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

Gwenael Giacinti (MPIK Heidelberg)

GG, In Prep. (2020) – *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*

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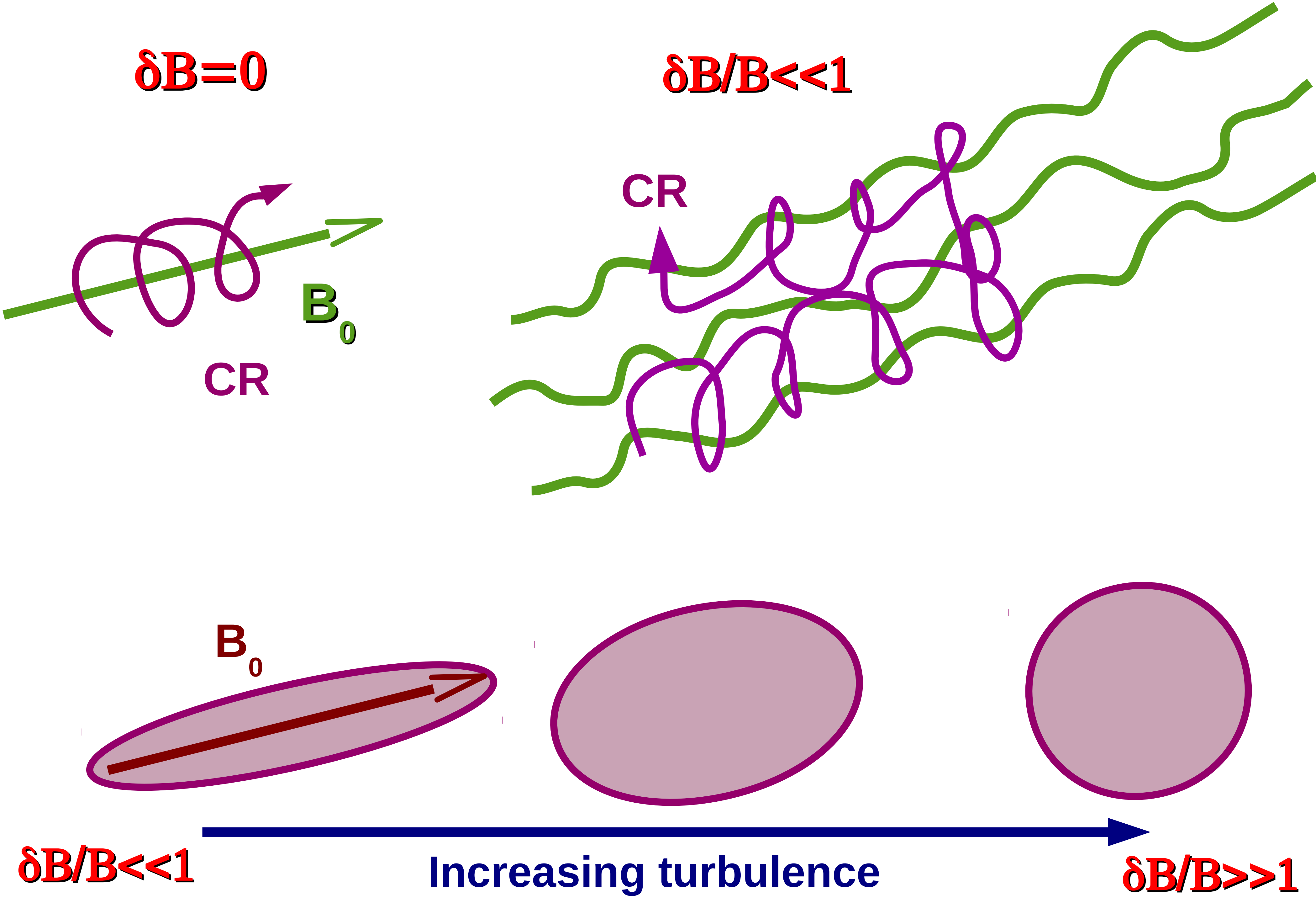
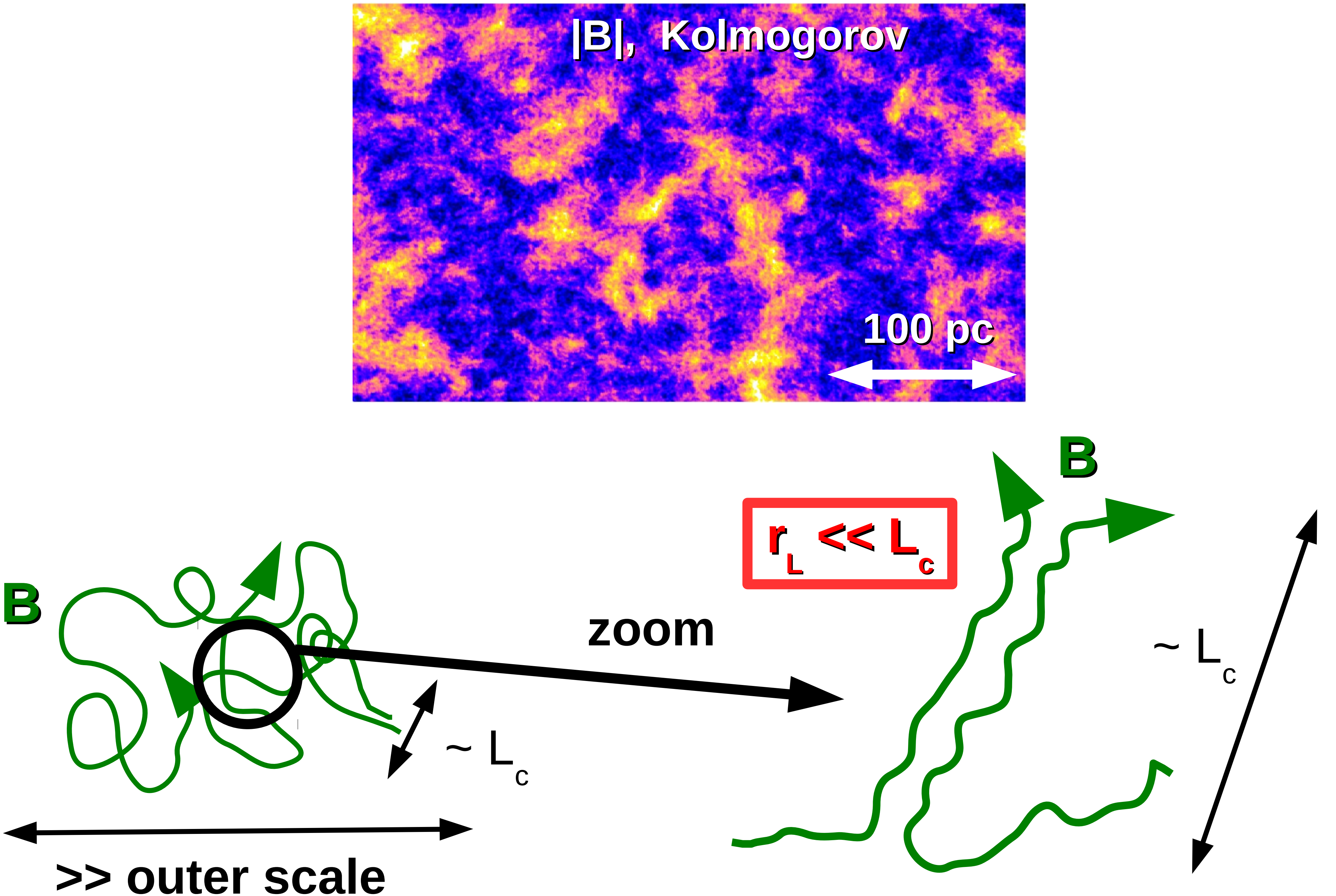
CR diffusion in the ISM



But is CR diffusion (ever) isotropic ?



