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Ultra High Energy Cosmic Rays from Early Decaying Primordial Black Holes

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Origin of ultra high energy cosmic rays (UHECR) is an unsolved problem in physics. Several proposals such as Z-burst, decay of super massive matter, susy particles as a primary, neutrino as a primary in extra dimension models exist in the literature which try to address this issue. Many of these proposals solve the problem of propagation of cosmic rays over cosmological distances by introducing new physics. However these do not explain the origin of such high energy cosmic rays. The possible astrophysics sites, such as active galactic nuclei, are highly constrained. Here we determine whether these cosmic rays originated from the decay of some exotic objects, such as the Primordial Black Holes (PBHs) in Brane World scenario, present in the early universe. In contrast to the usual Top Down scenario we do not assume that this exotic object necessarily has to decay in our astrophysical neighbourhood since we assume a beyond the standard model scenario, where the propagation problem is absent. We first consider the standard 4-dimension PBHs decaying in the early universe. We calculate UHE neutrino and proton flux from such PBHs. The density of these PBHs is constrained by low energy cosmic ray fluxes and cosmological observations. We repeat the flux calculation in the Brane World scenario. We find that in both cases it is unable to produce the observed ultra high energy cosmic ray flux. It will be interesting to repeat our calculations for other superheavy particles, decaying in the early universe, which may contribute to the ultra high energy cosmic ray flux.

1. Introduction

The observation of cosmic rays with energies in excess of $10^{20} eV$ present a major challenge to astro-particle physics due to the GZK cutoff. The standard cosmic ray primaries, such as protons, nuclei and photons are unable to propagate cosmological distances at such high energies. There exist many proposals in the literature which solve the propagation problem by introducing new physics. Examples of these explanations include violations of lorentz invariance, existence of magnetic monopoles, a strongly interacting neutrino at ultra high energies(UHE) etc. Alternative models such as topological defects and Z-burst solve the problem by introducing exotic sources of cosmic ray primaries in our astrophysical neighbourhood. However most of parameter space in the models like Z-burst and top-down scenarios are severly constrained by existing experiments or future planned experiments. Non-observation of UHE neutrinos in experiments by the year 2006 will rule out these models [1].

The known astrophysical sources for UHE neutrinos are mainly Active Glactic Nuclei (AGN) and Gamma Ray Bursts(GRB). In the present paper we consider alternate sources, which may be located at cosmological distances, for UHECR assuming that the propagation problem is solved within some new physics scenario. Some possibilities include primordial black holes or topological defects. These objects are interesting because they can survive till today and decay to produce all sorts of particles. Primordial black holes(PBH) as a source of UHECR are studied by the Ref. [2]. In this paper we consider the production of UHE protons and neutrinos from 4D PBHs and 5D braneworld PBHs decaying today or in early epoch of the cosmological evolution of the universe.

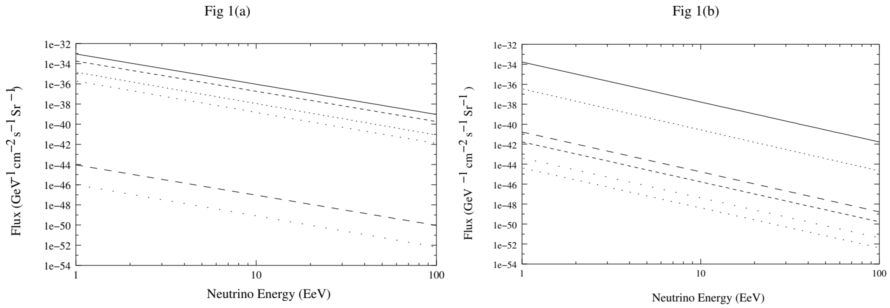

Figure 1. Fig 1(a): Direct Neutrino flux today from 4d PBHs evaporating at redshift $z = 0$(solid), $z = 1000$(short dashed) and $z = 10^6$ (long dashed). Similarly indirect neutrino flux today from 4d PBHs evaporating at redshift $z = 0$(dottted), $z = 1000$(small spaced dots) and $z = 10^6$ (large spaced dots). Fig 1(b): Direct Neutrino flux today from 5d BWPBHs evaporating at redshift $z = 0$(solid), $z = 1000$(dotted) and $z = 10^6$ (short dashed). Similarly indirect neutrino flux today from 5d BWPBHs evaporating at redshift $z = 0$(dottted), $z = 1000$(long dashed) and $z = 10^6$ (large spaced dots).

