TeV-PeV COSMIC-RAY ANISOTROPY AS A PROBE OF THE LOCAL INTERSTELLAR TURBULENCE

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GG, Brian Reville & Wenyi Bian (边稳懿), In Prep. (2021) –
see also arXiv:1810.06396

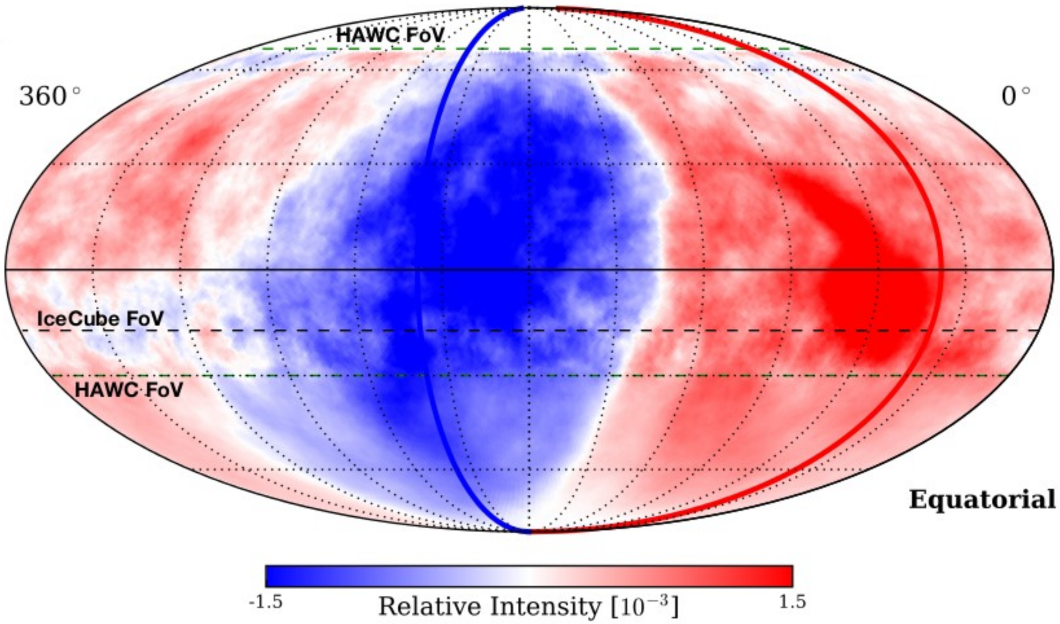
GG & Kirk, ApJ 835, 258 (2017),
arXiv:1610.06134

GG & Sigl, Phys. Rev. Lett. 109, 071101 (2012), *arXiv:1111.2536*

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

HAWC + IceCube Collab., ApJ (2018) [arXiv:1812.05682]:

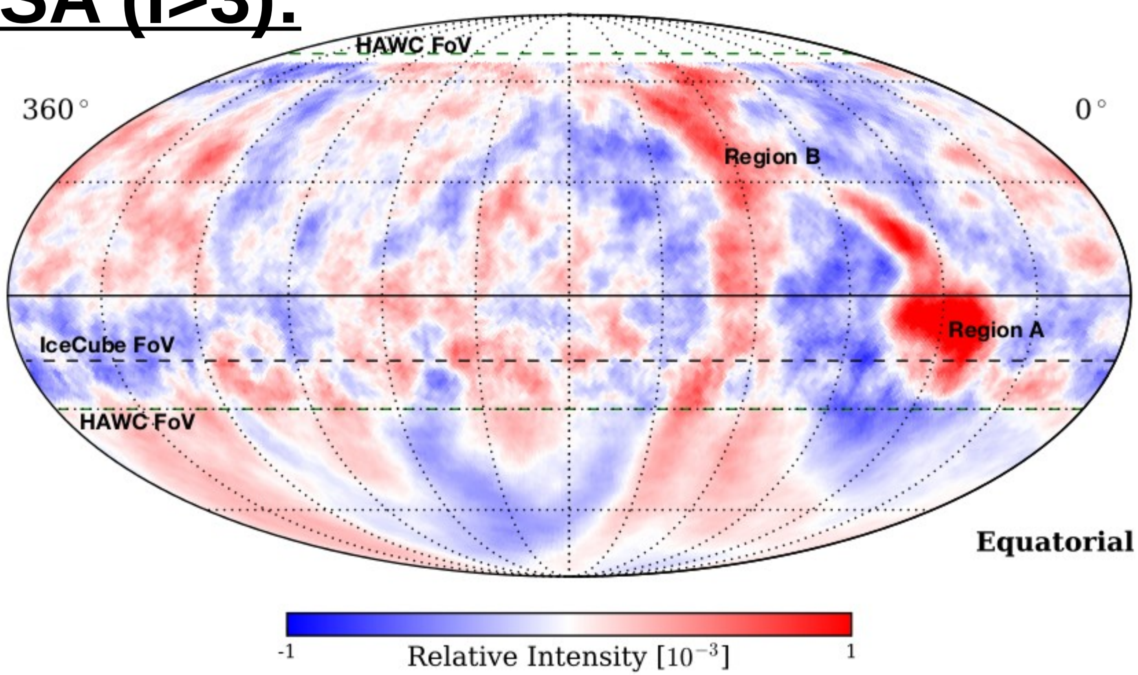
Large Scale Anisotropy (~0.1%) :



In the direction of field lines

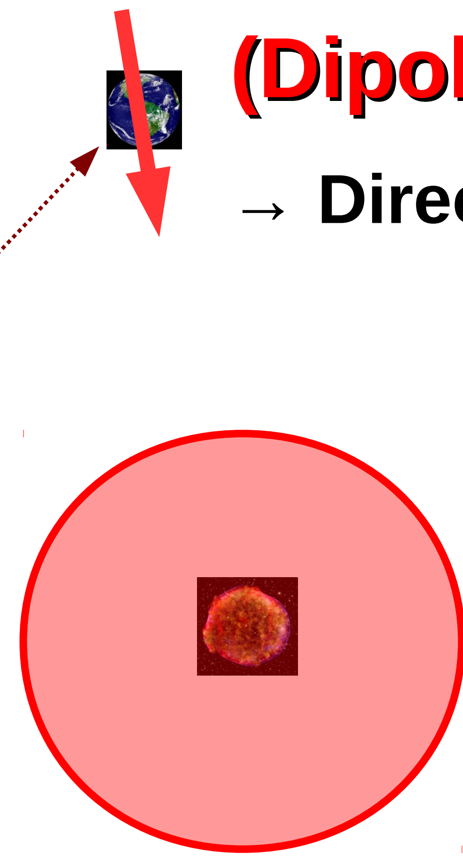
SHAPE: NOT a dipole in general

SSA (l>3):



- Energy-dependent,
- No/Litte time-dependence
- Amplitude: LSA/(few – 10)

CR Anisotropy



(Dipole) Anisotropy

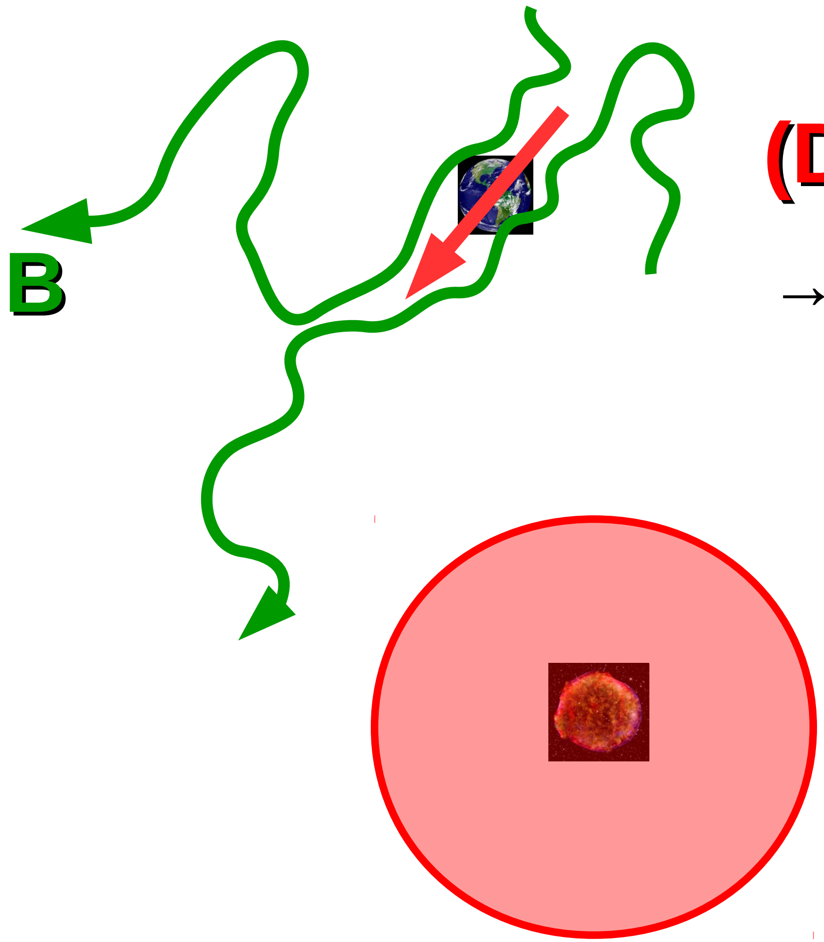
→ **Direction**

Amplitude

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

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

CR Anisotropy



(Dipole) Anisotropy

→ Direction B field

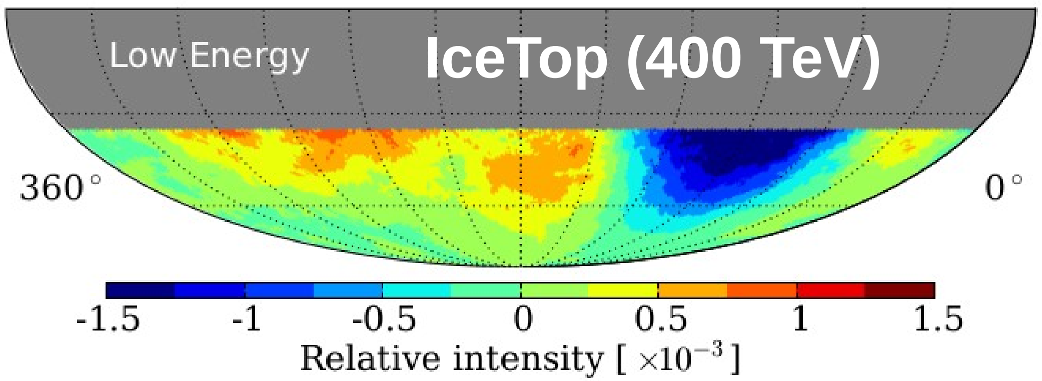
cf. Schwadron et al., Science (2014)

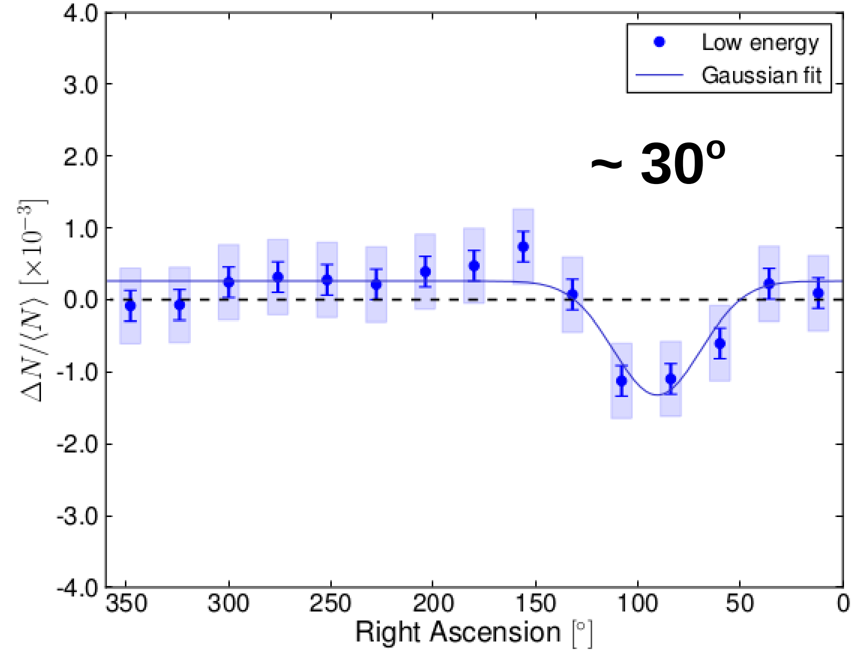
~ 180° flip at 100 TeV:

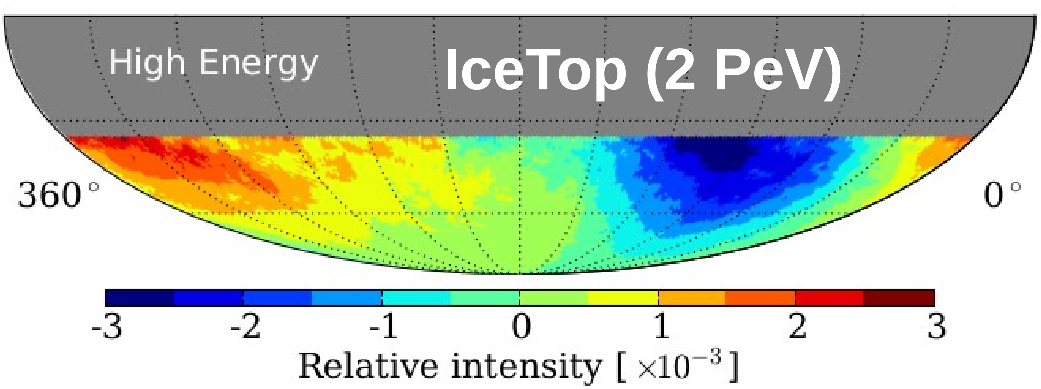
cf. Ahlers, PRL (2016)

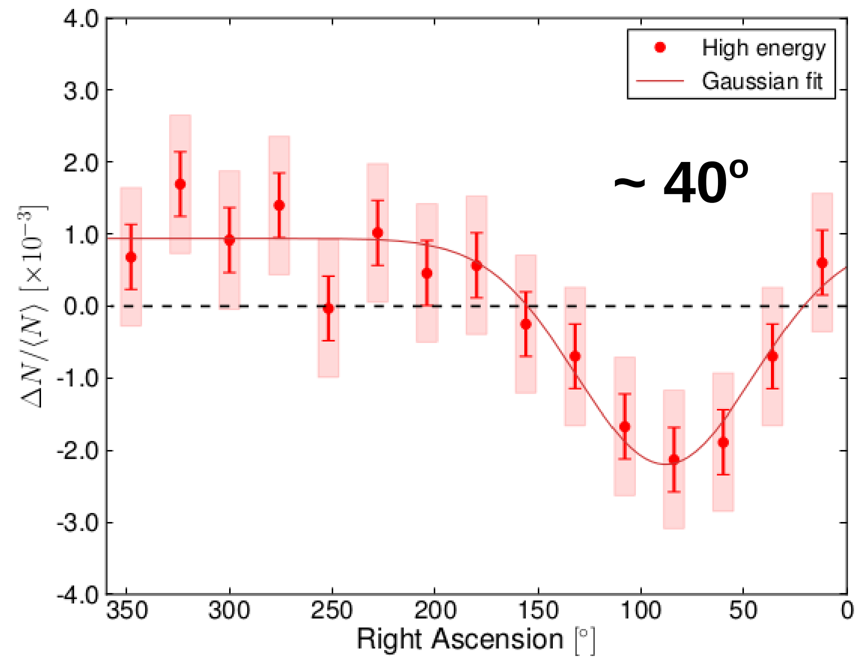
Observations (IceCube, IceTop)

Aartsen et al. (2013)



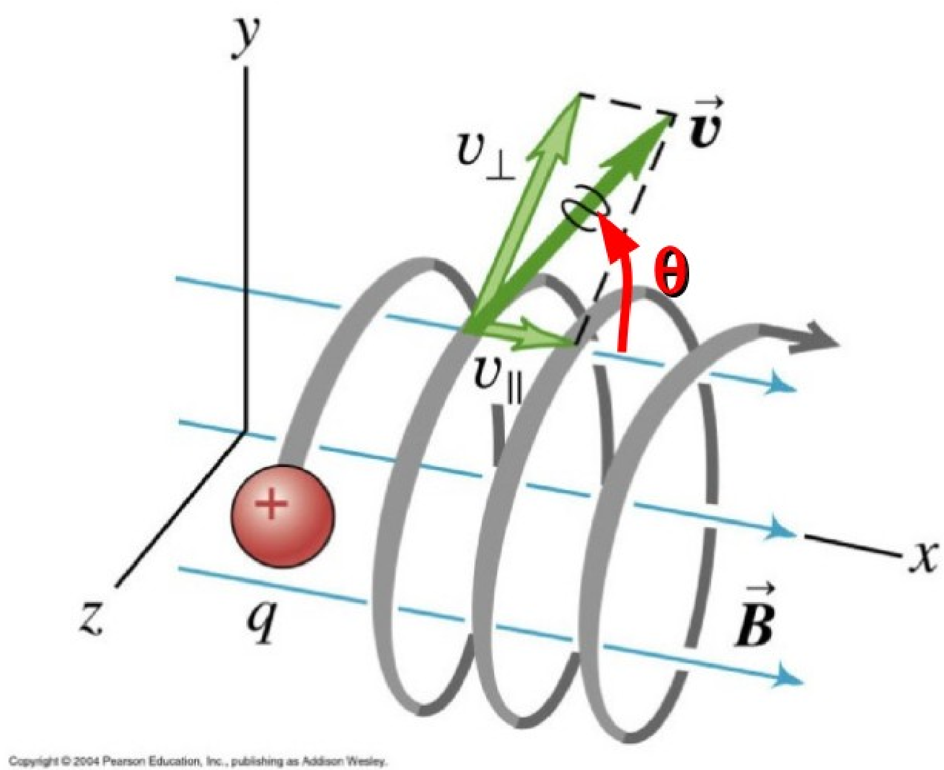




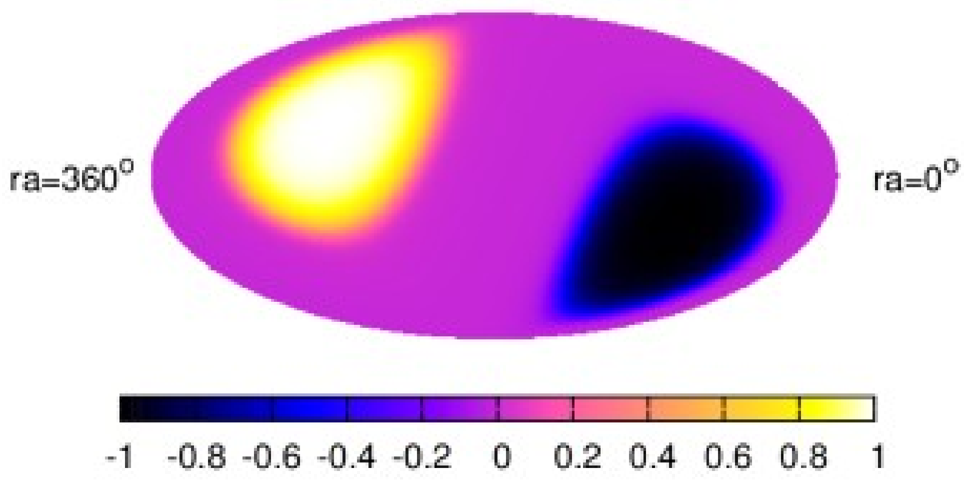


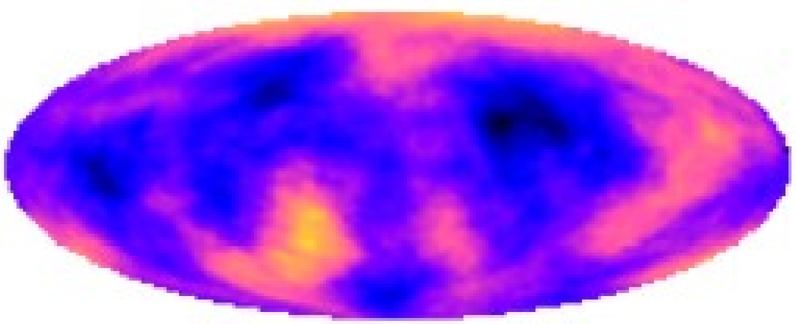
Also at 20 TeV...

Pitch-angle (θ) and gyrophase:

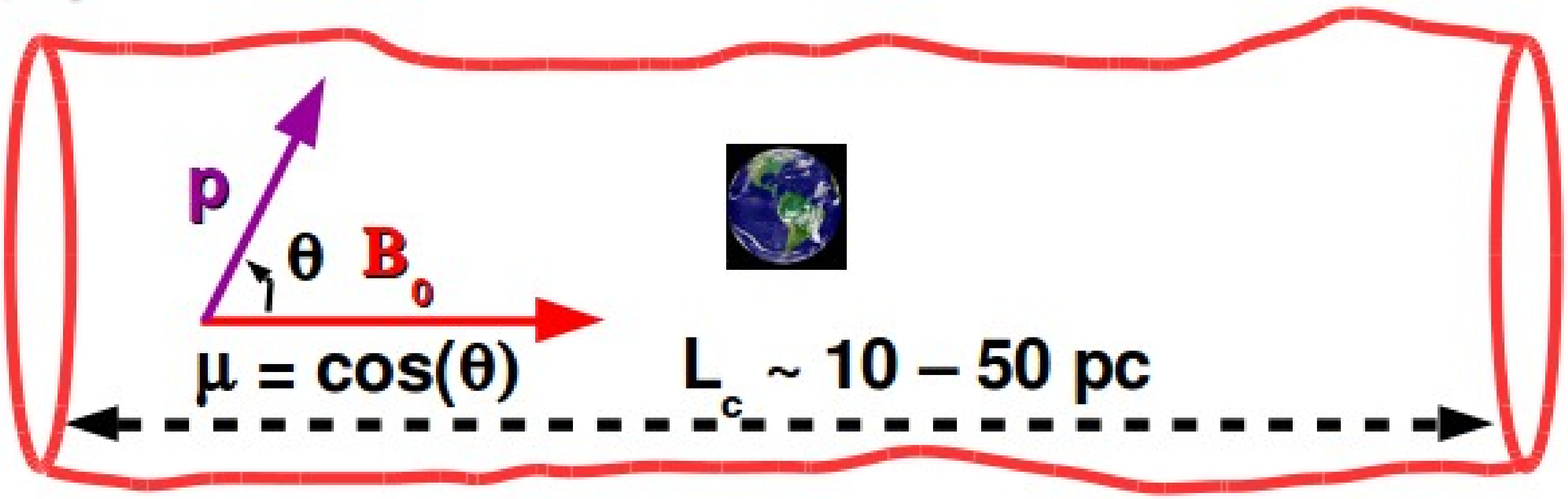


CRA = Large-scale + small-scales





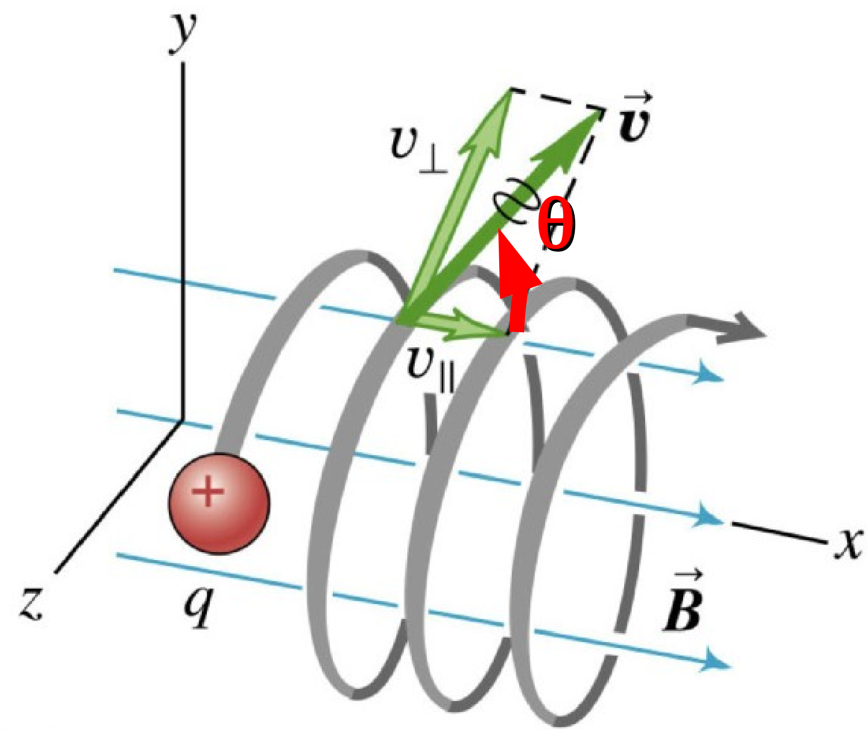
CR Anisotropy : Probe of turbulence



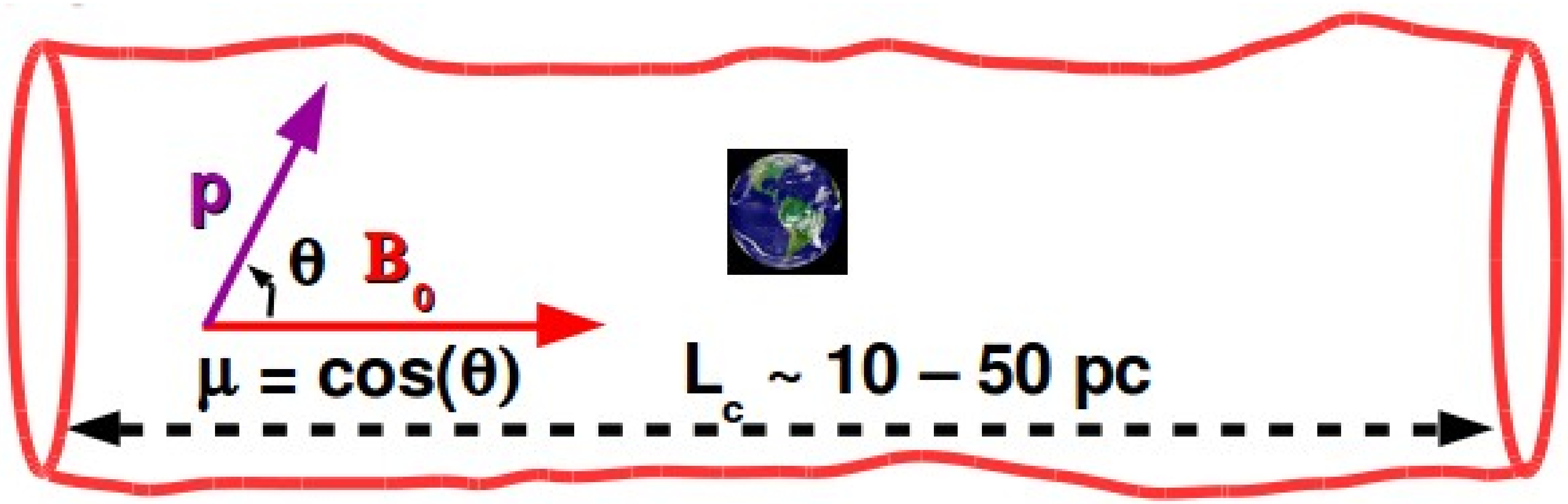
$$\mu v \frac{\partial f}{\partial x} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right)$$

Pitch-angle diffusion

(gyrophase-averaged)



CR Anisotropy : Probe of turbulence



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

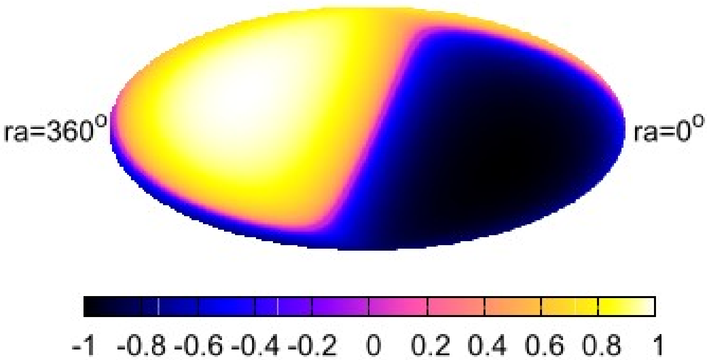
Aniso α $\int_0^{\mu} \mathrm{d}\mu' \, \frac{1 - \mu'^2}{D_{\mu'\mu'}}$

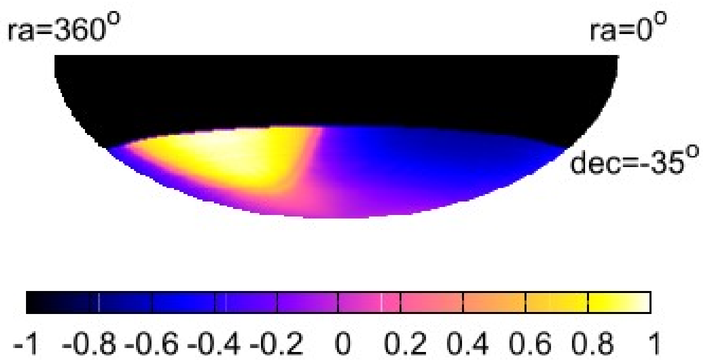
<u>NOT</u> 1 – μ^2
in general !

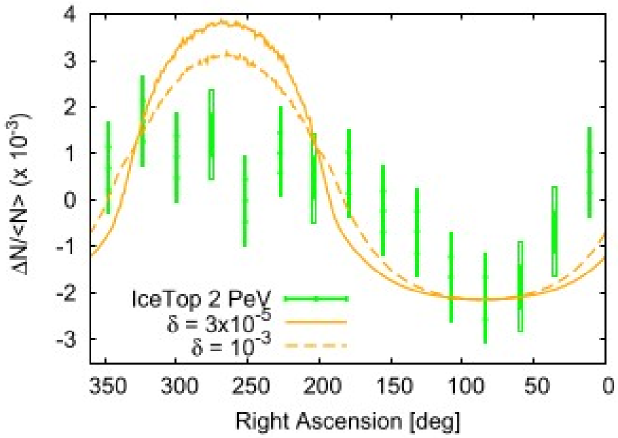
GG & Kirk, ApJ 835, 258 (2017), arXiv:1610.06134

Case 1 : Fast modes & Narrow RF

No dependence of the *shape* on CR energy







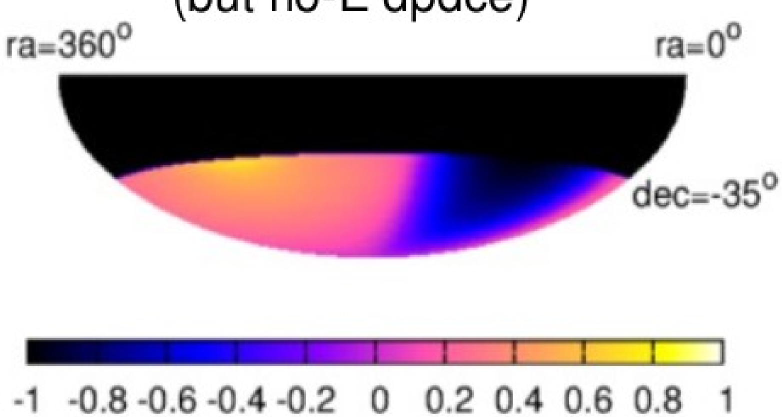
In general: Anisotropy too wide with narrow Res Fn =>

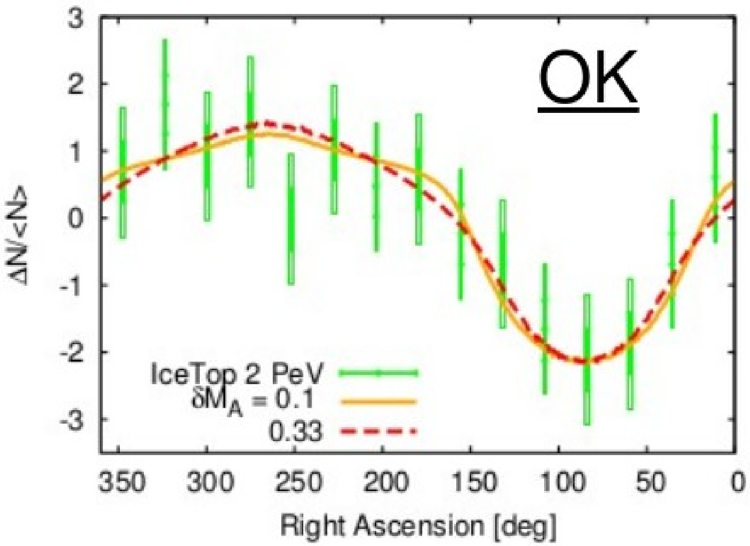
RULED OUT !

Case 2 : Fast modes & Broad RF

Can **fit the 2 PeV data** ! →

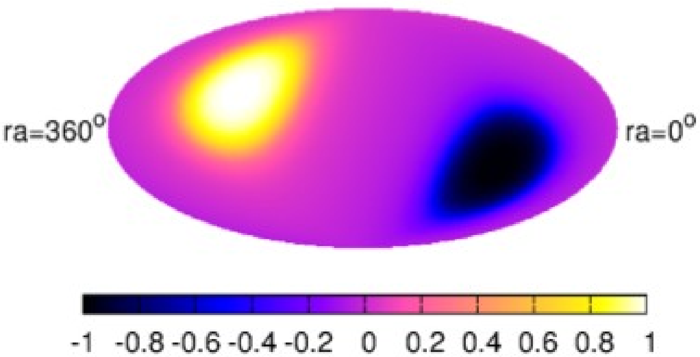
(but no-E dpdce)

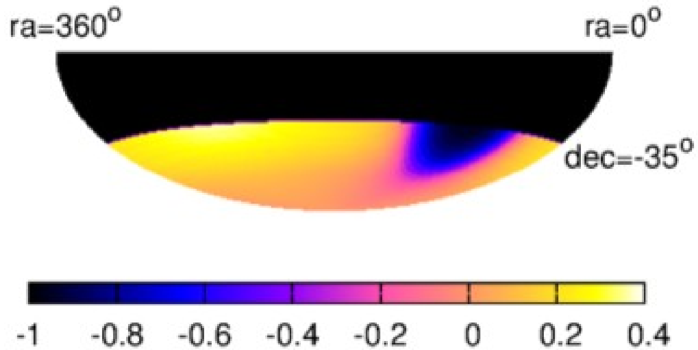


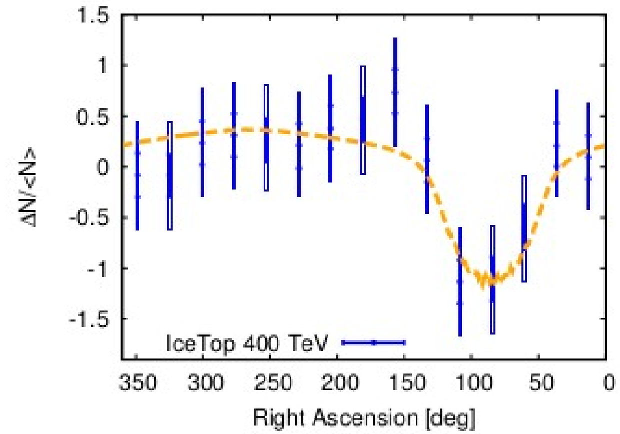


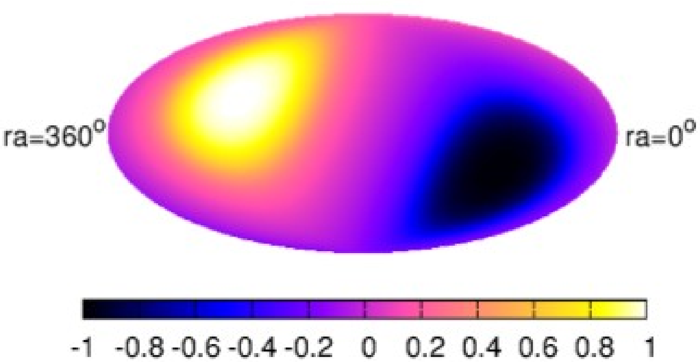
Flattening in directions perpendicular to B field

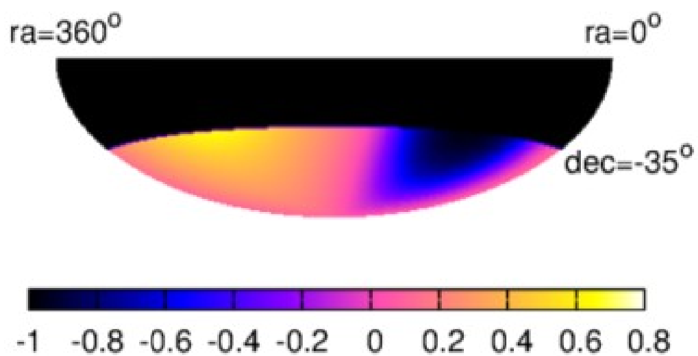
Case 3 : GS – Exponential & Broad RF

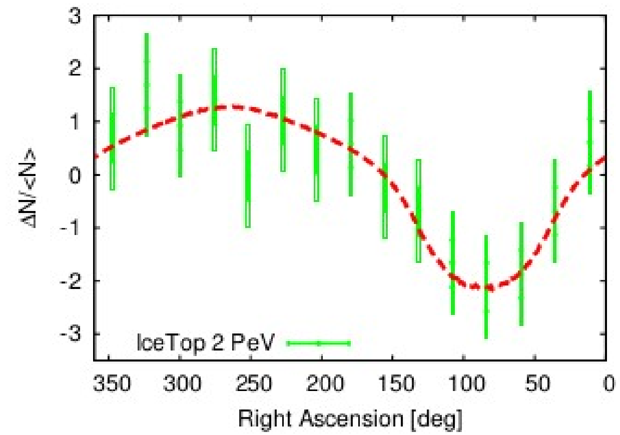












Can fit well the 400 TeV and the 2 PeV data !

