Constraints on neutrino masses from cosmological observations

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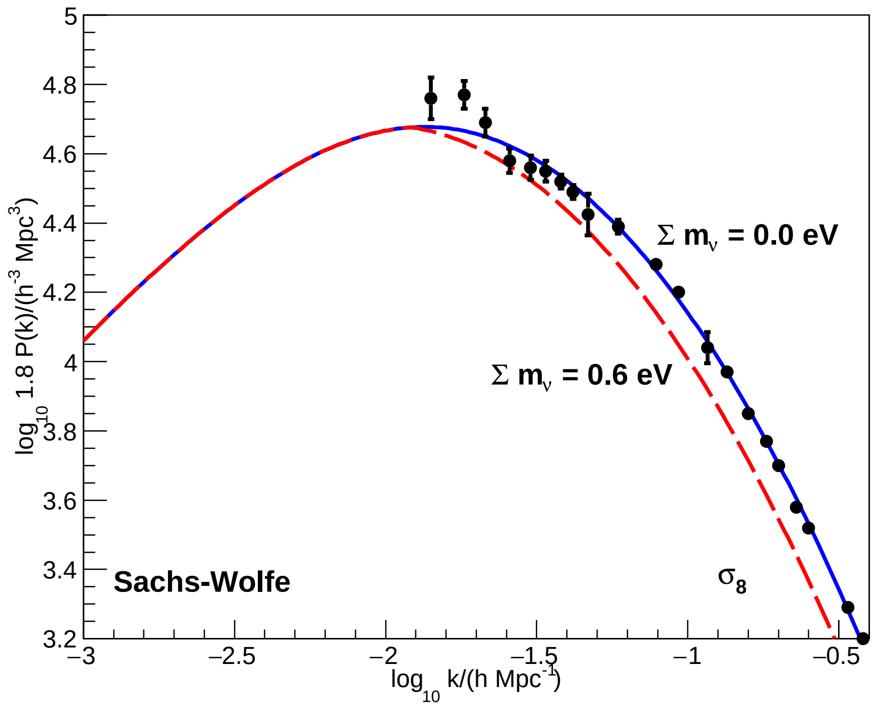
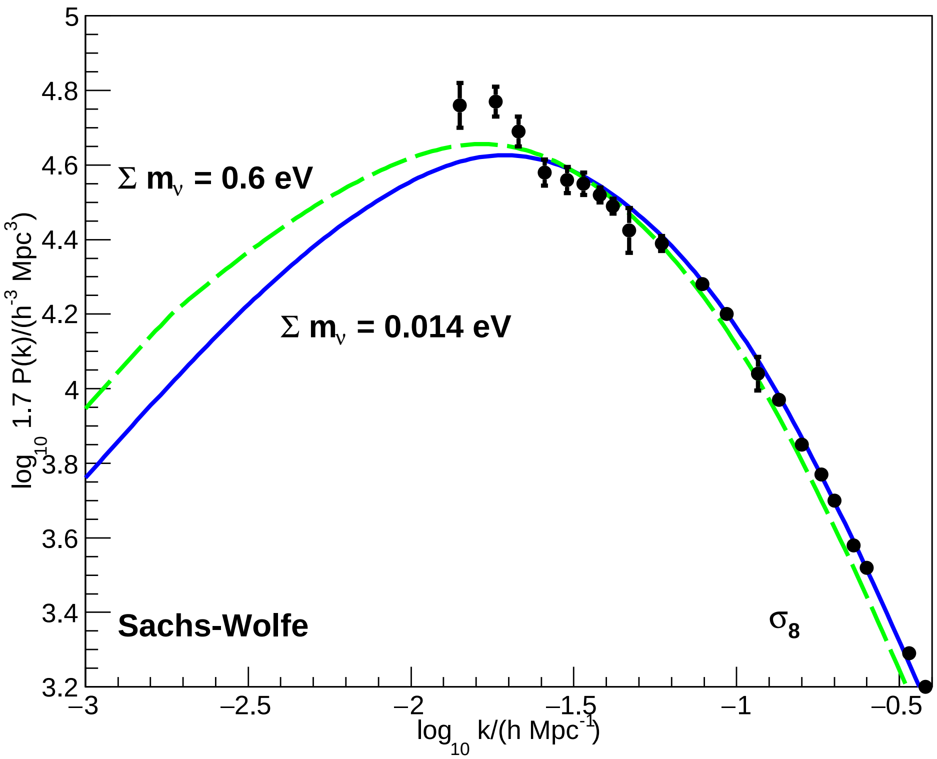
Introduction

