Constraints on Neutrino Mass from Galaxy Surveys

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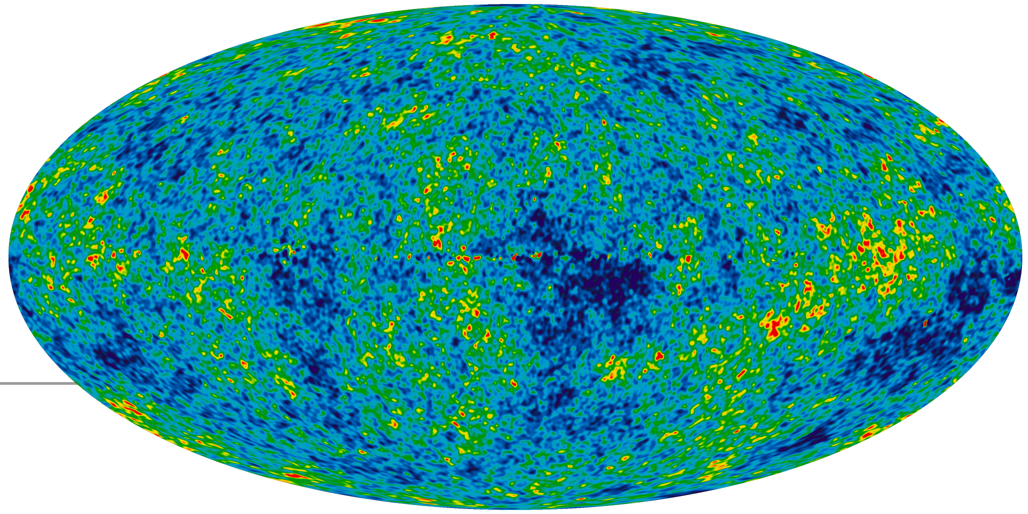
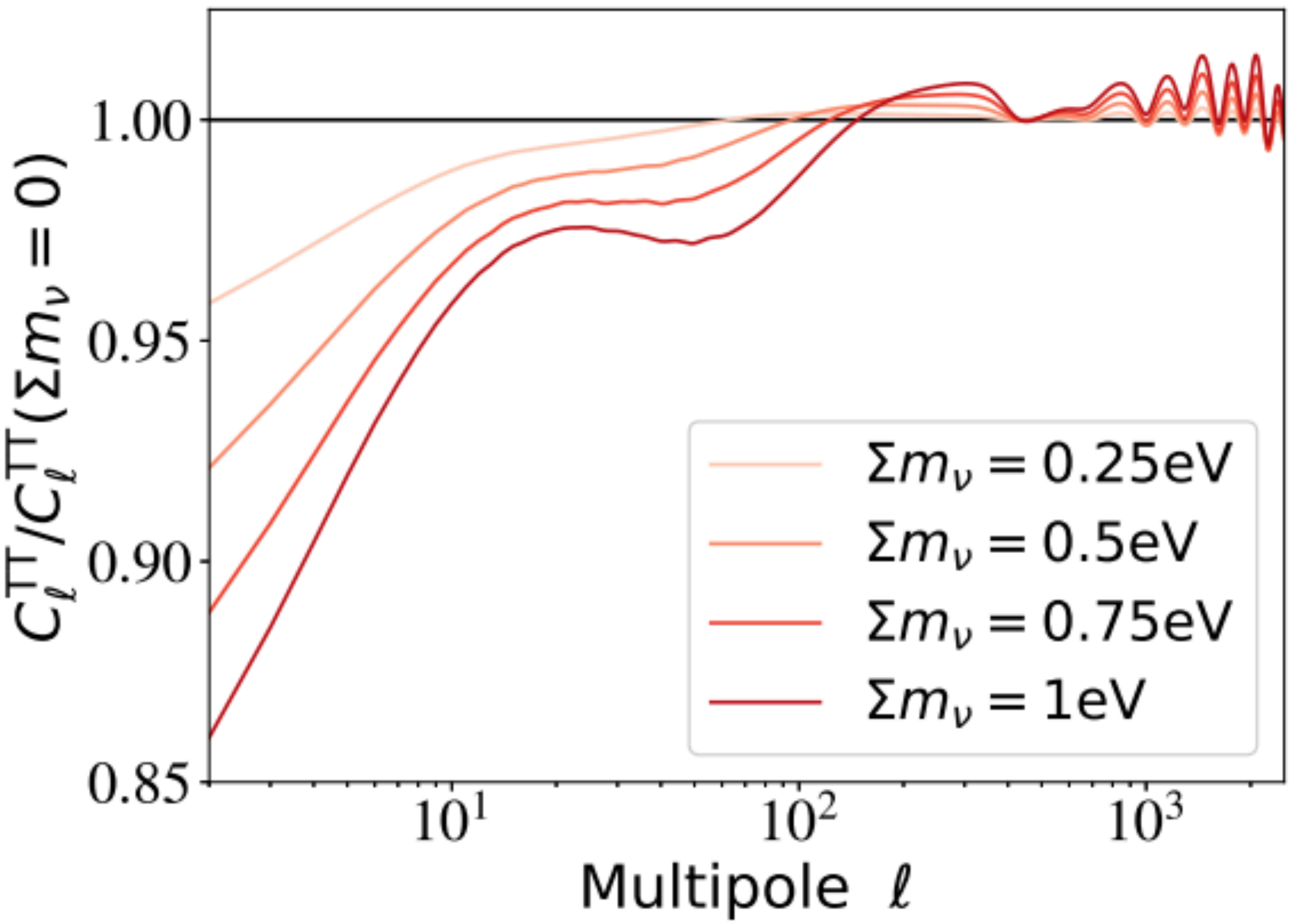
CMB Constraints

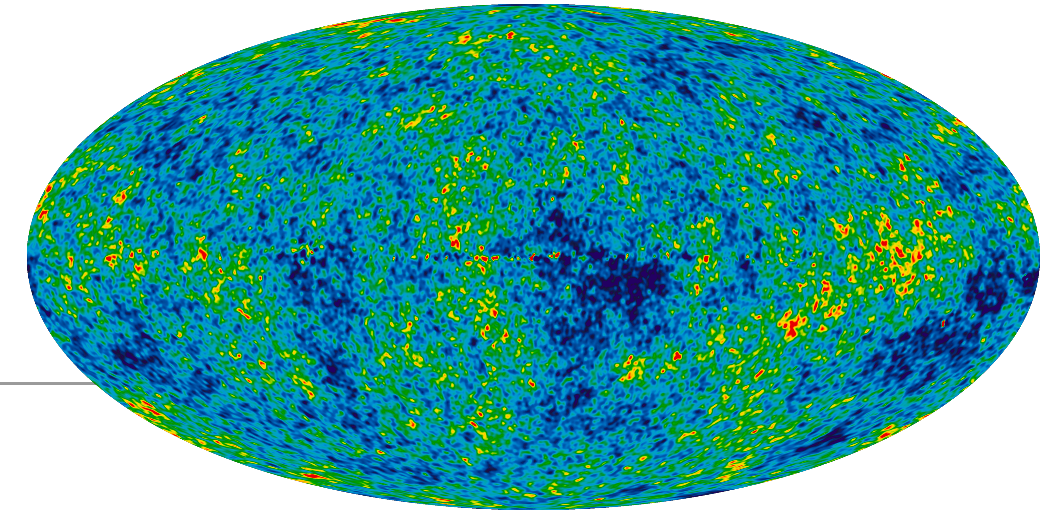


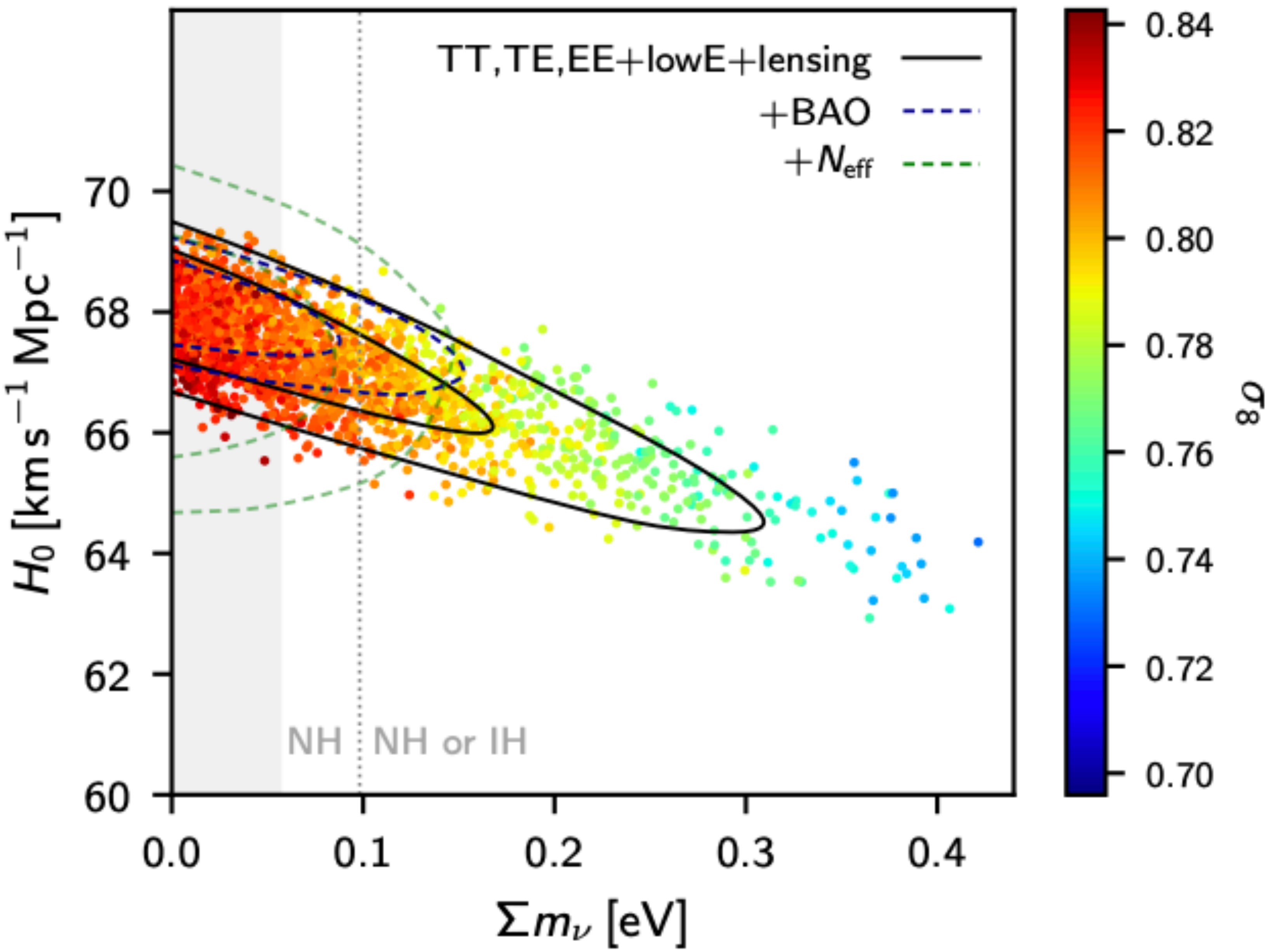


CMB constrains the neutrino masses through the (early+late)ISW effect when the CMB is released (affects low multipoles) and the lensing of CMB photons, or *CMB lensing* (affects high multipoles)

Neutrinos in Cosmology. Lesgourgues & Verde, Particle Data Group Review 2020.
https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrinos-in-cosmology.pdf

CMB Constraints





$$\sum m_\nu < 0.44 \text{ eV} \quad (95\,\%,\ \text{TT+lowE+lensing}),$$

$$\sum m_\nu < 0.24 \text{ eV} \quad (95\,\%,\ \text{TT,TE,EE+lowE+lensing}).$$

$$\sum m_\nu < 0.16 \text{ eV} \quad (95\,\%,\ \textit{Planck}\ \text{TT+lowE+BAO}),$$

$$\sum m_\nu < 0.13 \text{ eV} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE +BAO}),$$

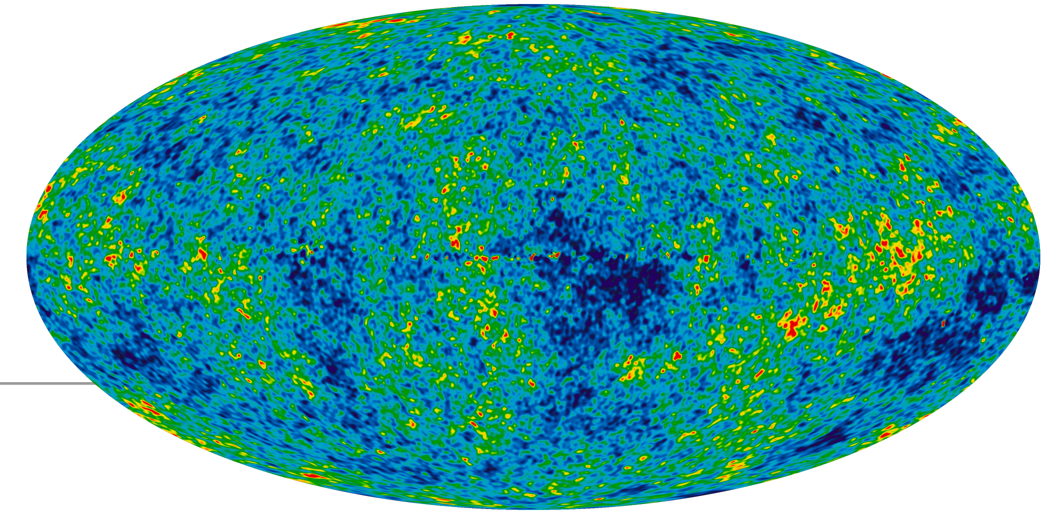
and combining with lensing the limits further tighten to