Energy-dependence reproduced for fixed turbulence parameters

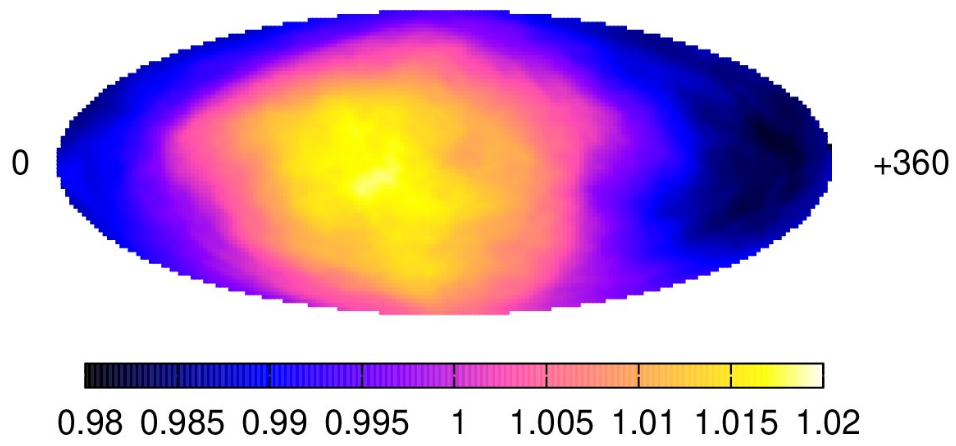
First theoretical model to fit this data

Change in shape with CR energy
- - -> |**k**|-dependent anisotropy in power spectrum?

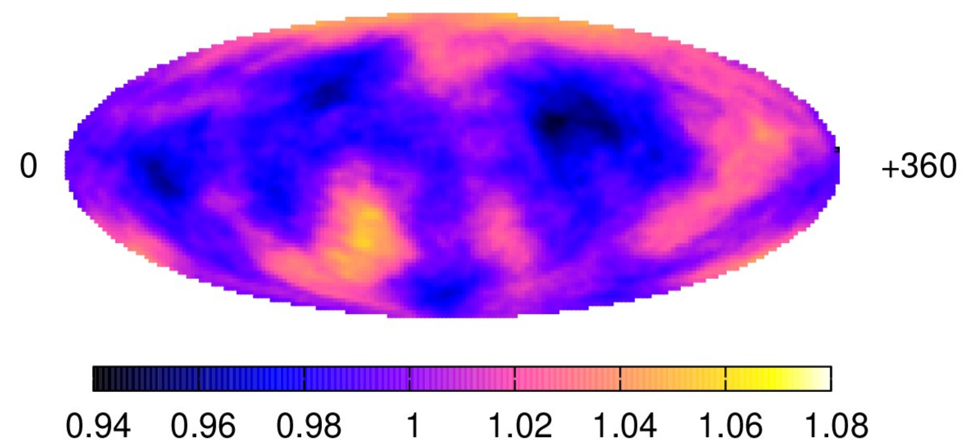
Small-scale aniso. & local turbulence

… What about the non-gyrotropic small scale anisotropies ?

90°smoothing

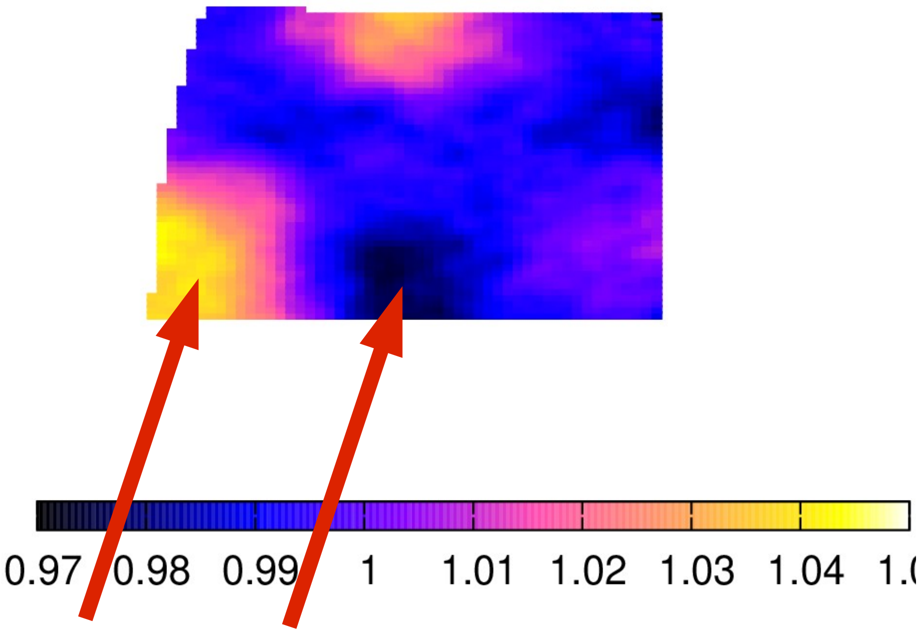


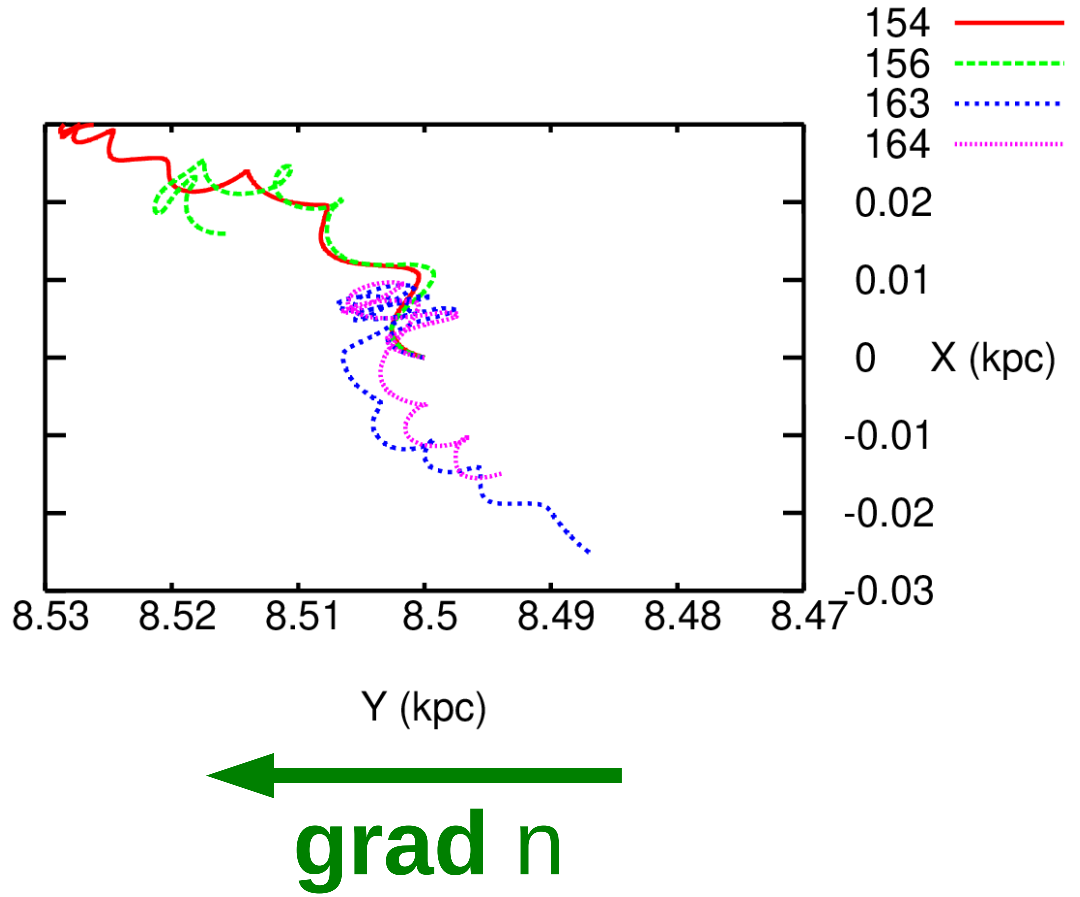
20° smoothing - {dipole}



GG & Sigl, PRL 109, 071101 (2012), *arXiv:1111.2536*

Local trajectories





→ SSA due to the local realization of the ISM turbulent field, within a CR MFP around Earth.

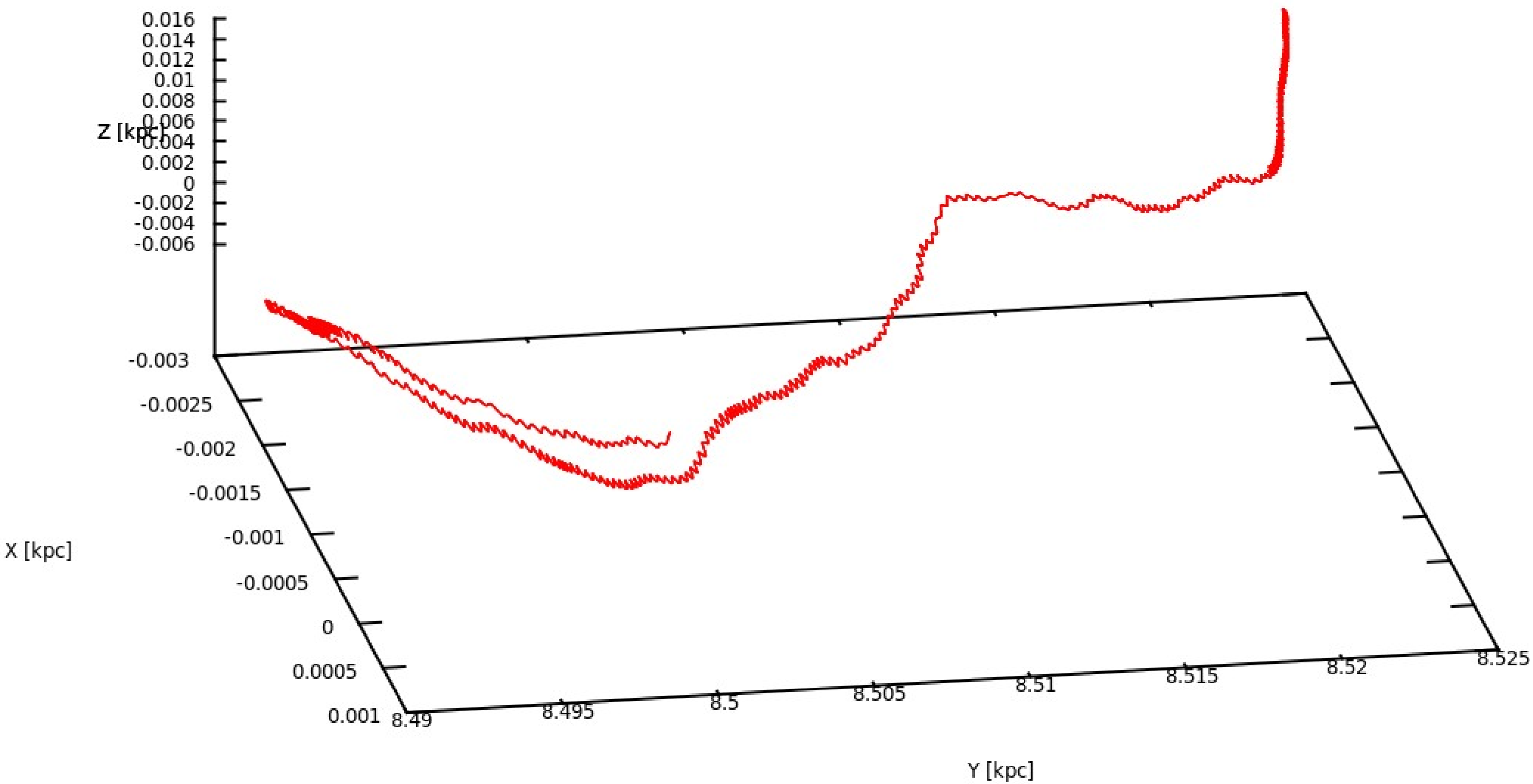
---> Contain signatures of our very local environment.

