Light (Sterile) Neutrinos and Cosmology

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PRL94:111801, 2005 [arxiv:hep-ph/0405067]

Neutrino Oscillations

- Solar + KamLAND: $\nu_e \leftrightarrow \nu_{\mu/\tau}$ $\Delta m_s^2 \approx 4 \times 10^{-5}\ \mathrm{eV}^2$
- Atmospheric: $\nu_\mu \leftrightarrow \nu_\tau$ $\Delta m_a^2 \approx 3 \times 10^{-3}\ \mathrm{eV}^2$
- Laboratory (LSND): $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ $\Delta m_{\mathrm{LSND}}^2 \approx 1\ \mathrm{eV}^2$
- LSND result to be tested by miniBooNe, late 2005
- 3-neutrino framework cannot incorporate all three results simultaneously!
- Simplest alternative: add 1 or more sterile neutrino(s): $m_s \approx 1\ \mathrm{eV};\quad \mathrm{Prob}(\nu_\mu \to \nu_s \to \nu_e) \approx 0.3\%$

Why Are Neutrinos Light?

- The "standard" answer: see-saw mechanism

$$\mathcal{L}_\nu = \lambda_\nu \bar{L} H n + \frac{M_n}{2} n^c n + \text{ h.c.}$$

$$\lambda_\nu v \sim M_D \sim 100 \text{ GeV}, \quad M_n \sim M_{\text{GUT}} \sim 10^{15} \text{ GeV}$$

- Diagonalize: $m_\nu \sim M_D^2/M_n \sim 10^{-2}$ eV (active)

$m_n \sim M_n \sim 10^{15}$ GeV (sterile)

⇒ Only active neutrinos are light!

- Attractive and minimal, but not tested!
- Light (e.g. LSND) sterile neutrino requires an alternative mechanism!

Light Neutrinos From Global Symmetries

- Idea: forbid all renormalizable neutrino mass terms (Dirac and Majorana) by global symmetries
[Chickashige, Mohapatra,Peccei,Gelmini, Georgi, Glashow, Nussinov, ... ~1981]

- Example: $U(1): \quad Q(n) = +1, Q(L) = Q(H) = 0$

- Introduce additional scalar fields allowing for non-renormalizable neutrino mass terms

- Example: $Q(\Phi) = -1$

$$\mathcal{L} = \frac{\Phi}{\Lambda}\bar{L}Hn + \frac{\Phi^2}{\Lambda}nn$$

$\langle H \rangle \sim \langle \Phi \rangle \sim v$ ⇒ $m_\nu \sim v \langle \Phi \rangle / \Lambda \ll v$ $\quad m_s \sim m_a$

"Late-Time" Neutrino Masses

- The original models [early 80's] assumed $\langle \Phi \rangle \sim v$
- This does not need to be the case: $\langle \Phi \rangle \ll v$ is OK!
- Example: $\Phi: \quad Q(\Phi) = -1; \qquad S: \quad Q(S) = -1$

$$\mathcal{L}_\nu = \frac{\Phi}{\Lambda}\bar{L}Hn + \frac{\Phi}{\Lambda}Snn + \text{ h.c.}$$

$$\langle H \rangle \sim \langle S \rangle \sim v \quad \Rightarrow \quad m_\nu \sim v \langle \Phi \rangle / \Lambda \ll v \qquad m_s \sim m_a$$

- Naturalness is a concern: can $\langle \Phi \rangle \ll v$ be stabilized against radiative corrections?
- Answer: YES, by SUSY broken at the TeV scale

Non-Standard Neutrino Cosmology

- Oscillation experiments cannot distinguish between see-saw and alternative (e.g. "late-time") scenarios for light neutrino masses
  [see Andre de Gouvea's talk]
- Neutrino cosmology can be very different in the alternative scenario
- Cosmological constraints on neutrino properties can be modified
- Explicit example: constraints on the LSND sterile neutrinos can be greatly relaxed!

