Impact of the Magnetic Horizon on the Interpretation of the Pierre Auger Observatory Spectrum and Composition Data

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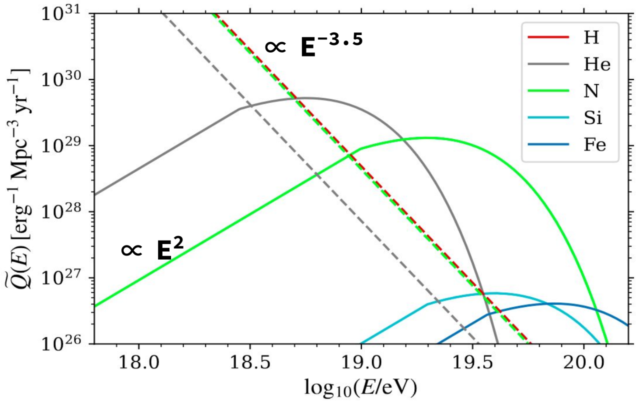
CONICET

PIERRE AUGER OBSERVATORY

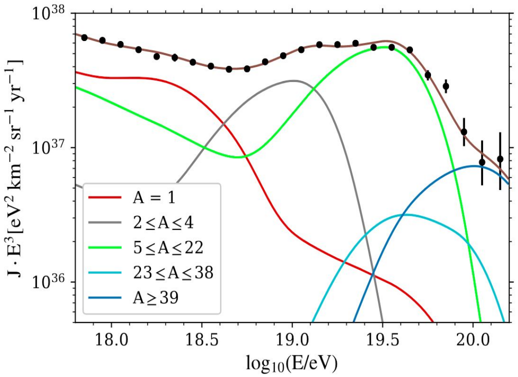
MOTIVATION

SPECTRUM AT THE SOURCES

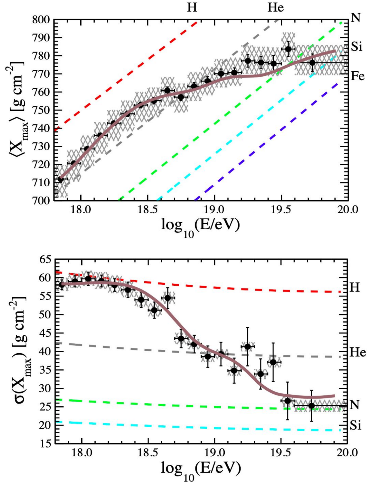


PROPAGATION

SPECTRUM AT EARTH



DEPTH OF SHOWER MAXIMA

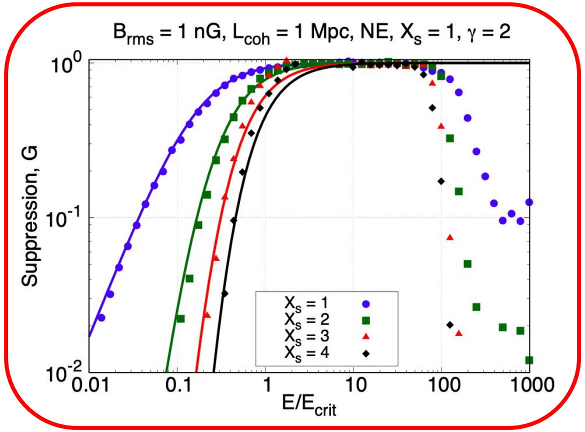


- To infer the properties of UHECR's sources a **combined fit to spectrum and depth of shower maxima (X_{max})** was carried out (*JCAP 04(2017)038, JCAP 05(2023)024*)
- **Two populations of sources** required: one dominating below a few EeV (L), and another above (H)
- Very **hard spectrum required** for the **high-energy component** → **incompatible** with expectations from **diffusive shock acceleration**, which are $\tilde{Q} \propto E^{-2}$
- Can we explain this as a consequence of the **magnetic horizon effect** (MHE)?
- MHE: Low energy particles do not reach Earth if the diffusion time from the closest sources is larger than the age of the sources

MAGNETIC HORIZON EFFECT

- Extragalactic magnetic fields (EGMF) between Earth and closest sources modelled as ***turbulent & isotropic*** with rms amplitude (***B_{rms}***) & coherence length (***L_{coh}***)
- Critical energy E_{crit} such that: $r_L(E_{\rm crit}) = L_{\rm coh} \longrightarrow R_{\rm crit} \equiv E_{\rm crit}/Z = 0.9 \frac{B_{\rm rms}}{\rm nG} \frac{L_{\rm coh}}{\rm Mpc} \, {\rm EeV}$
- Uniform source density, intersource distance d_s
- MHE suppresses the flux at low energies

$$J_Z(E) = G(E/E_{\rm crit}) \, J_Z|_{d_s \to 0}$$

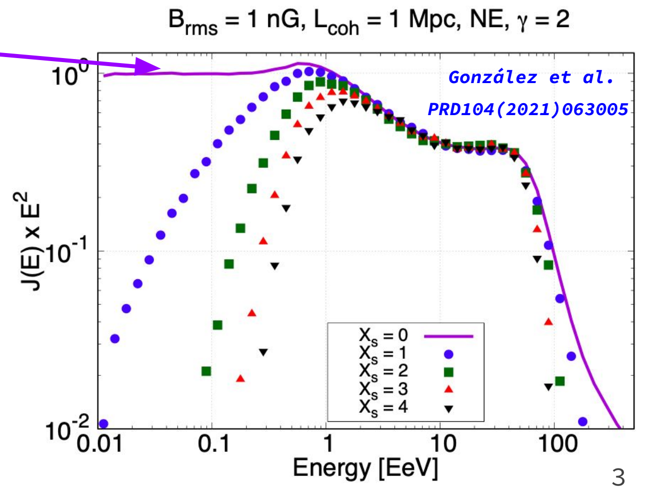


$$G(x) = \exp\left[-\left(\frac{aX_s}{x + b(x/a)^\beta}\right)^\alpha\right]$$

X_s: normalized distance

$$X_s = \frac{d_s}{\sqrt{r_H L_{\rm coh}}} \simeq \frac{d_s}{25\,{\rm Mpc}} \sqrt{\frac{\rm Mpc}{L_{\rm coh}}}$$

$r_H = c/H_0$



Proton flux at Earth.

