I summarize the discovery potential for physics beyond the electroweak scale at the Pierre Auger Observatory. This observatory is designed to study ultra-high energy cosmic rays with unprecedented precision, with the primary goal of shedding light on their composition and origins. In addition, since the center-of-mass energies of Auger events are well beyond those reached at terrestrial colliders, they provide an opportunity to search for new physics. I discuss here some of the relevant observables and techniques which may be used to weed out theories beyond the standard model.

1 GZK–end of the cosmic ray spectrum?

 Shortly after the cosmic microwave background (CMB) was discovered, Greisen, Zatsepin, and Kuzmin (GZK) pointed out that the relic photons make the universe opaque to cosmic rays (CRs) of sufficiently high energy. This occurs, for example, for protons with energies beyond the photopion production threshold,

\[ E_{\text{GZK}}^{\text{th}} = \frac{m_p (m_p + m_\pi/2)}{E_{\text{CMB}}} \approx 6.8 \times 10^{10} \left( \frac{E_{\text{CMB}}}{10^{-3} \text{ eV}} \right)^{-1} \text{ GeV}, \]

where \( m_p \) (\( m_\pi \)) denotes the proton (pion) mass and \( E_{\text{CMB}} \sim 10^{-3} \text{ eV} \) is a typical CMB photon energy. After pion production, the proton (or perhaps, instead, a neutron) emerges with at least 50% of the incoming energy. This implies that the nucleon energy changes by an e-folding after a propagation distance \( \lesssim (\sigma_{p\gamma} n_\gamma y)^{-1} \sim 15 \text{ Mpc} \). Here, \( n_\gamma \approx 410 \text{ cm}^{-3} \) is the number density of the CMB photons, \( \sigma_{p\gamma} > 0.1 \text{ mb} \) is the photopion production cross section, and \( y \) is the average energy fraction (in the laboratory system) lost by a nucleon per interaction. For heavy nuclei, the giant dipole resonance can be excited at similar total energies and hence, for example, iron nuclei do not survive fragmentation over comparable distances. Additionally, the survival probability for extremely high energy (\( \approx 10^{11} \text{ GeV} \)) \( \gamma \)-rays (propagating on magnetic fields \( \gg 10^{-11} \text{ G} \)) to a distance \( d \), \( P(d) \approx \exp[-d/6.6 \text{ Mpc}] \), becomes less than \( 10^{-4} \) after traversing a distance of 50 Mpc. All in all, as our horizon shrinks dramatically for energies \( \gtrsim 10^{11} \text{ GeV} \), one would expect a sudden cutoff in the energy spectrum if the CR sources follow a cosmological distribution.

At the beginning of summer 2002, in a pioneering paper Bahcall and Waxman noted that the energy spectra of CRs reported by the AGASA, the
Fly’s Eye, the Haverah Park, the HiRes, and the Yakutsk Collaborations are consistent with the expected GZK cutoff. As one can readily see in Fig. 1, after small adjustments (within the known uncertainties) of the absolute energy scale, all these spectra are shown to be in agreement with each other for energies below $10^{11}$ GeV. A point worth noting at this juncture: the analysis that follows, which is based on counting events above roughly the expected cutoff, takes the data at face value and consequently does not attempt to evaluate possible correlated systematic errors. The particulars of the present sensitivity to a super-GZK flux (i.e., CR intensity beyond $10^{11}$ GeV) are given in Table 1. Armed with the expected number of events and assuming Poisson statistics, it is easily seen that the existing data show significant evidence for a suppression in the CR flux beyond $10^{11}$ GeV. Such a suppression is found to be a $\sim 3.5\sigma$ effect according to the Fly’s Eye normalization, increasing up to $\sim 8\sigma$ if the selected normalization is that of Yakutsk. It is important to emphasise that with data sets as small as these and with the inherent uncertainty associated with energy fluctuations, this result should be treated with great caution.