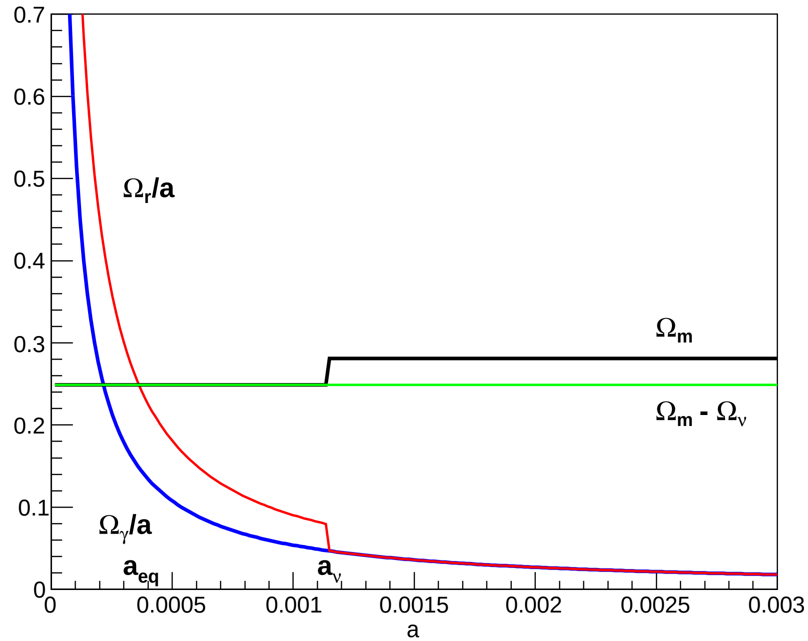


Suppression of $b^2 P(k)$ due to $\sum m_\nu$, and SDSS-III BOSS $P_{\mathrm{gal}}(k)$ data.