COMBINED FIT OF SPECTRUM AND COMPOSITION

1) Model of the sources

$$\dot{Q}(z,E) = \dot{Q}_0 \xi(z) \sum_A f_A \left(\frac{E}{E_0}\right)^{-\gamma} f_{\mathrm{cut}}\left(\frac{E}{Z_A R_{\mathrm{cut}}}\right)$$

Source evolution ξ(z): no evolution (NE) or star formation rate (SFR)

$$f_{\mathrm{cut}}(E, Z_A, R_{\mathrm{cut}}) = \mathrm{sech}\left[\left(\frac{\mathrm{E}}{\mathrm{Z_A R_{cut}}}\right)^{\Delta}\right]$$

Δ: steepness of the cutoff (1, 2, or 3)

5 elements (H, He, N, Si, Fe)

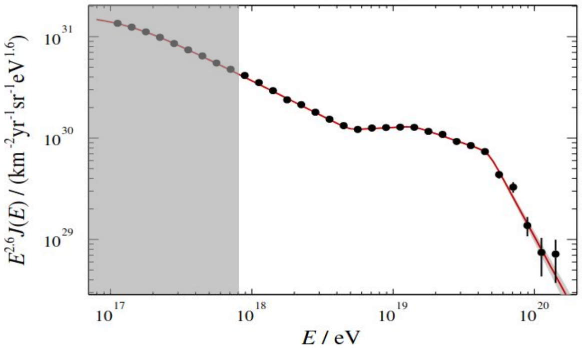
2) CRs propagated with SimProp (*JCAP 11 (2017) 009*): interactions with CMB & Gilmore EBL radiation backgrounds, TALYS photodisintegration

3) Account for EGMF multiplying by the suppression factor $G(E/E_{crit}, X_s)$

4) Air shower interactions modelled with EPOS-LHC or Sibyll2.3d

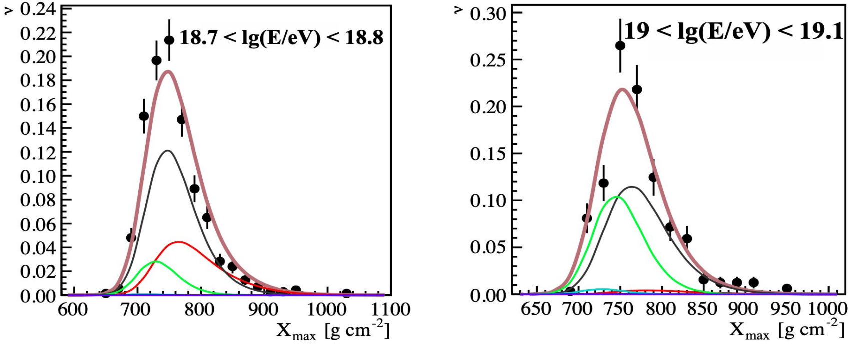
DATASETS (E > $10^{17.8}$ eV)

SPECTRUM (N_{data} = 24)



Eur. Phys JC 81 (2021) 966

X_{max} DISTRIBUTIONS (N_{data} = 329)



A. Yushkov, for Auger, PoS ICRC2019 (2020) 482

Fit Procedure

$$L_J = \prod_i \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{(J_i^{mod} - J_i^{obs})^2}{2\sigma_i^2}\right)$$

$$L_{X_{max}} = \sum_i n_i^{obs}! \sum_j \frac{1}{k_{i,j}^{obs}!} (G_{i,j}^{mod})^{k_{i,j}^{obs}}$$

$G_{i,j}^{mod}$: *Gumbel + resolution & acceptance*

Minimize the deviance

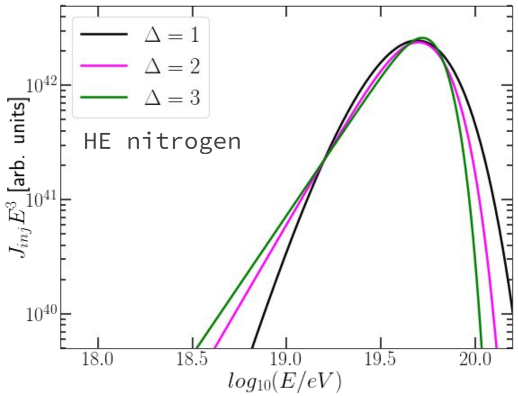
$$D = -2ln\left(\frac{L_J}{L_J^{sat}}\right) - 2ln\left(\frac{L_{X_{max}}}{L_{X_{max}}^{sat}}\right)$$

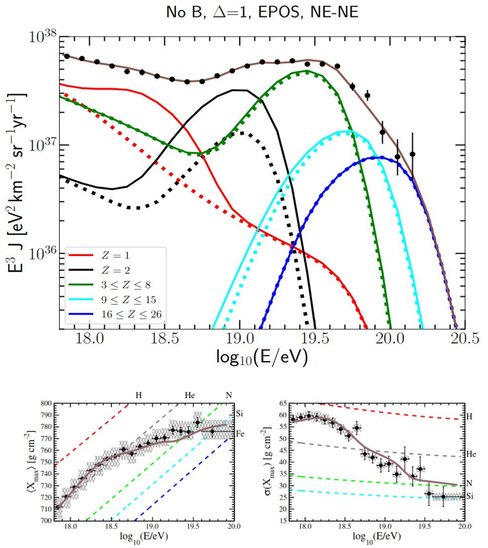
- Fit parameters: γ, R_{cut} and elemental fractions for both components
- X_s & R_{crit} for the less dense HE component

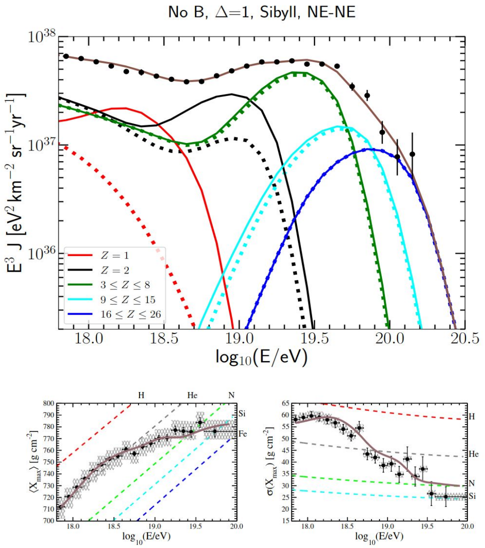
RESULTS OBTAINED IN THE ABSENCE OF MAGNETIC FIELDS

no EGMF, NE-NE

	EPOS-LHC					Sibyll 2.3d				
Δ	γ_H	R^H_{cut} [EeV]	γ_L	R^L_{cut} [EeV]	D ($N = 353$)	γ_H	R^H_{cut} [EeV]	γ_L	R^L_{cut} [EeV]	D ($N = 353$)
1	-2.19	1.35	3.54	> 60	572	-1.67	1.42	3.36	2.21	660
2	0.16	5.75	3.65	> 52	605	0.51	5.96	3.53	> 27	661
3	0.56	7.41	3.75	> 41	651	0.81	7.49	3.64	> 29	699







