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Probing the dark dimension with Auger data

Neena T. Noble [a,b], Jorge F. Soriano [a], Luis A. Anchordoqui [a,c,b,*]

[a] Department of Physics and Astronomy, Lehman College, City University of New York, NY 10468, USA
[b] Department of Astrophysics, American Museum of Natural History, NY 10024, USA
[c] Graduate Center, City University of New York, NY 10016, USA

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ABSTRACT

By combining swampland conjectures with observational data, it was recently pointed out that our universe could stretch off in an asymptotic region of the string landscape of vacua. Within this framework, the cosmological hierarchy problem (i.e. the smallness of the cosmological constant in Planck units: $\Lambda \sim 10^{-122} M_{\rm Pl}^4$) can be naturally resolved by the addition of one mesoscopic (dark) dimension of size $\sim \lambda \Lambda^{-1/4} \sim 1$ μm. The Planck scale of the higher dimensional theory, $M_{\rm UV} \sim \lambda^{-1/3} \Lambda^{1/12} M_{\rm Pl}^{2/3} \sim 10^{10}$ GeV, is tantalizingly close to the energy above which the Telescope Array (TA) and the Pierre Auger collaborations found conclusive evidence for a sharp cutoff of the flux of ultra-high-energy cosmic rays (UHECRs). It was recently suggested that since physics becomes strongly coupled to gravity beyond $M_{\rm UV}$, universal features deep-rooted in the dark dimension could control the energy cutoff of the source spectra $\propto E^{-\gamma} \exp(-E/M_{\rm UV})$, where E is the cosmic ray energy and γ a free parameter. Conversely, in the absence of phenomena inborn within the dark dimension, we would expect a high variance of the cosmic ray maximum energy $E_{\max}$ characterizing the source spectra $\propto E^{-\gamma} \exp(-E/E_{\max})$, reflecting the many different properties inherent to the most commonly assumed UHECR accelerators. The most recent analysis of Auger and TA data exposed strong evidence for a correlation between UHECRs and nearby starburst galaxies, with a global significance post-trial of 4.7σ. Since these galaxies are in our cosmic backyard, the flux attenuation factor due to cosmic ray interactions en route to Earth turns out to be negligible. This reasoning implies that for each source, the shape of the observed spectrum should roughly match the emission spectrum by the starburst, providing a unique testing ground for the dark dimension hypothesis. Using Auger data, we carry out a maximum likelihood analysis to characterize the shape of the UHECR emission from the galaxies dominating the anisotropy signal. We show that the observed spectra from these sources could be universal only if $\lambda \lesssim 10^{-3}$.

1. Introduction

The origin of ultra-high-energy cosmic rays (UHECRs) is a longstanding unresolved conundrum in modern astrophysics. Great advances have been made in uncovering the sources over the past two decades [1]. The most important is probably the unambiguous detection a flux suppression near $10^{10.6}$ GeV [2,3], as predicted by Greisen, Zatsepin, and Kuzmin (GZK) [4,5]. The GZK-limit is an example of the far-reaching connections between different regimes of physics, tying-up the behavior of the highest energy particles in nature to the low-energy ($\sim$ 2.7 K) photons of the cosmic microwave background (CMB), and can be explained by sub-GeV scale physics of photo-pion production and/or nucleus photodisintegration occurring in the extremely boosted relativistic frame of the cosmic ray. These highly boosted cosmic rays are also incisive probes of fundamental particle-physics properties at energies far exceeding those at the LHC (for comparison, the proton energy of nominal LHC beam is 7 TeV). In this paper we focus on the particle physics facet of UHECRs.

While the physics involved in the explanation of the UHECR origin needs often to be pushed to its extremes to accommodate observations [6–8], it is common ground that charged particles could be accelerated in magnetized astrophysical shocks, whose size and typical magnetic field strength determine the maximal achievable energy [9], akin to the conditions in (wo)man made particle accelerators. The most likely astrophysical accelerators of UHECRs are the shocks associated with: *(i)* active galactic nuclei (AGNs) [10], *(ii)* gamma-ray bursts (GRBs) [11,12], and *(iii)* powerful superwinds emanating from the core of starbursting galaxies [13].

The Pierre Auger Collaboration has reported evidence for a correlation between the arrival directions of the highest energy

* Corresponding author at: Department of Physics and Astronomy, Lehman College, City University of New York, NY 10468, USA.
E-mail address: luis.anchordoqui@gmail.com (L.A. Anchordoqui).

