NEW PHYSICS FROM ULTRAHIGH ENERGY COSMIC RAYS*

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Observations of cosmic rays with energies above $\sim 4 \times 10^{10}$ GeV have inspired several speculative suggestions concerning their origin. The crucial question is whether or not the spectrum exhibits the expected 'GZK cutoff' at this energy — concerning which there are presently contradictory results. If there is indeed a cutoff, then the sources are cosmologically distant and rather exotic in nature. If there is no cutoff then new physics is required.

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1. Introduction

As we approach the centennial of the discovery of cosmic radiation by Victor Hess in 1912, the astrophysical origin of these high energy particles remains still unknown. Even so the study of cosmic rays has been extremely rewarding for particle physics. As Hess noted in his Nobel Lecture in 1936: *"The investigation of ... cosmic rays ... has led to the discovery of the positron ... It is likely that further research into "showers" and "bursts" of the cosmic rays may possibly lead to the discovery of still more elementary particles ... of which the existence has been postulated by some theoretical physicists in recent years"*. Indeed several such discoveries were made in rapid succession — the muon in 1937, the pion in 1947 and strange particles (kaons, hyperons) also in 1947. However with the development of particle accelerators in the 1950's, the attention of particle physicists turned naturally to controlled laboratory experiments. No other new particles have subsequently been discovered in cosmic rays although there have been several false alarms (*e.g.* free quarks, monopoles, ...) and many claims of unexplained phenomena (*e.g.* 'Centauro' events). Today we have another such mystery

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— the observation of ultra high energy cosmic rays (UHECRs) which cannot propagate very far through the cosmic microwave background, are unlikely to be significantly affected by cosmic magnetic fields, and yet which do not point back to any plausible astrophysical sources in our vicinity [1, 2]. The intriguing question is whether an explanation is possible in terms of known physics or will require physics beyond the Standard Model.

2. Observational status

As we have just heard from Prof Teshima, the AGASA collaboration has reevaluated the energy determination method used for analysing their data on air showers collected over 12 years, with particular attention to the lateral distribution, attenuation with zenith angle, shower front structure, delayed particles observed far from the shower core, *etc.* [3]. They confirm that the energies assigned to AGASA events have an event-reconstruction accuracy of $\pm 25\%$ at 10^{11} GeV, while the systematic uncertainty is $\pm 18\%$ (independent of primary energy above 10^{10} GeV). As seen in Fig. 1, the AGASA data at the highest energies connects smoothly with the (better sampled) Akeno data at lower energies. There are 59 events with $E > E_{\mathrm{GZK}} \simeq 4 \times 10^{10}$ GeV (and 8 events beyond 10^{11} GeV) which have a spectrum distinctly flatter than at lower energies, suggestive of a different origin, but with no indication of the GZK cutoff expected if the sources are cosmologically distant.

By contrast the HIRES air fluorescence experiment, with a similar exposure in the mono mode, has reported only 1 event above 10^{11} GeV, consistent with a GZK cutoff [4]. But as is clear from Fig. 1, the absolute fluxes are lower than those measured by AGASA and the beginning of the 'ankle' in the spectrum is distinctly lower, suggestive of an energy calibration mismatch between the fluorescence and air shower detector data. (Since the spectrum falls as $\sim E^{-3}$ below the ankle, the fractional error in the flux is twice that in the energy, keeping in mind the change in the differential energy interval with the energy.) If the AGASA energies are lowered by $\sim 20\%$, the spectral shapes can be matched below 10^{11} GeV [5], however, 5 AGASA events still remain above this energy. Given the low event statistics, the significance of the discrepancy between the two experiments is not overwhelming, nevertheless it is clearly of paramount importance to resolve the issue and establish a consistent energy scale. The engineering array of the Pierre Auger Observatory [6] has already collected several 'hybrid' events observed using both type of detectors so progress is expected soon.

