The origin of the Ultra-High Energy Cosmic Ray dipole

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Rencontres du Vietnam
Very High Energy Phenomena in the Universe
International Center of Interdisciplinary Science Education (ICISE)
Quy Nhon, Vietnam

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Tsvi Piran, Denis Allard, Etienne Parizot, Yehuda Hoffman, Edoardo Carlesi, Daniel Pomarède

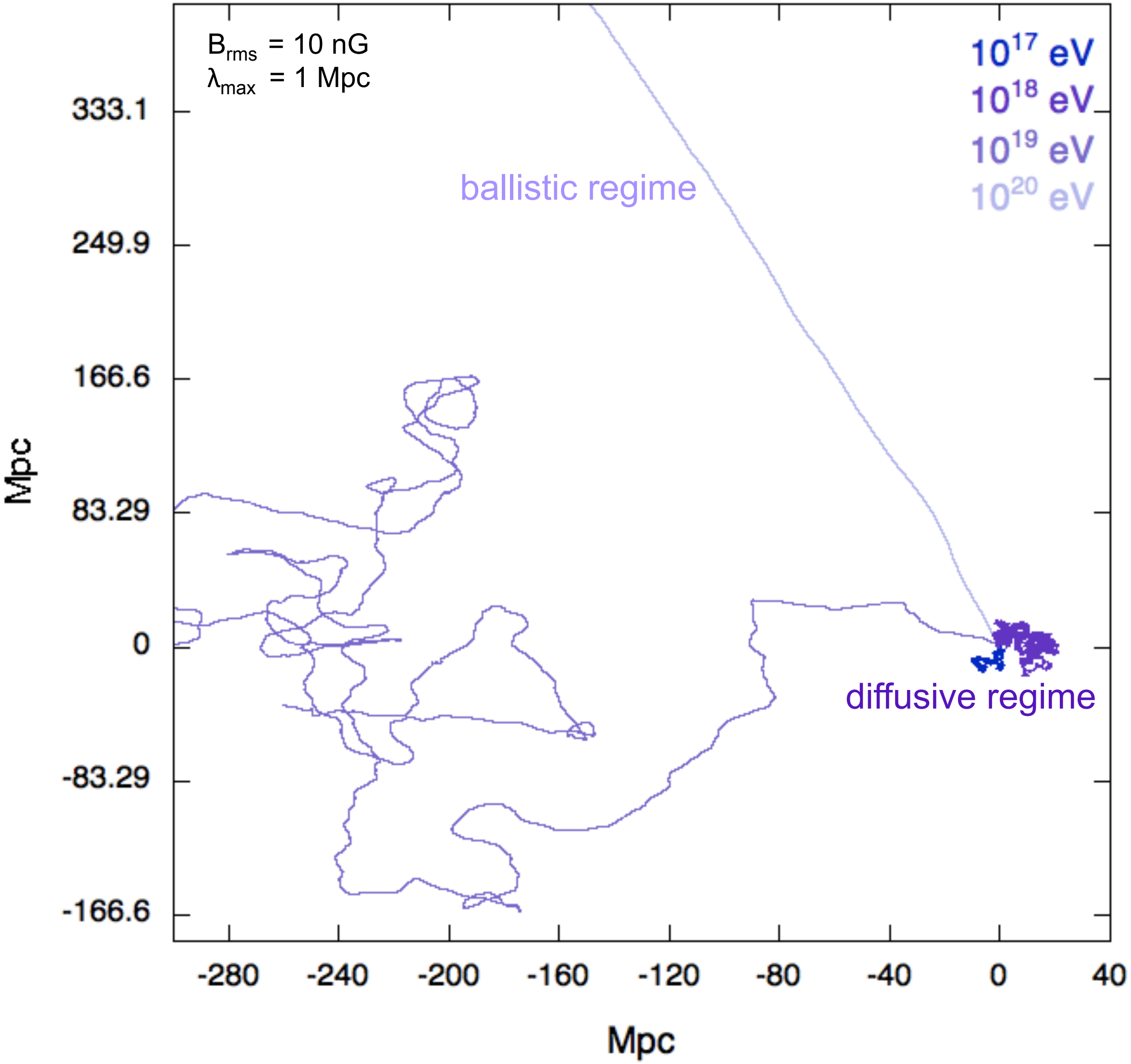
Outline

I. Ultra-High Energy Cosmic Rays (UHECRs) horizons

II. Observations of the dipole anisotropy (Auger)

III. Effect of intergalactic and Galactic magnetic fields on the UHECR dipole

Trajectories in a purely turbulent IGMF

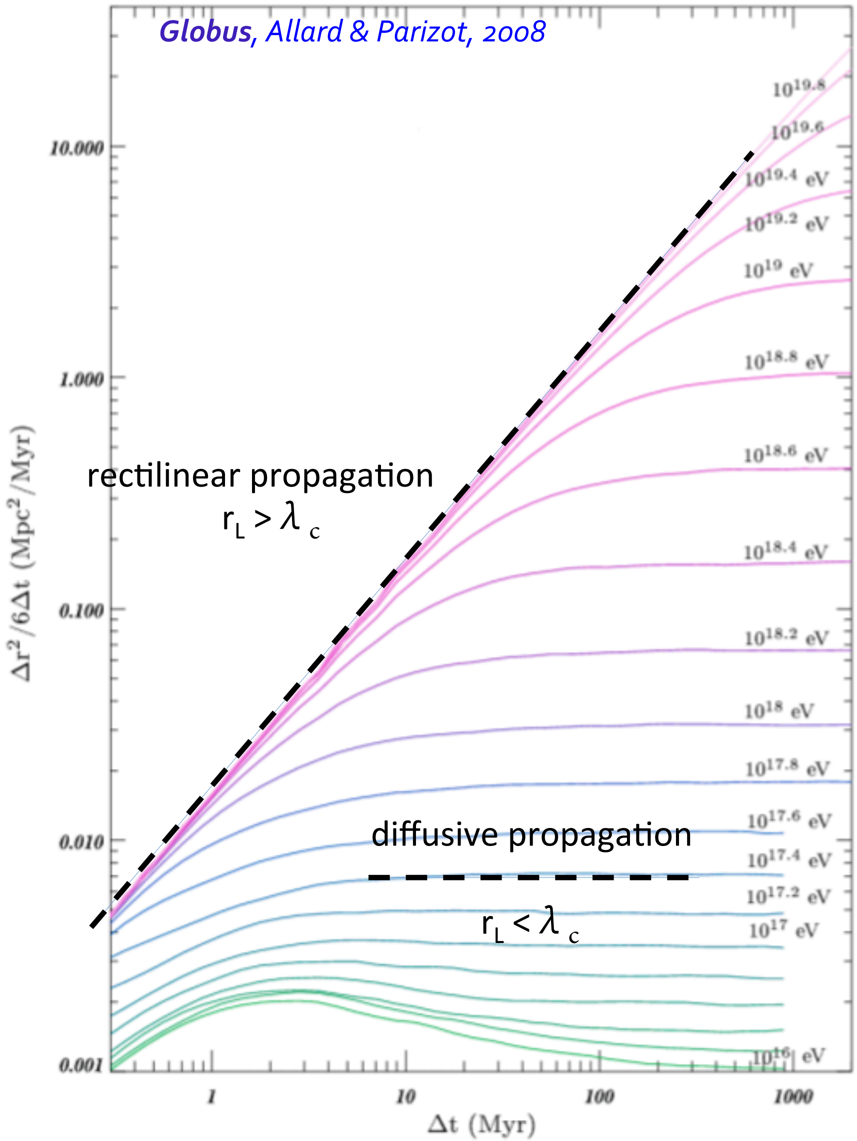


Larmor radius

$$r_L = 1.1 Mpc \times \frac{E_{EeV}}{ZB_{nG}}$$

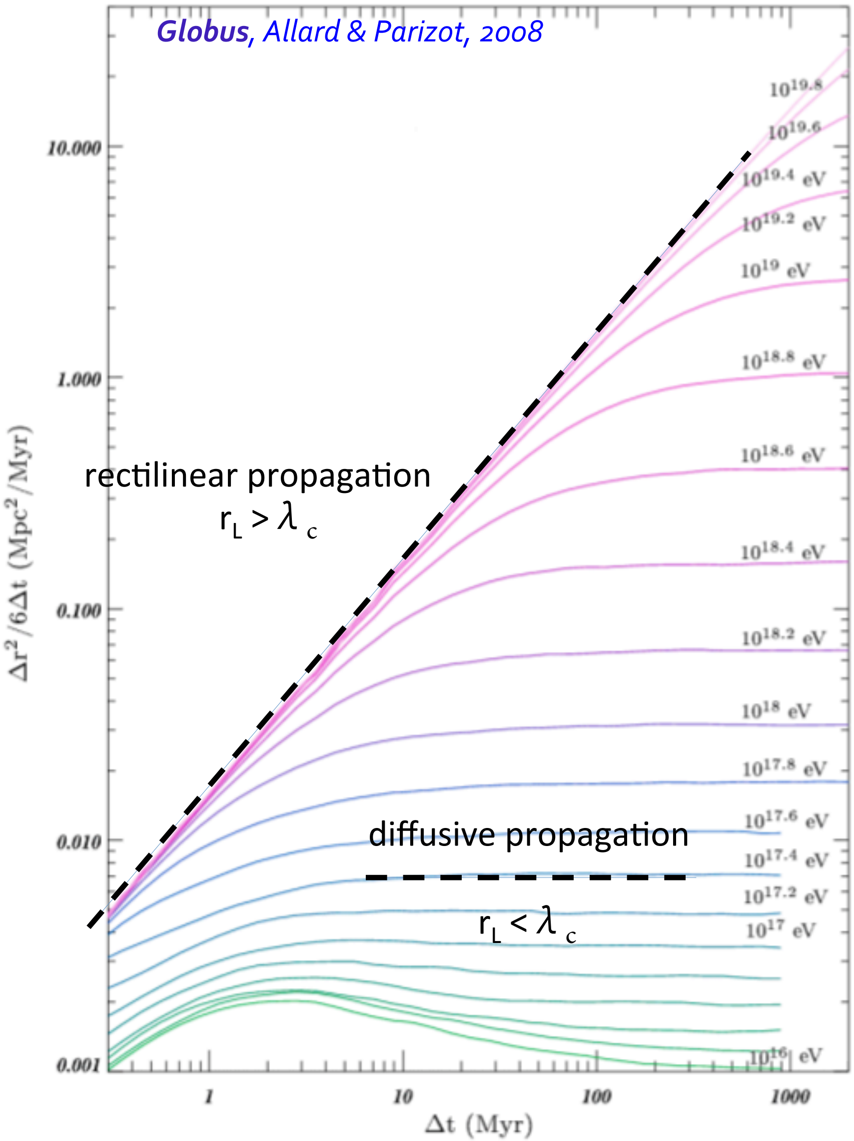
Globus, Allard & Parizot, 2008

Cosmic-Rays Horizons



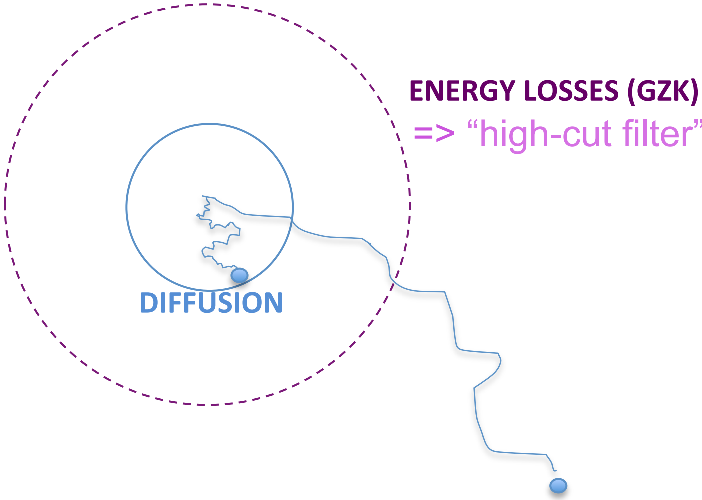
$$D \approx 0.03\left(\frac{\lambda_{\rm Mpc}^2 E_{\rm EeV}}{ZB_{\rm nG}}\right)^{1/3} + 0.5\left(\frac{E_{\rm EeV}}{ZB_{\rm nG}\lambda_{\rm Mpc}^{0.5}}\right)^2 \,{\rm Mpc}^2\,{\rm Myr}^{-1}$$

