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Possible interpretations of the joint observations of UHECR arrival directions using data recorded at the Telescope Array and the Pierre Auger Observatory

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Various hints for anisotropies in the distribution of arrival directions of ultra-high-energy cosmic rays (UHECRs) have been reported. Still, our poor knowledge about extragalactic and Galactic magnetic fields and about the UHECR mass composition makes it non-trivial to interpret such results in terms of possible models of UHECR sources. In this work, we apply the same analyses that have been performed on the Pierre Auger Observatory and the Telescope Array UHECR data to a variety of Monte Carlo simulations generated according to many different combinations of hypotheses about the sources, composition and magnetic deflections of UHECRs. We find that only some of these models can yield results similar to those obtained with the real data.

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1. Introduction

Ultra-high energy cosmic rays (UHECR) are extraterrestrial particles with energies up to a few 10^{20} eV. The identification of sources of these particles is one of the key problems in cosmic ray physics that has remained unsolved for many decades. While the arrival directions of incident cosmic rays are reconstructed quite accurately, with the precision of $\sim 1°$, the directions to the UHECR sources cannot be reconstructed with any precision because UHECRs are charged particles and are thus deflected in cosmic magnetic fields by larger angles, possibly tens of degrees. These deflections are uncertain because of both the unknown particle charge and and the poor knowledge of the Galactic and extragalactic magnetic fields.

Because of their tiny flux and high energies, UHECRs are observed only indirectly through the extensive air showers they produce in the atmosphere. Only a few thousand UHECRs have been detected at energies above 10 EeV by the two largest detectors in more than a decade of observations. These detectors are the Pierre Auger Observatory (Auger) [1], located in Argentina, with an area of ~ 3000 km^2 and in operation since 2004, and the Telescope Array (TA) [2], located in the USA, with an area of ~ 700 km^2 and in operation since 2008.

The UHECR data collected by Auger and TA appear quite isotropic, with no evident small-scale clustering found so far. There is a dipolar modulation in R.A. of $\sim 6\%$ reported at energies above 8 EeV with a significance above 5σ by Auger [3–6] and further studied in a joint analysis of Auger and TA [10]. At intermediate angular scales, TA has reported an excess of events — the "hot spot" at energies above 57 EeV with the significance requiring further confirmation [7]. Auger has reported an overdensity of events in the Centaurus region with an energy threshold of 38 EeV in an angular window of 27°, with a significance of 3.9σ [11]. An indication of correlation with nearby starburst galaxies (SBGs) has also been reported by Auger, with a significance of 4.0σ [8, 11]. This result was further supported by a joint Auger and TA study [9, 10]. The obtained anisotropic contribution to the total UHECR flux is approximately 10% for this given class of potential candidate sources.

In this study, we are trying to interpret this result by searching for a realistic UHECR flux model that would yield the observed correlation while being analysed with the same method as the data. We perform detailed numerical simulations of the UHECR flux expected from various sources.

