Cosmological constraints on the Sessaw Scale

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Motivation

Which is the simplest extension of the SM that can account for neutrino masses?
As simple as just adding singlet fermions (sterile neutrinos) to the SM field content.

If lepton number conservation is not imposed, the most general Lagrangian is given by

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kin}} - \frac{1}{2} \bar{\nu}_{si} M_{ij} \nu_{sj}^c - (Y)_{i\alpha} \bar{\nu}_{si} \tilde{\phi}^\dagger L_{\alpha} + \text{h.c.} \]

Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.
Seesaw Model

• As simple as just **adding singlet fermions** (sterile neutrinos) to the SM field content.

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\]

**New Physics Scale** \( m_\nu \sim Y^2 v^2 / M \)

Minkowski 77; Gell-Mann, Ramond, Slansky 79; Yanagida 79; Mohapatra, Senjanovic 80.
A New Physics scale

- Low scale models require small Yukawa couplings. With the exception of TeV scale models as the inverse seesaw.
  
  Mohapatra, Valle 1986

- Contrary to the high scale models, a low Majorana scale does not worsen the Higgs mass hierarchy problem.

\[ \left[ \delta M^2_H \right]_{N_R} \propto M^2 \]

Vissani 1998
The New Physics Scale is Unbounded
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Explanation to neutrino anomalies pointed out mainly by LSND and reactor experiments. Donini, Hernandez, JLP, Maltoni, Shwetz 2012
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Warm DM candidate. Moreover, after the recent X-ray signal/hint.
Bulbul et al.(arXiv:1402.2301)
Boyarsky et al.(arXiv:1402.4119)

Account for baryon asymmetry in the Universe.
Akhmedov, Rubakov, Smirnov 1998
Asaka, Blanchet, Shaposhnikov 2005
A different point of view...

- We start from the lowest level of complexity. Minimum number of extra fermionic degrees of freedom (fermion singlets) $n_R$

\[ n_R = 1 \quad \text{Excluded by neutrino oscillation data.} \]

Donini, Hernandez, JLP, Maltoni 2011

\[ n_R = 2 \quad \text{In agreement with neutrino oscillation data.} \]
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\[ n_R = 1 \quad \text{Excluded by neutrino oscillation data.} \]

\[ n_R = 2 \quad \text{In agreement with neutrino oscillation data.} \]

We do not assume any hierarchy for the new parameters of the model.
Can we obtain general bounds on the Majorana scale without assuming a priori anything about the parameters of the model?
3+2 Minimal Seesaw Model vs Cosmology

P. Hernandez, M. Kekic, JLP 2013
ArXiv:1311.2614
(PRD89 (2014) 073009)
Extra radiation, $N_{\text{eff}}$

The energy density of the extra sterile neutrino species is usually quantified in terms of

$$N_{\text{eff}} = \frac{\rho_s + \rho_\nu}{\rho_{1\nu}}$$

$$N_{\text{eff}}^{BBN} = 3.5 \pm 0.2 [1\sigma] \quad (N_{\text{eff}}^{BBN} < 4 [2.2\sigma])$$

Cooke et al; arXiv:1308.3240
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Active neutrino contribution

\[ N_{\text{eff}}^{BBN} = 3.5 \pm 0.2 \text{[}1\sigma\text{]} \quad (N_{\text{eff}}^{BBN} < 4 \text{[}2.2\sigma\text{]}) \]

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Cooke et al; arXiv:1308.3240
Extra radiation, $N_{\text{eff}}$

Planck Collaboration 2013 (arXiv:1303.076)
Extra radiation, $N_{\text{eff}}$

- The 3 active neutrinos contribute with $N_{\text{eff}}^{SM} \approx 3$

- One fully thermal extra sterile state that decouples being relativistic contributes with $\Delta N_{\text{eff}} \approx 1$ when freezes out.

