A Heavy-Metal Scenario of UHECR

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Abstract

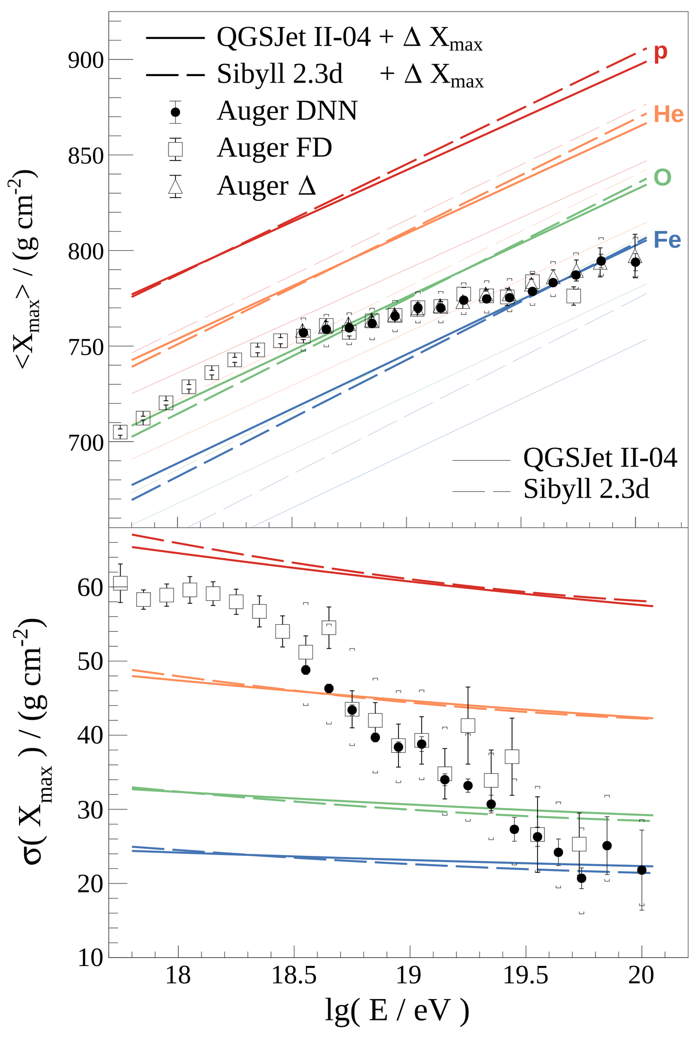
We assume an extreme scenario, in which the arriving cosmic rays are composed of **only iron nuclei at energies above $10^{19.6}$ eV**, while allowing a freedom in the scale of the depth of shower maximum ($X_{\max}$) and preserving the elongation rate a fluctuations of $X_{\max}$ predicted by models of hadronic interactions. We derive the **shift of the $X_{\max}$ scale for QGSJet-II-04 and Sibyll 2.3d** using the public data from the Pierre Auger Observatory. We then propose a **new mass-composition model** for the energy evolution of four primary species at the ultra-high energies by fitting the publicly-available $X_{\max}$ distributions. We show in detail the **consequences of our new mass-composition model on the hadronic interactions studies, energy spectrum of individual primaries, and the effect of the Galactic magnetic field (GMF) on the arrival directions**.

