On the Origin of the Ultra-High-Energy Cosmic Rays

Noémie Globus, *Racah Institute of Physics, the Hebrew University*

Windows on the Universe
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International Center of Interdisciplinary Science Education (ICISE)
Quy Nhon, Vietnam

Many thanks due to advisors and colleagues:
Tsvi Piran, Denis Allard, Etienne Parizot

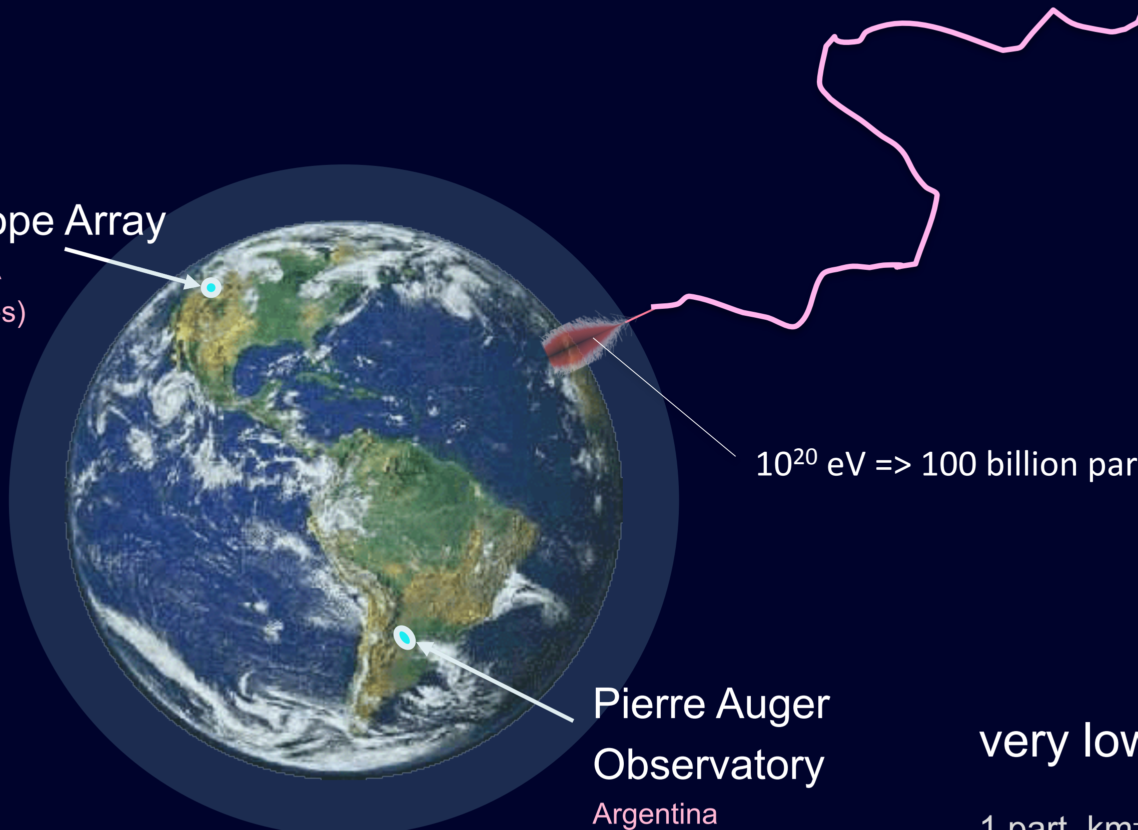
Outline

I. What are Ultra-High Energy Cosmic-Rays (UHECRs)?

II. How do we detect them?

III. Theoretical modelling of the UHECR observations

Ultra-High Energy Cosmic Rays (UHECRs):



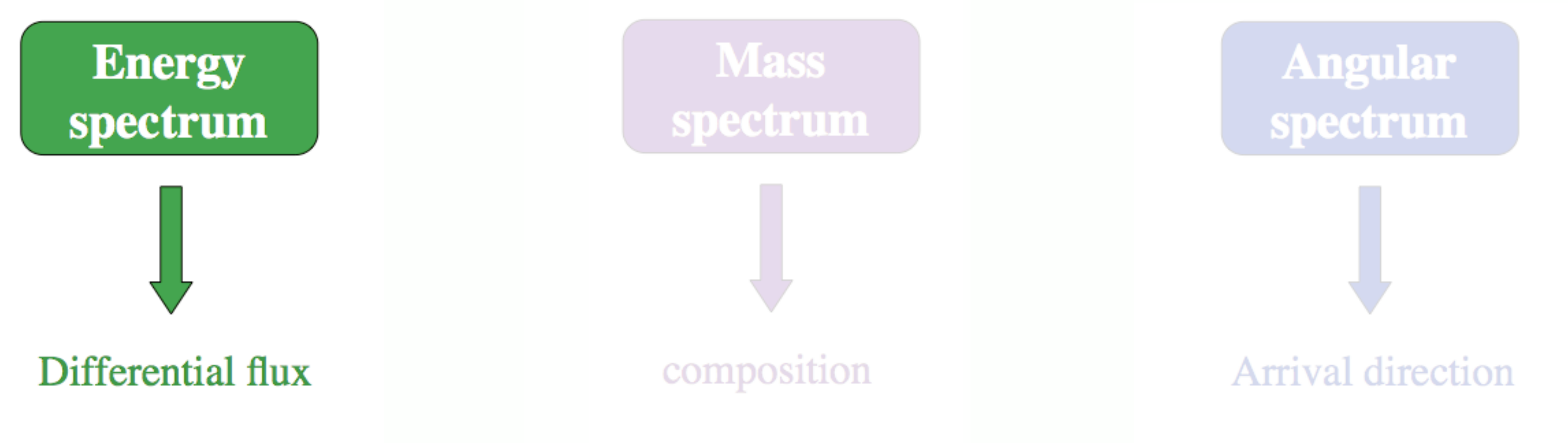
very low flux

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

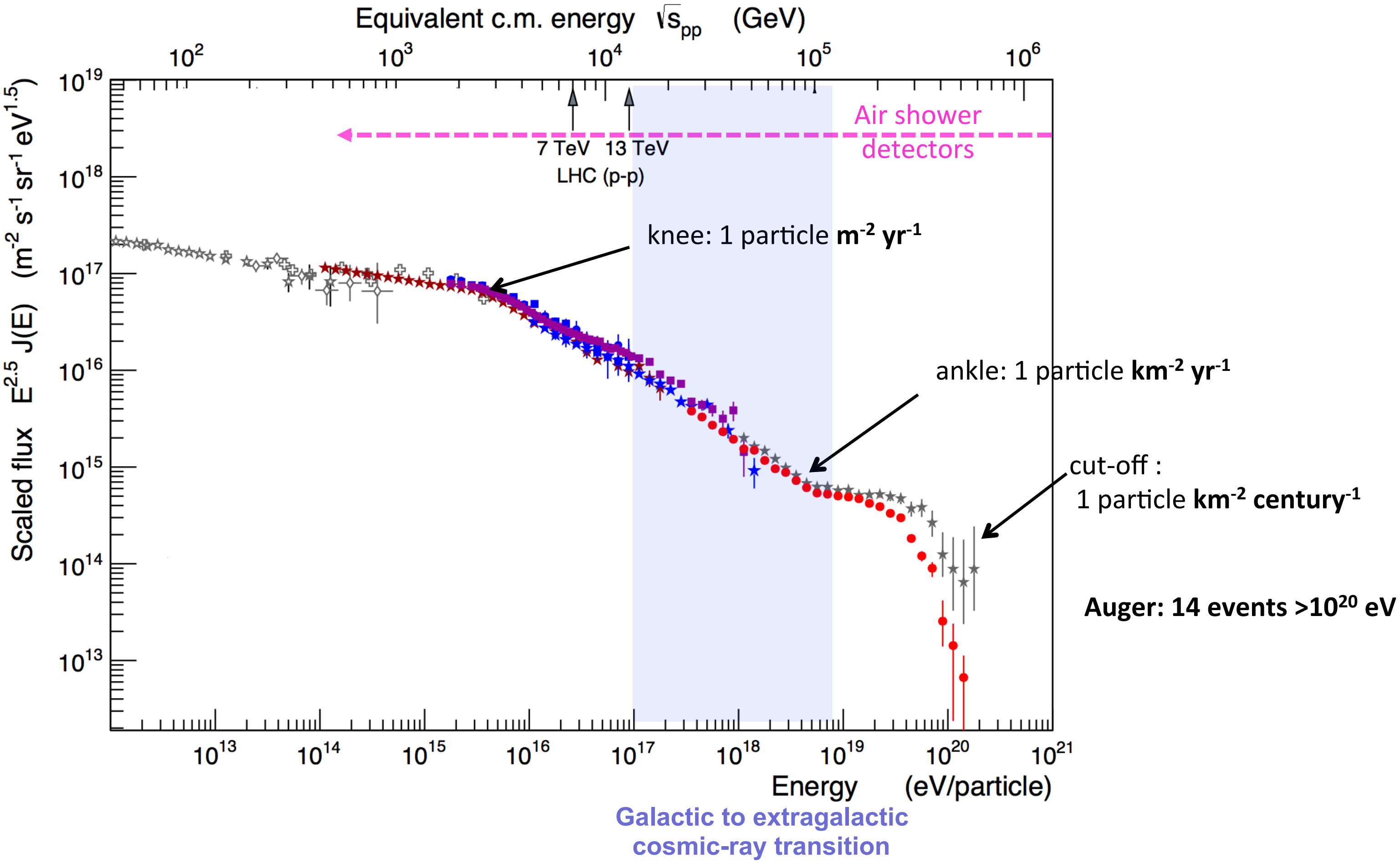
to

1 part. km^{-2} $century^{-1}$ (10^{20} eV)

Cosmic Rays primary observables



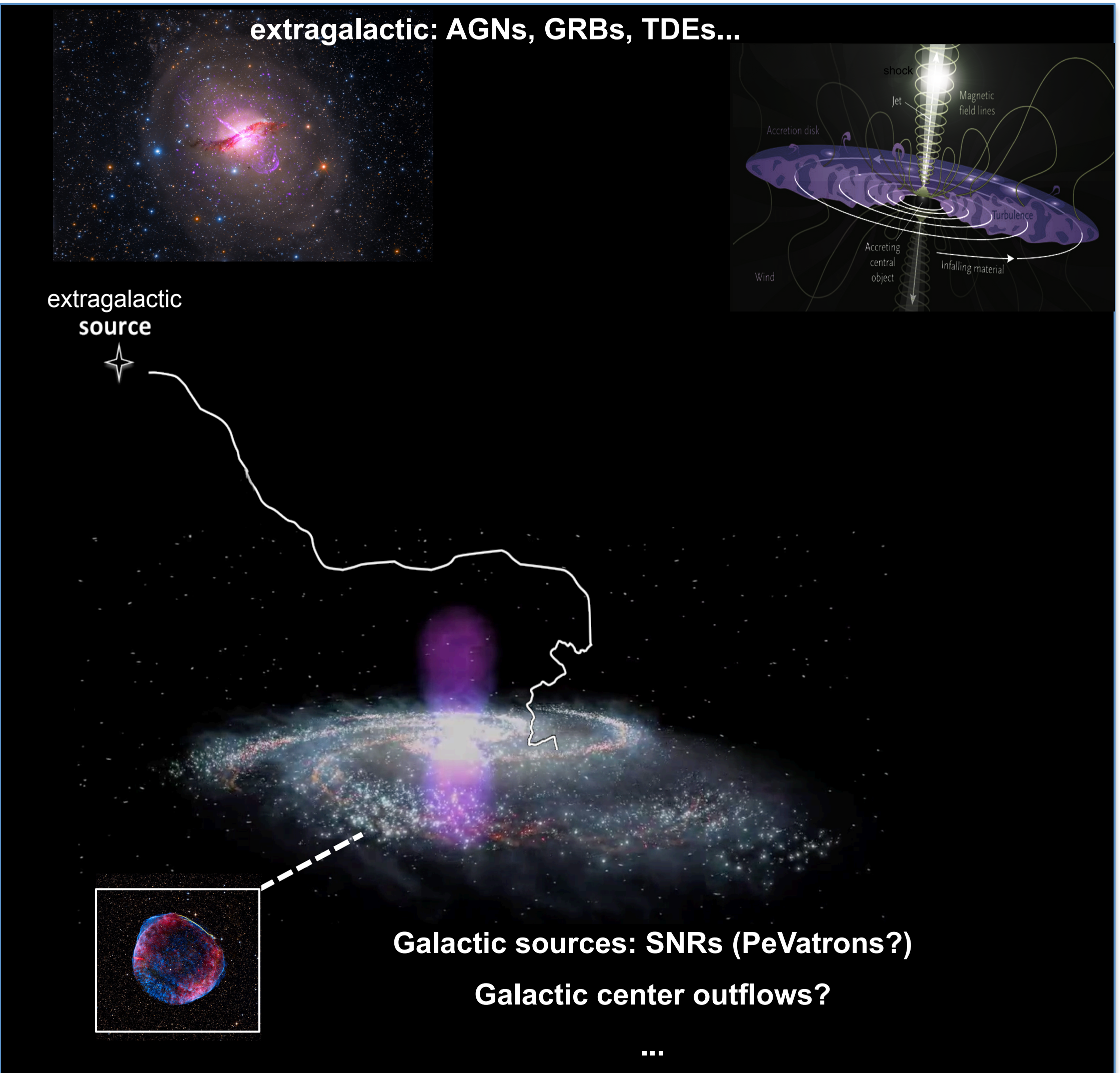
Energy Spectrum

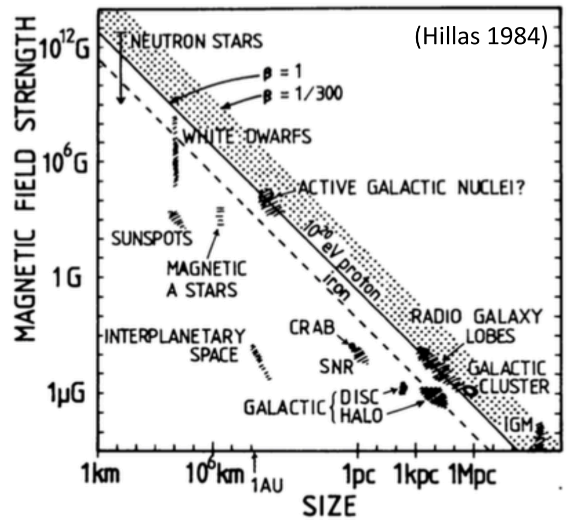


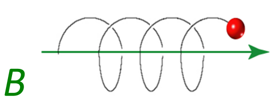
Auger: 14 events >10^{20} eV

above ~10^{19} eV : extragalactic origin

UHECR acceleration







$$r_L = 1.1\, kpc \times \frac{E_{EeV}}{Z B_{\mu G}}$$

Larmor radius < source size

$$r_L = \frac{E}{eZB} < d$$

(Hillas criterion 1984)

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How do we detect them?