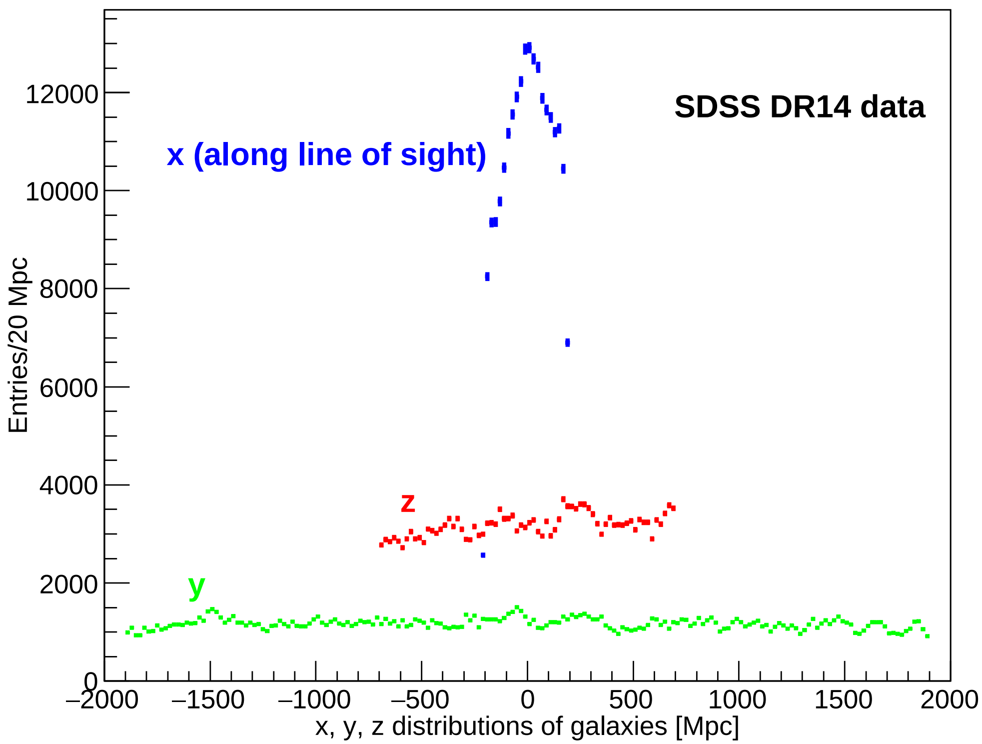


Comparison of $b^2P(k)$ to the Sachs-Wolfe effect, σ_8, and $P_{\text{gal}}(k)$. SDSS-III BOSS $P_{\text{gal}}(k)$ data. Fits with free $\sum m_\nu$, and $\sum m_\nu = 0.6$ eV fixed. b scale invariant.

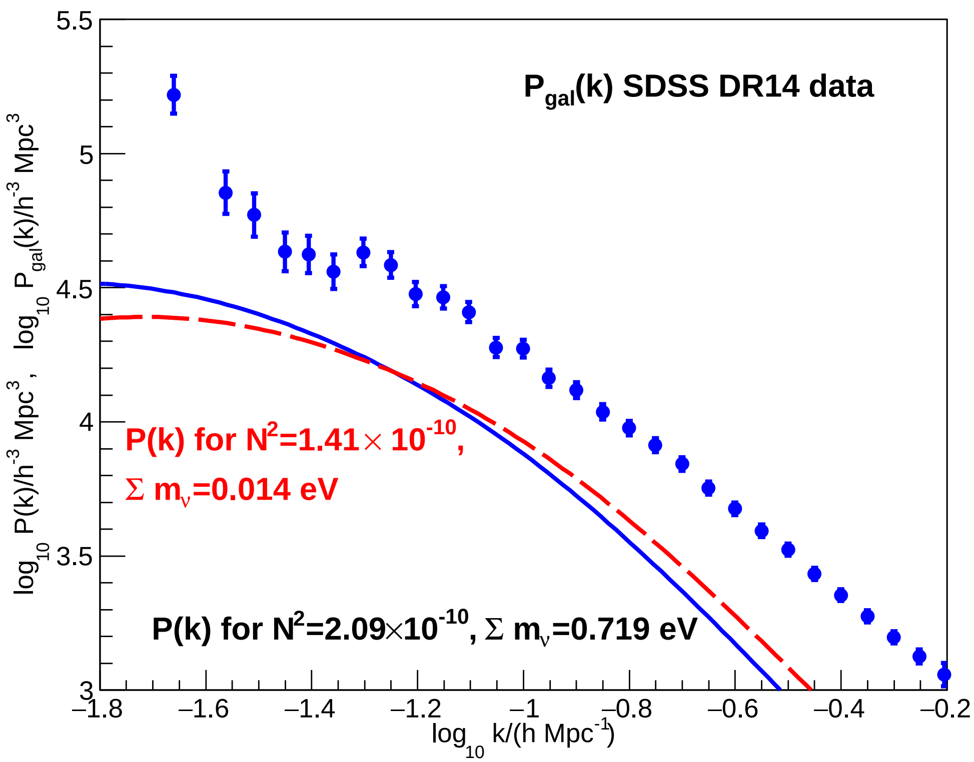
Measurement with galaxy fluctuations



Densities vs. a with $\sum m_\nu = 1.38$ eV.