▪ ▪ ▪ primaries

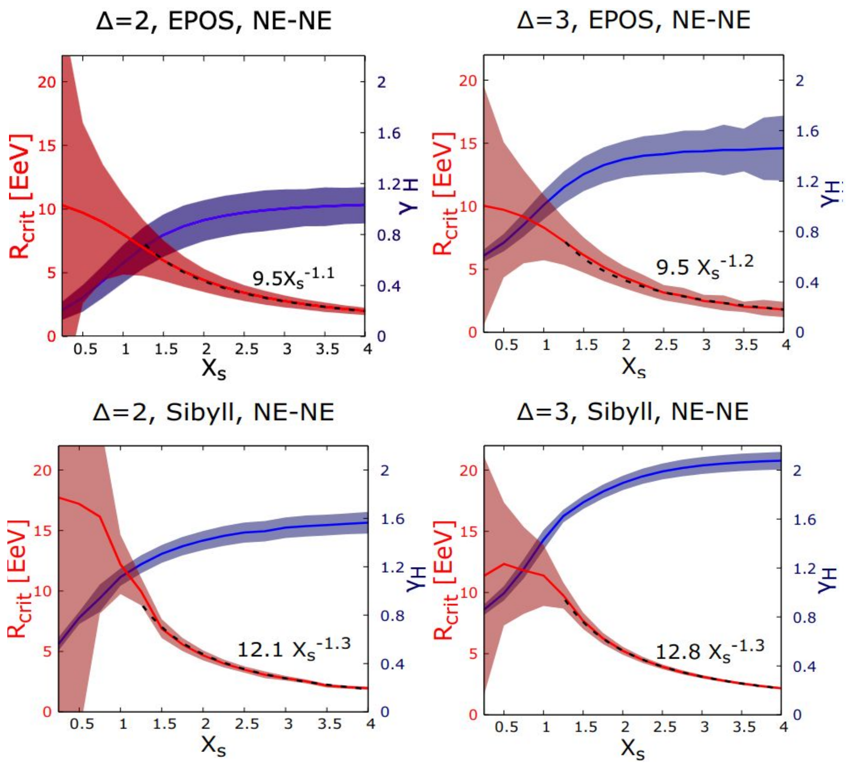
▬ primaries + secondaries

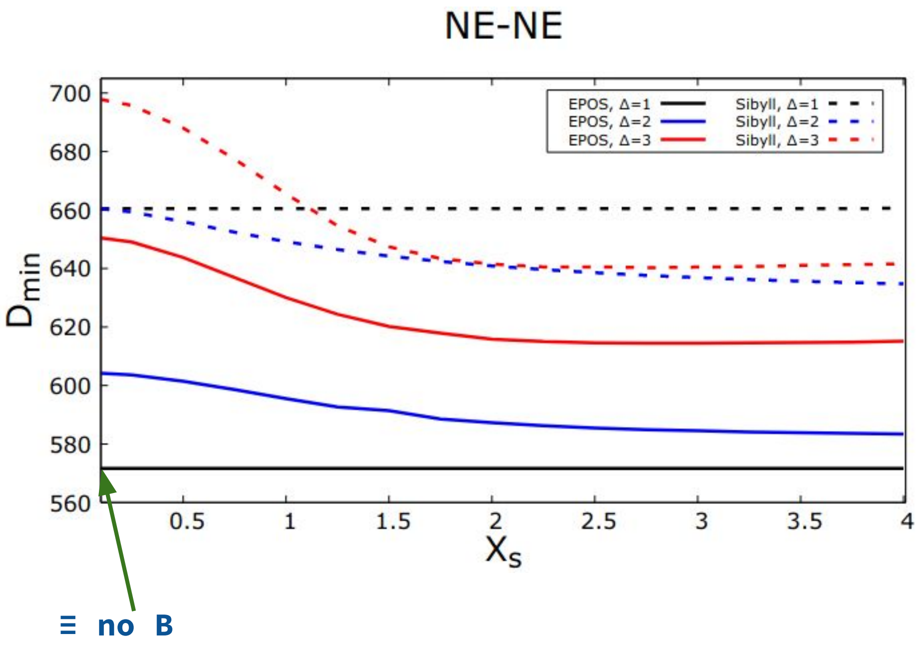
- **Δ=1 cutoff** leads to the **smallest deviance**, with the **hardest HE spectrum (γ<-1.6)**
- **Steeper cutoffs**, produce **softer HE spectra (0<γ<1)**
- **Sibyll** produces a **softer HE spectrum** with **larger deviances**
- **Scenarios** with **no B** result in **HE spectra with γ<1**

FIT INCLUDING MHE AS A FUNCTION OF X_s

$$X_s = \frac{d_s}{\sqrt{r_H L_{coh}}} \simeq \frac{d_s}{25\,\mathrm{Mpc}}\sqrt{\frac{\mathrm{Mpc}}{L_{coh}}}$$

$$r_H = c/H_0$$



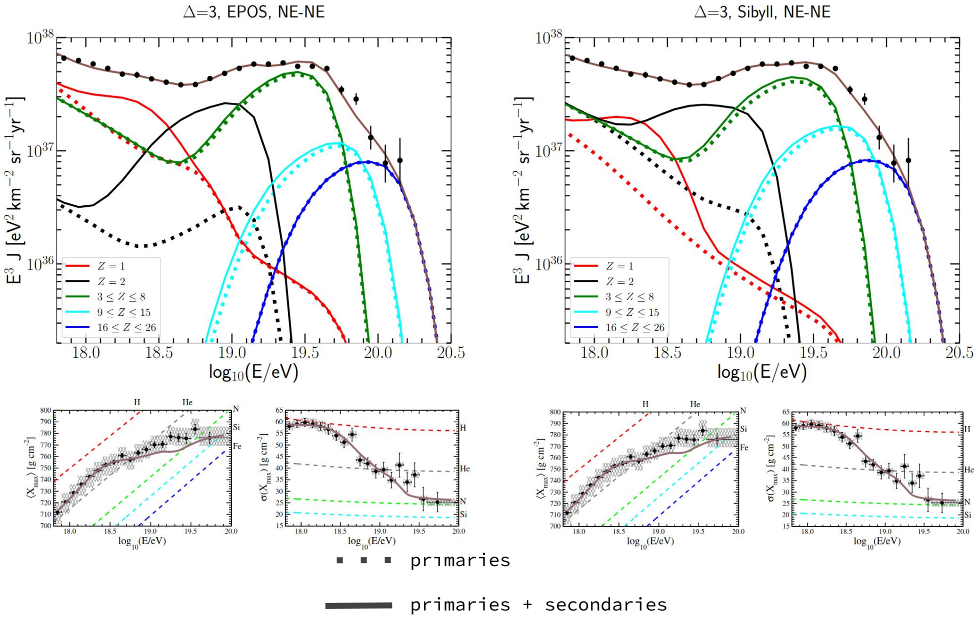


- **Larger X_s** results in **softer spectra** and **smaller R_{crit}**
- When MHE is relevant (X_s > 1), best fit for **$X_s R_{crit}$~ 10 EeV**
- Deviance is almost degenerate for $X_s \geq 2$

