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Trans-Planckian particle creation in cosmology and ultra-high energy cosmic rays

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We consider observational constraints on creation of particles induced by hypothetical trans-Planckian effects during the current stage of the Universe expansion. We show that compatibility with the diffuse γ-ray background measured by the EGRET experiment strongly restricts this creation. In particular, it rules out the possibility to detect signatures of such short distance effects in anisotropies of the cosmic microwave background radiation. On the other hand, a possibility that some part of ultra-high energy cosmic rays originates from new trans-Planckian physics remains open.

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Recently, much interest was attracted to the study of possible deviations of the dispersion law of quantum ultrarelativistic particles from the standard one $\omega(k) = k$ at very large ("trans-Planckian") momenta $k > M$ (presumably, $M \sim M_{\rm Pl} = \sqrt{G}$; we put $\hbar = c = 1$ in this paper). Such a suggestion was previously discussed in quantum theory of black holes [1] (where it does not lead to any new observable effects), but then it was applied in cosmology [2]. Reasons for the existence of such an effect may follow from explicit breaking of the Lorentz invariance either induced by the existence of additional spatial dimensions (e.g., with "asymmetric warping" of usual 4D curved space-time [3]), or suggested by analogy with quasiparticles in quantum liquids [4]. Non-standard dispersion laws arise in non-commutative geometry [5] and κ-Poincare symmetry algebra [6], too.

Almost all attempts to find observational signatures of this effect in cosmology were related to its influence on spectra of scalar perturbations and gravitational waves generated during inflation. However, as was emphasized in [7], if any correction to these spectra arises at all, it means creation of real particles with ultra-high energies (caused by some new trans-Planckian physics) due to *any* expansion of the Universe. In particular, it should occur at the present time, too. Note, that there is even no qualitative difference between the type of the Universe expansion during a de Sitter (inflationary) stage in the early Universe and nowadays: both are accelerating ones. Of course, the present value H_0 of the Hubble parameter $H \equiv \dot{a}/a$, where $a(t)$ is the scale factor of the Friedmann-Robertson-Walker (FRW) cosmological model and H_0 is the Hubble constant, is much less than H during inflation. But, as we will see, it is much easier to detect particles with ultra-high energy created now than those created long time ago during inflation (in spite of the fact discussed below that the number of created particles is second order in the parameter of non-adiabaticity $|\beta(k)|$ while corrections to the spectra of inflationary perturbations are first order in $|\beta(k)|$).

Following the general approach of [7] (see also more recent papers [8]), we will phenomenologically describe the effect of ultra-high energy particle creation in cosmology due to unknown trans-Planckian physics in the following way. Expansion of the Universe results in redshifting of spatial momenta: $k = n/a(t)$, $n = \text{const}$ where $k = |\mathbf{k}|$ (in the case of a non-commutative geometry, the quantities which are redshifted $\propto a^{-1}$ are not exactly the usual momenta $\mathbf{k}$, but the difference between them and $\mathbf{k}$ becomes small for $k \ll M$, see [5]). As a result, wave equations for time-dependent parts of quantum field operators in the Heisenberg representation have the following form in the regime of large momenta $k \gg H$:

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \omega^2\,(n/a)\,\phi_k = 0 \qquad (1)$$

for scalar particles, and

$$A_k'' + a^2\omega^2\,(n/a)\,A_k = 0 \qquad (2)$$

where the dot denotes the derivative with respect to the time t, the prime – the derivative with respect to the conformal time $\eta = \int dt/a(t)$, A_k is some quantity characterizing the electromagnetic field (it is proportional to covariant components of the vector-potential $\mathbf{A}$ in the standard case), and the 3D spatial Fourier expansion is assumed. Note that, in principle, $\omega(k)$ for the electromagnetic field may depend on photon polarization, too. Deviation of $\omega(k)$ from the standard law $\omega = k$ for $k \gtrsim M$ results in breaking of conformal invariance for photons (and massless neutrinos, too), so photon creation in the FRW metric becomes possible. Below we will argue that massive particles with a restmass $m \ll M$ must be created as well (even if $m \gg H$), if creation of massless particles is not suppressed.