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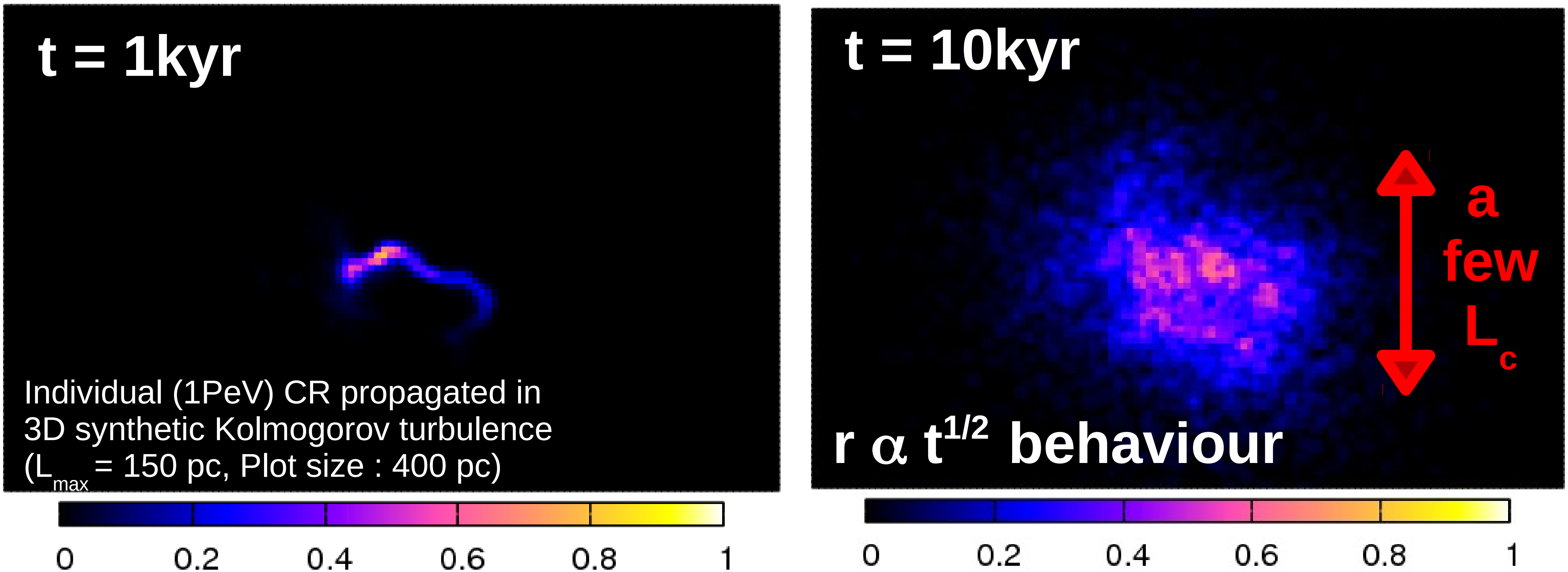
Filamentary Diffusion of Cosmic Rays on Small Scales

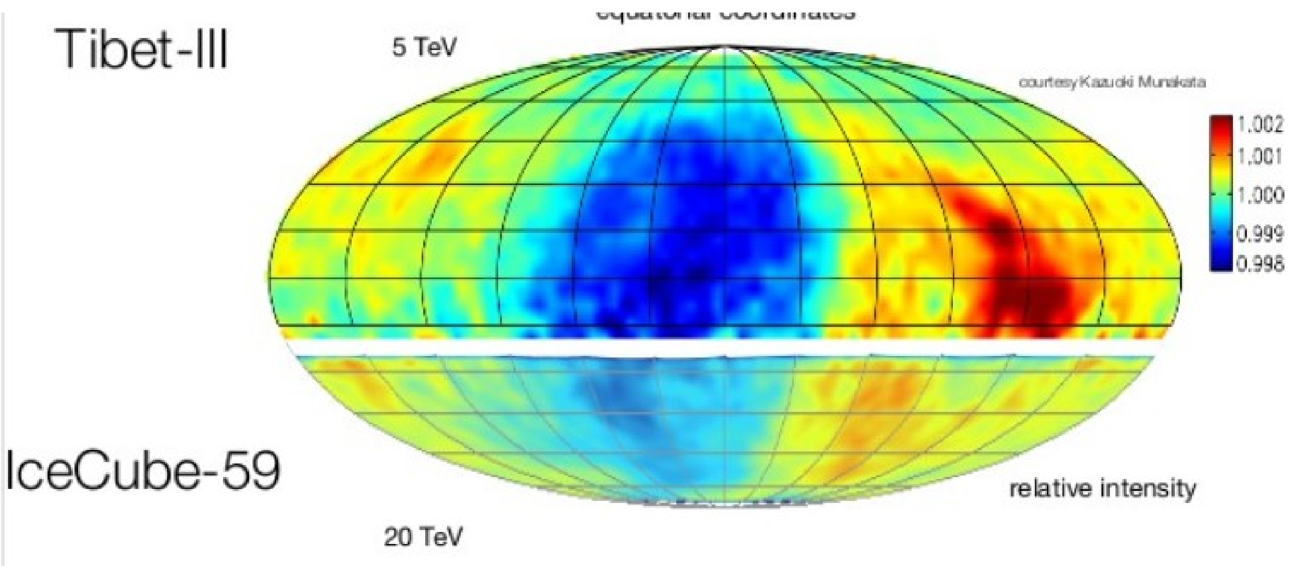
G. Giacinti,[1] M. Kachelrieß,[1] and D. V. Semikoz[2,3]

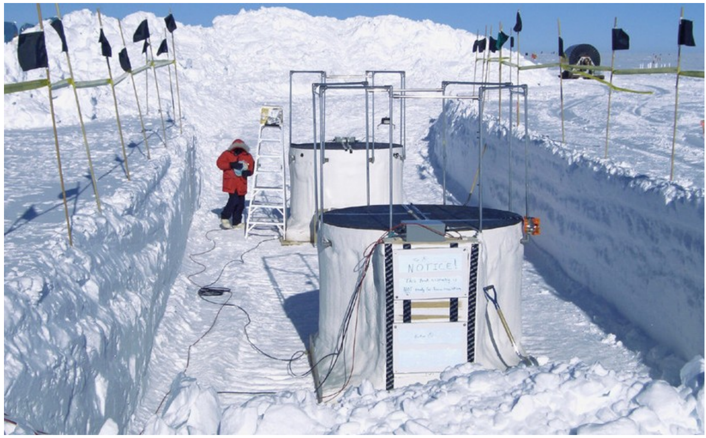


- See also Malkov et al., ApJ (2013).
- See Ruoyu (若愚)'s talk for Geminga and other PWNe.
- Hints of anisotropic diffusion around W44: Peron et al., ApJ (2020).

Observations :

Large Scale Anisotropy (~0.1%) :