Cosmic-Rays Horizons



intergalactic magnetic field (IGMF)

=> "low-cut filter"



If $d_{\rm diff}$ is smaller than $d_{\rm GZK}$ then the horizon from which the UHECRs can reach Earth becomes: $\sim (6Dd_{\rm GZK}/c)^{1/2}$. Combined the UHECR horizon is given by:

$$H(E) = \min(\sqrt{d_{\rm diff}d_{\rm GZK}}, d_{\rm GZK})\ .$$

(e.g Parizot 2004)


ballistic regime


diffusive regime
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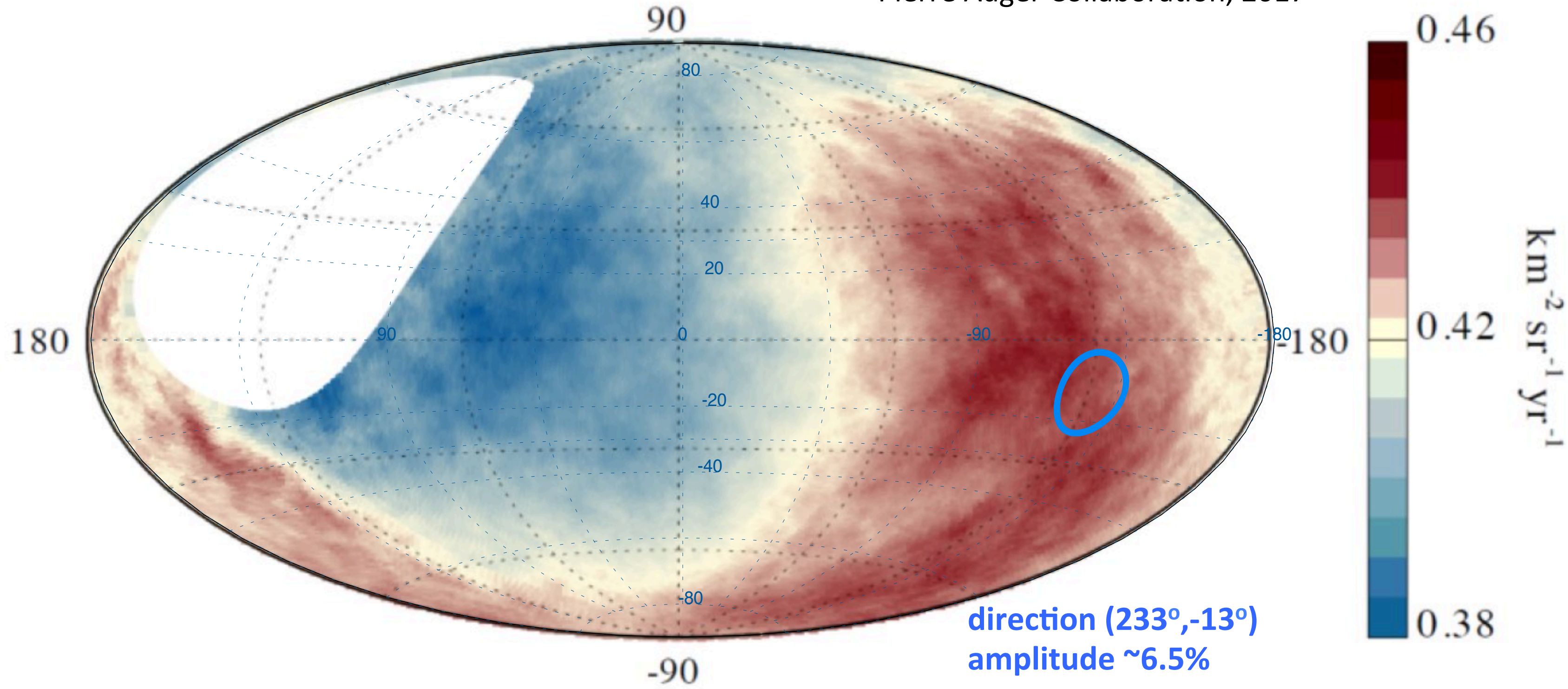
The magnetic fog seems to dissipate

discovery of a large scale anisotropy above 8 10^{18} eV

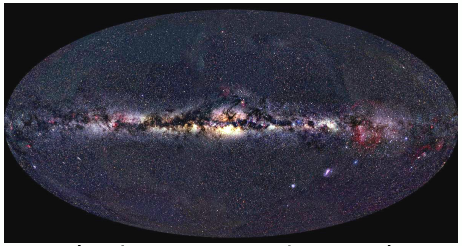
Pierre Auger Collaboration, 2017



direction (233°,-13°)
amplitude ~6.5%

[4 – 8] EeV: compatible with isotropy

E > 8 EeV: significant modulation @ 5.6σ



(galactic coordinates)

Updated... yesterday!

(arXiv 1808.03579)

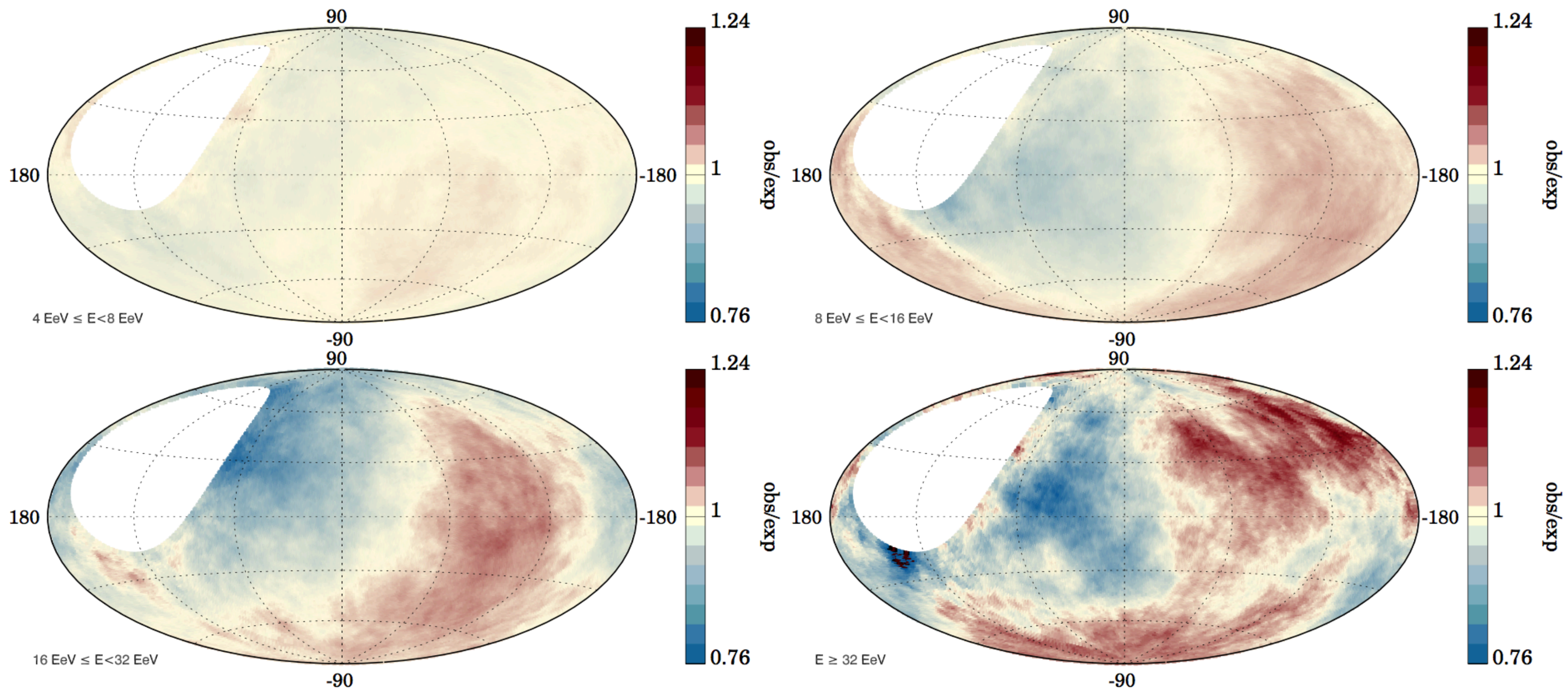
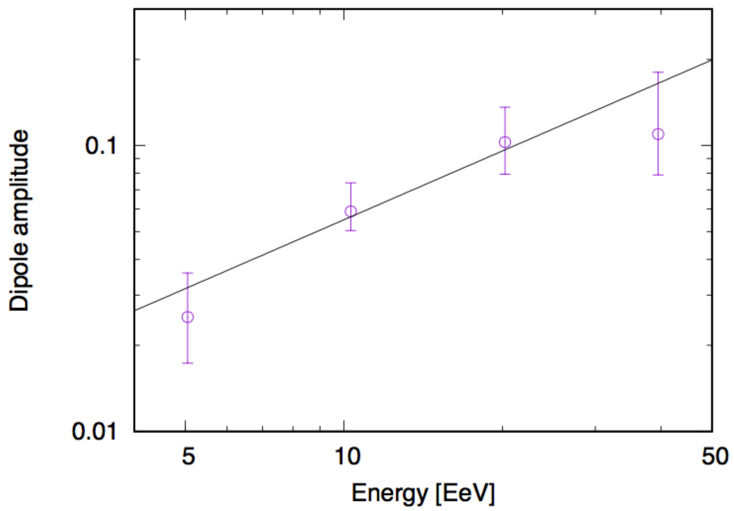
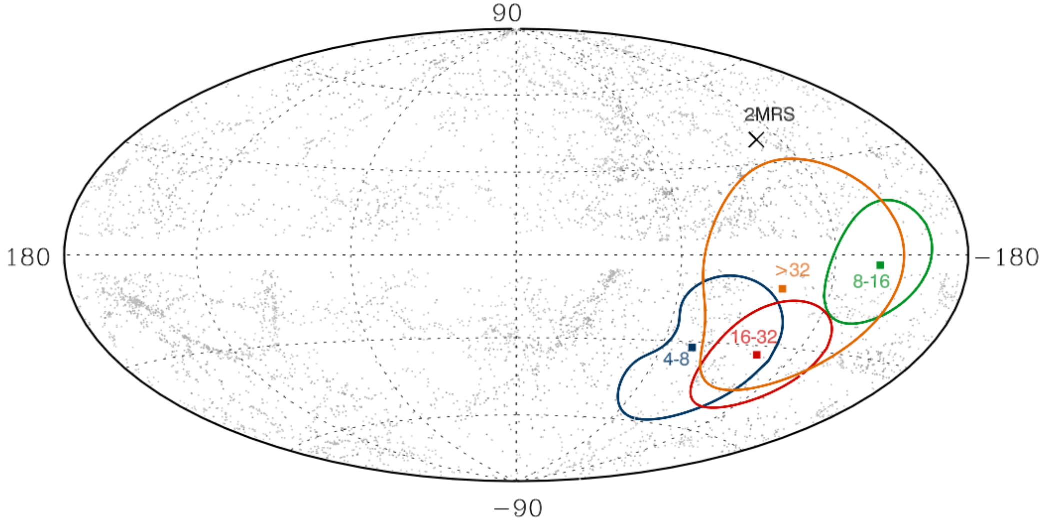


Figure 4. Maps in Galactic coordinates of the ratio between the number of observed events in windows of 45° over those expected for an isotropic distribution of arrival directions, for the four energy bins above 4 EeV.

Updated... yesterday!