BEST FIT RESULTS

with EGMF, NE-NE

	EPOS-LHC							Sibyll 2.3d						
Δ	γ_H	R^H_{cut} [EeV]	γ_L	R^L_{cut} [EeV]	X_s	R_{crit} [EeV]	D ($N = 353$)	γ_H	R^H_{cut} [EeV]	γ_L	R^L_{cut} [EeV]	X_s	R_{crit} [EeV]	D ($N = 353$)
1	−2.19	1.35	3.54	> 60	0	–	572	−1.67	1.42	3.37	2.21	0	–	660
2	1.03	6.02	3.62	> 51	> 3.2	1.97	583	1.35	6.22	3.53	> 25	> 3.1	1.54	635
3	1.43	7.50	3.69	> 61	2.8	2.79	614	2	7.50	3.62	> 31	2.6	3.77	640
	SFR-NE													
1	−2.09	1.39	3.24	> 63	0	–	578	−1.64	1.44	3.03	2.89	0	–	665
2	1.12	6.14	3.33	> 61	> 3.5	2.11	586	1.45	6.29	3.21	> 37	> 3.2	1.67	635
3	1.49	7.52	3.41	> 57	2.7	3.15	617	2.07	7.49	3.31	> 33	2.8	3.52	637



- **Δ=1 cutoff** leads to **results close to** the case with **B=0**
- **Steeper cutoffs**, produce **softer HE spectra (γ>1)**
- **Sibyll, Δ=3** produces a **HE spectrum consistent with expectations from diffusive shock acceleration**
- For a given scenario, **SFR evolution** of the **LE component** hardens its spectrum by about 0.3 units with a **small effect in deviance**

FIT PARAMETERS WITH STATISTICAL UNCERTAINTIES

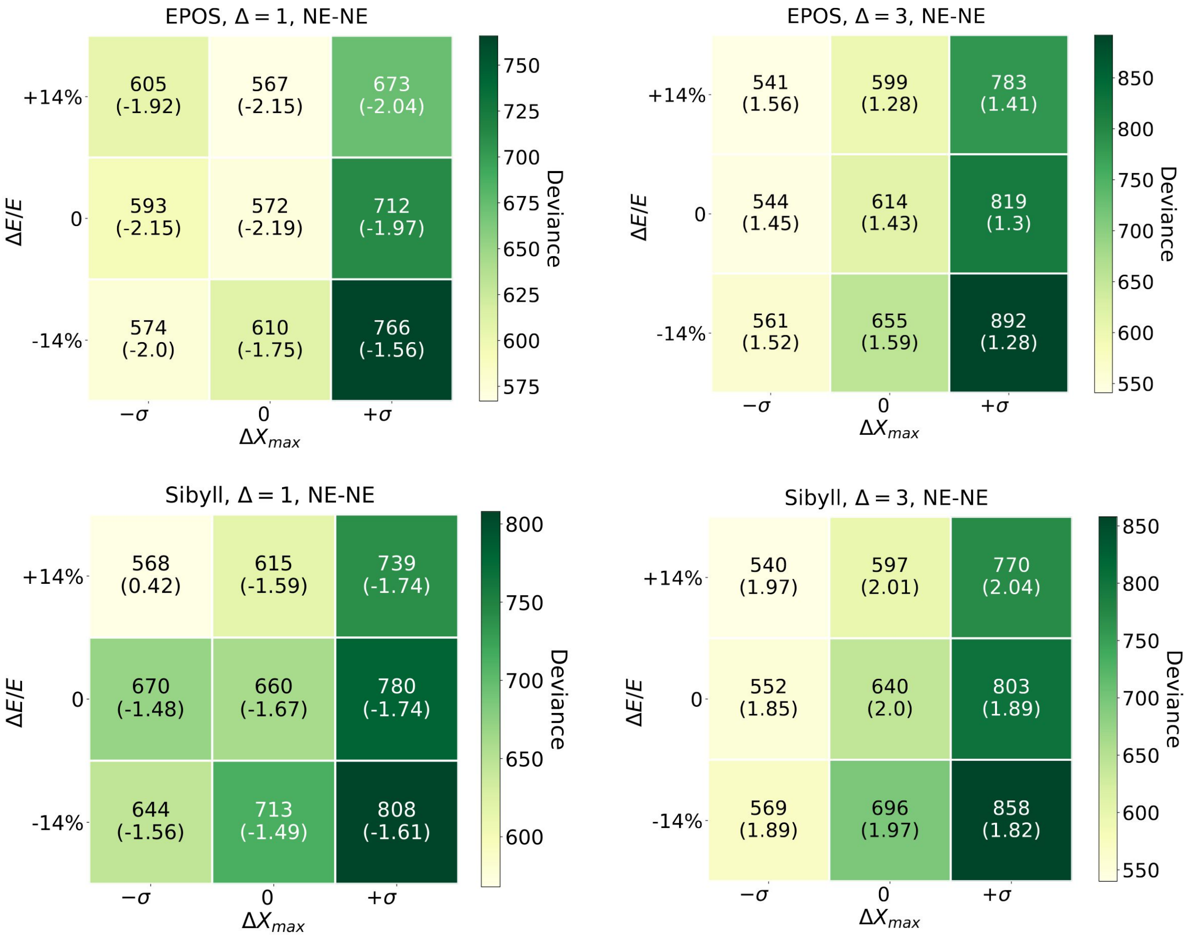
NE-NE	EPOS-LHC		Sibyll 2.3d	
Δ	1	3	1	3
X_s	—	$2.8^{+1.2}_{-0.7}$	—	$2.6^{+1.1}_{-0.5}$
R_{crit} [EeV]	—	2.8 ± 1.5	—	3.8 ± 1.4
High energy				
γ_H	-2.19 ± 0.10	$1.43^{+0.16}_{-0.22}$	-1.67 ± 0.13	$2.00^{+0.10}_{-0.11}$
R^H_{cut} [EeV]	1.35 ± 0.04	7.50 ± 0.15	1.42 ± 0.05	$7.50^{+0.18}_{-0.20}$
f_H	< 0.1	21 ± 11	$< 10^{-3}$	$< 10^{-2}$
f_{He}	$98.6^{+0.1}_{-0.2}$	10.1 ± 5.9	97.1 ± 0.6	5.0 ± 5.0
f_N [%]	$1.4^{+0.3}_{-0.5}$	$61.9^{+8.8}_{-10.4}$	$2.8^{+0.7}_{-0.6}$	$75.4^{+9.1}_{-9.7}$
f_{Si}	$< 10^{-3}$	$5.0^{+2.7}_{-2.4}$	$< 10^{-2}$	$15.2^{+4.7}_{-5.4}$
f_{Fe}	$< 10^{-4}$	$1.5^{+0.9}_{-0.7}$	$< 10^{-3}$	$4.4^{+1.7}_{-1.9}$
L^H_{44}	5.0 ± 0.1	9.3 ± 2.6	4.9 ± 0.1	18.4 ± 2.9
Low energy				
γ_L	3.54 ± 0.03	3.69 ± 0.04	$3.37^{+0.04}_{-0.05}$	3.62 ± 0.04
R^L_{cut} [EeV]	> 60	> 49	$2.21^{+0.55}_{-0.48}$	> 30
f_H	47.9 ± 2.6	51.7 ± 2.3	17.7 ± 2.5	21.9 ± 2.1
f_{He}	7.5 ± 4.1	4.8 ± 3.6	$43.5^{+3.6}_{-3.8}$	$38.1^{+3.4}_{-3.7}$
f_N [%]	$44.6^{+2.2}_{-2.5}$	$43.4^{+1.7}_{-2.5}$	38.7 ± 2.0	39.9 ± 1.9
f_{Si}	$< 10^{-4}$	$< 10^{-2}$	$< 10^{-4}$	$< 10^{-7}$
f_{Fe}	$< 10^{-5}$	$< 10^{-2}$	$< 10^{-5}$	$< 10^{-4}$
L^L_{44}	11.0 ± 0.2	11.6 ± 0.2	10.8 ± 0.1	11.4 ± 0.4
$D\,(N = 353)$	572	614	660	640