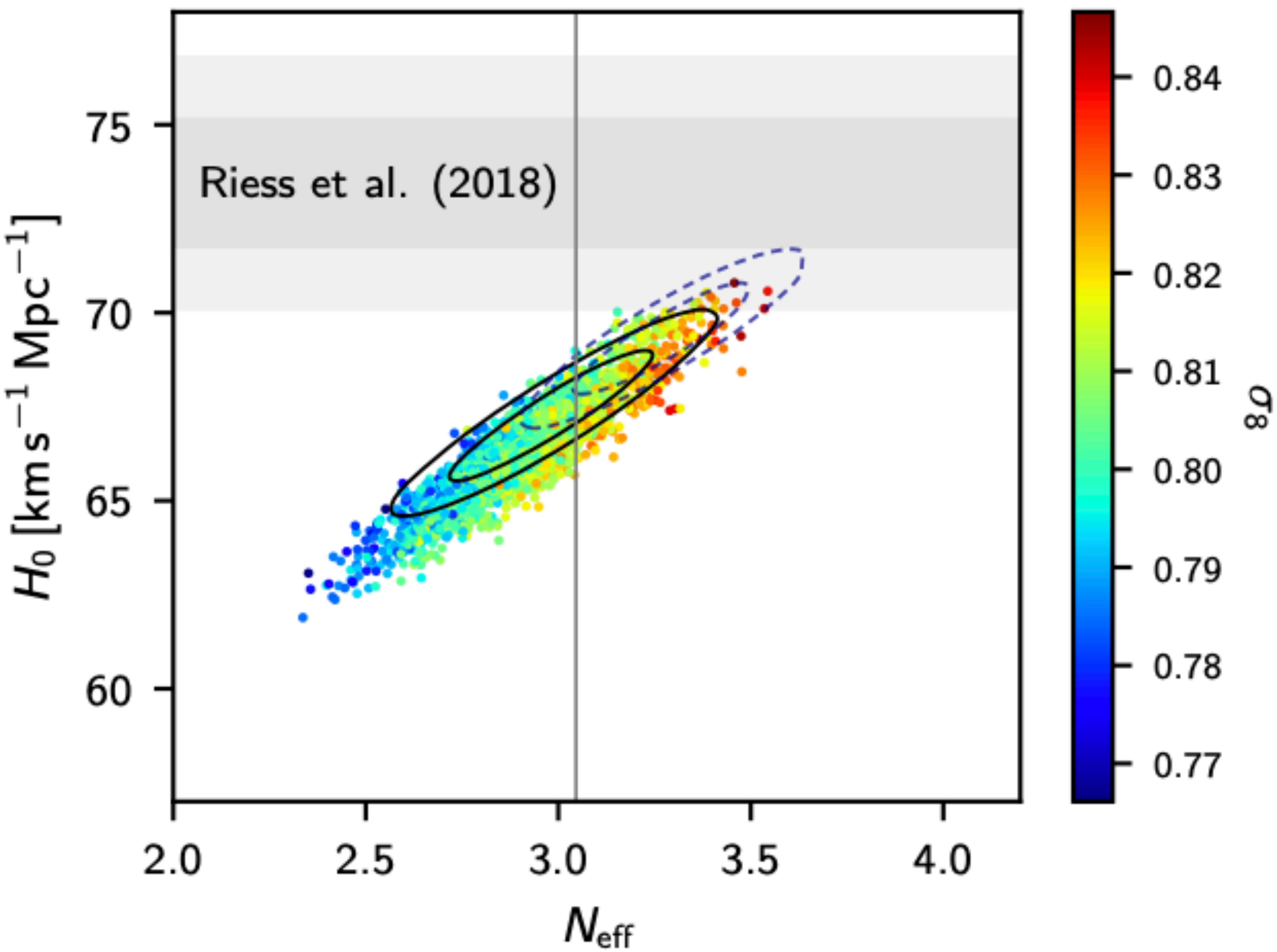
$$\sum m_\nu < 0.13 \text{ eV} \quad (95\,\%,\ \textit{Planck}\ \text{TT+lowE+lensing +BAO}),$$

$$\sum m_\nu < 0.12 \text{ eV} \quad (95\,\%,\ \textit{Planck}\ \text{TT,TE,EE+lowE +lensing+BAO}).$$

Planck 2018 results. VI. Cosmological parameters
Planck Collaboration: N. Aghanim et al. A&A 641 (2020) A6
[arXiv:1807.06209]

CMB Constraints





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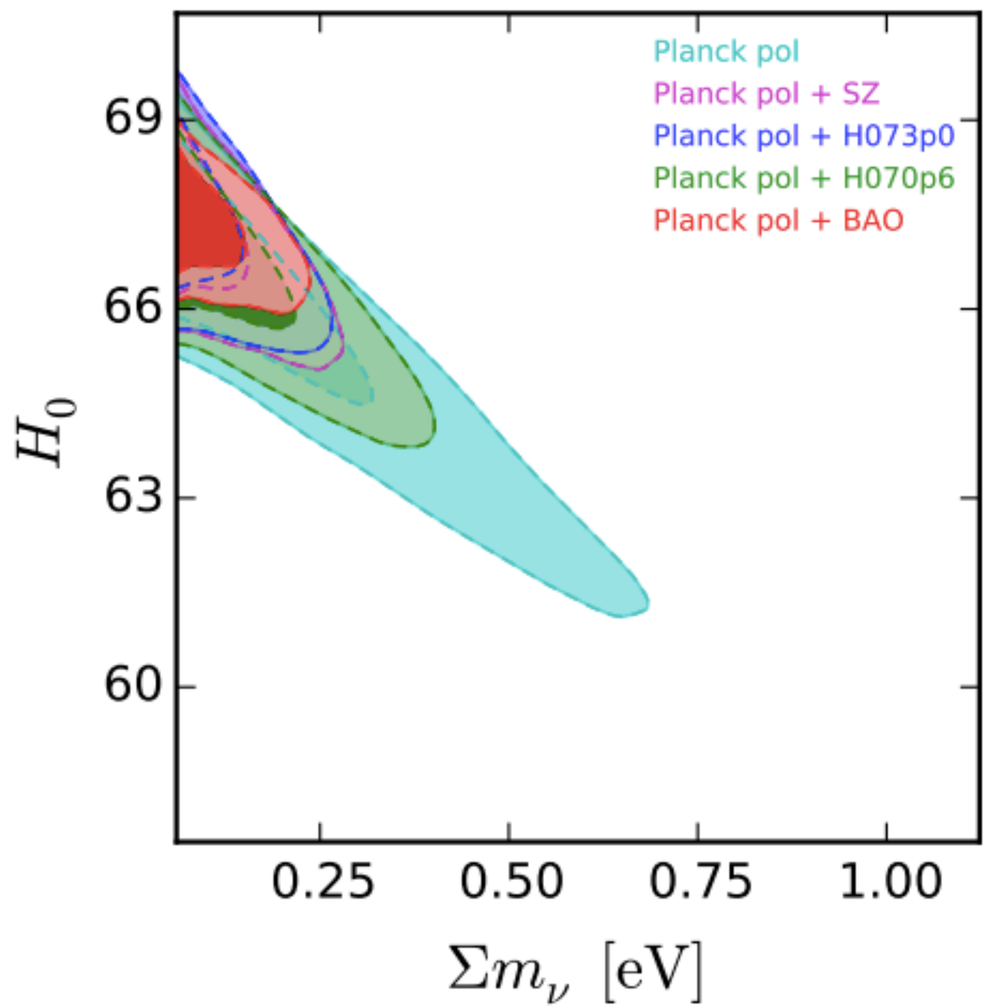
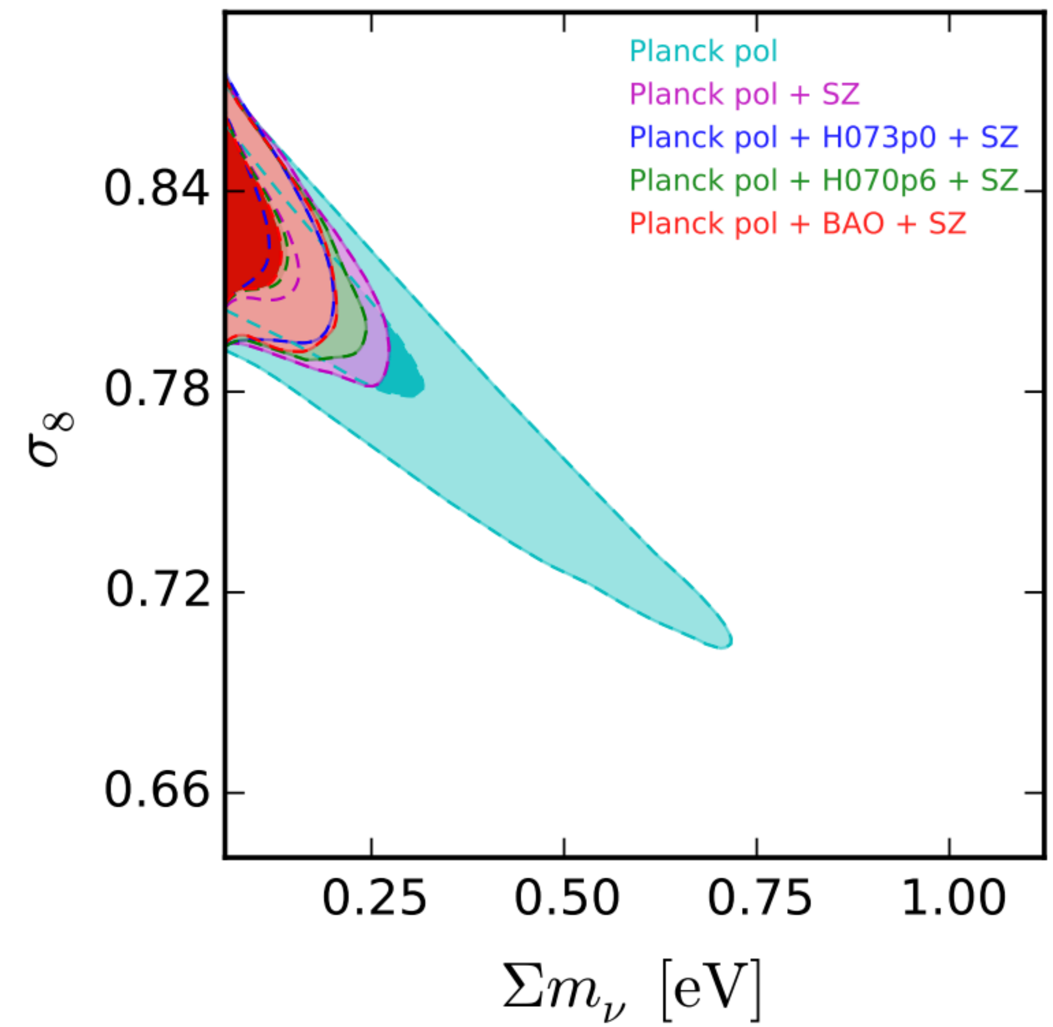
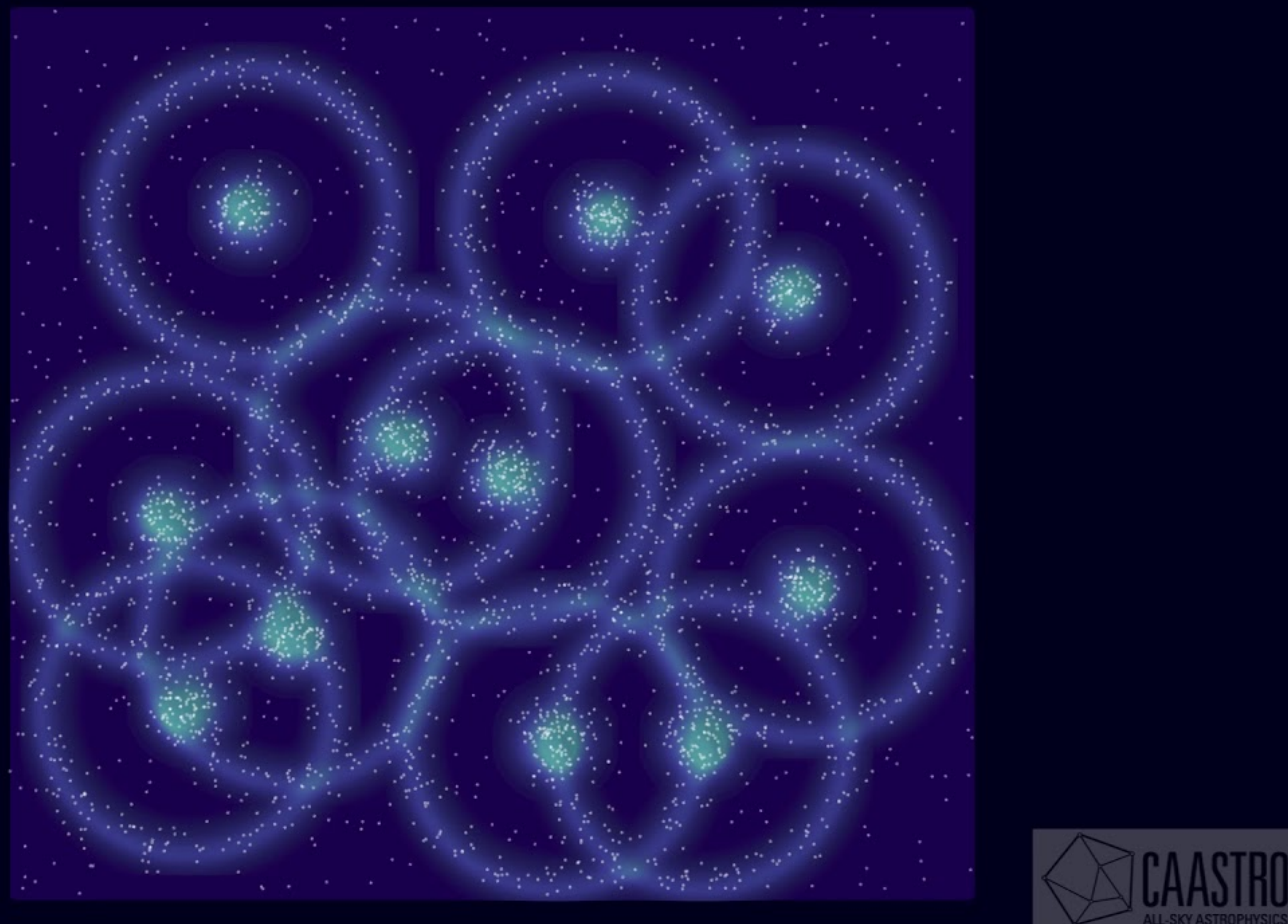




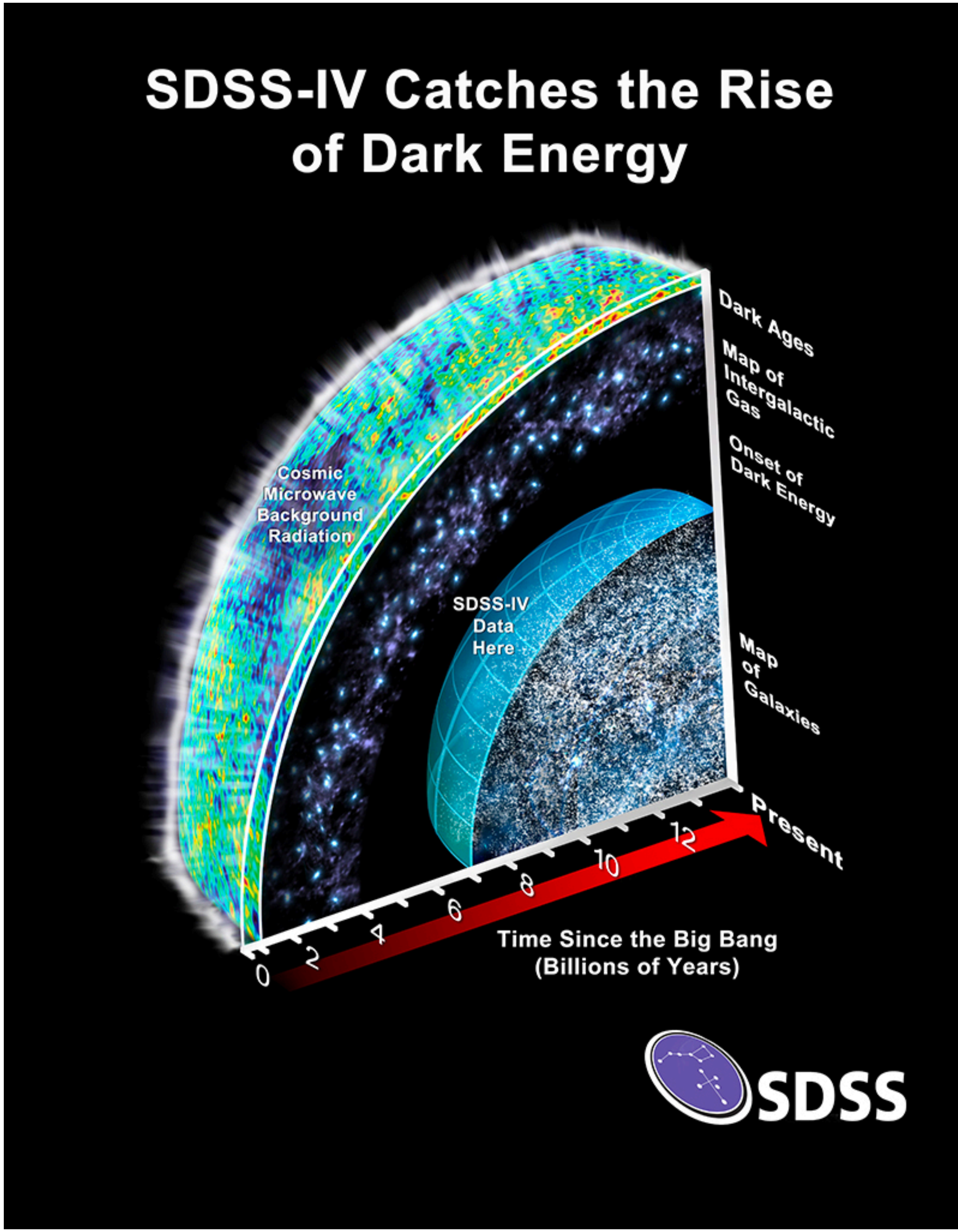
The presence of low redshift priors (H_0, σ_8) can break degeneracies and therefore result in stronger neutrino mass bounds

