Constraints on neutrino masses from cosmological observations

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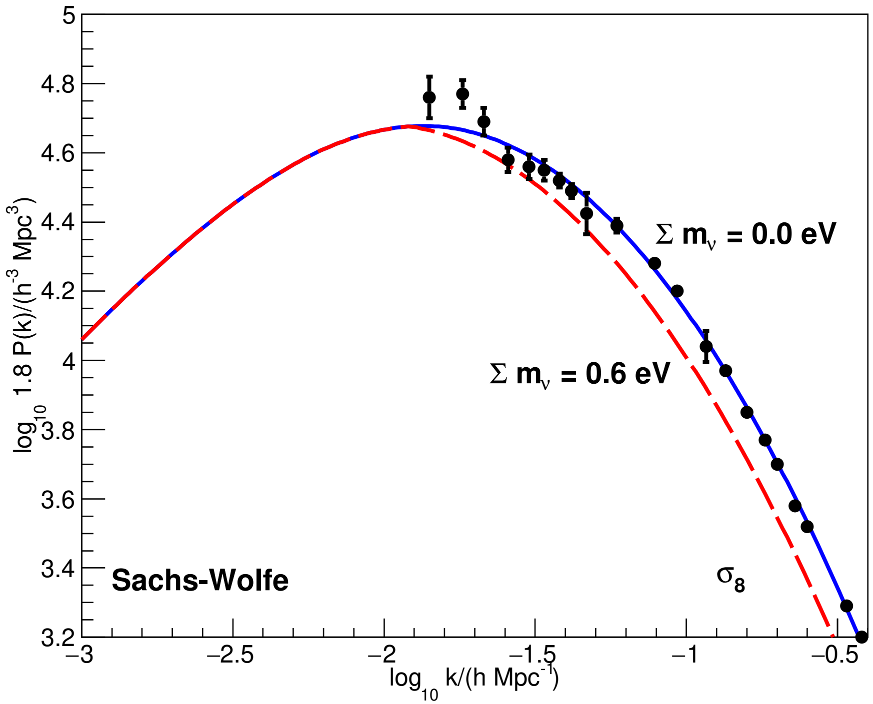
The galaxy power spectrum



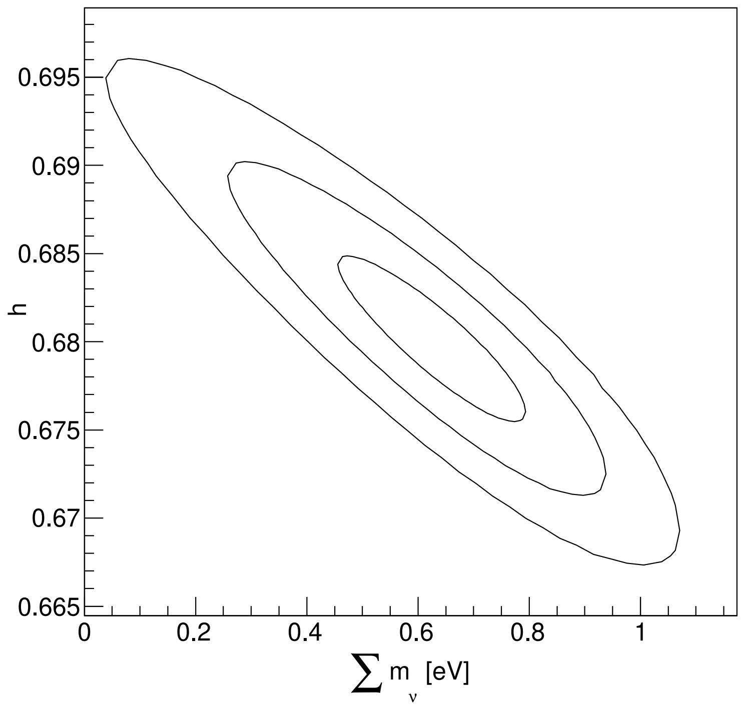
Suppression of $P_{\text{gal}}(k) \equiv b^2 P(k)$ due to $\sum m_\nu$, and SDSS-III BOSS $P_{\text{gal}}(k)$ data.