The other important new result concerns the AGASA data on the angular distribution of events on the sky [7]. As shown in Fig. 2, although the large-scale distribution of the 59 observed showers with $E > E_{\mathrm{GZK}}$ is consistent with isotropy, there are a number of 'clusters' — defined as a grouping of

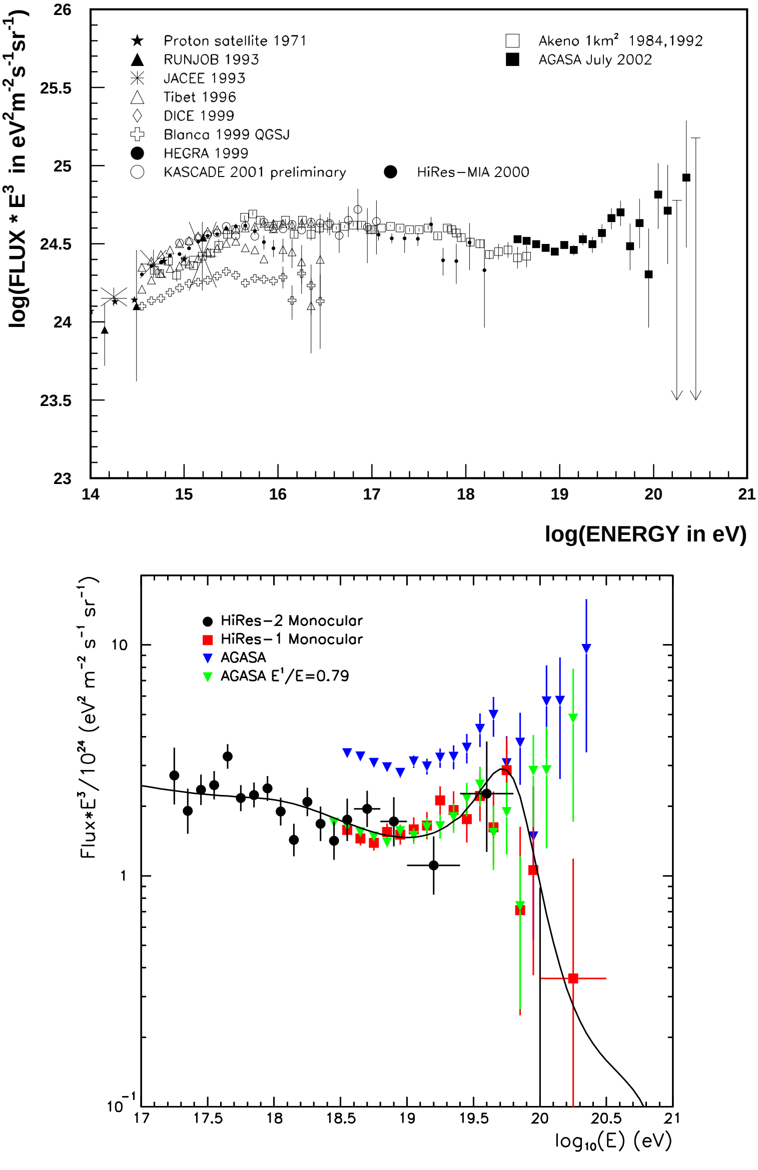

Fig. 1. The top panel shows the recalibrated AGASA spectrum along with data from other experiments at lower energies [3]. The bottom panel shows the HiRes data (fitted to a two-component source model incorporating a GZK cutoff for the extragalactic component); the AGASA data are shown for comparison, and with the event energies reduced by 20% [5]. (All fluxes have been multiplied by E^3.)

2 or more events within (approximately the experimental angular resolution of) 2.5°. The chance probability that the 5 observed doublets and 1 triplet result from an isotropic distribution is estimated by Monte Carlo to be less than 10^{-4} [7]. However Fig. 2 shows that when the events are partitioned by energy, small-scale clustering is seen only for events with $E < 6 \times 10^{10}$ GeV; at higher energies there is *no* clustering [8].