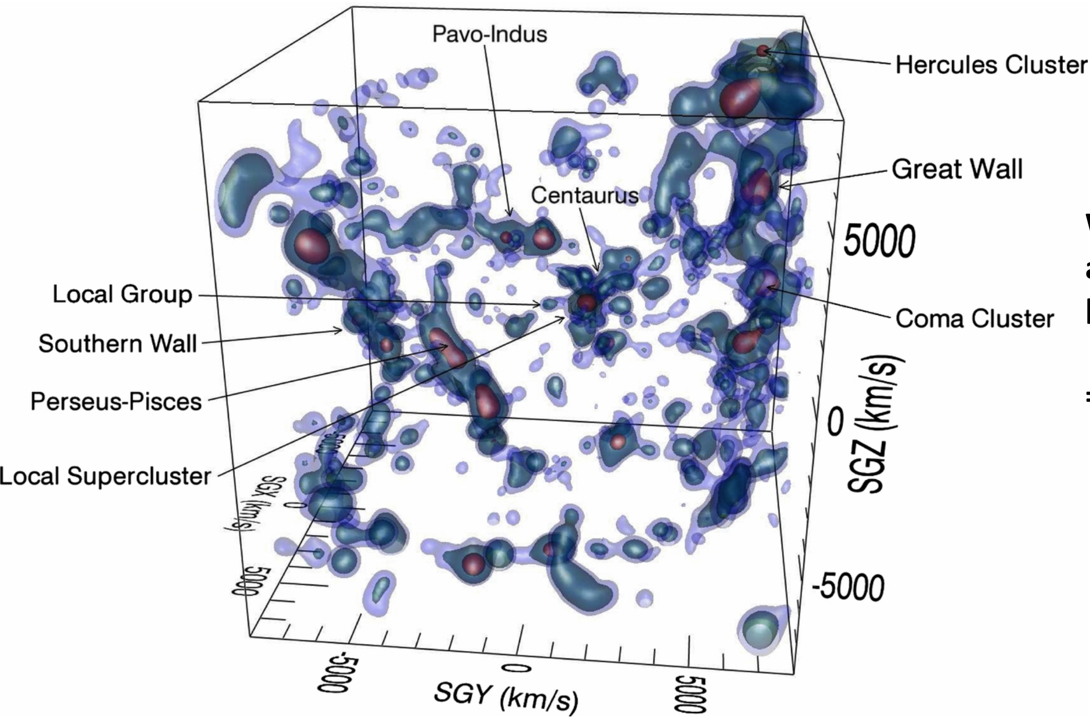
(arXiv 1808.03579)





Large scale structure induced UHECR anisotropy

We assume that the source follow the density fluctuations and take into account the diffusive transport in the intergalactic magnetic field (IGMF)



We use the QL density field derived by Hoffman et al., 2018, Nature Astronomy (arXiv 1807.03724) based on CosmicFlows-2

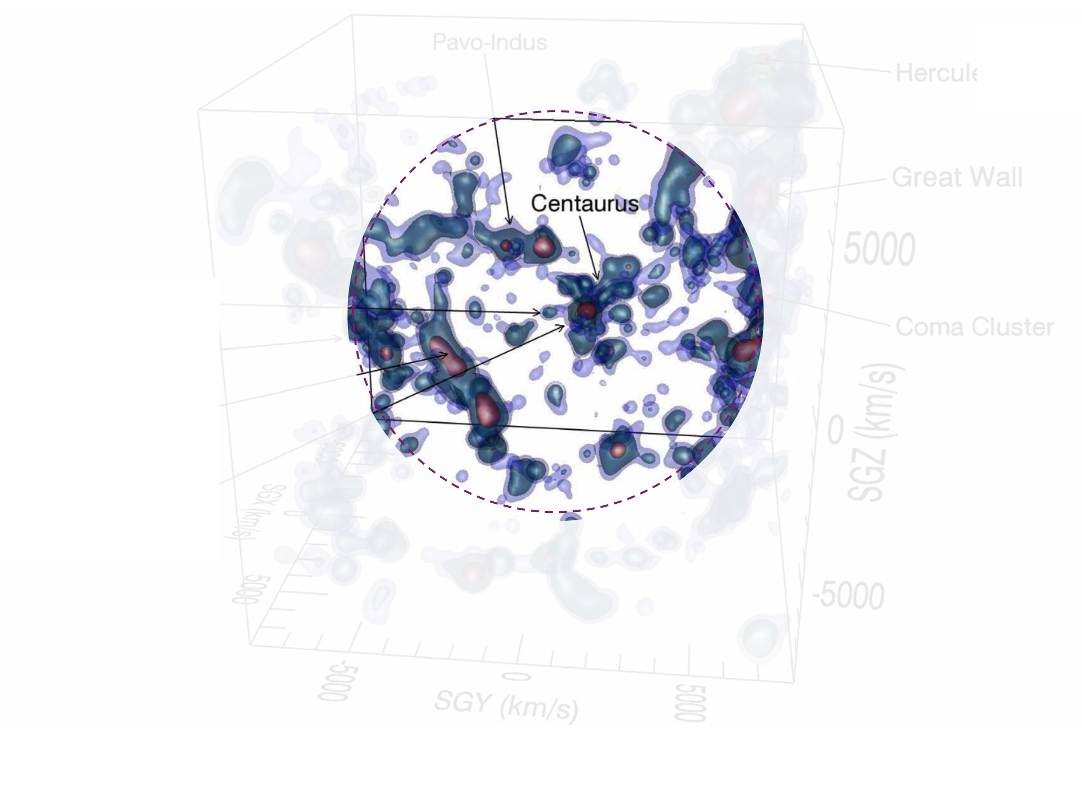
=> view shown at the link [[https://skfb.ly/6AFxT]](https://skfb.ly/6AFxT)

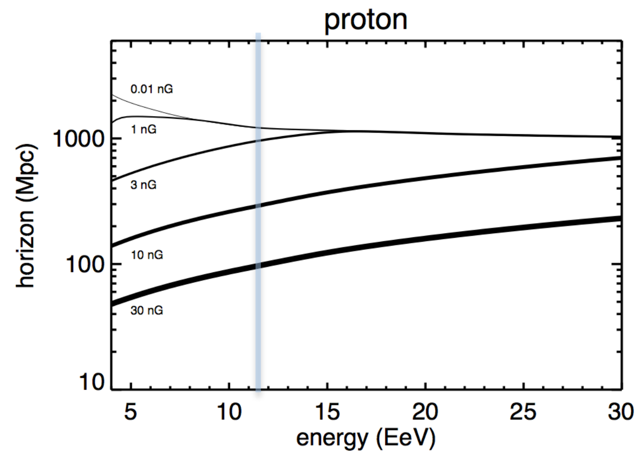
Large scale structure induced UHECR anisotropy

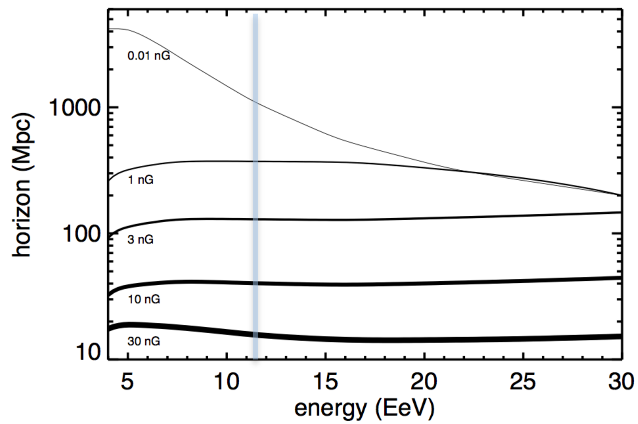
The amplitude of the LSS-induced UHECR dipole depends on the UHECR horizon which depends on the energy and composition

(Globus & Piran, 2017)

horizon = min (GZK horizon, magnetic horizon)

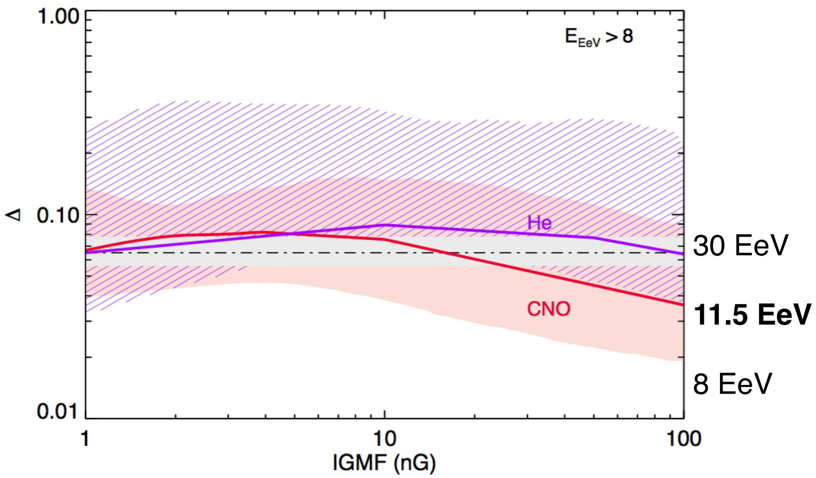






Large scale structure induced UHECR anisotropy

1) From the power spectrum of density fluctutations: **RMS** dipole amplitude *(Globus & Piran, 2017)*



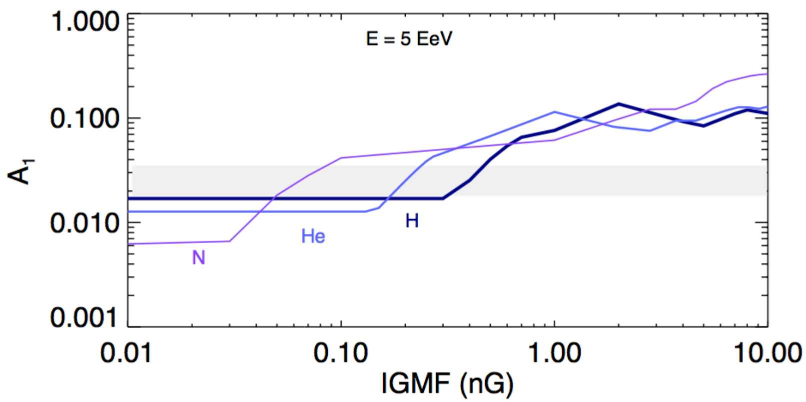
the rms fluctuations of different multipoles are

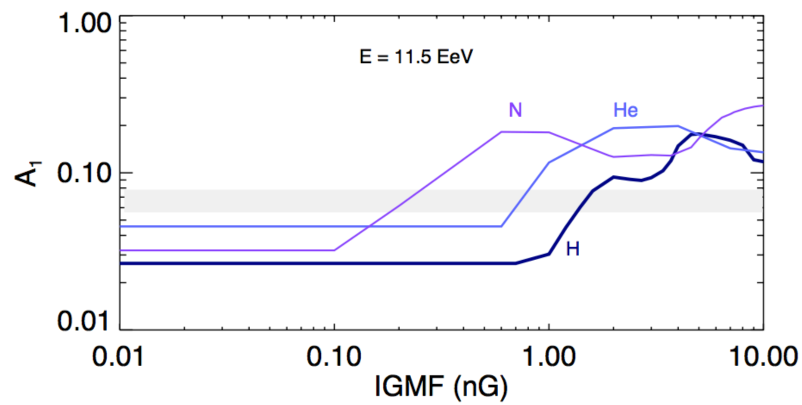
$$< |a_{lm}|^2 >= \frac{1}{(2\pi)^3}\rho_0^2 b^2 \int dk k^2 P(k) |\Psi_{lm}(k)|^2 \qquad (7)$$

where $\Psi_{lm}(k)$ is the window function,

$$\Psi_{lm}(k) \equiv \int_0^H dr j_l(kr) \alpha_{lm}(r) \,. \qquad (8)$$

2) From constrained simulations (CosmicFlows-2): *(Globus, Piran, Hoffman, Carlesi & Pomarède arxiv 1808.02048)*