- **ground based Cherenkov detectors / scintillators**
- **fluorescence detectors**

1. Arrival directions of cosmic rays

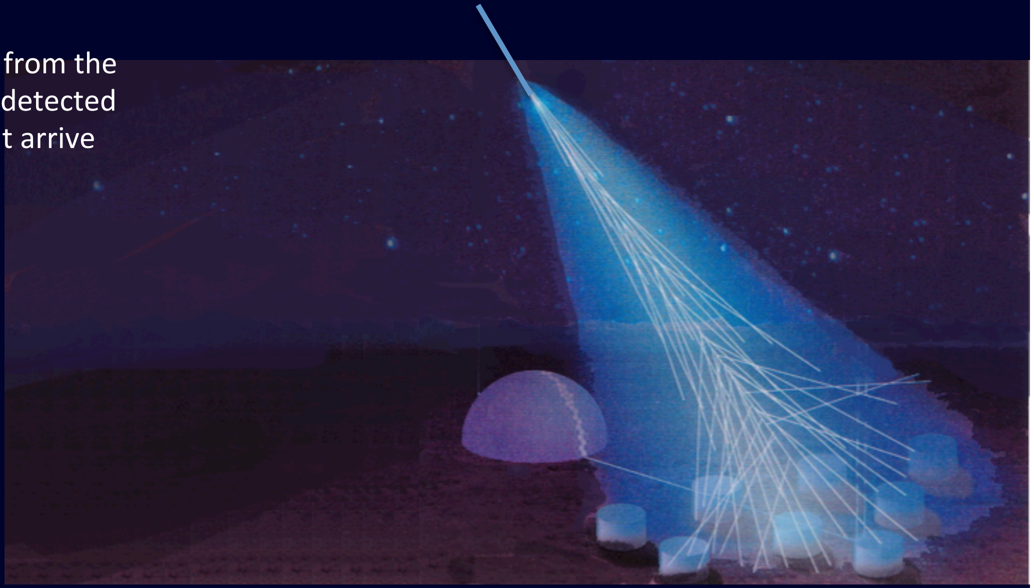
=> difference in detection times from different Cherenkov detector positions

2. Composition of the air shower

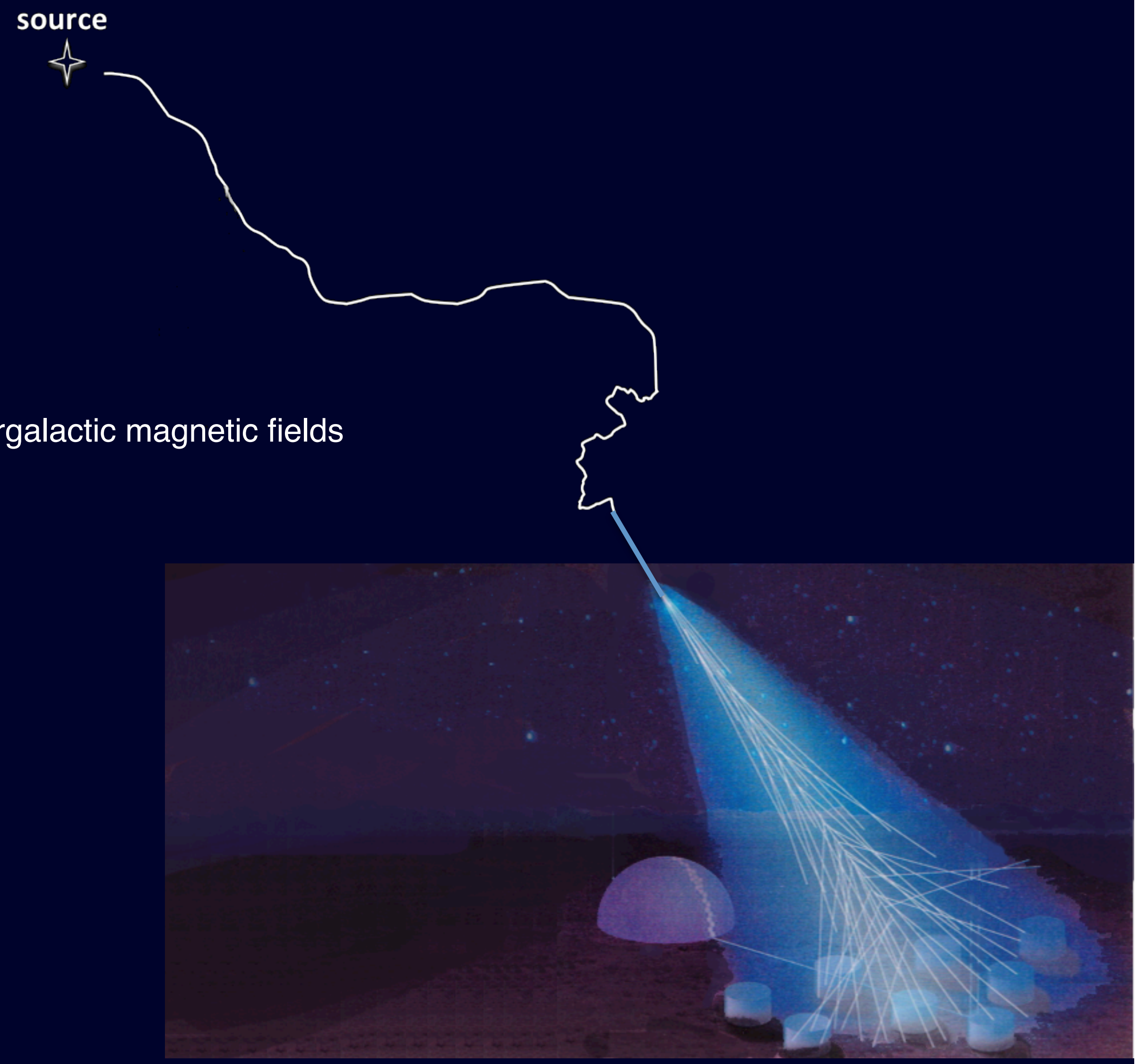
=> geometric shape and vertical profile of the air shower

3. Energy of cosmic rays

The energy of the primary cosmic ray particle can be inferred from the **intensity of light** produced by secondary air shower particles detected by fluorescence detectors and by **the number of particles** that arrive on the surface detectors

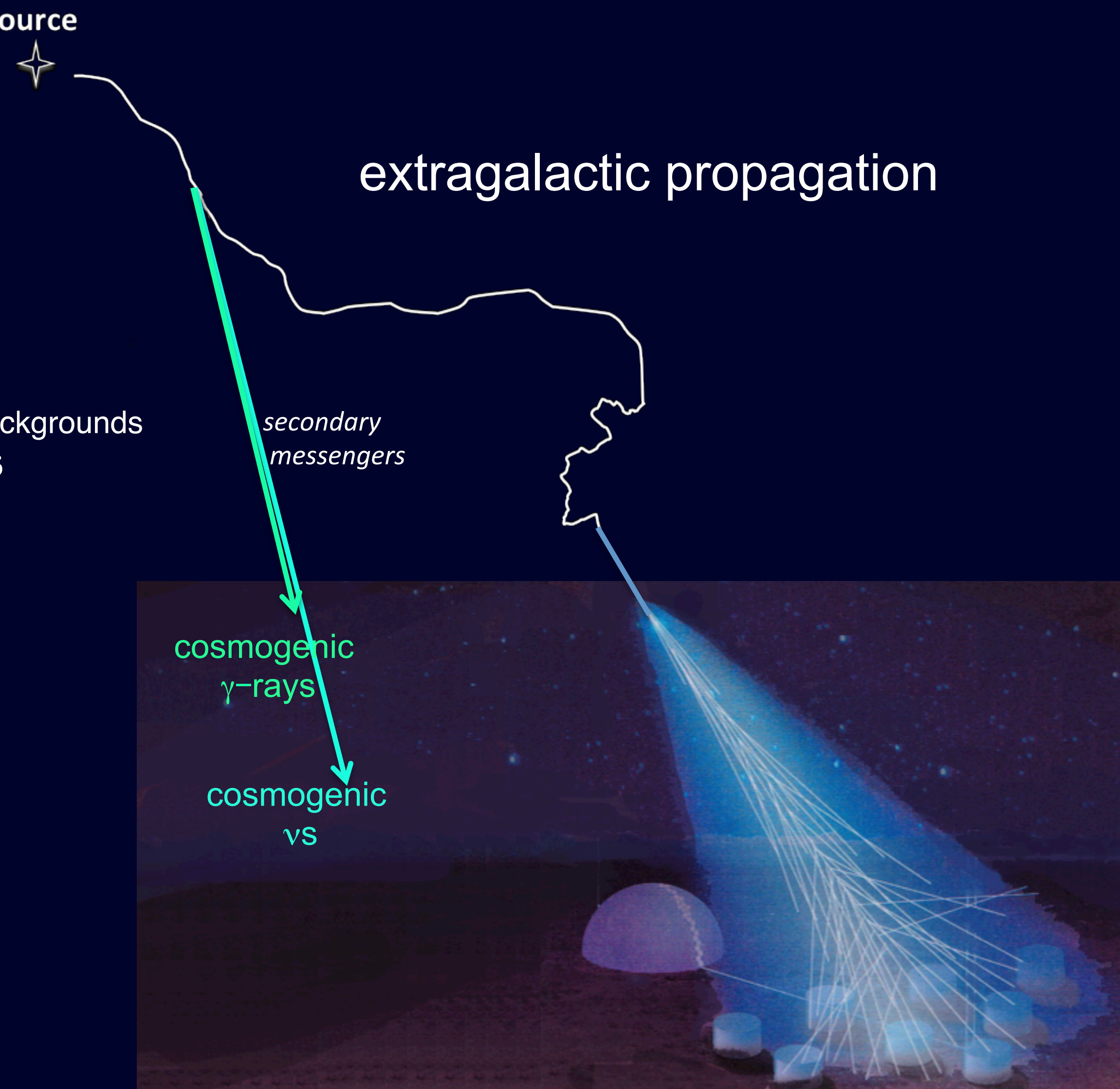


Source(s) direction(s) ≠ arrival directions



=> deflections by Galactic and intergalactic magnetic fields

Source spectrum ≠ observed spectrum



=> energy losses on the cosmological photon backgrounds

Greisen-Zatsepin-Kuzmin (GZK) effect, 1966

Photo-pion production
(mainly Δ resonance)

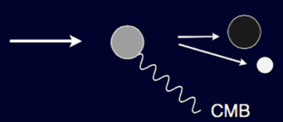
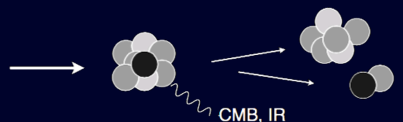


Photo-dissociation
(giant dipole resonance)



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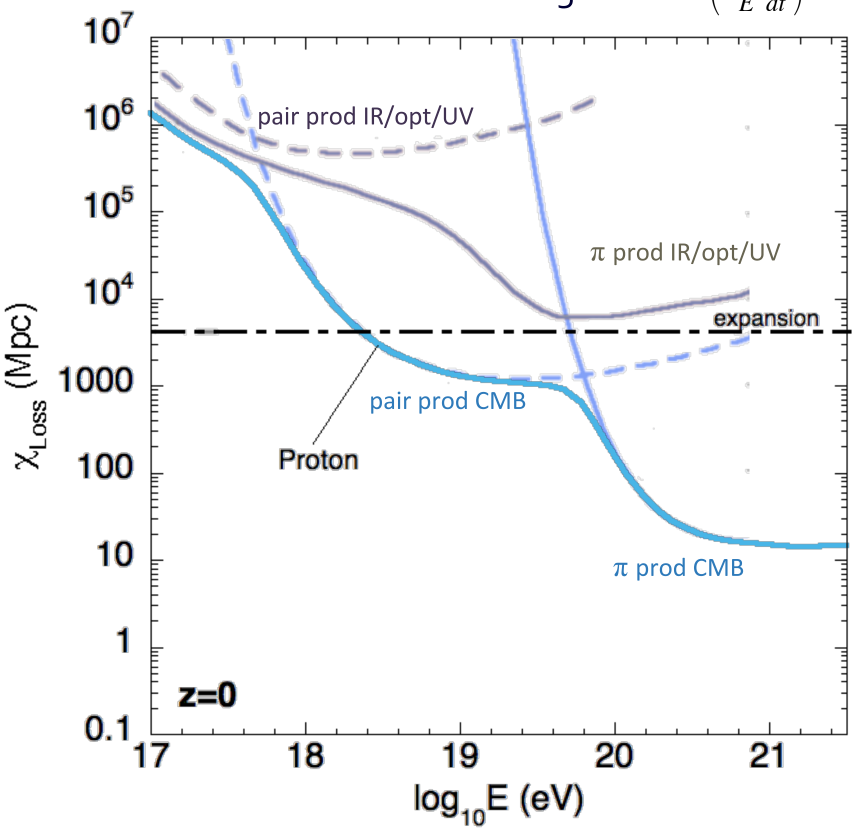
GZK horizon of protons

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

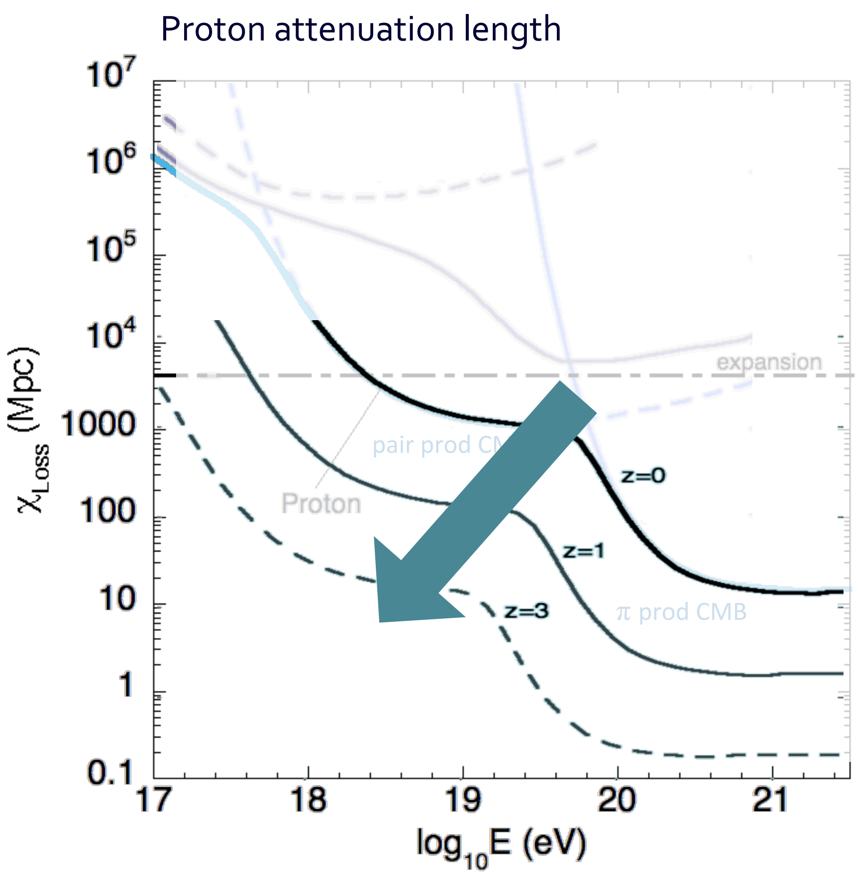
$$p + \gamma \rightarrow p + e^+ + e^-$$

