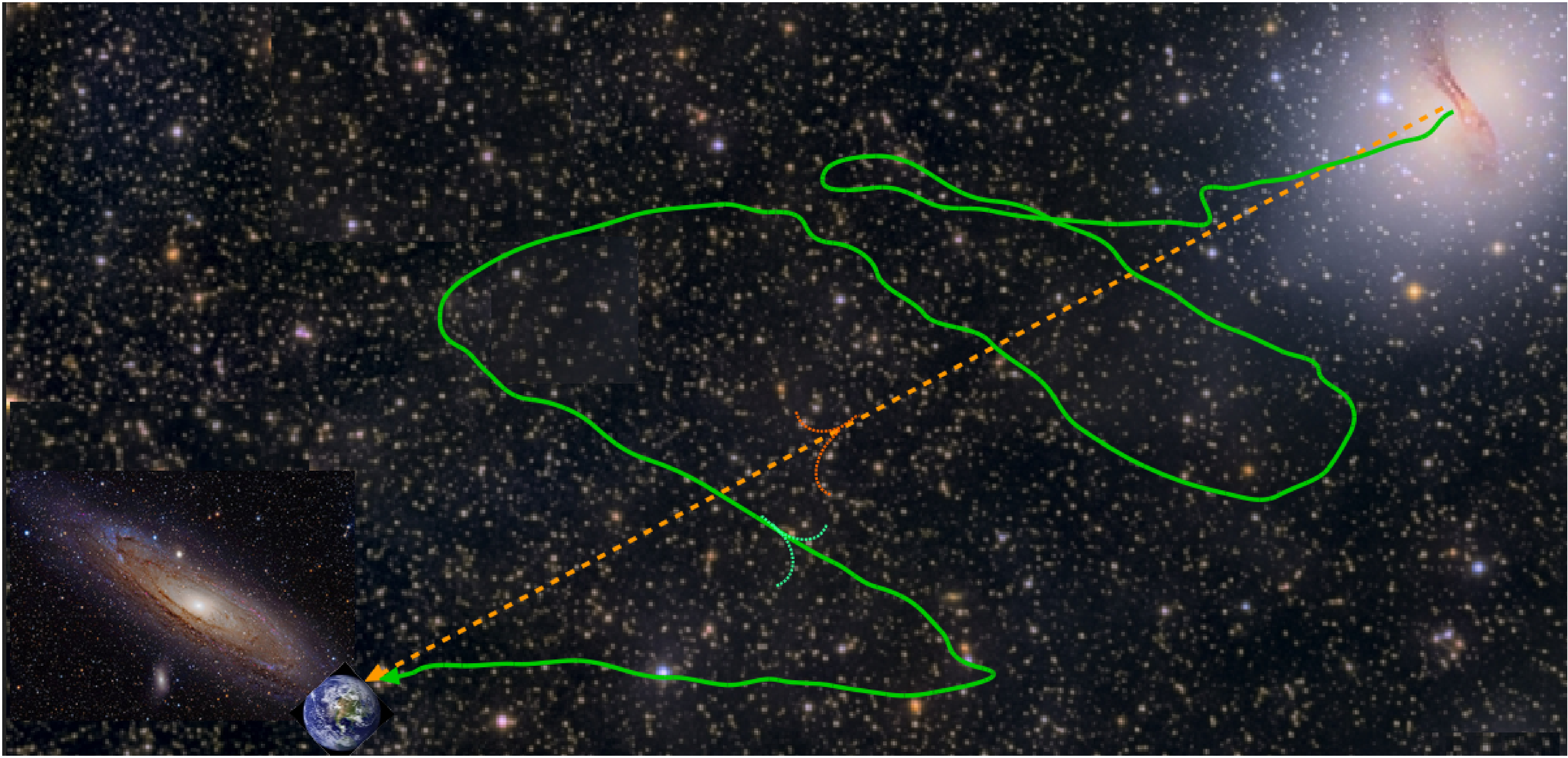
Propagation of ultra-high energy cosmic rays



Silvia Mollerach
CONICET, Centro Atomico Bariloche

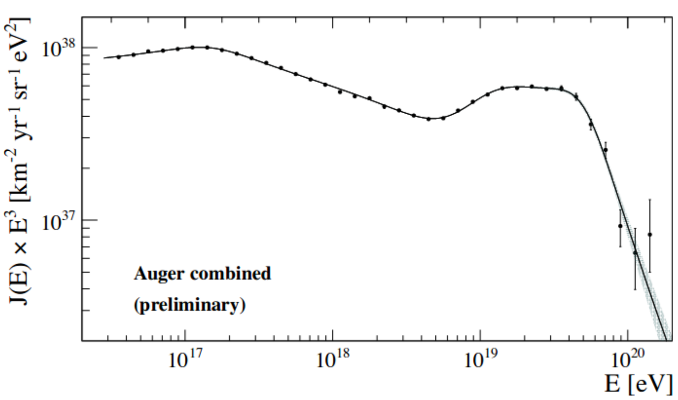
During propagation from their sources to the Earth UHECRs are subject to:

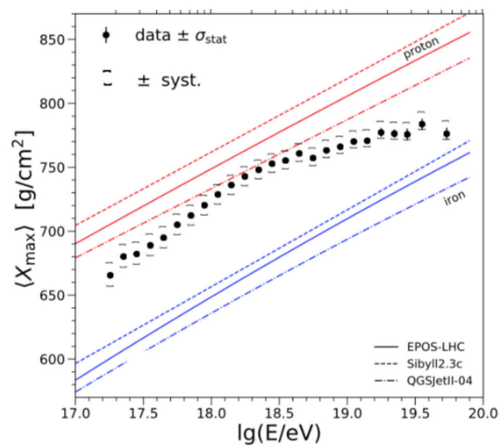
- energy redshift due to the expansion of the universe

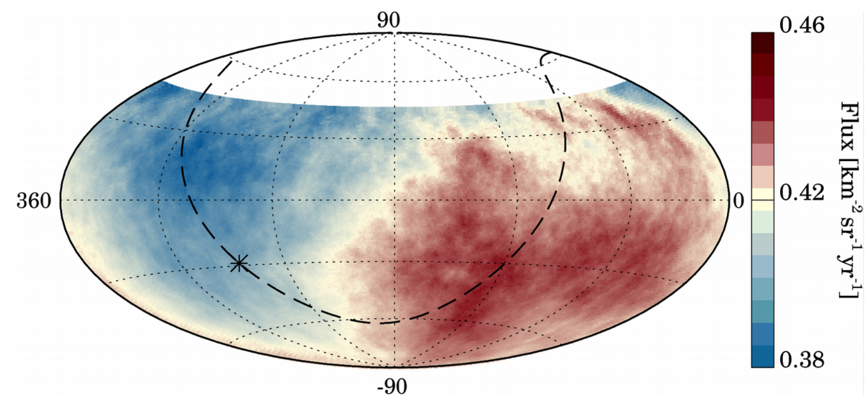
- interactions with radiation backgrounds (CMB and IR/visible/UV extragalactic background light)
  → energy losses, composition changes

- deflections in the intergalactic/Galactic magnetic fields

These processes change the spectrum, mass composition and arrival direction of the particles observed at Earth with respect to those of the particles emitted by the sources







spectrum composition anisotropy

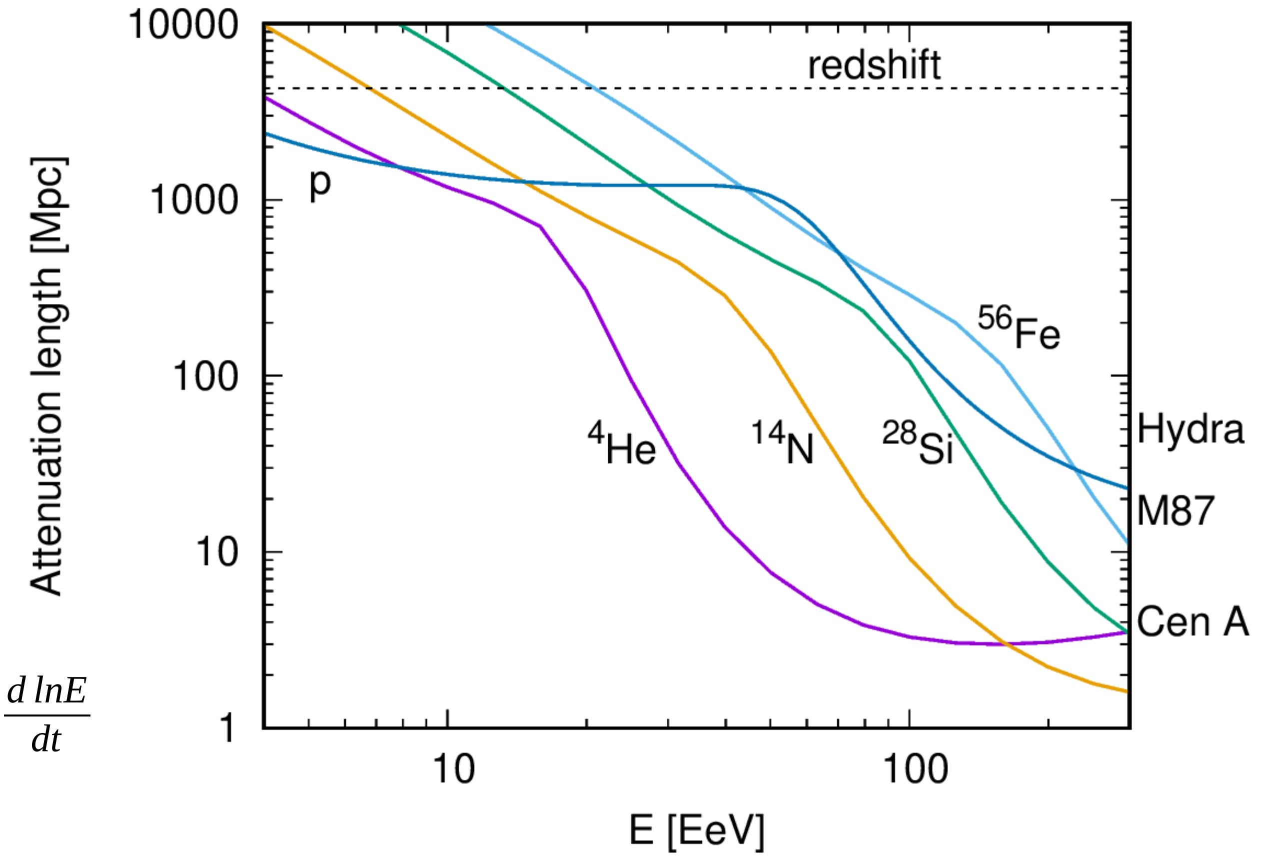
observed at Earth are shaped by source properties + propagation

