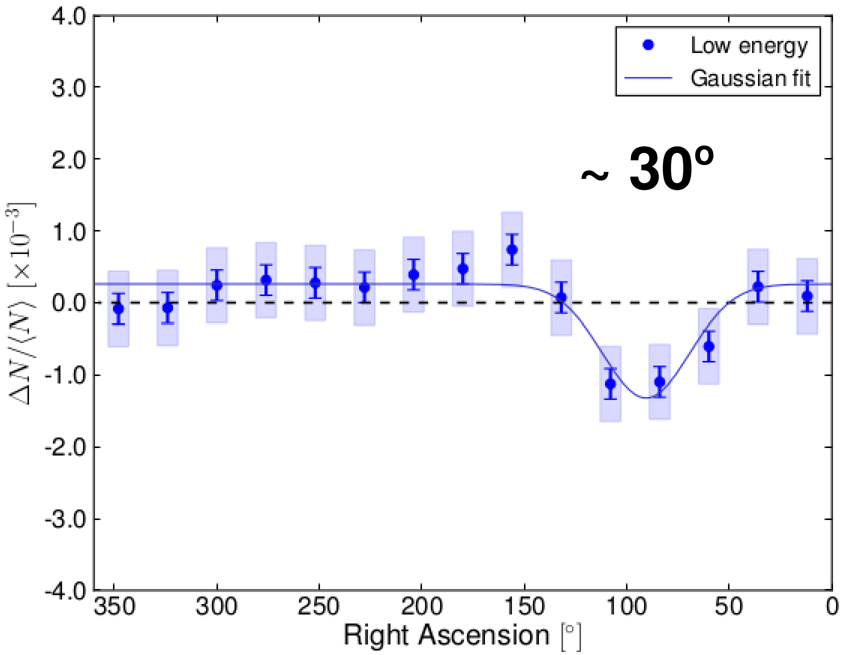


Observations (IceCube, IceTop)

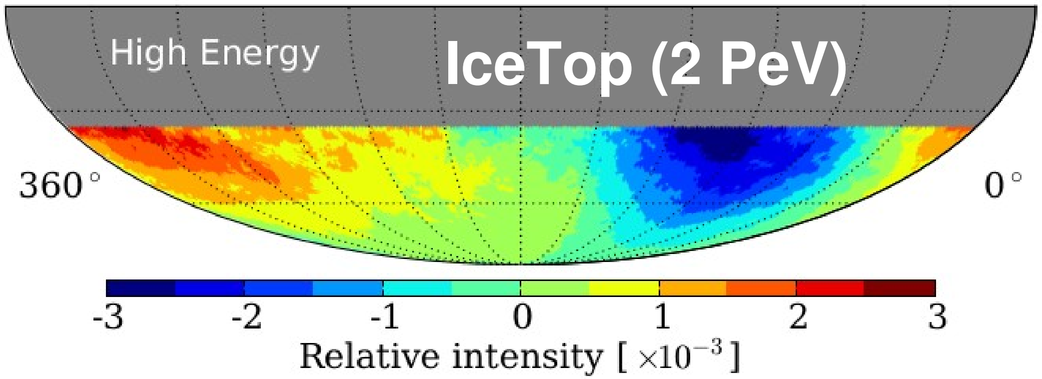
Aartsen et al. (2013)



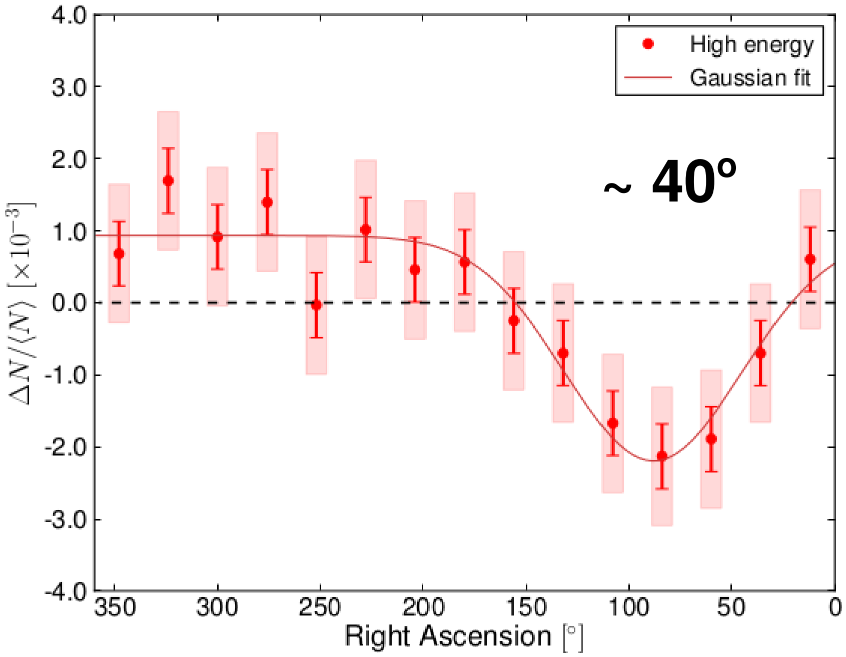
IceTop (400 TeV)



~ 30°



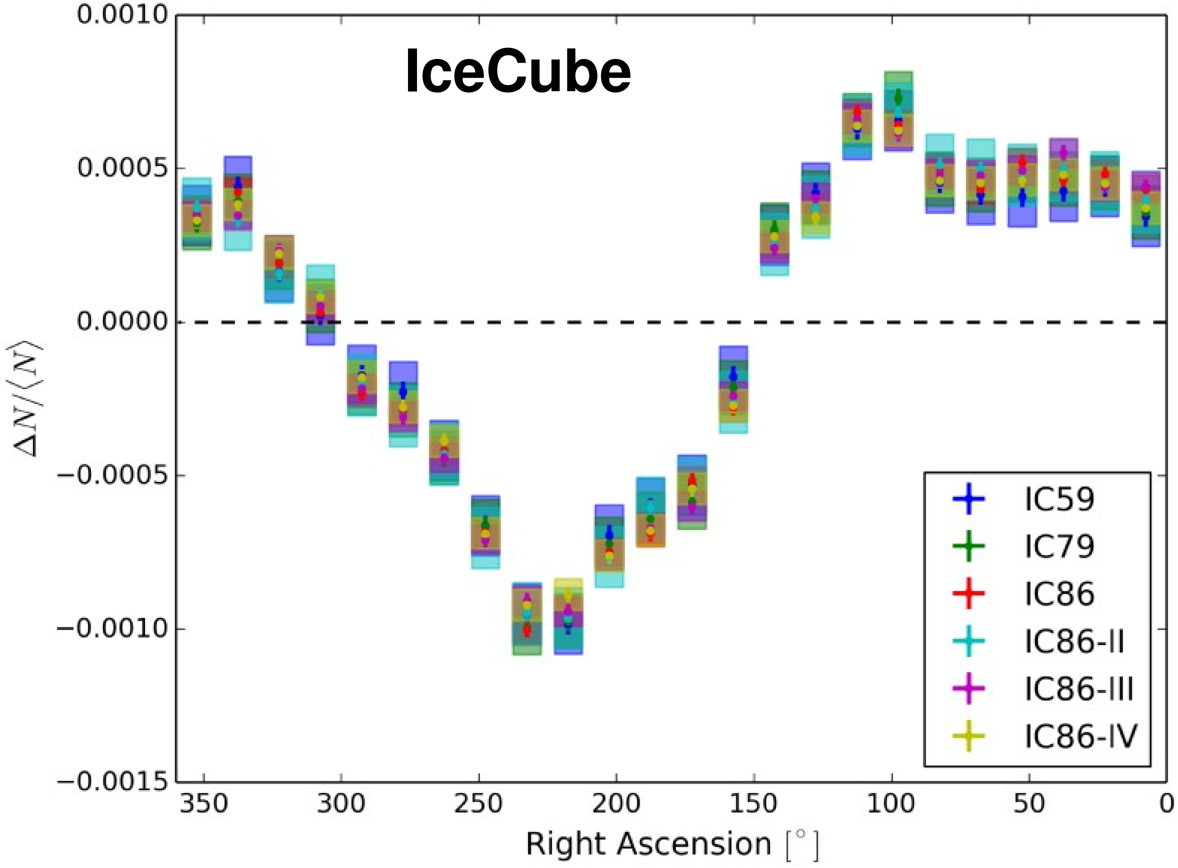
IceTop (2 PeV)

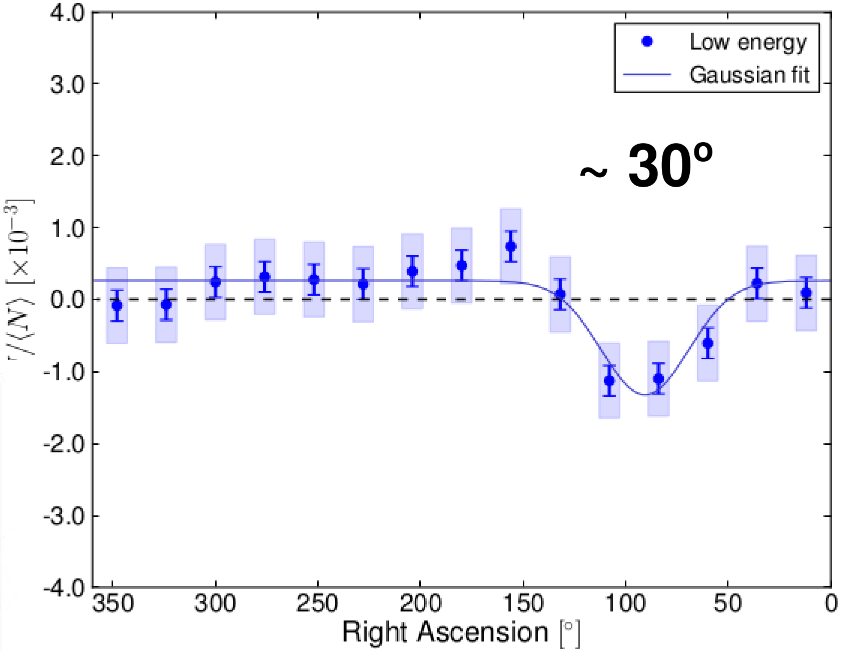


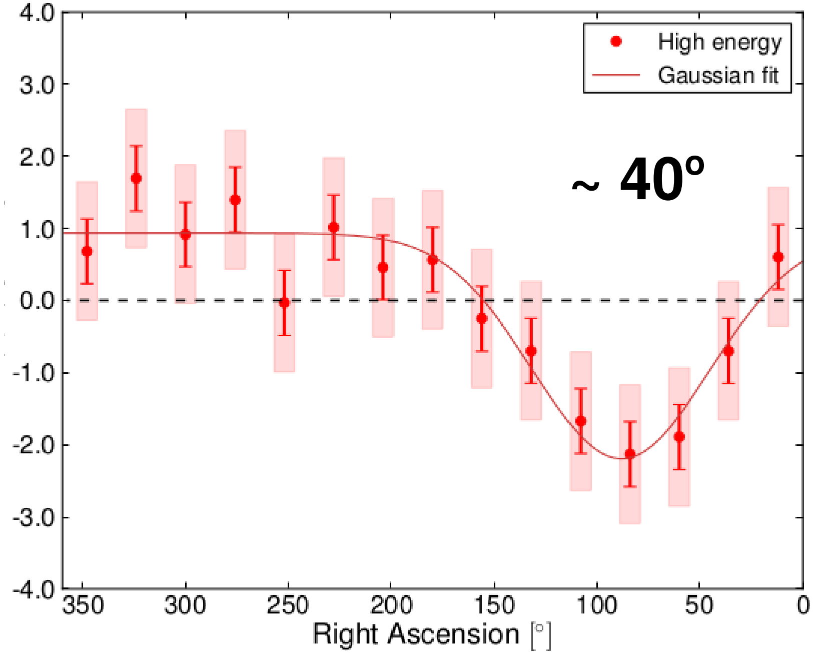
~ 40°

Observations (IceCube, IceTop)

Aartsen et al. (2016)

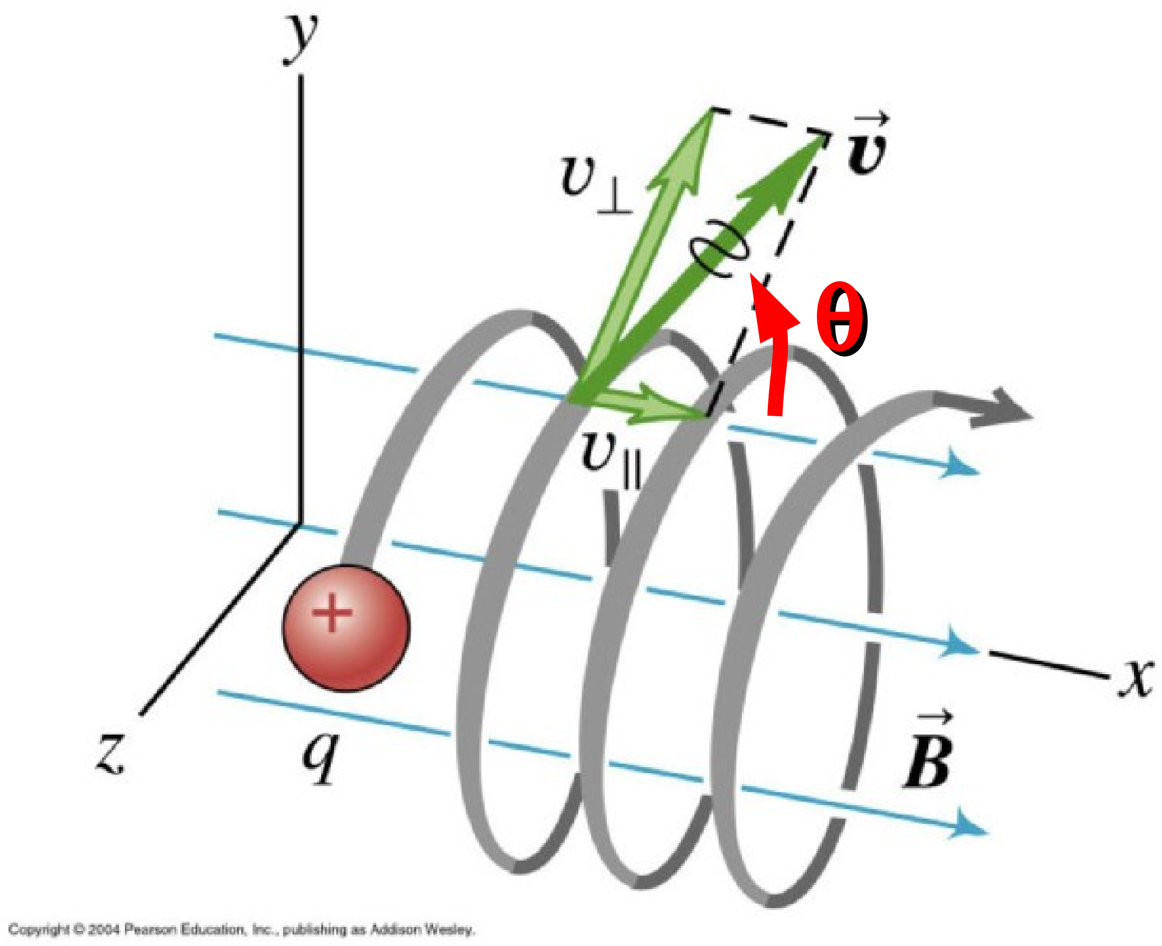






CR trajectories

$\delta B = 0$



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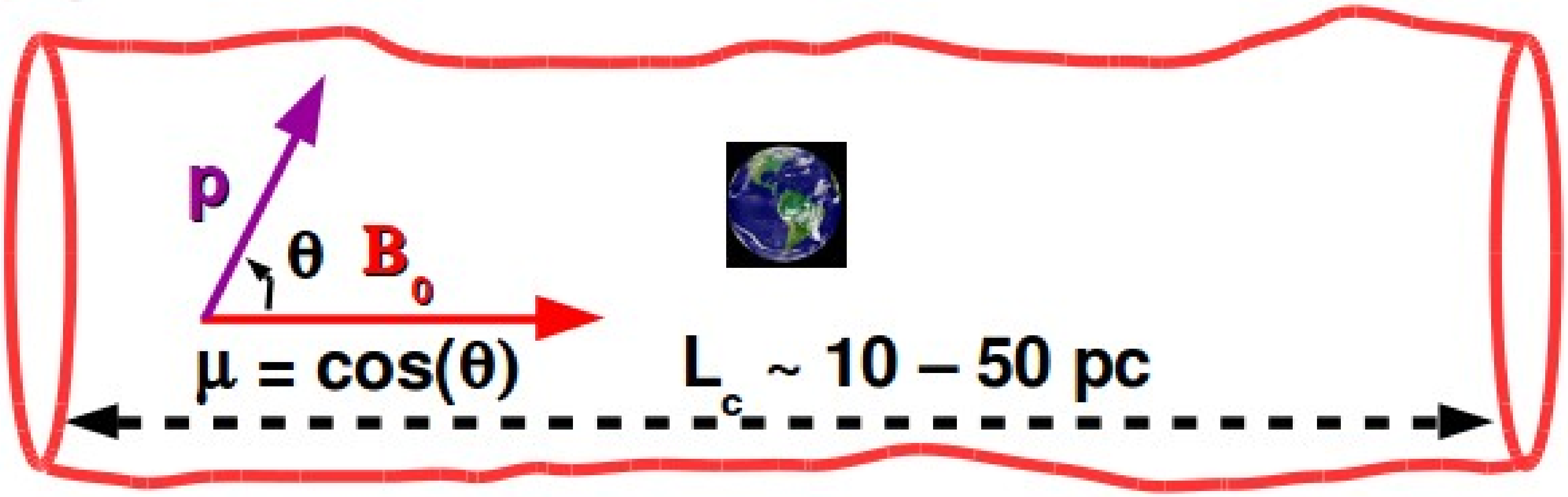
$\delta B / B_0 << 1$

