Bounds on Direct Couplings of Superheavy Metastable Particles to the Inflaton Field from Ultra High Energy Cosmic Ray Events

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Abstract

Top-down models for the origin of ultra high energy cosmic rays (UHECR's) propose that these events are the decay products of relic superheavy metastable particles, usually called X particles. These particles can be produced in the reheating period following the inflationary epoch of the early Universe. We obtain constraints on some parameters such as the lifetime and direct couplings of the X-particle to the inflaton field from the requirement that they are responsible for the observed UHECR flux.

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1 Introduction

The ultra high energy cosmic rays (UHECR's), events with primary energies above $E > 10^{20}\,$eV, constitute one of the most intriguing mysteries in nature. Their origin, source and composition are not understood since they were first observed by the Volcano Ranch experiment in 1963 [1].

According to conventional theories, cosmic rays are produced by the acceleration of charged particles in intense electromagnetic fields of astrophysical objects. This conventional wisdom, however, has some difficulties in explaining the observed flux of UHECR's. Most of the known astrophysical objects do not have an electromagnetic field strong enough neither a large acceleration site capable to accelerate particles up to 10^{19} eV [2]–[4].

Another problem is the propagation of the UHECR's through the intergalactic medium. If the particles are protons or nuclei, they should quickly degrade their energy due to interactions with the cosmic microwave background (CMB), producing a cut in the spectrum at energies above 3×10^{9} eV, the so-called GZK limit [5]–[7]. Simulations [8] show that in order that protons with energy larger than $10^{20}\,$eV arrive at Earth they must have traveled less than $\approx$100 Mpc, the attenuation length. A cut off is also expected if the primary particles are high energy photons in the range of 3×10^{12} eV to 10^{22} eV, which have attenuation length smaller than 100 Mpc, due to their interaction with various background photons (infrared/optical, CMB or universal radio background), mainly by pair production and inverse Compton scattering. These consecutive interactions produce electromagnetic cascades with decreasing energy that end up below 100 GeV resulting in a gamma-ray background.

Furthermore, UHECR's are usually not deflected by intergalactic magnetic fields, so their incoming directions should point to the sources. However, taking into account the arrival directions of the UHECR events [9] and constraining their origin to be in a distance of 100 Mpc around the Earth, no candidate sources were found so far (an exception is a suggestion that these events can be generated in M87 galaxy in the Virgo Cluster and made isotropic by the galactic magnetic field [10]).

A new scenario, the so-called top-down mechanism, was then proposed to explain these events [11]. In this scenario, UHECR's would originate from the decay of some superheavy particles ($m_X \gg 10^{20}\,$eV) inside the GZK volume. They could be either emitted by topological defects at the present epoch [12] or created in the pos-inflationary era [13]. In the second case, where the supermassive particles must be metastable ($\tau_X \geq 10^{10}\,$years), they could have been created perturbatively, by a mechanism that is called *reheating* [14], or by no-perturbative process like *preheating* [15], *instant preheating* [16] or *gravitational production* [17]. In this letter we will study bounds on the direct coupling of X-particles produced during the reheating phase to the inflaton field by requiring that they are sources of UHECR's. A preliminary version of this work appeared in [18].

2 Observed UHECR's flux and X-particle abundance

We will now derive a relation among the abundance Ω_X, the lifetime τ_X and the mass m_X of the X-particle in order to provide the observed flux of UHECR's on Earth.

It is reasonable to assume that X-particles decay into quarks and leptons. Particles are produced following the quark-hadron fragmentation process described by QCD that results in the production of nucleons ($\approx 10\%$) and pions ($\approx 90\%$) distributed equally among the three charge states. Charged pions produce basically electrons and neutrinos and neutral pions decay into photons. Photons dominate the primary spectrum over protons by a factor of ≈ 6 [19] –[20]. Following Sigl and Bhattacharjee [11], we will consider that the UHECR's are photons with energy $E \simeq 10^{20}\,\mathrm{eV}$ and an attenuation length of $l(E_\gamma) \approx 10\,\mathrm{Mpc}$. It was recently suggested that photons can indeed provide the bulk of UHECR's without violating EGRET bounds on GeV gamma-ray backgrounds [21].