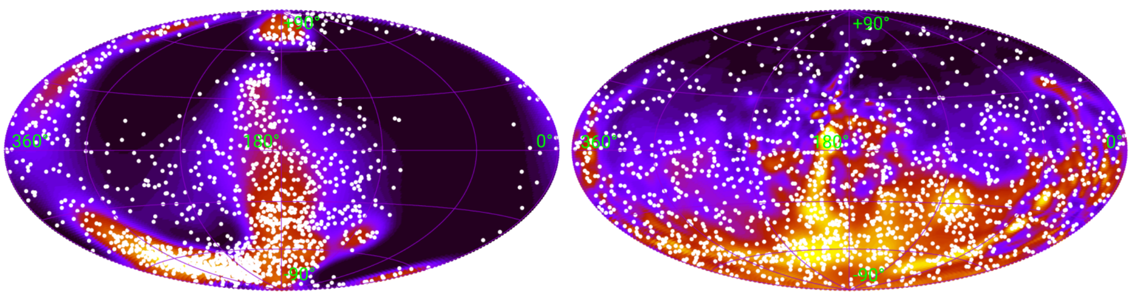

Figure 1: Examples of the maps of expected UHECR flux at $E > 40$ EeV used for mock sets simulations, in equatorial coordinates. In this example we inject pure oxygen and propagate the flux through the regular GMF of the JF2012 model [21] and a non-uniform random Galactic component [23]. We do not take into account the EGMF (see text for details). Each map is superimposed with a mock set generated from it. *Left panel:* SGB-only source model. *Right panel:* LSS-only source model.

We generate the respective Monte Carlo sets of events (mock sets) that whould be detected by the joint TA and Auger observatories. We analyze these sets with the same procedure that was used in our analysis of intermediate-scale anisotropy in the real TA plus Auger data [10]. By building the distribution of the results over the reconstructed likelihood parameters and by comparing them with that of the data, we estimate the confidence at which the data is compatible with each given flux model. A similar approach to the study of the possible origin of the SBG correlation indications was already used in several studies [12–14].

2. Searches for correlations with galaxy catalogs

In our recent [9] and previous [10, 15] searches for intermediate-scale anisotropy we performed a targeted likelihood analysis using two different source catalogs: 2MRS and SBG. In this contribution we focus on the SBG result as the most significant one. The construction of the SBG catalog is described in Ref. [24].

Here we briefly describe the methodology of the search. It is based on a maximum likelihood test to compare the observed distribution of events with the expected probability map generated from a given source model. Anisotropic probability maps are created by modeling the contribution of each source in the catalog with a von Mises–Fisher distribution with an angular width Θ. This angular width serves as the first free parameter in the analysis, it is expected to account for the unknown deflection of UHECR in magnetic fields. The contribution of each object is weighted with its relative flux in the 1.4 GHz band. Additionally, an isotropic map is added, that is expected to account for isotropized events either having large charge and magnetic deflections or originating from similar faint sources not included in the catalog. The relative weight of the anisotropic map, the signal fraction, f, is the second free parameter of the test statistics. The likelihood function $\mathcal{L}(f,\Theta)$ is then calculated as a product of all the events over the described probability map. The test statistics (TS) is defined by assuming an isotropic distribution of UHECR as the null hypothesis.

$$\mathrm{TS}(\Theta, f) = 2\ln\frac{\mathcal{L}(\Theta, f)}{\mathcal{L}(f=0)} \tag{1}$$

In this study we consider only the value $E = 38$ EeV as the lower energy threshold,where the recent result for SBGs has the largest TS value of TS = 31.1 [10]. The respective best-fit values of the parameters are: $f = (12.1^{+4.5}_{-3.1})\%$ and $\Theta = (15.1^{+4.6}_{-3.0})^\circ$ [1].

3. Models and simulations

To perform the mock sets simulations we fix the parameters of the flux following the recent results of the Auger–TA intermediate anisotropy search [10]. We consider two different source catalogs to simulate the expected UHECR flux [2]. First is the SBG catalog used for TS computation that is described above. Second is the large scale structure (LSS) catalog: the flux-limited galaxy sample with a high degree of completeness, derived from the 2MRS galaxy catalog [17] by cutting

[1] See also the updated result [9].

[2] We need to stress that in this study we always perform a likelihood analysis using SBG catalog and the flux model described in Sec. 2. But the mock sets are generated using either SBG or LSS catalog and more detailed flux models.