Let $H \ll M$. Then generic solutions of Eqs. (1), (2) have the following form in the WKB regime $H \ll k \ll \ll M$ (in the leading WKB approximation):

$$\phi_k = \frac{1}{\sqrt{2\omega a^3}} \left(\alpha_{n,0} e^{-i\int \omega dt} + \beta_{n,0} e^{i\int \omega dt}\right), \qquad (3)$$

$$A_k = \frac{1}{\sqrt{2\omega a}} \left(\alpha_{n,1} e^{-i\int \omega dt} + \beta_{n,1} e^{i\int \omega dt}\right), \qquad (4)$$

$$|\alpha_{n,s}|^2 - |\beta_{n,s}|^2 = 1, \quad s = 0,1 \qquad (5)$$

(we omit the spin index s further).

Usually, the adiabatic vacuum $\beta_n = 0$ is assumed for all modes of all quantum fields. However, trans-Planckian physics may result in a nonzero β_n (its actual value may be different for quantum fields of different spins and even for different polarizations, but we will not consider the latter possibility). So, supposing that particles with $k \gg M$ do not exist as individual particles or are not observable for other reasons (since we don't see them after all), we arrive to the following observational picture of the effect in consideration: in the course of the Universe expansion, pairs of particles and antiparticles with super-high energy M ($\sim M_{\rm Pl}$) are spontaneously created at the moment when their momentum $k(t) \equiv n/a(t) = M$, and their occupation number is $|\beta_n|^2$. The corresponding correction coefficient $\mathcal{K}^2(n)$ to the power spectrum of inflationary perturbations is obtained by matching of Eq. (3) (or its analog for gravitational waves) to the exact solution of massless scalar wave equation in the (approximately) de Sitter background with the Hubble parameter H estimated at the moment of the first Hubble radius crossing $k(t) = H$. It is equal to:

$$\mathcal{K}^2(n) = |\alpha_n - \beta_n|^2. \qquad (6)$$

We will see below that $|\beta_n|$ should be small. Then α_n can be made unity by a phase rotation, and $\mathcal{K}^2(n) = = 1 - 2\,\mathrm{Re}\,\beta_n$. Its difference from unity is first order in $|\beta_n|$.

Our approach is to take α_n and β_n (subjected to the condition (5)) as phenomenological quantities which should finally follow from a concrete model of non-trivial trans-Planckian physics, and investigate how they are limited by present observational data. Thus, we consider real particle creation (corresponding to an imaginary part of the effective action of quantum fields in a FRW background) only. This should be contrasted to real, vacuum polarization corrections to the effective action considered, e.g., in [9]. The latter corrections result in a refraction index different from unity for radiation. They can be strongly limited by observations of distant γ-bursts [10]. Note also that corrections to the effective volume in phase space leading to "trans-Planckian damping" which were recently proposed in [11] (in particular, they may explain why particles with $k \gg M$ are not observable) can be easily incorporated in the formalism used by changing the overall time-dependent prefactors in Eqs. (3), (4).

In [7], the first step in this investigation was made by considering back reaction of created ultra-high energy gravitons on the Universe expansion at present. It was assumed that β_n has the following expansion in terms of the small parameter H_n/M where $H_n \equiv H(t_n)$ is the Hubble parameter estimated at the moment of the trans-Planckian border crossing $n = Ma(t_n)$ for each Fourier field mode $\mathbf{k}$:

$$\beta_n = \beta_n^{(0)} + \beta_n^{(1)} \frac{H_n}{M} + ... \qquad (7)$$

Then it was shown that the first term in (15) is very suppressed: $|\beta_n^{(0)}|^2 \lesssim H_0^2/M^2 \equiv 10^{-122}\, M_{\rm Pl}^2/M^2$, while the second term is bounded by $|\beta_n^{(1)}|^2 \ll M_{\rm Pl}^2/M^2$ (so, it is also suppressed if $M \sim M_{\rm Pl}$). Note that time translation invariance (which we don't want to abandon) requires $|\beta_n^{(0)}|^2$ and $|\beta_n^{(1)}|^2$ to be independent on n that was noted in [7]. On the other hand, the phase of β_n is n-dependent and may be large. This leads to oscillations in $\mathcal{K}^2(n)$ and in resulting inflationary perturbation spectra which, however, are unobservable for $H \ll M$ due to their high frequency in k-space [8, 12].

