

Constraints on neutrino masses from cosmological observations

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Abstract

I present an overview of studies that lead to a measurement of the sum of masses of the three neutrino flavors using cosmological observations. The result is $\sum m_\nu = 0.27 \pm 0.08$ eV for $h = 0.6990 \pm 0.0030$. The correlation between these two parameters is $h + 0.020 \sum m_\nu = 0.7038 \pm 0.0060$.

1 Introduction

At the 2020 Guadeloupe conference I presented an overview of several studies of neutrino masses published in references [1], [2], and [3]. We measure the sum of the masses of the three neutrino flavors $\sum m_\nu$. The measurement is illustrated in Figure 2. Shown is the power spectrum of linear density perturbations $P(k)$ for $\sum m_\nu = 0$ and $\sum m_\nu = 0.6$ eV, multiplied by a bias factor, compared to the galaxy power spectrum $P_{\text{gal}}(k)$ [4]. k is the comoving wavenumber. The power spectrum depends on 5 independent cosmological parameters [2] [5] [6]: Ω_m , h , n_s , $\sum m_\nu$, and the amplitude $N^2 \equiv A_s/(4\pi) \equiv \Delta_R^2/(4\pi)$. (We use the standard notation in cosmology as defined in [7].) We treat Ω_r as a dependent parameter: it depends on h , and has contributions from photons and neutrinos. So we need at least 5 measurements to obtain $\sum m_\nu$.

The measurements, used in various combinations, are: (1) The Sachs-Wolfe effect, that constrains $P(k)$ in the range $-3.1 \lesssim \log_{10}(k/h \text{ Mpc}^{-1}) \lesssim -2.7$, from the COBE mission, and the Planck experiment. (2) σ_8 , that constrains $P(k)$ in the range $-1.3 \lesssim \log_{10}(k/h \text{ Mpc}^{-1}) \lesssim -0.6$, measured with gravitational lensing, and with galaxy clusters. (3) A measurement of Ω_m with Baryon Acoustic Oscillations (BAO) (used as an uncalibrated standard ruler), and the sound horizon angle θ_* obtained by the Planck collaboration. (4) A constraint between h , Ω_m , and $\sum m_\nu$ obtained with BAO (used as a calibrated standard ruler), and θ_* . (5) A combination of Ω_m from BAO, with the Planck global fit, to be described in Section 2. (6) The galaxy power spectrum measured by the BOSS collaboration. (7) Measurements of $P_{\text{gal}}(k)$ at four values of k . To use the measurements of $P_{\text{gal}}(k)$ we need to introduce two new parameters: a bias factor, and its slope.

2 Combination of Baryon Acoustic Oscillation and Planck data

We measure Ω_m with BAO used as an uncalibrated standard ruler (with Sloan Digital Sky Survey SDSS DR14 data [8, 9]), and the sound horizon angle θ_* from the Planck analysis [3]. Assuming $\Omega_k = 0$, and Ω_Λ independent of the expansion parameter a (assumptions that are consistent with



Figure 1: Guadeloupe Islands.