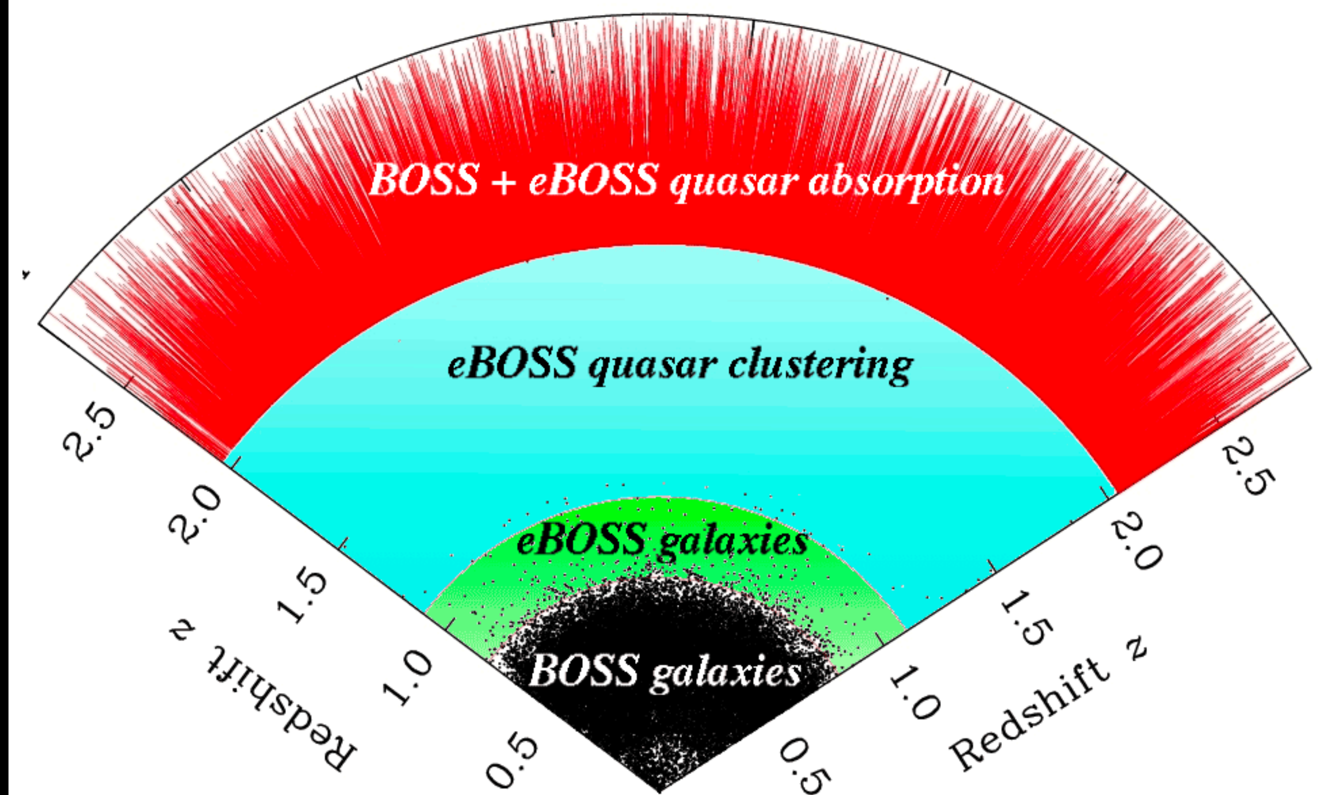
Cosmological limits on neutrino unknowns versus low redshift priors
Di Valentino et al. Phys. Rev. D 93, 083527 (2016) [arXiv:1511.00975]

What is “BAO”? Baryon Acoustic Oscillations



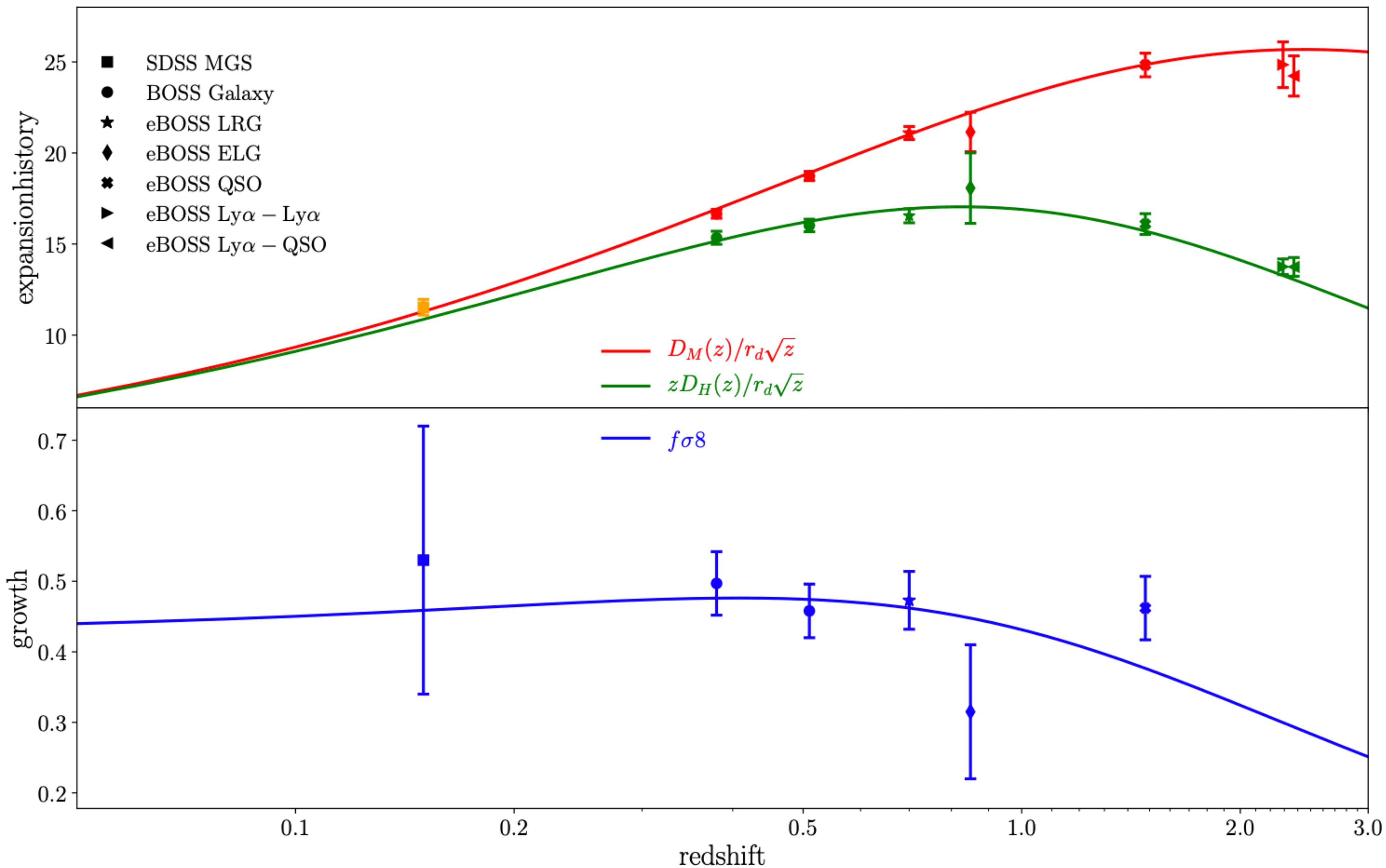
This “standard ruler” is calibrated using CMB: $r_{drag} = (147.18 \pm 0.29)\text{Mpc}$





SDSS: “2 decades of spectroscopic surveys”

Expansion history (+growth) is pinned down by BAO



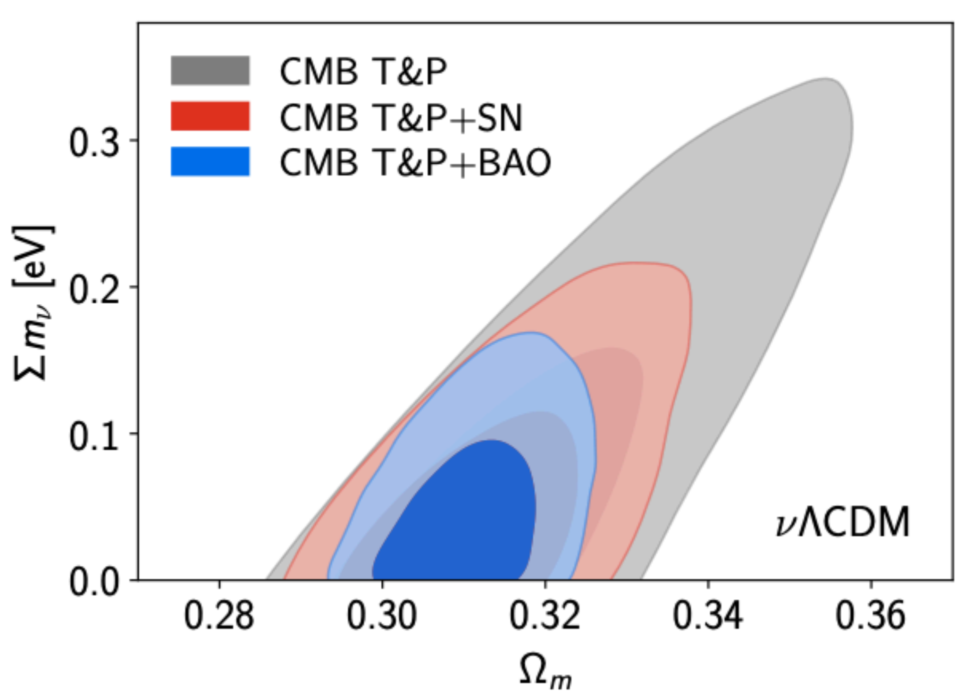
The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological Implications from two Decades of Spectroscopic Surveys at the Apache Point observatory. eBOSS Collaboration; Alam et al. [arXiv:2007.08991]

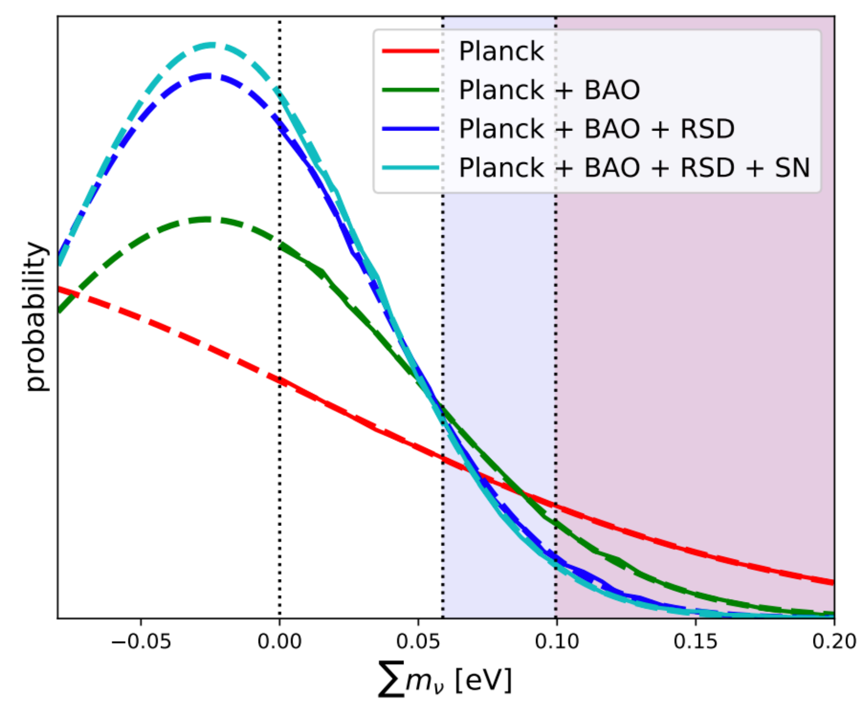
Current CMB+BAO bounds on neutrino mass

TABLE 8

Constraints on neutrino masses and relative probabilities of neutrino models with $\nu\Lambda$CDM and νwCDM cosmological models. The 95% upper limits are derived assuming a $\sum m_\nu > 0$ prior.