1. Assumptions

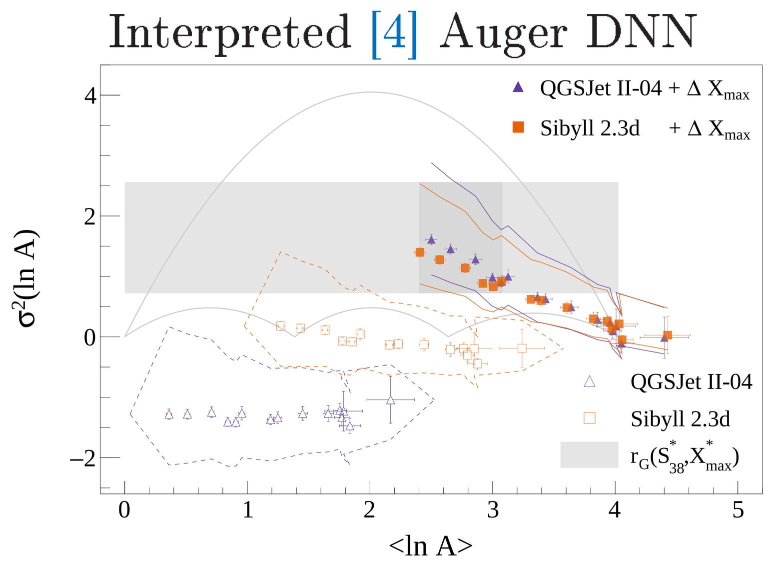
1. $X_{\max}$ fluctuations and elongation rate from Sibyll 2.3d [1] and QGSJet-II-04 [2]
2. Pure iron nuclei above $10^{19.6}$ eV
3. Freedom in predicted $X_{\max}$ scale, derived from Auger DNN [3]

   $\Rightarrow \Delta X_{\max} = 29 \pm 1\,^{+12}_{-7}$ g/cm^2 for Sibyll 2.3d

   $\Rightarrow \Delta X_{\max} = 52 \pm 1\,^{+11}_{-8}$ g/cm^2 for QGSJet-II-04



Interpreted [4] Auger DNN



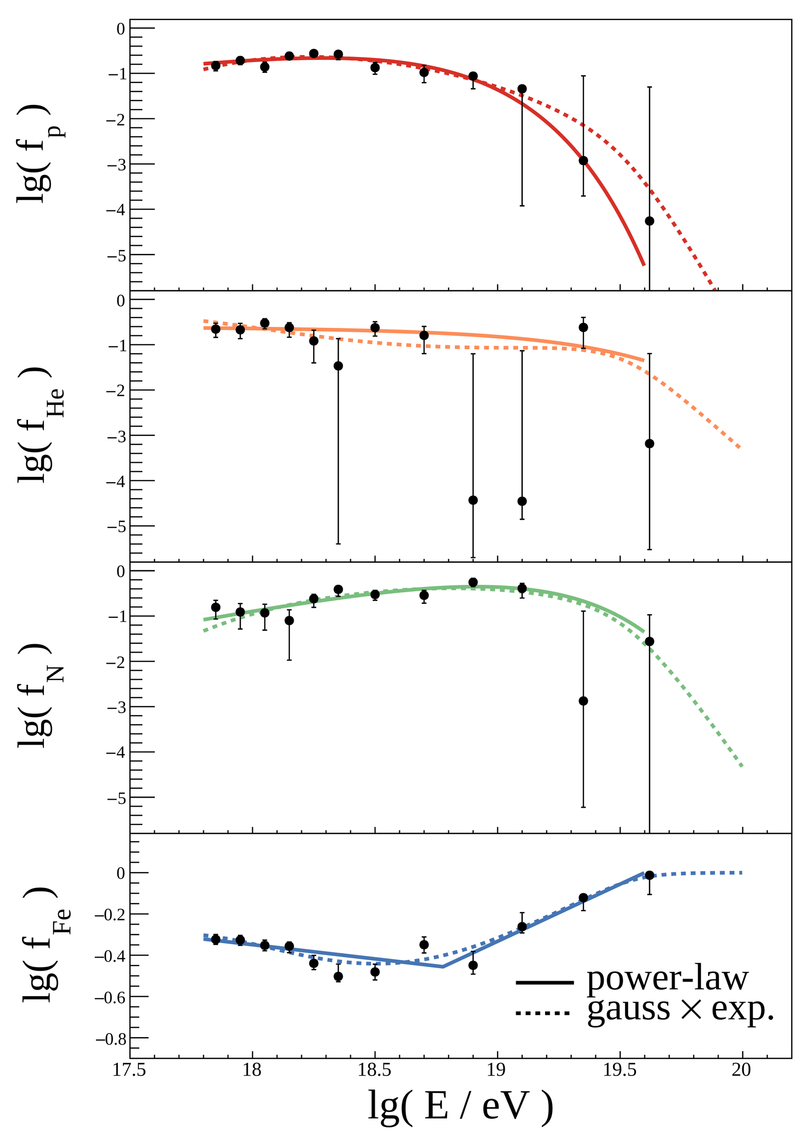
- **$\Delta X_{\max}$ consistent with [$X_{\max}$,$S(1000)$] fits [5]**
- **$\sigma^2(\ln A)$ consistent with $r_G(S^*_{38}, X^*_{\max})$ [6]**

