

Probing physics at extreme energies with cosmic ultra-high energy radiation

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Abstract. The highest energy cosmic rays observed possess macroscopic energies and their origin is likely to be associated with the most energetic processes in the universe. Their existence triggered a flurry of theoretical explanations ranging from conventional shock acceleration to particle physics beyond the standard model (SM) and processes taking place at the earliest moments of our universe. Furthermore, many new experimental activities promise a strong increase of statistics at the highest energies and a combination with γ -ray and neutrino astrophysics will put strong constraints on these theoretical models. We give an overview over this quickly evolving research field with focus on testing new particle physics.

Keywords. Ultra-high energy cosmic rays; γ -rays and neutrinos; fundamental interactions.

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1. Introduction

Over the last few years, several giant air showers have been detected confirming the arrival of cosmic rays (CRs) with energies up to a few hundred EeV ($1 \text{ EeV} \equiv 10^{18} \text{ eV}$) [1–3]. The existence of such ultra-high energy cosmic rays (UHECRs) pose a serious challenge for conventional theories of CR origin based on acceleration of charged particles in powerful astrophysical objects. The question of the origin of these UHECRs is, therefore, currently a subject of much intense debate and discussions as well as experimental efforts; see ref. [4] for recent brief reviews, and ref. [5] for a detailed review.

The problems encountered in trying to explain UHECRs in terms of ‘bottom-up’ acceleration mechanisms have been well-documented in a number of studies; see, e.g., refs [6–8]. It is hard to accelerate protons and heavy nuclei up to such energies even in the most powerful astrophysical objects such as radio galaxies and active galactic nuclei. Also, nucleons above $\simeq 70 \text{ EeV}$ lose energy drastically due to photo-pion production on the cosmic microwave background (CMB) – the Greisen–Zatsepin–Kuzmin (GZK) effect [9] – which limits the distance to possible sources to less than $\simeq 100 \text{ Mpc}$ [7]. Heavy nuclei are photodisintegrated in the CMB within a few Mpc [10]. There are no obvious astronomical sources within $\simeq 100 \text{ Mpc}$ of the earth [11,7].

The distance restriction imposed by the GZK effect can be circumvented if the problem of energetics is somehow solved separately and if one postulates new particles beyond the standard model; this will be discussed in §3.

In contrast, in the ‘top-down’ scenarios, which will be discussed in the last section, the problem of energetics is trivially solved. Here, the UHECR particles are the decay products of some supermassive ‘X’ particles of mass $m_X \gg 10^{20}$ eV, and have energies all the way up to $\sim m_X$. Thus, no acceleration mechanism is needed. The massive X particles could be metastable relics of the early universe with lifetimes of the order of the current age of the universe or could be released from topological defects that were produced in the early universe during symmetry-breaking phase transitions envisaged in grand unified theories (GUTs). If the X particles themselves or their sources cluster similar to dark matter, the dominant observable UHECR contribution would come from the galactic halo and absorption would be negligible.

The main problem of non-astrophysical solutions of the UHECR problem in general is that they are highly model dependent. On the other hand, they allow to at least test new physics beyond the standard model of particle physics (such as grand unification and new interactions beyond the reach of terrestrial accelerators) as well as early universe cosmology (such as topological defects and/or massive particle production in inflation) at energies often inaccessible to accelerator experiments.

The physics and astrophysics of UHECRs are intimately linked with the emerging field of neutrino astronomy (for reviews see refs [12,13]) as well as with the already established field of γ -ray astronomy (for reviews see, e.g., ref. [14]). Indeed, all scenarios of UHECR origin, including the top-down models, are severely constrained by neutrino and γ -ray observations and limits. In turn, this linkage has important consequences for theoretical predictions of fluxes of extragalactic neutrinos above a TeV or so whose detection is a major goal of next-generation neutrino telescopes. If these neutrinos are produced as secondaries of protons accelerated in astrophysical sources and if these protons are not absorbed in the sources, but rather contribute to the UHECR flux observed, then the energy content in the neutrino flux cannot be higher than the one in UHECRs, leading to the so called Waxman Bahcall bound for sources with soft acceleration spectra [15,17]. If one of these assumptions does not apply, such as for acceleration sources with injection spectra harder than E^{-2} and/or opaque to nucleons, or in the top-down scenarios where X particle decays produce much fewer nucleons than γ -rays and neutrinos, the Waxman Bahcall bound does not apply, but the neutrino flux is still constrained by the observed diffuse γ -ray flux in the GeV range.

