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Particle physics explanations for ultra-high energy cosmic ray events

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Abstract. The origin of cosmic ray events with $E \gtrsim 10^{11}$ GeV remains mysterious. In this talk I briefly summarize several proposed particle physics explanations: a breakdown of Lorentz invariance, the 'Z-burst' scenario, new hadrons with masses of several GeV as primaries, and magnetic monopoles with mass below 10^{10} GeV as primaries. I then describe in a little more detail the idea that these events are due to the decays of very massive, long-lived exotic particles.

Keywords. Cosmic rays; supermassive particles.

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1. Introduction

The observation [1] of cosmic ray (CR) events with energy $E \gtrsim 10^{11}$ GeV (ultra-high energy, UHE) poses at least two distinct problems:

- *The energy problem*: It is very difficult, if not impossible, to accelerate protons to such energies in any known astrophysical source [2].
- *The propagation problem*: Protons with $E \geq 5 \cdot 10^{10}$ GeV can photoproduce pions on the cosmic microwave background (CMB). The GZK effect [3] implies that protons with $E \geq 10^{11}$ GeV should have been produced within a few dozen Mpc of Earth. The same conclusion holds for photons (which get absorbed via $\gamma_{\rm UHE} + \gamma_{\rm radio} \to e^+e^-$, where $\gamma_{\rm radio}$ belongs to the (extra)galactic radio background) and heavier nuclei (which are broken up by collisions with CMB photons). Current estimates of (extra)galactic magnetic field strengths imply that protons with $E > 10^{10}$ GeV should point back to their source if they are produced within a few dozen Mpc. There are, however, no known near sources of high-energy particles in the direction of the most energetic events [3a].

Many suggested solutions of 'the UHECR puzzle' actually only address the second problem. I will briefly review these ideas in the following section. In §3, I will discuss two approaches that can solve both problems, the main emphasis being on decays of super-massive particles, before concluding in §4.

2. Partial solutions

2.1 *Breaking Lorentz invariance*

Calculations of the GZK effect assume that $\sigma(\gamma p \to N\pi)$ $(N = n, p)$ is the same for $E_\gamma \simeq E_{\rm CMB} \sim 10^{-3}$ eV, $E_p \sim 10^{11}$ GeV and $E_\gamma \sim 200$ MeV, $E_p = m_p$. This assumption may be wrong if Lorentz symmetry is violated. This is actually quite an old idea [6], which has been rediscovered recently [7]. By assuming different limiting velocities for different species of particles one can arrange for a suppression of the GZK effect; one can even avoid it altogether. In this case one would expect a completely smooth spectrum around the GZK cut-off. In particular, one would not expect a bump just below the GZK energy, which seems to be present in both the AGASA and HiRes results [1]. Besides, it seems to me a step backwards to give up one of the basic symmetries underlying our understanding of nature; it rather reminds me of Bohr's willingness to give up energy conservation to explain nuclear β decay spectra. Back then, Pauli's neutrinos saved the day; I am confident that the puzzle of the UHECR events can also be solved without giving up well-established principles.

2.2 *Exotic hadrons as UHECR primaries*

If an exotic hadron $h_{\rm E}$ with mass $m_{h_{\rm E}} = rm_p$ is [8] the primary of the UHECR events, the GZK 'cut-off' (better: spectral break) will be pushed upwards by a factor r. Even the AGASA data can be explained if $r \geq 4$. On the other hand, if $h_{\rm E}$ is too heavy, it looses energy too slowly in the air shower it initiates when hitting the Earth's atmosphere. It has been estimated [9] that the produced shower will only look sufficiently proton-like if $r \lesssim 50$.

There are at least two problems with this scenario. First, acceleration becomes much more difficult to explain. Producing UHE $h_{\rm E}$ particles by first accelerating protons and then colliding them with ambient matter (or photons) will likely over-produce neutrinos and UHE photons, since the (inclusive) cross-section for pion production is several orders of magnitude larger than the cross-section for $h_{\rm E}$ production; of course, this would also assume that protons can be accelerated to energies well beyond the most energetic observed CR event. Directly accelerating stable $h_{\rm E}$ particles is also problematic, since at least on Earth they only constitute at most a tiny fraction of all matter, so the heavenly accelerator would presumably also 'waste' most of its energy on accelerating ordinary protons and electrons. The second problem is that $h_{\rm E}$ particles, being strongly interacting and rather light, should have been produced abundantly in collider experiments; it is difficult to believe that they could have escaped detection.

2.3 *Z bursts*

The idea [10] is that UHE neutrinos are produced somewhere; since they can propagate almost freely through the Universe, this neutrino source may be anywhere

within one Hubble radius, 3 Gpc, or so. Within the GZK radius around the Earth, a small fraction of these UHE neutrinos annihilate on relic background antineutrinos to produce Z bosons, most of which decay hadronically, giving rise to the observed UHECR events. Of course, UHE $\bar{\nu}$ annihilating on relic ν also contribute.