2. Mass-Composition Model

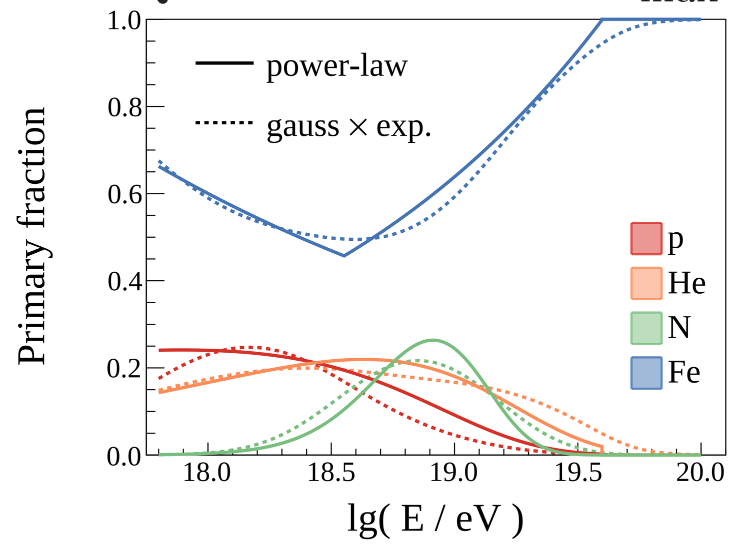
Energy evolution of primary fractions fitted by:

1. Power-law functions with breaks and exponential cutoff (solid lines)
2. Normalized gaussian ⊗ exponential functions (dotted lines)

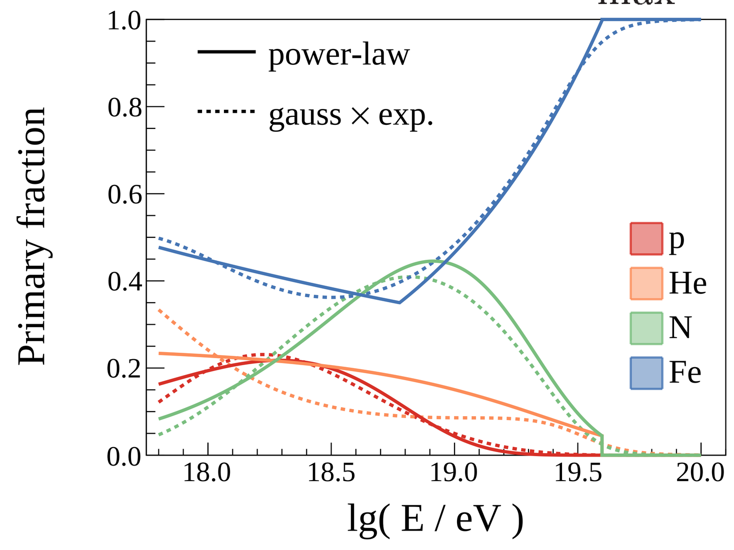
Auger FD $X_{\max}$ distributions [7] fitted by Sibyll 2.3d $+\Delta X_{\max}$