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cosmic rays and nearby starburst galaxies [14,15]. When Auger data are combined with the data set collected by the Telescope Array, there is *conclusive* evidence for the association, reaching a post-trial significance of 4.7σ [16]. Since these galaxies are in our cosmic backyard, the flux attenuation factor due to cosmic ray interactions en route to Earth turns out to be negligible. As a matter of fact, the anisotropy signal coincidentally emerges in the extreme-energy end of the spectrum, above about the GZK-limit.

Now, in the absence of new physics phenomena, we would expect a high variance of parameters characterizing the UHECR source spectra beyond the GZK-limit, reflecting the many different properties inherent to the acceleration environments in the market. However, the cutoff spectra could still be universal if some kind of new physics, with a higher energy loss rate than that of GZK interactions, is responsible for the cosmic ray maximum energy. In this paper we reexamine the test to search for new physics designed elsewhere [17], using the entire data sample collected by the Pierre Auger Observatory during phase I [15].

The layout of the article is as follows. In Section 2 we review recent developments in tests of fundamental physics using UHECRs. We particularized the discussion to the recently proposed dark dimension, which provides a natural solution of the cosmological hierarchy problem [18]. In Section 3 we review the Auger anisotropy signal and provide supplementary compelling arguments underpinning starburst galaxies as sources of UHECRs. In Section 4 we conjecture that starbursts are the sources of UHECRs and study their individual emission spectra in the search for universality signaling some new physics phenomena. We particularize the discussion to the dark dimension and use Auger data to constrain the model. Our conclusions are collected in Section 5.

Before proceeding, we pause to note that a recent study of the UHECR spectrum emerging from a population of sources with a power-law distribution of maximum energies suggests that source-to-source variance of the maximum energy must be small to describe the data [19]. This clearly provides further motivation for our study.

2. Strings at the end of the swampland

The quickly developing Swampland research program seeks to understand which are the "good" low-energy effective field theories (EFTs) that can couple to gravity consistently (e.g. the landscape of superstring theory vacua) and distinguish them from the "bad" ones that cannot [20]. In theory space, the border setting apart the good theories from those relegated to the swampland is characterized by a set of conjectures on the properties that an EFT should have/avoid in order to allow a consistent completion into quantum gravity. There are many swampland conjectures on the block, decidedly too many to be written down here and so we direct readers to comprehensive reviews [21–23].

It has long been known that the smallness of dark energy in Planck units ($\Lambda \sim 10^{-122} M_{\rm Pl}^4$, with $M_{\rm Pl} \sim 1.22 \times 10^{19}$ GeV) can be explained statistically [24] or even anthropically [25,26] by the large number of vacua in the string landscape. As an alternative, it has been recently proposed [18] that when the swampland distance conjecture [27] is combined with the smallness of dark energy in Planck units (as well as with other experimental observations on deviations from Newton's gravitational inverse-square law [28] and neutron star heating [29]), we turn out to be in a peculiar corner of the string landscape, endowed with a mesoscopic (dark) extra-dimension characterized by a length-scale in the micron range.

The swampland distance conjecture predicts the emergence of infinite towers of states that become exponentially light [27]. These towers drive a breakdown of the EFT at infinite distance limits in moduli space. The related anti-de Sitter (AdS) distance conjecture correlates the dark energy density to the mass scale m of an infinite tower of states,

$$m \sim |\Lambda|^{\alpha}\,, \tag{1}$$

as the negative AdS vacuum energy $\Lambda \to 0$, with α a positive constant of $\mathcal{O}(1)$ [30]. If we further assume that this scaling behavior holds in dS (or quasi dS) space (with a positive cosmological constant), the limit $\Lambda \to 0$ also yields an unbounded number of massless modes.

The AdS distance conjecture when generalized to dS space plays a key role in addressing the cosmological hierarchy problem and associates the length of the dark dimension to the dark energy scale as $\Lambda^{-1/4}$, modulo a correction factor λ. More concretely, the dark dimension opens up at the characteristic mass scale of the Kaluza–Klein tower,

$$m \sim \lambda^{-1} \Lambda^{1/4}\,, \tag{2}$$

and physics is described by a 5-dimensional theory up to the so-called "species scale" [31,32],

$$M_{\rm UV} \sim \lambda^{-1/3} \Lambda^{1/12} M_{\rm Pl}^{2/3}\,, \tag{3}$$

which represents the higher dimensional scale of quantum gravity, with $10^{-1} < \lambda < 10^{-4}$.