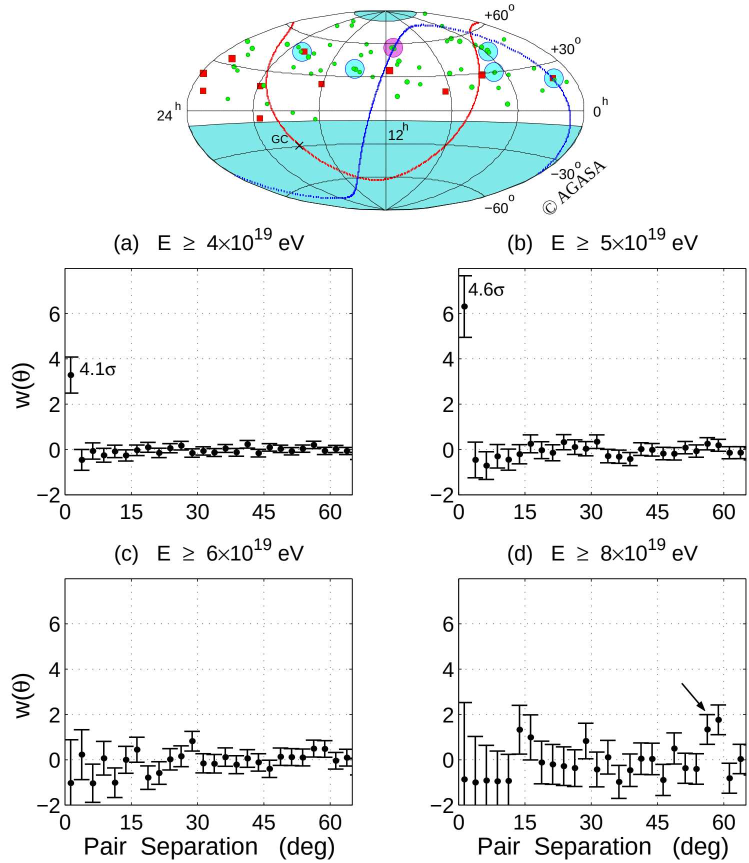

Fig. 2. Arrival directions of UHECRs of energy $E > 4 \times 10^{10}$ GeV (circles) and $E > 10^{11}$ GeV (squares) , with the 'doublets' and 'triplet' highlighted (the shaded area is unobservable by AGASA) [7]. The bottom panel shows the angular autocorrelation function for events above various energy thresholds [8].

To estimate the significance of the clustering reliably, one should calculate the 'penalty factor' for making *a posteriori* cuts (in energy thresholds and angular separations) on the data set in order to maximize the clustering signal. Secondly, as was emphasized earlier [9], the data set used to make

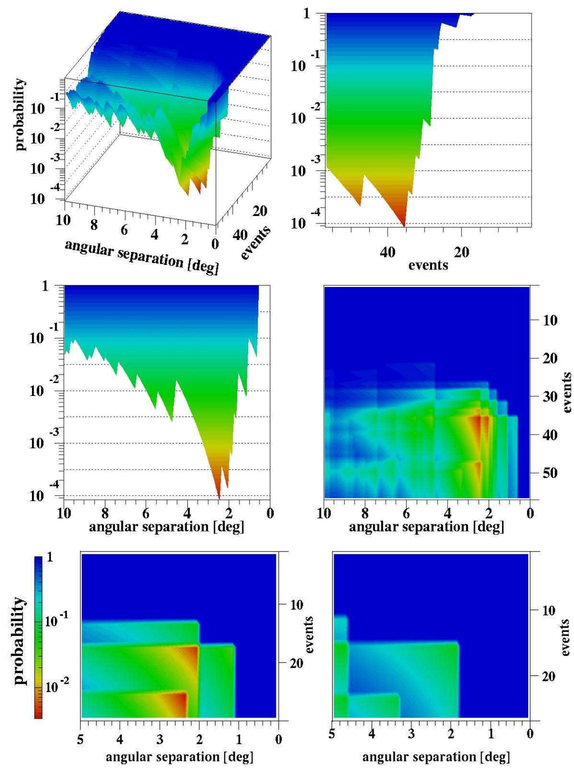

Fig. 3. Autocorrelation scan of 57 AGASA events with $E > 4 \times 10^{10}$ GeV shown in 4 views [10]. The bottom panel shows the chance probabilities for the observed clustering separately for the 30 and 27 events, observed before and after Oct 1995.

