A theory of extra radiation

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Nakayama, FT and Yanagida, 1010.5693

Introduction

- Measuring the cosmic expansion has been one of the central issues in cosmology.

$$3H^2 M_P^2 = \rho$$

- The observation of Type Ia SNe revealed the presence of dark energy.

- It is also possible infer the particle content of the Universe in the past by measuring the helium abundance, CMB and LSS.

^{4}He abundance

- n-p transformation decouples when

$$\Gamma_{n\leftrightarrow p} = H$$

$$n \quad \leftrightarrow p + e^- + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

⇒ n/p ratio fixes (except for neutron free decay) at T ~1 MeV.

$$\left(\frac{n}{p}\right)_{\rm EQ} = \exp\left(-\frac{Q}{T_*}\right)$$

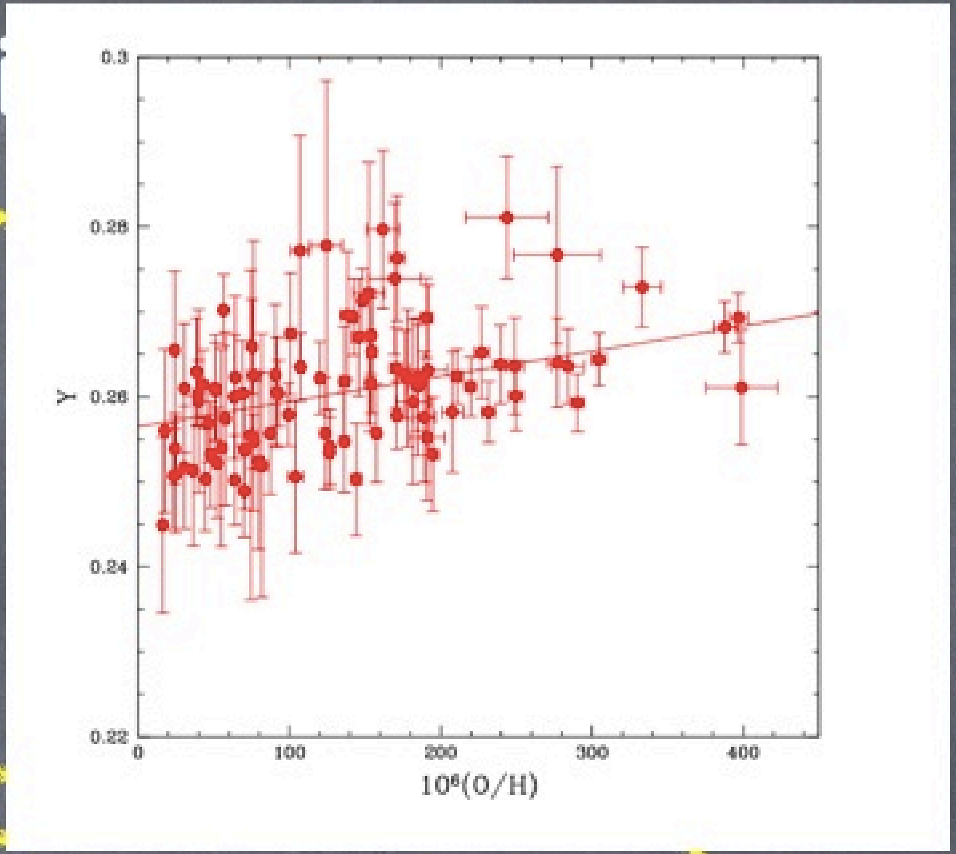
$$Q = m_n - m_p = 1.293\mathrm{MeV}$$

⇒ Almost all neutrons are absorbed in ^{4}He.

If there is extra radiation,

H ↗ Y_p ↗

Two recent results on the heli



Izotov and Thuan (1001.4440)

$$Y_p = 0.2565 \pm 0.0010\,(\mathrm{stat})$$

$$N_{\mathrm{eff}} = 3.68^{+0.80}_{-0.70} \quad (2\sigma)$$

Aver, Olive and Skillman (1001.5218)