Systematic uncertainties in normalization have been thus far a headache common to all surface arrays. Already in 1986, the SUGAR Collaboration instead of giving a unique primary energy for the observed events, they reported the showers’ equivalent vertical muon number $N_{\mu v}$ together with two possible conversions from $N_{\mu v}$ to primary energy. Interestingly, if one adopts the Hillas conversion factor, for which the SUGAR integral energy spectrum is in good agreement with the AGASA spectrum at $10^9$ GeV, the number of observed super-GZK events is consistent with the one expected from an extrapolation of the sub-GZK spectrum ($\propto E^{-2.7}$) at the 1$\sigma$ level. On the other hand, if one adopts the Sidney normalization there are no events with energy $> 10^{11}$ GeV. It should be noted that the SUGAR exposure given in Table 1 was obtained on the basis that the super-GZK detection probability over the entire array (with maximum collecting area of 70 km$^2$) is 85%. I have also assumed that the experiment operated in stable mode from January 1968 until February 1979, yielding a total area–time product of about 775 km$^2$ yr. However, since the sensitive area varied as the array was developed and as detectors require maintenance, the expected numbers of events given in the last row of Table 1 should be taken as upper limits.

To make the situation more confusing, the calibrations from the various experiments are themselves moving targets. Even in the time between this conference and the deadline for its proceedings the Yakutsk spectrum has change substantially. Nowadays it seems easier to predict the stock market or even the weather in Boston than the next revision in the energy spectrum. There is no doubt that more and better data is needed.

The arrival directions of the super-GZK events have no apparent counterparts in the Galactic plane nor in the Local Supercluster. Furthermore, the
data is consistent with an isotropic distribution of sources, in sharp contrast to the anisotropic distribution of light within 50 Mpc. The apparent isotropy in the arrival directions can be explained if the particle orbits are bent in extragalactic magnetic fields. However, the low statistics leaves a window open for less mundane explanations, which I discuss next.

Table 1. Numbers of events observed with average energy $> 10^{11}$ GeV and incident zenith angle $< 45^\circ$. The super-GZK exposure of Volcano Ranch, Haverah Park, Fly’s Eye, Yakutsk, AGASA, HiRes, and SUGAR (see main text) is given in the 3rd column. The last column indicates the expected number of events calculated based on the spectrum observed above $10^{10}$ GeV from Fly’s Eye and Yakutsk, and assuming no change in the spectral index.

| Experiment     | Events observed | Exposure $[m^2 \cdot s \cdot sr]$ | Expected events |
|----------------|-----------------|-----------------------------------|-----------------|
| Volcano Ranch  | 1               | $2.0 \times 10^{15}$              | 0.4             | 1.0             |
| Haverah Park   | 0               | $5.6 \times 10^{15}$              | 1.2             | 2.9             |
| Fly’s Eye      | 1               | $2.6 \times 10^{16}$              | 5.4             | 13.4            |
| Yakutsk        | 1               | $2.8 \times 10^{16}$              | 5.8             | 14.4            |
| AGASA          | 11              | $5.1 \times 10^{16}$              | 10.6            | 26.2            |
| HiRes          | 2               | $6.9 \times 10^{16}$              | 14.3            | 35.5            |
| SUGAR          | 5               | $< 3.1 \times 10^{16}$            | $< 6.4$         | $< 15.9$        |
2 The usual suspects

Physics from the most favored theories beyond the standard model (SM) like string/M theory, supersymmetry (SUSY), grand unified theories (GUTs), and TeV-scale gravity have been invoked to explain the super-GZK events. The conjectured origins fall into two basic categories: (i) exotic sources clustered nearby, (ii) GZK-evading messengers.

