Testing fundamental physics with high-energy cosmic rays(*)

J. Ellis

Theoretical Physics Division, CERN - CH-1211 Geneva, Switzerland

Summary. — Cosmic rays may provide opportunities for probing fundamental physics. For example, ultrahigh-energy cosmic rays might originate from the decays of metastable heavy particles, and astrophysical γ-rays can be used to test models of quantum gravity. Both scenarios offer ways to avoid the GZK cut-off.

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1. – Introduction

In this lecture I discuss two cosmic-ray topics where fundamental physics may be testable: the ultrahigh-energy cosmic rays that apparently evade the GZK cut-off may probe the decays of superheavy particles, and astrophysical sources of γ-rays may probe quantum gravity. At first sight, there is no obvious relations between the two subjects. However, as we see at the end, quantum-gravity effects might provide another mechanism for evading the GZK cut-off: see, for both ultrahigh-energy cosmic rays (see fig. 1) and astrophysical γ-rays.

2. – A top-down decay model for ultrahigh-energy cosmic rays

As is well known, one expects a suppression of ultrahigh-energy (UHE) protons above $E \sim 5 \times 10^{19}$ eV, due to absorption by cosmic microwave background photons: $p + \gamma_{CMBR} \to \Delta^+$ [1]: this and analogous cut-offs for Fe and γ's are seen in fig. 2 [2]. However, no such effect is seen (fig. 1) in the data [3], suggesting that these cosmic rays must originate from nearby: $d \lesssim 100$ Mpc for $E \sim 10^{20}$ eV. In this case, unless magnetic field effects are unexpectedly strong, one would expect the UHE cosmic rays to point
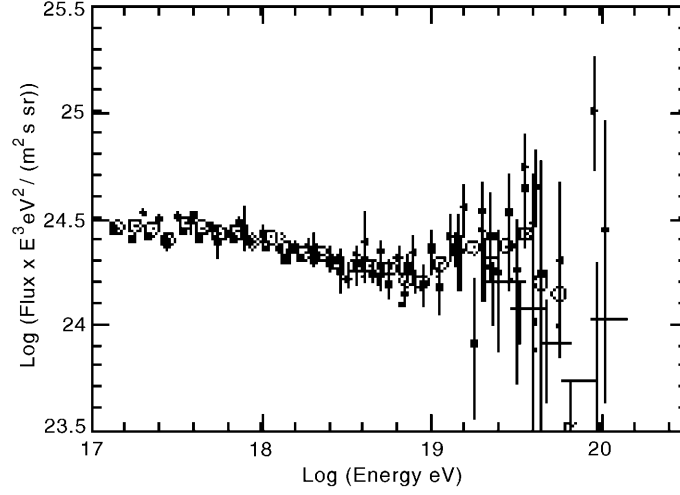

483

Fig. 1. – The ultrahigh-energy tail of the cosmic-ray spectrum, which does not turn down as expected on the basis of the GZK cut-off [1].

back to astrophysical sources. However, as seen in fig. 3, no clear evidence for any discrete sources has yet emerged, although there are some candidate doublets and triplets whose statistical significance is not yet overwhelming [2]—see, however [4].

Under these circumstances, it is natural to explore possible origins in new physics. In particular, the decays of supermassive, metastable dark matter particles [5] clustered in our galactic halo might lead to ultrahigh-energy cosmic rays that would evade the GZK cut-off [6], have no discrete sources, and yield an approximately isotropic distribution. One of the issues in such a top-down model is why the supermassive particle should be metastable [7].

An example of analogous metastability may be provided by the proton. The Standard Model symmetries do not admit any renormalizable interaction violating baryon number, but this is an accidental consequence of other symmetries of the theory: higher-dimension $\Delta B \neq 0$ interactions are permitted. In traditional GUTs, the first such interaction has dimension 6, and gives an amplitude scaled by $1/M^2$, where M is the GUT mass scale, leading to a proton lifetime $\tau \sim M^4/m_{\rm P}^5$. This may exceed 10^{33} y if $M \gtrsim 10^{15}$ GeV.

In many models, relic particles decay through higher-dimensional operators $\sim 1/M^n$, in which case the lifetime $\tau \sim M^{2n}/m_{\rm Relic}^{2n+1}$. This may comfortably exceed 10^{10} y if M and n are large enough, e.g., $M \sim 10^{17}$ GeV and $n \geq 9$ are sufficient if $m_{\rm Relic} \sim 10^{12}$ GeV.

Constraints on such metastable relics come from light-element abundances, the cosmic microwave background and the high-energy astrophysical ν flux [5]. An abundance of relic particles weighing 10^{12} GeV sufficient to yield $\Omega_{\rm Relic}h^2 \sim 1$ is possible if $\tau \sim 10^{16}$ y.

