What do the highest-energy cosmic-ray data suggest about possible new physics around 50 TeV?

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The latest observations of extensive air showers (EAS) induced by ultra-high-energy cosmic rays (UHECR) appear to indicate, \textit{prima facie}, a transition to heavy primaries at the highest energies. However, this interpretation, which is based on extrapolations of the Standard Model (SM) to ultra-LHC energies, is strained from both astrophysical and particle phenomenology perspectives. We consider the alternative that after some energy threshold, the first collision of the primary in the atmosphere results in a state, the decay of which leads to a considerably increased shower particle multiplicity, so that light-primary EAS appear heavy-like. We show that a minimal implementation of such a model yields predictions for the average EAS depth and shower-to-shower fluctuations that are consistent with each other, and an excellent fit to Auger data. If such an effect indeed takes place, we predict that: (a) the center-of-momentum (CM) energy threshold for the effect is of order 50 TeV; (b) the probability with which the effect occurs is high, and it will be detected easily by next-generation accelerators; (c) the increase in multiplicity compared to the SM prediction grows with CM energy roughly as $\sim E_{\text{CM}}$; (d) the cosmic-ray composition at the highest energies is light. Remarkably, if the latter is confirmed electromagnetically this would necessitate the existence of new physics by these energies.

\section*{Introduction}

Ultra-high-energy cosmic rays (UHECR) are the highest-energy particles in the Universe. They are extremely rare (one particle per km$^2$ per year at energies above $10^{18}$ eV). Even so, thanks to the operation of cosmic-ray observatories spanning thousands of km$^2$, there has been, in the past fifteen years, an explosion of unprecedented-quality data\textsuperscript{1,2}. Results from HiRes\textsuperscript{3}, the Pierre Auger Observatory\textsuperscript{6}, and Telescope Array\textsuperscript{7}, now allow the use of UHECR as probes of high-energy physics. The largest cumulative exposure at the highest energies ($>6.7\times10^4$ km$^2$sr yr, \textsuperscript{5}) has been achieved by the Auger Observatory, and it is the interpretation of the latest Auger data above $10^{17.5}$ eV\textsuperscript{2} that we focus on.

This plethora of high-quality data has exposed new puzzles in cosmic-ray physics. The most pressing one involves the composition of UHECR and its evolution with energy. All composition-sensitive observables appear to indicate, \textit{prima facie}, that, at the highest energies, heavier nuclei start to dominate over protons\textsuperscript{3,11,14}; however, the results from these observables are not fully consistent with each other\textsuperscript{9}.

The distribution, in a given primary energy range, of the atmospheric slant depth $X_{\text{max}}$ (expressed as column density) where the energy deposition rate of EAS particles in the atmosphere reaches its maximum value is both composition-sensitive\textsuperscript{12,13}, and directly observable by fluorescence detectors. For this reason, its first two moments (average shower depth, $\langle X_{\text{max}} \rangle$, and standard deviation, $\sigma_{X_{\text{max}}}$) are the most widely used composition-sensitive observables. Auger data on both $\langle X_{\text{max}} \rangle$ and $\sigma_{X_{\text{max}}}$ show a qualitative trend towards heavy-like EAS above $\sim 2\times10^{18}$ eV (see Fig.\textsuperscript{2}), however the two datasets are not straightforward to reconcile in detail, with the Auger Collaboration reporting strained fits to the observed $X_{\text{max}}$ distribution in more energy bins than what expected from random fluctuations alone: there is no primary composition that can fully reproduce the observed distributions\textsuperscript{9}. Additional composition-sensitive quantities obtained from the surface water-Cherenkov detectors, when interpreted using SM EAS simulations, yield a mass composition heavier than the one derived from $X_{\text{max}}$, with the discrepancy traced to an observed excess of muons compared to SM expectations\textsuperscript{2}. This is not surprising, as the interpretation of composition-sensitive observables relies on simulations of EAS development, which in turn draw on extrapolations of SM results to ultra-LHC energies.

The alternative, therefore, to the UHECR composition getting heavier, is that there is some new physical effect, yet-unseen in accelerators, that takes place in the first collision of UHECR primaries in the atmosphere above some energy threshold $E_{\text{th}}$, and affects the shower development. That this scenario is an open possibility is widely recognized by the Auger Collaboration (e.g., \textsuperscript{4,11,14}) and other authors (e.g., \textsuperscript{15,17}). Here, we quantify phenomenological constraints encoded in Auger data for any new phenomenon that could be affecting EAS development.

