Reconciling cosmology and short-baseline experiments with invisible decay of light sterile neutrinos

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Neutrino Oscillations - I

- neutrino existence proposed by Pauli (1930) to explain β decay
- first time observed in 1956 by C. Cowan, F. Reines
- oscillations proposed in 1957 by B. Pontecorvo
- "massless" until oscillations detected in 1998 (SuperKamiokande)
- ν oscillate only if they have different masses (even if very small)
  $\Rightarrow$ not all of them are massless

Neutrino oscillations: analogous to CKM mixing for quarks, with

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

ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

Neutrino Oscillations - II

Oscillations sensitive only to mass differences, not to absolute mass scale!

Effective 2 neutrino mixing ($\Delta m^2_{21} = m^2_2 - m^2_1$, θ_{12} mixing angle):

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Current knowledge of the active ν mixing:

$$\begin{aligned} \Delta m^2_{SOL} &= (7.50 \pm 0.20)\cdot 10^{-5}\ \mathrm{eV}^2 &&= \Delta m^2_{21} \\ \Delta m^2_{ATM} &= (2.32^{+0.12}_{-0.08})\cdot 10^{-3}\ \mathrm{eV}^2 &&= |\Delta m^2_{32}| \simeq |\Delta m^2_{31}| \end{aligned}$$

$$\begin{aligned} \sin^2(2\theta_{12}) &= 0.857 \pm 0.024 \\ \sin^2(2\theta_{23}) &> 0.95 \\ \sin^2(2\theta_{13}) &= 0.095 \pm 0.010 \end{aligned}$$

[PDG - Beringer et al. (2013)]

CP violation possible only if $\sin\theta_{13} \neq 0$

CP violating phase still unknown.

SBL and reactor anomaly

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 [Aguilar et al., 2001]
- *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 excess detected, but $\bar{\nu}_e$ excess observed at 2.8σ [MiniBooNE Collaboration, 2013]
- *Reactor anomaly*: re-evaluation of the expected anti-neutrino flux $\Rightarrow$ excess of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Azabajan et al, 2012]
- *Gallium anomaly*: GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e) [Giunti, Laveder, 2011]

Possible explanation:

$$\Delta m^2_{SBL} \simeq 1\ \mathrm{eV}^2$$

Further details: [Giunti et al., 2013]

Sterile Neutrino mass

SBL anomaly $\Rightarrow \Delta m^2_{SBL} \simeq 1\ \mathrm{eV}^2$ [Giunti et al., 2013]

$\Downarrow$

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

$\Downarrow$

3 active ($m_i \ll 1$ eV) + 1 sterile ($m_s \simeq 1$ eV) ν scenario

We must update our mixing paradigm:

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

[Giunti et al, 2013]
$0.82 \leq \Delta m^2_{SBL} / \mathrm{eV}^2 \leq 2.19$
(3σ)

ν_s is mainly ν_4:

$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{SBL}}$$

Additional Neutrino in Cosmology

Sterile 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]

- $\Delta N_{\rm eff} = N_{\rm eff} - 3.046$: $\rho_R = \left[1 + \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 N_{\rm eff}\right]\rho_\gamma$, it becomes $\Delta N_{\rm eff} = \beta_s \alpha_s^4$
- $m_s^{\rm eff} = (94.1\,{\rm eV})\,\omega_{\rm s} = \rho_{\rm s}/\rho_{\rm c}^0$, from which we obtain $m_s^{\rm eff} = m_s \beta_s \alpha_s^3$
  Constant is given by $\sum m_i = (94.1\,{\rm eV})\,\omega_\nu$ for SM neutrinos.

Problem: 2 observables ($\Delta N_{\rm eff}$, $m_s^{\rm eff}$), 3 parameters (α_s, β_s, m_s)!

