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

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About H_0

Measuring H_0 is a complex problem since in a curved Universe the knowledge of a method for measuring distances is required. Due to the Hubble law, $v_r = H_0 d$, H_0 is fundamental to determine the age and fate of the Universe, but it has been a long struggle against systematic error, bias, and complexity in distance ladder, cosmic-background and geometric measurements.
In our analysis we used a gaussian prior on H_0 obtained from different recent measurements:

- by SH0ES team [1], we used two values, obtained using only *Cepheids and SN Ia* as standard candles, measured by the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST): $H_0 = 73.8 \pm 2.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$;
- the *Carnegie Hubble Program* (CHP) team [2], descended from the Hubble Key Project on the Distance Scale, observed MW and LMC Cepheids with Spitzer and obtained $H_0 = 74.3 \pm 2.1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$;
- using COSmological MOnitoring of GRAvItational Lenses (*COSMOGRAIL*) and Hubble Space Telescope data, [3] obtained a value $H_0 = 78.7^{+4.3}_{-4.5}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ in a flat ΛCDM model with fixed $\Omega_\Lambda = 0.73$.

The prior we used is a weighted mean of the reported measurements: $H_0 = 74.7 \pm 1.6\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

SBL analysis

Recent Short Baseline experiments show neutrino oscillations generated by a mass difference $\Delta m^2_{SBL} \geq 0.1\,\mathrm{eV}^2$, that is much larger than the measured solar $\Delta m^2_{SOL} = (7.6 \pm 0.2) \cdot 10^{-5}\,\mathrm{eV}^2$ and atmospheric $\Delta m^2_{ATM} = (2.32^{+0.12}_{-0.08}) \cdot 10^{-3}\,\mathrm{eV}^2$ squared-mass differences. The minimal neutrino mixing schemes that can provide a third squared-mass difference require the introduction of a sterile neutrino ν_s.
The neutrino flavor eigenstates are written in term of the mass eigenstates:

$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k} \nu_k \,, \tag{1}$$

so that ν_s is mainly composed of a heavy neutrino ν_4, having:

$$m_1,\ m_2,\ m_3 \ll m_4 \,. \tag{2}$$

$U_{\alpha k}$ is the unitary mixing matrix, which can be written in term of the squared-mass differences $\Delta m^2_{ij} = m_i^2 - m_j^2$ and the effective mixing angles

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \,,\quad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2) \tag{3}$$

with $i, j = 1, 2, 3, 4$ and $\alpha, \beta = e, \mu, \tau, s$.
We consider the four-neutrino mixing as a perturbation of the three-neutrino mixing:

$$|U_{e4}|^2,\ |U_{\mu 4}|^2,\ |U_{\tau 4}|^2 \ll 1 \,,\quad |U_{s4}|^2 \simeq 1$$

For the analysis of SBL data in a 3+1 neutrino mass model we used the marginalized posterior probability for m_s obtained in Ref. [4] and printed in Fig. 1.

References

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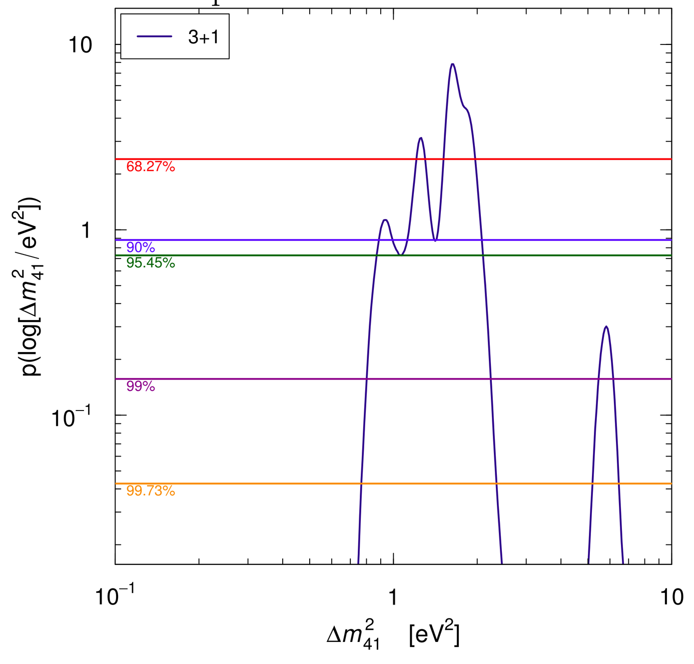
Figure 1: Marginalized posterior of m_s from SBL experiments.