2. Propagation of ultra-high energy radiation: Simulations

Before discussing specific scenarios for UHECR origin we give a short account of the numerical tools used to compute spectra of ultra-high energy cosmic and γ -rays, and neutrinos [18–20]. In the following we assume a flat universe with a Hubble constant of $H = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a cosmological constant $\Omega_\Lambda = 0.7$, as favored by current observations.

The relevant nucleon interactions implemented are pair production by protons ($p\gamma_b \rightarrow pe^-e^+$), photoproduction of single or multiple pions ($N\gamma_b \rightarrow N n\pi$, $n \geq 1$), and neutron decay.

γ -rays and electrons/positrons initiate electromagnetic (EM) cascades on low energy radiation fields such as the CMB. The high energy photons undergo electron–positron pair production (PP; $\gamma\gamma_b \rightarrow e^-e^+$), and at energies below $\sim 10^{14}$ eV they interact mainly with

the universal infrared and optical (IR/O) backgrounds, while above ~ 100 EeV they interact mainly with the universal radio background (URB). In the Klein–Nishina regime, where the CM energy is large compared to the electron mass, one of the outgoing particles usually carries most of the initial energy. This ‘leading’ electron (positron) in turn can transfer almost all of its energy to a background photon via inverse Compton scattering (ICS; $e\gamma_b \rightarrow e'\gamma$). EM cascades are driven by this cycle of PP and ICS. The energy degradation of the ‘leading’ particle in this cycle is slow, whereas the total number of particles grows exponentially with time. All EM interactions that influence the γ -ray spectrum in the energy range $10^8 \text{ eV} < E < 10^{25} \text{ eV}$, namely PP, ICS, triplet pair production (TPP; $e\gamma_b \rightarrow ee^-e^+$), and double pair production (DPP, $\gamma\gamma_b \rightarrow e^-e^+e^-e^+$), as well as synchrotron losses of electrons in the large scale extragalactic magnetic field (EGMF), are included.

Similarly to photons, ultra-high energy (UHE) neutrinos give rise to neutrino cascades in the primordial neutrino background via exchange of W and Z bosons [21]. Besides the secondary neutrinos which drive the neutrino cascade, the W and Z decay products include charged leptons and quarks which in turn feed into the EM and hadronic channels. Neutrino interactions become especially significant if the relic neutrinos have masses m_ν in the eV range and thus constitute hot dark matter, because the Z boson resonance then occurs at an UHE neutrino energy $E_{\text{res}} = 4 \times 10^{21} (\text{eV}/m_\nu) \text{ eV}$. In fact, the decay products of this ‘Z-burst’ have been proposed as a significant source of UHECRs [22]. The big drawback of this scenario is the need of enormous primary neutrino fluxes that cannot be produced by known astrophysical acceleration sources [19], and thus most likely requires a more exotic top-down type source such as X particles exclusively decaying into neutrinos [23]. Even this possibility appears close to being ruled out due to a tendency to overproduce the diffuse GeV γ -ray flux observed by EGRET [24,20]

The two major uncertainties in the particle transport are the intensity and spectrum of the URB for which there exist no direct measurements in the relevant MHz regime [25,26], and the average value of the EGMF. Simulations have been performed for different assumptions on these. A strong URB tends to suppress the UHE γ -ray flux by direct absorption whereas a strong EGMF blocks EM cascading (which otherwise develops efficiently especially in a low URB) by synchrotron cooling of the electrons. For the IR/O background we used the most recent data [27].

In top-down scenarios, the particle injection spectrum is generally dominated by the ‘primary’ γ -rays and neutrinos over nucleons. These primary γ -rays and neutrinos are produced by the decay of the primary pions resulting from the hadronization of quarks that come from the decay of the X particles. In contrast, in acceleration scenarios the primaries are accelerated protons or nuclei, and γ -rays, electrons, and neutrinos are produced as secondaries from decaying pions that are in turn produced by the interactions of nucleons with the CMB.