The dark dimension has the benefits of a rich phenomenology [33–39]. Of particular interest here, in this model the scale of quantum gravity associated to the higher dimensional theory ($\sim 10^{10}$ GeV) is captivatingly close to the predicted energy of the GZK-limit in the cosmic ray spectrum [18]. In the spirit of [17], in what follows we explore whether the observed spectra from nearby sources (i.e. sources from which cosmic rays would avoid GZK interactions) could be used to distinguish if the sharp suppression observed in the spectrum is due to cosmic rays scattering off the CMB or due to new physics processes inborn within the dark dimension; see the Appendix for an illustrative example.

3. Anisotropy from our cosmic backyard

The Pierre Auger Collaboration reported evidence for a correlation between the arrival directions of the highest energy cosmic rays and a model based on a catalog of bright starburst galaxies [14,15]. The null hypothesis of isotropy was tested through an unbinned maximum-likelihood analysis. The adopted test statistic (TS) for deviation from isotropy being the standard likelihood ratio test between the starburst-generated UHECR sky model and the null hypothesis, with

$${\rm TS}(\psi, f, E_{\rm min}) = 2 \ln \frac{\mathcal{L}(\psi, f, E_{\rm min})}{\mathcal{L}(\psi, 0, E_{\rm min})}, \tag{4}$$

and likelihood

$$\mathcal{L}(\psi, f, E_{\rm min}) = \prod_{E_i \geq E_{\rm min}} \frac{\Phi(\hat{n}_i;\, \psi, f)\ \omega(\hat{n}_i)}{\int_{4\pi} \Phi(\hat{n};\, \psi, f)\ \omega(\hat{n})\ d\Omega}, \tag{5}$$

where $\omega(\hat{n})$ is the combined directional exposure of the dataset, f is the anisotropic fraction, and where the UHECR flux model is given by

$$\Phi(\hat{n};\, \psi, f) = f\ \Phi_{\rm signal}(\hat{n};\, \psi) + (1-f)\ \Phi_{\rm background}\,. \tag{6}$$

Here, the contribution of each source is modeled as a von Mises-Fisher distribution (i.e., the analog of a Gaussian on a 2-sphere) centered on the source position

$$\Phi_{\rm signal}(\hat{n};\, \psi) = \frac{1}{\sum_j w_s} \sum_j w_s \frac{\psi^{-2}}{4\pi \sinh \psi^{-2}} \exp\left(\psi^{-2} \hat{n}_s \cdot \hat{n}\right) \tag{7}$$

and the background is given by

$$\Phi_{\text{background}} = \frac{1}{4\pi}, \tag{8}$$

where E_i and $\hat{n}_i$ are the energy and arrival direction of the ith event, w_s and $\hat{n}_s$ are the weight and position of the sth source candidate, and ψ is the root-mean-square (rms) deflection per transverse dimension (i.e. the total r.m.s. deflection is $\sqrt{2}\,\psi$ and the equivalent top-hat radius is $\Psi = 1.59\psi$).[1] For a given energy threshold, the TS for isotropy follows a χ^2 distribution with two degrees of freedom.

The analysis is based on the catalog of [40], which after selected cuts contains 44 starbursts, with distance in the range $1 \leq d/\text{Mpc} < 130$. The analysis is repeated by varying the energy threshold of the selected events between $10^{10.5}$ GeV and $10^{10.9}$ GeV in steps of 10^9 GeV.

The best-fit model to Auger data yields TS = 25.0, with smearing angle $\psi = 15^{+8}_{-4}{}^{\circ}$ and anisotropic fraction $f = 9^{+6}_{-4}$ [15]. Remarkably, the energy threshold of largest statistical significance $E_{\min} \simeq 10^{10.6}$ GeV coincides with the observed suppression in the spectrum [2,3], implying that when we properly account for the barriers to UHECR propagation in the form of GZK-energy loss mechanisms [4,5] we obtain a self consistent picture for the observed UHECR horizon. The scan in energy thresholds comes out with a penalty factor, which is estimated through Monte-Carlo simulations. The post-trial 1-sided Gaussian significance is 4.0σ. The anisotropy signal is dominated by four galaxies: NGC 4945, NGC 253, M83, and NGC 1068.[2]