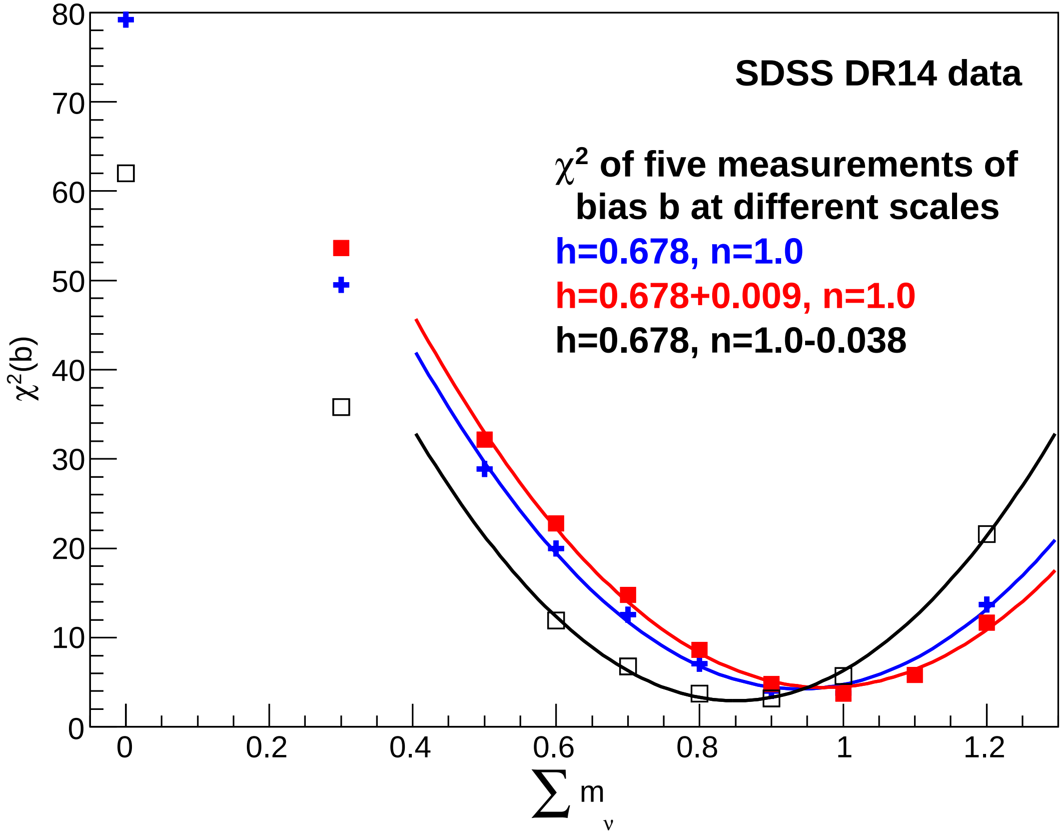


SDSS DR14 galaxies in the northern galactic cap. 400 Mpc along line of sight ($z = 0.5 \pm 0.046$), $\times$3800 Mpc (86^0) $\times$1400 Mpc (32^0).



Measured $P_{\text{gal}}(k)$ and calculated $P(k)$ for $\sum m_\nu = 0.014$ eV and 0.719 eV. $P_{\text{gal}}(k) \equiv b^2 P(k)$. Is the galaxy bias b scale invariant?