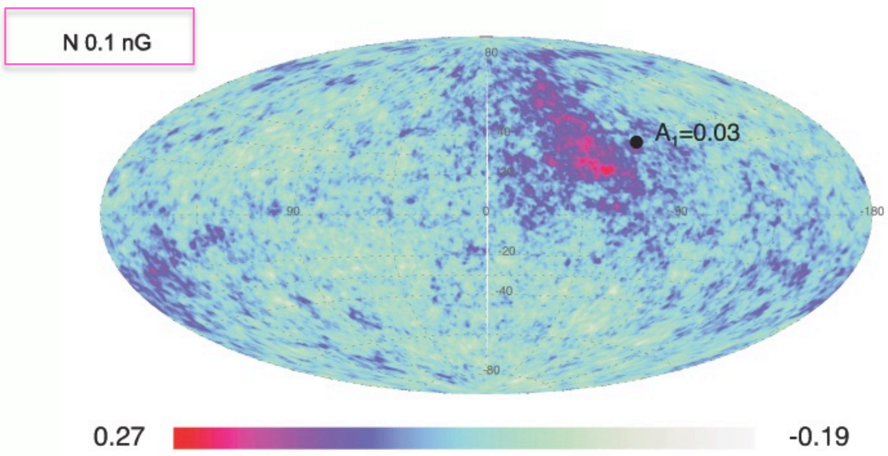


Large scale structure induced UHECR anisotropy

Globus, Piran, Hoffman, Carlesi & Pomarède arxiv 1808.02048

nitrogen @11.5 EeV

IGMF

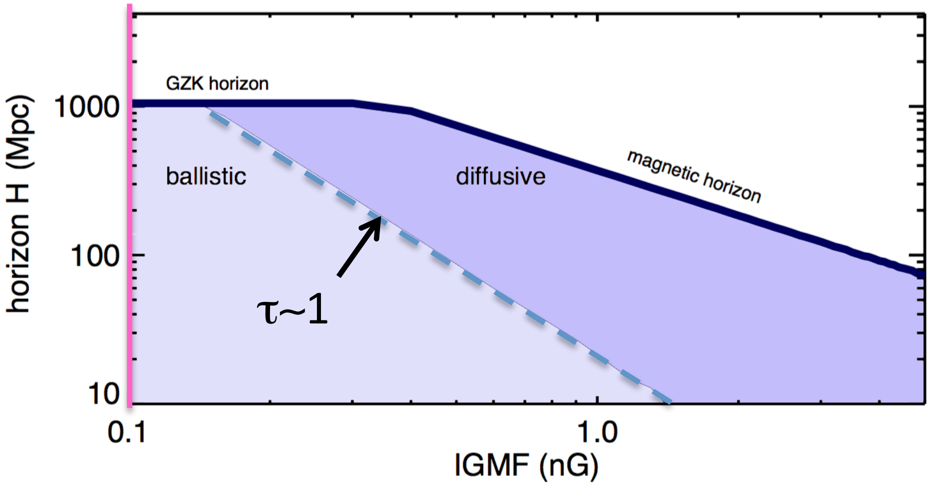


Diffusion in purely turbulent IGMF

$$D \approx 0.03 \left(\frac{\lambda_{\rm Mpc}^2 E_{\rm EeV}}{Z B_{\rm nG}} \right)^{1/3} + 0.5 \left(\frac{E_{\rm EeV}}{Z B_{\rm nG} \lambda_{\rm Mpc}^{0.5}} \right)^2 \rm Mpc^2\, Myr^{-1}$$

The image of a single source depends on the single scattering angle δθ and the **optical depth τ~rc/D** (e.g Kotera & Lemoine 08)

Within 350 Mpc we use the density field constrained by CosmicFlows-2 catalog (Hoffman+ 18)



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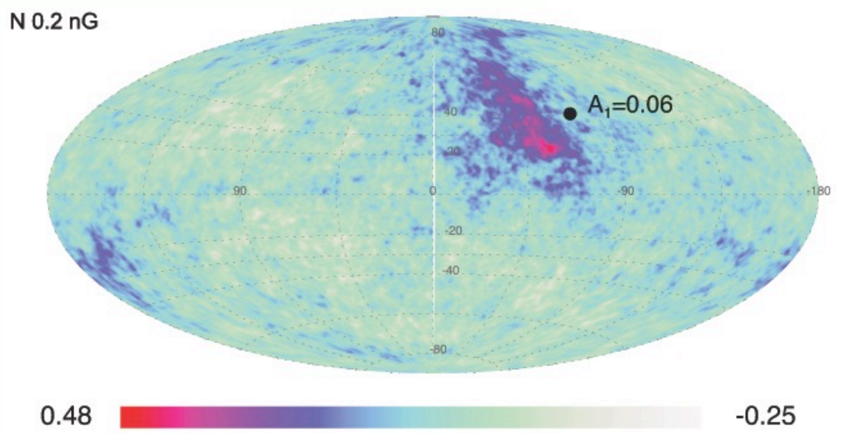

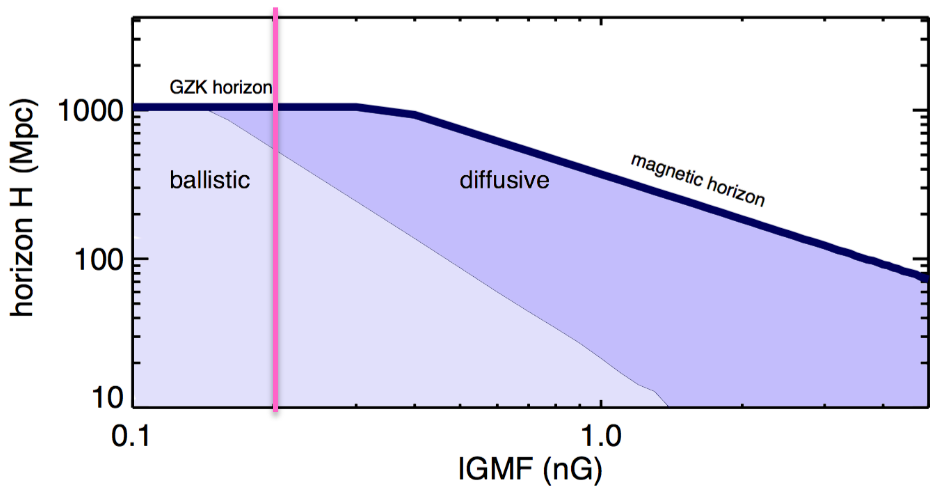

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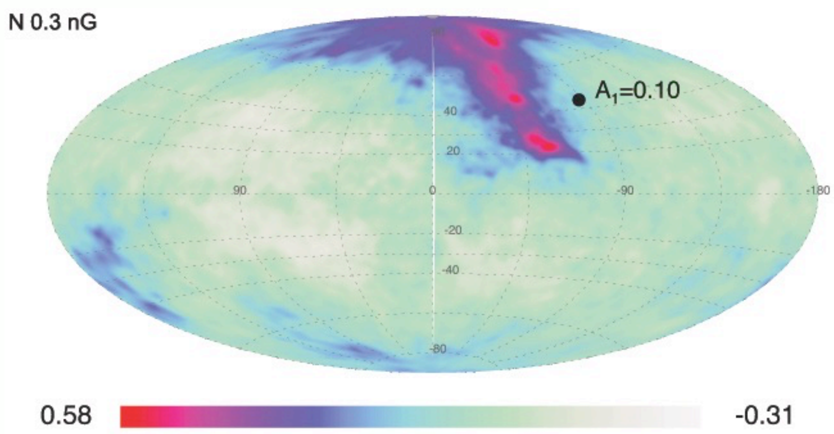

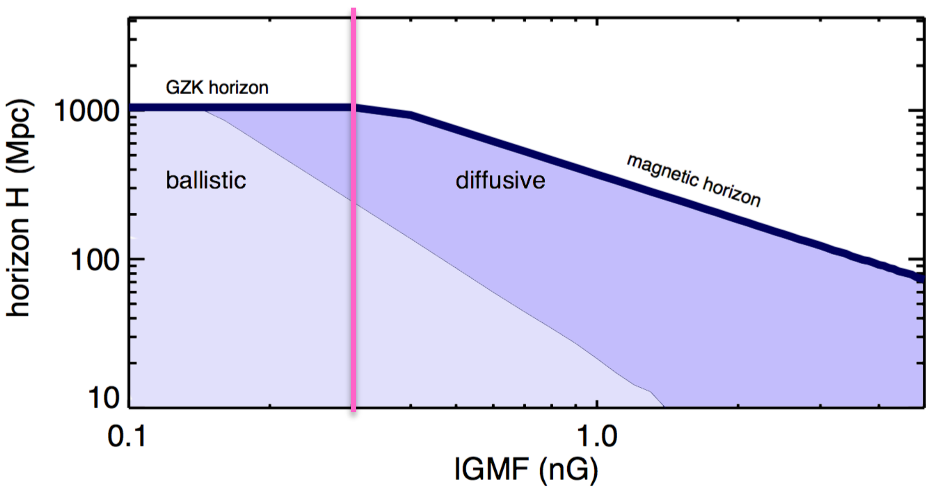

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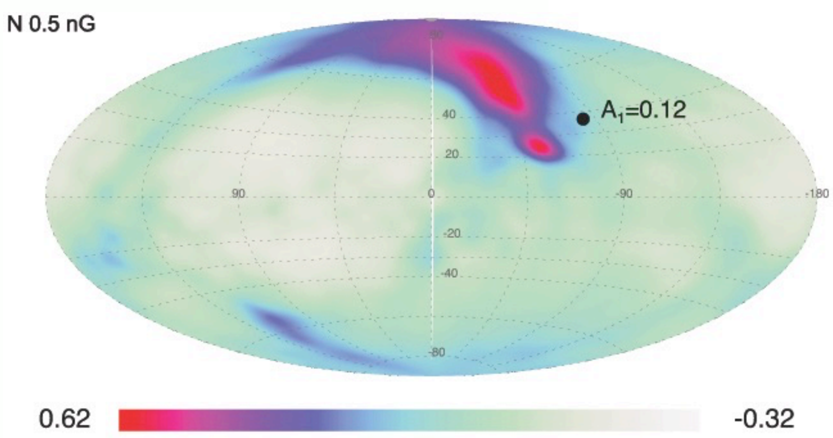

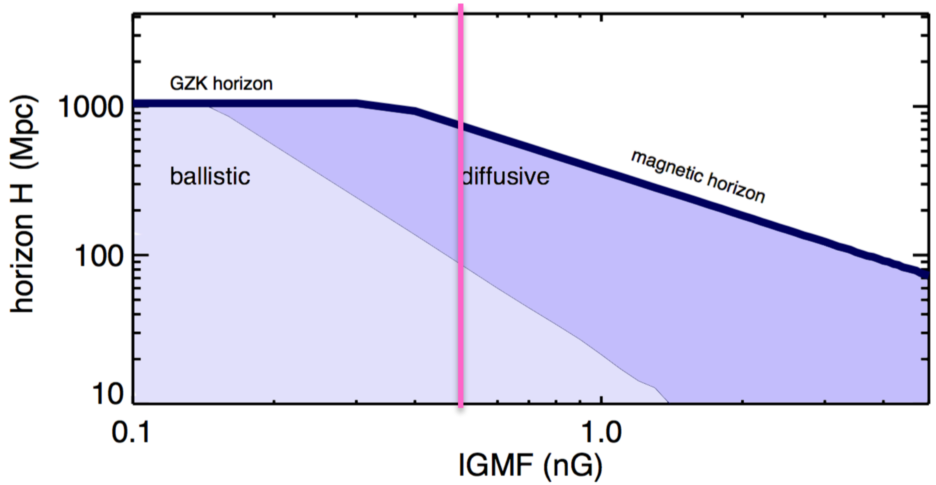

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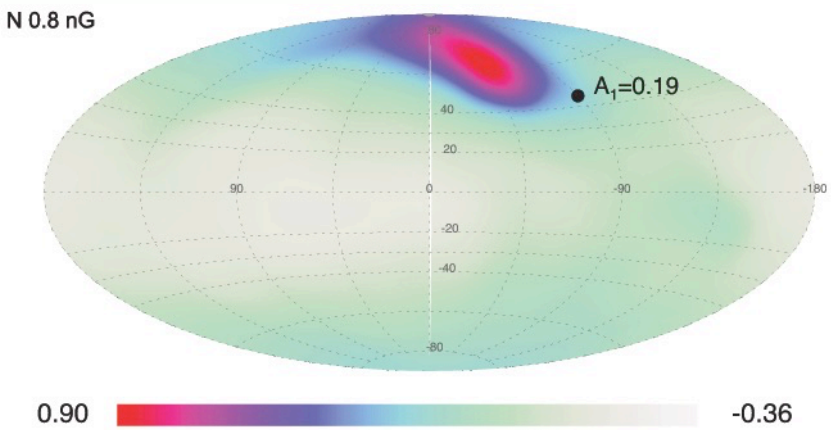

