1. Introduction

The motivation for a fourth generation neutrino comes from the Standard Model of Particel Physics (SM). In fact, there is nothing in the SM stating that there should be three generations of leptons...

FRW-universe... λ-CDM universe... more basic assumptions.

The implications of a fourth generation neutrino has already been studied...

The present limits on the mass of a fourth generation of neutrinos are...

For an excellent introduction to neutrino cosmology, see for example Dolgov & Zeldovich (1981).

Extra quark-lepton generations and precision measurements (isys:files:NeutrinoRefs:Q3), Maltoni et al. (2000).

neutrinos or even more weakly interacting particles such as wimps and gravitons from the very early universe would offer a much deeper "look back time", Silk & Stodolsky (2006).

Astrophysical and Cosmological Constraints on Neutrino Masses, Kainulainen & Olive (2003).

Ultra High Energy Neutrino-Relic Neutrino Interactions In Dark Halos to Solve Infrared-Tev And GZK Cut-Off, Fargion et al. (2001b).

(*Shadows of Relic Neutrino Masses and Spectra on Highest Energy GZK Cosmic,* Fargion & et al. (2001).)

Bounds on very heavy relic neutrinos by their annihilation in the Galactic halo, Fargion et al. (1995).

2. Heavy Neutrinos as Dark Matter

Is Dark Matter Heavy Because of Electroweak Symmetry Breaking? Revisiting Heavy Neutrinos, Schuster & Toro (2005).

Limits from primordial nucleosynthesis on the properties of massive neutral leptons, Dicus et al. (1978).

Implications of a solar-system population of massive 4th generation neutrinos for underground searches of monochromatic neutrino-annihilation signals, Belotsky et al. (2002).

3. Photon Background from $N\bar{N}$ Annihilation

Separate section for production and subsequent N density?

3.1. Introduction

Context + Short summary of what we wish to accomplish and the way there

If Heavy Neutrinos ($M_N \gtrsim 50$ GeV) exist, they were created in the early universe. They were in thermal equilibrium in the early stages of the hot big bang but froze out relatively early. After freeze out, the annihilation of $N\bar{N}$ continued at an ever decreasing rate until today. Since the photons produced before the decoupling of photons are lost in the CMB, only the subsequent annihilation will contribute to the photon background as measured on Earth.

The intensity of the photons from $N\bar{N}$-annihilation is affected by the number density of heavy neutrinos, n_N and the mean density is decreasing as a^{-3}, where a is the expansion factor of the universe. However, in structures, such as galaxies, the mean density will not change so dramatically and since the number of such structures are growing with time, this will compensate for the lower mean density. Note that the photons are also redshifted with a factor a due to their passage thorugh spacetime. This also means that the closer annihilations will give photons with higher energy then the farther ones.

The integrated photons from annihilations of $N\bar{N}$ from decoupling until today give a characteristic spectrum that might be measureable, for example with EGRET *ref*.

3.2. Theory

Details of Intro Freeze-out = Decoupling Index d or N,d? $c = \hbar = k_B = 1$ $k = k_B$

3.2.1. Annihilation

Until the decoupling of the heavy neutrinos from the radiation, they are in thermal equilibirum. At the moment of decoupling, the reaction rate of $N\bar{N}$ is

$$\left\langle n_{N,d}^2 v\sigma \right\rangle_d = \frac{8}{3\pi} G_F^2 m_N^8 I(x_d), \tag{1}$$

Dicus et al. (1978), where m_N is the mass of the heavy neutrino, $G_F = 1.166 \times 10^{-5}$ GeV^{-2} is the Fermi constant, n_N is the concentration of heavy neutrinos, v is the speed of the heavy neutrinos and σ is the $N\bar{N}$ cross section and the index d is for decoupling. The function $I(x)$ is given by

$$I(x) = 2(I_{2,2}(x))^2 + \frac{2}{3}(I_{0,4}(x)) + 3(I_{1,2}(x))^2 + (I_{0,2}(x))^2, \tag{2}$$

where $x = m_N/k_B T$ (k_B is Boltzmann's constant) and

$$I_{m,n} = \int_0^\infty \frac{(\cosh y)^m (\sinh y)^n}{1 + \exp(x \cosh y)} dy, \tag{3}$$

where $E/k_B T = x \cosh y$, E is the neutrino energy, and T is the temperature.