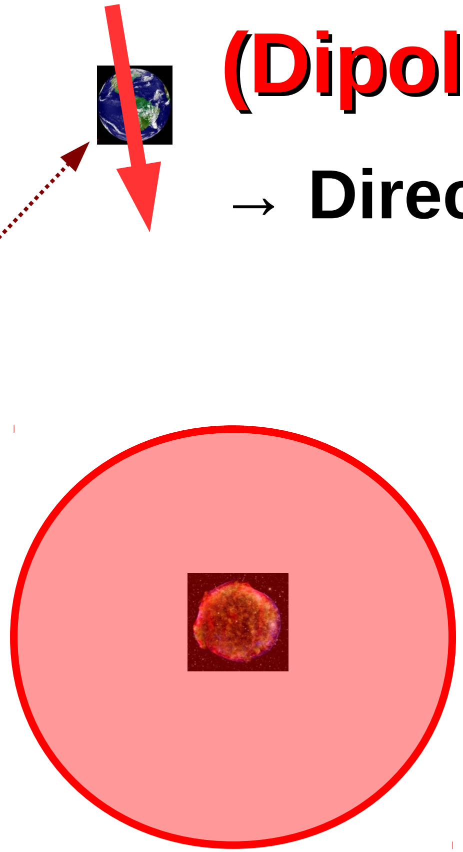




Dipole: → **Amplitude**

→ **Phase (Direction)**

CR Anisotropy



(Dipole) Anisotropy

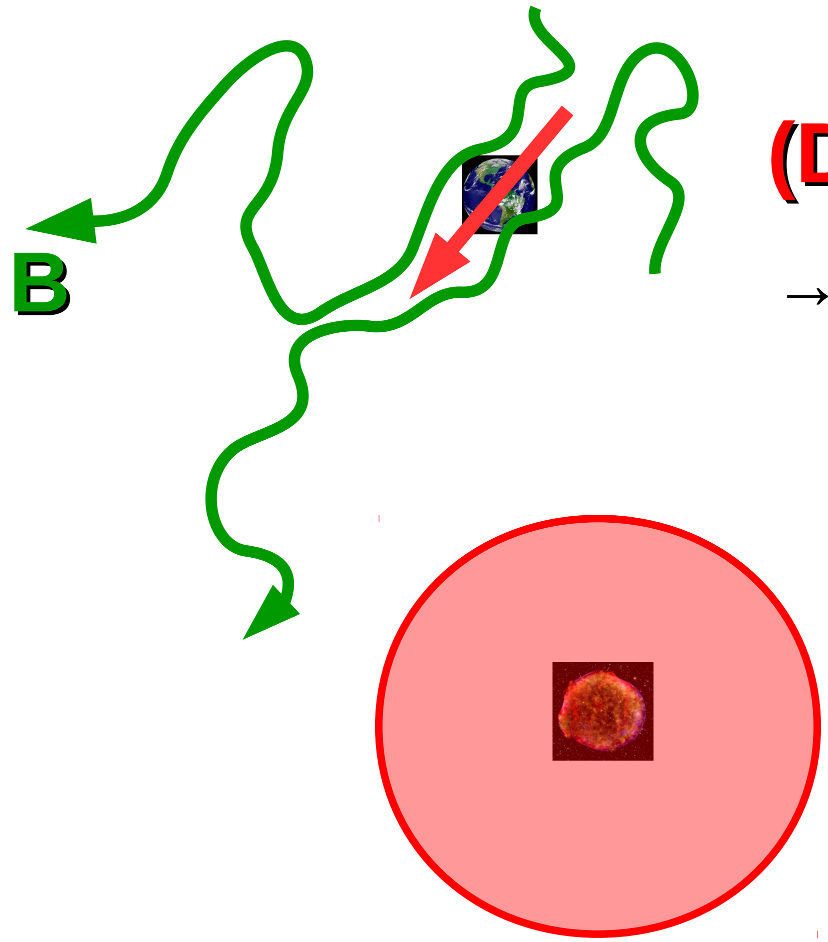
→ **Direction**

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**

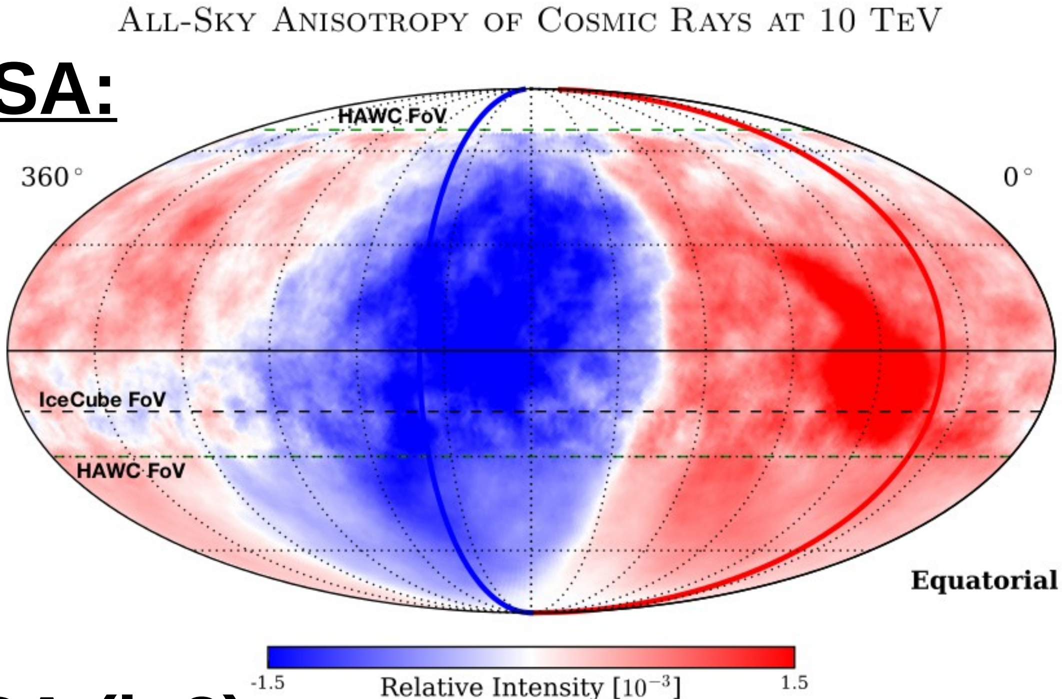
cf. Schwadron et al., Science (2014)

~ 180^{o} flip at 100 TeV

→ See Markus' talk

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

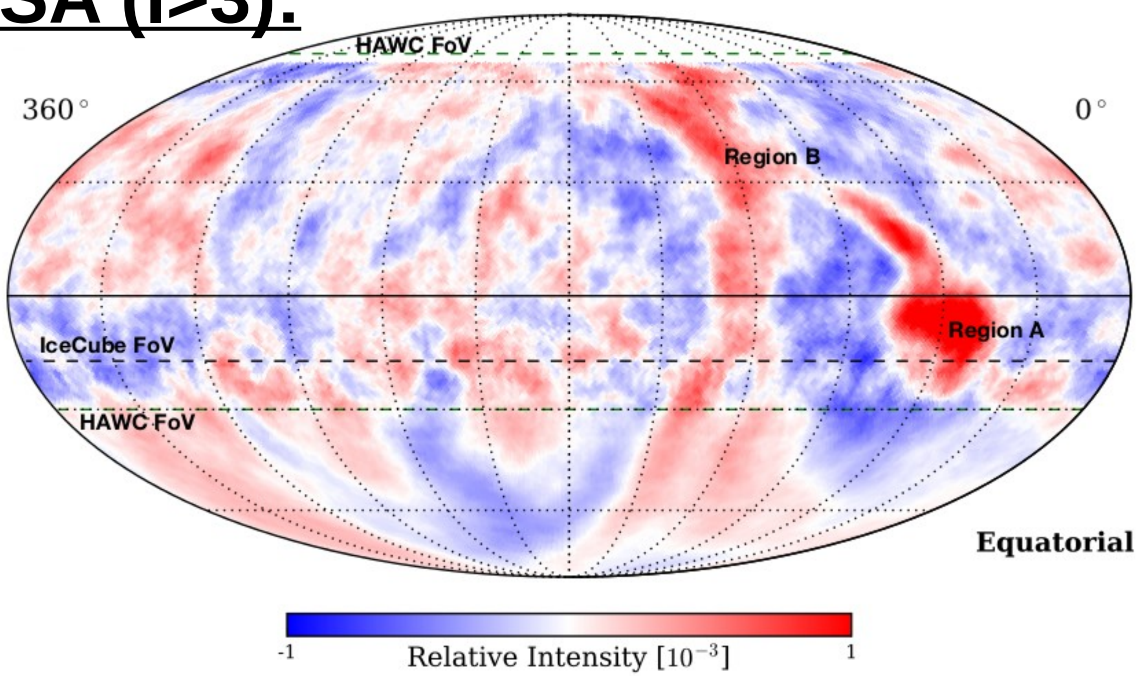
LSA:



In the direction of field lines

SHAPE: NOT a dipole in general

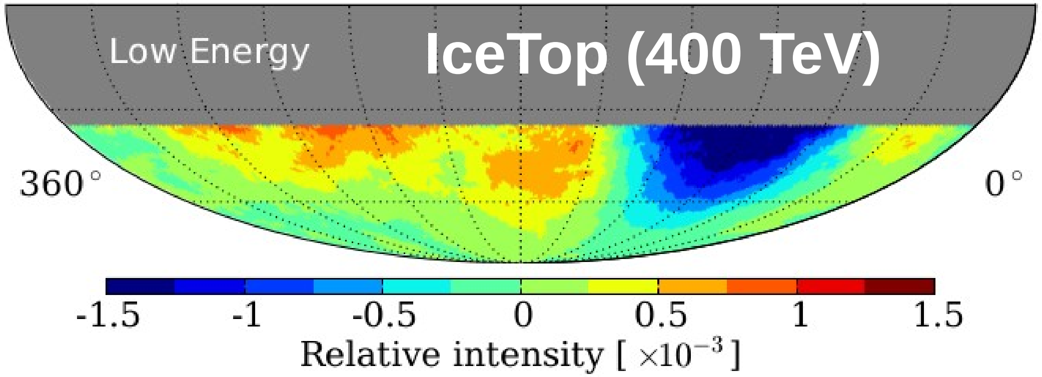
SSA (l>3):