The top suspect belongs to the first category. In this scenario charged and neutral primaries simply arise in the quantum mechanical decay of supermassive elementary $X$ particles. Sources of these exotic particles could be: (i) topological defects (TDs) left over from early universe phase transitions associated with the spontaneous symmetry breaking that underlies GUTs\[13\] (ii) some long-lived metastable super-heavy relic (MSR) particles which may constitute (a fraction of) the dark matter in galactic haloes. Arguably, the observed magnitude of the CMB fluctuations fixes the reheat temperature following inflation to $10^{13\pm1}$ GeV, allowing gravitational and thermal production of MSRs during the inflationary stage of the universe with just the right mass ($m_X > 10^{12}$ GeV) for producing $10^{11}$ GeV secondary particles via decay.\[15\] Due to their topological stability, the TDs (magnetic monopoles, cosmic strings, domain walls, etc.) can survive forever with $X$ particles ($m_X \sim 10^{16}$ – $10^{19}$ GeV) trapped inside them. Nevertheless, from time to time, TDs can be destroyed through collapse, annihilation, or other processes, and the energy stored would be released in the form of massive quanta that would typically decay into quarks and leptons. Discrete gauge symmetries or hidden sectors are introduced to stabilize the MSRs and so generally higher dimensional operators are required to break the new symmetry super-softly to maintain an appreciable decay rate today (collisional annihilation has been considered, too). MSRs would also have quarks and leptons as the ultimate decay products. The strongly interacting quarks fragment into jets of hadrons containing mainly pions together with a 3% admixture of nucleons. The injection spectrum is therefore a rather hard fragmentation-type shape with an upper limit usually fixed by the GUT scale. Of course, the precise decay modes of the $X$ particles and the detailed dynamics of the first secondary particles depend on the exact nature of the particles under consideration.\[16\] However, one expects the bulk flow of outgoing particles to be almost independent of such details: all top-down scenarios predict a spectrum dominated by photons and neutrinos produced via pion decay.

The neutrino is the only known stable particle immune to the GZK degradation. The corresponding $\nu \bar{\nu}$ annihilation mean free path on the cosmic neutrino background, $\lambda_\nu = (n_\nu, \sigma_{\nu \bar{\nu}})^{-1} \approx 4 \times 10^{28}$ cm, is just above the present size of the horizon (recall that $H_0^{-1} \sim 10^{28}$ cm). One may then entertain the notion that neutrinos are indeed the super-GZK primaries. Unfortunately, perhaps, $\sigma_{\nu N}$ is, within the SM, about five orders of magnitude too small to explain the observed atmospheric cascades. On the other hand, the limit
imposed by unitarity is relatively weak and consequently does not impact on new interactions beyond the electroweak scale to increase significantly the neutrino-nucleon cross section.\textsuperscript{17}

On a different track, if some flavor of neutrinos has a mass $\sim 0.1$ eV, the relic neutrino background is a target for everyday weakly interacting neutrinos to form a $Z$-boson that subsequently decays producing a “local” flux of nucleons, photons and neutrinos.\textsuperscript{18} To reproduce the observed spectrum, the $Z$-burst mechanism requires very luminous sources of extremely high energy neutrinos throughout the universe (see Fig. 2).\textsuperscript{20}

A novel beyond–SM–model proposal to break the GZK barrier is to assume that ultrahigh energy CRs are not known particles but a new species of particle, generally referred to as the uhecron, $U$.\textsuperscript{21} The meager information we have about super-GZK particles allows a naive description of the properties of the $U$. The muonic content in the atmospheric cascades suggests $U$’s should interact strongly. At the same time, if $U$’s are produced at cosmological distances, they must be stable, or at least remarkably long lived, with mean-lifetime $\tau \gtrsim 10^6 \left( m_U / 3\text{ GeV} \right) (d / \text{Gpc})$ s, where $d$ is the distance to the source and $m_U$, the uhecron’s mass. Additionally, since the threshold energy increases linearly with $m_U$, to avoid photopion production on the CMB $m_U \gtrsim 1.5$ GeV. In this direction, light supersymmetric baryons (made from a light gluino + the usual quarks and gluons, $m_U \lesssim 3$ GeV) produce atmospheric cascades very similar to those initiated by protons.\textsuperscript{22}

Another interesting possibility in which super-GZK CRs can reach us from very distance sources may arise out of photons that mix with light axions in extragalactic magnetic fields.\textsuperscript{23} These axions would be sufficiently weakly coupled to travel large distances unhindered through space, and so they can convert back into high energy photons close to the Earth. An even more radical proposal postulates a tiny violation of local Lorentz invariance, such that some processes become kinematically forbidden.\textsuperscript{24} In particular, photon-photon pair production and photopion production may be affected by Lorentz invariance violation. Hence, the absence of the GZK-cutoff would result from the fact that the threshold for photopion production “disappears” and the process becomes kinematically not allowed.