- Can the sterile neutrinos escape from thermalization in the 3+2 Minimal Seesaw Models?
Sterile Neutrino Thermalization

- Sterile neutrino thermalization is controlled by:

\[ f_{s,j}(T) \equiv \frac{\Gamma_{s,j}(T)}{H(T)} \]
Sterile Neutrino Thermalization

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f_{s_j}(T) \equiv \frac{\Gamma_{s_j}(T)}{H(T)}
\]

Barbieri, Dolgov 1990; Kainulainen 1990;

\[
\Gamma_{s_j}(T) \approx \frac{1}{2} \sum_{\alpha} \langle P (\nu_\alpha \rightarrow \nu_{s_j}) \rangle \times \Gamma_{\nu_\alpha}
\]

Sterile neutrino collision rate
Sterile Neutrino Thermalization

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Sterile neutrino collision rate

\[ H(T) = \sqrt{\frac{4\pi^3 g_*(T)}{45} \frac{T^2}{M_{Planck}}} \]

Hubble expansion rate
Sterile Neutrino Thermalization

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Sterile neutrino collision rate

\[ H(T) = \sqrt{\frac{4\pi^3 g_*(T)}{45}} \frac{T^2}{M_{Planck}} \]

Hubble expansion rate

- The sterile neutrinos thermalize if \( f_s(T) \geq 1 \)
Sterile Neutrino Thermalization

- $f_s(T)$ reaches a maximum at some temperature $T_{\text{max}}$ and if the maximum is larger than one, thermalization will be achieved. At decoupling we can estimate:

$$N_{\text{eff}} \approx N_{\text{eff}}^{SM} + \sum_j (1 - \exp(-\alpha f_{s_j}(T_{\text{max}})))$$

$$\Delta N_{\text{eff}}$$
Sterile Neutrino Thermalization

- Thermalization rate basically independent of the seesaw scale.
- In the 3+2 type-I seesaw model, for the whole parameter space, the sterile neutrinos always thermalize at some point of the thermal history.
Sterile Neutrino Decoupling

For parameters of the model that minimize $f_s(T_{max})$

$T_d = M$

Minimum $T_d$ + bounds from direct searches

Boltzman suppression

Relativistic region

$\log_{10}[T_d/\text{MeV}]$

$\log_{10}[M_i/\text{MeV}]$
Sterile Neutrino Decoupling

• Above $\sim 100\, MeV$ there is Boltzman suppression. The bounds do not apply for

$$M \gtrsim 100\, MeV$$

• Moreover, after sterile neutrino decoupling two effects could modify $\Delta N_{eff}$, before BBN:

  (i) Dilution

  (ii) Decay
Entropy dilution

\[ M_2 = 1 \text{KeV} \]
\[ M_1 = 20 \text{eV} \]

Dilution could be relevant for \( M \gtrsim 10 \text{KeV} \)

\[ M_2 = 10 \text{MeV} \]
\[ M_1 = 0.1 \text{MeV} \]
Entropy dilution

• Dilution effects allow to relax the bounds for the range of masses

\[ 10 \text{keV} \lesssim M \lesssim 100 \text{MeV} \]

• However, those sterile neutrinos would give a huge contribution to the energy density when they become non-relativistic later, modifying in a drastic way CMB and structure formation.

• The only way CMB and BBN bounds can be evaded for this range of masses is if the sterile neutrinos decay before BBN.
Sterile neutrino decay

• Bounds on short-lived sterile neutrinos with masses on the range $[10\,MeV, 140\,MeV]$ have been studied by
  Dolgov, Hansen, Raffelt, Semikoz 2000
  Fuller, Kishimoto, Kusenko, 2011
  Ruchayskiy, Ivashko, 2012

• Very strong bounds found combining BBN and direct accelerator searches, excluding the sterile neutrino decay before BBN in the minimal model for $M \lesssim O(100\,MeV)$
  Ruchayskiy, Ivashko, 2012
  Vincent, Fernandez-Martinez, Hernandez, Lattanzi, Mena 2014
In summary, cosmology allow us to exclude a huge part of the parameter space and the seesaw scale (8 orders of magnitude!) of the 3+2 MM.