Pitch-angle diffusion

CR Anisotropy : Probe of turbulence



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

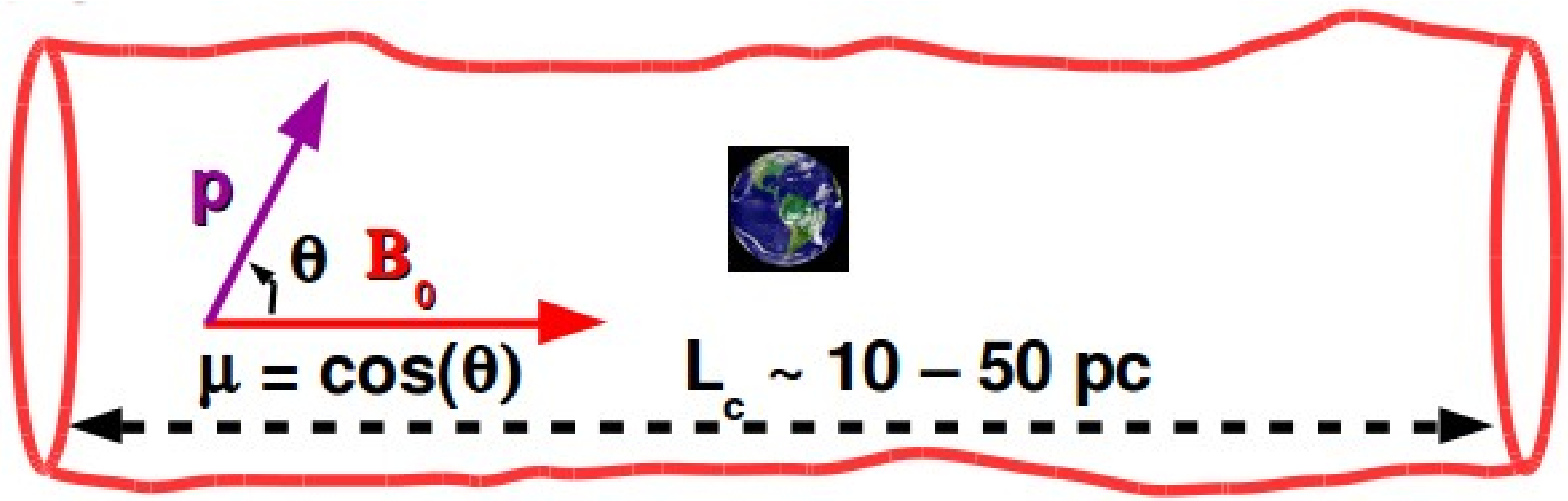
(gyrophase-averaged)

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

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>

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

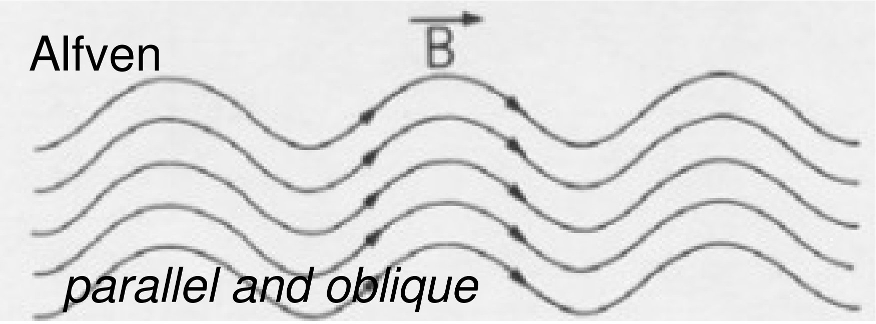
=> $$f(x,\mu) = \cancel{\sum_i a_i e^{\Lambda_i x/v} Q_i(\mu)} + a_{\text{diff}}\left[x + \overset{\alpha}{\boxed{g(\mu)}}\right]$$

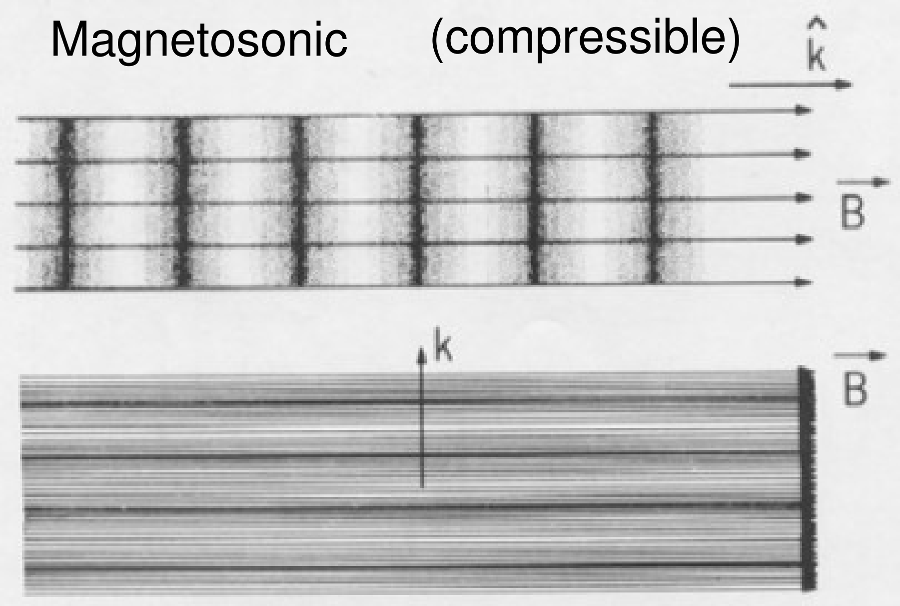
if $\exp\left(-\Lambda_1 d/v\right) \ll 1$

(« boundary layer »)

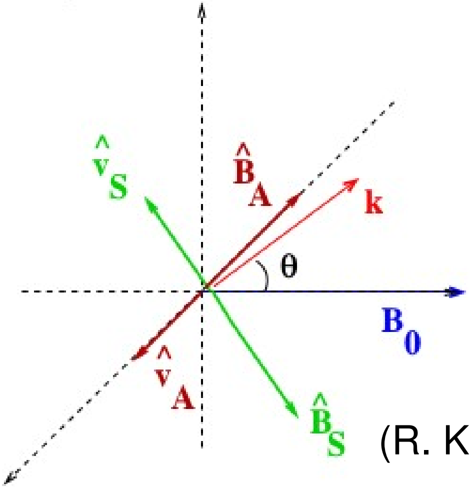
Magnetohydrodynamic waves

Alfven, Slow and Fast modes (compressible)



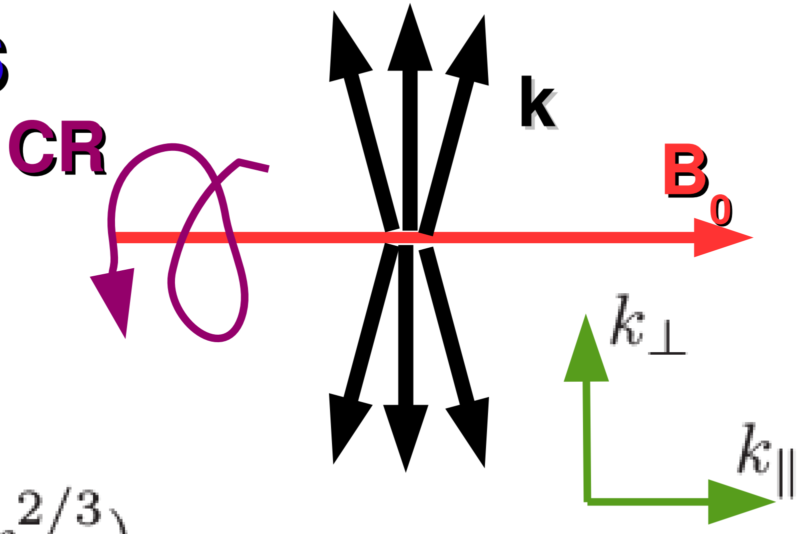


Alfven and pseudo-Alfven modes (incompressible)



(R. Keppens)

Alfven (and Slow) modes



Goldreich & Sridhar (1995)

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

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

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

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

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

Fast magnetosonic modes

MHD simulations of Cho & Lazarian (2002) :

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

Pitch-angle diffusion coefficient

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

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

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:

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

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

=>

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

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

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 »**

$$\underline{R_{\mathrm{n},1}(k_\parallel v_\parallel - \omega + n\Omega)}$$

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

$$= \frac{\tau_\mathrm{w}^{-1}}{(k_\parallel v_\parallel - \omega + n\Omega)^2 + \tau_\mathrm{w}^{-2}}$$

see Chandran (2000)

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

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

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

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

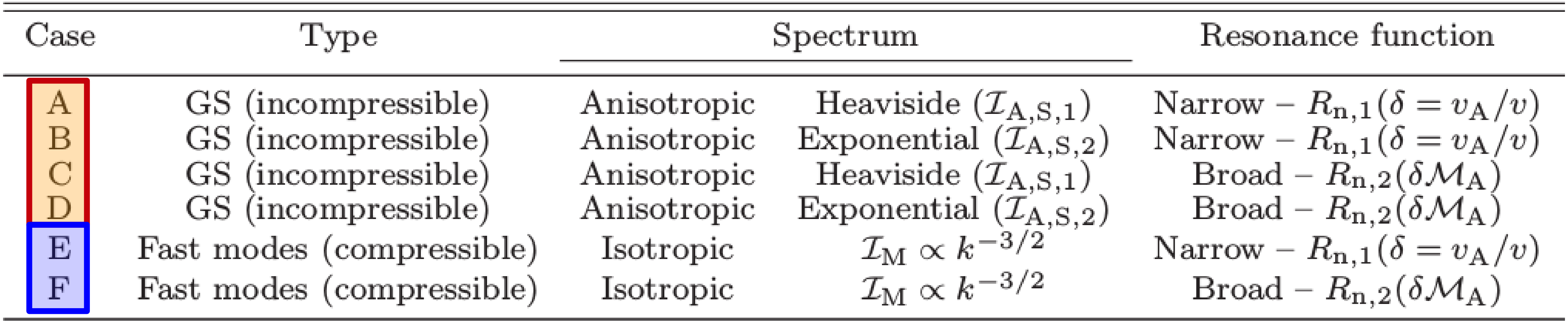
$$\underline{R_{\mathrm{n},2}(k_\parallel v_\parallel - \omega + n\Omega)}$$

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

$$= \frac{\sqrt{\pi}}{k_\parallel v_\perp \delta\mathcal{M}_\mathrm{A}^{1/2}} \exp\left(-\frac{(k_\parallel v_\parallel - \omega + n\Omega)^2}{k_\parallel^2 v_\perp^2 \delta\mathcal{M}_\mathrm{A}}\right)$$

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

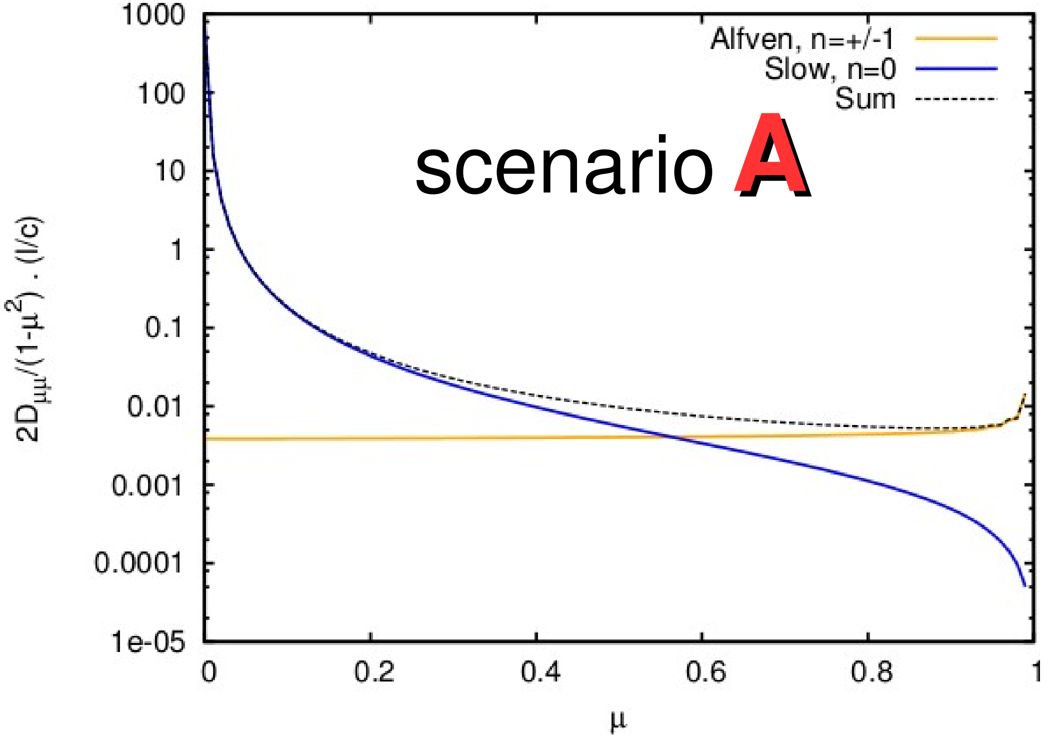
Properties of the 6 turbulence models



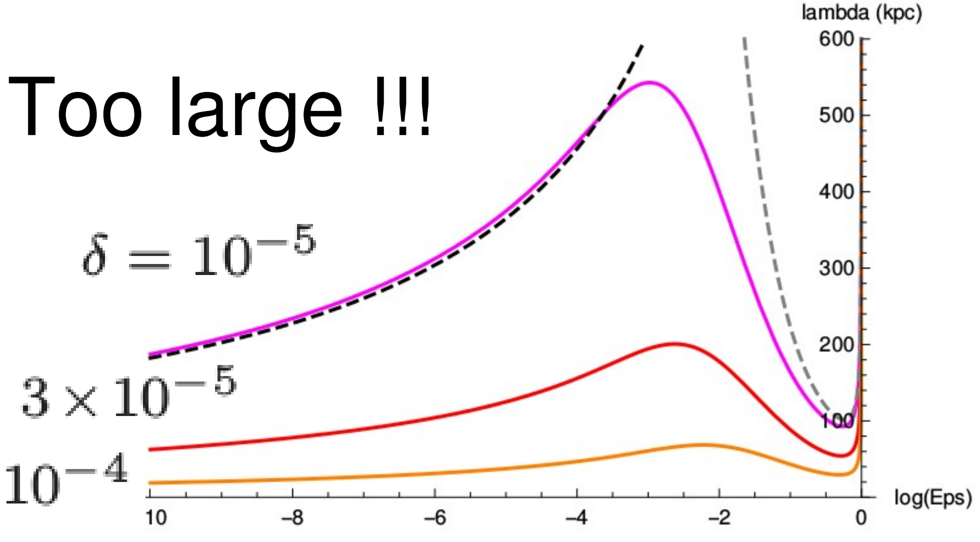
Case	Type	Spectrum		Resonance function
A	GS (incompressible)	Anisotropic	Heaviside ($\mathcal{I}_{\mathrm{A,S},1}$)	Narrow – $R_{\mathrm{n},1}(\delta = v_{\mathrm{A}}/v)$
B	GS (incompressible)	Anisotropic	Exponential ($\mathcal{I}_{\mathrm{A,S},2}$)	Narrow – $R_{\mathrm{n},1}(\delta = v_{\mathrm{A}}/v)$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