The first, H-independent term in (15) describes "pure" trans-Planckian particle creation where the Universe expansion plays a kinematic role only. The second term in (15) is responsible for a mixed effect where both small-scale trans-Planckian physics and large-scale space-time curvature participate. A concrete toy model producing the latter term was proposed in [7], namely, the quantum state of any Fourier field mode $\mathbf{k}$ which has a minimal energy density just at the moment of the trans-Planckian border crossing (this state differs from the adiabatic vacuum in the next term of the WKB expansion). Since the minimal energy state may not appear as a result of the adiabatic evolution in the WKB regime $|\dot{\omega}| \ll \omega^2$ (even for a non-standard dispersion law), this model implicitly assumes that something radical happens for $k > M$: either that any mode does not exist in this regime at all, and is instantaneously "created" at the moment when its momentum falls down to M, or that the WKB condition is suddenly violated for $k > M$, i.e., because of $\omega(k)$ becoming very small for $k > M$ (as it occurs, e.g., in the model considered in [13]). Then, if $\omega(k) = k$ for $k < M$ exactly, the model leads to $|\beta_n^{(1)}| = 1/2$ for minimally coupled scalar particles (1) (see [7], the recent papers [8] arrived to essentially the same result).

To create photons, some deviation from the standard dispersion law $\omega(k) = k$ should exist for $k \leq M$ already. Let us assume that the quantity to be diagonalized for each Fourier mode $\mathbf{k}$ is $\tilde{\varepsilon}_k = (\hat{A}'^2_k + a^2\omega^2\hat{A}_k^2)/2a^4$, then equations for α_n and β_n in the representation (4) take the form (c.f. [14] for the case of a conformally coupled massive scalar field):

$$\alpha'_n = \frac{\Omega'_n}{2\Omega_n}\, e^{2i\int\Omega_n d\eta}\, \beta_n, \quad \Omega_n = a\omega\left(\frac{n}{a}\right) = \frac{n\omega}{k}, \quad (8)$$

$$\beta'_n = \frac{\Omega'_n}{2\Omega_n}\, e^{-2i\int\Omega_n d\eta}\, \alpha_n. \quad (9)$$

The diagonalization condition at $\eta = \eta_0(n)$ (when $k = M$) is $\beta_n(\eta_0) = 0$. If particle creation is small, $|\beta_n| \ll 1$, then $\beta_n \approx -i\,(\Omega'_n/\Omega_n^2)_{\eta_0}/4$ (up to a phase factor and an additional strongly oscillating term). Therefore,

$$|\beta_n^{(1)}| = \frac{M}{4}\left[\frac{k^2}{\omega^2}\left|\frac{d}{dk}\left(\frac{\omega}{k}\right)\right|\right]_{k=M} \sim 1 \quad (10)$$

for photons.

Note that the expression (10) remains valid for conformally coupled massive particles as far as their rest-mass $m \ll M$. So, this toy model shows that the second term in the expansion (15) need not be suppressed for massive particles with $m \gg H$. This remarkable fact fact may be understood using the following argument: any non-standard dispersion law $\omega(k)$ is equivalent to the appearance of an effective mass term $m^2(k) \equiv \omega^2(k) - k^2$ (m^2 may be negative, of course). For $k \sim M$, where a significant deviation from the standard dispersion law occurs, the rest mass $m^2(0)$ is completely irrelevant.

Equations for creation of massive fermions in a FRW background are similar to those in the case of conformally coupled massive scalar particles (with an additional multiplier n/ma in the r.h.s. of Eqs. (8), (9) for the standard dispersion law $\omega^2 = k^2 + m^2$, see e.g. [15]). Therefore, if photons are created due to trans-Planckian effects at all, one may expect that massive fermions with $m \ll M$ including leptons are created with a comparable (or even slightly larger) rate due to the present expansion of the Universe.

Now we make a next step and study limits on trans-Planckian particle creation following from the direct observability of created particles (photons, in particular). Also, we omit the assumption $M \sim M_{\rm Pl}$ and consider the case $M \ll M_{\rm Pl}$, too. We show that high energy cosmic rays data require much more suppression of $\beta_n^{(0)}$ and $\beta_n^{(1)}$ as compared to the results obtained in [7].