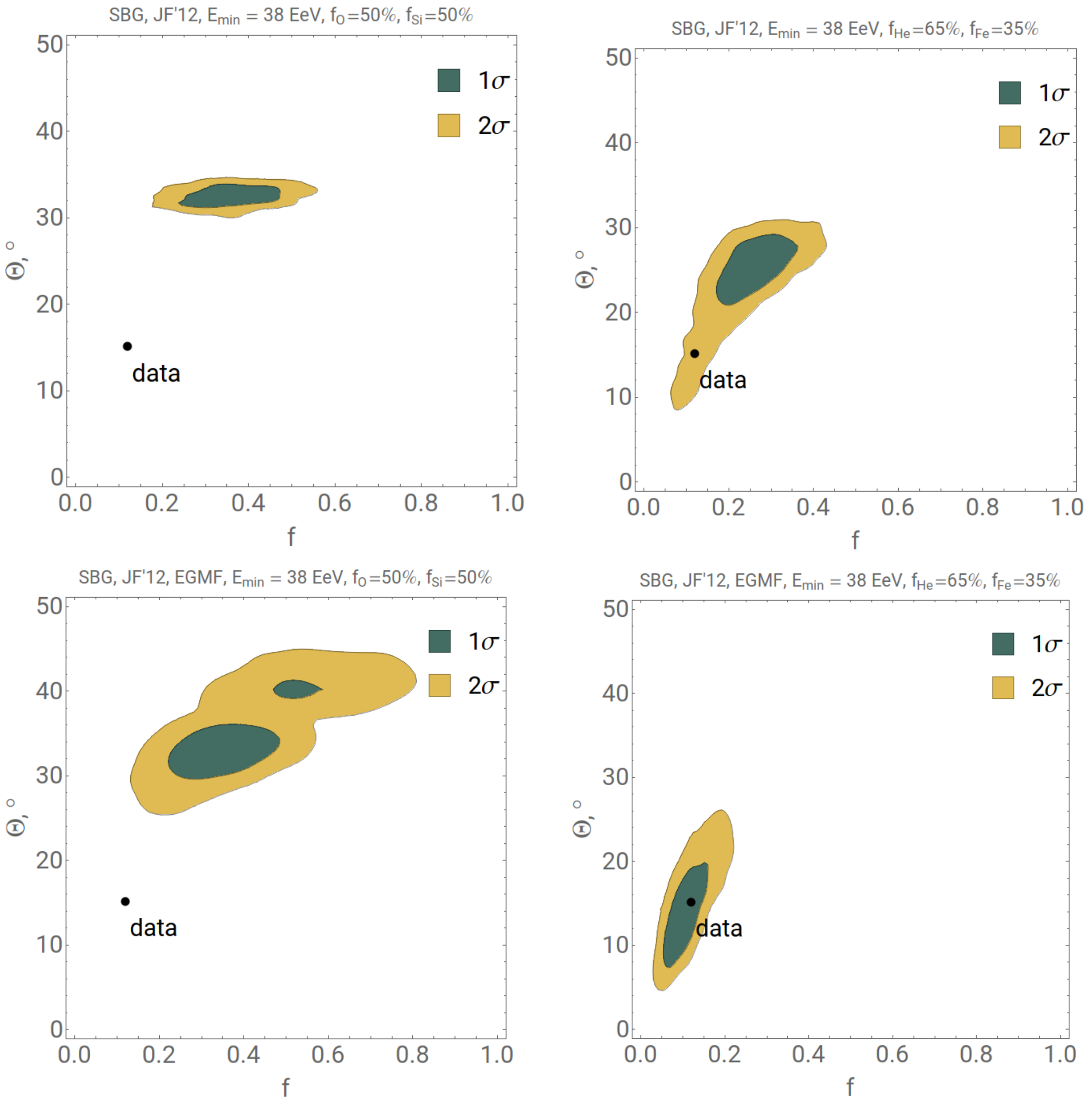

Figure 2: Results of the likelihood analysis for the SBG-only mock event sets compared with the result for the data (black dot). Two characteristic injected mass composition mixes are considered: 50% O + 50% Si (left) and 65% He + 35% Fe (right). *Top*: deflections in regular GMF + random GMF. *Bottom*: deflections in regular GMF + random GMF + EGMF (see text for details).