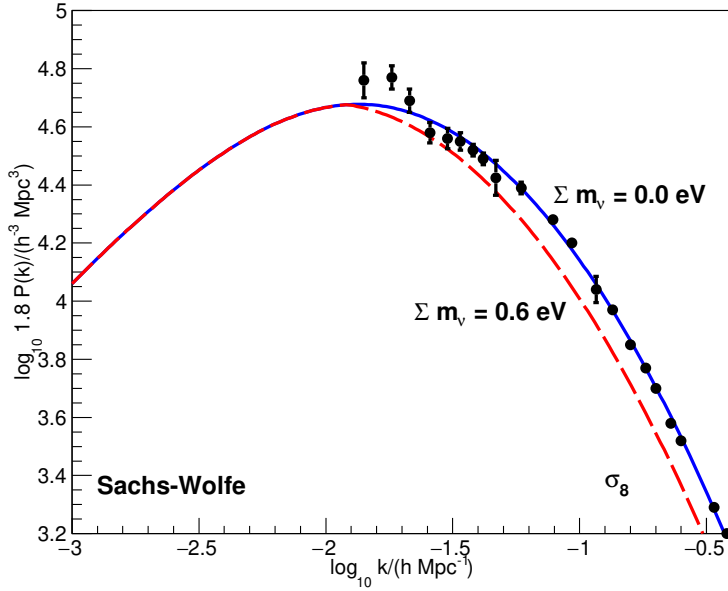


Figure 2: Comparison of $P_{\text{gal}}(k)$ obtained from the SDSS-III BOSS survey [4] (“reconstructed”) with $b^2 P(k)$ for $\sum m_\nu = 0$ eV. Also shown for comparison is the curve with the same parameters, except $\sum m_\nu = 0.6$ eV.

data [10]), we obtain $\Omega_m = 0.2724 \pm 0.0047$ [3]. This result is independent of any other cosmological parameter. This measurement of Ω_m has a 4.9σ tension with the Planck analysis.

We embark on a study of the Cosmic Microwave Background fluctuation spectra, and find that a 10% shift in Ω_m results in a 0.11% root-mean-square deviation of the CMB spectra relative to the first acoustic peak, see Figure 3. So the Planck analysis can benefit with a combination with Ω_m from BAO. The combination, obtained with the “base_mnu_plikHM_TTTEEE_lowTEB_lensing_*.txt MC chains”, made public by the Planck Collaboration [11], is presented in Table 1. This combination is preliminary due to the sparseness of the MC chains at low values of Ω_m .

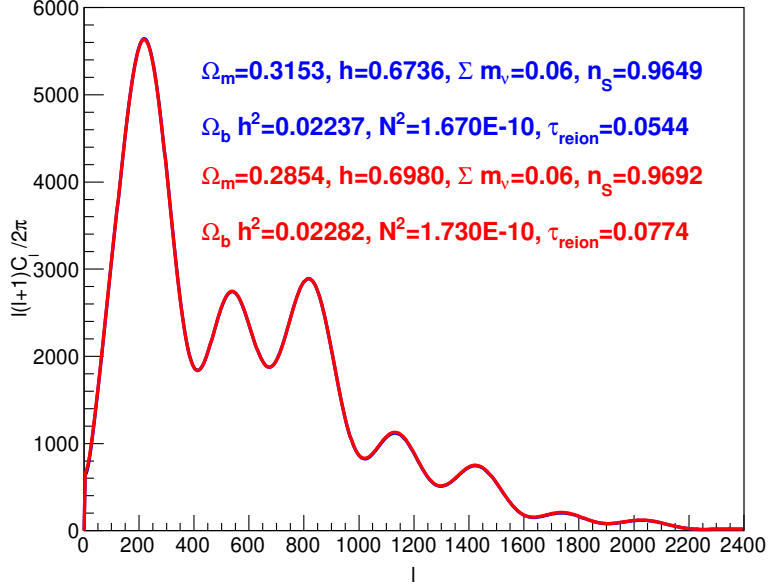


Figure 3: Comparison of the power spectra $l(l+1)C_{TT,l}^S/(2\pi)$ [μK^2] for the Planck 2018 “TT,TE,EE+lowE+lensing” parameters, with the best fit spectra with $\Omega_m = 0.2854$ and $\sum m_\nu = 0.06$ eV fixed, calculated with the approximate Equation (7.2.41) of [5] (modified to include $\sum m_\nu$). The r.m.s. difference is $6.07\mu\text{K}^2$, corresponding to 0.11% of the first acoustic peak, so the two spectra can not be distinguished by eye.

Note that this combination raises the Planck χ^2 from 12956.78 to 12968.64, while it lowers the Planck+ Ω_m combination χ^2 from 13040.09 to 12976.17. Note that the combination obtains $\Omega_m = 0.2853 \pm 0.0040$, and $h = 0.6990 \pm 0.0030$.