Is it at all possible or plausible that a superheavy relic might have $\Omega_{\rm Relic}h^2 \sim 1$? With the standard mechanism of freeze-out following thermal equilibrium, one would expect that $m_{\rm Relic} \lesssim 1$ TeV in order to obtain an interesting relic density. However, it has recently been realized that this upper limit may be avoided by non-thermal and gravitational production mechanisms around and after inflation [8]. Depending on the details of the model, $\Omega_{\rm Relic}h^2 \sim 1$ may be possible for 10^8 GeV $\lesssim m_{\rm Relic} \lesssim 10^{18}$ GeV.
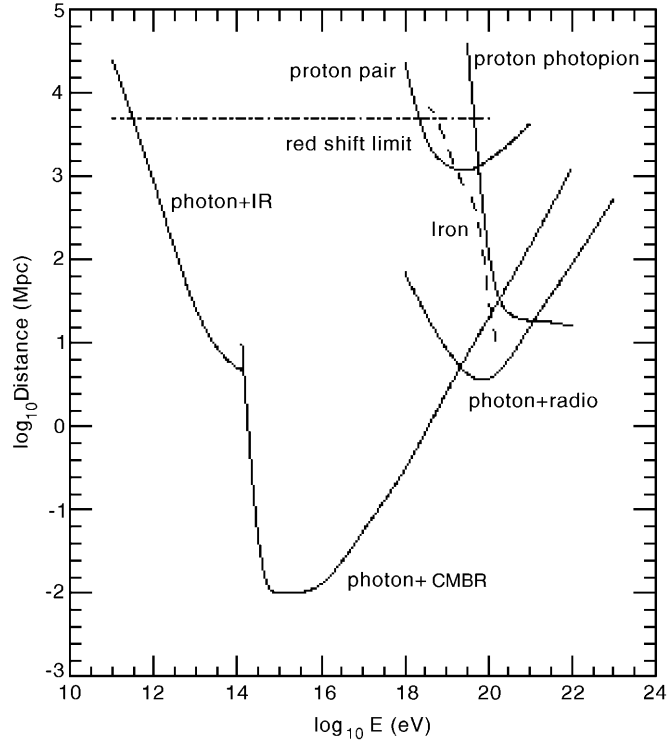
Fig. 2. – The cut-offs expected for high-energy protons [1], iron nuclei and photons, due to photo-absorption processes and e^+e^- pair production, respectively [2].

We have explored possible candidates for such a metastable superheavy relic in string/M theory [9]. These contain Kaluza-Klein states ("hexons") that acquire masses when $10 \rightarrow 4$ or $11 \rightarrow 5$ dimensions, but these are not expected to be metastable, and may be too heavy. In M theory, more Kaluza-Klein states appear when $5 \rightarrow 4$ dimensions ("pentons"), but these are also expected to be very unstable. The last candidates may
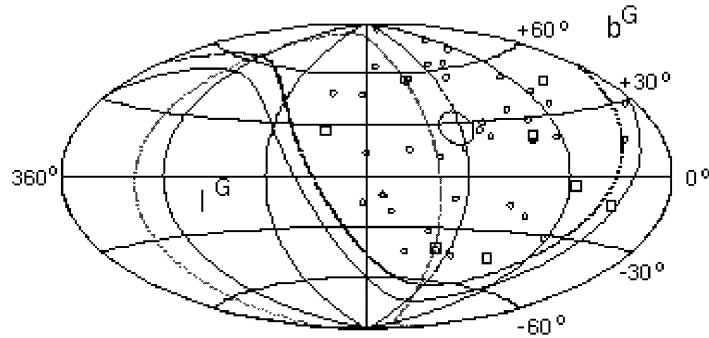

Fig. 3. – The arrival directions of ultrahigh-energy cosmic rays seen by the AGASA array: the shaded regions are invisible to this experiment [2].
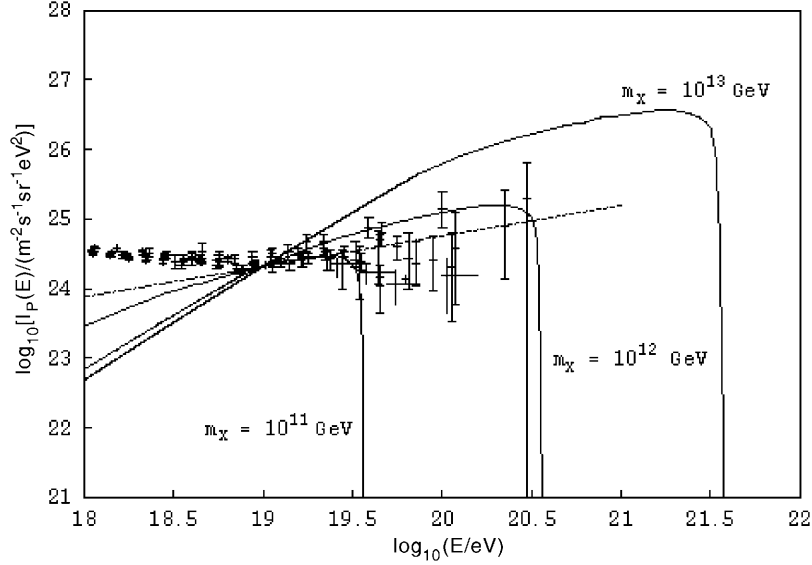
Fig. 4. – The observed spectrum of ultrahigh-energy cosmic rays compared with a calculation of crypton decays, for various different choices of the crypton mass [11].

