SIMULATIONS OF THE TeV-PeV COSMIC-RAY ANISOTROPY

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

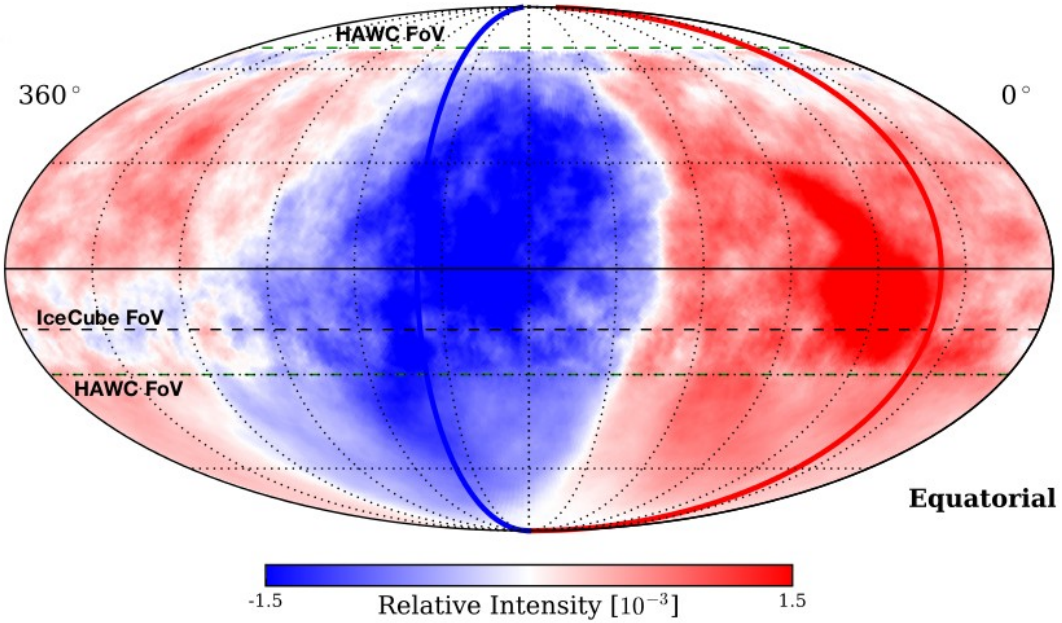
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

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

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

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

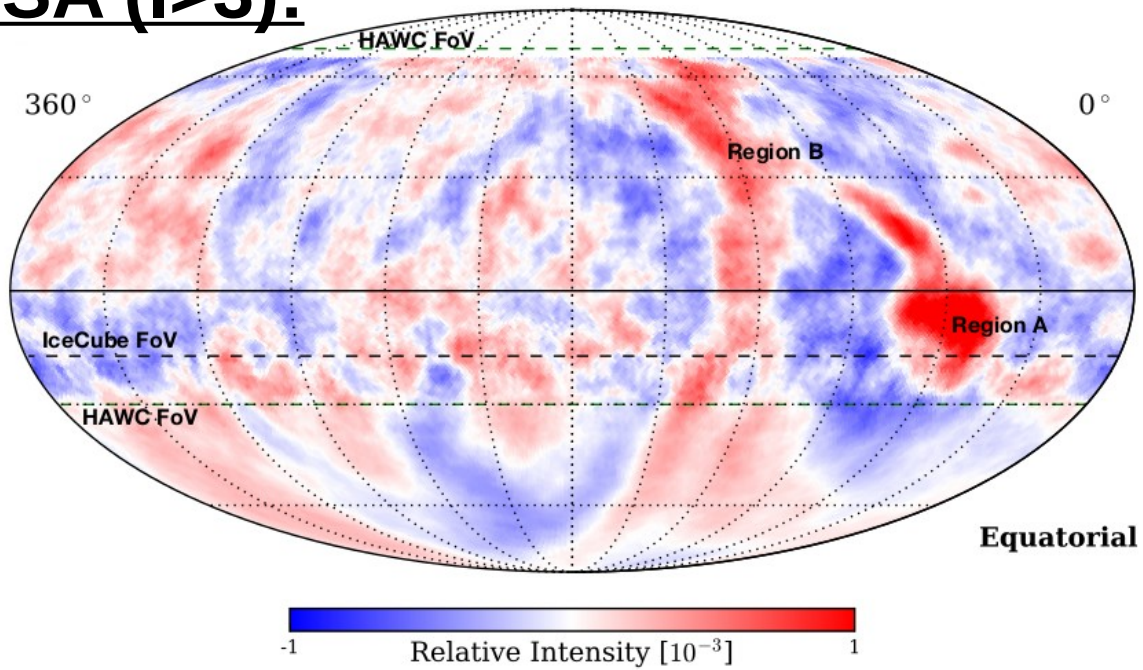
Large Scale Anisotropy (~0.1%) :



In the direction of field lines

SHAPE: NOT a dipole in general

SSA (I>3):

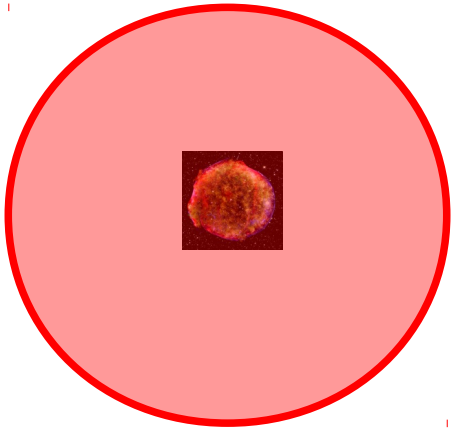


- Energy-dependent,
- No/Litte time-dependence
- Amplitude: LSA/(few – 10)

CR Anisotropy

(Dipole) Anisotropy

→ **Direction**

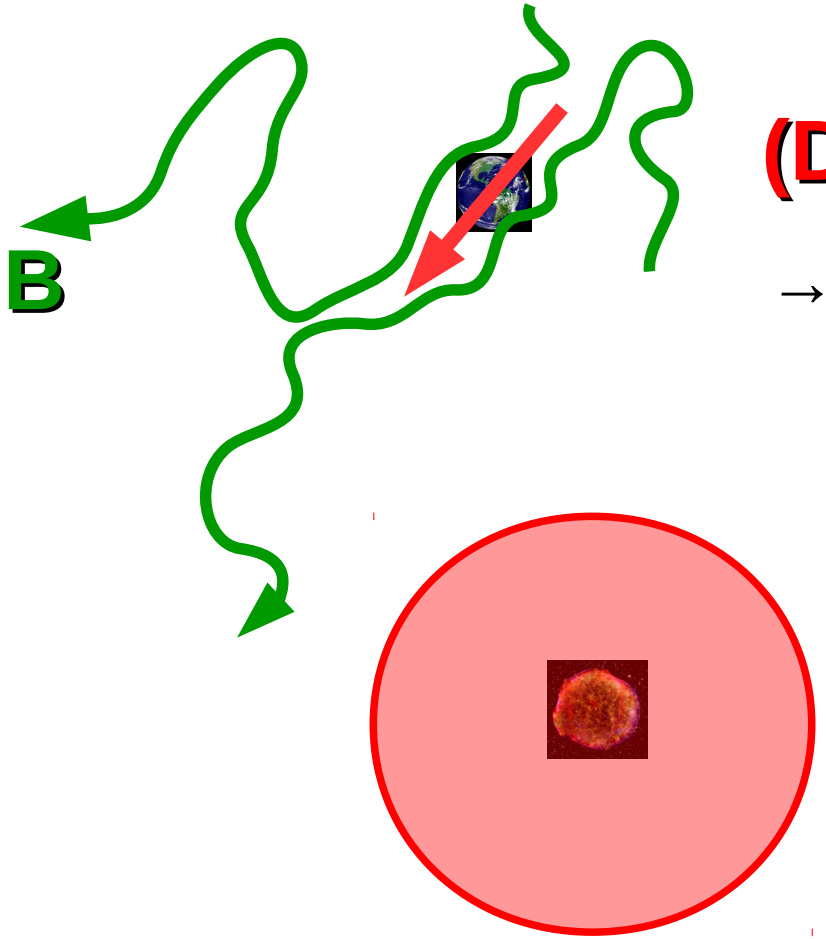


Amplitude

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

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

CR Anisotropy



(Dipole) Anisotropy

→ **Direction B field**

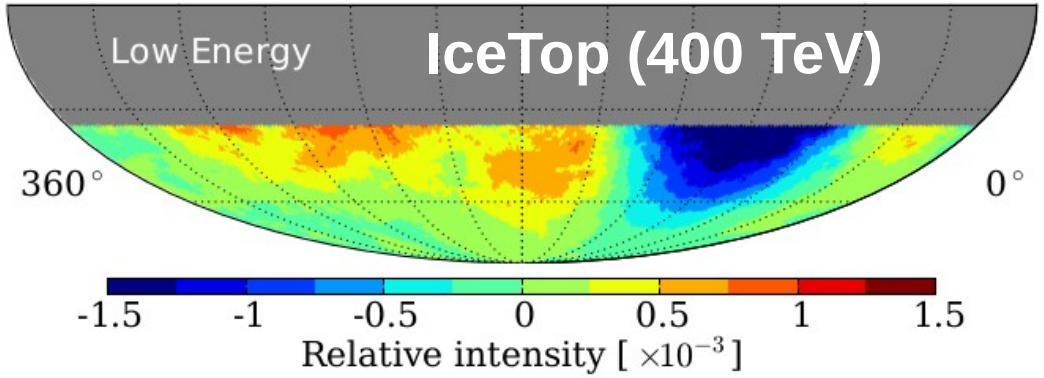
cf. Schwadron et al., Science (2014)

~ 180° flip at 100 TeV:

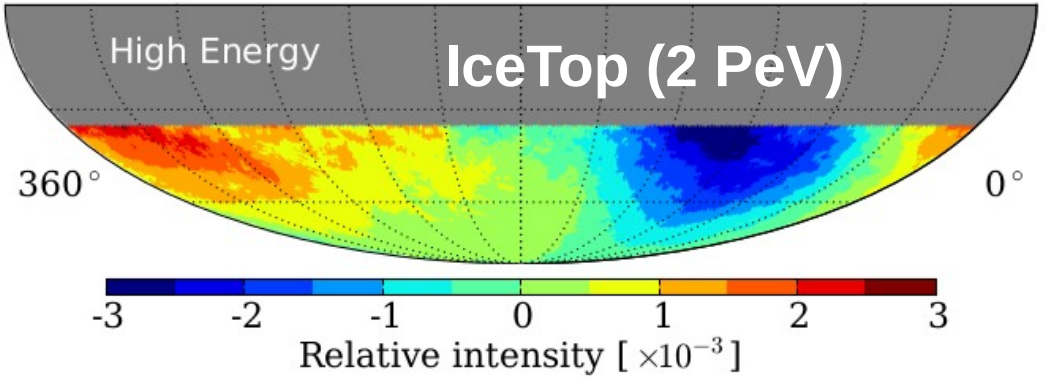
cf. Ahlers, PRL (2016)

Large-Scale Anisotropy is NOT a dipole!