3. New primary particles and interactions

A possible way around the problem of missing counterparts within acceleration scenarios is to propose primary particles whose range is not limited by interactions with the CMB. Within the standard model the only candidate is the neutrino, whereas in extensions of the standard model one could think of new neutrals such as axions or stable supersymmetric elementary particles. Such options are mostly ruled out by the tension between enforcing

small EM coupling and large hadronic coupling to ensure normal air showers [28]. Also suggested have been new neutral hadronic bound states of light gluinos with quarks and gluons, so-called R-hadrons that are heavier than nucleons, and therefore have a higher GZK threshold [29]. Since this too seems to be disfavored by accelerator constraints [30] we will here focus on neutrinos.

In both the neutrino and new neutral stable particle scenario the particle propagating over extragalactic distances would have to be produced as a secondary in interactions of a primary proton that is accelerated in a powerful AGN which can, in contrast to the case of extensive air showers (EAS) induced by nucleons, nuclei, or γ -rays, be located at high redshift. Consequently, these scenarios predict a correlation between primary arrival directions and high redshift sources. In fact, possible evidence for a correlation of UHECR arrival directions with compact radio quasars and BL-Lac objects, some of them possibly too far away to be consistent with the GZK effect, was recently reported [31]. Only a few more events could confirm or rule out the correlation hypothesis. Note, however, that these scenarios require the primary proton to be accelerated up to at least 10^{21} eV, demanding a very powerful astrophysical accelerator.

3.1 New neutrino interactions

Neutrino primaries have the advantage of being well established particles. However, within the standard model their interaction cross section with nucleons, whose charged current part can be parameterized by [32]

$$\sigma_{\nu N}^{\text{SM}}(E) \simeq 2.36 \times 10^{-32} (E/10^{19} \text{ eV})^{0.363} \text{ cm}^2, \quad (1)$$

for $10^{16} \text{ eV} \lesssim E \lesssim 10^{21} \text{ eV}$, falls short by about five orders of magnitude to produce ordinary air showers. However, it has been suggested that the neutrino–nucleon cross section, $\sigma_{\nu N}$, can be enhanced by new physics beyond the electroweak scale in the center of mass (CM) frame, or above about a PeV in the nucleon rest frame. Neutrino induced air showers may therefore rather directly probe new physics beyond the electroweak scale.

One possibility consists of a large increase in the number of degrees of freedom above the electroweak scale [33]. A specific implementation of this idea is given in theories with n additional large compact dimensions and a quantum gravity scale $M_{4+n} \sim \text{TeV}$ that has recently received much attention in the literature [34] because it provides an alternative solution (i.e., without supersymmetry) to the hierarchy problem in grand unifications of gauge interactions. It turns out that the largest contribution to the neutrino–nucleon cross section is provided by the production of microscopic black holes centered on the brane representing our world, but extending into the extra dimensions. The cross sections can be larger than the standard model one by up to a factor 100 [35]. This is not sufficient to explain the observed UHECR events [36].

However, the UHECR data can be used to put constraints on cross sections satisfying $\sigma_{\nu N}(E \gtrsim 10^{19} \text{ eV}) \lesssim 10^{-27} \text{ cm}^2$. Particles with such cross sections would give rise to horizontal air showers which have not yet been observed. Resulting upper limits on their fluxes assuming the standard model cross section (eq. (1)) are shown in figure 1. Comparison with the ‘cosmogenic’ neutrino flux produced by UHECRs interacting with the CMB then results in upper limits on the cross section which are about a factor 1000 larger than eq. (1) in the energy range between $\simeq 10^{17} \text{ eV}$ and $\simeq 10^{19} \text{ eV}$ [42]. The projected sensitivity of

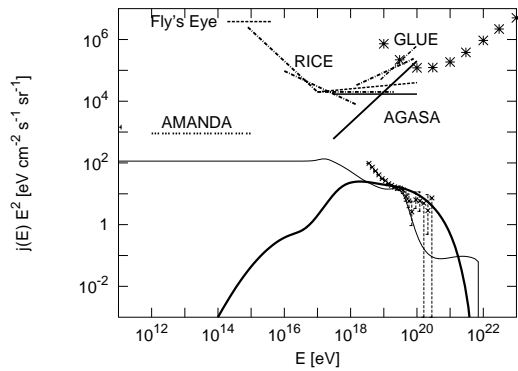


Figure 1. (from work in ref. [20]). Cosmogenic neutrino flux per flavor (thick line, assuming maximal mixing among all flavors) from primary proton flux (thin line) fitted to the AGASA cosmic ray data [3] above 3×10^{18} eV (error bars). The UHECR sources were assumed to inject a E^{-2} proton spectrum up to 10^{22} eV with luminosity $\propto (1+z)^3$ up to $z=2$. Also shown are existing upper limits on the diffuse neutrino fluxes from AMANDA [37], AGASA [38], the Fly's Eye [39] and RICE [40] experiments, and the limit obtained with the Goldstone radio telescope (GLUE) [41].