Interactions with radiation backgrounds: studied in detail since Greisen, Zatsepin & Kuz'min (1966)

- e^--e^+ pair production ($A+\gamma \rightarrow A+e^-+e^+$)

- disintegration of nuclei ($(A+i)+\gamma \rightarrow A+ i\,N$)

- photopion production ($p+\gamma \rightarrow p+\pi^0, n+\pi^+$ or $n+\gamma \rightarrow n+\pi^0, p+\pi^-$)



$$\lambda^{-1} = -\frac{1}{c}\frac{d\,lnE}{dt}$$

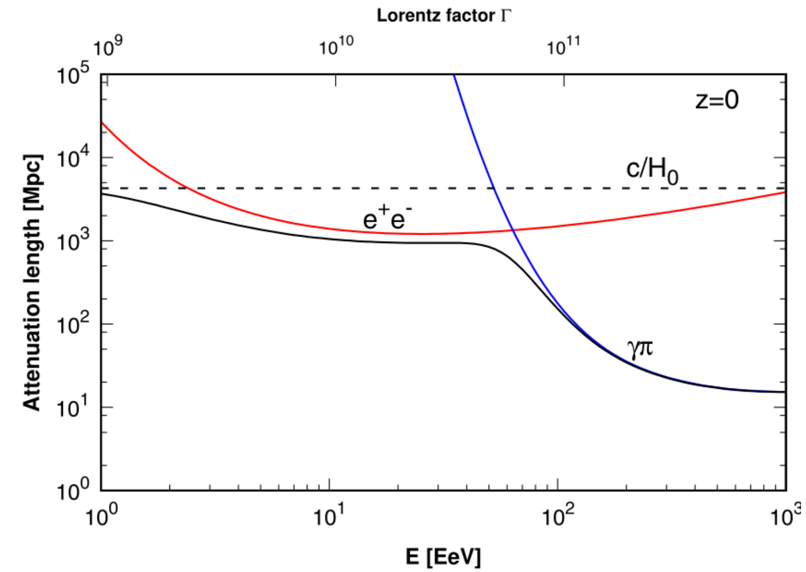
These processes also lead to the production of secondary particles: nucleons, e^--e^+ pairs, neutrinos, gamma rays

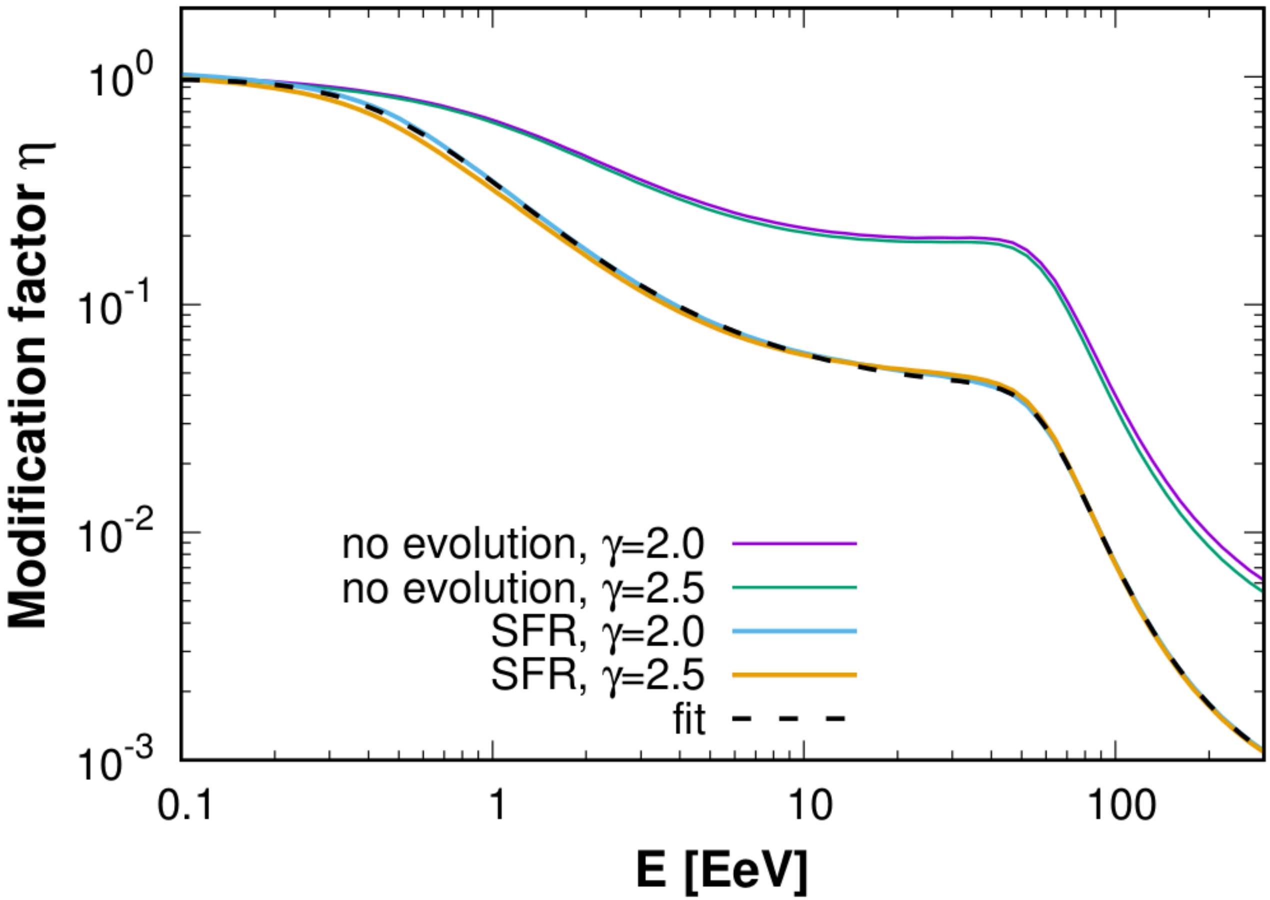
Few public Monte Carlo codes available: SimProp (Aloisio et al. 2018), CRPropa (Alves Batista et al. 2016)

Modification of the proton spectrum due to interactions

$$\eta = \frac{actual\ spectrum}{spectrum\, in\, the\ absence\ of\ interactions}$$

Berezinsky,Gazizov, Grigorieva 2006





Protons with spectrum $E^{-\gamma}$ and two hypothesis for source evolution

modification factor independent of γ

source evolution:
Star Formation Rate

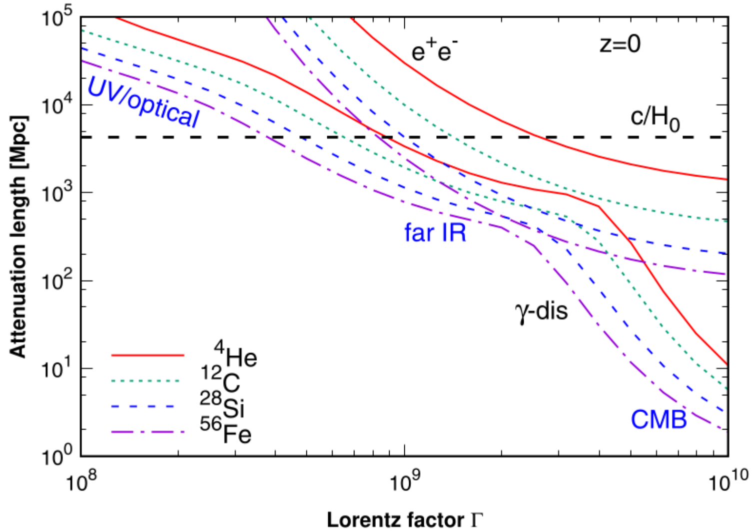
$$\begin{cases} (1+z)^{3.44} & z<0.97 \\ (1+z)^{-0.26} & z>0.97 \end{cases}$$

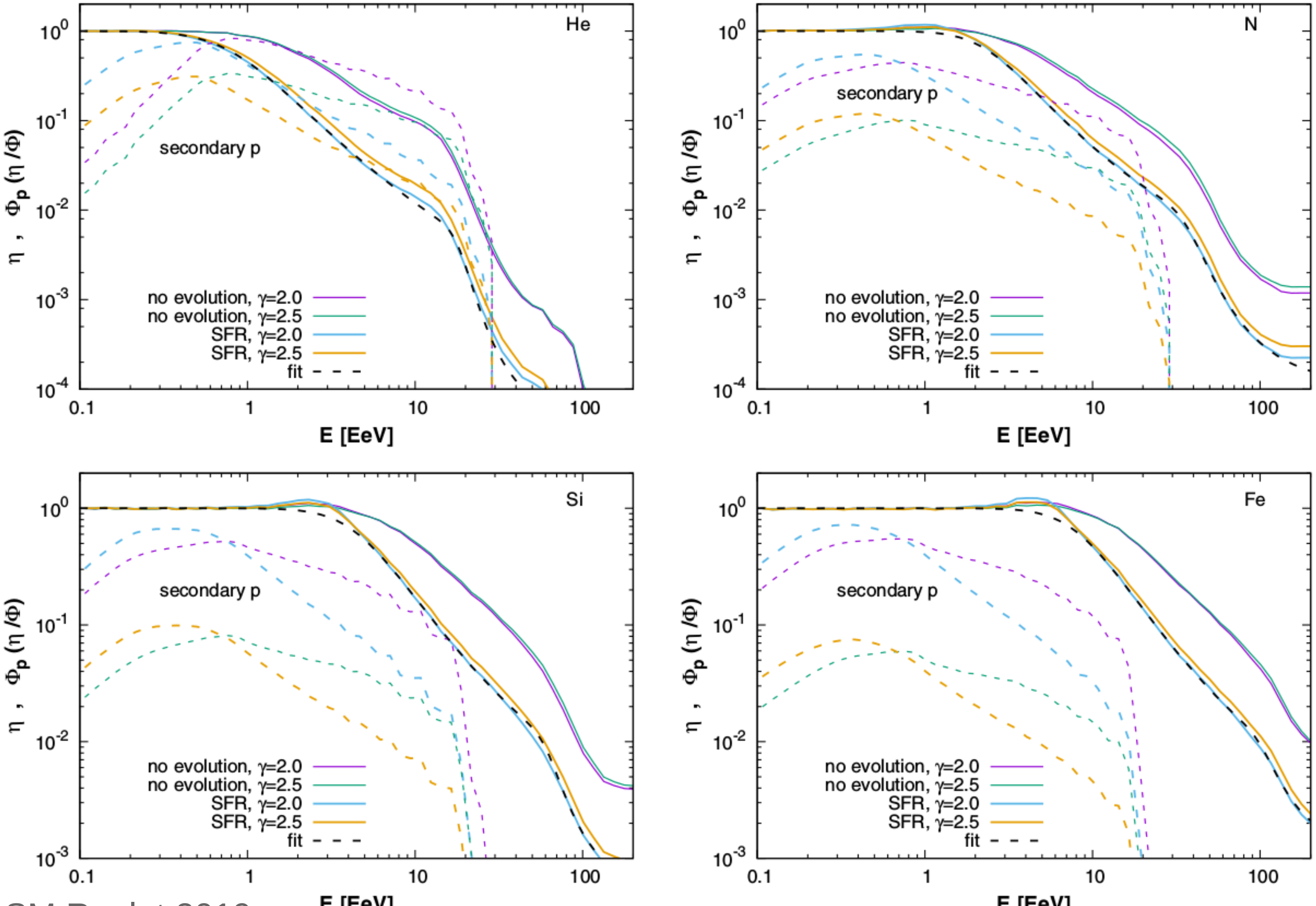
→ more weight to far away sources
→ relative enhancement of flux at low energies wrt the no evolution case

