PROCEEDINGS OF SCIENCE

Ultra-high-energy cosmic rays from accretion shocks in galaxy clusters

A.D. Supanitsky[a,*] **and S.E. Nuza**[b,*]

[a] *Instituto de Tecnologías en Detección y Astropartículas (ITeDA,CNEA-CONICET-UNSAM), Av. Gral Paz 1499, General San Martín, Argentina*

[b] *Instituto de Astronomía y Física del Espacio (IAFE,CONICET-UBA), Intendente Güiraldes 2160, Ciudad Autónoma de Buenos Aires, Argentina*

E-mail: daniel.supanitsky@iteda.gob.ar, snuza@iafe.uba.ar

The origin of ultra-high-energy cosmic rays is still unknown. Despite strong evidence suggesting an extragalactic origin of the sources that accelerate the most energetic cosmic rays, they have not yet been identified. Galaxy cluster accretion shocks have been considered as a possible acceleration site for cosmic ray particles. External accretion shocks in galaxy clusters arise from the inflow of material in the cosmic web into their gravitational potential well. The size of these shocks can reach values on the order of megaparsecs, placing them among the largest shocks found in nature. In this work, we investigate the possibility that the ultra-high-energy cosmic rays are accelerated in galaxy cluster accretion shocks. For that purpose, we develop a model considering a set of discrete sources, corresponding to nearby massive clusters (including Virgo), superimposed to a continuous distribution of sources which considers both low-mass and non-local massive clusters. We fit the cosmic ray energy spectrum and the composition profile measured by the Pierre Auger Observatory in order to obtain a set of parameters corresponding to the injection spectrum assumed in the model. The possibility of ultra-high-energy cosmic rays being accelerated in these astronomical objects is examined. The impact of the high-energy hadronic interaction model used to analyse the composition data is also presented.

7th International Symposium on Ultra High Energy Cosmic Rays (UHECR2024)
17-21 November 2024
Malargüe, Mendoza, Argentina

*Speaker

https://pos.sissa.it/

PoS(UHECR2024)119

1. Introduction

Although the origin of ultra-high-energy cosmic rays (UHECRs) remains unknown, significant progress has been made in recent years, primarily due to the observatories currently in operation. These include the Pierre Auger Observatory (Auger) in the southern hemisphere [1] and the Telescope Array (TA) in the northern hemisphere [2].

The cosmic ray flux has been measured with great accuracy thanks to the very large exposure accumulated, particularly by Auger. It presents three features: a hardening at $\sim 5 \times 10^{18}$ eV, known as the ankle, a steepening at $\sim 10^{19}$ eV known as the instep; and a sharp drop at $\sim 5 \times 10^{19}$ eV known as the suppression [3, 4]. Although several models attempt to explain these features, their origin remains a topic of ongoing debate. The composition of the UHECRs is mainly determined from the atmospheric depth corresponding to the maximum air-shower development, X_{max}. This parameter can be measured with fluorescence telescopes, such as those in Auger and TA. The composition is determined by comparing the experimental data with simulations of the atmospheric air showers. Since the hadronic interactions relevant for the cosmic rays are unknown, these simulations are performed by using models that extrapolate the low-energy accelerator data to the highest energies. Even though the composition determination present systematic uncertainties originated by the use of different high-energy hadronic interaction models (HEHIMs), the Auger data, analysed with current versions of the HEHIMs, shows that the composition becomes progressively lighter from energies below 10^{18} eV up to $\sim 10^{18.3}$ eV, where a change occurs [5, 6]. Above this energy, the composition seems to become increasingly heavier.

Many potential sources of UHECRs have been proposed, one of which is the accretion shocks in galaxy clusters [7–10]. These immense shock waves can span radii on the order of megaparsecs, arising from the inflow of material from the intergalactic medium into the gravitational potential well of galaxy clusters. In this work, we investigate whether this type of source can explain the Auger data. To this end, we develop a model for the source and fit the flux and composition profile measured by Auger, assuming a mixed composition injected by the sources. Nearby, more massive clusters, such as Virgo, are considered based on their masses and distances, while the remaining clusters are assumed to be uniformly distributed. In particular, we study the impact on the fit caused by the use of different HEHIMs to infer the composition profile from the X_{max} data.