Additional neutrinos in cosmology

For a relativistic fermion s, one can assume the distribution function:

$$f_s(p) = \frac{\beta}{e^{p/\alpha T_\nu} + 1} \tag{4}$$

(p is the particle momentum, $T_\nu = (4/11)^{1/3}\, T_\gamma$ is the temperature of the neutrino plasma, T_γ is the temperature of CMB photons, $\alpha = T_s/T_\nu$ and β describe a family of distribution functions).
If s becomes non-relativistic after photon decoupling, its physical effects on the cosmological background and perturbation evolution are described mainly by [5]:

- its contribution to the relativistic energy density before photon decoupling, usually parametrized through an effective neutrino number N_{eff}:

$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\mathrm{eff}}\right] \rho_\gamma \tag{5}$$

(ρ_R energy density provided by the radiation in the early universe, ρ_γ and T_γ photon energy density and temperature).
If Eq. 4 holds for s, one can obtain:

$$\Delta N_{\mathrm{eff}} = \beta_s \alpha_s^4 \,. \tag{6}$$

- its current energy density, parametrized by the dimensionless number $\omega_s = \Omega_s h^2$, where h is the reduced Hubble parameter, or equivalently by an effective mass m_s^{eff}:

$$m_s^{\mathrm{eff}} = (94.1\ \mathrm{eV})\, \omega_s \tag{7}$$

where the constant is given by $\sum m_i = (94.1\ \mathrm{eV})\, \omega_\nu$ for SM neutrinos.
$\omega_s = \rho_s/\rho_c^0$ is defined from $\rho_s = m_s n_{s,0}$, the energy density today for the not more relativistic s population, where ρ_c^0 is the critical density today and m_s the mass of one s particle. If Eq. 4 holds for the specie s, we obtain:

$$m_s^{\mathrm{eff}} = m_s \beta_s \alpha_s^3 \,. \tag{8}$$

We cannot solve for (m_s, α_s, β_s) having only two experimental data (Eq. 6, 8).
As a simpler case, we can consider:

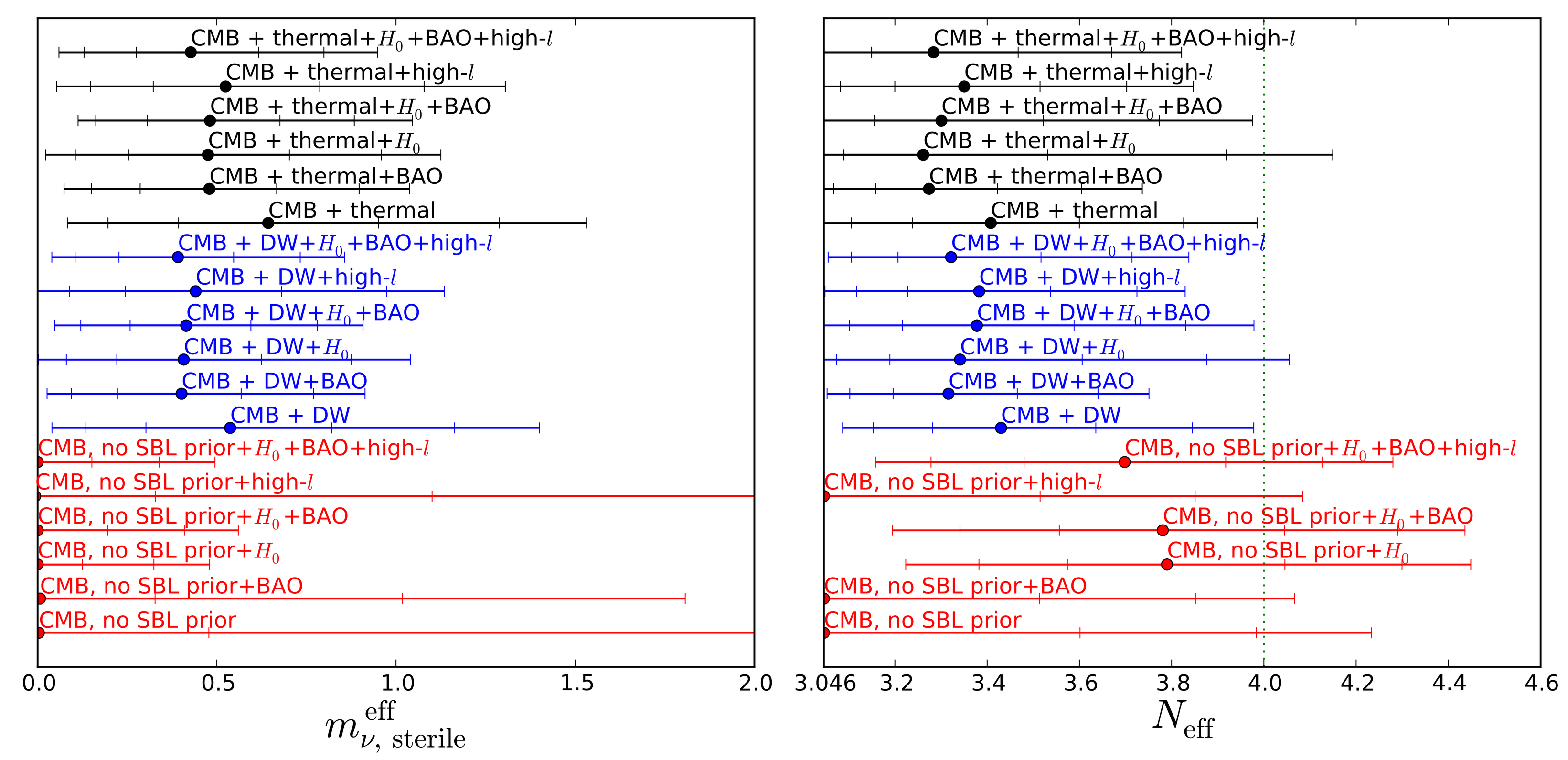
- a light thermal relic with a Fermi-Dirac distribution at a temperature $T_s = \alpha_s T_\nu$ with $\alpha_s \neq 1$ and $\beta = 1$ (*thermal scenario*): this scenario can be motivated by the existence of massive neutrinos that had decoupled long before the SM ones. For one family of additional neutrinos, we have

$$m^{\mathrm{eff}}_{thermal} = m_s\, \alpha_s^3 = m_s\, (\Delta N_{\mathrm{eff}}^{thermal})^{3/4} \,. \tag{9}$$

- a light non-thermal relic. Requiring the $f_s(p)$ as in Eq. 4, we can consider the *Dodelson - Widrow (DW) scenario* [6], motivated by early active-sterile neutrino oscillations in the limit of small mixing angle and zero lepton asymmetry, corresponding to $\alpha_{DW} = 1$ and $\beta_{DW} \neq 1$. For one family of additional neutrinos, we have

$$m^{\mathrm{eff}}_{DW} = m_s\, \beta_{DW} = m_s\, \Delta N_{\mathrm{eff}}^{DW} \,. \tag{10}$$

Figure 6: m_s^{eff} and N_{eff} in different models. Red points are models without SBL prior, blue points correspond to DW scenario, black points to thermal scenario. Error bars are 68%, 95% and 99% CL.



Data analysis

We used a modified version of the publicly available software `CosmoMC` [7].
To include the neutrino analysis, the ΛCDM model is expanded to a Λ Mixed Dark Matter (MDM) model (component of HDM in form of massive neutrinos). To parametrize the neutrino component we used:

- the sum of the standard neutrino masses $\sum m_{\nu,\mathrm{SM}} = 0.06$ eV ($m_1 \simeq 0$, $m_2^2 \simeq \Delta m^2_{SOL}$, $m_3^2 \simeq \Delta m^2_{ATM}$);
- the effective number of neutrinos N_{eff} (Eq. 5), with $3.046 \leq N_{\mathrm{eff}} \leq 6$;
- the effective mass of the additional neutrinos $m^{\mathrm{eff}}_{\mathrm{sterile}}$ (Eq. 7), with $0 \leq m_s^{\mathrm{eff}}/(\mathrm{eV}) \leq 5$.