3 Fingerprints in the sky: The distribution of arrival directions

The distribution of arrival directions is perhaps the most helpful observable in yielding clues about cosmic ray origin. Neutral GZK-evading messengers should point back to distant active galaxies, thereby enabling point–source astronomy. The earliest super-GZK events did in fact point towards high-redshift compact, radio-loud quasars.\textsuperscript{25} However, the current world data set

\textsuperscript{a}Similarly, gravi-burst fragmentation jets can contribute to the super-GZK spectrum.\textsuperscript{19}
show that such association is controversial. Another revealing signature of discrete sources would be the clustering on a small angular scale. The data recorded by AGASA suggest that the pairing of events on the celestial sphere is occurring at a higher than random rate. Moreover, event directions in a combined data sample from AGASA, Haverah Park, Yakutsk and Volcano Ranch also support no chance-association. However, it is interesting to remark that to calculate a meaningful statistical significance of CR clustering, one must define the search procedure a priori in order to ensure it is not (inadvertently) devised especially to suite the particular data set after having studied it. In the above mentioned analyses, for instance, the angular bin size was not defined ahead of time.

Surface arrays in stable operation have nearly continuous observation over the entire year, yielding a uniform exposure in right ascension, $\alpha$. A traditional technique to search for large-scale anisotropies is then to fit the right ascension distribution of events to a sine wave with period $2\pi/m$ ($m$th harmonic) to determine the components $(x, y)$ of the Rayleigh vector:

$$x = \frac{2}{N} \sum_{i=1}^{N} \cos(m\alpha_i), \quad y = \frac{2}{N} \sum_{i=1}^{N} \sin(m\alpha_i).$$

(2)

The $m$th harmonic amplitude of $N$ measurements $\alpha_i$ is given by the Rayleigh vector length $R = (x^2 + y^2)^{1/2}$. The expected length of such a vector for values randomly sampled from a uniform phase distribution is $R_0 = 2/\sqrt{N}$. The chance probability of obtaining an amplitude with length larger than that measured is $p(\geq R) = e^{-k_0}$, where $k_0 = R^2/R_0^2$. To give a specific example, a vector of length $k_0 \geq 6.6$ would be required to claim an observation whose probability of arising from random fluctuation was 0.0013 (a “$3\sigma$” result). For the ultra-high energy ($>10^{10.6}$ GeV) regime, all experiments to date have reported $k_0 \ll 6.6$. This does not imply an isotropic distribution, but it merely means that available data are too sparse to claim a statistically significant measurement of anisotropy by any of these experiments. In other words, there may exist anisotropies at a level too low to discern given existing statistics. For example, a clean signature of the MSR–X hypothesis is the anisotropy imposed by the asymmetric position of the sun in the Galactic halo. As seen in the Northern hemisphere, the amplitude $\sim 0.3$ predicted by isothermal haloes with realistic core radii is in agreement with existing data (the most restrictive being the AGASA sample with $R_{m=1} \approx 0.3$ and $k_0 \approx 1.0$).

The $\alpha$ harmonic analyses are completely blind to intensity variations which depend only on declination, $\delta$. Furthermore, combining anisotropy

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Footnote: Since Fly’s Eye has had a nonuniform exposure in sidereal time, $R$ was computed using weighted showers. A shower’s weight depends on the hour of its sidereal arrival time. The 24 different weights are such that every time bin has the same weighted number of showers.
searches in $\alpha$ over a range of declinations could dilute the results, since significant but out of phase Rayleigh vectors from different declination bands can cancel each other out. An unambiguous interpretation of anisotropy data requires two ingredients: exposure to the full celestial sphere and analysis in terms of both celestial coordinates. Though the statistics are very limited at present, the analysis of data from the SUGAR and the AGASA experiments, taken during a 10 yr period with nearly uniform exposure to the entire sky, shows no significant deviation from isotropy beyond $10^{10.6}$ GeV$^3$.