out galaxies with mag > 12.5 and with distances below 5 Mpc and beyond 250 Mpc. We assign a progressively larger flux to more distant galaxies to compensate for the observational selection inherent in a flux-limited sample. The sources beyond 250 Mpc are assumed to be distributed uniformly with the same mean density as those within this distance. Their contribution is added as a properly normalized fraction of isotropic events. The exact procedure is described in Ref. [18]. [3]

We consider the *injected* mass compositions of up to five different components: protons, helium, oxygen, silicon and iron. We fix the injection spectrum for each nucleus by deriving it

[3]Note that the LSS catalog used in this study for mock sets simulation is different from the catalog used for the intermediate anisotropy searches in our contributions [9, 10].

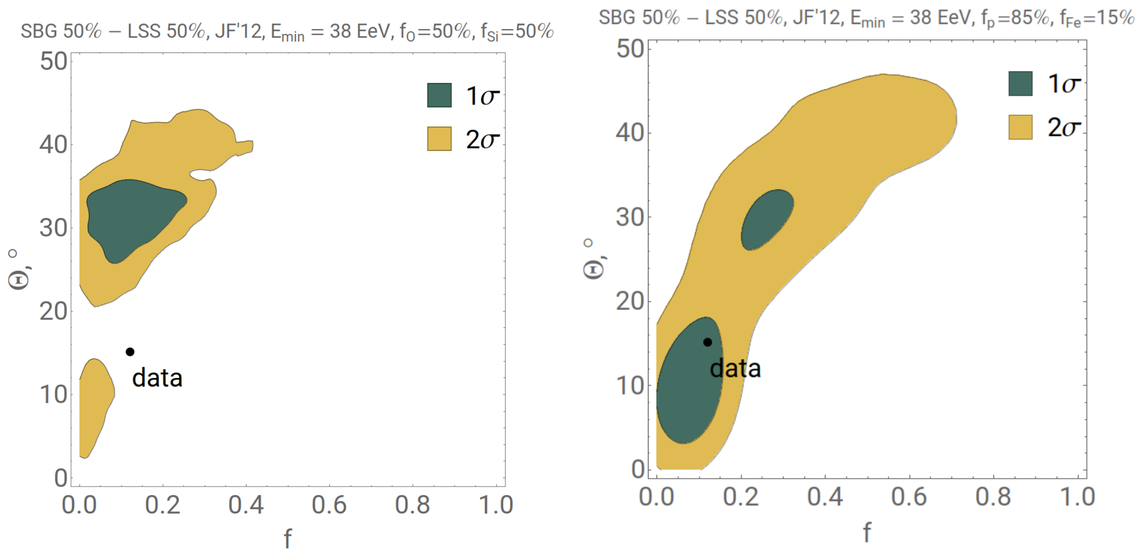

Figure 3: Results of the likelihood analysis for the SBG-LSS mock event sets compared with the result for the data (black dot). Two characteristic injected mass composition mixes are considered: 50% O + 50% Si (left) and 85% p + 15% Fe (right). Deflections in regular GMF + random GMF are assumed (see text for details).

from the separate fit to the observed TA and Auger spectra [20]. Namely, the injected spectra are: power law with the slopes −2.55, −2.20 and −2.10 and without the cut-off for protons, helium and oxygen, respectively; power law with the slope −1.50 and with a sharp cut-off at 280 EeV for silicon; power law with the slope −1.95 and with a sharp cut-off at 560 EeV for iron. For the flux from the LSS we take into account the attenuation of the primary particles, which is computed with the SimProp v2r4 code [19]. The secondary particles produced upon propagation of injected primary nuclei through the interstellar medium are taken into account for helium and oxygen nuclei and reasonably neglected for other primaries; the details are given in Ref. [20]. As the most bright SBGs in the catalog lie within 5 Mpc from us, we neglect the attenuation for the flux coming from SBGs (similarly as for the TS construction).

