Ultra High Energy Cosmic Rays and Inflation.

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Abstract. Two processes of matter creation after inflation: 1) gravitational creation of superheavy (quasi)stable particles, and 2) non-thermal phase transitions leading to formation of topological defects, may be relevant to the resolution of the puzzle of cosmic rays observed with energies beyond GZK cut-off. Both possibilities are reviewed in this talk.

INTRODUCTION

According to the modern tale, all matter in the Universe was created in reheating after inflation. While this happened really long ago and on very small scales, this process is obviously of such vital importance that one may hope to find some observable consequences, specific for particular models of particle physics. And, indeed, we now believe that there can be some clues left. Among those are: topological defects production in non-thermal phase transitions [1], GUT scale baryogenesis [2], generation of primordial background of stochastic gravitational waves at high frequencies [3], just to mention a few. However, matter appears in many kinds and forms, and it is hard to review all possibilities in one talk. I'll concentrate on a possible relation to a mounting puzzle of the Ultra High Energy Cosmic Rays (UHECR).

When proton (or neutron) propagates in CMB, it gradually looses energy colliding with photons and creating pions [4]. There is a threshold energy for the process, so it is effective for very energetic nucleons only, which leads to the famous Greisen-Zatsepin-Kuzmin (GZK) cutoff of the high energy tail of the spectrum of cosmic rays. All this means that detection of, say, 3×10^{20} eV proton would require its source to be within ~ 50 Mpc. However, many events above the cut-off were observed by Yakutsk, Haverah Park, Fly Eye and AGASA collaborations [5] (for the review see Ref. [6]).

Results from the AGASA experiment [7] are shown in Fig. 1. The dashed curve represents the expected spectrum if conventional extragalactic sources of UHECR would be distributed uniformly in the Universe. This curve displays the theoretical GZK cut-off, but we see events which are way above it. (Numbers attached to the data points show the number of events observed in each energy bin.) Note that no candidate astrophysical source, like powerful active galaxy nuclei, were found in the directions of all six events with $E > 10^{20}$ eV [7]

There were no conventional explanation found to these observations, and the question arises, is it indication of the long awayted new physics, at last ?

Many solutions to the puzzle were suggested, which rely on different extensions of the standard model, in one way or the other. Among those are:

- A particle which is immune to CMBR. In this scenario, primary particle is produced in conventional astrophysical accelerators and is able to travel cosmological distances. There are variations to this scheme. This can be a new exotic particle able to produce normal air showers in Earth's atmosphere [8], or this can be an accelerated (anti)neutrino annihilating via Z^0 resonance on the relic neutrinos in a local high density neutrino clump, thus producing energetic gamma or nucleon [9]. Massiveness of neutrino, $m_\nu \sim$ eV, is a necessary requirement in this scheme.
- Another possibility is that UHECR are produced when topological defects destruct near the lab (on the cosmological scale) [10]. Topological defects which were considered in these kinds of scenarios were: strings [11], superconducting strings [10], networks of monopoles connected by strings [12], magnetic monopoles [13].
- Conceptually the simplest possibility is that UHECR are produced (again cosmologically locally) in decays of some new particle [14]. The candidate X-particle must obviously obey constraints on mass, number density and lifetime.

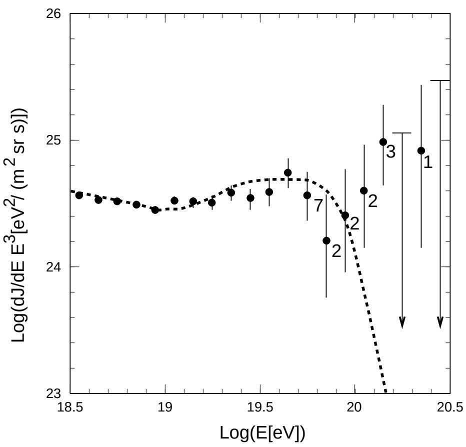

FIGURE 1. AGASA data set [7], February 1990 – October 1997.