The photon flux generated by the decay of an uniform distribution of X-particles is given by:

$$J_\gamma = \frac{1}{4\pi}\, l(E_\gamma)\, \dot{n}_X \,\frac{dN_\gamma}{dE_\gamma}\,, \tag{1}$$

where dN_γ/dE_γ is the photon injection spectrum from X-decay and $\dot{n}_X(= n_X/\tau_X)$ is the X-decay rate.

From the observed UHECR's flux [11], $J(E \simeq 10^{20}\,\mathrm{eV}) = 10^{-27}\,(\mathrm{m}^2\,\mathrm{sr}\,\mathrm{s}\,\mathrm{GeV})^{-1}$ and using $dN_\gamma/dE_\gamma \approx E_\gamma^{-1.5}$ from a QCD model [11], one gets:

$$\dot{n}_X = 3.7\times 10^{-46}\left(\frac{m_X}{10^{12}\,\mathrm{GeV}}\right)^{-1/2} \mathrm{cm}^{-3}\mathrm{s}^{-1}\ . \tag{2}$$

So, we can obtain a relation between $\Omega_X h^2$ and τ_X:

$$\tau_X = \frac{\Omega_X \rho_c}{\dot{n}_X m_X} \simeq 10^{22}(\Omega_X h^2)\left(\frac{10^{12}\mathrm{GeV}}{m_X}\right)^{1/2} \mathrm{years}, \tag{3}$$

where $\Omega_X = \rho_X/\rho_c$, ρ_X is the X-particle mass density, $\rho_c \simeq 10^{-5} h^2\,\mathrm{GeV\,cm}^{-3}$ is the critical density, and h is the present value of Hubble's constant in units of $100\,\mathrm{km\,s}^{-1}\mathrm{Mpc}^{-1}$.

It could be interesting that these unknown X-particles constitute a fraction of the cold dark matter (CDM). In this case, they could be concentrated in galactic haloes and should not be uniformly distributed along the whole universe, as assumed in (1). Considering just the contribution of our galactic halo the correct equation to describe the flux of UHECR's is:

$$J_\gamma^h = \frac{1}{4\pi}\, R^h\, \dot{n}_X^h \,\frac{dN_\gamma}{dE_\gamma}\,, \tag{4}$$

where R^h is the radius of the galactic halo and $\dot{n}_X^h$ is the decay rate of the X-particles clustered in the halo.

The flux above can be written in terms of J_γ, given in (1), so that $J_\gamma^h = f J_\gamma$ and:

$$\begin{aligned} f &= \frac{J_\gamma^h}{J_\gamma} = \frac{n_X^h R^h}{n_X l(E_\gamma)} = \\ &= 1.5 \times 10^3 \left(\frac{0.2}{\Omega_{CDM} h^2}\right) \left(\frac{R^h}{100\,\mathrm{Kpc}}\right) \left(\frac{10\,\mathrm{Mpc}}{l(E_\gamma)}\right) \left(\frac{\rho_{CDM}^h}{0.3\ \mathrm{GeV\,cm}^{-3}}\right) \end{aligned}$$

where ρ_{CDM}^h is the cold dark matter energy density in the halo. We recall that if X-particles are a fraction of CDM, it can be written as $\rho_X^h = \varepsilon \rho_{CDM}^h$. The fraction ε is the same everywhere in the universe, so that $\varepsilon = \Omega_X / \Omega_{CDM}$.

The halo concentration of X-particles implies a modification of equation (3):

$$\tau_X = 10^{22} f\, \Omega_X h^2 \left(\frac{10^{12}\,\mathrm{GeV}}{m_X}\right)^{1/2} \quad \text{years} , \tag{5}$$

Considering $m_X = 10^{12}\,\mathrm{GeV}$, for a minimum τ_X of 10^{10} years and a maximum $\Omega_X h^2$ of the order of 1, we obtain the following limits (for $f \approx 10^3$) (see also [20]):

$$\begin{array}{llll} \text{for } (\Omega_X h^2) \simeq 1 & \rightarrow & \tau_X \simeq 10^{25}\,\text{years}, \\ \text{for } \tau_X \simeq 10^{10}\,\text{years} & \rightarrow & (\Omega_X h^2) \simeq 10^{-15} & . \end{array} \tag{6}$$

Therefore, cosmologically interesting abundances of X-particles which at the same time provide a solution to the UHECR events require a very large life-time τ_X. These requirements are generally difficult to obtain in realistic theories, but examples do exist [22].

