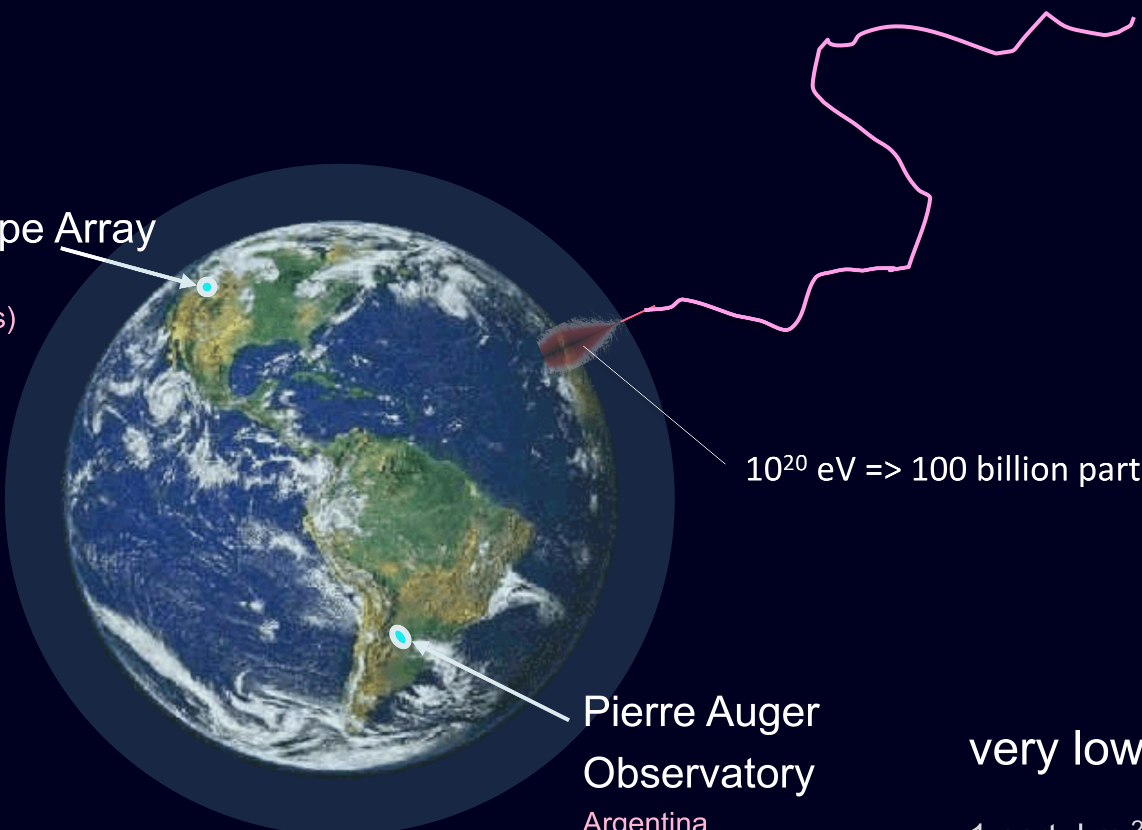
Understanding the ultra-high energy cosmic-rays

Noemie Globus
NYU/CCA (visitor at RIKEN)



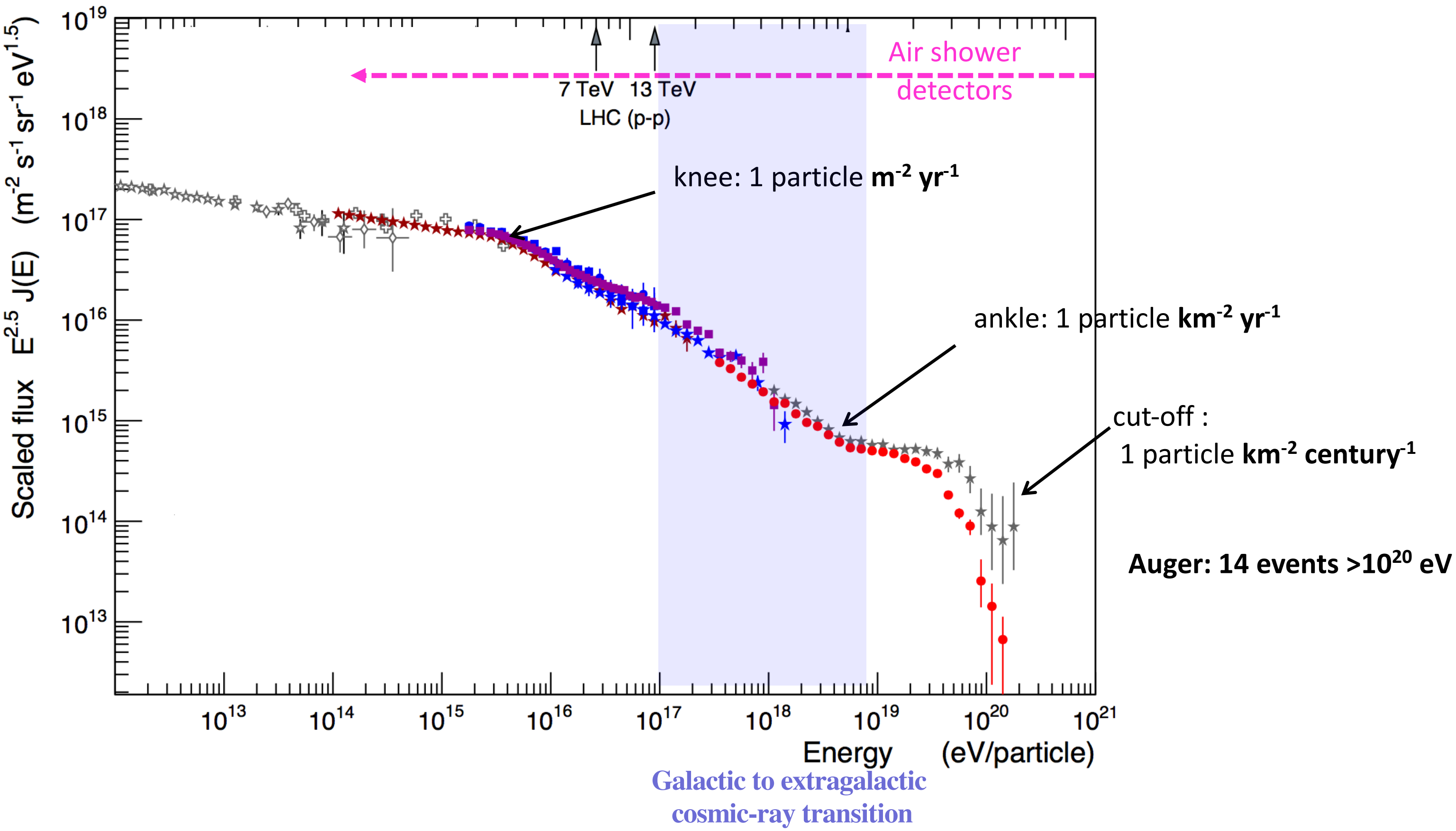
very low flux

1 part. km^{-2} yr^{-1} (10^{18} eV)
to
1 part. km^{-2} century^{-1}(10^{20} eV)

Cosmic Rays primary observables

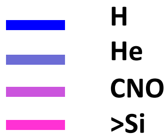
Energy spectrum	Mass spectrum	Angular spectrum
↓	↓	↓
Differential flux	composition	Arrival direction

Energy Spectrum

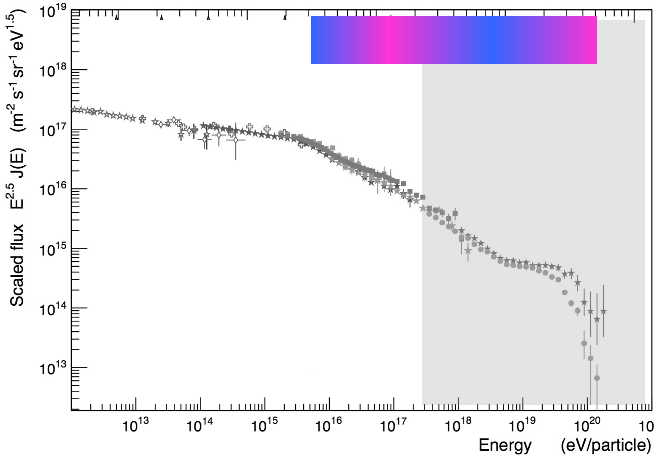


above ~10^{19} eV : extragalactic origin

Auger composition analyses



The composition is getting heavier above the ankle



nitrogen-like @~10^{19} eV

Yushkov et al, ICRC 2019

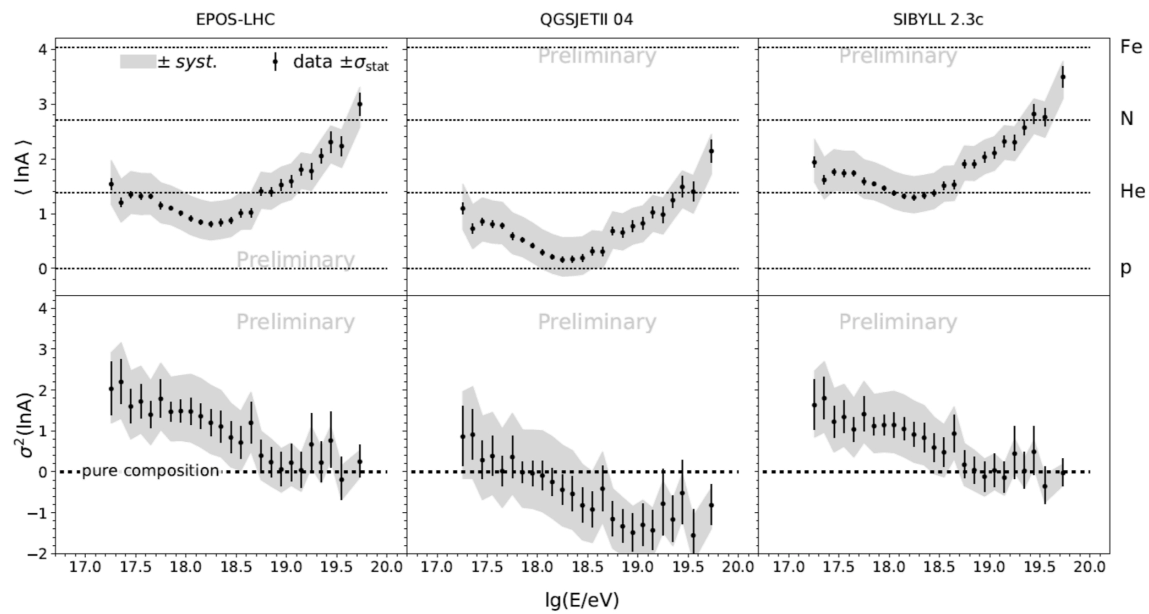
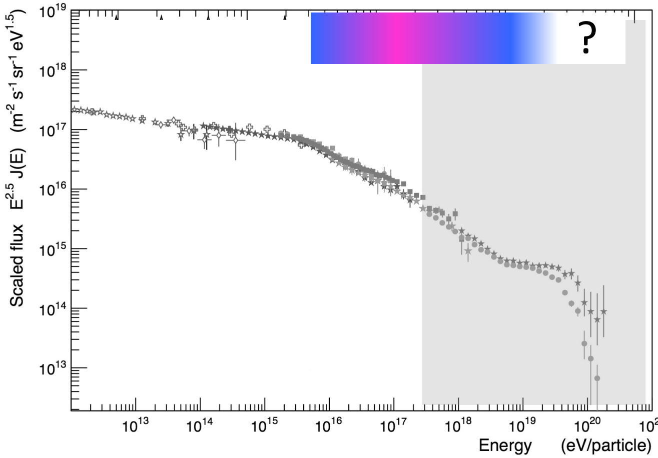


Figure 5: The mean (top) and the variance (bottom) of ln$A$ estimated from data with EPOS-LHC (left), QGSJetII-04 (middle) and Sibyll2.3 (right) hadronic interaction model

TA composition analyses

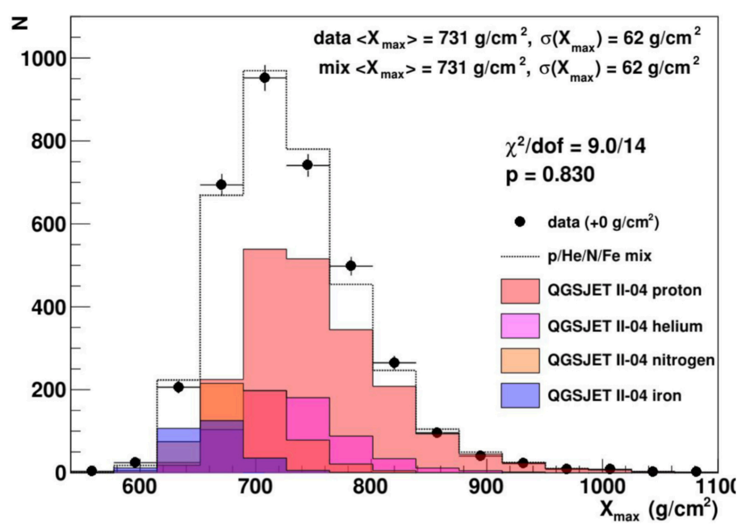
H
He
CNO
>Si

The composition seems to be lighter than Auger (however less statistical power)



lighter composition than Auger @~10^{19} eV

Composition by Telescope Array between $10^{18.2}$ and $10^{19.1}$ eV



- Proton only model would require shift of X_{max} scale; not totally excluded within systematic uncertainties
- Mixed Composition preferred