UHECR FROM DECAYING PARTICLES

In order to produce cosmic rays in the energy range $E > 10^{11}$ GeV, the decaying primary particle has to be **heavy**, with the mass well above GZK cut-off, $m_X > 10^{12}$ GeV. The lifetime, τ_X, cannot be much smaller than the age of the Universe, $\tau_U \approx 10^{10}$ yr. Given this shortest possible lifetime, the observed flux of UHE cosmic rays will be generated with the rather low density of X-particles, $\Omega_X \sim 10^{-12}$, where $\Omega_X \equiv m_X n_X/\rho_{\rm crit}$, n_X is the number density of X-particles and $\rho_{\rm crit}$ is the critical density. On the other hand, X-particles must not overclose the Universe, $\Omega_X < 1$. With $\Omega_X \sim 1$, the X-particles may play the role of cold dark matter and the observed flux of UHE cosmic rays can be matched if $\tau_X \sim 10^{22}$ yr.

The problem of the particle physics mechanism responsible for a long but finite lifetime of very heavy particles can be solved in several ways. For example, otherwise conserved quantum number carried by X-particles may be broken very weakly due to instanton transitions, or quantum gravity (wormhole) effects [14]. Other interesting models of superheavy long-living particles were found in Refs. [15].

Spectra of UHE cosmic rays arising in decays of relic X-particles were successfully fitted to the data for m_X in the range $10^{12} < m_X/\mathrm{GeV} < 10^{14}$ [16].

Here I address the issue of X-particle abundance. It was noticed [17,18] that such heavy particles are produced in the early Universe from the vacuum fluctuations and their abundance can be correct naturally, if the standard Friedmann epoch in the Universe evolution was preceded by the inflationary stage. This is a fundamental process of particle creation unavoidable in the time varying background and it requires no interactions. Temporal change of the metric is the single cause of particle production. Basically, it is the same process which during inflation had generated primordial large scale density perturbations. No coupling (e.g. to the inflaton or plasma) is needed. All one needs are stable (very long-living) X-particles with the mass of order of the inflaton mass, $m_X \approx 10^{13}$ GeV. Inflationary stage is not required to produce superheavy particles from the vacuum. Rather, the inflation provides a cut off in excessive gravitational production of heavy particles which would happen in the Friedmann Universe if it would start from the initial singularity [18]. Resulting abundance is quite independent of detailed nature of the particle which makes the superheavy (quasi)stable X-particle a very interesting dark matter candidate. New particle needs good name. I like Wimpzilla [19].

Friedmann Cosmology. For particles with conformal coupling to gravity (fermions or scalars with $\xi = 1/6$ in $\xi R\phi^2$ interaction term with the curvature), it is the particle mass which couples the system to the background expansion and serves as the source of particle creation. Therefore, just on dimensional grounds, we expect $n_X \propto m_X^3 a^{-3}$ at late times when particle creation diminishes. In Friedmann cosmology, $a \propto (mt)^\alpha \propto (m/H)^\alpha$ and the anticipated formulae for the X-particles abundance can be parameterised as $n_X = C_\alpha m_X^3 (H/m_X)^{3\alpha}$. It is expansion of the Universe which is responsible for particle creation. Therefore, this equation which describes simple dilution of already created particles is valid when already $H << m_X$. On the other hand particles with $m_X >> H$ cannot be created by

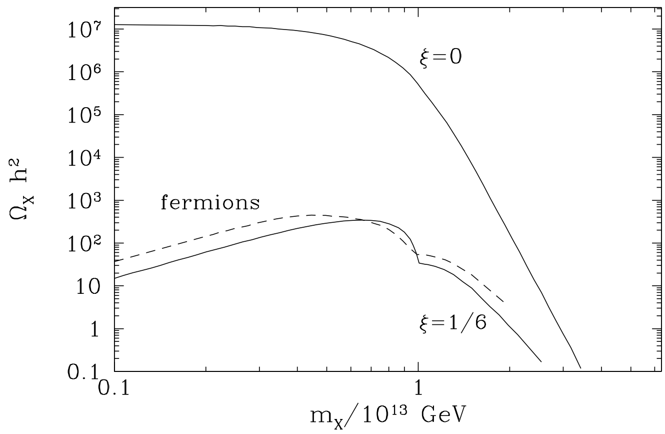

FIGURE 2. Ratio of the energy density in X-particles, gravitationally generated in inflationary cosmology, to the critical energy density is shown as a function of X-particle mass, Ref. [18].

this mechanism. Creation occurs when $H \sim m_X$. Coefficient C_α can be found numerically [18], its typical value is $O(10^{-2})$, and we find that stable particles with $m_X > 10^9$ GeV will overclose the Universe. There is no room for Superheavy particles in our Universe if it started from the initial Friedmann singularity [18], since the value of the Hubble constant is limited from above only by the Planck constant in this case.

