Supernova Bounds on Weinberg's Goldstone Bosons

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Motivation

- CMB data:
  - WMAP9 $N_\nu = 3.55^{+0.49}_{-0.48}$ at 68% CL
  - Planck $N_\nu = 3.52^{+0.48}_{-0.45}$ at 95% CL
  - BICEP2?
- Big Bang Nucleosynthesis: $N_\nu = 3.71^{+0.47}_{-0.45}$
  [Steigman, Ad. High Energy Phys. 2012 (2012) 268321]
- Standard scenario prediction: $N_\nu = 3.046$
  [Mangano et al., Phys. Lett. B 534 (2002) 8]
- Weinberg: Goldstone bosons? Massless and derivative coupling [Weinberg, Phys. Rev. Lett. 110 (2013) 241301]
- Requirements and constraints:
  - decouple from thermal bath early enough
  - colliders [Cheung, Keung, Yuan, PRD 89 (2014) 015007]
  - astrophysics: e.g. Supernova [Keung, Ng, HT, Yuan, PRD]

Effective Number of Neutrinos

Contribution of neutrinos to total energy density

$$\rho = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_\nu^{\rm eff}\right]\rho_\gamma$$

Temperature of species X after neutrino decoupling

$$\frac{T_X}{T_\nu} = \left(\frac{h_{\rm eff}(T_{\nu\,\rm dec})}{h_{\rm eff}(T_{X\,\rm dec})}\right)^{1/3}$$

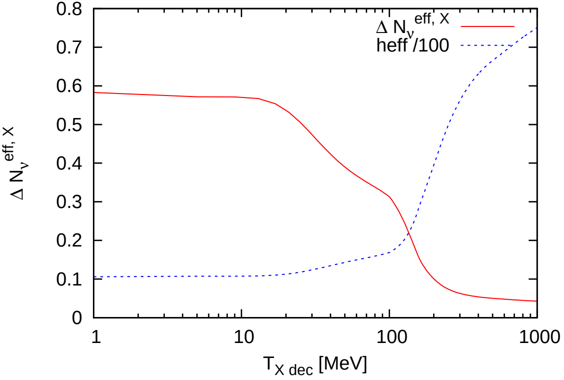
Contribution of species X to $N_{\rm eff}$

$$\Delta N_\nu^{\rm eff,X} = \frac{4}{7}\, C_X\, g_X \left(\frac{h_{\rm eff}(T_{\nu\,\rm dec})}{h_{\rm eff}(T_{X\,\rm dec})}\right)^{4/3}$$

$h_{\rm eff}$: effective dof for entropy density
$C_X = 1$ for boson; g_X: internal dof of species X

Contribution to $N_\nu^{\rm eff}$ from Species X

For $C_X = 1$, $g_X = 1$, and $T_c = 150$ MeV



[Ng, HT, Yuan, JCAP 09 (2014) 035]

$h_{\rm eff}$ by [Srednicki, Watkins, Olive, Nucl. Phys. B 310 (1988) 693]

Weinberg's Model

[Weinberg, Phys. Rev. Lett. 110 (2013) 241301]

Lagrangian

$$\mathcal{L} = (\partial_\mu S^\dagger)(\partial^\mu S) + \mu^2 S^\dagger S - \lambda (S^\dagger S)^2 - g (S^\dagger S)(\Phi^\dagger \Phi) + \mathcal{L}_{\rm SM}$$

Define

$$S(x) = \frac{1}{\sqrt{2}} \left(\langle r \rangle + r(x)\right) e^{2\imath\alpha(x)}$$

$\alpha(x)$: Goldstone boson field; $r(x)$: radial field

Lagrangian becomes

$$\begin{aligned} \mathcal{L} &= \frac{1}{2}(\partial_\mu r)(\partial^\mu r) + \frac{1}{2}\frac{(\langle r \rangle + r)^2}{\langle r \rangle^2}(\partial_\mu \alpha)(\partial^\mu \alpha) + \frac{\mu^2}{2}(\langle r \rangle + r)^2 \\ &\quad - \frac{\lambda}{4}(\langle r \rangle + r)^4 - \frac{g}{4}(\langle r \rangle + r)^2(\langle \varphi \rangle + \varphi)^2 + \mathcal{L}_{\rm SM} \end{aligned}$$

$\varphi(x)$: SM physical Higgs field

Collider Bounds from Higgs Invisible Width

Mixing

$$\tan 2\theta = \frac{2g \langle \varphi \rangle \langle r \rangle}{m_\varphi^2 - m_r^2}$$