QGSJet-II-04 $+\Delta X_{\max}$

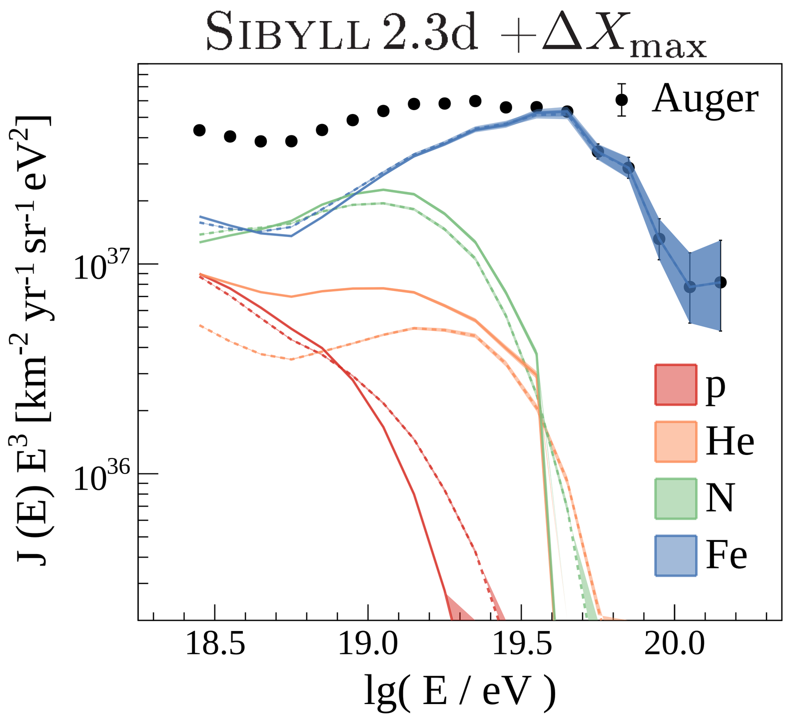


Sibyll 2.3d $+\Delta X_{\max}$

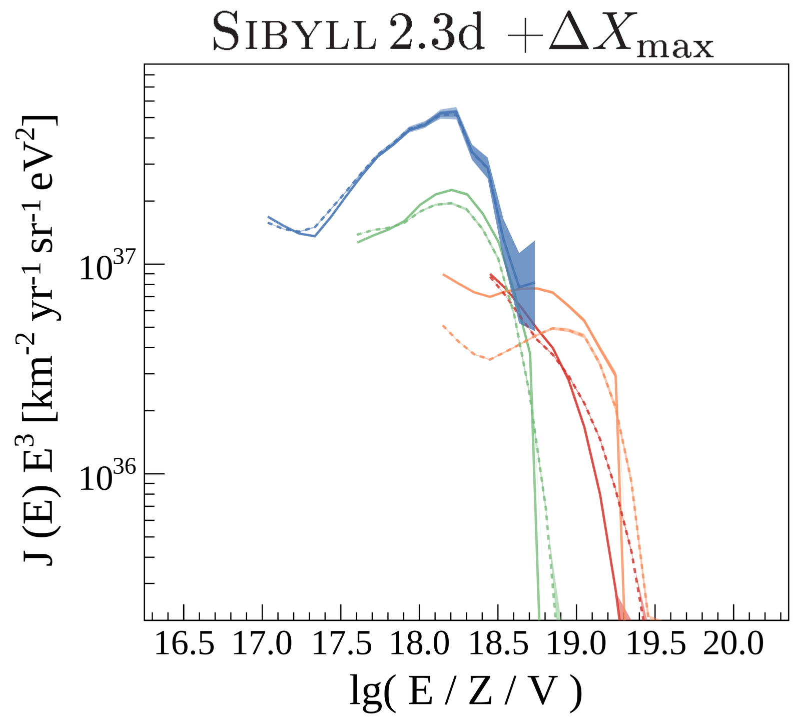


3. Energy Spectrum of Individual Primaries

Sibyll 2.3d $+\Delta X_{\max}$



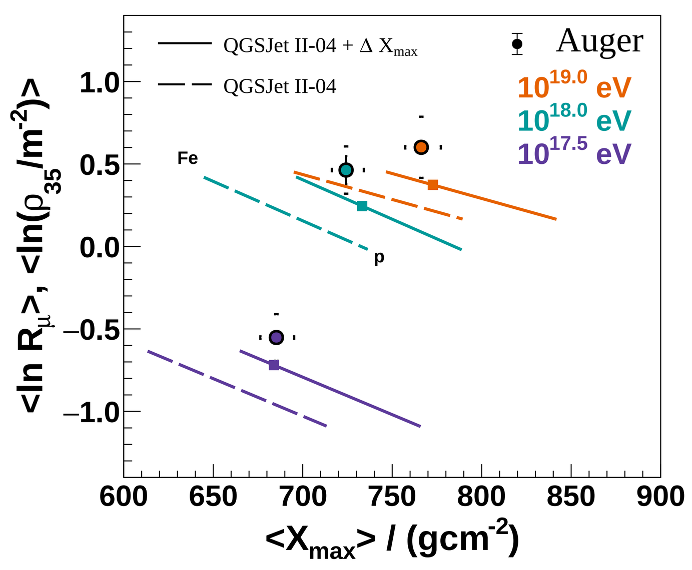
Sibyll 2.3d $+\Delta X_{\max}$

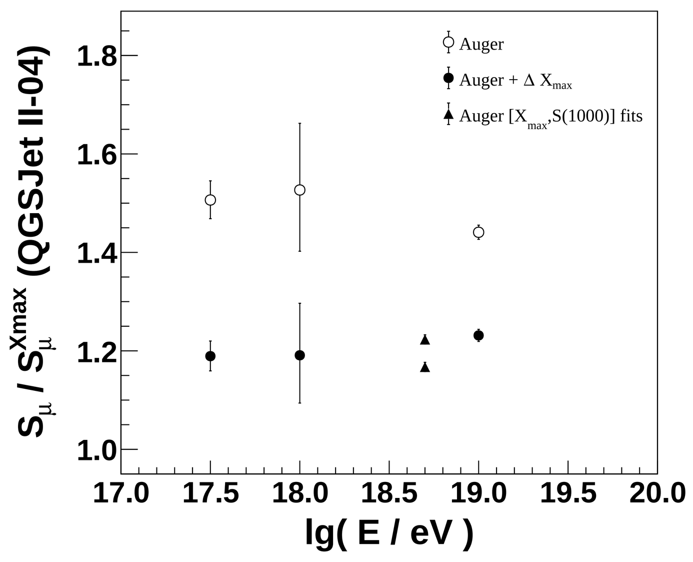


- Auger-flux [8] suppression caused by Fe nuclei by assumption