Inflationary Cosmology. If there was inflation, the Hubble constant (in effect) did not exceeded the inflaton mass, $H < m_\phi$. The mass of the inflaton field has to be $m_\phi \approx 10^{13}$ GeV as constrained by the amplitude of primordial density fluctuations relevant for the large scale structure formation. Therefore, production of particles with $m_X > H \sim 10^{13}$ GeV has to be suppressed in inflationary cosmology. Results of direct numerical integration of gravitational particle creation in chaotic inflation model with the potential $V(\phi) = m_\phi^2 \phi^2/2$ is shown in Fig. 2.

This figure was calculated assuming $T_{\rm R} = 10^9$ GeV for the reheating temperature. (At reheating the entropy of the Universe was created in addition to X-particles. In general, multiply this figure by the ratio $T_{\rm R}/10^9$ GeV and divide it by the fractional entropy increase per comoving volume if it was significant at some late epoch.) Reheating temperature is constrained, $T_{\rm R} < 10^9$ GeV, in supergravity theory [20]. We find that $\Omega_X h^2 < 1$ if $m_X \approx$ (few) $\times\, 10^{13}$ GeV. This value of mass is in the range suitable for the explanation of UHECR events [18]. Gravitationally created superheavy X-particles can even be the dominating form of matter in the Universe today if X-particles are in this mass range [17,18].

TOPOLOGICAL DEFECTS AND INFLATION

Decaying topological defect can naturally produce very energetic particles, and this may be related to UHECR [10] - [13], for recent reviews see [6]. However,

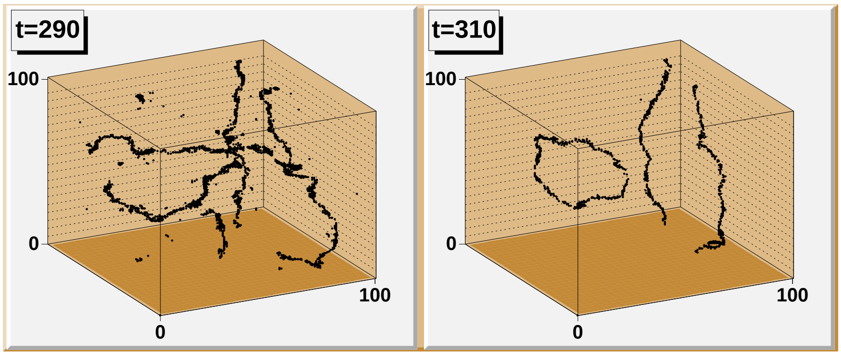

FIGURE 3. String distribution at two successive moments of time.

among motivations for inflation there was the necessity to get rid of unwanted topological defects. And inflation is excellent doing this job. Since temperature after reheating is constrained, especially severely in supergravity models, it might be that the Universe was never reheated up to the point of GUT phase transitions. Topological defects with a sufficiently high scale of symmetry breaking cannot be created. How then topological defects could populate the Universe?

The answer may be provided by non-thermal phase transitions [1] which can occur in preheating [21] after inflation. Explosive particle production caused by stimulated decay of inflaton oscillations lead to anomalously high field variances which restore symmetries of the theory even if actual reheating temperature is small. Defects form when variances are reduced by the continuing expansion of the Universe and phase transition occur. This problem is complicated, and while some features can be anticipated and some quantities roughly estimated, the problem requires numerical study. In recent papers [22] the defect formation and even the possibility of the first order phase transitions during preheating was demonstrated explicitly. Fig. 3 shows string distribution in a simulation with symmetry breaking scale $v = 3 \times 10^{16}$ GeV, when a pair of "infinite" strings and one big loop had formed. Size of the box is comparable to the Hubble length at this time.