Specifically, assuming that, at energies $>2\times10^{18}$ eV:
(a) a single population of extragalactic cosmic rays dominates;
(b) the composition of extragalactic cosmic rays remains light;
(c) the - abnormal for protons and light nuclei - growth of $\langle X_{\text{max}} \rangle$ with energy reflects the phenomenology of this new physical effect,
we show that Auger data on $\langle X_{\text{max}} \rangle$ and $\sigma_{X_{\text{max}}}$ can be readily reproduced.

\section*{What kind of new physics?}

The primary require-
ment for a candidate new physical effect is to make light-primary EAS appear “heavy-like”, which in practice translates to (a) having a smaller $\langle X_{\text{max}}\rangle$ and (b) having smaller $\sigma_{X_{\text{max}}}$ than the SM prediction for protons.

The phenomenology we consider is that the first collision of the primary in the atmosphere results, with high probability, in a state the decay of which leads to a considerably increased particle multiplicity early in the shower. A large number of particles injected early in the shower development will lead to showers that reach their maximum at smaller values of $X$, as well as smaller $\sigma_{X_{\text{max}}}$ (as shower-to-shower fluctuations will average out).

Several candidate particles and new physics mechanisms that might lead to such a behavior are reviewed in [12, 13]. They are based either on the possible existence of yet undiscovered particles (mini black holes, strangelets) or on special phases of QCD, such as the disoriented chiral condensate (DCC). The mini black hole paradigm has been analyzed in detail in [20], while a reorientation of the discovery process has been discussed in [18, 19]. They are based either on the possible existence of yet undiscovered particles (mini black holes, strangelets) or on special phases of QCD, such as the disoriented chiral condensate (DCC). The mini black hole paradigm has been analyzed in detail in [20], while a reorientation of the discovery process has been discussed in [18, 19].

**Growth of $\langle X_{\text{max}}\rangle$ with energy.** For a single shower, $X_{\text{max}} = X_1 + X_D$, with $X_1$ being the depth of the first interaction and $X_D$ being the additional column density required for the shower to reach its maximum development. For energies below $E_{\text{th}}$, SM predictions hold: $\langle X_1 \rangle = m/\sigma_{p-\text{air}}$ where $m$ is the average atomic mass of air ($\approx 14.5$ proton masses, e.g. [21]) and $\sigma_{p-\text{air}}$ is the proton-air cross section. We parameterize $\sigma_{p-\text{air}} \simeq \sigma_0 + \beta \log \epsilon$ for $\epsilon \leq 1$, where $\epsilon = E/E_{\text{th}}$. Any new phenomenon will likely affect $\sigma_{p-\text{air}}$, so that $\sigma_{p-\text{air}} \simeq \sigma_0 + \beta' \log \epsilon$ for $\epsilon \geq 1$, assuming that $\sigma_{p-\text{air}}$ is continuous as the slope change from its SM value $\beta$ to $\beta'$. Thus, for $\epsilon \geq 1$, $\langle X_1 \rangle \simeq (m/\sigma_0) - (m/\sigma_0^2) \beta \log \epsilon$.

The change in $X_D$ is entirely due to an increase in particle multiplicity at the first collision, since the products will have, on average, energies below $E_{\text{th}}$. We parameterize the change in multiplicity by $n(\epsilon) = N(\epsilon)/N_{\text{SM}}(\epsilon) > 1$ for $\epsilon \geq 1$, where $N(\epsilon)$ and $N_{\text{SM}}(\epsilon)$ are the actual and SM-predicted (by shower simulations) number of first collision products. We can then empirically model the shower as $n(\epsilon)$ “component-showers” (CS) of energy, on average, $\epsilon/n(\epsilon)$, developing independently. Since for $\epsilon \leq 1$ the SM prediction is $\langle X_D \rangle \simeq \langle X_D \rangle(1) + (65\text{g/cm}^2) \log \epsilon$, for $\epsilon \geq 1$ we obtain $\langle X_D \rangle \simeq \langle X_D \rangle(1) + (65\text{g/cm}^2) \log \epsilon/n(\epsilon)$ (where we have assumed $n(1) = 1$).