4 Smoking guns: Photon and neutrino fluxes

Another telltale discriminator to be thought is the primary composition of the super-GZK events. Every model wherein the primaries arise from QCD jets (these models include Z-bursts, and decaying TDs and MSRs) produce many more mesons than baryons, and consequently the injection spectrum would be dominated by $\gamma$-rays produced through $\pi^0$ decay. Additionally, any technique used to distinguish photon-initiated showers from hadron-initiated showers would be well suited to test the validity of the photon-axion mixing model.

At large zenith angles, hadrons and $\gamma$-rays develop cascades in the upper layers of the atmosphere. The electromagnetic component, with mean interaction length $\sim 45 - 60$ g/cm$^2$, is absorbed long before reaching the ground by the greatly enhanced atmospheric slant depth ($\approx 3000$ g/cm$^2$ at 70° from the zenith). Then surface arrays are practically only sensitive to the high energy muons created in the first few generations of particles. The shape of the shower front in this type of cascade is extremely flat (with radius of curvature above 100 km), and the particle time spread is very narrow ($\Delta t < 50$ ns). Since showers initiated by $\gamma$-rays produce fewer muons than those initiated by hadrons, one expects the rate of $\gamma$-ray showers detected by surface arrays to be reduced relative to the rate from hadron showers. Therefore, the determination of the CR-flux through vertical shower measurements using fluorescence eyes (which are fairly independent of the primary composition) provides a powerful tool for discriminating between hadron and $\gamma$-ray showers when comparing with the inclined shower rate. For example, a comparison of the showers recorded by the Haverah Park experiment (in the angular range $60^\circ < \theta < 80^\circ$) with predictions from the observed Fly’s Eye spectrum yields strong bounds on the $\gamma$-ray flux: above $10^{10}$ GeV, less than 48% of the primary cosmic rays can be $\gamma$-rays and above $10^{10.6}$ GeV less than 50% can be $\gamma$-rays. Both of these statements are made at the 95%CL.

Even though $\gamma$-rays dominate at production, there are some viable TD scenarios which predict proton fluxes that are comparable or even higher than the $\gamma$-ray flux at all energies. Conversely, due to the lack of absorption, relics clustered in the Galactic halo predict compositions directly given by the fragmentation function. Note that mechanisms which successfully deplete the
\(\gamma\)-rays (such as efficient absorption on the universal radio background) require an increase in the neutrino flux to maintain the overall normalization of the observed spectrum. Within the SM, the mean free path of neutrinos is larger than even the horizontal atmospheric depth. Neutrinos therefore interact with roughly equal probability at any point in the atmosphere and may initiate quasi-horizontal showers in the volume of air immediately above the detector. These will appear as hadronic vertical showers, with large electromagnetic components, curved fronts (a radius of curvature of a few km), and signals well spread over time (on the order of microseconds).

The event rate for quasi-horizontal deep showers from ultra-high energy neutrinos is

\[
N = \sum_{i,X} \int dE_i N_A \frac{d\Phi_i}{dE_i} \sigma_{iN\rightarrow X}(E_i) \mathcal{E}(E_i),
\]

where the sum is over all neutrino species \(i = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\), and all final states \(X\). \(N_A = 6.022 \times 10^{23}\) is Avogadro’s number, and \(d\Phi_i/dE_i\) is the source flux of neutrino species \(i\), \(\sigma\) as usual denotes the cross section, and \(\mathcal{E}\) is the exposure measured in cm\(^3\) w.e. sr time. The Fly’s Eye and the AGASA Collaborations have searched for quasi-horizontal showers that are deeply-penetrating, with depth at shower maximum \(X_{\text{max}} > 2500 \text{ g/cm}^2\). There is only 1 event that unambiguously passes this cut with 1.72 events expected from hadronic background, implying an upper bound of 3.5 events at 95%CL from neutrino fluxes.\(^3\)