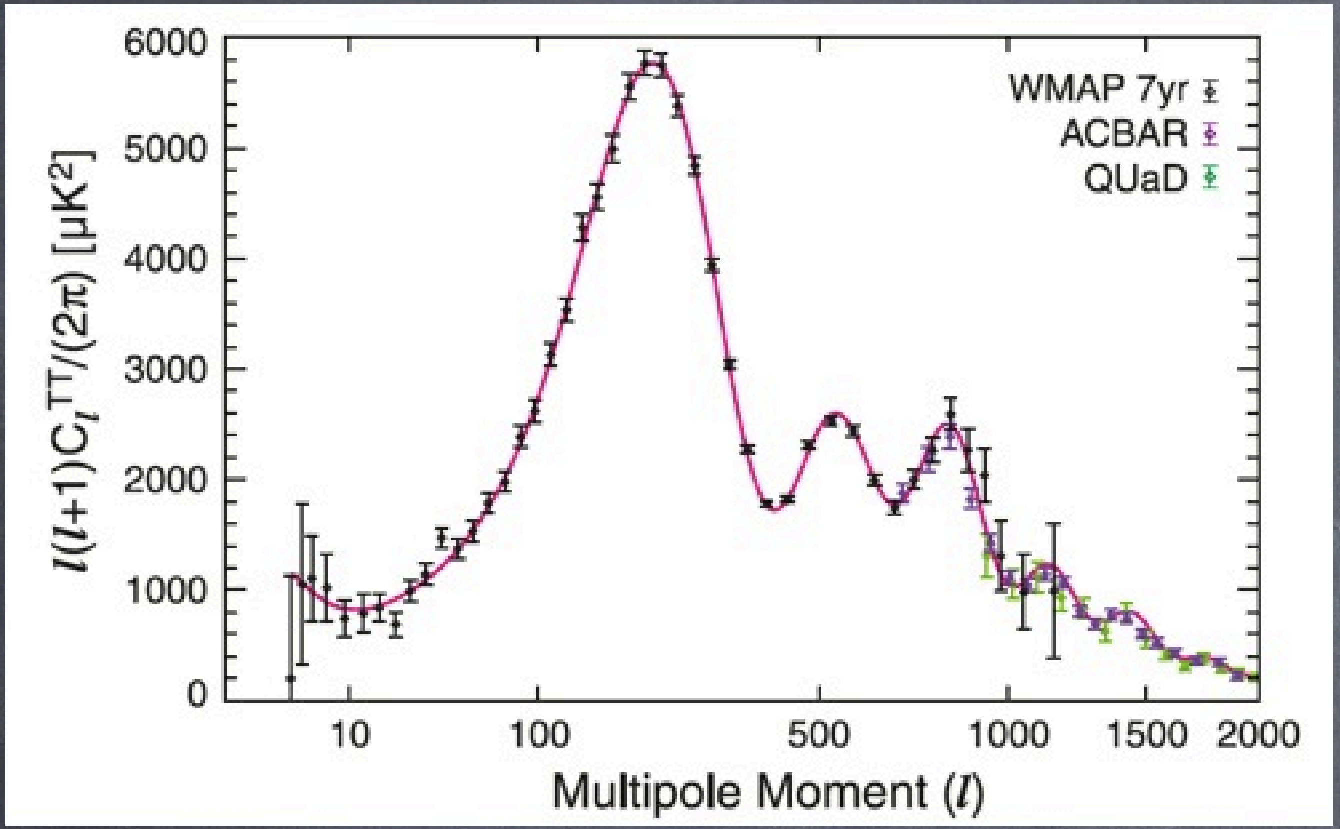
$$Y_p = 0.2561 \pm 0.0108 \quad (68\%\mathrm{CL})$$