The deflections in the regular galactic magnetic field (GMF) are simulated using the backtracking technique with the PT'11 regular GMF model [22] or the JF'12 regular GMF model [21]. The deflections in the random GMF are simulated as galactic-latitude-dependent smearing according to the data-driven relation of Ref. [23]. The deflections in the extragalactic magnetic field (EGMF) are also included in some of the flux models (see next Section). Finally, the event distribution is modulated by the combined exposure of the TA and Auger as it is described in our anisotropy search study [9]. The exposure ratio between Auger and TA is set to 123.7/17.2 and the number of events in each set is 3030 above E = 32 EeV [4]. The energies of the events in the mock sets are generated according to the observed Auger full-sky spectrum [25]. Note that we do not need to rescale the energy inside the set as we did for the data — the assumptions of the energy spectrum and exposure makes the simulations self-consistent. The examples of SBG and LSS maps used for mock sets generation are given in Fig. 1 superimposed with mock sets generated from them.

[4]We do not use the events between 32 EeV and 38 EeV in the analysis.

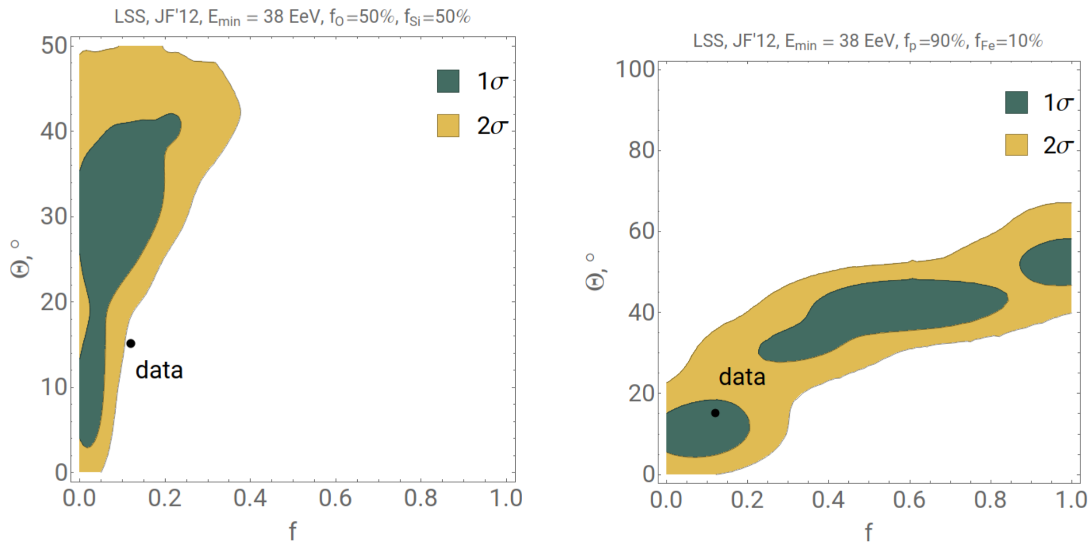

Figure 4: Results of the likelihood analysis for the LSS-only mock event sets compared with the result for the data (black dot). Two characteristic injected mass composition mixes are considered: 50% O + 50% Si (left) and 90% p + 10% Fe (right). Deflections in regular GMF of JF'12 model + random GMF are assumed (see text for details). Note that the right plot has a larger y axis scale than the others presented in this proceedings.

For the overall calibration of our method, we simulate the mock sets using the same flux model as for the TS calculation. We found that the TS is reconstructed properly and the distribution of results over f and Θ are indeed centered around their input values.