From Dicus et al. (1978) we also obtain the interaction time

$$t_i = \frac{\langle n_N \rangle}{\left\langle n_N^2 v\sigma \right\rangle} \approx 3.3 \cdot 10^{19} T^{-2}, \tag{4}$$

and the mean concentration

$$\langle n_N \rangle = 8\pi m_N^3 I_{1,2}(x). \tag{5}$$

These equations allow us to calculate the decoupling temperature and concentration of the heavy neutrinos as a function of their mass. The results are presented in figures 1 and 2 and can be approximated by

$$T_d \approx 5.0 \cdot 10^{12} + 2.7 \cdot 10^{11} \cdot M_N \tag{6}$$

and

$$n_d \approx 4.0 \cdot 10^{36} + 36 \cdot M_N^{-0.16}, \tag{7}$$

in the mass range $50 \lesssim M_N \lesssim 500$.

We start by calculating the total energy density pent up in the heavy neutrinos, as an upper bound. The concentration of heavy neutrinos today would be $n_d/(z_d+1)^3 \sim 2 \cdot 10^{36}/(4 \cdot 10^{13}/T_{CMB})^3 \sim 10^{-3}$, which means that their total density would be $\rho_N \sim m_N c^2 \cdot 10^{-3} \sim 10^{-28}$ kg/m^3 which is in the order of magnitude of 1% of ρ_c, see figure 3.

$$\Omega_N = \frac{m_N}{\rho_c}\frac{n_d}{(\frac{T_d}{T_{CMB}})^3} = \frac{T_{CMB}^3 m_N}{\rho_c}\frac{n_d}{\left(\frac{3.3 \cdot 10^{19}}{t_d}\right)^{3/2}}$$

$$= \frac{T_{CMB}^3 m_N}{\rho_c (3.3 \cdot 10^{19})^{3/2}} n_d t_d^{3/2} = \frac{T_{CMB}^3 m_N}{\rho_c (3.3 \cdot 10^{19})^{3/2}} \frac{n_d^{5/2}}{\left\langle n_N^2 v\sigma \right\rangle^{3/2}}$$

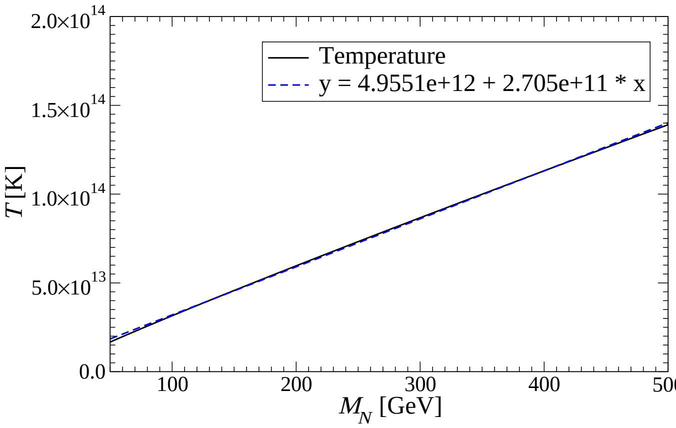

Fig. 1. The decoupling temperature (in Kelvin) of heavy neutrions as a function of their mass (in GeV).

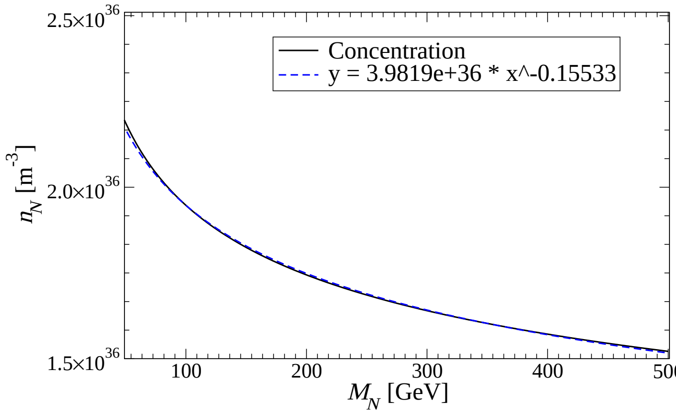

Fig. 2. The decoupling concentration (in m^{-3}) of heavy neutrions as a function of their mass (in GeV).