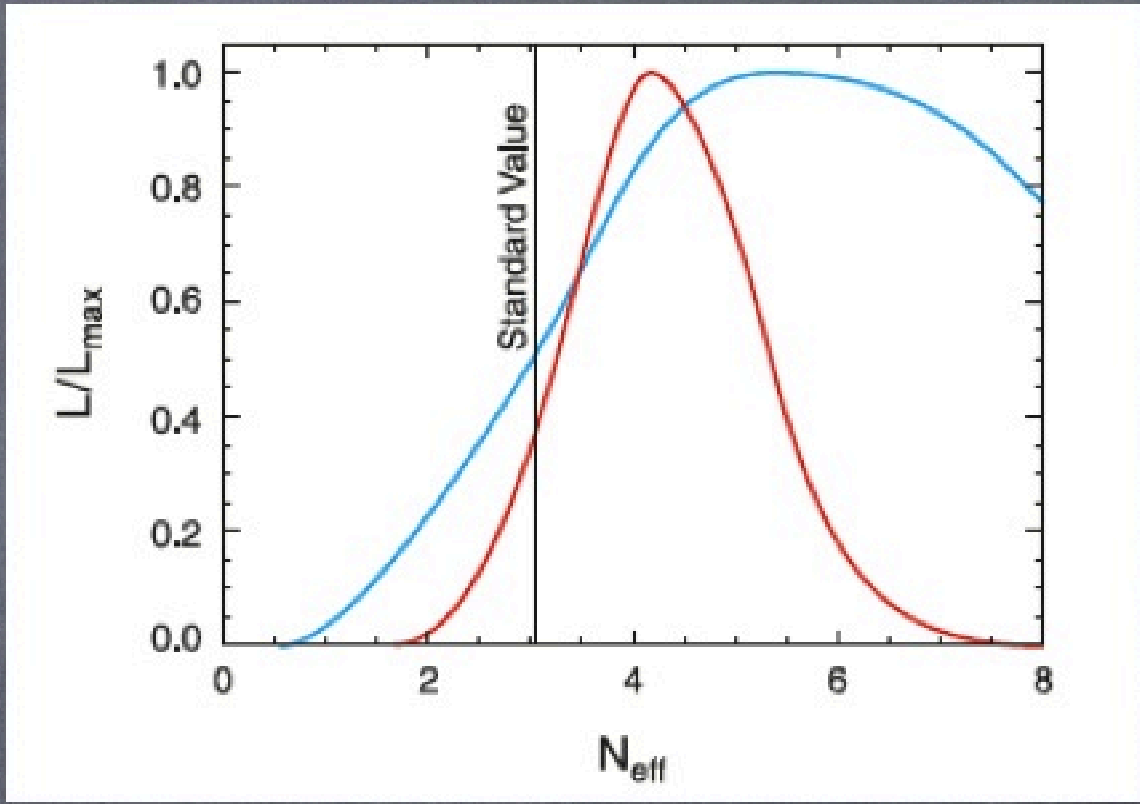
For comparison, the WMAP value is

$$Y_p = 0.2486 \pm 0.0002 \quad (68\%\mathrm{CL})$$

$$N_{\mathrm{eff}} = 3.046$$

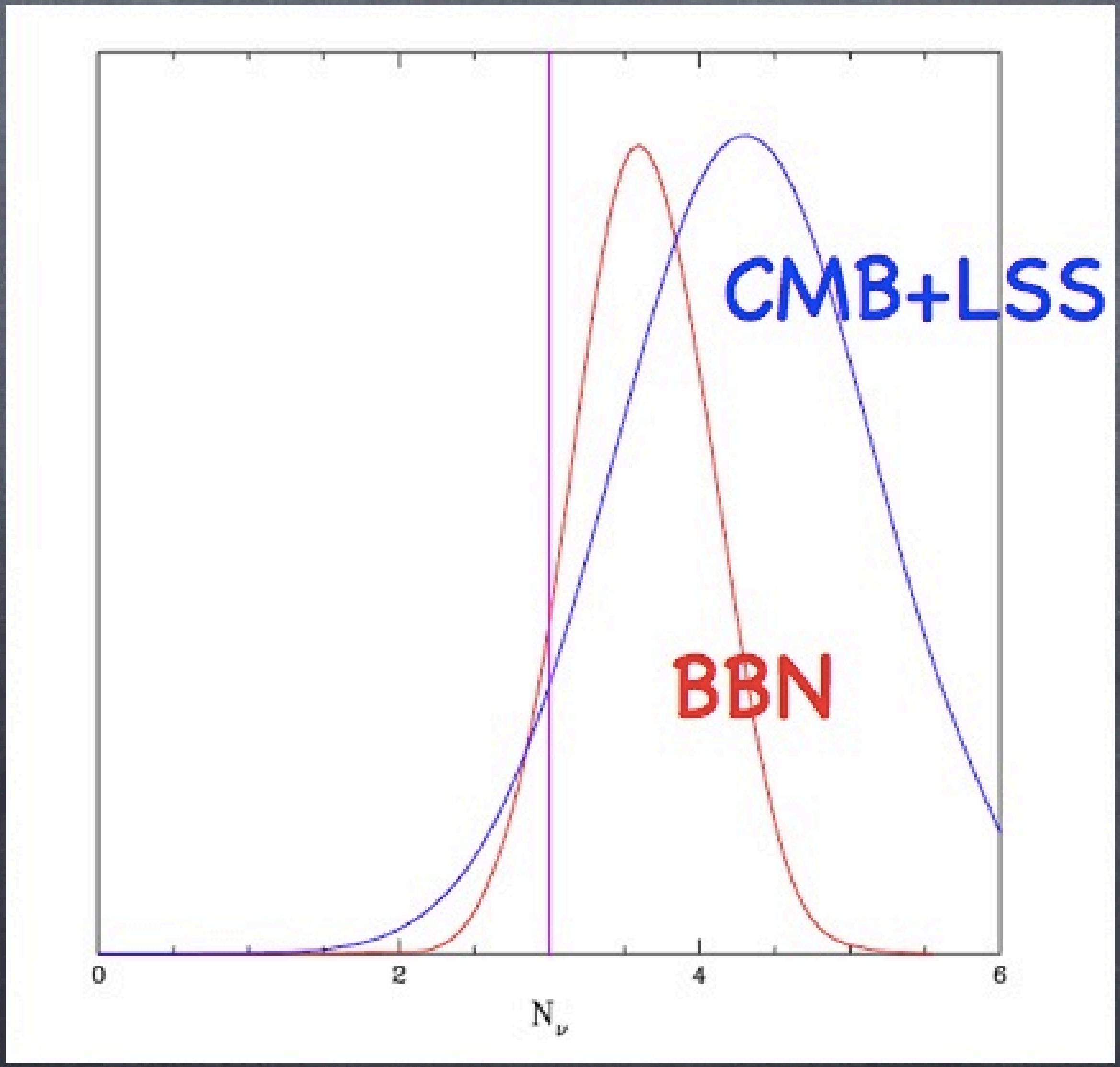
CMB+LSS





- WMAP 7-yr + BAO + H_0 : $N_{\rm eff} = 4.34^{+0.86}_{-0.88}$ (68%CL) (Komatsu et al, 2010)
- +ACT : $N_{\rm eff} = 4.56 \pm 0.75$ (68%CL) (Dunkley et al, 2010)

- It is intriguing that both the helium abundance and CMB/LSS mildly prefer the presence of extra radiation, $\Delta N_{\rm eff} \sim 1$.
- Here we would like to consider its implications for particle physics, assuming that there is indeed extra radiation both at the BBN and CMB epochs.



(Steigman,1008.4765)