Data	95% upper limit [eV]	$P_{\rm inv}/P_{\rm norm}$	$P_{\rm unphy}$	Gaussian fit [eV]
Planck	0.252	0.64	0.43	
Planck + BAO	0.129	0.36	0.64	-0.026 ± 0.074
Planck + BAO + RSD	0.102	0.24	0.76	-0.026 ± 0.060
Planck + SN	0.170	0.49	0.56	-0.076 ± 0.106
Planck + BAO + RSD + SN	0.099	0.22	0.78	-0.024 ± 0.057
Planck + BAO + RSD + SN + DES	0.111	0.27	0.71	-0.014 ± 0.061
Planck + BAO + RSD + SN (νwCDM)	0.139	0.40	0.61	-0.033 ± 0.082
Planck + BAO + RSD + SN + DES (νwCDM)	0.161	0.48	0.56	-0.048 ± 0.097





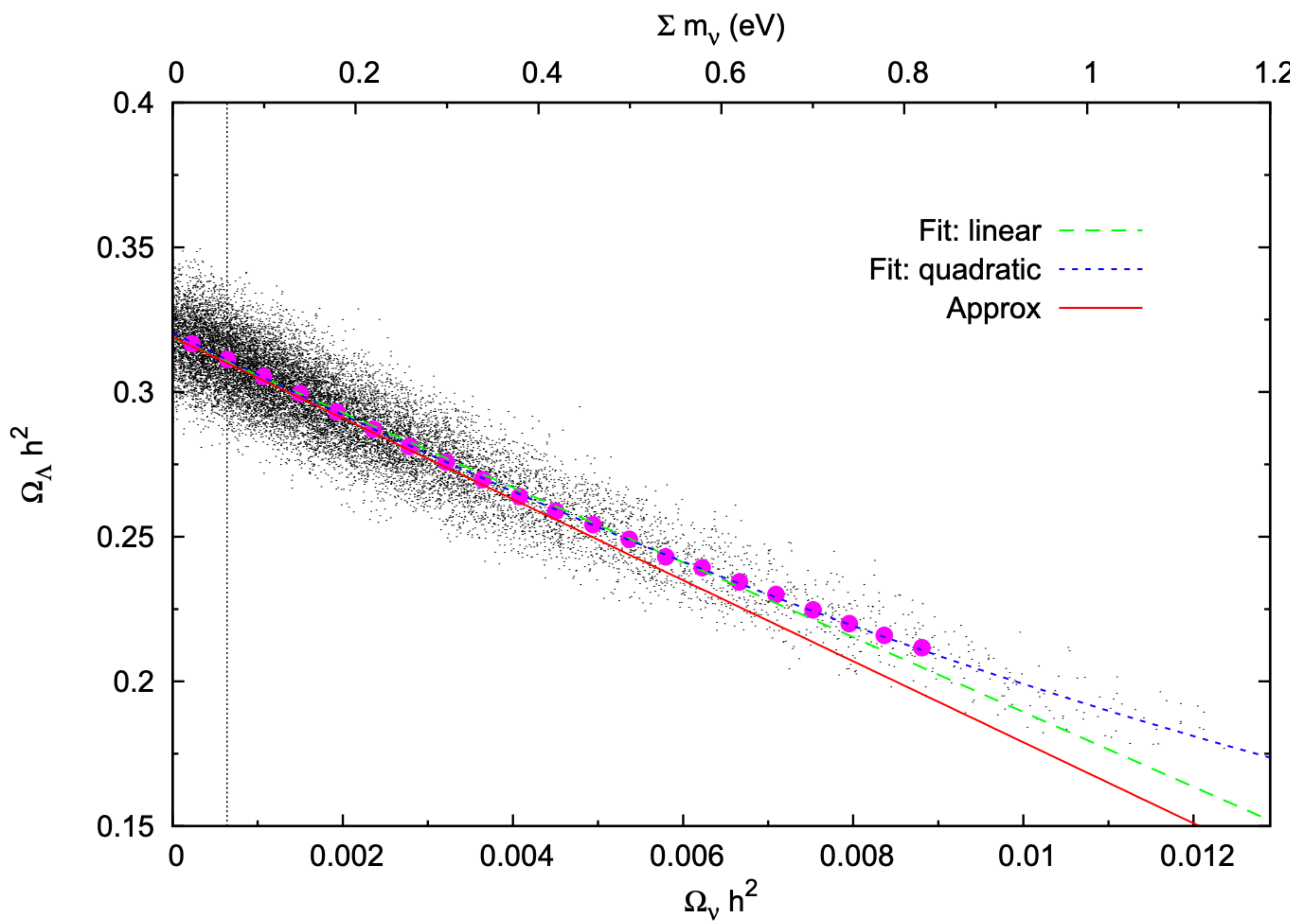
$$P_{\rm norm} = \int_{0.0588\,{\rm eV}}^{\infty} p(m_\nu) dm_\nu,$$

$$P_{\rm inv} = \int_{0.0995\,{\rm eV}}^{\infty} p(m_\nu) dm_\nu,$$

$$P_{\rm unphy} = \int_{0}^{0.0588\,{\rm eV}} p(m_\nu) dm_\nu.$$

The Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological Implications from two Decades of Spectroscopic Surveys at the Apache Point observatory. eBOSS Collaboration; Alam et al. [arXiv:2007.08991]

Neutrino mass (with CMB) is degenerate with DE



Type Ia SNe help break this degeneracy

The CMB neutrino mass / vacuum energy degeneracy: a simple derivation of the degeneracy slopes. Sutherland, W. MNRAS 477, 2 (2018) 1913-1920 [arXiv:1803.02298]

“Extremely” extended cosmological models

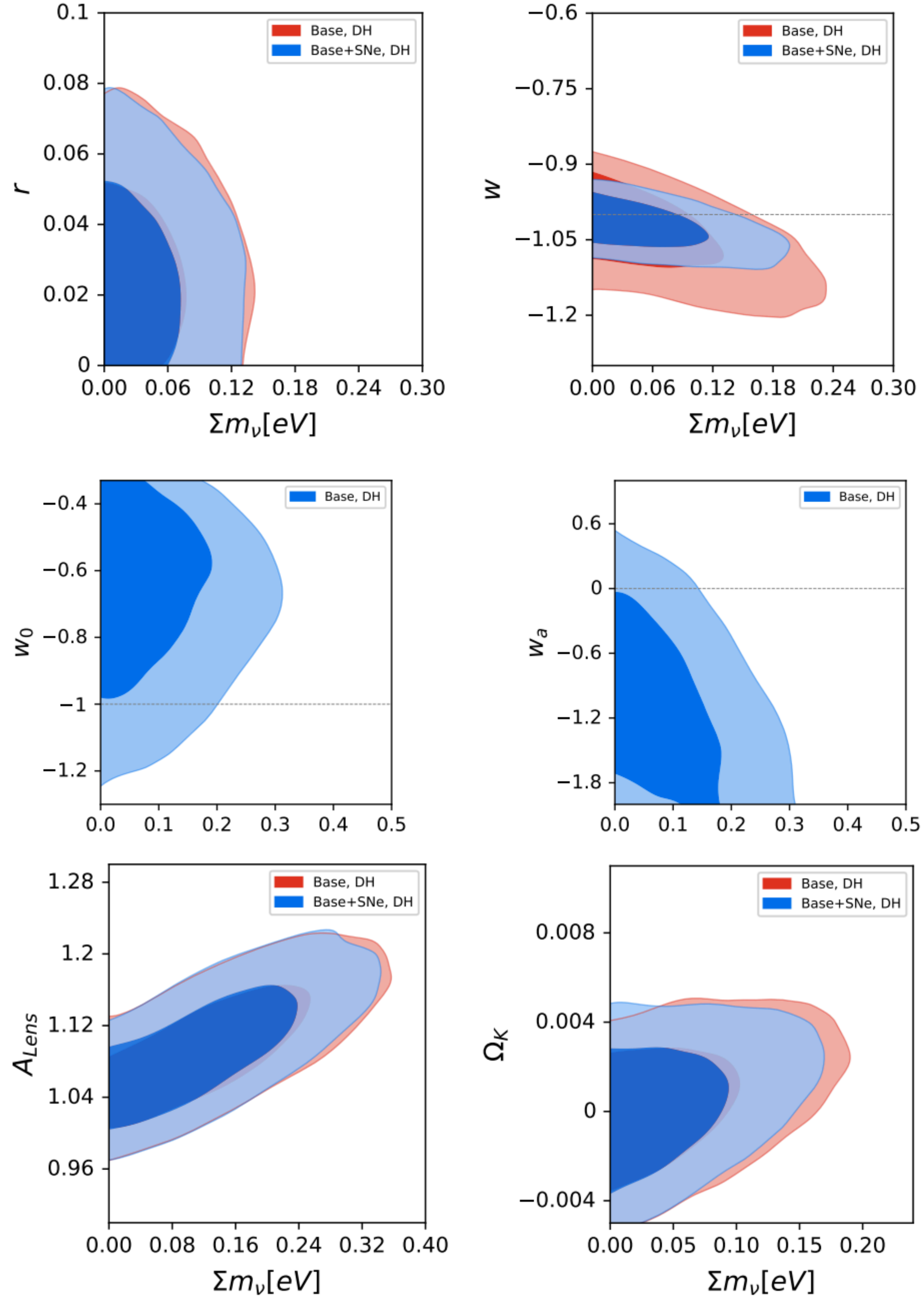
“12-parameter” cosmological model (adds $\Sigma m_\nu, N_{\rm eff}, w, w_a, A_L, \alpha_s$ to the ΛCDM model)

Parameters	Planck	Planck +R19	Planck +lensing	Planck +BAO	Planck + Pantheon
$\Omega_b h^2$	0.02245 ± 0.00027	0.02246 ± 0.00027	0.02228 ± 0.00026	0.02255 ± 0.00026	0.02245 ± 0.00027
$\Omega_c h^2$	0.1173 ± 0.0035	0.1173 ± 0.0033	0.1163 ± 0.0033	0.1172 ± 0.0035	0.1174 ± 0.0034
$100\theta_{\rm MC}$	1.04113 ± 0.00052	1.04113 ± 0.00050	1.04123 ± 0.00052	1.04118 ± 0.00051	1.04107 ± 0.00052
τ	0.0500 ± 0.0087	$0.0516^{+0.0083}$ [illegible]	0.0498 ± 0.0085	0.0504 ± 0.0085	$0.0497^{+0.0088}$ [illegible]
Σm_ν [eV]	< 0.906	< 0.857	$0.35^{+0.16}_{-0.26}$	< 0.515	< 0.928
w	-1.02 [illegible] $_{-0.96}$	-1.22 ± 0.33	-1.03 [illegible] $_{-0.26}$	-0.62 [illegible] $_{-0.26}$	-1.02 ± 0.16
w_a	*unconstrained*	*unconstrained*	*unconstrained*	-1.29 ± 0.87	$-0.39^{+0.98}_{-0.70}$
$N_{\rm eff}$	2.95 ± 0.24	2.95 ± 0.24	2.85 ± 0.23	2.99 ± 0.24	2.96 ± 0.24
A_L	$1.23^{+0.09}_{-0.12}$	$1.21^{+0.09}_{-0.10}$	$1.106^{+0.059}_{-0.089}$	$1.203^{+0.080}_{-0.089}$	$1.236^{+0.087}_{-0.098}$
$\ln(10^{10}A_s)$	3.028 ± 0.020	$3.031^{+0.019}_{-0.022}$	3.024 ± 0.020	3.029 ± 0.019	3.027 ± 0.020
n_s	0.964 ± 0.012	0.964 ± 0.012	0.958 ± 0.012	0.967 ± 0.012	0.964 ± 0.012
α_S	-0.0053 ± 0.0087	-0.0053 ± 0.0086	-0.0067 ± 0.0084	-0.0054 ± 0.0085	-0.0052 ± 0.0085
H_0[km/s/Mpc]	72 ± 20	74.0 ± 1.4	72 ± 20	$64.8^{+2.5}_{-2.9}$	66.8 ± 2.1
σ_8	$0.78^{+0.15}_{-0.14}$	$0.811^{+0.053}_{-0.035}$	$0.79^{+0.17}_{-0.12}$	0.751 ± 0.033	$0.745^{+0.056}_{-0.043}$
S_8	0.760 ± 0.054	$0.758^{+0.040}_{-0.029}$	0.766 ± 0.047	$0.799^{+0.030}_{-0.027}$	$0.772^{+0.037}_{-0.029}$

Cosmological constraints in extended parameter space from the Planck 2018 Legacy release.
Di Valentino et al. JCAP 01 (2020) 013 [arXiv:1908.01391]

	Base			Base+SNe		
	DH	NH	IH	DH	NH	IH
$\Lambda\mathrm{CDM} + \sum m_\nu + r$						
r	< 0.0626	< 0.0632	< 0.0618	< 0.0610	< 0.0629	< 0.0624
m_0 (eV)	< 0.038	< 0.039	< 0.040	< 0.037	< 0.035	< 0.038
$\sum m_\nu$ (eV)	< 0.11	< 0.14	< 0.17	< 0.11	< 0.13	< 0.16
H_0 (km/s/Mpc)	$67.78^{+0.52}_{-0.46}$	$67.48^{+0.48}_{-0.45}$	67.21 ± 0.44	67.86 ± 0.48	$67.58^{+0.44}_{-0.45}$	$67.30^{+0.43}_{-0.44}$
σ_8	$0.815^{+0.010}_{-0.007}$	$0.807^{+0.008}_{-0.006}$	$0.800^{+0.008}_{-0.006}$	$0.816^{+0.010}_{-0.007}$	$0.808^{+0.008}_{-0.007}$	$0.800^{+0.007}_{-0.006}$
S_8	0.832 ± 0.011	$0.825^{+0.011}_{-0.010}$	0.822 ± 0.011	0.828 ± 0.011	0.824 ± 0.010	0.820 ± 0.010
$w\mathrm{CDM} + \sum m_\nu$						
w	$-1.042^{+0.072}_{-0.052}$	$-1.068^{+0.071}_{-0.052}$	$-1.089^{+0.070}_{-0.055}$	$-1.025^{+0.037}_{-0.033}$	$-1.037^{+0.036}_{-0.032}$	-1.048 ± 0.034
m_0 (eV)	< 0.062	< 0.066	< 0.066	< 0.053	< 0.053	< 0.054
$\sum m_\nu$ (eV)	< 0.19	< 0.21	< 0.23	< 0.16	< 0.18	< 0.20
H_0 (km/s/Mpc)	$68.67^{+1.33}_{-1.59}$	$69.01^{+1.31}_{-1.60}$	$69.24^{+1.38}_{-1.61}$	68.33 ± 0.82	68.31 ± 0.82	68.27 ± 0.82
σ_8	$0.821^{+0.016}_{-0.017}$	0.820 ± 0.016	0.819 ± 0.016	$0.818^{+0.013}_{-0.011}$	0.814 ± 0.012	0.810 ± 0.012
S_8	0.825 ± 0.011	$0.822^{+0.012}_{-0.011}$	0.822 ± 0.011	0.826 ± 0.011	0.823 ± 0.011	0.821 ± 0.011
$w_0 w_a\mathrm{CDM} + \sum m_\nu$						
w_0	$-0.68^{+0.26}_{-0.14}$	$-0.68^{+0.26}_{-0.14}$	$-0.68^{+0.25}_{-0.13}$	$-0.94^{+0.08}_{-0.09}$	-0.94 ± 0.09	-0.93 ± 0.09
w_a	$-1.06^{+0.37}_{-0.79}$	< -0.085	< -0.164	$-0.41^{+0.46}_{-0.29}$	$-0.49^{+0.44}_{-0.30}$	$-0.56^{+0.43}_{-0.32}$
m_0 (eV)	< 0.083	< 0.080	< 0.083	< 0.089	< 0.088	< 0.088
$\sum m_\nu$ (eV)	< 0.25	< 0.26	< 0.28	< 0.27	< 0.28	< 0.29
H_0 (km/s/Mpc)	$65.70^{+1.60}_{-2.47}$	$65.78^{+1.61}_{-2.47}$	$65.80^{+1.62}_{-2.43}$	68.28 ± 0.83	68.23 ± 0.84	68.23 ± 0.82
σ_8	$0.795^{+0.018}_{-0.023}$	$0.792^{+0.017}_{-0.023}$	$0.790^{+0.018}_{-0.023}$	$0.817^{+0.015}_{-0.013}$	$0.813^{+0.014}_{-0.012}$	$0.811^{+0.013}_{-0.012}$
S_8	0.837 ± 0.014	$0.834^{+0.014}_{-0.013}$	0.832 ± 0.013	0.827 ± 0.012	0.826 ± 0.012	0.824 ± 0.012
$w_0 w_a\mathrm{CDM} + \sum m_\nu (w(z) \geq -1)$						
w_0	< -0.873	< -0.888	< -0.900	< -0.937	< -0.944	< -0.949
w_a	$0.009^{+0.057}_{-0.067}$	$0.007^{+0.049}_{-0.058}$	$0.007^{+0.044}_{-0.050}$	$0.028^{+0.034}_{-0.056}$	$0.022^{+0.029}_{-0.047}$	$0.020^{+0.025}_{-0.043}$
m_0 (eV)	< 0.032	< 0.034	< 0.035	< 0.032	< 0.033	< 0.035
$\sum m_\nu$ (eV)	< 0.10	< 0.13	< 0.16	< 0.09	< 0.13	< 0.16
H_0 (km/s/Mpc)	$66.64^{+0.97}_{-0.66}$	$66.46^{+0.88}_{-0.62}$	$66.33^{+0.83}_{-0.57}$	$67.23^{+0.63}_{-0.53}$	$67.01^{+0.57}_{-0.51}$	$66.81^{+0.54}_{-0.48}$
σ_8	$0.801^{+0.012}_{-0.010}$	$0.795^{+0.011}_{-0.009}$	$0.789^{+0.010}_{-0.008}$	$0.807^{+0.010}_{-0.008}$	$0.799^{+0.009}_{-0.008}$	0.793 ± 0.008
S_8	0.826 ± 0.011	0.823 ± 0.011	0.820 ± 0.011	0.824 ± 0.010	0.821 ± 0.011	0.817 ± 0.011
$\Lambda\mathrm{CDM} + \sum m_\nu + A_{\mathrm{Lens}}$						
A_{Lens}	$1.100^{+0.046}_{-0.056}$	$1.107^{+0.042}_{-0.055}$	$1.116^{+0.040}_{-0.050}$	$1.098^{+0.044}_{-0.058}$	$1.106^{+0.042}_{-0.053}$	$1.116^{+0.040}_{-0.050}$
m_0 (eV)	< 0.098	< 0.094	< 0.092	< 0.094	< 0.090	< 0.087
$\sum m_\nu$ (eV)	< 0.29	< 0.29	< 0.30	< 0.28	< 0.28	< 0.29
H_0 (km/s/Mpc)	$67.76^{+0.71}_{-0.60}$	$67.66^{+0.66}_{-0.59}$	$67.56^{+0.63}_{-0.53}$	$67.86 \pm^{+0.68}_{-0.57}$	67.76 ± 0.59	$67.66^{+0.58}_{-0.51}$
σ_8	$0.782^{+0.029}_{-0.018}$	$0.777^{+0.025}_{-0.013}$	$0.772^{+0.022}_{-0.012}$	$0.784^{+0.028}_{-0.017}$	$0.779^{+0.024}_{-0.013}$	$0.773^{+0.021}_{-0.011}$
S_8	$0.793^{+0.023}_{-0.020}$	$0.790^{+0.022}_{-0.017}$	$0.786^{+0.020}_{-0.016}$	$0.793^{+0.023}_{-0.019}$	$0.790^{+0.021}_{-0.017}$	$0.785^{+0.019}_{-0.016}$
$\Lambda\mathrm{CDM} + \sum m_\nu + \Omega_{\mathrm{k}}$						
Ω_{k}	0.0004 ± 0.0020	$0.0012^{+0.0020}_{-0.0021}$	$0.0019^{+0.0019}_{-0.0021}$	0.0004 ± 0.0021	0.0012 ± 0.0020	0.0019 ± 0.0020
m_0 (eV)	< 0.050	< 0.051	< 0.053	< 0.044	< 0.047	< 0.049
$\sum m_\nu$ (eV)	< 0.15	< 0.17	< 0.20	< 0.13	< 0.16	< 0.19
H_0 (km/s/Mpc)	67.87 ± 0.67	67.75 ± 0.67	$67.67^{+0.67}_{-0.68}$	67.95 ± 0.67	67.84 ± 0.66	67.77 ± 0.66
σ_8	$0.813^{+0.011}_{-0.008}$	$0.807^{+0.010}_{-0.008}$	$0.801^{+0.009}_{-0.008}$	$0.814^{+0.010}_{-0.009}$	$0.807^{+0.010}_{-0.008}$	$0.801^{+0.009}_{-0.008}$
S_8	0.826 ± 0.011	0.823 ± 0.011	0.819 ± 0.011	0.825 ± 0.011	0.822 ± 0.011	0.818 ± 0.010