f_p = 57.3 ± 1.3%
f_{He} = 18.0 ± 0.7%
f_N = 16.8 ± 0.7%
f_{Fe} = 8.0 ± 0.5%

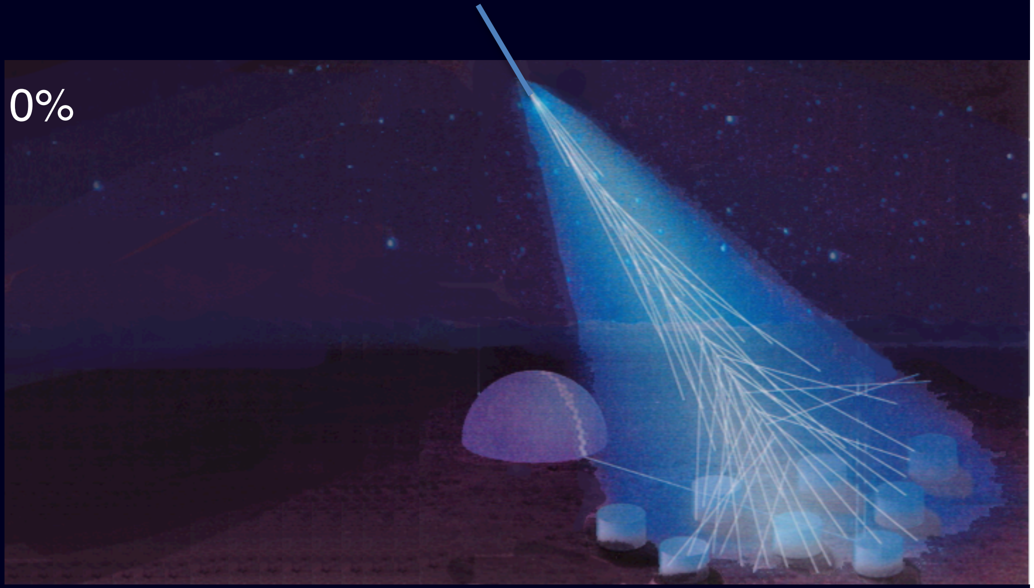
Hanlon et al, ICRC 2019

Uncertainties

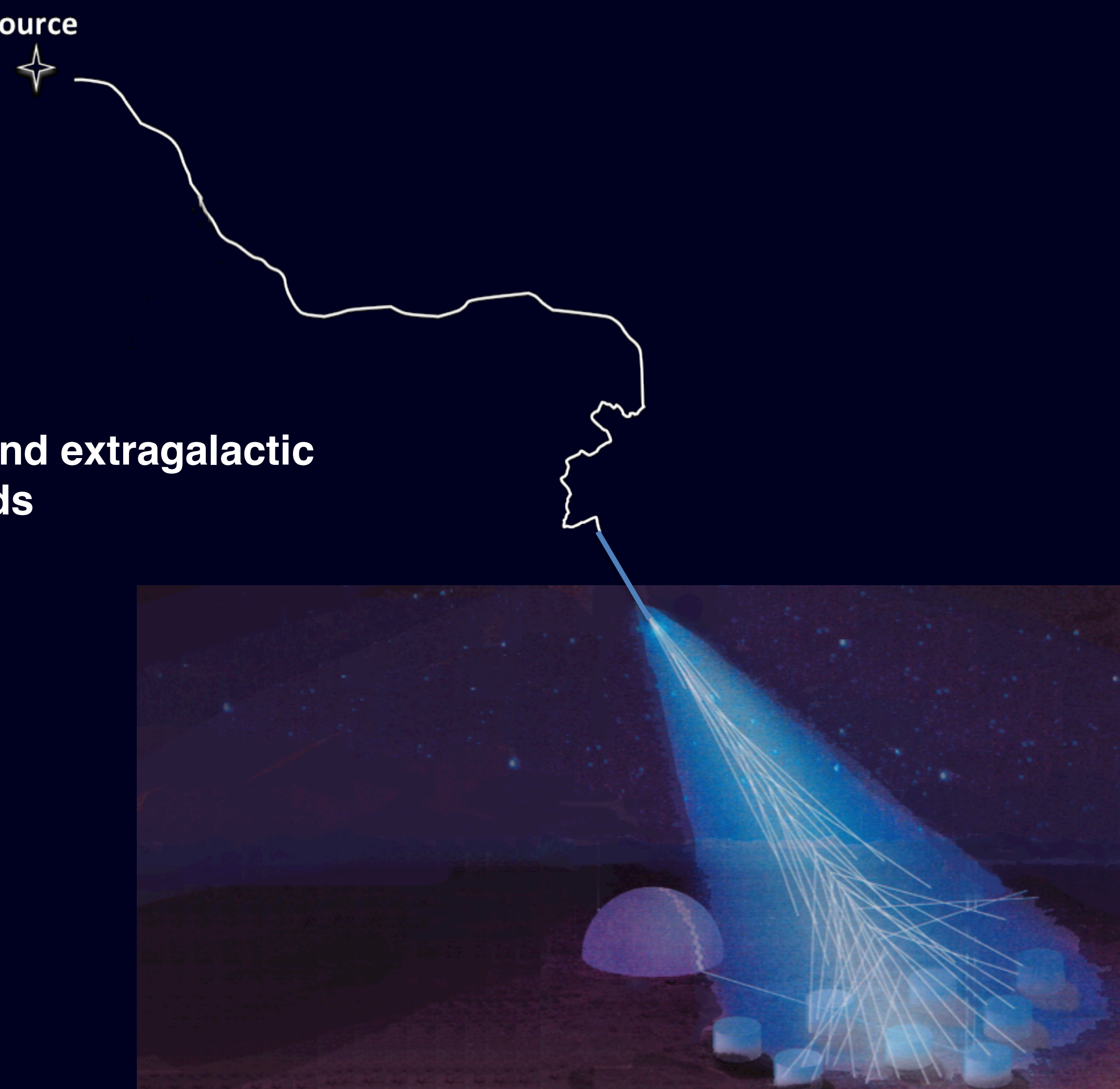
1. Arrival directions of cosmic rays: <1 degree

2. Composition of the air shower: mostly unknown

3. Energy of cosmic rays: ~10%



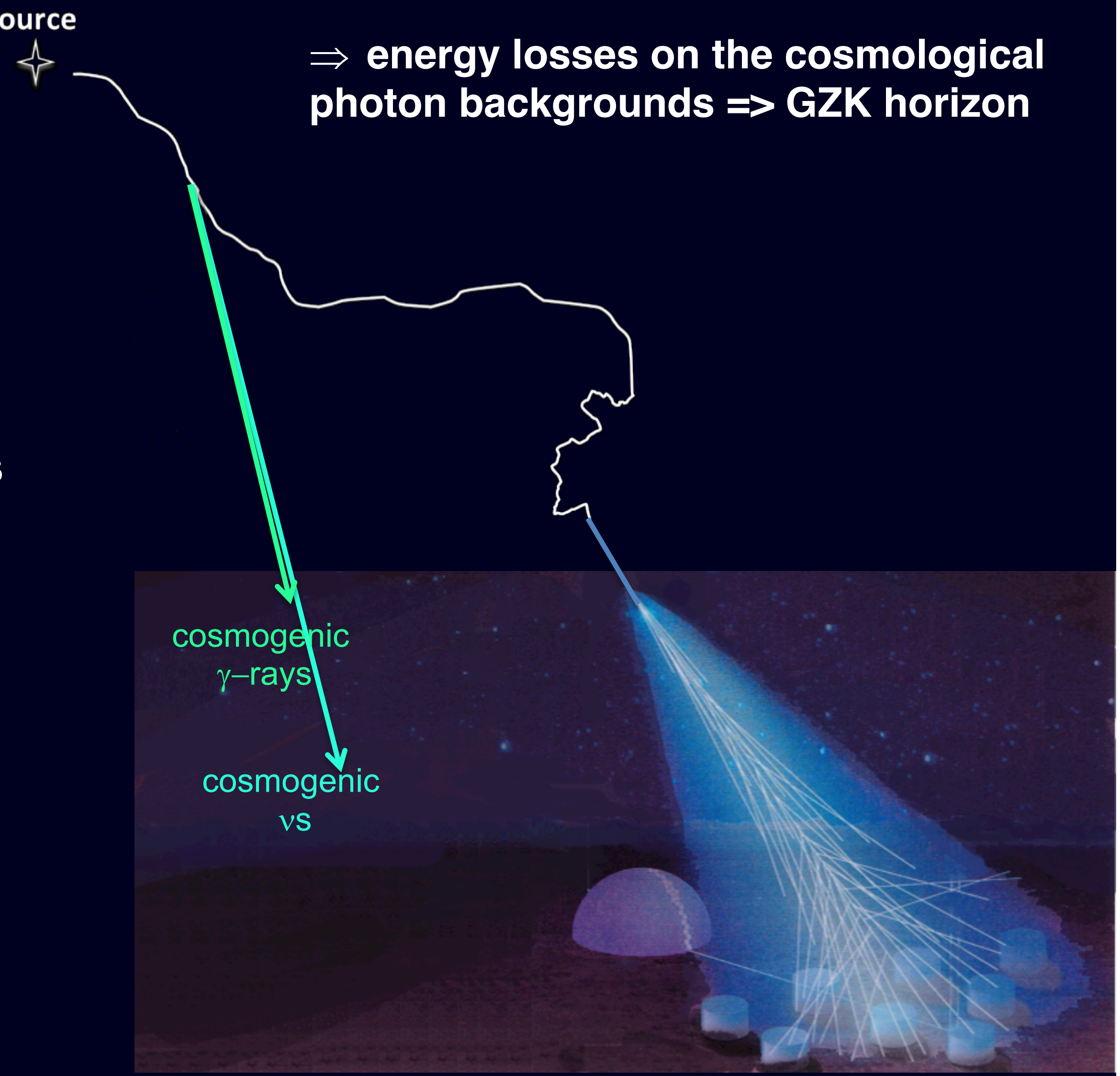
Source(s) direction(s) ≠ arrival directions



=> deflections by Galactic and extragalactic magnetic fields

Source spectrum ≠ observed spectrum

$\Rightarrow$ **energy losses on the cosmological photon backgrounds => GZK horizon**



Greisen-Zatsepin-Kuzmin (GZK) effect, 1966

Photo-pion production
(mainly Δ resonance)

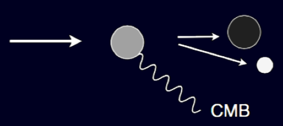
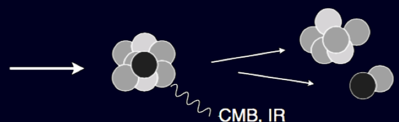
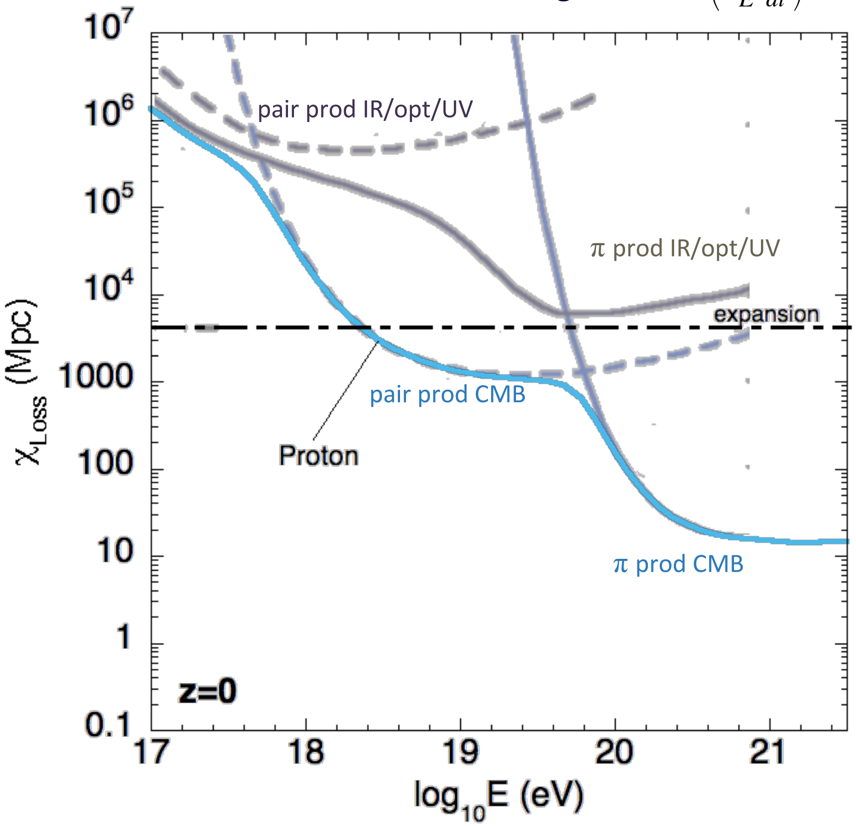


Photo-dissociation
(giant dipole resonance)



GZK horizon of protons

Proton attenuation length $\chi_{loss} = c\left(-\frac{1}{E}\frac{dE}{dt}\right)^{-1}$



Protons suffer of:

$$\frac{dE}{dz} = \frac{E}{(1+z)}$$

expansion of the Universe

low inelasticity process
interaction with CMB ~ 10^{18} eV

$$p + \gamma \to p + e^+ + e^-$$

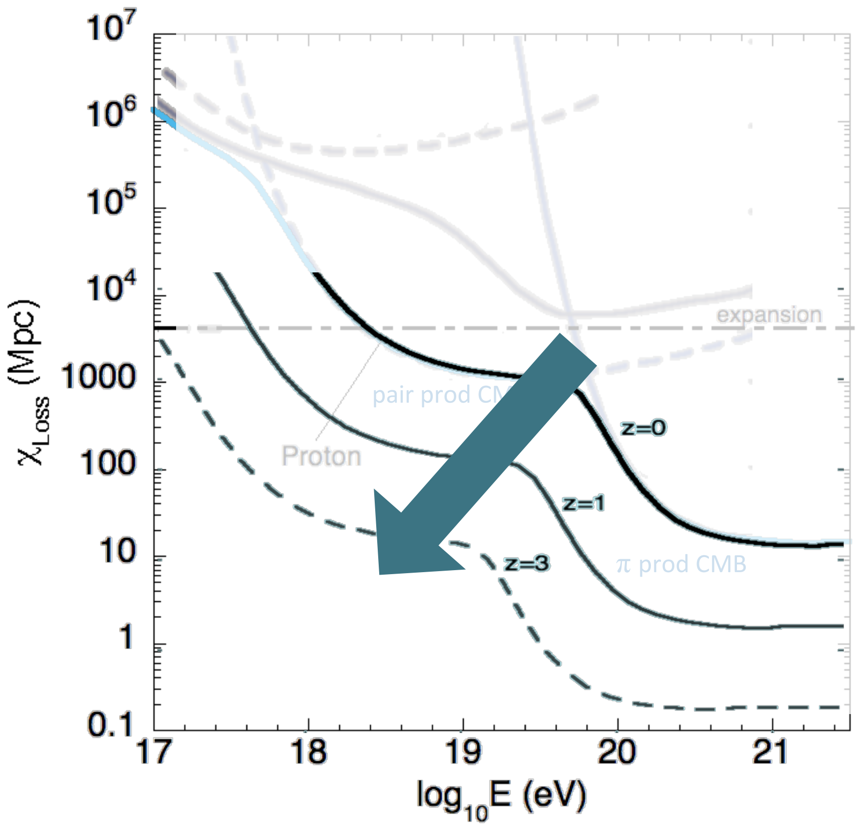
large inelasticity process (~20%)
interaction threshold ~7.10^{19} eV

$$p + \gamma \to p|n + \Pi^0|\Pi^+|\Pi^-$$

$$\pi^0 \to 2\gamma$$
$$\pi^+ \to \mu^+ + \nu_\mu,\ \mu^+ \to \overline{\nu_\mu} + e^+ + \nu_e$$
$$\pi^- \to \mu^- + \overline{\nu_\mu},\ \mu^- \to \nu_\mu + e^- + \overline{\nu_e}$$

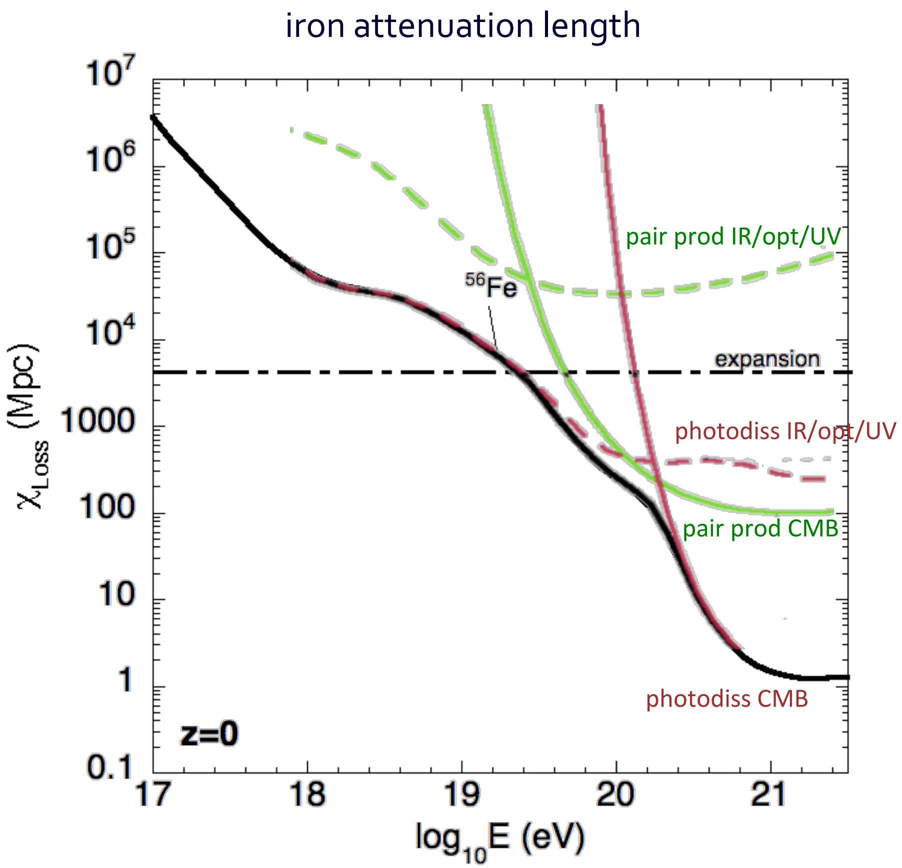
GZK horizon of protons

Proton attenuation length



The energy loss length evolves rapidly with redshift due to the temperature and density evolution of the CMB
=> enhanced emission of secondary neutrinos, photons