Modification of the spectrum for nuclei: heaviest fragment and secondary protons

expansion & pair creation → change Γ

photo-disintegration → changes A





notice that composition at Earth is changed

modification factor independent of γ

more secondary protons for harder spectrum

SFR evolution → enhancement of flux at low energies

Effect of the intergalactic magnetic field

turbulent field with rms amplitude B and coherence length l_c

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

Critical energy $r_L(E_c) = l_c$ → for $E < E_c$ large deflections for distances $< l_c$

$$E_c = ZeBl_c \simeq 0.9Z \frac{B}{\mathrm{nG}} \frac{l_c}{\mathrm{Mpc}} \,\mathrm{EeV}$$

Diffusion length: deflection ~1 rad $$l_D(E) \simeq l_c \left[4\left(\frac{E}{E_c}\right)^2 + 0.9\left(\frac{E}{E_c}\right) + 0.23\left(\frac{E}{E_c}\right)^{1/3} \right]$$ (Kolmogorov spectrum)

For a source at distance r_s

$l_D(E) \simeq r_s$ — **E**

Diffusion — Quasi rectilinear

Angular distribution wrt the source direction

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

$$R \equiv r_s/l_D$$

Harari SM Roulet 2014

Magnetic horizon effect: suppression of the flux at low energies for a discrete source distribution in the presence of a turbulent magnetic field

Lemoine (2005), Berezinsky and Gazizov (2006)

Solution of diffusion eq. for protons in an expanding universe

$$J_{\rm tot}(E) = \sum_s J_s(E) = \frac{c}{4\pi}\int_0^{z_{\max}} \mathrm{d}z \left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \frac{Q[E_g(E,z),z)]}{(4\pi\lambda^2)^{3/2}} \frac{\mathrm{d}E_g}{\mathrm{d}E} \sum_s \exp[-r_s^2/(4\lambda^2)]$$

$$\lambda^2(E,z) \simeq \frac{c}{3H_0}\int_0^z \mathrm{d}z' \frac{1+z'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}} l_D((1+z')E)$$

$E_g(E,z)$ accounts for energy losses

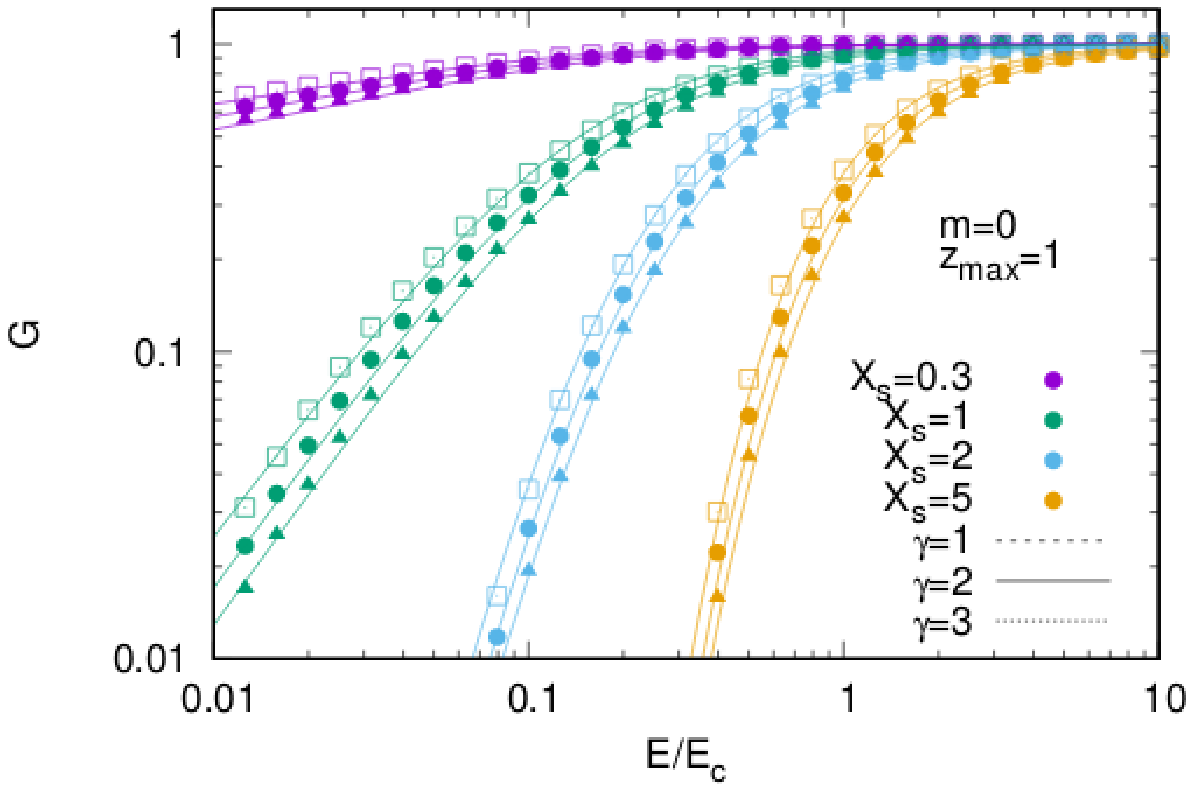
For small source separation (large density) $\sum_s \to n_s \int \mathrm{d}r\, 4\pi r^2$

$$\int_0^\infty \mathrm{d}r\, 4\pi r^2 \frac{\exp(-r^2/4\lambda^2)}{(4\pi\lambda^2)^{3/2}} = 1$$

→ no effect on the spectrum: Propagation theorem

Aloisio & Berezinsky 2004

Discrete distribution of sources: the spectrum gets suppressed at low energies
Low energy particles take longer than the age of the universe to arrive from the closest sources



$$G(E/E_c) = \frac{J_{tot}(E)}{J_{cont}(E)}$$

$$G(x) = \exp\left[-\left(\frac{a\,X_s}{x + b(x/a)^\beta}\right)^\alpha\right]$$

$$x = E/E_c$$

Suppression factor depends on the source density through

$$X_s \equiv \frac{d_s}{\sqrt{R_H l_c}} \simeq \frac{d_s}{65\ \mathrm{Mpc}}\sqrt{\frac{\mathrm{Mpc}}{l_c}},$$

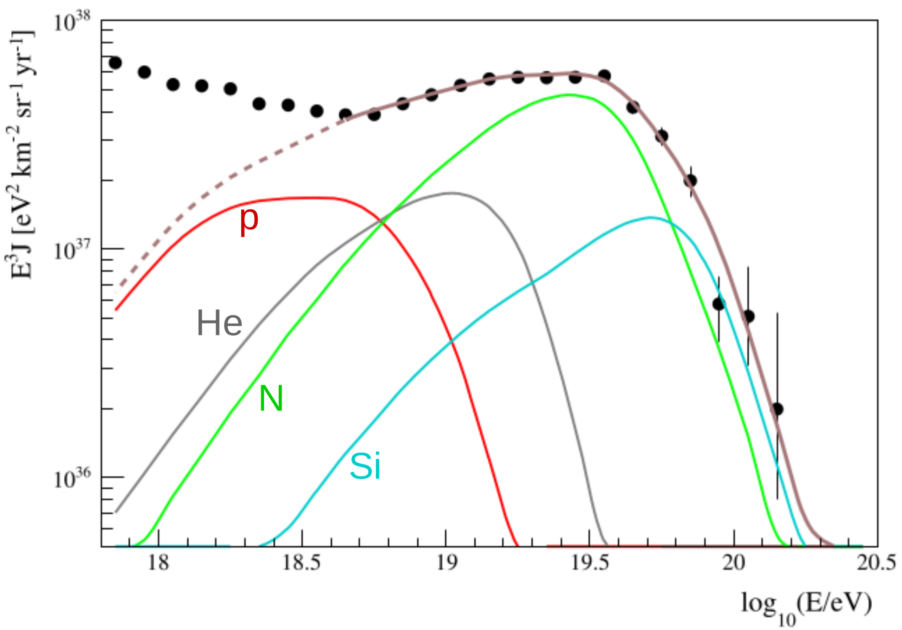
$d_s = 1/n_s^{1/3}$ larger X_s → more suppression: sources farther away