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

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

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

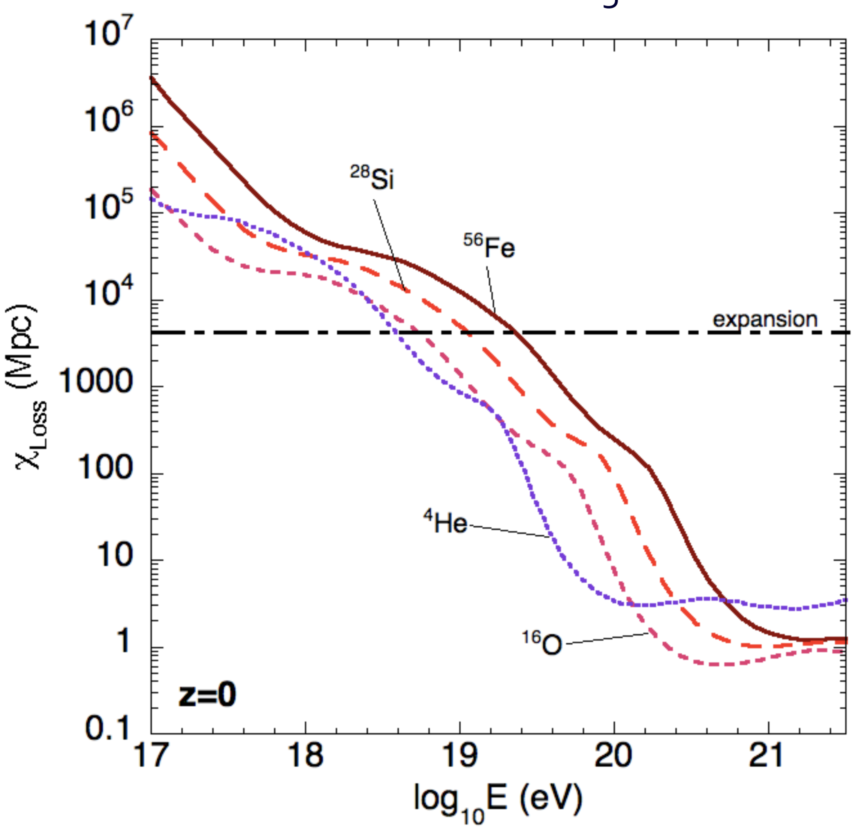
GZK horizon of protons



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

nuclei attenuation length

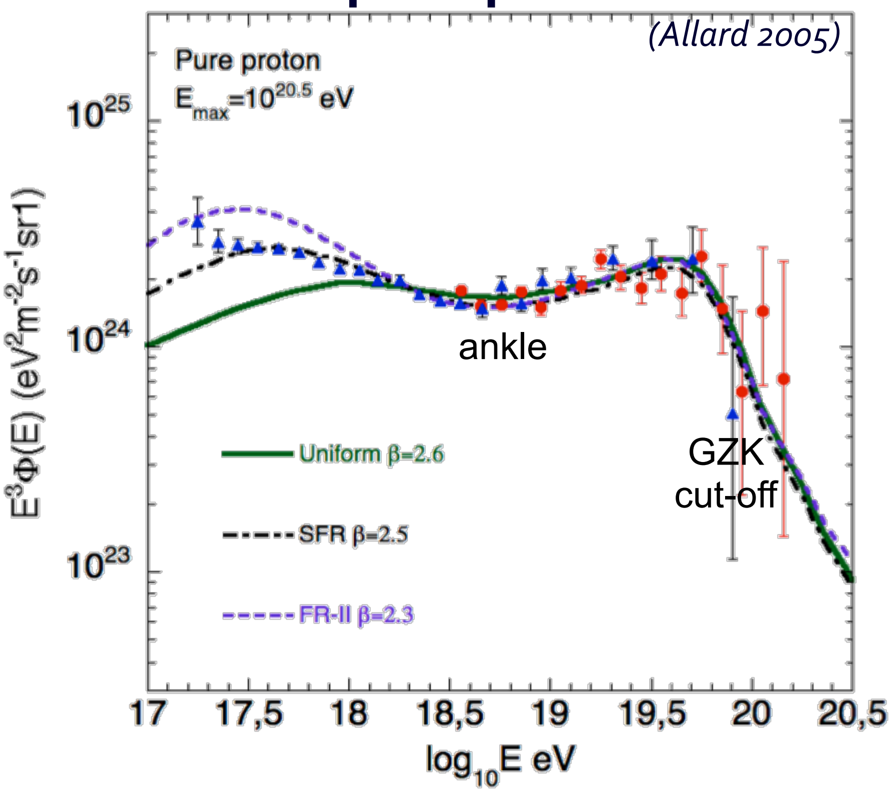


Compound nuclei suffer of:

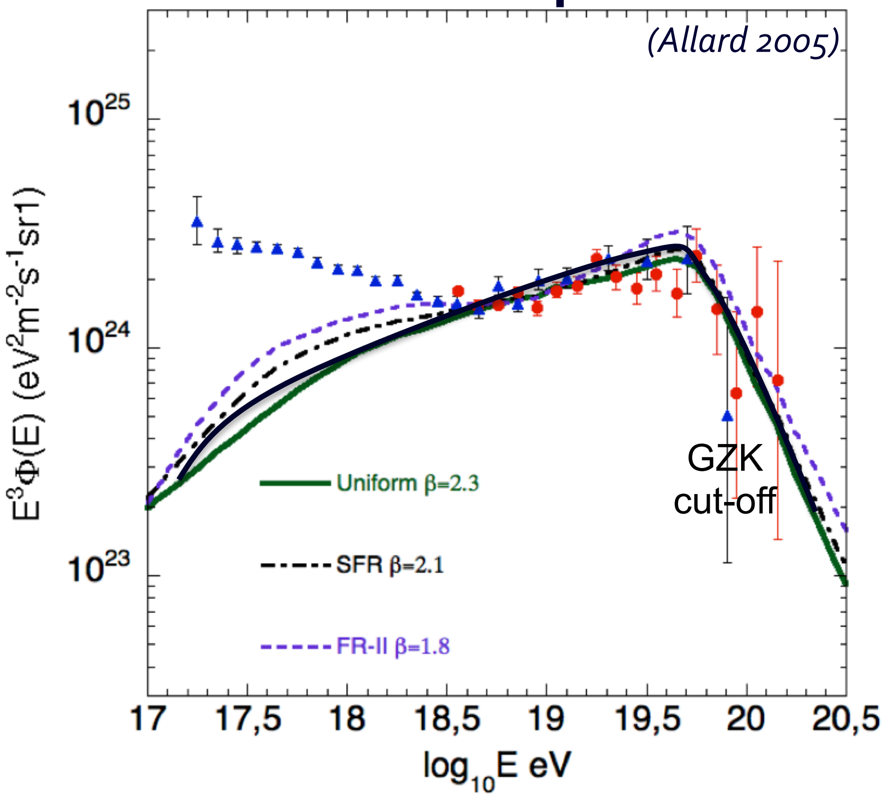
- Processes triggering a decrease of the Lorentz Factor
  - Adiabatic losses
  - Pair production losses (energy threshold ~A·10^{18} eV)
- Photodisintegration processes
  - Giant Dipole Resonance (GDR); threshold ~ 8 - 20 MeV largest σ and lowest threshold (Khan et al., 2005)
  - Quasi-Deuteron process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

Propagated spectrum

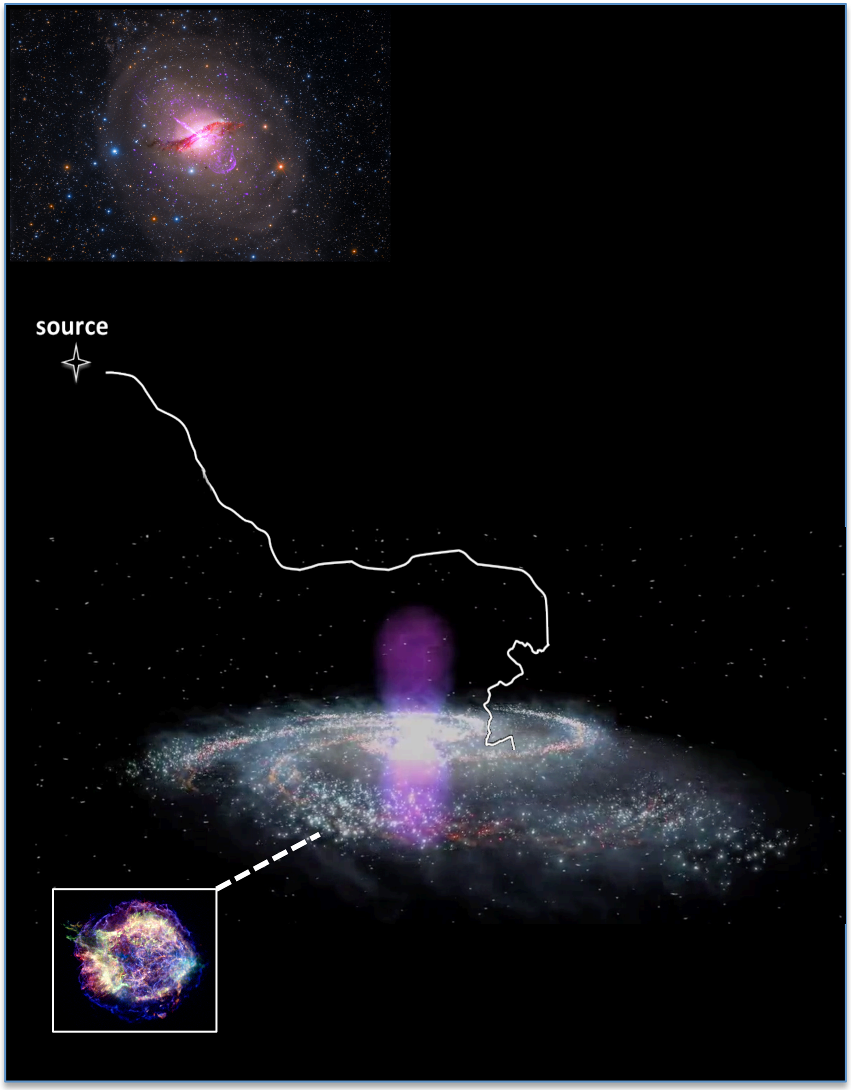
pure proton

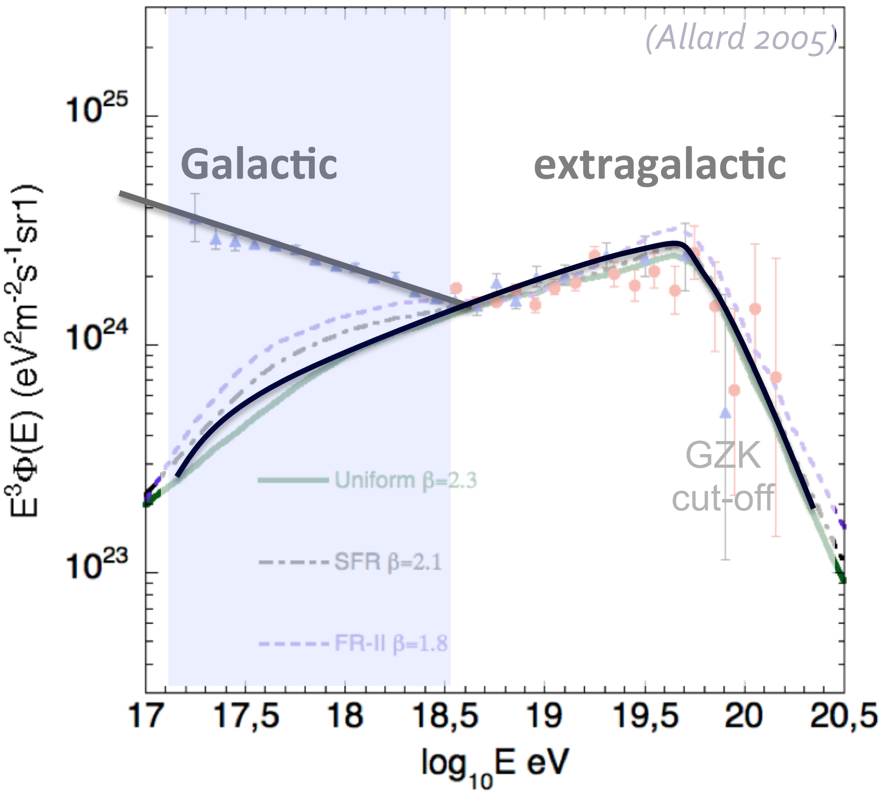


mixed composition



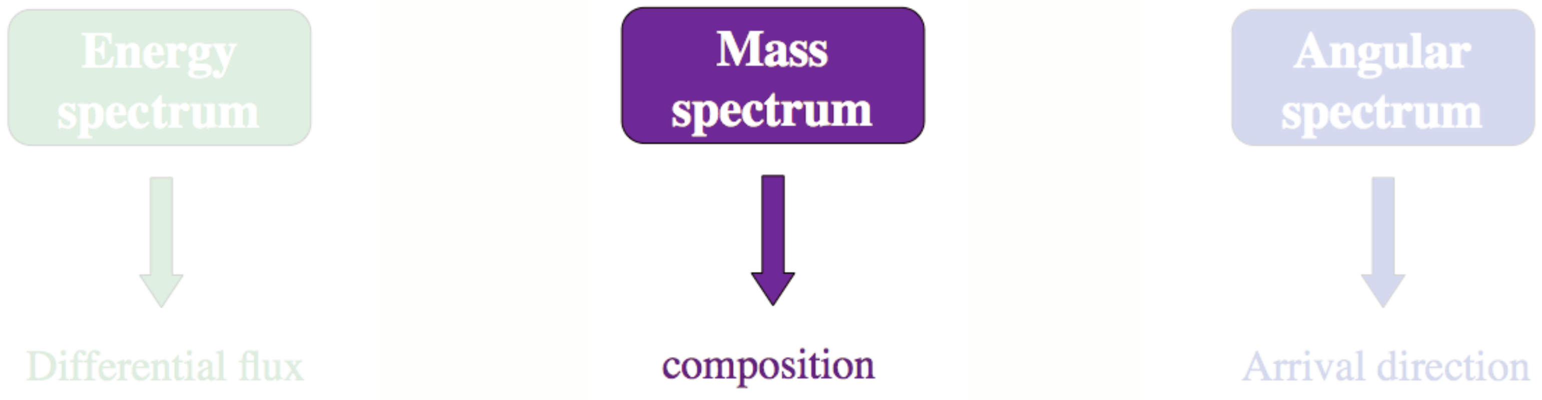
Propagated spectrum: mixed composition



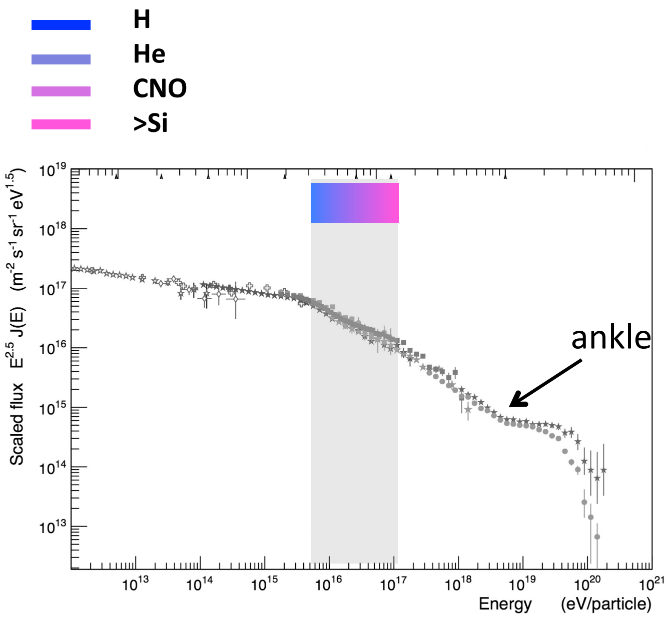


The ankle marks the end of the transition between the Galactic and extragalactic cosmic-rays

