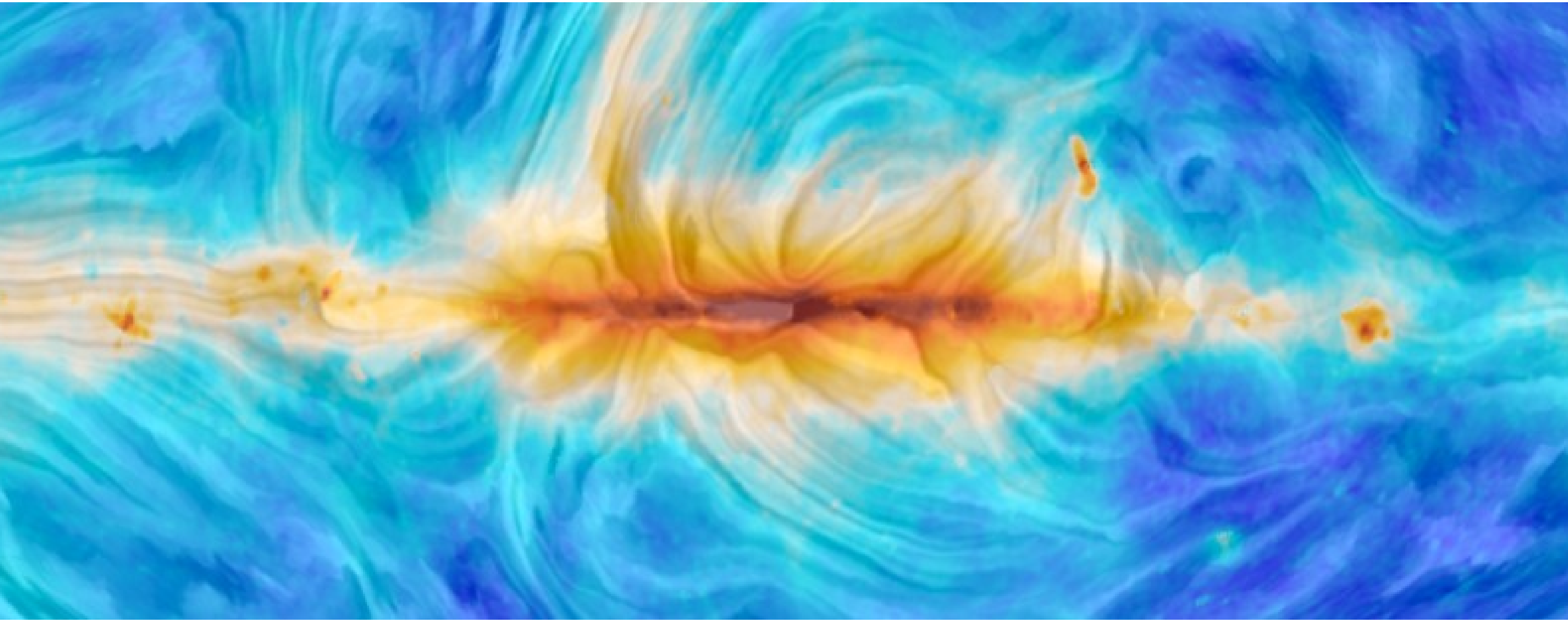
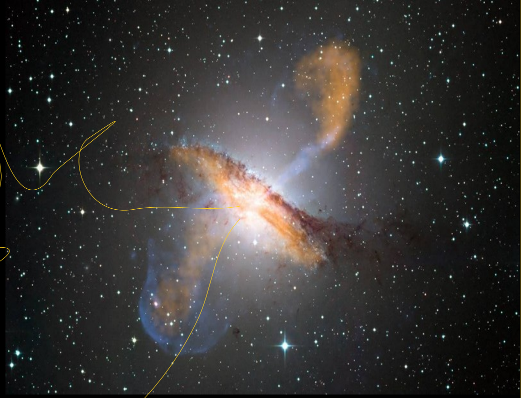
MAGNETIC FIELD EFFECTS ON UHECR PROPAGATION



Silvia Mollerach
Centro Atómico Bariloche, CONICET

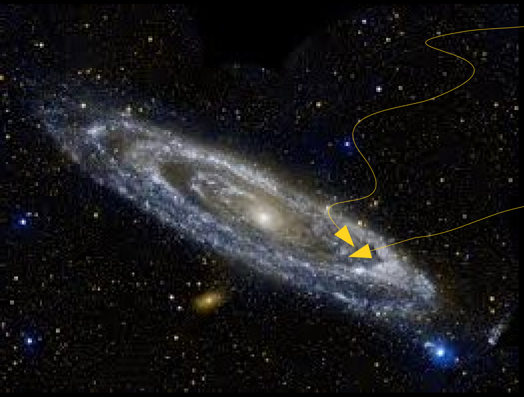


Deflections $\propto Z/E$

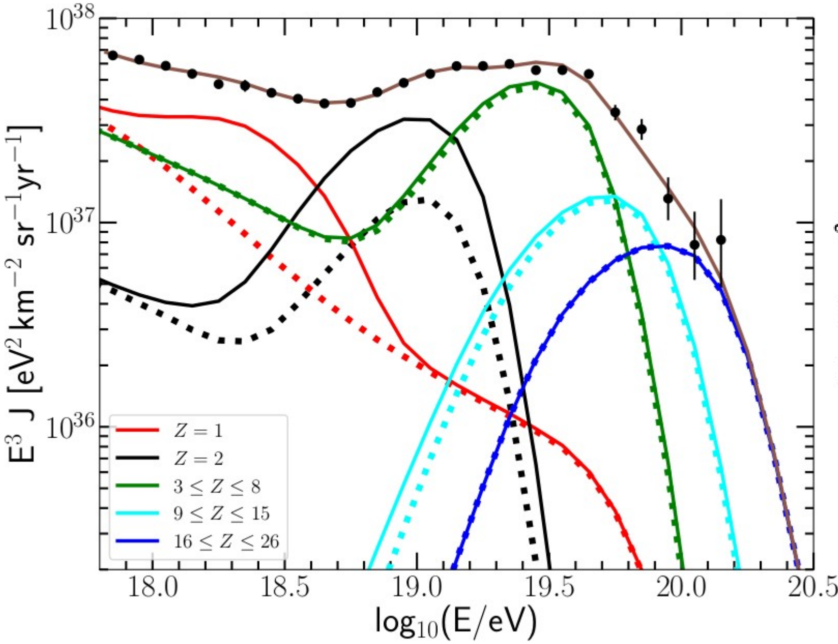
Diffusive or quasirectilinear?

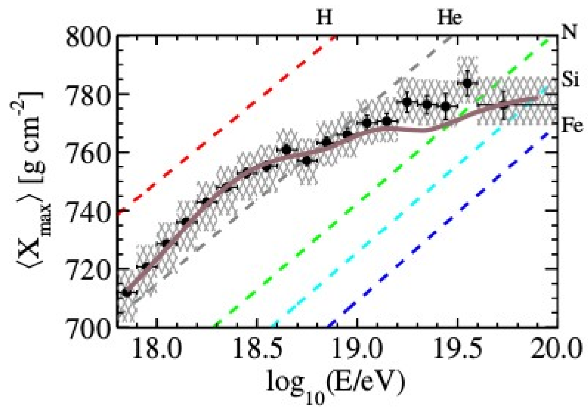
- arrival directions distribution

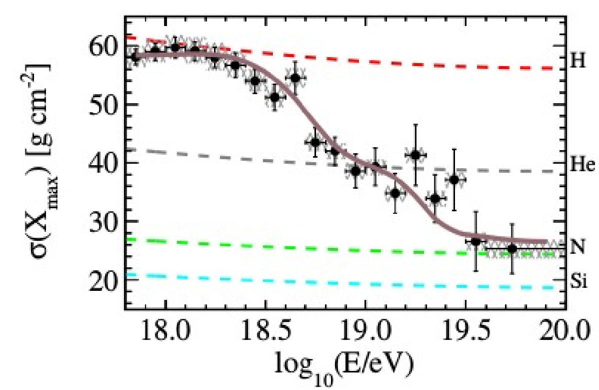
- spectrum



Interpretation of recent results of spectrum and composition:





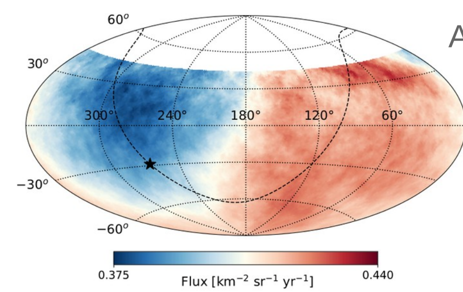


Auger, JCAP 05 (2023) 024

CR composition becomes progressively heavy above ~ 3 EeV and with little mixing

Anisotropies:

Auger, Science (2017), ApJ(2024)

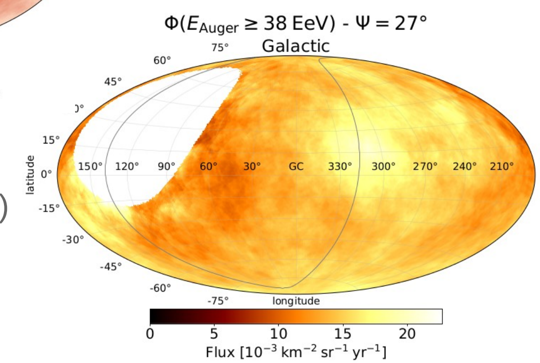


- Significant dipole of 7.3 % amplitude for E > 8 EeV

- Hints at Intermediate angular scales at ~ 40 EeV:
  ~ 4σ from Centaurus region

- No evidence of small scale anisotropies

Auger, ICRC (2023)



→ PROBABLY INDICATING LARGE DEFLECTIONS IN GALACTIC AND/OR

EXTRAGALACTIC B FIELD (consistent with heavy composition at highest energies)

Main problem to identify UHECR sources:

Galactic/extragalactic magnetic fields and composition of individual CRs are not well known

Regular B field: $\delta \simeq 10^\circ \frac{10\,\mathrm{EeV}}{E/Z} \left| \int_0^L \frac{\mathrm{d}\vec{x}}{\mathrm{kpc}} \times \frac{\vec{B}}{2\,\mu\mathrm{G}} \right|$