One problem with this explanation is that it aggravates the energy problem by several orders of magnitude. One will need UHE neutrinos of at least five times the energy of the most energetic UHECR event, since Z bosons decay into typically $\gtrsim 20$ hadrons. In order to produce such neutrinos, one needs protons whose energy is higher by at least another factor of five or so, i.e., one would need a source of protons extending to $E \gtrsim 10^{13}$ GeV. Moreover, the flux $\Phi_{\nu,\mathrm{UHE}} \gg \Phi_{\mathrm{exp.\ UHECR}}$, i.e., the intensity of this source must be *much* higher than that needed to directly accelerate the observed UHECR flux [10a]. Indeed, the required UHE neutrino flux is at best marginally compatible with existing limits [11].

3. Complete solutions

3.1 *Magnetic monopoles as UHECR primaries*

This is another old idea [12] that has been rediscovered recently [13]. The main observation is that magnetic monopoles can actually be accelerated (rather than only deflected) by (extra)galactic magnetic fields. Indeed, this acceleration is quite efficient, partly due to the large effective charge ($\geq 1/\alpha_{\mathrm{em}}$) of the monopoles. According to current estimates, energies beyond 10^{11} GeV are easily accommodated in this way. Of course, monopoles are stable and so they can have been produced in the very early Universe, most plausibly during a phase transition. The density, or flux, of monopoles required to explain the observed UHECR events is safely below all known bounds [14], as long as these monopoles do not catalyze nucleon decay.

The biggest difficulty of this model is to explain why the observed events look so much like proton-induced air showers. In order to produce a shower at all, the monopole must be ultra-relativistic, i.e. $m_M < 10^{10}$ GeV. These monopoles therefore cannot be associated with a grand unified symmetry; instead one has to postulate the existence of an 'intermediate' scale $\mathcal{O}(m_M)$. Of course, direct monopole searches at colliders imply $m_M \gg m_p$. Simple kinematics then implies that a monopole-induced air shower will penetrate much more deeply into the atmosphere than a p-initiated shower does, unless the cross-section for inelastic scattering of a monopole on an air nucleus is much *larger* than the corresponding cross-section for protons. The authors of [14] argue that bound states of monopoles carrying non-trivial $SU(3)_{\mathrm{c}}$ charge might conceivably have this property. In this view, successive collisions could increase the length of the color-magnetic QCD string (or flux tube) between the constituents, and hence the area of the bound state. Note that this string can only break into monopole–antimonopole pairs. Since monopoles are heavy, a purely color-magnetic string might therefore store many orders of magnitude more energy, and could correspondingly be many orders of magnitude longer, than the more familiar color-electric string does, which can break up into light $q\bar{q}$ pairs. The effective monopole–air cross-section can grow quickly through this mechanism, leading to the desired short air shower. Note, however, that the monopoles,

being stable, should still reach the Earth (with non-relativistic velocity); detecting these monopoles would be the ultimate test of this explanation.

3.2 *Decaying superheavy particles*

Another exotic possibility is that the UHECR events are due to the decay (or annihilation) of some superheavy long-lived X particle [15]. We obviously need $m_X \gtrsim 10^{12}$ GeV in order to generate a significant flux of UHECR primaries at $E \geq 3 \cdot 10^{11}$ GeV. Just as obviously, the lifetime of X must be at least comparable to the age of the Universe, $\tau_X \gtrsim 10^{10}$ yrs. This immediately raises two particle physics questions: how can such massive particles be so long-lived, with $\Gamma_X / m_X \lesssim 10^{-54}$? And how could such massive particles ever have been created?

One way to ensure the longevity of the X particles is to embed them into topological defects. The original proposal [15] envisioned annihilating monopole–antimonopole pairs as source of UHECR events. This idea has later been refined to the concept of a 'cosmic necklace', (anti)monopoles strung along a cosmic string [16]. Cosmic strings themselves become unstable when they intersect. Such kinds of defects could be formed during a phase transition via the Kibble mechanism [17].

Note that we now need the scale of symmetry breaking to be $\gtrsim 10^{12}$ GeV (as opposed to $\lesssim 10^{10}$ GeV in the previous subsection). This may be problematic, since with the scale of (four-dimensional) inflation determined to be $\sim 10^{13}$ GeV, it is quite possible that the post-inflationary Universe never was hot enough to have been in the 'unbroken' phase, which would require $T \gtrsim 10^{12}$ GeV. Moreover, the increasingly well-measured CMB anisotropies do not seem to show any evidence that topological defects (like cosmic strings) played a role in structure formation. In these topological defect models, the X particles could be superheavy gauge or Higgs bosons, and/or their superpartners.