Hp: ν_s follows a thermal distribution with $T_s = \alpha_s T_\nu$ and $\beta_s = 1$.

$$\Rightarrow m_{TH}^{\rm eff} = m_s\,(\Delta N_{\rm eff}^{TH})^{3/4}$$

Parameters

In the following we will study the Universe evolution considering a $\Lambda CDM + r_{0.002} + \nu_s$ model with 9 free parameters:

$$\{\omega_{CDM}, \omega_b, \theta_s, \tau, \ln(10^{10}A_s), n_s\} + r_{0.002} + \{\Delta N_{\rm eff}, m_s\}$$

ω_{CDM} - CDM density today
ω_b - baryon density today
θ_s - angular sound horizon
τ - optical depth to reionization
$\ln(10^{10}A_s)$ - amplitude and
n_s tilt of the primordial power spectrum

$r_{0.002}$ - tensor to scalar ratio at 0.002 Mpc^{-1}

$\Delta N_{\rm eff}$ effective number of ν_s
m_s physical mass of ν_s

Assume:

- $\sum m_{\nu,\rm active} = 0.06$ eV (minimal for Normal Hierarchy)
- $0 \leq m_s/\mathrm{eV} \leq 3.5$
- $0 \leq \Delta N_{\rm eff} \leq 3$

Datasets for the `CosmoMC` analysis

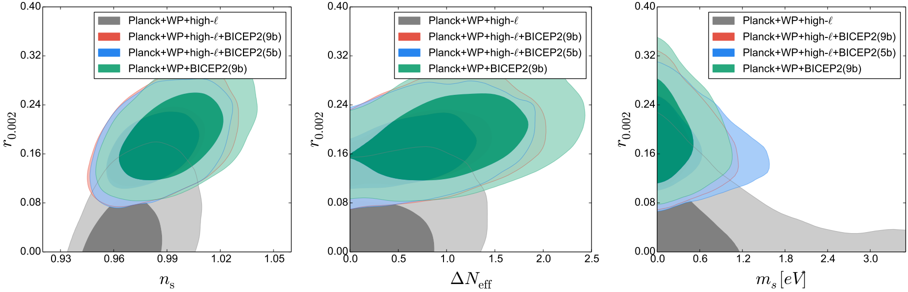
MCMC with `CosmoMC` with different cosmological data:

- *Planck*: Planck TT spectra
- *WP*: WMAP 9-year polarization data.
- *high-ℓ* spectra from Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT).
- *BICEP2* B-modes autocorrelation power spectrum.
- *LSS*: WiggleZ Dark Energy Survey matter power spectrum at 4 different redshifts.
- *H_0*: $H_0 = 73.8 \pm 2.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, using *Cepheids and SN Ia*.
- *CFHTLens*: the CFHTLens 2D cosmic shear correlation function (from redshifts and shapes of 4.2 million galaxies with $0.2 < z < 1.3$).
- *PSZ*: 189 galaxy clusters identified through the Sunayev Zel'Dovich effect from Planck SZ catalogue.

SBL data included as a prior on m_s.

In the following: CMB = Planck+WP+high-ℓ+BICEP2(9b)

Results - I



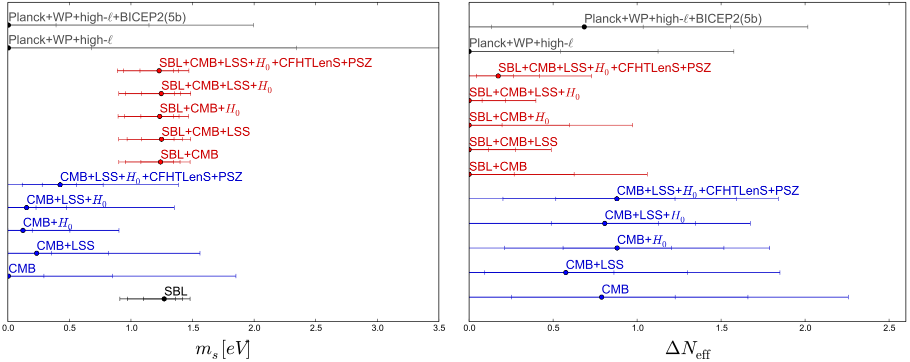
First tension: $r_{0.002}$ (with and without BICEP2)
We must wait Planck 2014 data release, with polarization data

No significant variations using different CMB dataset:

- Planck+WP+high-ℓ+BICEP2(9b)
- Planck+WP+high-ℓ+BICEP2(5b)
- Planck+WP+BICEP2(9b)

Notice: $\Delta N_{\rm eff}$ larger with BICEP2 (indirect correlation with $r_{0.002}$ through n_s)