3 Production of X-particles in the reheating phase

In the inflationary scenario, following the exponential expansion of the universe, particles are created by the oscillation of inflaton field ϕ about its minimum. The coupling of the inflaton with other fields becomes important and allows the transference of its energy to other particles. In the perturbative reheating process [14], the inflaton decays mostly into relativistic particles (radiation) that reheat the universe. In this context, the superheavy particle X could be created by either radiation annihilation process (indirect production) or by direct inflaton decay $\phi \rightarrow X\bar{X}$ (direct production), if such a coupling is allowed. The study of the latter mechanism is the main focus of this work.

In order to study quantitatively X-particle production during reheating, we have to solve the coupled differential Boltzmann equations for the energy densities of X particles (ρ_X), radiation (ρ_R) and inflaton (ρ_ϕ) :

$$\dot{\rho_\phi} + 3H\rho_\phi + \Gamma_\phi = 0, \tag{7}$$

$$\dot{\rho_R} + 4H\rho_R - (1 - B_X)\Gamma_\phi\rho_\phi - \frac{\langle\sigma|v|\rangle}{m_X}[(\rho_X)^2 - (\rho_X^{eq})^2] = 0, \tag{8}$$

$$\dot{\rho_X} + 3H\rho_X - \frac{m_X}{m_\phi}B_X\Gamma_\phi\rho_\phi + \frac{\langle\sigma|v|\rangle}{m_X}[(\rho_X)^2 - (\rho_X^{eq})^2] = 0, \tag{9}$$

where:

$$H^2 = \frac{8\pi}{m_{pl}^2}(\rho_\phi + \rho_R + \rho_X). \tag{10}$$

In the above equations H is the expansion rate of the universe, B_X is the branching ratio for the $\phi \to X\bar{X}$ decay, ρ_X^{eq} is the equilibrium value for the X-particle energy density and $\langle\sigma|v|\rangle$ is the thermal average of the X annihilation cross section times the Møller flux factor. The third term in equation (9) has a factor m_X/m_ϕ that corrects a similar equation in [23]. According to [24], the annihilation cross section can be estimated as $\langle\sigma|v|\rangle \sim \alpha^2/T^2$ where $g = \sqrt{4\pi\alpha}$ is the gauge coupling strength and T is the characteristic temperature for the process. Γ_ϕ is the inflaton total width and is obtained as a function of the reheating temperature, T_{RH}, assuming instantaneous conversion of the inflaton energy density into radiation:

$$\Gamma_\phi = 1.93 \times 10^{-18} \left(\frac{T_{RH}}{\mathrm{GeV}}\right)^2 \mathrm{GeV}\ . \tag{11}$$

It is important to notice that the reheating temperature (T_{RH}) is not the highest temperature achieved by the universe during reheating. For example, in this paper we are using a simple chaotic inflation model where $V = m_\phi^2\phi^2/2$ and $m_\phi = 10^{13}\,\mathrm{GeV}$. Following [23] it can be shown that, even if $T_{RH} = 10^9$ GeV, the universe can achieve temperatures as high as 10^{12} GeV. In this case, for $g = 1$ we have $\langle\sigma|v|\rangle = 10^{-26}\,\mathrm{GeV}^{-2}$, which allows the process $\gamma\gamma \to X\bar{X}$.

It is convenient to work with co-moving and dimensionless variables and therefore we defined appropriate parameters [23] and solved the equations numerically for the scaled variable $X \equiv \rho_X {m_X}^{-1}a^3$, where $a(t)$ is the scale factor. In this case, the new independent variable is $x = am_\phi$.

In Figure 1, we illustrate the behavior of $X(x)$. The curves A, B and C show two plateaus associated with two mechanisms of X-particle production: the first one is the indirect production ($\gamma\gamma \to X\bar{X}$) and the second is the direct one ($\phi \to X\bar{X}$). Modifying B_X and keeping T_{RH} constant (B and C curves) only the second plateau changes, reflecting the dependence of the direct decay on B_X. On the other hand, when T_{RH} is much smaller than 10^9 GeV, there is not enough energy for the indirect process and hence, the first plateau tends to disappear.