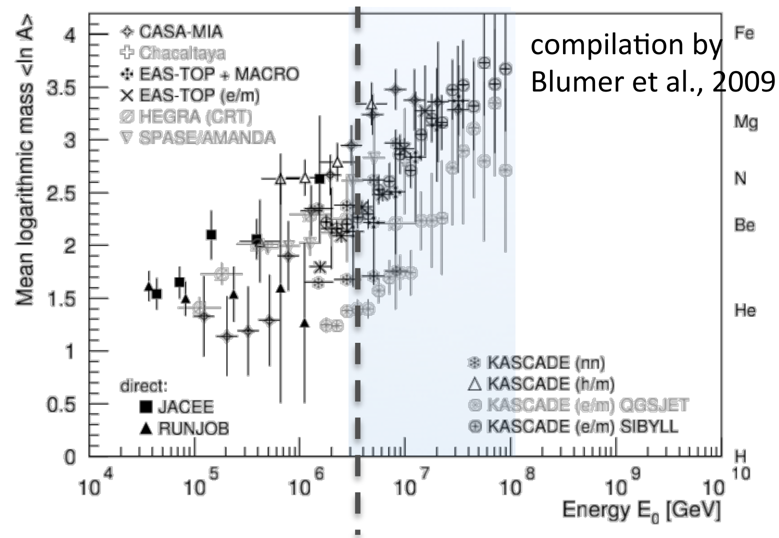
Cosmic Rays primary observables



Compositions analyses: beyond the knee

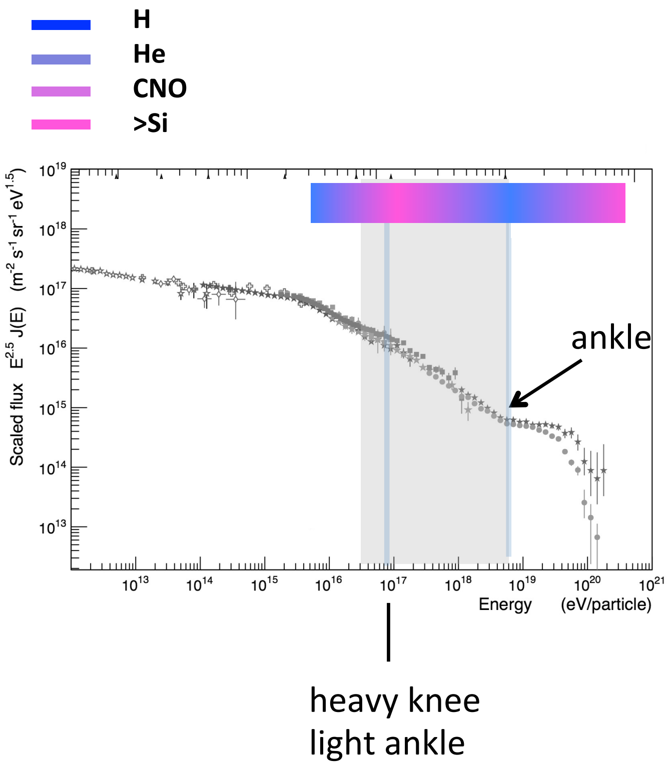


knee
$E \sim 3\ 10^{15}$ eV

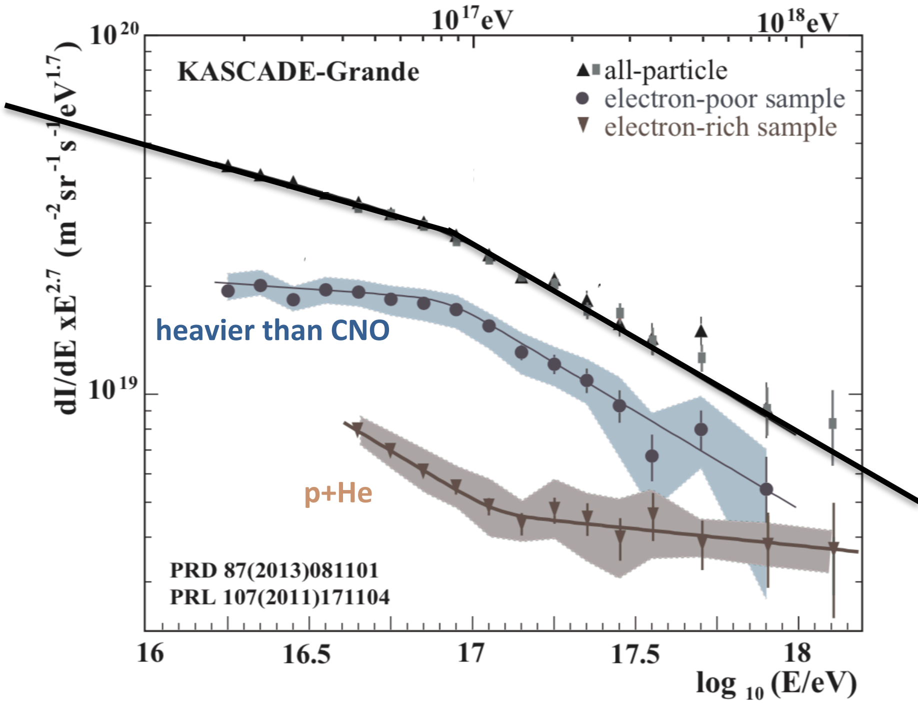


==> composition getting heavier in the energy decade following the knee

Compositions analyses: KASCADE-Grande



A second knee?
E ~ 10^{17} eV

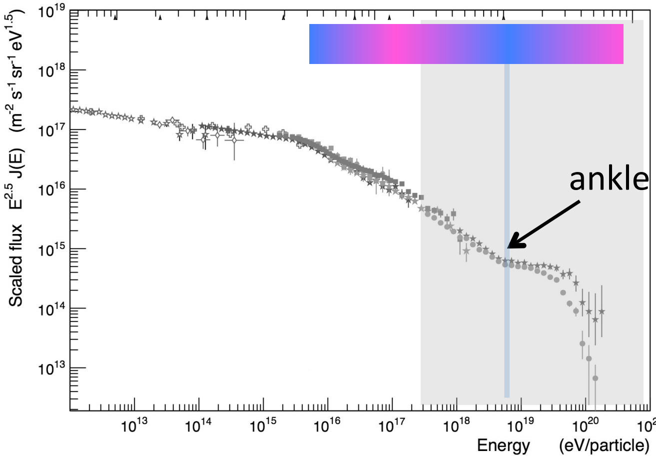


KArlsruhe Shower Core and Array DEtector measurements of air showers 100 TeV - 1 EeV January 2004 to November 2012

Auger composition analyses

H
He
CNO
>Si

The composition is getting heavier above the ankle



nitrogen-like @~10^{19} eV

ankle

Bellido et al, ICRC 2017

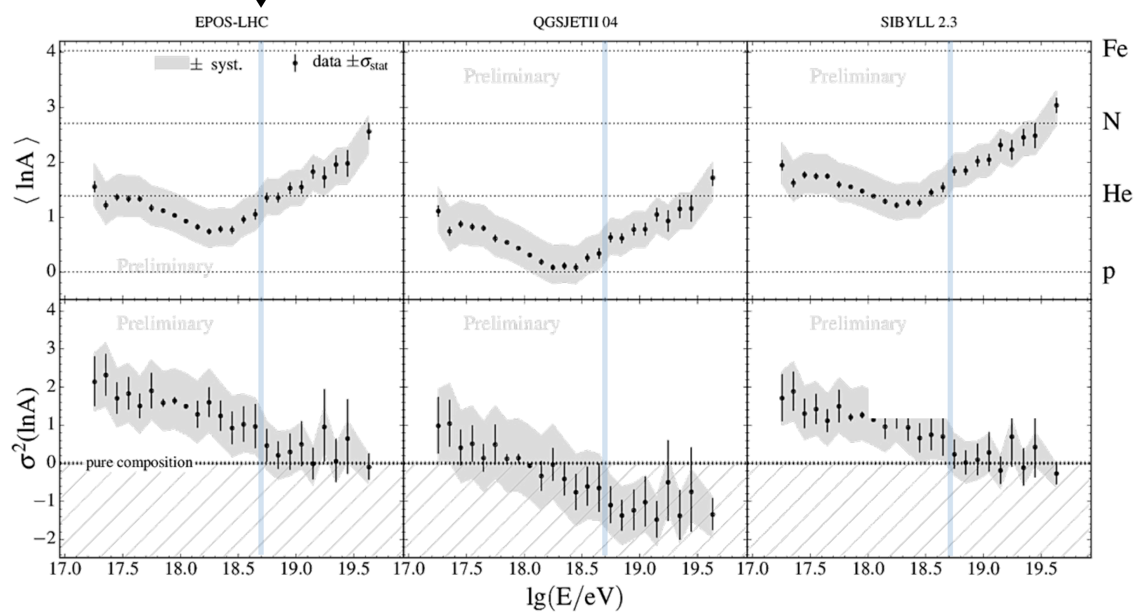
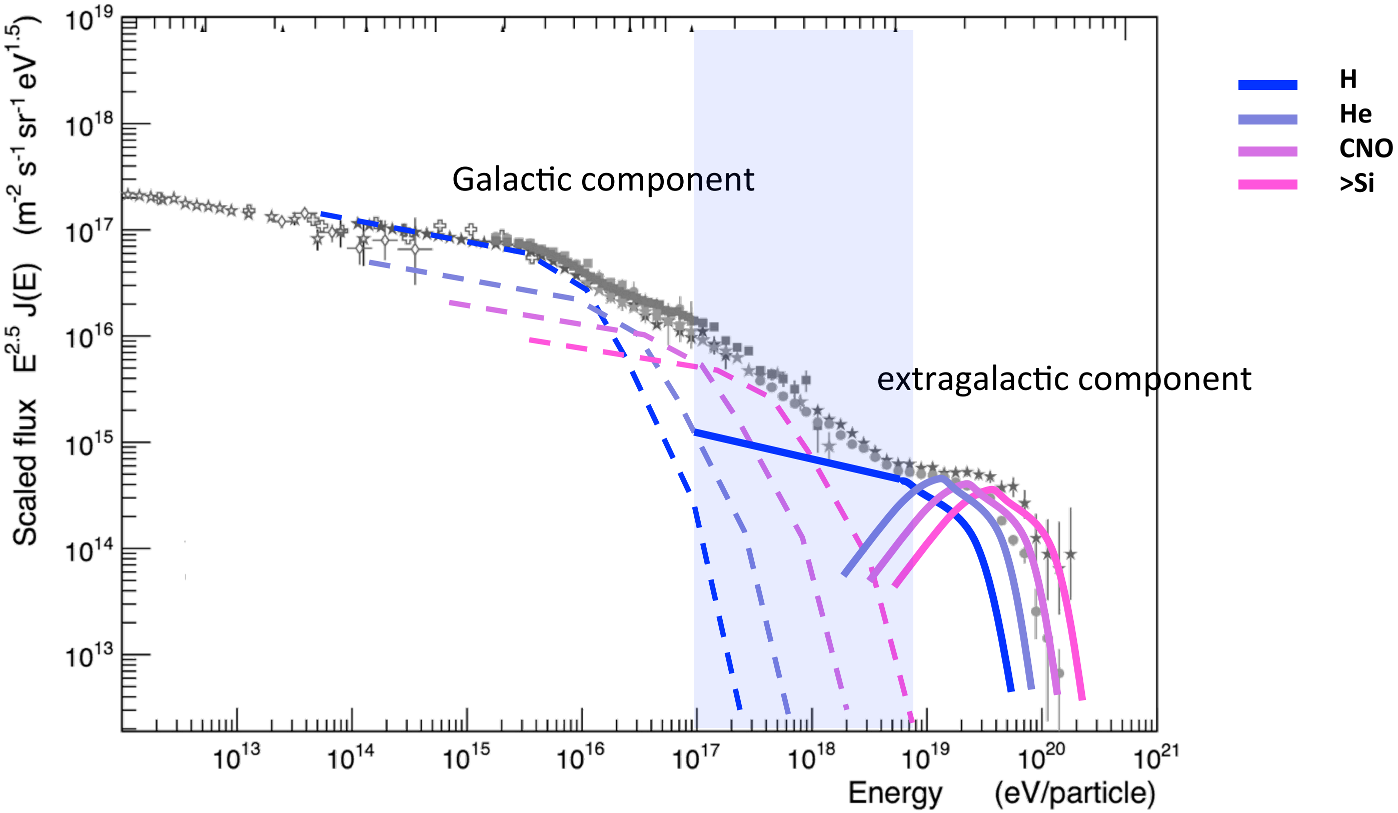


Figure 5: The mean (top) and the variance (bottom) of ln$A$ estimated from data with EPOS-LHC (left), QGSJetII-04 (middle) and Sibyll2.3 (right) hadronic interaction model

A generic two-component model

Generic features > 10^{17} eV (extragalactic): soft proton component + hard nuclei spectra



Galactic to extragalactic cosmic-ray transition

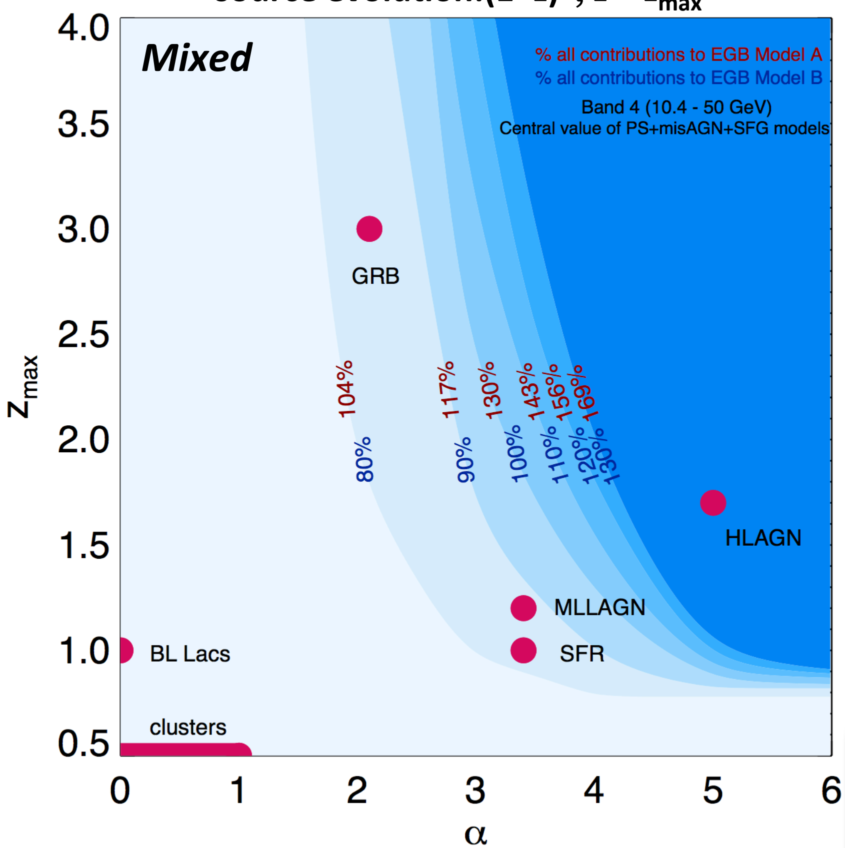
Cosmogenic νs, γ–rays

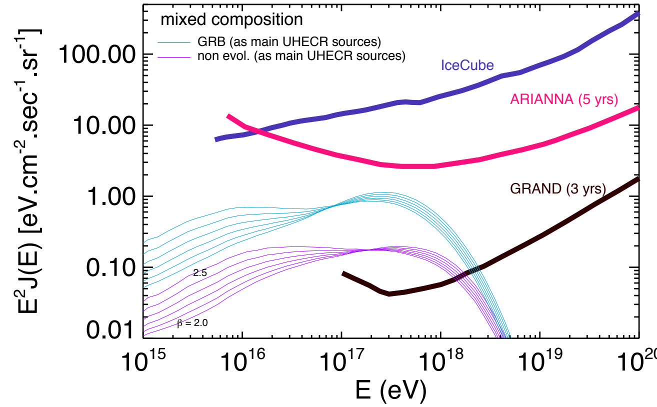
Globus, Allard, Parizot & Piran 2017, ApJ Letters, 839, 2

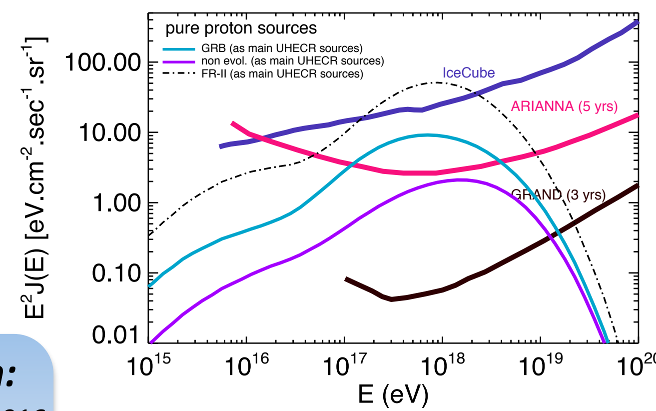
Gev-TeV γ–rays: only strongly evolving sources (HLAGNs) are excluded by the current observations

PeV-EeV νs: mixed-composition models predict ν fluxes too low to be detected by Icecube or ARIANNA; future neutrinos detectors should be able to probe powerful **proton** sources

source evolution: $(1+z)^{\alpha}$, $z < z_{max}$







pure proton:
Gavish & Eichler 2016;
Berezinsky et al. 2016;
Supanitsky 2016;
Heinze et al. 2016 (ν)