Turbulent B field: $\delta_{\mathrm{rms}} \simeq \frac{BZe}{E}\sqrt{\frac{Ll_c}{2}} \simeq 4^\circ \frac{B}{\mathrm{nG}} \frac{10\,\mathrm{EeV}}{E/Z} \frac{\sqrt{Ll_c}}{\mathrm{Mpc}}$

Measuring cosmic magnetic fields is difficult:

- Faraday rotation measures → $\int n_e B_\parallel \, dl$

- Synchrotron emission → $\int n_e B_\perp \, dl$

Magnetic fields in the Galaxy:

- Regular component (disk, halo, X, …)

- Random component (turbulent)

- Few µG strength

-Talks by Unger & Korochkin

NASA, SOFIA science team, ESA, STScI

Magnetic fields in the universe:

Strength strongly depends on the environment: B larger in more dense regions

Galaxies & cluster centers: B ~ few μG

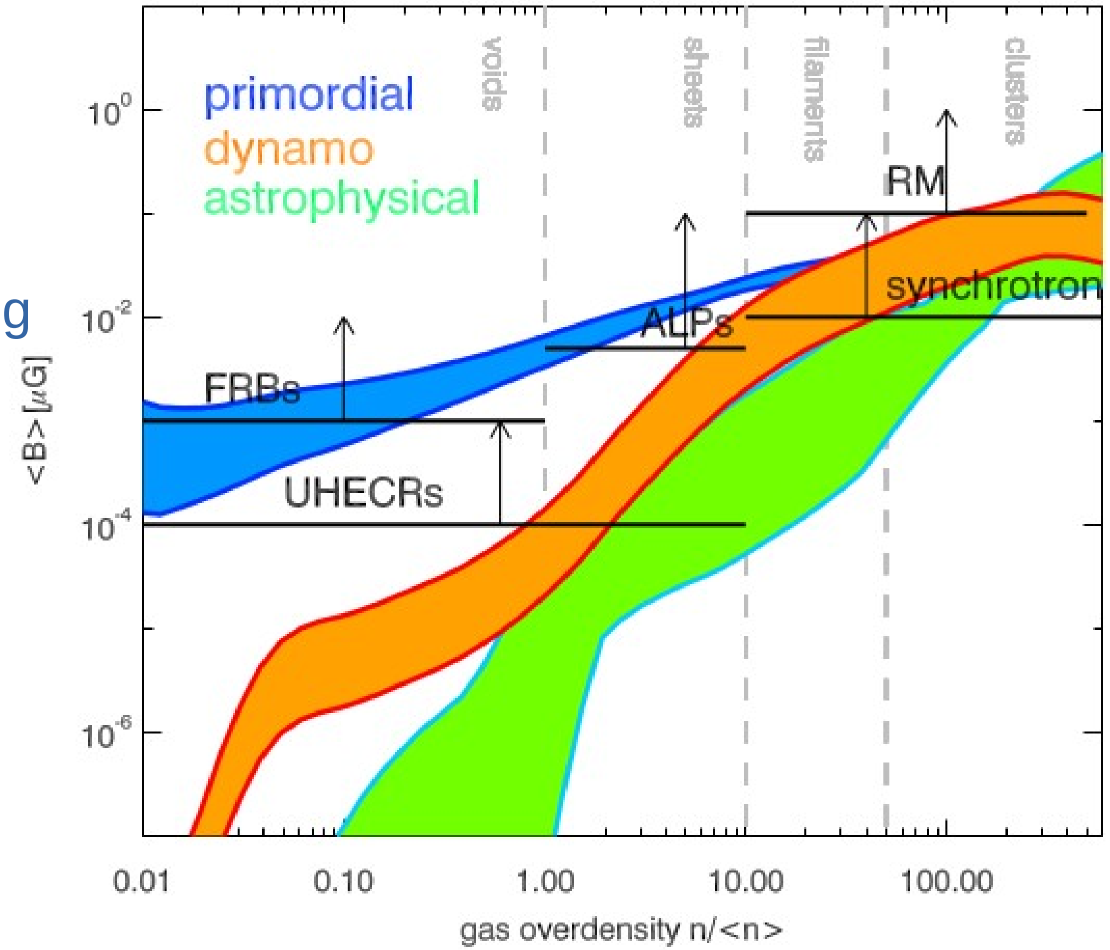
Cluster outskirts: B ~100 nG

Filaments: B ~ 10 – 100 nG

Voids: B ≤ nG

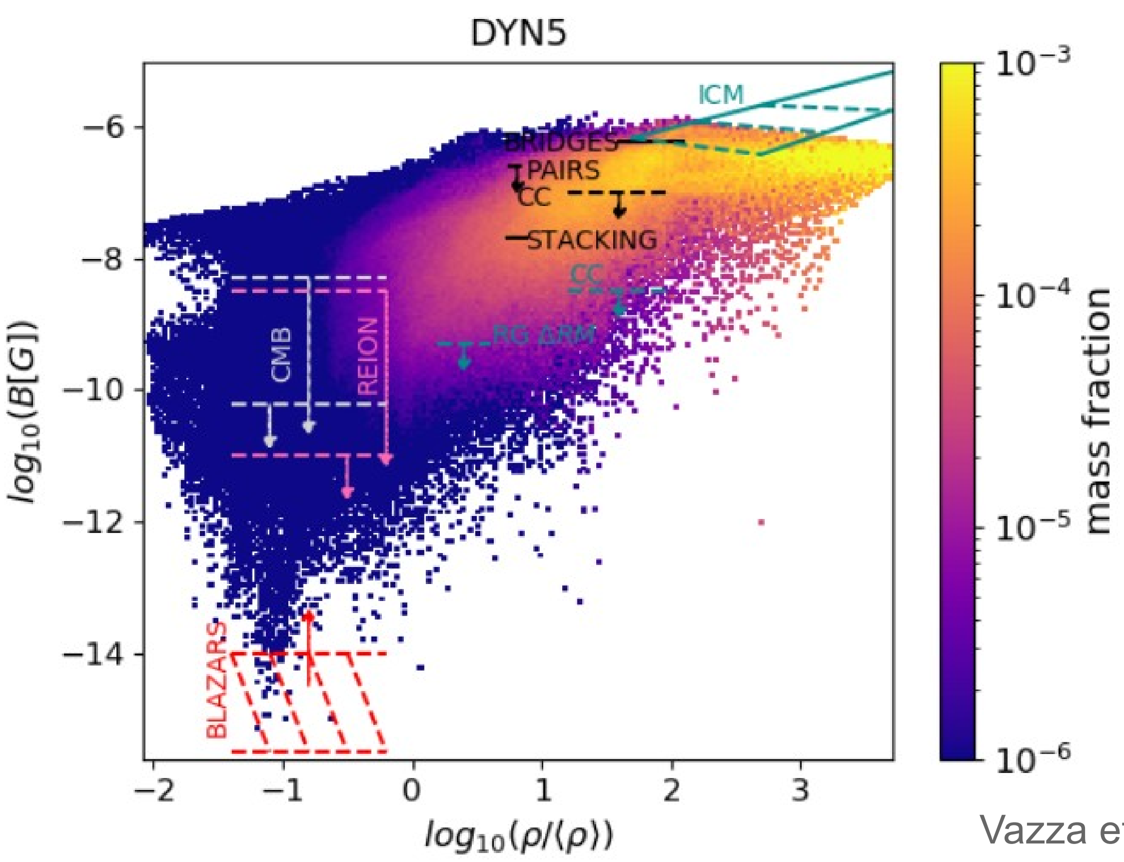
Huge computational work incorporating
magneto-hydrodynamics to
LSS formation simulations
to understand magnetogenesis

Expectations depend on
generation mechanism:
primordial, astrophysical, dynamo?



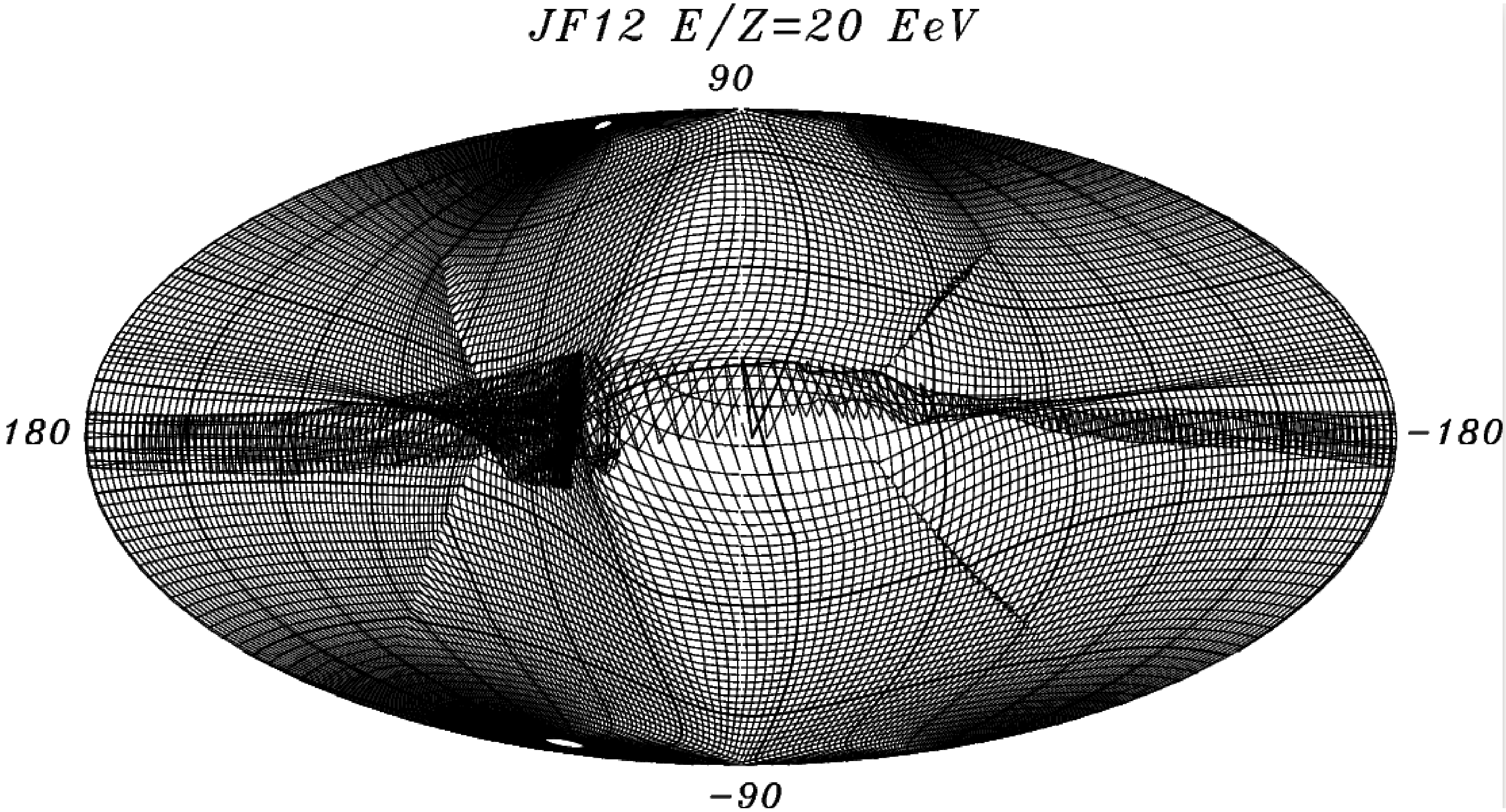
Vazza et al, CQG (2017)