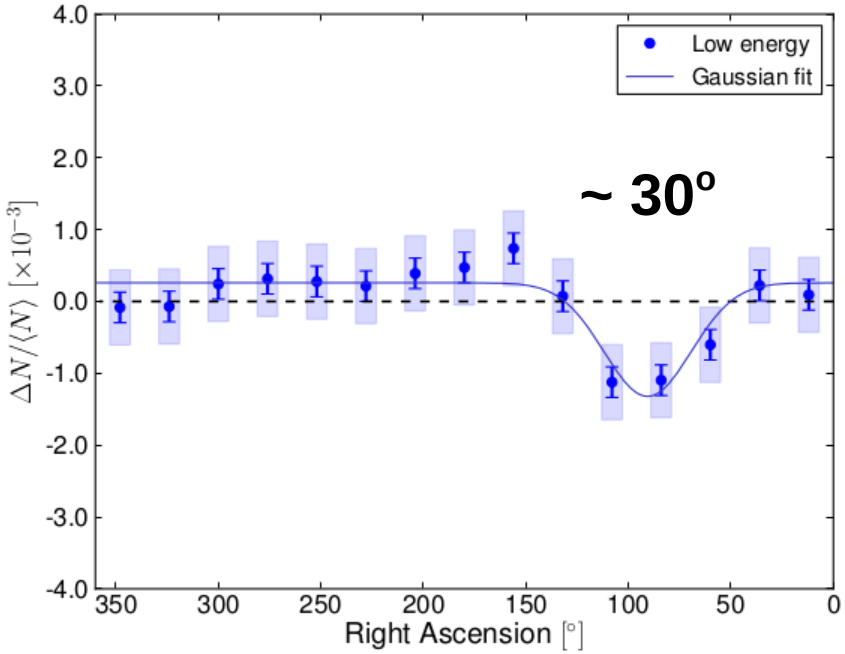
SHAPE of the **L-S Anisotropy**

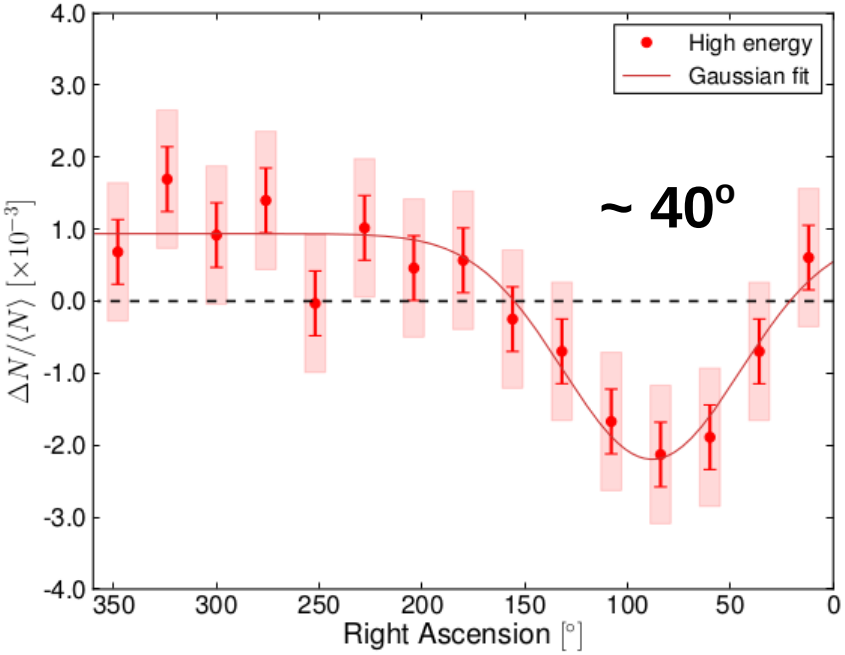


Aartsen et al. (2013)

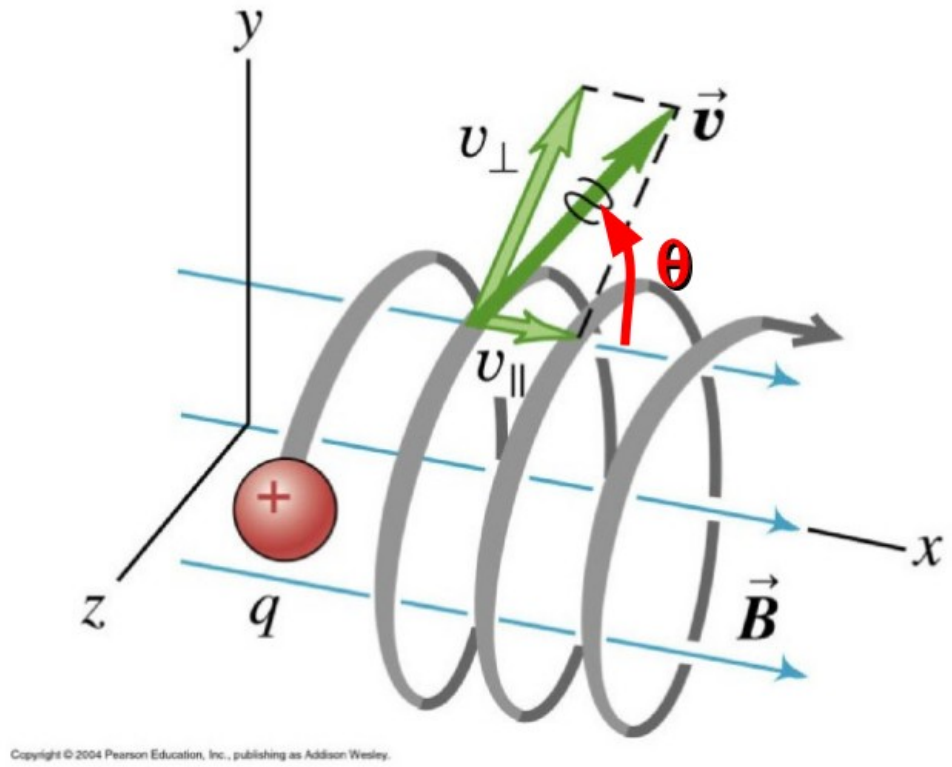


Also at 20 TeV...

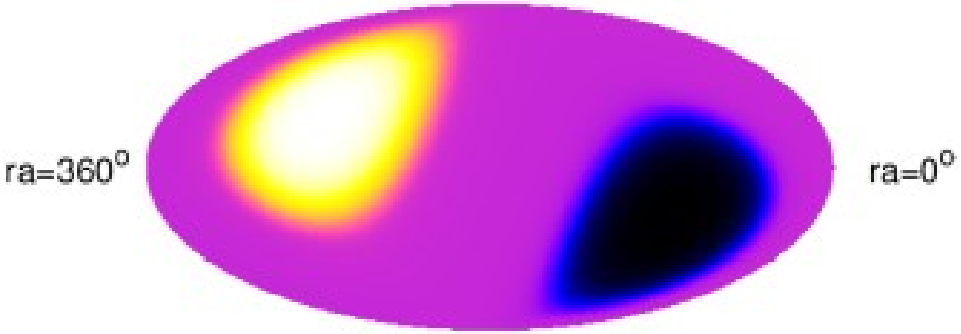


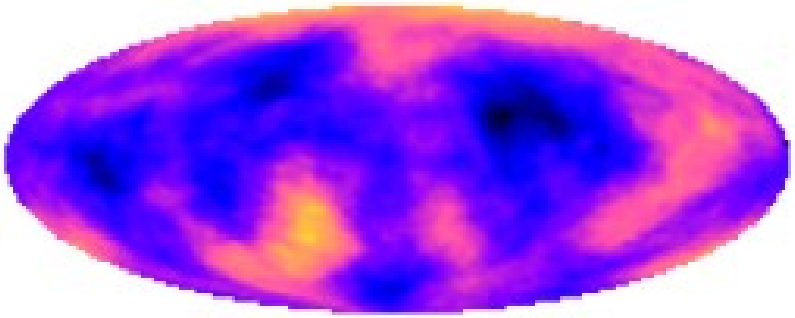


Pitch-angle (θ) and gyrophase:

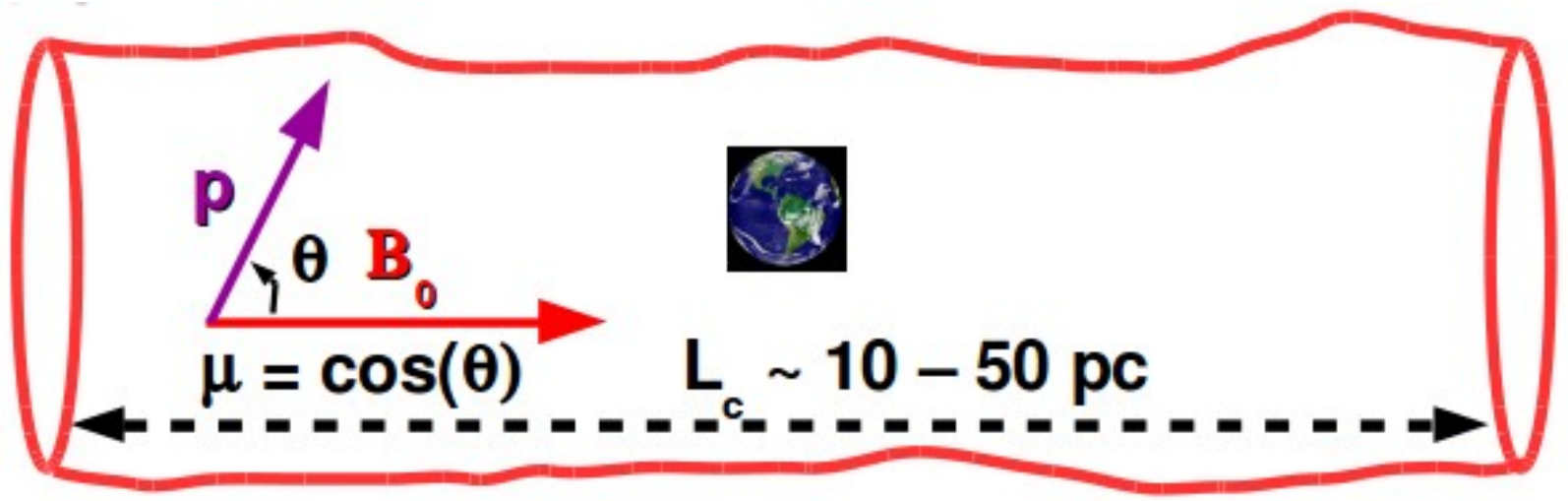


CRA = Large-scale + small-scales





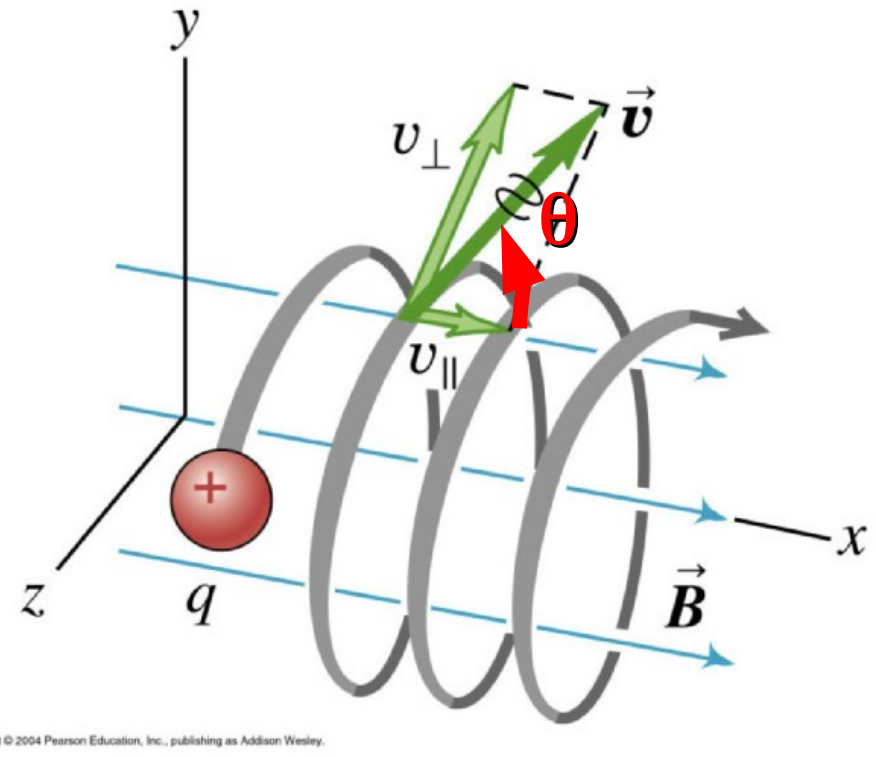
CR Anisotropy : Probe of turbulence



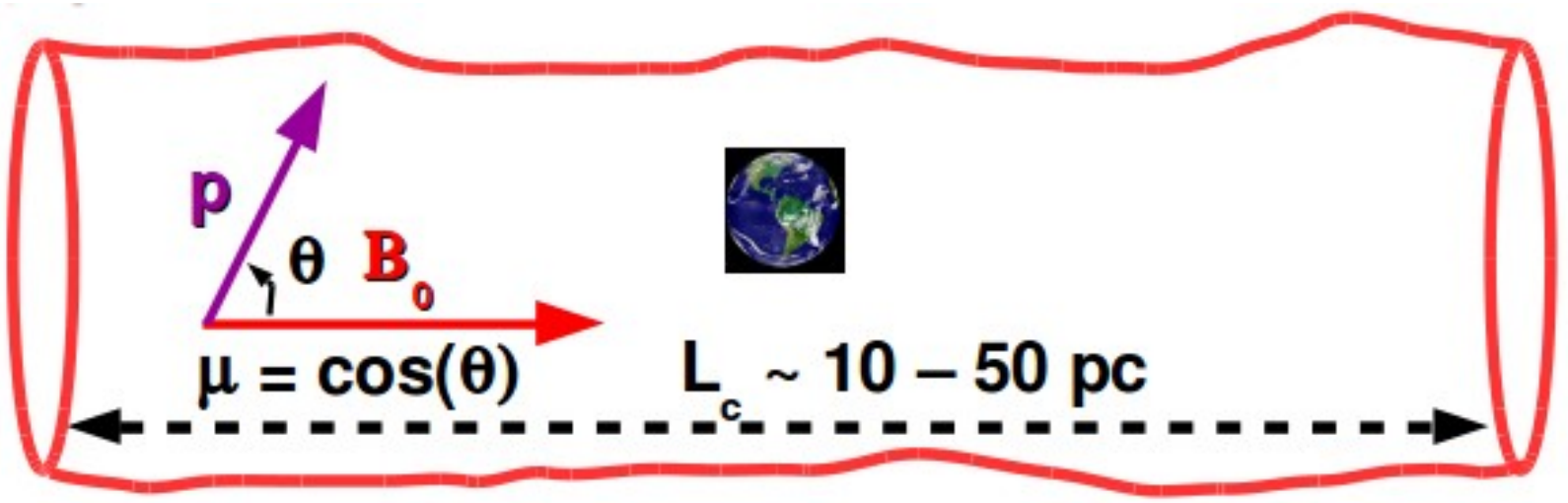
$$\mu v \frac{\partial f}{\partial x} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right)$$

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

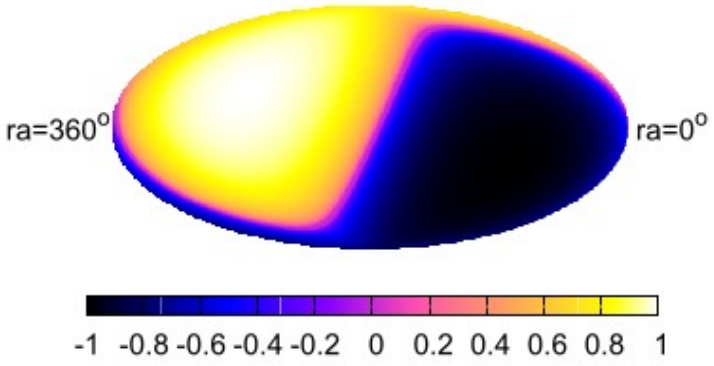
$$\int_0^{\mu} \mathrm{d}\mu' \, \frac{1-\mu'^2}{D_{\mu'\mu'}}$$

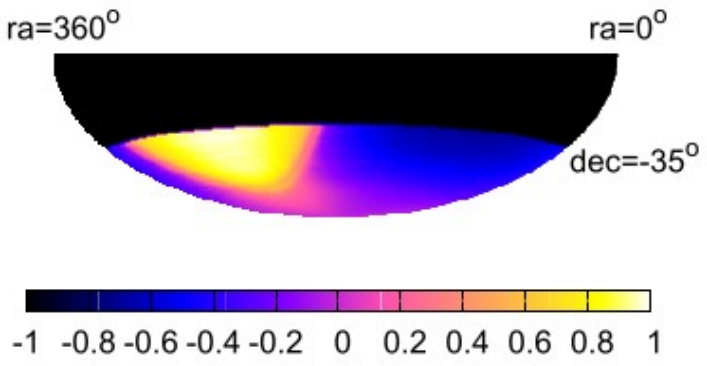
NOT $1 - \mu^2$ **in general !**

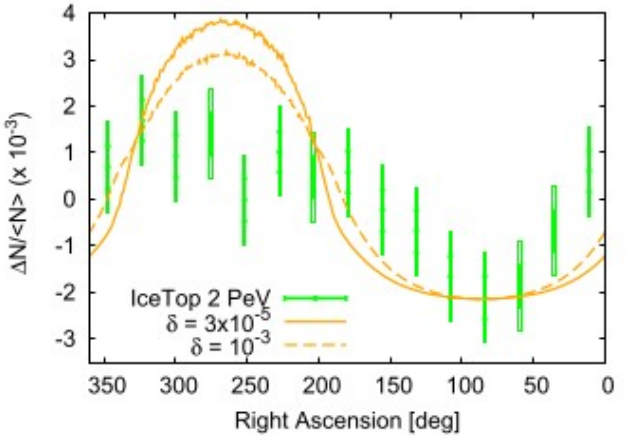
GG & Kirk, ApJ 835, 258 (2017), arXiv:1610.06134

Case 1 : Fast modes & Narrow RF

No dependence of the *shape* on CR energy





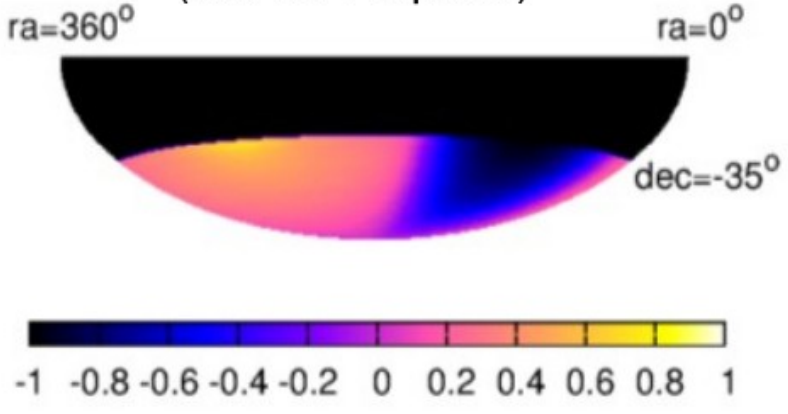


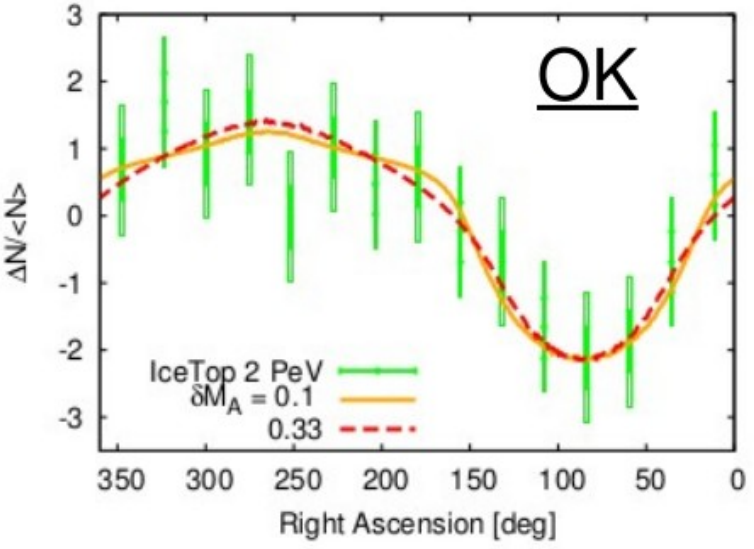
In general: Anisotropy **too wide** with narrow Res Fn => **RULED OUT !**