Alternatively, the X particles could exist as (more or less) free particles in today's Universe. Such particles might have been created at the end of inflation, when the energy density of the Universe was more than one hundred orders of magnitude higher than it is today. Several production mechanisms have been suggested, e.g. gravitational production due to the rapidly varying metric (which could work for X particles as heavy as 10^{16} GeV) [18], or in (inclusive) inflaton decays [19]. The X particles would then serve as 'batteries', storing energy from this extremely violent early epoch of the Universe and releasing it in our much balmier times.

In order to explain the longevity of such free X particles one has to postulate that their couplings to ordinary matter are very strongly suppressed. Some such suppression is actually expected if X resides in the 'hidden sector' thought to be responsible for the spontaneous breaking of supersymmetry [20], which by definition only has $M_{\rm Planck}$ suppressed couplings to the visible sector, although it is by no means guaranteed that this suppression is sufficient. The relevant couplings could also be suppressed by (approximate) symmetries [21], or geometrically in brane world scenarios [22,22a].

The spectrum of UHECR primaries (and other stable particles) at source is determined by the physics of X decays [25]. This is quite non-trivial, as indicated in figure 1, which is taken from ref. [26]. The primary few-body X decay initi-

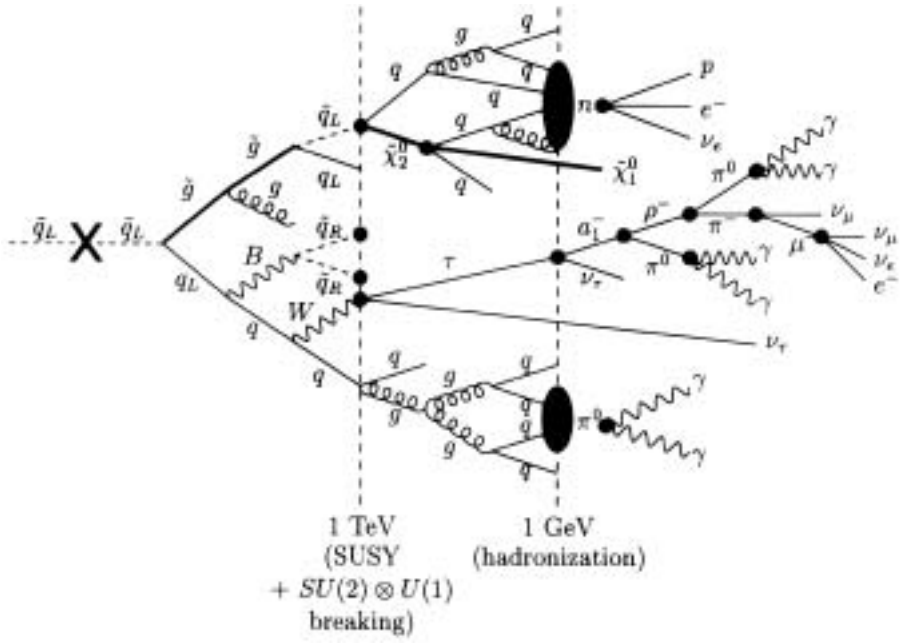

Figure 1. Schematic MSSM cascade for an initial squark with a virtuality $Q \simeq M_X$. The full circles indicate decays of massive particles, in distinction to fragmentation vertices. The two vertical dashed lines separate different epochs of the evolution of the cascade: at virtuality $Q > M_{\rm SUSY}$, all MSSM particles can be produced in fragmentation processes. Particles with mass of order $M_{\rm SUSY}$ decay at the first vertical line. For $M_{\rm SUSY} > Q > Q_{\rm had}$ light QCD degrees of freedom still contribute to the perturbative evolution of the cascade. At the second vertical line, all partons hadronize, and unstable hadrons and leptons decay. See the text for further details.

ates a generalized parton shower. This is similar to, e.g., the hadronic decay of Z bosons, which have been studied in great detail at LEP and SLC. From a theorist's perspective, a Z boson decays into a $q\bar{q}$ pair, whereas experimentally one observes twenty or so hadrons in the final state. The transition from the two (anti)quarks to the $\mathcal{O}(20)$ hadrons entails both perturbative and non-perturbative physics. The perturbative part is called a parton shower. It can be envisioned by assuming that the original $q\bar{q}$ pair is not produced on-shell, but with initial time-like virtualities of order m_Z. The showering occurs when these partons move closer to the mass shell by emitting additional partons, mostly gluons, with smaller time-like virtualities.

Similarly, the particles produced in primary X decay should be considered to have initial time-like virtualities $\mathcal{O}(m_X)$. At such high energy scales parton showers are expected to develop quite differently from parton showers at scale m_Z. To begin with, the existence of a (real, four-dimensional) energy scale $m_X \gg m_Z$ strongly indicates the existence of superparticles, which can stabilize this very large ratio of scales against radiative corrections [27]. Since the superparticle mass scale $m_{\rm SUSY} \lesssim 1$ TeV $\ll m_X$, superparticles can be produced (i.e., will be 'active') in the

initial part of the shower development, even if X decays primarily into SM particles. Moreover, we know that at energy scales near m_X all three gauge interactions are of approximately equal strength. In [26,28] we therefore included all gauge interactions as well as third generation Yukawa interactions in the description of the parton shower.