4 Finding Ω_X

We can find the X-particle mass density Ω_X today using the present value ($x = x_0$) of the radiation abundance Ω_R ($\Omega_R h^2 = 4.3 \times 10^{-5}$):

$$\frac{\Omega_X h^2}{\Omega_R h^2} = \frac{\rho_X(x_0)}{\rho_R(x_0)} \tag{12}$$

In thermal equilibrium, $T \propto {g_*}^{-1/3} a^{-1}$ [24], and hence ρ_R can be written as:

$$\rho_R(x_0) = \rho_R(x_{RH}) \left(\frac{g_*(x_{RH})}{g_*(x)}\right)^{1/3} \left(\frac{x_{RH}}{x_0}\right)^4 \tag{13}$$

where g_* is the effective number of degrees of freedom (we used $g_*(x_{RH}) = 200$).

Assuming that X particles are created already decoupled, we can write that $\rho_X(x_0) = \rho_X(x_{RH})(x_{RH}/x_0)^3$, where:

$$\rho_X(x_{RH}) = X_F {x_{RH}}^{-3} m_\phi m_X. \tag{14}$$

The parameter X_F is the X value in the second plateau (Figure 1) and corresponds to $X(x_{RH})$. So, we get:

$$\begin{aligned} \Omega_X h^2 &= \Omega_R h^2 \frac{\rho_X(x_{RH})}{\rho_R(x_{RH})} \frac{T_{RH}}{T_0} \\ &= 1.5 \times 10^9 \left(\frac{T_{RH}}{\mathrm{GeV}}\right) \frac{X_F m_X m_\phi^3}{x_i^3 H_i^2 m_{pl}^2}, \end{aligned} \tag{15}$$

where m_{pl} is the Planck mass and $T_0 = 2.37 \times 10^{-13}\,\mathrm{GeV}$ is the present-epoch CMB temperature.

5 Numerical Results

We worked with acceptable reheating temperatures in the range of $10^{-2}\mathrm{GeV} \leq T_{RH} \geq 10^9\mathrm{GeV}$. The lower limit is imposed by nucleosyntesis and the upper one is chosen not to lead to overproduction of gravitinos [25]. The subscript i refers to the epoch before inflaton decay. For chaotic inflation models we have $H_i \approx m_\phi$. As initial condition for the differential equations we choose $x_i = 1$.

Solving the Boltzmann equations numerically for different B_X and T_{RH}, we obtain the respective X_F and consequently its associated $\Omega_X h^2$, as it is shown in the table 1.

B_X	$T_{RH} = 10^9$ GeV		$T_{RH} = 10^3$ GeV		$T_{RH} = 10^{-2}$ GeV	
	X_F	$\Omega_X h^2$	X_F	$\Omega_X h^2$	X_F	$\Omega_X h^2$
0	3.3×10^{-6}	0.38	0	0	0	0
1×10^{-15}	1.8×10^{-4}	20.97	1.78×10^{-4}	2.06×10^{-5}	1.78×10^{-4}	2.06×10^{-10}
1×10^{-11}	1.78	2.06×10^{5}	1.78	2.06×10^{-1}	1.78	2.06×10^{-6}
1×10^{-9}	1.78×10^{2}	2.06×10^{7}	1.78×10^{2}	2.06×10^{1}	1.78×10^{2}	2.06×10^{-4}
1×10^{-5}	1.78×10^{6}	2.06×10^{11}	1.78×10^{6}	2.06×10^{5}	1.78×10^{6}	2.06
1×10^{-3}	1.78×10^{8}	2.06×10^{13}	1.78×10^{8}	2.06×10^{7}	1.78×10^{8}	2.06×10^{2}

Table 1: Numerical results for the final abundance obtained by solving the Boltzmann equations, for $T_{RH} = 10^9, 10^3, 10^{-2}$ GeV and $B_X < 10^{-3}$.

For $B_X = 0$, the X particle production is not effective if the reheating temperature is lower than $T = 10^9$ GeV. From table 1 we also get the expressions below, related to the direct production process that prevails over the indirect one, for $B_X > 10^{-16}$:

$$X_F = 1.78 \times 10^{11} B_X, \tag{16}$$

$$\Omega_X h^2 \simeq 2.06 \times 10^7 \left(\frac{T_{RH}}{\mathrm{GeV}}\right) B_X. \tag{17}$$

An excellent analytical approximation to the numerical results can be obtained by requiring that $n_X = n_\phi B_X$, in which case we find:

$$X_F = \frac{3}{8\pi} \frac{m_{pl}^2}{m_\Phi^2} B_X \tag{18}$$

Substituting the numerical values the above equation reproduces (17) exactly.