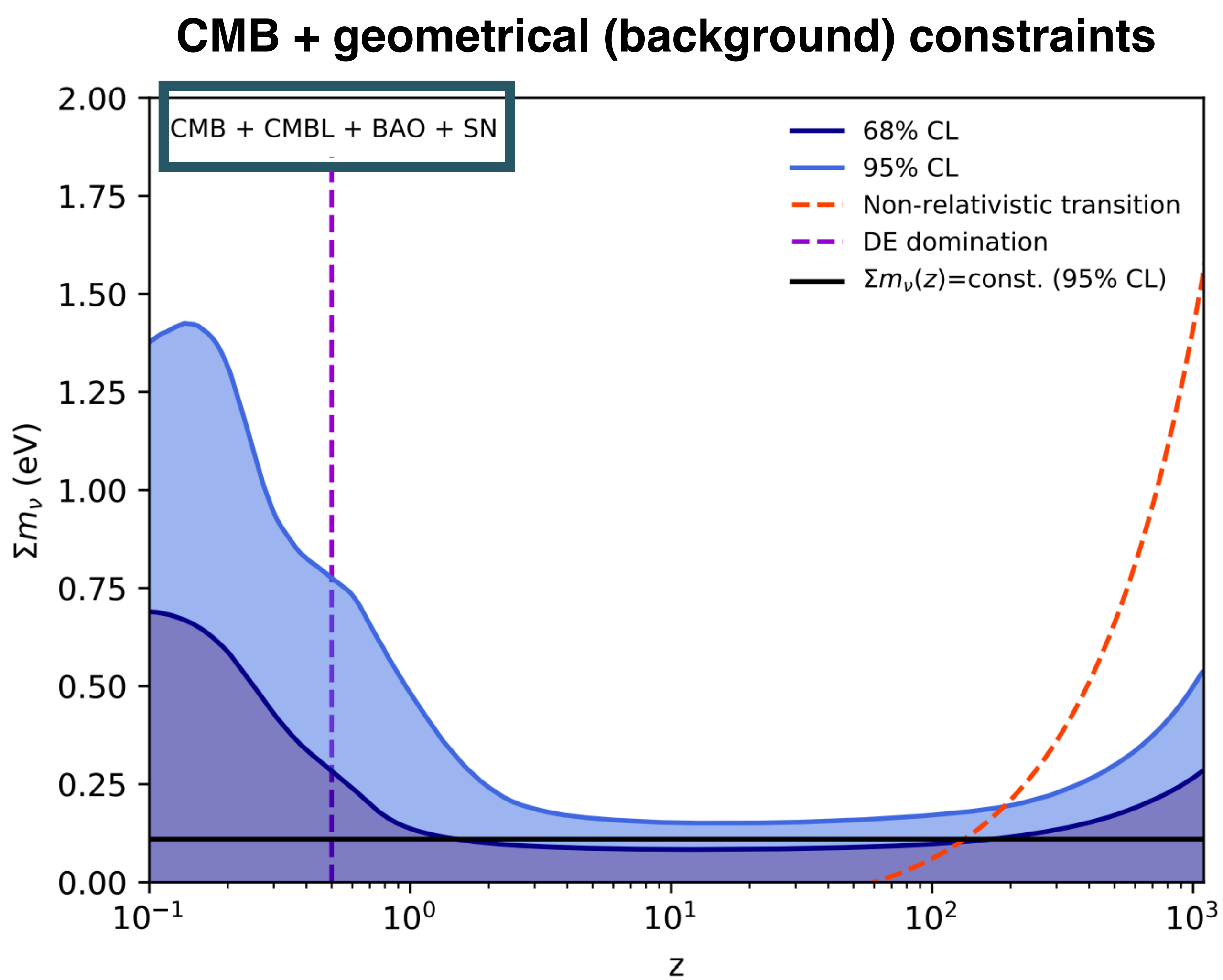
Table 3. Constraints on selected cosmological parameters in the extended models considering three different hierarchies (degenerate, normal, and inverted) with the Base and Base+SNe datasets. In the $\Lambda\mathrm{CDM} + \sum m_\nu + r$ model Base data also includes BK15.



Updated results on neutrino mass and mass hierarchy from cosmology with Planck 2018 likelihoods. Choudhury et al. JCAP 07 (2020) 037 [arXiv:1907.12598]

No significant difference in the neutrino hierarchy assumed in the MCMC chains

Sensitivity of cosmological probes is z-dependent

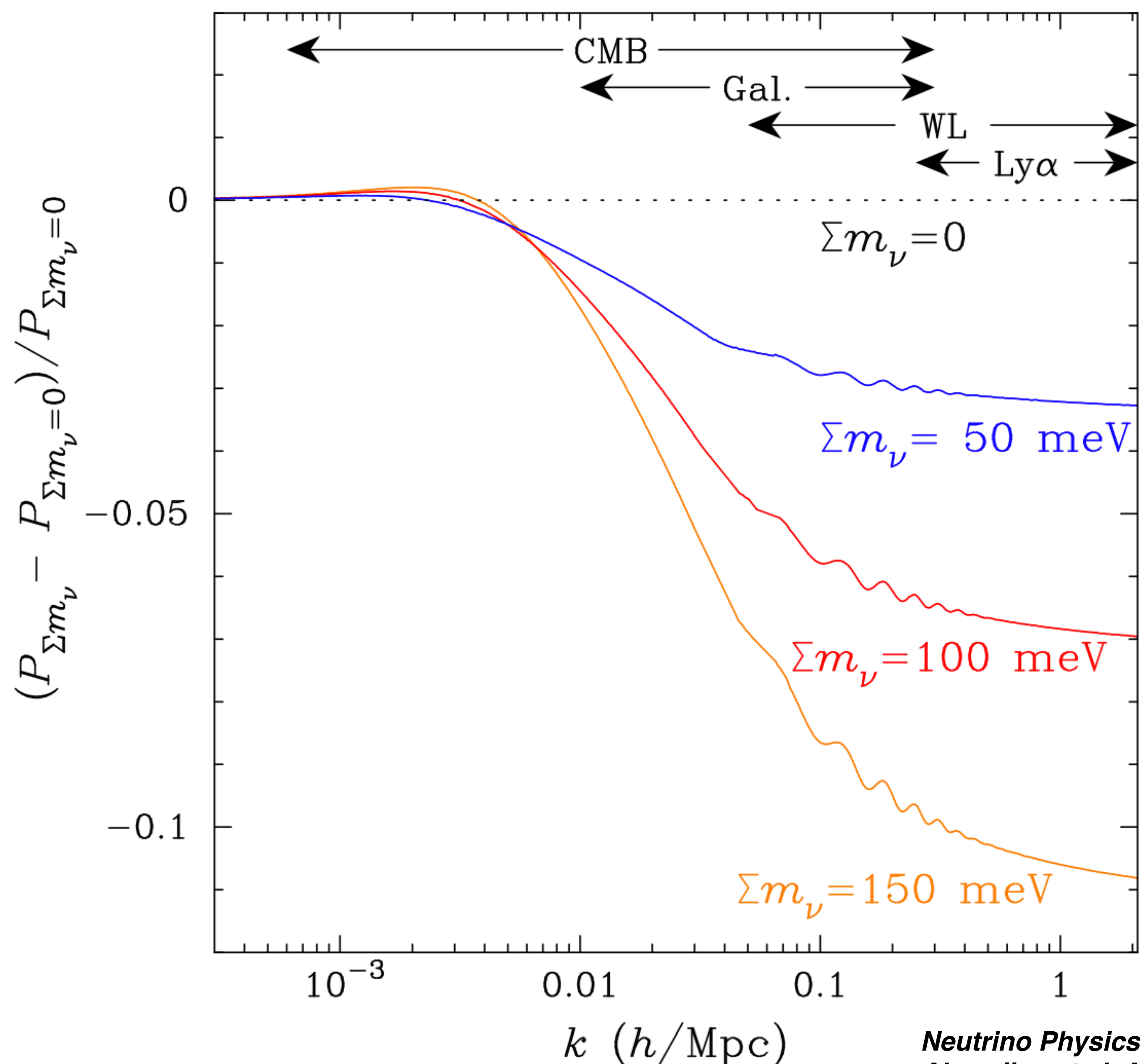


Reconstruction of the neutrino mass as a function of redshift
Lorenz et al. 2021 [arXiv:2102.13618]

Model-independent constraint

$$\Sigma m_\nu(z=0) < 1.41\text{eV}\ (95\,\%\ \text{CL})$$

The signature in the 2-point correlation function



The main signature of massive neutrinos on the galaxy power spectrum is a **suppression** of power at small scales

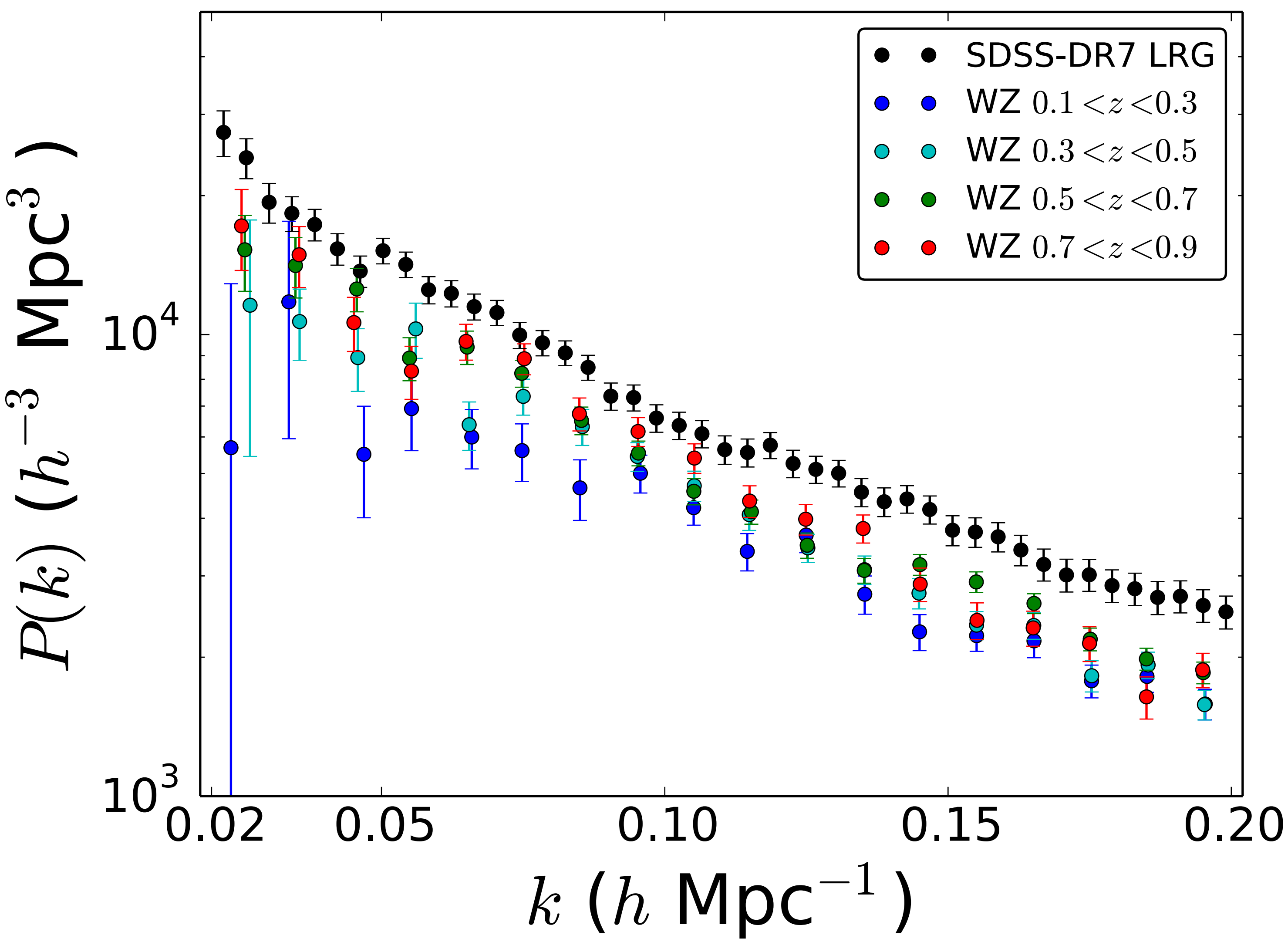
ΔP/P (linear theory) ≈ $-8f_\nu = -8\Omega_\nu/\Omega_m$ = $-8\Sigma m_\nu/(93.14\Omega_m h^2 \mathrm{eV})$