2. Standard 4D Primordial Black Holes

It is well known that black holes would have formed in very early universe through density fluctuations [3]. If one assumes the production of a black hole of mass of the order of horizon mass at some time 't'',

$$M_{BH}(t) \approx \frac{c^3 t}{G} \approx 10^{15} \left(\frac{t}{10^{-23} s} \right) g \, , \tag{1}$$

then a black hole of mass 10^{15}g would be evaporating now. Masses less than this would have evaporated by now. From mass loss we find a relation between temperatute and their evapoartion time as

$$dt_* = 1.5 \times 10^{-15} \frac{dT_*}{T_*^4} \tag{2}$$

where $t_* = t/(1sec)$ and $T_* = T/(1EeV)$. Particles with energies above 1 EeV will be produced instantly when the temperature of the black hole reaches a $kT \geq 1EeV$.

3. BraneWorld Primordial Black Holes(BWPBH)

Braneworld cosmological models provide an interesting alternative to the standard cosmology. In this scenario PBHs can also be formed in very early universe by density perturbations [4]. In ref. [4] the authors have calculated the mass-lifetime relation for black holes formed on the brane due to collapse of matter on the brane. We also obtain a relation between time and temperature of the BWPBH as

$$dt_* = \frac{0.009 \tilde{g}^{-1}}{512 \pi A} \frac{dT_*}{T_*^5} \, , \tag{3}$$

where $t_* = t/1sec$, $T_* = T/1EeV$ and $A = \frac{l}{l_4}$. $\tilde{g}$ is the effective bulk and brane degrees of freedom of the particles. The parameter A determines the size of the extra dimension at which 5D BHs dominate the dynamics.

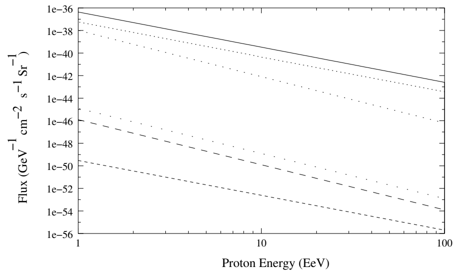

Figure 2. Proton flux today from 4d PBHs evaporating at redshift $z = 0$(solid), $z = 1000$ (dotted) and $z = 10^6$ (small spaced dots). Similarly Proton flux today from 5d BWPBHs evaporating at redshift $z = 0$(large spaced dots), $z = 1000$(long dashed) and $z = 10^6$ (short dashed).

4. Neutrino Flux

Let $f(E_\nu, T)$ represent the total neutrino flux of energy E_ν, then the diffuse direct flux per unit area today is:

$$\frac{dN_\nu}{dE_{\nu 0}} = \frac{1}{4\pi} \times 1.5 \times 10^{-15} \int_{z_{min}}^{z_{max}} \int_{kT_{i*}(1+z)}^{kT_{pl*}} \frac{d(kT_*)}{(kT_*)^4} \frac{1}{(1+z)^2} \frac{dn}{dz} f(E_\nu, T) dz \tag{4}$$

where $E_\nu = E_{\nu 0}(1+z)$, z_{max} corresponds to max redshift from which particles of energies $100EeV$ can reach us and $z_{min} = 0$. n is distribution of the PBHs present throughout the evolution of the universe from their time of formation [5].

Indirect neutrino flux and proton flux is evaluated by incorporating fragmentation functions and modified $f(E_\nu, T)$. Finally we repeat the above procedure for BWPBHs for calculating direct, indirect neutrino flux and proton flux.

5. Discussion

As we observe that neutrino flux at energy $10^{20}eV$ from 4d PBHs evaporating today is roughly ten orders of magnitude smaller compared to the existing neutrino flux limit. For early decaying 4dPBHs it can be noticed that neutrino flux at $10^{20}eV$ is even smaller. UHE neutrino fluxes and proton fluxes from 5d BWPBHs are considerably smaller compared to 4D PBHs even for maximum densities.

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