GS turbulence and narrow RF (A, B)

$$\lambda_{\parallel} = \frac{3}{v}\kappa_{\parallel} = \frac{3v}{8}\int_{-1}^{1} \mathrm{d}\mu \, \frac{\left(1-\mu^2\right)^2}{D_{\mu\mu}}$$



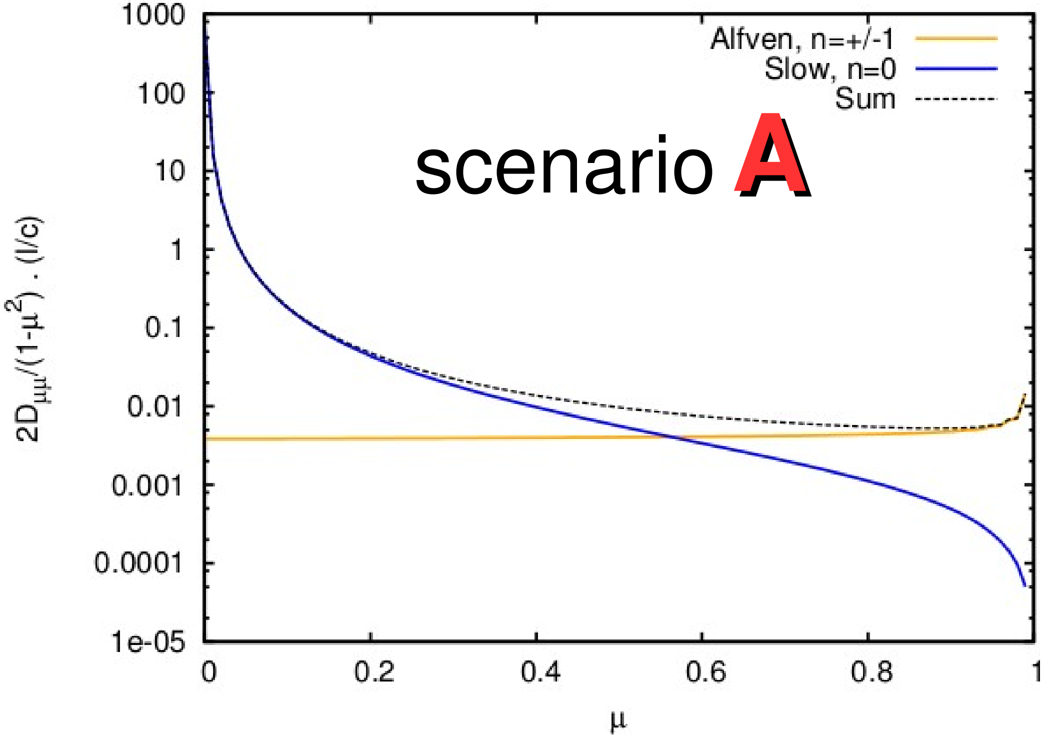
scenario **A**

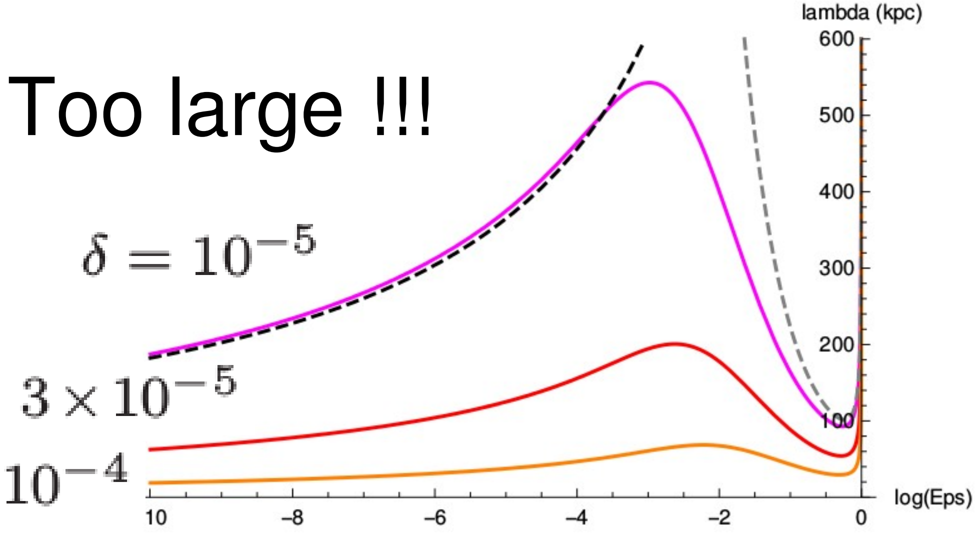


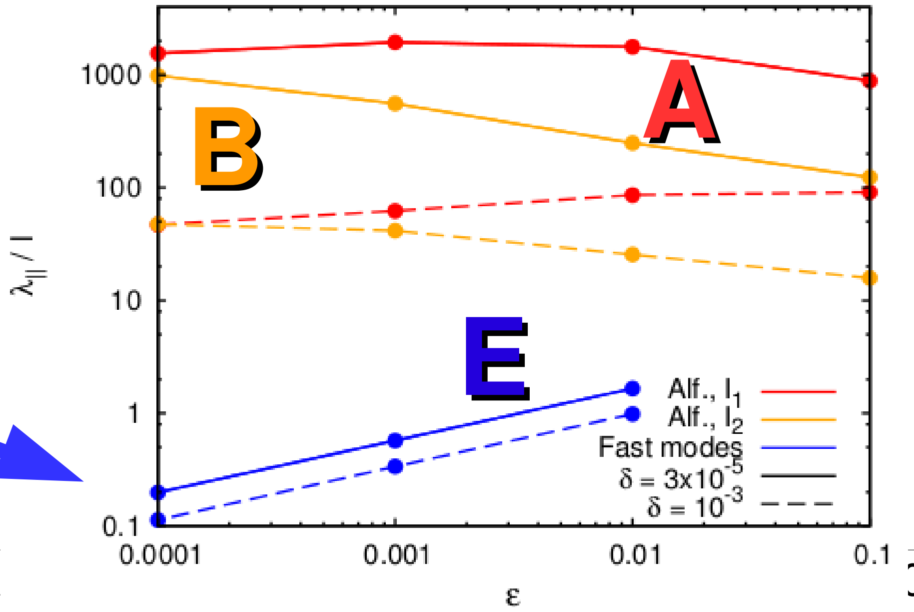
Too large !!!

GS turbulence and narrow RF (A, B)

$$\lambda_\parallel = \frac{3}{v}\kappa_\parallel = \frac{3v}{8}\int_{-1}^{1} \mathrm{d}\mu \, \frac{\left(1-\mu^2\right)^2}{D_{\mu\mu}}$$

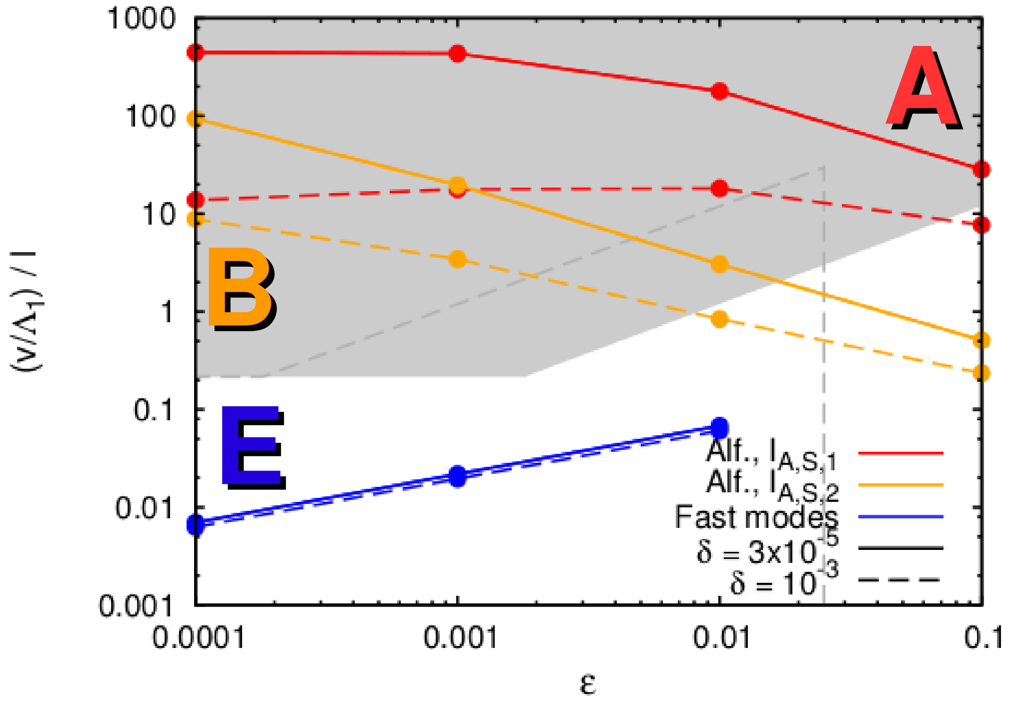


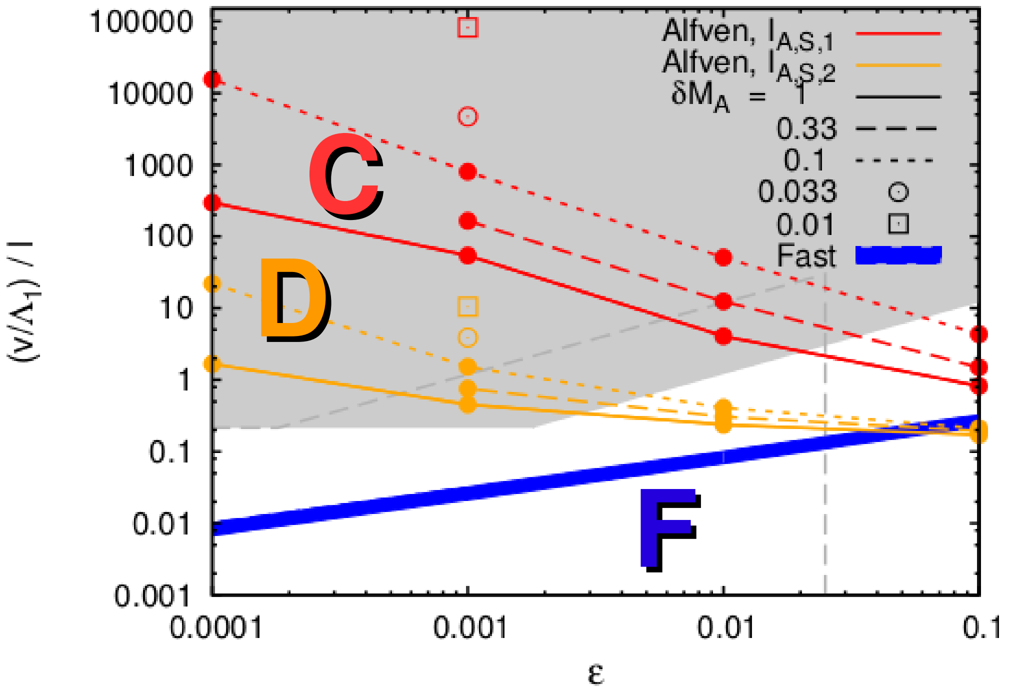

Too large !!!



If present, iso. fast modes dominate CR scattering (→ Lazarian et al.)
… at least, in most cases.