When the shower virtuality scale reaches $m_{\rm SUSY}$, superparticles decouple from the shower and decay; the electroweak gauge and Higgs bosons, as well as top quarks, decouple at essentially the same scale. A careful treatment of these decays is mandatory if one wants to account for the entire energy released in X decays. As well-known, sparticle decays can be somewhat complicated even at the parton level, involving lengthy decay cascades. We treated these with the help of ISASUSY [29].

At shower scales between $m_{\rm SUSY}$ and $Q_{\rm had} \sim 1$ GeV only standard QCD is important for the evolution of the parton shower, as at LEP. At scale $Q_{\rm had}$ the non-perturbative parton $\rightarrow$ hadron transition occurs. Most hadrons, as well as heavy μ and τ leptons, eventually decay as well, as indicated in the figure. At the end, one is thus left with seven species of particles (plus their antiparticles): protons, electrons, photons, three kinds of neutrinos, and LSPs.

Out of the multitude of particles produced in a far-away X decay, at most one will be observed on Earth. We therefore 'only' have to compute the one-particle inclusive X decay spectra into the seven stable decay products. In QCD the notion of fragmentation functions (FFs) has been developed precisely in order to describe single-particle inclusive spectra [30]. These FFs depend on two variables: the energy scale of the shower, here m_X, and the scaled energy $x_P = 2E_P/m_X$ of the stable decay product P in the X rest frame. The x dependence of hadronic FFs at some reference scale has to be taken from data, since non-perturbative effects are important here; we used the fits of ref. [31,31a]. The scale dependence of the FFs is described by the appropriate generalization of the well-known DGLAP evolution equations [32]. The decays of superparticles and other massive partons can also be treated in this framework, as long as their energy is much larger than their mass, in which case a collinear treatment is adequate. Finally, at very small x, color coherence effects should be included [26].

The main results of this analysis can be summarized as follows [26,28]:

- For $x \lesssim 0.01$, the ν_e, ν_μ, e, γ and p fluxes [32a] have essentially fixed ratios, independent of the primary X decay mode(s) and of the details of the SUSY spectrum. The ν_μ flux is largest, exceeding the p flux by a factor $\sim$3, while the photon and $e \simeq \nu_e$ fluxes exceed the proton flux by a factor $\sim$2.5 and $\sim$2, respectively. All these fluxes can be described by a simple power law in this region, $\mathrm{d}\Phi/\mathrm{d}E \propto E^{-1.4}$. These features are due to QCD evolution effects. Note that most $\nu_{e,\mu}$, e and γ at $x \lesssim 0.01$ originate from pion decays, and are thus subject to the same QCD effects [32b]. On the other hand, the ν_τ and lightest superparticle (LSP) fluxes, which decouple much earlier in the shower, are model-dependent even at small x. Generally they increase more slowly with decreasing x, and thus become subdominant for $x \lesssim 0.01$.
- For $x \gtrsim 0.1$, the fluxes at source depend very strongly on the primary X decay mode(s), and less strongly (typically at the factor of two level) on details of the SUSY spectrum, the relative ordering of and mass splitting between states being more important than the overall sparticle mass scale. For all

X decays into MSSM particles the photon flux at source is larger than the proton flux. In case of hadronic X decays the ratio Φ_γ/Φ_p reaches a minimum (slightly above 1) at $x \simeq 0.3$. At larger x it increases due to the emission of hard photons early in the shower, illustrating the importance of including electroweak interactions in the description of the shower. At smaller x this ratio increases because the ratio of FFs to pions and to protons increases with decreasing x [31]. For primary X decays into only weakly interacting particles the photon flux at $x \gtrsim 0.1$ exceeds the proton flux by at least one order of magnitude, since in this case hadrons can only be produced after two electroweak branching processes, while photons can be emitted already in the first branching. The ν_μ and ν_e fluxes also exceed the proton flux at large x; these two neutrino fluxes approach each other at $x \gtrsim 0.5$, where most neutrinos come directly from electroweak branching and decay processes, rather than from pion decays.

- The LSP flux is important even if the primary X decay only involves SM particles. For example, bino-like LSPs carry 2–3% of the total energy if X decays into leptons, 5–6% if X decays into quarks, 20–30% if X decays into squarks, and 30–50% if X decays into sleptons. The percentage is higher for X decays into $SU(2)$ singlet sfermions, since they have shorter supersymmetric decay chains, and also shower less (due to the absence of $SU(2)$ couplings).