Weirdness I: Late Time Phase Transition

- In the early universe, global symmetry is restored by thermal effects ($\langle \Phi \rangle = 0$) and neutrinos are massless, do not oscillate!
- The symmetry-breaking phase transition occurs (generically) at $T \sim \langle \Phi \rangle$
- If $\langle \Phi \rangle \ll v$, the phase transition can occur at late times (e.g., after the BBN) - hence the name!

Weirdness II: Light (Pseudo) Goldstone Bosons

- Broken global symmetry yields Goldstone bosons (Majorons): $\Phi = e^{-iG/f}\, f \qquad (f = \langle \Phi \rangle)$
- G.B.s are massless if the global symmetry is exact, small mass if some explicit violation (e.g. by gravitational effects) is present
- G.B.s are coupled to neutrinos but not to other SM states - exp. constraints are poor
- New light states - can play a role in cosmology!

Example: LSND Sterile Neutrino vs. Cosmology

- Oscillations ⇨ thermal abundance for ν_s in the early Universe ($T \geq 1\ \mathrm{MeV}$)
- Big Bang Nucleosynthesis (BBN) constraint:

  $N_\nu^{\mathrm{eff}} < 3.4$ at 95% c.l. ⇨ $N_\nu \geq 4$ is ruled out!

- Large Scale Structure + normalization from CMB:

  no hot DM ⇨ $\sum m_\nu < 0.7\ \mathrm{eV}$

- Claim: sterile neutrino interpretation of LSND is inconsistent with cosmological data [Murayama, Pierce, hep-ph/0302131; Cirelli, Marandella, Strumia, Viscani, hep-ph/0403158; ...]

LSND Sterile Neutrino vs. Cosmology: Are We Sure?

- If the LSND result is correct, global symmetry is preferable to see-saw on theoretical grounds: it can explain $m_s \sim m_a$
- If the phase transition occurs after the BBN, all neutrinos are massless at and before BBN - no thermal abundance for ν_s at BBN!
- Also $\nu_s \to \nu_a + \phi$ eliminates ν_s contribution to Dark Matter - avoid the LSS constraint! [see also Beacom, Bell, Dodelson, astro-ph/0404585]

Explicit Model I

- Start with a supersymmetric theory; need extra EW singlet -> NMSSM

- Add 3 right-handed neutrino superfields n_i + 2 singlet fields $\phi, \tilde{\phi}$

- Superpotential: $W^M = W_{NMSSM} + W_\nu^M,$

$$W_\nu^M = \lambda_{ij} l_i n_j h \frac{\phi}{M} + \frac{\kappa}{3}\phi^3 + \tilde{\lambda}_{ij} n_i n_j s \frac{\tilde{\phi}}{M} + \frac{\tilde{\kappa}}{3}\tilde{\phi}^3$$

- This is unique under a set of discrete symmetries, Z_3^3

Explicit Model II

- Below the SUSY breaking and EWSB scales, the neutrino sector is described by

$$\mathcal{L}_\nu^M = g_{ij}\nu_i n_j \phi + \tilde{g}_{ij} n_i n_j \tilde{\phi} + \text{h.c.} + V(\phi, \tilde{\phi})$$

$$g = \langle h \rangle \lambda / M, \quad \tilde{g} = \langle s \rangle \tilde{\lambda} / \tilde{M}$$

$$V = -\mu^2 |\phi|^2 + \kappa^2 |\phi|^4 - \tilde{\mu}^2 |\tilde{\phi}|^2 + \tilde{\kappa}^2 |\tilde{\phi}|^4$$

- At low energies, $m^D = g\left\langle \phi \right\rangle, \quad m^M = \tilde{g}\left\langle \tilde{\phi} \right\rangle$

[see Andre de Gouvea's talk]

$$\mathcal{L} \sim g_{\alpha\beta}\nu'_\alpha \nu'_\beta G + \tilde{g}_{\alpha\beta}\nu'_\alpha \nu'_\beta \tilde{G}$$