With these choices, $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - 3.046$ is the effective number of additional neutrinos.
For our analysis we used different data sets and likelihood calculators:

- *Planck*: TT spectra, `CamSpec`, `Commander` likelihoods.
- *WMAP* 9-year polarized data and likelihood. We will refer to the WMAP set plus the *Planck* set as *CMB*.
- *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: $H_0 = 74.7 \pm 1.6\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

When including the prior by SBL experiments, we consider the models listed before: *thermal scenario* ($m_s^{\mathrm{thermal}} = m^{\mathrm{eff}}_{thermal}/(\Delta N^{thermal}_{\mathrm{eff}})^{3/4}$) and *DW scenario* ($m_s^{\mathrm{DW}} = m^{\mathrm{eff}}_{DW}/\Delta N^{DW}_{\mathrm{eff}}$).
We considers three different possibilities for the additional neutrino:

- *no SBL prior* on m_s;
- SBL prior on m_s for a *DW* neutrino;
- SBL prior on m_s for a *thermal* neutrino.

For each of these possibilities, we run `CosmoMC` with different cosmological data set inclusions: CMB only (base model), CMB + BAO, CMB + H_0, CMB + H_0 + BAO, CMB + high-l and CMB + H_0 + BAO + high-l.

Results

Results are resumed in Fig. 2 to 6.
The SBL prior imposes the presence of an additional neutrino with mass of about 1 eV: the tail at $\Delta N_{\mathrm{eff}} \simeq 0$ and large m_s^{eff} is suppressed when including the prior on m_s. Furthermore, small m_s^{eff} is suppressed and the permitted zone in the m_s^{eff}-N_{eff} plane changes significantly (Fig. 5) when including the SBL prior.
Tension between Planck data and H_0 prior (yet discussed in [8, 9]).
Tension between SBL prior and H_0 prior:

- SBL prior $\Rightarrow$ massive ν_4, small ΔN_{eff}.
- H_0 prior $\Rightarrow$ massless relativistic additional degrees of freedom, high ΔN_{eff}.

Considering SBL prior, $m_s^{\mathrm{eff}} > 0$ at 99% CL with all the cosmological data sets included (Fig. 6, left).

Considering SBL prior and all the cosmological data sets, $N_{\mathrm{eff}} < 4$ at 99% CL. For the DW scenario, $N_{\mathrm{eff}} > 3.046$ at 99% CL, while for the thermal scenario this is true only at 95% CL (Fig. 6, right). These limits suggest that an additional neutrino with $m_s \simeq 1$ eV should exist and account as part of the radiation component of the universe at CMB time ($N_{\mathrm{eff}} > 3.046$), but it cannot be thermalized at the same temperature of the SM neutrinos ($N_{\mathrm{eff}} < 4$).

Figure 5: Admitted regions in the plane m_s^{eff}-N_{eff}.