2. Source model

In this work, it is assumed that the particle acceleration in the accretion shocks occurs via the first-order Fermi mechanism, as described in [7]. The acceleration length of the cosmic ray particles is given by [11]

$$\lambda_{\text{acc}}(E) = \frac{\chi}{\chi - 1} \left(\frac{c}{v_{\text{sh}}} \right)^2 r_{\text{g}}(E)\, \eta\, \mathcal{J}(\theta, \chi, \eta)\,, \tag{1}$$

where χ is the compression ratio, c is the speed of light, v_{sh} is the shock velocity, r_{g} the gyroradius, θ is the angle between the magnetic field and the shock normal, η is the proportionality constant between the diffusion coefficient parallel to the magnetic field and the Bohm diffusion coefficient, and $\mathcal{J}(\theta, \chi, \eta)$ is a function given in [11].

In this study, the following parameter values are assumed: $\chi = 4$, corresponding to a strong shock; $\eta = 1$, which represents the Bohm diffusion coefficient; and $\theta = 45°$, chosen as a representative intermediate angle. This value is motivated by cosmological simulations, which suggest that the angle θ for accretion shocks in galaxy clusters is nearly uniformly distributed [12].

Magnetic fields at the shock fronts are assumed to be in equipartition with the thermal energy. The dependence of the magnetic field intensity, B, and the accretion shock velocity with respect to cluster mass are derived using a hybrid approach that combines insights from both cosmological simulations and observations. Specifically, the Mach number distribution around galaxy clusters is inferred from the simulations of Ref. [13], while the universal temperature and pressure profiles from Refs. [14] and [15] are used to model the global thermodynamic properties. The resulting expressions are

$$v_{\rm sh} \cong 2.83 \times 10^3 \left[\frac{M_{\rm vir}}{10^{15}\,{\rm M}_\odot} \right]^{0.33} {\rm km\,s^{-1}} \tag{2}$$

$$B \cong 1.71 \left[\frac{M_{\rm vir}}{10^{15}\,{\rm M}_\odot} \right]^{0.31} \mathcal{E}(z)^{4/3}\ \mu{\rm G}\,, \tag{3}$$

where $M_{\rm vir}$ is the galaxy cluster virial mass, z is the cosmological redshift of the cluster, and $\mathcal{E}(z) = \sqrt{\Omega_{\rm M}\,(1+z)^3 + \Omega_\Lambda}$ with a total matter density parameter of $\Omega_{\rm M} = 0.315$ and a cosmological constant density of $\Omega_\Lambda = 1 - \Omega_{\rm M}$, corresponding to a flat Universe. Throughout this work, a value of $h = 0.673$ for the reduced Hubble constant parameter is assumed.

The energy that cosmic rays can attain during acceleration is limited by their interactions with the photon field present in the acceleration region. This photon field consists of the cosmic microwave background (CMB) and the extragalactic background light (EBL). The processes affecting the accelerated particles include photopion production, pair production, photodisintegration, and energy loss due to the adiabatic expansion of the Universe. In this work, five nuclear species are considered: proton, helium, nitrogen, silicon, and iron. The interaction lengths for each process, considering both the primary particle type and photon field (CMB or EBL), used are the ones provided in the `CRPropa 3` [16] package. The maximum energy for each nuclear species is then calculated by solving the equation, $\lambda_{\rm int}(E_{\rm max}, z, Z) = \lambda_{\rm acc}(E_{\rm max}, Z, M_{\rm vir})$, where $\lambda_{\rm int}$ represents the total interaction length for all processes and both photon fields, and Z is the charge number of the nuclear species under consideration. Among the various models of the EBL, the one used in this work is that of Ref. [17]. For clusters with a virial mass of $M_{\rm vir} \sim 10^{15}$ $\rm M_\odot$ the maximum energy for protons at $z = 0$ is approximately $10^{19.6}$ eV, while for iron nuclei, it is around $10^{19.8}$ eV.