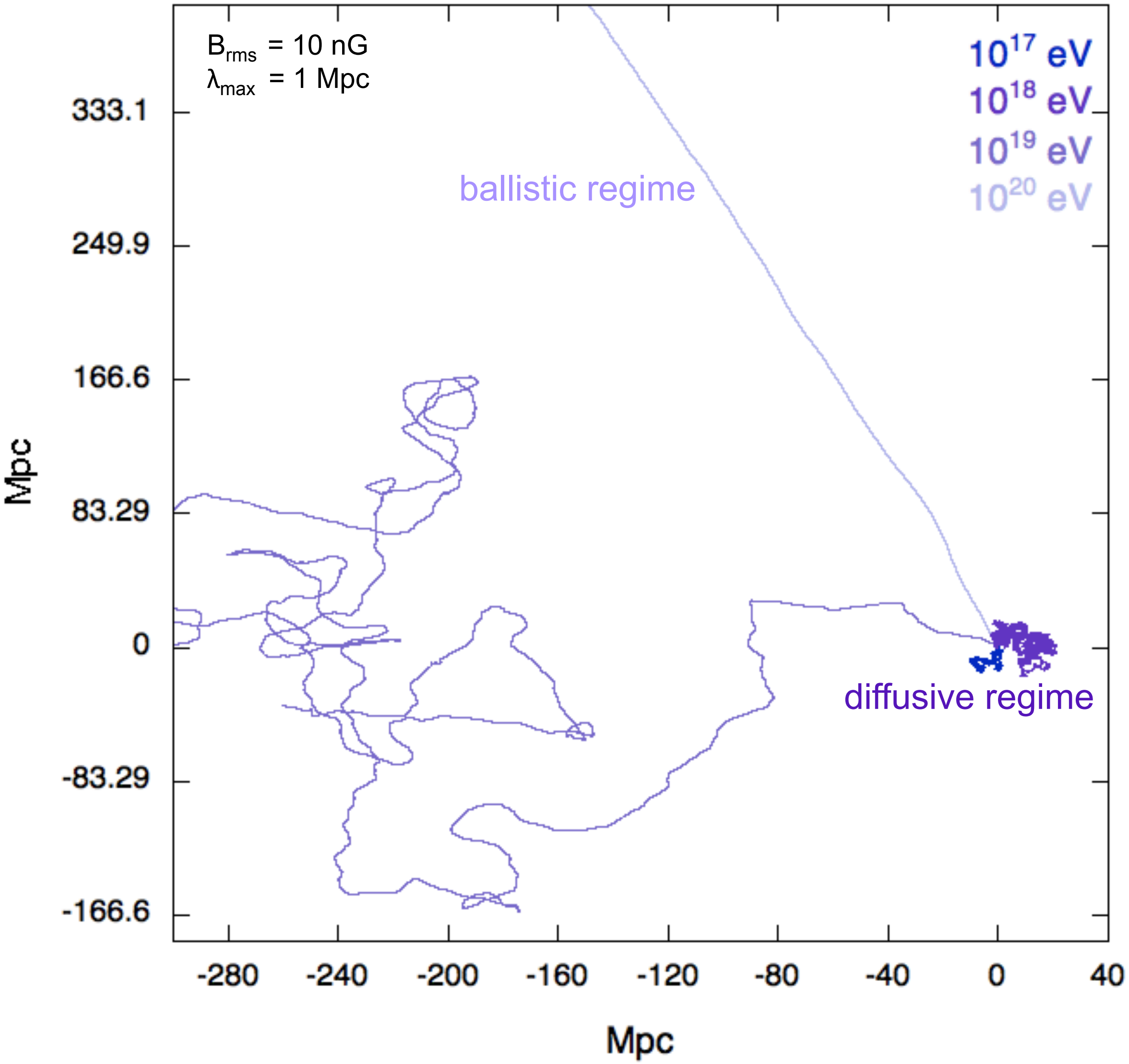
Cosmic Rays primary observables

Energy spectrum → Differential flux

Mass spectrum → composition

Angular spectrum → Arrival direction

Trajectories in a purely turbulent IGMF



Larmor radius

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

Globus, Allard, Parizot 2008

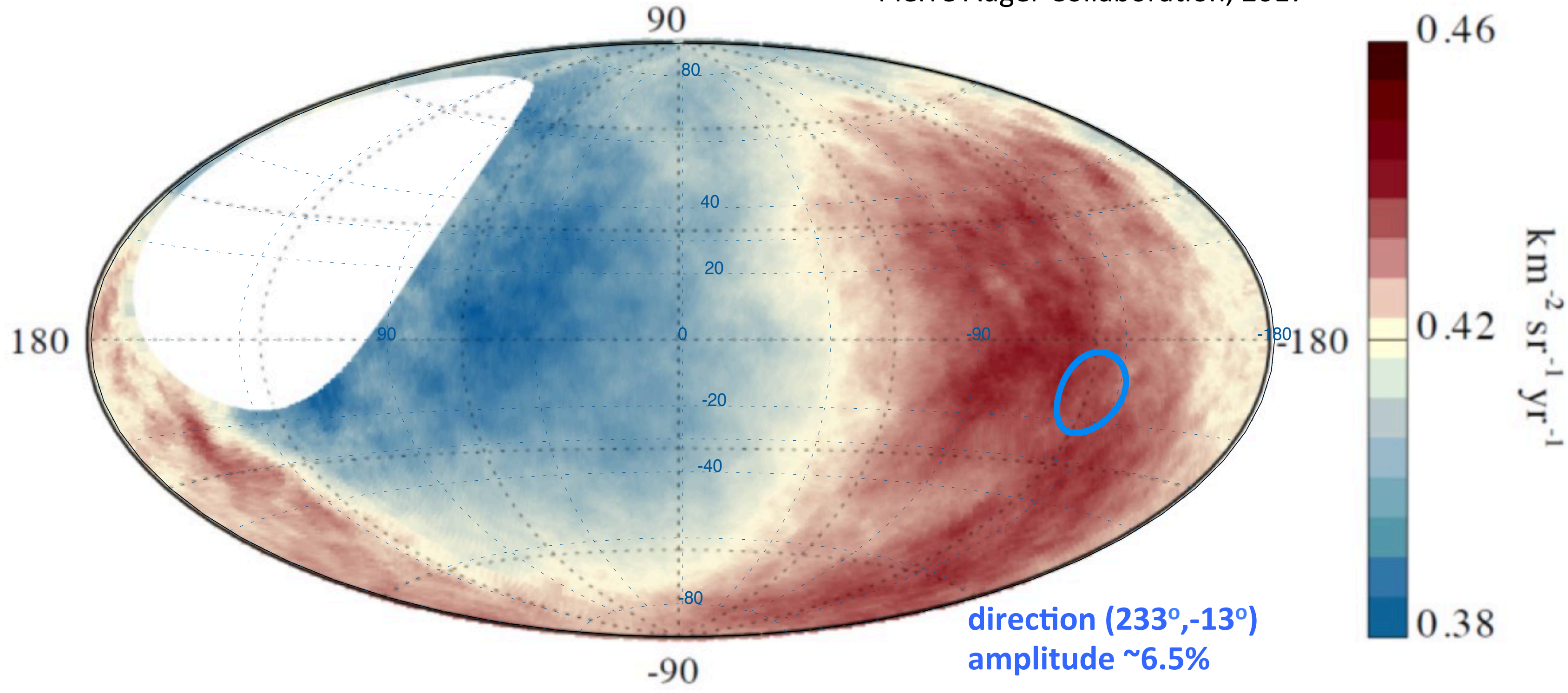

ballistic regime


diffusive regime
© Pierre-Paul Feyte

The magnetic fog seems to dissipate

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

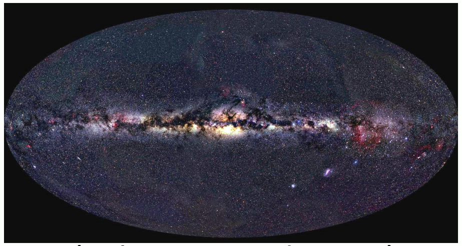
Pierre Auger Collaboration, 2017



direction (233°,-13°)
amplitude ~6.5%

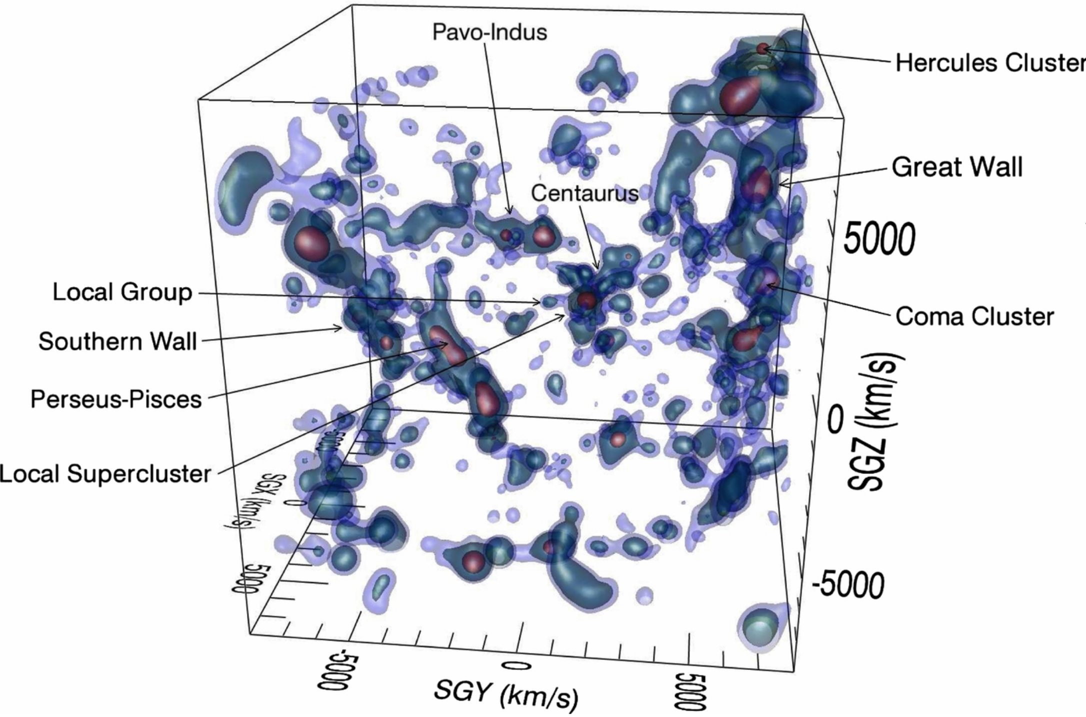
[4 – 8] EeV: compatible with isotropy

E > 8 EeV: significant modulation @ 5.6σ



(galactic coordinates)

Large scale structure induced UHECR anisotropy



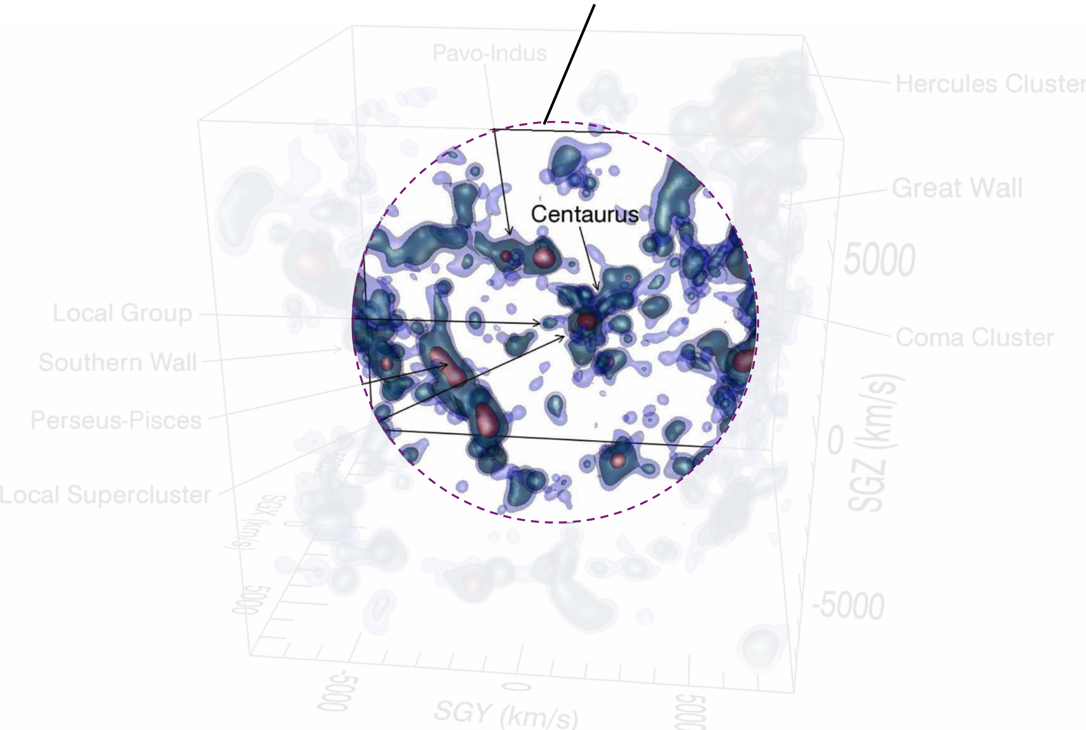
We use the QL density field derived by Hoffman et al., 2018, Nature Astronomy (arXiv 1807.03724) based on CosmicFlows-2

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

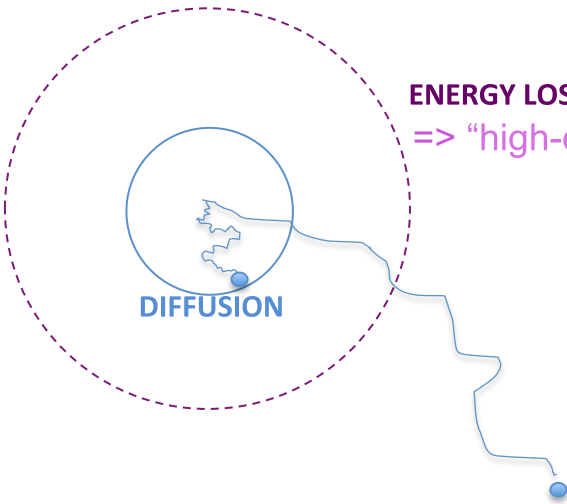
We assume that the source follow the density fluctuations and take into account the diffusive transport in the intergalactic magnetic field (IGMF)

Large scale structure induced UHECR anisotropy

horizon = min (GZK horizon, magnetic horizon)



intergalactic magnetic field (IGMF)
=> "low-cut filter"



We assume that the source follow the density fluctuations and take into account the diffusive transport in the intergalactic magnetic field (IGMF).
The amplitude of the LSS-induced UHECR dipole depends on the UHECR horizon *(Globus & Piran, 2017)*

Large scale structure induced UHECR anisotropy

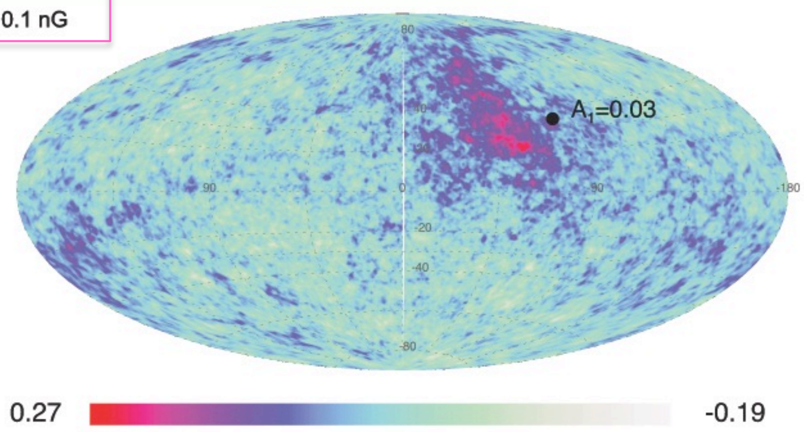
Globus, Piran, Hoffman, Carlesi & Pomarède submitted

eprint arXiv:1808.02048

nitrogen @11.5 EeV

IGMF

N 0.1 nG

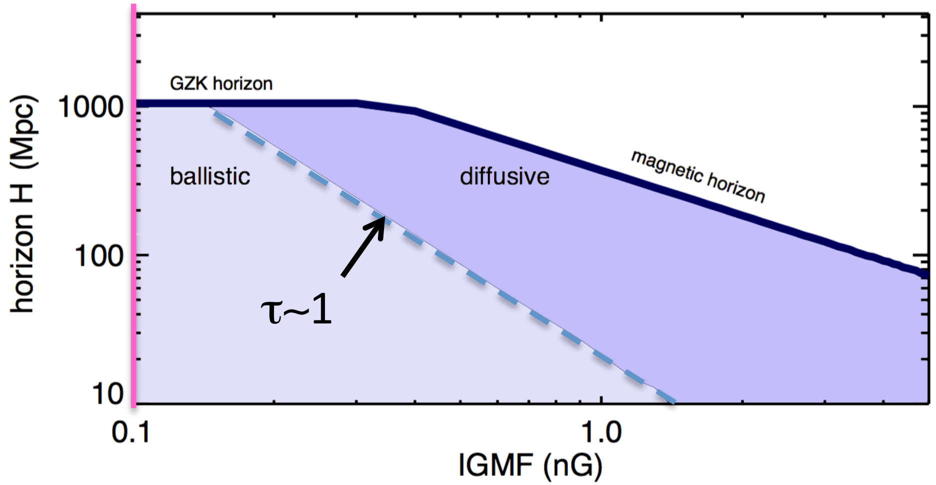


Diffusion in purely turbulent IGMF

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

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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Globus, Piran, Hoffman, Carlesi & Pomarède submitted

eprint arXiv:1808.02048

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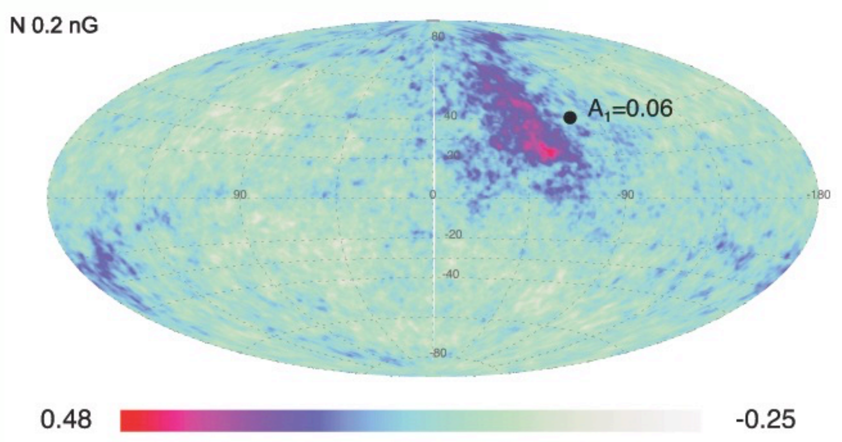