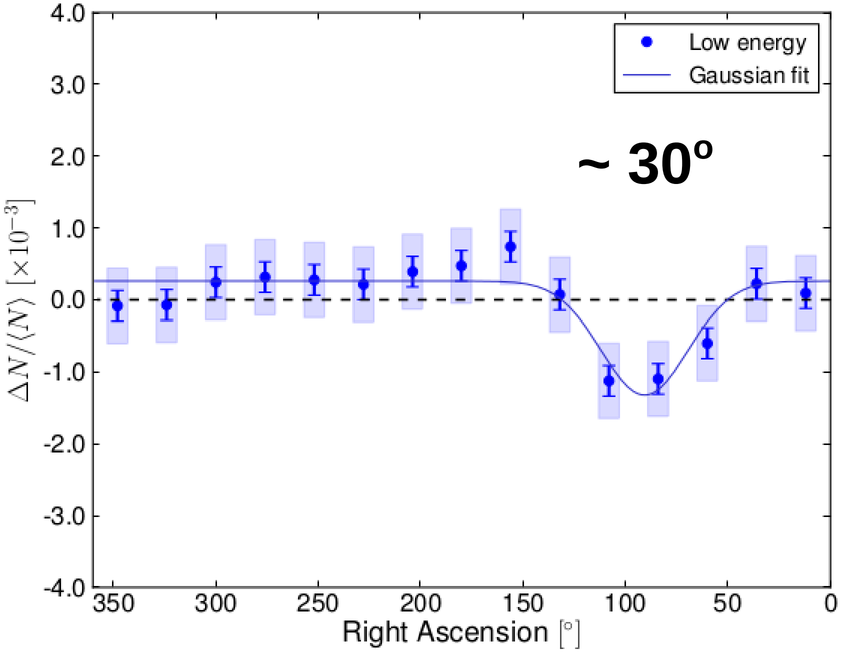


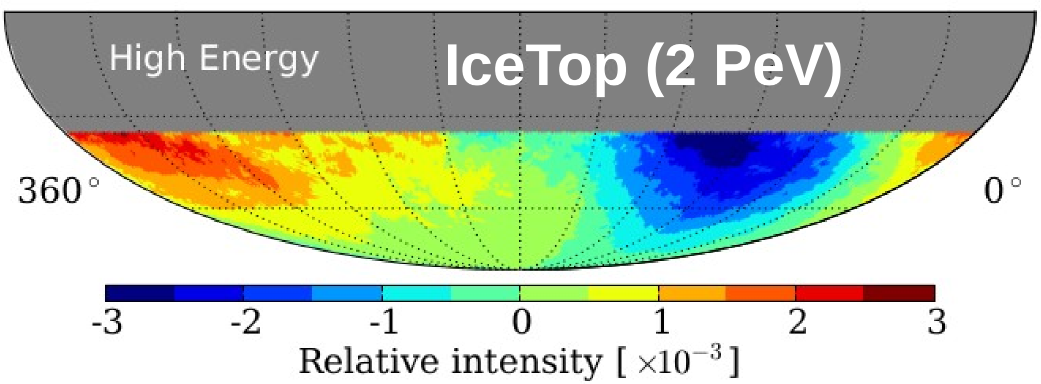
- Energy-dependent,
- No/Litte time-dependence
- Amplitude: LSA/(few – 10)

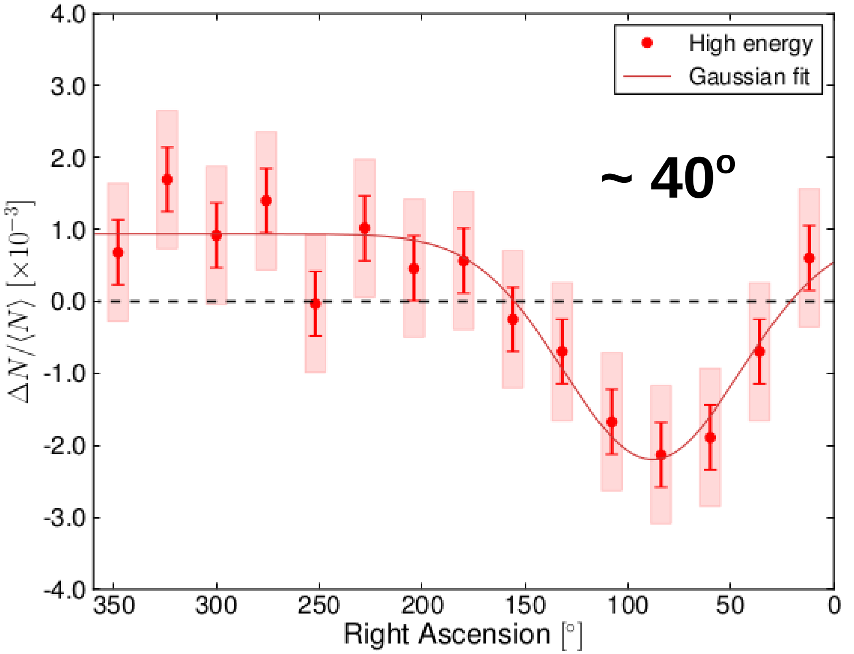
Observations (IceCube, IceTop)

Aartsen et al. (2013)



