Sterile Neutrinos in the Early Universe

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Outline

★ Hints for light sterile neutrinos
★ Sterile neutrinos as candidates for the dark radiation
★ Thermalization of sterile neutrinos in the early universe
★ Conclusions and perspectives

This talk is based on a project in collaboration with S. Hannestad and T. Tram [JCAP 1207 (2012) 025].
Experimental hints for sterile neutrinos

Observations at odds with standard 3-neutrino interpretation of global oscillation data:

★ LSND anomaly [A. Aguilar et al., PRD 64, 112007 (2001)]
★ MiniBooNE data [A.A.Aguilar-Arevalo et al., PRL 102, 101802 (2009)]
★ Short-baseline disappearance data (Bugey, ROVNO, ILL)
★ Reactor anomaly [Mention et al. PRD 83, 073006 (2011), Huber, PRC 84, 024617 (2011)]
★ Gallium anomaly [Giunti, Laveder, PRC 83, 065504 (2011)]
★ ICARUS search for the “LSND anomaly” [M. Antonello et al., arXiv: 1209.0122]

Light sterile neutrinos explain quite well these anomalies.*
[See talks by C. Giunti, C. Rubbia, L. Stanco]

* See the white paper on sterile neutrinos for more details: K.N. Abazajian et al., arXiv: 1204.5379.
Radiation content of the universe

The radiation content of the universe is expressed in terms of a parameter ($N_{\text{eff}}$) representing any relativistic degree of freedom.

The standard value is $N_{\text{eff}} = 3.046$, and it is associated to 3 neutrino families. It exceeds 3 because $e^+e^-$ annihilation provides neutrino heating.

Recent results:

WMAP-7 (Wilkinson Microwave Anisotropy probe)+ LSS (Large Scale Structure) found

$$N_{\text{eff}} = 4.34^{+0.86}_{-0.88}$$

A similar study including SDSS data release 7 (Sloan Digital Sky Survey) found

$$N_{\text{eff}} = 4.78^{+1.86}_{-1.79}$$

Recent analysis point towards $N_{\text{eff}} > 3$. [See talk by A. Melchiorri]

How is the radiation excess explained?

**Main radiation components:**
- three different light active neutrino families
- photons

**Extra-Radiation components:**

Viable candidates for the excess of radiation, often called “dark radiation,” are **sterile neutrinos**. However other possible candidates might be considered.

Assuming the existence of light sterile neutrinos, they can mix with the active ones.

Sterile neutrinos can be thermally excited by the interplay of oscillations and collisions.
In this scenario, \( m_s = 0 \) and 3.046 species of ordinary neutrinos have a common mass \( m_{\nu} \).

In this scenario, \( m_{\nu} = 0 \) and 2 species of sterile neutrinos have a common mass \( m_s \).

In the \( 3 + N_s \) scenario, 2D marginalized probability at \( N_s < 1 \) has a long and narrow tail towards larger \( m_s \), the fewer sterile states there are, the larger the mass they are allowed to possess.

However, \( m_s \gtrsim 1 \text{ eV} \) is cosmologically viable only if additional ingredients are included since otherwise the sterile states would contribute too much hot dark matter.**


**J. Hamann et al., JCAP 1109 (2011) 034.

Concerning BBN: both $^4He$ and $D$ prefer $N_s > 0$, but it may be difficult to accommodate $N_s = 2$. *

Bounds on dark radiation from BBN point towards a more constrained value for $N_s$ than what is implied by CMB+LSS data.

Thermalization of Sterile Neutrinos

Big Bang Nucleosynthesis constraints assume sterile neutrinos are thermalized at the BBN epoch. Is this assumption justified? To study their thermalization, we assume (1 active+1 sterile) scheme and adopt the density matrix formalism. The matrix associated with each momentum bin can be decomposed in terms of the Bloch vector components

$$\rho = \frac{1}{2} f_0 (P_0 + \mathbf{P} \cdot \mathbf{\sigma}) \quad , \quad \bar{\rho} = \frac{1}{2} f_0 (\overline{P}_0 + \overline{\mathbf{P}} \cdot \mathbf{\sigma})$$