We quote from Reference [3]: “We consider four direct measurements: (i) $h = 0.7348 \pm 0.0166$ by the Sh₀es Team [12], (ii) $\sigma_8 \approx [0.746 \pm 0.012$ (stat) ± 0.022 (syst)] $(0.3/\Omega_m)^{0.47}$ from the abundance of rich galaxy clusters [7, 13], (iii) $\sigma_8 \approx [0.745 \pm 0.039] (0.3/\Omega_m)^{0.5}$ from weak gravitational lensing [7, 14], and (iv) $\Omega_m = 0.2724 \pm 0.0047$ from galaxy BAO and θ_* from Planck, this analysis. Comparing these measurements with Planck (left hand column of Table 1) we obtain differences of 3.5σ , 2.5σ , 1.8σ , and 4.9σ , respectively. Comparing these measurements with the Planck+ Ω_m combination (right hand column of Table 1) we obtain differences of 2.1σ , 2.3σ , 1.5σ , and 2.1σ , respectively. In conclusion, the Planck+ Ω_m combination reduces the tensions with the direct measurements, including h , leaving no significant anomalies. Note that the Planck+ Ω_m combination has σ_8 greater than the direct measurements. This 2.7σ tension may be due to neutrino masses.”

3 Results

The final measurement of $\sum m_\nu$ is obtained by fitting 6 parameters to minimize a χ^2 with 8 terms. The 6 fitted parameters are $\sum m_\nu$, N^2 , h , n_s , and the $P_{\text{gal}}(k)$ bias and slope. The 8 terms of the χ^2 are $N^2 = (2.08 \pm 0.33) \times 10^{-10}$, $h = 0.6990 \pm 0.0030$, and $n_s = 0.9726 \pm 0.0017$ from the Ω_m +Planck combination, σ_8 from a combination of gravitational lensing [7, 14] and galaxy cluster [7, 13] measurements, and 4 measurements of $P_{\text{gal}}(k)$. This fit has no significant pulls. The calibrated BAO measurement

	Planck	Planck+ Ω_m
$\Omega_b h^2$	0.02237 ± 0.00015	0.02265 ± 0.00012
$\Omega_c h^2$	0.1200 ± 0.0012	0.1155 ± 0.0005
$100\theta_*$	1.04092 ± 0.00031	1.04125 ± 0.00022
τ	0.0544 ± 0.0073	0.078 ± 0.006
$\ln 10^{10} A_s$	3.044 ± 0.014	3.102 ± 0.020
n_s	0.9649 ± 0.0042	0.9726 ± 0.0017
Ω_Λ	0.6847 ± 0.0073	0.7147 ± 0.0040
Ω_m	0.3153 ± 0.0073	0.2853 ± 0.0040
h	0.6736 ± 0.0054	0.6990 ± 0.0030
σ_8	0.8111 ± 0.0060	0.8346 ± 0.0054
χ_p^2	12956.78	12968.64
χ_G^2	83.31	7.53
χ_{tot}^2	13040.09	12976.17

Table 1: Combination of the Planck 2018 “TT,TE,EE+lowE+lensing” analysis [11] with the directly measured $\Omega_m = 0.2724 \pm 0.0047$ [3]. Uncertainties are at 68% confidence. The Planck $\chi_p^2 \equiv -2 \cdot \ln \mathcal{L}$ increases from 12956.78 to 12968.64 with this combination. The galaxy $\chi_G^2 \equiv (\Omega_m - 0.2724)^2 / 0.0047^2$. Preliminary.