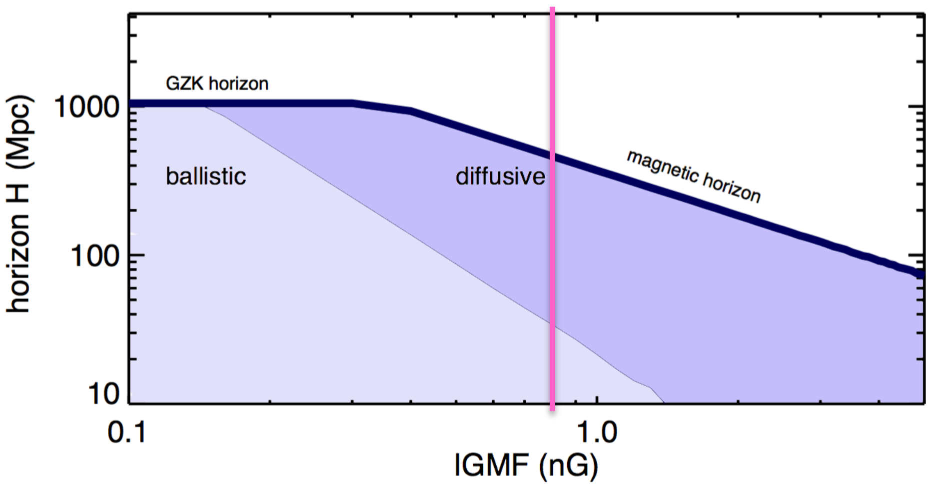

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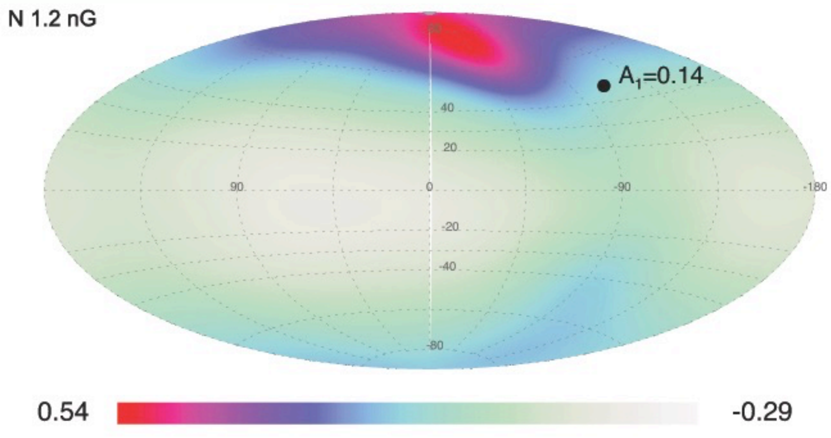

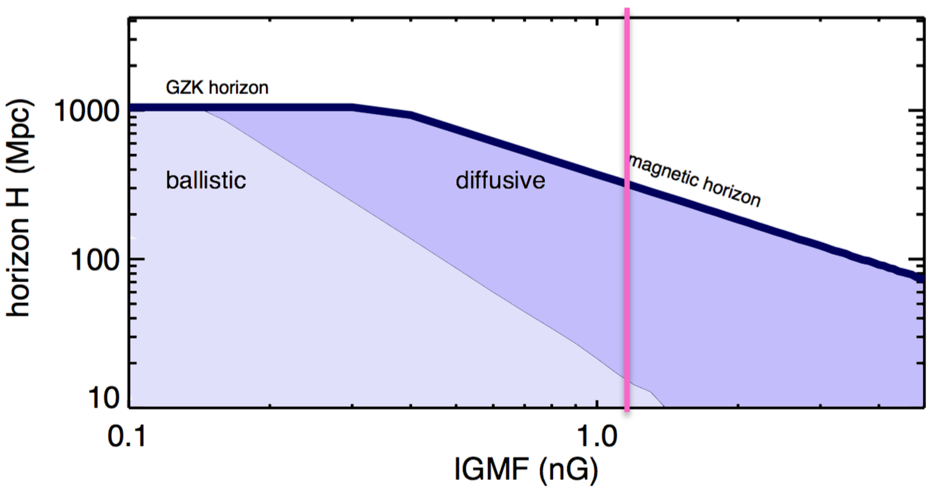

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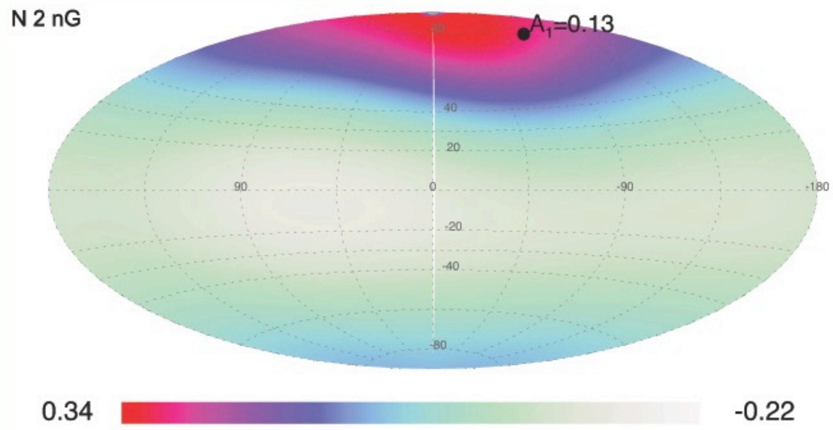

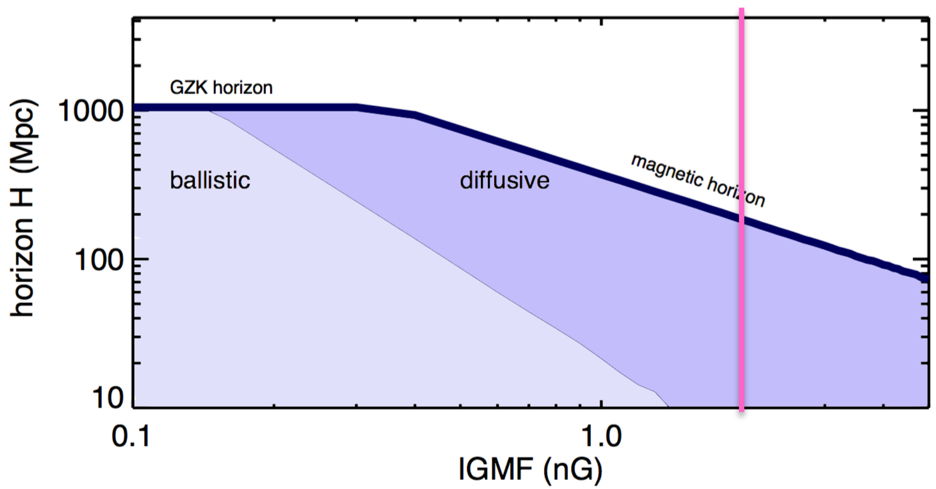

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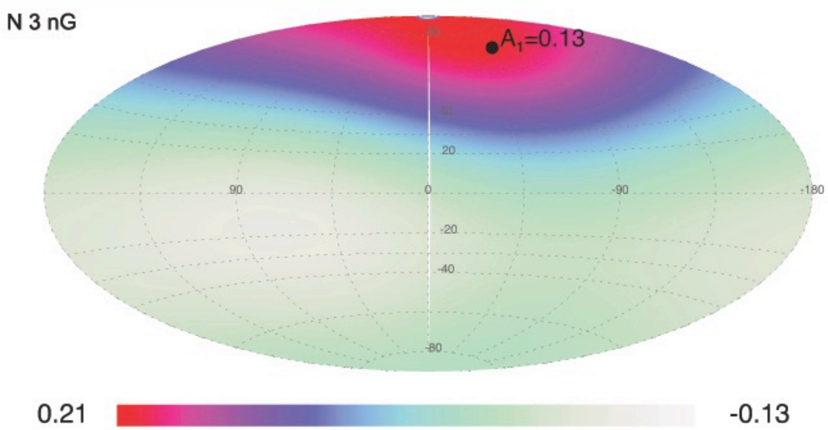
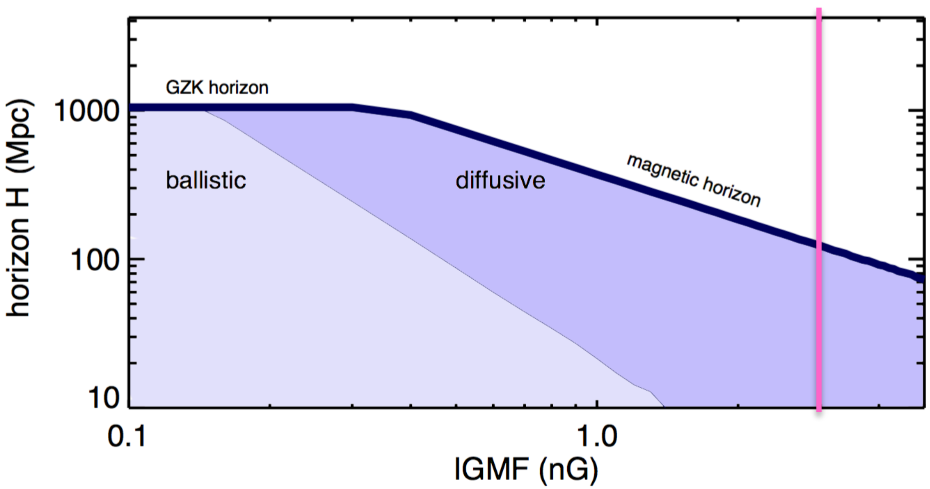
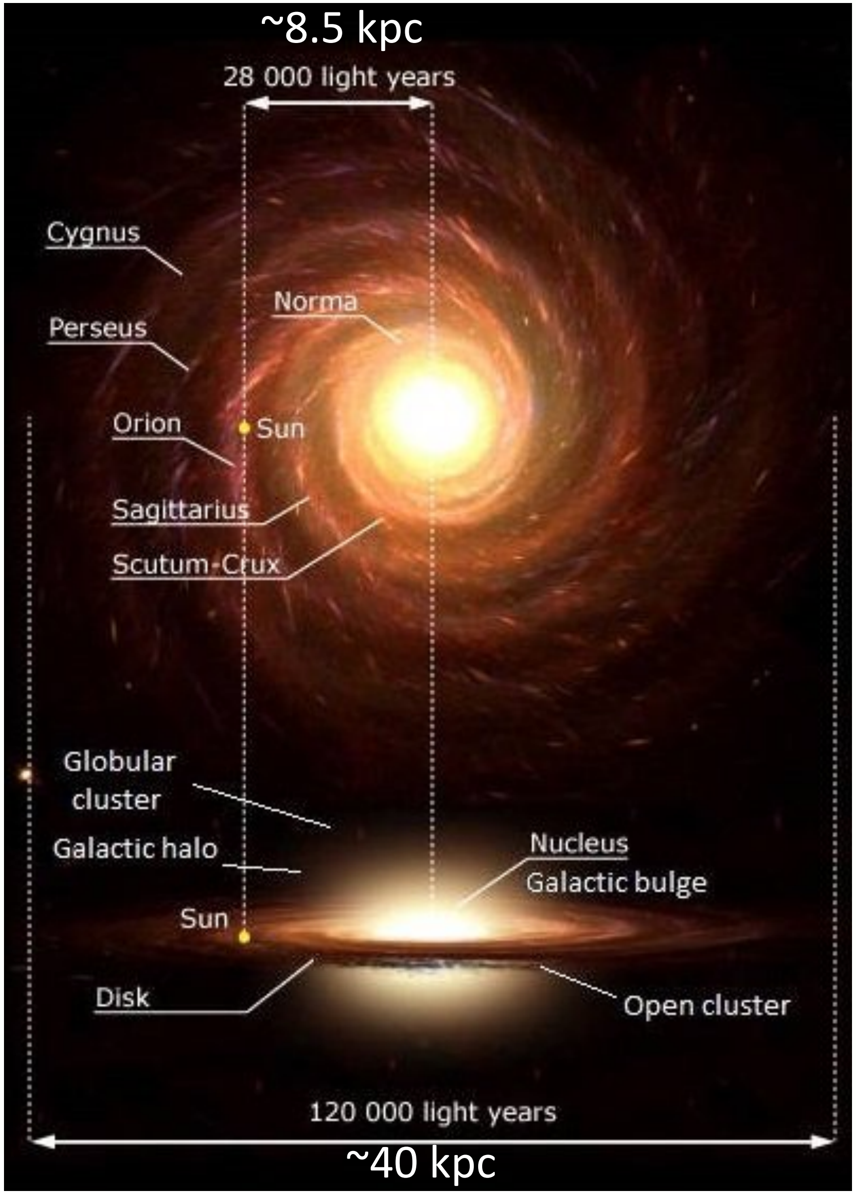
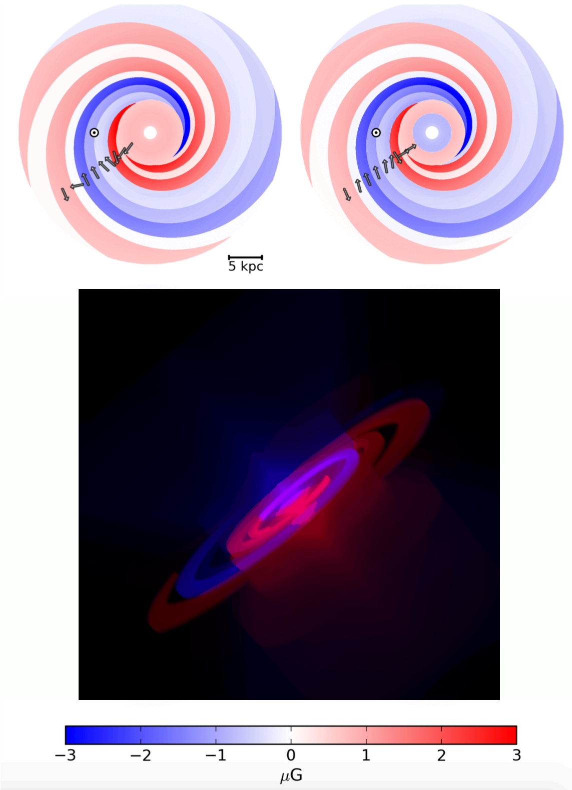