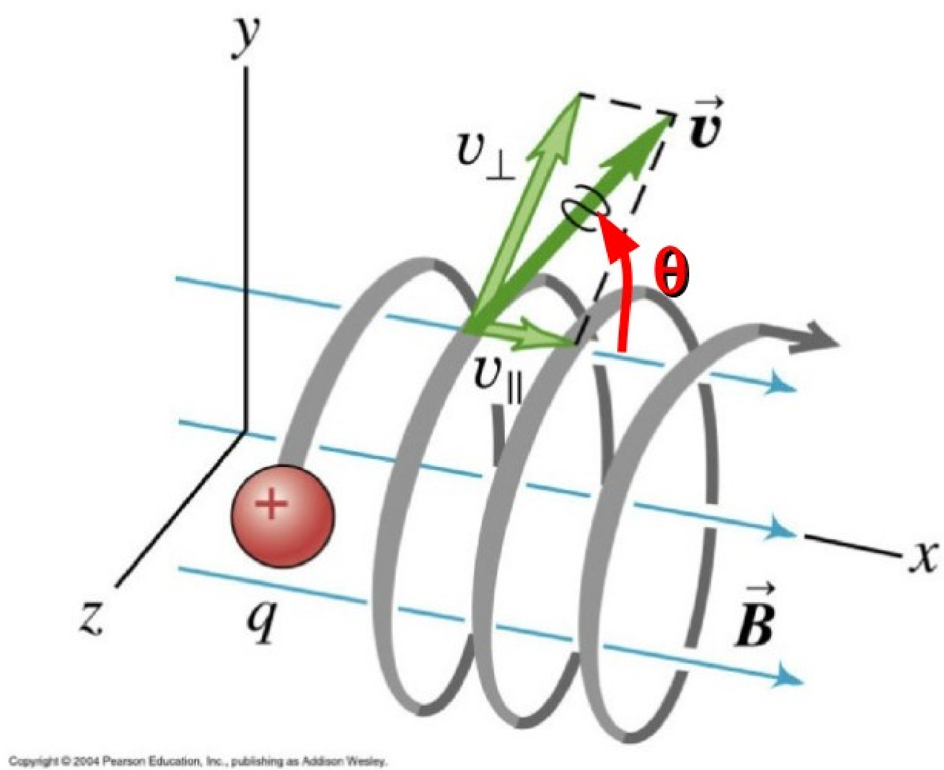




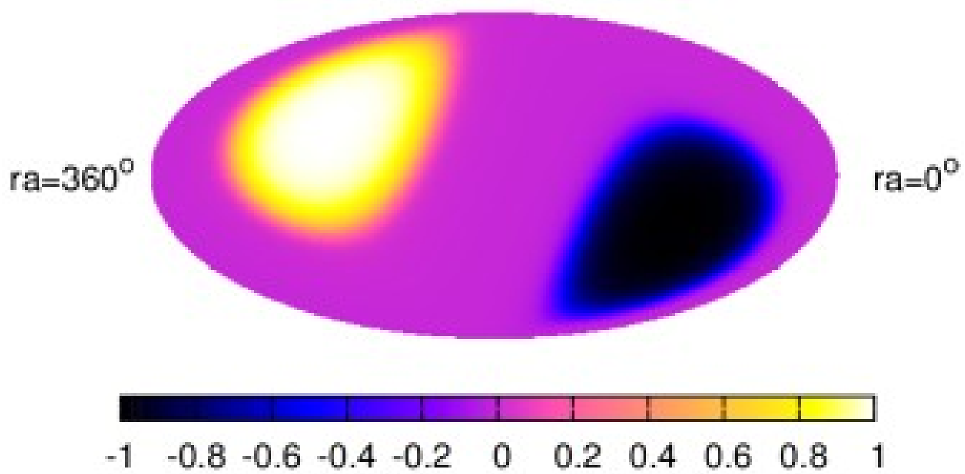


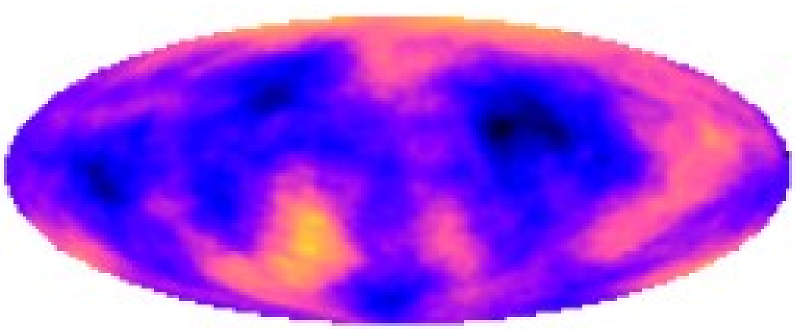
Also at 20 TeV...

Pitch-angle (θ) and gyrophase:

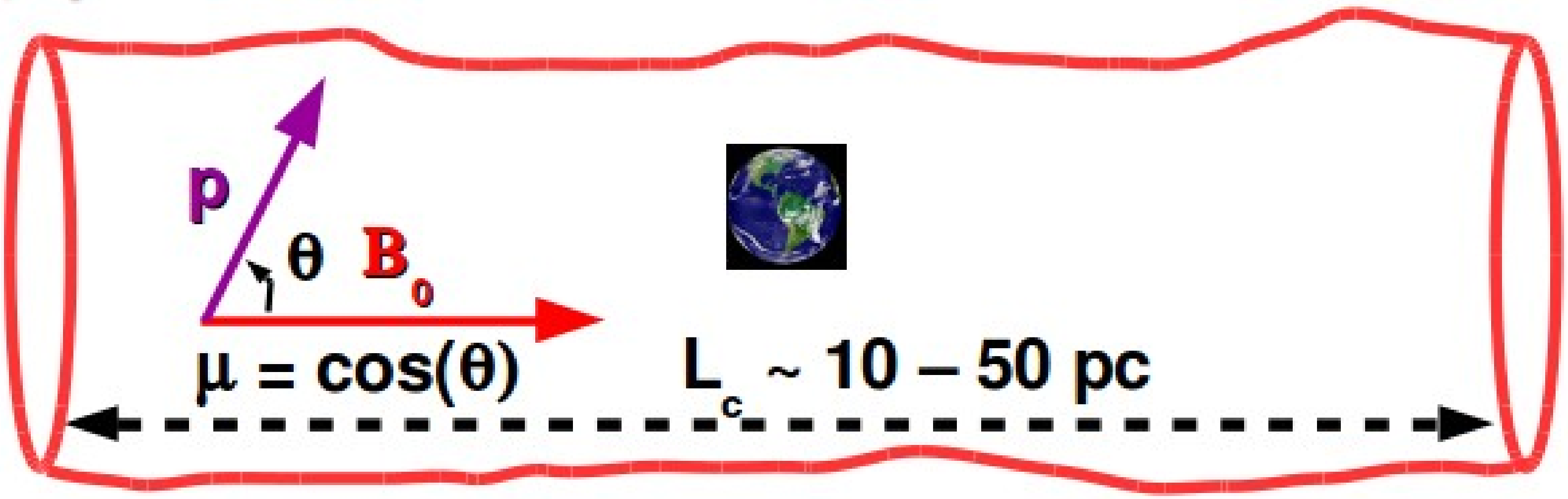


CRA = Large-scale + small-scales





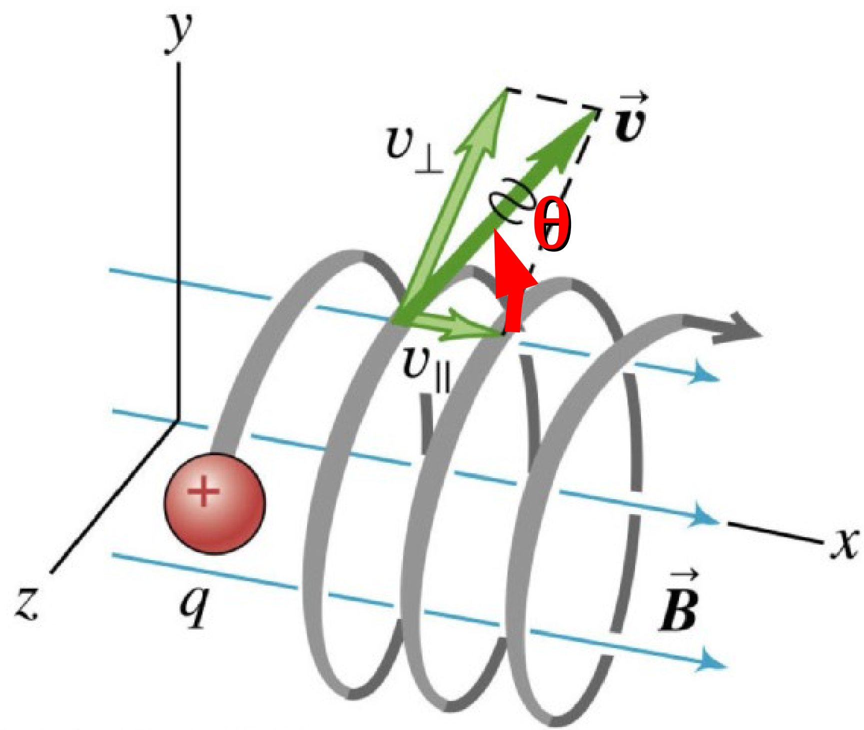
CR Anisotropy : Probe of turbulence



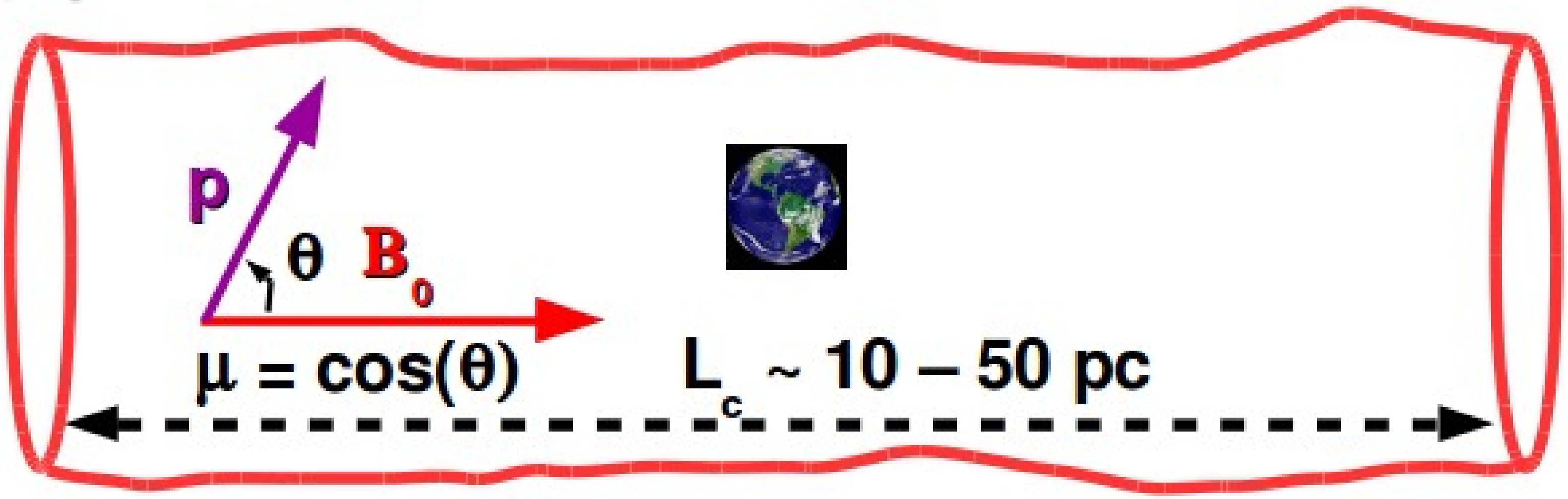
$$\mu v \frac{\partial f}{\partial x} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right)$$

Pitch-angle diffusion

(gyrophase-averaged)



CR Anisotropy : Probe of turbulence



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

=> $f(x,\mu) = \sum_{\rm i} a_{\rm i} e^{\Lambda_{\rm i} x/v} Q_{\rm i}(\mu) + a_{\rm diff}\left[x + g(\mu)\right] + f_0$

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

<u>NOT</u> $1 - \mu^2$

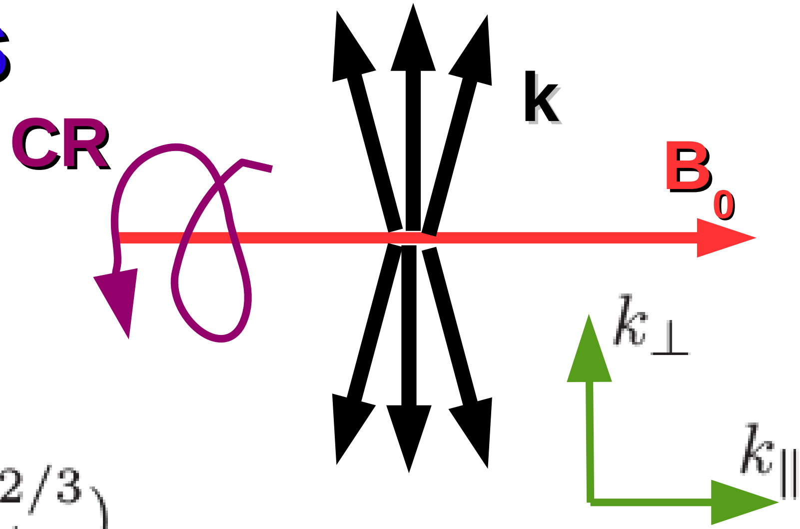
in general !

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

(« boundary layer »)

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

Alfven (and Slow) modes



Goldreich & Sridhar (1995)

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

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

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

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

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

Fast magnetosonic modes

MHD simulations of Cho & Lazarian (2002) :

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

Pitch-angle diffusion coefficient

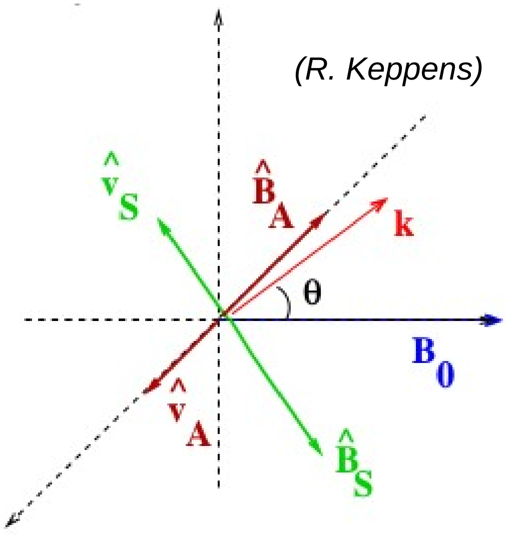
$$D_{\mu\mu} = \Omega^2 \left(1-\mu^2\right) \int \mathrm{d}^3k \sum_{n=-\infty}^{\infty} \left(\frac{n^2 J_{\mathrm{n}}^2(z)}{z^2} \mathcal{I}_{\mathrm{A}}(\mathbf{k}) + \frac{k_{\parallel}^2 J_{\mathrm{n}}'^2(z)}{k^2} \mathcal{I}_{\mathrm{S,F}}(\mathbf{k}) \right) \times R_{\mathrm{n}}(k_{\parallel}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

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.

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

(R. Keppens)



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

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

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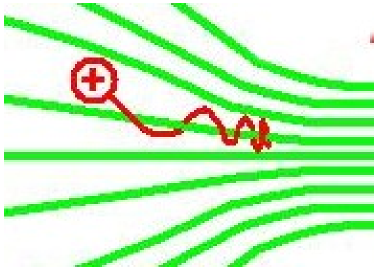
(2) BROAD: Conservation of the adiabatic invariant $v_\perp^2/B$



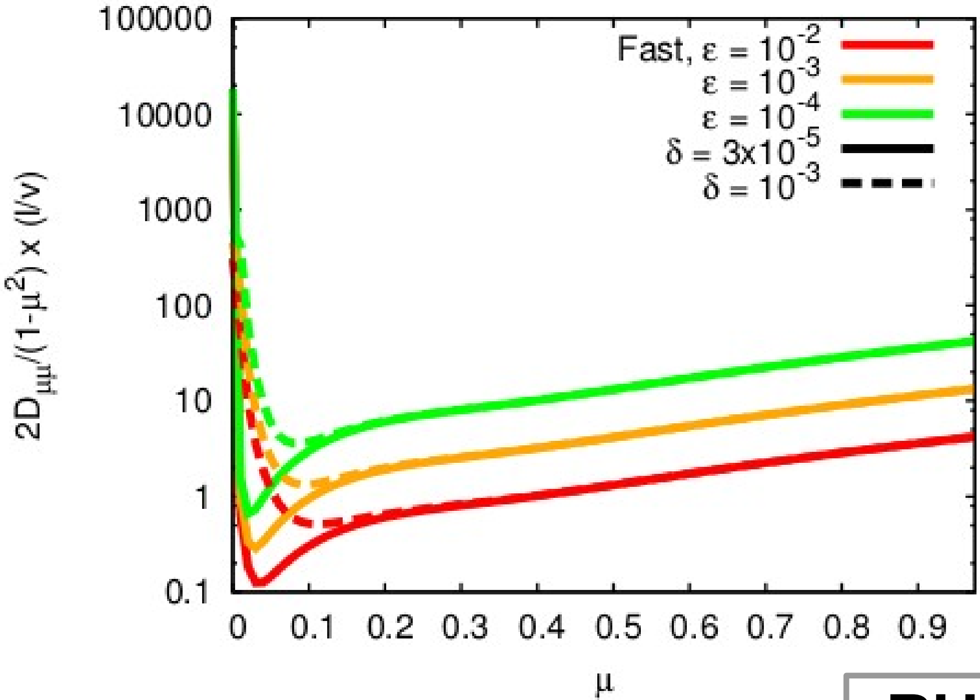
Yan & Lazarian (2008)