the initial claim for clustering ought not to be used in the actual analysis. Recently both these issues have been investigated in detail [10]. As shown in Fig. 3, the strongest autocorrelation signal ($P_{\rm min}^{\rm data} \simeq 8.4 \times 10^{-5}$) is seen at separation angle $\theta_{\rm c} = 2.5°$, with energy threshold $E_{\rm c} = 4.9 \times 10^{10}$ GeV. However Monte Carlo tests show that 3475 out of 10^6 simulated AGASA data sets have $P_{\rm min}^{\rm MC} \leq P_{\rm min}^{\rm data}$ so the chance probability for this is 0.35%. This is 10 times higher than the value claimed earlier [11] — these authors did not allow for their (arbitrary) choice of $\theta_{\rm c}$ to maximise the clustering signal and interpreted their result as implying that the *"Correlation function of ultra-high energy cosmic rays favors point sources"*. Secondly, when the AGASA data is divided into 2 roughly equal sets (30 events detected before October 1995 and 27 events detected afterwards), the chance probabilities jump to 4.4% ($\theta_{\rm c} = 2.4°$) and 27% ($\theta_{\rm c} = 4.7°$) respectively for the observed clustering [10]! The reason appears to be that the two sub-sets of data are strongly correlated — the 'triplet' being made of 2 events from the first set and 1 from the second. Moreover AGASA has announced more events bringing to 42 the number detected since October 1995. There are 2 'doublets' separated by less than 2.5° in this data set but the chance probability for having observed these is 19% [10]. Thus the clustering observed by AGASA is *not* statistically significant, so does not require the observed UHECRs to originate from point sources.

Nevertheless, some authors have sought for and found statistically significant correlations between UHECR arrival directions and possible sources such as (specific subsets of) active galactic nuclei. In particular a selected sample of 39 AGASA events (with $E > 4.8 \times 10^{10}$ GeV) and 26 Yakutsk events (with $E > 2.4 \times 10^{10}$ GeV) are claimed to have significant alignments within 2.5° with 22 selected BL Lacartae objects (having redshift $z > 0.1$ or unknown, magnitude $m < 18$ and 6 cm radio flux $F_6 > 0.17$ Jy). The value of $P_{\rm min}^{\rm data}$ is 4×10^{-6} and the penalty factor for making cuts on the BL Lac catalogue is estimated to be only 15, yielding a chance probability of 6×10^{-5} [12]. However the Yakutsk experiment has an angular resolution worse than 4° at the low (sub-GZK) energy cut made to maximise the coincidences, so these cannot be physically meaningful; dropping these events increases the chance probability for the remaining coincidences (with AGASA events) to 0.15% [13]. Also the assumption that the *"energies of the events are not important for correlations at small angles"* [12] is clearly wrong since a mild drop in the energy threshold for AGASA events to $E > 4 \times 10^{10}$ GeV decreases the significance further by a factor of 5 [13]. Relaxing the cuts on the BL Lac catalogue yields only 2 coincidences between BL Lacs and AGASA 'doublets', with a chance probability of 6.3% [13]. Moreover an independent sample of 27 Haverah Park and 6 Volcano Ranch events with $E > 4 \times 10^{10}$ GeV do not coincide at all with the chosen 22 BL Lacs [14]. Thus, as shown in Fig. 4, there is no justification for the claim that *"BL Lacertae are sources of the observed ultra-high energy cosmic rays"* [12].