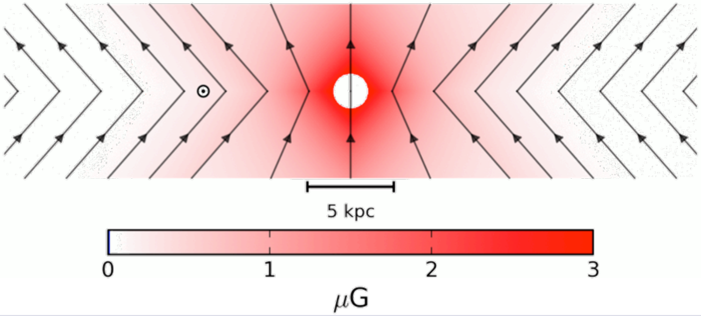


The Galactic Magnetic Field *(Jansson & Farrar 2012, JF12)*



GMF: regular component





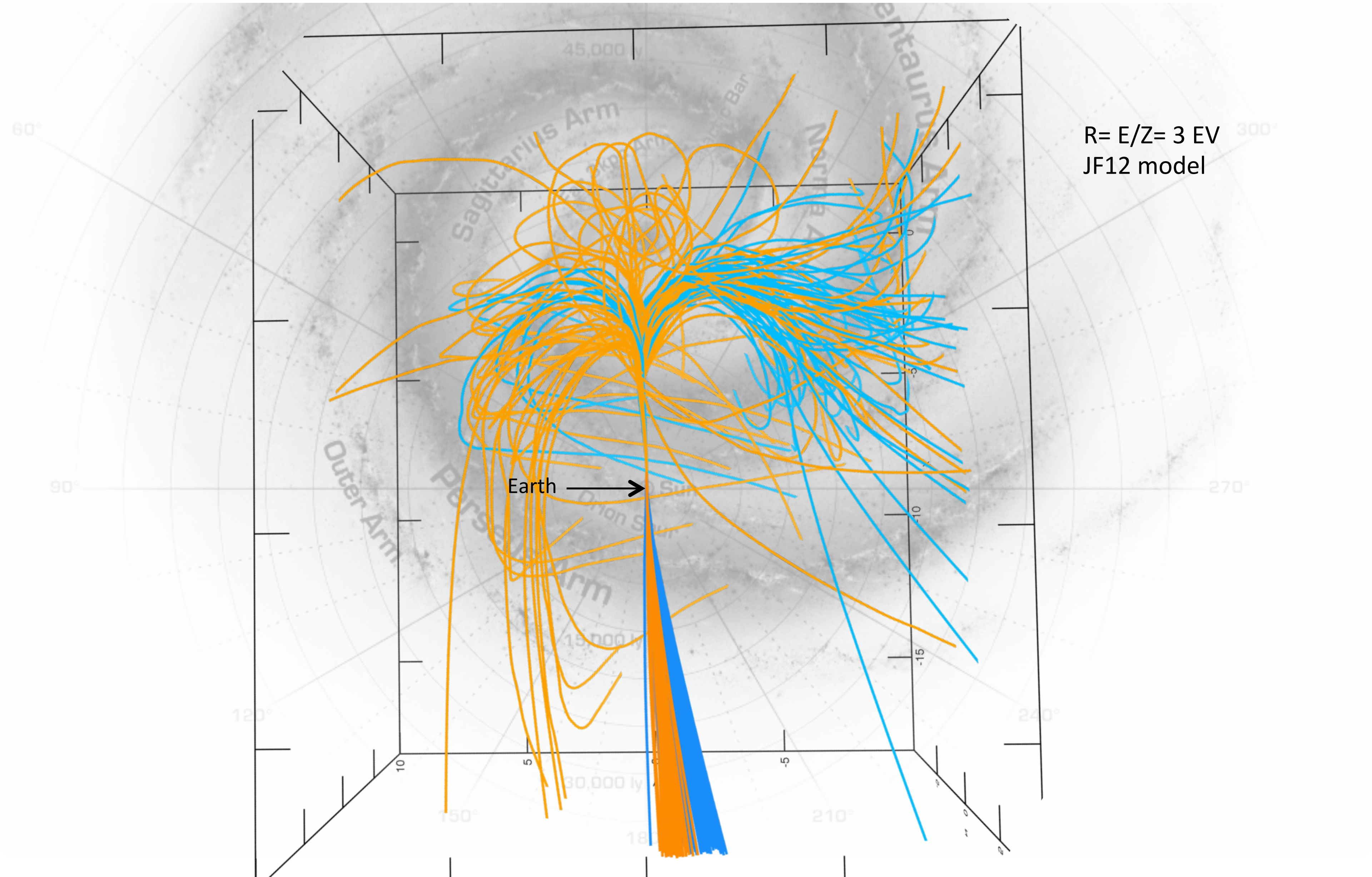
The GMF of the Milky Way

regular, large scale coherent field

Field	Best fit Parameters	Description
Disk	$b_1 = 0.1 \pm 1.8\,\mu$G	field strengths at $r = 5$ kpc
	$b_2 = 3.0 \pm 0.6\,\mu$G	
	$b_3 = -0.9 \pm 0.8\,\mu$G	
	$b_4 = -0.8 \pm 0.3\,\mu$G	
	$b_5 = -2.0 \pm 0.1\,\mu$G	
	$b_6 = -4.2 \pm 0.5\,\mu$G	
	$b_7 = 0.0 \pm 1.8\,\mu$G	
	$b_8 = 2.7 \pm 1.8\,\mu$G	inferred from $b_1, ..., b_7$
	$b_{\rm ring} = 0.1 \pm 0.1\,\mu$G	ring at 3 kpc $< r <$ 5 kpc
	$h_{\rm disk} = 0.40 \pm 0.03$ kpc	disk/halo transition
	$w_{\rm disk} = 0.27 \pm 0.08$ kpc	transition width
Toroidal halo	$B_{\rm n} = 1.4 \pm 0.1\,\mu$G	northern halo
	$B_{\rm s} = -1.1 \pm 0.1\,\mu$G	southern halo
	$r_{\rm n} = 9.22 \pm 0.08$ kpc	transition radius, north
	$r_{\rm s} > 16.7$ kpc	transition radius, south
	$w_{\rm h} = 0.20 \pm 0.12$ kpc	transition width
	$z_0 = 5.3 \pm 1.6$ kpc	vertical scale height
X halo	$B_{\rm X} = 4.6 \pm 0.3\,\mu$G	field strength at origin
	$\Theta^0_{\rm X} = 49 \pm 1°$	elev. angle at $z = 0, r > r^c_{\rm X}$
	$r^c_{\rm X} = 4.8 \pm 0.2$ kpc	radius where $\Theta_{\rm X} = \Theta^0_{\rm X}$
	$r_{\rm X} = 2.9 \pm 0.1$ kpc	exponential scale length
striation	$\gamma = 2.92 \pm 0.14$	striation and/or $n_{\rm cre}$ rescaling