future experiments shown in figure 2 indicate that these limits could be lowered down to the standard model one [43]. In case of the detection of penetrating events the degeneracy of the cross section with the unknown flux could be broken by comparing horizontal air showers with earth skimming events [44].

4. Top-down scenarios

As mentioned in the introduction, all top-down scenarios involve the decay of X particles of mass close to the GUT scale which can basically be produced in two ways: If they are very short lived, as usually expected in many GUTs, they have to be produced continuously. The only way this can be achieved is by the emission from topological defects left over from cosmological phase transitions that may have occurred in the early universe at temperatures close to the GUT scale, possibly during reheating after inflation. Topological defects necessarily occur between regions that are causally disconnected, such that the orientation of the order parameter associated with the phase transition, cannot be communicated between these regions and consequently will adopt different values. Examples are cosmic strings, magnetic monopoles, and domain walls. The defect density is consequently given by the particle horizon in the early universe. The defects are topologically stable, but time dependent motion leads to the emission of particles with a mass comparable to the temperature at which the phase transition took place. The associated phase transition can also occur during reheating after inflation.

Alternatively, instead of being released from topological defects, X particles may have been produced directly in the early universe and, due to some unknown symmetries, have a very long lifetime comparable to the age of the universe. In contrast to weakly-interacting massive particles (WIMPs) below a few hundred TeV which are the usual dark matter

candidates motivated by, for example, supersymmetry and can be produced by thermal freeze out, such superheavy X particles have to be produced non-thermally (see ref. [45] for a review). In all these cases, such particles, also called ‘WIMPZILLAs’, would contribute to the dark matter and their decays could still contribute to UHECR fluxes today, with an anisotropy pattern that reflects the dark matter distribution in the halo of our galaxy.

It is interesting to note that one of the prime motivations of the inflationary paradigm was to dilute excessive production of ‘dangerous relics’ such as topological defects and superheavy stable particles. However, such objects can be produced right after inflation during reheating in cosmologically interesting abundances, and with a mass scale roughly given by the inflationary scale which in turn is fixed by the CMB anisotropies to $\sim 10^{13}$ GeV [45]. The reader will realize that this mass scale is somewhat above the highest energies observed in CRs, which implies that the decay products of these primordial relics could well have something to do with UHECRs which in turn can probe such scenarios!

For dimensional reasons the spatially averaged X particle injection rate can only depend on the mass scale m_X and on cosmic time t in the combination

$$\dot{n}_X(t) = \kappa m_X^p t^{-4+p}, \quad (2)$$

where κ and p are dimensionless constants whose value depend on the specific top-down scenario [46]. For example, the case $p = 1$ is representative of scenarios involving release of X particles from topological defects, such as ordinary cosmic strings [47], necklaces [48] and magnetic monopoles [49]. This can be easily seen as follows: The energy density ρ_s in a network of defects has to scale roughly as the critical density, $\rho_s \propto \rho_{\text{crit}} \propto t^{-2}$, where t is cosmic time, otherwise the defects would either start to overclose the universe, or end up having a negligible contribution to the total energy density. In order to maintain this scaling, the defect network has to release energy with a rate given by $\dot{\rho}_s = -a\rho_s/t \propto t^{-3}$, where $a = 1$ in the radiation dominated era, and $a = 2/3$ during matter domination. If most of this energy goes into emission of X particles, then typically $\kappa \sim \mathcal{O}(1)$. In the numerical simulations presented below, it was assumed that the X particles are nonrelativistic at decay.

The X particles could be gauge bosons, Higgs bosons, superheavy fermions, etc. depending on the specific GUT. They would have a mass m_X comparable to the symmetry breaking scale and would decay into leptons and/or quarks of roughly comparable energy. The quarks interact strongly and hadronize into nucleons (N s) and pions, the latter decaying in turn into γ -rays, electrons, and neutrinos. Given the X particle production rate, dn_X/dt , the effective injection spectrum of particle species a ($a = \gamma, N, e^\pm, \nu$) via the hadronic channel can be written as $(dn_X/dt)(2/m_X)(dN_a/dx)$, where $x \equiv 2E/m_X$, and dN_a/dx is the relevant fragmentation function (FF).