Numerical simulations down to 3 TeV

GG, Reville & Bian, In Prep. (2021) – *see also arXiv:1810.06396*

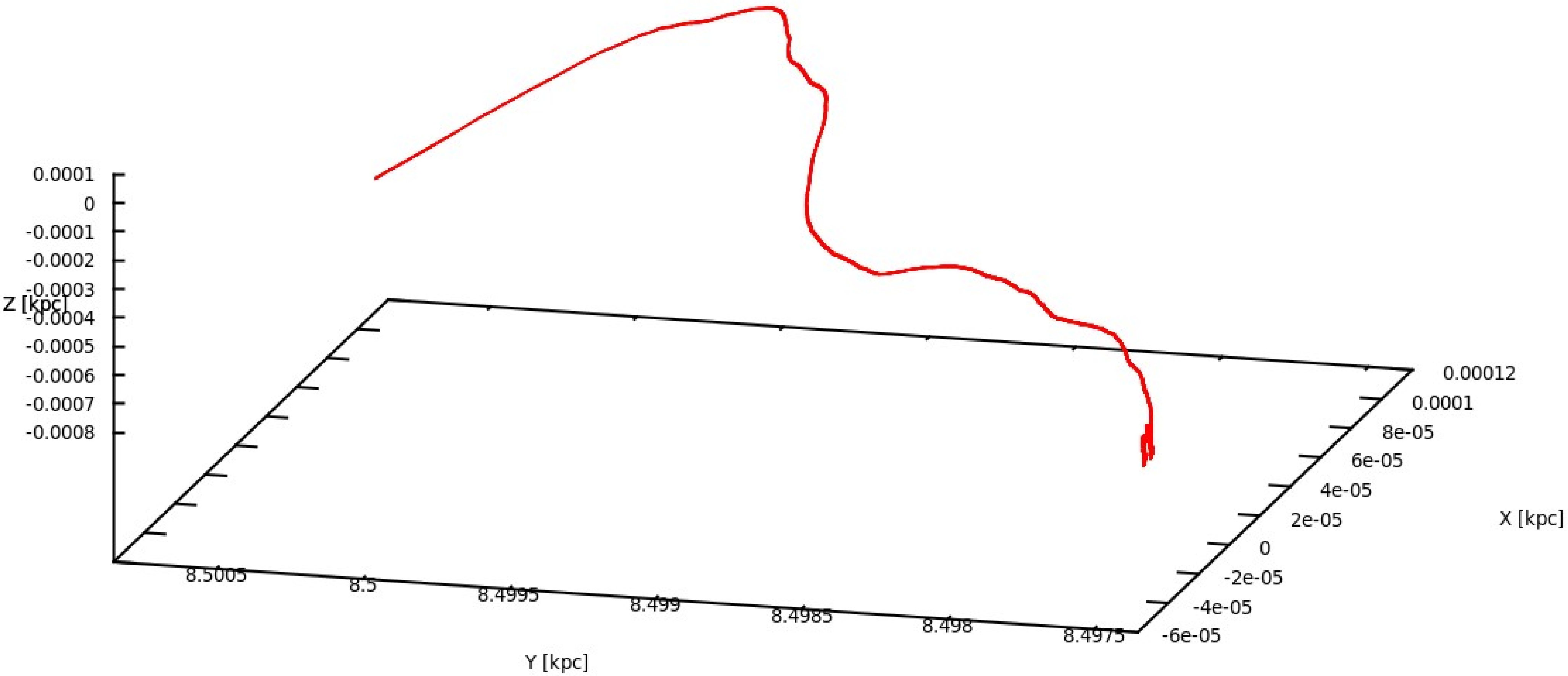
Individual CR trajectories

300 TeV, Kolmogorov, L_{max} = 150 pc, B_{rms} = 4 μG.



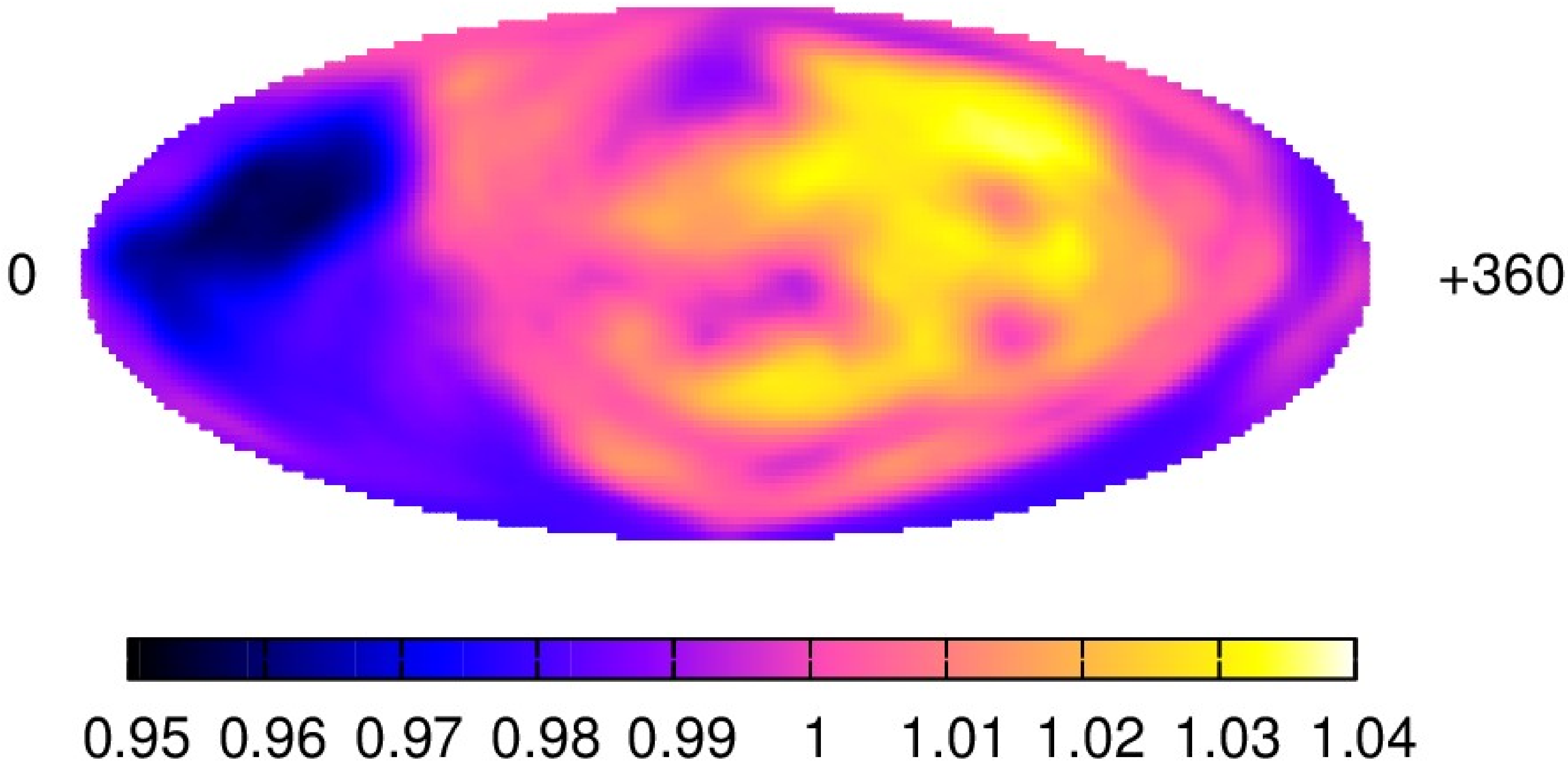
Individual CR trajectories

3 TeV, Kolmogorov, L_{max} = 150 pc, B_{rms} = 4 μG.



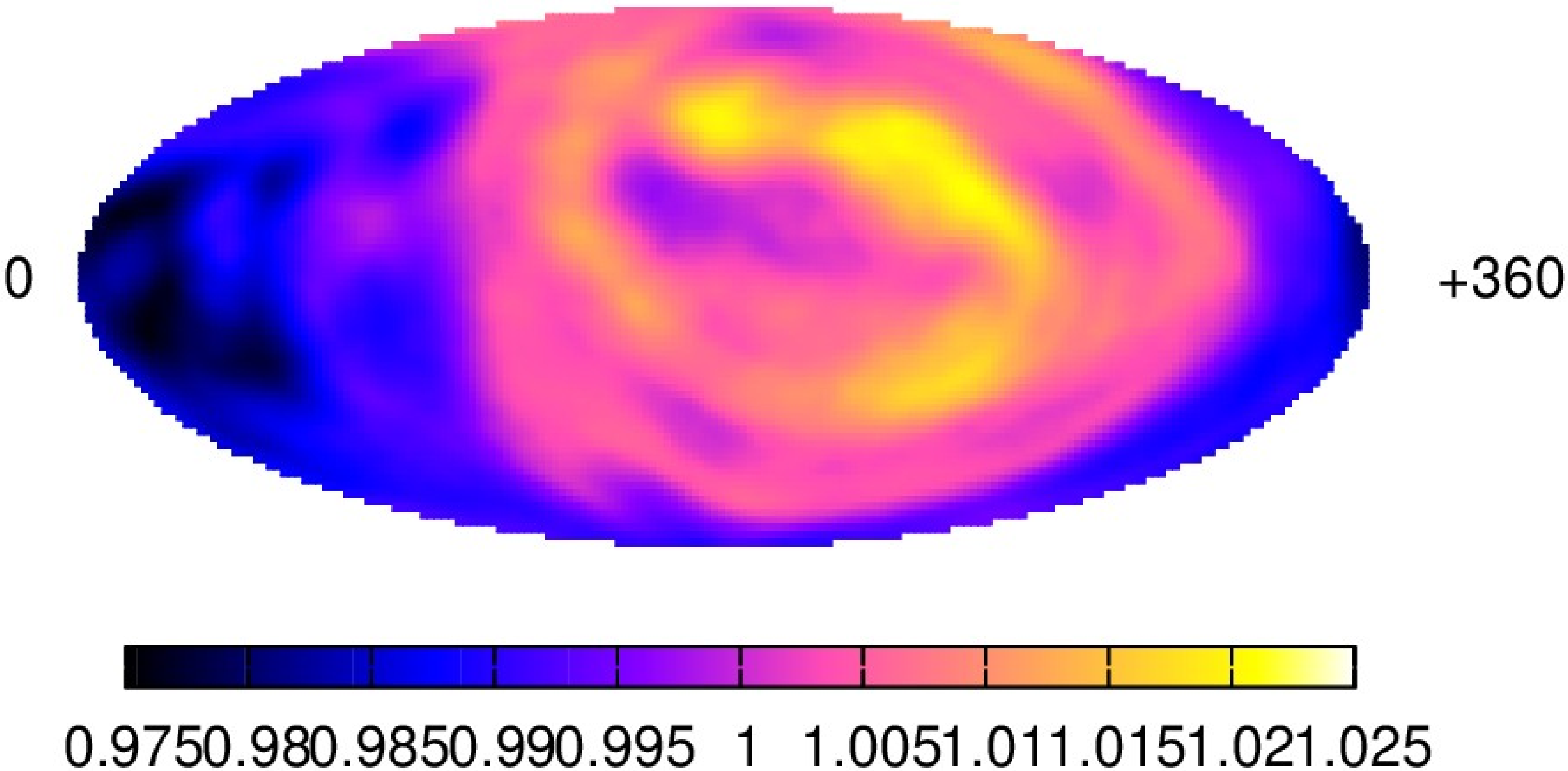
CR Anisotropy – Simulations

E_{CR} = 3 PeV



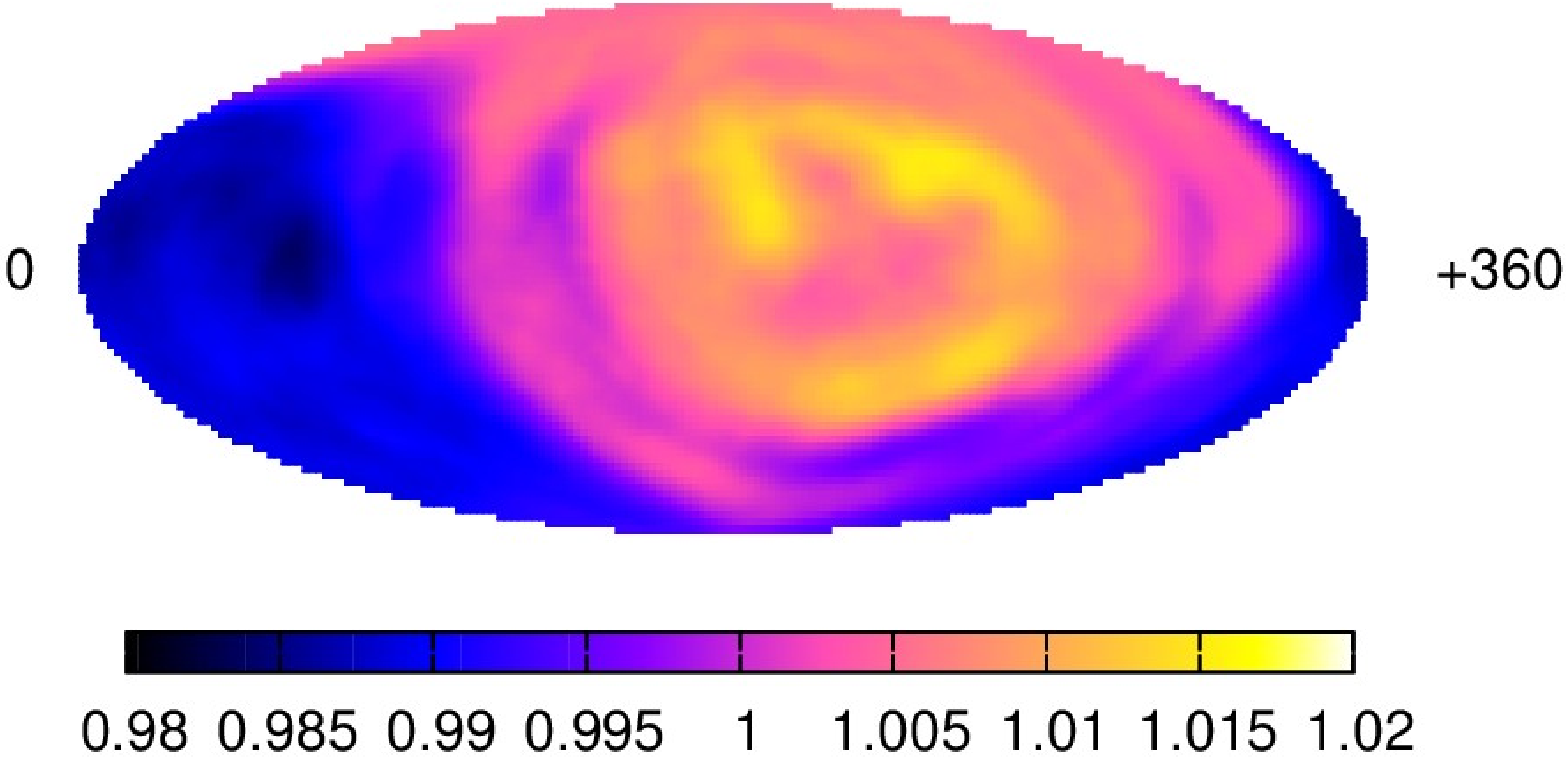