Observation	Estimate on $\|B\|$	Approx. Density Range	Instrument(s)
Sync.in cluster bridges	$\sim$0.2–0.5 μG	$\rho/\langle\rho\rangle \sim 50$–$200$	LOFAR-HBA (120 MHz)
Sync. in cluster pairs	$\leq$0.25 μG	$\rho/\langle\rho\rangle \sim 5$–$50$	LOFAR-HBA (120 MHz)
Optical-radio cross-corr.	$\leq$0.25 μG	$\rho/\langle\rho\rangle \sim 10$–$10^2$	MWA-EoR0 (180 MHz)
Sync. stacking of cluster pairs	$\sim$10–20 nG	$\rho/\langle\rho\rangle \sim 5$–$50$	MWA+LWA (50–120 MHz)
$\Delta RM(\theta)$ of radio gal. pairs	$\leq$40 nG	$\rho/\langle\rho\rangle \sim 1$–$10$	VLA-NVSS (1400 MHz)
$\Delta RM(\theta)$ of radio gal. pairs	$\leq$4 nG	$\rho/\langle\rho\rangle \sim 1$–$10$	LOFAR-HBA (120 MHz)
RM cross-correlation	$\leq$30 nG	$\rho/\langle\rho\rangle \sim 1$–$10$	VLA-NVSS (1400 MHz)
Excess RM across z	$\leq$1.7 nG	$\rho/\langle\rho\rangle \sim 1$	VLA-NVSS (1400 MHz)
CMB anisotropies T&P	$\leq$2.8 nG	$\rho/\langle\rho\rangle \sim 1$	PLANCK2018+BK15+SPTPol
CMB heating	$\leq$0.83 nG	$\rho/\langle\rho\rangle \sim 1$	PLANCK-2015
Excess Sync. Radiation	$\leq 10^{-3}$–3.7 nG	$\rho/\langle\rho\rangle \sim 1$	ARCADE2+LW1 (78 MHz)
Blazar Inv. Compton	$\geq 10^{-7}$–10^{-5} nG	$\rho/\langle\rho\rangle \sim 10^{-2}$–$1$	VERITAS, HAWC, FERMI



Vazza et al, Galaxies (2021)

REGULAR GALACTIC MAGNETIC FIELD EFFECTS ON CR



- Rigidity-dependent deflections of arrival directions at Earth

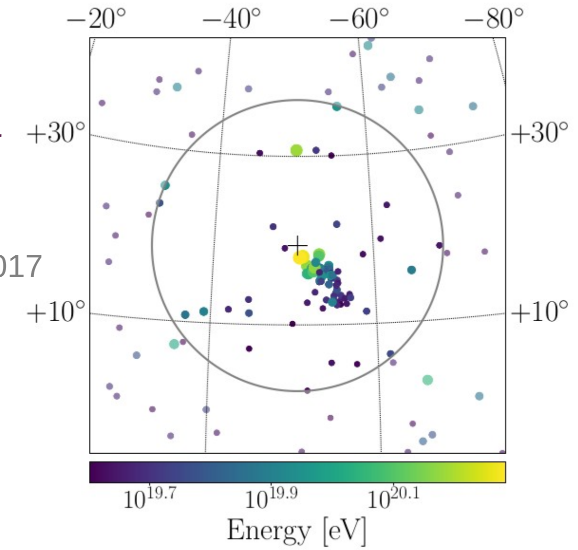
- Multiple images of a source at a given rigidity

- (De)amplification of the flux of individual sources

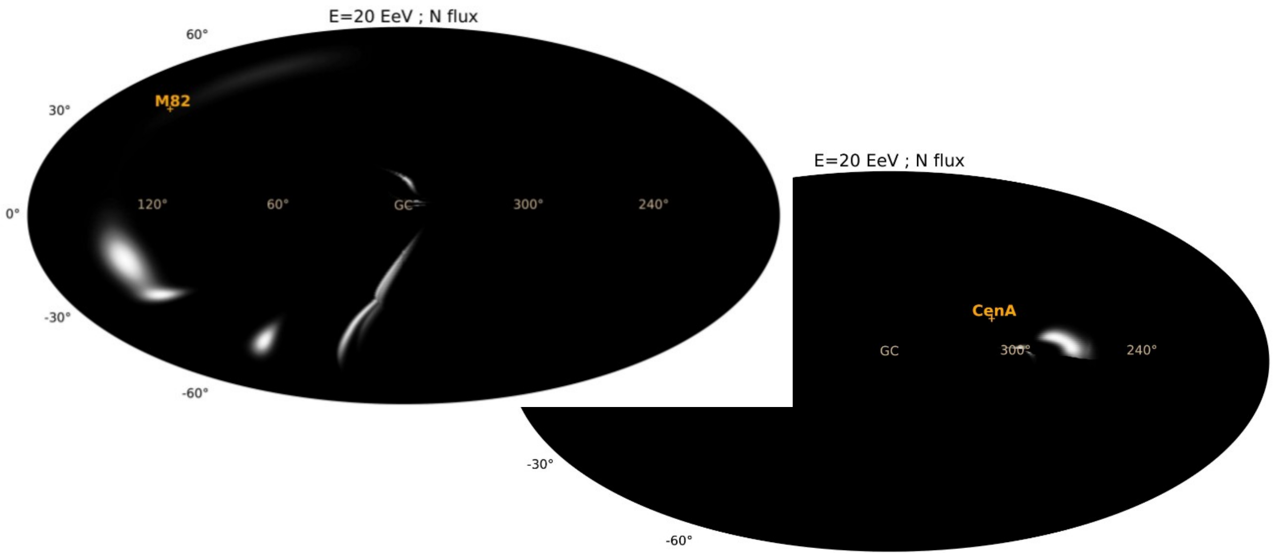
- Galactic B field does not create anisotropies from an isotropic flux (Liouville) but distort features of an anisotropic sky

Possible signatures

Magnetic multiplets: set of aligned events ordered in 1/E (expected if a fraction of CR is light at highest energy) → no significant detection



Auger, JCAP 06 (2020) 017

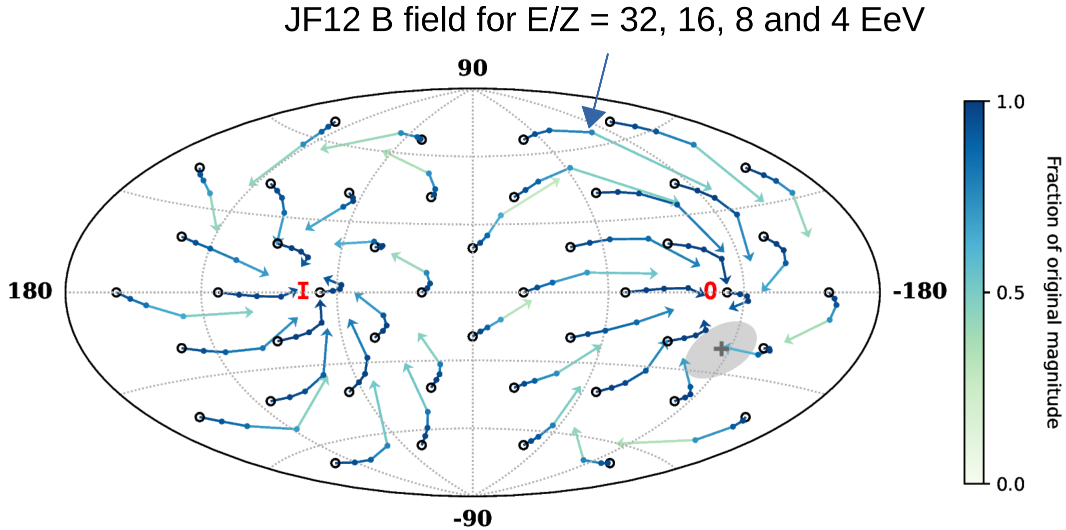


Multiple images probably relevant up to the highest energies

SM, E Roulet, PRD 105 (2022) 6

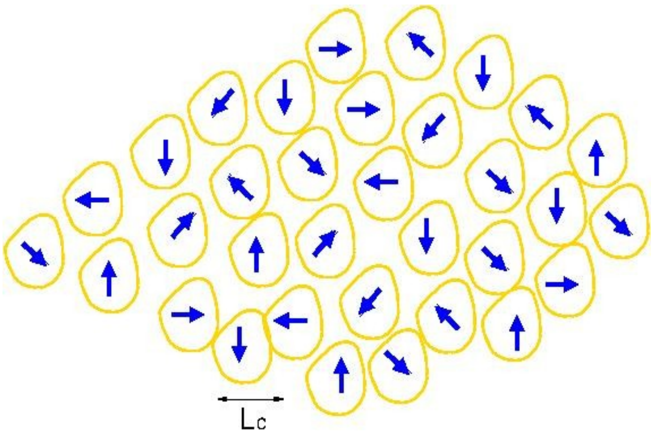
Shift of extragalactic dipole direction and decrease of amplitude

Auger, ApJ 868 (2018) 4



TURBULENT MAGNETIC FIELD EFFECTS ON CR:

spectrum and arrival directions significantly affected



B: rms amplitude
L_c: coherence length

$$r_L = \frac{E}{ZeB}$$ Larmor radius

Critical energy: $r_L(E_c) = L_c$

$$E_c = ZeBL_c = 0.9\,Z\,\frac{B}{nG}\,\frac{L_c}{Mpc}\,EeV$$

for $E < E_c$ resonant diffusion
for $E > E_c$ small deflections for distances $\sim L_c$