GZK horizon of nuclei

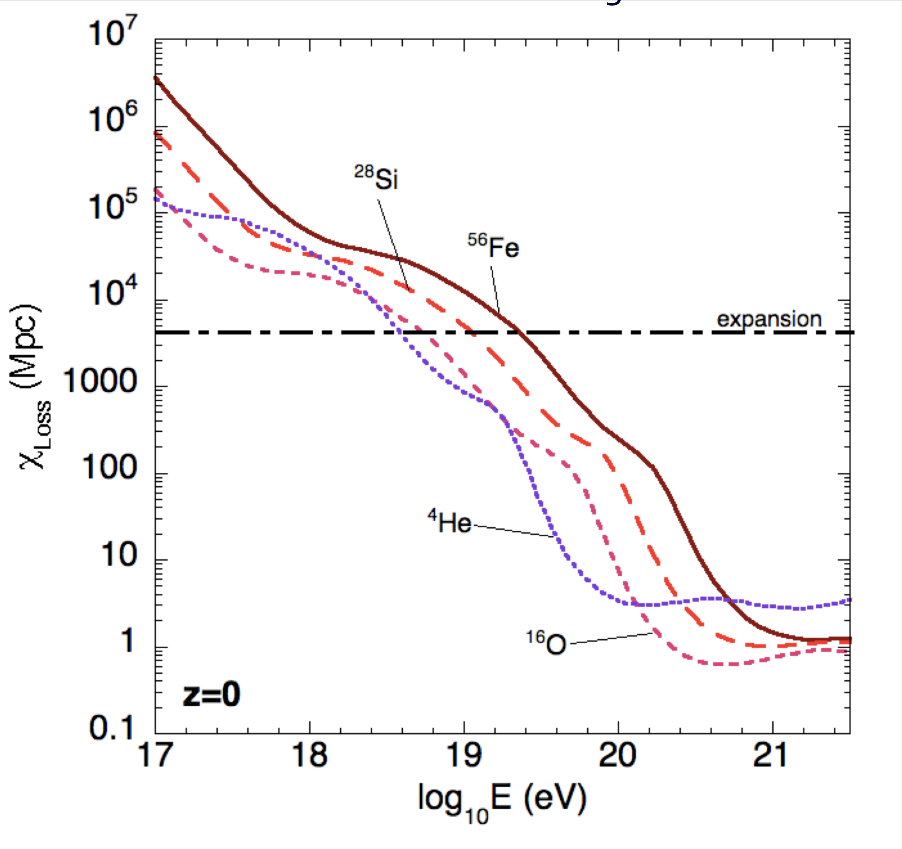


Compound nuclei suffer of:

- Processes triggering a decrease of the Lorentz Factor
  - Adiabatic losses
  - Pair production losses (energy threshold ~A × 10^{18} eV)
- Photodisintegration processes
  - Giant Dipole Resonance (GDR); threshold ~ 8 - 20 MeV largest σ and lowest threshold (Khan et al., 2005)
  - Quasi-Deuteron process (QD); threshold ~ 30 MeV
  - Pion production (BR); threshold ~ 145 MeV

GZK horizon of nuclei

nuclei attenuation length



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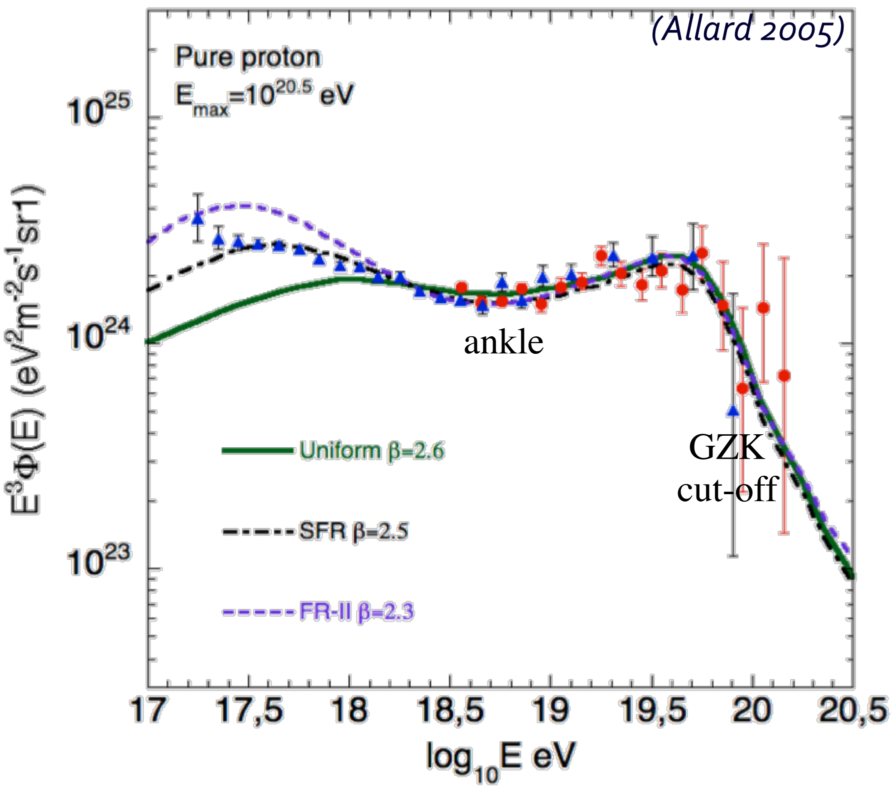
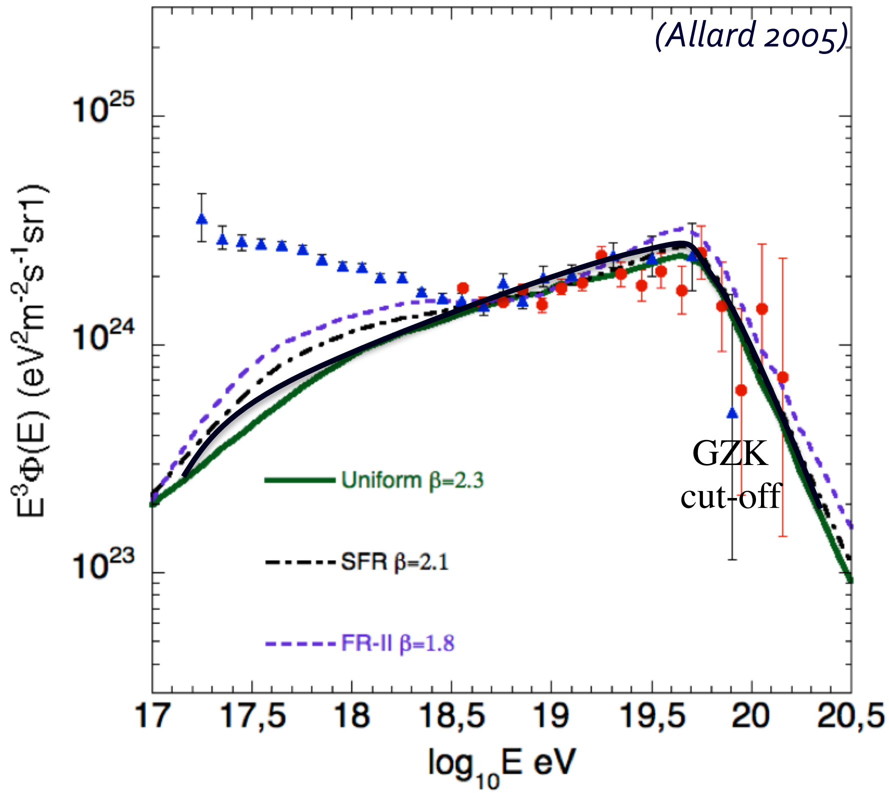
Propagated spectrum

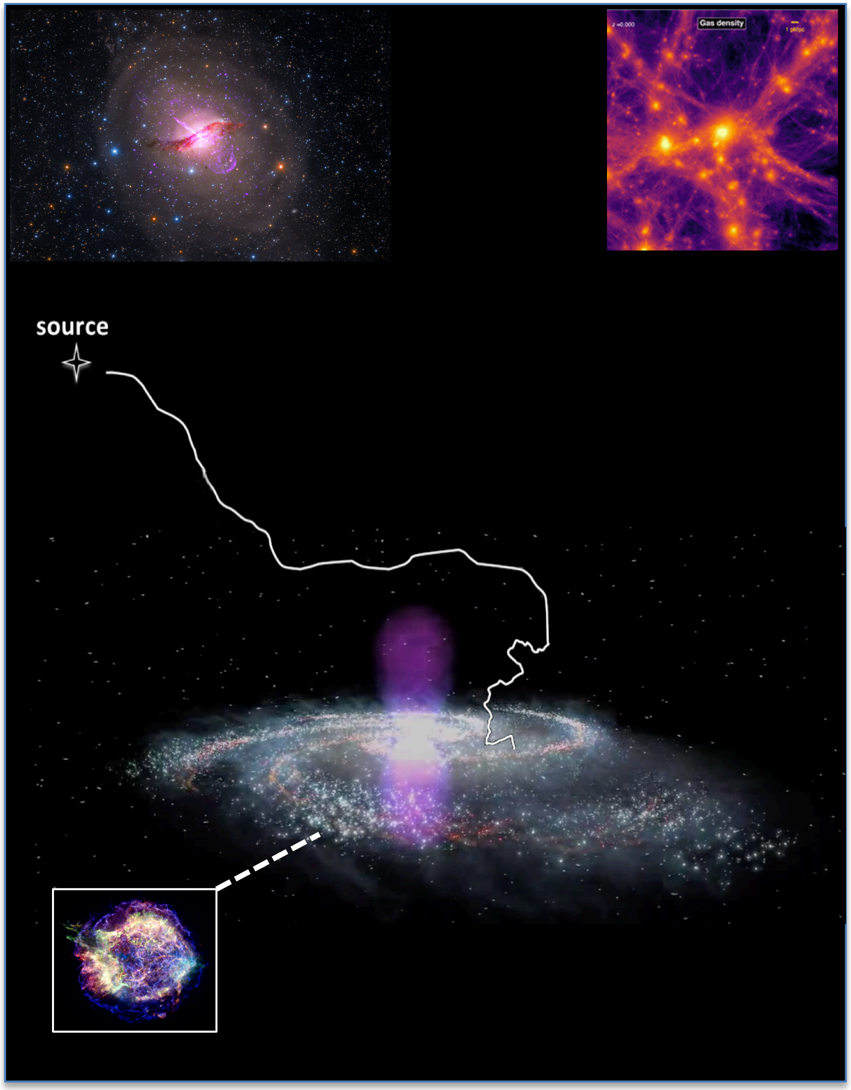
pure proton

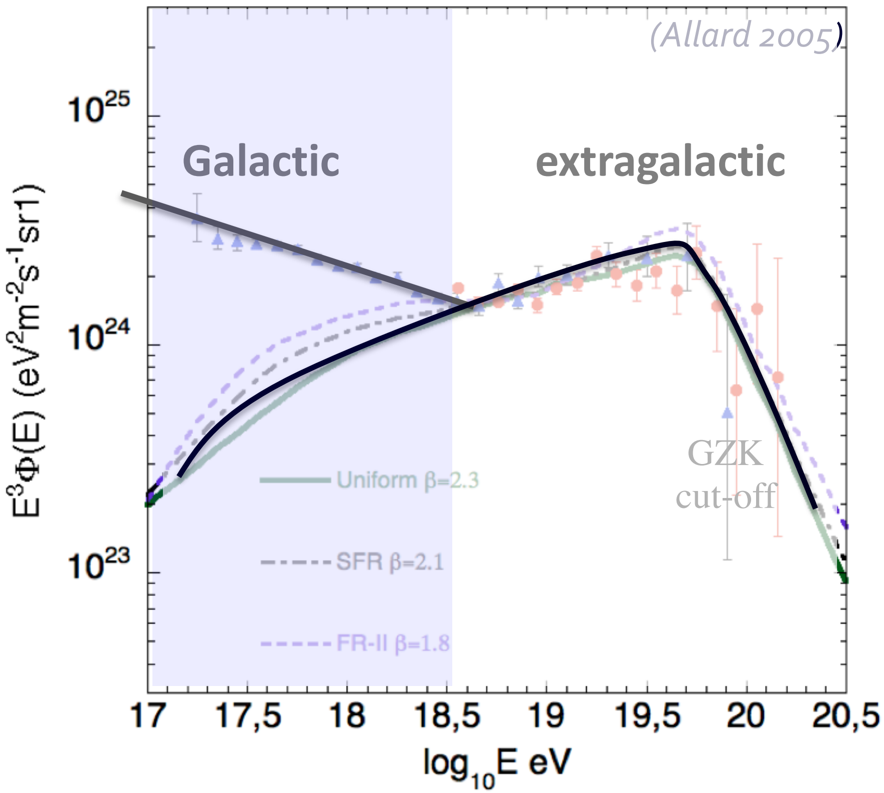


mixed composition



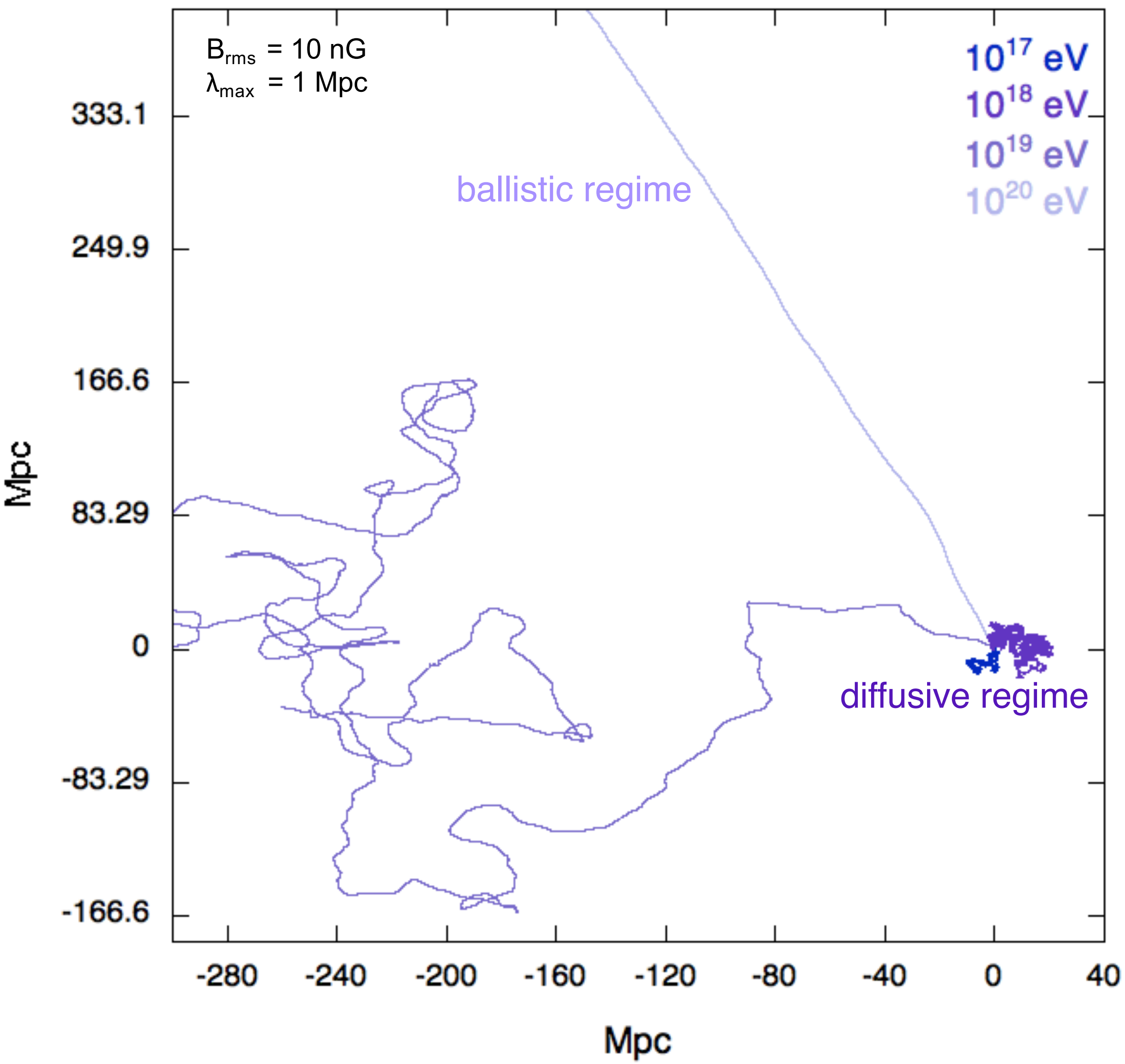
Propagated spectrum: mixed composition





The ankle marks the end of the transition between the Galactic and extragalactic cosmic-rays