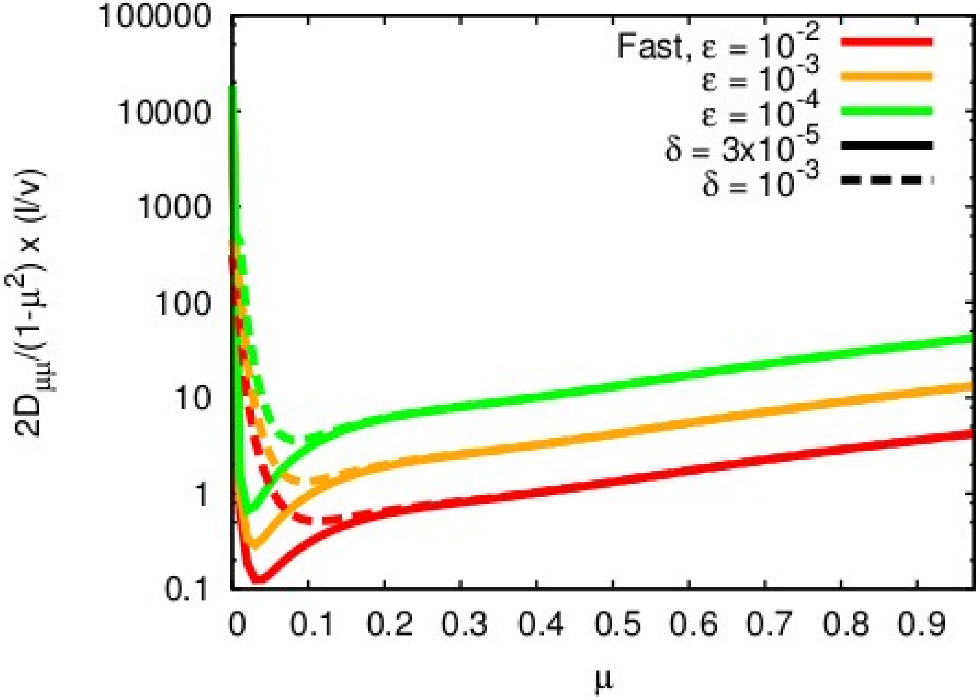
First Eigenvalue and « Boundary layer »

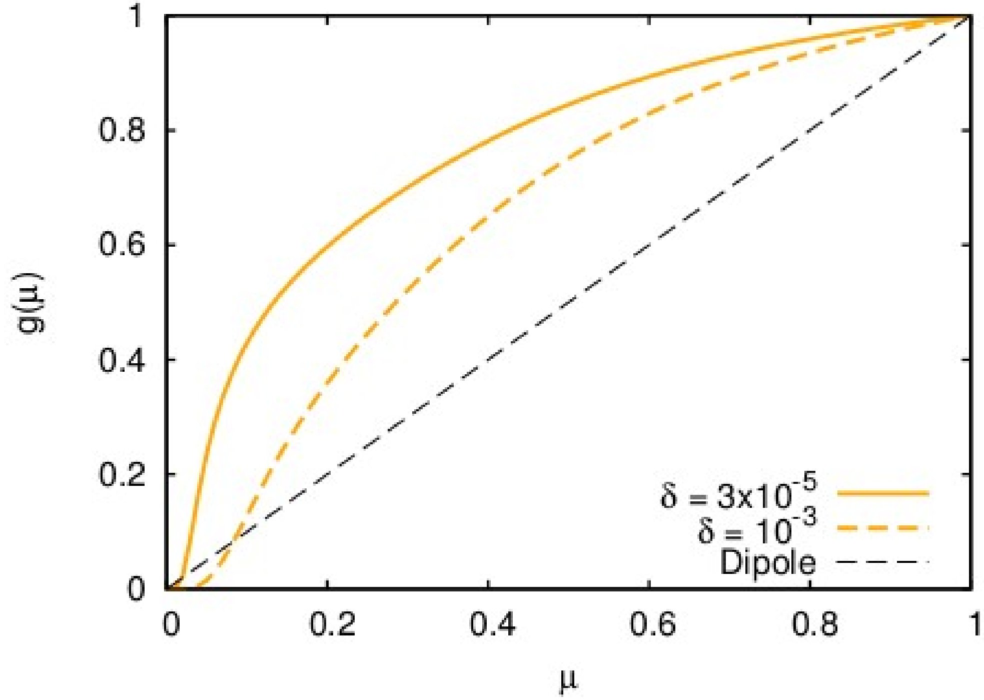


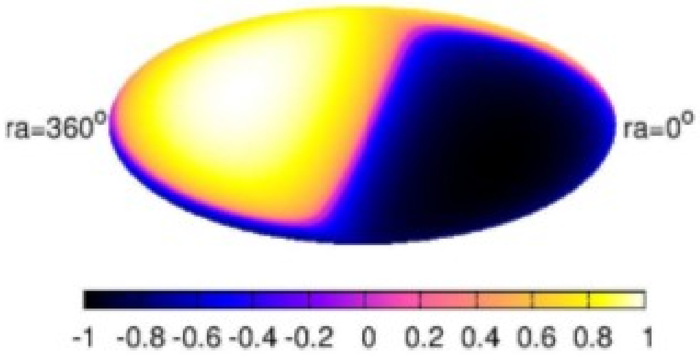


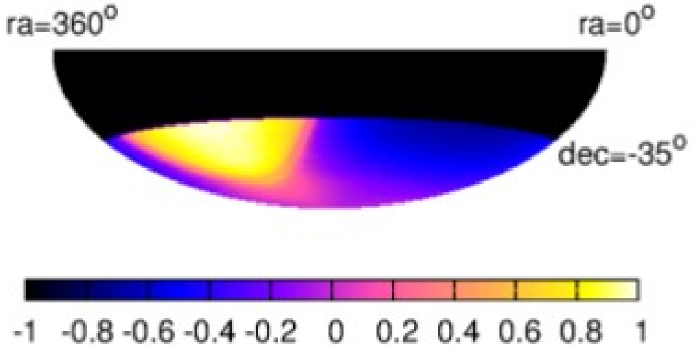
Case E : Fast modes ('Narrow')

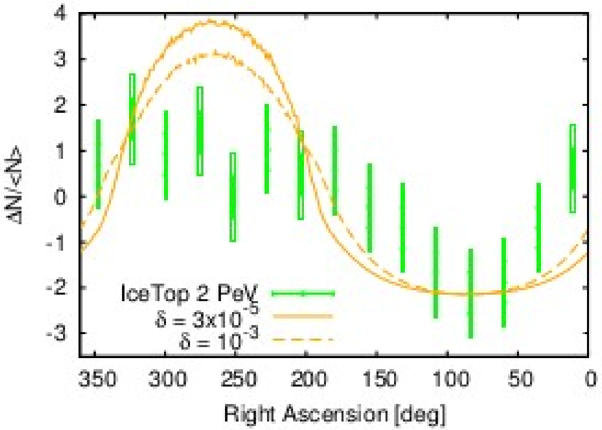
No visible dependence of the *shape* on CR energy







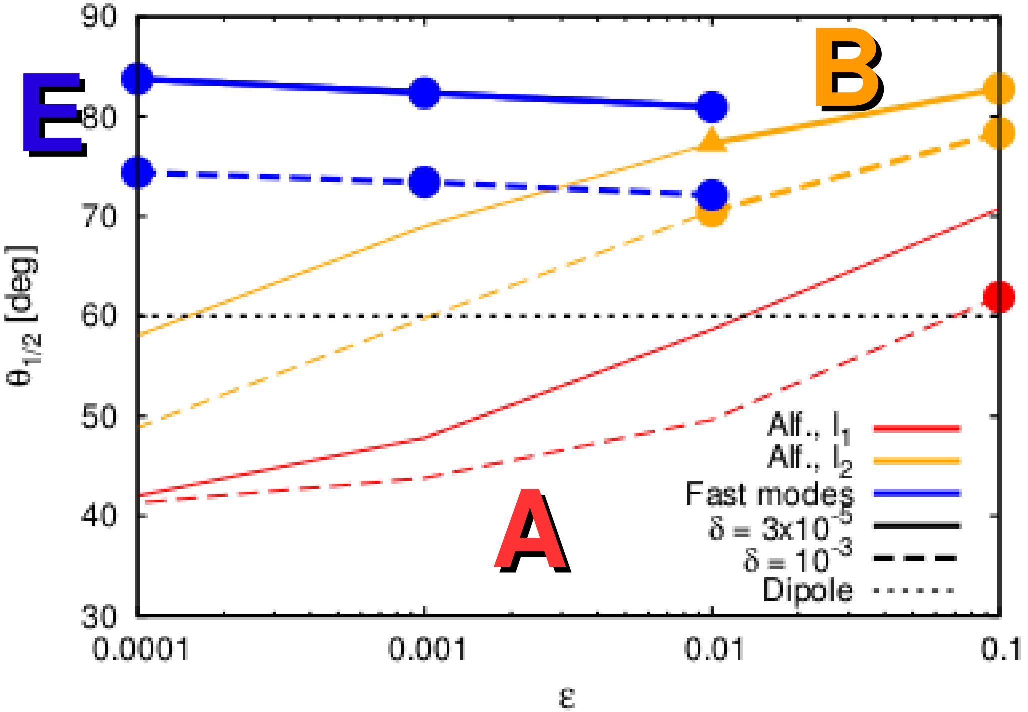




RULED OUT !

Half-width of the anisotropy

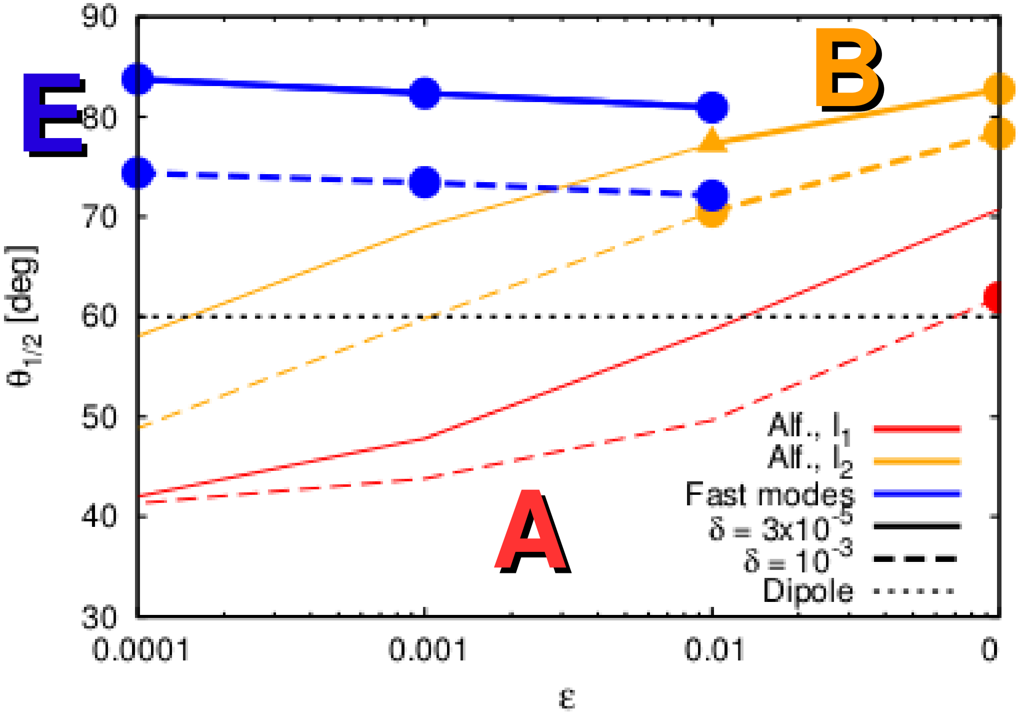
$$g\left(\cos\vartheta_{1/2}\right) = \frac{1}{2}$$

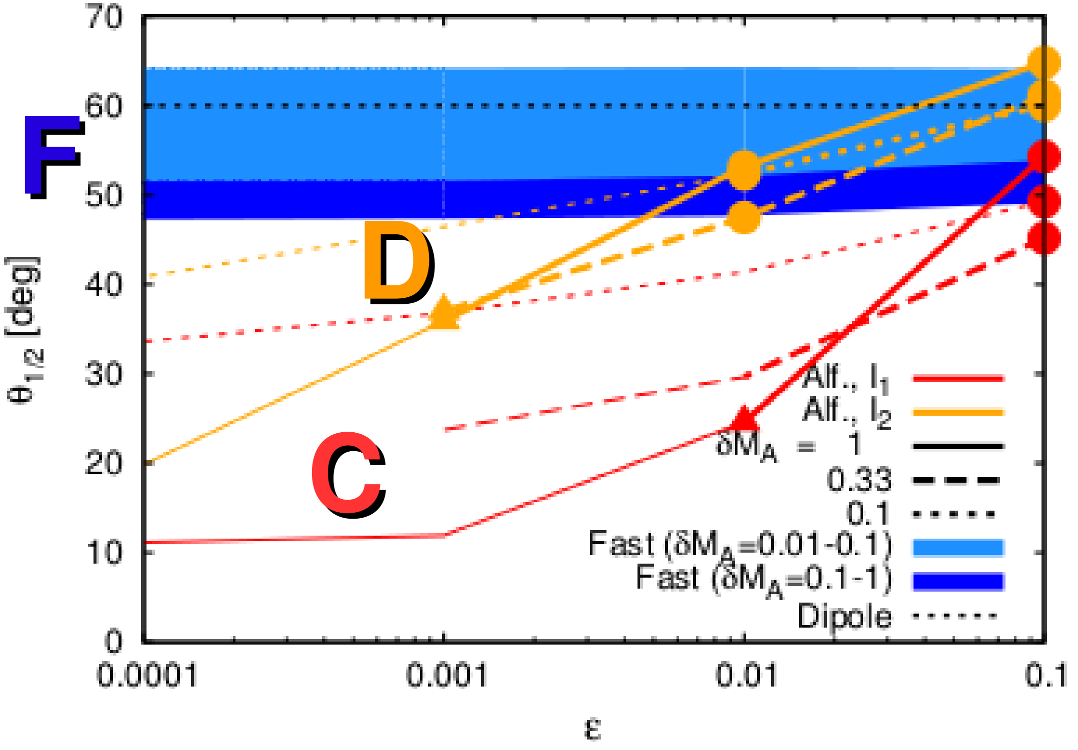


Within the allowed parameter-space, the **anisotropy is too wide with the narrow RF**.