Diffusion length: deflection ~1 rad

$$l_D(E) \simeq L_c\left[4\left(\frac{E}{E_c}\right)^2 + 0.9\left(\frac{E}{E_c}\right) + 0.23\left(\frac{E}{E_c}\right)^{1/3}\right]$$

for Kolmogorov spectrum

For a source at distance r_s

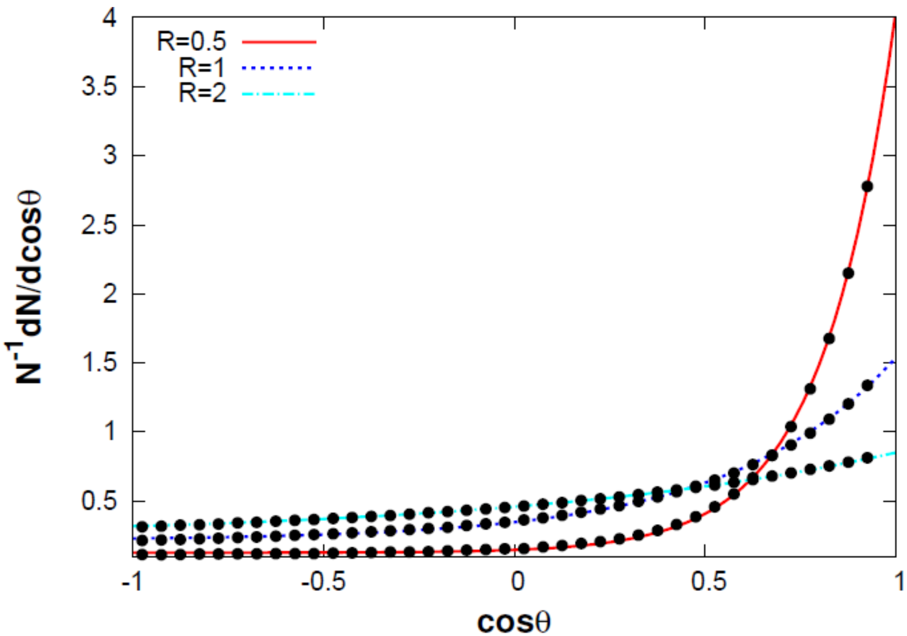
$l_D(E) \simeq r_s$

E

Diffusion

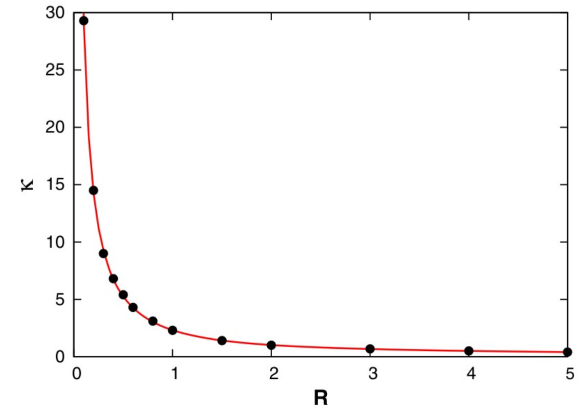
Quasi rectilinear

Angular distribution of CRs with respect to the source direction



$$\frac{dN}{d\cos\theta} \propto \exp(\kappa(R)\cos\theta)$$

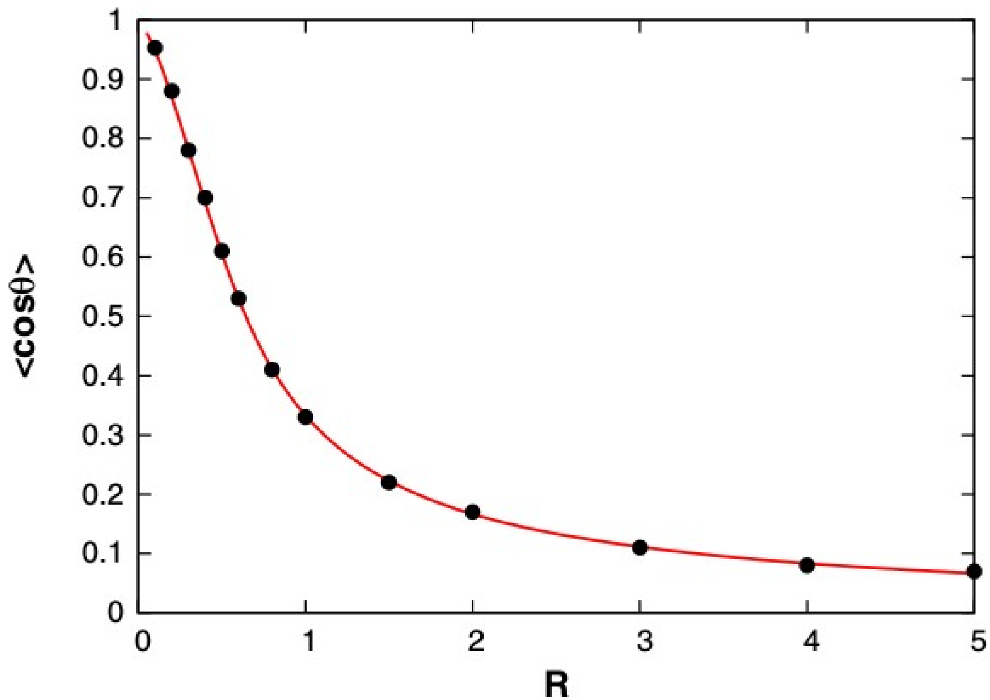
$$R \equiv r_s / l_D(E)$$



Dipole amplitude

$$\Phi(\hat{u}) = f(\cos\theta) = \Phi_0 + \Phi_1 \hat{u} \cdot \hat{r}_s + \ldots .$$

$$\Delta = \frac{\Phi_1}{\Phi_0} = 3\langle\cos\theta\rangle$$



$$\langle\cos\theta\rangle = \frac{1}{3R}\left[1 - \exp\left(-3R - \frac{7}{2}R^2\right)\right] \equiv C(R) \simeq \begin{cases} 1 - r_s/3\,l_D, & r_s \ll l_D \\ l_D/r_s, & r_s \gg l_D \end{cases}$$

small deflections

Fick's law (diffusion)

D Harari, SM, E Roulet, PRD 93 (2016) 6

Flux from one source: diffusion leads to enhancement of the density around it

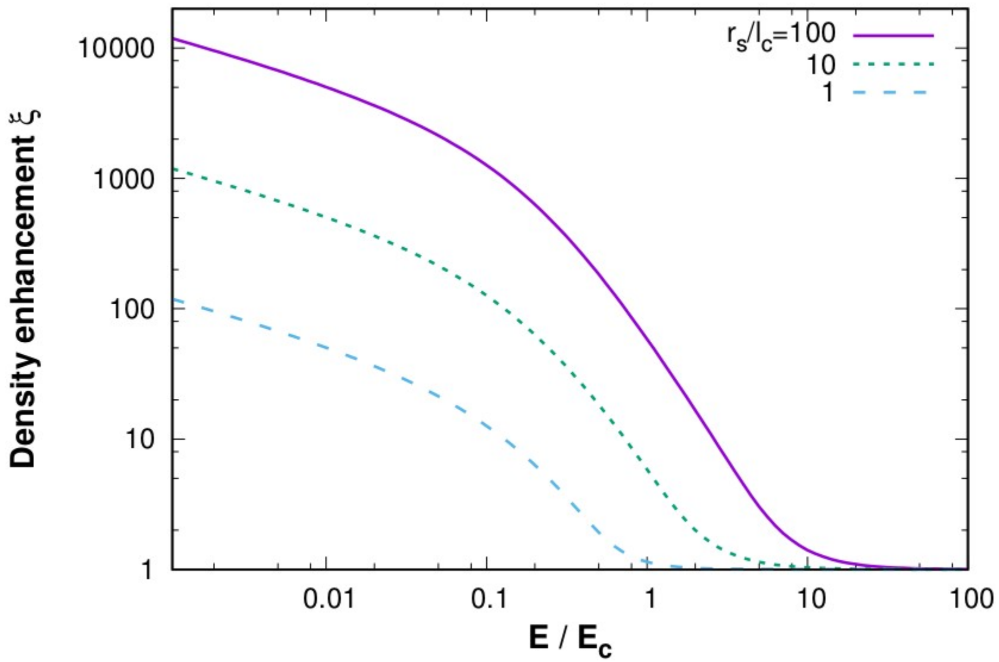
Steady source

$$n(E, r_s) 4\pi r_s^2 c \langle \cos\theta(E, r_s) \rangle = Q(E)$$

(flux through any sphere around the source = # emitted particles per u.t.)

density enhanced wrt rectilinear propagation by

$$\xi \equiv \frac{n(E, r_s)}{Q(E)/(4\pi r_s^2 c)} = \frac{1}{\langle \cos\theta \rangle}$$



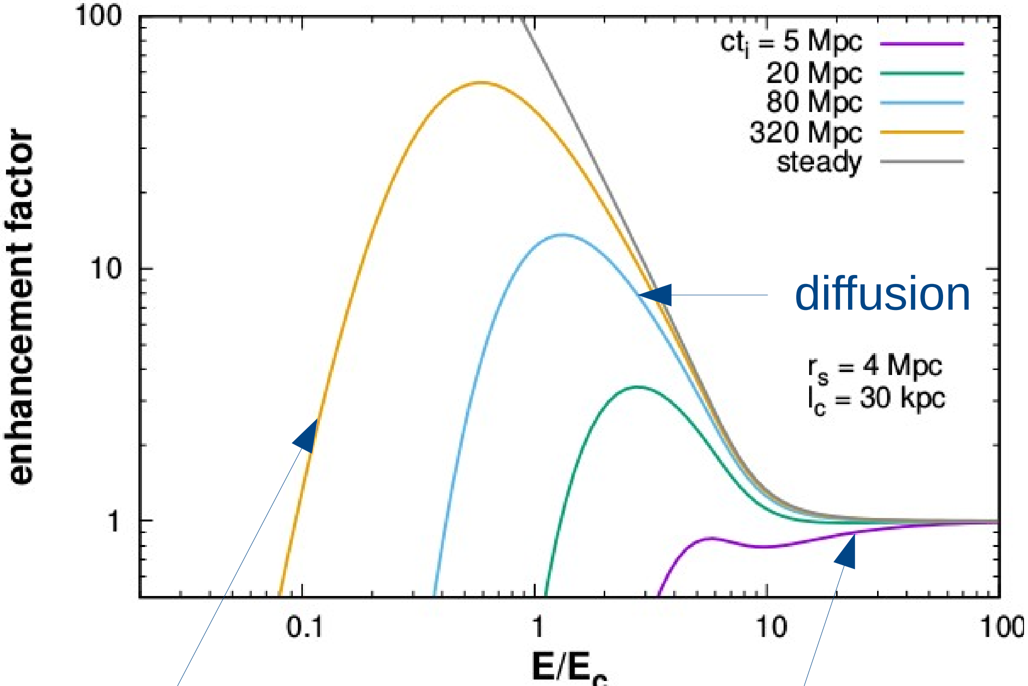
enhancement factor inversely proportional to dipolar amplitude