Note that if the number of events integrated over energy is bounded by 3.5, then it is certainly true bin by bin in energy. Thus, using Eq. (3) one obtains

\[
\sum_{i,X} \int dE_i N_A \frac{d\Phi_i}{dE_i} \sigma_{iN\rightarrow X}(E_i) \mathcal{E}(E_i) < 3.5,
\]

at 95% CL for some interval \(\Delta\). Here, the sum over \(X\) takes into account charge and neutral current processes. In a logarithmic interval \(\Delta\) where a single power law approximation

\[
\frac{d\Phi_i}{dE_i} \sigma_{iN\rightarrow X}(E_i) \mathcal{E}(E_i) \sim E_i^\alpha
\]

is valid, a straightforward calculation shows that

\[
\int_{(E) e^{-\Delta/2}}^{(E) e^{\Delta/2}} \frac{dE_i}{E_i} \frac{d\Phi_i}{dE_i} \sigma_{iN\rightarrow X} \mathcal{E} = \langle \sigma_{iN\rightarrow X} \mathcal{E} E_i d\Phi_i/dE_i \rangle \frac{\sinh \delta}{\delta} \Delta,
\]

where \(\delta = (\alpha + 1)\Delta/2\) and \(\langle A \rangle\) denotes the quantity \(A\) evaluated at the center of the logarithmic interval. The parameter \(\alpha = 0.363 + \beta - \gamma\), where 0.363 is the power law index of the SM neutrino cross sections,\(^3\) and \(\beta\) and \(-\gamma\) are the power law indices (in the interval \(\Delta\)) of the exposure and flux \(d\Phi_i/dE_i\),
respectively. Since \( \sinh \delta / \delta > 1 \), a conservative bound may be obtained from Eqs. (4) and (6):

\[
N_A \sum_{i,X} \langle \sigma_{iN \rightarrow X} (E_i) \rangle \langle \mathcal{E}(E_i) \rangle \langle E_i d\Phi_i/dE_i \rangle < 3.5/\Delta .
\]  

(7)

By taking \( \Delta = 1 \) as a likely interval in which the single power law behavior is valid (this corresponds to one \( \epsilon \)-folding of energy), and setting \( \langle E_i d\Phi_i/dE_i \rangle = \frac{1}{6} \langle E_i d\Phi_\nu/dE_\nu \rangle \) (\( \Phi_\nu \equiv \) total neutrino flux) from Eq. (7) it is straightforward to obtain 95\%CL upper limits on the neutrino flux. Similar concepts are used by the Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE) to set upper bounds on the neutrino flux at the ultimate energy frontier. All these bounds are collected in Fig. 2.

Unfortunately, due to the limited size of the current ultra-high energy CR sample, no conclusive statement can yet be made on the hypothesized models discussed in Sec. 2. The jury awaits further evidence.

5 Heavenly black holes: Probes of TeV-scale gravity

It is intriguing – and at the same time suggestive – that the observed flux of CRs beyond the GZK-energy is well matched by the flux predicted for cosmogenic neutrinos. Of course, this is not a simple coincidence: any proton flux beyond \( E_{pGZK} \) is degraded in energy by photoproducing \( \pi^0 \) and \( \pi^\pm \), with the latter in turn decaying to produce cosmogenic neutrinos. The number of neutrinos produced in the GZK chain reaction compensates for their lesser energy, with the result that the cosmogenic flux matches well the observed CR flux beyond \( 10^{11} \) GeV. Recently, the prospect of an enhanced neutrino cross section has been explored in the context of theories with large compact dimensions. In these theories, the extra spatial dimensions are responsible for the extraordinary weakness of the gravitational force, or, in other words, the extreme size of the Planck mass. For example, if spacetime is taken as a direct product of a non-compact 4-dimensional manifold and a flat spatial \( n \)-torus \( T^n \) (of common linear size \( 2\pi r_c \)), one obtains a definite representation of this picture in which the effective 4-dimensional Planck scale, \( M_{Pl} \sim 10^{19} \) GeV, is related to the fundamental scale of gravity, \( M_D \), according to \( M_{Pl}^2 = 8\pi M_D^{2+n} r_c^n \).