combined with the acoustic angular scale θ_* obtains the following constraint [3] [7]:

$$\begin{aligned} \theta_* &\equiv \frac{d_*}{\chi(z_*)} = 0.0104092 \pm 0.0000031 \\ &= 0.010427 \left(\frac{h + 0.020 \sum m_\nu}{0.70} \right)^{0.503} \times \left(\frac{\Omega_m}{0.28} \right)^{0.156} \left(\frac{0.0225}{\Omega_b h^2} \right)^{0.097}, \end{aligned} \quad (1)$$

with $\Omega_b h^2 = 0.02265 \pm 0.00012$ [7]. σ_8 is obtained from the combination of $\sigma_8 \approx [0.746 \pm 0.012 \text{ (stat)} \pm 0.022 \text{ (syst)}] (0.3/\Omega_m)^{0.47}$ from the abundance of rich galaxy clusters [7, 13], and $\sigma_8 \approx [0.745 \pm 0.039] (0.3/\Omega_m)^{0.5}$ from weak gravitational lensing [7, 14], with Ω_m obtained from the constraint (1).

The final fit obtains

$$\sum m_\nu = 0.27 \pm 0.08 \text{ eV}, \quad (2)$$

with $\chi^2 = 1.6$ for two degrees of freedom. The correlation between h and $\sum m_\nu$ is [3]

$$h + 0.020 \sum m_\nu = 0.7038 \pm 0.0060. \quad (3)$$

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References

- [1] Hoeneisen, B. (2018) Constraints on Neutrino Masses from Baryon Acoustic Oscillation Measurements. *International Journal of Astronomy and Astrophysics*, 8, 1-5.
<https://doi.org/10.4236/ijaa.2018.81001>

- [2] B. Hoeneisen (2018) Study of Galaxy Distributions with SDSS DR14 Data and Measurement of Neutrino Masses. *International Journal of Astronomy and Astrophysics*, 8, 230-257, 2018.
<https://doi.org/10.4236/ijaa.2018.83017>
- [3] Hoeneisen, B.(2018) Measurements of the Cosmological Parameters Ω_m and H_0 . *International Journal of Astronomy and Astrophysics*, 8, 386-405.
<https://doi.org/10.4236/ijaa.2018.84027>
- [4] Anderson, L. *et al.* (2012) The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: baryon acoustic oscillations in the Data Release 9 spectroscopic galaxy sample. *MNRAS* **427**, 3435.
- [5] Steven Weinberg, *Cosmology*, Oxford University Press, 2008.
- [6] Lesgourgues, J., and Pastor, S. (2006) Massive neutrinos and cosmology. *Phys. Rep.* 429, 307.
- [7] Tanabashi, M. *et al.* (Particle Data Group) (2018), The Review of Particle Physics, *Phys. Rev. D* 98, 030001.
- [8] Blanton, M.R. *et al.*, Sloan Digital Sky Survey IV: Mapping the Milky Way, Nearby Galaxies, and the Distant Universe, *The Astronomical Journal*, Volume 154, Issue 1, article id. 28, 35 pp. (2017)
- [9] Dawson, K.S., *et al.*, The Baryon Oscillation Spectroscopic Survey of SDSS-III, *The Astronomical Journal*, Volume 145, Issue 1, article id. 10, 41 pp. (2013)
- [10] Hoeneisen, B. (2017) Study of Baryon Acoustic Oscillations with SDSS DR13 Data and Measurements of Ω_k and $\Omega_{de}(a)$. *International Journal of Astronomy and Astrophysics*, 7, 11-27.
<https://doi.org/10.4236/ijaa.2017.71002>
- [11] Planck Collaboration: Aghanim, N. *et al.* (2018) Planck 2018 results. VI. Cosmological parameters, arXiv:1807.06209.
- [12] Riess, A. G., Casertano, S., Yuan W., *et al.* (2018) New Parallaxes of Galactic Cepheids from Spatially Scanning the Hubble Space Telescope: Implications for the Hubble Constant, *ApJ*, 861, 126. arXiv:1801.01120.
- [13] Vikhlinin, A. *et al.* (2009) Chandra Cluster Cosmology Project III: Cosmological Parameter Constraints, *Astrophys. J.* 692, 1060.
- [14] Hildebrandt, H. *et al.* (2017) KiDS-450: cosmological parameter constraints from tomographic weak gravitational lensing, *Mon. Not. R. Astron. Soc* 465, 1454.