Case 2 : Fast modes & Broad RF

Can **fit the 2 PeV data** ! →

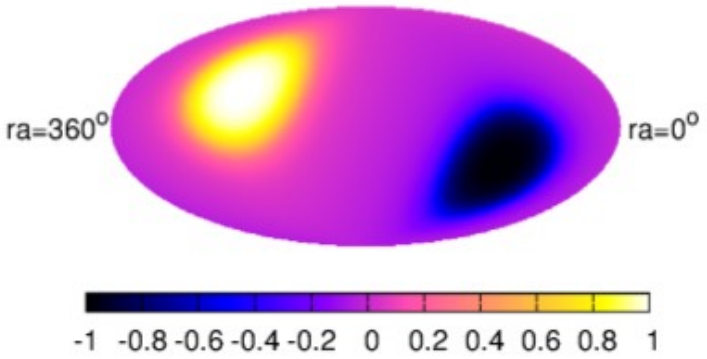
(but no-E dpdce)

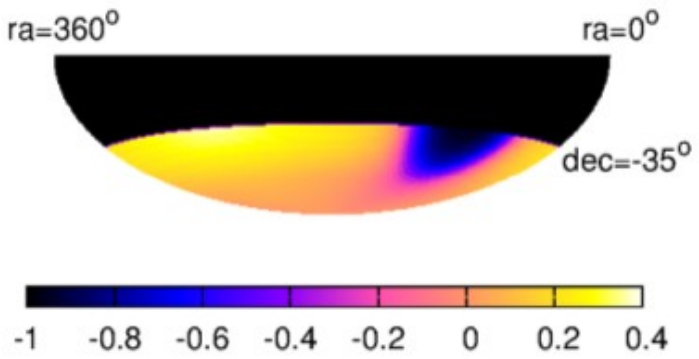


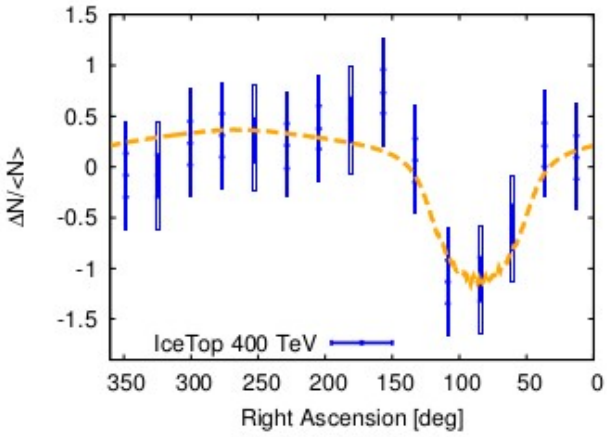


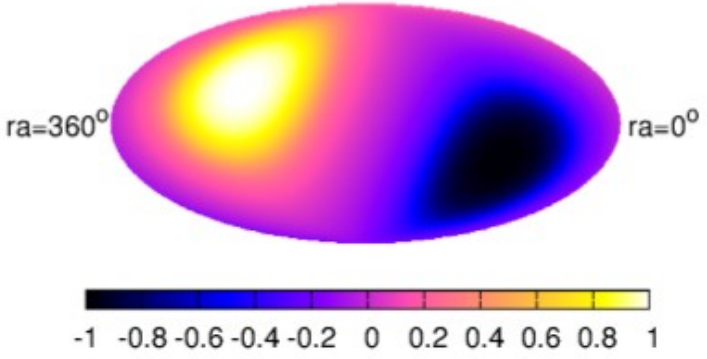
Flattening in directions perpendicular to B field

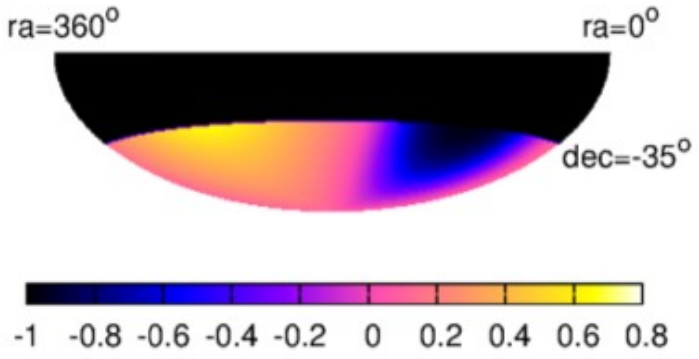
Case 3 : GS – Exponential & Broad RF

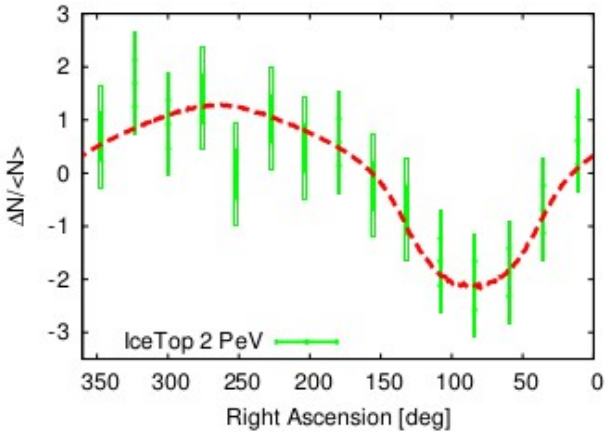












Can fit well the 400 TeV and the 2 PeV data !

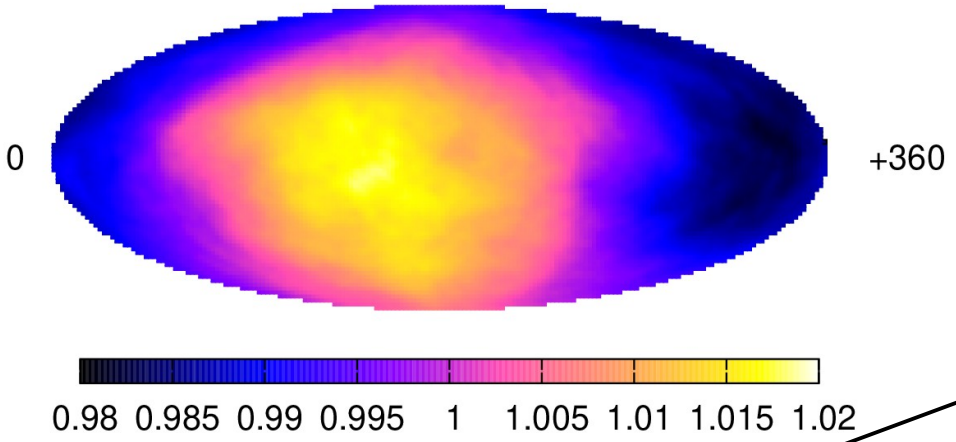
Energy-dependence reproduced for fixed turbulence parameters

First theoretical model to fit this data

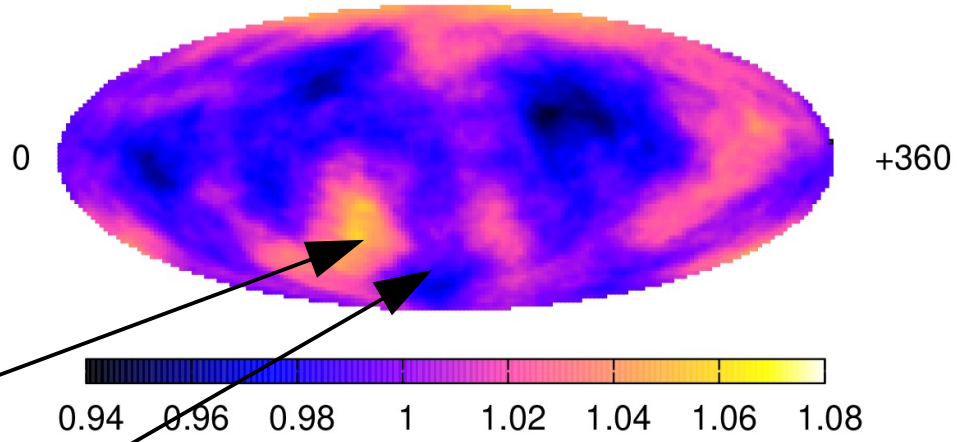
Change in shape with CR energy
- - -> |**k**|-dependent anisotropy in power spectrum?

And the small-scale anisotropies?