Allowed sterile neutrino spectra

Log$_{10}[M_i(\text{eV})]$

see Ninetta Saviano's talk
3+3 Minimal Seesaw Model

vs

Cosmology

P. Hernandez, M. Kekic, JLP 2014
ArXiv:1406.2961
(PRD 90 (2014) 065033)
3+3 Minimal Seesaw Model

- Larger parameter space: 3 light masses + 3 heavy masses + 6 angles + 6 CP-phases.

- We have explored the whole parameter space allowed by neutrino oscillation data.

- In spite of the larger parameter space, only one sterile neutrino can escape from thermalization. The thermalization being basically controlled by the lightest neutrino mass.
If $m_1 \geq \mathcal{O}(10^{-3} eV)$ the 3 sterile neutrinos thermalize
Analytical lower bound

Lower bound can be saturated by only one sterile neutrino.
Possible scenarios

- $m_1 \geq \mathcal{O}(10^{-3} \text{eV})$: the three sterile neutrinos thermalize.
Possible scenarios

- $m_1 \leq 10^{-3} \text{eV}$: one sterile neutrino does not thermalize. The other two contribute as in the 3+2 model.

![Allowed sterile neutrino spectra](image)
Impact on neutrinoless double beta decay

More about NMEs and Lepton number violation: Raina Prabhu and Julian Heek
Conclusions

• We have studied in detail the simplest low scale models that can accommodate light neutrino masses: just adding singlet fermions (sterile neutrinos) to the SM.

• In these models the new physics scale introduced to account for neutrino masses is the Majorana mass of the sterile neutrinos. The scale is in general unconstrained.

• The minimal model requires 2 sterile neutrinos and is strongly constrained by cosmology, 8 orders of magnitude of the seesaw scale are excluded, since the sterile neutrinos can not scape from thermalization.

• Low scale 3+3 minimal seesaw models are also very constrained by cosmology. Only one sterile neutrino might escape from thermalization. Thermalization is controlled by the lightest neutrino mass, being the threshold:

\[ m_1 = \mathcal{O}(10^{-3} \text{eV}) \]

• Strong impact of the cosmological bounds on neutrinoless double beta decay.
Thanks!
Extending Casas-Ibarra parameterization

Donini, Hernandez, JLP, Maltoni, Schwetz 2012; arXiv:1205.5230

$U = \begin{pmatrix} U_{aa} & U_{as} \\ U_{sa} & U_{ss} \end{pmatrix}$

Keep in mind!

“Sterile neutrinos” interact with particles in thermal bath via this mixing.

$U_{aa} = U_{PMNS} \begin{pmatrix} 1 & 0 \\ 0 & H \end{pmatrix}$,

$H^{-2} = I + m^{1/2} R^\dagger M^{-1/2} R m^{1/2}$

$U_{as} = i U_{PMNS} \begin{pmatrix} 0 \\ H m^{1/2} R^\dagger M^{-1/2} \end{pmatrix}$,
**Extending Casas-Ibarra parameterization**

Donini, Hernandez, JLP, Maltoni, Schwetz 2012; arXiv:1205.5230

\[
U = \begin{pmatrix}
U_{aa} & U_{as} \\
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\end{pmatrix}
\]

Keep in mind!