$$\boxed{\Delta = 3 \langle \cos\theta \rangle = 3 / \xi}$$

SM, E Roulet, Phys.Rev.D 99 (2019) 10

Flux from one source

Finite emission time: source emitting since t_i

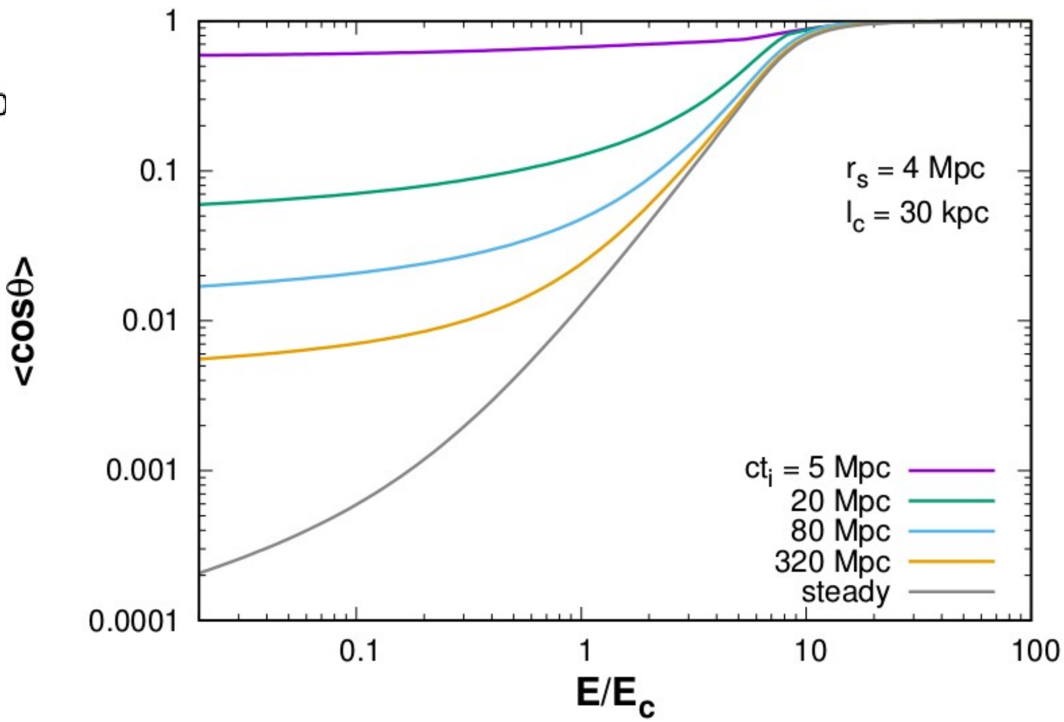


diffusion

rectilinear propagation

magnetic horizon: low energy particles need longer than the source emission time to reach r_s

Angular distribution



SM, E Roulet,Phys.Rev.D 99 (2019) 10

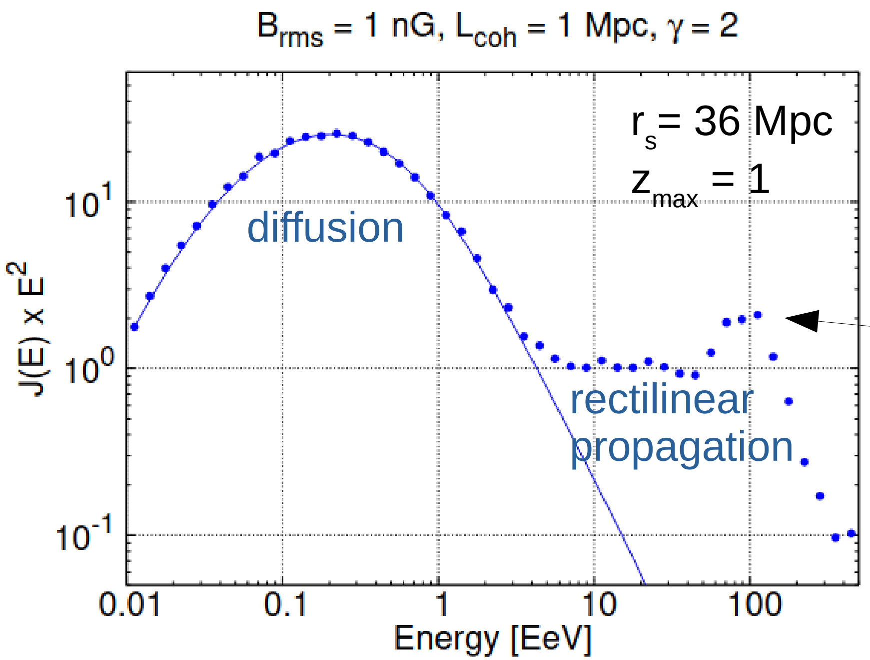
Solution of diffusion in expanding universe: proton source at distance r_s

$$n(E) = \int_0^{z_{max}} dz \left|\frac{dt}{dz}\right| Q_s(E_g, z) \frac{\exp\left[-r_s^2/4\lambda^2\right]}{(4\pi\lambda^2)^{3/2}} \frac{dE_g}{dE}$$

V Berezinsky, A Gazizov, ApJ 643 (2006) 8

$$\lambda^2(E,z) = \int_0^z dz' \left|\frac{dt}{dz'}\right| \frac{D(E_g, z')}{a^2(z')}$$

$$D = \frac{c\, l_D}{3}$$



pile-up interactions CMB

Flux from a distribution of sources: Propagation theorem

R Aloisio, V Berezinsky, ApJ 612 (2004) 900

as long as the distance to the nearest sources is smaller than the diffusion and the energy loss lengths the total CR flux is the same as that for B=0 and continuous distribution of sources

Proof: add sources, $\sum \rightarrow n_s \int dr\, 4\pi r^2$, and use $\int_0^\infty dr\, 4\pi r^2 \frac{\exp(-r^2/4\lambda^2)}{(4\pi\lambda^2)^{3/2}} = 1$

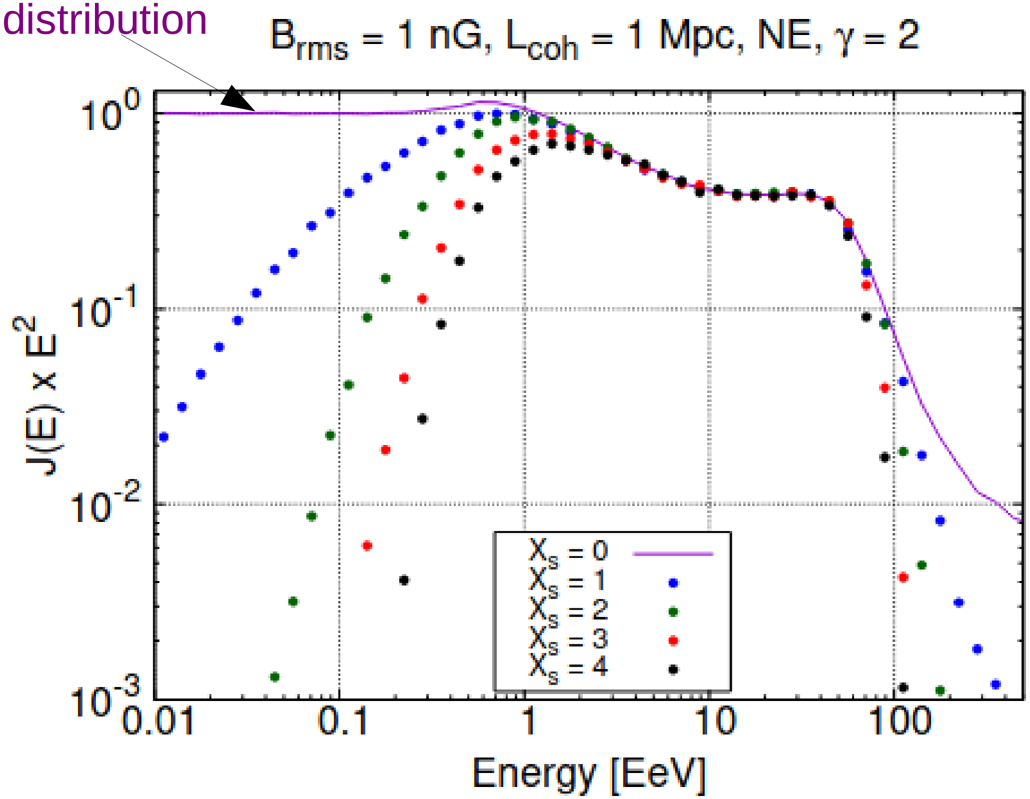
Magnetic horizon effect:

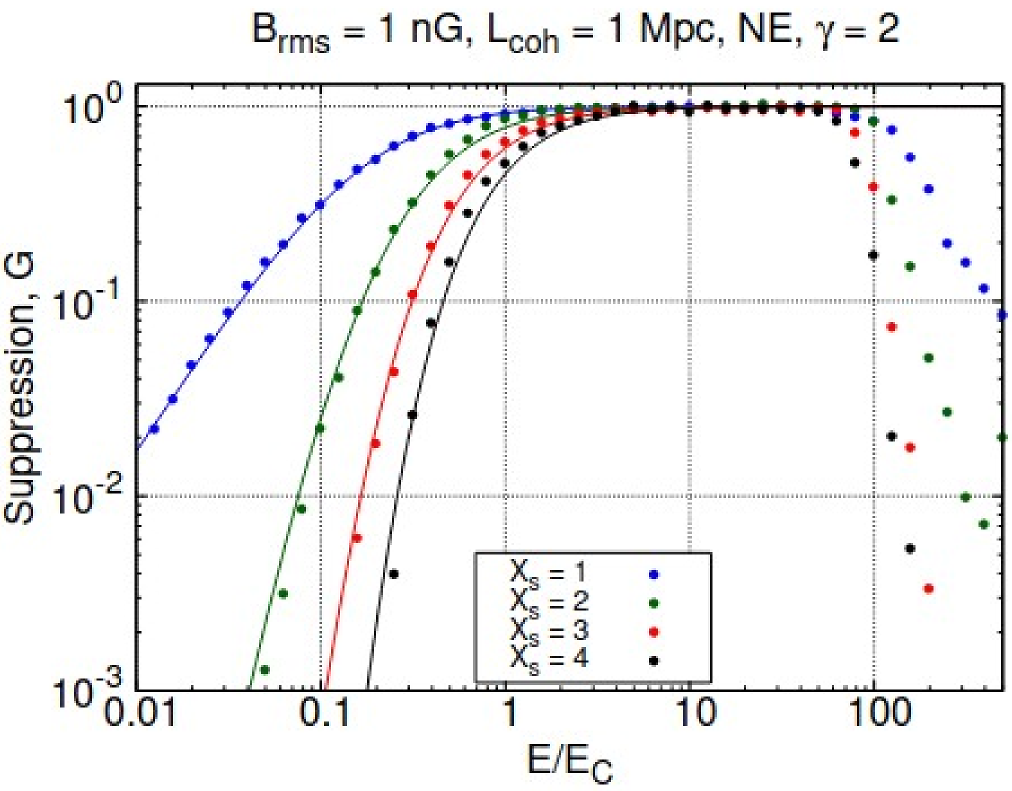
when the diffusion length is smaller than the distance to the closest sources, low energy particles have not enough time to reach the Earth → low energy suppression

(relevant B and L_C: between closest sources and observer)

protons

continuous distribution





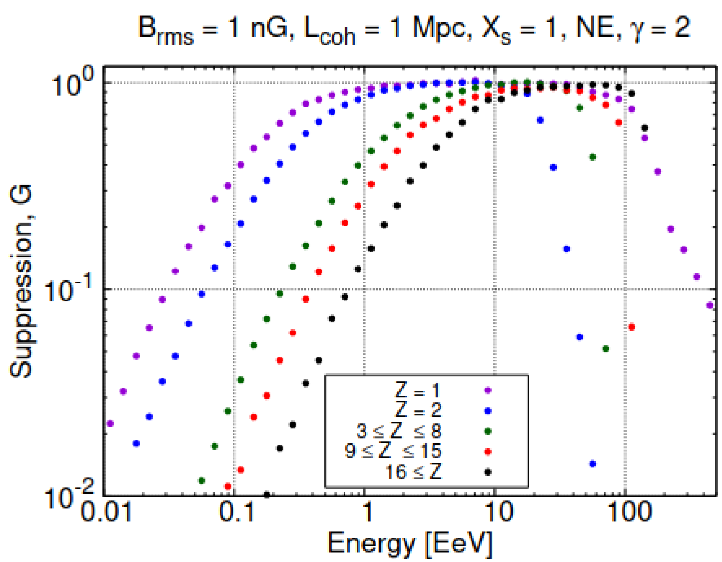
$$X_s = \frac{d_s}{20\,Mpc}\sqrt{\frac{100\,kpc}{L_c}} \qquad d_s = n_s^{-1/3}$$

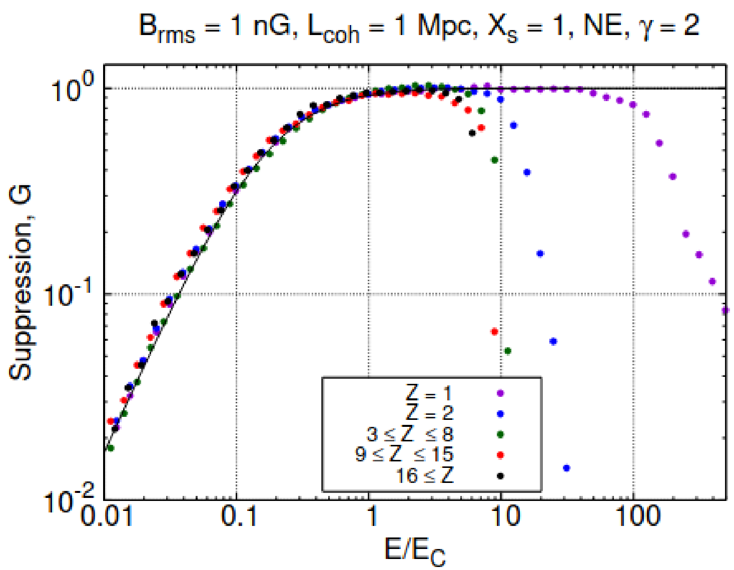
$$G(E/E_c) = \frac{J_Z(E)}{J_Z(E)_{d_s \to 0}}$$

González, SM & Roulet, PRD104(2021)

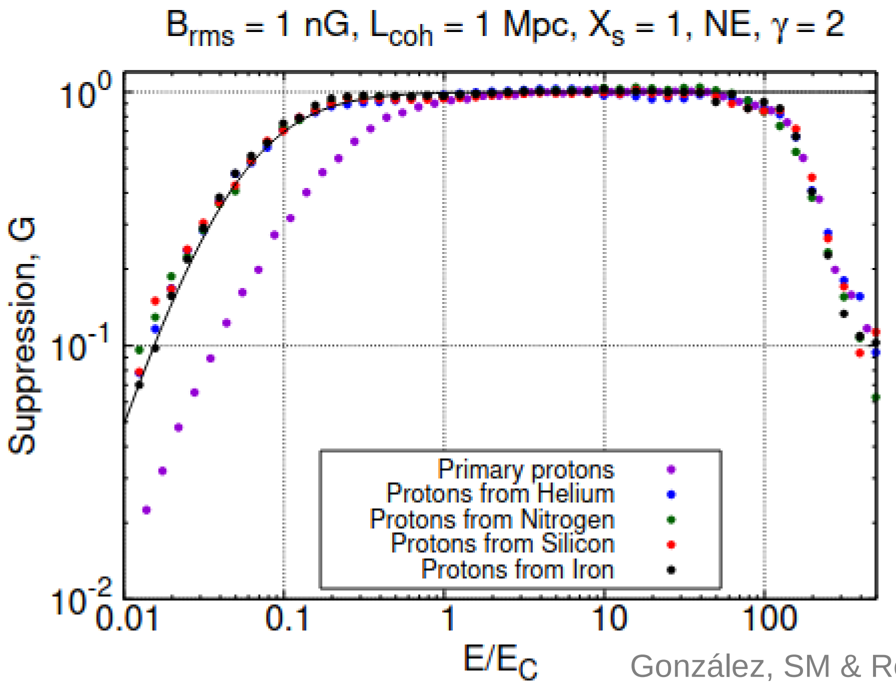
MHE for nuclei: similar suppression **as protons** as a function of E/E_c

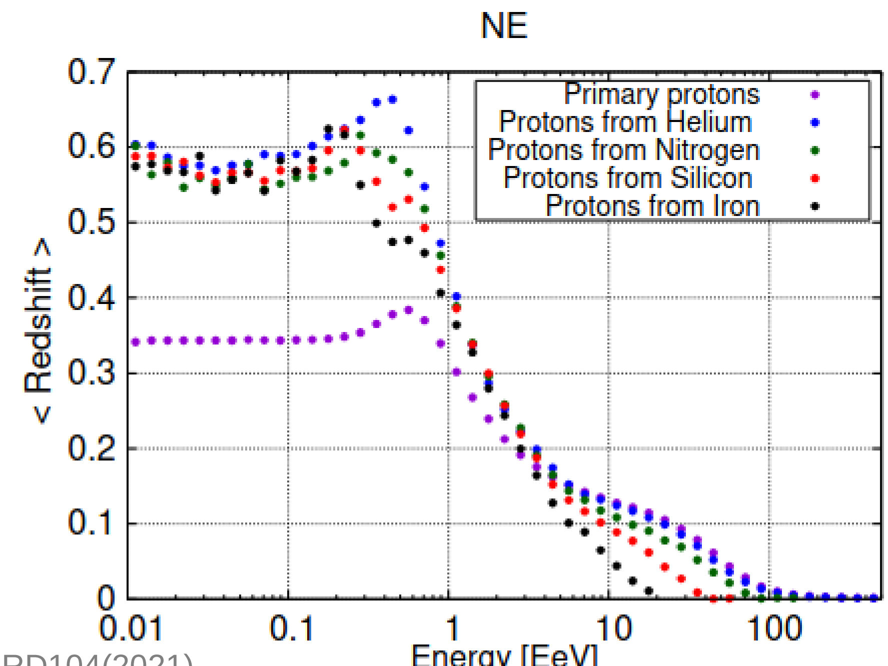
$E_c = eZBL_c$





Secondary particles produced from photodisintegration of heavier nuclei are less suppressed
They are produced on average at higher redshifts → have more time to reach Earth from closest sources

