Testing 3+1 Neutrino Mass Models with Cosmology and Short-Baseline Experiments

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Neutrino models

Short Baseline (SBL) experiments $\Rightarrow$ mixing parameters:

- mixing angles and phases
- mass differences:

$$\left.\begin{array}{l}\Delta m^2_{SOL} = (7.6 \pm 0.2) \cdot 10^{-5}\ \mathrm{eV}^2 \\ \Delta m^2_{ATM} = (2.32^{+0.12}_{-0.08}) \cdot 10^{-3}\ \mathrm{eV}^2 \\ \Delta m^2_{SBL} \geq 0.1\ \mathrm{eV}^2\end{array}\right\} \Rightarrow$$

Existence of an additional neutrino degree of freedom, mass around 1 eV, no weak interaction $\Rightarrow$ *sterile*.

Mixing: $\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau, s)$

Neutrino oscillations anomaly: Δm^2_{SBL}.
See Hannen lecture, or
Giunti, Laveder, 2011.

Additional ν in cosmology: distribution function $f_s(p) = \dfrac{\beta_s}{e^{p/\alpha_s T_\nu} + 1}$

Contribution of the ν_s to cosmology described with: Acero, Lesgourgues, 2009

- $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - 3.046$: $\rho_R = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\mathrm{eff}}\right]\rho_\gamma$, it becomes $\Delta N_{\mathrm{eff}} = \beta_s \alpha_s^4$
- $m_s^{\mathrm{eff}} = (94.1\ \mathrm{eV})\,\omega_{\mathrm{s}} = \rho_{\mathrm{s}}/\rho_{\mathrm{c}}^0$, from which we obtain $m_s^{\mathrm{eff}} = m_s \beta_s \alpha_s^3$

  Constant is given by $\sum m_i = (94.1\ \mathrm{eV})\ \omega_\nu$ for SM neutrinos.

Problem: 2 observables (ΔN_{eff}, m_s^{eff}), 3 parameters (α_s, β_s, m_s)!

Grid of models for the `CosmoMC` analysis

For the SBL prior on m_s, we must simplify. Consider different scenarios:

- *Thermal (TH)*: thermalized ν_s, $\alpha_{TH} \neq 1$, $\beta_{TH} = 1 \Rightarrow m^{\mathrm{eff}}_{TH} = m_s \, (\Delta N^{TH}_{\mathrm{eff}})^{3/4}$
- Dodelson, Widrow, 1994 (DW): $\alpha_{DW} = 1$, $\beta_{DW} \neq 1 \Rightarrow m^{\mathrm{eff}}_{DW} = m_s \, \Delta N^{DW}_{\mathrm{eff}}$

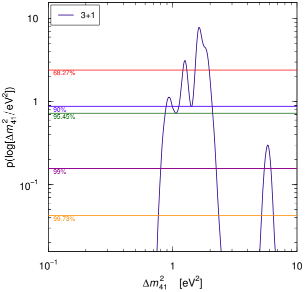
MCMC with `CosmoMC` with different cosmological data:

- *CMB*: Planck TT spectra and WMAP 9-year full data.
- *high-l* spectra from Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT).
- *Barionic Acoustic Oscillations (BAO)*: values obtained from the SDSS-DR7, the SDSS BOSS-DR9 and the 6dFGS.
- *H_0 prior*: $H_0 = 74.7 \pm 1.6 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$, from
  - $H_0 = 73.8 \pm 2.4 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$, using *Cepheids and SN Ia* Riess et al., 2011;
  - $H_0 = 74.3 \pm 2.1 \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$, by the *Carnegie Hubble Program* Freedmann et al., 2012;
  - $H_0 = 78.7^{+4.3}_{-4.5} \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$, using COSmological MOnitoring of GRAvItational Lenses (*COSMOGRAIL*) and Hubble Space Telescope data, Suyu et al., 2012.
- *All datasets*: CMB+H_0+BAO+high-l

Assume: $\sum m_{\nu,\mathrm{active}} = 0.06$ eV, $\quad 0 \leq m^{\mathrm{eff}}_s/\mathrm{eV} \leq 5, \quad 3.046 \leq N_{\mathrm{eff}} \leq 6$.