be bound states from a hidden sector of string/M theory ("cryptons") [7]. Their masses are determined by the non-perturbative dynamics of this hidden sector, and they may well have masses in the range $m_{\rm Relic} \sim 10^{12}$ to 10^{13} GeV of interest for ultrahigh-energy cosmic rays. For example, in the flipped $SU(5)$ model derived from string, the hidden-sector gauge group is $SU(4) \times SO(10)$, and some of the states bound by the former factor ("tetrons") decay via higher-dimensional operators, plausibly weighing $\sim 10^{12}$ GeV and with lifetimes $\gtrsim 10^{15}$ y [9].

The hadronization of quarks produced in crypton decay has been modelled both with [10] and without supersymmetry [11], and the spectrum appears compatible with the few ultrahigh-energy cosmic rays observed, as seen in fig. 4. The Auger [12] and EUSO [13] projects offer the best prospects for distinguishing cryptons from alternative explanations of the existing data [14].

3. – Space-time foam

We know that space-time is quite flat on large distance scales. For example, we learnt Euclidean geometry at school, not the Riemannian geometry of curved space, and cosmological microwave background experiments indicate that the Universe is flat on a scale of 10^{10} light years. However, in any quantum theory of gravity one expects large fluctuations in the fabric of space-time at the Planck scale: fluctuations in the energy $\Delta E \sim m_{\rm P} \sim 10^{19}$ GeV, accompanied by topology changes $\Delta \chi \sim 1$, over distance scales $\Delta x \sim l_{\rm P} \sim 10^{-33}$ cm, lasting for times $\Delta t \sim t_{\rm P} \sim 10^{-43}$s [15].

Are there any observable consequences of such microscopic quantum-gravitational fluctuations [16]? Does loss of information occur across microscopic event horizons, modifying conventional quantum mechanics so as to allow pure quantum-mechanical states to evolve into mixed ones [17], as suggested by fig. 5? And, more relevant to this
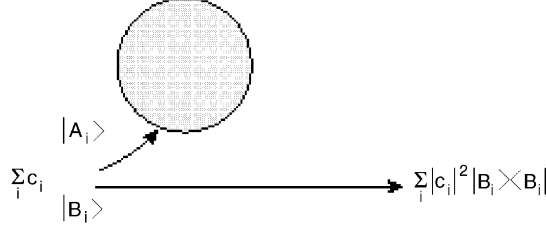
Fig. 5. – A process which (might) lead to quantum decoherence in the neighbourhood of a (microscopic) black hole: information about the phase of component $|A\rangle$ of the wave function is lost across the (microscopic) horizon [16, 17].

meeting, as a particle passes by, does its gravitational effect make the vacuum react to its energy, and does this recoil of the vacuum reduce the effective velocity of the particle [18]:

$$(1) \qquad\qquad c(E) \simeq c_0(1 - E/m_{\mathrm{QG}} + \ldots) \, ?$$

Here, c_0 is the "classical" (low-energy) velocity of light and m_{QG} is some high mass scale that might be $\mathcal{O}(m_{\mathrm{P}})$.

In order to address such questions, one must formulate a model of space-time foam. We imagine that it contains virtual topological "defects", $\mathcal{O}(1)$ per Planck-size four-volume, appearing and disappearing as quantum fluctuations, perhaps like instantons in QCD. We model these defects as solitonic p-dimensional "lumps" of string called D particles, or more generally Dp branes [19], as seen in fig. 6. The formal technology of string theory can be used to describe the interaction of an energetic particle hitting such a "lump". Among the effects of such a collision are a modified (reduced) velocity for the energetic particle, recoil motion of the struck defect and, at the quantum level, excitation of the defect to a higher state [20].

We argue that the recoil of the defect does indeed modify the background metric by an amount

$$(2) \qquad\qquad h_{0_i} \propto \bar{U}_i \, \Theta(t)$$

at large times t, where $\bar{U}_i$ is the defect's recoil velocity, and the collision is assumed to have taken place at time $t = 0$. One may consider the propagation of a photon [21] or other (almost) massless particle, such as a neutrino [22], by computing the null geodesic [23]:

$$(3) \qquad\qquad c_0^2(\mathrm{d}t)^2 = (\mathrm{d}x)^2 + 2h_{0_i}\mathrm{d}t\mathrm{d}x_i \, ,$$

using (2) for h_{0_i}. For symmetry reasons, the effective $\bar{U}_i$ must be in the direction of the particle motion. Labelling its magnitude by $\bar{U}$, one finds

$$(4) \qquad\qquad c_0 \, \frac{\mathrm{d}t}{\mathrm{d}x} \simeq \bar{U} + \sqrt{1 + \bar{U}^2} \simeq 1 + \bar{U} + \cdots$$

implying a *reduced* velocity:

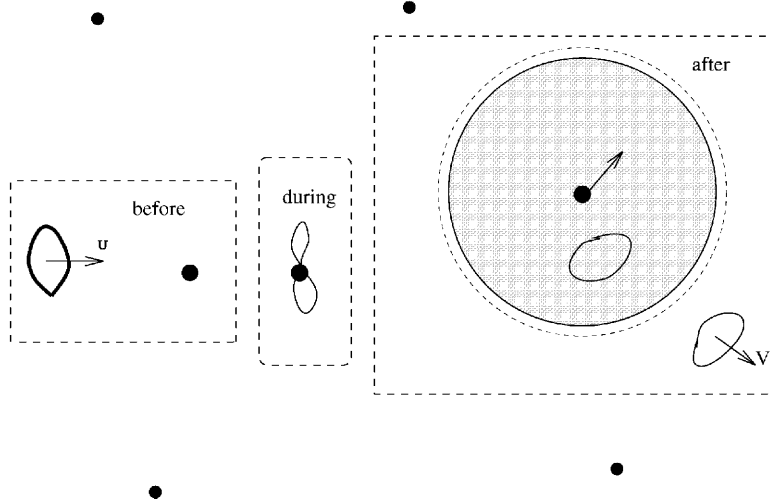$$(5) \qquad\qquad c(E) = s\frac{\mathrm{d}x}{\mathrm{d}t} = c_0 \left(1 - \bar{U} + \cdots\right).$$

Fig. 6. – Sketch of a (closed-string) particle state hitting a (D-brane) defect in space-time. After impact, the defect is excited and an expanding horizon is formed. Particles may be trapped inside, losing information, and the propagation of the incident particle may be slowed [20].

As a rough order-of-magnitude estimate, one may guess that the recoil momentum $k \sim E$, so that the recoil velocity $\bar{U} \sim k/M$, where M is the effective mass of the defect, that one could expect to be $\mathcal{O}(m_{\rm P})$. Thus one finds $U \sim E/M$ and hence

$$(6) \qquad\qquad c(E) \simeq c(1 - E/M + \cdots),$$

similar to that suggested for photons ([1]).

A similar result can be derived from Maxwell's equations [25]:

$$(7) \qquad \begin{aligned} \boldsymbol{\nabla} \cdot \mathbf{B} = 0, \ \boldsymbol{\nabla} \times \mathbf{H} = \tfrac{1}{c_0} \tfrac{\partial}{\partial t} \mathbf{D} = 0\,, \\ \boldsymbol{\nabla} \cdot \mathbf{D} = 0, \ \boldsymbol{\nabla} \times \mathbf{E} = -\tfrac{1}{c_0} \tfrac{\partial}{\partial t} \mathbf{B} = 0 \end{aligned}$$

in empty space, where

$$(8) \qquad\qquad \mathbf{D} = \frac{\mathbf{E}}{\sqrt{h}} + \mathbf{H} \times \mathbf{G}, \ \mathbf{B} = \frac{\mathbf{H}}{\sqrt{h}} + \mathbf{G} \times \mathbf{E}\,,$$

with

$$(9) \qquad\qquad G_{00} = -h, \ \frac{G_{0i}}{G_{00}} = -G_i\,.$$

Using (2), it is easy to find the following wave equations, to leading order:

$$(10) \qquad\qquad \left(\frac{1}{c_0^2} - \boldsymbol{\nabla}^2 - 2(\bar{\mathbf{U}} \cdot \boldsymbol{\nabla}) \frac{1}{c_0} \frac{\partial}{\partial t} \right) (\mathbf{B}, \mathbf{E}) = 0\,.$$

([1]) A different suggestion is made in [24].

If one looks for a plane-wave solution

$$(11) \qquad E_x = E_z = 0, \quad E_y = E_0\, e^{i(kx-wt)}, \quad B_x = B_y = 0, \quad B_z = B_0\, e^{i(kx-wt)},$$

one finds the modified dispersion relation

$$(12) \qquad k^2 - w^2 - 2\bar{U}kw = 0.$$

This leads, as before, to "subluminal" propagation at a velocity $c(E) \simeq c_0(1 - \bar{U} + \cdots)$.

There are other ways of seeing how such a non-trivial refractive index *in vacuo* might arise. For example, a particle hitting such a defect creates an expanding horizon. It is possible for particles to be trapped inside this horizon, providing a possible mechanism for loss of information [17]. However, for our present purposes, the relevant observation is that the particle slows down as it passes through the horizon, as seen in fig. 6, in line with the estimate (2) [26].