The Auger Collaboration [3] already gets $\langle X_{\text{max}} \rangle > 2 \times 10^{18} \text{eV}$, $\langle X_{\text{max}} \rangle/g \text{cm}^{-2} \sim (26 \pm 2) \log \epsilon$. In the simplest case where the composition is fixed, every EAS for $\epsilon \geq 1$, assuming that the composition at these energies remains constant, and the difference with the SM prediction is purely due to new physics, we can obtain $n(\epsilon)$ by demanding that,

$$65 \log[\epsilon/n] - \frac{m_{\beta'}}{\sigma_0^2} \log \epsilon = 26 \log \epsilon \, .$$

This yields

$$n(\epsilon) \simeq \epsilon^{0.52 - 0.08\delta} \, .$$

where $\delta = \beta'/\beta - 1$.

**Change of $\sigma_{X_{\text{max}}}$ with energy.** The $X_{\text{max}}$ spread between showers is the joint effect of fluctuations in $X_1$ and in shower development, $\sigma_{X_{\text{max}}}^2 = \sigma_{X_1}^2 + \sigma_{X_D}^2$, with $\sigma_{X_1} = \langle X_1 \rangle$ (Poisson statistics). To estimate $\sigma_{X_D}$, we take the average $(1/n) \sum_i X_{D,i}$ of individual CS maxima to be a reasonable estimator of the overall $X_D$. Then $X_D$ is the “sample mean” of $n$ “draws” from the underlying distribution of $X_{D,i}$, and the distribution of these “sample means” has a spread that is given by the “error in the mean” formula, $\sigma_{X_D} = \sigma_{X_{D,1}}/\sqrt{n}$. Here $\sigma_{X_{D,1}}$ is the spread of $X_{D,i}$, and it can be assumed to follow the SM predictions, since the individual energies of the decay products initiating the CS are $< E_{\text{th}}$. The SM predicts that $\sigma_{X_{D,1}}$ is approximately constant (the mild energy dependence predicted by SM shower simulations for $\sigma_{X_{max}}$ in the case of protons can be reproduced by the logarithmic rise of $\sigma_{p-\text{air}}$ with energy). Therefore

$$\sigma_{X_{max}}^2(\epsilon) = \sigma_{X_1}^2(1) - 10.7 \frac{\text{g}}{\text{cm}^2} \sigma_{X_1}(1)(1+\delta) \log \epsilon + \frac{\sigma_{X_D}^2(1)}{n(\epsilon)} \, .$$

A proof-of-principle minimal model. As a proof of principle for this concept, we show how a simple two-component astrophysical scenario (heavy Galactic cosmic rays cutting off; light extragalactic cosmic rays dominating at high energies) with EAS obeying Eqs. 2 and 4 above $E_{\text{th}}$ reproduces well Auger data on $\langle X_{\text{max}} \rangle$, $\sigma_{X_{max}}$, and yields reasonable flux spectra for the two populations.

For a mixture of Galactic and extragalactic cosmic rays with a fraction of Galactic over total particles $f(\epsilon)$, the probability density function of $X_{\text{max}}$ will be $p(X_{\text{max}}) = f p_G(X_{\text{max}}) + (1-f) p_{EG}(X_{\text{max}})$, so that $\langle X_{\text{max}} \rangle$ will be given by

$$\langle X_{max} \rangle = \langle X_{\text{max}} \rangle_G + (1-f) \langle X_{\text{max}} \rangle_{EG} \, ,$$

and $\sigma_{X_{max}}^2$ by

$$\sigma_{X_{max}}^2 = f \sigma_{X_{max}}^2_G + (1-f) \sigma_{X_{max}}^2_{EG} + (1-f)(\langle X_{\text{max}} \rangle_G - \langle X_{\text{max}} \rangle_{EG})^2 \, .$$

with subscripts $G$ and $EG$ referring to the Galactic and extragalactic populations respectively.

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1. We use the Sibyll 2.1 extrapolation $\sigma_{p-\text{air}} \simeq 520\text{mb} + 60\text{mb} \log(E/10^{17.5} \text{eV})$ [21]; our results are not sensitive to this choice.