CONCLUSIONS

Next generation cosmic ray experiments, which will be soon operational, will tell us which model for UHECR may be correct and which has to be ruled out. One unambiguous signature is related to homogeneity and anisotropy of cosmic rays. If particles immune to CMBR are there, the UHECR events should point towards distant, extraordinary astrophysical sources [23]. If wimpzillas are in the game, the Galaxy halo will be reflected in anisotropy of the UHECR flux [24]. It is remarkable that we might be able to learn about the earliest stages of the Universe's evolution. Discovery of heavy X-particles will mean that the model of inflation is likely correct, or that at least "standard" Friedmann evolution from the singularity is ruled out, since otherwise X-particles would have been inevitably overproduced [18].

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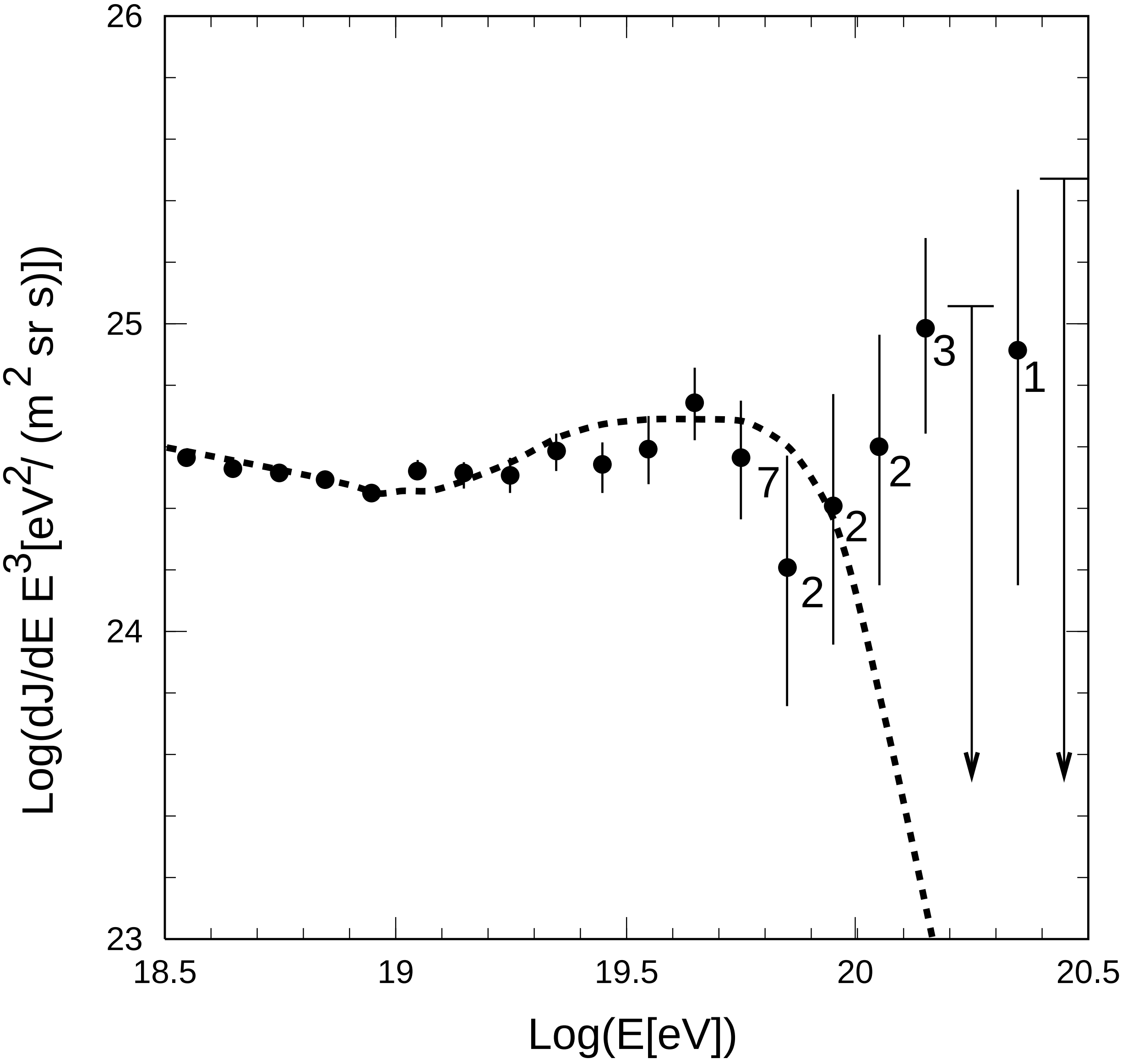

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