The differential number of cosmic rays with mass number A injected by the sources into the intergalactic medium is assumed to follow a power-law distribution with an exponential cutoff, which begins at the maximum energy

$$\frac{dN_{{\rm CR},A}}{dt\, dE} = C_0 \left(\frac{E}{E_0} \right)^{-\gamma} \begin{cases} 1 & E < E_{\rm max} \\ \exp\left(1 - E/E_{\rm max}\right) & E \geq E_{\rm max} \end{cases} \tag{4}$$

where C_0 is a normalization constant, γ is the spectral index, and $E_{\rm max} \equiv E_{\rm max}(z, M_{\rm vir}, Z)$ is the maximum energy. The normalization constant C_0 is obtained from the cosmic ray luminosity, which is assumed to be proportional to the accretion shock kinetic energy. In particular, C_0 is determined assuming that the luminosity corresponding to a nuclei of mass number A is a constant fraction I_A of the total CR luminosity, i.e.

$$\int_{E_{\min}}^{\infty} dE \, \frac{dN_{\mathrm{CR},A}}{dt dE} \, E = I_A \, \mathcal{L}_{\mathrm{CR}}, \tag{5}$$

where $E_{\min} = 10^{18}$ eV is the minimum energy of the cosmic rays considered and the cosmic ray luminosity is given by [18],

$$\mathcal{L}_{\mathrm{CR}}(M_{\mathrm{vir}}, z) = 1.98 \times 10^{46} \left[\frac{M_{\mathrm{vir}}}{10^{15}\,\mathrm{M}_\odot} \right]^{1.95} (1 + 1.17\, z)\, \mathcal{E}(z)\, f_{\mathrm{CR}}\, \mathrm{erg\, s^{-1}}. \tag{6}$$

Here f_{CR} is the fraction of the accretion shock kinetic energy that goes into the acceleration of the cosmic rays.

3. Characterization of the flux and composition profile

The dominant contribution to the flux at the highest energies is expected to come from nearby clusters, including the Virgo cluster, the largest galaxy cluster near Earth. Consequently, the nearby clusters are considered by assuming a discrete flux composed of sources from the catalogue in Ref. [19]. The clusters considered in this calculation are located within a comoving distance of 150 Mpc ($z = 0.03395$), ensuring the approximate completeness of the sample for cluster virial masses of $M_{\mathrm{vir}} \gtrsim 10^{14.57}\,\mathrm{M}_\odot$. Since the fit of the experimental data is performed above $10^{18.7}$ eV (see below), the sources that contribute to the flux at Earth must be located at redshifts between $z = 0$ and 1 [20]. Therefore, the cosmic ray flux is modeled by considering a discrete component, as described previously, along with two additional contributions based on a uniform distribution of sources following the halo mass function of [21]. The first of these corresponds to massive, distant sources with $M_{\mathrm{vir}} > 10^{14.57}\,\mathrm{M}_\odot$, located in the redshift range $z = [0.03395, 1]$. The second contribution is from less-massive sources with $M_{\mathrm{vir}} \in [10^{13}, 10^{14.57}]\,\mathrm{M}_\odot$ and $z \in [0, 1]$.