The measured flux of ultra-high energy cosmic rays (UHECR) extends to energies of order $E \sim E_0 \equiv 10^{11}$ GeV only. On the other hand, a typical energy of particles emerging from the trans-Planckian region can be much higher, up to $E \sim 10^{19}$ GeV. May the highest energy particles pass undetected? The answer is negative. First, measurements place the following constraint on the integral flux of high energy particles (see, e.g., [16]):

$$F_{E>E_0} \approx 10^{-2}\,{\rm km}^{-2}\cdot{\rm yr}^{-1}\cdot{\rm sr}^{-1} \approx 10^{-71}\,{\rm GeV}^3\cdot{\rm sr}^{-1}. \quad (11)$$

Second, the Universe is not transparent for high energy radiation. Particles which are injected with any $E > E_0$ will rapidly (on the cosmological time scale) migrate into a lower energy range. For our purposes, it it sufficient to consider attenuation of high energy particles on photons of the cosmic microwave background (CMB) radiation.

Protons loose energy in the process of pion photoproduction. This gives rise to the famous Greisen-Zatsepin-Kuzmin (GZK) cut-off. The attenuation length for this process (that is the distance over which the energy of a primary particle decreases by one e-fold) is less than 20 Mpc at $E > E_0$. Roughly half of released energy ends up in the electromagnetic cascade, the rest is carried out by neutrinos. The Universe becomes transparent for protons with $E \approx E_0$. Therefore, the number of protons which could have been produced by trans-Planckian effects (and which conserve) is subject to the constraint (11). This can be re-written as a constraint on the quantum gravity scale M in a way similar to what follows. However, a somewhat stronger and less model dependent constraint can be obtained by considering an electromagnetic cascade which migrates to even lower energies. From this point of view, it is unimportant whether the electromagnetic cascade was initiated by propagation of high energy protons, or photons (or, to this end, electrons) which were created by the trans-Planckian effects directly. Even neutrino production in the trans-Planckian region is not harmless. Neutrino will create the electromagnetic cascade in interactions with the cosmic background of relic neutrinos. Since about 1% of high energy neutrinos interact over the horizon scale [17], our final constraint, Eq. (15), would be only an order of magnitude weaker even in the unrealistic case of pure neutrino creation. For these reasons, we concentrate on the constraint imposed by the electromagnetic cascade in what follows.

A high energy photon cascades to lower energies in the chain of the following reactions. First, it creates e^+e^- pairs in collisions with CMB photons. Secondary electrons re-create photons with energies somewhat lower than the energy of the original photon via the inverse Compton process, and so on. The corresponding attenuation length at $E \gg E_0$ is about 0.1 of the present horizon size, and it is even smaller for smaller energies. Therefore, the cascade migrates to lower energies until it reaches the sub-TeV scale which corresponds to the threshold of pair creation on cosmic backgrounds.

Therefore, the integrated energy flux of particles emerging from the trans-Planckian region may not exceed the integrated energy flux in the sub-TeV range where the diffuse γ-ray background was measured by the EGRET telescope [18]. The measured value of this background is

$$S_0 \approx 10^3 \text{ eV cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \sim 10^{-58} \text{ GeV}^4 \cdot \text{sr}^{-1}. \tag{12}$$

Let us relate this flux to the energy production rate. The rate of growth of energy density in particles emerging from the trans-Planckian region due to the expansion of the Universe is [7]

$$J \equiv \frac{d(a^4\epsilon)}{a^4 dt} = \frac{gNM^4H}{2\pi^2}|\beta_n|^2. \tag{13}$$

In this relation, both particles and antiparticles are counted, $g = 2$ for photons and neutrinos, $g = 4$ for massive fermions. N counts for all particle species which can create the electromagnetic cascade at the end, since one expects that the trans-Plankian creation is "democratic" and insensitive to particle masses as far as $m \ll M$. Omitting neutrino, $N = 26$ in the standard model. In supersymmetric or Grand Unified models, $N \sim 10^2 - 10^3$. The integrated flux of energy accumulated during the age of the Universe will be $S_1 \approx J\, H^{-1}$. Requiring $S_1 < S_0$, we get

$$|\beta_n^{(0)}|^2 < 10^{-133}\ \frac{1}{N}\left(\frac{M_{\rm Pl}}{M}\right)^4. \tag{14}$$

We see that the constraint on the $\beta_n^{(0)}$ term in the decomposition (15) is very strong. Thus, this term should be practically absent regardless of the value of M. A contribution from the second term is strongly suppressed by the small quantity $H_0^2/M_{\rm Pl}^2 \approx 10^{-122}$. As a result, for the $\beta_n^{(1)}$ coefficient we obtain

$$|\beta_n^{(1)}| < 10^{-6}\ \frac{1}{\sqrt{N}}\ \frac{M_{\rm Pl}}{M}. \tag{15}$$