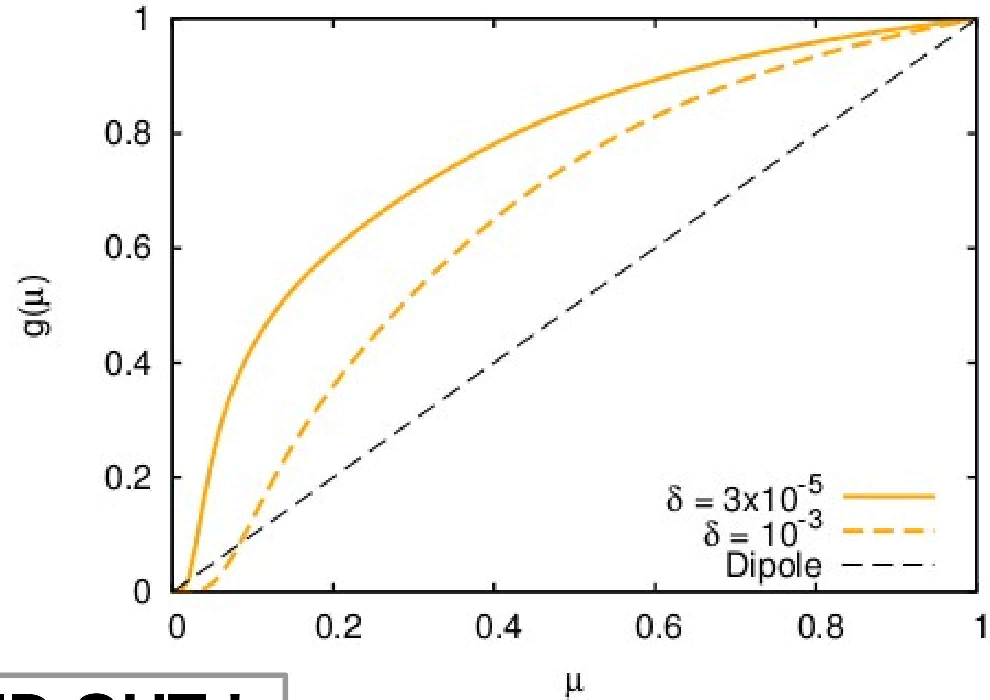
$$\delta\mathcal{M}_A = \sqrt{\langle \delta B_\|^2 \rangle / B_0^2}$$

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

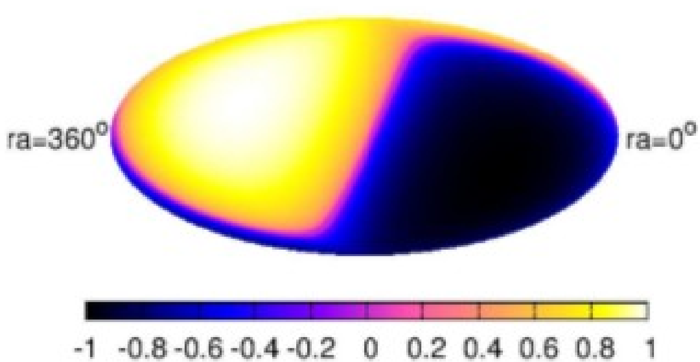
Case 1 : Fast modes & Narrow RF

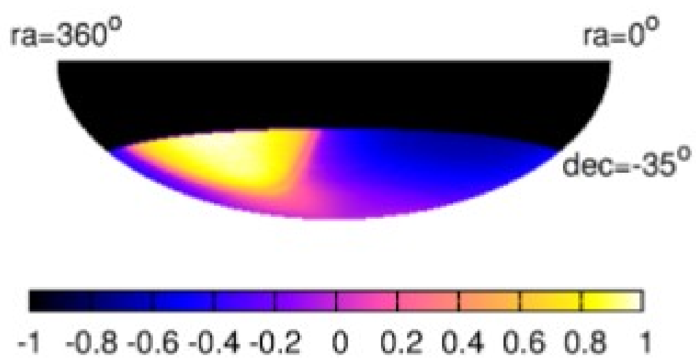
No visible dependence of the *shape* on CR energy $\varepsilon = v/(l\Omega) = r_{\mathrm{L}}/l$

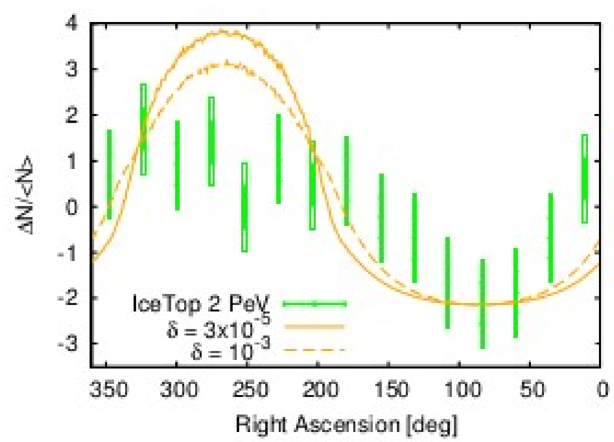




RULED OUT !

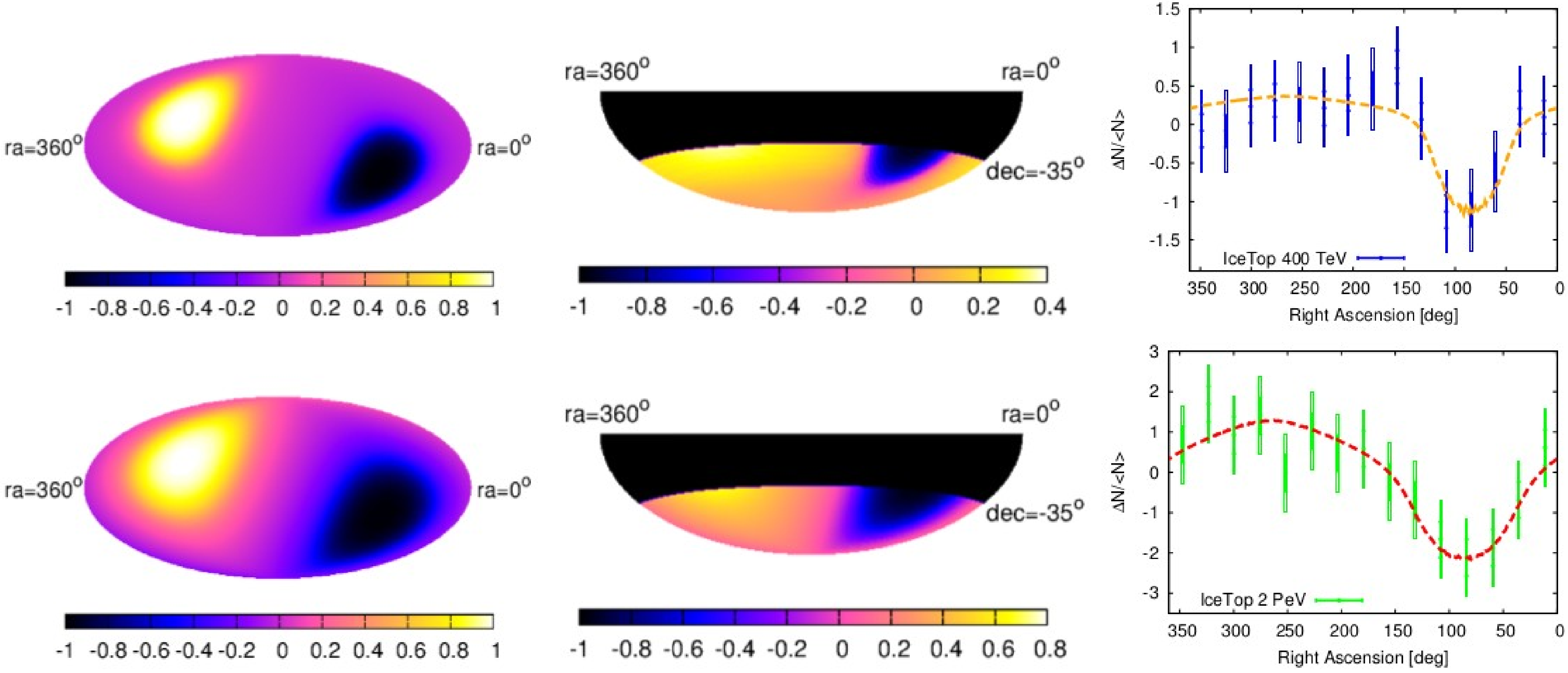






In general: Anisotropy is too wide with the narrow RF.