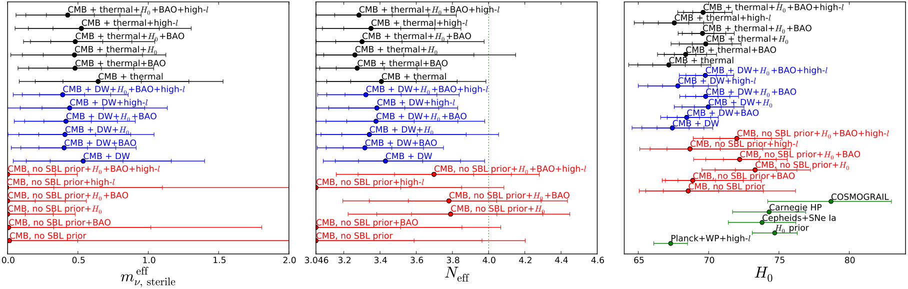
Results (briefly) - I

SBL prior on m_s from
Giunti et al, 2012:

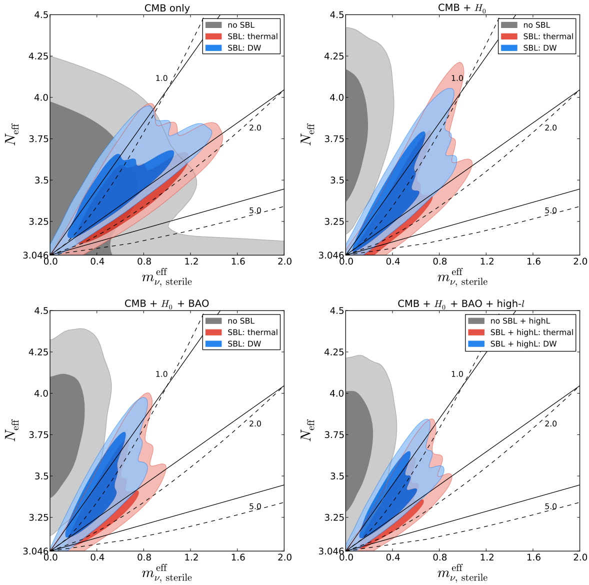


If we include SBL prior on m_s (DW or TH scenario):

- $m_s^{\rm eff} > 0$ eV at 99% CL (All datasets)
- $N_{\rm eff} < 4$ at 99% CL (All datasets) $\Rightarrow$ no more than one ν-equivalent relativistic dof
- $N_{\rm eff}$ lower limit:
  - $N_{\rm eff} > 3.046$ at 99% CL (DW, All datasets)
  - $N_{\rm eff} > 3.046$ at 95% CL (TH, All datasets)
- $\Rightarrow$ existence of additional relativistic dof, but *not thermalized as the active SM neutrinos*



Results (briefly) - II



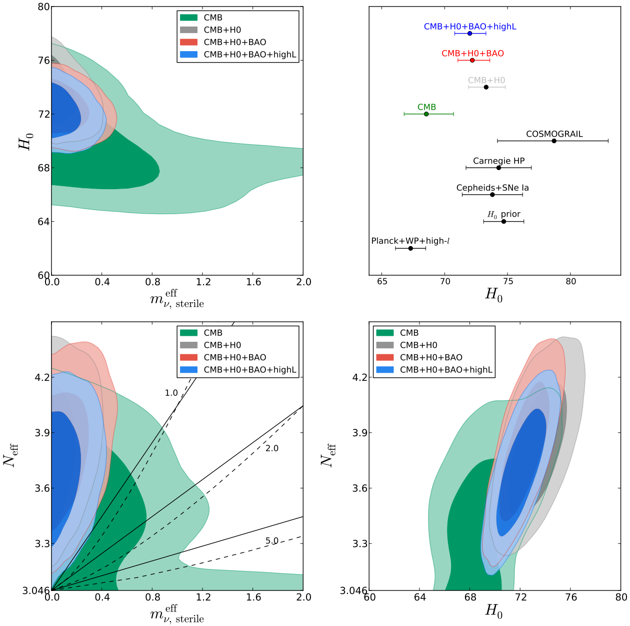
SBL prior effect on $m_s^{\rm eff}$, $\Delta N_{\rm eff}$ joint posterior:

- it removes tail at $\Delta N_{\rm eff} \simeq 0$, $m_s^{\rm eff} > 1$ eV (ν_s as CDM)
- it forces the shape of the joint 2D posterior
- tension between SBL and H_0 prior:
  - SBL: $m_s^{\rm eff} > 0$
  - H_0: $m_s^{\rm eff} \simeq 0$, high $N_{\rm eff}$