- The MHE increases the required luminosity of the sources
- Since only a fraction of the low energy accelerated particles reach the Earth, a higher emission rate at the sources is needed

$$L^a_A \equiv \int_{E_{th}}^{\infty} \mathrm{d}E\, E\tilde{Q}^a_A(E, z=0)$$

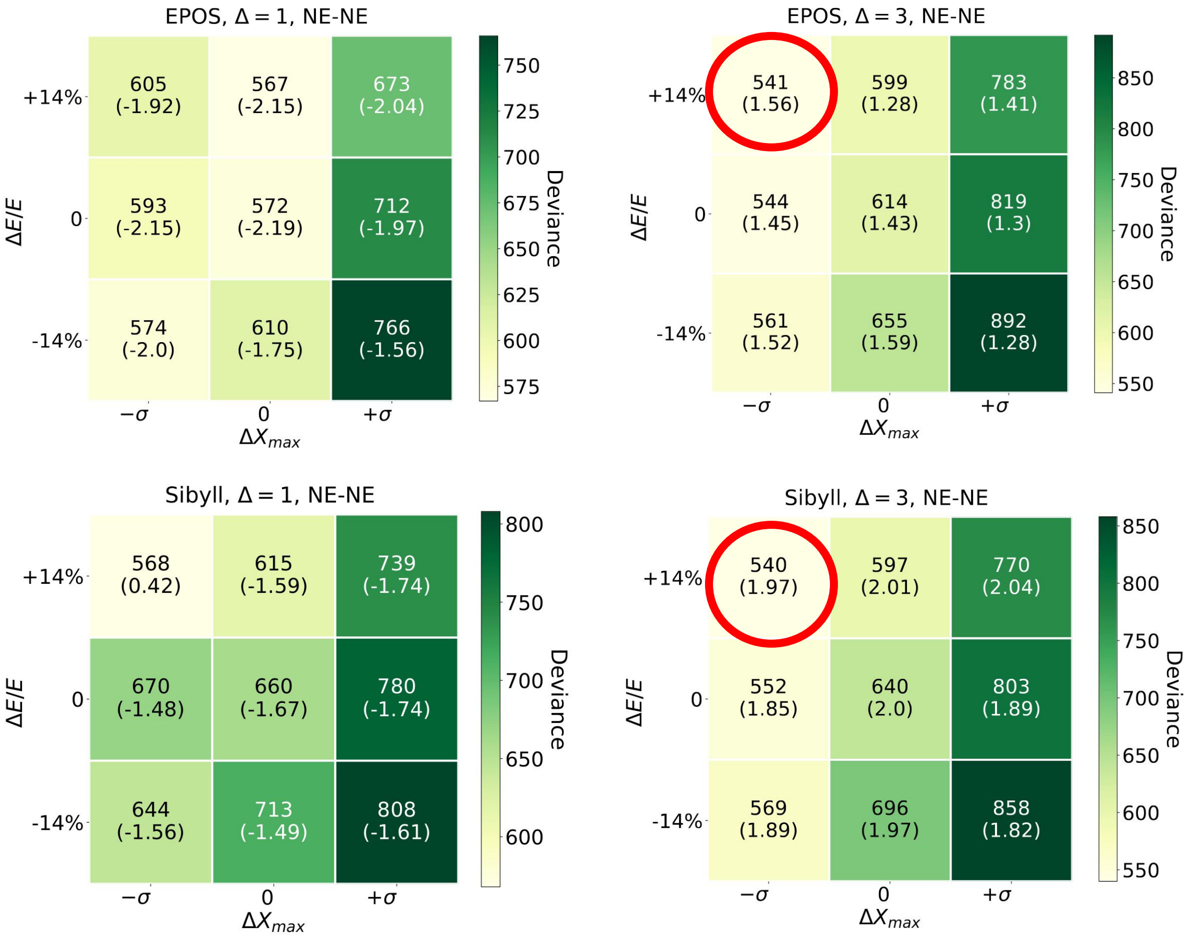
$$L^a_{44} \equiv \sum_A L^a_A / (10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}})$$

EFFECT OF SYSTEMATIC UNCERTAINTIES



- When including EGMF the **fit generally improves** for a **positive shift in energy and a negative shift in X_{max}**
- The **smallest deviance** is reached for **Δ=3 cutoff, ΔE/E=+14% & $\Delta X_{max}=-\sigma$**