These fluxes are modified by propagation effects. Even if most relevant X decays occur in the halo of our own galaxy, which is expected [33] if X particles can move freely under the influence of gravity, electrons will loose most of their energy in synchrotron radiation on galactic $\vec{B}$-fields. Moreover, the propagation distance is so large that oscillations essentially wash out all information about the original neutrino flavor dependence, i.e., approximately equal fluxes of ν_e, ν_μ and ν_τ will reach Earth independent of the ratios of these fluxes at source.

How can one test this class of models? Given that m_X and the source density $\propto \Omega_X/\tau_X$ are considered to be free parameters, it is not surprising that one can fit [25,34] the observed UHECR flux. These models are even compatible with a GZK spectral break, as indicated by the current HiRes (but not AGASA) data, if X particles are distributed more or less uniformly throughout the Universe, as would e.g. be expected if they are confined to cosmic strings. As mentioned earlier, freely moving X particles are expected [33] to have a large overdensity ($\sim 10^4$ to 10^5) in our galaxy, in which case most relevant X decays would occur at distance well below one GZK interaction length. Even in this case the HiRes spectrum can be described by X decays, simply by choosing m_X such that the spectrum cuts off just above 10^{11} GeV.

The composition of UHECR primaries is more problematic, however. Observations indicate that most primaries are protons or heavier nuclei, not photons. This follows from an analysis [35] of the longitudinal shower profile of the most energetic event ever observed; from the large number of muons in the Haverah Park [36] and AGASA [37] data; and from the absence of a south–north asymmetry in the AGASA data [37], which would be expected for photon primaries, since photons with $E_\gamma > 10^{10}$ GeV split into e^+e^- pairs already high in the Earth's magnetosphere. In contrast, as mentioned earlier, X decay models predict the photon flux

at source to be higher than the proton flux. If most sources are at cosmological distances, propagation effects may well suppress Φ_γ at post-GZK energies even more than Φ_p. However, if most sources reside in the halo of our galaxy, propagation effects on Φ_γ are expected to be significant only if the galactic radio background has been underestimated by at least an order of magnitude. I do not know how (im)plausible this might be.

Fitting the observed UHECR flux to Φ_p alone increases the predicted flux of neutrinos and LSPs on Earth by about a factor of three if $m_X \gg 10^{12}$ GeV; if $m_X \sim 10^{12}$ GeV, the enhancement amounts to a factor $\sim$2 for hadronic primary X decays, and to roughly one order of magnitude for leptonic decays [37a]. Even without this enhancement the neutrino flux might be detectable by future experiments [38]. One can look for long muon tracks as well as high-energy particle showers due to NC and $\nu_{e,\tau}$ CC events in neutrino telescopes like IceCube [39]. Another technique, used by the RICE experiment at the South Pole [40], is to look for coherent Cherenkov emission of radio waves, which is mostly sensitive to electromagnetic showers, i.e., to ν_e CC events. Finally, future air shower detectors like the Pierre Auger array [41] can look for 'horizontal' air showers, which originate too deep in the atmosphere to be due to photons or protons, and for τ leptons coming out of the Earth at shallow angles and decaying in the atmosphere. In all cases one has to require $E > 100$ TeV in order to suppress the atmospheric neutrino background.

Some estimated [34] event rates per year are collected in table 1, for two extreme values of m_X and two extreme X distributions. 'Galactic' here means that essentially all relevant sources are closer than one GZK interaction length. In contrast, if X particles are distributed homogeneously throughout the Universe, X decays occurring at distances well beyond one GZK interaction length contribute to Φ_ν, but not to Φ_p (at post-GZK energies). A homogeneous distribution therefore leads to $\sim$10 times higher neutrino event rates than a galactic distribution does. Similarly, $m_X \sim 10^{12}$ GeV leads to an about ten times higher neutrino event rate than $m_X \sim 10^{16}$ GeV does. The reason is that, in particular for a galactic distribution of X particles, models with $m_X \gg 10^{12}$ GeV only allow to fit the very highest energy end of the UHECR spectrum, leading to significantly smaller fluxes at source. Notice also that the cross-sections for νp scattering grow significantly less rapidly than linearly with energy once $E_\nu \gg 1$ TeV [42]. Finally, the ranges in the table indicate the spread between different X decay models. For $m_X \sim 10^{16}$ GeV all relevant particles are at $x \ll 1$, in which case this model dependence disappears, as mentioned above.