The maximum efficiency of the direct decay process ($\phi \to X\bar{X}$) is obtained when T_{RH} is minimum. Recently, low temperature reheating models were explored in [26]. Taking for the minimum value of $T_{RH} \simeq 10^{-2}$ GeV and using the upper limit for X abundance ($\Omega_X h^2 \simeq 1$) we get the maximum value for the branching ratio of $B_X = 10^{-5}$.

More generally, we can find bounds on B_X by requiring that X-particles are sources of UHECR's, in which case the limits of (6) apply. These bounds are shown in figure 2 as a function of the reheating temperature for two limits on the abundance: $\Omega_X h^2 \leq 1$ ($\tau_X \simeq 10^{25}$ years) and $\Omega_X h^2 \geq 10^{-15}$ ($\tau_X \simeq 10^{10}$ years).

6 Conclusion

We have investigated the constraints on the properties of supermassive relic metastable particles demanding that their decay products are responsible for the observed UHECR flux. In particular, we found the relevant range for the branching ratio of inflaton decay into the X-particle as a function of the reheating temperature.

For very small branching ratio of the inflaton to the X-particle, $B_X \geq 10^{-16}$, the direct production ($\phi \to X\bar{X}$) dominates over the indirect thermal production even for $T_{RH} = 10^9$ GeV. For the smallest possible reheat temperature, $T_{RH} = 10^{-2}$ GeV, thermal production of X-particle does not occur and the direct mechanism with $B_X \leq 10^{-5}$ is required.

Further consequences of the top-down scenario are the dominance of photons and neutrinos as primaries of UHECR's [19] and an anisotropy of these events as a result of the large concentration of X-particles in the galactic center[27]. More recently, it was suggested that clumps of dark matter in the halo could explain the observed multiplets (12 doublets and 2 triplets) of UHECR's events [28]. A detailed analysis including several models for galactic haloes of our and other galaxies was performed in [29]. We look forward to new experimental results from current and future experiments to elucidate the composition and anisotropy of the UHECR events. In particular, the first site of the Auger Observatory in the southern hemisphere, being sensitive to the galactic center, will be important in testing the anisotropy resulting from the top-down scenario.

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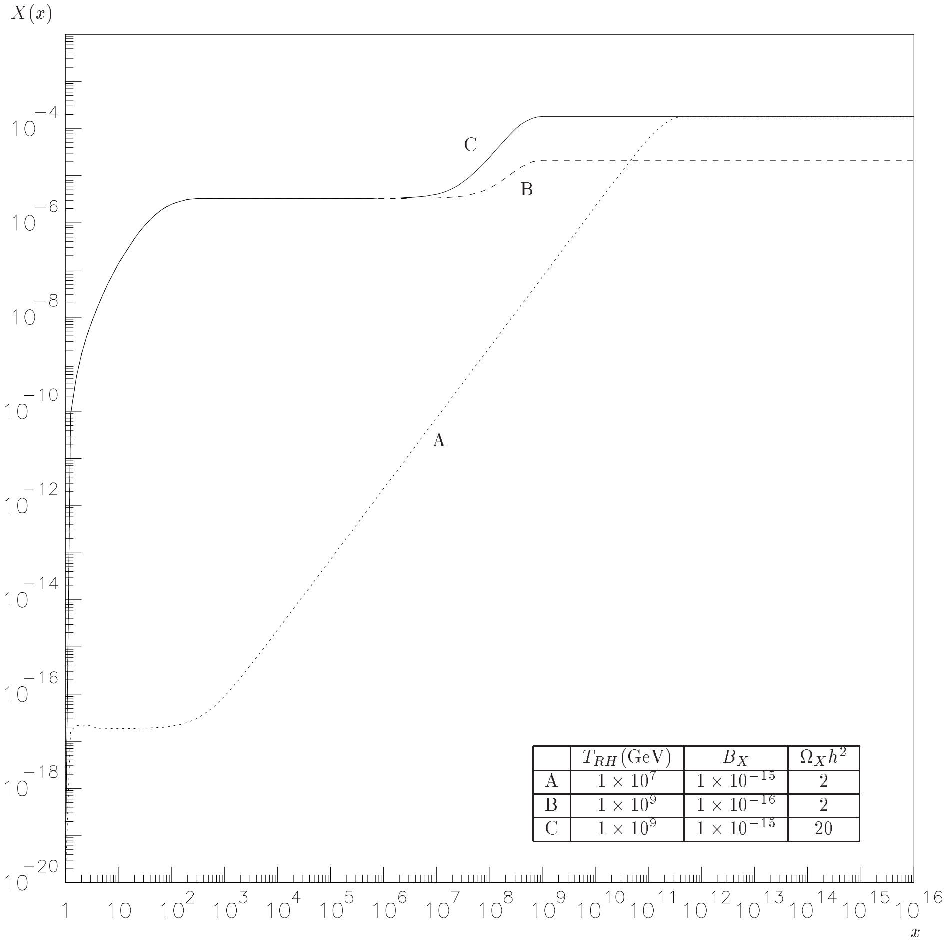