EFFECT OF SYSTEMATIC UNCERTAINTIES



- When including EGMF the **fit generally improves** for a **positive shift in energy and a negative shift in X_{max}**
- The **smallest deviance** is reached for **Δ=3 cutoff, ΔE/E=+14% & ΔX_{max}=−σ**

EFFECT OF SYSTEMATIC UNCERTAINTIES

Sibyll 2.3d, $\Delta = 3$, NE-NE

$\Delta X_{\max}$	$\Delta E/E$		γ	$R_{\rm cut}$ [EeV]	$X_{\rm s}$	$R_{\rm crit}$ [EeV]	$f_{\rm H}$ [%]	$f_{\rm He}$ [%]	$f_{\rm N}$ [%]	$f_{\rm Si}$ [%]	$f_{\rm Fe}$ [%]	L_{44}	D $N = 353$
$-\sigma_{\rm sys}$	−14%	LE	3.53	> 26	—	—	25.7	12.7	61.6	0	0	10.0	569
		HE	1.89	7.11	3.34	1.72	0	0	83.9	11.8	4.3	8.7	
	0	LE	3.51	2.8	—	—	26.6	4.0	59.6	9.8	0	11.7	552
		HE	1.85	7.88	> 3.8	1.30	0	0	70.5	24.8	4.7	9.5	
	+14%	LE	3.49	> 34	—	—	24.1	8.3	40.4	27.2	0	13.2	540
		HE	1.97	8.75	> 3.2	1.39	0	0	59.7	33.1	7.2	13.7	
0	−14%	LE	3.66	> 26	—	—	18.1	60.0	21.9	0	0	9.5	696
		HE	1.97	6.69	> 3.5	2.12	0	14.2	73.7	8.5	3.6	15.1	
	0	LE	3.62	> 30	—	—	21.9	38.1	39.0	0	0	11.20	640
		HE	2.00	7.50	2.6	3.77	0	4.89	75.4	15.3	4.4	18.4	
	+14%	LE	3.60	> 63	—	—	27.4	16.8	55.8	0	0	13.0	597
		HE	2.01	8.17	2.1	5.10	0.9	0	69.6	24.2	5.3	22.6	
$+\sigma_{\rm sys}$	−14%	LE	3.73	> 33	—	—	24.9	75.1	0	0	0	9.5	858
		HE	1.82	6.92	> 3.8	2.73	0	17.7	76.9	2.4	3.0	15.2	
	0	LE	3.72	> 39	—	—	18.7	70.8	10.5	0	0	10.9	803
		HE	1.89	7.40	> 2.7	2.77	0	10.7	76.0	9.2	4.1	21.1	
	+14%	LE	3.76	> 39	—	—	20.7	52.7	26.6	0	0	12.4	770
		HE	2.04	7.80	> 2.3	2.94	0	5.6	74.6	14.0	5.8	33.9	

- The **best fit scenario** has a **large X_s value** with a LE component dominated by protons, He and N and the **HE one dominated by N**, with a significant Si contribution
- $\gamma_H \approx 2$ in all cases, $X_s R_{crit} \sim$ 5 EeV for best fit scenarios
- Positive shifts in X_{max} for Sibyll and Δ=3 are disfavoured by more than a 100 units