Cross-correlation studies with other catalogs have been carried out, including: *(i)* the large-scale distribution of matter using the Two Micron All-Sky Survey (2MASS) [42], taking out sources closer than 1 Mpc; *(ii)* AGNs observed in hard X-rays with *Swift*-BAT [43], which includes both radio loud and quite AGNs; and *(iii)* a selected γ-AGN sample from the Fermi-LAT 3FHL catalog [44], which traces jetted AGNs. For all of these catalogs, the resulting statistical significance is considerably smaller; namely, TS = 18.0 for the 2MASS, TS = 19.4 for AGNs observed in X-rays, and TS = 17.9 for jetted-AGNs, in all cases with similar threshold energy. In addition, we note that given the ubiquity of GRBs, if these explosions were sources of UHECRs we would expect a correlation of the highest energy cosmic rays with the 2MASS catalog as opposed to a particular class of objects [45]. Altogether, the preceding discussion clearly favors starburst galaxies as sources of UHECRs.

Furthermore, when the likelihood analysis is duplicated enlarging the Auger Phase I data sample with UHECRs detected with the Telescope Array, the statistical significance of the correlation between the highest energy cosmic rays and starburst galaxies increases, reaching a conclusive evidence of 4.7σ [16].

4. What can Auger data tell us about UV physics?

In this section we assume that starburst galaxies are sources of UHECRs and study the shape of their emission spectra in the search for universality.

There exists "lore" that convinces us that acceleration mechanisms are driven by the particle's rigidity $R = E/Z$ up to a maximum $R_{\max}$ leading to consecutive flux suppressions of the elemental spectra at energies of

$$E_{\max} = Z R_{\max}\,, \tag{9}$$

where Z is the charge of the UHECR in units of the proton charge. If the sources of UHECRs trace such a "Peters cycle" [46], emission spectra characterized by a power law of spectral index γ with an exponential suppression above a cutoff energy $E_{\max}$

$$\frac{dN}{dt} \propto E^{-\gamma} \exp\{-E/E_{\max}\} \tag{10}$$

give a good description of the flux and nuclear composition measured at Earth at ultra-high energies, see e.g. [47,48]. However, a major caveat of this type of analyses is that the sources are typically assumed to be identical, a description which is highly unlikely to be an accurate reflection of the many different properties inherent to the acceleration environments in the market.

Moreover, as we discussed Section 2, the cutoff spectra could be universal (and Z independent) if physics becomes strongly coupled to gravity above about 10^{10} GeV. If this were the case, it is reasonable to assume that the source spectra would described by

$$\frac{dN}{dt} \propto E^{-\gamma} \exp\{-E/E_c\}\,, \tag{11}$$

where E_c is a critical energy that can be identified, e.g., with the species scale M_{UV}.

In what follows we performed a likelihood analysis to determine the parameters γ and E_c that best describe the emission spectrum of each starburst galaxy. In our analysis we consider UHECRs measured by the Pierre Auger Observatory during Phase I, i.e., 2635 events detected between 2004 and 2020, with energies in the range $3.2 < E/10^{10}\ \text{GeV} < 16.5$ [15]. The strongest correlation between UHECRs and starbursts is found to have $E_{\min} \simeq 10^{10.6}$ GeV, so we ignore events below this energy. We consider the four starbursts dominating the Auger anisotropy signal and NGC 891, which is a starburst in a quiescent state [8]. NGC 891 has a non-negligible contribution to the statistical significance in the analysis of [16], but is located outside the Auger field-of-view. Because of deflections on the Galactic magnetic field the Auger data sample can contain a few events emitted by NGC 891. The study of this particular source helps to illustrate that the effect on the search for universality from starbursts without significant contribution to the Auger anisotropy signal is negligible. For the selected five sources, we define a circular window around their location in the sky with angular radius $\theta = 20^{\circ}$. Such an angular scale is a good compromise of the favored top-hat radius Ψ in the Auger anisotropy search [15]. We have verified that our results do not change significantly by varying the angular scale within the range $16^{\circ} < \theta < 24^{\circ}$. The probability distribution is given by the normalized spectrum

$$f(E) = E_c^{\gamma-1} \frac{E^{-\gamma}\ e^{-E/E_c}}{\int_{E_{\text{th}}/E_c}^{\infty} x^{-\gamma}\ e^{-x}\ dx}\,, \tag{12}$$

with likelihood function

$$\mathcal{L}(\gamma, E_c) \equiv \text{prob(data|model)} = \prod_{k=1}^{N} f(E_k)\,. \tag{13}$$

Due to the proximity of some of these sources there are events that could have more than one possible origin.