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Parameters of the model:

- \(\theta_{23}, \theta_{12}, \theta_{13}, m_2, m_3\)
- \(M_1, M_2, \delta, \alpha, \theta_{45}, \gamma_{45}\)

Fixed by neutrino oscillation experiments

Free parameters
\( m_1 \leq \mathcal{O}(10^{-3} \text{eV}) \): one sterile neutrino does not thermalize. The other two contribute as in the 3+2 model.
Sterile Neutrino Thermalization

- This is because all favours participate in oscillations. The mixing with the three different flavous can not be small enough at the same time due to the correlation.
Analytical lower bound

\[ f_B(T) \equiv \min \left[ \frac{C_T(T)}{\sqrt{g_* (T)}} \right] \frac{G_F^2 \rho T^4 \sqrt{g_*(T)}}{H(T)} \left( \frac{M_j^2}{2 p V_e - M_j^2} \right)^2 \sum_{\alpha = e, \mu, \tau} \left| (U_{as})_{\alpha j} \right|^2 \leq f_{s_j}(T) \]

\[ f_B(T_{max}) \leq f_{s_j}(T_{max}) \leq f_{s_j}(T_{max}). \]

\[ f_{s_j}(T_{max}) \geq f_B(T_{max}) = \frac{\sum_{\alpha} \left| (U_{as})_{\alpha j} \right|^2 M_j}{3.25 \cdot 10^{-3} \text{eV}}. \]

\[ h_j \equiv \sum_{\alpha} \left| U_{\alpha s_j} \right|^2 M_j = \sum_i \left| R_{ij} \right|^2 m_i \geq m_1 \]

Independent of PMNS parameters
Sterile neutrino decay

- For sufficiently large $M$ the sterile neutrino could decay before BBN and our analysis does not apply to this case.

\[ \tau \sim 6 \times 10^{11} \text{s} \left( \frac{\text{MeV}}{M} \right)^4 \frac{0.05 \text{eV}}{|U_{\alpha s}|^2 M} \]

- For natural choices of the mixing decay takes place after BBN. However, for extreme mixings of $O(1)$, sterile neutrinos as light as 10 MeV could decay before BBN.
\[ f_{s_j}(T) = \sum_{\alpha=e,\mu,\tau} \frac{\Gamma_{\nu_\alpha}(T)}{H(T)} \left( \frac{M_j^2}{2 p V_\alpha(T) - M_j^2} \right)^2 |(U_{as})_{\alpha j}|^2 \]

\[ H(T) = \sqrt{\frac{4\pi^3 g_*(T)}{45}} \frac{T^2}{M_{\text{Planck}}} \]

\[ \Gamma_{\nu_\alpha} \simeq C_\alpha(T) G_F^2 T^4 p \]

\[ T^* \equiv \left( \frac{M_j^2}{59.5 |A|} \right)^{1/6} \leq T_{\text{max}} \leq \left( \frac{M_j^2}{59.5 |B|} \right)^{1/6} \]

T > 180 \text{ MeV}: \quad C_{e,\mu,\tau} \simeq 3.43 \text{ and } V_\alpha = A T^4 p \text{ for } \alpha = e, \mu, \tau; 

T \simeq 20 \text{ MeV} \lesssim T \lesssim 180 \text{ MeV}: \quad C_{e,\mu} \simeq 2.65, \quad C_{\tau} \simeq 1.26, \quad V_e = V_\mu = A T^4 p \text{ and } V_\tau = B T^4 p; 

T \lesssim 20 \text{ MeV}: \quad C_e \simeq 1.72, \quad C_{\mu,\tau} \simeq 0.95, \quad V_e = A T^4 p \text{ and } V_\mu = V_\tau = B T^4 p. 