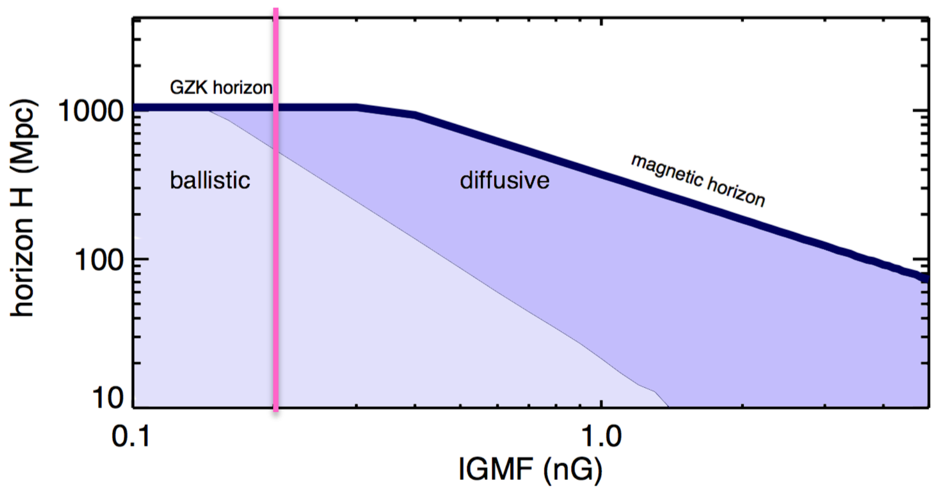

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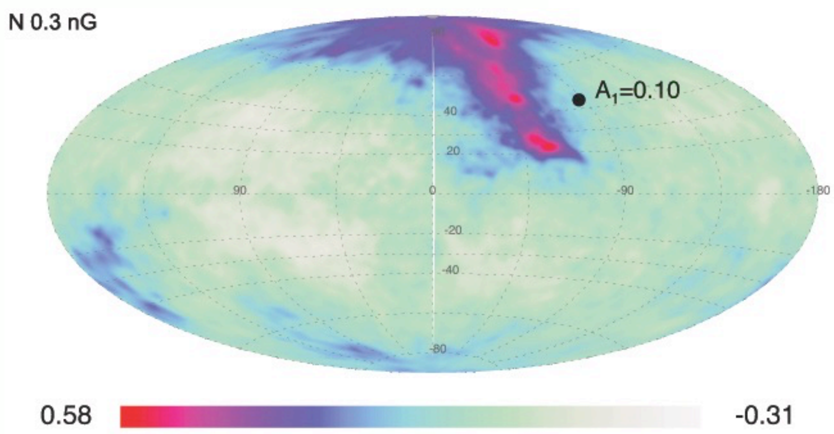

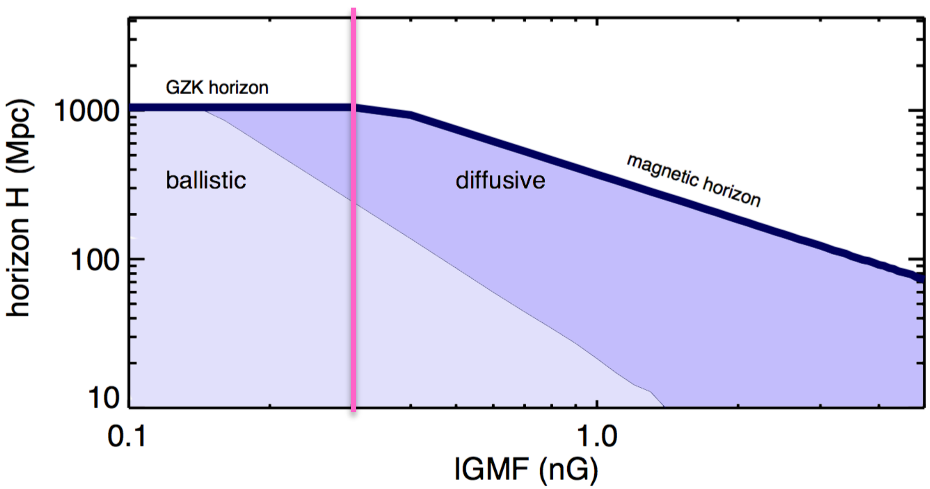

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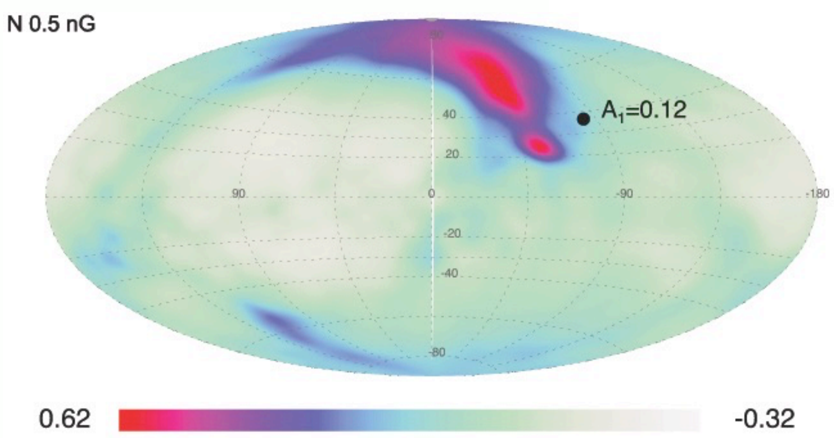

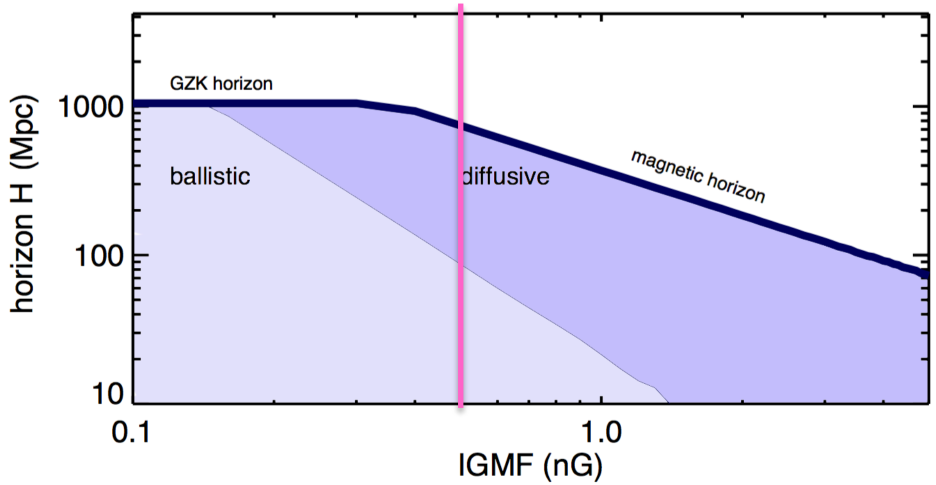

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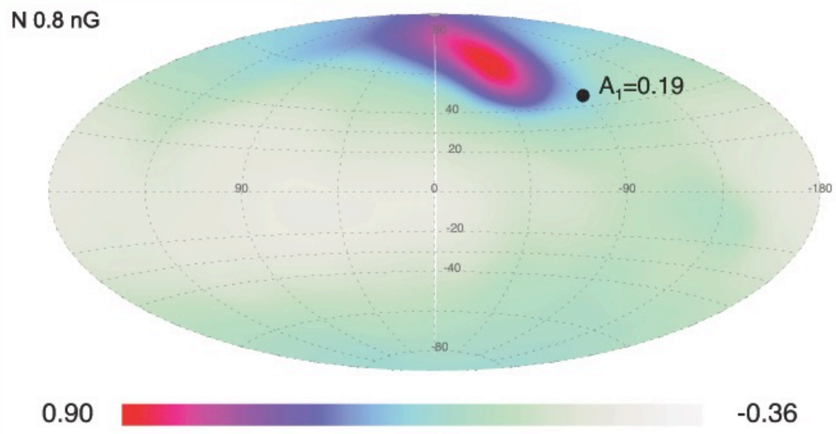

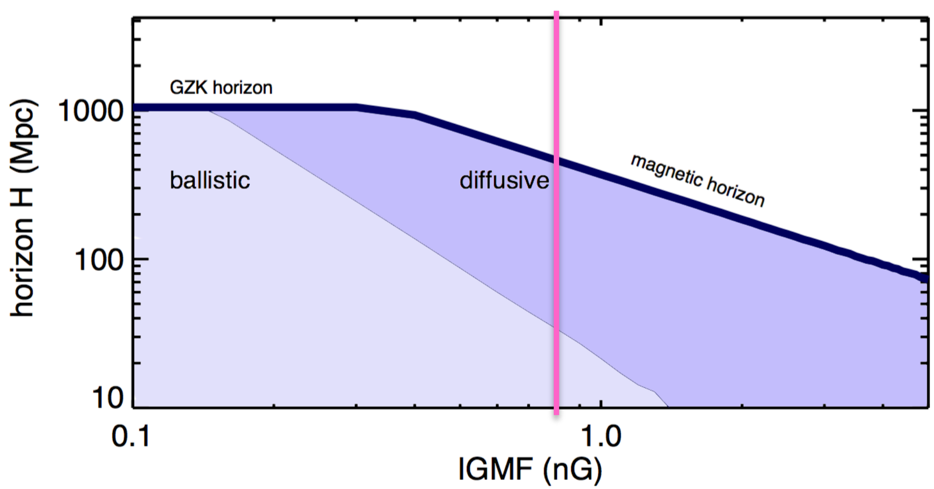

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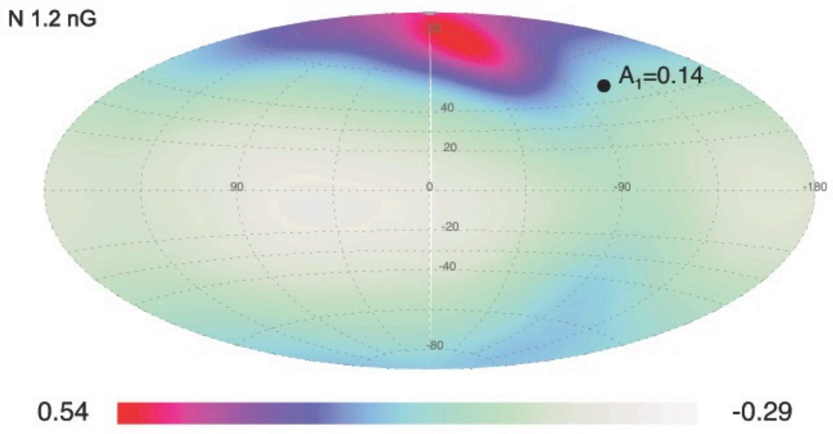

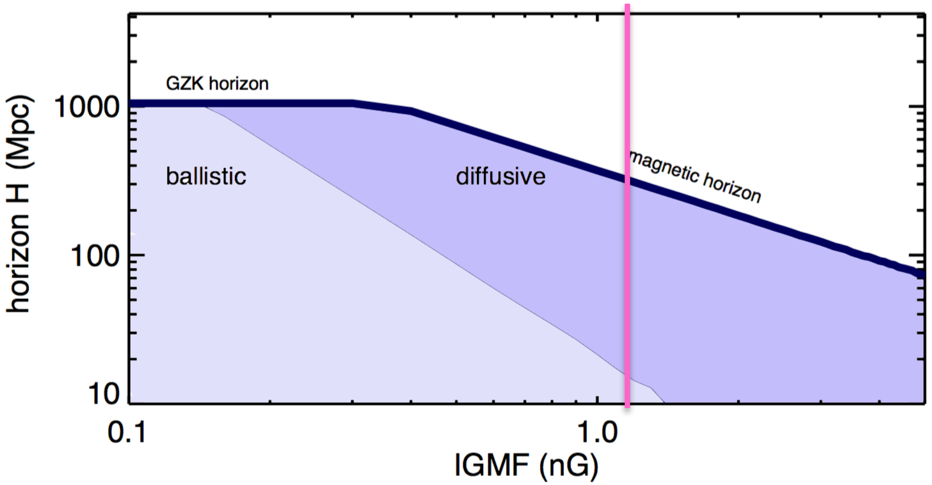

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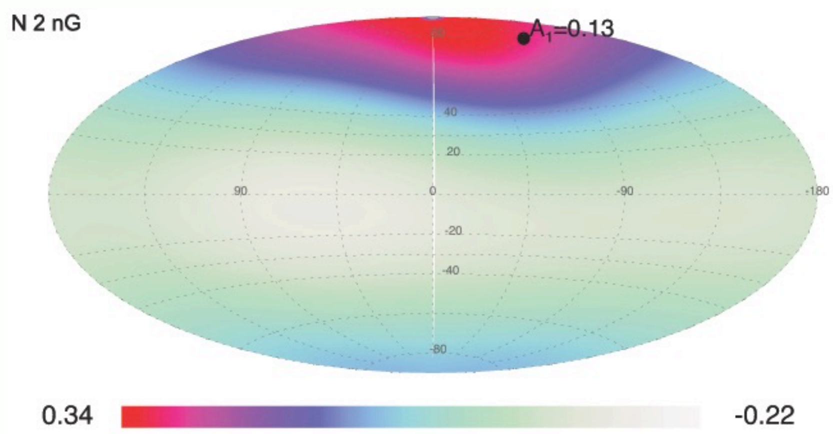