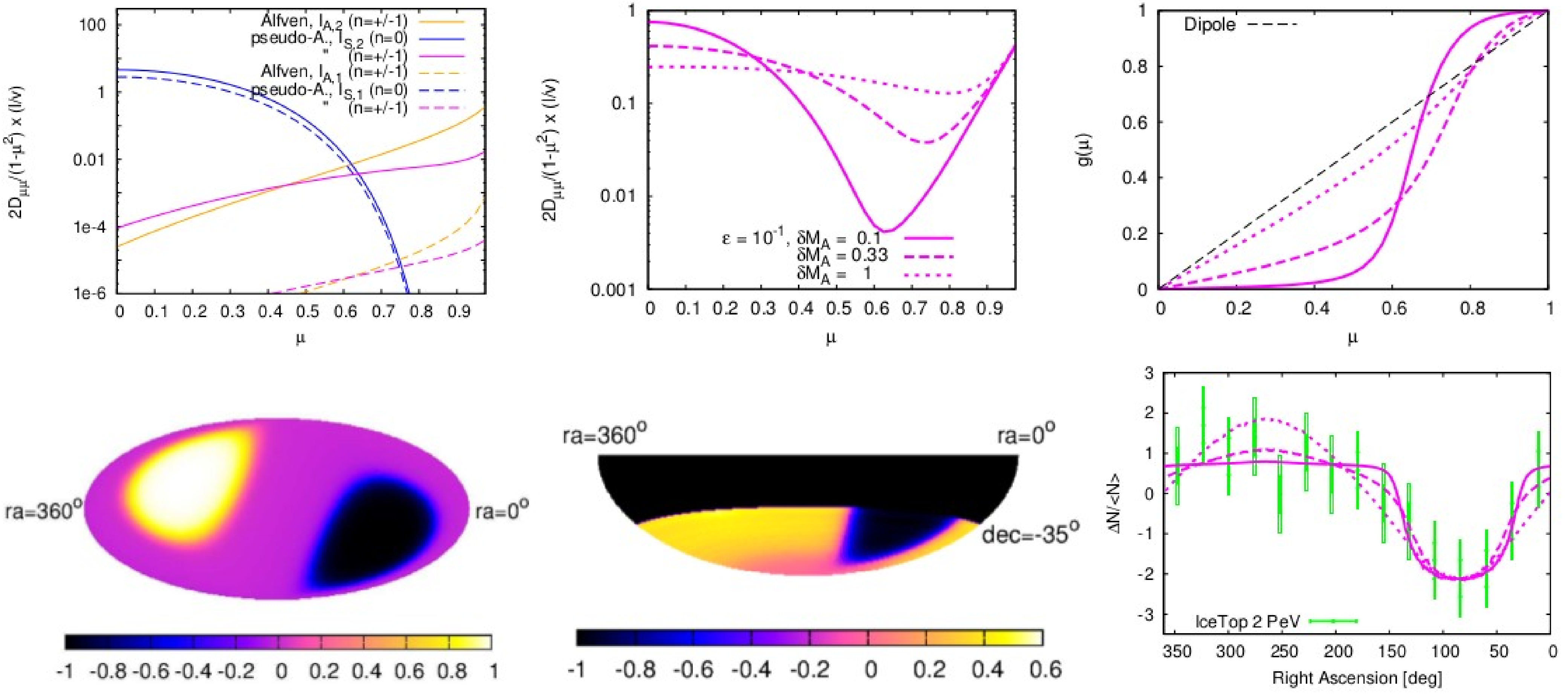
Half-width of the anisotropy

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

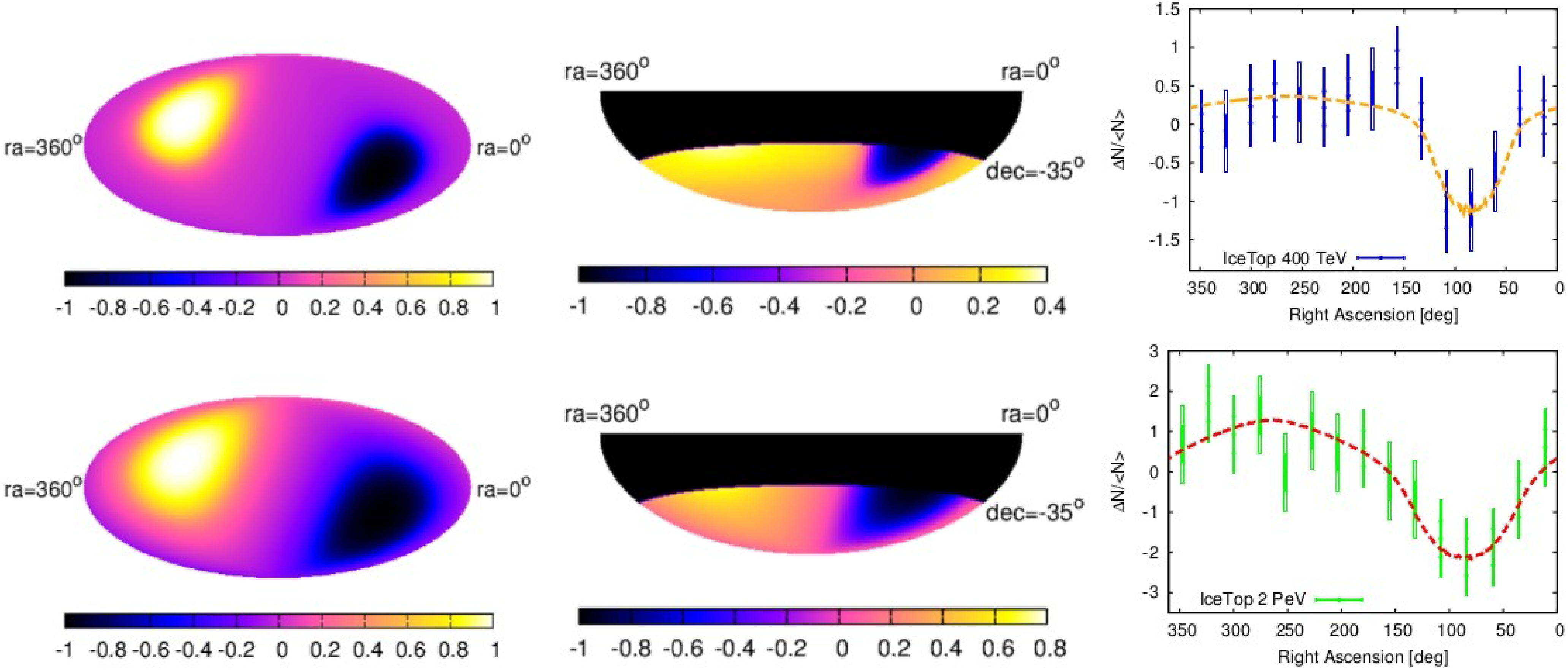




Case C : GS ('Heaviside, Broad')



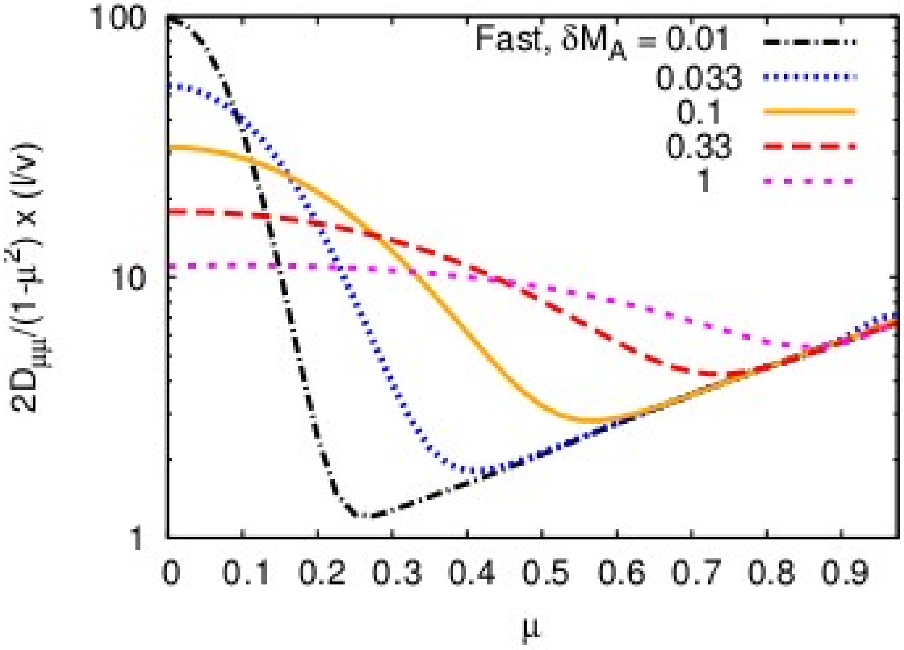
Case D : GS ('Exponential, Broad')

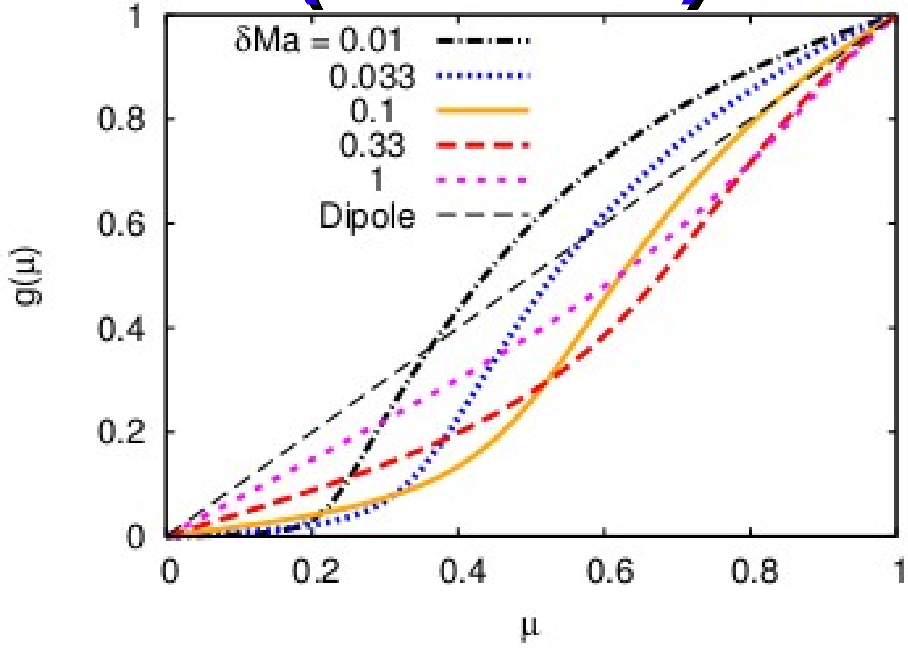


Can fit well the 400 TeV and the 2 PeV data !

Energy-dependence reproduced for fixed turbulence parameters

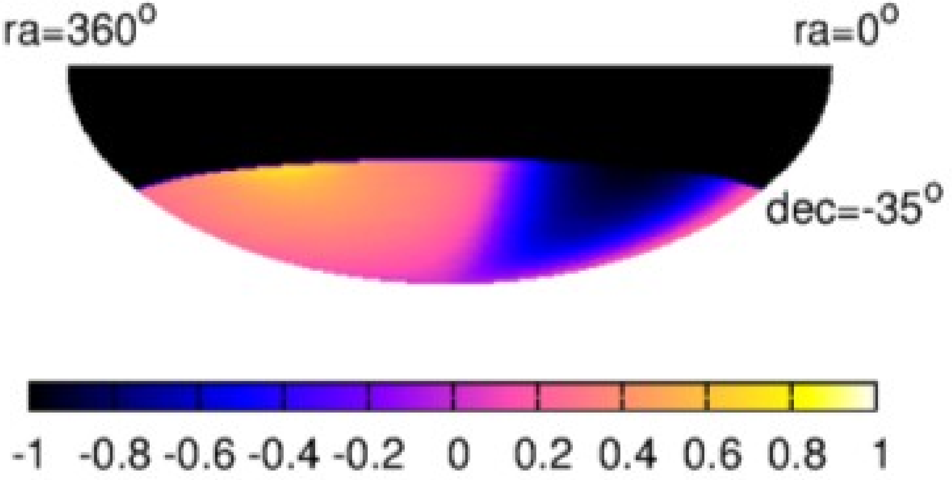
Case F : Fast modes ('Broad')

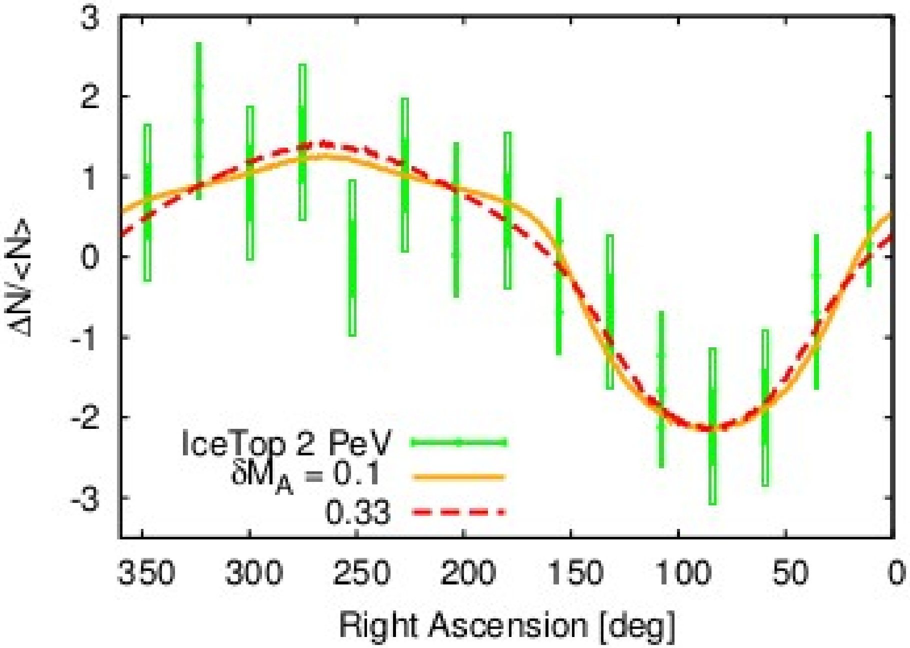




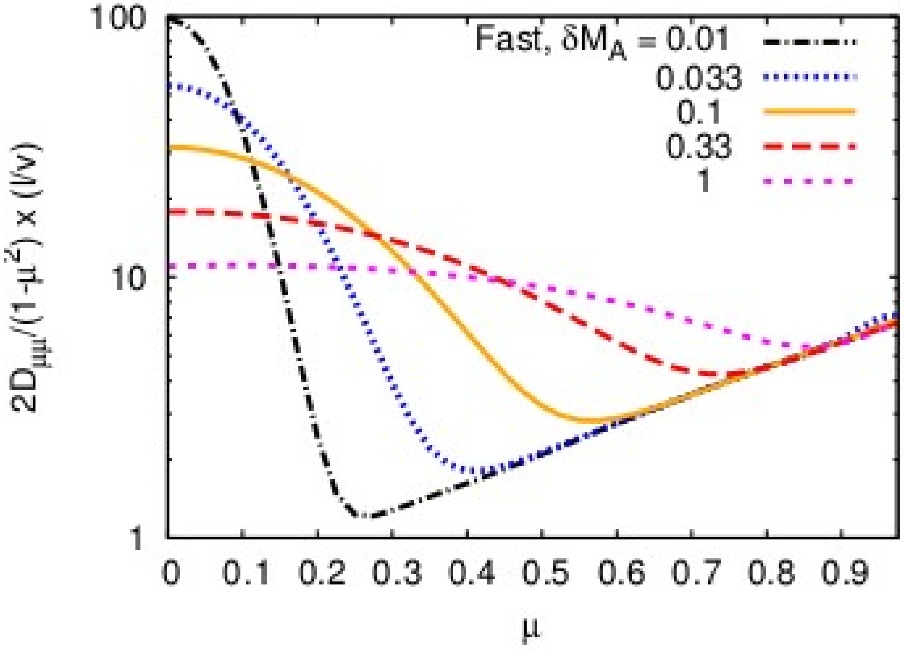
No dependence of the *shape* on E

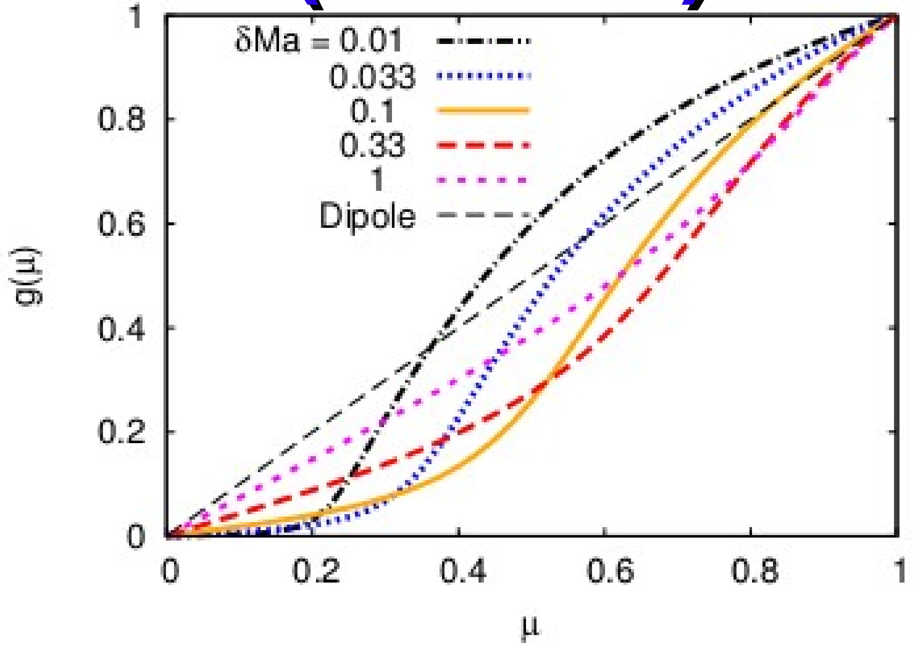
Can fit well the 2 PeV data !