A similar effect appears if one considers our three-dimensional space as a membrane in a higher-dimensional space-time. This may fluctuate spontaneously by emitting or absorbing string states propagating through the "bulk" extra dimensions. The passage of an energetic photon or other particle along our three-brane will in general modify these interactions with "bulk" degrees of freedom, distorting the three-brane and modifying the propagation of the photon [27]. As a result, the photon experiences a stochastic time delay:

$$(13) \qquad \delta t \simeq g_s \frac{L \cdot E}{M_s}$$

where g_s is the string coupling and M_s the string scale. This effect is below present experimental upper limits in conventional strings with $g_s = \mathcal{O}(1)$ and $M_s \sim m_P$. However, it might be problematically large in some low-scale string models with $M_s \ll m_P$, unless also $g_s \ll 1$.

There are other approaches to the modelling of space-time foam. For example, it has been proposed that quantum gravity be treated as a "thermal bath" that provides a decohering medium [28]. Another interesting approach is that of loop gravity, which yields a cellular structure in space-time reminiscent of spin networks [29]. Its vacuum may be characterized as a "weave state" $|w\rangle$ with the property that

$$(14) \qquad \langle w|G_{\mu\nu}|w\rangle = \eta_{\mu\nu} + \mathcal{O}(EL_w),$$

where L_w is the "weave-length" at which quantum gravity appears. Both the above approaches lead to a breaking of Lorentz invariance. The vacuum may have other non-trivial optical and thermal properties, leading, *e.g.*, to birefringence [30]. One may also expect light-cone fluctuations, as found in our own approach to space-time foam.

Quantum-gravity effects can be distinguished from those of a conventional plasma by their different energy dependences. The former should increase with energy, while the latter should decrease at high energies. Consider, for example, photon propagation in a thermal electromagnetic plasma at temperature T:

$$(15) \qquad E^2 = q^2 + \pi_T : v \equiv \frac{\partial E}{\partial q}.$$

In the limit $T \ll q$, $qT \gg m_{\mathrm{e}}^2$, one finds

$$(16) \qquad\qquad v \simeq c \left[1 - \frac{\alpha^2}{6} \left(\frac{T}{q} \right)^2 \ln^2(qT/m_{\mathrm{e}}^2) + \cdots \right] ,$$

so that [31]

$$(17) \qquad\qquad v(E) \simeq c \left[1 - \mathcal{O} \left(\frac{1}{E^2} \ln E \right) \right] .$$

Even smaller effects are expected if only the background photons are thermalized, as in the Universe today. One finds [32]

$$(18) \qquad\qquad v \simeq c(1 - \gamma) : \gamma = \frac{44\pi^2}{2025} \, \alpha^2 \left(\frac{T}{m_{\mathrm{e}}} \right)^4 ,$$

i.e. a constant reduction in velocity that is unobservably small in the present Universe with $T \simeq 2.7$ K.

4. – Astrophysical probes of the velocity of light

Astrophysical sources, many of which are at cosmological distances, offer some of the best prospects for probing the possible energy dependence of the velocity of light: $c(E) \simeq c_0(1 - E/M + \cdots)$ and a possible stochastic spread in velocities of photons of given energy: $\delta c \sim c_0 E/\Lambda + \cdots$ [33]. These effects would yield at a time delay (or spread):

$$(19) \qquad\qquad \delta t \simeq \frac{L}{c_0} \frac{E}{M \text{ or } \Lambda} ,$$

where L is the distance of propagation. The figure of merit for probing M (or Λ) is clearly $L \cdot E/\delta t$, *i.e.* one wants distant, high-energy sources with short intrinsic time-scales. Examples of interesting sources are pulsars ($L \sim 10^4$ light years, $E \sim 1$ GeV, $\delta t \sim 300$ s), active galactic nuclei (AGNs) ($L \sim 100$ Mpc, $E \sim 2$ TeV, $\delta t \sim 300$ s) and gamma-ray bursters (GRBs) ($L \sim 10^{10}$ light-years, $E \to$ TeV?, $\delta t \to 10$ ms), providing prospective sensitivities to M (or Λ) in the range 10^{15} to 10^{18} GeV [33].

Some of the best prospects may be offered by GRBs [33, 25]. One is visible per day on average, throughout the Universe, and BATSE has recorded almost 3000 GRB triggers. Their durations range between seconds and hundreds of seconds, and some exhibit microburst structures on the millisecond scale: a spectacular recent example is shown in fig. 7. Several have now been seen at other wavelengths (energies) including radio (afterglows), optical (in flagrante and afterglows), X-ray (afterglows) and possibly TeV γ-rays (in flagrante). The afterglow observations have confirmed that there is a substantial population (at least of multi-second GRBs) with high redshifts $z = \mathcal{O}(1)$, ideal for our purpose!