Trajectories in a purely turbulent EGMF

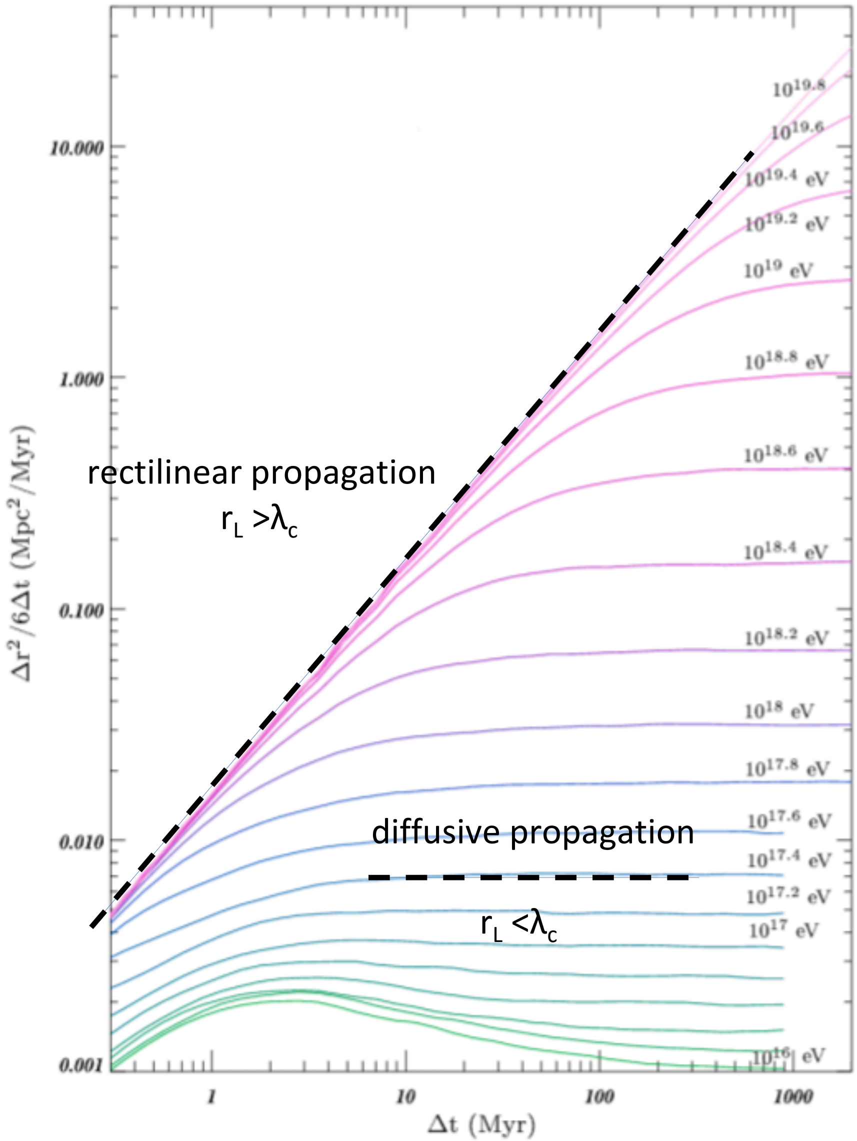


Larmor radius

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

Globus, Allard, Parizot 2008

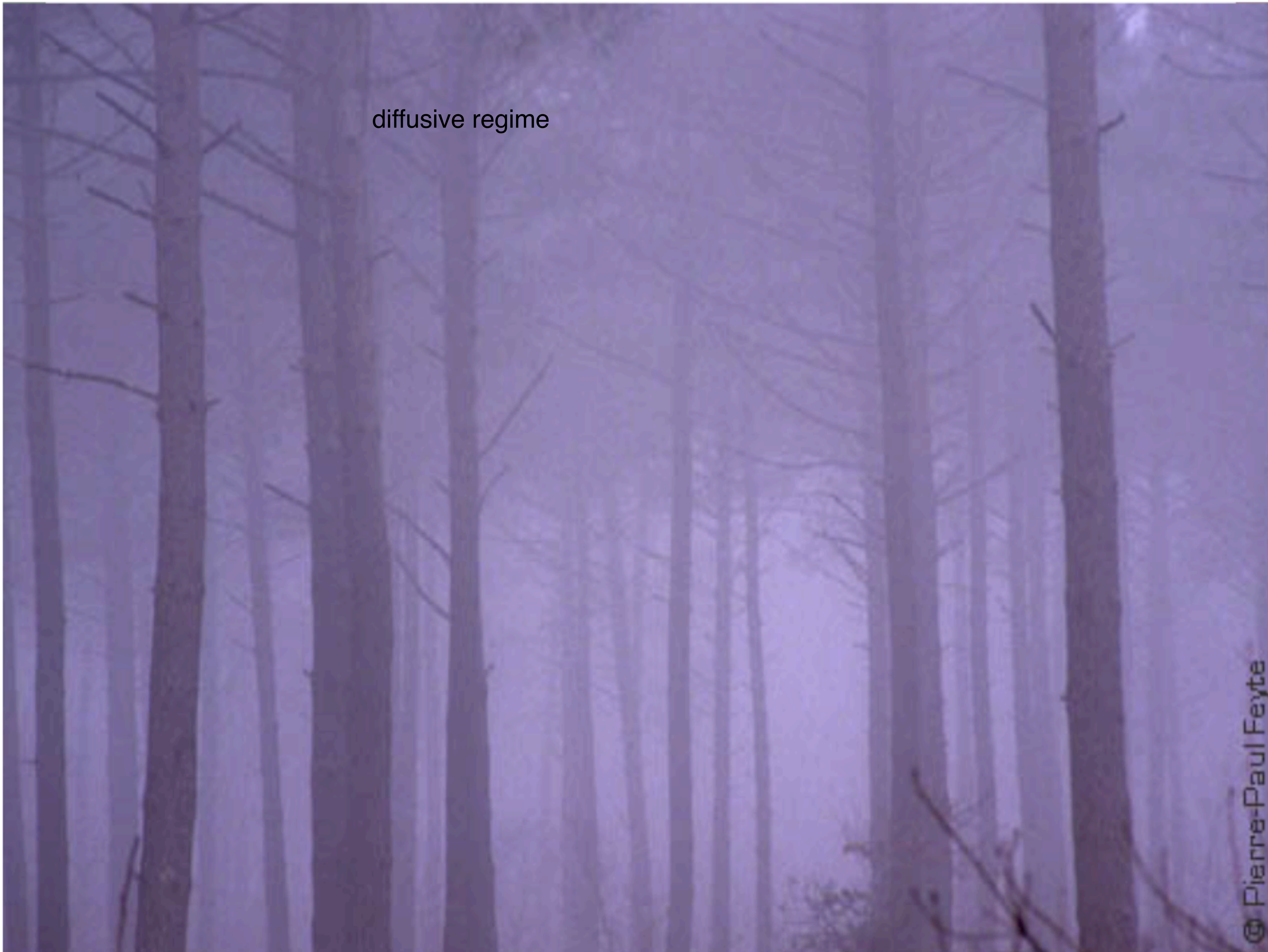
Diffusion coefficients



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

***Globus**, Allard, Parizot 2008*

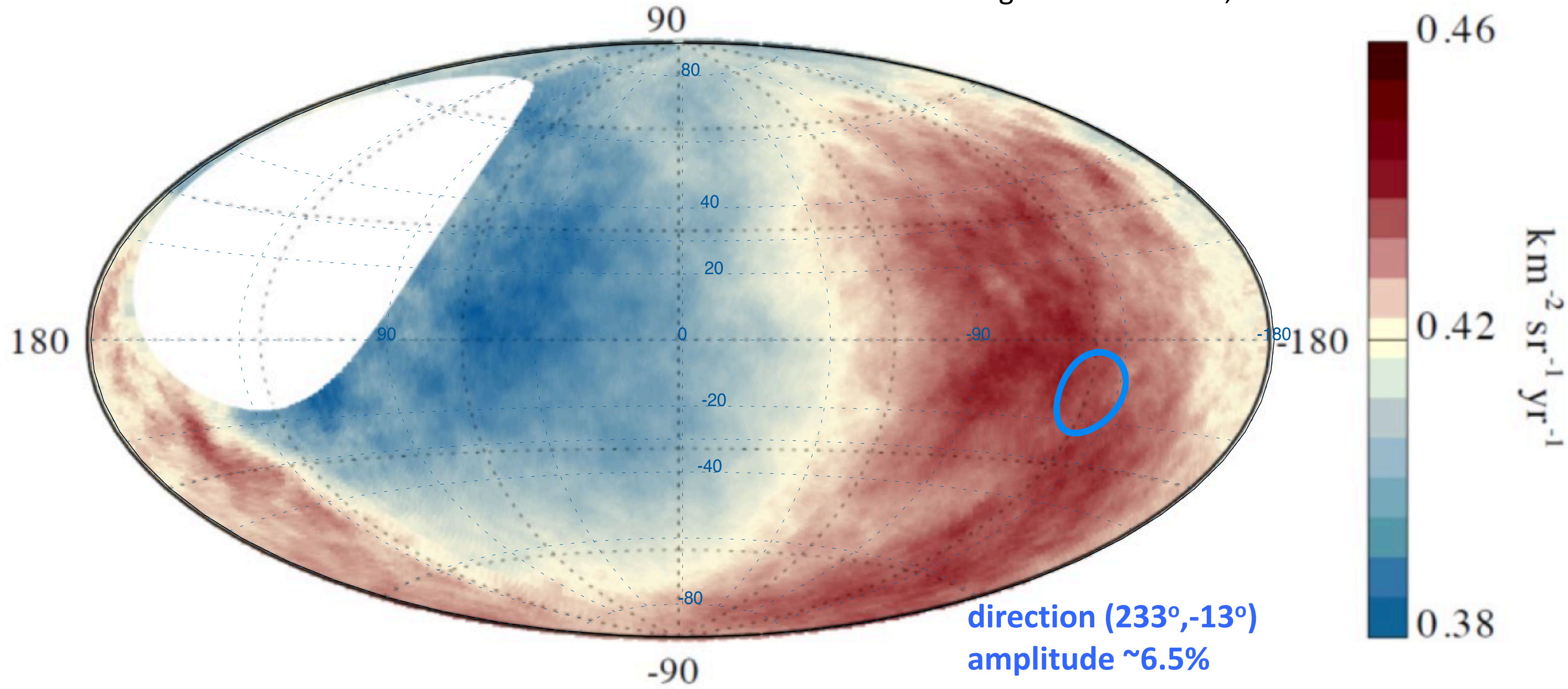

ballistic regime


diffusive regime
© Pierre-Paul Feyte

The magnetic fog seems to dissipate

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

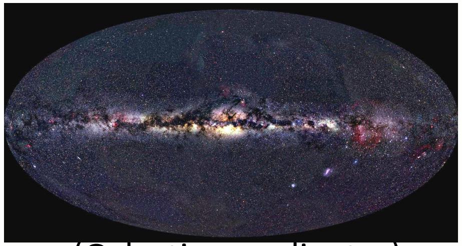
Pierre Auger Collaboration, 2017



direction (233°,-13°)
amplitude ~6.5%

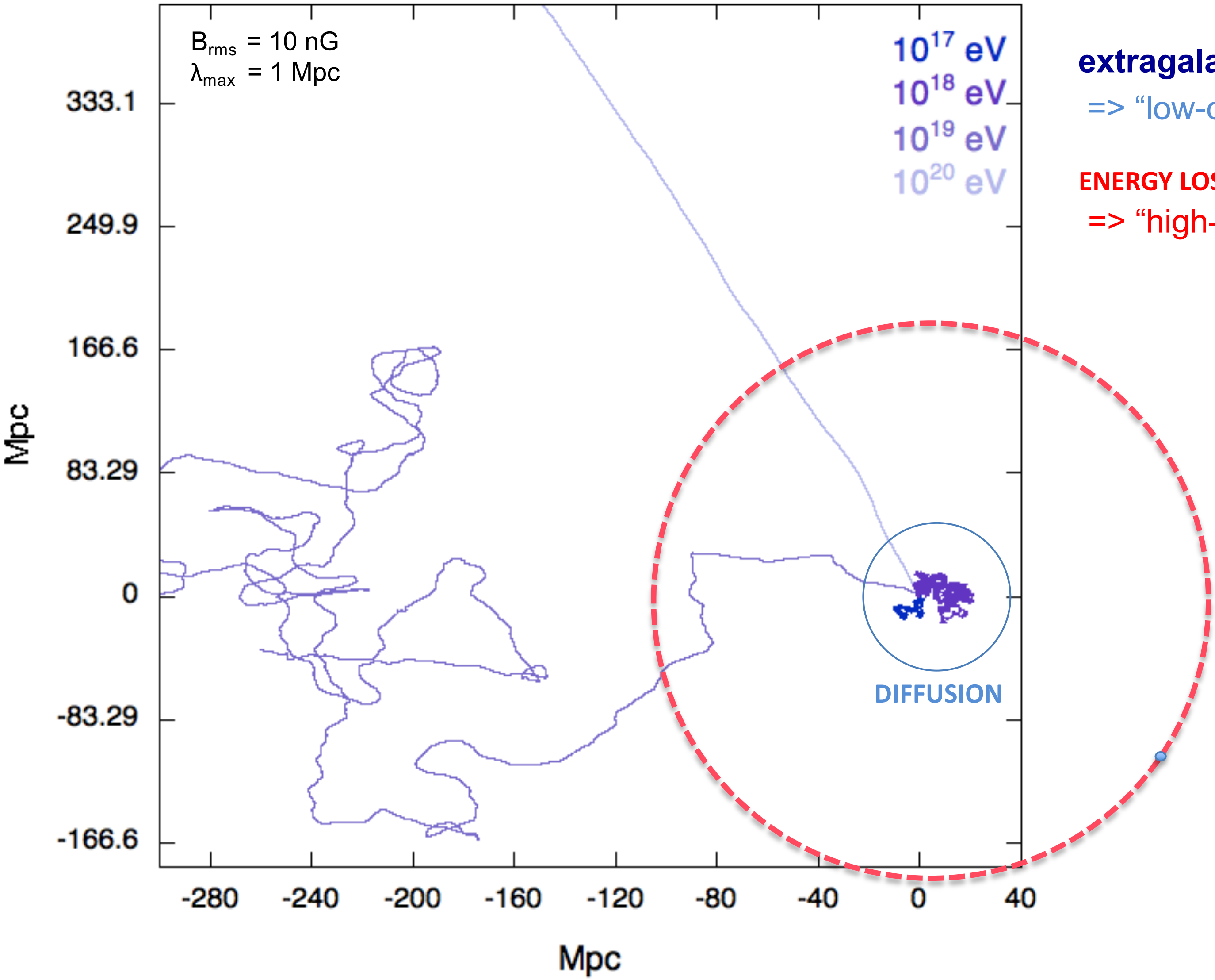
[4 – 8] EeV: compatible with isotropy

E > 8 EeV: significant modulation @ 5.6σ



(Galactic coordinates)

UHECR magnetic horizons



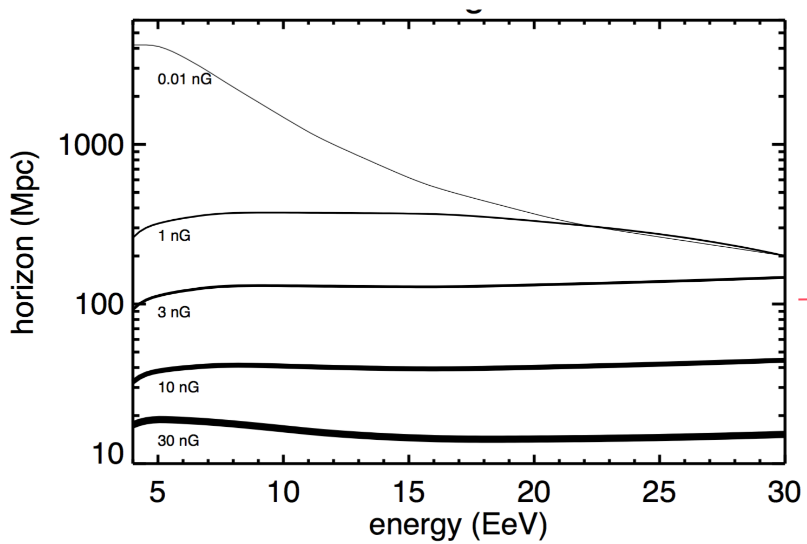
extragalactic magnetic field (EGMF)
=> "low-cut filter"

ENERGY LOSSES (GZK)
=> "high-cut filter"

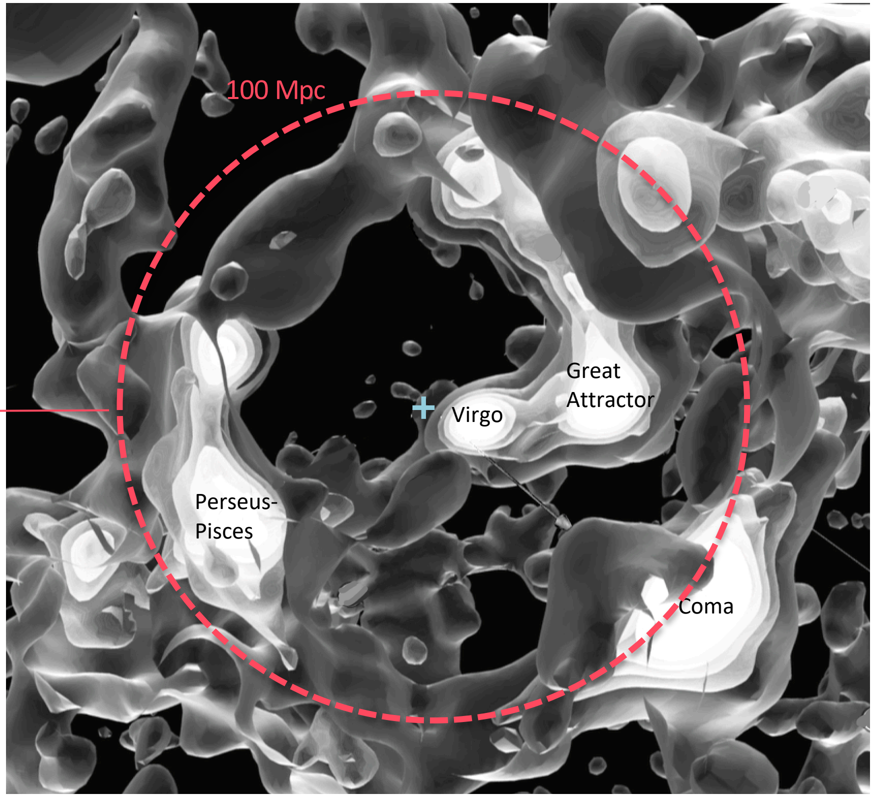
The amplitude of the UHECR dipole depends on the UHECR horizon *(Globus & Piran, 2017)*