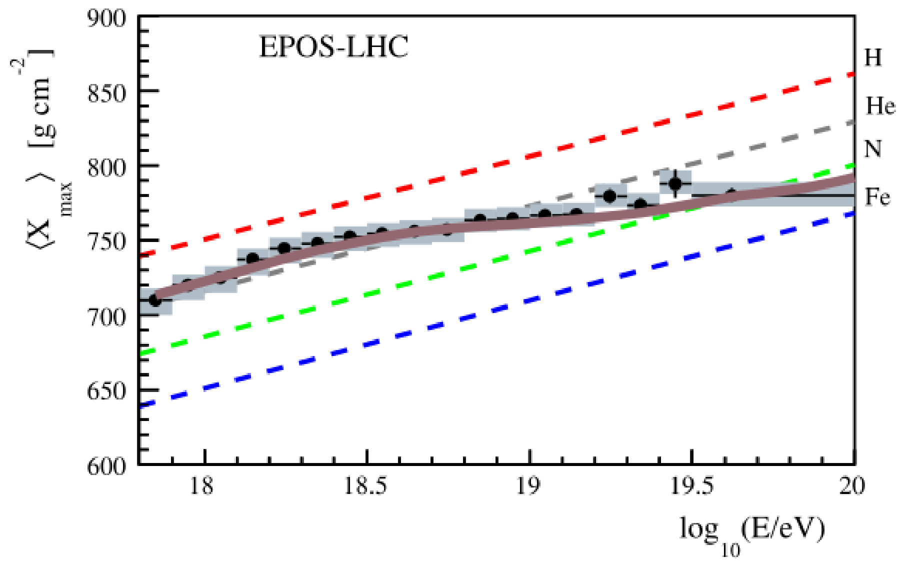
and on B through E_c

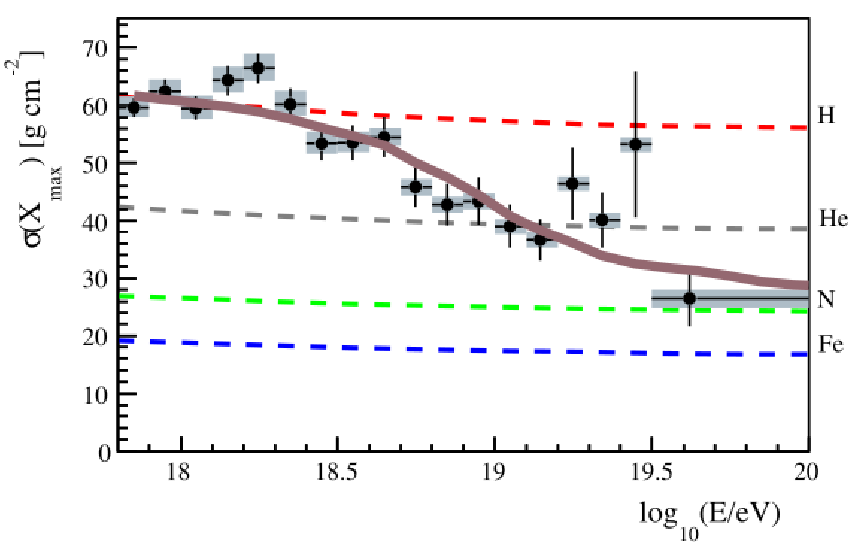
It has a (weaker) dependence on z_{max}, spectral index and evolution of the sources, $(1+z)^m$

SM Roulet 2013

Combined fit of spectrum & composition measurements above the ankle







Each mass component significantly contributes to the flux in a limited range of energies

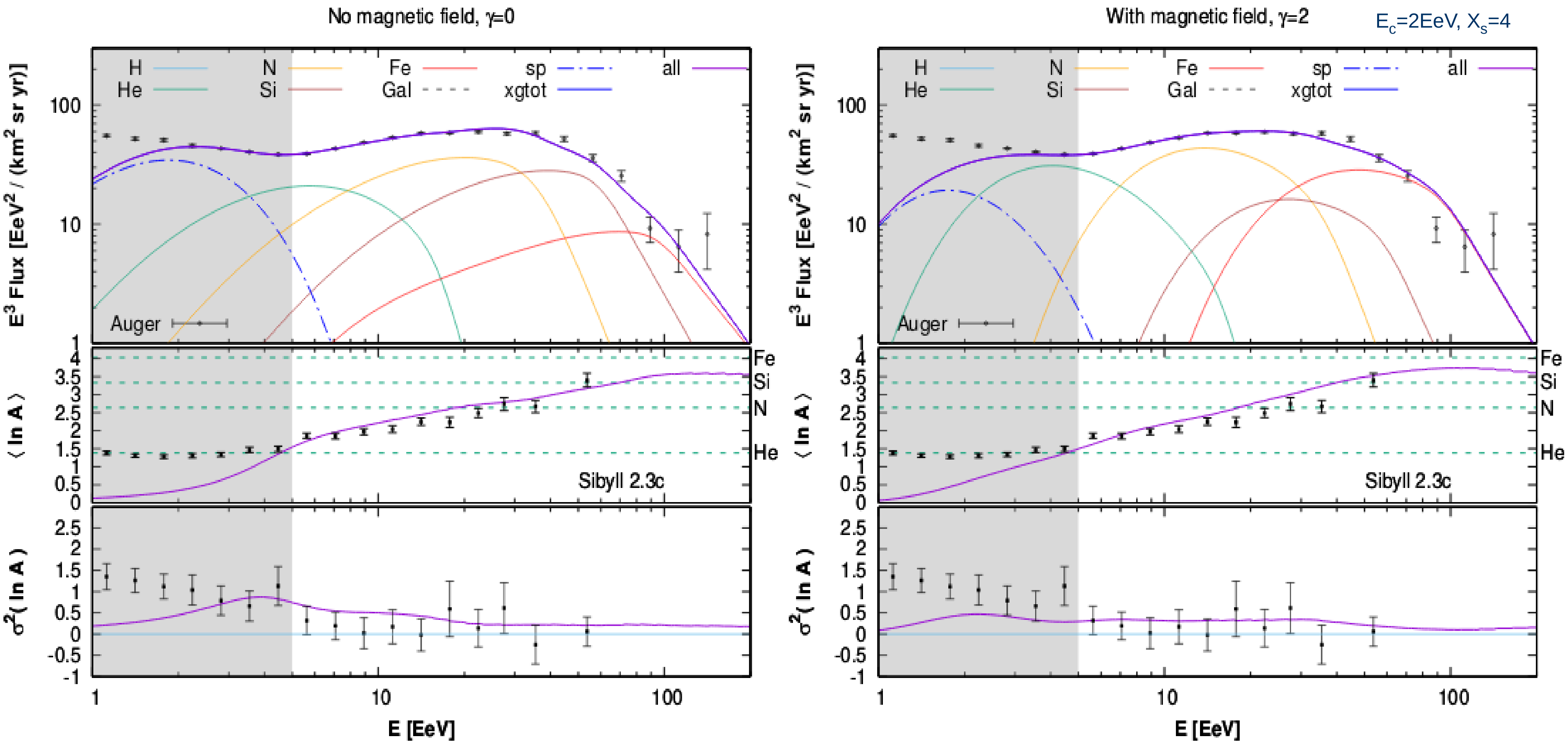
$$J_A(E) \propto E^{-\gamma} \times \begin{cases} 1 & for\ E/Z_A < R_{cut} \\ \exp(1 - E/Z_A R_{cut}) & for\ E/Z_A > R_{cut} \end{cases}$$

Sources with low rigidity cutoff and hard spectrum:

R_{cut} ~ 5 EV, γ ~ [0 - 1]

Auger 2017

Effect of the magnetic horizon suppression on a combined fit to spectrum and composition



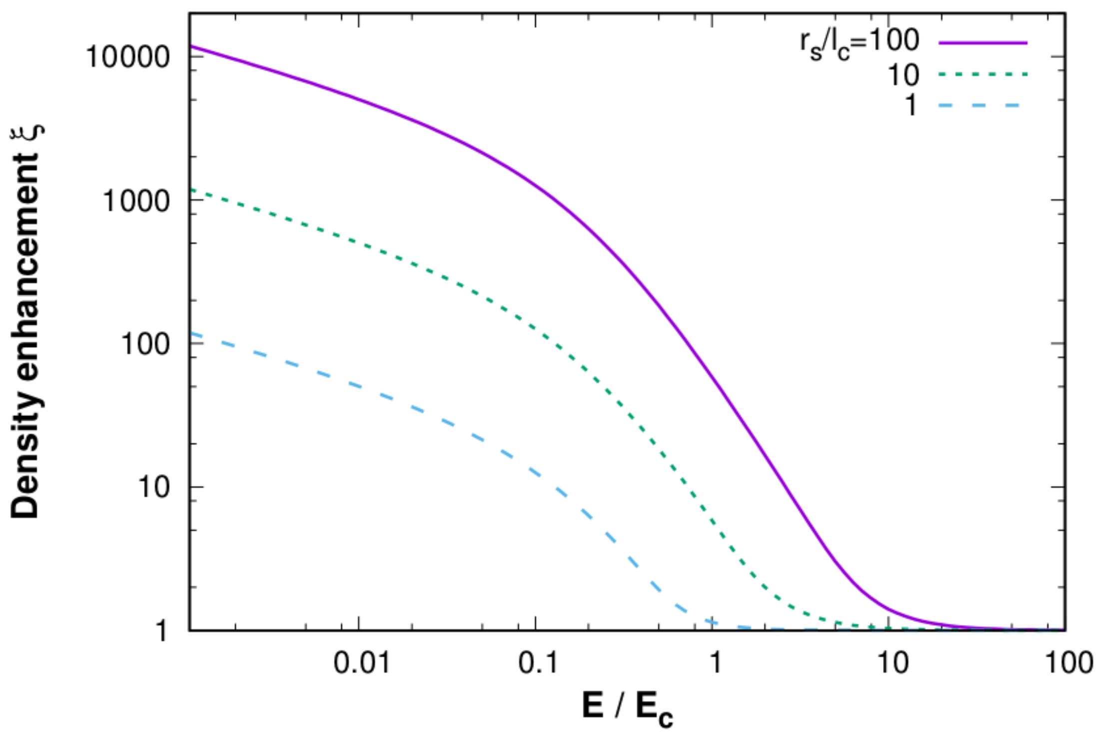
Spectrum and composition may be fitted with Fermi type spectrum (γ~2) and the effectively harder spectrum at low energies be due to magnetic horizon effects