Constraints on Parameters

- Phase transition after the BBN -> $f, \tilde{f} \leq 1 \text{ MeV}$
- Neutrino masses: $m \sim gf \sim 0.1 \text{ eV}$ ⇨ $g \geq 10^{-7}$
- Two sectors: "hidden" [$n, \phi, \tilde{\phi}$] and "visible" [everything else], coupled with strength g
- At BBN, need $T_{\text{hid}} \ll T_{\text{vis}}$ ⇨ the two sectors should be decoupled:

$$\Gamma(\nu_a\nu_a \leftrightarrow \nu_s\nu_s, \nu_a\nu_a \leftrightarrow \phi\phi, \ldots) < H \text{ @ } T \geq \text{ MeV}$$

$$g_{ij},\ g_{i\alpha} \leq 10^{-5}, \quad g_{ij}\kappa,\ \ g_{i\alpha}\kappa \leq 10^{-10} \quad g_{ij}\tilde{g}_{ij},\ \ g_{i\alpha}\tilde{g}_{i\alpha} \leq 10^{-10}$$

Parameters and Naturalness

- Summary of the constraints:

$$10 \text{ keV} \leq f \leq 1 \text{ MeV}, \quad 10^{-7} \leq g \leq 10^{-5}$$

- Supernova constraints on g are in the similar range, but very model-dependent
- Low f is natural: SUSY breaking scale in the hidden sector is suppressed: $f \sim g M_{\text{SUSY}}^{\text{vis}}$
- Low-scale SUSY breaking (e.g. gauge mediation) is required: $f = 100 \text{ keV} \;\; \text{for } M_{\text{SUSY}}^{\text{vis}} = 1 \text{ TeV}$

Post-BBN Cosmology

- After BBN, ν_a decouple from the visible sector, and recouple to the hidden sector:

$$\Gamma(\nu\nu \to nn) \sim g^4 T,$$

$$\Gamma > H \quad \text{at} \quad T < T_{\rm rec}$$

$$g \geq 10^{-7} \Rightarrow \quad T_{\rm rec} > 1 \text{ eV}$$

- Energy density in $\nu_a + n + \phi$ is conserved during recoupling -> $T(\nu_a)$ decreases

- At $T < \nu_s$, sterile neutrinos decay: $\nu_s \to \nu_a + G$

- The decays reheat $\nu_a + G$ sector -> enhanced relativistic energy density at CMB decoupling

Signatures in the CMB Spectrum

- Total relativistic energy density is larger than in the SM:

N_G/N_s	1	2	3
2	3.15	3.28	3.40
3	3.12	3.23	3.33
8	3.06	3.11	3.17

- Neutrinos do not free stream due to their coupling to Goldstones: e.g. $\nu_i \leftrightarrow \nu_j + G$

Signatures in the CMB Spectrum II

- Non-free-streaming -> uniform shift in the peak positions at large l [Bashinsky, Seljak, astro-ph/0310198]

$$\Delta l_n = 23.3 - 13.1 \left(\frac{g_\nu (3 - n_S)}{(3 g_\nu + n_G)(1/N_{\nu,\mathrm{CMB}} + .23)} \right)$$

- Numerical analysis of a related scenario [Hannestad, astro-ph/0411475] - negative result BUT the scenario considered has substantially higher relativistic energy density $N_\nu^{\mathrm{eff}} = 6.58$

Late-Time Neutrinos and Domain Wall Dark Energy

- A network of domain walls could account for the observed dark energy [Spergel, Buchel, astro-ph/9812022; Friedland, Murayama, MP, astro-ph/0205520]
- The required wall tension is about 100 keV - same as the global symmetry breaking scale for late-time neutrinos!
- Neutrino mass and domain walls are created in the same late-time phase transition

Conclusions I

- Models with spontaneously broken global symmetries provide an alternative to see-saw to explain smallness of neutrino masses

- Sterile and active neutrino masses are naturally at the same scale in these models -> attractive if LSND is right

- Neutrino cosmology is non-standard: light Goldstone bosons, possible late-time phase transition

Conclusions II

- Example: Cosmological constraints on the LSND sterile neutrino are not applicable in this scenario
- Phase transition after BBN (10-100 keV) -> no oscillations into sterile before/during BBN -> no energy density constraint
- Sterile neutrinos unstable ($\nu_s \rightarrow \nu_a + G$) -> do not contibute to dark matter -> LSS bounds do not apply
- Interesting signatures in the CMB!