2. More generally, $\sigma_{p-\text{air}}$ might also exhibit a discontinuity at $\epsilon = 1$. For simplicity, we do not make use of this extra freedom.
There is little freedom in this model. Assuming that extragalactic cosmic rays have completely dominated for $E > 2 \times 10^{18}$ eV, the evolution of $(X_{\text{max}})_{\text{EG}}$ can be directly read off of the Auger data in this energy range, $(X_{\text{max}})_{\text{EG}} / \text{g cm}^{-2} = 728 \pm 26 \log (\epsilon / 17.5)$, where $\epsilon_{17.5} = 10^{17.5} \text{eV} / E_{\text{th}}$. The continuity assumption for $n(\epsilon)$, and, consequently for $(X_{\text{max}})_{\text{EG}}(\epsilon)$ then fully determines the behavior of $(X_{\text{max}})_{\text{EG}}$ at Auger energies, if the value of $E_{\text{th}}$ is known.

A similarly strong statement can be made for $f$. The shape of the extragalactic population flux spectrum is affected by intergalactic losses (which in turn depend on the composition of extragalactic cosmic rays, the distribution and cosmic evolution of extragalactic cosmic-ray sources, and the cosmic density of diffuse photon backgrounds) and the pileup of particles down-cascading from higher energies \cite{24, 28}. These are non-trivial to calculate theoretically, because of the uncertainties involved in the inputs, but also because any systematic uncertainties in the energy reconstruction of cosmic-ray events shift the energy location where specific absorption features appear. In contrast, the Galactic cosmic-ray flux is reasonably expected to be a declining power law (from Fermi acceleration) with an exponential cutoff (induced by Galactic accelerators reaching the maximum energy they can achieve), $F_G(\epsilon) = F_{G,0}(\epsilon/\epsilon_{17.5})^{-\gamma_G} \exp [-\epsilon/\epsilon_G]$. The values of $F_{G,0}$ and $\gamma_G$ are well-constrained by KASCADE-Grande data at lower energies\cite{4} with $F_{G,0} \approx 2 \times 10^{-15}$ km$^{-2}$yr$^{-1}$sr$^{-1}$eV$^{-1}$ and $\gamma_G \approx 3$ (see Fig. 1). The value of $\epsilon_G = E_G/E_{\text{th}}$ can then be constrained by the requirement that the flux residuals $F_{\text{total},\text{Auger}}(\epsilon) - F_G(\epsilon)$ in the lower-energy part of the Auger range, before any intergalactic propagation losses set in, are consistent with a power law (again assuming Fermi acceleration for extragalactic sources). For values outside the range $6.5 \times 10^{17} \text{eV} < E_G < 8.5 \times 10^{17} \text{eV}$ the low-energy Auger residuals (see Fig. 1, upper panel, green open circles) start to exhibit curvature in a log-log plot. We adopt $E_G = 7.5 \times 10^{17} \text{eV}$, in the middle of this range (purple line, Fig. 1, upper panel). This then fixes $f(\epsilon)$ to $F_G(\epsilon)/F_{\text{total},\text{Auger}}(\epsilon)$ (Fig. 1, lower panel).

The Galactic component is heavy. The exact composition is subject to various systematic uncertainties\cite{22, 23}, so for simplicity, we take the SM predictions for carbon nuclei $(X_{\text{max}})_{G,0} \approx 670 \text{g/cm}^2$ and $\sigma_{X_{\text{max}},G,0} \approx 38 \text{g/cm}^2$ at $10^{17.5} \text{eV}$, from a naive extrapolation of data presented in \cite{4, 24} to be representative, on average, of the behavior of EAS initiated by Galactic cosmic ray\cite{3}. We have however verified that more complex mixtures also give good fits with other model inputs within their respective allowed ranges. Since $\sigma_{X_{\text{max}}}$ evolves very little for heavier nuclei in the energy range relevant for the Galactic population, we take it to be constant for simplicity. Because $f(\epsilon)$ is highly suppressed by the energy new physics sets in, these choices affect neither our fit to Auger data at the high end of their energy range, nor our conclusions on possible new physics phenomenology.

For both a pure proton population and any reasonable light mix, $\sigma_{X_{\text{max}},G,0}$ will be $68 \pm 2 \text{g/cm}^2$ at $10^{17.5} \text{eV}$\cite{3}. We take $\sigma_{X_{\text{max}},G,0} = 68 \text{g/cm}^2$.