SM Higgs decay width

$$\Gamma_{\varphi \to 2\alpha} = \frac{g^2 \langle \varphi \rangle^2 m_\varphi^3}{32\pi \left(m_\varphi^2 - m_r^2\right)^2}$$

- LHC: $\Gamma_{\varphi \to 2\alpha} + \Gamma_{\varphi \to 2r} < 1.2\ \mathrm{MeV}$ (branching ratio $< 22\%$)

  [Cheung, Lee, Tseng, JHEP 05 (2013) 134]

$$\Rightarrow \boxed{|g| < 0.011}$$

[Cheung, Keung, Yuan, PRD 89 (2014) 015007]

- ILC: branching ratio $< 0.4 - 0.9\%$
  $\Rightarrow$ bound improved by factor $5 \sim 7$

  [Bechtle, Heinemeyer, Stal, Stefaniak, Weiglein, arXiv:1403.1582]

Freeze-Out of Goldstone Bosons

Goldstone bosons in thermal bath:

$$\alpha\alpha \leftrightarrow \mu^+\mu^- \,, e^+e^- \,, \gamma\gamma \,, \pi\pi \,, \ldots$$

Effective interaction between Goldstone bosons and SM fermion f

$$+\frac{g\, m_f}{m_\varphi^2 m_r^2}\, \bar{f} f\, \partial_\mu\alpha\, \partial^\mu\alpha$$

Require: freeze out before muons become non-relativistic

$$\Gamma_{\rm ann}(T_f \approx m_\mu) \simeq H(T_f \approx m_\mu) \Rightarrow \frac{g^2 m_\mu^7 M_{\rm Pl}}{m_\varphi^4 m_r^4} \approx 3$$

$$\Rightarrow g = 0.005 \quad \text{for } m_r \approx 500 \text{ MeV}$$

[Weinberg, Phys. Rev. Lett. 110 (2013) 241301]

SN Emissivity bound or the "Raffelt Criterion"

Demand: the cooling agent X should not have affected the SN cooling time significantly

$$\boxed{\epsilon_X \equiv \frac{Q_X}{\rho} \lesssim 10^{19}\,\mathrm{erg}\cdot\mathrm{g}^{-1}\cdot\mathrm{s}^{-1} = 7.324\cdot 10^{-27}\,\mathrm{GeV}}$$

applied at $\rho = 3\cdot 10^{14}$ g/cm^3 and $T = 30$ MeV

[Raffelt, Phys. Rept. 198 (1990) 1]

Q_X: SN energy loss rate due to species X

- axions
- right-handed neutrinos
- Kaluza-Klein gravitons
- unparticles
- ...

Reaffirmed by simulations

[Hanhart, Pons, Phillips, Reddy, PLB 509 (2001) 1]

Particle Abundances at Supernova Core

- Baryon density: $n_B = n_n + n_p$
- β-equilibrium: $\mu_e + \mu_p = \mu_n + \mu_{\nu_e}$
- Charge neutrality: $n_p = n_e$
- Lepton fraction: $Y_L\, n_B = n_e + n_{\nu_e}$

$\Rightarrow$ At $T = 30\ \mathrm{MeV}$, for $Y_L = 0.3$

$$\begin{aligned}\mu_n &= 971\ \mathrm{MeV}\,,\quad \mu_p = 923\ \mathrm{MeV}\,,\\ \mu_e &= 200\ \mathrm{MeV}\,,\quad \mu_{\nu_e} = 152\ \mathrm{MeV}\end{aligned}$$

Neutron degeneracy parameter $\eta_n \equiv (\mu_n - m_n)/T \approx 1.05$
Electrons highly degenerate

Higgs Effective Coupling at Low Momentum Transfer

- $\varphi\,\gamma\gamma$:

$$\mathcal{A}_{\varphi\to\gamma\gamma} = \frac{\alpha}{4\pi}\left(\frac{8\,G_F}{\sqrt{2}}\right)^{1/2} F(q^2)\cdot(k_1\cdot k_2 g^{\mu\nu} - k_1^\mu k_2^\nu)\,\epsilon_\mu^*(k_1)\epsilon_\nu^*(k_2)$$

[Ellis, Gaillard, Nanopoulos, Nucl. Phys. B 106 (1976) 292; Leutwyler, Shifman, Phys. Lett. B 221 (1989) 384]