The impact of neutrino mass on the matter power spectrum is at the level of 5%, requiring exquisite control of **systematics**

In particular, we need a careful modeling of the **non-linear regime** and **galaxy bias**

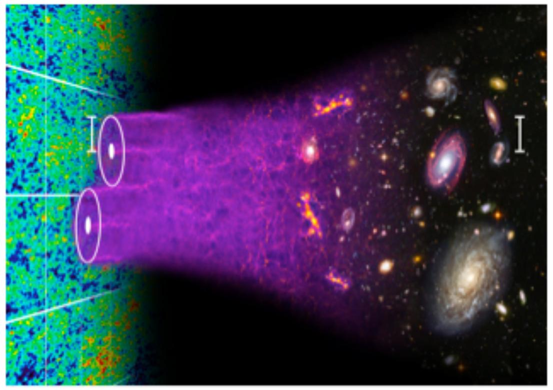
Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure. Abazajian et al. Astropart.Phys. 63 (2015) 66-80 [arXiv:1309.5383]

Galaxy power spectra from large-scale surveys

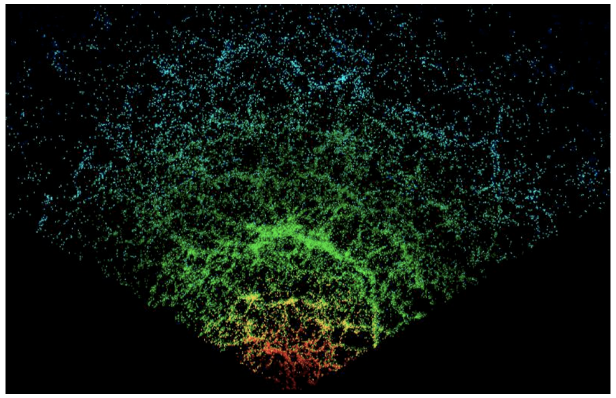


We have used P(k) measurements from two surveys targeting completely different types of tracers:

the **SDSS** sample probes *Luminous Red Galaxies*, whereas the **WiggleZ** survey probes *Emission Line Galaxies*



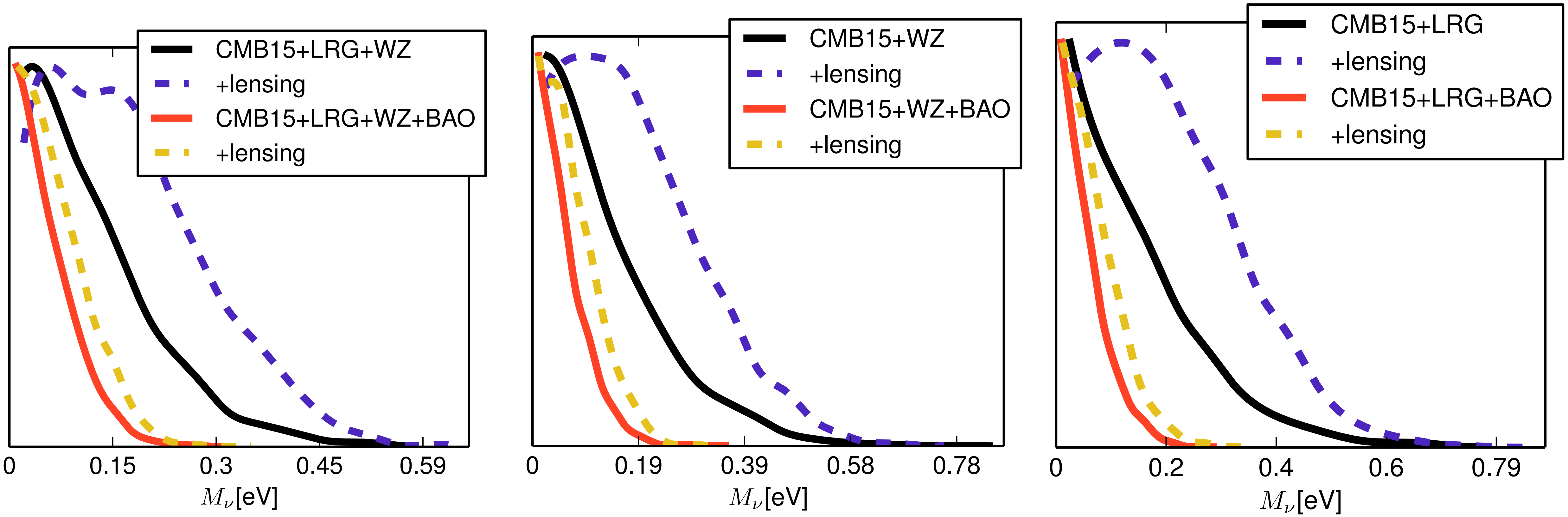
WiggleZ

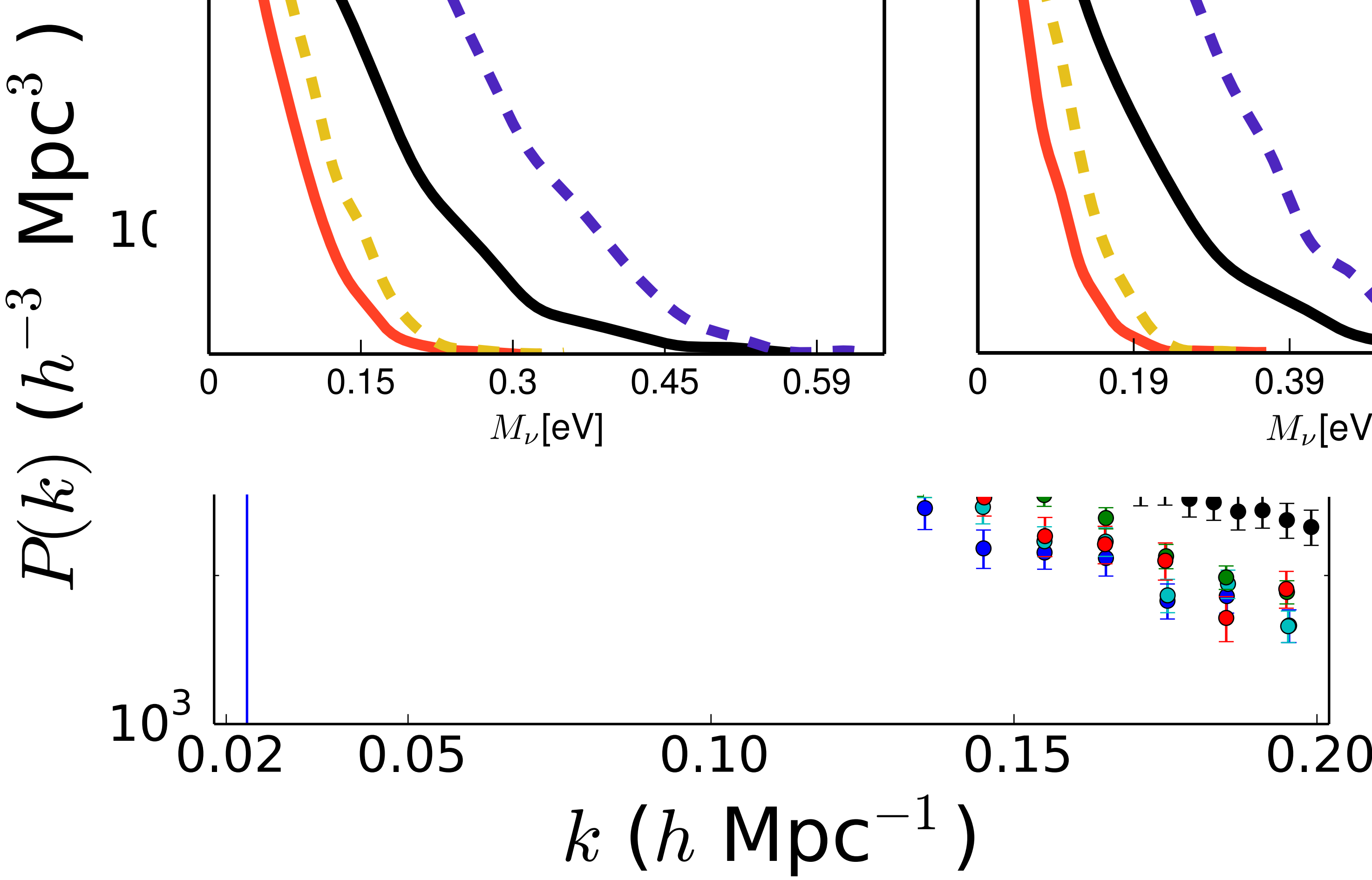


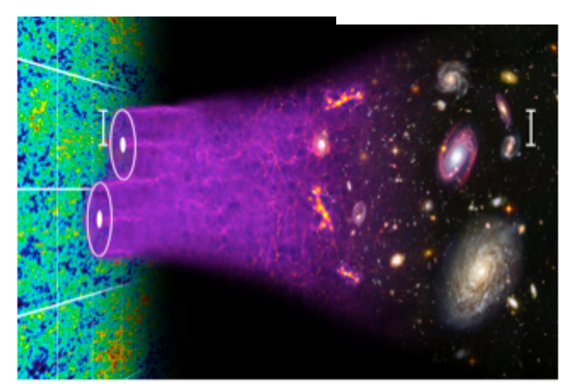
SDSS

Neutrino mass limits: robust information from the power spectrum of galaxy surveys
Cuesta et al. PDU 13 (2016) 77-86 [arXiv:1511.05983]

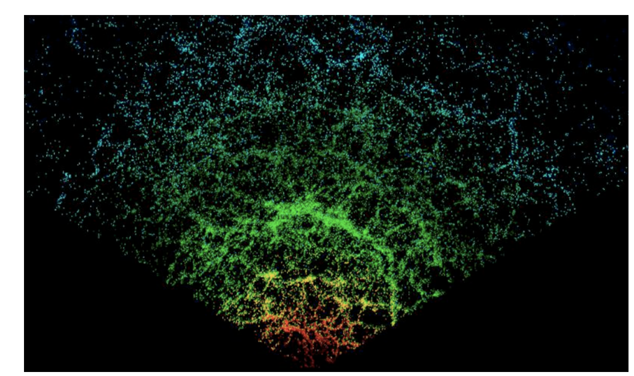
Galaxy power spectra from large-scale surveys