A nominally free parameter in our model is the threshold energy, $E_{\text{th}}$, where new physics sets in. However its value is very well bounded. By the requirement that $(X_{\text{max}})_{\text{EG}}$ does not, at any energy, exceed (within systematic uncertainties) the SM predictions for protons, $E_{\text{th}} \gtrsim 10^{17.5} \text{eV}$ (see Fig. 2, upper panel). This corresponds to $E_{\text{CM},\text{th}} \gtrsim 25$ TeV, in agreement with the non-detection by the LHC of any effects deviating from SM predictions. By the assumption that new physics has already set in by the break observed by Auger in $(X_{\text{max}})$, $E_{\text{th}} \lesssim 10^{18.5} \text{eV}$. Good fits to the Auger dataset can be obtained throughout this narrow range, given the uncertainties in the Auger data and the allowed range in other model inputs. In what follows, we will use $E_{\text{th}} \approx 10^{18} \text{eV}$ ($E_{\text{CM},\text{th}} \approx 45$ TeV). For heavier primary nuclei, the per-nucleon threshold for mass number $A$ is reached at a higher primary energy, $A E_{\text{th}}$. For this reason, the new physics never becomes relevant for Galactic cosmic rays, as extragalactic cosmic rays have completely dominated before $A E_{\text{th}}$ is reached, for any reasonable $A$ (hence the “agnostic” dotted lines for the Galactic population at high energies in Fig. 2).

This leaves a single free parameter in our model, $\delta$, which affects $X_1$. $(X_{\text{max}})$ shows no sensitivity to $\delta$, because it is dominated by $(X_P)$. In contrast $\sigma_{X_{\text{max}}}$ is more sensitive to $\delta$; however, at the high energies where its effect becomes important, Auger $\sigma_{X_{\text{max}}}$ data have large statistical uncertainties. In Fig. 2 we show two cases: $\delta = 0$ ($\sigma_{P,\text{air}}$ is not affected by new physics, orange line), and $\delta = 2.9$ (cyan line). Note that even the latter case is consistent with SM predictions within uncertainties\cite{21}.

**Results and Discussion.** The resulting $(X_{\text{max}})(E)$ and $\sigma_{X_{\text{max}}}(E)$ curves are shown in Fig. 2. In the same energy range, the two datasets resemble broken logarithmic growth with two different slopes; the Auger Collaboration fits them as such\cite{4}. Each such relation involves four free parameters, so fitting the two datasets in this way would require eight free parameters. We have incorporated in our model the slope and normalization of the second branch of $(X_{\text{max}})$, so a purely empirical model would need another six free parameters to fit both datasets well. Without using any of this freedom, we have produced model curves for two very different values of $\delta$ that perform better than Astrophysical scenarios (extragalactic accelerator composition getting heavier)\cite{11, 28, 30, 32}; and all other inputs in our model are driven by astrophysics and/or the requirement of consistency with the

\footnote{We adopt purely empirically, the 2015 ICRC QGSJetII-04 - based energy reconstruction of KASCADE-Grande events\cite{22}, which results in a near-perfect continuity with Auger measurements at overlapping energies, see Fig. 1.}

\footnote{The composition of Galactic cosmic rays evolves strongly between the knee ($\approx 10^{15.5}$ eV) and their final cutoff at $E_G$. Our simple assumption cannot capture this behavior and thus we do not expect to fit the data below $10^{17.5}$ eV.}
The increase in multiplicity relative to the SM, the composition of the extragalactic cosmic ray
energy threshold
\[ \delta \]
ICRC 2017 data (error bars are statistical). Orange line: panel: \[ \sigma \]
EPOS/QGSJet instead of Sibyll). Thick lines: our model systematic uncertainty of SM predictions (result of using protons/iron, from \[ 8 \]). The hatched boxes indicate the systematic). Red/blue dashed lines: SM (Sibyll) predictions for models that treat the entire Auger energy range.