- **Instep caused by fading of N nuclei**
- Fe and N nuclei might originate in the same sources

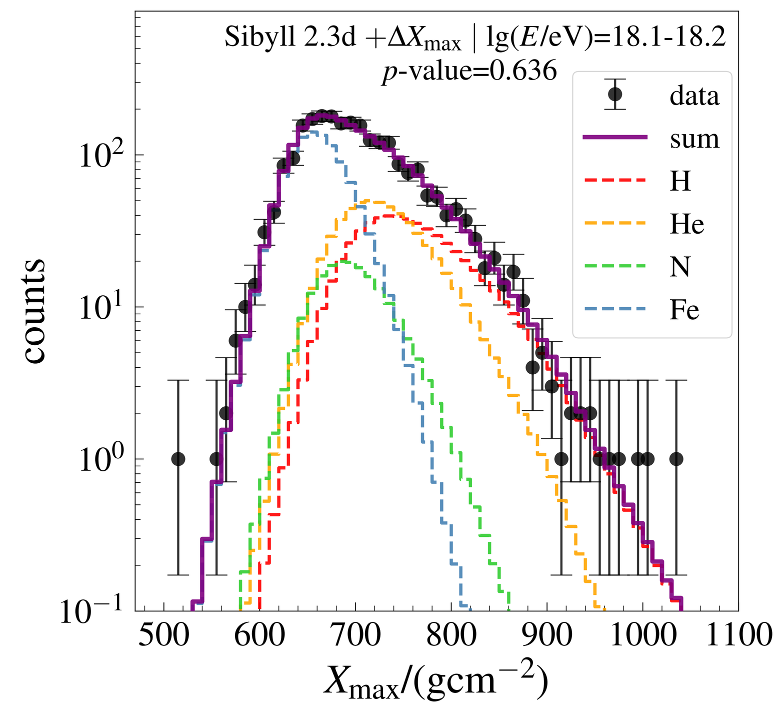
4. Hadronic Interaction Studies

Interpreting direct muon measurements [9,10] using QGSJet-II-04 predictions





Example of fitted $X_{\max}$ distribution measured by Auger [7] using templates for Sibyll 2.3d $+\Delta X_{\max}$