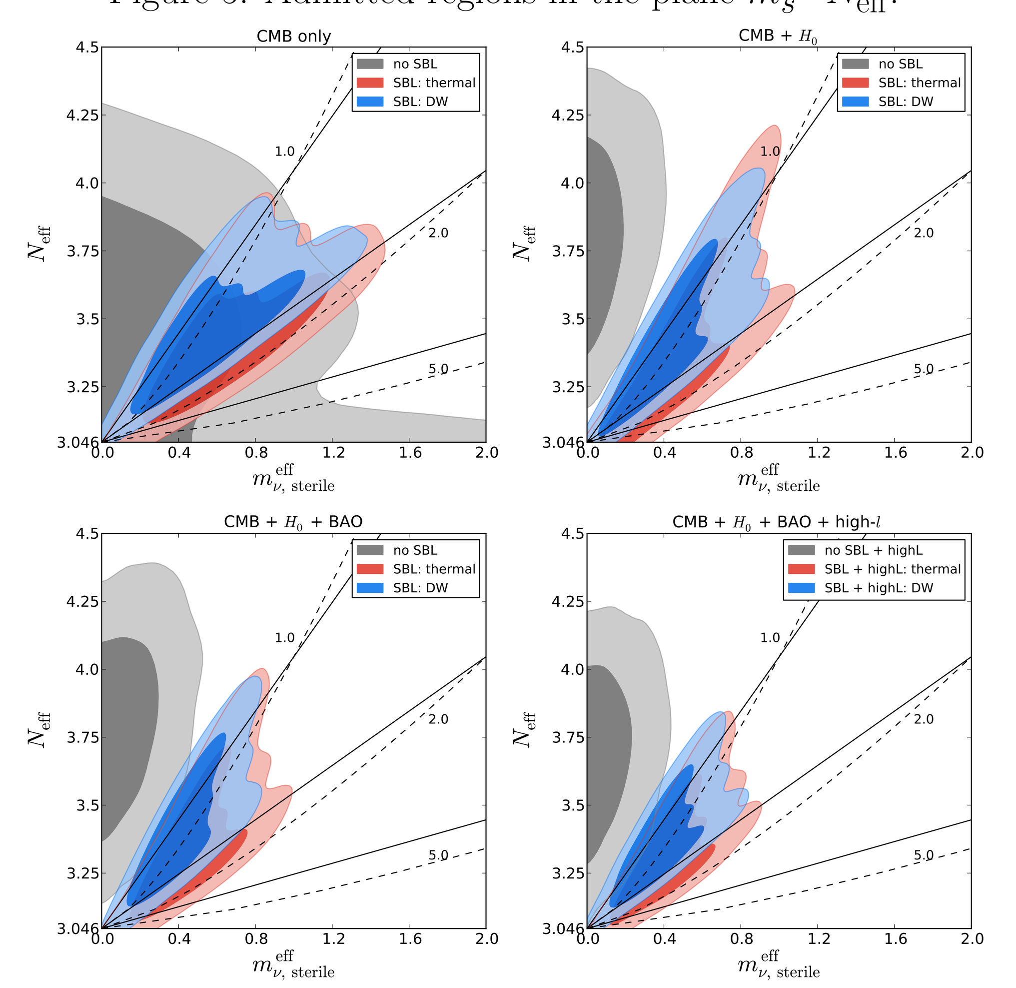


Figure 2: No SBL prior

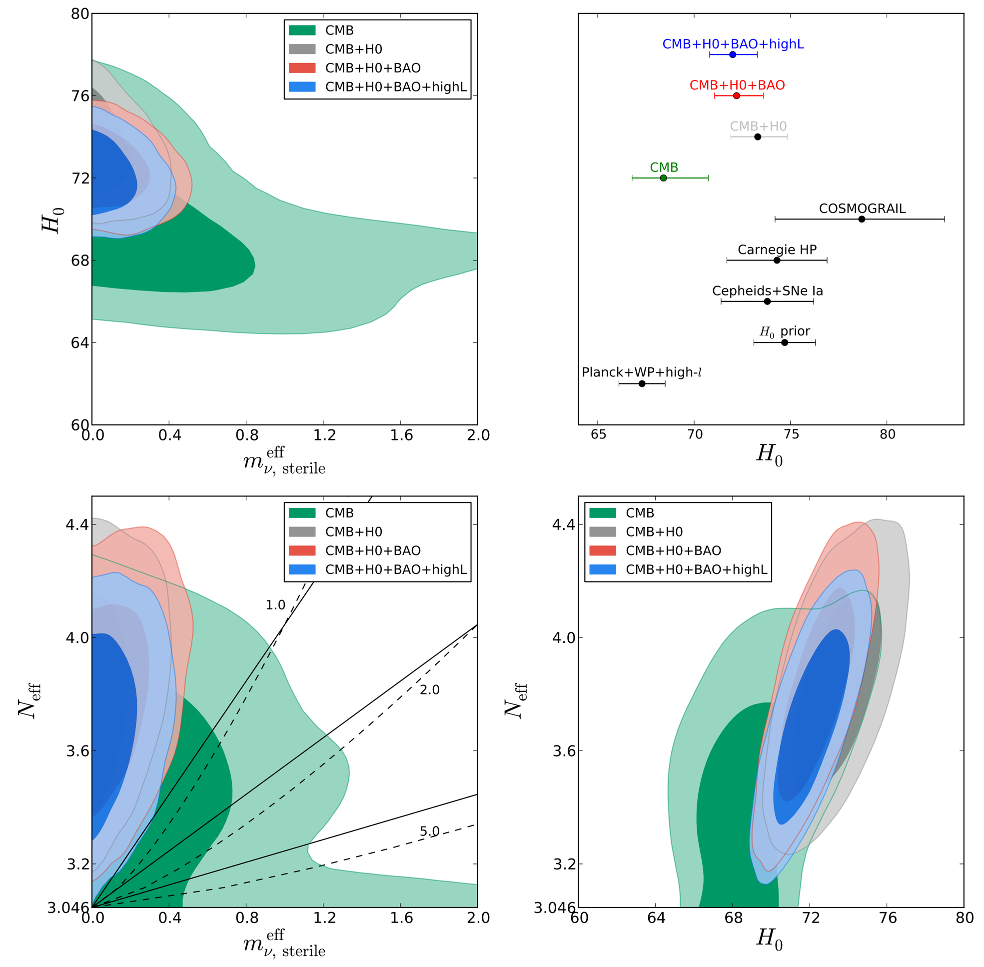