$$= \frac{T_{CMB}^3 m_N}{\rho_c (3.3\cdot 10^{19})^{3/2}} \frac{[8\pi m_N^3 I_{1,2}(x_d)]^{5/2}}{[\frac{8}{3\pi} G_F^2 m_N^8 I(x_d)]^{3/2}}$$

$$= \frac{T_{CMB}^3 8\pi^4}{\rho_c (1.1\cdot 10^{19})^{3/2} G_F^3} \frac{I_{1,2}(x_d)^{5/2}}{I(x_d)^{3/2}} m_N^{-7/2} \quad (8)$$

can in the region $50 \lesssim M_N \lesssim 500$ be well approximated by:

$$\Omega_N = 165.15 * M_N^{-1.9202} \quad (9)$$

3.2.2. Evolution

First we estimate the relative number of neutrinos that are annihilated during the course of history.

According to Dolgov & Zeldovich (1981), the relative concentration of heavy neutrinos to photons, $r = n_N/n_\gamma$, changes as

$$\dot{r}_N = -k(t)(r_N^2 - r_{Neq}^2), \quad (10)$$

where the reaction constant, $k(t)$, is

$$k(t) = \sigma(t)v(t)n_\gamma(t) \quad (11)$$

and

$$r_{Neq} \approx \begin{cases} 1 & \text{if } \theta = T/m_N > 1 \\ \frac{1}{4} g_s \theta^{-3/2} e^{-1/\theta} & \text{if } \theta < 1 \end{cases}$$

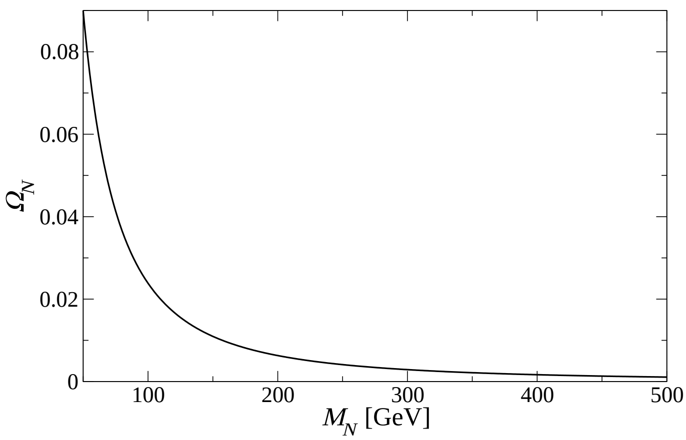

Fig. 3. The relative neutrino density of heavy neutrions as a function of their mass (in GeV).

representes the relative equilibrium concentration of heavy neutrinos. As the temperature decreases from equilibrium, the production term r_{Neq} rapidly drops to zero (due to the exponential $e^{-1/\theta}$). This means that we can safely neglect r_{Neq} and thus the relative reaction rate can be written as

$$\dot{r} = -k(t)\cdot r^2, \quad (12)$$

which can be solved for $r(t)$:

$$r^{-1}(t) = r_f^{-1} + \int_{t_f}^{t} k(t')dt', \quad (13)$$

where t_f and r_f are the time and relative concentration at freeze-out of the heavy neutrinos.

We know from (Dolgov 2002, Eq. 31,37) that $n_\gamma(T) \approx 0.2404\cdot T^3 = 2.0021 \cdot 10^7 T^3$ (in SI-units) and during the radiation dominated era, $z \gtrsim 10^4$, $\frac{dt}{dT} = -2\cdot 2.42\cdot T^{-3}/\sqrt{g_*}(\mathrm{MeV})^2\mathrm{s} = 6.5183\cdot 10^{20} T^{-3}/\sqrt{g_*} \approx 10^{20} T^{-3}$ (in SI-units, K^2s) since $g_* = 106.75$ ($\approx$ 200 for SUSY) for high temperatures in the Standard Model. Since the heavy neutrinos are so heavy, the cross section is almost completely temperature (and thus time) independant. Furthermore, there will be very little friction and thus the mean velocities of the neutrinos can also be considered to be constant with respect to time.