In recent literature (see e.g. [19]) there were optimistic expectations regarding possible imprints of short distance physics on the spectrum of CMB anisotropies generated in the inflationary scenario of the early Universe. Let us estimate now the impact of the restriction (15) on a possible magnitude of the effect. According to Eqs. (6), (15), (14), a fractional correction to the power spectrum of inflationary perturbations which arise due to trans-Planckian physics is given by

$$\frac{\delta P}{P} = \beta_n^{(1)}\ \frac{H_{\rm inf}}{M} \tag{16}$$

where $H_{\rm inf}$ is the value of the Hubble parameter during the last 60 e-folds of inflation, $H_{\rm inf}/M_{\rm Pl} < 10^{-5}$. In view of the constraint (15), we find

$$\frac{\delta P}{P} < 10^{-11}\ \frac{1}{\sqrt{N}}\left(\frac{M_{\rm Pl}}{M}\right)^2. \tag{17}$$

On the other hand, astrophysical data on the constancy of the light velocity yield the lower limit $M > 10^{15}$ GeV [10].[1)] This gives $\delta P/P < 10^{-3}$ for the maximum possible magnitude of corrections to the perturbation power spectrum. We conclude that trans-Planckian particle creation is so strongly restricted by observations of UHECR that it will be impossible to detect signatures of short distance physics in CMB anisotropies, since the allowed contribution is smaller than the cosmic variance at all multipoles of interest, $l < 10^4$.

Returning to UHECR themselves, one may consider a speculative possibility that observed events above the GZK cut-off energy are due to peculiarities of trans-Planckian physics. However, trans-Planckian creation of particles would occur homogeneously in the Universe, and therefore should lead to the GZK cut-off in the spectrum of created protons at high energies and to the pile-up of protons at $E \sim 4 \cdot 10^{19}$ eV. Thus, protons can not explain super-GZK events despite the trans-Planckian creation does occur within the GZK sphere of ~ 50 Mpc, from where protons can reach us. On the other hand the attenuation length for photons grows with energy and

1) Strictly speaking, this limit was obtained assuming that a correction to the standard dispersion law for $k \to 0$ starts with the cubic term, $\omega^2 = k^2(1 \pm (k/M) + \dots)$. If the cubic term is absent and the correction begins from a larger power of k/M, there is no lower limit on M. However, the constraint (15) remains valid. So, even in this specific case, to obtain significant corrections to the perturbation power spectrum generated during inflation, either a specific mechanism for trans-Planckian particle creation producing $|\beta_n^{(1)}| \gg 1$ should be invented, or one has to postulate a low $M \le 10^{-6}\ M_{\rm Pl}$ which is not compatible with the condition $H_{inf} \ll M$ (necessary for general relativistic description of inflation and generation of perturbations) for many inflationary models.

therefore photons may produce spectrum of cosmic rays compatible with the AGASA data [20] at highest energies. One problem which may arise here is related to an overall normalization. At $E \sim 10^{20}$ eV the attenuation length for photons is about 100 times smaller than the horizon scale. This gives the distance scale to sources which contribute to the flux at ultra-high energies. On the other hand, by-products of the electromagnetic cascade will pile-up at the EGRET energies and are accumulated from the entire Universe. On this grounds, one expects that the ratio of the energy flux in UHECR ($S \sim 10^{-60}$ Gev$^4 \cdot$ sr^{-1}, see Eq. (11)) to the diffuse EGRET background can not be larger than 0.01. This value comfortably fits the data, and the numerical coincidence may indicate that these two backgrounds can be related indeed. However, to maintain this level of the UHECR flux in photons one should assume small extragalactic magnetic fields and small universal radio background (c.f. [21]). In addition, one would need to fine-tune the rate of trans-Planckian creation to the level of the observed UHECR flux. Also, this mechanism is disfavoured by the observed angular clustering of UHECR [20, 22]. One should note, however, that the same problems arise in many other models which attempt to explain super-GZK events.

We conclude that at least some part of cosmic rays with energies beyond the GZK limit may have origin due to new physics in the trans-Planckian region. This striking possibility remains open and deserves further study, while the constraint (17) makes expected contribution of trans-Planckian physics to the CMB anisotropies to be unobservable.

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