Large scale structure induced UHECR anisotropy

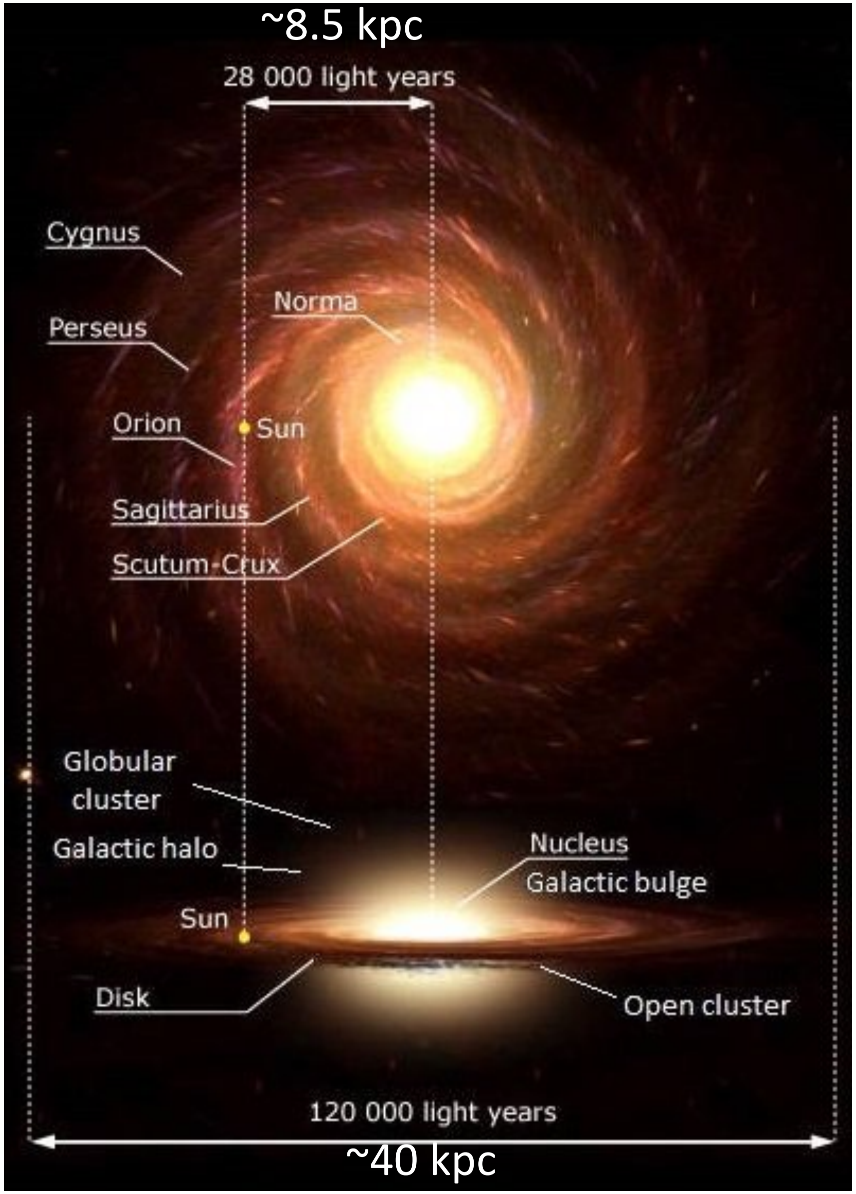
We use the QL density field derived by Hoffman et al. 2018, Nature Astronomy based on CosmicFlows-2



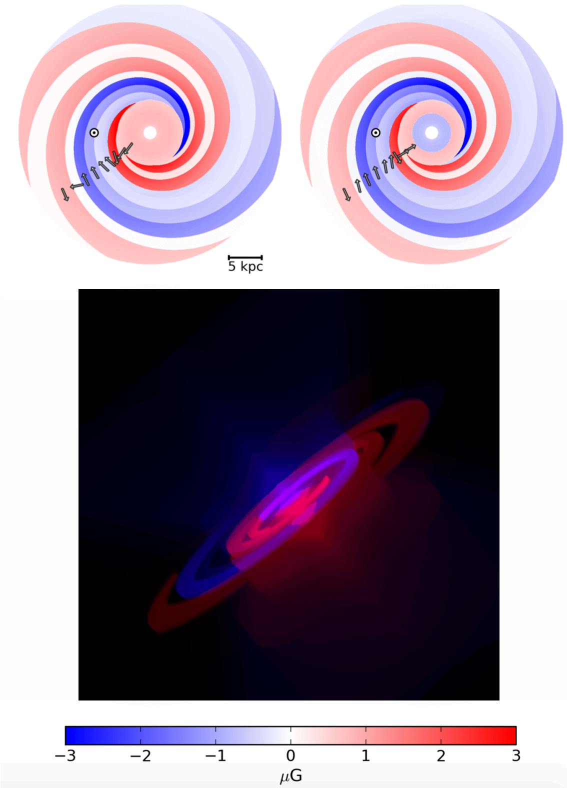
Cosmic-Ray magnetic horizon for nitrogen (Z=7) for different magnitudes of the EGMF

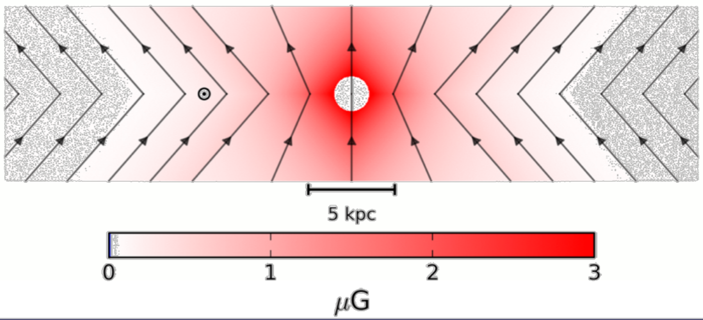


The Galactic Magnetic Field *(Jansson & Farrar 2012, JF12)*



GMF: regular component





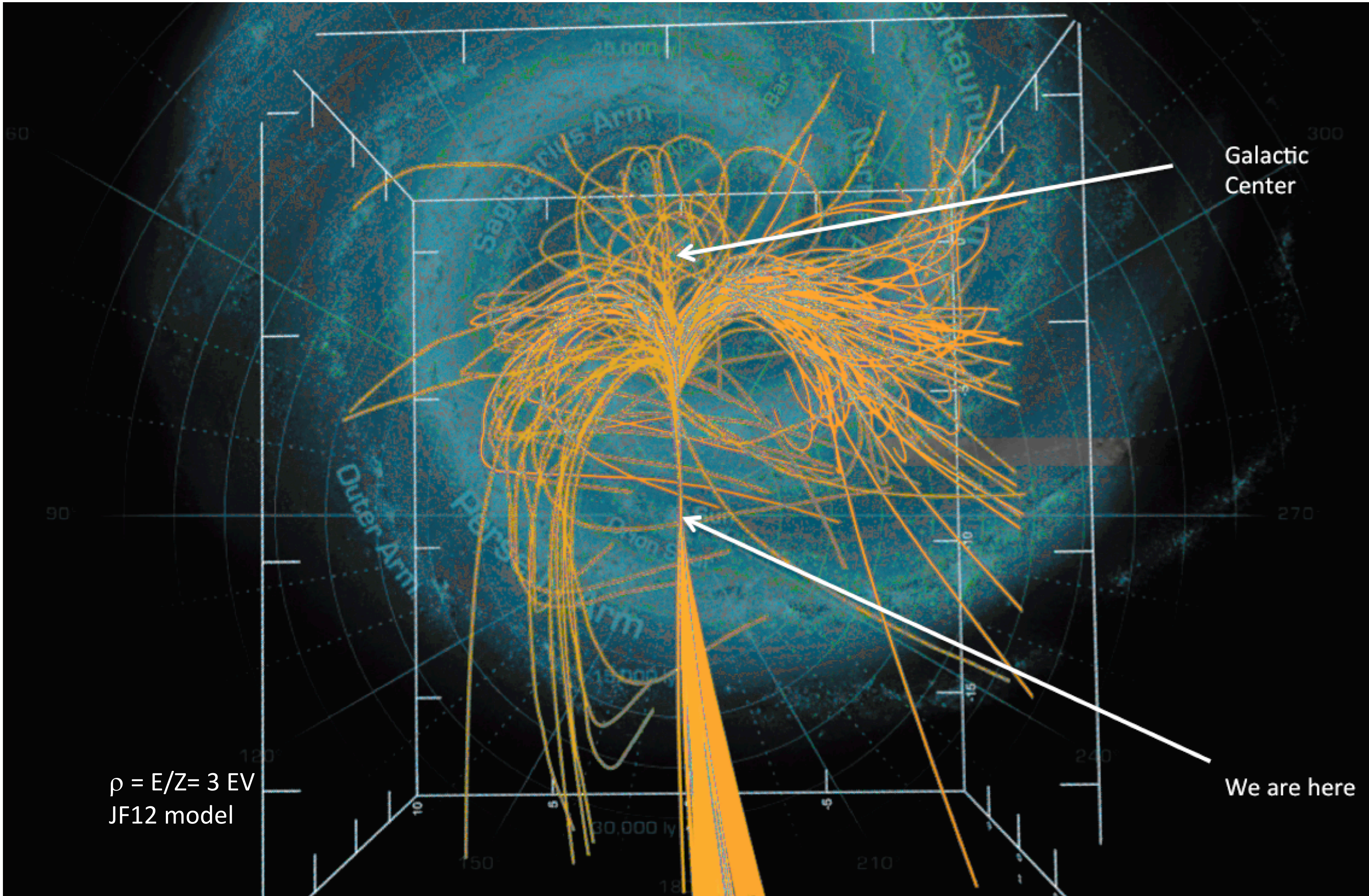
The GMF of the Milky Way

regular, large scale coherent field

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

Jansson & Farrar 2012

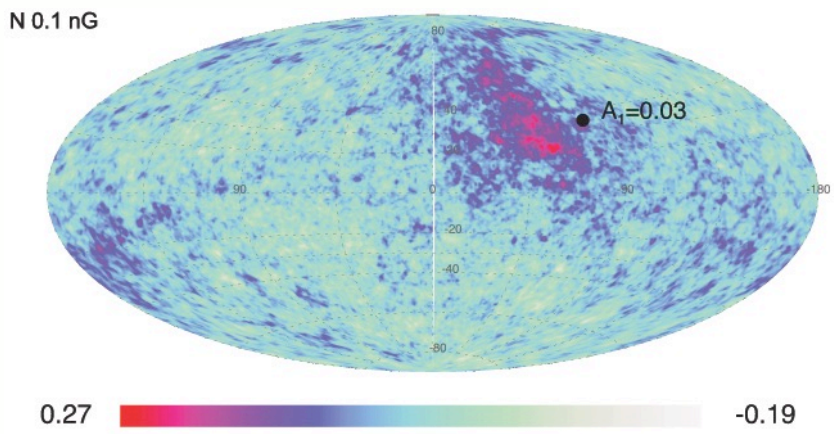
Trajectories in the Galactic magnetic field



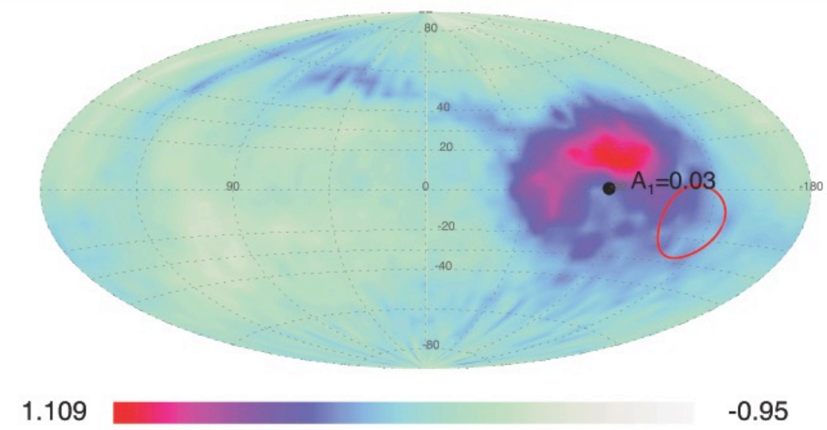
Large scale structure induced UHECR anisotropy

Globus et al. MNRAS 2019

nitrogen @11.5 EeV
EGMF only



EGMF + GMF (JF12)



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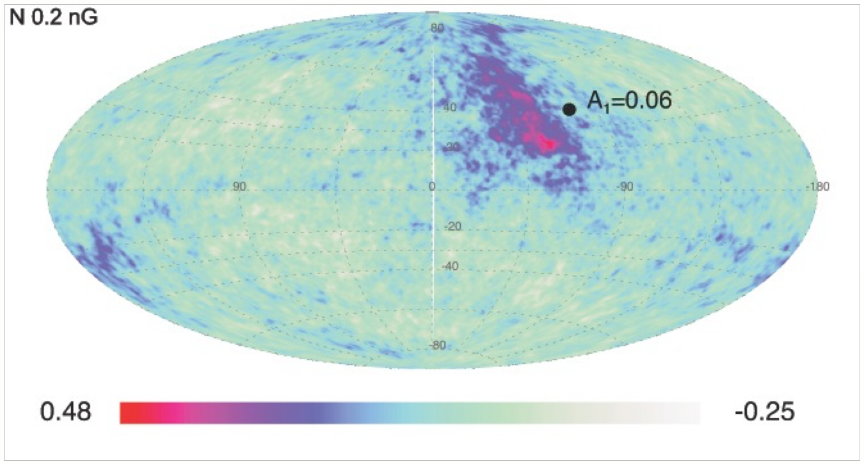

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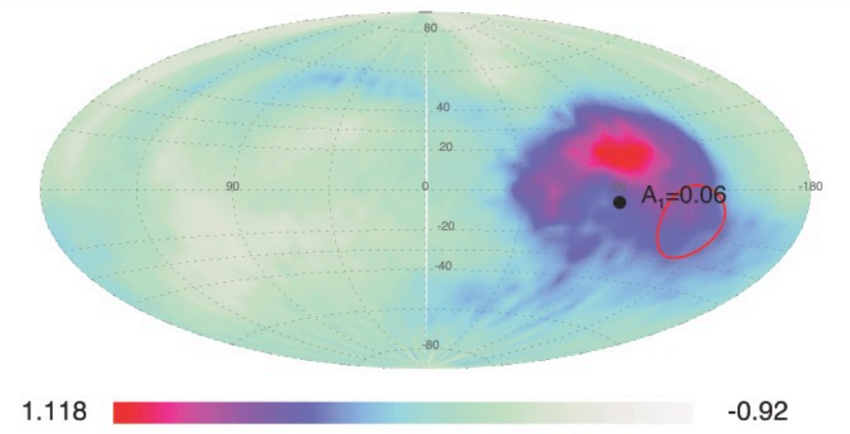

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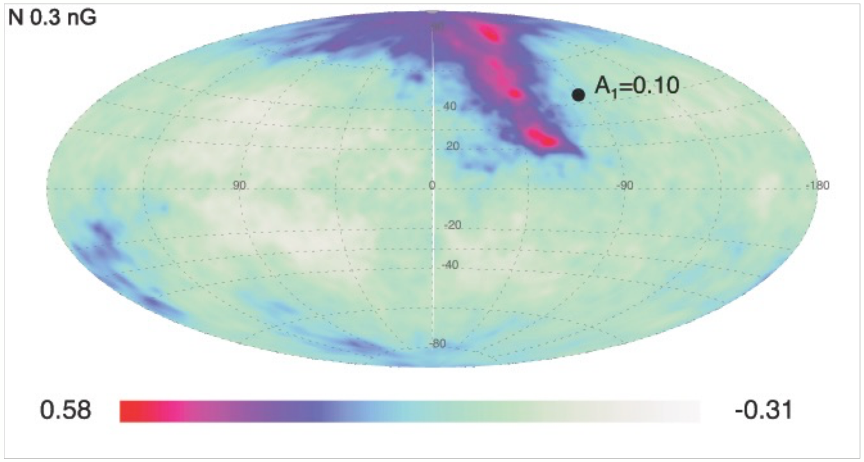