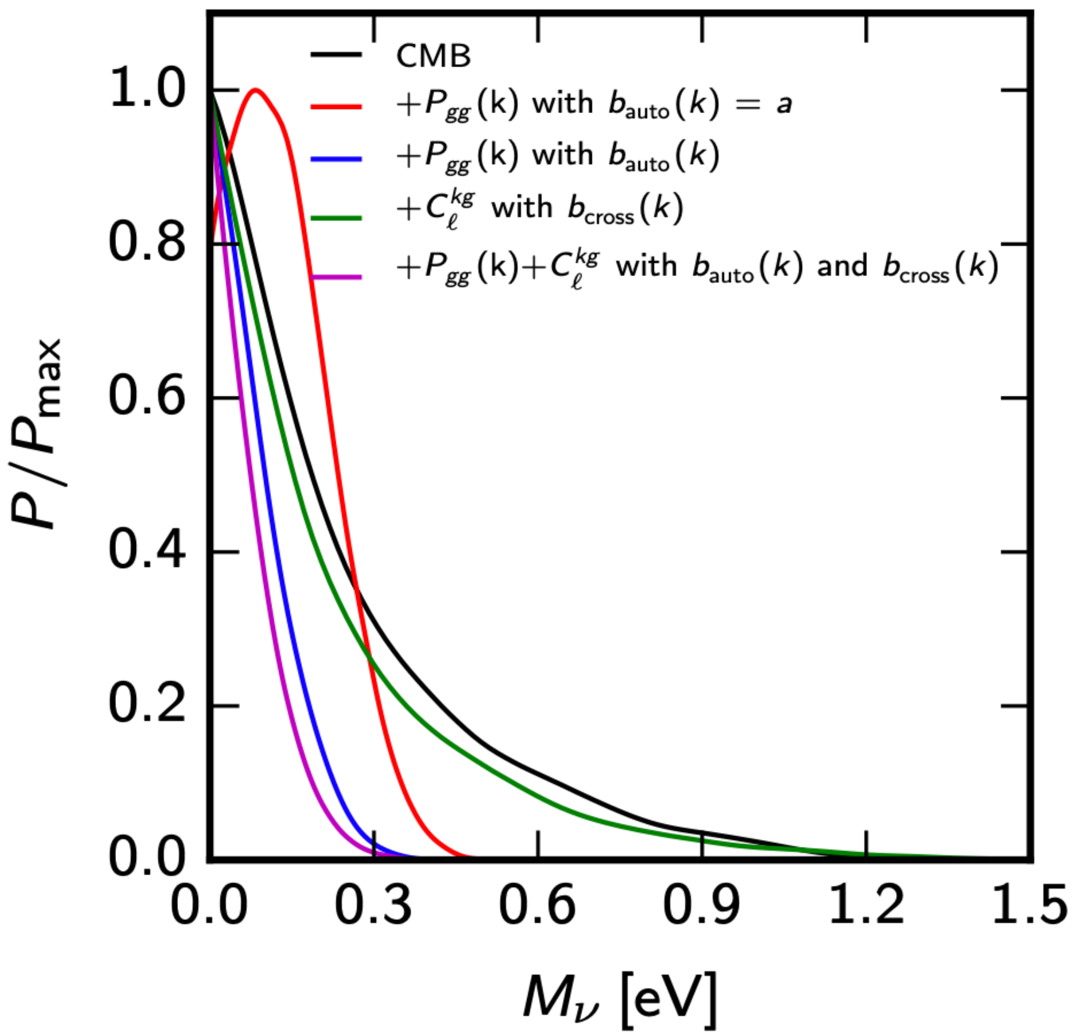
WiggleZ

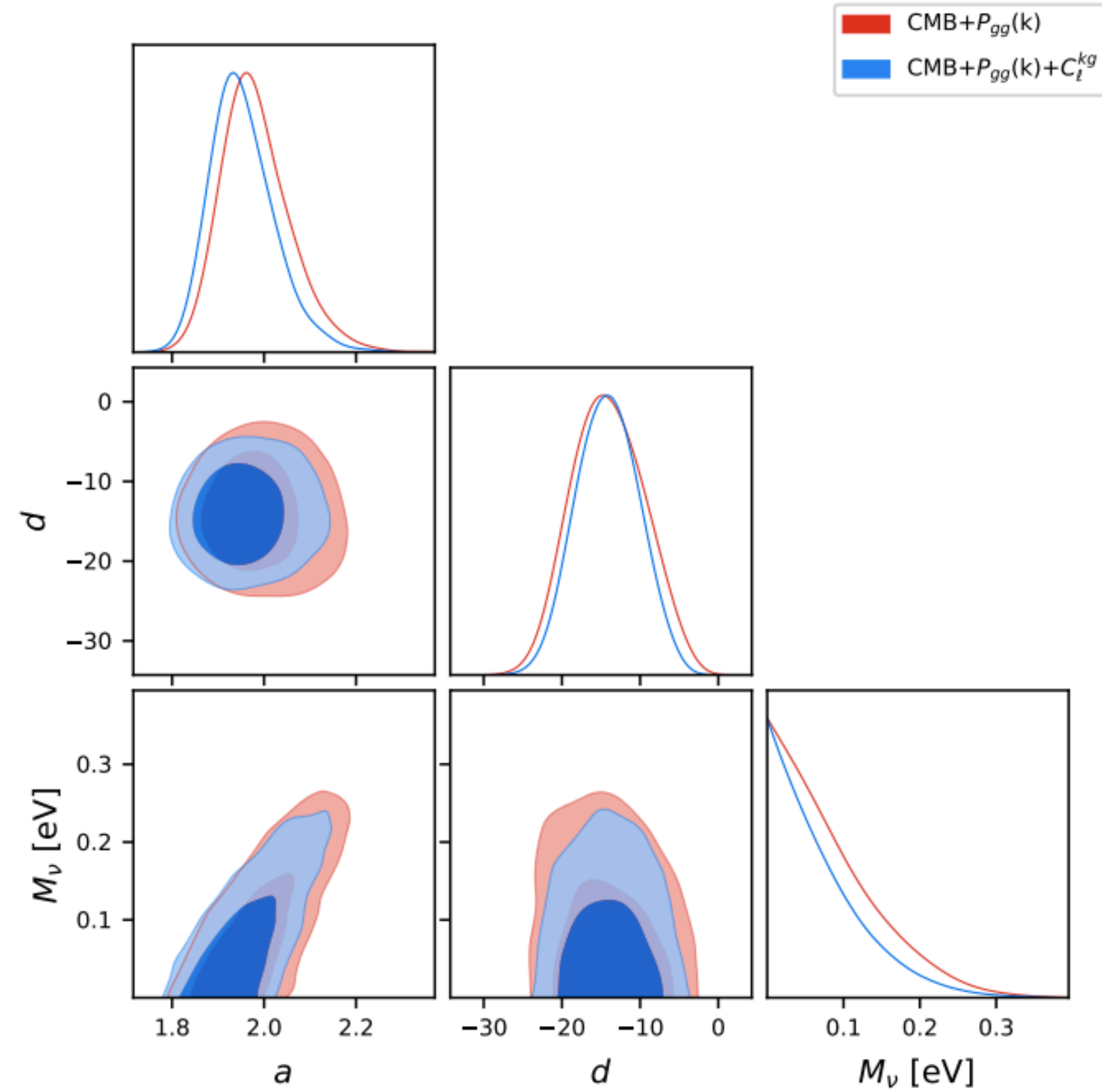


SDSS

Neutrino mass limits: robust information from the power spectrum of galaxy surveys
Cuesta et al. PDU 13 (2016) 77-86 [arXiv:1511.05983]

CMB+LSS

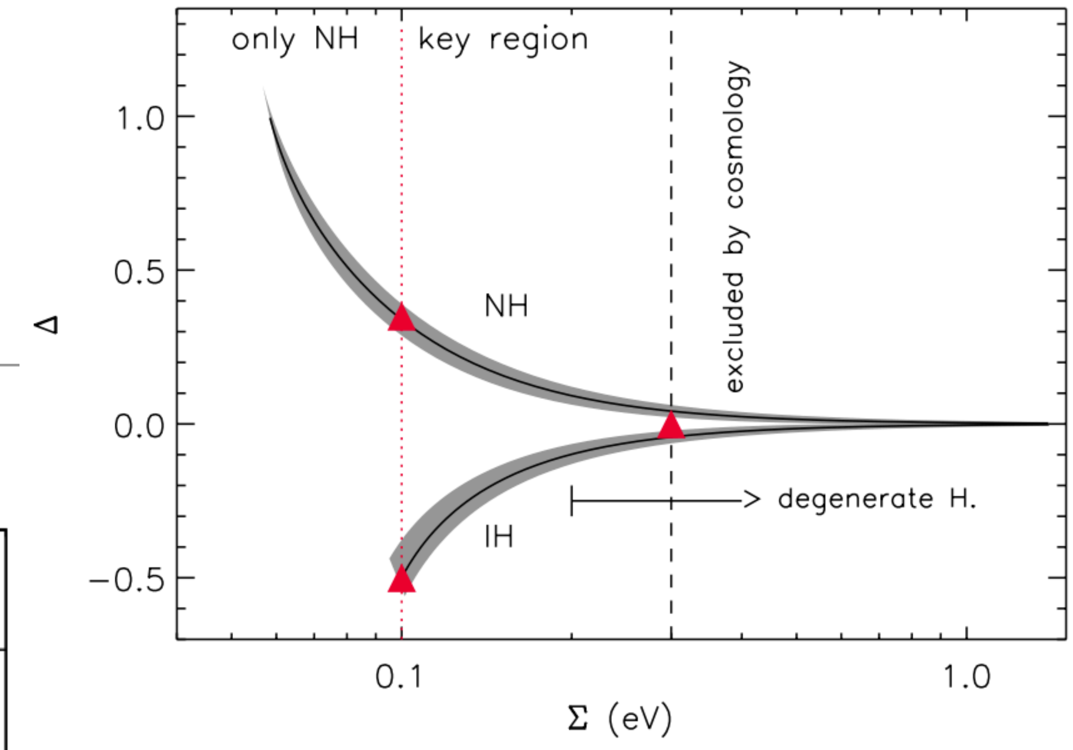


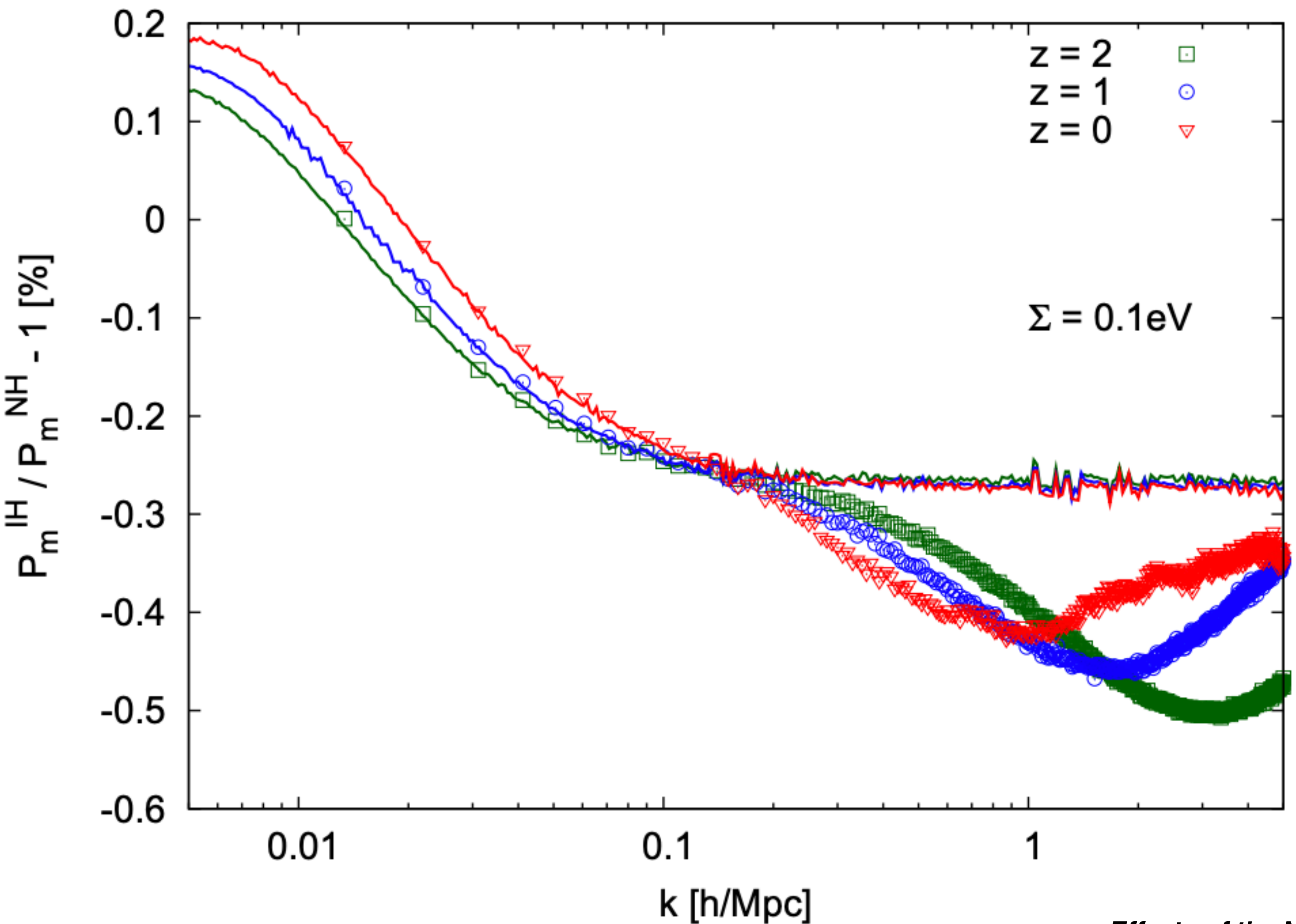


Scale-dependent galaxy bias, CMB lensing-galaxy cross-correlation, and neutrino masses. Giusarma et al. Phys. Rev. D98 (2018) 123526 [arXiv:1802.08694].

Dataset	a (68% C.L.)	c (68% C.L., h^{-2} Mpc^2)	d (68% C.L., h^{-2} Mpc^2)	M_ν [eV] (95% C.L.)	
CMB ≡ *PlanckTT+lowP*				< 0.72	$[< 0.77]$
CMB+$C_\ell^{\kappa g}$	1.45 ± 0.19	2.59 ± 1.22		**0.06**	
	1.50 ± 0.21	2.97 ± 1.42		< 0.72	$[< 0.77]$
CMB+P_{gg}(k)	1.97 ± 0.05		-13.76 ± 4.61	**0.06**	
	1.98 ± 0.08		-14.03 ± 4.68	< 0.22	$[< 0.24]$
CMB+P_{gg}(k)+$C_\ell^{\kappa g}$	1.95 ± 0.05	0.45 ± 0.87	-13.90 ± 4.17	**0.06**	
	1.95 ± 0.07	0.48 ± 0.90	-14.13 ± 4.02	< 0.19	$[< 0.22]$

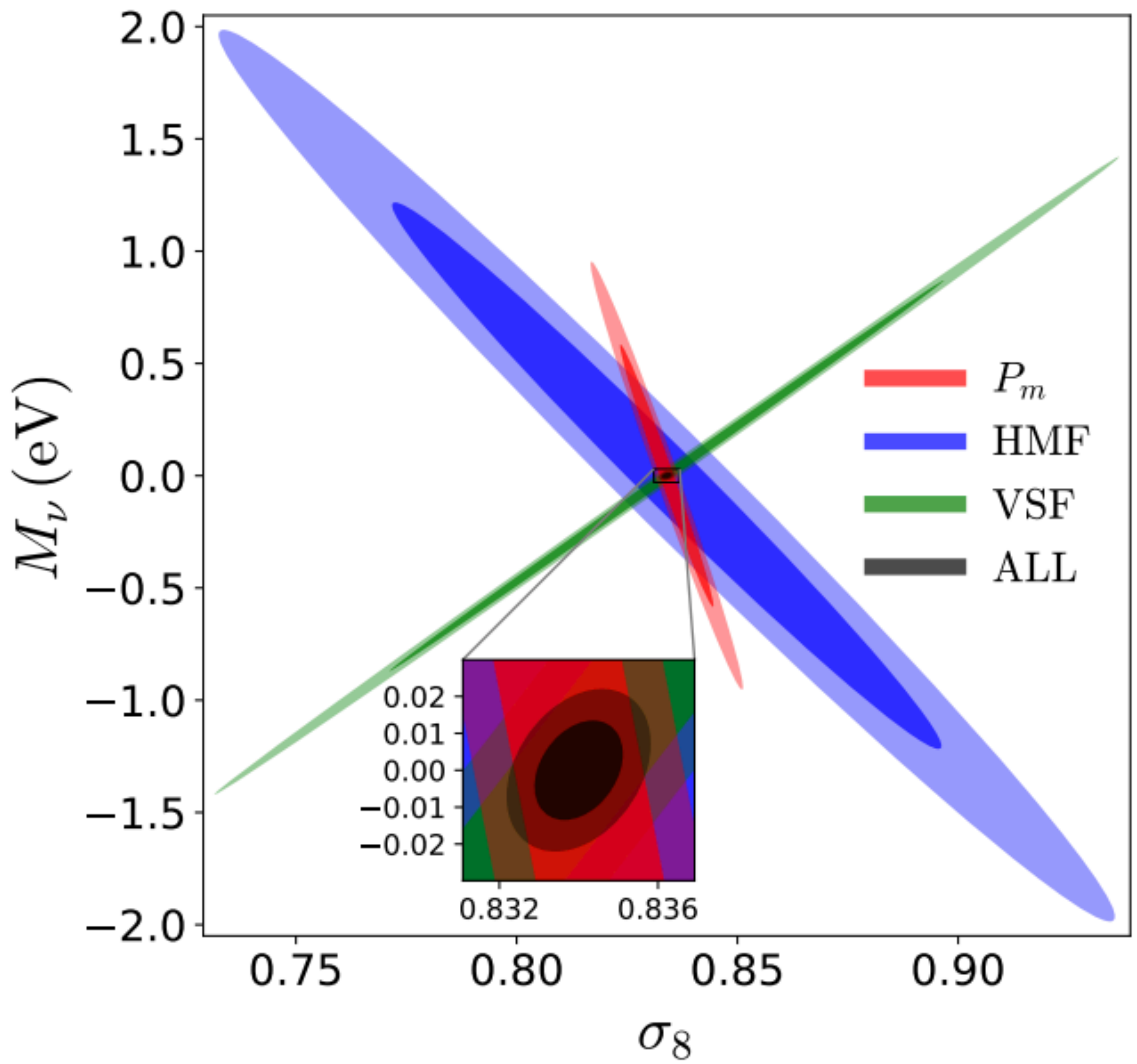
Mass Hierarchy with LSS





Effects of the Neutrino Mass Splitting on the Nonlinear Matter Power Spectrum. Wagner et al. ApJL (2012) 752, 31 [arXiv:1203.5342]

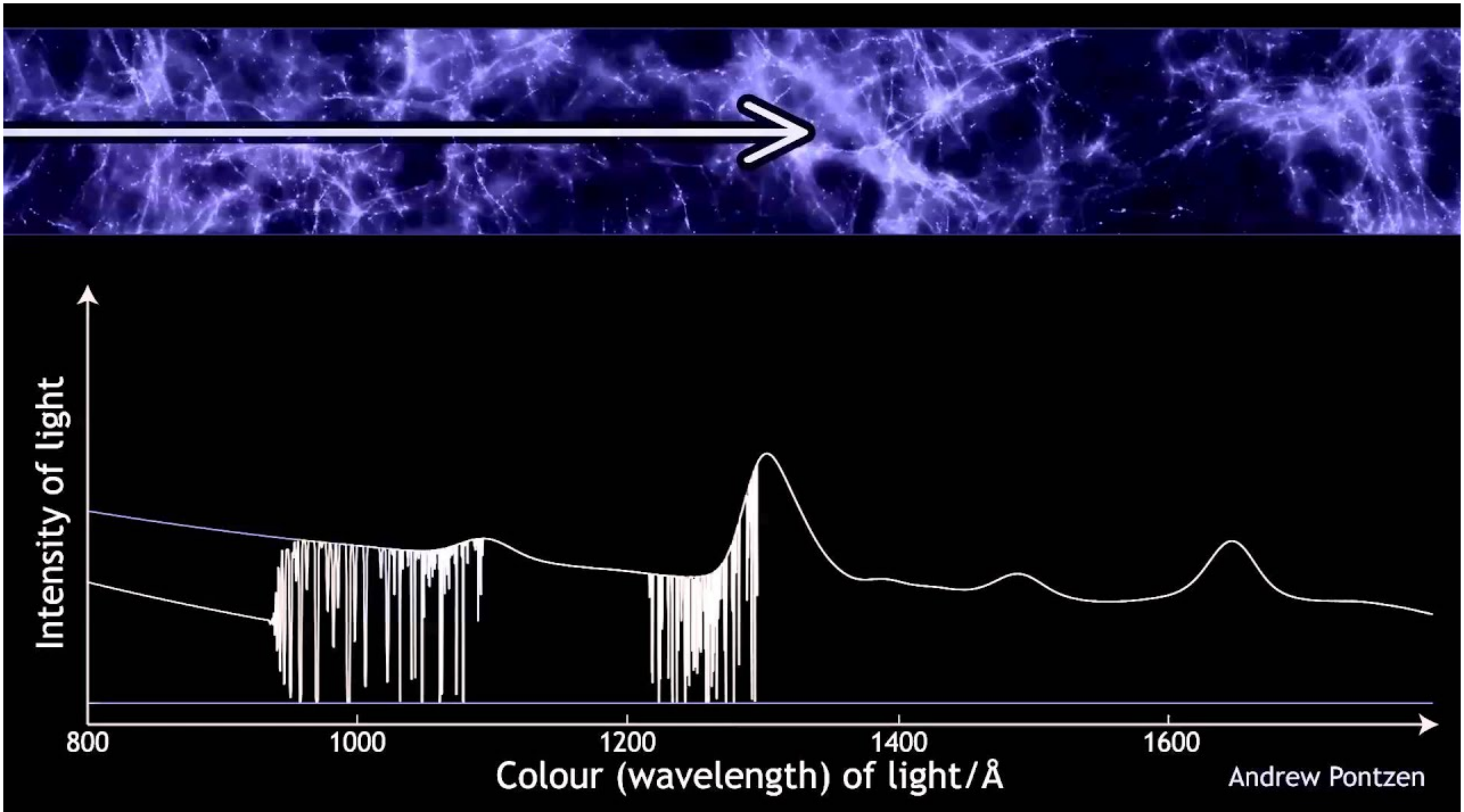
Why not voids as well?