Assumptions

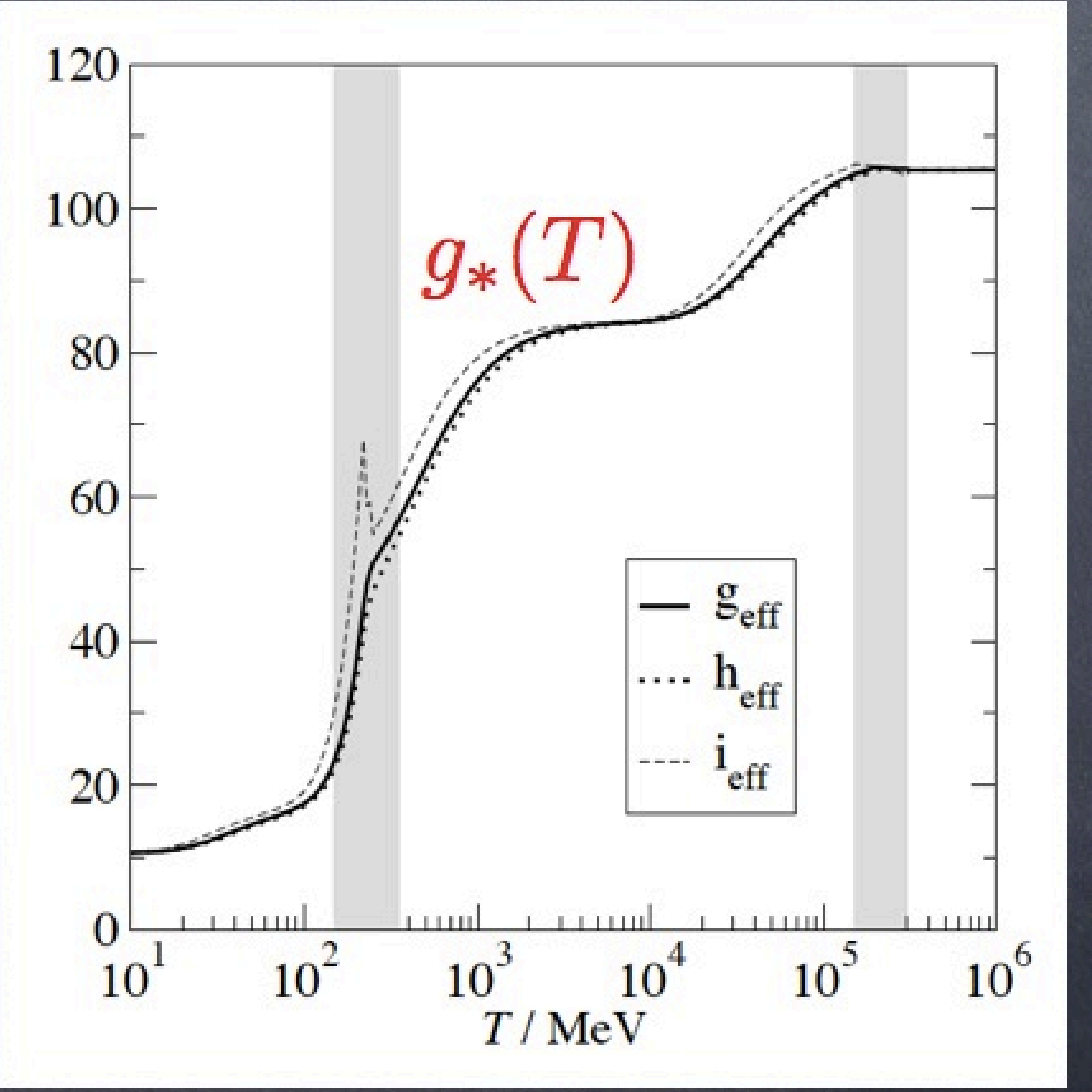
- We assume that the extra radiation is ``dark radiation" made of unknown light and relativistic particles, X_i.
- We also assume that the X_i was once in thermal equilibrium in the early Universe, since some (mild) tuning is necessary to obtain right abundance, otherwise (e.g. non-thermal production).

Light degrees of freedom g_*

$$\Delta N_{\rm eff} = \frac{\rho_X}{\rho_\nu} \sim \left(\frac{T_X}{T_\nu}\right)^4 \sim \left(\frac{g_{*\nu}}{g_{*X}}\right)^{4/3},$$

Broadly speaking, there are 2 cases.

- (5-10) particles decoupled (much) before the QCD phase transition.
- one or a few particles that decouple after the QCD phase transition before BBN.



(Laine, Schroeder, `06)

Then the question is why they are so light?

$$m < \mathcal{O}(0.1)\,\mathrm{eV}$$

It is natural to expect that the bare mass is forbidden by symmetry.

1) Gauge symmetry

2) Shift symmetry

3) Chiral symmetry

We consider these cases in turn.

* Here I do not consider the sterile neutrino which mixes with the active neutrinos.

See Melchiorri et al, `08
Hamman et al, `10.

Case 1: Gauge boson

- U(1) hidden photon

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\chi}{2}F_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 B_\mu B^\mu,$$

Redefining

$$A'_\mu = (1-\chi^2)^{1/2}A_\mu$$

$$B'_\mu = B_\mu - \chi A_\mu$$

they become canonically normalized, but with a mixing in the mass term:

$$\mathcal{M}^2 = m_{\gamma'}^2 \begin{pmatrix} \chi^2/(1-\chi^2) & \chi/\sqrt{1-\chi^2} \\ \chi/\sqrt{1-\chi^2} & 1 \end{pmatrix}$$

The production rate of the hidden photon is

$$\Gamma(\gamma e \to \gamma' e) \simeq \begin{cases} \chi^2 \left(\dfrac{m_{\gamma'}}{m_\gamma}\right)^4 \Gamma_C & \text{for } \; m_{\gamma'} \ll m_\gamma \\ \chi^2 \Gamma_C & \text{for } \; m_{\gamma'} \gg m_\gamma \end{cases}$$

where $\Gamma_C \sim \alpha_e^2 T$ and $m_{\gamma'} \lesssim 0.1\,\mathrm{eV}$

We can easily show that the hidden photon is never thermalized before the BBN.