The UHECR flux is calculated through simulations performed with the `CRPropa 3` package. As in the acceleration case, the UHECRs interact with the low-energy photons of the CMB and the EBL when they propagate from their sources to the Earth. Therefore, the same interactions considered to calculate the maximum energy are included in the simulations. The EBL model of Ref. [17] is also used to propagate the particles. By using Eqs. (2), (3), and (4) and the maximum energy calculated numerically it is possible to calculate the flux at Earth and the composition profile. The parameters of the model are: the spectral index γ, the cosmic ray fraction f_{CR}, and the luminosity fractions I_A with $A \in \{\mathrm{p, He, Si, N, Fe}\}$ (with $\sum_A I_A = 1$). These parameters are determined by fitting the experimental data obtained by Auger by using a chi-square likelihood for the data points and a Poisson likelihood for the upper limits on the flux. The data corresponding to the flux is taken from Ref. [4], the upper limits on the flux are taken from Ref. [3], and the first two moments of $\ln A$ data are taken from Ref. [5]. The first two moments of the $\ln A$ distribution are obtained from the $X_{\max}$ data, by using air-shower simulations which are performed assuming a given high-energy hadronic interaction model. In this work, the data obtained by using EPOS-LHC [22] and Sibyll 2.3c [23] are considered. Figure 1 shows the fit of the flux corresponding to two

HEHIMs under consideration. The figure shows that, at the highest energies in both cases, the flux is predominantly dominated by Virgo, while the contribution from other nearby clusters is minimal. In both hadronic scenarios, the model fits the experimental data well, with only minor differences between the results obtained.

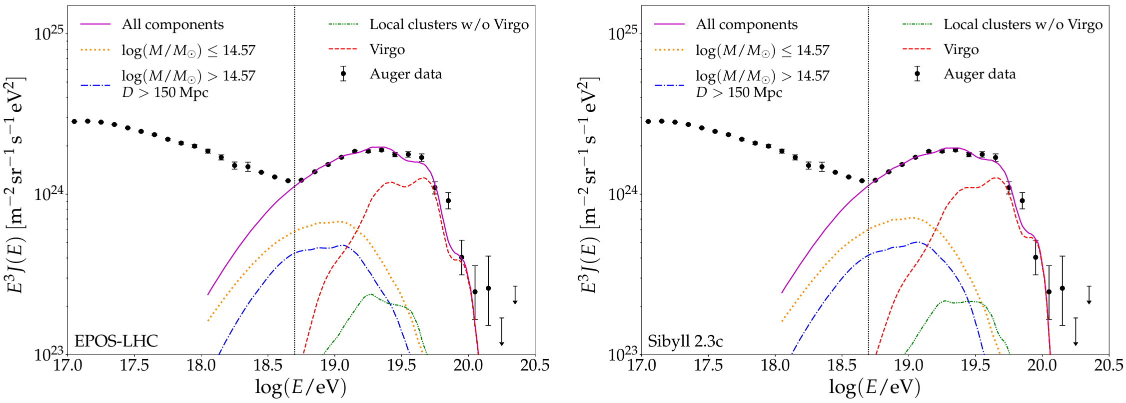

Figure 1: The cosmic ray flux, scaled by the cubic of the energy, as a function of the logarithm of the primary energy obtained for the EPOS-LHC (left panel) and Sibyll 2.3c (right panel). The data points represent the Auger measurements and the solid line our best fit model. Different contributions to the total flux are also shown: the Virgo cluster (dashed red line); nearby galaxy clusters without Virgo (dash-double-dotted green line); galaxy clusters with virial masses larger than $10^{14.57}$ M$_\odot$ located at redshifts $z \in [0.03395, 1]$ (dash-dotted blue line), and galaxy clusters with virial masses smaller than $10^{14.57}$ M$_\odot$ (dotted orange line). The vertical lines mark the lower energy limit of the data used in the fit.

Figure 2 shows the fits of the first two moments of $\ln A$ obtained considering EPOS-LHC and Sibyll 2.3c. From the figure it can be seen that the fits of the mean value of $\ln A$ are very good but the fits of the variances are not so good between $\sim 10^{18.7}$ and $\sim 10^{19.2}$ eV. However, the significance of this incompatibility decreases substantially when the systematic uncertainties in the determination of Var[$\ln A$] are taken into account.

In Table 1, the best-fit values for γ and f_{CR}, derived using EPOS-LHC and Sibyll 2.3c to determine the two moments of the $\ln A$ distribution, are presented. The cosmic ray fractions are similar, but the value of γ is higher for Sibyll 2.3c. This is because the composition obtained with Sibyll 2.3c is heavier than that of EPOS-LHC, and since heavier species have higher maximum energies, the required injected spectrum results steeper than in the EPOS-LHC case.