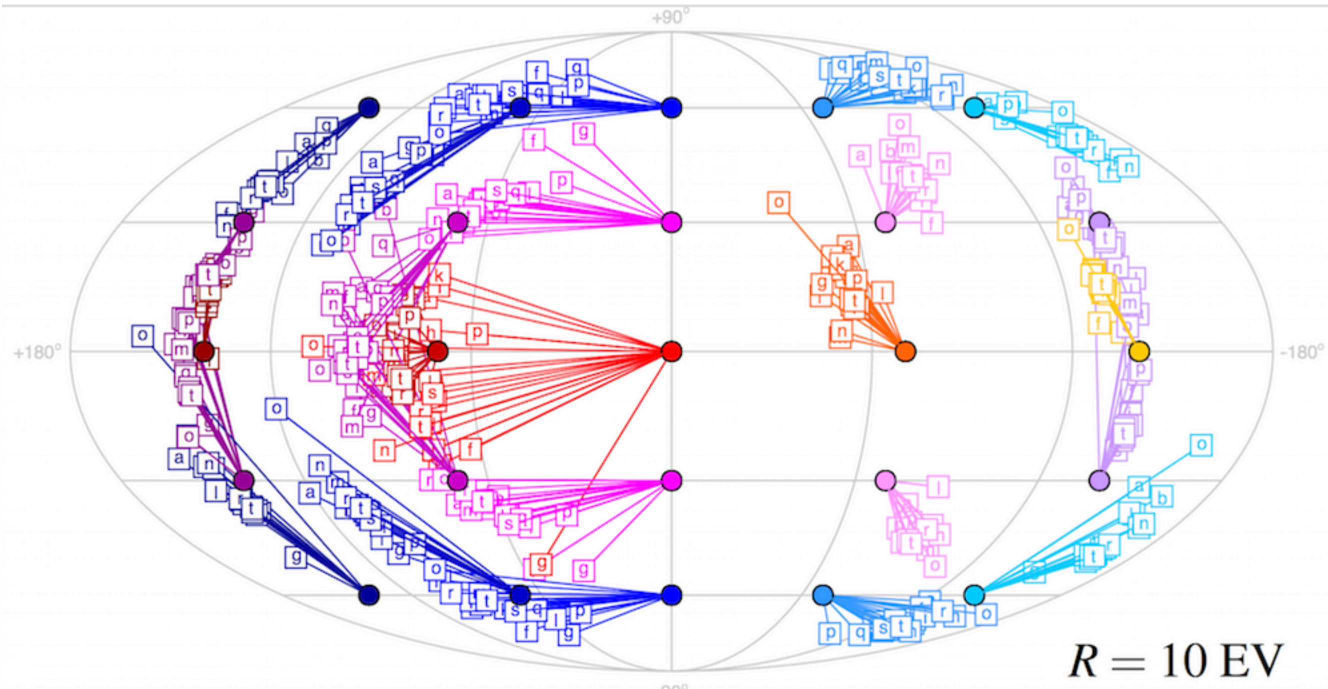
Jansson & Farrar 2012

Trajectories in the Galactic magnetic field



R= E/Z= 3 EV
JF12 model

Uncertainties on the GMF parameters

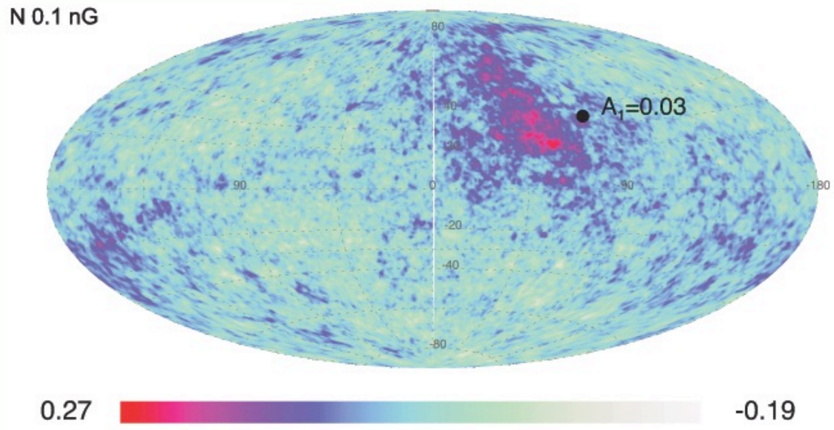


Farrar 2016

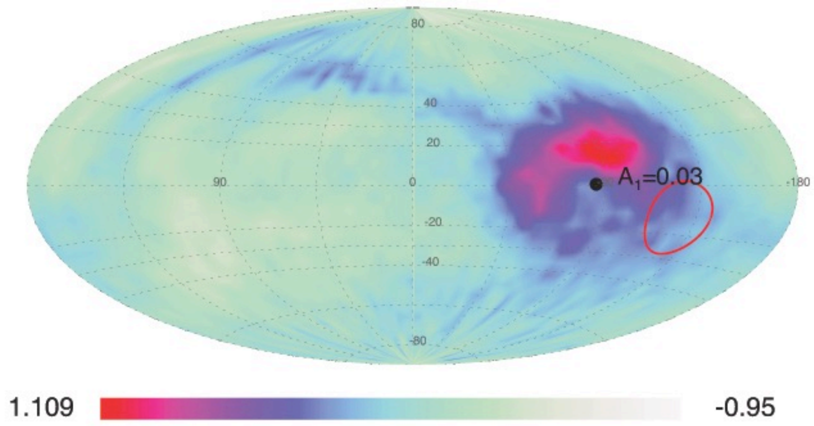
Large scale structure induced UHECR anisotropy

Globus, Piran, Hoffman, Carlesi & Pomarède arxiv 1808.02048

nitrogen @11.5 EeV
IGMF only



IGMF + GMF (JF12)



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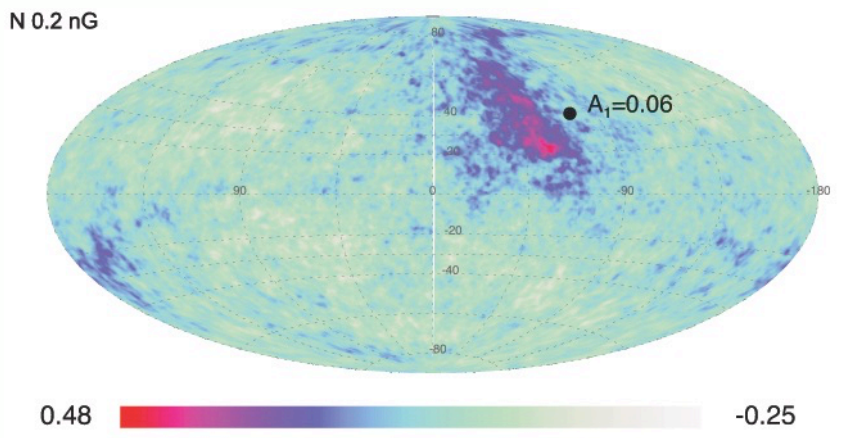

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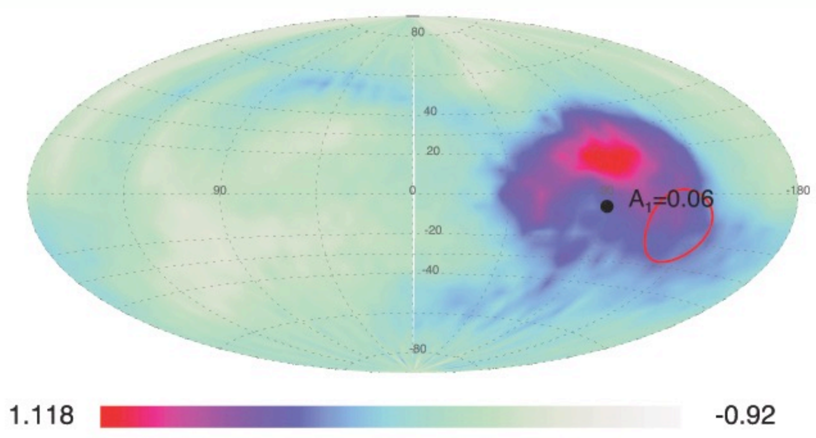

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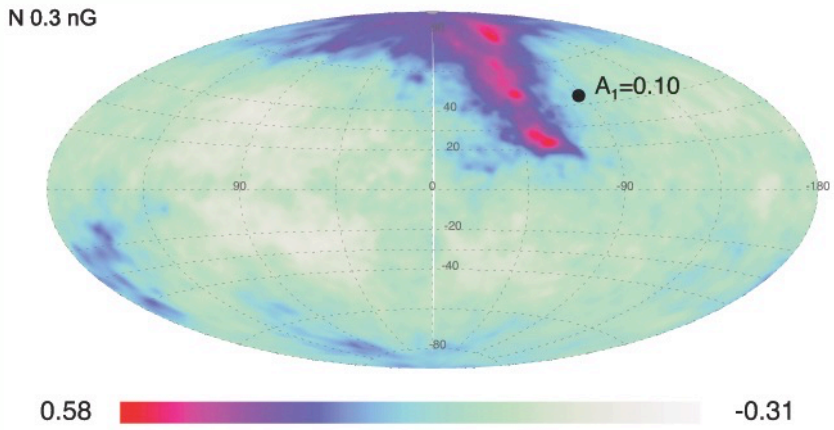

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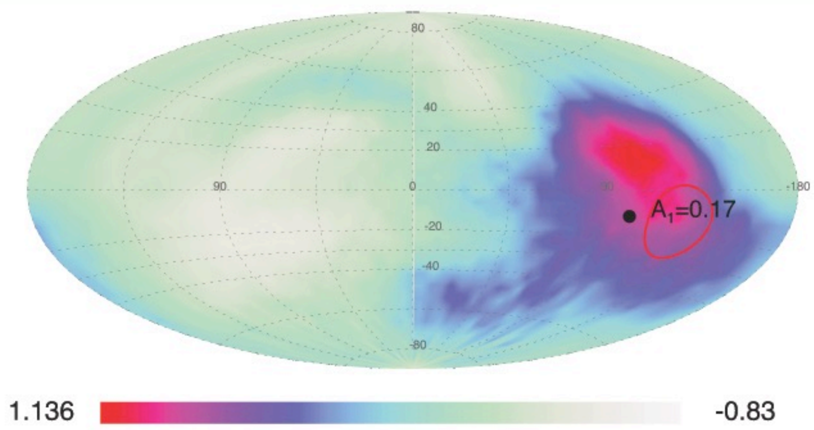

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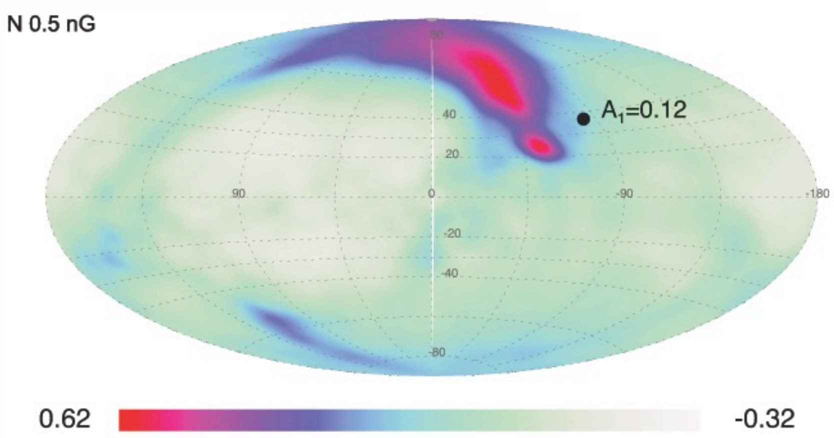

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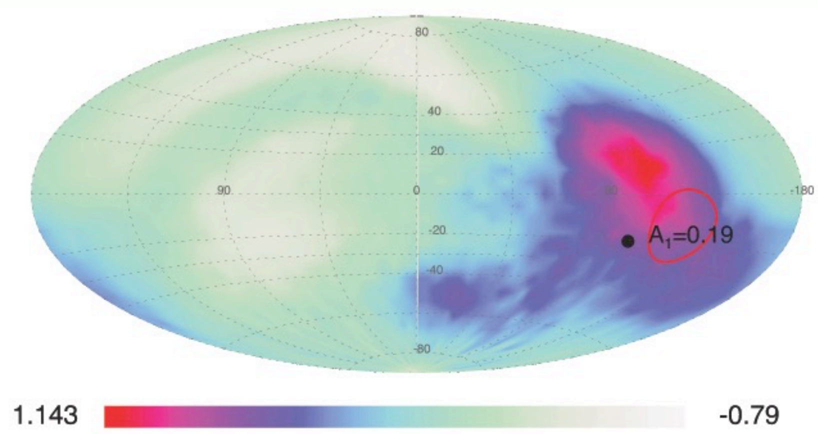

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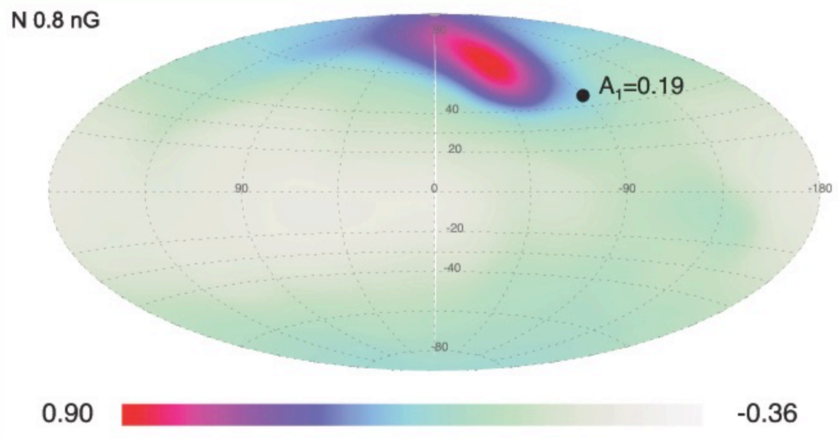

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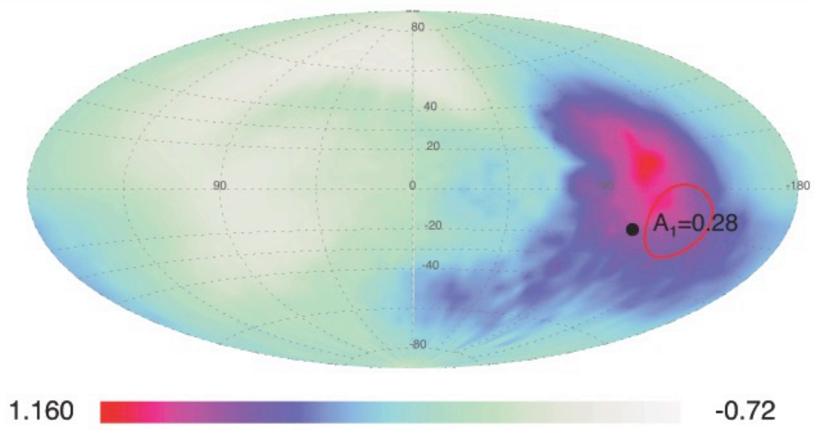