Results - II

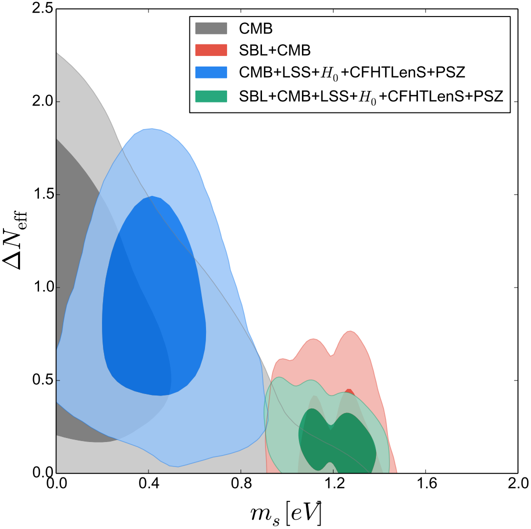


Second tension: m_s vs $\Delta N_{\rm eff}$ (with and without SBL)

Notice: small $\Delta N_{\rm eff}$ if $m_s \sim 1$ eV
$\Rightarrow \nu_s$ cannot be fully thermalized, $\Delta N_{\rm eff} \ll 1 \to T_s \ll T_\nu$

Notice: CFHTLenS and PSZ data give a preference ($> 2\sigma$) for $m_s > 0$, but $m_s \sim 0.5$ eV and lower than 1 eV at $> 2\sigma$

Results - III



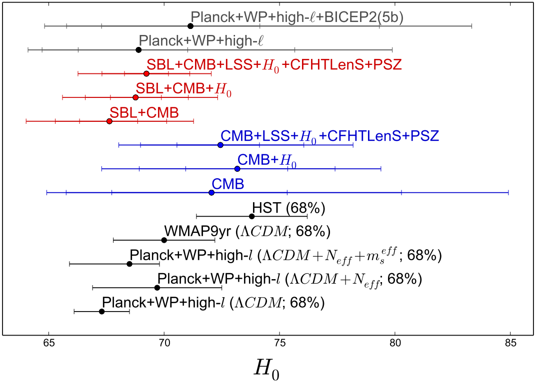
2D marginalized posterior distribution for $\Delta N_{\rm eff}$, m_s

Comparison:

- CMB only
- complete dataset

with and without SBL data

Results - IV



Third tension: H_0

- Planck vs local measurements
- value inferred from CMB highly model-dependent: correlation with $N_{\rm eff}$

  $\Rightarrow$ higher values if BICEP2 included (higher $N_{\rm eff}$)
  $\Rightarrow$ smaller values if SBL included (smaller $N_{\rm eff}$)

Cosmological invisible decay of light sterile neutrinos

Proposed solution for solve the encountered tensions:
ν_s can decay - lifetime τ_s comparable with Age of the Universe t_U

Decay products belong to the sterile sector ⇒ very weak interaction, invisible

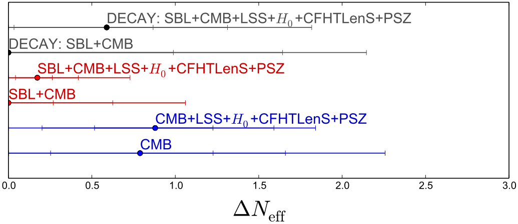
Effective number of ν_s: $N_s(t) = \Delta N_{\mathrm{eff}} \cdot e^{-t/\tau_s}$
τ_s assumed to be constant (no energy dependent).

Decay products have negligible mass: they can be accounted as radiation with effective number $N_{dp}(t) = \Delta N_{\mathrm{eff}} \cdot (1 - e^{-t/\tau_s})$
Energy distribution of the invisible decay products neglected for simplicity.

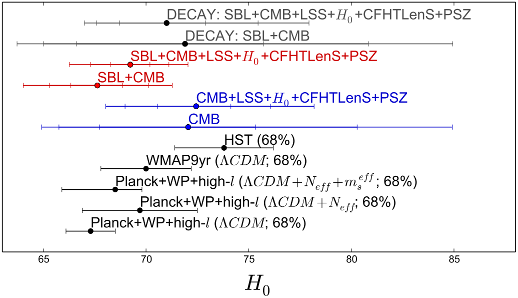
Computational problem: time t depends on the energy density contributions.
Approximation: t calculated considering matter dominated universe. True except:

- initial radiation domination - very short
- final Λ domination - largest part of ν_s has decayed