Our results are encapsulated in Fig. 1 (where we show the 68% and 95% C.L. contours maximizing the likelihood) and Table 1 (where we give the best fit values of γ and E_c together with their 68% C.L. intervals after marginalizing over the free parameters). The results can be summarized as follows:

[1] Note that the rms of the north-south deflection $(\delta - \delta_0)$ is ψ and the rms of the east–west deflection $\approx (\alpha - \alpha_0)\cos\delta$ is also ψ, so that the rms of the total deflection is $\sqrt{2} \times \psi$.

[2] We note in passing that very recently the Pierre Auger Collaboration reported the outcome of a novel likelihood analysis considering a simultaneous fit of arrival directions, energy spectrum, and nuclear composition data [41]. The starburst galaxy model is favored with a significance of 4.5σ (taking into account experimental systematic effects) compared to a reference model with only homogeneously distributed background sources.

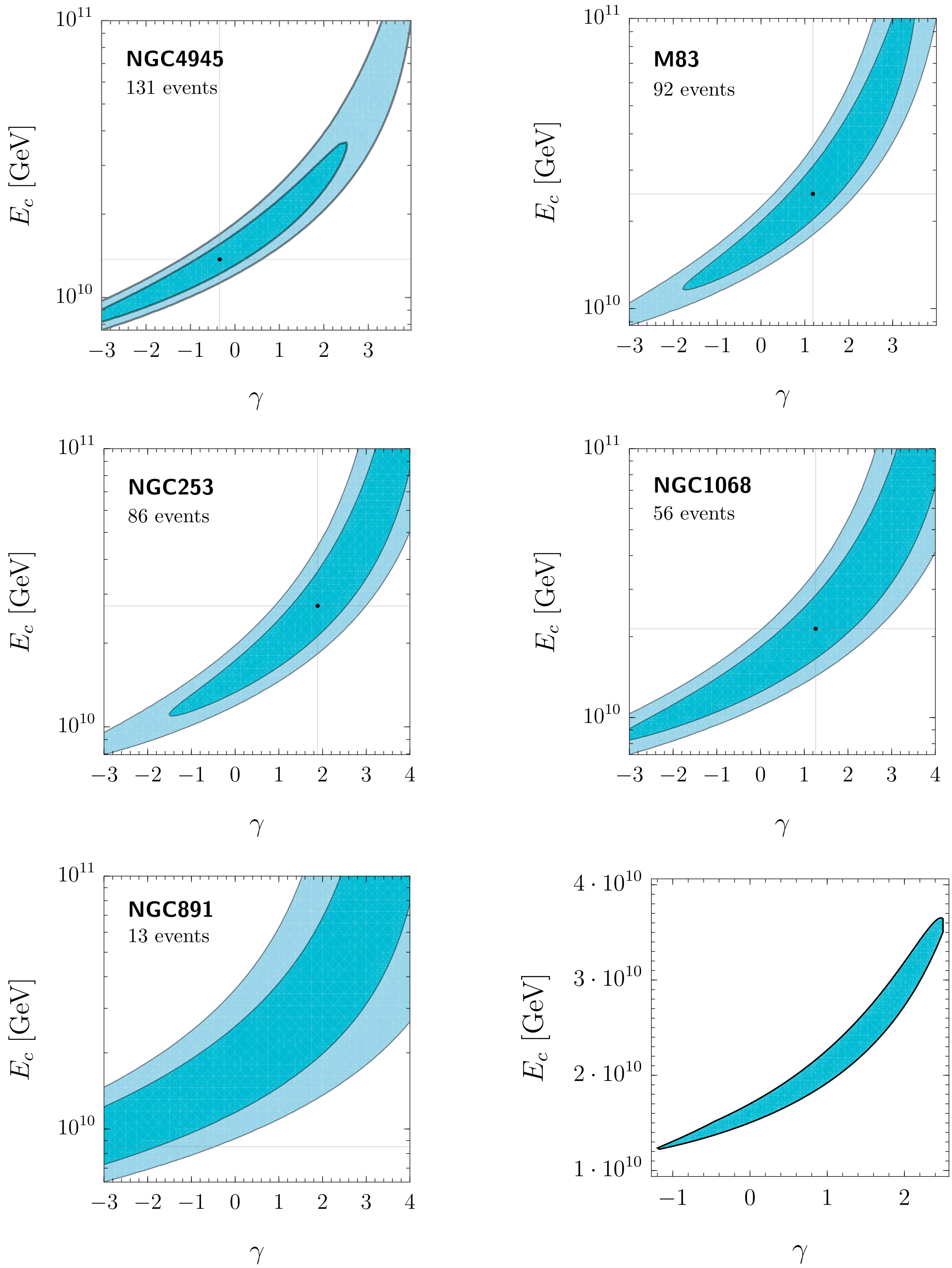

Fig. 1. 68% and 95% C.L. contours and the overlapping region of the 68% C.L. contours.