CR Anisotropy – Simulations

E_{CR} = 1 PeV



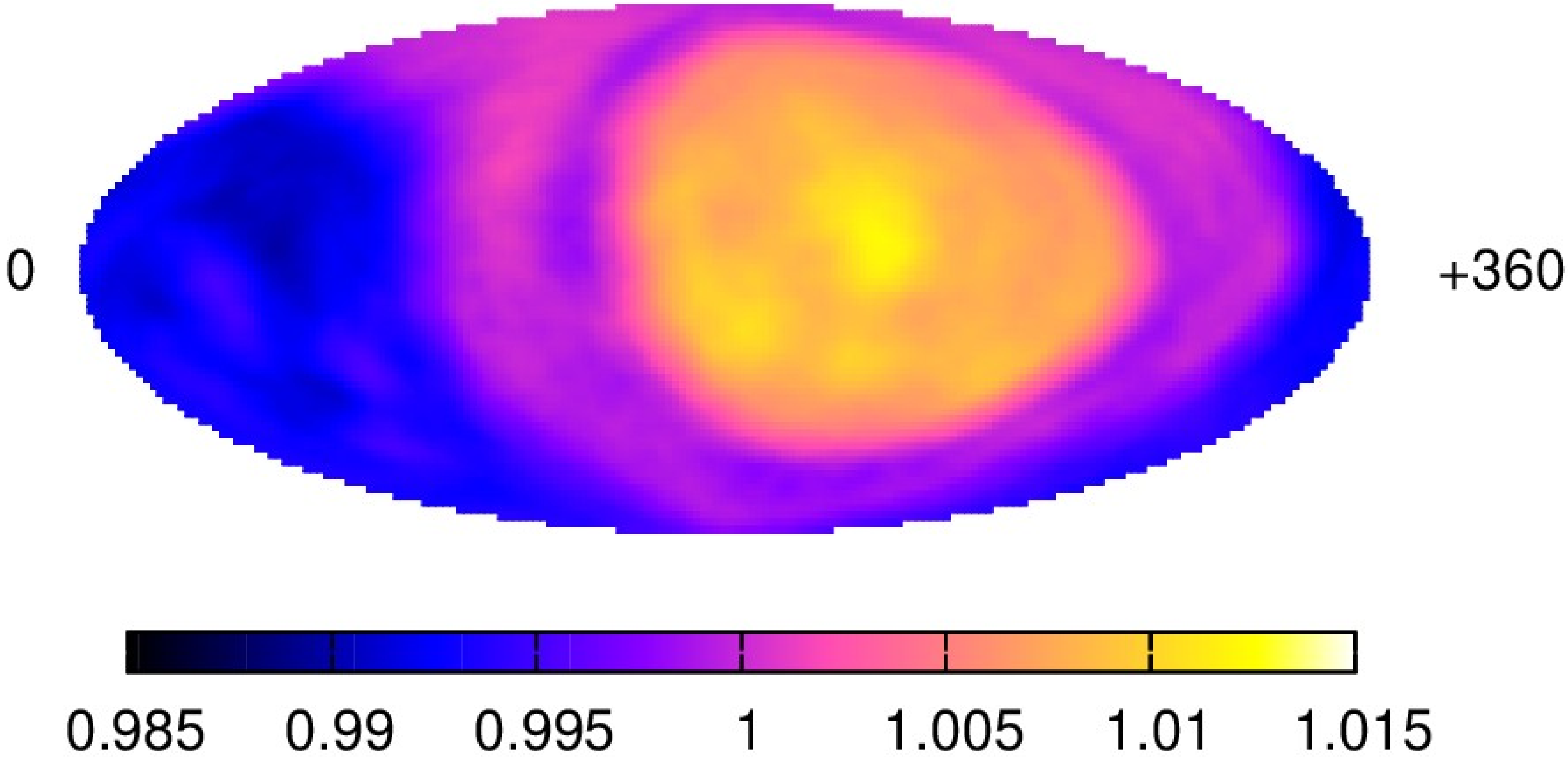
CR Anisotropy – Simulations

E_{CR} = 300 TeV



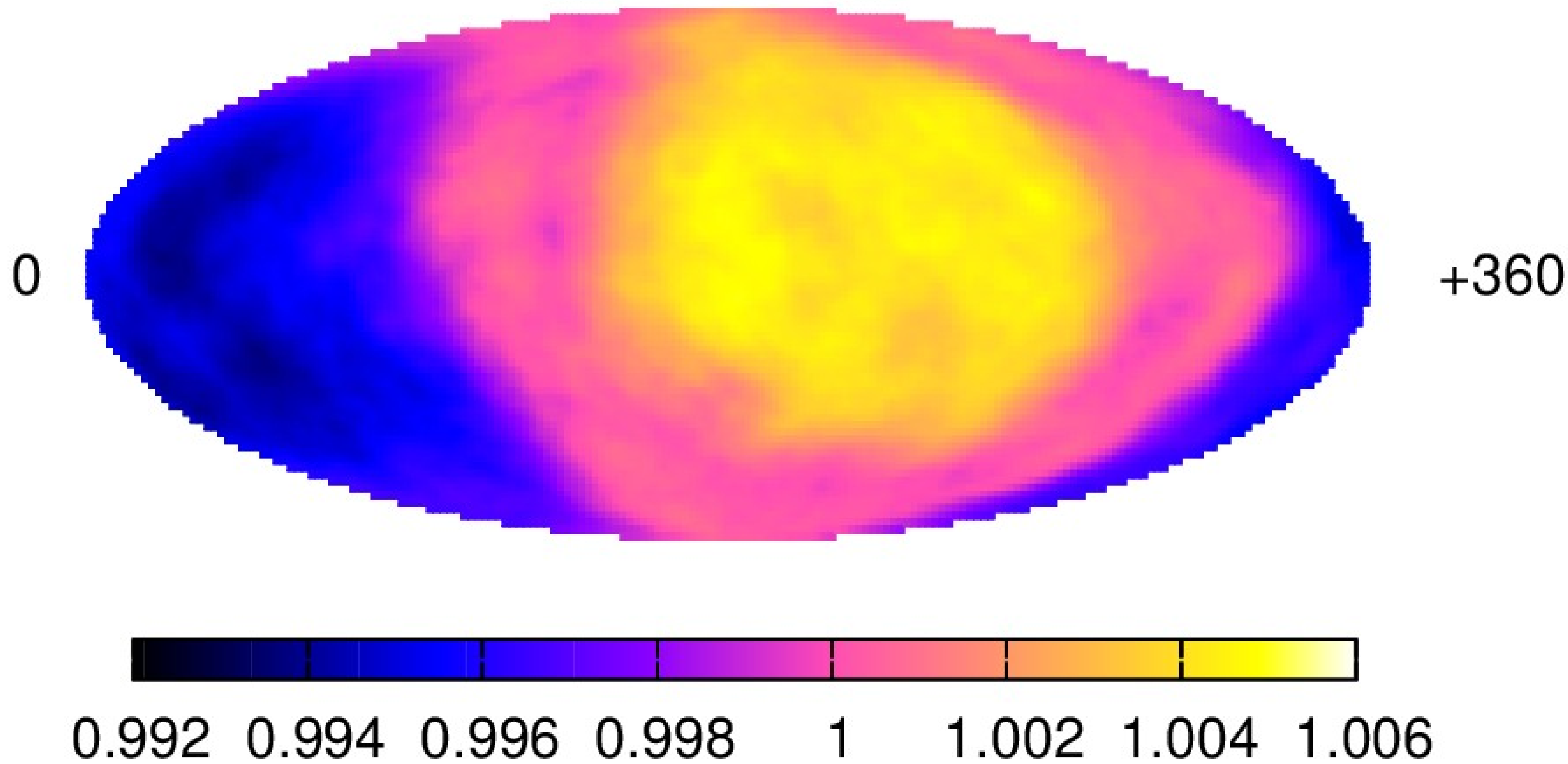
CR Anisotropy – Simulations

E_{CR} = 100 TeV



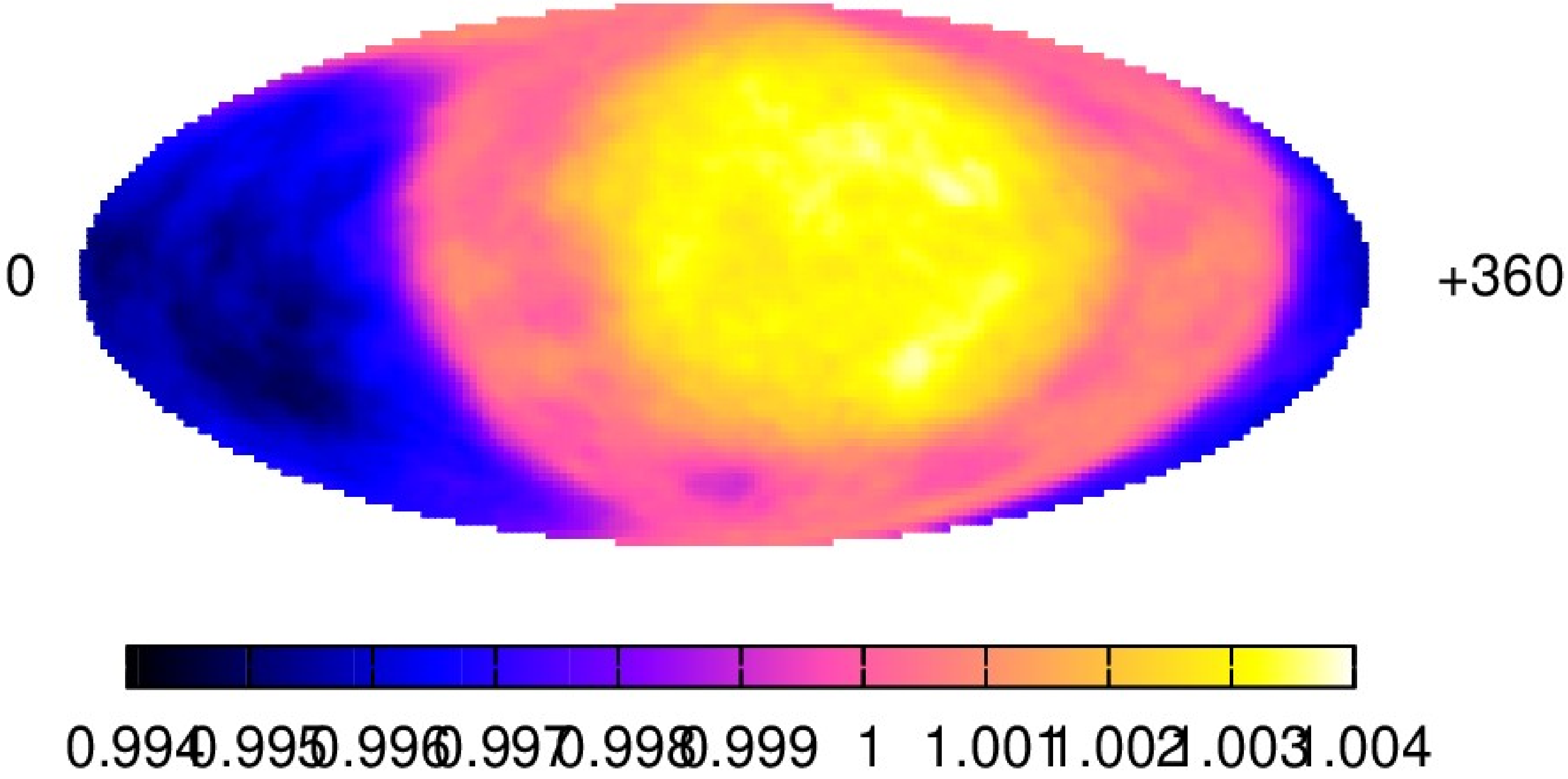
CR Anisotropy – Simulations

E_{CR} = 30 TeV



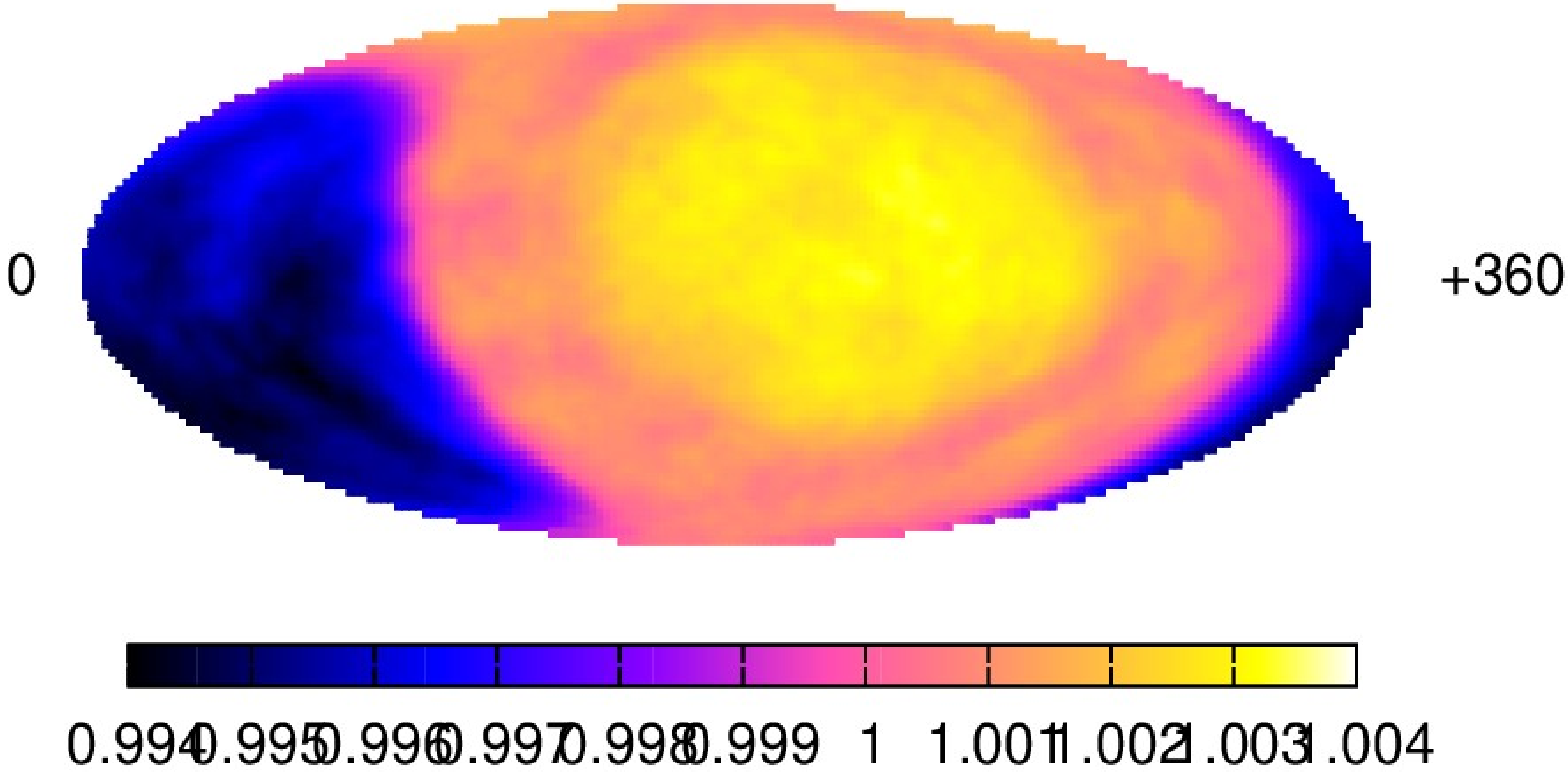
CR Anisotropy – Simulations

E_{CR} = 10 TeV



CR Anisotropy – Simulations

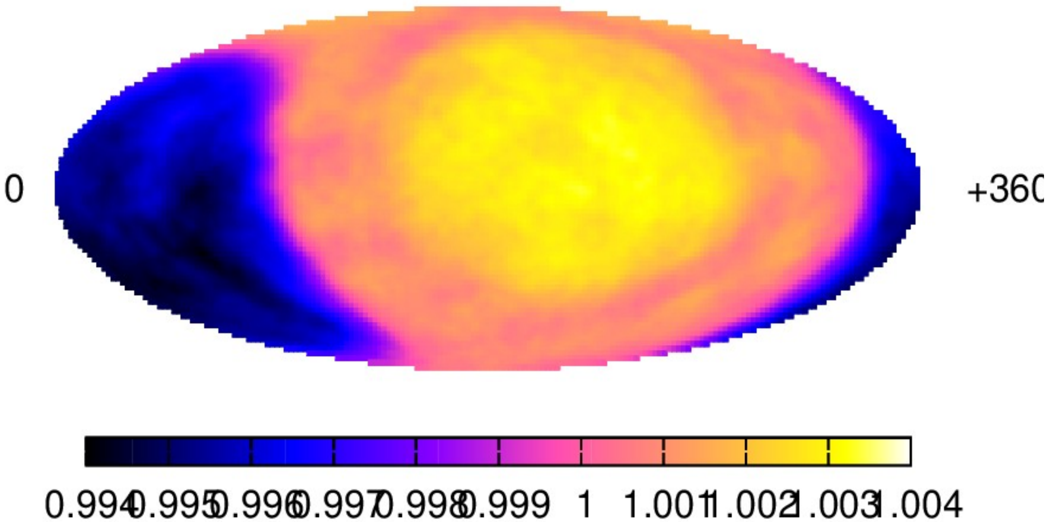
E_{CR} = 3 TeV