In the ΛCDM model, $P(k)$ depends on 5 independent parameters: $N^2 \equiv A_s/(4\pi) \equiv \Delta^2_R/(4\pi)$, Ω_m, h, n, $\sum m_\nu$, (and the dependent parameter Ω_r that has contributions from photons and neutrinos). So we need $\geqq 5$ measurements to obtain $P(k)$ and σ_8.

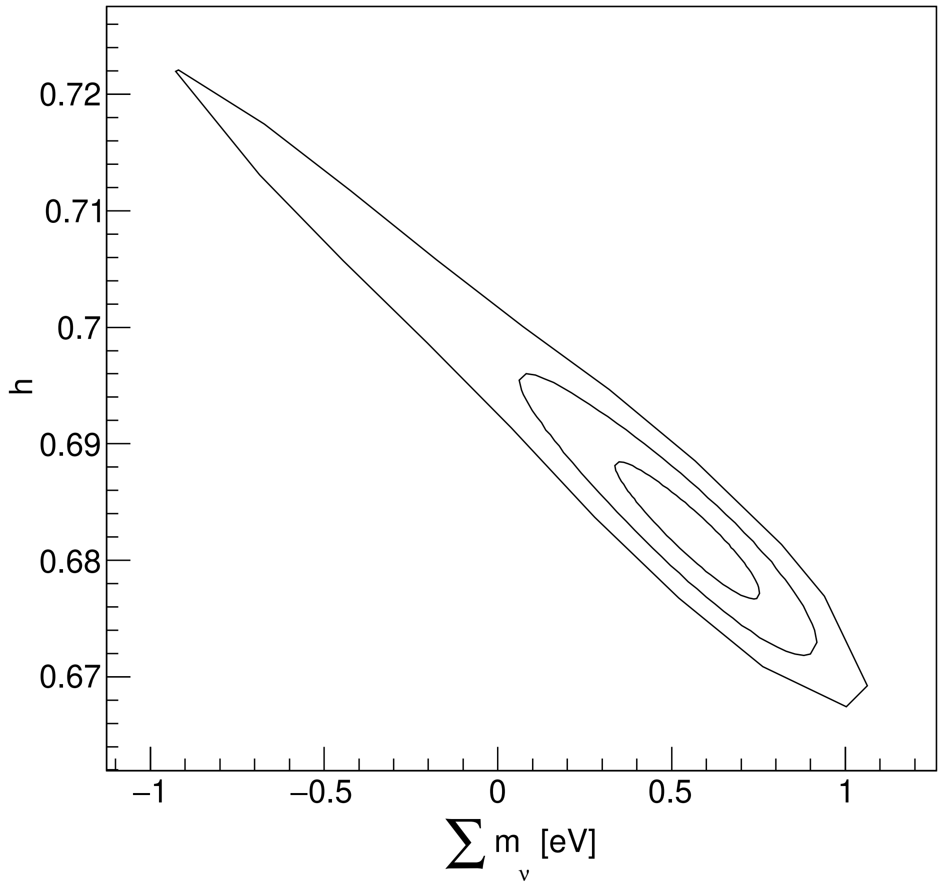
There are two measurements of $P(k)$: (1) the Sachs-Wolfe effect (in the range $-3.1 \lesssim \log_{10}(k/h\ \text{Mpc}^{-1}) \lesssim -2.7$) that determines N^2, and (2) σ_8 (in the range $-1.3 \lesssim \log_{10}(k/h\ \text{Mpc}^{-1}) \lesssim -0.6$). σ_8 is measured with gravitational lensing, and galaxy clusters.

(3) We measure Ω_m with Baryon Acoustic Oscillations (BAO). To reduce the uncertainty, we also include the sound horizon angle θ_* from Planck. (4) We fix $n = 1$, and take (5) $h = 0.678 \pm 0.009$.

We minimize a χ^2 with respect to N^2 and obtain contours in the $(\sum m_\nu, h)$ plane, with 1 degree of freedom.