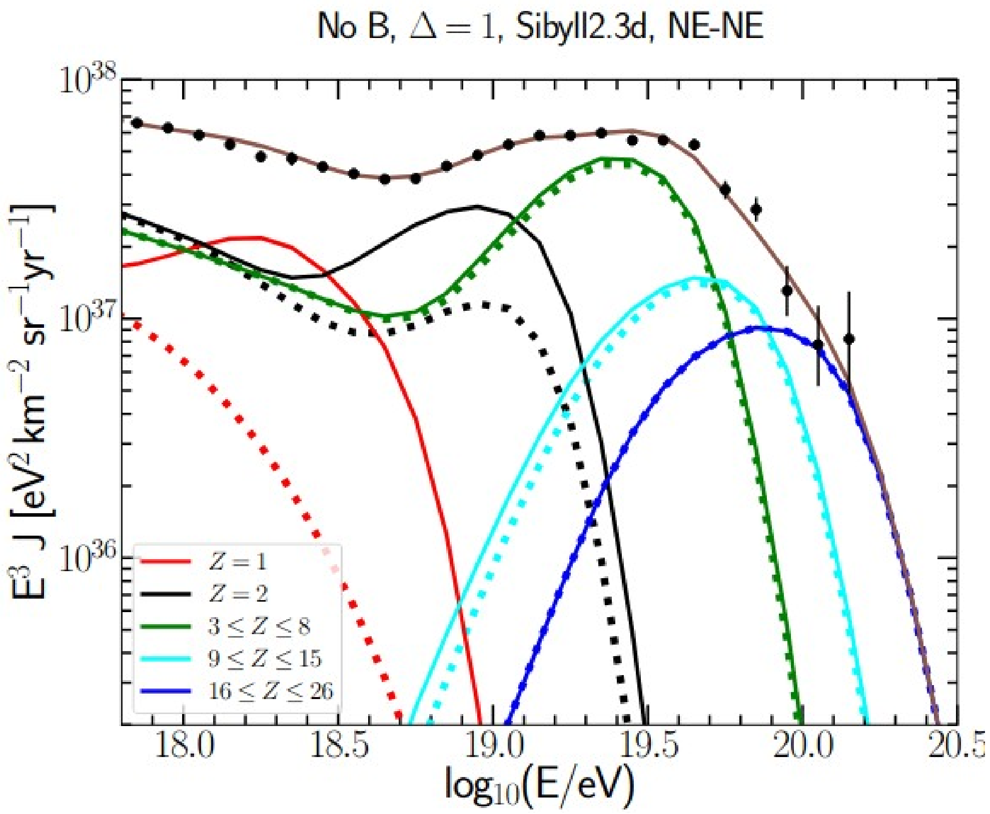


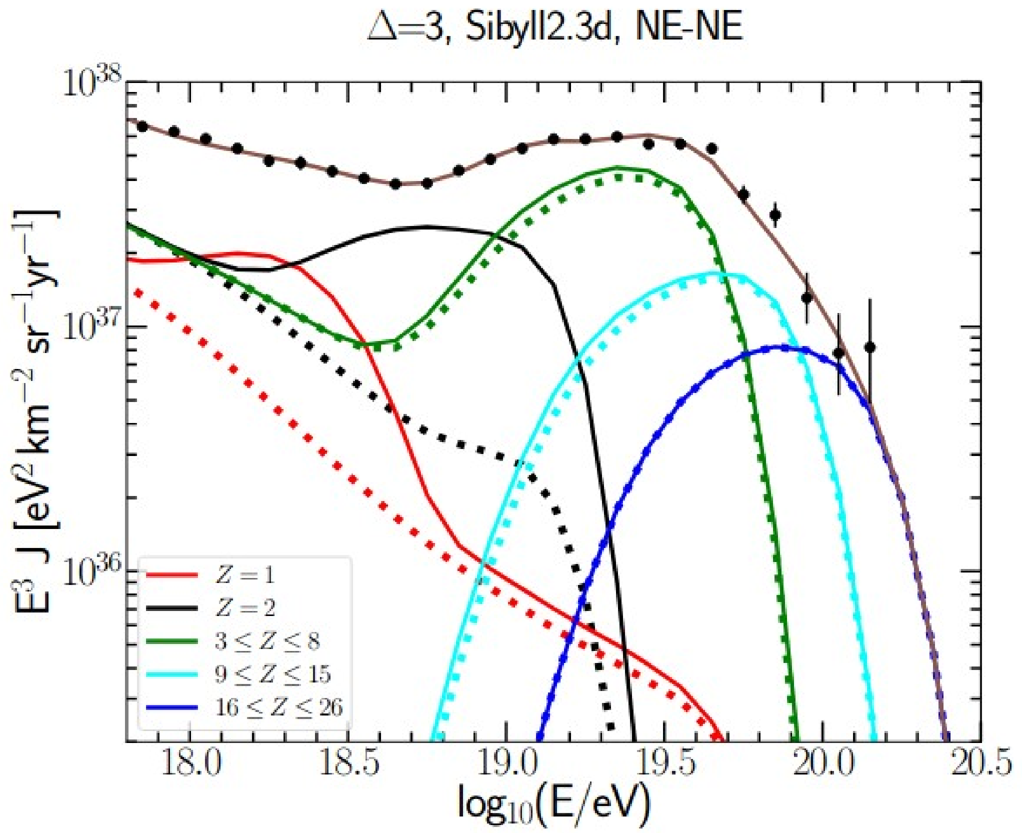


González, SM & Roulet, PRD104(2021)

Diffusive propagation provides alternative explanations to very hard spectra at the sources

Uniform distribution of sources accelerating a mixed mass composition with power-law spectrum and rigidity-dependent cutoff





No EGMF: fit to spectrum and composition requires very hard spectrum at the sources $\propto E^2$

With MHE (and steeper cutoff) the fit leads to a much softer spectrum $\propto E^{-2}$

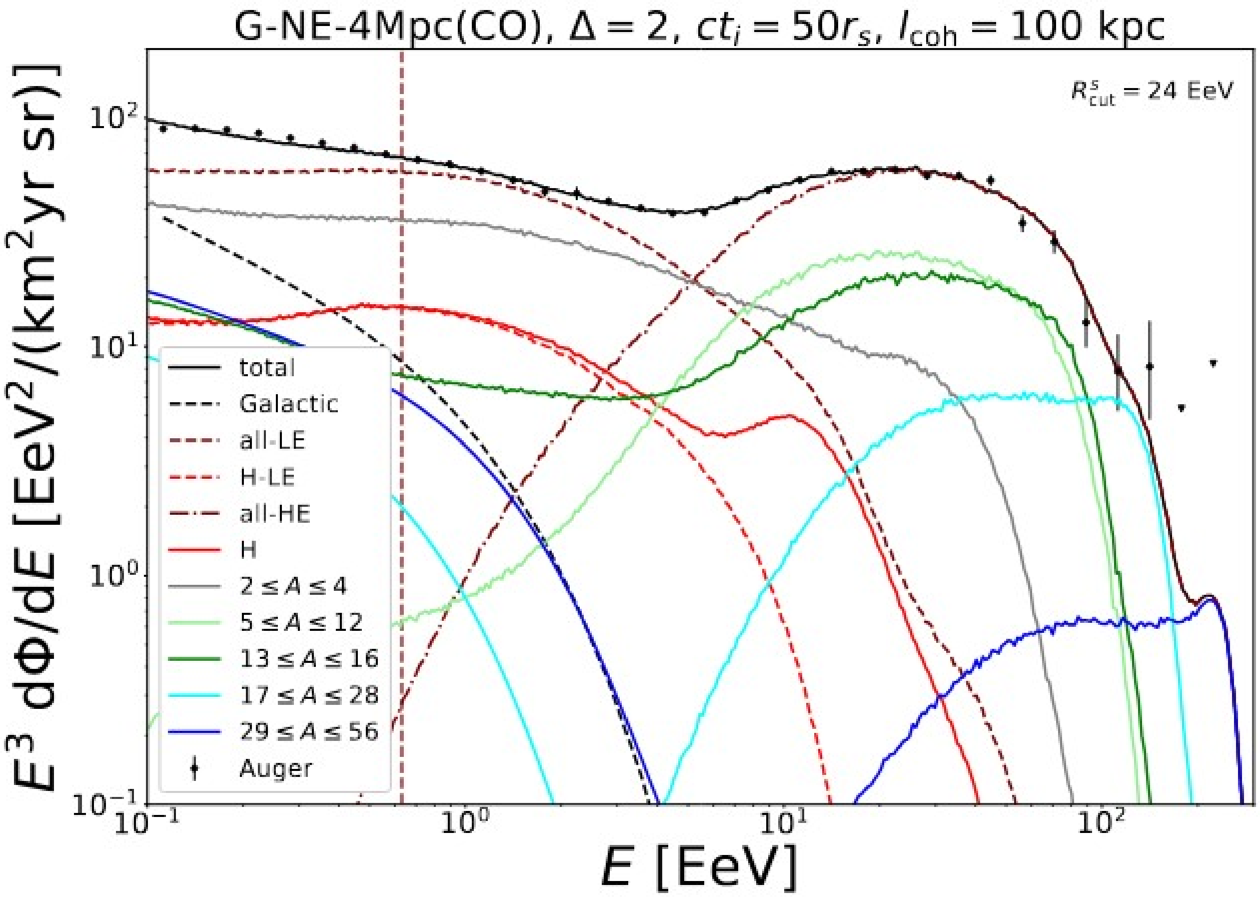
Talk by J Gonzalez

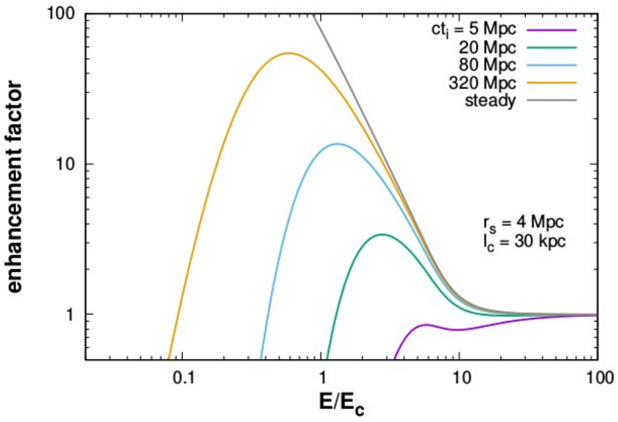
Auger, JCAP07(2024)094

Or single source dominating above the ankle: Cen A?