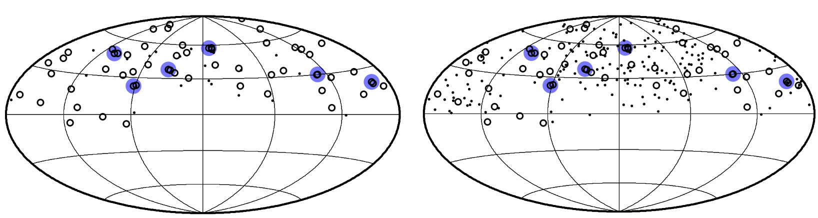

Fig. 4. The sky distribution of 57 UHECRs (circles) with $E > 4{\times}10^{10}$ GeV observed by AGASA, with the 5 'doublets' and 1 'triplet' highlighted. The left panel shows the 22 BL Lacs (dots) satisfying specific cuts on redshift, magnitude and 6 cm radio flux [12], while the right panel shows all 306 BL Lacs in the catalogue [13].

Finally, the inferred composition of UHECRs (as well as their energies) is sensitive to the UHE interaction model used [15] and this realization has muddled the picture suggested earlier by Fly's Eye and HiRes of a change from heavy nucleus domination at 3×10^8 GeV to nucleon domination at 10^{10} GeV. Present data is consistent with a mixed composition at all energies. Reanalysis of 'horizontal showers' at Haverah Park requires that no more than 50% of UHECRs above 4×10^{10} GeV can be photons [16] and a similar (but weaker) limit has been set by AGASA on the basis that photon-initiated showers tend to be muon-poor [17]. However the showering of UHE photons is rather complex (because of pair conversion in the geomagnetic field and the LPM effect), *e.g.* it cannot be excluded that the highest energy Fly's Eye event ($E \sim 3 \times 10^{11}$ GeV) was in fact initiated by a photon [18].

3. Conventional explanations

No astrophysical object has ever been definitively identified (*e.g.* through γ-ray or ν emission) as an accelerator of high energy nucleons. However there do exist energetic objects such as γ-ray bursts, active galactic nuclei, or extended lobes of radio galaxies which satisfy the 'Hillas criterion' of being big enough and/or having sufficiently large (estimated) magnetic fields to be able to confine UHECRs upto $\sim 10^{12}$ GeV [1]. The issue of whether particles can actually be accelerated to the observed energies in such objects is an open one, in particular considerations of radiative energy losses during the acceleration process set very strong constraints [19, 20]. Ultrarelativistic bulk flows in γ-ray bursts (GRBs) remain a possibility, and this coupled with the HiRes claim of a GZK cutoff in the energy spectrum, have revitalized the suggestion that such cosmologically distant objects are the sources of UHECRs [21, 22]. However the energetic requirements are formidable — such sources must inject $\sim 10^{44}$ erg/Mpc^3/yr in UHECRs of energy $10^{10} - 10^{12}$ GeV in order to match the observed flux, while GRBs are observed to emit roughly this much power at far smaller energies of $\mathcal{O}(1)$ MeV. It is hard to conceive of a particle acceleration mechanism that can generate comparable amounts of power in such widely separated energy regions. Nevertheless if there is indeed a GZK cutoff, this is probably the most attractive possibility for the sources of UHECRs.

4. Models involving new physics

However if the UHECR spectrum does extend without a GZK cutoff as indicated by AGASA, then new physics would appear to be required. We discuss below only those possibilities which have not been ruled out already. (In particular we do not consider whether the primaries might be neutrinos having enhanced interaction cross-sections through new physics such as

TeV-scale extra dimensions — this *cannot* explain the observed UHECRs, although studies of airshowers can in principle probe such new physics [2]. We also disregard the hypothesis that the primaries are new light stable hadrons (for which the GZK cutoff energy can be higher), since such particles are *excluded* by laboratory experiments [23].)