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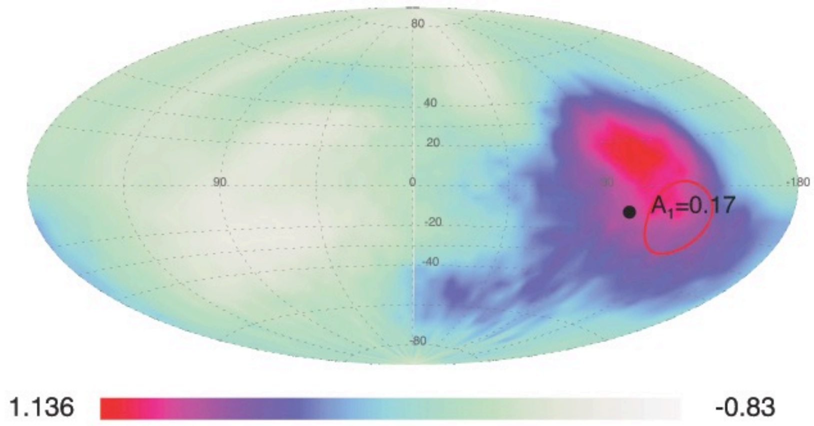

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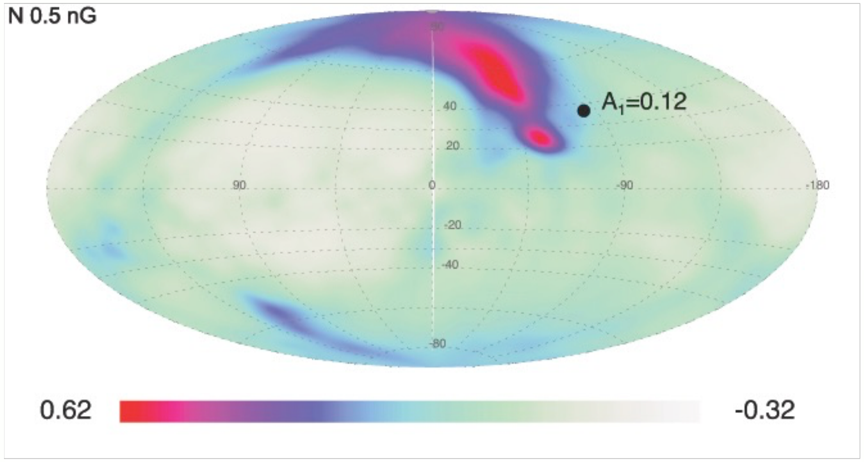

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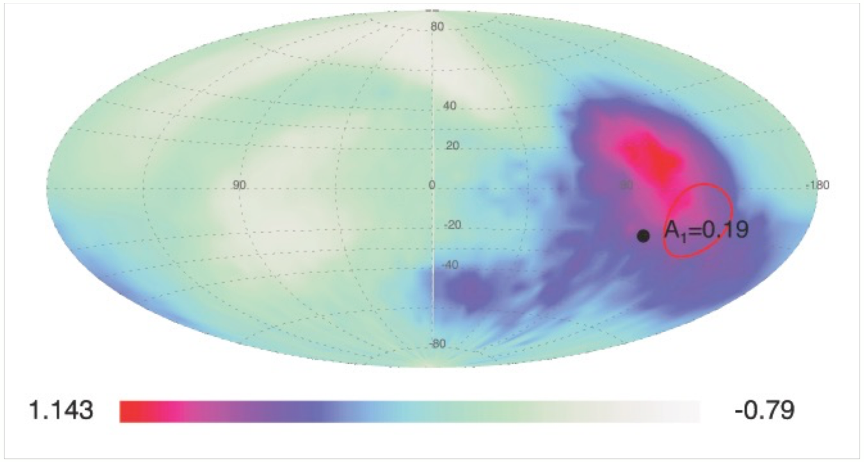

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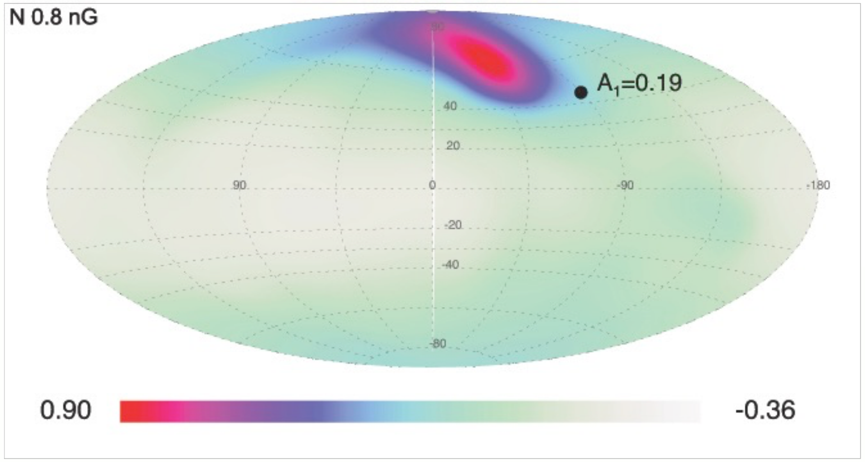

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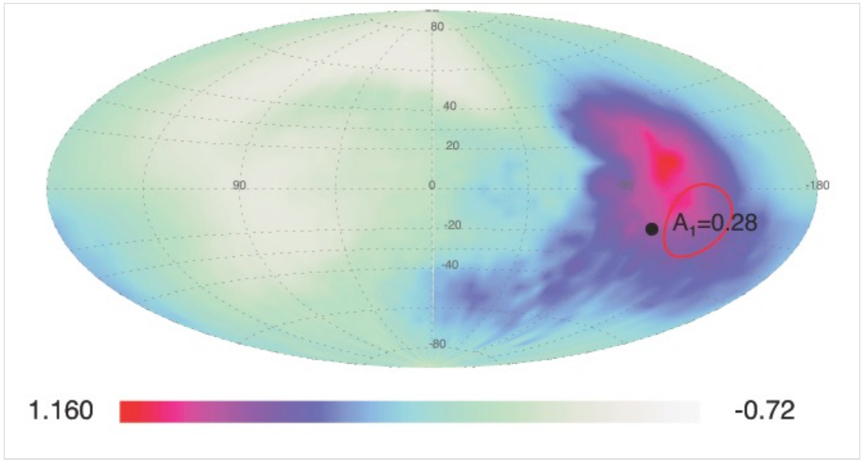

Large scale structure induced UHECR anisotropy

Globus et al. MNRAS 2019

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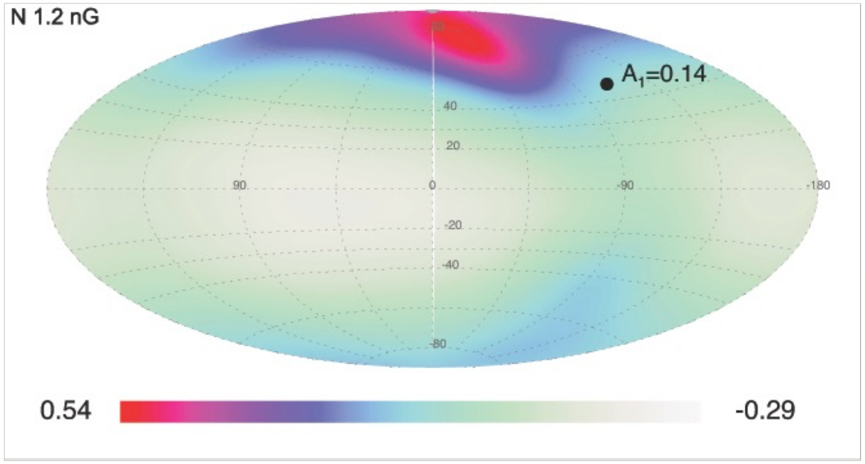
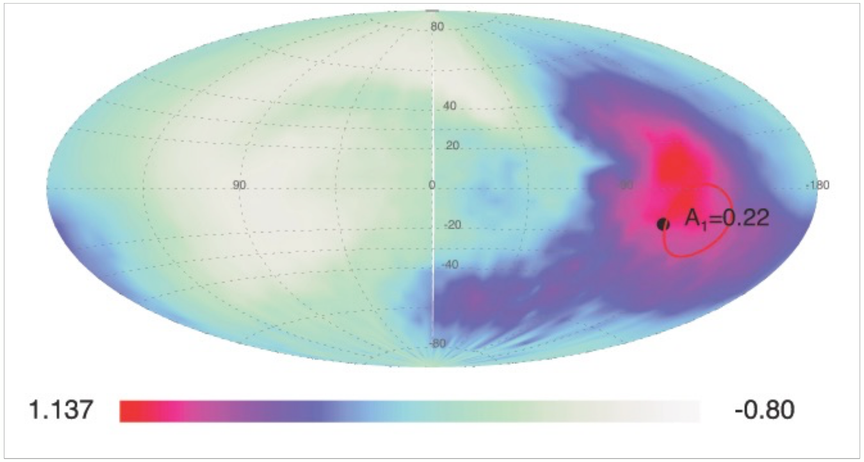
EGMF only



EGMF + GMF (JF12)



Large scale structure induced UHECR anisotropy

Globus et al. MNRAS 2019

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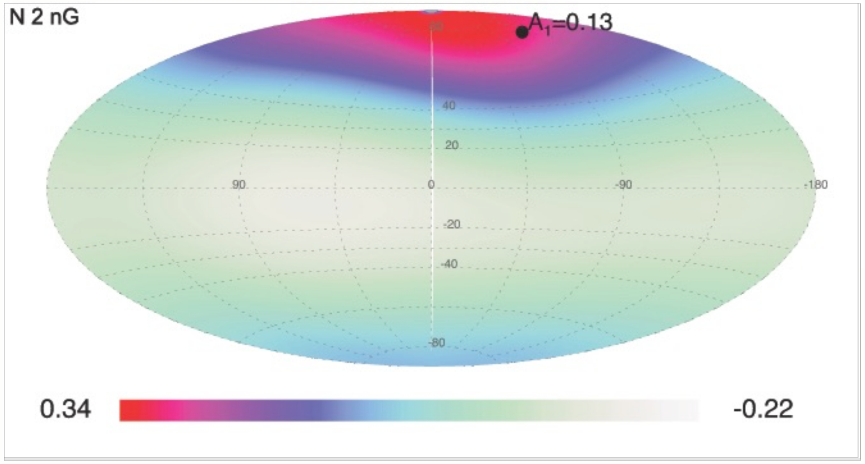
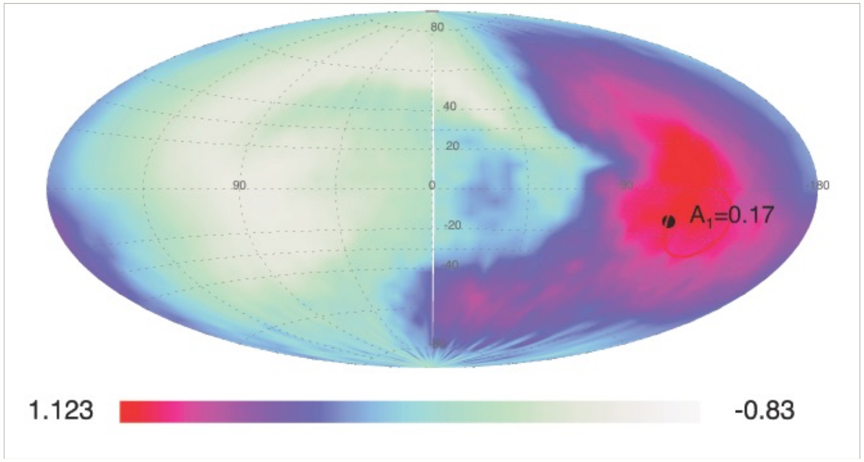
EGMF only



EGMF + GMF (JF12)



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Globus et al. MNRAS 2019

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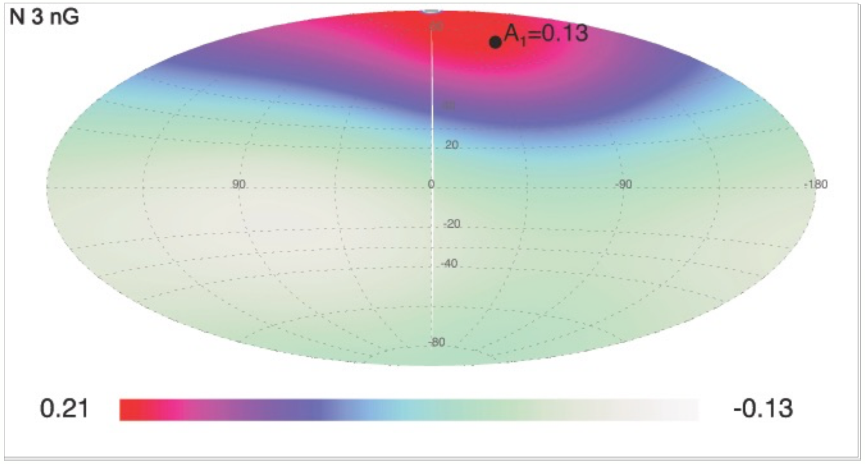
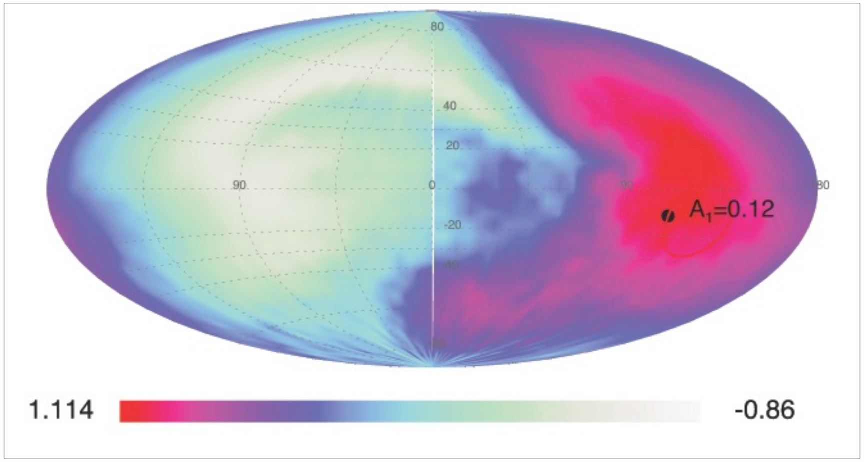


EGMF + GMF (JF12)



Auger dipole anisotropy

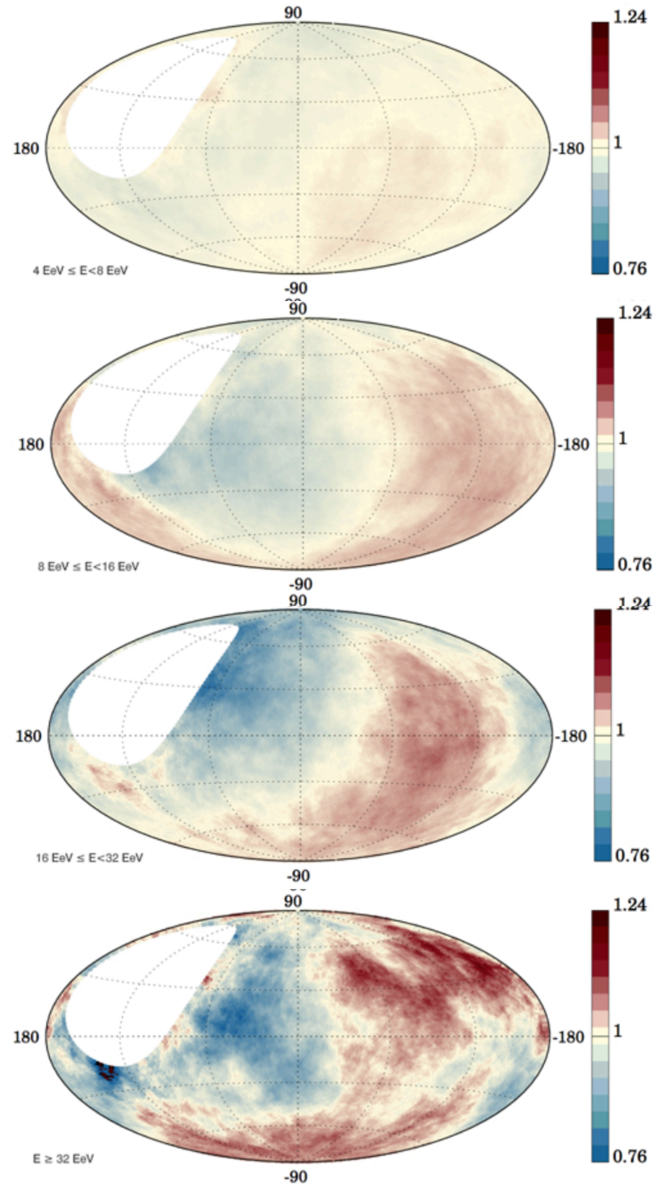
Pierre Auger Collaboration 2018

4-8 EeV

8-16 EeV

16-32 EeV

> 32 EeV



Can we explain this?