r_s/h [Mpc]	16	32	64	128	256	
r_s [Mpc]	23.60	47.20	94.40	188.79	377.58	
$N_y \times N_z$	75×27	37×13	19×7	9×3	4×1	
$\bar{N}$	6.781	52.279	410.74	3092.3	21810.0	
$1/\sqrt{\bar{N}}$	0.3840	0.1383	0.0493	0.0180	0.0068	
rms/$\bar{N}$	0.873	0.443	0.210	0.0870	0.0346	
$\sigma/\bar{N}$	0.784 ± 0.009	0.421 ± 0.006	0.204 ± 0.004	0.085 ± 0.003	0.034 ± 0.003	
$\sigma_{r_s/h}$, 0.0 eV	0.4457	0.2255	0.0987	0.0374	0.0124	χ^2
b, $\sum m_\nu = 0.0$ eV	2.257 ± 0.025	2.398 ± 0.036	2.650 ± 0.056	2.925 ± 0.119	3.503 ± 0.349	79.2
$\sigma_{r_s/h}$, 0.3 eV	0.2321	0.1036	0.0402	0.0136		
b, $\sum m_\nu = 0.3$ eV	2.228 ± 0.024	2.329 ± 0.035	2.523 ± 0.053	2.722 ± 0.111	3.193 ± 0.318	49.5
$\sigma_{r_s/h}$, 0.6 eV	0.4603	0.2425	0.1113	0.0443	0.0152	
b, $\sum m_\nu = 0.6$ eV	2.185 ± 0.024	2.230 ± 0.033	2.350 ± 0.049	2.468 ± 0.100	2.862 ± 0.285	20.0
$\sigma_{r_s/h}$, 0.7 eV	0.4640	0.2468	0.1144	0.0460	0.0158	
b, $\sum m_\nu = 0.7$ eV	2.168 ± 0.024	2.191 ± 0.033	2.285 ± 0.048	2.379 ± 0.097	2.755 ± 0.275	12.6
$\sigma_{r_s/h}$, 0.8 eV	0.4682	0.2516	0.1179	0.0478	0.0165	
b, $\sum m_\nu = 0.8$ eV	2.148 ± 0.023	2.149 ± 0.032	2.218 ± 0.047	2.289 ± 0.093	2.648 ± 0.264	7.1
$\sigma_{r_s/h}$, 0.9 eV	0.4729	0.2570	0.1218	0.0497	0.0171	
b, $\sum m_\nu = 0.9$ eV	2.127 ± 0.023	2.104 ± 0.032	2.147 ± 0.045	2.198 ± 0.089	2.541 ± 0.253	4.0
$\sigma_{r_s/h}$, 1.0 eV	0.4782	0.2630	0.1261	0.0519	0.0179	
b, $\sum m_\nu = 1.0$ eV	2.103 ± 0.023	2.056 ± 0.031	2.073 ± 0.044	2.107 ± 0.086	2.434 ± 0.243	3.8
$\sigma_{r_s/h}$, 1.2 eV	0.4911	0.2775	0.1363	0.0568	0.0196	
b, $\sum m_\nu = 1.2$ eV	2.048 ± 0.022	1.948 ± 0.029	1.919 ± 0.040	1.923 ± 0.078	2.220 ± 0.221	13.7



χ^2 of 5 b's assumed to be scale invariant.

From $\sigma/\bar{N}$ of spheres with $r_s = 16/h, 32/h, 64/h, 128/h,$ and $256/h$ Mpc, assuming scale invariance of the galaxy bias b:

$$\sum m_\nu = 0.939 + 0.035 \cdot \delta h + 0.089 \cdot \delta n \pm 0.008 \text{ eV},$$

with minimum $\chi^2 = 3.2$ for four degrees of freedom. We have defined $\delta h \equiv (h - 0.678)/0.009$, and $\delta n \equiv (n - 1)/0.038$.