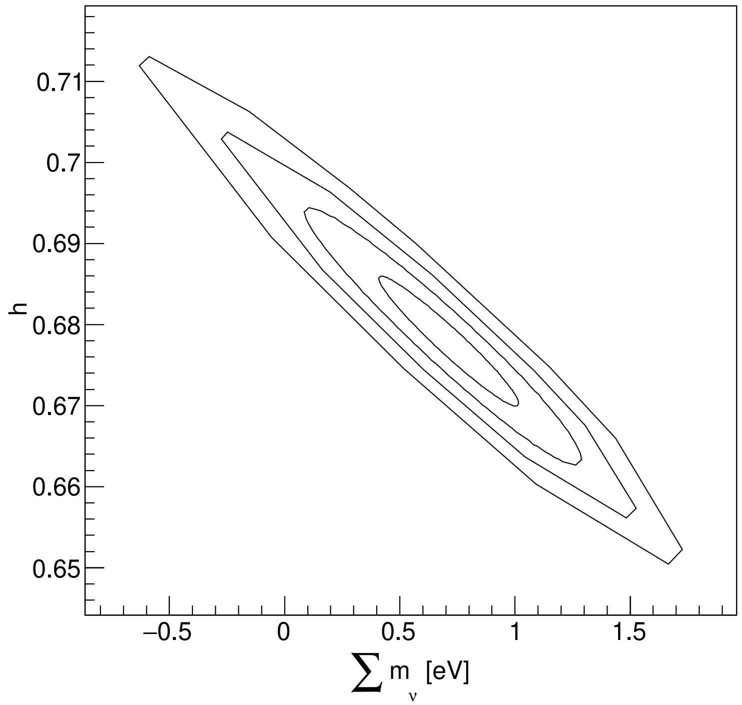
Contours corresponding to 1, 2, and 3 standard deviations in the $(\sum m_\nu, h)$ plane, from Sachs-Wolfe, σ_8, $h = 0.678 \pm 0.009$ and BAO measurements. Points on the contours have $\chi^2 - \chi^2_{\text{min}} = 1, 4$, and 9, respectively, where χ^2 has been minimized with respect to N^2. $n = 1$.



Same with $h = 0.72 \pm 0.03$.

Adding information from $P_{\mathsf{gal}}(k)$:

We count galaxies in spheres of radii $R = 16/h$, $32/h$, $64/h$ and $128/h$ Mpc, and obtain the standard deviations of these counts, and compare with the expected standard deviation calculated from $P(k)$. The galaxy bias b is defined as $P_{\mathsf{gal}}(k) \equiv b^2 P(k)$. We allow b to depend linearly on R: $b \equiv b_0 + i_s b_s$, with $i_s = 0, 1, 2, 3$ for $R = 16/h$, $32/h$, $64/h$ and $128/h$ Mpc respectively. The 4 measured standard deviations therefore add 2 new constraints. So we can free the spectral index slope n. Setting $h = 0.678 \pm 0.009$ we are left with 2 degrees of freedom.



Contours corresponding to 1, 2, 3, and 4 standard deviations in the $(\sum m_\nu, h)$ plane, from Sachs-Wolfe, σ_8, 4 $\sigma/\bar{N}$, BAO, and $h = 0.678 \pm 0.009$ measurements. Points on the contours have $\chi^2 - \chi^2_{\text{min}} = 1, 4, 9$, and 16, respectively, where χ^2 has been minimized with respect to N^2, n, b_0, and b_s.

From the Sachs-Wolfe effect, σ_8, 4 $\sigma/\bar{N}$ measurements, BAO, and $h = 0.678 \pm 0.009$, minimizing the χ^2 with respect to $\sum m_\nu$, N^2, n, h, b_0, and b_s, we obtain

$$\begin{aligned}
\sum m_\nu &= 0.719 \pm 0.312 \text{ (stat)}^{+0.055}_{-0.028} \text{ (syst) eV}, \\
N^2 &= (2.09 \pm 0.33) \times 10^{-10}, \\
n &= 1.021 \pm 0.075, \\
h &= 0.678 \pm 0.008, \\
b_0 &= 1.751 \pm 0.060, \\
b_s &= -0.053 \pm 0.041,
\end{aligned} \tag{1}$$

with $\chi^2 = 1.1$ for 2 degrees of freedom.

	$\sum m_\nu$	N^2	n	h	b_0	b_s
$\sum m_\nu$	1.000	-0.019	0.856	-0.966	-0.226	0.779
N^2	-0.019	1.000	-0.491	0.018	-0.155	0.428
n	0.856	-0.491	1.000	-0.834	-0.303	0.427
h	-0.966	0.018	-0.834	1.000	0.219	-0.755
b_0	-0.226	-0.155	-0.303	0.219	1.000	-0.037
b_s	0.779	0.428	0.427	-0.755	-0.037	1.000

Parameter correlation coefficients.