Table 1. Number of neutrino events with $E_\nu > 100$ TeV per year expected in different detectors. See the text for further details.

m_X (GeV)	X distribution	IceCube	RICE	Auger
$2 \cdot 10^{12}$	Galactic	10–30	1–4	1–3
$2 \cdot 10^{12}$	Homogeneous	80–300	10–35	10–25
$2 \cdot 10^{16}$	Galactic	1	0.4	0.3
$2 \cdot 10^{16}$	Homogeneous	10–15	6	5

Table 2. Number of LSP events with $E_{\tilde{\chi}} > 10^9$ GeV emerging from at least 5° below the horizon expected each year in space–borne fluorescence detectors, for $\sigma_{\tilde{\chi}p} = \sigma_{\nu p}/10$; a ten times smaller scattering cross section gives about 8 to 9 times smaller rates. The notation is as in table 1.

m_X (GeV)	Galactic dist.	Homogeneous dist.
$2 \cdot 10^{12}$	2–30	30–400
$2 \cdot 10^{16}$	0.2–0.6	3–10

Unfortunately the prediction of a detectable neutrino flux at energies beyond that reached by atmospheric neutrinos is hardly unique for this explanation of the UHECR events. The very GZK effect itself gives rise to extremely energetic neutrinos through the decay of charged pions. Note also that the numbers in table 1 differ by more than two orders of magnitude, i.e., a large range of neutrino fluxes is broadly compatible with X decay models. These models generically predict that the neutrino flux extends to somewhat higher energies than the proton flux does [26]. However, testing this prediction would require a fairly accurate measurement of the neutrino flux at energies well beyond 10^{11} GeV, where the expected event rate in the experiments covered in table 1 is very low.

An unambiguous test of this kind of model could be achieved by detecting the flux of very energetic LSPs. In 'bottom-up' scenarios, where the observed UHECR events are explained by the acceleration of protons (or heavier nuclei), very energetic superparticles could only be produced when the accelerated protons (or nuclei) collide with ambient matter. However, the inclusive cross-section for pion production is at least seven orders of magnitude larger than that for the production of superparticles. In this kind of model a detectable LSP flux would therefore be accompanied by a huge flux of extremely energetic neutrinos, which would be (comparatively) easily detectable. In contrast, we saw earlier that LSPs are expected to carry a significant fraction of the energy released in X decays.

Detecting this UHE LSP flux is difficult, but may not be entirely hopeless [43]. The cross-section for LSP–nucleon scattering is estimated [44] to be 10 to 100 times smaller than the neutrino–nucleus cross-section, if the LSP is bino-like, which is the case in most SUSY models. These LSPs will therefore be absorbed less strongly in the Earth than neutrinos are. For $E_\nu = 10^9$ GeV, only one in a thousand neutrinos impinging on Earth at an angle at least 5° below the horizon can transverse it without interacting. ν_τs can be regenerated via $\tau \to \nu_\tau$ decays even if they undergo CC scattering, but the emerging ν_τ will only carry 20% or so of the energy of the original one. If the UHE neutrino 'background' comes from X decays, one can therefore show that very few events with $E > 10^9$ GeV can emerge at an angle $\theta > 5°$ below the horizon, and essentially none at $\theta > 10°$. In contrast, if $\sigma_{\tilde{\chi}p} = \sigma_{\nu p}/10$, at $E_{\tilde{\chi}} = 10^9$ GeV the LSP flux will be depleted significantly only at $\theta > 60°$; the depletion becomes altogether negligible for $\sigma_{\tilde{\chi}p} = \sigma_{\nu p}/100$, up to energies well beyond 10^{10} GeV.

Due to the LSPs' small flux and cross-section, one will need huge targets. These might be provided by space-borne fluorescence detectors like EUSO [45] and OWL [46]. Table 2 shows estimated [43] rates of LSP events with $\theta > 5°$ and $E_{\tilde{\chi}} > 10^9$

GeV, assuming $\sigma_{\tilde{\chi}p} = \sigma_{\nu p}/10$ and a target area of 150,000 km^2. Since LSPs can interact either in the atmosphere or in $\sim$10 m water-equivalent (w.e.) below it, this corresponds to an approximate target size of 2000 km^3 w.e. Even in that case the expected event rates are not very large, and we have not included any efficiencies yet. Optical observations of air showers are typically only possible on clear, moonless nights, i.e., some 10% of the time. Once this is included, only the most optimistic scenario (a homogeneous distribution of 10^{12} GeV particles, and an LSP–nucleon scattering cross-section near the upper end of the expected range) will give a clear signal in this kind of experiment. However, an enlargement of the target area is at least conceivable, e.g., by simply launching more satellites, or by using a higher orbit (with correspondingly tougher requirements on the optics).

4. Summary and conclusions

In this contribution I discussed particle physics explanations of the post-GZK cosmic ray events. My personal favorite remains the explanation in terms of superheavy late decaying particles, which can solve both the energy and propagation problems. The biggest current challenge of this class of models seems to be how to explain the paucity of photons as primaries in the observed events. A first minnowing of models should be achieved by measuring the flux of neutrinos with $E_\nu > 10^5$ GeV. A decisive test may require measuring (or excluding) the predicted flux of LSPs with $E_{\tilde{\chi}} \gtrsim 10^9$ GeV, which will be difficult, but may be possible using space-based experiments. Proving the existence of such mysterious superheavy but long-lived particles would revolutionize our understanding of physics. If these models are still viable after the next generation of cosmic ray observatories and neutrino telescopes have presented their data, no effort should be spared to search for these extremely energetic cosmic LSPs.