Figure 3: DW scenario

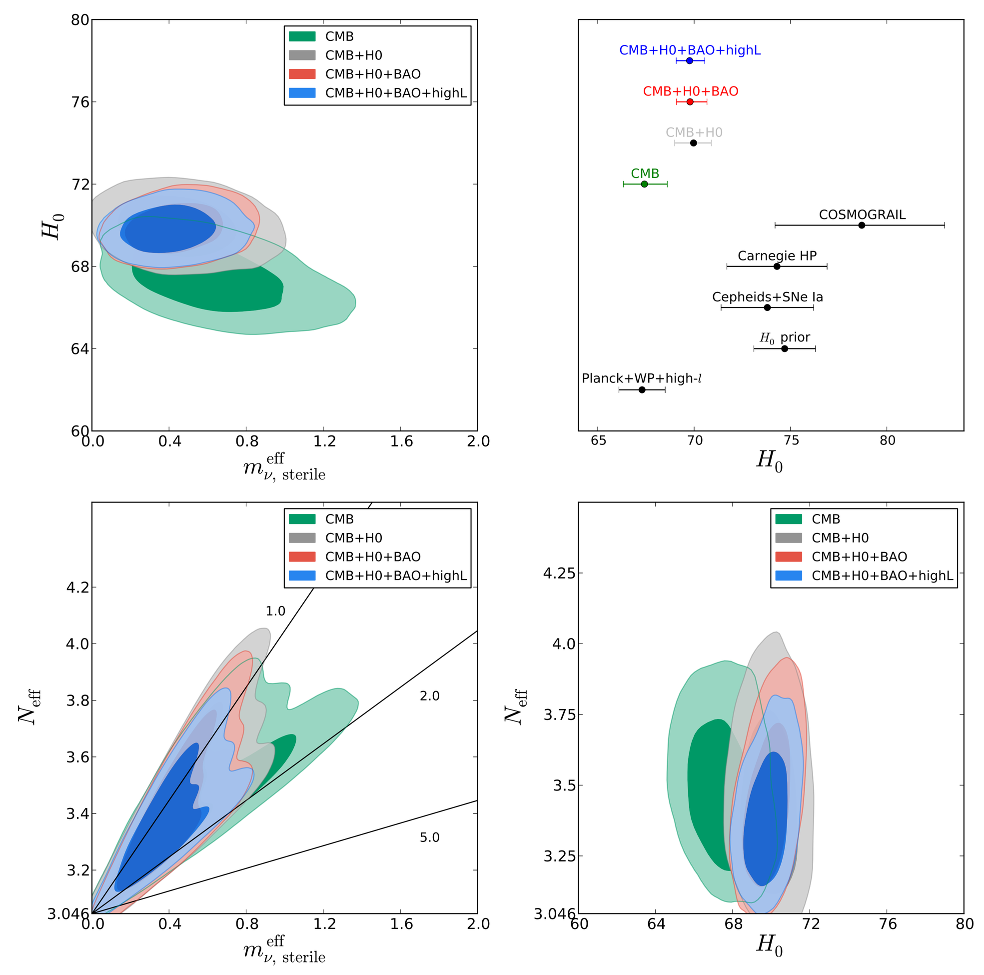


Figure 4: Thermal scenario