The neutrino kinetic equations for each mode are (with $d_t = \partial_t - H p \partial_p$)**

$$\mathbf{V} = \mathbf{V}(\delta m_s^2, \theta_s, L^{(a)}, p, T)$$

$$\dot{\mathbf{P}} = \mathbf{V} \times \mathbf{P} - D(P_x \mathbf{x} + P_y \mathbf{y}) + \dot{P}_0 \mathbf{z}$$

$$\dot{P}_0 = \Gamma \left[ \frac{f_{eq}}{f_0} - \frac{1}{2} (P_0 + P_z) \right]$$

[See talk by N. Saviano]

Thermalization of Sterile Neutrinos

Iso-$\delta N_{\text{eff}}$ contours for $L'^{a} = 0$.

** best fit point of 3+1 global analysis (solar, reactor, short baseline)**

$(\delta m^{2}_{s}, \sin^{2} 2\theta_{s}) = (0.9 \text{ eV}^2, 0.089)$

CMB+LSS data analysis contours**

MiniBooNE+ICARUS common region centered on***

$(\delta m^{2}_{s}, \sin^{2} 2\theta_{s}) = (0.5 \text{ eV}^2, 0.005)$

Sterile neutrinos with $\sim \text{O(eV/sub-eV)}$ mass are thermalized for initial null leptonic asymmetries at $T \sim 1 \text{ MeV}$.

** [J. Hamann et al., PRL 105, 181301 (2010).]
*** [C. Giunti and M. Laveder, PLB 706, 200 (2011).]
**** [M. Antonello et al., arXiv: 1209.0122.]
Thermalization of Sterile Neutrinos

Iso-$\delta N_{\text{eff}}$ contours for $L^a = 10^{-2}$.

Partial or no-thermalization occurs for sterile neutrinos with $\sim O(\text{eV/sub-eV})$ mass and large initial leptonic asymmetries at $T \approx 1 \text{ MeV}$.

** J. Hamann et al., PRL 105, 181301 (2010).
**** M. Antonello et al., arXiv: 1209.0122.
Conclusions and perspectives

★ Cosmological data favor extra-radiation in the universe beyond photons and neutrinos. Low-mass sterile neutrinos are one natural possibility, introduced also to explain the LSND/MiniBooNE+reactor anomalies.

★ One/two sterile states are allowed from cosmology (CMB+LSS), BBN is more constraining (one thermalized sterile state allowed).

★ Small/null initial leptonic asymmetry: one eV (sub-eV) mass sterile family is thermalized at the BBN epoch. Tension between cosmology and reactor data.

★ Large initial leptonic asymmetry: eV (sub-eV) sterile neutrinos are partially or not thermalized at the BBN epoch. eV sterile states compatible with CMB+LSS constraints. Agreement between cosmology and reactor anomalies.

★ The Planck results will give us more precise constraints.
Thank you for your attention!
Back-up slides
Thermalization dependence from mixing

Thermalization begins earlier and is more efficient for larger mass differences and larger mixing angles (L=0)

Thermalization cartoon

$$(\delta m_s^2, \sin^2 \theta_s) = (-3.3 \text{ eV}^2, 6 \times 10^{-4})$$

$$L^a = 0$$

The diatomic region: 68.27% (red), 90.00% (light blue), 95.45%, 99.00% and 99.73% C.L.

**FIG. 6:** Allowed regions in the parameter space for 

The marginalized 95% credible interval for the two neutrino masses are: 

- The sterile neutrino can be massless. The combined analysis for the 3+2 scheme is shown in Fig. 6, again for the case of CMB–only data (left panel) and (2+2) + cosmological data (right panel).

- The combined analysis of short-baseline + cosmological data adds SDSS and HST information to the CMB + SBL analysis. For the 3+1 scheme, the combined analysis for the 3+1 scheme, for the fit SBL + (CMB+LSS) gives an allowed region for 
  
  \[ 0.85 \text{ eV} < m_4 < 1.18 \text{ eV} \]

- For the 3+2 scheme, the combined analysis for the 3+2 scheme, for the fit SBL + (CMB+LSS) gives an allowed region for 
  
  \[ m_4 < 0.7 \text{ eV} \]
  \[ 0.67 \text{ eV} < m_5 < 1.35 \text{ eV} \]

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**References**