Spectrum from one source:

diffusion leads to enhancement of the density around it

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

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



related to dipolar amplitude by $\Delta = 3\,\langle\cos\theta\rangle = 3/\xi$

Source emitting since initial redshift z_i: enhancement of local density

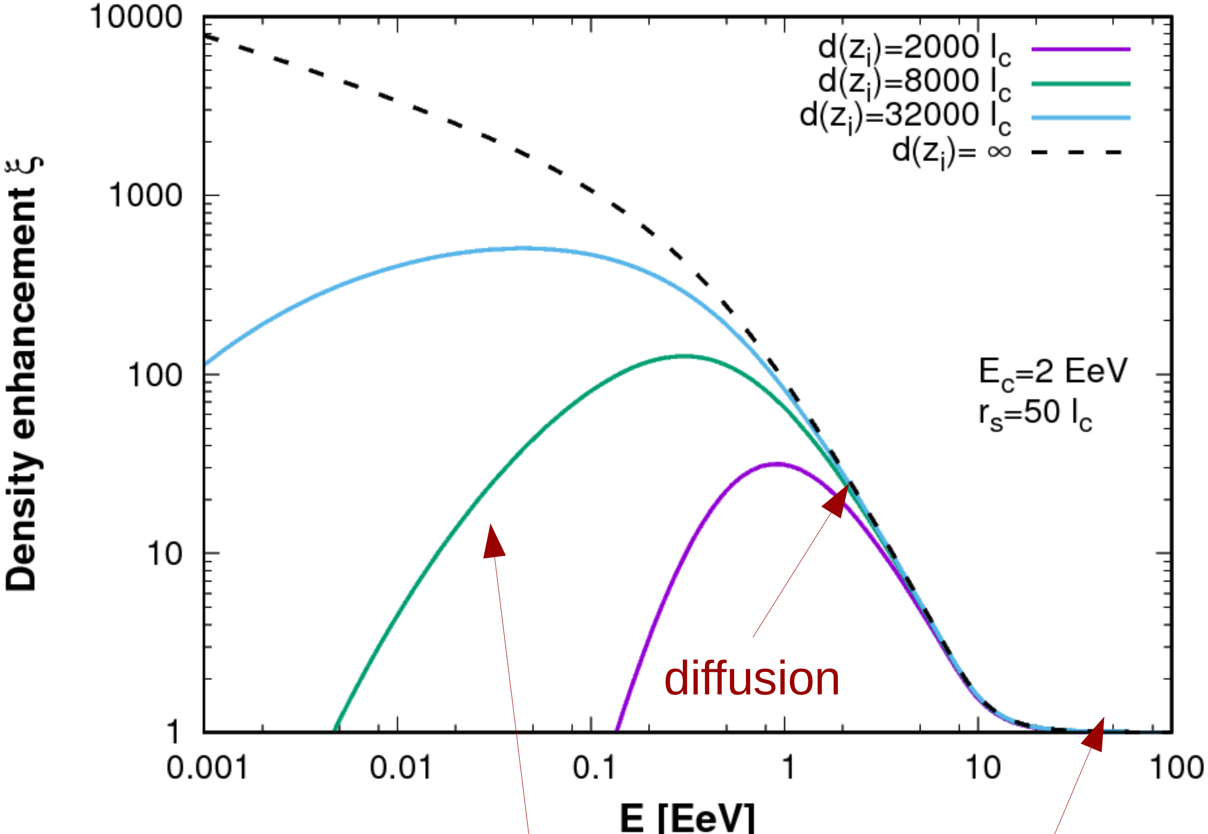
density $n(E,r_s)$ obtained from the solution of diffusion eq. (Berezinsky & Gazizov 2006)

$$n(E,r_s) = \frac{Q(E)}{4\pi c r_s^2}\xi_i$$

$$\xi_i \simeq \frac{1}{C(r_s/l_D)} \exp\left[-\left(\frac{r_s^2}{0.7 l_D(E) d(z_i)}\right)^{0.82}\right]$$

$$d(z_i) = \int_0^{z_i} dz \frac{c}{H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}}$$

protons



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

rectilinear propagation

maximum at

$$l_D(E_{max}) \simeq 1.1\ r_s^2/d(z_i)$$

$$\xi_i^{max} \simeq 0.8\ d(z_i)/r_s$$

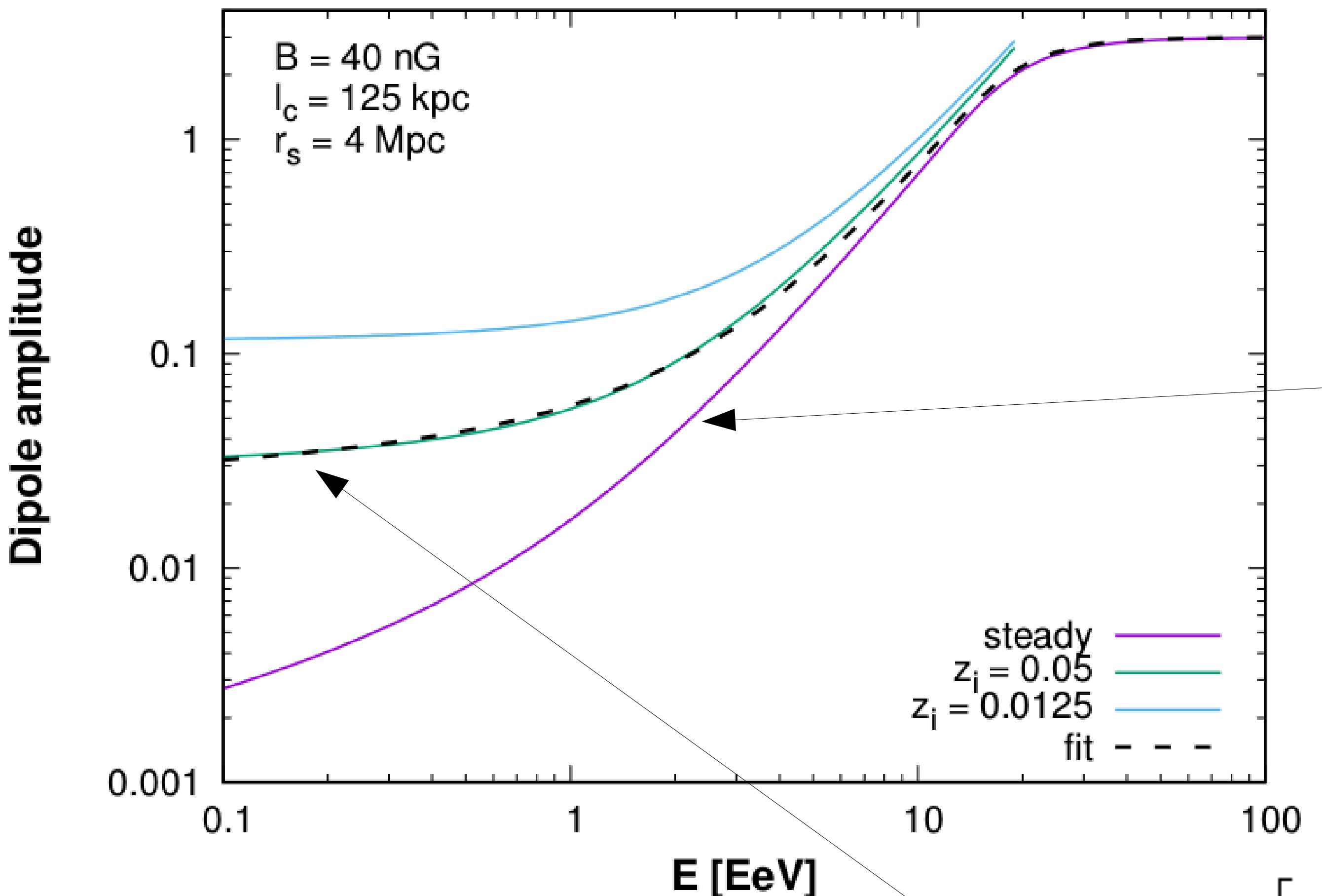
independent parameters:

$$E_c, r_s/l_c, d(z_i)/l_c$$

Source emitting since initial redshift z_i: dipolar anisotropy

anisotropy at low energies larger than for the steady source (particles with long trajectories arriving from behind are missing)

protons



$$\Delta = l_D |\nabla n| / n$$

$$\Delta = 3\langle \cos\theta \rangle \simeq 3\ C(r_s/l_D)$$

$$\Delta \simeq 3\ C(r_s/l_D)\left[1 + 1.64\left(\frac{r_s^2}{0.7 l_D d(z_i)}\right)^{0.82}\right]$$

nuclei: change E → E/Z
(good approximation: attenuation is small at these energies for a nearby source)