This means that we can calculate

$$r^{-1}(T) \approx r_f^{-1} + \sigma_f v_f 10^{27} \int_T^{T_f} dT' \lesssim r_f^{-1} + \sigma_f v_f 10^{27} T_f \approx r_f^{-1} \quad (14)$$

since $r_f^{-1} \sim n_{\gamma,f}/n_{N,f} \sim 2\cdot 10^7 \cdot (4\cdot 10^{13})^3/2\cdot 10^{36} \sim 10^{12}$ while $\sigma_f v_f 10^{27} T_f \sim 10^{-38+7+27+13} \sim 10^9$. This means that there will be no significant loss of heavy neutrinos due to annihilation.

Supposing that the neutrinos are homogeneously distributed in the universe the comoving number density of photons can be calculated thorugh:

Supposing that the decrease in number density due to annihilation is small...

3.3. xyz

The evolution calculations are most easily done in terms of the CMB temperature $T_{CMB} \propto (1+z)^{-1}$ rather then time. The contribution from the $N\bar{N}$ annihilation to the measured intensity today would be:

$$dI = \frac{f\cdot c}{4\pi} 2 m_N c^2 \left\langle n_{N,d}^2 v\sigma \right\rangle_d T_d^{-6} \cdot x(3K)^4 \int_{T=1000T_0}^{T=T_0} T^{-1/2} dT \quad (15)$$

(where $T_0 = 2.73$ is the temperature of the CMB today) which gives

$$\frac{dI}{dT} = 2.4 \cdot 10^{-21} \times T^{-1/2} \quad (16)$$

which means that the total contribution $1.3 \cdot 10^{-19}$ Jm^{-2}sr^{-1}s^{-1}. This is not very much, but since each decay give rise to $\sim$ 10 GeV photons, which is redshifted to $\sim$ 10 MeV photon it amounts to $10^{-7} \sim 100$ MeV photons per square meter and second.

EGRET has measured this energy range an according to Strong et al. (2004), there are $2.22 \times 10^{-3} (s \cdot sr \cdot MeV \cdot m^2)^{-1}$ photons in the range 70-100 MeV, which is far more than our 10^{-7} from heavy neutrinos.

During galaxy formation and matter accretion ($z \sim 15 - 0$), the heavy neutrinos will become more densely packed and the annihilation rate will increase, since it is proportional to the square of ρ_N. The mean density of a halo is $\lesssim 100$ times higher than ρ_c, which gives an increase of $\sim 10^3$ from within halos.

Depeletion within galaxies

130, 100, 70, 50 GeV.

4. EGRET data

EGRET Excess of Diffuse Galactic Gamma Rays as a Trace of the Dark Matter Halo de Boer et al. (2006b).

Is the Dark Matter interpretation of the EGRET gamma ray excess compatible with antiproton measurements? de Boer et al. (2006a).

Clumpiness of Dark Matter and Positron Annihilation Signal: Computing the odds of the Galactic Lottery, Lavalle et al. (2006).

Diffuse Gamma Rays from the Galactic Plane: Probing the "GeV Excess" and Identifying the "TeV Excess" Prodanović et al. (2007).

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Clustering, Anisotropy, Spectra of Ultra High Energy Cosmic Ray: Finger-prints of Relic Neutrinos Masses in Dark Halos, Fargion et al. (2001a).

On the Heavy Relic Neutrino - Galactic Gamma Halo Connection, Fargion et al. (1999).

Possible Effects of the Existence of the 4th Generation Neutrino, Golubkov et al. (1999).

Galactic Gamma Halo by Heavy Neutrino annihilations, Fargion (2000).

Expected cosmic-ray fluxes from the annihilation of heavy stable neutrinos in the galactic halo, Golubkov & Konoplich (1998).

5. More Implications of Heavy Stable Neutrinos

Possible detection in soft recoil... Barbeau et al. (2007)

Stable matter of 4th generation: hidden in the Universe and close to detection? Belotsky et al. (2006)

LEP...

Possibility of searching for heavy neutrinos at accelerator, Fargion et al. (1996).

LHC...

Neutralinos...

DAMA...

May Heavy neutrinos solve underground and cosmic ray puzzles? Belotsky et al. (2004).

Signature of relic heavy stable neutrinos in underground experiments, Fargion et al. (1998).

(*Z-lineshape versus 4th generation masses,* Bulanov et al. (2003).)

Higgs... *Invisible Higgs Boson Decay into Massive Neutrinos of 4th Generation,* Belotsky et al. (2003).

6. Conclusions

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