4.1. Violation of Lorentz invariance

It was noted long ago that a small modification of the relation between momentum and energy in special relativity may undo the GZK cutoff [24]. If the clustering of events claimed by AGASA is substantiated by the forthcoming high statistics data from Auger, then point sources of UHECRs would be implicated. In that case it may be appropriate to invoke such violation of Lorentz invariance to explain the absence of the GZK cutoff in the spectrum. However it is hard to see how this possibility can be falsified since the required violation is so small that it need not manifest itself in any other astrophysical or laboratory phenomenon [25].

4.2. Z-bursts

Since at least one species of relic neutrinos must have a mass $\gtrsim 0.1$ eV, it is attractive to suppose that these provide a target for UHE neutrinos from distant sources to annihilate on. This would create 'Z-bursts' with an energy of $m_Z^2/2m_\nu \sim 4 \times 10^{12}(m_\nu/1\ \mathrm{eV})^{-1}\,\mathrm{GeV}$, *i.e.* in the right energy range to be a source for UHECRs [26,27]. The energy spectrum of the nucleons and γ-rays resulting from Z decays is well known so a detailed comparison can be made with the AGASA data. Agreement is obtained for a relic neutrino mass of 0.08–1.3 eV [28], however the required UHE ν flux is very large, taking into account that such light relic neutrinos cannot cluster significantly [29]. Although there are no direct bounds yet at these energies, it seems implausible that the required extragalactic sources of $\sim 10^{13}$ GeV neutrinos can exist, given the restrictive bounds on deeply penetrating air showers from experiments such as Fly's Eye, as well as AGASA and RICE [30]. Moreover it is not clear how such high energy neutrinos can be created in the hypothetical cosmic sources — usually this would require the acceleration of even higher energy nucleons!

4.3. Decaying supermassive dark matter

The possible existence of relic metastable massive particles whose decays can create high energy cosmic rays and neutrinos had been discussed [31,32] before the detection of the famous Fly's Eye event with $E \sim 3 \times 10^{10}$ GeV which focused attention on the possible absence of the GZK cutoff. Subsequently this idea was revived and it was noted that such particles, being cold dark matter, would naturally have a overdensity by a factor of $\sim 10^4$ in the halo of our Galaxy [33, 34]. Hence if their slow decays generate UHECRs, all propagation effects will be unimportant (except possibly for photons) in determining the observed spectrum and cosmposition, and, moreover, there should be a detectable anisotropy in the arrival directions, given our asymmetric position in the Galaxy. In order to account for the highest energy events with the observed rates, the particle mass should exceed $m_X \gtrsim 10^{12}$ GeV while to match the UHECR flux its lifetime must be $\tau_X \simeq 3 \times 10^{19} \zeta_X$ yr, where ζ_X is the fraction of the halo dark matter in the form of such particles. It is conceivable that such particles exist in the 'hidden sector' of string/M-theory [35] and can be produced with a cosmologically interesting abundance at the end of inflation [36].