Case 2 : GS – Exponential & Broad RF



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

Energy-dependence reproduced for fixed turbulence parameters

Intermediate conclusions – L-S CRA :

Large-scale CR Anisotropy = NEW Probe of

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

(ii) local CR transport properties

→ Flattening in directions perpendicular to field lines,

→ Can fit the 2 PeV data with GS turbulence or fast modes with a moderately broad RF,

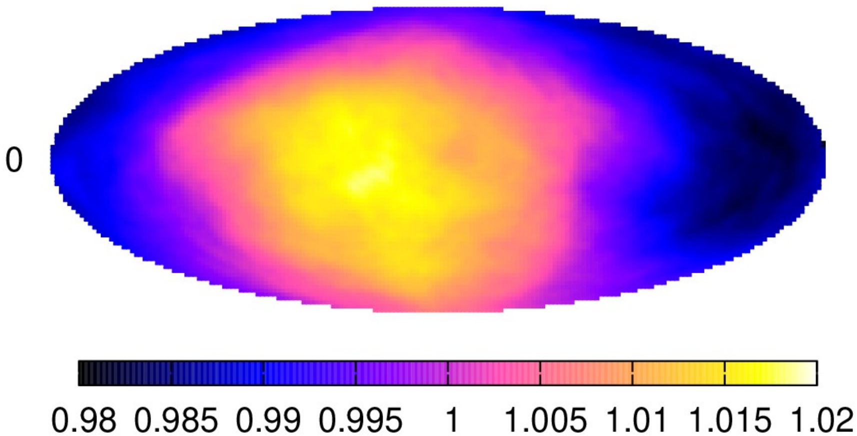
→ Constraints on res. functions : Narrow ones disfavoured,

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

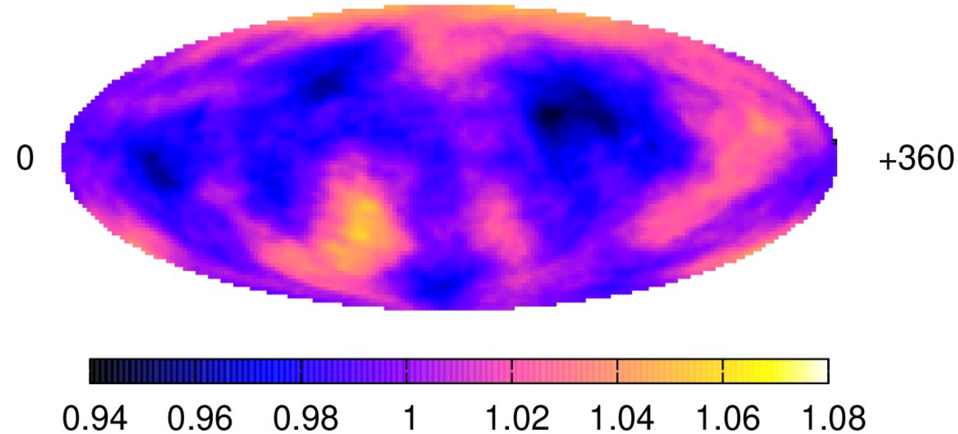
Small-scale aniso. & local turbulence

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

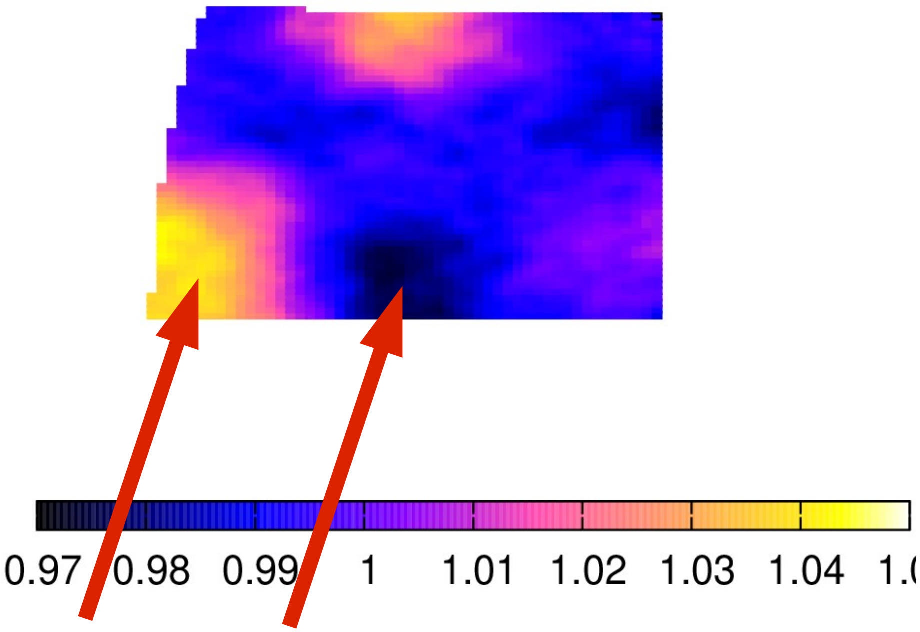
90°smoothing

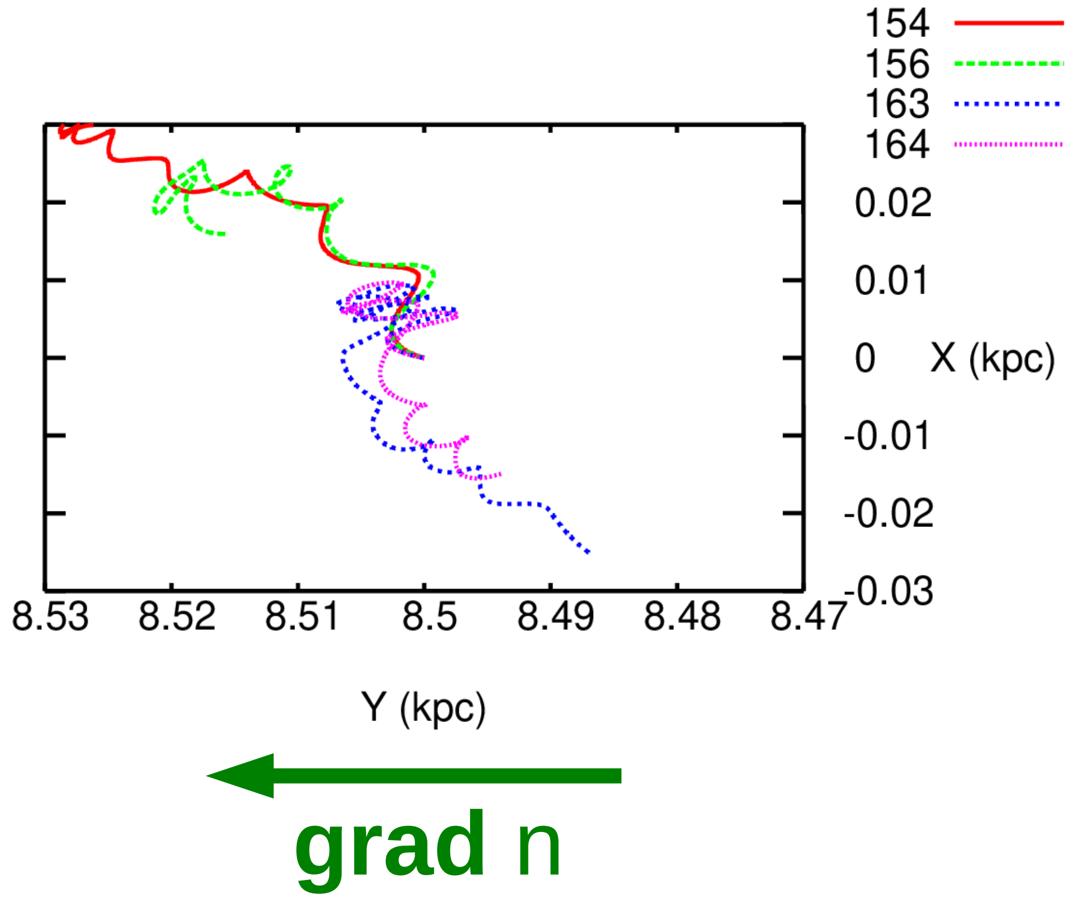


20° smoothing - {dipole}



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.

Conclusions & Perspectives for LHAASO

(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 $\delta B/B$.*

=> Important opportunities for LHAASO to do novel and groundbreaking science with CRs !

谢谢！ Grazie !