Model	γ	f_{CR}
EPOS-LHC	0.801 ± 0.036	$(1.80 \pm 0.01) \times 10^{-2}$
Sibyll 2.3c	1.079 ± 0.023	$(1.75 \pm 0.01) \times 10^{-2}$

Table 1: Best fit values of γ and f_{CR} for the two high-energy hadronic models considered.

It is worth noting that, although Virgo dominates the flux at the highest energies in this model, the experimental data from Auger and TA do not show any significant excess in its direction [24, 25]. This is a problem which has been discussed previously in the literature since Virgo is the host of powerful sources. In the model of Ref. [26], the ultra-high-energy particles accelerated in Virgo can

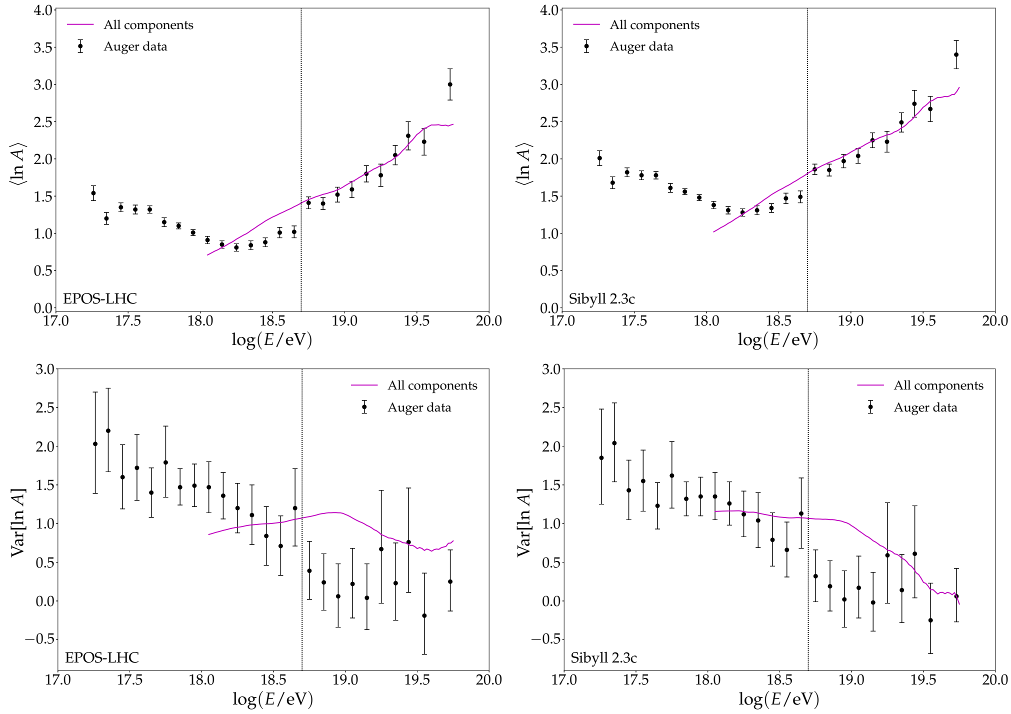

Figure 2: The mean value (top panels) and the variance (bottom panels) of ln A as a function of the logarithm of the primary energy obtained for the high-energy hadronic interaction models EPOS-LHC (left panels) and Sibyll 2.3c (right panels). The vertical lines mark the lower energy limit of the data used in the fit.

escape through magnetized filaments before being scattered towards the Earth. Another explanation is related to the galactic magnetic field of our Galaxy. In Ref. [27] it is shown that a strong magnetic demagnification could explain the absence of an excess in this region of the sky.