- $\varphi\,NN$:

evaluate $\left\langle N|\sum_q m_q\,\bar{q}q + \sum_Q m_Q\,\bar{Q}Q|N\right\rangle$
using

$$\sum_Q m_Q\,\bar{Q}Q \to -\frac{2}{3}\frac{\alpha_s}{8\pi} n_h\,G^a_{\mu\nu}G^{a\,\mu\nu}$$

$$\Rightarrow \mathcal{L}_{\text{eff}} \quad = \quad \frac{2}{27}\,n_h\,g\,\frac{m_N}{m_r^2\,m_\varphi^2}\,\partial_\mu\alpha\,\partial^\mu\alpha\,\bar{\psi}_N\psi_N$$

[Shifman, Vainshtein, Zakharov, Nucl. Phys. B 147 (1979) 385; Nucl. Phys. B 147 (1979) 448]

Goldstone Boson Emission from Pair Annihilation

Energy loss rate

$$Q_{e^+e^-\to\alpha\alpha} = \frac{1}{2!}\int\prod_{j=1}^{2}\frac{d^3\vec{q}_j}{(2\pi)^3 2\omega_j}\int\prod_{i=1}^{2}\frac{2\,d^3\vec{p}_i}{(2\pi)^3\,2E_i} f_1 f_2\,(\omega_1+\omega_2)$$
$$\times\frac{1}{4}\sum_{\rm spins}|\mathcal{M}_{e^+e^-\to\alpha\alpha}|^2(2\pi)^4\delta^4(p_1+p_2-q_1-q_2)$$

- $e^+\,e^- \to \alpha\,\alpha$

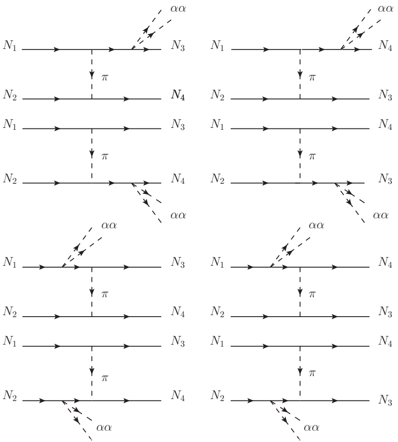
$$\epsilon_{e^+e^-\to\alpha\alpha} = 1.73\cdot 10^{-28}\ {\rm GeV}\, g^2\left(\frac{m_r}{500\ {\rm MeV}}\right)^{-4} \ll \epsilon_X$$

- $\gamma\,\gamma \to \alpha\,\alpha$

$$\epsilon_{\gamma\gamma\to\alpha\alpha} \sim \frac{6.32\cdot 10^{-29}\ {\rm GeV}}{(\rho/3\cdot 10^{14}\ {\rm g/cm^3})}\frac{g^2}{\left(\frac{m_r}{500\ {\rm MeV}}\right)^4}\left(\frac{T}{30\ {\rm MeV}}\right)^{13} \ll \epsilon_X$$

Goldstone Boson Emission from Nuclear Bremsstrahlung

$N\,N \rightarrow N\,N\,\alpha\,\alpha$



One Pion Exchange (OPE) approximation as [Brinkmann, Turner, Phys. Rev. D 38 (1988) 2338]

Goldstone Boson Emission from Nuclear Bremsstrahlung Processes (II)

Emissivity in non-degenerate case

$$\epsilon^{\mathrm{ND}}_{nn\to nn\alpha\alpha} \simeq \frac{6.65\cdot 10^{-22}\ \mathrm{GeV}}{(\rho/3\cdot 10^{14}\ \mathrm{g/cm^3})}\, g_N^2 \left(\frac{m_r}{500\ \mathrm{MeV}}\right)^{-4}\left(\frac{T}{30\ \mathrm{MeV}}\right)^{9.5} \lesssim \epsilon_X$$

$$\Rightarrow g_N^2 \left(\frac{m_r}{500\ \mathrm{MeV}}\right)^{-4} \lesssim 1.1\cdot 10^{-5}$$

$$\Rightarrow \boxed{|g| \lesssim 0.011\ \left(\frac{m_r}{500\ \mathrm{MeV}}\right)^2}$$

Summary

- We determined the allowed range for the coupling constant g in dependence of the mass of the radial field m_r in Weinberg's model
- We estimated energy loss rates in post-collapse supernova core due to e^+e^- annihilation, photon scattering and nuclear bremsstrahlung processes
- For SN core temperature $T = 30\ \mathrm{MeV}$, we found $|g| \lesssim 0.011\ \left(\frac{m_r}{500\ \mathrm{MeV}}\right)^2$;
  in comparison colliders constrain $|g| \lesssim 0.011$
- If ILC improves to $|g| < 0.0015$, freeze-out condition requires $m_r < 274\ \mathrm{MeV}$. Our SN bounds would be at least as good as $|g| < 0.0033$
- Modifications to our SN bound will be studied in a subsequent work