Results - I



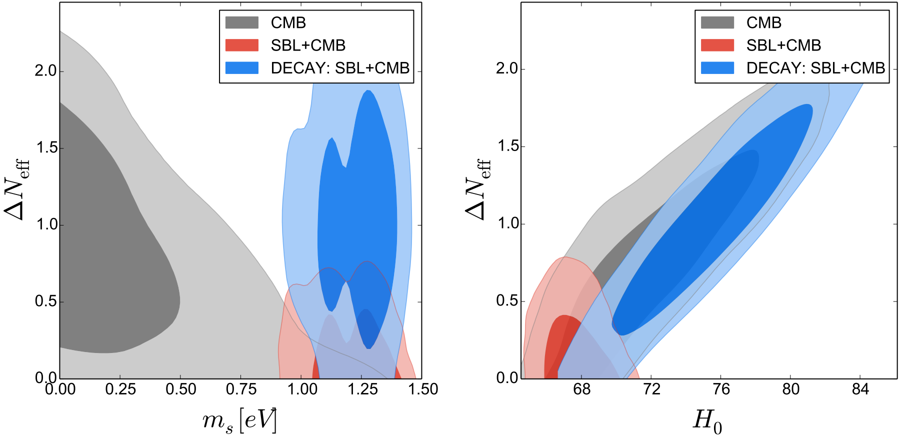
$\Delta N_{\rm eff} = 1$ is allowed



H_0 compatible with local measurements (HST)

With sterile neutrino decay, $\Delta N_{\rm eff}$ and H_0 are at the same level than the ones without SBL prior

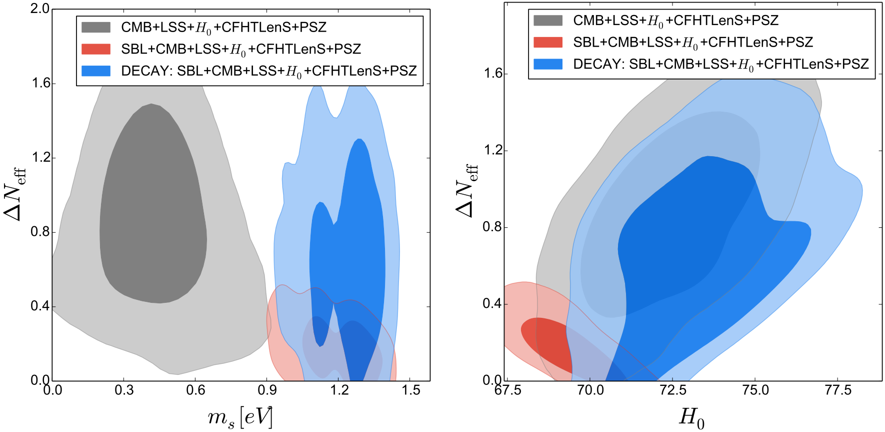
Results - II - CMB only



High $\Delta N_{\rm eff}$ even with SBL mass

Correlation between $\Delta N_{\rm eff}$ and H_0 recovered

Results - III - full dataset



Ω_{ν_s} can explain cluster data since it is related both to m_s and $\Delta N_{\rm eff}$:

$$\Omega_{\nu_s} \propto N_s(t)^{3/4} m_s$$

Correlation between $\Delta N_{\rm eff}$ and H_0 recovered

Shape in $\Delta N_{\rm eff} - H_0$ plot due to volume effects in the Bayesian analysis

Conclusions

- Anomalies with the 3-ν mixing scenario, solved with additional sterile neutrino.
- Analysis with cosmological and SBL data has some problems:
    - tensor to scalar ratio, Planck vs BICEP2
    - properties of the additional sterile neutrino
    - H_0 parameter
- invisible decay of ν_s can explain part of these problems.

Thank you for the attention!

Further details:
[Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, arxiv:1404.1794]
[Gariazzo, Giunti, Laveder, arxiv:1404.6160]

Correlation between $r_{0.002}$ and $\Delta N_{\rm eff}$

BICEP2: higher $r_{0.002}$ that correspond to more large-scale fluctuations.

Primordial power spectrum:

$$\mathcal{P}_k = A_s (k/k_0)^{n_s - 1}$$

k_0 pivot scale, A_s amplitude, n_s tilt

Higher $r_{0.002}$ can be compensated with an increase of $n_s \rightarrow$ decrease of large-scale fluctuations

Increase of $n_s \rightarrow$ increase of small-scale fluctuations ($k \gg k_0$)

$$\Downarrow$$

Effect can be compensated with an increase of $N_{\rm eff} \rightarrow$ decrease of small-scale fluctuations due to free streaming of relativistic particles