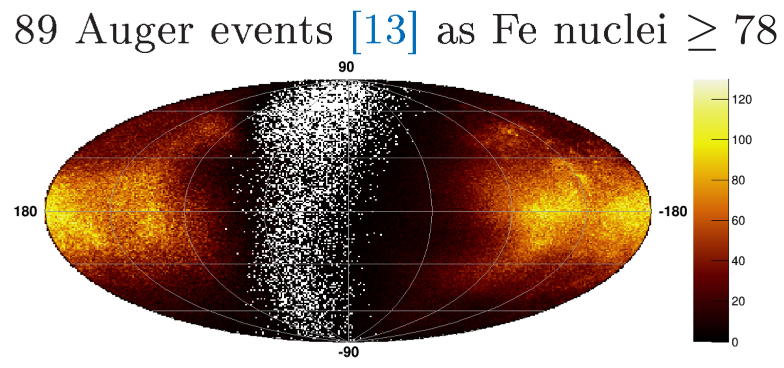


- **Muon deficit of QGSJet-II-04 ≈ 20%, ∼energy independent**
- **No need to modify elasticity or cross-section in Sibyll 2.3d**

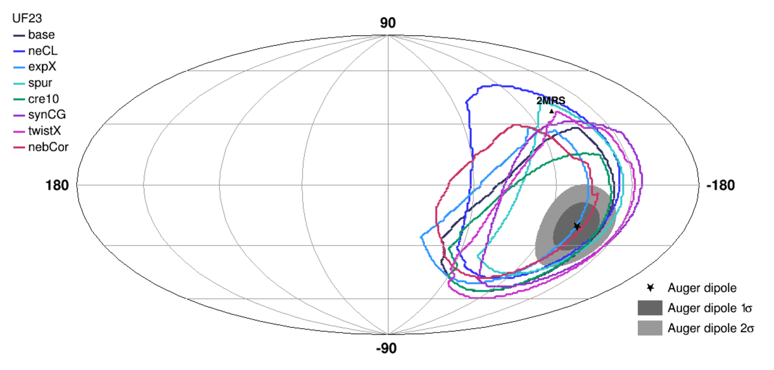
5. Effect of GMF on Arrival Directions

Backtracking particles using UF23 [11] models of GMF

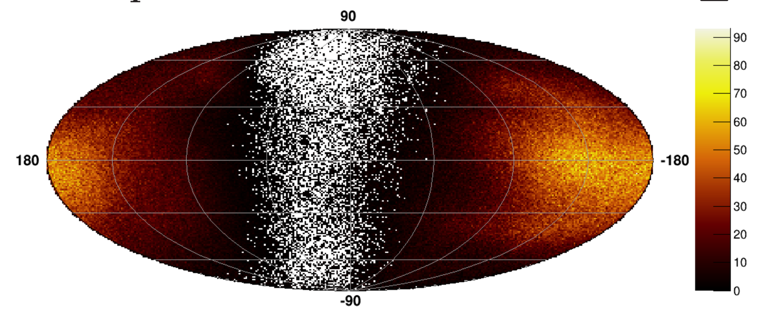
89 Auger events [13] as Fe nuclei ≥ 78 EeV



Directions of an extragalactic dipole above 8 EeV that are consistent within 2σ with Auger dipole [12] after accounting for the GMF effect



Isotropic distribution of Fe nuclei ≥ 78 EeV



References

[1] Phys. Rev. D **102** (2020) 063002. [2] Phys. Rev. D **83** (2011) 014018. [3] arXiv:2406.06315 [astro-ph.HE], accepted in Phys. Rev. D. [4] JCAP **02** (2013) 026. [5] Phys. Rev. D **109** (2024) 102001. [6] Phys. Lett. B **762** (2016) 288. [7] Phys. Rev. D **90** (2014) 122005. [8] Phys. Rev. D **102** (2020) 062005. [9] Eur. Phys. J. C **210** (2020) 751. [10] Phys. Rev. D **91** (2015) 032003. [11] ApJ **970** (2024) 1. [12] Science **357** (2017) 1266. [13] ApJS **264** (2023) 50.

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