There are several models for GRBs on the market, including mergers of neutron stars and/or black holes, anisotropic supernovae that squirt in particular directions, and hypernovae (collapses of massive stars) [35]. The internal engine is of secondary importance to us, as is its possible anisotropy. What is important to us is that all models agree on the formation of a highly relativistic ($\gamma = \mathcal{O}(100)$) optically thin plasma
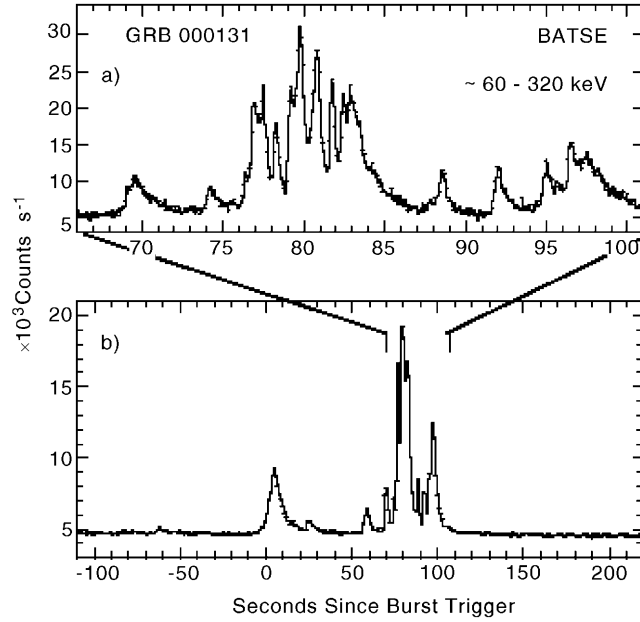
Fig. 7. – A spectacular GRB with a large redshift $z = 4.5$, whose pulse exhibits many microbursts [34].

that exhibits stochastic fluctuations on short time scales, presumably because of internal shocks.

We would like to probe the simultaneity of these pulses in different energy bands. For example, BATSE observed GRBs in four bands (25 to 50 keV, 50 to 100 keV, 100 to 300 keV and > 300 keV) and OSSE (also aboard the CGRO) observed at energies > 2 MeV. EGRET has reported some multi-GeV photons, for example with $E \sim 30$ GeV during the first 200 ms of GRB 930131 [36]. Most exciting is the report of a possible signal in TeV photons coincident with GRB 970417a [37], shown in fig. 8. If one assumes that the source was at $z \sim 0.1$, that $\delta t \sim 10$ s and $E_\gamma \sim 1$ TeV, one finds a sensitivity to $M \gtrsim 10^{18}$ GeV. Unfortunately, the statistical significance of this first Milagrito event was not overwhelming, its redshift was not measured, and no more such coincidences have been reported so far.

Several pioneering analyses have been made, but each is subject to some question. The analysis of [38] uses GRBs whose redshift was not measured, and whose distances are therefore unknown. The analysis of a flare of Mkn 421 in [39] is sensitive to $M \sim 4 \times 10^{16}$ GeV, but the detection of the flare is not secure, having a 5% probability of being spurious, as mentioned by the authors themselves. On the other hand, the γ-ray signal from the Crab pulsar used by [40] is statistically secure, but there is a known time difference between the γ and radio pulses, and this is comparable to variable dispersion effects in the interstellar medium. A joint statistical analysis of signals from several pulsars would be needed to disentangle possible source and medium effects.

We made a systematic analysis [25] of all the GRBs with measured cosmological redshifts, analyzing BATSE and OSSE data and comparing arrival times in the highest- and lowest-energy channels. We tried several different fitting functions for the peaks
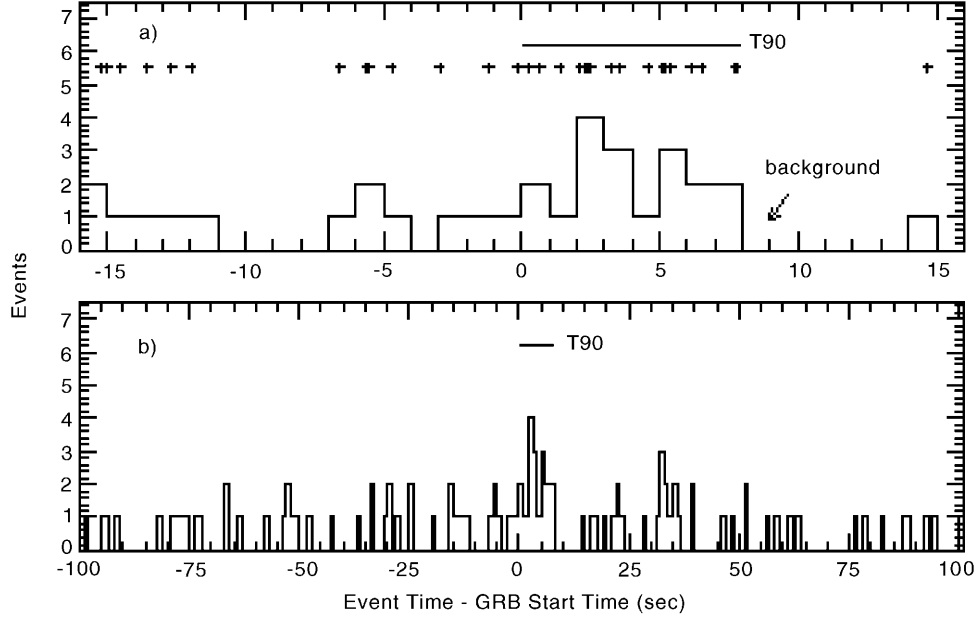
Fig. 8. – The Milagrito time series at the time of GRB 970417a, indicating a possible concidence with TeV photons [37].