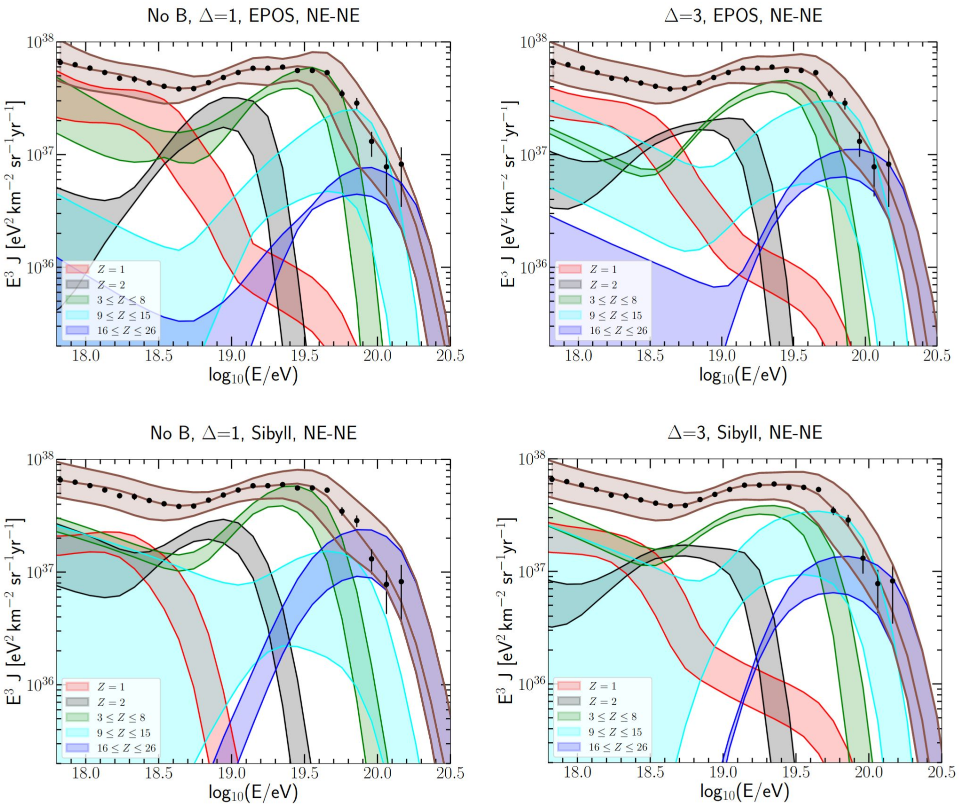
EFFECT OF SYSTEMATIC UNCERTAINTIES

Sibyll 2.3d, $\Delta = 3$, NE-NE

$\Delta X_{\max}$	$\Delta E/E$		γ	$R_{\rm cut}$ [EeV]	$X_{\rm s}$	$R_{\rm crit}$ [EeV]	$f_{\rm H}$ [%]	$f_{\rm He}$ [%]	$f_{\rm N}$ [%]	$f_{\rm Si}$ [%]	$f_{\rm Fe}$ [%]	L_{44}	D $N = 353$
$-\sigma_{\rm sys}$	−14%	LE	3.53	> 26	—	—	25.7	12.7	61.6	0	0	10.0	569
		HE	1.89	7.11	3.34	1.72	0	0	83.9	11.8	4.3	8.7	
	0	LE	3.51	2.8	—	—	26.6	4.0	59.6	9.8	0	11.7	552
		HE	1.85	7.88	> 3.8	1.30	0	0	70.5	24.8	4.7	9.5	
	+14%	LE	3.49	> 34	—	—	24.1	8.3	40.4	27.2	0	13.2	540
		HE	1.97	8.75	> 3.2	1.39	0	0	59.7	33.1	7.2	13.7	
0	−14%	LE	3.66	> 26	—	—	18.1	60.0	21.9	0	0	9.5	696
		HE	1.97	6.69	> 3.5	2.12	0	14.2	73.7	8.5	3.6	15.1	
	0	LE	3.62	> 30	—	—	21.9	38.1	39.0	0	0	11.20	640
		HE	2.00	7.50	2.6	3.77	0	4.89	75.4	15.3	4.4	18.4	
	+14%	LE	3.60	> 63	—	—	27.4	16.8	55.8	0	0	13.0	597
		HE	2.01	8.17	2.1	5.10	0.9	0	69.6	24.2	5.3	22.6	
$+\sigma_{\rm sys}$	−14%	LE	3.73	> 33	—	—	24.9	75.1	0	0	0	9.5	858
		HE	1.82	6.92	> 3.8	2.73	0	17.7	76.9	2.4	3.0	15.2	
	0	LE	3.72	> 39	—	—	18.7	70.8	10.5	0	0	10.9	803
		HE	1.89	7.40	> 2.7	2.77	0	10.7	76.0	9.2	4.1	21.1	
	+14%	LE	3.76	> 39	—	—	20.7	52.7	26.6	0	0	12.4	770
		HE	2.04	7.80	> 2.3	2.94	0	5.6	74.6	14.0	5.8	33.9	

- The **best fit scenario** has a **large X_s value** with a LE component dominated by protons, He and N and the **HE one dominated by N**, with a significant Si contribution
- $\gamma_H \approx 2$ in all cases, $X_s R_{crit} \sim 5$ EeV for best fit scenarios
- Positive shifts in X_{max} for Sibyll and Δ=3 are disfavoured by more than a 100 units

EFFECT OF SYSTEMATIC UNCERTAINTIES



Systematic uncertainties for ΔE/E=0,±14% and the best fitting ΔX_{max} for each case

- Large uncertainties in the Si and Fe flux for the LE component
- In most cases the instep is due to a He bump.
- In all cases the N contribution dominates the flux between the instep and the high energy suppression

CONCLUSIONS

- For **Δ=2 & 3 and $X_s \gtrsim 2$** we found scenarios where the magnetic horizon plays an important role with **better deviance than for B=0**, and with **softer spectral index for the HE component ($\gamma \in [1,2]$)**

- **Sibyll2.3d** leads to **spectral indices** for the **HE component closer to 2**

- EPOS-LHC leads to smaller deviances, but systematic shifts can change this

- Larger X_s results in smaller R_{crit} and a softer spectrum

- We find that $X_s R_{crit} \sim (5 - 10)$ EeV when the magnetic horizon effect is responsible for the hardness of the observed spectrum

$$X_s R_{crit} \simeq 5 \text{ EeV} \frac{d_s}{20\,\text{Mpc}} \frac{B_{rms}}{50\,\text{nG}} \sqrt{\frac{L_{coh}}{100\,\text{kpc}}}$$

→ **large inter-source distances and strong magnetic fields** required between Earth and the closest sources

- When the MHE effect plays an important role, the fit improves for a positive shift in energy and a negative shift in X_{max}

- The best fit results were obtained for the case with **Sibyll, Δ=3 cutoff, ΔE/E=+14% & $\Delta X_{max}=-\sigma$**

CONCLUSIONS

- For **Δ=2 & 3 and X_s ≳ 2** we found scenarios where the magnetic horizon plays an important role with **better deviance than for B=0**, and with **softer spectral index for the HE component (γ ∈ [1,2])**
- **Sibyll2.3d** leads to **spectral indices** for the **HE component closer to 2**
- EPOS-LHC leads to smaller deviances, but systematic shifts can change this
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$$X_s R_{crit} \simeq 5\ \mathrm{EeV} \frac{d_s}{20\,\mathrm{Mpc}} \frac{B_{rms}}{50\,\mathrm{nG}} \sqrt{\frac{L_{coh}}{100\,\mathrm{kpc}}}$$

→ **large inter-source distances and strong magnetic fields** required between Earth and the closest sources

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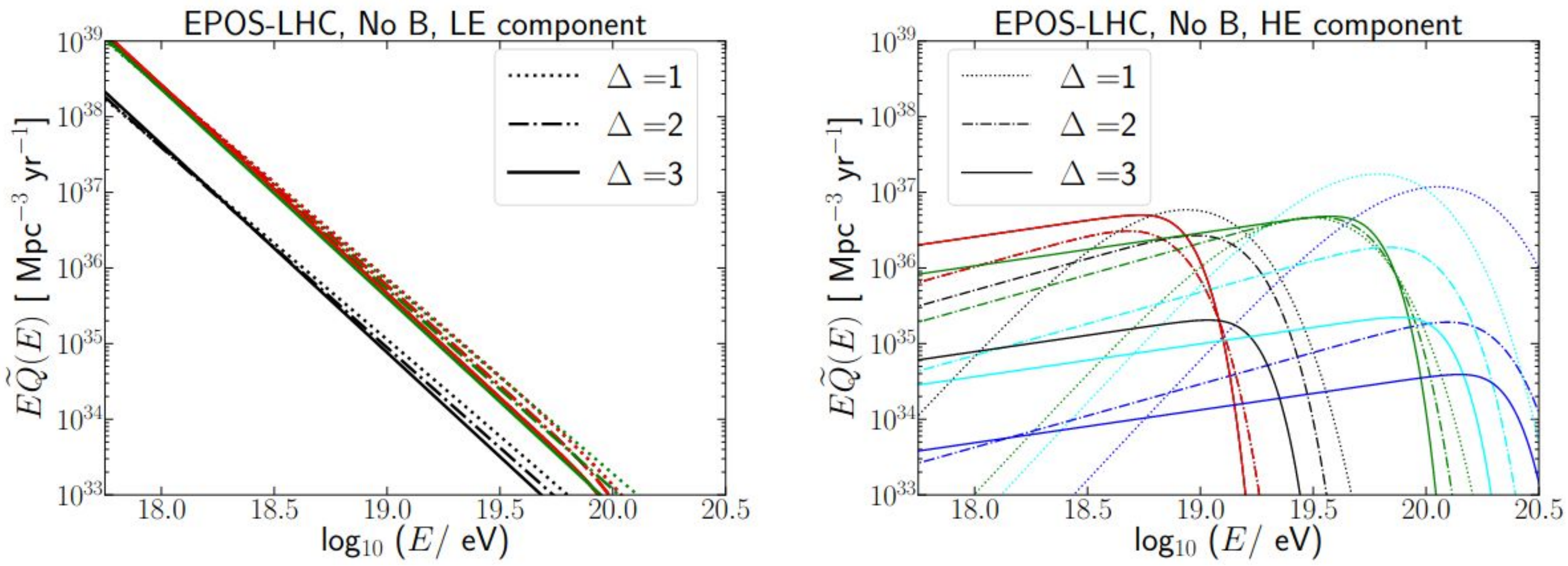
- The best fit results were obtained for the case with **Sibyll, Δ=3 cutoff, ΔE/E=+14% & ΔX_{max}=-σ**

Thank you!