New analysis:

- SDSS DR14 galaxies.

- New Sachs-Wolfe measurement, or full Planck to obtain new N^2.

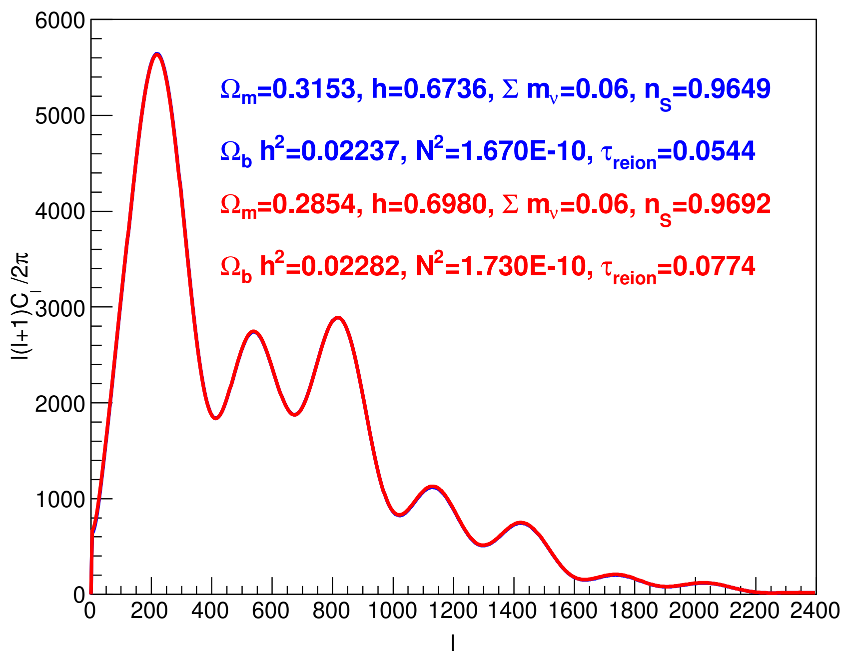
- New measurements of σ_8 with lensing, and with galaxy clusters.

- New BAO measurement of Ω_m including the $d_{\text{drag}}/d_* = 1.0184 \pm 0.0004$ correction.

- Combination of BAO measurement of Ω_m with Planck (using Planck MC chains)

Combination of the Planck 2018 "TT,TE,EE+lowE+lensing" analysis with the directly measured $\Omega_m = 0.2724 \pm 0.0047$. Uncertainties are at 68% confidence. The Planck $\chi^2_{\mathrm{P}} \equiv -2 \cdot \ln \mathcal{L}$ increases from 12956.78 to 12968.64 with this combination. The galaxy $\chi^2_{\mathrm{G}} \equiv (\Omega_m - 0.2724)^2/0.0047^2$.

	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^2_{P}	12956.78	12968.64
χ^2_{G}	83.31	7.53
χ^2_{tot}	13040.09	12976.17



Comparison of the power spectra $l(l+1)C^S_{TT,l}/(2\pi)$ [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. The r.m.s. difference is 6.07μK^2, corresponding to 0.11% of the first acoustic peak, so the two spectra can not be distinguished by eye.

Tensions before and after combination:

- h: $3.5\sigma \rightarrow 2.1\sigma$
- σ_8 from galaxy clusters: $2.5\sigma \rightarrow 2.3\sigma$
- σ_8 from weak lensing: $1.8\sigma \rightarrow 1.5\sigma$
- Ω_m: $4.9\sigma \rightarrow 2.1\sigma$

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Final result:

Combining the direct BAO measurement $\Omega_m = 0.2724 \pm 0.0047$ with the 2018 Planck "TT,TE,EE+lowE+lensing" analysis obtains $\Omega_m = 0.2853 \pm 0.0040$ and $h = 0.6990 \pm 0.0030$, at the cost of an increase of the Planck χ^2_{P} from 12956.78 to 12968.64.

$$\begin{gathered}\sum m_\nu = 0.27 \pm 0.08 \text{ eV}, \\ h = 0.6990 \pm 0.0030, \\ h + 0.020 \sum m_\nu = 0.7038 \pm 0.0060.\end{gathered}$$