4. Conclusions

In this work, we have developed a model in which the flux of ultra-high-energy cosmic rays is primarily dominated by particles accelerated in external accretion shocks within galaxy clusters. We determined the model parameters by fitting the flux and composition data from the Pierre Auger Observatory. Our results show that the highest-energy part of the spectrum is dominated by Virgo, with negligible contributions from other nearby galaxy clusters. The model is consistent with Auger data (within systematic uncertainties) for both high-energy hadronic interaction models used to obtain the moments of the ln A distribution from the $X_{\max}$ parameter. Notably, we found that a steeper injected spectrum is required to match the data obtained using Sibyll 2.3c compared to EPOS-LHC. This is due to the heavier composition obtained with Sibyll 2.3c compared to EPOS-LHC. Since heavier nuclei have higher maximum energies, a steeper injection spectrum is required in the Sibyll 2.3c case to fit the data.

References

[1] Pierre Auger collaboration, *The Pierre Auger Cosmic Ray Observatory*,

Nucl. Instrum. Meth. A **798** (2015) 172 [1502.01323].

[2] H. Kawai, S. Yoshida, H. Yoshii, K. Tanaka, F. Cohen, M. Fukushima et al., *Telescope Array Experiment*, *Nuclear Physics B - Proceedings Supplements* **175-176** (2008) 221.

[3] The Pierre Auger Collaboration collaboration, *Measurement of the cosmic-ray energy spectrum above* 2.5×10^{18} eV *using the pierre auger observatory*, *Phys. Rev. D* **102** (2020) 062005.

[4] P. Abreu, M. Aglietta, J.M. Albury, I. Allekotte, A. Almela, J. Alvarez-Muñiz et al., *The energy spectrum of cosmic rays beyond the turn-down around* 10^{17} *eV as measured with the surface detector of the Pierre Auger Observatory*, *European Physical Journal C* **81** (2021) 966 [2109.13400].

[5] A. Yushkov, *Mass Composition of Cosmic Rays with Energies above* $10^{17.2}$ *eV from the Hybrid Data of the Pierre Auger Observatory*, in *36th International Cosmic Ray Conference (ICRC2019)*, vol. 36 of *International Cosmic Ray Conference*, p. 482, July, 2019.

[6] E.W. Mayotte, The Pierre Auger Collaboration, A.A. Halim, P. Abreu, M. Aglietta, I. Allekotte et al., *Measurement of the mass composition of ultra-high-energy cosmic rays at the Pierre Auger Observatory*, in *38th International Cosmic Ray Conference*, p. 365, Sept., 2024.

[7] H. Kang, J.P. Rachen and P.L. Biermann, *Contributions to the Cosmic Ray Flux above the Ankle: Clusters of Galaxies*, *MNRAS* **286** (1997) 257 [astro-ph/9608071].

[8] S. Inoue, G. Sigl, F. Miniati and E. Armengaud, *Ultrahigh energy cosmic rays as heavy nuclei from cluster accretion shocks*, *arXiv e-prints* (2007) astro [astro-ph/0701167].

[9] V.N. Zirakashvili and V.S. Ptuskin, *Cosmic ray acceleration in accretion flows of galaxy clusters*, in *Journal of Physics Conference Series*, vol. 1181 of *Journal of Physics Conference Series*, p. 012033, IOP, Feb., 2019.

[10] P. Simeon, N. Globus, K.S.S. Barrow and R. Blandford, *Ultra-High-Energy Cosmic Rays from Accretion Shocks of Galaxy Clusters and Filaments*, *PoS* **ICRC2023** (2023) 369.

[11] J.R. Jokipii, *Rate of Energy Gain and Maximum Energy in Diffusive Shock Acceleration*, *ApJ* **313** (1987) 842.

[12] F. Vazza, D. Paoletti, S. Banfi, F. Finelli, C. Gheller, S.P. O'Sullivan et al., *Simulations and observational tests of primordial magnetic fields from cosmic microwave background constraints*, *MNRAS* **500** (2020) 5350.

[13] A.M. Rost, S.E. Nuza, F. Stasyszyn, U. Kuchner, M. Hoeft, C. Welker et al., *The three hundred project: thermodynamical properties, shocks, and gas dynamics in simulated galaxy cluster filaments and their surroundings*, *MNRAS* **527** (2024) 1301 [2310.12245].