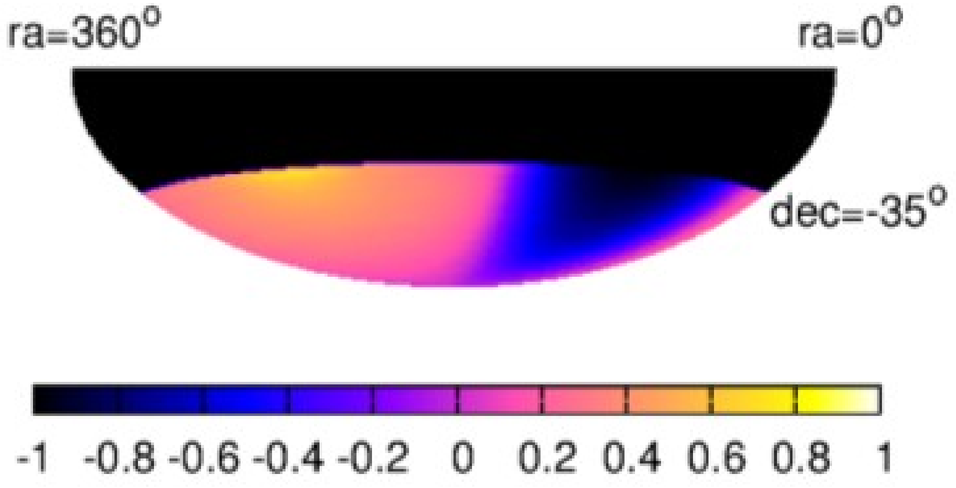


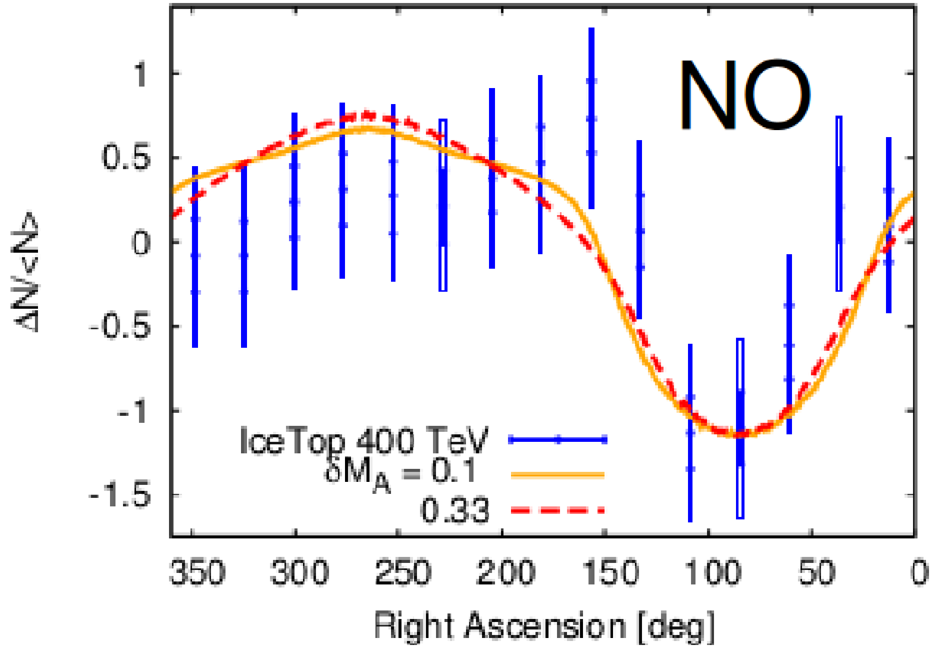
Case F : Fast modes ('Broad')





No dependence of the *shape* on E
Can fit well the 2 PeV data !





L-S CRA: Conclusions and perspectives

---> Explanation for the data

- 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 = NEW PROBE of

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

Probe of turbulence in collisionless magnetized fluids

(2) local CR transport properties

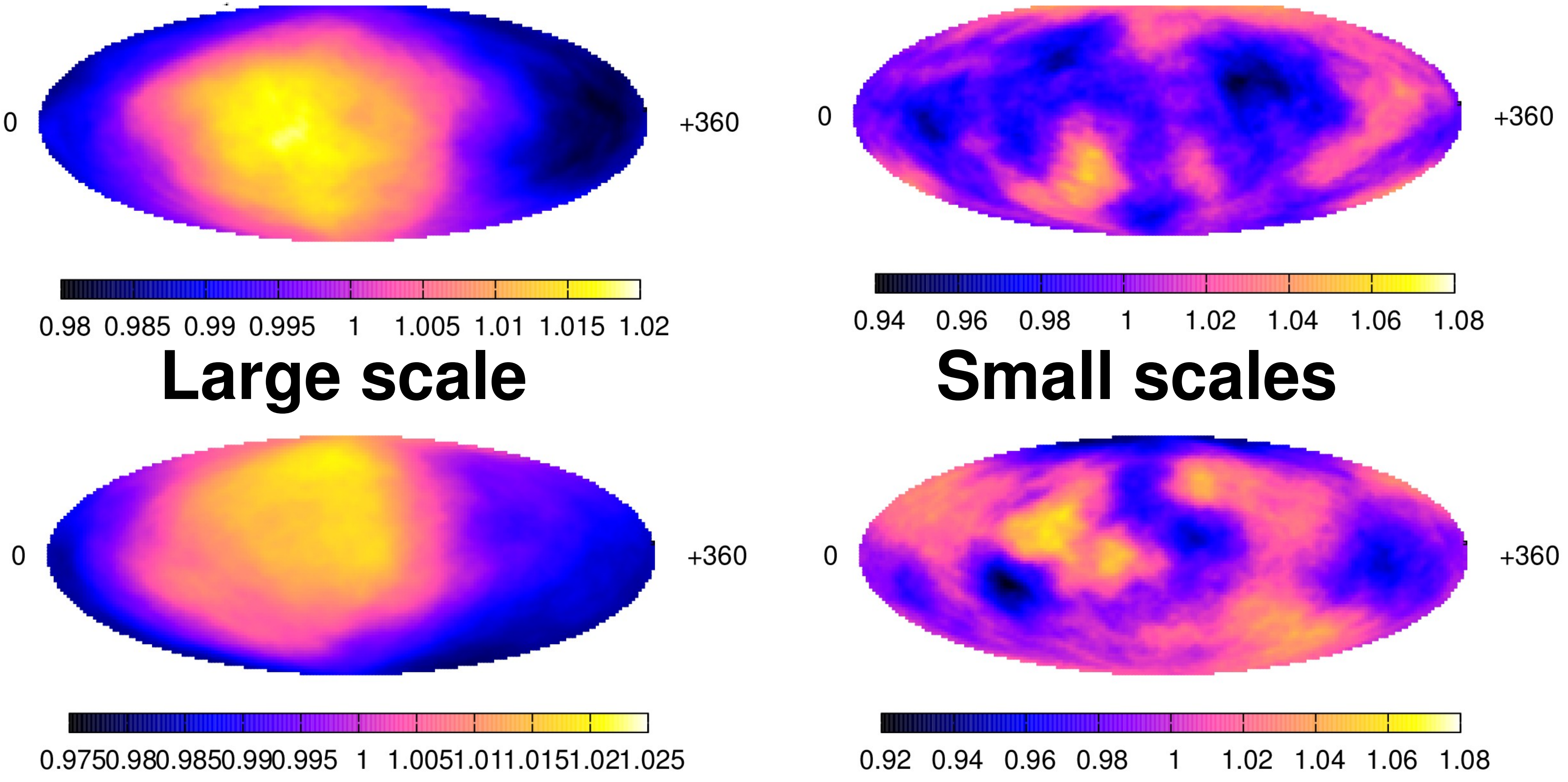
Data already puts constraints !

Anisotropies at smaller scales

PRL **109,** 071101 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Local Magnetic Turbulence and TeV–PeV Cosmic Ray Anisotropies

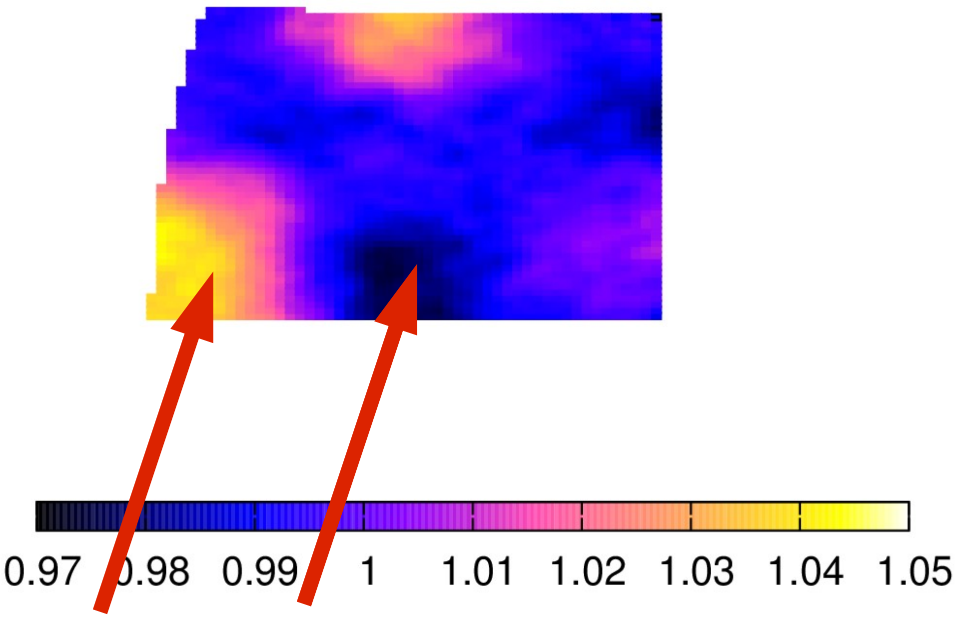
Gwenael Giacinti[1,2,3] and Günter Sigl[1]

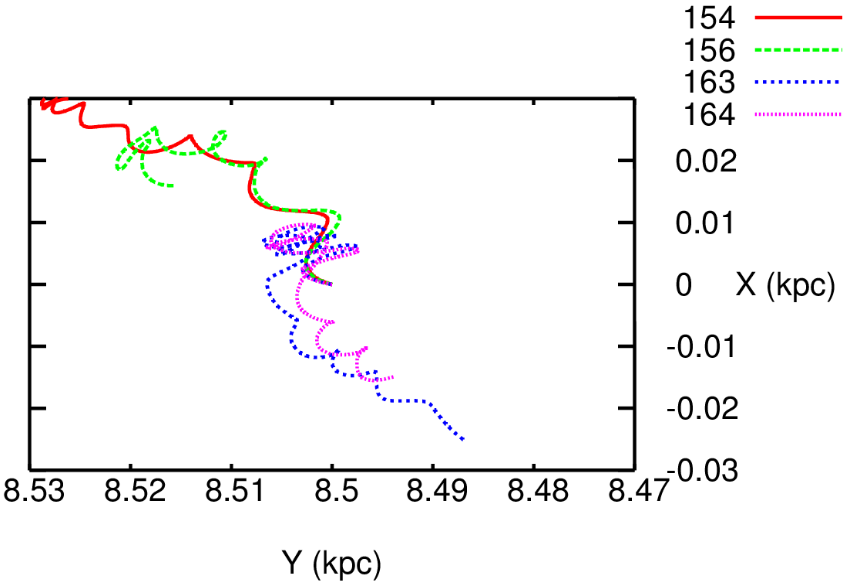


Large scale

Small scales

Local trajectories





grad n

SSA spectrum - interstellar turbulence

Ahlers, PRL (2014)

Ahlers & Mertsch (2015)

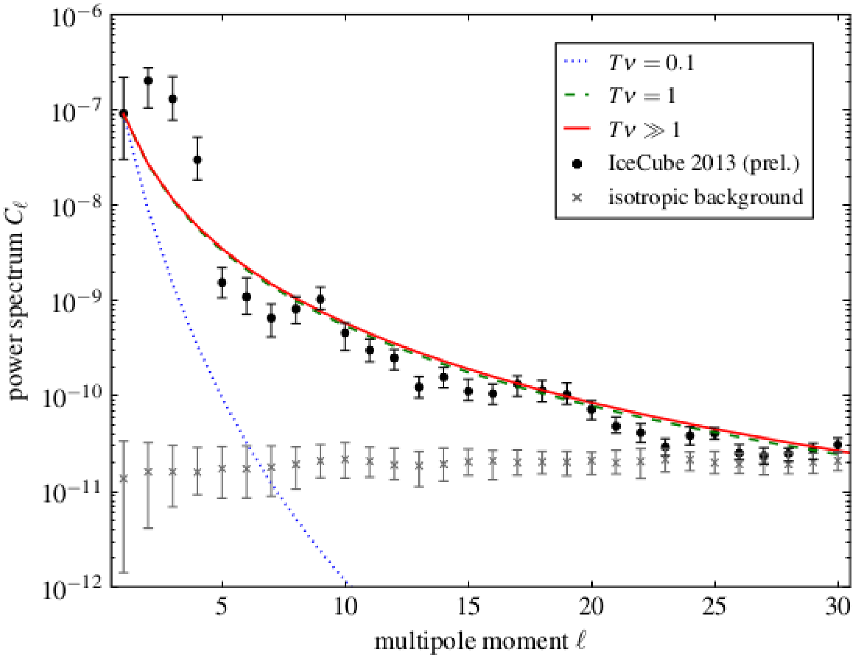
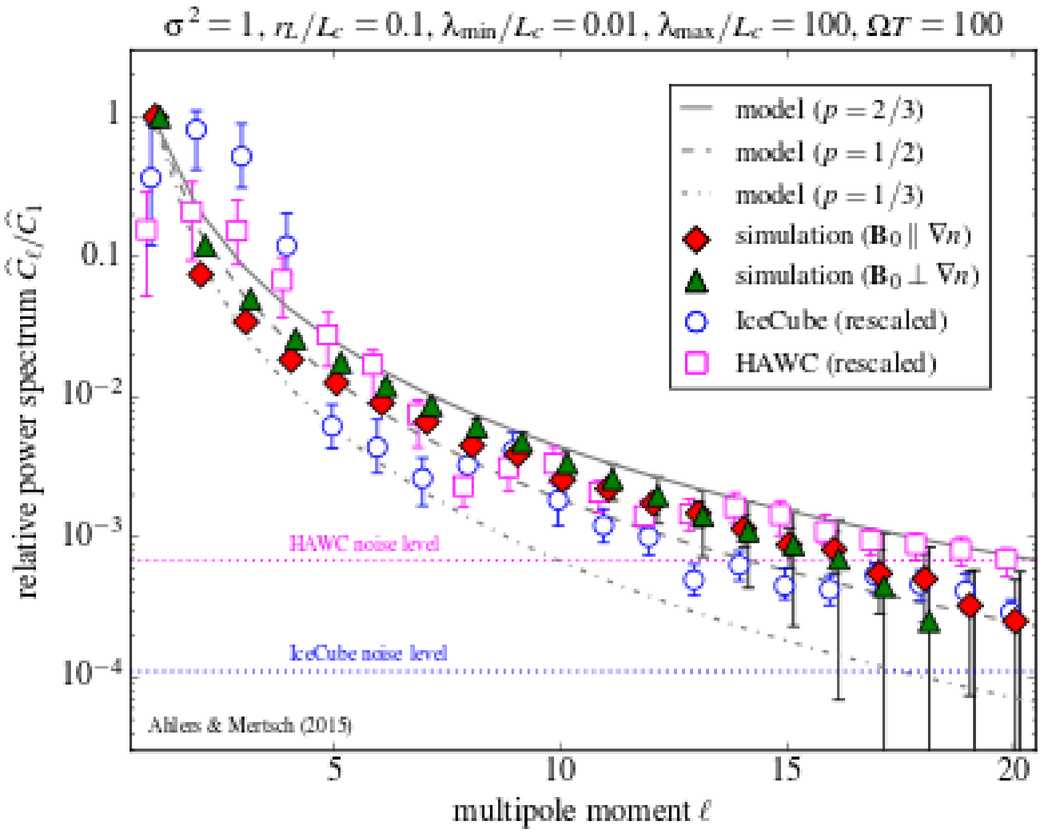


FIG. 1 (color online). Angular power spectrum (black dots) at the 68% confidence level measured with IceCube [16] at median energy of 20 TeV compared to the model prediction (20) for $\nu T = 0.1$ (blue dotted line) and $\nu T = 1$ (green dashed line) as well as the asymptotic value (21). We also show the power spectrum of scrambled (i.e., isotropized) data from Ref. [16] (gray crosses).