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References

[1] The most important data are: AGASA Collaboration: M Takeda *et al*, *Phys. Rev. Lett.* **81**, 1163 (1998); astro-ph/9807193
HiRes Collaboration: T Abu-Zayyad *et al*, astro-ph/0208301
[2] A M Hillas, *Ann. Rev. Astron. Astrophys.* **22**, 425 (1984)
[3] K Greisen, *Phys. Rev. Lett.* **16**, 748 (1966)
G T Zatsepin and V A Kuzmin, *JETP Lett.* **4**, 78 (1966); *Pisma Zh. Eksp. Teor. Fiz.* **4**, 114 (1966)
[3a] There have been claims [4] of statistically significant correlations between the arrival directions of UHECR events and certain kinds of active galactic nuclei (AGN), thought

to be possible sources of UHE particles. However, an independent analysis did not confirm this [5]

[4] D S Gorbunov, P G Tinyakov, I I Tkachev and S V Troitsky, *Astrophys. J.* **577**, L93 (2002); astro-ph/0204360

[5] N W Evans, F Ferrer and S Sarkar, astro-ph/0212533

[6] H Sato and T Tati, *Prog. Theor. Phys.* **47**, 1788 (1972)

[7] S R Coleman and S L Glashow, hep-ph/9808446
See also the New York Times, December 31, 2002

[8] D J H Chung, G R Farrar and E W Kolb, *Phys. Rev.* **D57**, 4606 (1998); astro-ph/9707036

[9] I F M Albuquerque, G R Farrar and E W Kolb, *Phys. Rev.* **D59**, 015021 (1999); hep-ph/9805288

[10] T J Weiler, *Phys. Rev. Lett.* **49**, 234 (1982); *Astropart. Phys.* **11**, 303 (1999); hep-ph/9710431

[10a] Such a source could easily over-produce protons just below the GZK cut-off

[11] Z Fodor, S D Katz and A Ringwald, *J. High Energy Phys.* **0206**, 046 (2002); hep-ph/0203198
Note that the authors of this paper do not include bounds by RICE and AGASA on the UHE neutrino flux; these bounds are very close to the predicted fluxes

[12] N A Porter, *Nuovo Cimento* **16**, 958 (1960)

[13] T W Kephart and T J Weiler, *Astropart. Phys.* **4**, 271 (1996); astro-ph/9505134

[14] S D Wick, T W Kephart, T J Weiler and P L Biermann, *Astropart. Phys.* **18**, 663 (2003); astro-ph/0001233

[15] C T Hill, D N Schramm and T P Walker, *Phys. Rev.* **D36**, 1007 (1987)
P Bhattacharjee, C T Hill and D N Schramm, *Phys. Rev. Lett.* **69**, 567 (1992)

[16] V Berezinsky and A Vilenkin, *Phys. Rev. Lett.* **79**, 5202 (1997); astro-ph/9704257
This configuration seems to have first been proposed (in a different context) by M Hindmarsh and T W B Kibble, *Phys. Rev. Lett.* **55**, 2398 (1985)

[17] T W B Kibble, *J. Phys.* **A9**, 1387 (1976)

[18] D J H Chung, P Crotty, E W Kolb and A Riotto, *Phys. Rev.* **D64**, 043503 (2001); hep-ph/0104100

[19] R Allahverdi and M Drees, *Phys. Rev. Lett.* **89**, 091302 (2002); hep-ph/0203118

[20] J Ellis, J Lopez and D V Nanopoulos, *Phys. Lett.* **B247**, 257 (1990)
C Coriano, A E Faraggi and M Plümacher, *Nucl. Phys.* **B614**, 233 (2001); hep-ph/0107053

[21] K Hamaguchi, Y Nomura and T Yanagida, *Phys. Rev.* **D58**, 103503 (1998); hep-ph/9805346; *Phys. Rev.* **D59**, 063507 (1999); hep-ph/9809426
K Hamaguchi, K I Izawa, Y Nomura and T Yanagida, *Phys. Rev.* **D60**, 125009 (1999); hep-ph/9903207

[22] K Hagiwara and Y Uehara, *Phys. Lett.* **B517**, 383 (2001); hep-ph/0106320

[22a] It is sometimes claimed [23] that the required long lifetime of X needs severe fine-tuning. This is not really true, since τ_X could be as large as 10^{20} yrs [24] if X particles constitute the bulk of dark matter. Model builders therefore have some ten orders of magnitude in τ_X to aim for. Of course, the observed UHECR flux determines the ratio Ω_X/τ_X to within a factor of a few, but this does not require any more fine-tuning of model parameters than in any other explanation of the UHECR events