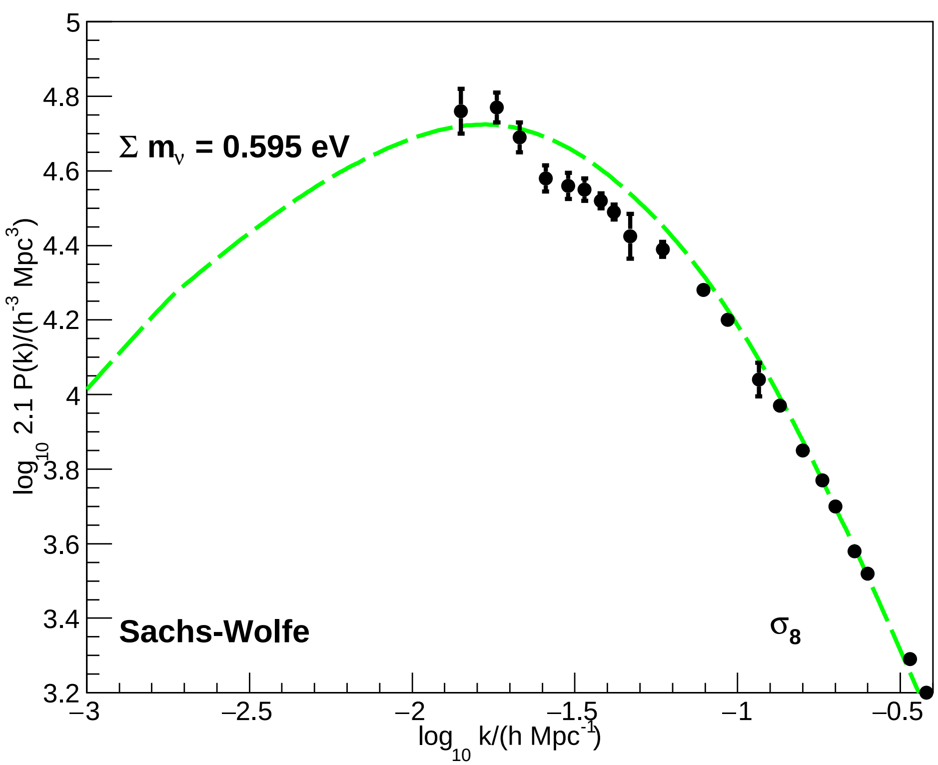
Either $\sum m_\nu$ has this value, or scale invariance of b is broken.

Measurement with the Sachs-Wolfe effect and σ_8

$P(k)$ of ΛCDM model depends on N^2, $\sum m_\nu$, h, Ω_m, and n.
We define
$\delta h \equiv (h - 0.678)/0.009$,
$\delta\Omega_m \equiv (\Omega_m - 0.281)/0.003$, and
$\delta n \equiv (n - 1)/0.038$,
fit with respect to N^2, and obtain

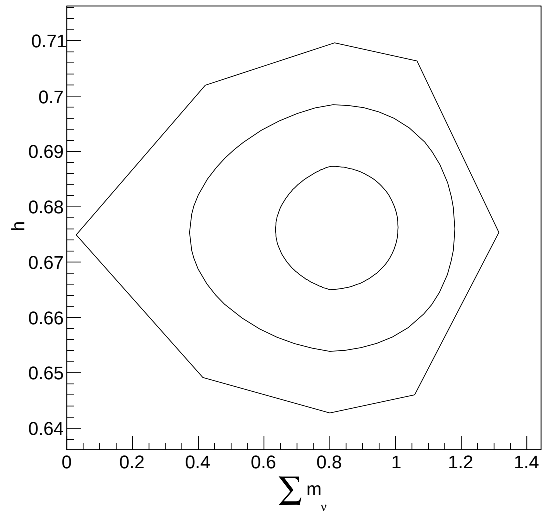
$$\sum m_\nu = 0.595 + 0.047 \cdot \delta h + 0.226 \cdot \delta n + 0.022 \cdot \delta\Omega_m \pm 0.225 \text{ (stat)}^{+0.484}_{-0.152} \text{ (syst) eV}, \quad (1)$$

with zero degrees of freedom.



Comparison of $b^2 P(k)$ fit with the Sachs-Wolfe effect and σ_8, with $P_{\text{gal}}(k)$ of SDSS-III BOSS, assuming scale invariant b.