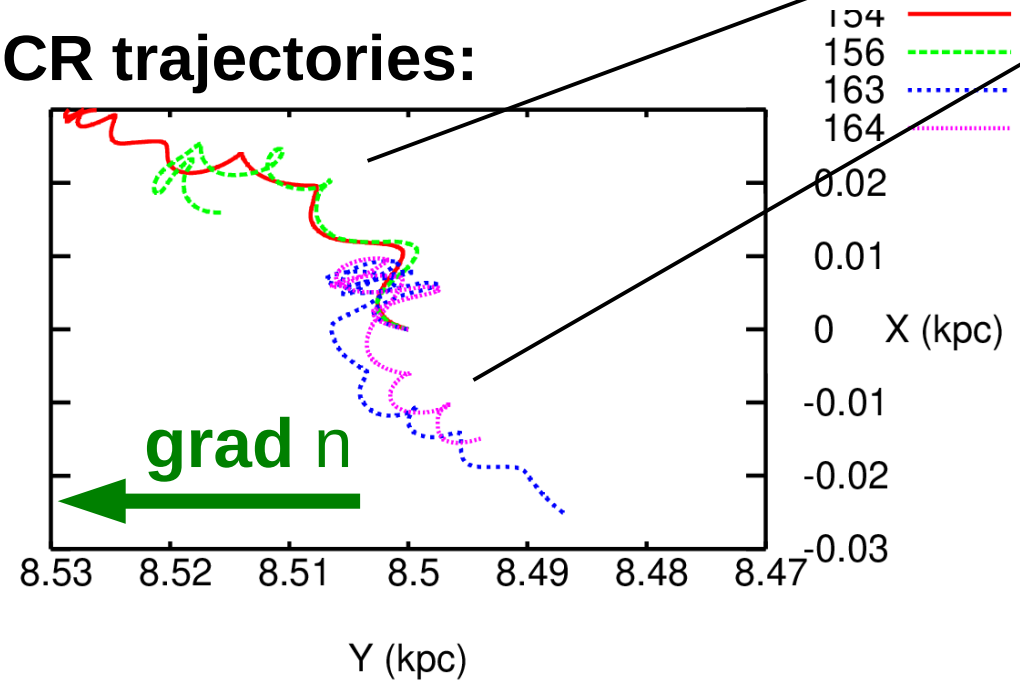
90°smoothing:



20°smoothing – {Dipole}:



CR trajectories:



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

→ Contain signatures of our local environment!