- Using the 68% C.L. intervals given in Table 1 it is straightforward to see that the observed spectra of nearby starbursts can be universal in origin if $\gamma \in [-0.3, 1.6]$ and $E_c/10^{10}$ GeV $\in [1.4, 2.4]$.
- When the critical energy at the accelerators is identified with the species scale, the allowed range of universality leads to the constraint $M_{\rm UV} \gtrsim 10^{10}$ GeV, corresponding to $\lambda \lesssim 10^{-3}$.
- As can be seen in Fig. 1, the effect of NGC 891 in constraining the free parameters of the model is negligible.
- The range of the source spectral index which allows for universality is consistent with the one predicted by shock acceleration [49].

5. Conclusions

Motivated by the curious case of near-identical cosmic-ray accelerators [19], we revisited the statistical test to search for exotic physics proposed in [17] using the entire data sample collected by the Pierre Auger Observatory during Phase I [15]. The test procedure is based on the search for universality in

Table 1
Maximum likelihood estimates and 68% C.L. intervals for γ and E_c.

Source	γ	γ (68% C.L.)	$E_c/10^{10}$ GeV	$E_c/10^{10}$ GeV (68% C.L.)
NGC4945	−0.34	[−2.52, 1.61]	1.37	[0.918, 2.413]
NGC253	1.89	[−0.28, 3.72]	2.72	[1.403, 10.52]
M83	1.18	[−0.72, 2.83]	2.48	[1.44, 6.11]
NGC1068	1.26	[−1.68, 3.69]	2.14	[1.056, 9.91]
NGC891	−3.65	[−11.8, 2.50]	0.85	[0.391, 4.67]

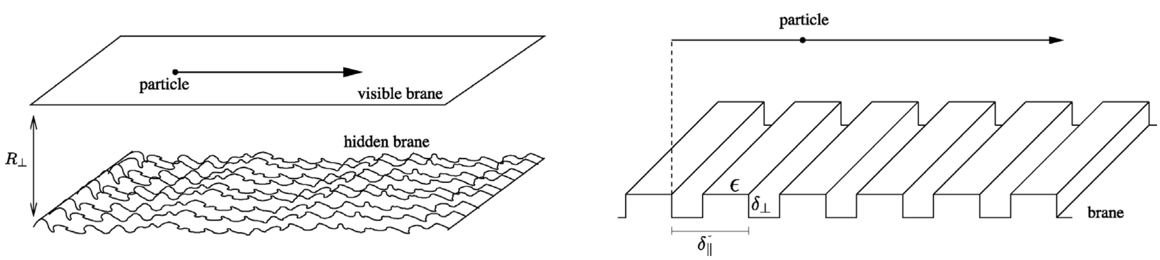

Fig. 2. Pictorial representation of the scenario described in the text (left) with periodic longitudinal brane perturbations ϵ (right).

the UHECR spectra of nearby sources. UHECRs emitted by these nearby sources can avoid GZK interactions *en route* to Earth and therefore a signal of universality in the spectral shape is a marker of new physics processes. This is because universality is at odds with the typically high variances of intrinsic properties for the most commonly assumed astrophysical sources.

The study was performed through a maximum likelihood method. The dramatic growth in the number of UHECRs when compared to the data sample considered in [17] allowed us to refine the functional form of the probability distribution, leaving two parameters free in the likelihood analysis: the source spectral index γ and the cutoff energy E_c, herein identified with the species scale $M_{\rm UV}$. We have shown that the spectra of nearby sources can be universal if $M_{\rm UV} \gtrsim 10^{10}$ GeV, corresponding to $\lambda \lesssim 10^{-3}$.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Luis Anchordoqui reports financial support was provided by National Science Foundation. Luis Anchordoqui reports a relationship with National Science Foundation that includes: funding grants.