observed in the different channels, comparing their positions and widths, as seen in fig. 9. We then looked for a possible correlation between the time lags (spreads) and the light travel distances, which increase with redshift, as seen in fig. 10. A real propagation effect should exhibit such a correlation, but a source and/or selection effect need not. The data were consistent with the absence of any such correlation, allowing us to conclude that, parametrizing a subliminal velocity $v(E) \simeq c_0(1 - E/M)$,

$$(20) \qquad\qquad\qquad M > 10^{15}\,\mathrm{GeV}\,,$$

and parametrizing a stochastic spread in velocities at fixed energy $\delta v(E) \simeq C_0 \cdot E/\Lambda$:

$$(21) \qquad\qquad\qquad \Lambda > 2 \times 10^{15}\,\mathrm{GeV}\,.$$

These are somewhat below the possible magnitudes $M, \Lambda = \mathcal{O}(10^{19})$ GeV ([2]), but not so far away!

Several exciting future steps seem possible. We expect the redshifts of many GRBs to be measured shortly, using new early-warning satellites such as HETE-II. Also, more γ-ray telescopes sensitive to higher energies are coming on-line. In addition to ground-based telescopes such as MILAGRO, satellites such as AMS and GLAST [41] may make important contributions. Another exciting possibility is to look for (the smearing of)

([2]) The GRB shown in fig. 7 has not yet been included in this analysis. With its many short-time structures and large redshift $z = 4.5$ [34], its inclusion should strengthen these limits significantly.
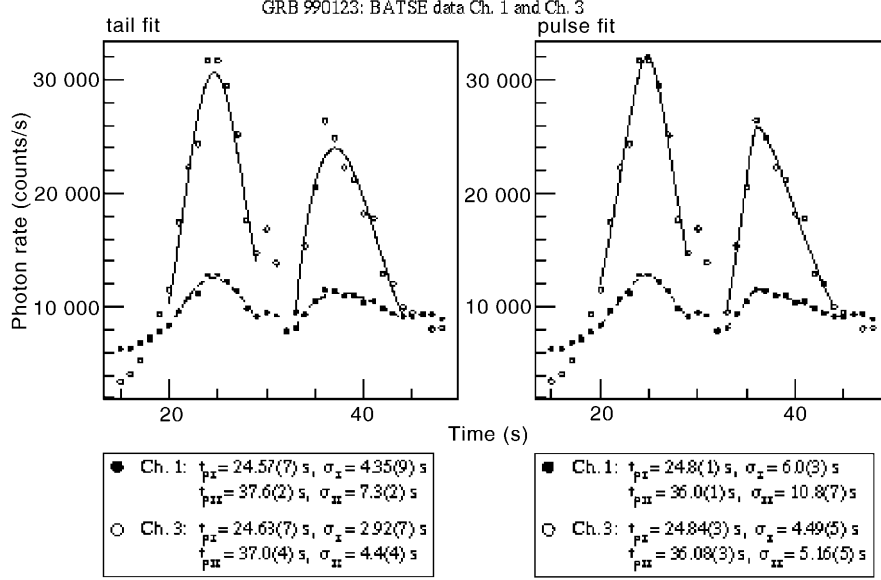
Fig. 9. – Fits to the pulses of GRB 990123 in different BATSE energy channels, using two different fitting functions [25].
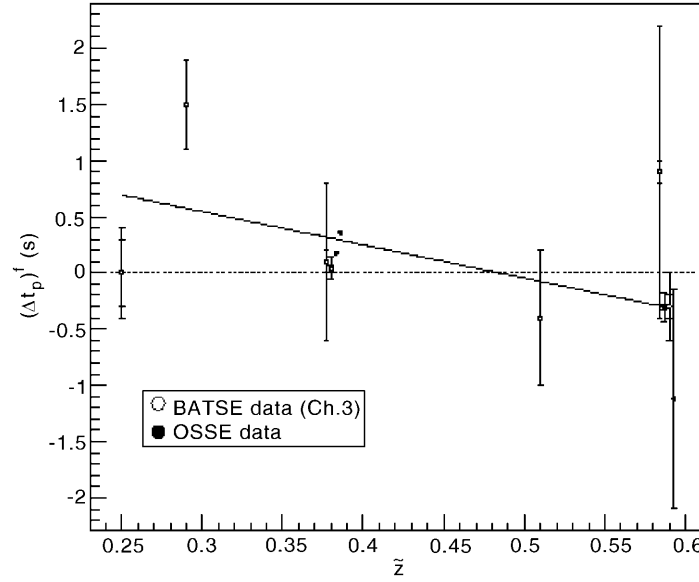