4. Results

Our main goal is to test several realistic UHECR flux models. The first is the model where all the flux is coming from SBGs and the mass composition is mixed ("SBG-only" models later on): in this case, we would expect the lighter part of the mix to account for the anisotropic fraction f and the heavier part — to mimic the isotropic contribution. The second is the model where the half of the flux is coming from SBGs and another half — from LSS ("SBG-LSS" models later on). In this model, we would naively expect the more isotropic LSS part of the flux to mimic the isotopic fraction measured by the TS. The third is the model with the total flux coming from LSS ("LSS-only" models later on). As most of the SBGs are a part of our LSS catalog (though with different weights) it is possible to expect, that for some mass compositions the signal from the LSS would mimic the one we have from the SBGs with some specific values of Θ and f. Note that we consider deflection by regular and random components of the GMF in all flux models, as it was described in Sec. 3. The deflections by EGMF are also considered for the SBG-only flux model, while the LSS-only flux model yields quite isotropic event sets even without EGMF. These deflections are simulated as a direction-independent smearing of the sources with the von Mises-Fischer distribution. The parameters of the field follow the maximum allowed for a local filament field from simulations of Ref. [26]: $B = 3$ nG, $\lambda = 1$ Mpc, in a radius of 5 Mpc around our Galaxy. This yields a deflection by $1.7°$ for the proton at $E = 10^{20}$ eV. The distance of 5 Mpc

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Composition \ Sources model	SBG only	SBG only (EGMF)	SBG-LSS	LSS only
Intermediate nuclei	$> 2\sigma$	$> 2\sigma$	$> 2\sigma$	$> 2\sigma$
Light nuclei + iron	2σ	1σ	1σ	1σ

Table 1: Summary of degree of compatibility between given UHECR flux models and the data.

is chosen because most bright sources in the SBG catalog lie within this radius. Note that for this distance the mentioned deflection is larger than the one maximally allowed by observational EGMF limit of Ref. [27].

For each flux model we simulate 1000 event sets and compute the test statistics described in Sec. 2 for each set. We present the results for SBG-only models in Figs. 2, for SBG-LSS models in Figs. 3 and for LSS-only models in Figs. 4, all in comparison with TS computed for the data. We should note that not only the presented mass compositions fractions were studied but larger families of intermediate and light+heavy mixes. We are showing only characteristic examples that are reflecting the behavior of the given composition family with respect to the data. In all these flux models the JF'12 regular GMF model is used for simulations. The results for the PT'11 model are quite similar. We also need to note that all the statistical effects are contained in the mock sets distribution over Θ and f parameters. Therefore we do not show the uncertainty for the data point to avoid double counting. The results are summarised in a Table 1.

5. Discussion and conclusion

In this study we quantified the compatibility of the various UHECR flux models with the recent measurement of the correlation between cosmic rays and starburst galaxies preformed by joint Auger and TA collaborations. We found that the SBG-only flux model is incompatible with the data at more than 2σ level for the family of injected compositions of the intermediate nuclei only, that we have considered, even if the deflections in the strong EGMF are assumed. Contrary, for the studied mixed light+heavy composition the SBG-only model is compatible with the data at 2σ level without EGMF and at 1σ level if the deflections in strong EGMF are assumed. Therefore the initial hypothesis that the heavy admixture can mimic the isotropic component is supported, though the input fraction of the light component is much larger than the reconstructed one. The results for the SBG-LSS flux model are quite similar: it is incompatible with the data at more than 2σ level for the given family of intermediate injected compositions but compatible at 1σ level for a light+heavy mix. We also need to note that we did not test models with all the possible ratios between SBG and LSS parts of the flux. Therefore we cannot exclude that there exist a specific ratio for which an intermediate composition reproduces the data well. Finally, the LSS-only model is also more than 2σ incompatible with the data for the intermediate composition but 1σ compatible — for the light+heavy mix. All these conclusions are independent of the assumed regular GMF model. Note that in this study we did not consider the composition mixes beyond two component approximation, therefore the possibility to reconcile the data with any of the source models assuming intermediate composition plus light or heavy admixture cannot be rejected.