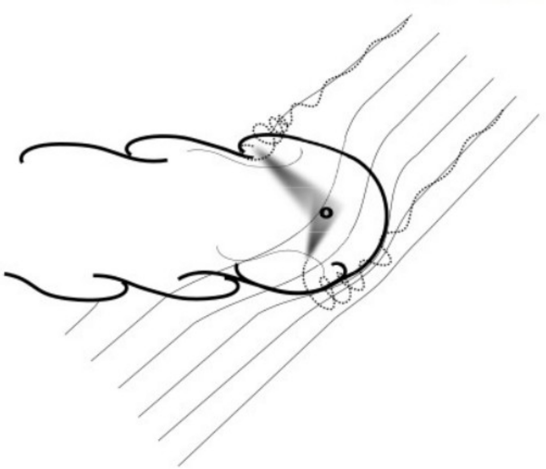
SSA from relative diffusion

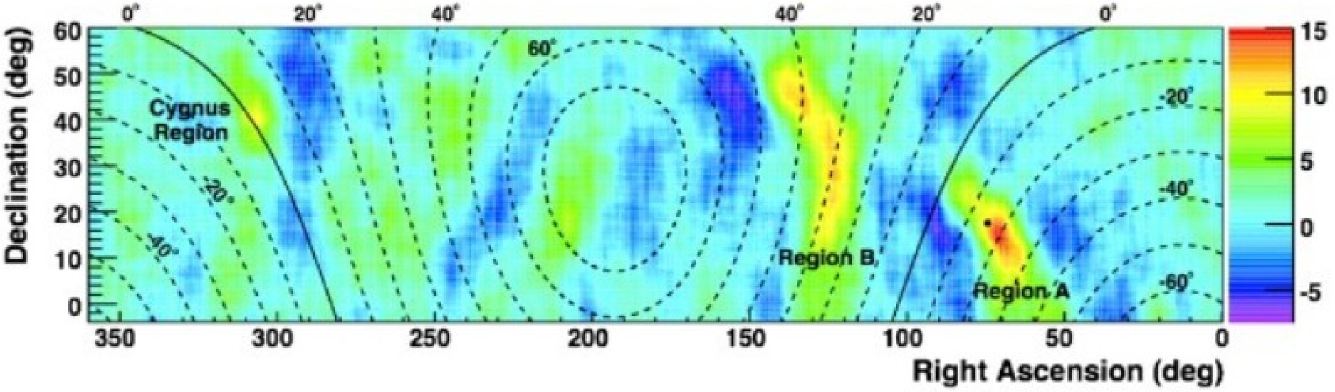
Heliospheric B fields at ~ TeV energies ?

→ **<u>At PeV energies :</u>** **probe realization ISMF up to ~10s of pc**

→ **<u>At 1 - 10 TeV energies :</u>** **Same argument ; may start to probe magnetic fields in the heliosphere.**

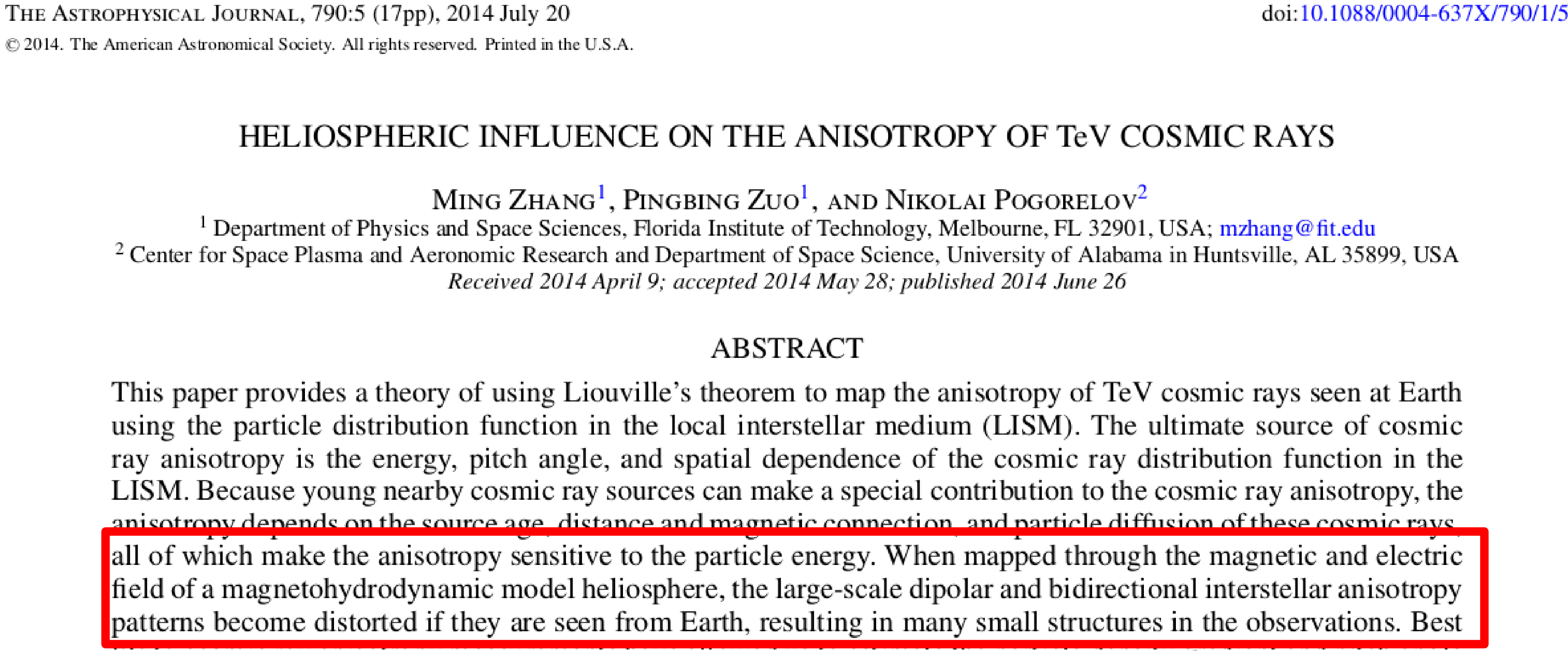
=> see Desiati & Lazarian, ApJ (2012)





… and/or <u>electric fields</u> (E = - U x B) in the heliosphere,
See : <u>L. Drury, Proc. ICRC 2013 [arXiv:1305.6752].</u>

Heliospheric E and B fields



The Astrophysical Journal, 790:5 (17pp), 2014 July 20 doi:10.1088/0004-637X/790/1/5

HELIOSPHERIC INFLUENCE ON THE ANISOTROPY OF TeV COSMIC RAYS

Ming Zhang[1], Pingbing Zuo[1], and Nikolai Pogorelov[2]
[1] Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA; mzhang@fit.edu
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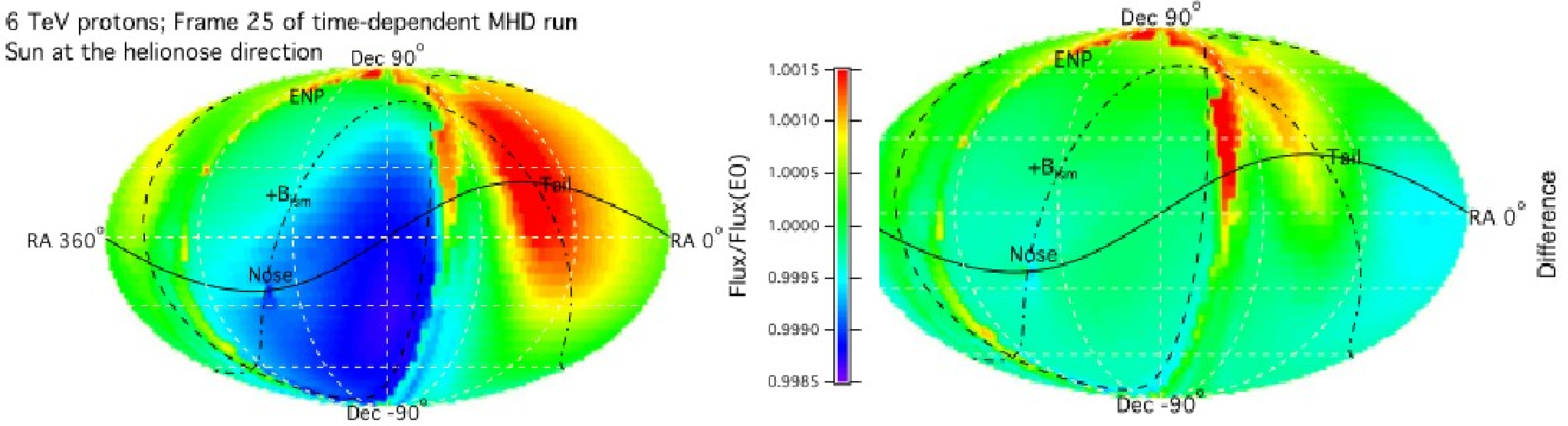
ABSTRACT

This paper provides a theory of using Liouville's theorem to map the anisotropy of TeV cosmic rays seen at Earth using the particle distribution function in the local interstellar medium (LISM). The ultimate source of cosmic ray anisotropy is the energy, pitch angle, and spatial dependence of the cosmic ray distribution function in the LISM. Because young nearby cosmic ray sources can make a special contribution to the cosmic ray anisotropy, the anisotropy depends on the source age, distance and magnetic connection, and particle diffusion of these cosmic rays, all of which make the anisotropy sensitive to the particle energy. When mapped through the magnetic and electric field of a magnetohydrodynamic model heliosphere, the large-scale dipolar and bidirectional interstellar anisotropy patterns become distorted if they are seen from Earth, resulting in many small structures in the observations. Best



6 TeV protons; Frame 25 of time-dependent MHD run

Sun at the helionose direction

Conclusions and perspectives

(i) Large scale CRA = New probe of the modes and anisotropy (in k-space) of ISMFs

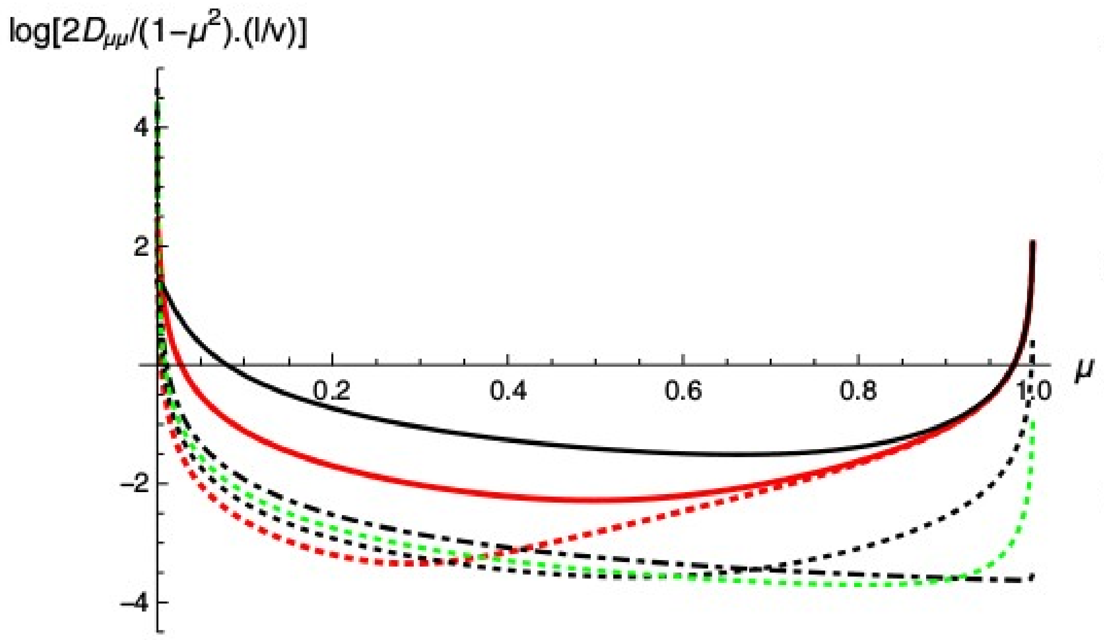
=> NEW OBSERVABLE !

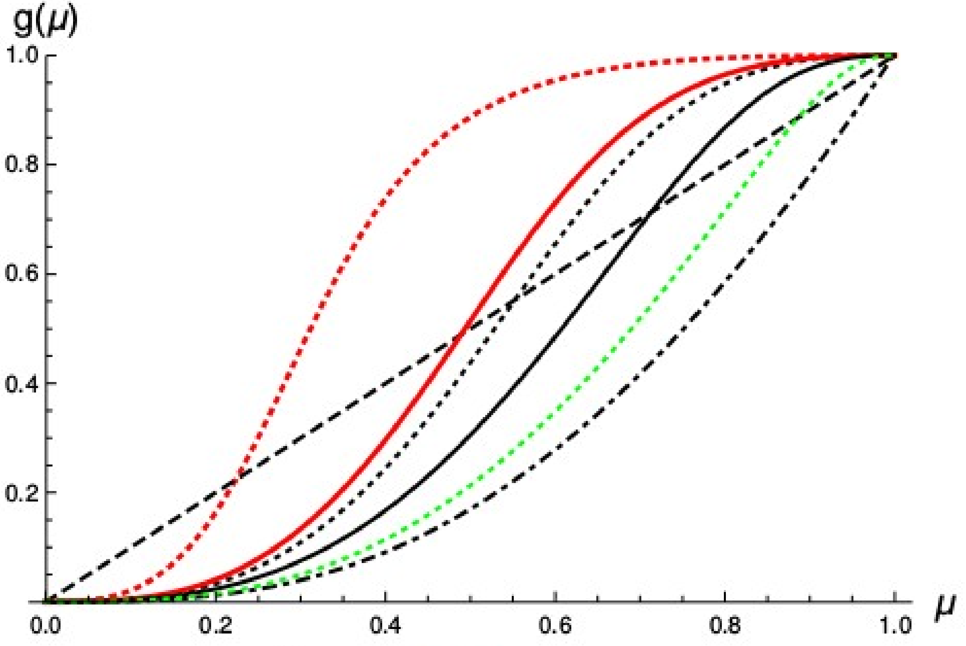
---> RELEVANT FOR ASTRO. IN GENERAL

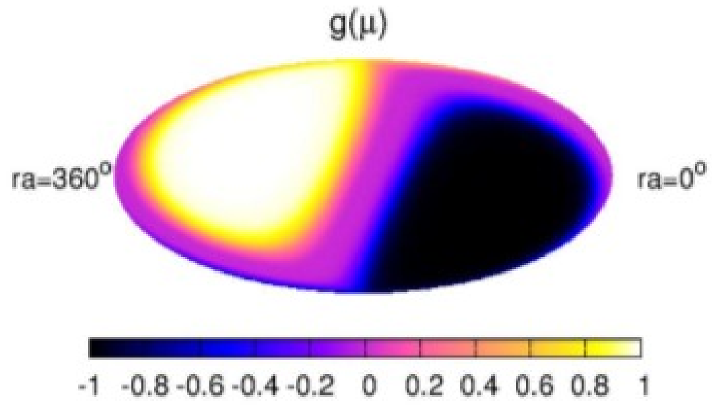
(ii) Medium and small scale CRA must be present because of the local MF structure within ~ a CR mean free path, or vxB

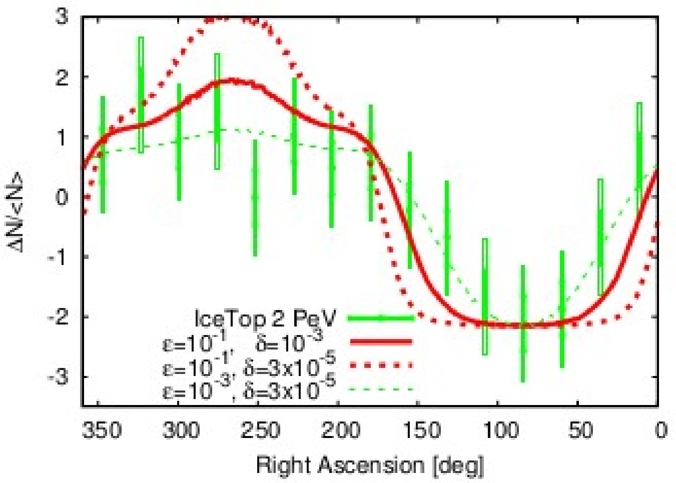
---> Interesting way to probe the structure of our very local environment.