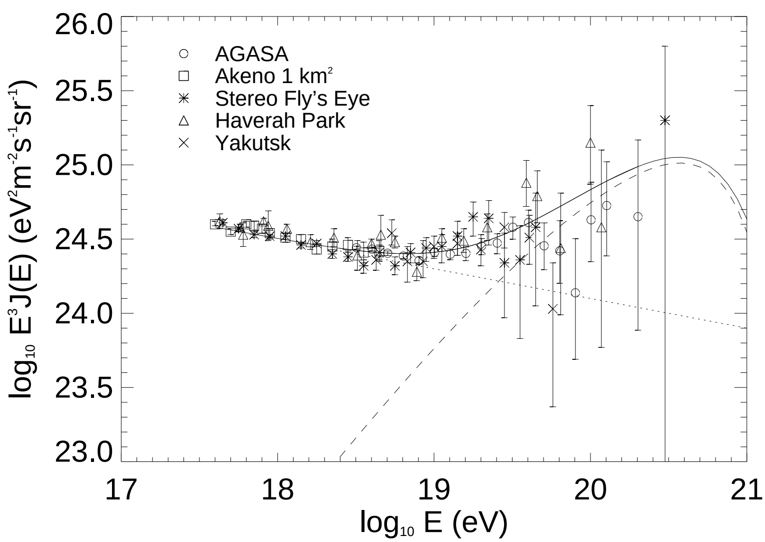

Fig. 5. Fit to the UHECR spectrum beyond E_{GZK} (excluding the HiRes data) with a decaying dark matter particle mass of 5×10^{12} GeV (dashed line); the dotted line is the extension of the spectrum observed at lower energies [39].

The spectra of the decay products is essentially determined by the physics of QCD fragmentation so can be calculated *e.g.* by evolving the fragmentation functions measured in Z^0 decay upto the energies of interest using the DGLAP equations [37–39]. Recent work [40] has included electroweak corrections and a more careful treatment of the possible effects of supersymmetry. As seen in Fig. 5, the evolved spectrum of nucleons is in good agreement with the 'flat' component of UHECR extending beyond E_{GZK}.

However the decay photons, which have a similar spectral shape are more abundant by a factor of ~ 2, so this model (as well as a similar subsequent proposal involving annihilations rather than decays [41]) would seem to be ruled out by the experimental bounds [16, 17] on the photon component of UHECRs. It is possible that the attenuation of such UHE photons in the halo of the Galaxy (through pair production on ∼MHz frequency radio photons) has been underestimated — the radio background intensity assumed for such calculations is very uncertain [42]. However, such attenuation would in turn generate a background of low energy γ-rays and it is necessary to check that this does not exceed observational limits, particularly from EGRET at

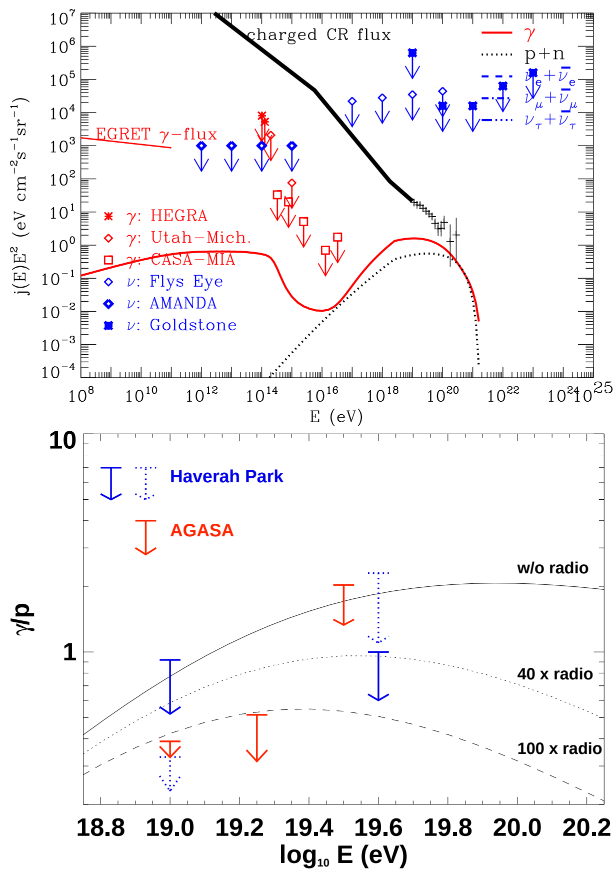

Fig. 6. The expected processing of the UHE photon spectrum from decaying dark matter in the Galactic halo is shown (top panel) for a radio background 10 times higher than is usually assumed and the γ/p ratio for various assumed values of the radio background is compared with experimental limits (bottom panel) [43].