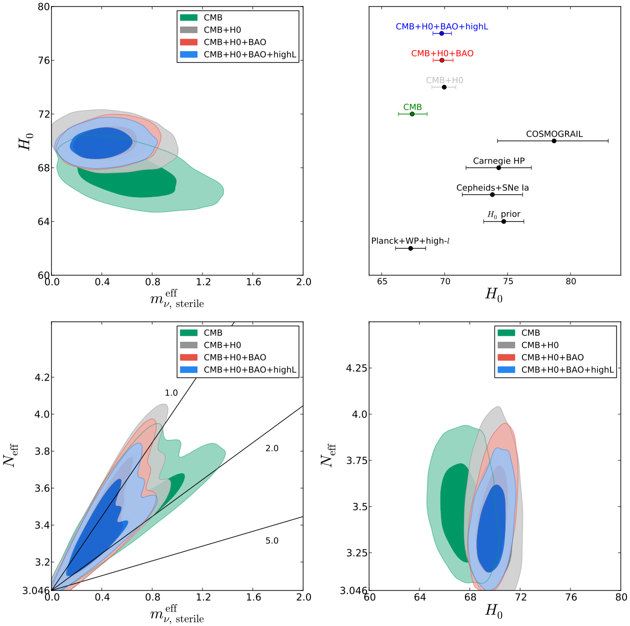
Thank you for the attention!

See also: Gariazzo, Giunti, Laveder (in preparation)

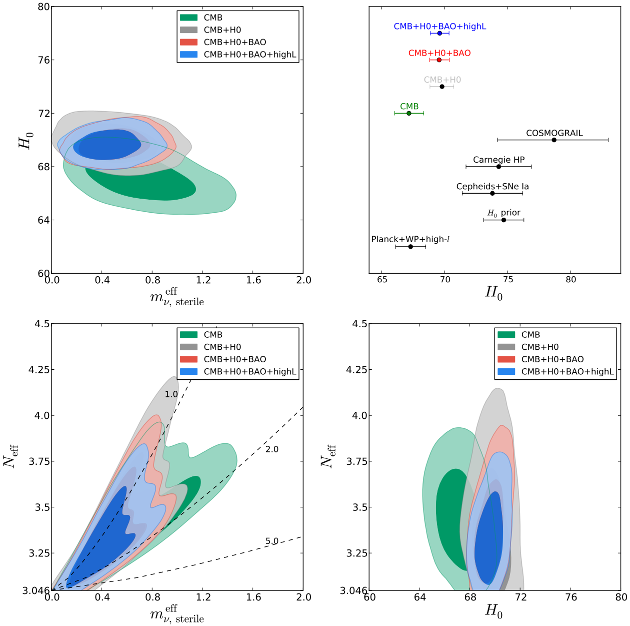
Backup pictures - Results without SBL prior



Backup pictures - SBL prior, DW scenario



Backup pictures - SBL prior, thermal scenario



SBL and reactor anomaly

Neutrino oscillations $\Rightarrow$ angles in the mixing matrix, Δm^2_{ij}.
Problem: observed anomalies in short baseline experiments $\Rightarrow$ deviations from standard 3-ν description?
A short review: Fan, Langacker, 2012

- *LSND*: search for $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a 3.8σ excess of $\bar{\nu}_e$ events.
- *MiniBooNE*: search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.2 \div 2.6$ m/MeV. No ν_e eccess detected, but $\bar{\nu}_e$ excess observed at 2.75σ (2010). 2011 results: excess favored at 91.1% CL for $L/E = 0.2 \div 1.13$ m/MeV.
- *Reactor anomaly*: re-evaluation of the expected anti-neutrino flux $\Rightarrow$ deficit of $\bar{\nu}_e$ events compared to predictions (mean 5.7%, at 98.6% CL) with $L < 100$ m.

Possible explanation: oscillations between active ν and a sterile ν at eV scale.
Possible models:

- 3 active ($m_i \ll 1$ eV) + 1 sterile ($m_s \simeq 1$ eV)
- 3 active ($m_i \ll 1$ eV) + 2 sterile ($m_s \simeq 1$ eV)

Some analysis: Giunti, Laveder, 2011 and Kopp, Maltoni, Schwetz, 2011