with

\[ B \equiv -2\sqrt{2} \left( \frac{7\zeta(4)}{\pi^2} \right) \frac{G_F}{M_Z^2}, \quad A \equiv B - 4\sqrt{2} \left( \frac{7\zeta(4)}{\pi^2} \right) \frac{G_F}{M_W^2}. \quad (11) \]
\begin{align*}
\dot{\rho} &= -i[H, \rho] - \frac{1}{2}\{\Gamma, \rho - \rho_{eq} I_A\}; \\
\dot{\rho}_A &= -i(H_A \rho_A - \rho_A H_A + H_A S \rho_A^\dagger - \rho_A S H_A^\dagger) - \frac{1}{2}\{\Gamma_A, \rho_A - \rho_{eq} I_A\} \\
\dot{\rho}_{AS} &= -i(H_A \rho_{AS} + H_A S \rho_S - \rho_{AS} H_S) - \frac{1}{2}\Gamma_A \rho_{AS}, \\
\dot{\rho}_S &= -i(H_{AS}^\dagger \rho_{AS} - \rho_{AS}^\dagger H_A S + H_S \rho_S - \rho_S H_S). \\
\Gamma_{\nu_\alpha} &\gg H \quad \Rightarrow \quad \dot{\rho}_A = \dot{\rho}_{AS} = 0 \\
\dot{\rho}_{ss} &= -\left(H_{AS}^\dagger \left\{\Gamma_{AA} \over (H_{AA} - H_{ss})^2 + \Gamma_{AA}^2/4\right\} H_{AS}\right)_{ss} \tilde{\rho}_{ss} \\
&\approx -\frac{1}{2} \sum_a \langle P(\nu_s \rightarrow \nu_a)\rangle \Gamma_a \tilde{\rho}_{ss}, \\
\tilde{\rho}_S &\equiv \rho_S - \rho_{eq} I_S
\end{align*}
\[ x = \frac{a(t)}{a_{\text{BBN}}}, \quad y = x \frac{p}{T_{\text{BBN}}}, \]

\[ g_{S*}(T) T^3 a(t)^3 = \text{constant} \]

\[ H x \frac{\partial}{\partial x} \rho(x, y) \bigg|_y = -i[\hat{H}, \rho(x, y)] - \frac{1}{2} \{ \Gamma, \rho(x, y) - \rho_{eq}(x, y) I_A \}, \]

\[ \rho_{eq}(x, y) = \frac{1}{\exp \left[ y \left( g_{S*}(T(x)) / g_{S*}(T_{\text{BBN}}) \right)^{1/3} \right] + 1} \]

\[ x_f = 1 \]

\[ H x \frac{\partial}{\partial x} \rho_{ss}(x, y) \bigg|_y = - \left( H_{AS}^\dagger \left\{ \frac{\Gamma_A}{(H_A - \tilde{H}_s)^2 + \Gamma_A^2/4} \right\} H_{AS} \right)_{ss} \tilde{\rho}_{ss}(x, y), \]

\[ x_i \to 0, \quad \rho_{ss} = 0, \]

\[ \Delta N_{\text{eff}}^{(j)_{\text{BBN}}}_{\text{energy}} = \frac{\int dy \ y^2 E(y) \rho_{s_j s_j}(x_f, y)}{\int dy \ y^2 p(y) \rho_{eq}(x_f, y)}, \]

\[ p(y) = \frac{y}{x_f} T_{\text{BBN}} \quad \text{and} \quad E(y) = \sqrt{p(y)^2 + M_j^2}. \]
Bounds from neutrino oscillations

• Can we obtain general bounds on the Majorana scale without assuming a priori anything about the parameters of the model?

• We performed a global analysis of neutrino oscillation experiments, studying the whole parameter space for $n_R = 2$ with degenerate Majorana masses.

\[ M \lesssim 10^{-9}(10^{-10}) \text{eV} \]

bound mainly from solar data
Dirac limit
Gouvea, Huang, Jenkins 2009
Donini, Hernandez, JLP, Maltoni 2011

\[ M \gtrsim 0.6(1.6) \text{eV} \]

constraint mainly from LBL and reactor data
\textit{Seesaw limit}

Donini, Hernandez, JLP, Maltoni 2011
Analytical lower bound

• Thermalization threshold

\[ h_j = \sum_i |R_{ij}|^2 m_i \leq 3.2 \cdot 10^{-3} \text{ eV} \]

\[ f_{s_j}(T_{max}) \leq 1 \]

\[ N_j \text{ does NOT thermalizes} \]

How many sterile neutrinos can simultaneously satisfy this thermalization bound?