[14] C. Loken, M.L. Norman, E. Nelson, J. Burns, G.L. Bryan and P. Motl, *A Universal Temperature Profile for Galaxy Clusters*, *ApJ* **579** (2002) 571 [astro-ph/0207095].

[15] M. Arnaud, G.W. Pratt, R. Piffaretti, H. Böhringer, J.H. Croston and E. Pointecouteau, *The universal galaxy cluster pressure profile from a representative sample of nearby systems (REXCESS) and the Y_{SZ} - M_{500} relation*, *A&A* **517** (2010) A92 [0910.1234].

[16] R. Alves Batista, J. Becker Tjus, J. Dörner, A. Dundovic, B. Eichmann, A. Frie et al., *CRPropa 3.2 - an advanced framework for high-energy particle propagation in extragalactic and galactic spaces*, *JCAP* **2022** (2022) 035 [2208.00107].

[17] R.C. Gilmore, R.S. Somerville, J.R. Primack and A. Domínguez, *Semi-analytic modelling of the extragalactic background light and consequences for extragalactic gamma-ray spectra*, *MNRAS* **422** (2012) 3189 [1104.0671].

[18] K. Fang and A.V. Olinto, *High-energy Neutrinos from Sources in Clusters of Galaxies*, *ApJ* **828** (2016) 37 [1607.00380].

[19] E. Hernández-Martínez, K. Dolag, B. Seidel, J.G. Sorce, N. Aghanim, S. Pilipenko et al., *Simulating the LOcal Web (SLOW) – II: Properties of local galaxy clusters*, *arXiv e-prints* (2024) arXiv:2402.01834 [2402.01834].

[20] A. Aab, P. Abreu, M. Aglietta, I.A. Samarai, I.F.M. Albuquerque, I. Allekotte et al., *Combined fit of spectrum and composition data as measured by the Pierre Auger Observatory*, *JCAP* **2017** (2017) 038 [1612.07155].

[21] J. Tinker, A.V. Kravtsov, A. Klypin, K. Abazajian, M. Warren, G. Yepes et al., *Toward a Halo Mass Function for Precision Cosmology: The Limits of Universality*, *ApJ* **688** (2008) 709 [0803.2706].

[22] T. Pierog, I. Karpenko, J.M. Katzy, E. Yatsenko and K. Werner, *Epos lhc: Test of collective hadronization with data measured at the cern large hadron collider*, *Phys. Rev. C* **92** (2015) 034906.

[23] Riehn, Felix, Engel, Ralph, Fedynitch, Anatoli, Gaisser, Thomas K. and Stanev, Todor, *The hadronic interaction model sibyll 2.3c and muon production in extensive air-showers*, *EPJ Web Conf.* **208** (2019) 11002.

[24] The Pierre Auger Collaboration, A.A. Halim, P. Abreu, M. Aglietta, I. Allekotte, K. Almeida Cheminant et al., *An update on the arrival direction studies made with data from the Pierre Auger Observatory*, in *38th International Cosmic Ray Conference*, p. 252, Sept., 2024.

[25] J. Kim, D. Ivanov, K. Kawata, H. Sagawa, G. Thomson and Telescope Array Collaboration, *Anisotropies in the arrival direction distribution of ultra-high energy cosmic rays measured by the Telescope Array surface detector*, in *38th International Cosmic Ray Conference*, p. 244, Sept., 2024.

[26] J. Kim, D. Ryu, H. Kang, S. Kim and S.-C. Rey, *Filaments of galaxies as a clue to the origin of ultrahigh-energy cosmic rays*, *Science Advances* **5** (2019) eaau8227 [1901.00627].

[27] D. Allard, J. Aublin, B. Baret and E. Parizot, *What can be learnt from UHECR anisotropies observations. II. Intermediate-scale anisotropies*, *A&A* **686** (2024) A292 [2305.17811].

PoS(UHECR2024)119