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

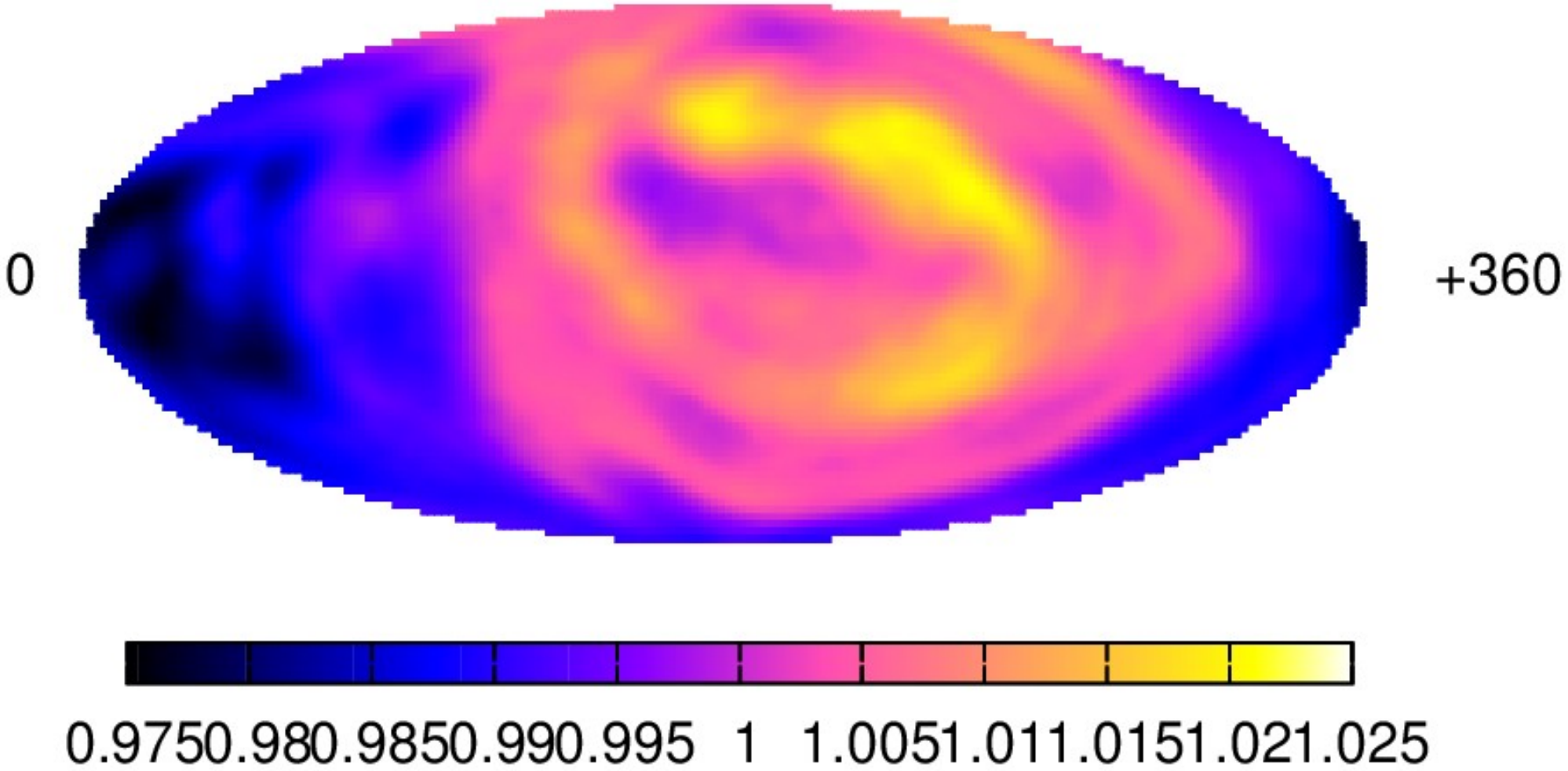
Numerical simulations down to 3 TeV

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

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

CR Anisotropy – Simulations

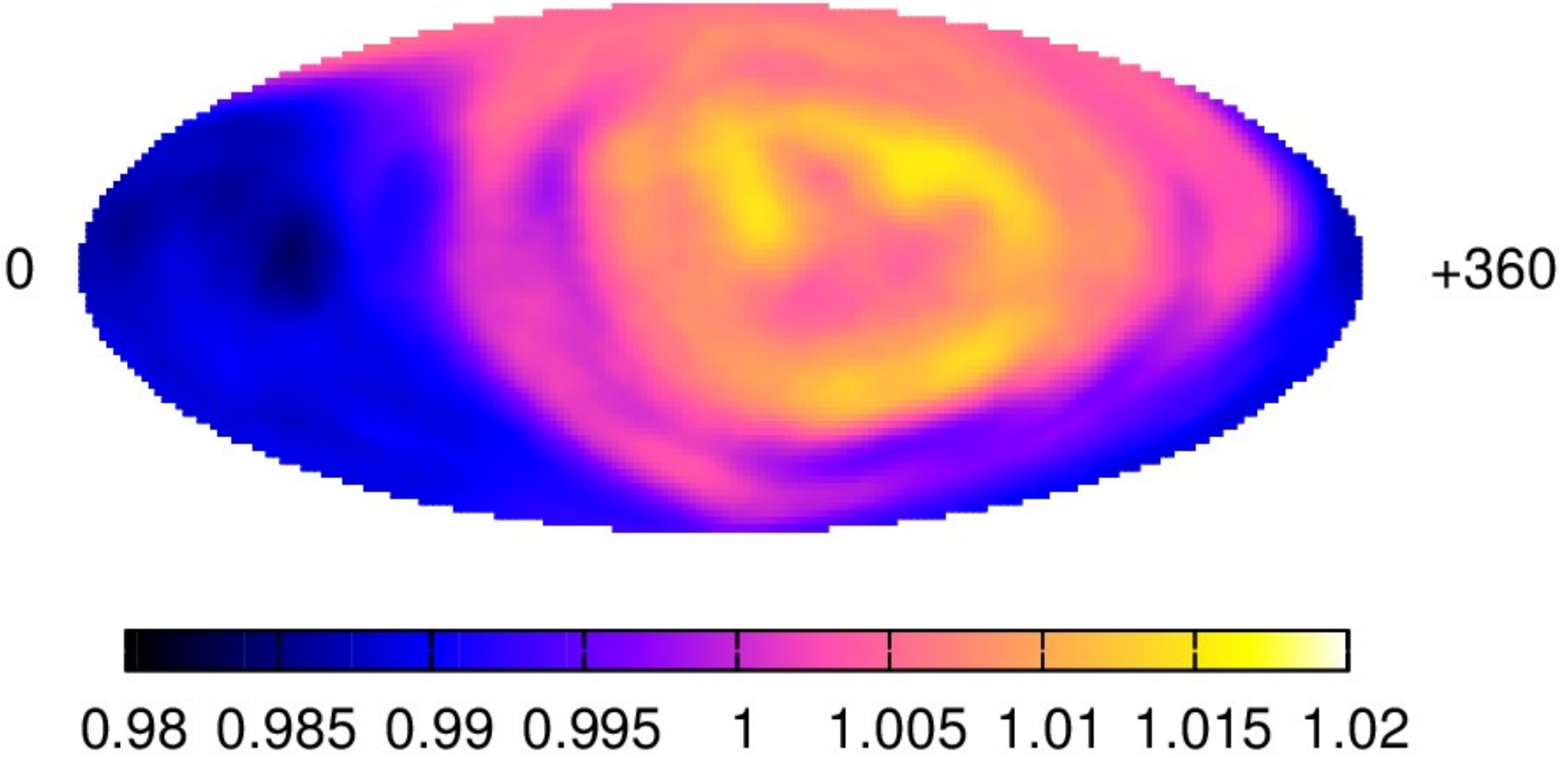
E_{CR} = 1 PeV



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

CR Anisotropy – Simulations

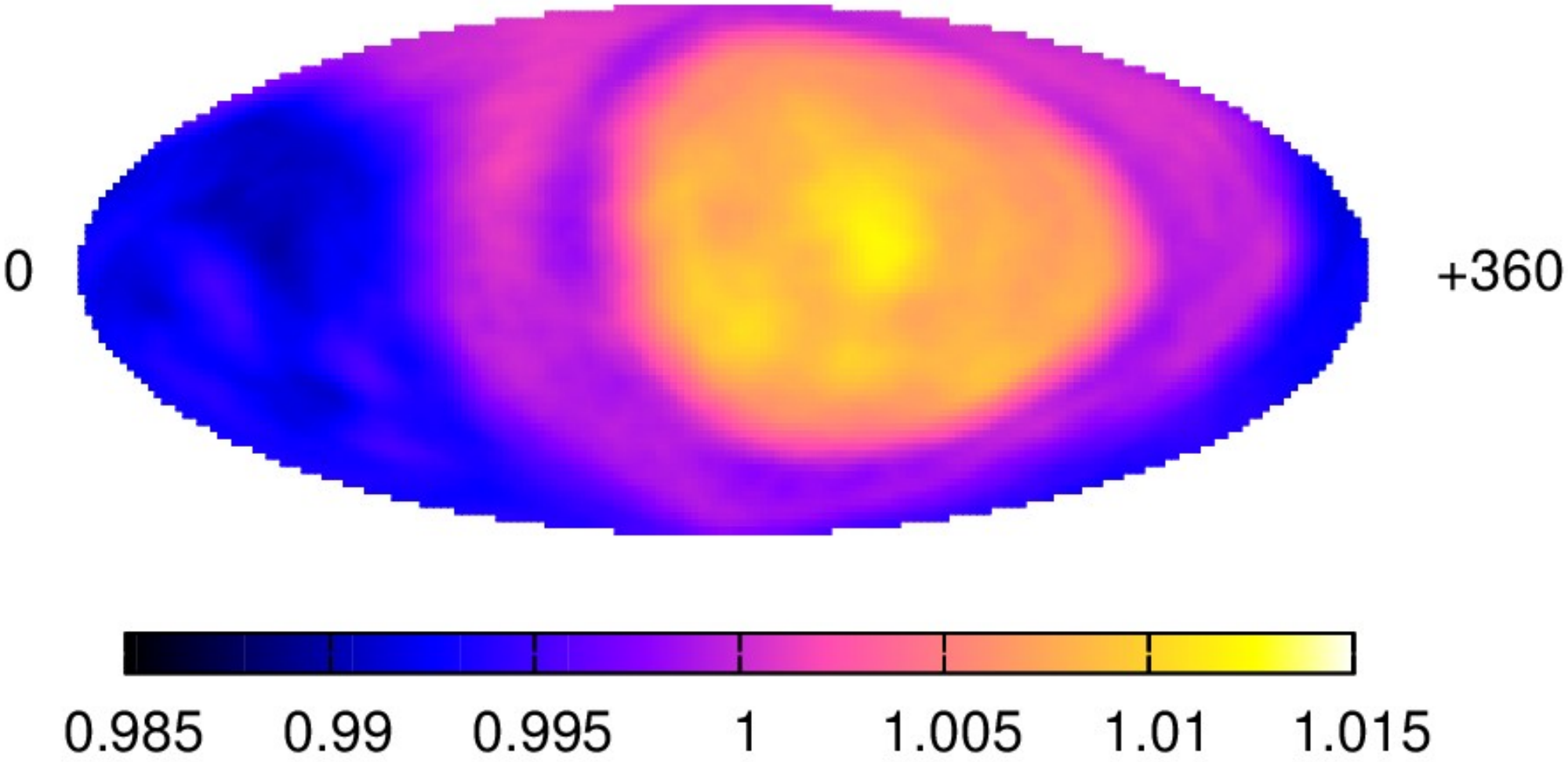
E_{CR} = 300 TeV



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

CR Anisotropy – Simulations

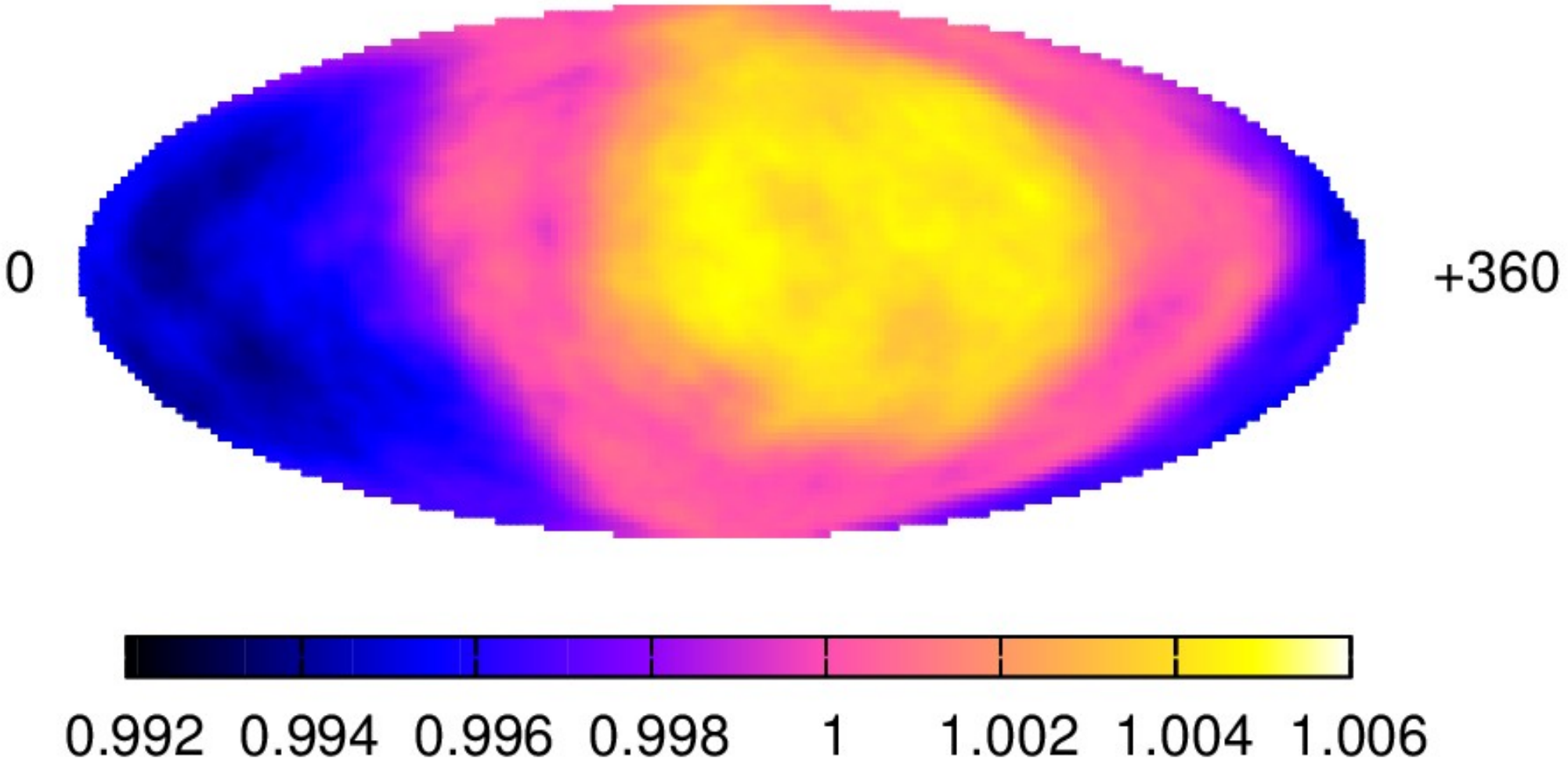
E_{CR} = 100 TeV