Fig. 10. – A fit to the time-lags extracted from the pulses of GRBs with measured redshifts. No significant dependence on the redshift was found [25].
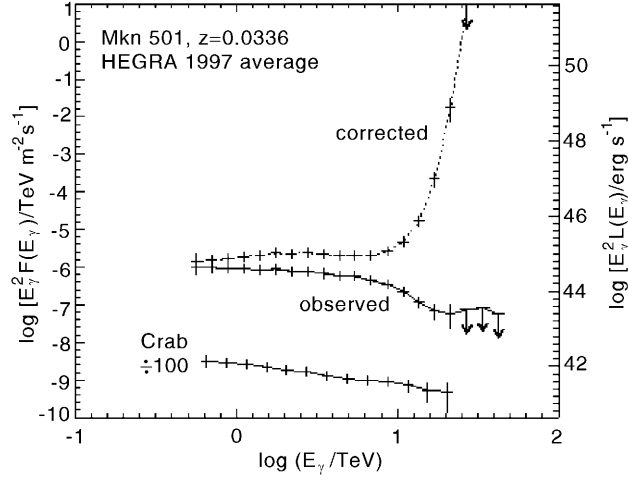
Fig. 11. – The signal observed by HEGRA [48] from Mkn 501, compared with the corrected spectrum calculated using the expected absorption (see also fig. 2 by infra-red background photons [47].

neutrino pulses from GRBs. Some models predict that they might emit observable ν fluxes at energies up to 10^{20} eV [42]. If a GRB pulse from $z \sim 1$ were seen at this energy, it would be sensitive to $M \sim 10^{26}$ GeV! Conversely, if $M \sim 10^{19}$ GeV, such a neutrino pulse would be spread over years of arrival times, and hence be invisible [22]!

5. – Avoiding the GZK cut-off?

Now let us return to the UHECR, and see how the possible modification of Lorentz kinematics discussed in the previous sections could be relevant to their interpretation. The point is that an energetic particle with

$$(22) \qquad\qquad c_0^2 p^2 = E^2(1 + E/M) + \cdots$$

may not, when it strikes a low-energy photon, be able to create particles via the reaction $p + \gamma_{CMB} \to \Delta \to n + \pi$ or $\gamma + \gamma_{IRB} \to e^+ e^-$, because its energy is "too small" compared with its momentum. In this way the GZK cut-off might be avoided [43, 44]. However, before reaching this conclusion, it is necessary also to analyze particle interactions and decays in a quantum-gravitational framework [45]: it is expected that energy would be conserved only in a statistical sense [17, 46].

We have already discussed the GZK cut-off for cosmic-ray protons, and noted its apparent absence. It has recently been pointed out that the corresponding cut-off on energetic astrophysical photons might also be absent [47]. The story starts with the HEGRA report of TeV γ-rays from Mkn 501 [48]. These should have been attenuated by absorption on the infra-red background. The exercise has recently been performed of inverting this attenuation, as seen in fig. 11, to calculate what the flux at the source would have to be in order to produce the observed high-energy flux from Mkn 501 [47]. The calculated source flux is remarkably high at energies > 1 TeV. Moreover, if the source were emitting so many energetic photons, then one would expect it to emit comparably

many neutrinos. However, the AMANDA neutrino telescope can rule out such a high neutrino flux [49].

Does this mean that Lorentz kinematics is violated? Surely not, since there are many more prosaic interpretations of the data, starting with the possibility that the HEGRA flux and/or energy calibration might need adjustment, etc. Nevertheless, this little mystery serves to remind us that (at least some) quantum-gravitational speculations may not be very far from experimental tests ([3]).

6. – Conclusions and prospects

In this lecture I have discussed two speculative fundamental physics ideas that might be subject to tests using cosmic rays—the possibility that UHECR might be due to the decays of ultraheavy metastable particles, and the possibility that quantum gravity might modify the velocity of light. These provide two rival interpretations of the UHECR: the violation of Lorentz kinematics in collisions might evade the GZK cut-off just as well as relic decays.

There are many other astrophysical sources suitable for probing the proposed deviation from Lorentz kinematics, including GRBs and AGNs. Searches for timing delays for energetic γ's have already been used to limit possible deviations from the Lorentzian momentum-energy relation for relativistic particles. Also, there is the puzzle of energetic γ-rays from Mkn 501 that could be resolved simultaneously. Ultrahigh-energy neutrinos from GRBs would be a great way to probe deviations from Lorentz kinematics.

However, one should always remember that all conservative interpretations should be tried and rejected before one embraces such a speculative interpretation of cosmic-ray data. The good news is that many new experiments, such as Auger and EUSO for UHECR, and a new generation of γ-ray experiments, will soon provide us with plenty of data to compare with both conservative and radical hypothesis. We may hope that new fundamental physics will be revealed, but should nevertheless brace ourselves for disappointment.

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