Within this framework, virtual graviton exchange would disturb high energy neutrino interactions, and in principle, could increase the neutrino interaction cross section in the atmosphere by orders of magnitude beyond the SM value; namely \( \sigma_{\nu N} \sim [E_\nu/(10^{10}) \text{ GeV}] \text{ mb} \). However, it is important to stress that a cross section of \( \sim 100 \) mb would be necessary to approach obtaining consistency with observed showers which start within the first 50 g/cm\(^2\) of the atmosphere. This is because Kaluza–Klein modes couple to neutral currents and the scattered neutrino carries away 90\% of the incident energy per interaction. Moreover, models which postulate strong neutrino interac-
Figure 2. Current limits on neutrino fluxes. Upper bound 95% CL on $d\Phi_{\nu_i+\bar{\nu}_i}/dE_{\nu_i}$ derived by replacing the combined exposures for deeply-developing showers of AGASA and Fly’s Eye into Eq. (7). The point with error bars indicates the total neutrino flux required by the $Z$-burst mechanism and the dotted line indicates a typical $d\Phi_{\nu_\mu+\bar{\nu}_\mu}/dE_{\nu_i}$ from top down cascades with $m_X = 10^{16}$ GeV. In these models, $d\Phi_{\nu_e+\bar{\nu}_e}/dE_{\nu_i} \approx d\Phi_{\nu_\mu+\bar{\nu}_\mu}/dE_{\nu_i}$. The diamonds indicate the sensitivity of the Pierre Auger Observatory, i.e., any flux lying above these points for at least one decade of energy will give more than 1 observed event per year.

Theories at super-GZK energies also predict that moderately penetrating showers should be produced at lower energies, where the neutrino-nucleon cross section reaches a sub-hadronic size. Within TeV scale gravity $\sigma_{\nu N}$ is likely to be sub-hadronic near the energy at which the cosmogenic neutrino flux peaks, and so moderately penetrating showers should be copiously produced. Certainly, the absence of moderately penetrating showers in the CR data samples should be understood as a serious objection to the hypothesis of neutrino progenitors of the super-GZK events.

Large extra dimensions still may lead to significant increases in the neutrino cross section. Should we be so lucky that this scenario is true, we
might hope to observe black hole (BH) production (somewhat more massive than $M_D$) in elementary particle collisions with center-of-mass energies $\sqrt{s} \gtrsim \text{TeV}$. In particular, BHs occurring very deep in the atmosphere (revealed as intermediate states of ultrahigh energy neutrino interactions) could trigger quasi-horizontal showers and be detected by cosmic ray observatories. Interestingly, $\sigma_{\nu N \rightarrow \text{BH}} \propto M_D^{-4+2n}/(1+n)$. Therefore, using Eq. (3), the non-observation of the almost guaranteed flux of cosmogenic neutrinos can be translated into bounds on the fundamental Planck scale. In the case of $n$ extra spatial dimensions compactified on $T^n$ with a common radius, the bounds derived using AGASA+Fly’s Eye exposure represent the best existing limits on the scale of TeV-gravity for $n \geq 4$ extra spatial dimensions. A summary of the most stringent present bounds on $M_D$ for $n \geq 2$ extra dimensions is given in Fig. 3. Certainly, the lack of observed deeply-penetrating showers can be used to place more general, model-independent, bounds on $\sigma_{\nu N}$.

Up to now we have only discussed how to set bounds on physics beyond the SM. An actual discovery of new physics in cosmic rays is a tall order because of large uncertainties associated with the depth of the first interaction in the atmosphere, and the experimental challenges of reconstructing cosmic air showers from partial information. However, a similar technique to that employed in discriminating between photon and hadron showers can be applied to search for signatures of extra-dimensions. Specifically, if an anomalously
large quasi-horizontal deep shower rate is found, it may be ascribed to either an enhancement of the incoming neutrino flux, or an enhancement in the neutrino-nucleon cross section. However, these two possibilities may be distinguished by separately binning events which arrive at very small angles to the horizontal, the so-called “Earth-skimming” events. An enhanced flux will increase both quasi-horizontal and Earth-skimming event rates, whereas a large BH cross section suppresses the latter, because the hadronic decay products of BH evaporation do not escape the Earth’s crust.