We adopt the local parton hadron duality (LPHD) approximation [50] according to which the total hadronic FF, dN_h/dx , is taken to be proportional to the spectrum of the partons (quarks/gluons) in the parton cascade (which is initiated by the quark through perturbative quadron chromodynamic (QCD) processes) after evolving the parton cascade to a stage where the typical transverse momentum transfer in the QCD cascading processes has come down to $\sim R^{-1} \sim$ few hundred MeV, where R is a typical hadron size. The parton spectrum is obtained from solutions of the standard QCD evolution equations in modified leading logarithmic approximation (MLLA) which provides good fits to accelerator data at LEP energies [50]. Within the LPHD hypothesis, the pions and nucleons after hadronization have essentially the same spectrum. The LPHD does not, however, fix the relative

abundance of pions and nucleons after hadronization. Motivated by accelerator data, we assume the nucleon content f_N of the hadrons to be $\simeq 10\%$, and the rest pions distributed equally among the three charge states. Recent work suggests that the nucleon-to-pion ratio may be significantly higher in certain ranges of x values at the extremely high energies of interest here [51], but the situation is not completely settled yet.

4.1 Predicted fluxes

Figure 2 shows results for the time averaged nucleon, γ -ray, and neutrino fluxes in a typical TD scenario, along with low energy γ -ray flux constraints and neutrino flux sensitivities of future experiments. The spectrum was optimally normalized to allow for an explanation of the observed UHECR events, assuming their consistency with a nucleon or γ -ray primary. The flux below $\lesssim 2 \times 10^{19}$ eV is presumably due to conventional acceleration in astrophysical sources and was not fit. The PP process on the CMB depletes the photon flux above 100 TeV, and the same process on the IR/O background causes depletion of the photon flux in the range 100 GeV–100 TeV, recycling the absorbed energies to energies below 100 GeV through EM cascading. The predicted background is *not* very sensitive to the specific IR/O background model, however [52]. The scenario in figure 2 obviously obeys all current constraints within the normalization ambiguities and is therefore quite viable. Note that the diffuse γ -ray background measured by EGRET [24] up to 10 GeV puts a strong constraint on these scenarios, especially if there is already a significant contribution to this background from conventional sources such as unresolved γ -ray blazars [53]. However, this constraint is much weaker for TDs or decaying long lived X particles with a non-uniform clustered density [54].

The energy loss and absorption lengths for UHE nucleons and photons are short ($\lesssim 100$ Mpc). Thus, their predicted UHE fluxes are independent of cosmological evolution. The γ -ray flux below $\simeq 10^{11}$ eV, however, scales as the total X particle energy release integrated over all redshifts and increases with decreasing p [55]. For $m_X = 2 \times 10^{16}$ GeV, scenarios with $p < 1$ are therefore ruled out, whereas constant comoving injection models ($p = 2$) are well within the limits.

It is clear from the above discussions that the predicted particle fluxes in the TD scenario are currently uncertain to a large extent due to particle physics uncertainties (e.g., mass and decay modes of the X particles, the quark fragmentation function, the nucleon fraction f_N , and so on) as well as astrophysical uncertainties (e.g., strengths of the radio and infrared backgrounds, extragalactic magnetic fields, etc.). More details on the dependence of the predicted UHE particle spectra and composition on these particle physics and astrophysical uncertainties are contained in ref. [63].

We stress here that there are viable TD scenarios which predict nucleon fluxes that are comparable to or even higher than the γ -ray flux at all energies, even though γ -rays dominate at production. This occurs, e.g., in the case of high URB and/or for a strong EGMF, and a nucleon fragmentation fraction of $\simeq 10\%$. Some of these TD scenarios would therefore remain viable even if UHECR induced EAS should be proven inconsistent with photon primaries (see, e.g., ref. [64]). This is in contrast to scenarios with decaying massive dark matter in the galactic halo which, due to the lack of absorption, predict compositions directly given by the fragmentation function, i.e. domination by γ -rays.