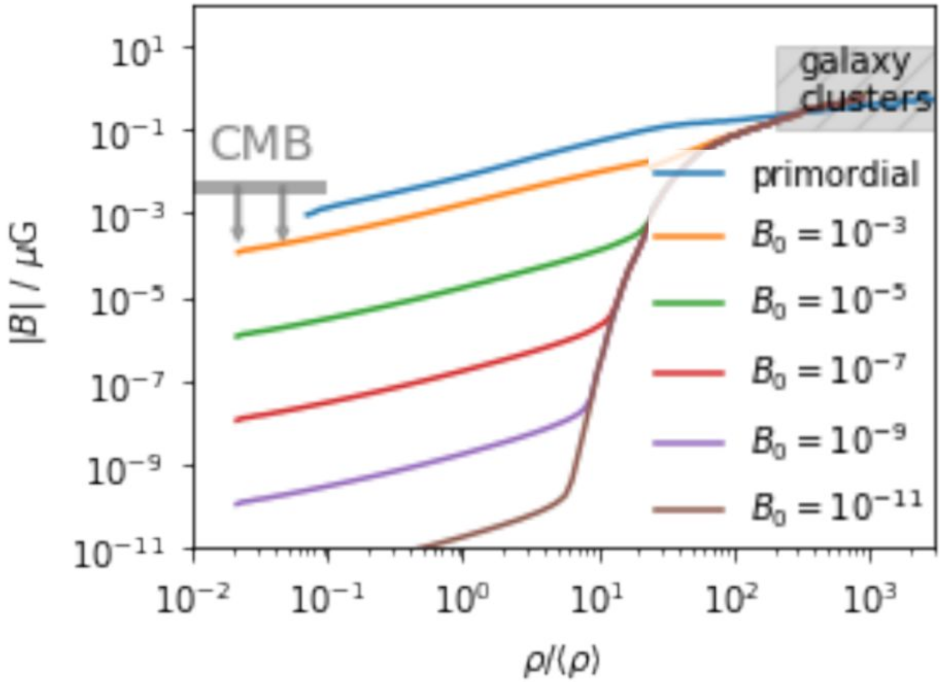
Backup slides

Effect of the cutoff shape on the injected spectra



Notice how the parameters combine to produce a similar shape at the energy at which each element is dominant

EXTRAGALACTIC MAGNETIC FIELDS EXPECTATIONS



Median magnetic field strength |B| as function of over-density ρ/<ρ> for a number of MHD models with identical dynamo physics, starting with different strengths of the primordial magnetic field B0 , indicated by the label in μG

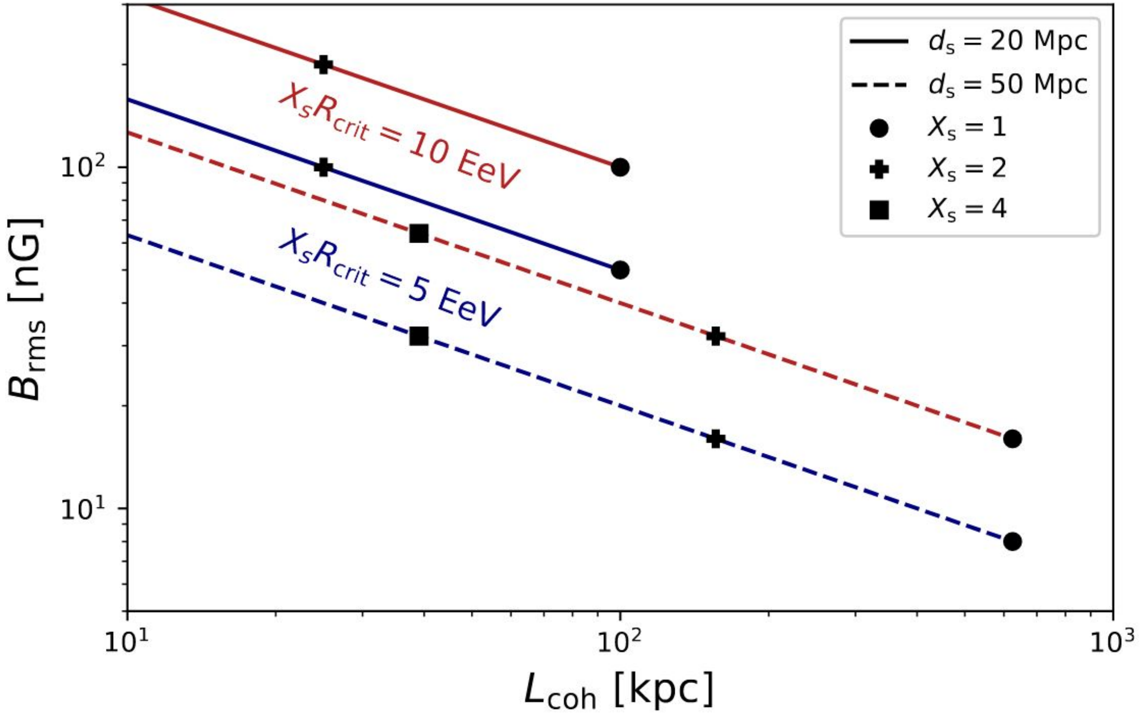
Hackstein, Brüggen, Vazza & Rodrigues, MNRAS (2020) 498 4811

Required magnetic fields close to the maximum values

B_{rms} vs. L_{coh}

$$X_s R_{crit} \simeq 5\ \mathrm{EeV} \frac{d_s}{20\,\mathrm{Mpc}} \frac{B_{rms}}{50\,\mathrm{nG}} \sqrt{\frac{L_{coh}}{100\,\mathrm{kpc}}}$$

$$d_s > 20\mathrm{Mpc}\sqrt{\frac{\mathrm{L_{coh}}}{100\mathrm{kpc}}}$$



- Scenarios with magnetic horizon require strong magnetic fields within the Local Supercluster and large inter-source separation (low source density)