[23] See e.g. H J de Vega and N Sanchez, astro-ph/0301039

[24] S Sarkar, talk presented at *Cosmo '01*, Rovaniemi, Finland, September 2001; hep-ph/0202013

[25] M Birkel and S Sarkar, *Astropart. Phys.* **9**, 297 (1998); hep-ph/9804285

V Berezinsky and M Kachelriess, *Phys. Rev.* **D63**, 034007 (2001); hep-ph/0009053
C Coriano and A E Faraggi, *Phys. Rev.* **D65**, 075001 (2002); hep-ph/0106326
S Sarkar and R Toldra, *Nucl. Phys.* **B621**, 495 (2002); hep-ph/0108098
Z Fodor and S D Katz, *Phys. Rev. Lett.* **86**, 3224 (2001); hep-ph/0008204
A Ibarra and R Toldra, *J. High Energy Phys.* **0206**, 006 (2002); hep-ph/0202111
V Berezinsky, M Kachelriess and S Ostapchenko, *Phys. Rev. Lett.* **89**, 171802 (2002); hep-ph/0205218

[26] C Barbot and M Drees, *Astropart. Phys.* **20**, 5 (2003); hep-ph/0211406

[27] E Witten, *Nucl. Phys.* **B188**, 513 (1981)
N Sakai, *Z. Phys.* **C11**, 153 (1981)
S Dimopoulos and H Georgi, *Nucl. Phys.* **B193**, 150 (1981)
R K Kaul and P Majumdar, *Nucl. Phys.* **B199**, 36 (1982)

[28] C Barbot and M Drees, *Phys. Lett.* **B533**, 107 (2002); hep-ph/0202072

[29] H Baer, F E Paige, S D Protopopescu and X Tata, hep-ph/9305342

[30] See e.g. E Reya, *Phys. Rep.* **69**, 195 (1981)

[31] B A Kniehl, G Kramer and B Pötter, *Nucl. Phys.* **B582**, 514 (2000); hep-ph/0010289

[31a] Some of these 'input' FFs are still not well-determined, e.g. those starting from a b or c quark

[32] V N Gribov and L N Lipatov, *Yad. Fiz.* **15**, 781 (1972); *Sov. J. Nucl. Phys.* **15**, 438 (1972)
G Altarelli and G Parisi, *Nucl. Phys.* **B126**, 298 (1977)
Y L Dokshitzer, *Sov. Phys. JETP* **46**, 641 (1977); *Zh. Eksp. Teor. Fiz.* **73**, 1216 (1977)

[32a] All fluxes are summed over particle and antiparticle, if they are distinct

[32b] These effects also imply that the results are largely independent of the necessary extrapolation of the 'input' FFs towards small x, as long as this extrapolation conserves energy and has a milder small-x behavior than $x^{-1.4}$

[33] V Berezinsky, M Kachelriess and A Vilenkin, *Phys. Rev. Lett.* **79**, 4302 (1997)
Birkel and Sarkar in [25].

[34] C Barbot, M Drees, F Halzen and D Hooper, *Phys. Lett.* **B555**, 22 (2003); hep-ph/0205230

[35] R A Vazquez *et al*, *Astropart. Phys.* **3**, 151 (1995)

[36] M Ave, J A Hinton, R A Vazquez, A A Watson and E Zas, *Phys. Rev. Lett.* **85**, 2244 (2000); astro-ph/0007386; *Phys. Rev.* **D65**, 063007 (2002); astro-ph/0110613

[37] AGASA Collaboration: K Shinozaki *et al*, *Astrophys. J.* **571**, L117 (2002)

[37a] Leptonically decaying X particles with $m_X \lesssim 10^{13}$ GeV are thus particularly difficult to reconcile with the experimental evidence against photons as main UHECR primaries

[38] P Gondolo, G Gelmini and S Sarkar, *Nucl. Phys.* **B392**, 111 (1993); hep-ph/9209236

[39] E Andres *et al*, *Nature* **410**, 441 (2001)

[40] I Kravchenko *et al*, astro-ph/0206371

[41] X Bertou, P Billoir, O Deligny, C Lachaud and A Letessier-Selvon, *Astropart. Phys.* **17**, 183 (2002); astro-ph/0104452

[42] R Gandhi, C Quigg, M H Reno and I Sarcevic, *Phys. Rev.* **D58**, 093009 (1998); hep-ph/9807264

[43] C Barbot, M Drees, F Halzen and D Hooper, hep-ph/0207133

[44] V Berezinsky and M Kachelriess, *Phys. Lett.* **B422**, 163 (1998); hep-ph/9709485

[45] http://www.euso-mission.org

[46] http://owl.gsfc.nasa.gov