Case A : GS ('Heaviside, Narrow')



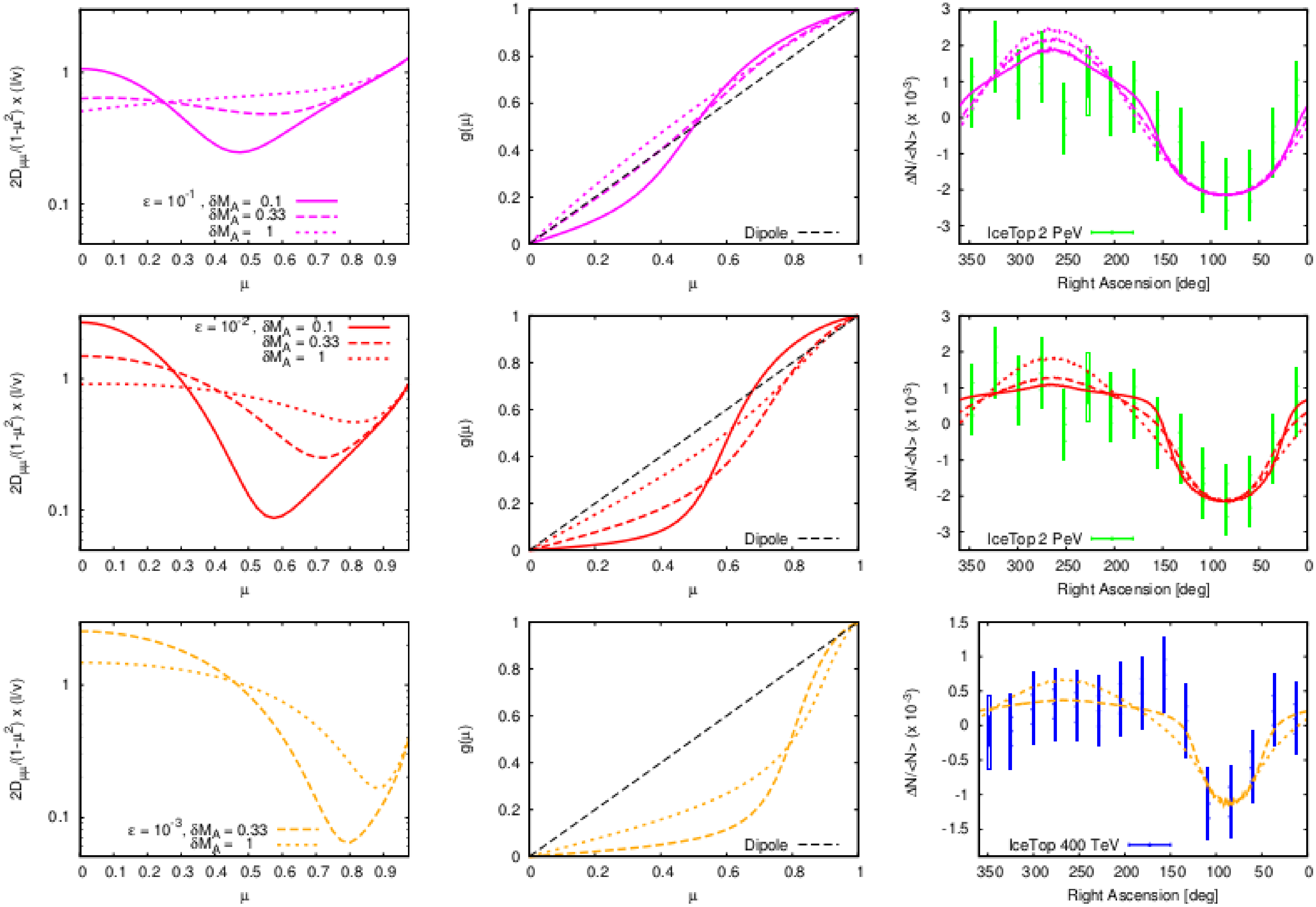




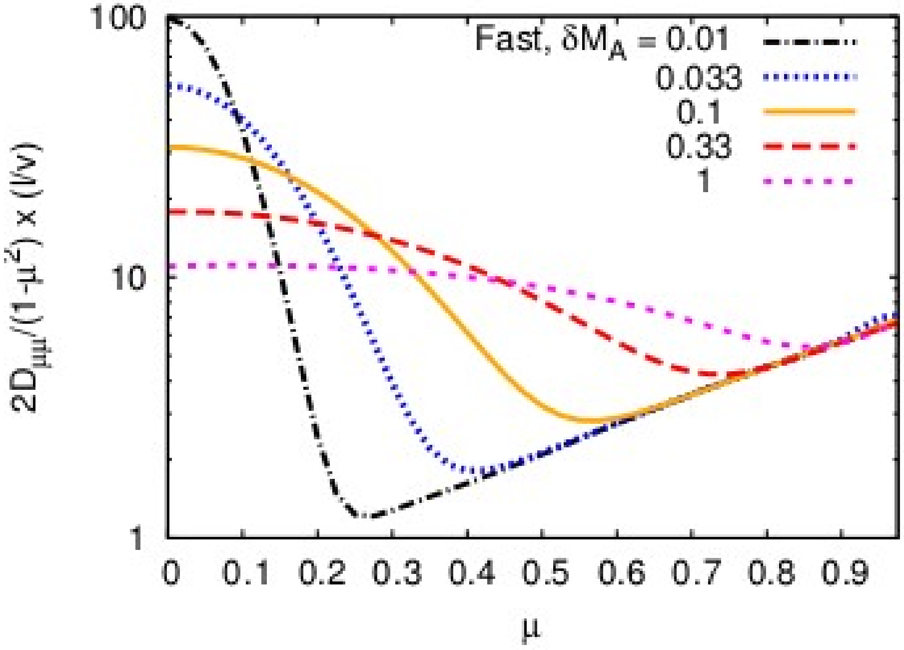


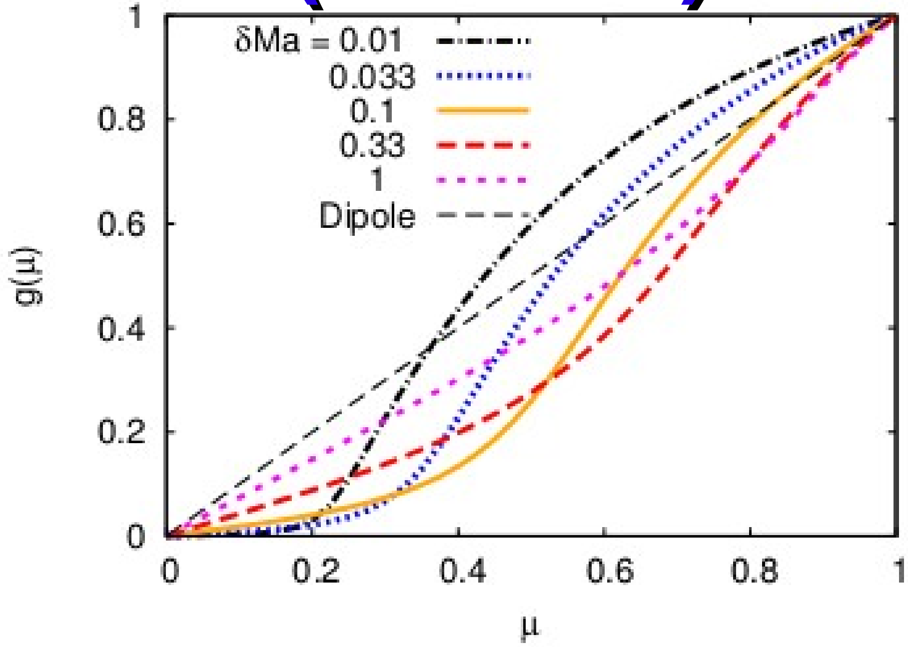
'Allowed' parameter-space : **Anisotropy too wide with the narrow RF**.

Case D : GS ('Exponential, Broad')



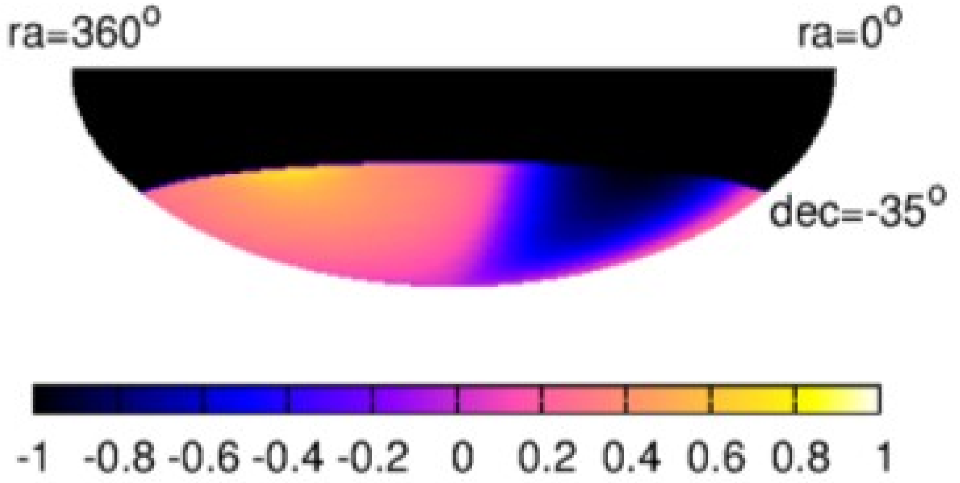
Case F : Fast modes ('Broad')

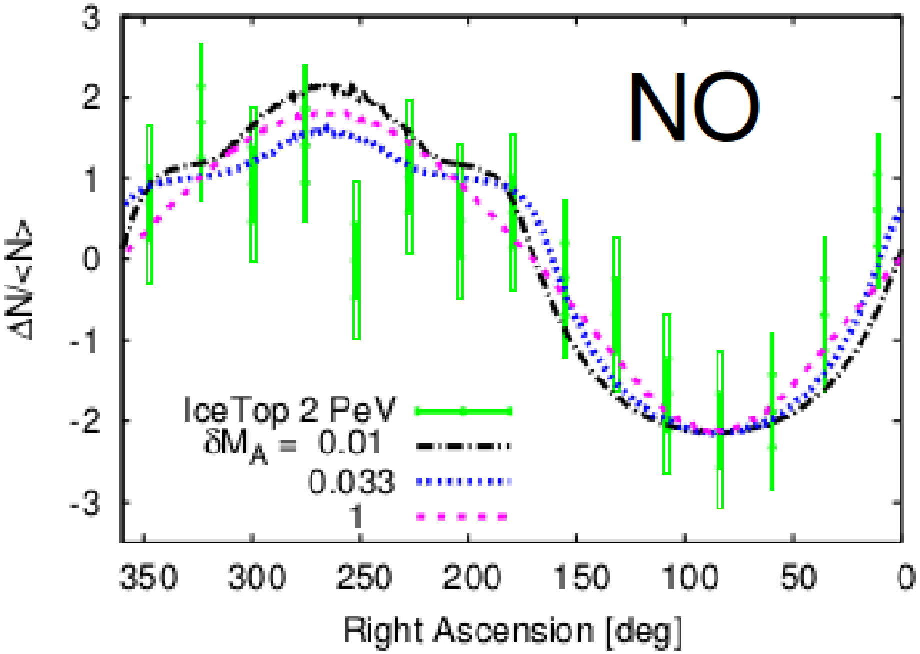




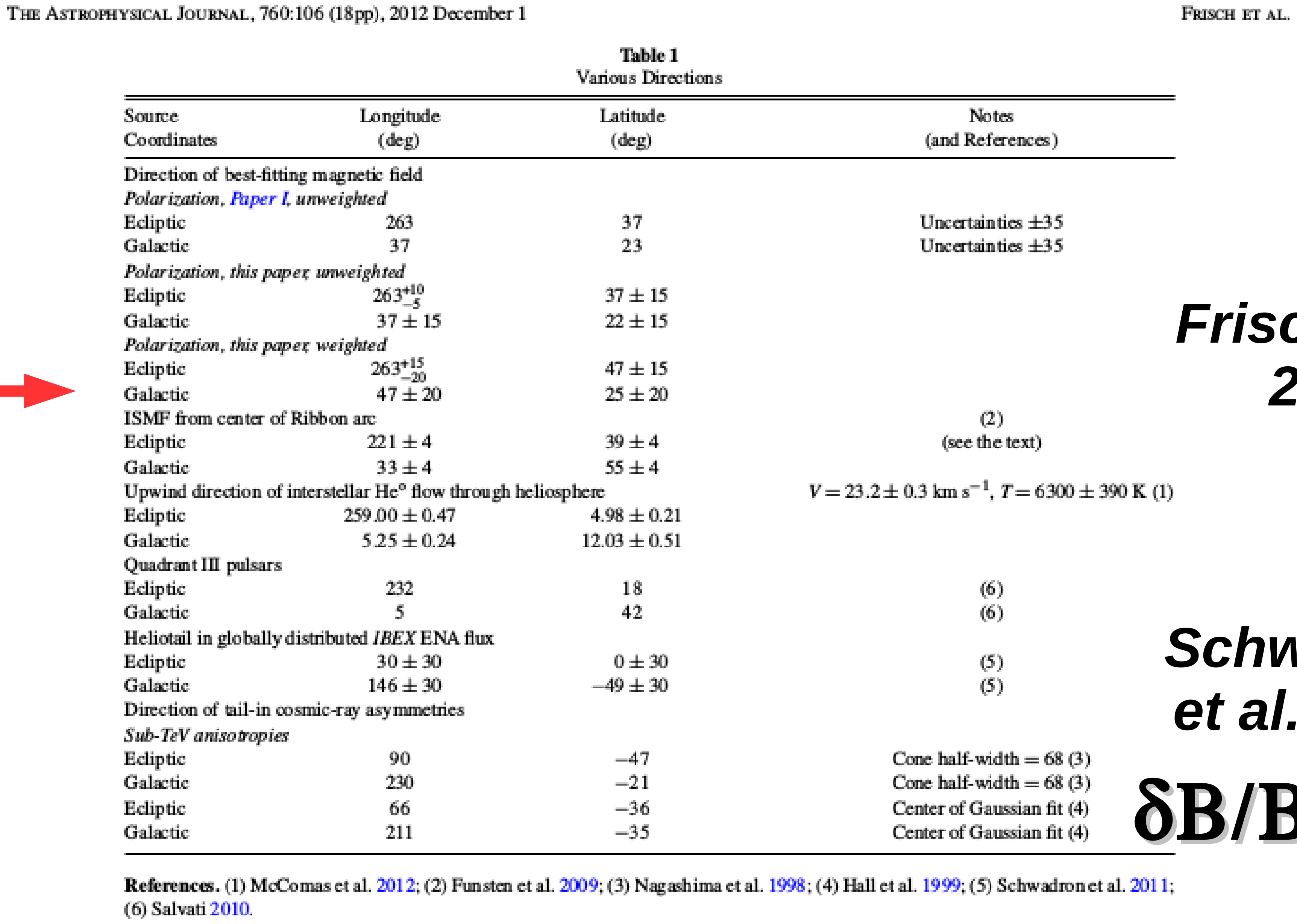
No dependence of the *shape* on E

Can fit well the 2 PeV data !





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

$\delta B/B << 1$