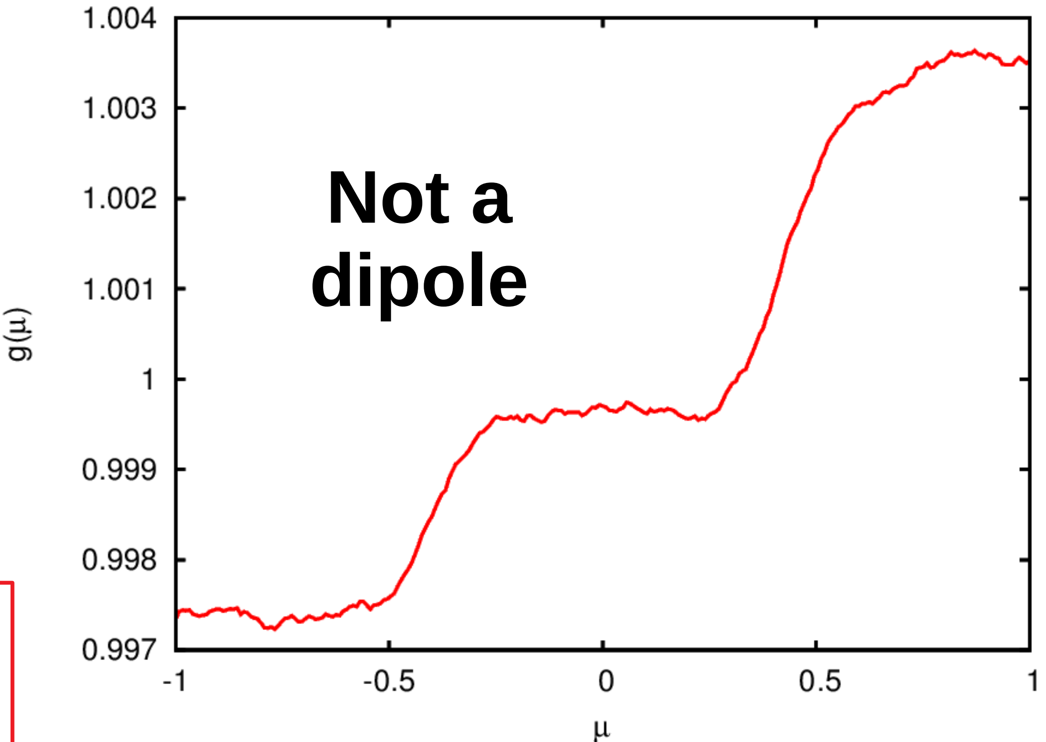
Simulations down to 3 TeV

First simulations that reach TeV energies with L_{max} = 150 pc

Kolmogorov, B_{rms} = 4 μG



Shape of the large-scale anisotropy:



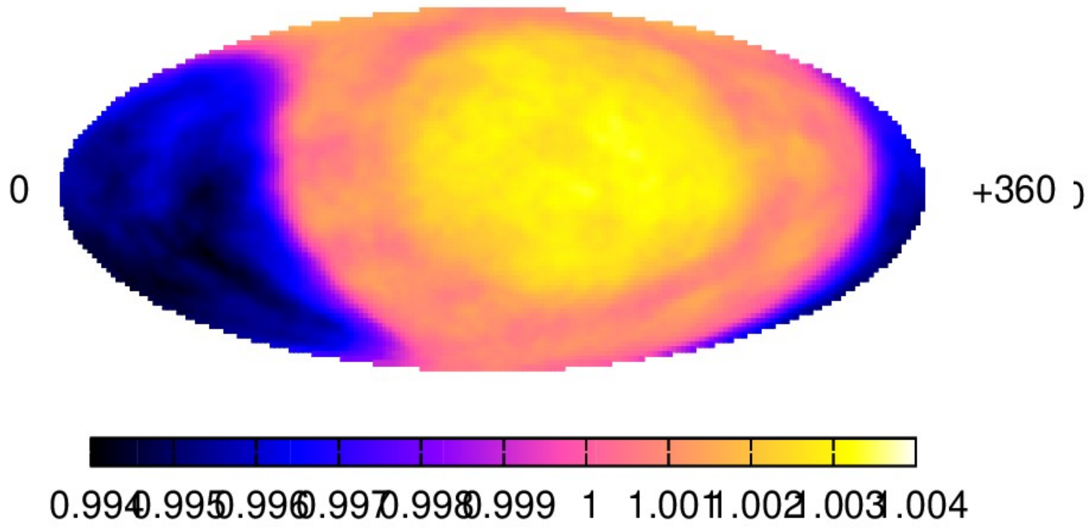
→ LSA aligns with the direction of local magnetic field lines,

→ LSA **not a dipole.**

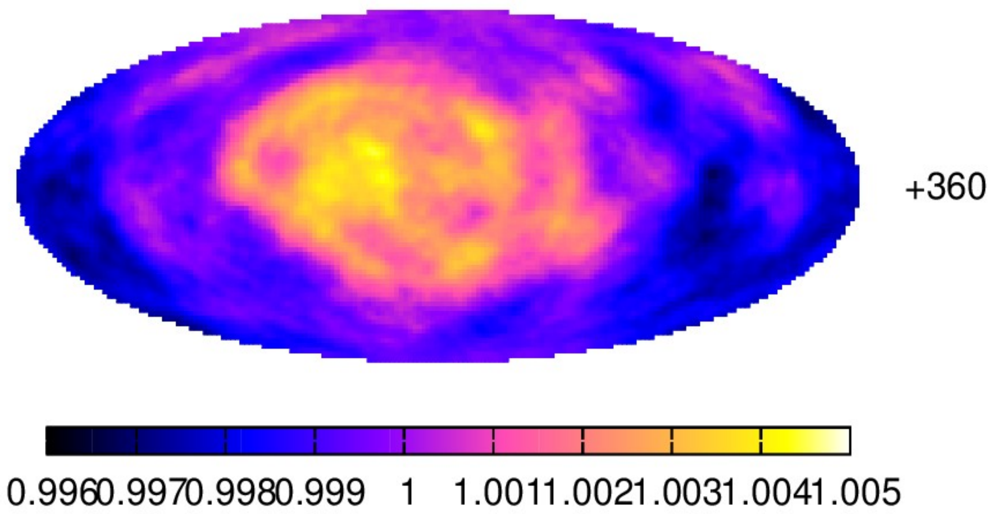
Simulations down to 3 TeV

First simulations that reach TeV energies with L_{max} = 150 pc

Observer 1 (Low δB/B):