Scenario with a strong nearby extragalactic source

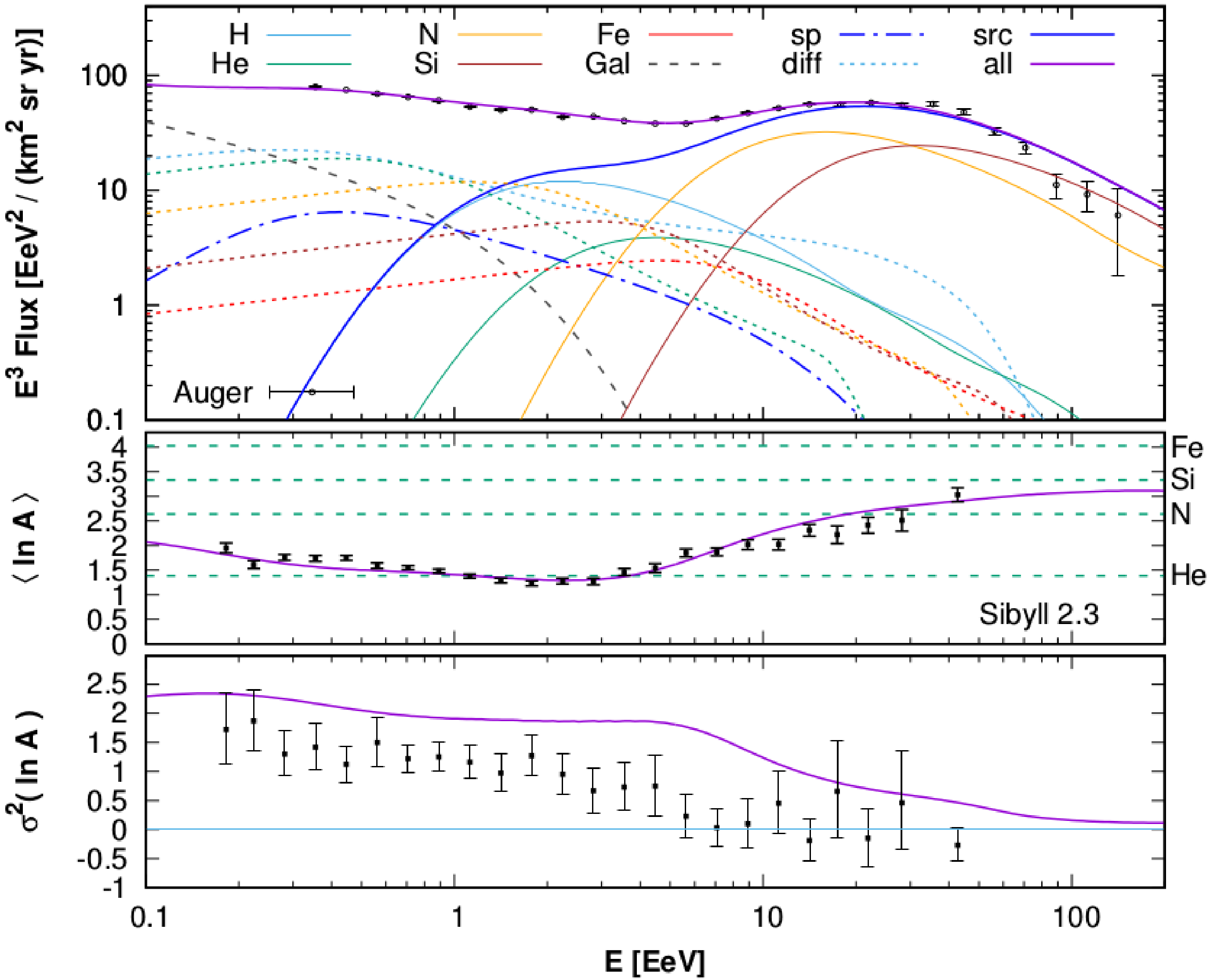
- A nearby source within the Local Supercluster:

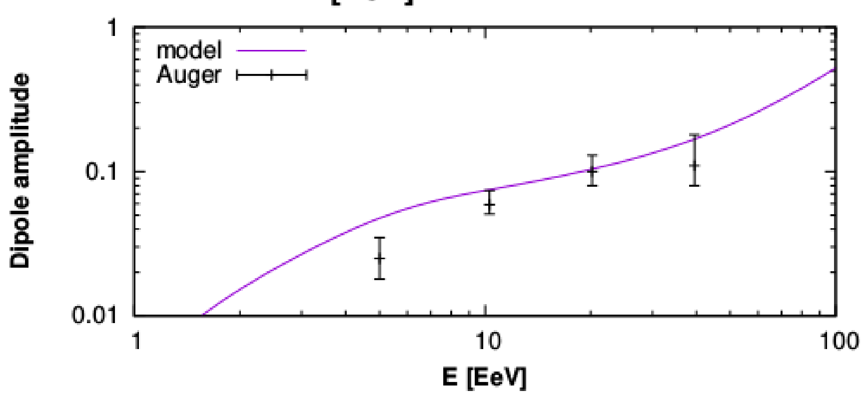
with large magnetic field in the region enclosing observer & source (Vallee 2002)
emitting since a recent z_i (or with a burst at a recent z_b),
and a mixed composition with common rigidity-dependent spectrum
(power law index γ_s and cutoff at ZE^s_{cut})
→ each component contributes in a limited energy range as result of the diffusion and magnetic horizon effects

- Diffuse extragalactic contribution from farther away sources:

assumed isotropic, with mixed composition (power law spectrum $E^{-\gamma}$ and cutoff ZE_{cut})
with SFR source evolution

Local source scenario: Source emitting since z_i





magnetic field

$$B = 100 \text{ nG}$$
$$l_c = 0.03 \text{ Mpc}$$

($E_c \approx 2.7$ EeV)

nearby source

$$r_s = 4 \text{ Mpc}$$
$$z_i = 0.07$$

($\xi_{max} \approx 60$)

$$\gamma_s = 2.3$$
$$f^s_{\rm H} = 0.45, \; f^s_{\rm He} = 0.09$$
$$f^s_{\rm N} = 0.31, \; f^s_{\rm Si} = 0.15$$
$$f^s_{\rm Fe} = 0$$

diffuse flux

$$\gamma = 2.7$$
$$f_{\rm H} = 0.45, \; f_{\rm He} = 0.33$$
$$f_{\rm N} = 0.15, \; f_{\rm Si} = 0.05$$
$$f_{\rm Fe} = 0.02$$

$$E^s_{\rm cut} = E_{\rm cut} = 20 \text{ EeV}$$

SM Roulet 2019

Summary

The interaction of UHECRs with the radiation backgrounds modifies the spectrum at the highest energies and constrains the distance of the possible sources

The effect of a turbulent extragalactic magnetic field is to suppress the spectrum at low energies of a distribution of sources

A good combined fit to the spectrum and composition data with a softer spectral index at source can be obtained considering the EGMF effect

If local EGMF is strong, most of CRs above the ankle could come from a single local source, with the diffuse flux from farther away sources explaining the extragalactic contribution at lower energies

Scenario with a strong nearby extragalactic source

Flux from the nearby source: mixed composition - 5 components with common rigidity-dependent spectrum (power law index γ_s and cutoff at ZE^s_{cut})

$$\Phi^s(E, r_s) = \Phi_0^s \sum_i f_i^s \left(\frac{E}{\mathrm{EeV}}\right)^{-\gamma_s} \xi(E/Z_i, r_s) \frac{1}{\cosh(E/Z_i E^s_{\mathrm{cut}})}$$

cutoff

i = H, He, N, Si, Fe

ξ_i → for source emitting since z_i

ξ_b → for burst at z_b

(function of $E_c \propto Bl_c$, r_s/l_c, $d(z_{i/b})/l_c$)

Diffuse extragalactic contribution: assumed isotropic
- 5 components (power law γ and ZE_{cut}) with SFR source evolution

$$\Phi^{\mathrm{dif}}(E) = \Phi_0 \sum_j f_j \left(\frac{E}{\mathrm{EeV}}\right)^{-\gamma} \eta_j(E) \frac{1}{\cosh(E/Z_j E_{\mathrm{cut}})}$$

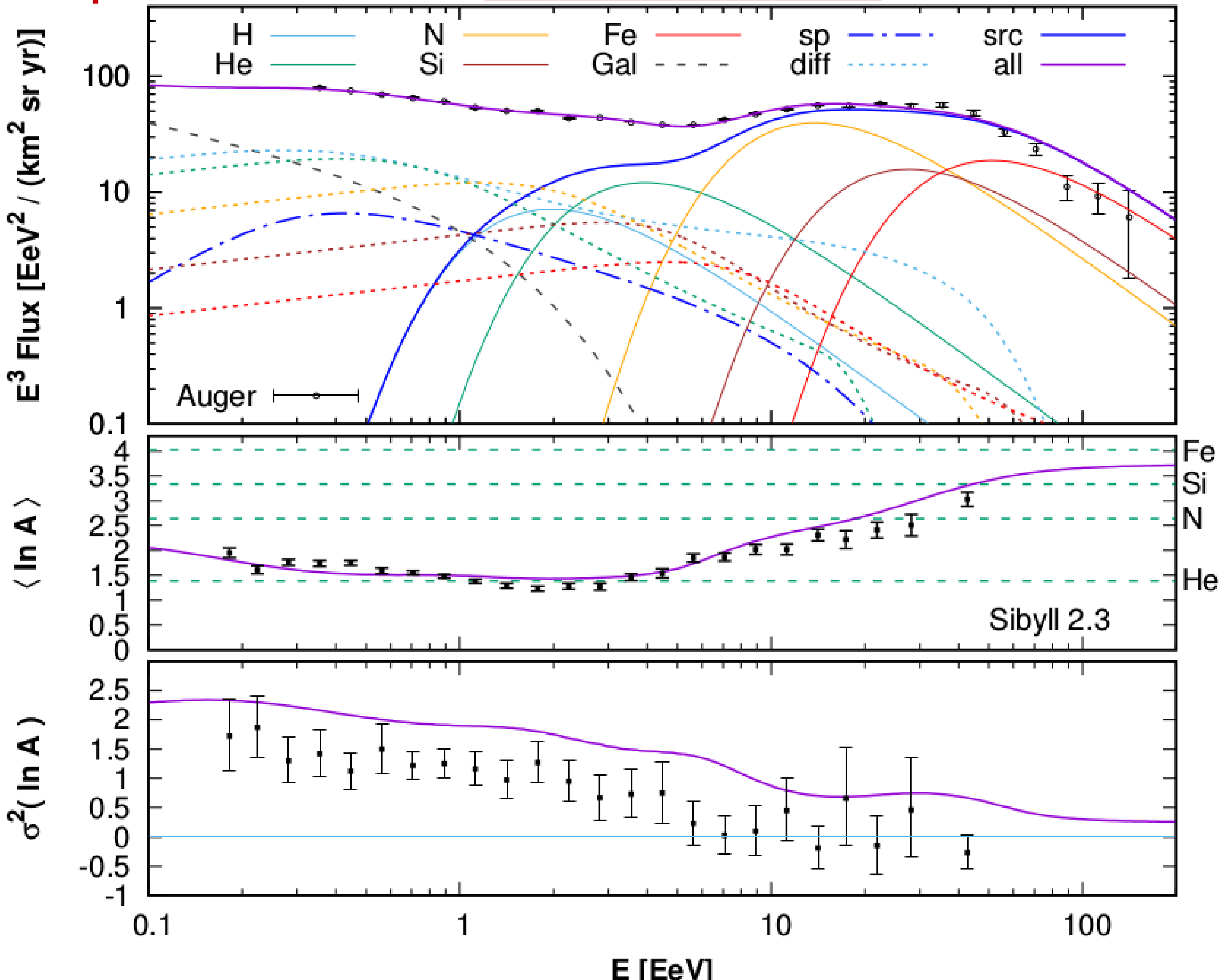
modification factor fit for each component