Figure 1: Evolution of X ($\equiv \rho_X m_X^{-1} a^3$) as a function of the modified scale factor, x. We used $m_\phi = 10^{13}\,\mathrm{GeV}$ and $m_X = 10^{12}\,\mathrm{GeV}$.

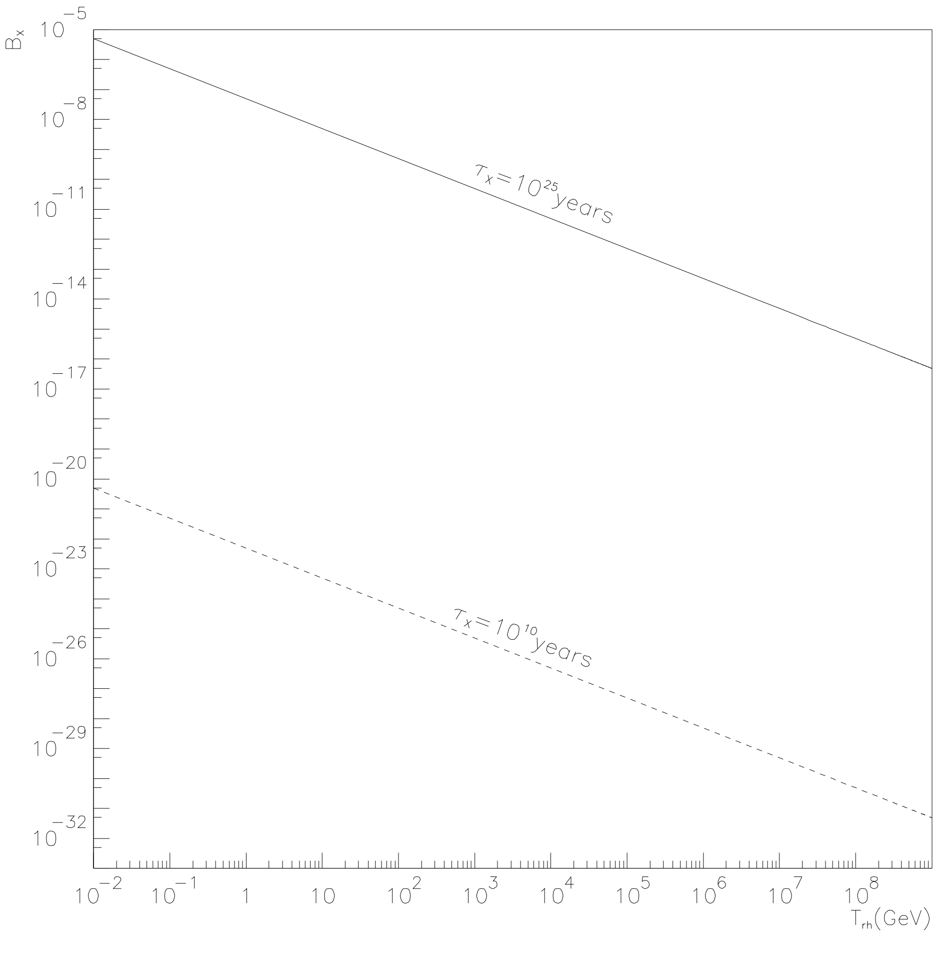

Figure 2: Branching ratio B_X of the inflaton into X-particles as a function of the reheating temperature T_{RH} for two limiting values of $\Omega_X h^2$.