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We can mention two implications of our results. First, the fact that some compositions are incompatible with the UHECR-SBG correlation measured with the data, makes this measurement a viable tool for injected compositions discrimination under the assumptions made (cf. Refs. [28, 29]). In particular one could try to narrow down the window of allowed compositions by scanning over them and simultaneously varying source models. Second, we found that the measured correlation can be reproduced by physically different but observationally resembling source models, such as SBG and LSS. This implies that it may be promising to introduce some additional parameters into our likelihood analysis to discriminate between such scenarios.

References

[1] A. Aab et al. [Pierre Auger], *Nucl. Instrum. Meth. A* **798** (2015) 172 [1502.01323].
[2] T. Abu-Zayyad et al. [Telescope Array], *Nucl. Instrum. Meth. A* **689** (2012) 87 [1201.4964].
[3] A. Aab et al. [Pierre Auger], *Science* **357** (2017) 1266 [1709.07321].
[4] A. Aab *et al.* [Pierre Auger], Astrophys. J. **868** (2018) no.1, 4
[5] A. Aab *et al.* [Pierre Auger], Astrophys. J. **891** (2020), 142
[6] G. Golup et al. [Pierre Auger], these proceedings.
[7] R. U. Abbasi *et al.* [Telescope Array], Astrophys. J. Lett. **790** (2014), L21.
[8] A. Aab *et al.* [Pierre Auger], Astrophys. J. Lett. **853** (2018), L29.
[9] L. Caccianiga et al. [Pierre Auger and Telescope Array], these proceedings.
[10] F. Urban et al. [Pierre Auger and Telescope Array], *EPJ Web Conf.* **283** (2023) 03002 [2302.04502].
[11] P. Abreu *et al.* [Pierre Auger], Astrophys. J. **935** (2022), 170.
[12] A. van Vliet, A. Palladino, A. Taylor and W. Winter, Mon. Not. Roy. Astron. Soc. **510** (2021), 1289-1297.
[13] R. Higuchi, T. Sako, T. Fujii, K. Kawata and E. Kido, Astrophys. J. **949** (2023), 107.
[14] D. Allard, J. Aublin, B. Baret and E. Parizot, [arXiv:2305.17811 [astro-ph.HE]].
[15] A. di Matteo et al. [Pierre Auger and Telescope Array], *PoS* **395** (ICRC2021) 308 [2111.12366].
[16] C. Lunardini et al., *JCAP* **10** (2019) 073 [1902.09663].
[17] J. P. Huchra et al. Astrophys. J. Suppl. **199** (2012), 26.
[18] H. B. J. Koers and P. Tinyakov, Mon. Not. Roy. Astron. Soc. **399** (2009), 1005.
[19] R. Aloisio, D. Boncioli, A. Di Matteo, A. F. Grillo, S. Petrera and F. Salamida, JCAP **11** (2017), 009.
[20] A. di Matteo and P. Tinyakov, Mon. Not. Roy. Astron. Soc. **476** (2018), 715-723.
[21] R. Jansson and G. R. Farrar, Astrophys. J. **757** (2012), 14.
[22] M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg and K. J. Newton-McGee, Astrophys. J. **738** (2011), 192.
[23] M. S. Pshirkov, P. G. Tinyakov and F. R. Urban, Mon. Not. Roy. Astron. Soc. **436** (2013), 2326.
[24] P. Abreu *et al.* [Pierre Auger], PoS **ICRC2021** (2021), 307.
[25] A. Aab *et al.* [Pierre Auger], Phys. Rev. Lett. **125** (2020), 121106.
[26] S. Hackstein et al. Mon. Not. Roy. Astron. Soc. **475** (2018), 2519-2529.
[27] M. S. Pshirkov, P. G. Tinyakov and F. R. Urban, Phys. Rev. Lett. **116** (2016), 191302.
[28] M. Y. Kuznetsov and P. G. Tinyakov, JCAP **04** (2021), 065
[29] M. Kuznetsov and P. Tinyakov, EPJ Web Conf. **283** (2023), 03004

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