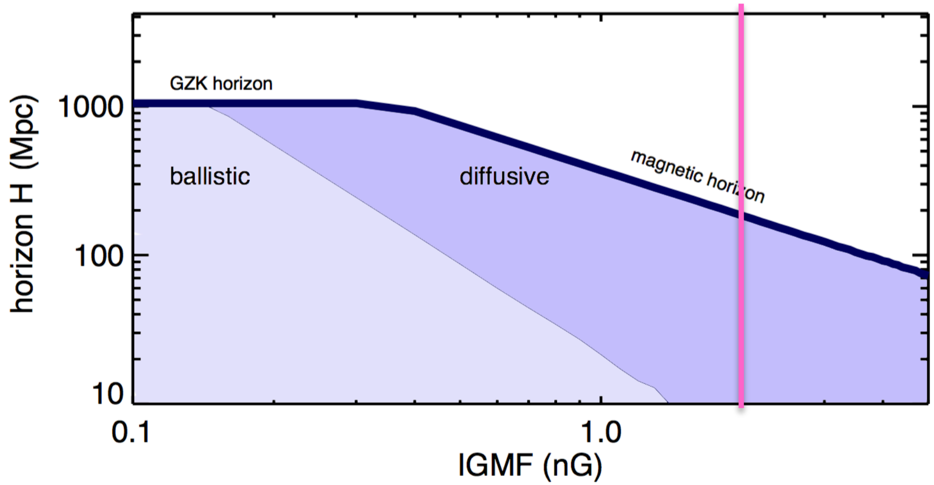

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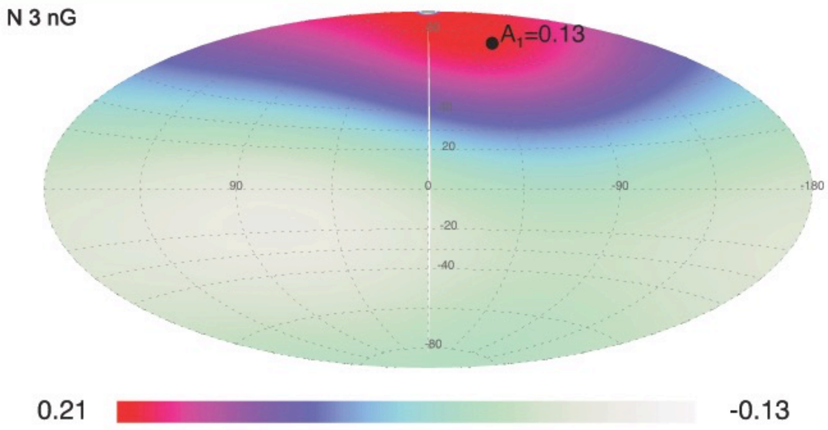
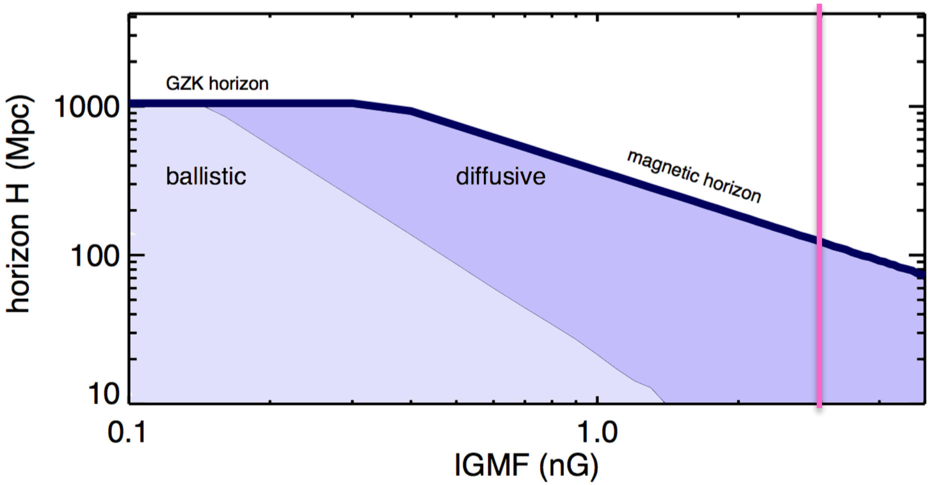
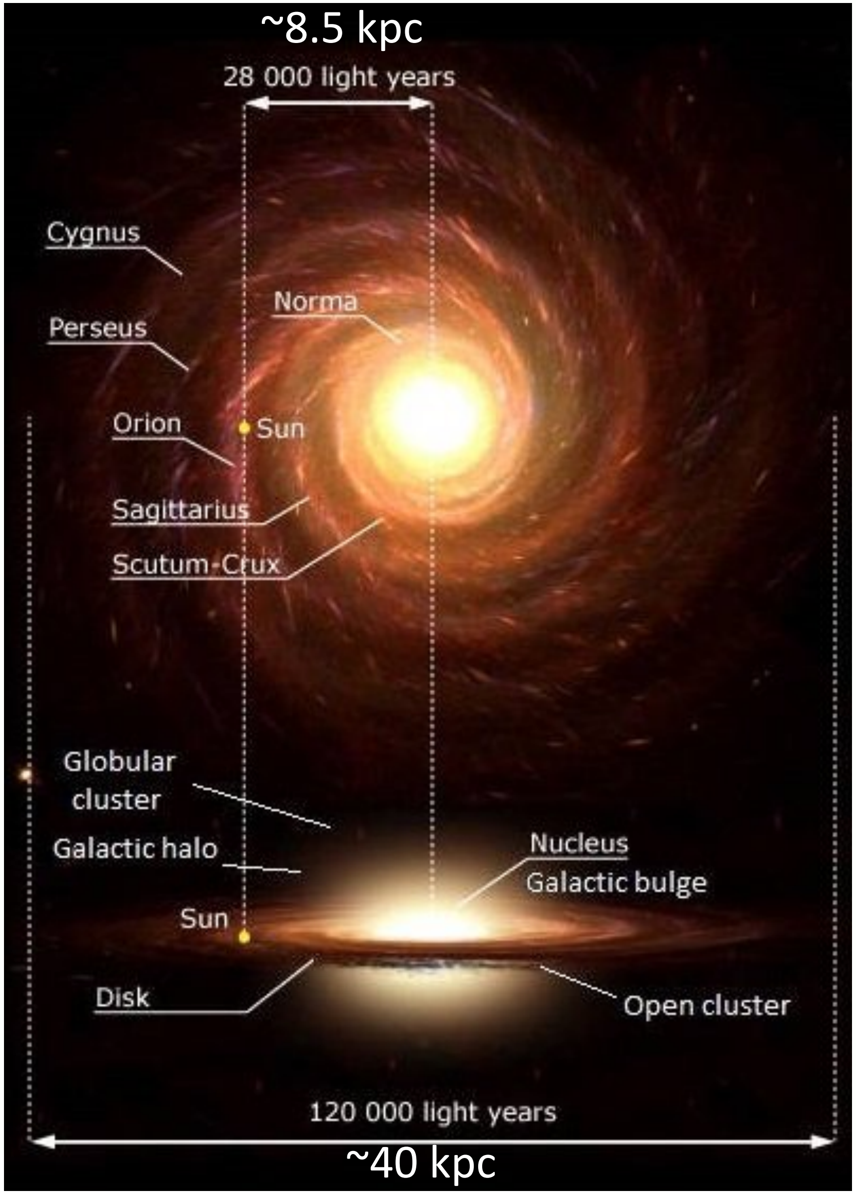
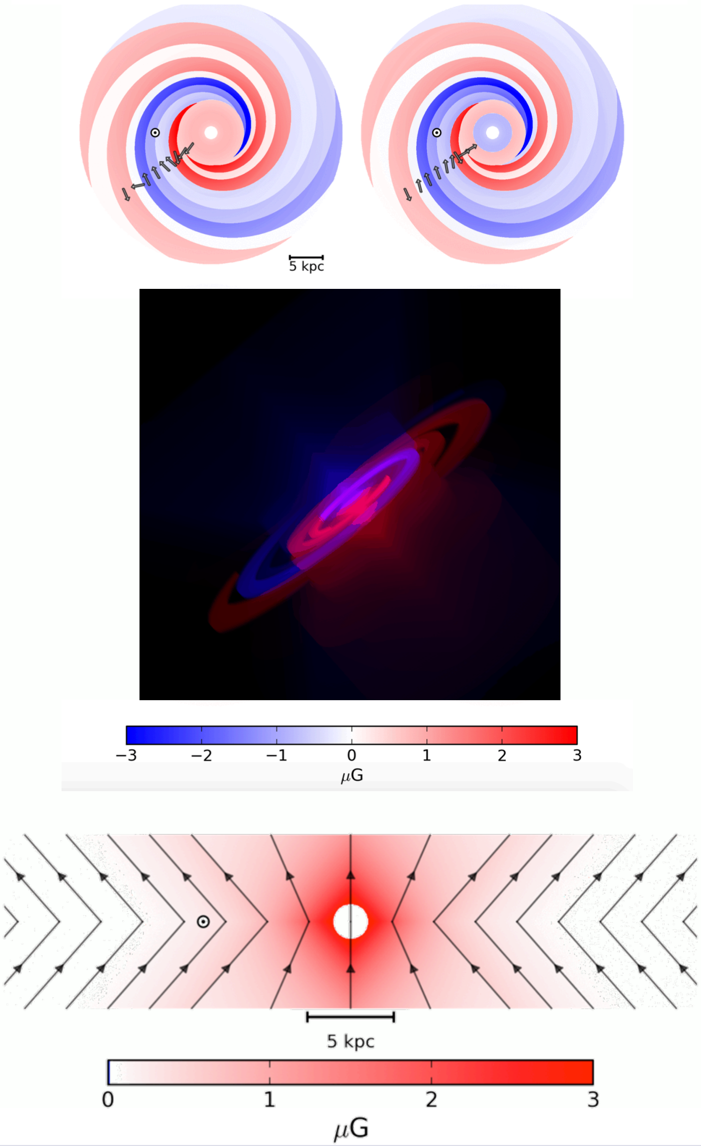




The Galactic Magnetic Field *(Jansson & Farrar 2012, JF12)*



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

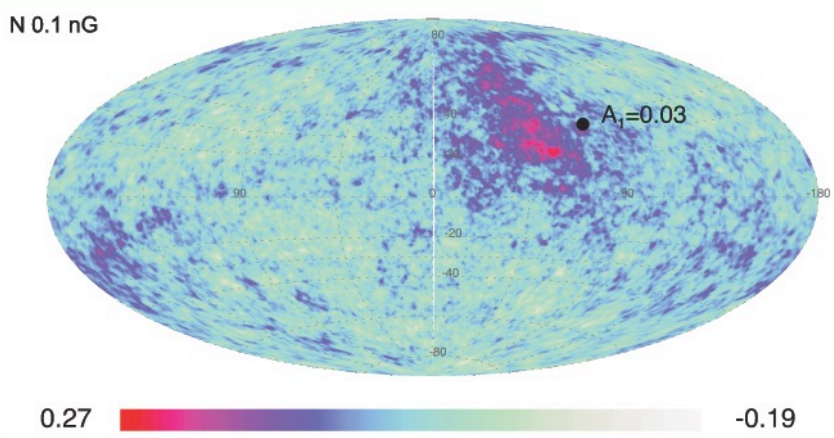
Jansson & Farrar 2012

Large scale structure induced UHECR anisotropy

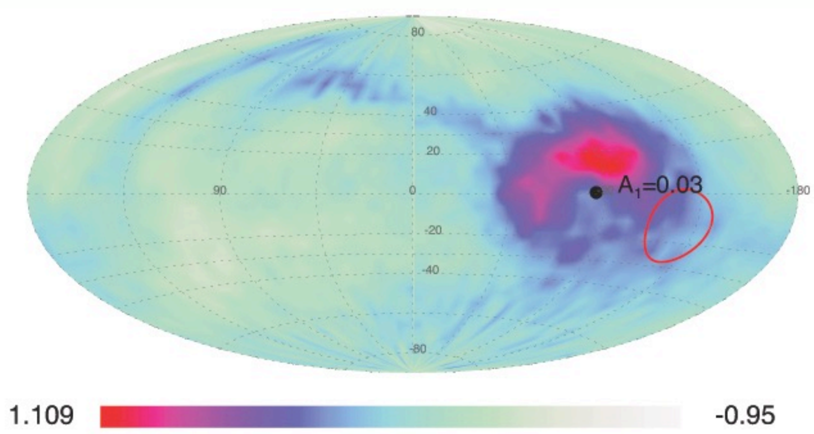
Globus, Piran, Hoffman, Carlesi & Pomarède submitted

eprint arXiv:1808.02048

nitrogen @11.5 EeV
IGMF only



IGMF + GMF (JF12)



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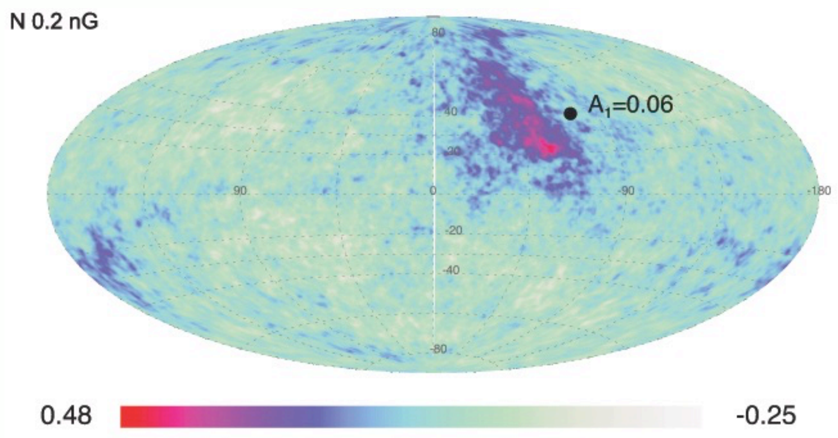

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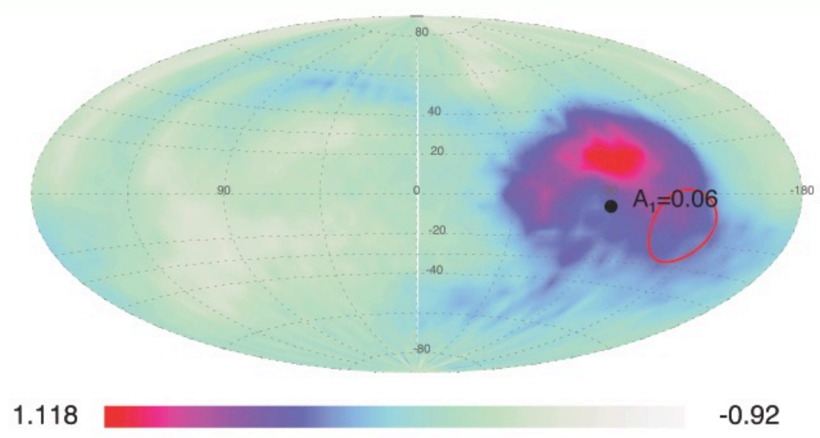

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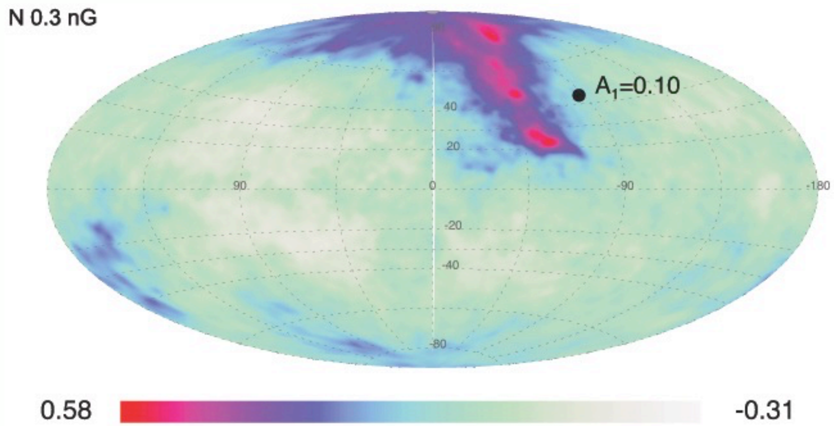

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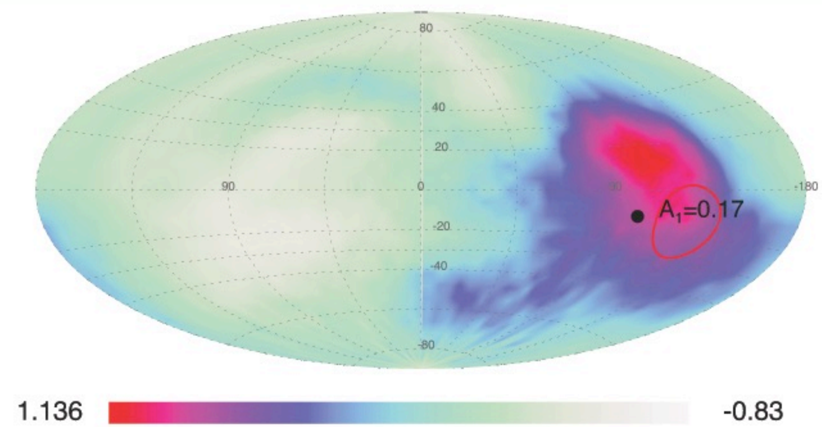