Cf. It is possible to generate $\Delta N_{\rm eff} \sim 1$ by using resonance for $\chi \sim 10^{-5}$ and $m_{\gamma'} \sim 1\,\mathrm{meV}$ at the CMB epoch.

(Jaeckel, Redondo, Ringwald, 0804.4157)

Case 2: Nambu-Goldstone boson

Consider an axion-like particle coupled to the photon:

$$\mathcal{L} = \frac{\alpha_e}{8\pi}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}.$$

Production rate: $\Gamma(\gamma e \leftrightarrow a e) \sim \langle \sigma v \rangle n_e \sim \frac{\alpha_e^3 T^3}{f_a^2},$

The freeze-out temperature is given by

$$T_f \sim 10\,\mathrm{MeV}\left(\frac{f_a}{10^5\mathrm{GeV}}\right)^2$$

However, the cooling argument using the HB stars gives

$$f_a \gtrsim 10^8\,\mathrm{GeV}$$

Next consider an axion interacting predominantly with the hadrons.

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}F^a_{\mu\nu}\tilde{F}^{\mu\nu a} + \frac{a}{f_a} i m_q \bar{q}\gamma_5 q.$$

Then, the freeze-out temperature is higher than 10 MeV, if

$$f_a \lesssim 10^8\,\mathrm{GeV}$$

The hadronic axion window is

$$3\times 10^5\,\mathrm{GeV} \lesssim f_a \lesssim 2\times 10^6\,\mathrm{GeV}$$

$$3\,\mathrm{eV} \lesssim m_a \lesssim 20\,\mathrm{eV}$$ **Axion HDM**

However, the window was closed by the recent analysis.

Hannestad, Mirizzi, Raffelt, hep-ph/0504059
Hannestad, Mirizzi, Raffelt, Wong, 1004.0695

Case 3: Chiral fermion

Consider a chiral fermion ψ charged under a new U(1) gauge symmetry, which forbids the mass.

$$\mathcal{L}_{\rm int} = ig_{A\psi\psi} A^{\mu}_{H} \bar{\psi}\gamma_\mu \psi + ig_{A\psi\psi} A^{\mu}_{H} \bar{f}\gamma_\mu f$$

f : SM fermions

Assuming that the U(1) is spontaneously broken, we have

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{\psi}\gamma_\mu \psi),$$

in the low energy.

$$\Lambda^2 = m_A^2 g_{A\psi\psi}^{-1} g_{Aff}^{-1}$$

Using the production rate,

$$\Gamma(e^+e^- \leftrightarrow \psi\psi) \sim \langle\sigma v\rangle n_e \sim \frac{T^5}{\Lambda^4},$$

the freeze-out temperature is given by

$$T_f \sim 100\,\mathrm{MeV}\left(\frac{\Lambda}{6\,\mathrm{TeV}}\right)^{4/3}$$

The star cooling const. can be evaded because the emission rate is suppressed by

$$\frac{G_F^{-2}}{\Lambda^4} \sim 10^{-6}\left(\frac{\Lambda}{3\,\mathrm{TeV}}\right)^{-4}$$

compared to the neutrino emission.

The SN limit reads $\quad \dfrac{G_F^{-2}}{\Lambda^4} \lesssim 10^{-5}$

Implications

A chiral fermion coupled to the SM fermions with interactions suppressed by TeV scale is a viable candidate for extra rad.

- We need a new gauge symmetry broken at TeV scale.
- A new heavy gauge boson may be produced at the LHC. The strategy is same as the Z′ boson search.
  - ✓ With 10 fb^{-1}, 3TeV Z′ can be discovered at LHC.

Example of a new U(1)

One candidate is $U(1)_{B-L}$, which naturally appears in the SO(10) GUT. However it should be broken at a high scale to explain the nu mass thru the seesaw mechanism.