Good fit to spectrum and composition for:

Cen A + low energy component dominating below the ankle + Galactic component





$r_s = 4$ Mpc

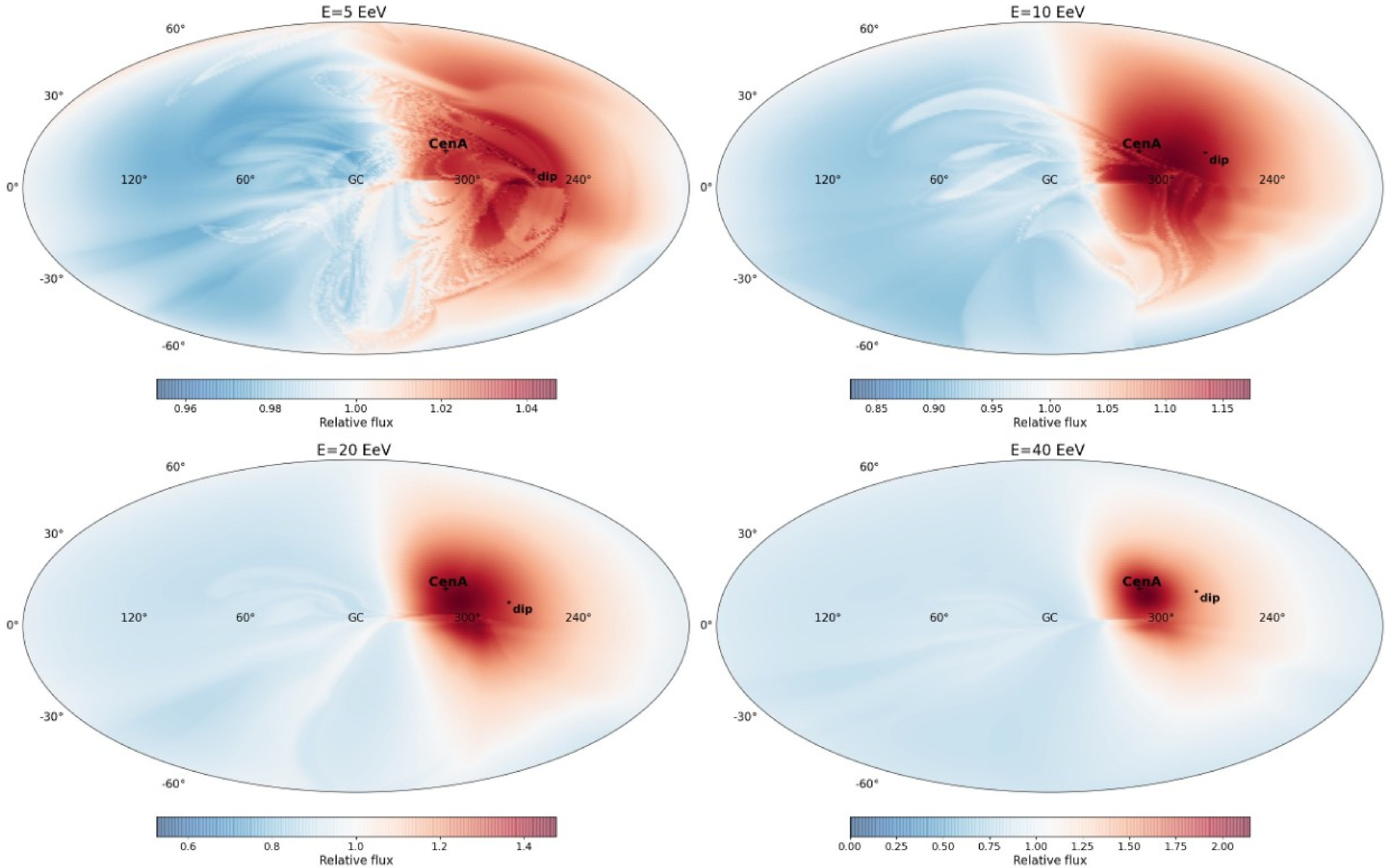
$ct_i = 200$ Mpc

$R_c = 3.6$ EeV

$\gamma_s = 1.7$

SM, E Roulet, PRD (2024)

Cen A scenario: arrival directions



DIPOLE AMPLITUDE FOR A DISTRIBUTION OF SOURCES: effect of EGMF

steady sources and neglecting energy losses

$$\vec{\Delta}(E) = \sum_{i,j} \frac{n_i^{(j)}(E)}{n_t(E)} \vec{\Delta}_i^{(j)}(E)$$

sources — mass components

$$\vec{\Delta}_i^{(j)} = 3\langle \cos\theta_i^{(j)} \rangle \hat{n}_i$$

$$n_i^{(j)} \propto \frac{1}{r_i^2 \langle \cos\theta_i^{(j)} \rangle}$$

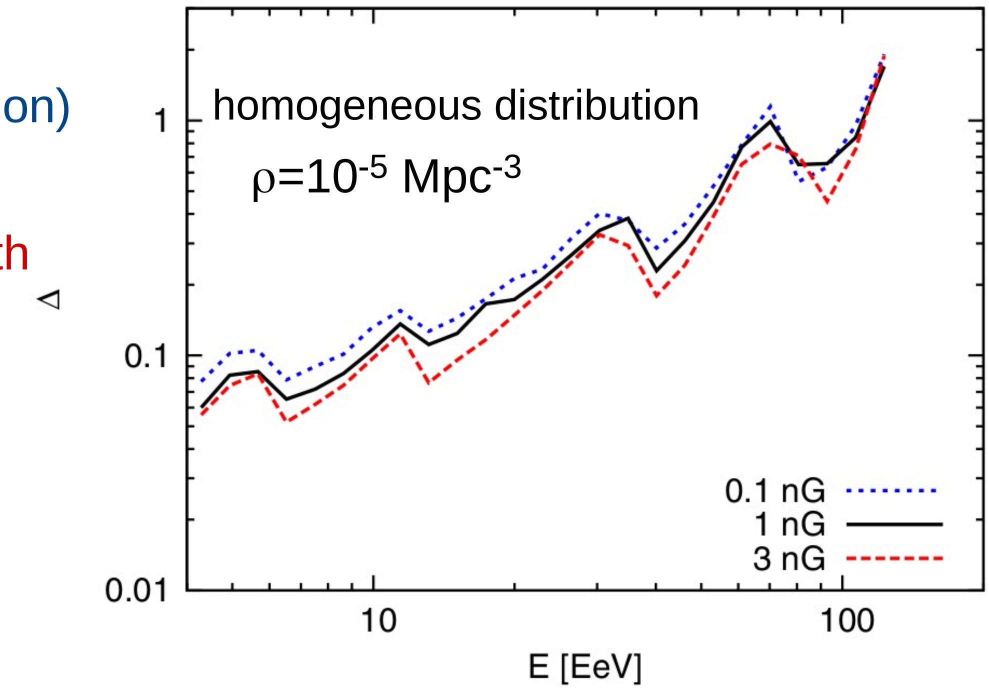
$$n_i^{(j)} \vec{\Delta}_i^{(j)} \propto \frac{3}{r_i^2} \hat{n}_i$$

independent of EGMF strength
(same as for rectilinear propagation)

As long as $n_t(E)$ does not depend on EGMF strength
(i.e. propagation theorem holds):

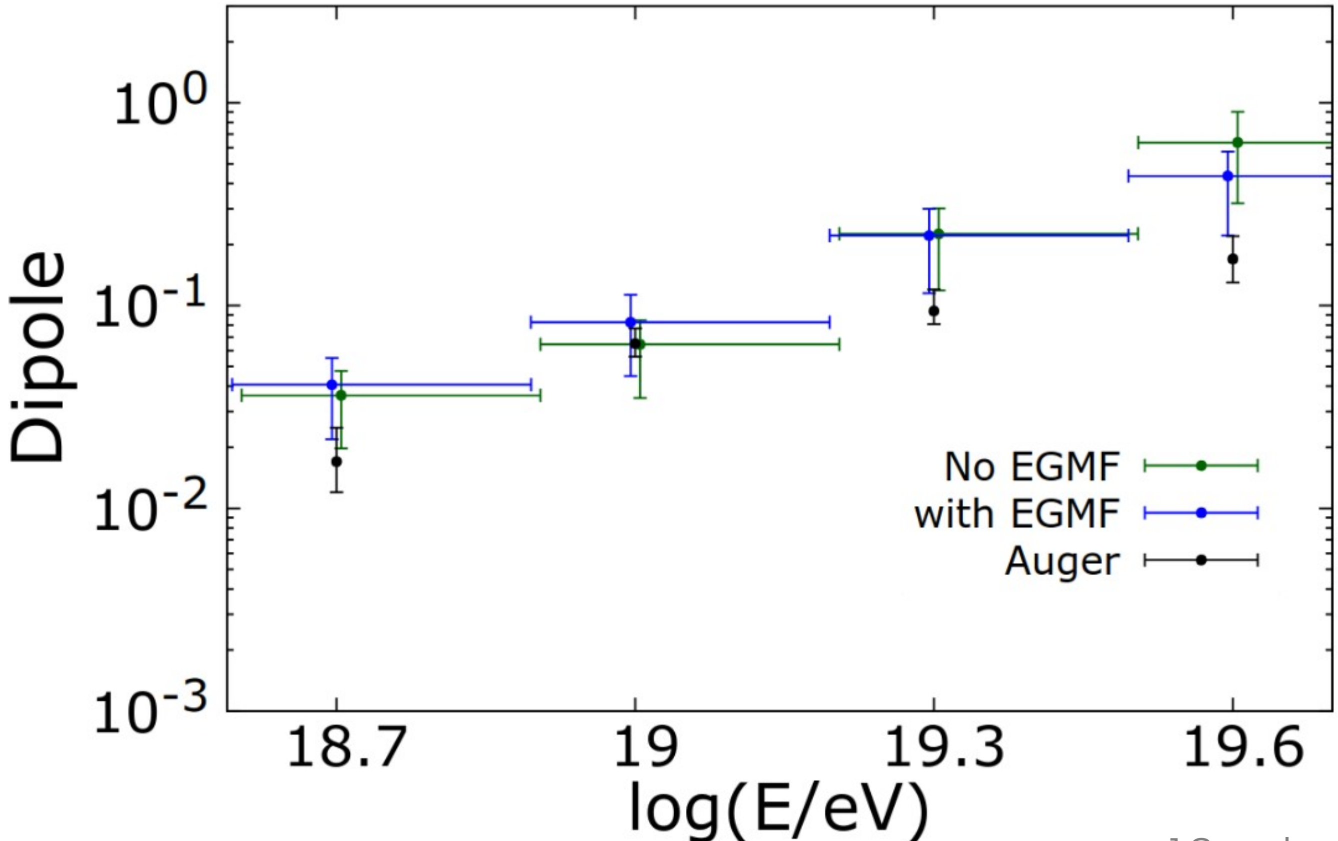
the total dipole Δ(E) is nearly independent of the EGMF strength

Smaller scale anisotropies are affected by EGMF



D Harari, SM, E Roulet, PRD 92 (2015) 6

DIPOLE AMPLITUDE FOR A DISTRIBUTION OF SOURCES: effect of EGMF



J Gonzalez,

2MRS distribution
$\rho \sim 10^{-4}$ Mpc^{-3}

B = 50 nG
L_c = 25 kpc

SUMMARY

- anisotropy and composition measurements provide indications that Galactic and/or EGMF significantly affect CRs reaching the Earth

- probably we are seeing multiple images up to the highest energies difficult to identify sources

- MHE provides possible explanation for observed spectrum hardness of the high energy component

- single dominant source at the highest energies?

- magnetic field effect in the source environment can also be significant

- dipole amplitude quite insensitive to EGMF strength

Several possible scenarios to explain the observations and

understanding of cosmic magnetic fields plays a key role