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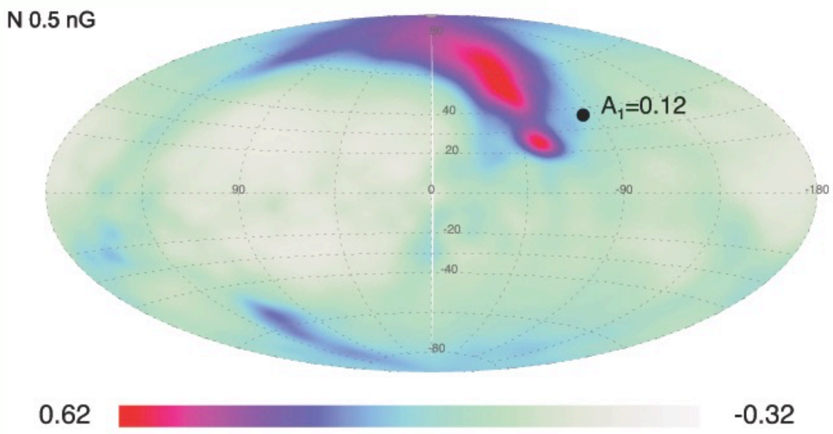

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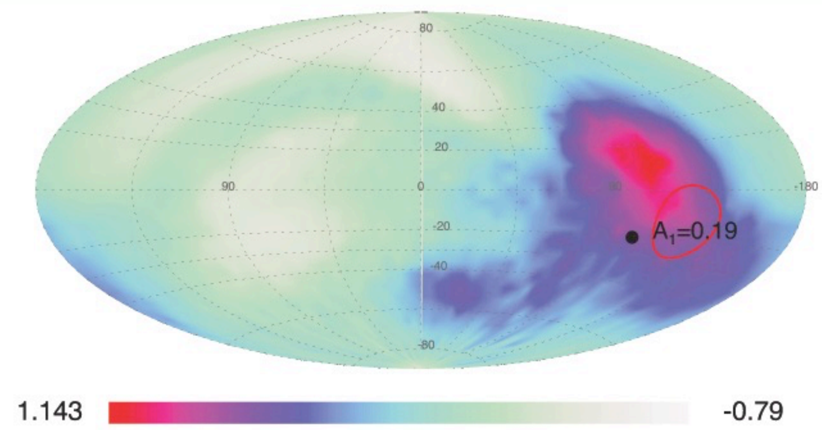

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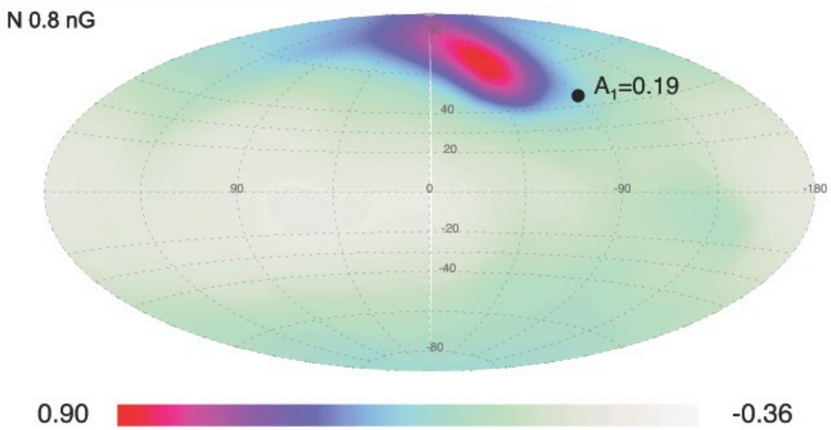

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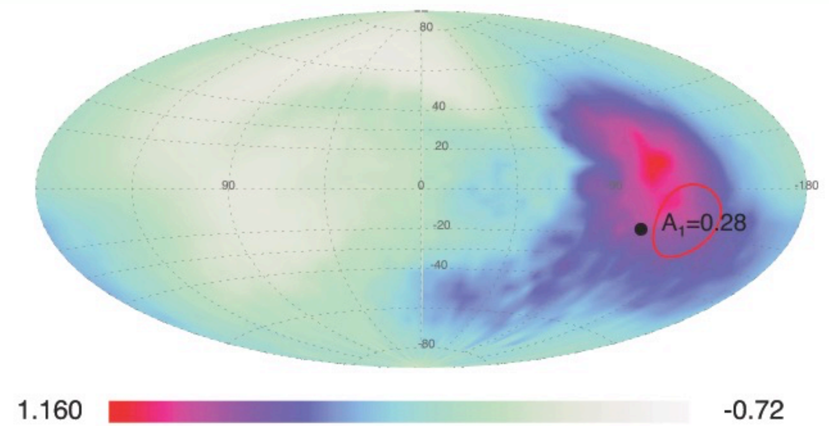

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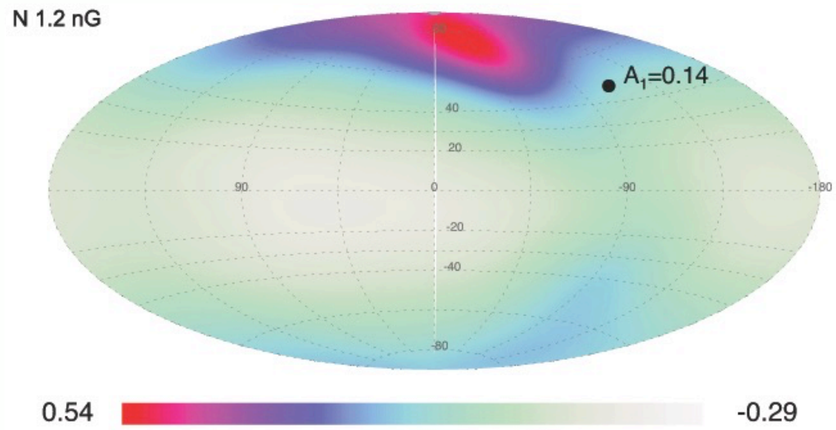

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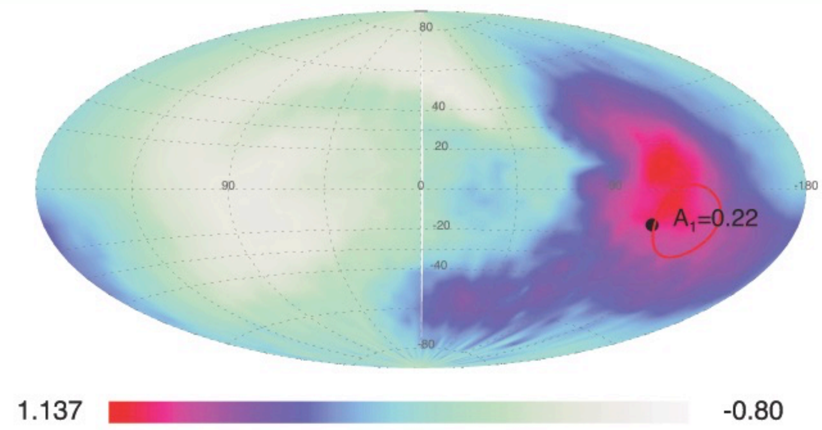

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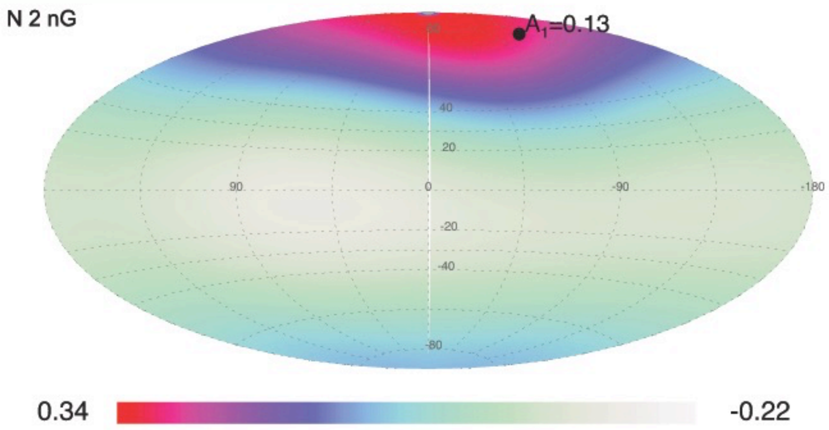

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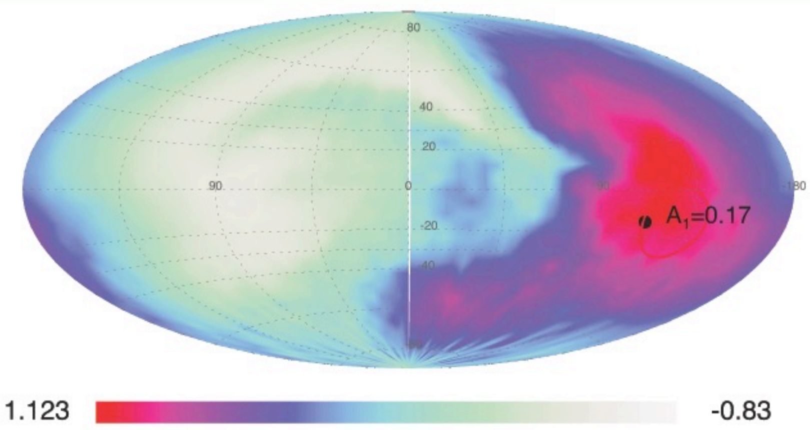

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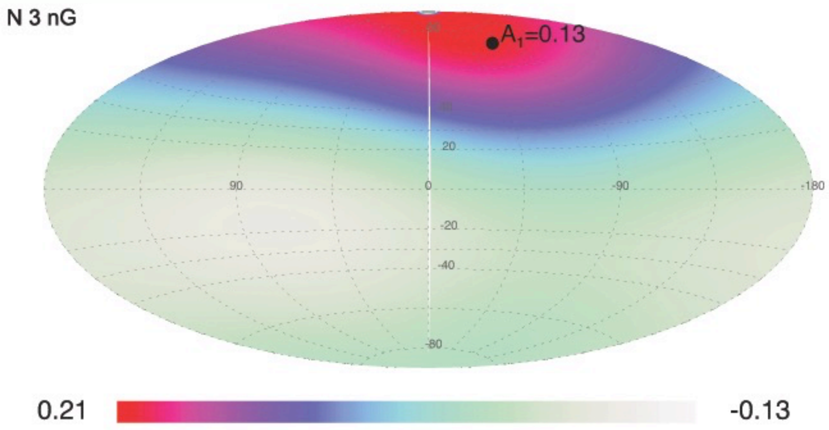

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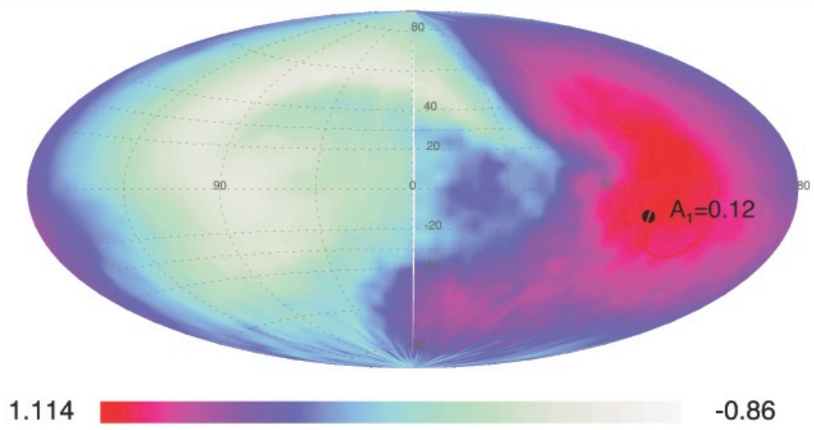

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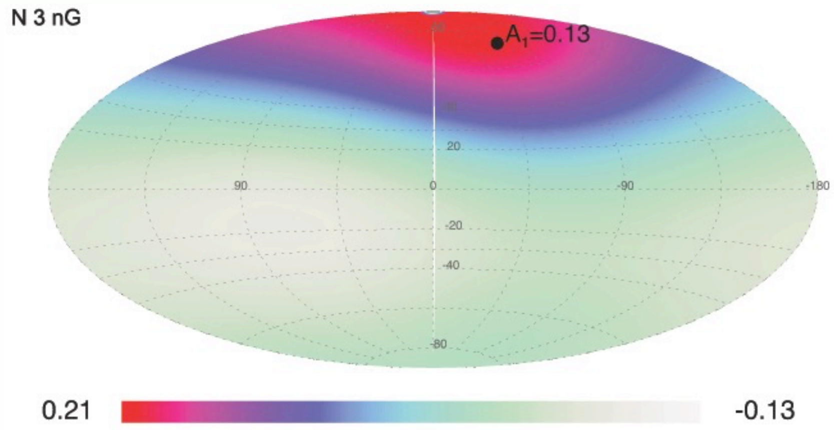

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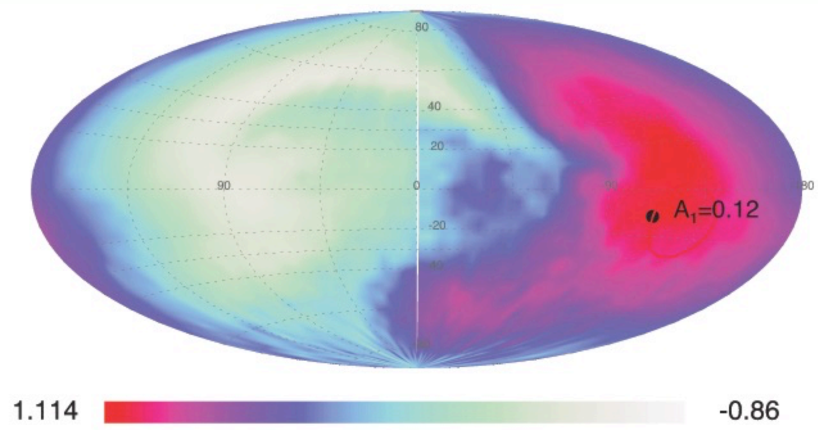

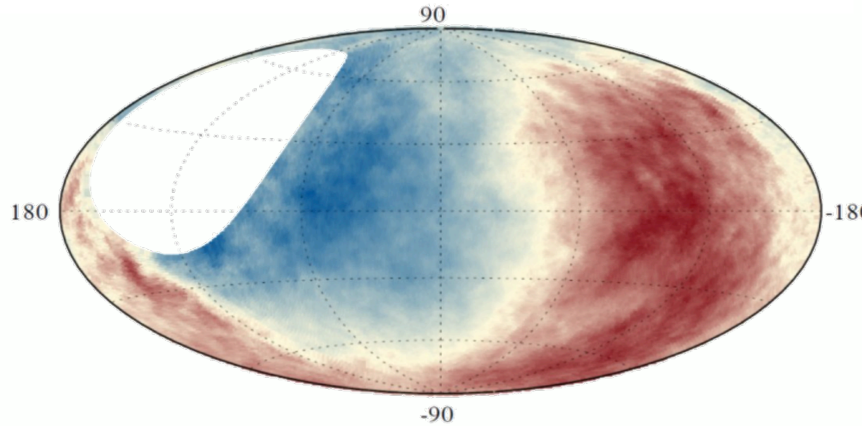

Summary

- ## Energy spectrum

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

- ## Composition

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,...)

At the highest energies, future neutrinos detectors should be able to probe powerful proton sources

- ## 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 (IGMF and GZK distance)
Based on the power spectrum of density fluctuations **the flux-weighted** (extragalactic) **RMS** dipole amplitude is ~ 8*b*% in a few nG IGMF (Globus & Piran 2017) where b is the bias factor if the UHECR sources are more clustered than dark matter
==> 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