Astrophysical explanations of the shallow growth of \[ \langle X_{\max} \rangle \] at the highest energies have to invoke two "cosmic coincidences": (a) the Galactic/extragalactic accelerator coincidence at \[ 10^{18.5} \] eV: the energy where the extragalactic accelerators cut off is close to the energy where the composition of extragalactic accelerators starts getting heavier; (b) the extragalactic accelerator / cosmic photon background coincidence at \[ 10^{19.5} \] eV: the maximum energy achievable by extragalactic accelerators is close to the energy threshold for photopion/photodissociation energy losses (the Greisen - Zatsepin - Kuzmin, GZK, cutoff \[ 22, 43 \]). Neither issue appears in our scenario, where extragalactic accelerators remain efficient and their output light throughout the Auger energy range. In our scenario, the energy scale of \[ 2 \times 10^{18} \] eV where the slopes of \[ \langle X_{\max} \rangle \] and \[ \sigma_{X_{\max}} \] are seen to change in the data does not represent the energy where new physics sets in; rather, this break is astrophysical, and signifies extragalactic cosmic rays dominating over the Galactic population. The new effect has already appeared at a lower energy.

Our empirical model does not treat the muon excess; we note however that both production of mini black holes and the restoration of chiral symmetry paradigms might in principle alleviate the muon deficit problem. The simple implementation of the new effect we have presented here is only meant as a proof of principle. Ultimately, the impact of specific models on EAS phenomenology, including their ability to alleviate the muon excess, can be best studied using EAS simulations as, e.g., in \[ 13, 20 \].

The phenomenology we have considered here leads to four specific predictions with important implications for future astroparticle and particle physics experiments.

1. The increase in multiplicity relative to the SM, \[ n(E) \], grows with lab-frame primary energy as \( E^{0.52-0.08\delta} \) (and with CM energy as \( E_{\text{CM}}^{1.04-0.16\delta} \)). Curiously, the multiplicity of the decay of mini black holes depends on the black hole mass \( M_{\text{BH}} \sim E_{\text{CM}}^{(n+2)/(n+1)} \) (where \( n \) is the number of extra dimensions), in general agreement with the empirical relation; however the estimated cross-section for mini black hole production is generally too small to affect the majority of EAS.

2. The energy threshold \( E_{\text{thr}} \) for the new effect lies between \( 10^{17.5} - 10^{18.5} \) eV (CM energy 25 - 60 TeV), within reach of any next-generation accelerators.

3. The compositon of the extragalactic cosmic ray population is light and stable with energy. This

FIG. 1. Upper panel: cosmic ray spectrum between \( 10^{16} \) and \( 10^{20} \) eV. Filled circles: Auger 2017 ICRC spectrum (error bars are statistical). Brown triangles: KASCADE-Grande 2015 all-particle spectrum (QGSJET II - 04 reconstruction (error bars are systematic). Purple line: Galactic population model spectrum (this work). Open green circles: Auger 2017 ICRC data (error bars are systematic). Red/blue dashed lines: SM (Sibyll) predictions (the Greisen - Zatsepin - Kuzmin, GZK, cutoff \[ 22, 43 \]). Neither issue appears in our scenario, where extragalactic accelerators remain efficient and their output light throughout the Auger energy range. In our scenario, the energy scale of \( 2 \times 10^{18} \) eV where the slopes of \( \langle X_{\max} \rangle \) and \( \sigma_{X_{\max}} \) are seen to change in the data does not represent the energy where new physics sets in; rather, this break is astrophysical, and signifies extragalactic cosmic rays dominating over the Galactic population. The new effect has already appeared at a lower energy.

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FIG. 2. Upper panel: \( \langle X_{\max} \rangle \) as a function of energy. Filled circles: Auger 2017 ICRC data (error bars are systematic). Red/blue dashed lines: SM (Sibyll) predictions for protons/iron, from Sibyll. Thick lines: our model (purple: Galactic; green: extragalactic; orange: total). Lower panel: \( \sigma_{X_{\max}} \) as a function of energy. Filled circles: Auger ICRC 2017 data (error bars are statistical). Orange line: \( \delta = 0 \). Cyan line: \( \delta = 2.9 \). Other lines as above. For clarity, the extragalactic model is only shown for \( \delta = 0 \).
could, in principle, be independently tested electromagnetically, for example by propagation studies in the Galactic magnetic field, provided that an accurate tomographic mapping for the latter becomes available. Should such a confirmation be made, it would necessitate the existence of new physics around 50 TeV. Another central factor in such efforts is good statistics at the highest energies. Next-generation cosmic-ray experiments will thus play a key role in our ability to use UHECR as probes of new physics.

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