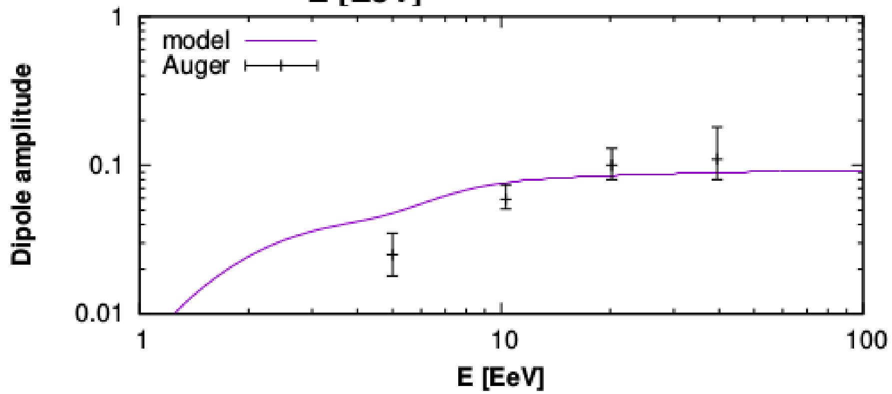
- secondary protons

$$\Phi^p(E) \simeq \Phi_0 \sum_j f_j \left(\frac{E}{\mathrm{EeV}}\right)^{-\gamma} \frac{A^{2-\gamma} G(E)}{\cosh(2E/E_{\mathrm{cut}})}$$

Examples:

Bursting source





magnetic field

$$B = 50 \text{ nG}$$
$$l_c = 0.05 \text{ Mpc}$$

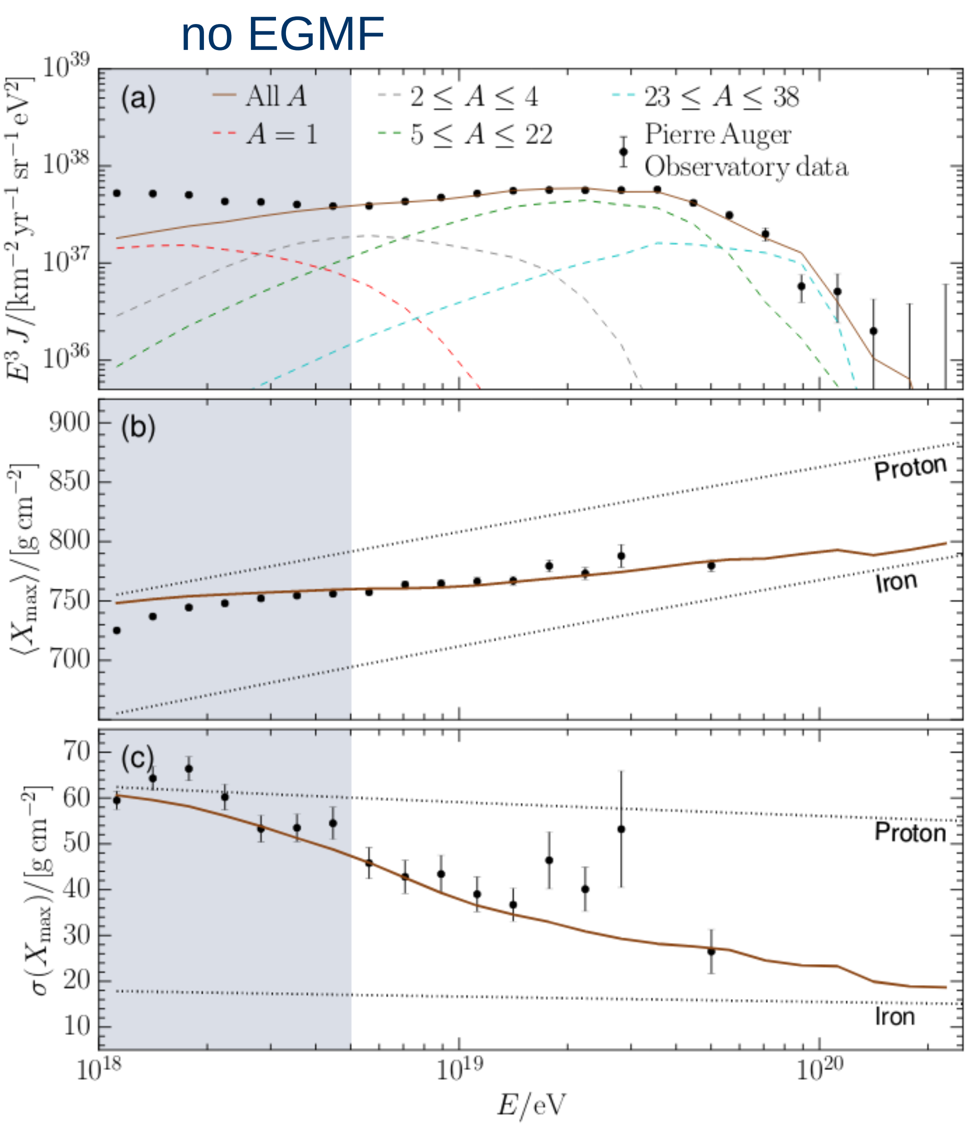
($E_c \approx 2.2$ EeV)

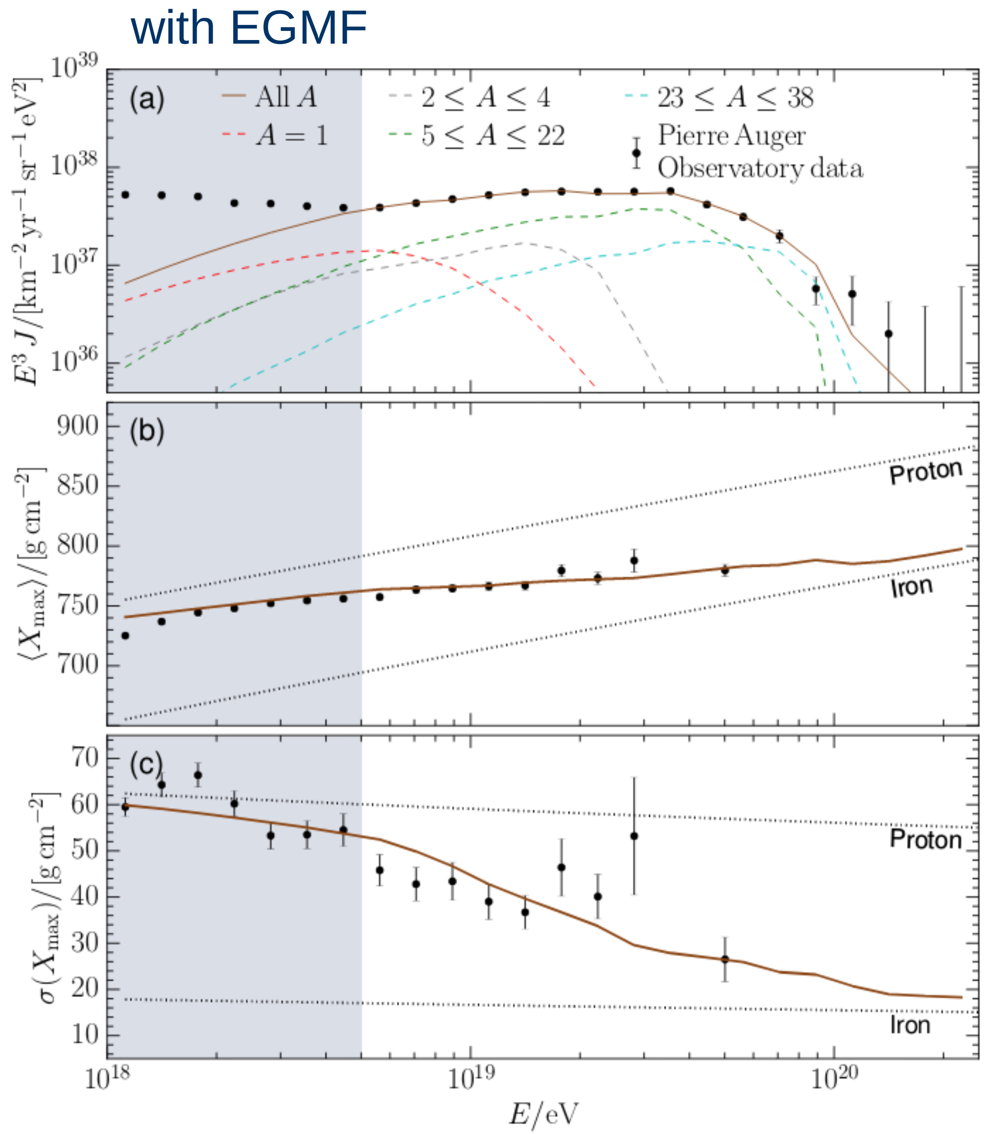
nearby source

$$r_s = 4 \text{ Mpc}$$
$$z_b = 0.015$$

$$\gamma_s = 2$$
$$f_{\rm H}^s = 0.34,\ f_{\rm He}^s = 0.30$$
$$f_{\rm N}^s = 0.27,\ f_{\rm Si}^s = 0.05$$
$$f_{\rm Fe}^s = 0.04$$

diffuse flux:
same parameters as
previous example





Source properties	**4D with EGMF**	**4D no EGMF**	**1D no EGMF[1]**
γ	$1.61^{+0.08}_{-0.07}$	$0.61^{+0.05}_{-0.06}$	$0.87^{+0.08}_{-0.06}$
$\log_{10}(R_{cut}/\mathrm{eV})$	$18.88^{+0.03}_{-0.07}$	$18.48^{+0.01}_{-0.02}$	$18.62^{+0.02}_{-0.02}$