Measurement with the Sachs-Wolfe effect, σ_8, and P_{gal}



1, 2, and 3 standard deviation contours in the $(\sum m_\nu, h)$ plane. Points on the contours have $\chi^2 - \chi^2_{\mathrm{min}} = 1, 4$, and 9, respectively, where χ^2 has been minimized with respect to N^2, n, b_0, and b_1. $\sum m_\nu = 0.80 \pm 0.23$ eV. $\chi^2 = 27.8$ for 18 d.f.. $\chi^2 = 36.3$ for 19 d.f. for scale invariance: $b_1 = 0$.

Measurement with the Sachs-Wolfe effect, σ_8, and galaxy fluctuations

From the Sachs-Wolfe effect, σ_8, and the 4 $\sigma/\bar{N}$ measurements we obtain

$$\begin{aligned}\sum m_\nu &= 0.618 + 0.042 \cdot \delta h + 0.206 \cdot \delta n + 0.019 \cdot \delta\Omega_m \\ &\pm 0.209 \text{ (stat)}^{+0.420}_{-0.139} \text{ (syst) eV,}\end{aligned}$$

with $\chi^2 = 1.10$ for 2 degrees of freedom. The variables that minimize the χ^2 are $\sum m_\nu$, N^2, b_0, and b_s.

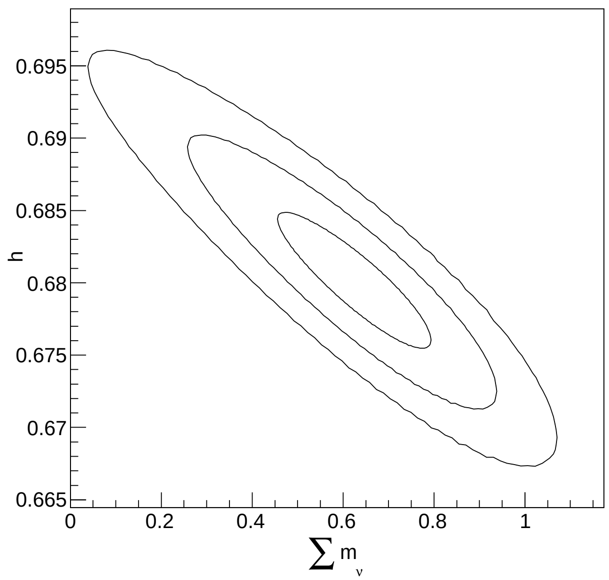
Measurement with Baryon Acoustic Oscillations (BAO)

This measurement was covered in my talk on 25 June.
We obtain

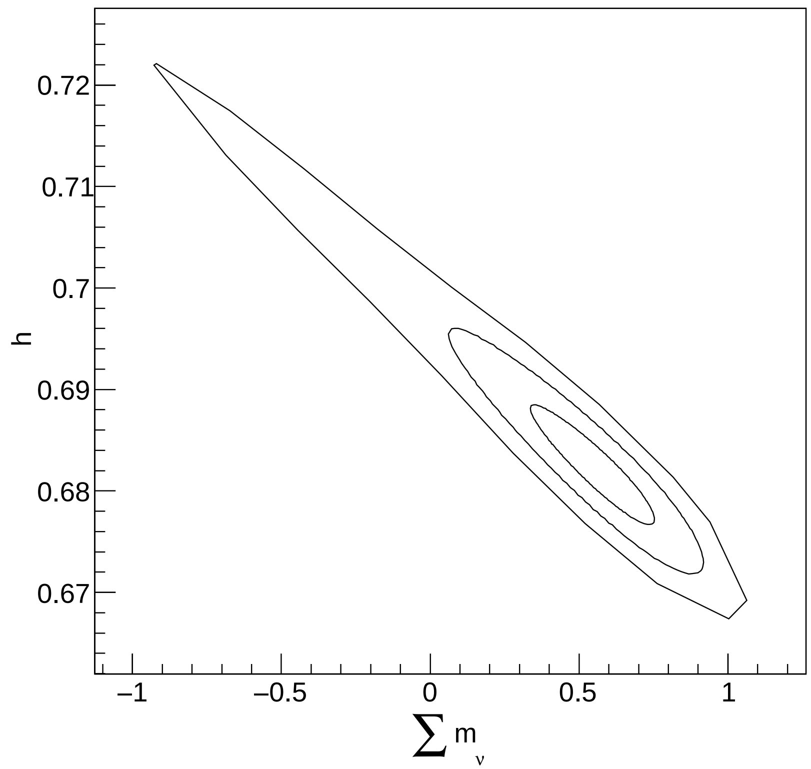
$$\sum m_\nu = 0.711 - 0.335 \cdot \delta h + 0.050 \cdot \delta b \pm 0.063 \text{ eV},$$