We therefore consider

$$SU(5) \times U(1)_\psi \times U(1)_\chi$$

inspired by the E_6-GUT.

$$E_6 \to SO(10) \times U(1)_\psi$$

$$SO(10) \to SU(5) \times U(1)_\chi$$

Matter content

$$\mathbf{27 = 16_1 + 10_{-2} + 1_4}$$

$$\mathbf{16 = 10 + \bar{5} + 1}$$

$$\mathbf{10 = 5 + \bar{5}}$$

	$SO(10)\times U(1)_\psi$	$SU(5)\times U(1)_\psi \times U(1)_\chi$	
Fermion	$\Psi_{\mathbf{16}}(1)$	$\psi_{\mathbf{10}}^{(\mathrm{SM})}(1,1)$ $\psi_{\bar{\mathbf{5}}}^{(\mathrm{SM})}(1,-3)$ $\psi_{\mathbf{1}}^{(\mathrm{SM})}(1,5)=\nu_{\mathrm{R}}$	
Fermion	$\Psi_{\mathbf{10}}(-2)$	$\psi_{\mathbf{5}}^{(\mathbf{10})}(-2,-2)$ $\psi_{\bar{\mathbf{5}}}^{(\mathbf{10})}(-2,2)$	
Fermion	$\Psi_{\mathbf{1}}(4)$	$\psi_{\mathbf{1}}(4,0)$	Dark rad.
Boson	$\Phi_{\mathbf{16}}(1)$	$\phi_{\mathbf{10}}^{(\mathbf{16})}(1,1)$ $\phi_{\bar{\mathbf{5}}}^{(\mathbf{16})}(1,-3)$ $\phi_{\mathbf{1}}^{(\mathbf{16})}(1,5)$	
Boson	$\Phi_{\mathbf{10}}(-2)$	$\phi_{\mathbf{5}}(-2,-2)\supset$ SM Higgs $\phi_{\bar{\mathbf{5}}}(-2,2)\supset$ SM Higgs	
Boson	$\Phi_{\mathbf{1}}(4)$	$\phi_{\mathbf{1}}(4,0)=\phi_X$	Breaks U(1)

The right-handed neutrino acquires a mass from

$$\Phi_{\overline{\mathbf{126}}}\Psi_{\mathbf{16}}\Psi_{\mathbf{16}}$$

if the singlet component of $\Phi_{\overline{\mathbf{126}}}$ develops a vev.

The vev leaves the following U(1) unbroken:

$$U(1)_X \equiv 5U(1)_\psi - U(1)_\chi$$

The ψ_1 remains massless if $U(1)_X$ is unbroken.

$SO(10)\times U(1)_\psi$	$SU(5)\times U(1)_\psi\times U(1)_\chi$
$\Psi_{\mathbf{16}}(1)$	$\psi_{\mathbf{10}}^{(\mathrm{SM})}(1,1)$ $\psi_{\bar{\mathbf{5}}}^{(\mathrm{SM})}(1,-3)$ $\psi_{\mathbf{1}}^{(\mathrm{SM})}(1,5)=\nu_{\mathrm{R}}$
$\Psi_{\mathbf{10}}(-2)$	$\psi_{\mathbf{5}}^{(10)}(-2,-2)$ $\psi_{\bar{\mathbf{5}}}^{(10)}(-2,2)$
$\Psi_{\mathbf{1}}(4)$	$\psi_{\mathbf{1}}(4,0)$

Assuming that $U(1)_X$ is broken by $\langle \phi_X \rangle = \xi$,
ψ_1 acquires a mass from

$$\mathcal{L} = \frac{\phi_X^* \phi_X^* \psi_{\mathbf{1}} \psi_{\mathbf{1}}}{M} + \mathrm{h.c.},$$

The mass m is given by

$$m \sim \frac{\xi^2}{M} \sim 10^{-3}\,\mathrm{eV},$$

for $\xi = 1\,\mathrm{TeV}$ and $M = M_P$

Comments

If there is ψ_1 in each generation, we would have $\Delta N_{\rm eff} = 3$. $\Delta N_{\rm eff} = 1$ can be achieved by slightly increasing ξ.

The colored fermion $\Psi_{\mathbf{10}}^{\rm (color)}$ is long-lived. Cosmological problem can be avoided if

1. Low reheating
2. Mix with SM quarks via $Z_{2(B-L)}$ breaking
3. SUSY

Conclusions

- If there is indeed extra radiation $\Delta N_{\rm eff} \sim 1$ as suggested by the recent observation, a chiral fermion is a plausible candidate.
- Interestingly the U(1) gauge boson should be at TeV scale, and may be within the reach of collider experiments such as the LHC (Z-prime search)
- One example for such a light chiral fermion is a SU(5) singlet fermion Ψ_1 in the **27** rep. of E_6.