$\sim$ 100 MeV. As shown in Fig. 6, such constraints can indeed be satisfied although the required increase in the intensity of the radio background is rather large [43]. Perhaps one should wait for Auger to establish whether photons are indeed ruled out as the UHECRs.

Detailed calculations have also been made of the expected anisotropy, adopting different possible models of the dark matter halo (cusped, isothermal, triaxial and tilted) [44]. The amplitude of the anisotropy is controlled by the extent of the halo, while the phase is controlled by its shape. As seen in Fig. 7, the amplitude of the first harmonic is ~ 0.5 for a cusped 'NFW' halo but falls to ~ 0.3 for an isothermal halo which is more favoured by observations [45], while the maximum is in the direction of the Galactic Centre with deviations of up to 30° for triaxial and tilted haloes. To detect the predicted anisotropy (for the likely case of an isothermal halo with large core radius) will require detection of ~ 500 UHECRs by Auger; this should also suffice to determine the angular phase to within $\pm 20°$ [44].

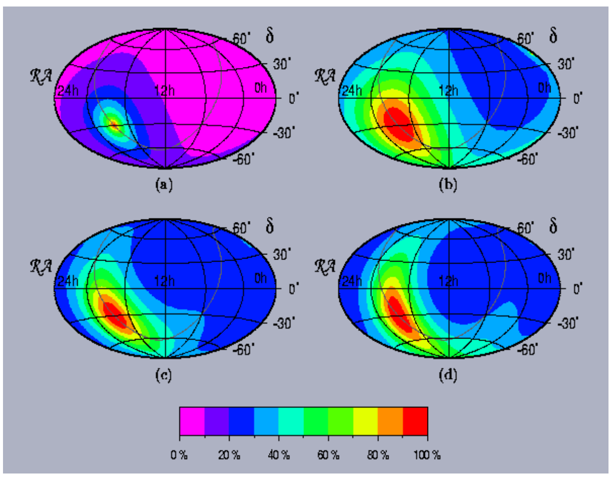

Fig. 7. Contour plots of the UHECR sky for (a) cusped, (b) isothermal, (c) triaxial and (d) tilted models of the dark matter halo of our Galaxy [44].

Another signature of this hypothesis is the expected UHE neutrino flux, which was indeed the first to be studied [32]. Recent detailed calculations [46] indicate that the expected flux should yield $\sim$ 10–40 events/yr with $E > 10^5$ GeV in IceCube [49] and a similar number of events in RICE [50]. Of course other proposed models for UHECRs also predict associated fluxes of UHE neutrinos. However an unique test is the expected flux of neutralinos if these are the lightest stable supersymmetric particles [47]. In principle EUSO [51] can discriminate such events from neutrino-induced ones [48].

5. Conclusions

After a long hiatus, high energy cosmic rays have again become very interesting for particle physicists looking for evidence of physics beyond the Standard Model. The source of the highest energy particles in Nature is an equally interesting enigma for astrophysicists. As Lemaître first suggested, the origin of such particles may even be linked to the early universe, although not quite as he imagined! Presently the data are tantalising but not sufficient in either quantity or quality to distinguish definitively between proposed models. The good news that this will soon be remedied by the Pierre Auger Observatory [6]. About 100 water Cerenkov detectors and 2 fluorescence detectors are now operational, covering an area twice that of AGASA, and the full array should be operational by the end of 2005. Moreover the ambitious space-based experiment EUSO [51], scheduled for a 3-year engineering flight on the International Space Station 'Columbus' in 2007, will provide another substantial increase in collecting power. This is an exciting time for cosmic ray physics and we look forward to the surprises that Nature has in store for us.

It is a particular pleasure to present this talk at Kraków which has had such a distinguished history of cosmic ray research — I understand that the first international IUPAP conference on cosmic rays was in fact held here in 1947, during which Powell announced the discovery of the pion! I wish to thank Paolo Lipari and Henryk Wilczyński for their kind invitation, and all the organisers of this meeting for their efficiency and hospitality.

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