with $\chi^2/\text{d.f.} = 19.9/19$.
This result is obtained from BAO measurements alone.

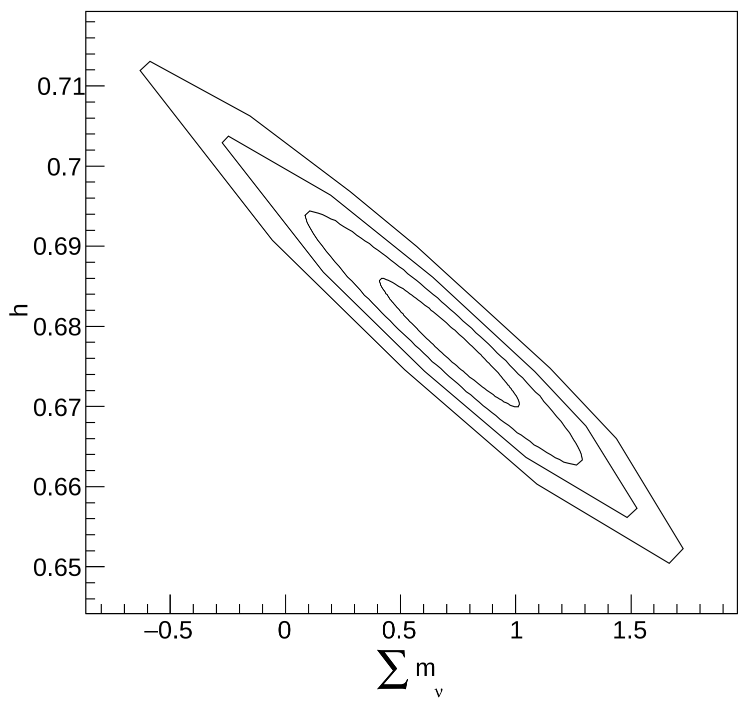
Combinations with BAO



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 $h = 0.72 \pm 0.03$.



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.

Final results

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

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

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.

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	This analysis	PDG 2018
Ω_Λ	0.718 ± 0.003	0.692 ± 0.012
Ω_k	0.002 ± 0.007	$-0.005^{+0.008}_{-0.009}$
d'_{BAO}	$(150.3 \pm 0.9) \times \frac{0.678}{h}$ Mpc	144.9 ± 0.4 Mpc
N_{eff} ($m_\nu = 0$)	2.64 ± 0.20	3.13 ± 0.32
$\sum m_\nu$	$0.719 \pm 0.312^{+0.055}_{-0.028}$ eV	< 0.68 eV, 95% conf.
n_S	1.021 ± 0.075	0.968 ± 0.006
h		0.678 ± 0.009

Comparison of this analysis (BAO + SW $+\sigma_8 + P_{\mathrm{gal}}(k)$) with PDG 2018 (mostly CMB, Planck collab. (2015)). 68% confidence. (See references for details.)