Full parametric analysis

With Chen Ding, Glennys Farrar (NYU) ICRC Proceeding: PoS(ICRC2019)243

- **Different composition models (**allowing shift in $<X_{max}>$ and shift in energy (within 1 σ), testing different hadronic models: EPOS-LHC and Sibyll 2.3)

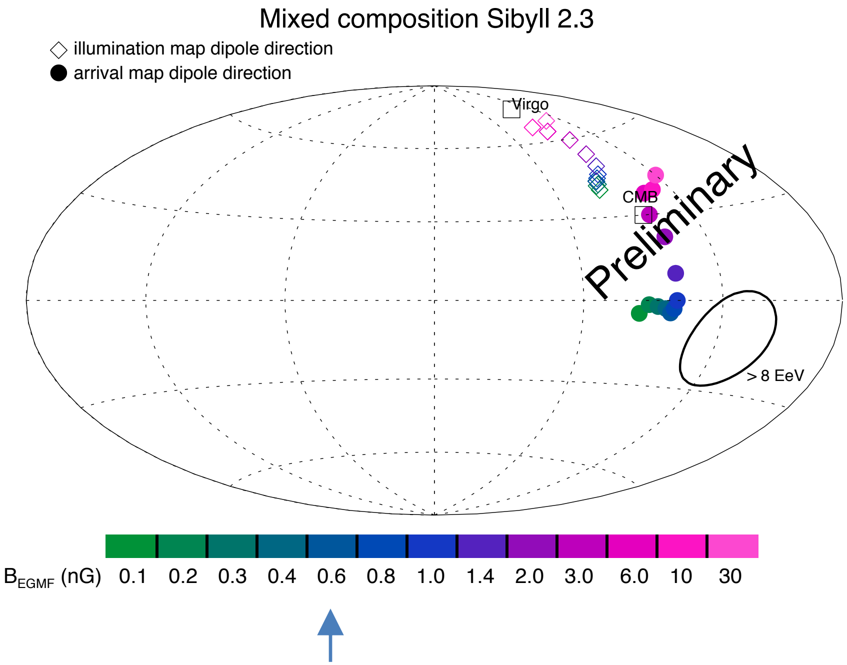
- **Different diffusion coefficients in the extragalactic medium**
  - purely turbulent EGMF with variance between 0.1 and 30 nG
  - coherence length $0.08 < \lambda_{EGMF} < 0.5$ Mpc

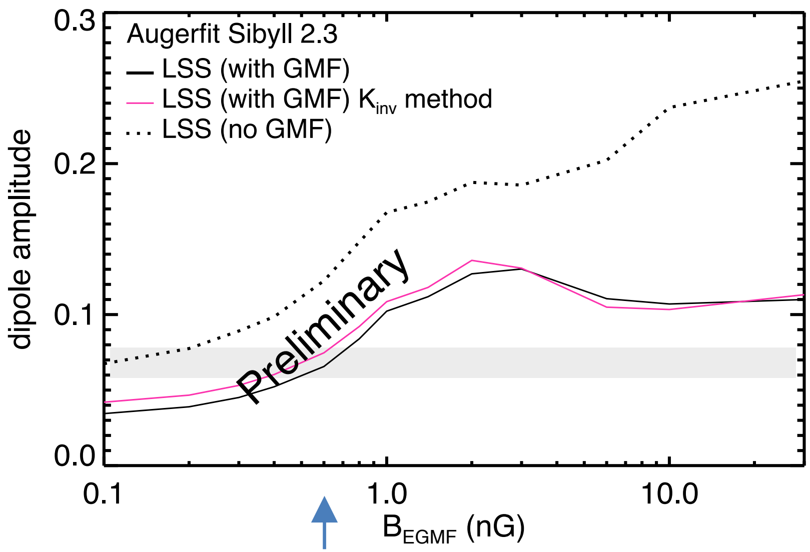
- **Different coherence length for the Galactic magnetic field**
  - JF12 model for the regular component** (Faraday rotation measurements)
  - coherence length $30 < \lambda_{GMF} < 100$ pc

**uncertainty due to variation of the regular halo field is under investigation. Here we use the nominal JF12 model.

Mixed composition: prediction >8 EeV

With Chen Ding, Glennys Farrar (NYU) ICRC Proceeding: PoS(ICRC2019)243





EGMF ~0.6 nG, coherence length 0.2 Mpc, GMF coherence length ~75pc

Pure proton does not work

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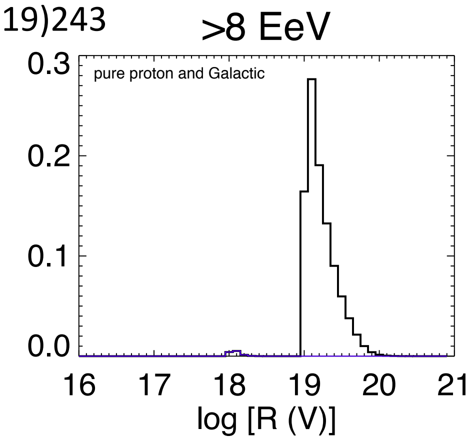

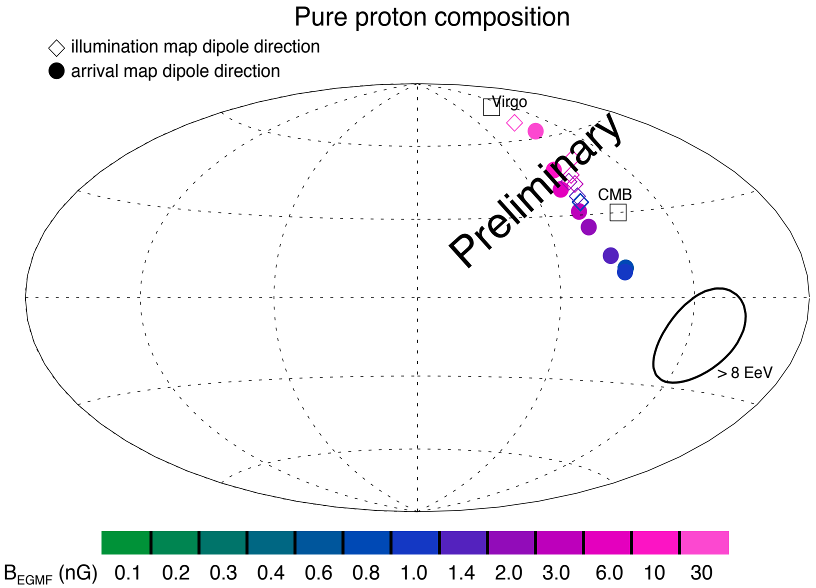

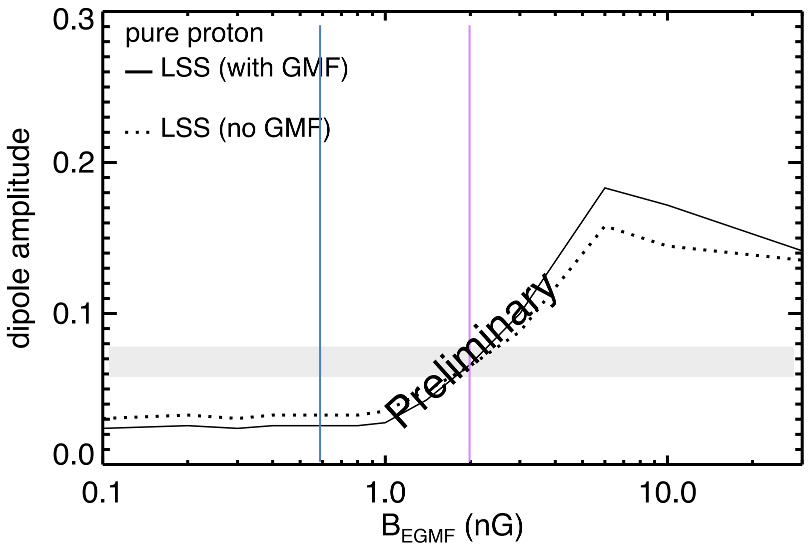

Cannot simultaneously explain amplitude and direction

Pure helium does not work

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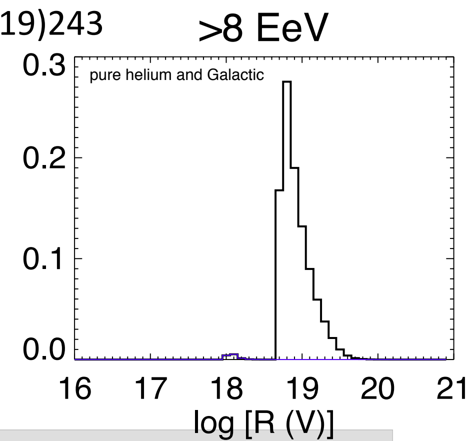
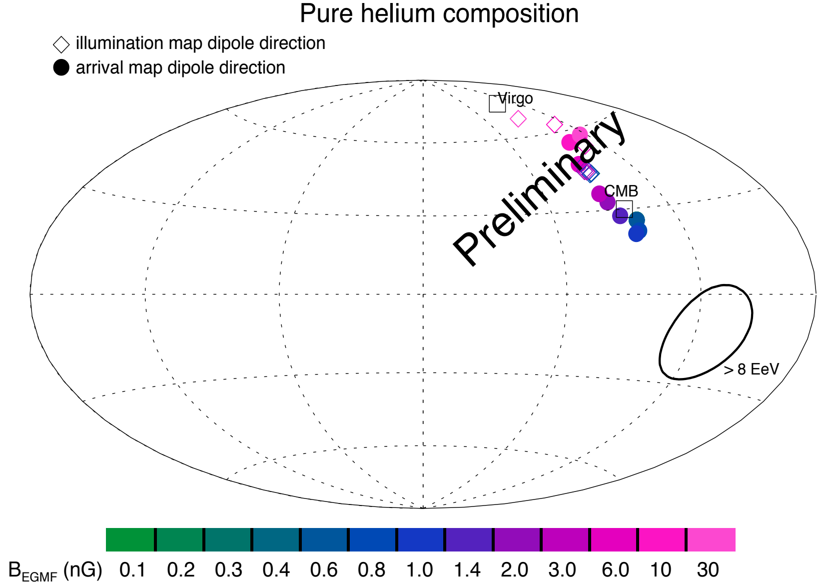
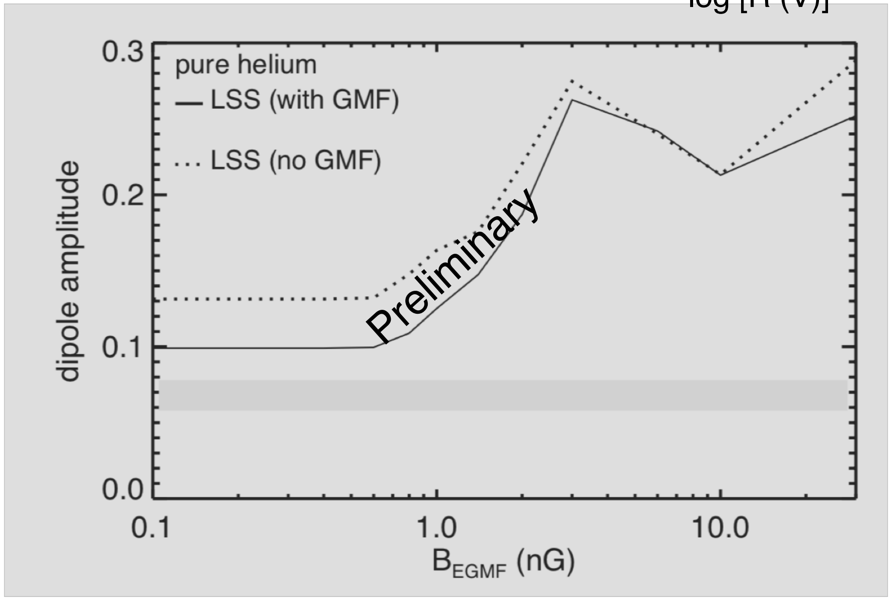
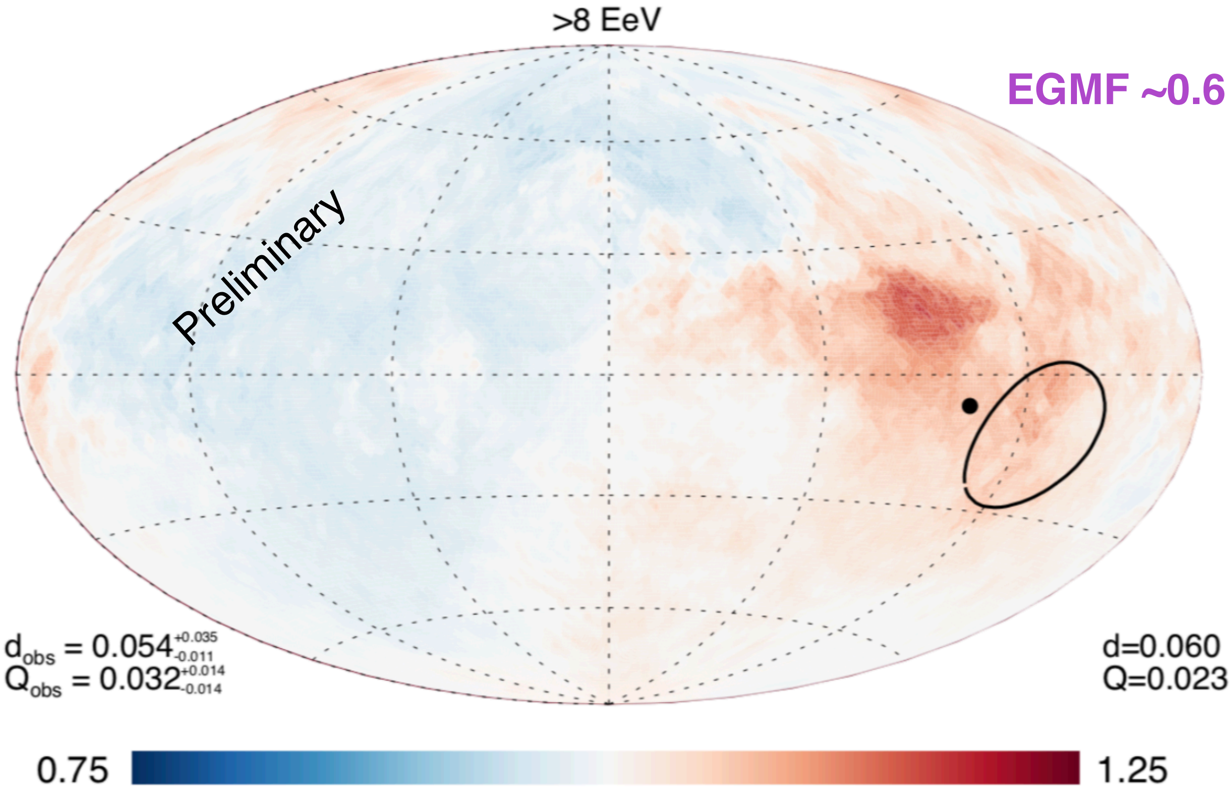