6 The PAO inquisition

The Pierre Auger Observatory (PAO) is designed to work in hybrid mode, employing fluorescence detectors overlooking a ground array of deep water Čerenkov radiators. During clear, dark nights, events will be simultaneously observed by fluorescence light and particle detectors at ground level. The PAO is expected to measure the energy, arrival direction and primary species with unprecedented statistical precision. It will eventually consist of two sites, one in the Northern hemisphere and one in the Southern, each covering an area of 3000 km$^2$ and each consisting of 1600 particle detectors overlooked by 4 fluorescence detectors. For showers with zenith angle $< 60^\circ$, the overall acceptance (2 sites) is 14000 km$^2$ sr. The angular and energy resolutions of the ground array (without coincident fluorescence data) are typically less than 1.5$^\circ$ and less than 20%, respectively. “Golden events,” those detected by both methods simultaneously, will have a directional reconstruction resolution of about 0.3$^\circ$ for energies near $10^{11}$ GeV. If an event trigger is assumed to require 5 detectors above threshold, the array is fully efficient at $10^{10}$ GeV. In three years of running, the surface arrays in both hemispheres will collect more than 1000 showers above $10^{10}$ GeV with approximately uniform sky exposure. This will enable a straightforward search for correlations with discrete sources and also a sensitive large scale anisotropy analysis.

For showers with zenith angle exceeding 60$^\circ$, the aperture of PAO increases by roughly 50%. For a pure hadronic composition, there will be over 1000 well reconstructed events beyond $10^{10}$ GeV, with a mean energy error $\sim 25\%$. On the other hand, if $\gamma$-rays are dominant at high energy, the rate will be reduced by an order of magnitude allowing for a clear discrimination between these two cases. PAO will be able to establish strong bounds on the $\gamma$-ray flux at energies as high as $10^{11}$ GeV.

In addition, PAO offers a window for neutrino astronomy above $10^8$ GeV. For standard neutrino interactions in the atmosphere, each site of PAO reaches $\sim 15$ km$^3$ w.e. sr of target mass around $10^{10}$ GeV, which is comparable to other neutrino detectors being planned. Moreover, the sensitivity of PAO could be significantly enhanced by triggering on neutrinos that skim the Earth, traveling at low angles along chords with lengths of order their interaction...
As can be seen in Fig. 2, PAO will provide us with statistics to begin discriminating among the many promising ideas so far proposed to explain the origin and nature of CRs above the GZK energy limits. Measurements of quasi-horizontal neutrino fluxes will also allow better limits to be placed on low scale gravity (see Fig. 3).

7 Coda

Statistics and better experimental handles should enable us to reconstruct the energy spectrum beyond $10^{11}$ GeV, to locate the CR sources in the sky, and to discern the primary chemical composition. Future CR data will not only provide clues to the CR origin, but could enhance our understanding of fundamental particle physics. For example, if CR primaries are found to have a significant $\gamma$-ray component above $10^{11}$ GeV, this could suggest an exotic ingredient in CRs, such as the decay products of TDs/MSRs, and thus could provide insight into the description of the early universe as well as particle physics beyond the SM. The puzzle of ultrahigh energy CRs may even have something to say about issues as fundamental as local Lorentz invariance: the absence of photo-pion production above the GZK-limit would imply no cosmogenic neutrino flux and possibly undeflected pointing of the primary back to its source. Additionally, contrasting the observed quasi-horizontal neutrino flux with the expected neutrino flux can help to constrain TeV-scale gravity interactions and improve current bounds on the fundamental Planck scale. An optimist might even imagine the discovery of microscopic BHs, the telltale signature of the universe’s unseen dimensions. We are entering this new High Energy Physics era with the Pierre Auger Observatory.

Acknowledgments

I am thankful to all my collaborators, especially to Jonathan Feng, Haim Goldberg and Al Shapere for enlightening discussions on neutrino air showers and TeV-scale gravity BHs, and to Steve Reucroft for a critical reading of this manuscript. I would also like to thank John Bahcall for valuable email correspondence and permission to reproduce Fig. 1. This work has been partially supported by the US National Science Foundation (NSF), under grant No. PHY-0140407.

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