Data availability

We have used public data referenced in the paper.

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Appendix

It has long been known that charged particles moving above a diffraction grating (without crossing it) emit Smith–Purcell (SP) electromagnetic radiation [50]. As most radiation processes accompanying the motion of charged particles, the SP effect can be explained as a result of scattering of the Coulomb field of the moving charged particles on the irregularities of media. It is important to note that the charged particles are not scattered in the material of the target. For this reason, the flow of charged particles does not damage the target, providing the reliability and long survival time for practical SP based radiation sources.

The gravitational analog of the SP effect was first entertained in [51] as a mechanism that could degrade the energy of UHECRs; the role of the diffraction grating being played by the inhomogeneities of the extra-dimensional space, such as a hidden brane at finite distance.

Envision the situation portrayed in Fig. 2, in which an UHECR moves parallel and close to an inhomogeneous hidden brane. A periodically inhomogeneous surface is just one of the special cases of a grating. Thus, the hidden brane can be visualized here as a diffraction grating, with the cosmic ray propagating in a direction perpendicular to the grating rulings. To generate gravitational radiation the cosmic ray must transfer momentum along the particle's trajectory to the inhomogeneous structure.

As an illustration of this gravitational phenomenon, we compute the power radiated by UHECRs in the presence of a hidden brane, with typical longitudinal perturbations of length scale ϵ and transverse perturbations of length scale $\delta_\perp$. Following [51], we model these perturbations as a $\delta_\parallel$-periodic lamellar grating with rulings of width ϵ perpendicular to the particle direction of motion; see Fig. 2. The energy loss per unit distance due to graviton emission is estimated to be

$$\frac{d\ln E}{dx} \sim -8\pi \frac{E}{M_{\rm UV}^3} \frac{\delta_\perp^2}{\delta_\parallel^5} \exp\left\{-\frac{2\pi R_\perp}{\Gamma \delta_\parallel}\right\} \sim -0.1 \left(\frac{E}{10^{10}\ {\rm GeV}}\right) {\rm Mpc}^{-1}\,, \tag{14}$$

where Γ is the UHECR Lorentz boost, $R_\perp \sim 1/m$ the compactification radius, $\delta_\parallel = 2\epsilon$, and where in the second rendition we have taken $\delta_\perp \sim 0.1\delta_\parallel$ and $\delta_\parallel \sim 10^{-3} R_\perp$ [17]. Note that for $\Gamma > 10^5$ the fractional energy loss traces the particle's energy and is independent of the Lorentz boost. In Fig. 3 we show the energy attenuation length of cosmic rays in the intergalactic medium. Due to the fast energy loss rate above the species scale $M_{\rm UV}$ it is reasonable to assume the source spectra can be described by (11).

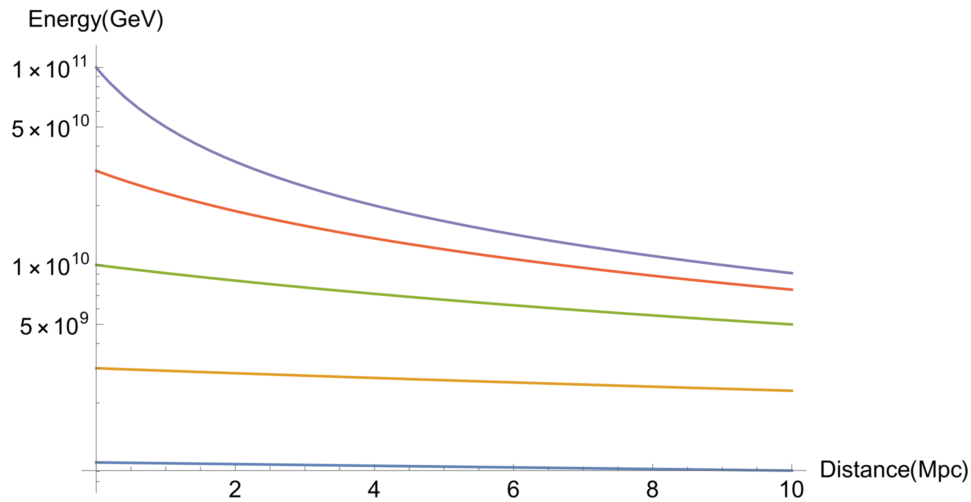

Fig. 3. Energy attenuation length of cosmic rays in the intergalactic medium.

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