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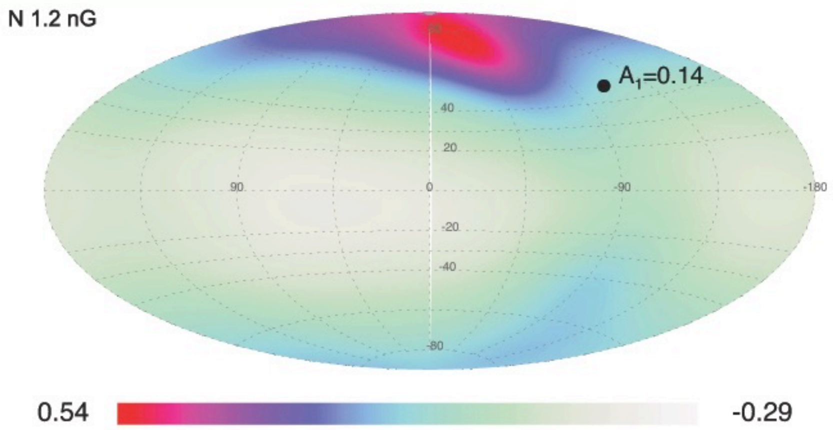

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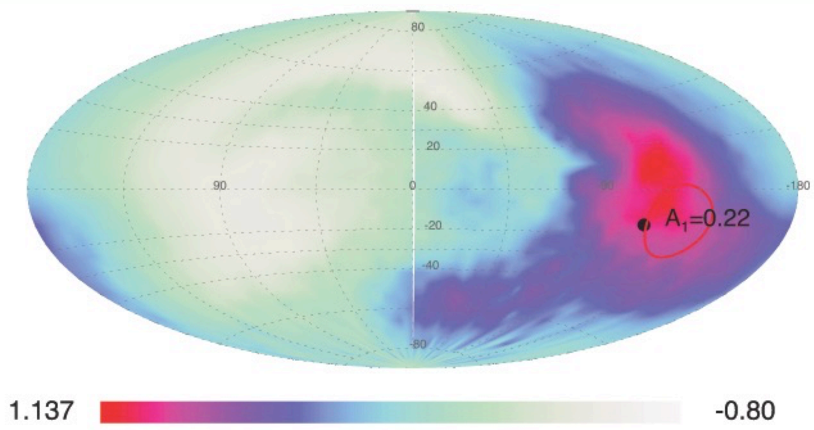

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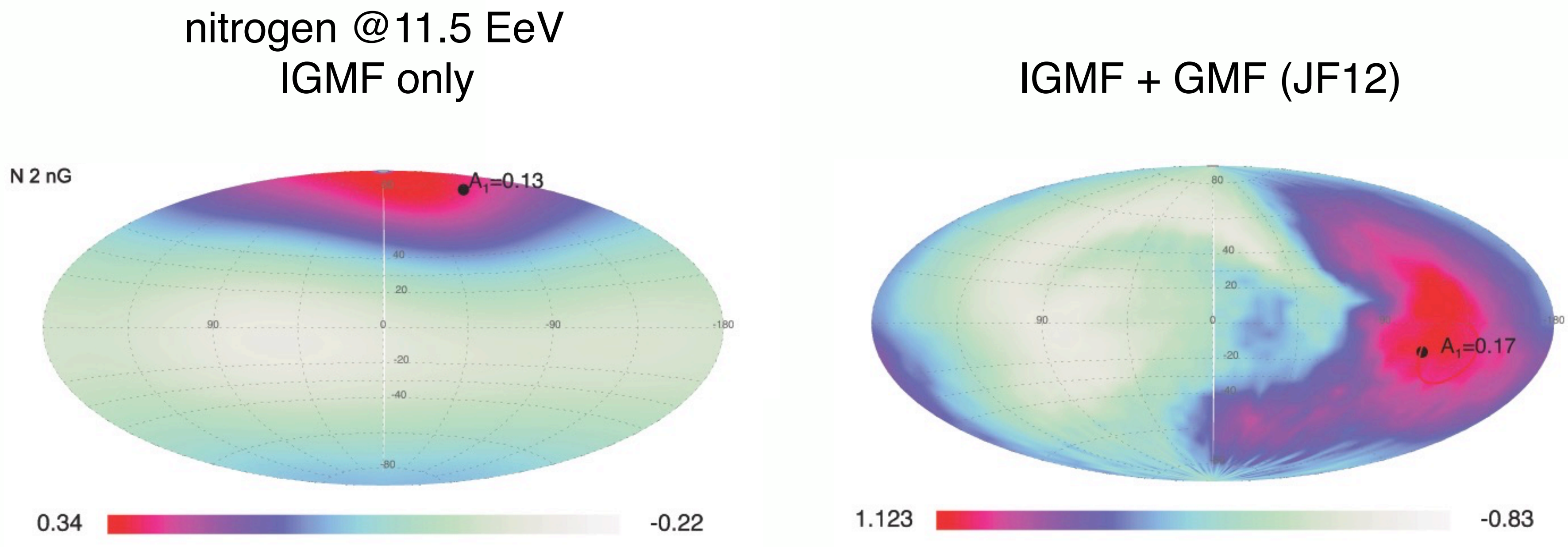

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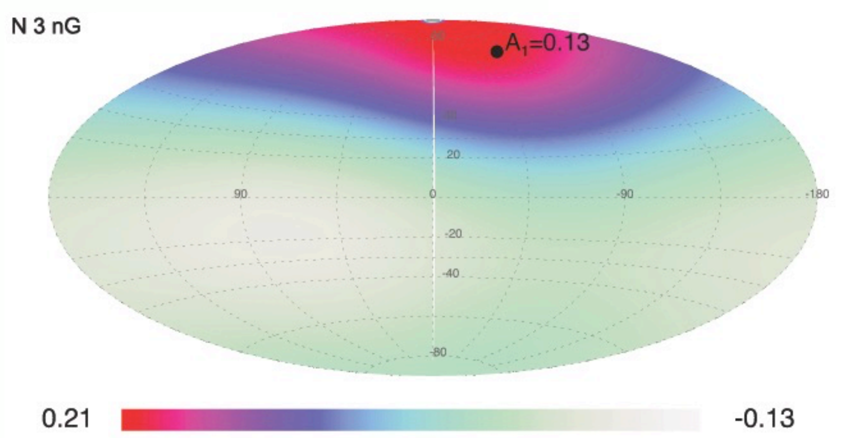

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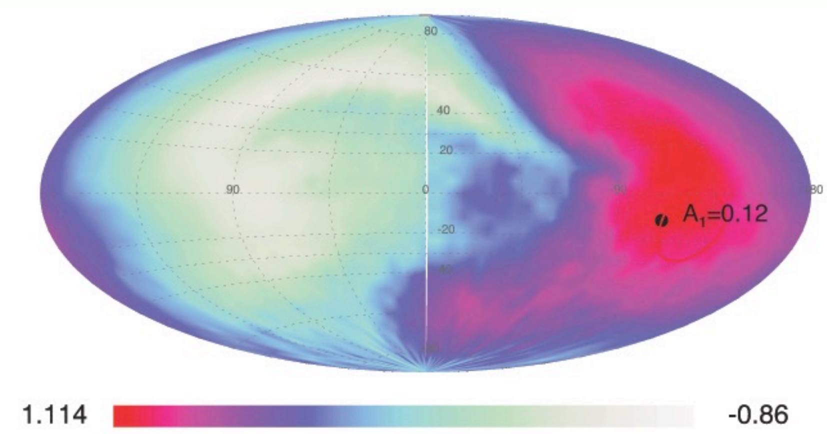

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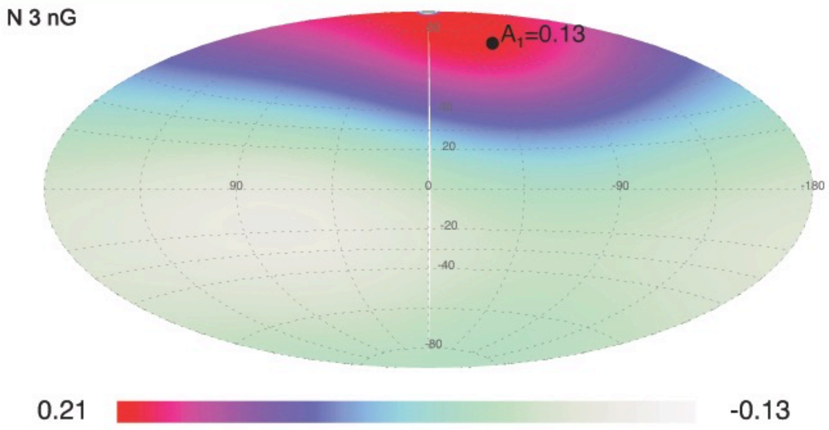
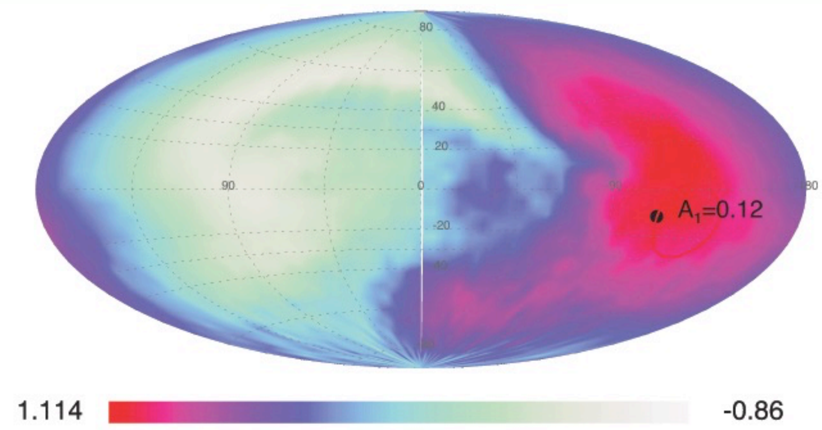
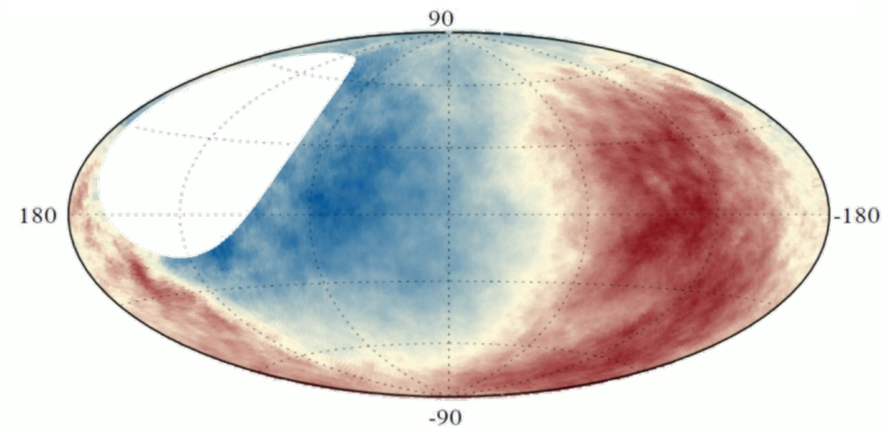
IGMF only

IGMF + GMF (JF12)







Summary

Auger reported **the first 5σ detection** of large scale (~dipole) anisotropy (ICRC 2017).
The amplitude of the dipole increases with energy (Auger 2018)

For a LSS-induced cosmic ray anisotropy:

1) The dipole amplitude and direction are determined by the UHECR horizon (magnetic horizon and GZK distance)

2) The increase of the dipole with energy can be understood as an effect of the horizon

3) Based on the power spectrum of density fluctuations the flux-weighted RMS dipole amplitude is ~ 0.1 for a few nG intergalactic magnetic field

4) The effect of the Galactic magnetic field is significant at rigidities < 10 EV (e.g. Farrar 2016) and **changes the direction and amplitude** of the dipole

Thank you !