Observer 2 (High δB/B):

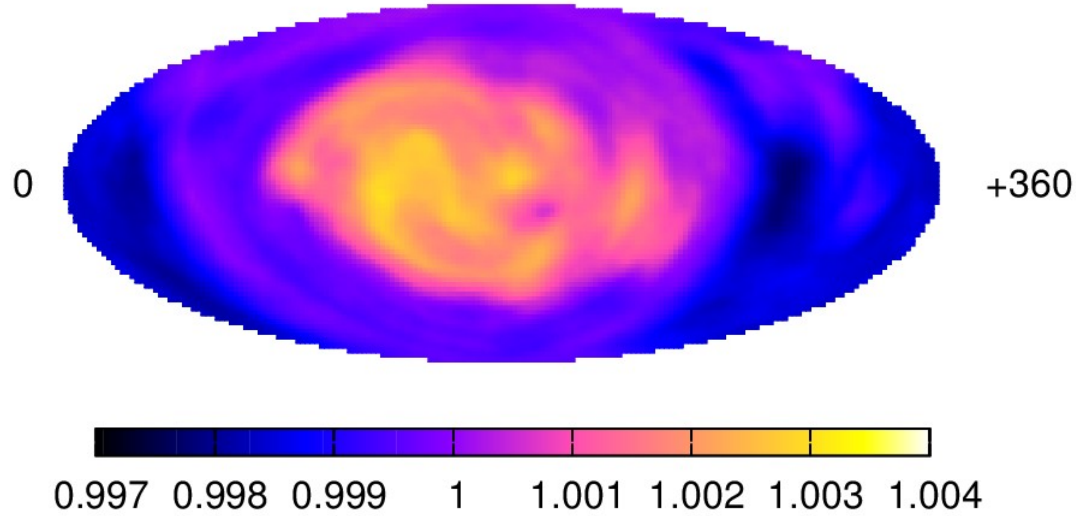


→ "Non-gyrotropic", smaller-scale anisotropies appear too,

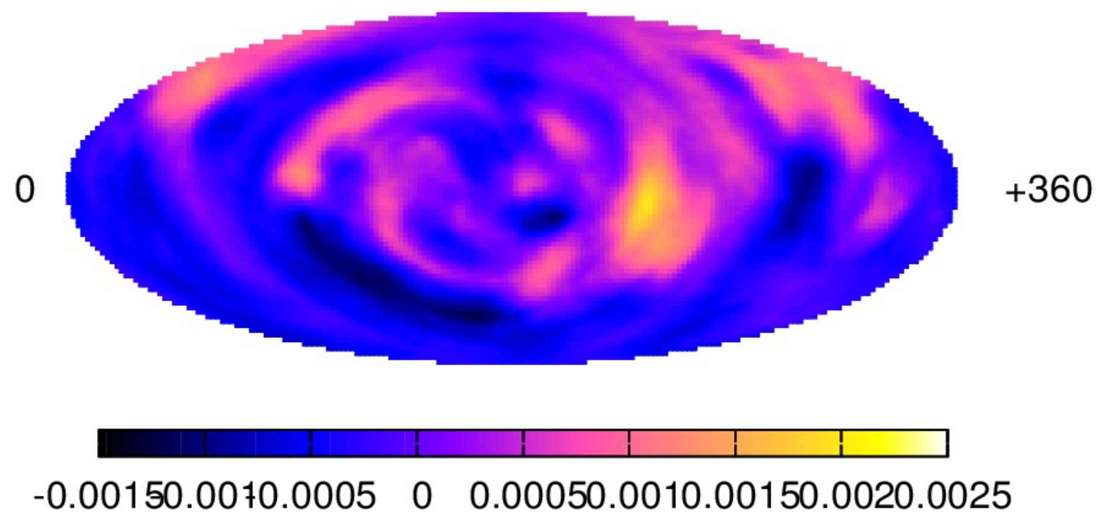
→ Ampl. SSA/LSA related to local δB/B on gyroresonant scales.

(non-gyrotropic) small-scale anisotropies

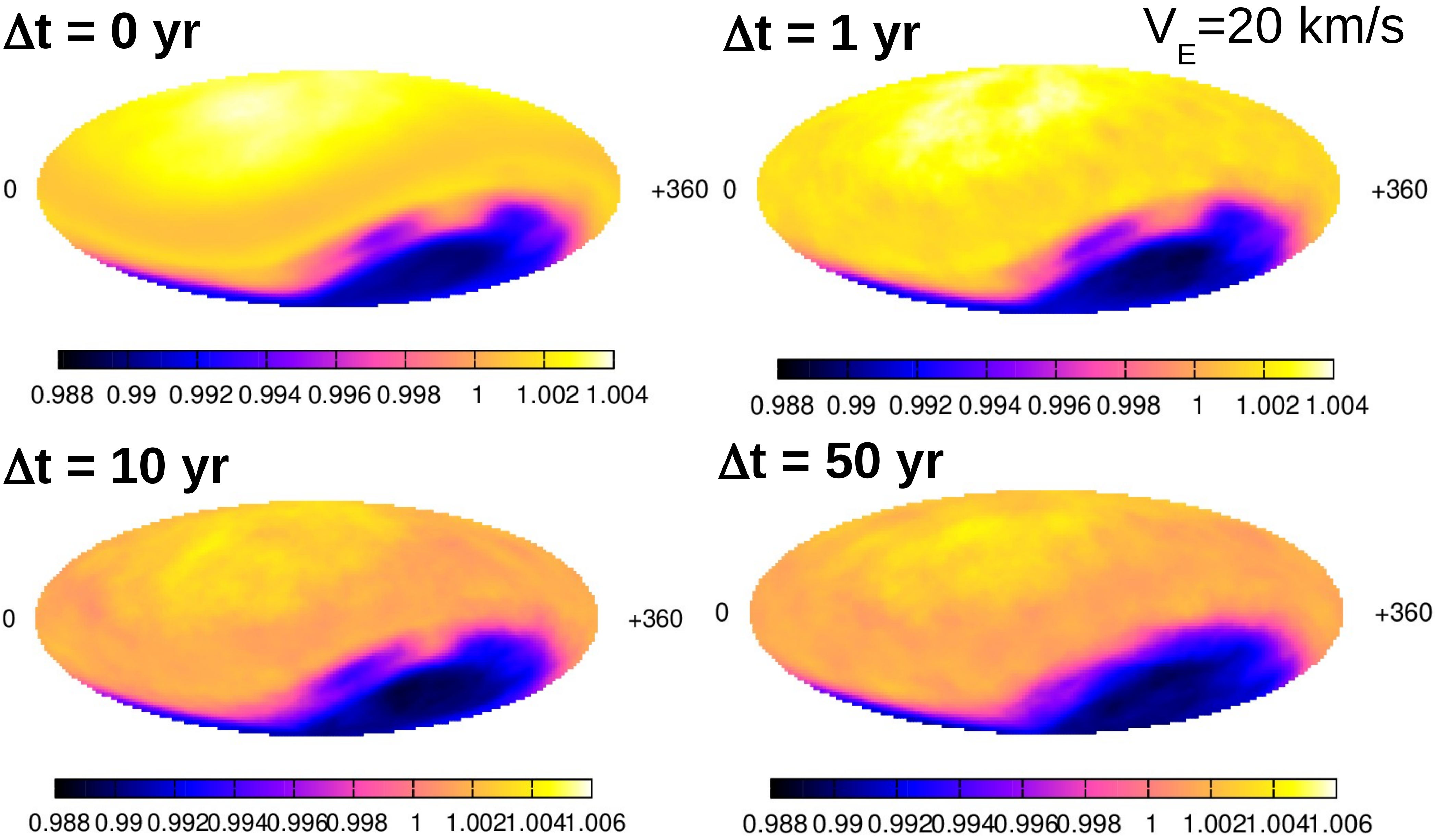
Total anisotropy



SSA



Time variability at 3 TeV



At E ~ TeV, SSA should vary on ~ 10 yr timescale

Conclusions

(1) Large-scale CR Anisotropy = New probe of local ISMFs and CR transport properties.

→ *Aligns with local B field. Shape in μ contains crucial information on the properties of the local turbulence.*

(2) Small Scales (non-gyrotropic) : Probe of the local realization of the ISM turbulent fields, within a CR MFP around Earth.

→ *Relative amplitude with respect to large-scale CRA depends on local $\delta B/B$.*

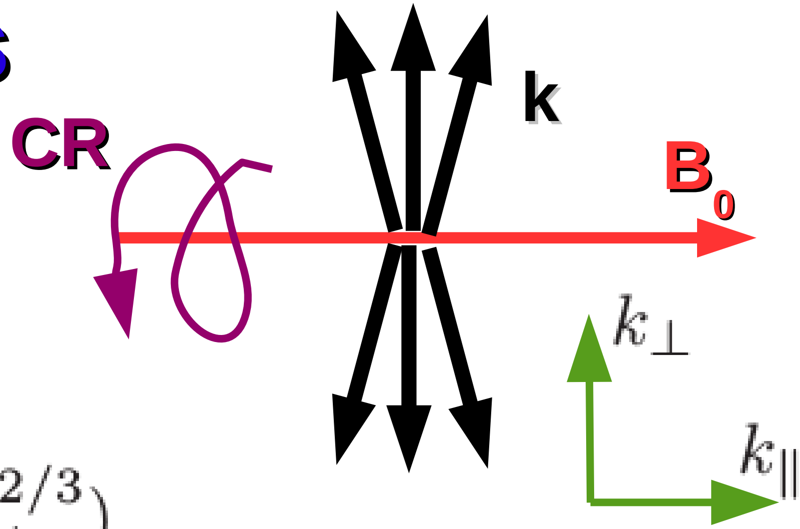
Conclusions

→ LSA : Aligns with local B field lines. Gyrotropy assumption ~ OK at E <~ 100 TeV – 1 PeV,

→ LSA : Flattening in directions perpendicular to field lines. Shape in μ contains crucial information on the properties of the local turbulence,

→ SSA : Do appear with the correct amplitude at TeV energies. Amplitude also depends on local $\delta B/B$.

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

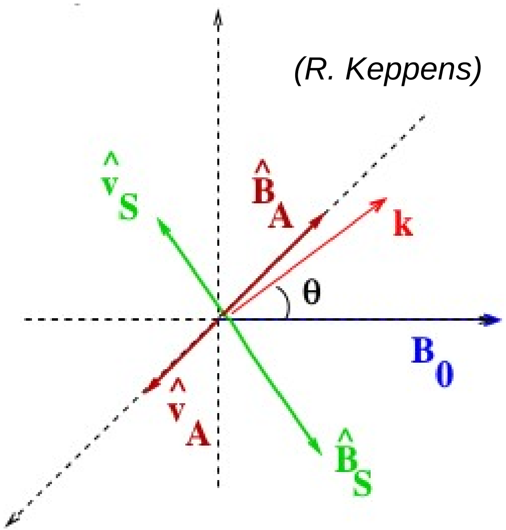
Pitch-angle diffusion coefficient

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

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

$z = k_{\perp} l \varepsilon \sqrt{1-\mu^2}$, and Ω is the Larmor frequency.

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



Resonance functions (RF)

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

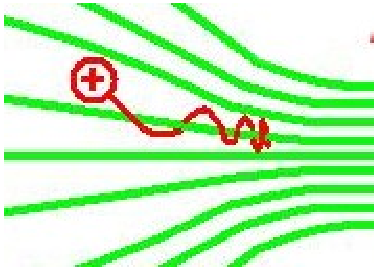
Chandran (2000)

$$R_{n,1}(k_{\|}v_{\|} - \omega + n\Omega) = \frac{\tau_w^{-1}}{(k_{\|}v_{\|} - \omega + n\Omega)^2 + \tau_w^{-2}}$$

Lagr. corr. time for strong aniso. incompr. MHD turb. → $\tau_{A,S} = l^{1/3}/(v_A k_\perp^{2/3})$

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

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



Yan & Lazarian (2008)

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

$$R_{n,2}(k_{\|}v_{\|} - \omega + n\Omega) = \frac{\sqrt{\pi}}{k_{\|}v_\perp \delta\mathcal{M}_A^{1/2}} \exp\left(-\frac{(k_{\|}v_{\|} - \omega + n\Omega)^2}{k_{\|}^2 v_\perp^2 \delta\mathcal{M}_A}\right)$$