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

CR Anisotropy – Simulations

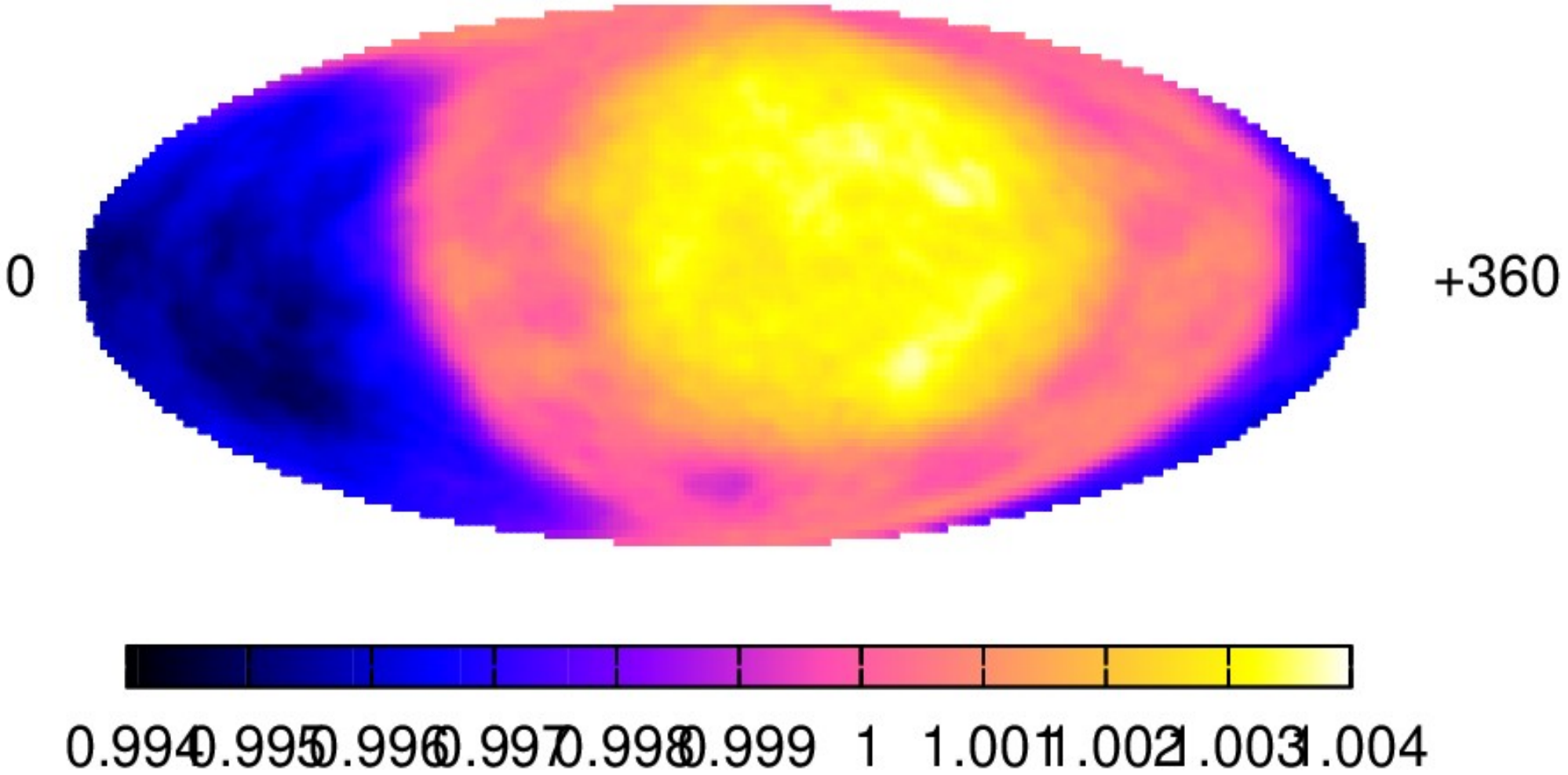
E_{CR} = 30 TeV



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

CR Anisotropy – Simulations

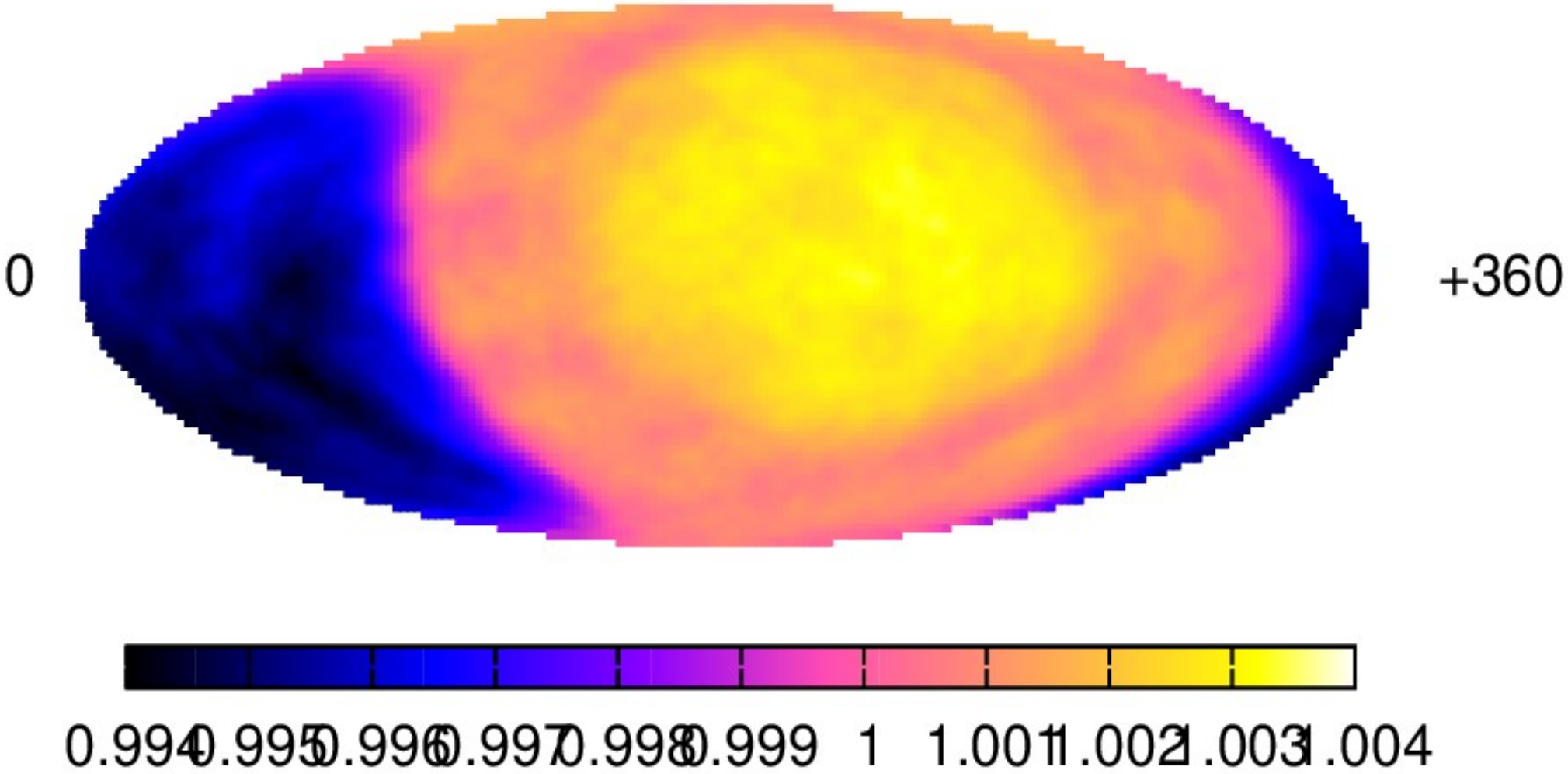
E_{CR} = 10 TeV



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

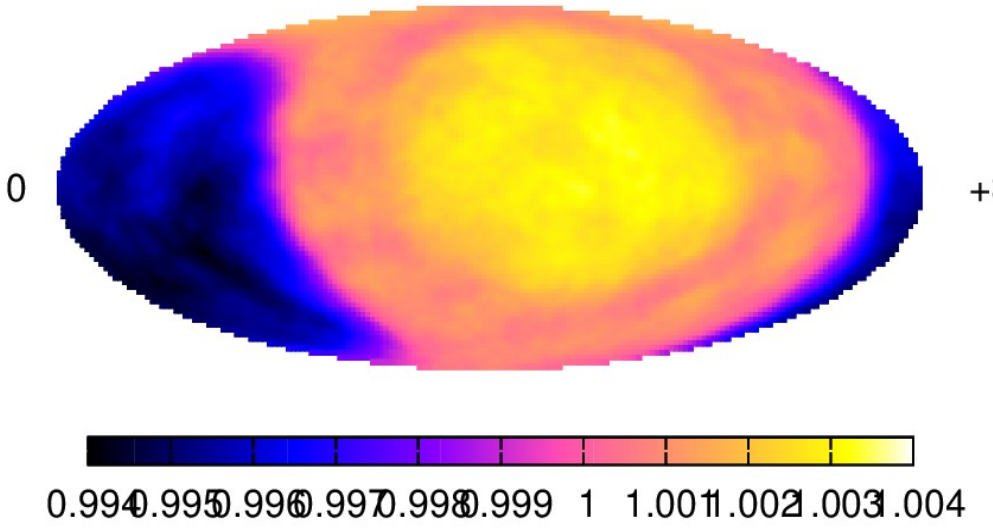
CR Anisotropy – Simulations

E_{CR} = 3 TeV



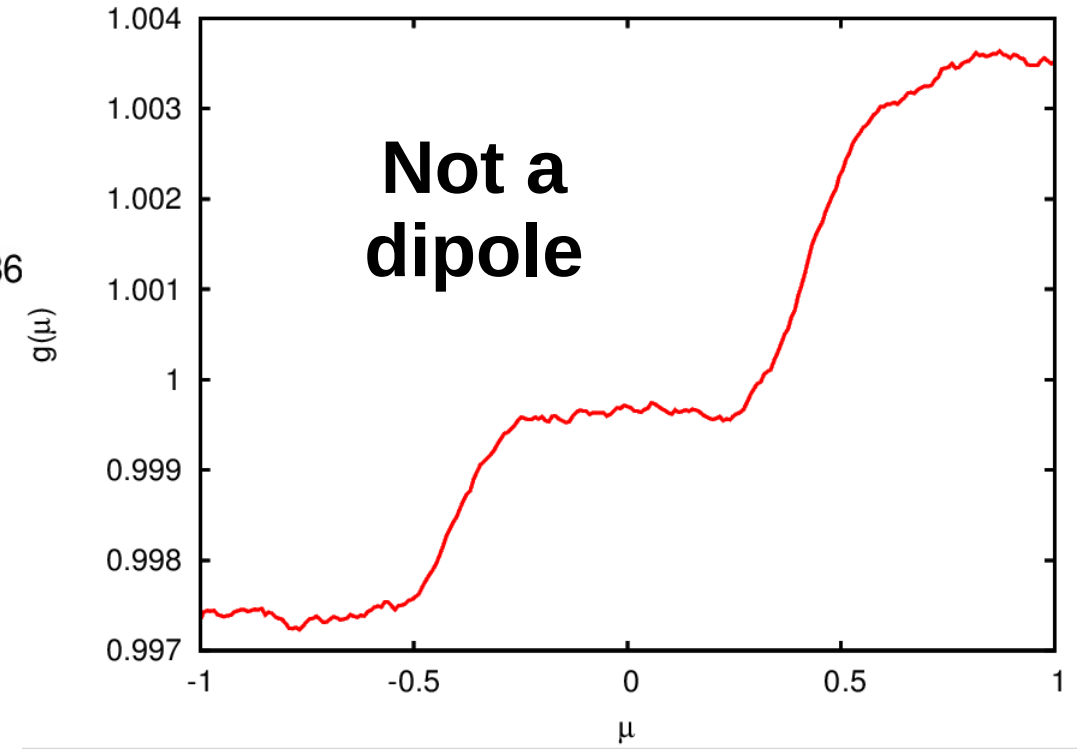
Kolmogorov, B_{rms} = 4μG, L_{max} = 150pc

Simulations down to 3 TeV



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

Shape of the large-scale anisotropy:

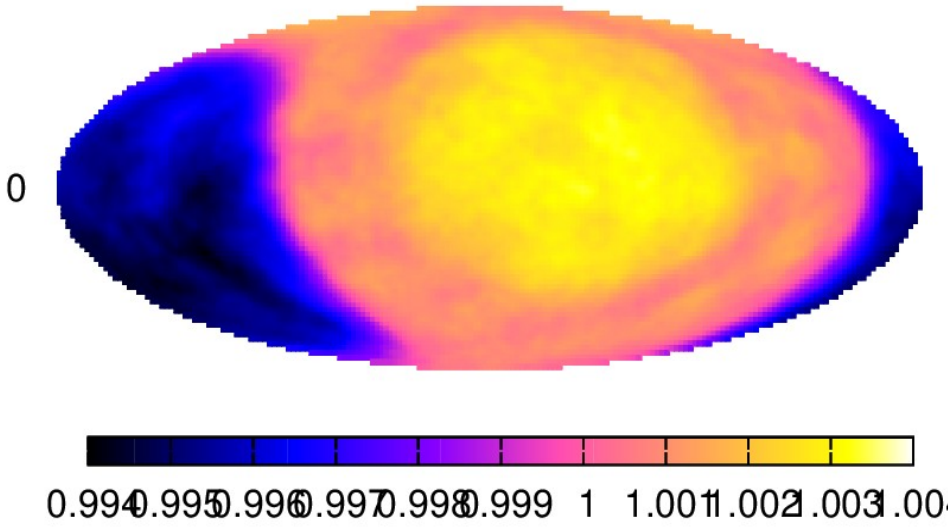


→ **LSA aligns with the direction of local magnetic field lines,**

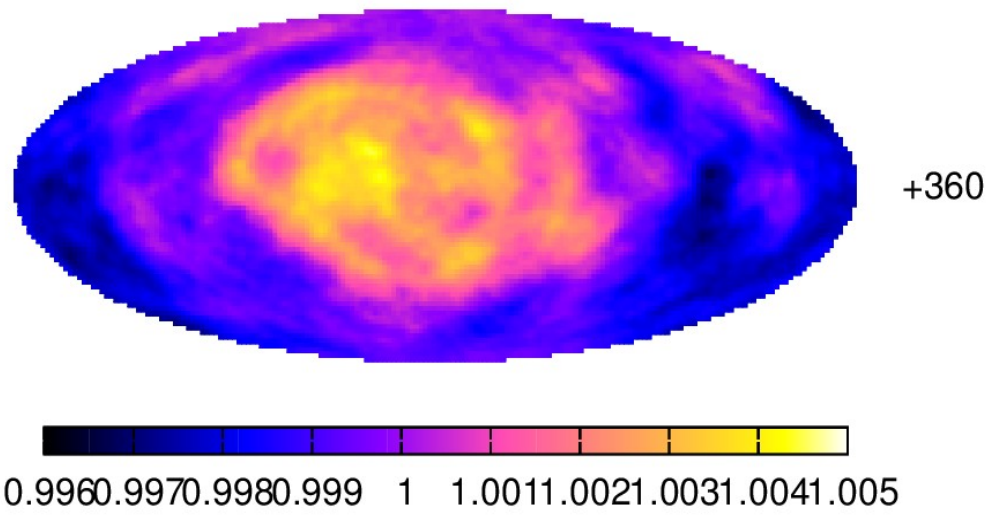
→ **LSA <u>not a dipole</u>.**

Simulations down to 3 TeV

Observer 1 (Low δB/B):



Observer 2 (High δB/B):

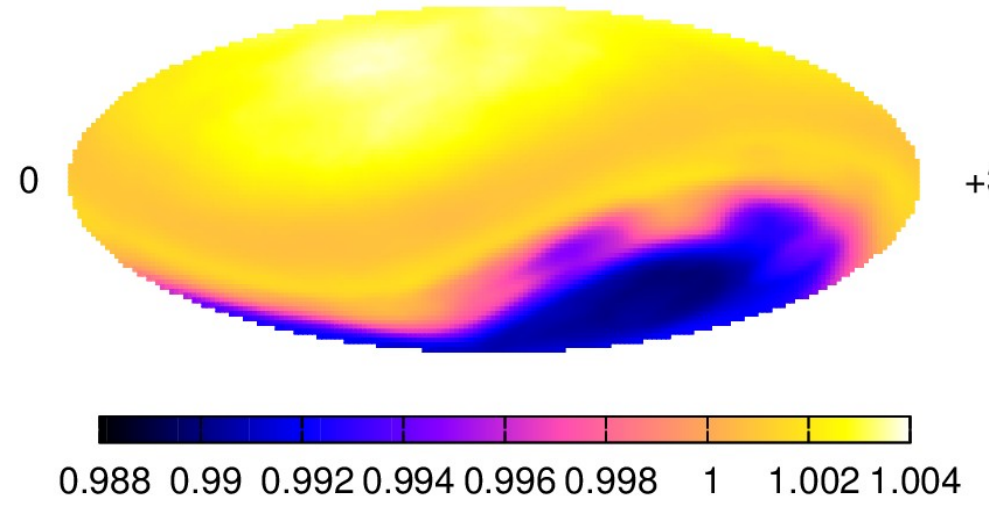


→ **“Non-gyrotropic”, smaller-scale anisotropies appear too,**
→ **Ampl. SSA/LSA related to local δB/B on gyroresonant scales.**

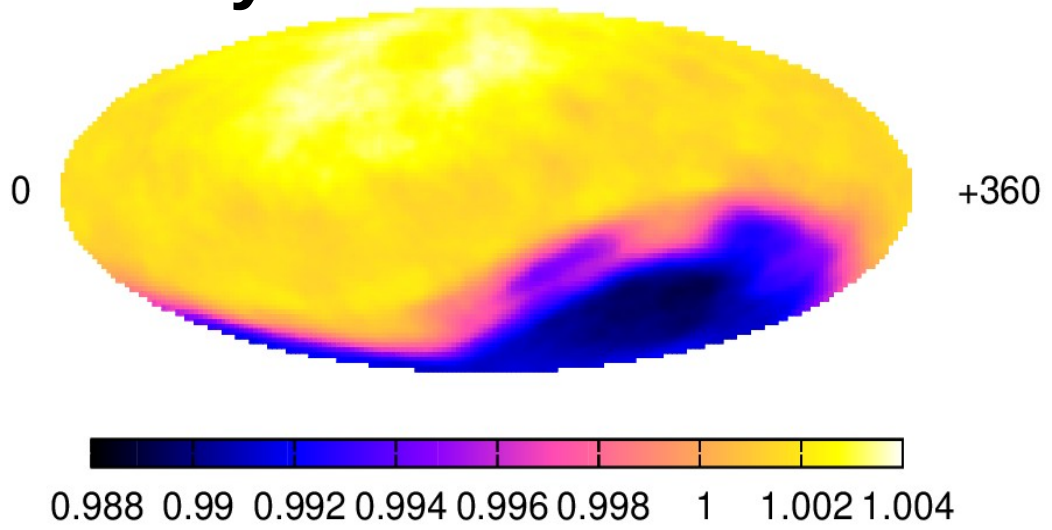
Time variability at 3 TeV

V_E=20 km/s

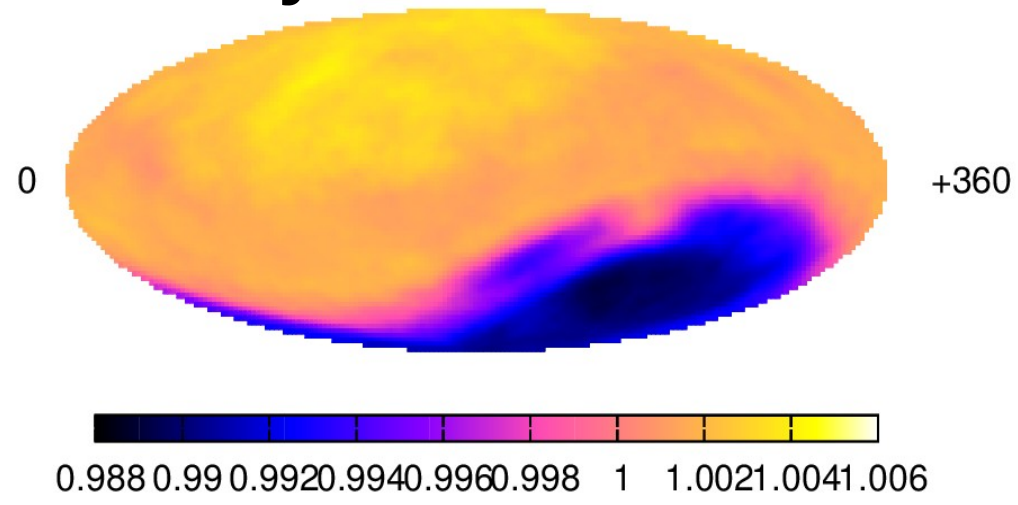
Δt = 0 yr



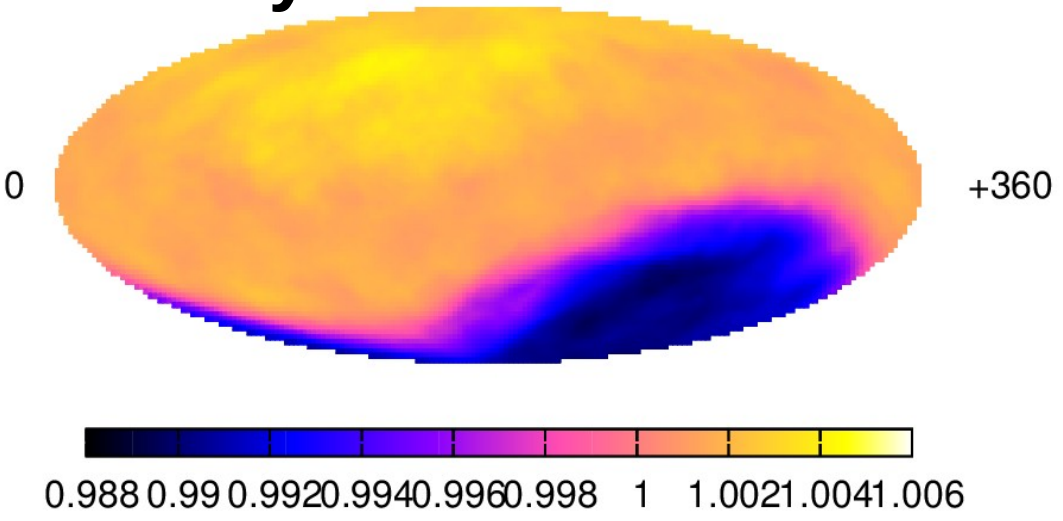
Δt = 1 yr



Δt = 10 yr



Δt = 50 yr



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

Conclusions

NEW OBSERVABLES!

(1) <u>Large-scale CR Anisotropy:</u>

= 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) <u>Non-gyrotropic small scale anisotropies:</u>

= Probe of the local realization of the interstellar turbulent B fields, within a CR MFP from Earth.

→ Relative amplitude (compared with the large-scale CRA) depends on the local $\delta B/B$.

=> Important opportunity for CR experiments to do <u>groundbreaking</u> science with the CR Anisotropy.

Thank you! 谢谢！

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