Amplitude is too large

Best fit parameters: prediction >8 EeV



EGMF ~0.6 nG, λ_{EGMF} 0.2 Mpc, λ_{GMF} ~75pc

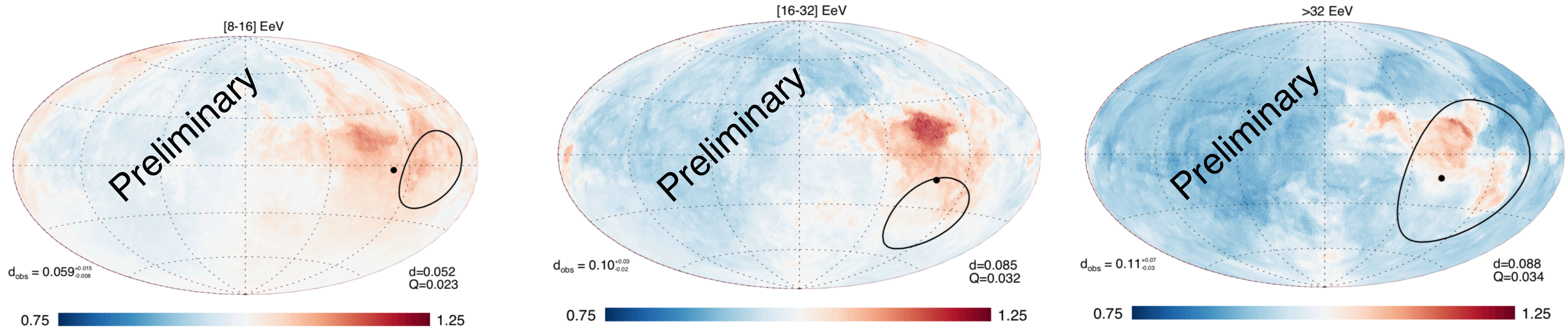
- dipole only
  $d_{obs} = 6.5^{+1.3}_{-0.9}\%$
  $d_{model} = 6.6\%$
- dipole and quadrupole
  $d_{obs} = 5.4^{+3.5}_{-1.1}\%$
  $d_{model} = 6.0\%$
  $Q_{obs} = 0.032 \pm 0.014$
  $Q_{model} = 0.023$

Consistent with Auger dipole & quadrupole observations >8 EeV

PoS(ICRC2019)243

(to be updated with latest data from ICRC 2019)

Different energy bins: 8-16, 16-32, >32 EeV



Consistent with Auger dipole & quadrupole observations >8 EeV

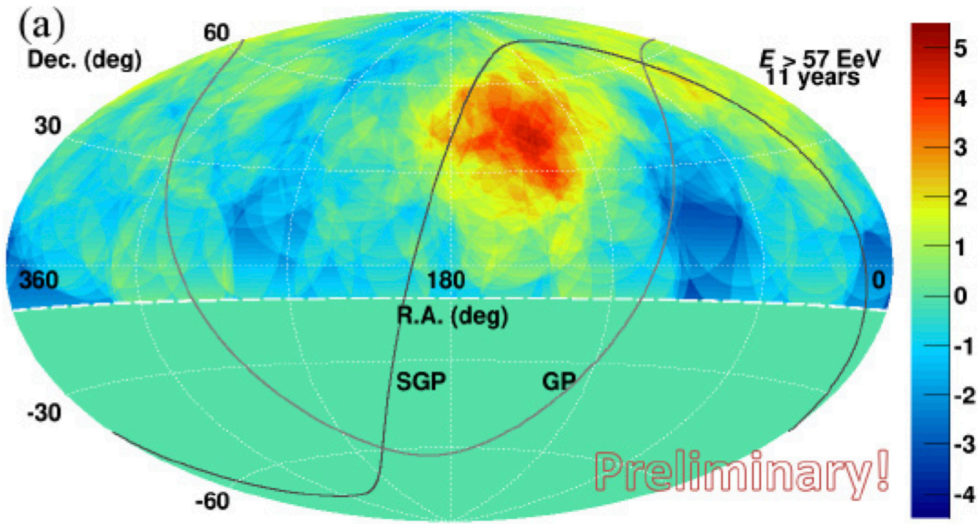
PoS(ICRC2019)243

(to be updated with latest data from ICRC 2019)

A few words about hot spots

Telescope Array - Hotspot

- number of events grows slightly slower than in the past, but still grows faster than background rate



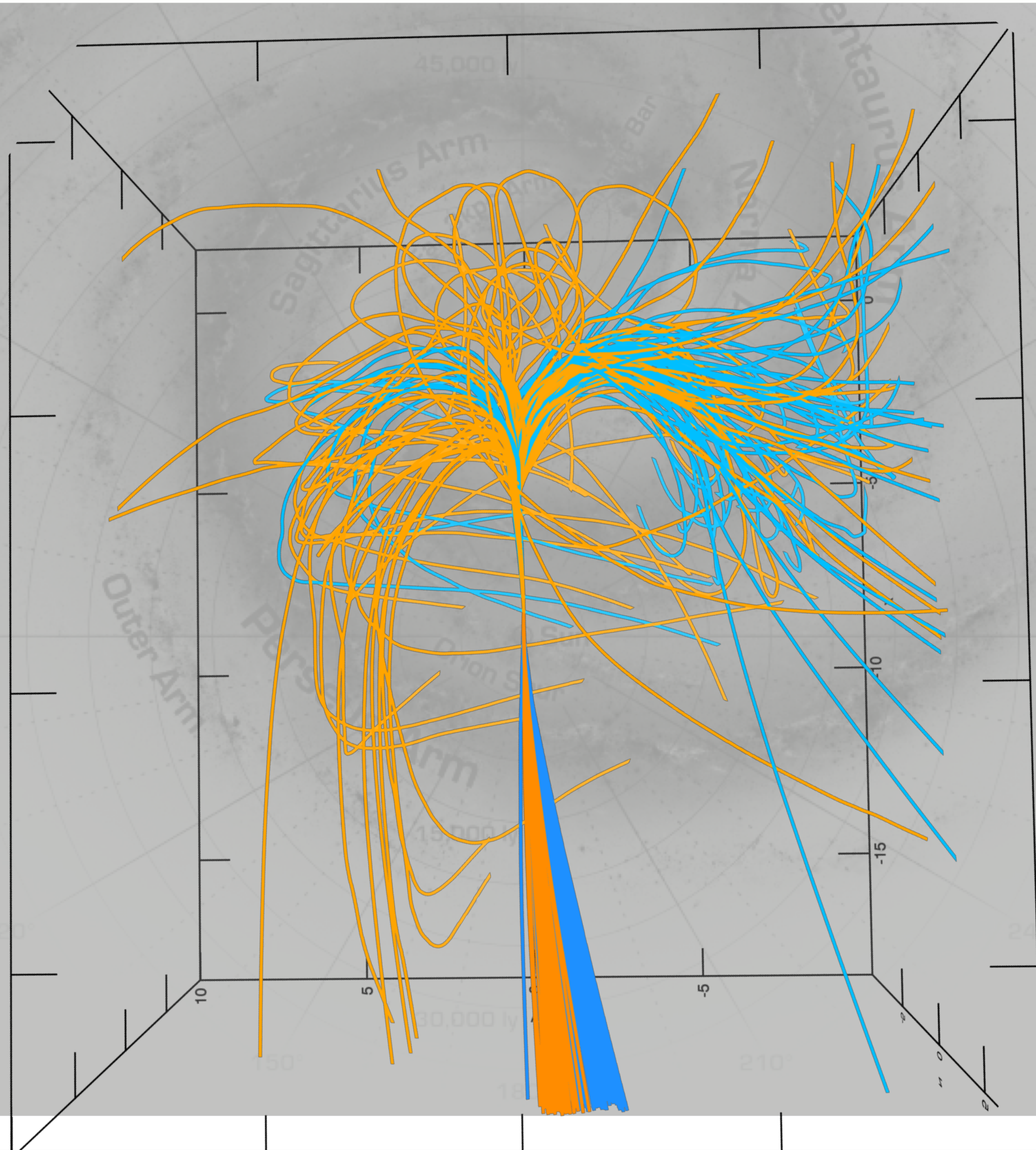
Kawata et al, ICRC 2019

Hotspot from 11 years of TA SD data, from May 11, 2008 to May 11, 2019

E > 57 EeV, in total 168 events
38 events fall in Hotspot (α=144.3°, δ=40.3°, 25° radius, 22° from SGP), expected=14.2 events
local significance = 5.1 σ, chance probability → 2.9σ
25° over-sampling radius shows the highest local significance (scanned 15° to 35° with 5° step)

"Time-domain" cosmic-ray astronomy ?

Angular decorrelation due to the Earth motion



Globus & Eichler 2016

ρ = 3 EV

2 configurations of the magnetic turbulence

l= 0° (Galactic center)

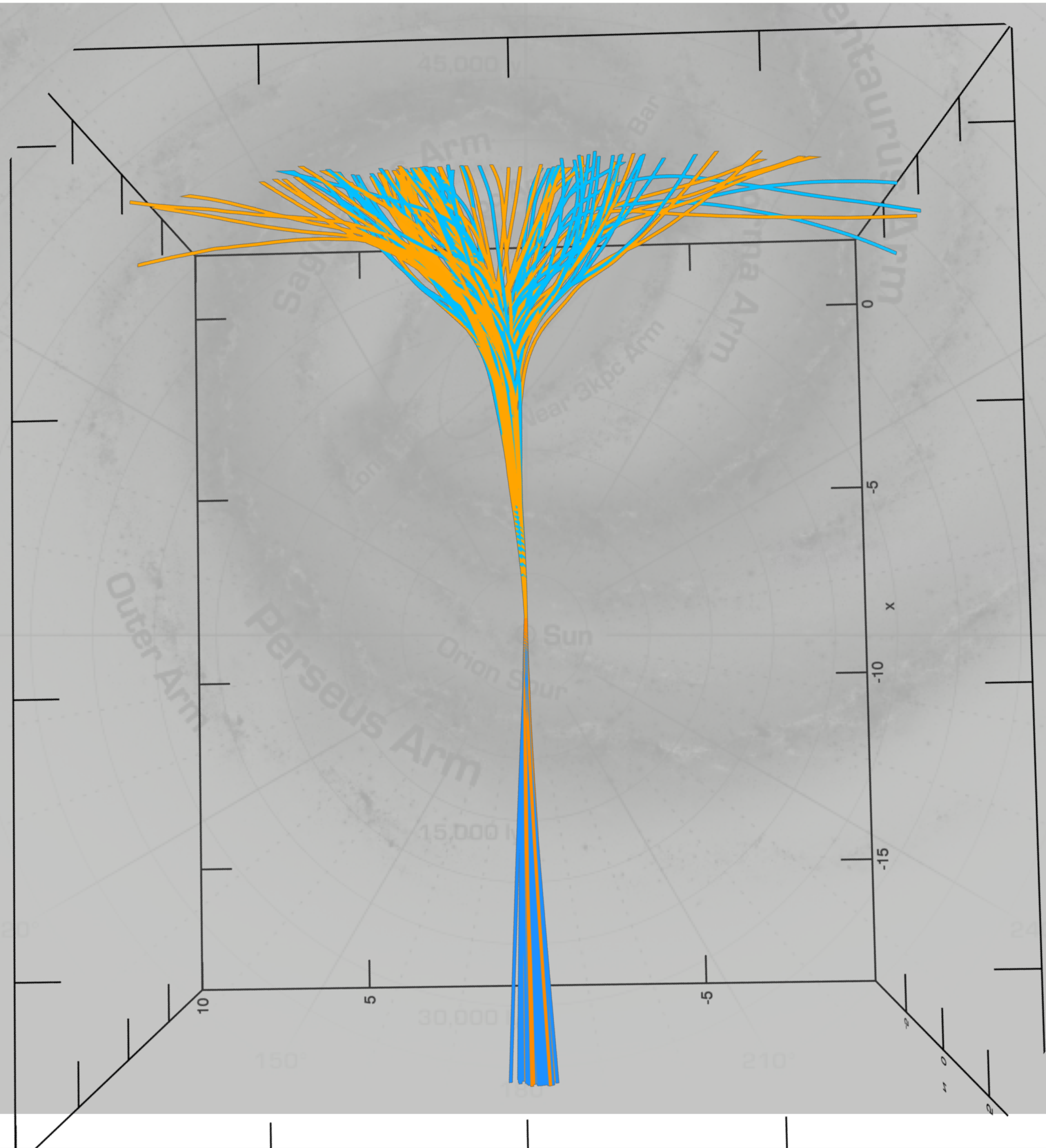
l= 180° (anticenter)

b= 90°

JF12 model

Angular decorrelation due to the Earth motion

Globus & Eichler 2016



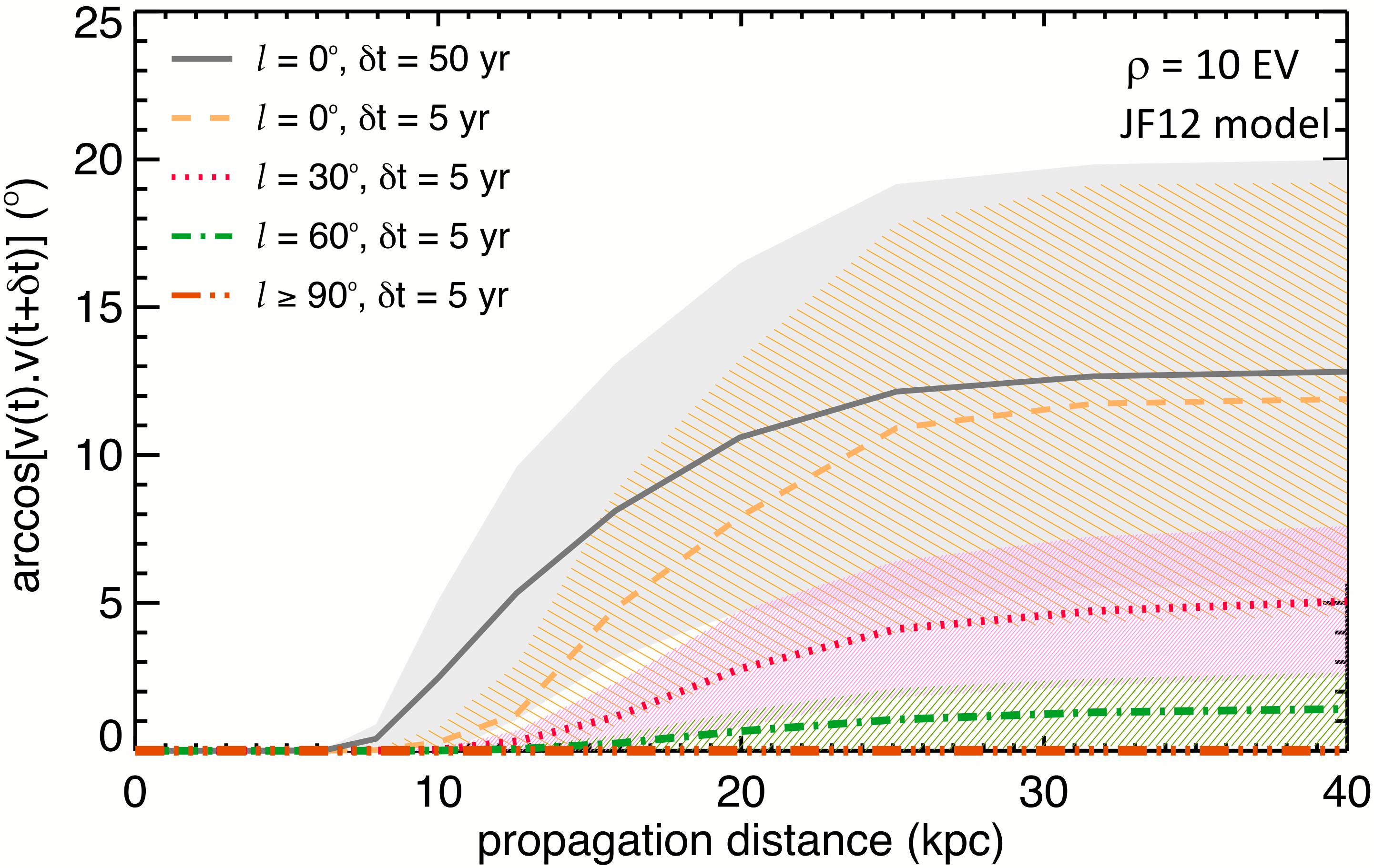
ρ = 10 EV

2 configurations of the magnetic turbulence

JF12 model

Angular decorrelation due to the Earth motion (5 years)

Globus & Eichler 2016



=> other rigidities and l_{GMF} (**with Kusenko-san, Nagataki-san, He-san**)

Summary

• Energy spectrum, composition

Auger and Telescope Array confirm the high energy cut-off in the UHECR spectrum (2010)

TA-Auger analyses **agree on a mixed composition** (ICRC 2017)
Auger composition analyses shows a composition **which is getting heavier above the ankle**

KASCADE-Grande reported the existence of **a light ankle at 10^{17} eV**
(Auger and KASCADE-Grande unfortunately do not have a strong overlap in energy; this problem should be solved in a few years e.g**. LHAASO**,...)

• Arrival directions

Auger reported the first 5σ detection of large scale (~dipole) anisotropy (ICRC 2017)

==> The dipole amplitude and direction are determined by the UHECR horizon (EGMF and GZK distance) (Globus & Piran 2017)

==> The effect of the GMF starts to become significant at rigidities below ~ 10 EV (e.g. Farrar 2016) and it changes the direction and amplitude of the dipole

==> The dipole anisotropy > 8 EeV can be well accounted for with UHECR sources following the LSS (Virgo being the dominant source), EGMF ~0.6 nG and JF12 model

=> Importance of composition for anisotropy studies (dipole, hotspots…)

ありがとう