The normalization procedure to the UHECR flux described above imposes the constraint $Q_{\text{UHECR}}^0 \lesssim 10^{-22} \text{ eV cm}^{-3} \text{ s}^{-1}$ within a factor of a few [63,65,66] for the total energy

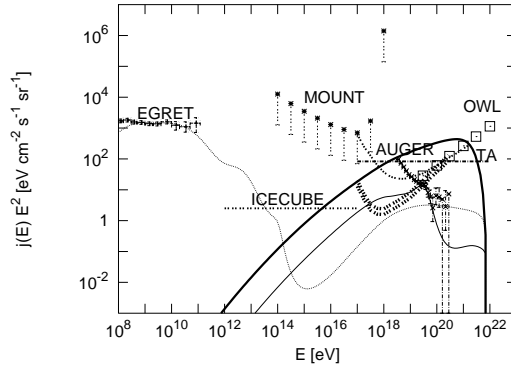


Figure 2. (from work in ref. [20]) Predictions for the differential fluxes of γ -rays (dotted line), nucleons (thin solid line), and neutrinos per flavor (thick solid line, assuming maximal mixing among all flavors) in a TD model characterized by $p = 1$, $m_X = 2 \times 10^{14}$ GeV, and the decay mode $X \rightarrow q + q$, assuming the QCD fragmentation function in MLLA approximation [50], with a fraction of 10% nucleons. The calculation used the code described in ref. [18] and assumed the minimal URB version consistent with observations [26] and an EGMF of 10^{-12} G. Cosmic ray data are as in figure 1 and the EGRET data on the left margin represents the diffuse γ -ray flux between 30 MeV and 100 GeV [24]. Also shown are expected sensitivities of the Auger project currently in construction to electron/muon and tau-neutrinos [56], and the planned projects telescope array [57], the water-based ANTAARES [58], the ice-based ICECUBE [59], the fluorescence/Čerenkov detector MOUNT [60], and the space based OWL [61] (we take the latter as representative also for EUSO [62]).

release rate Q_0 from TDs at the current epoch. In most TD models, because of the unknown values of the parameters involved, it is currently not possible to calculate the exact value of Q_0 from first principles, although it has been shown that the required values of Q_0 (in order to explain the UHECR flux) mentioned above are quite possible for certain kinds of TDs. Some cosmic string simulations and the necklace scenario suggest that defects may lose most of their energy in the form of X particles and estimates of this rate have been given [67,48]. If that is the case, the constraint on Q_{UHECR}^0 translates via eq. (2) into a limit on the symmetry breaking scale η and hence on the mass m_X of the X particle: $\eta \sim m_X \lesssim 10^{13}$ GeV [68]. Independently of whether or not this scenario explains UHECR, the EGRET measurement of the diffuse GeV γ -ray background leads to a similar bound, $Q_{\text{EM}}^0 \lesssim 2.2 \times 10^{-23} h(3p-1) \text{ eV cm}^{-3} \text{ s}^{-1}$, which leaves the bound on η and m_X practically unchanged. Furthermore, constraints from limits on CMB distortions and light element abundances from ${}^4\text{He}$ -photodisintegration are comparable to the bound from the directly observed diffuse GeV γ -rays [55]. That these crude normalizations lead to values of η in the right range suggests that defect models require less fine tuning than decay rates in scenarios of metastable massive dark matter.

As discussed above, in TD scenarios most of the energy is released in the form of EM particles and neutrinos. If the X particles decay into a quark and a lepton, the quark hadronizes mostly into pions and the ratio of energy release into the neutrino versus EM channel is $r \simeq 0.3$. The energy fluence in neutrinos and γ -rays is thus comparable. However, whereas the photons are recycled down to the GeV range where their flux is

constrained by the EGRET measurement, the neutrino flux is practically not changed during propagation and thus reflects the injection spectrum. Its predicted level is consistent with all existing upper limits (compare figure 2 with figure 1) but should be detectable by several experiments under construction or in the proposal stage (see figure 2). This would allow to directly see the quark fragmentation spectrum.

5. Conclusions

Ultra-high energy cosmic rays have the potential to open a window to and act as probes of new particle physics beyond the standard model as well as processes occurring in the early universe at energies close to the grand unification scale. Even if their origin will turn out to be attributable to astrophysical shock acceleration with no new physics involved, they will still be witnesses of one of the most energetic processes in the universe. The future appears promising and exciting due to the anticipated arrival of several large scale experiments.

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