EGMF

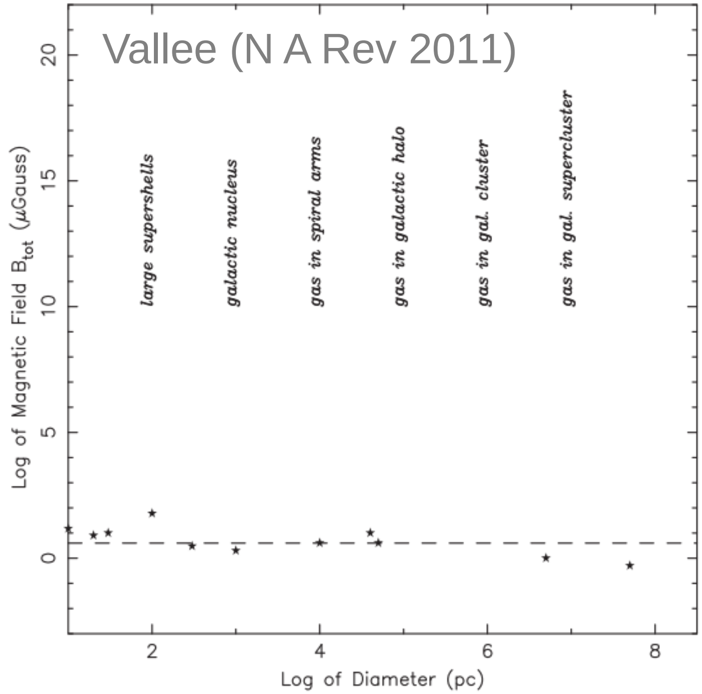
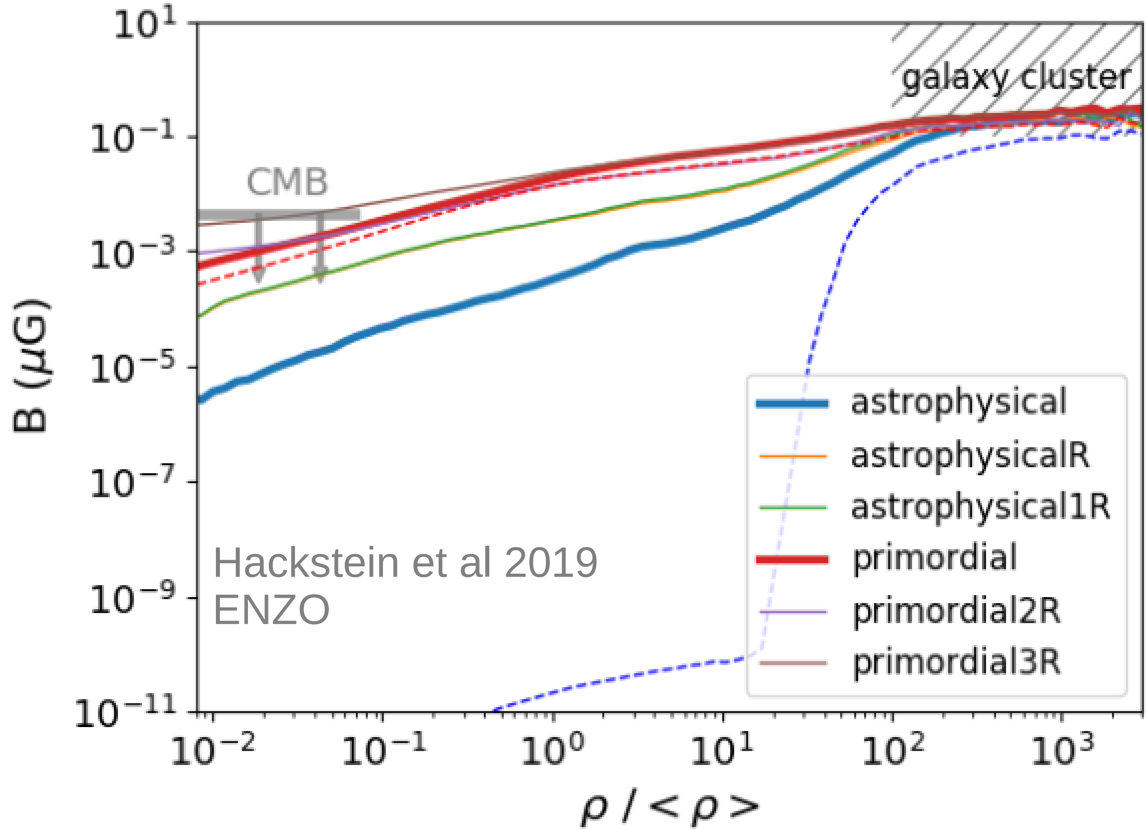
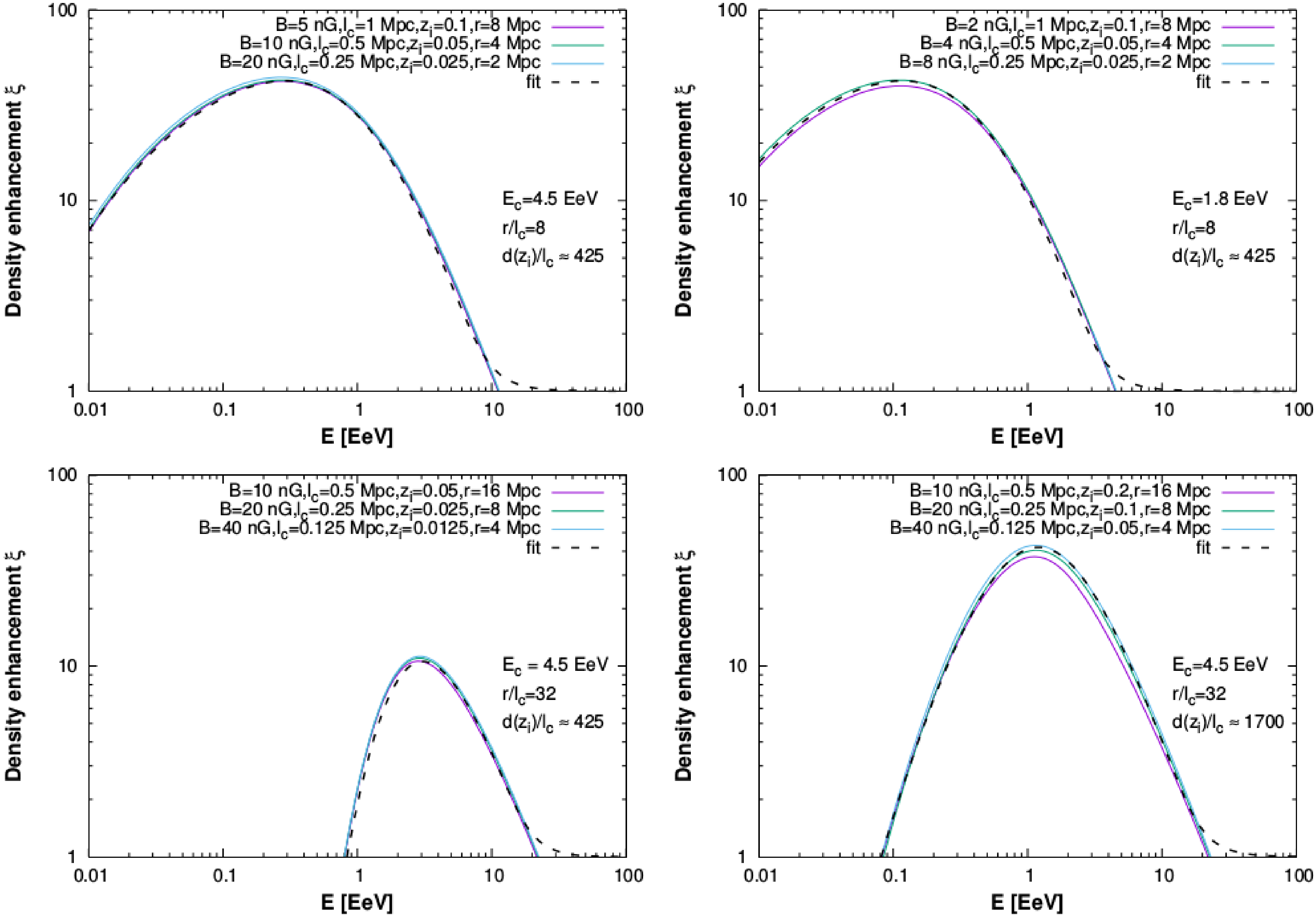


Fig. 55. Mean observed magnetic field, as a function of different source diameters. The dotted line has a slope of 0.



Physical properties of some large astronomical objects

Object type	Mean density n (cm^{-3})	Mean magnetic field B (μG)	Mean size D (pc)	Mean temperature T (K)	References
Gas in supercluster of galaxies	10^{-6}	0.5	5×10^7	10^7	Vallée (1990d)
Gas in clusters of galaxies	10^{-4}	1	5×10^6	10^7	Vallée (1990d)
Gas in galactic halos	10^{-3}	4	5×10^4	10^6	Vallée (1990d)
Spiral arm interstellar gas	0.5	4	10^4	10^4	Vallée (1991c)
Large supershells-initial	0.8	3	300	10^3	Vallée (1993e)
Large supershells-actual	2	8	20	10^3	Vallée (1993e)
Large HII regions	5	10	30	10^4	Heiles and Chu (1980)
HI gas in diffuse clouds	3	5	10	100	Troland and Heiles (1986)
HI gas in interclumps	90	15	10	100	Troland and Heiles (1986)



B=5 nG,l_c=1 Mpc,z_i=0.1,r=8 Mpc
B=10 nG,l_c=0.5 Mpc,z_i=0.05,r=4 Mpc
B=20 nG,l_c=0.25 Mpc,z_i=0.025,r=2 Mpc
fit
E_c=4.5 EeV
r/l_c=8
d(z_i)/l_c ≃ 425
B=2 nG,l_c=1 Mpc,z_i=0.1,r=8 Mpc
B=4 nG,l_c=0.5 Mpc,z_i=0.05,r=4 Mpc
B=8 nG,l_c=0.25 Mpc,z_i=0.025,r=2 Mpc
fit
E_c=1.8 EeV
r/l_c=8
d(z_i)/l_c ≃ 425
B=10 nG,l_c=0.5 Mpc,z_i=0.05,r=16 Mpc
B=20 nG,l_c=0.25 Mpc,z_i=0.025,r=8 Mpc
B=40 nG,l_c=0.125 Mpc,z_i=0.0125,r=4 Mpc
fit
E_c = 4.5 EeV
r/l_c=32
d(z_i)/l_c ≃ 425
B=10 nG,l_c=0.5 Mpc,z_i=0.2,r=16 Mpc
B=20 nG,l_c=0.25 Mpc,z_i=0.1,r=8 Mpc
B=40 nG,l_c=0.125 Mpc,z_i=0.05,r=4 Mpc
fit
E_c=4.5 EeV
r/l_c=32
d(z_i)/l_c ≃ 1700
Density enhancement ξ
E [EeV]