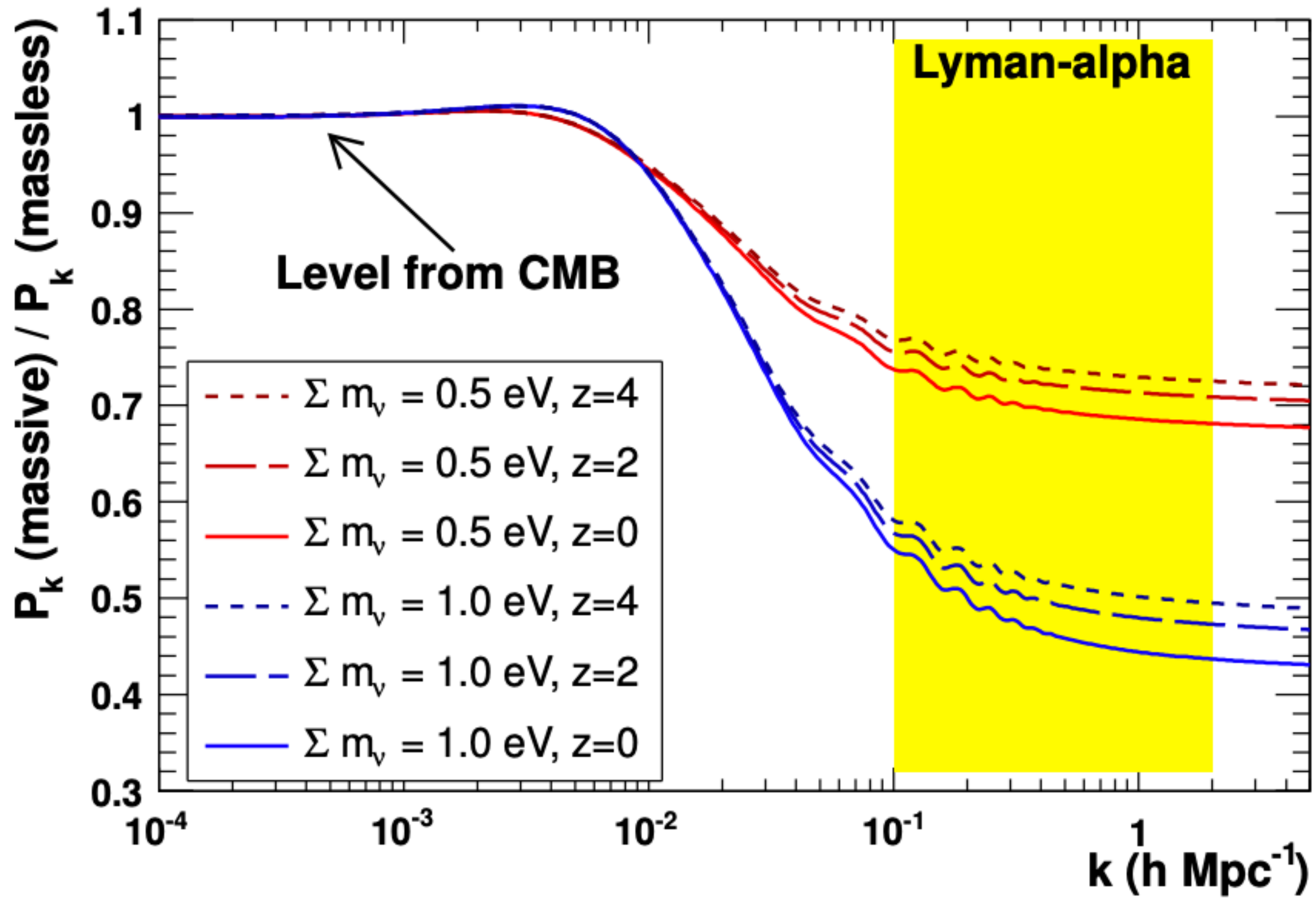
(Forecasts with mock data)

Detecting neutrino mass by combining matter clustering, halos, and voids.
Bayer et al. (2021) [arXiv:2102.05049]

What is Lyα? Lyman-alpha forest



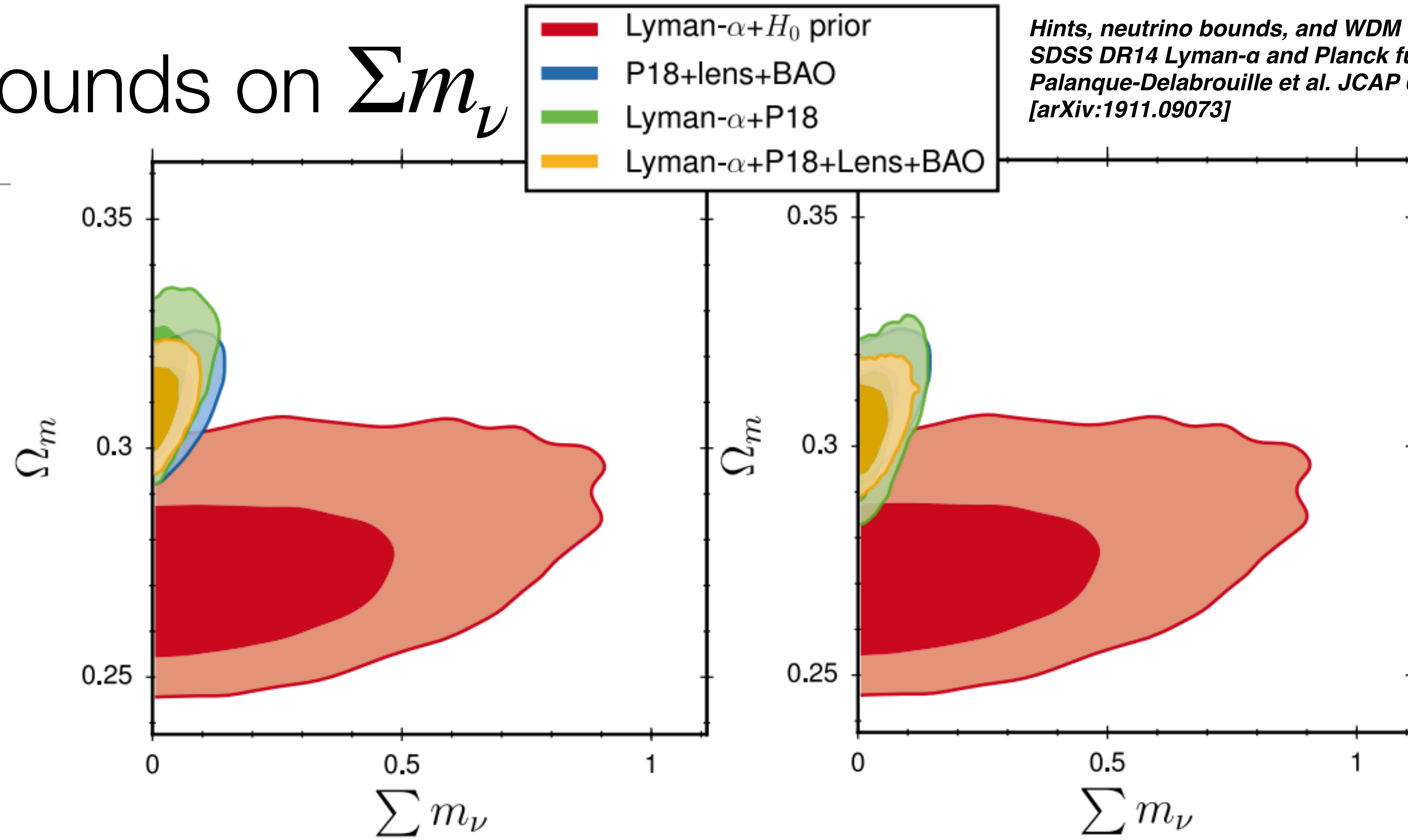
Ly-α probes smaller scales



Neutrino masses and cosmology with Lyman-alpha forest power spectrum. Palanque-Delabrouille et al. JCAP 11 (2015) 011 [arXiv:1506.05976]

Ly-α bounds on Σm_ν

Hints, neutrino bounds, and WDM constraints from SDSS DR14 Lyman-α and Planck full-survey data. Palanque-Delabrouille et al. JCAP 04 (2020) 038 [arXiv:1911.09073]



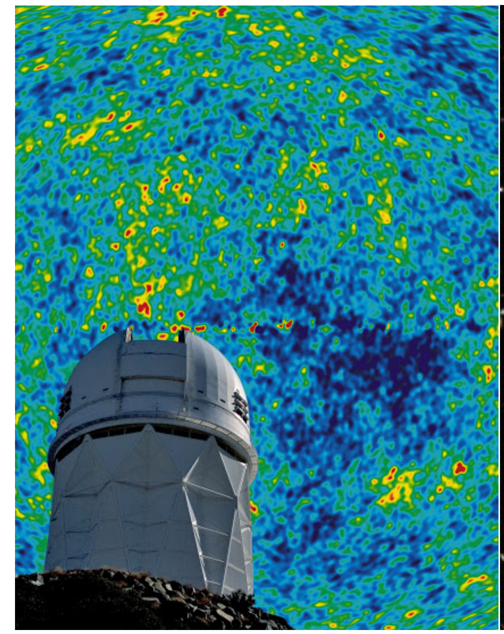
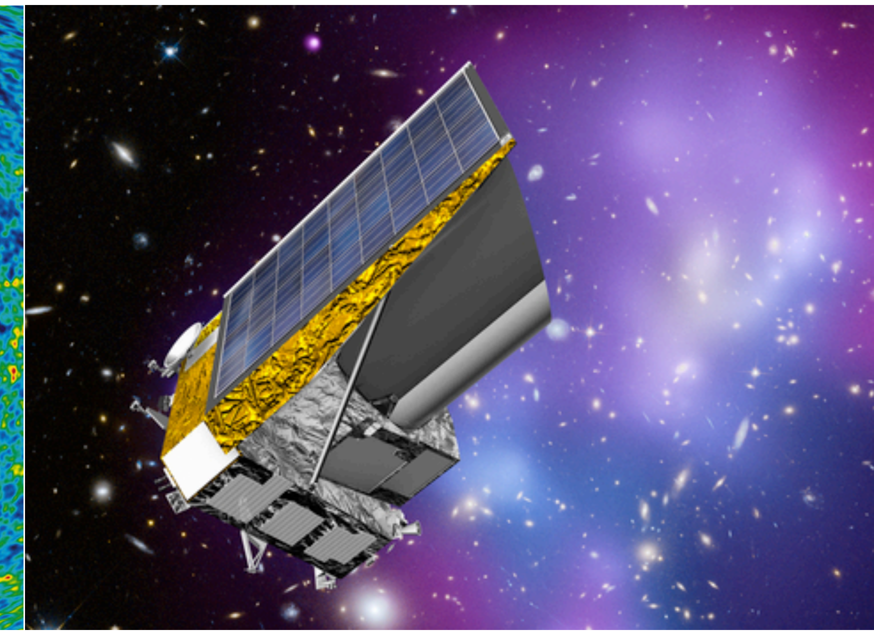
	Frequentist		Bayesian	
	P18 + Lyman-α	P18 + Lyman-α +lens. +BAO	P18 + Lyman-α	P18 + Lyman-α +lens. +BAO
T_0 (z=3) (10^3K)	9.7 ± 1.7	9.8 ± 2.0	9.5 ± 1.8	9.5 ± 1.8
γ	0.69 ± 0.10	0.68 ± 0.11	0.71 ± 0.10	0.71 ± 0.10
σ_8	0.825 ± 0.006	0.819 ± 0.008	0.818 ± 0.010	0.818 ± 0.007
n_s	0.958 ± 0.003	0.961 ± 0.003	0.959 ± 0.004	0.960 ± 0.003
Ω_m	0.311 ± 0.006	0.308 ± 0.006	0.316 ± 0.009	0.310 ± 0.006
$\sum m_\nu$ (eV , 95% CL)	< 0.099	< 0.089	< 0.099	< 0.074

Table 6. Preferred astrophysical and cosmological parameter values (68.3% confidence level) for the ΛCDM + m_ν model, for combined Lyman-α, CMB and BAO data.

	Frequentist		Bayesian	
	P18 + Lyman-α	P18 + Lyman-α +lens. +BAO	P18 + Lyman-α	P18 + Lyman-α +lens. +BAO
T_0 (z=3) (10^3K)	7.6 ± 1.9	7.6 ± 1.8	8.2 ± 1.6	8.2 ± 1.6
γ	0.88 ± 0.13	0.88 ± 0.08	0.90 ± 0.12	0.89 ± 0.12
σ_8	0.824 ± 0.008	0.820 ± 0.008	0.814 ± 0.010	0.818 ± 0.008
n_s(Planck)	0.965 ± 0.004	0.968 ± 0.004	0.968 ± 0.005	0.967 ± 0.004
n_s(Lyman-α)	0.942 ± 0.006	0.942 ± 0.005	0.941 ± 0.006	0.941 ± 0.006
Ω_m	0.304 ± 0.010	0.304 ± 0.006	0.305 ± 0.009	0.305 ± 0.006
$\sum m_\nu$ (eV , 95% CL)	< 0.126	< 0.104	< 0.109	< 0.087

Table 7. Preferred astrophysical and cosmological parameter values (68.3% confidence level) for the ΛCDM + m_ν model, for combined Lyman-α, CMB and BAO data, when introducing artificially two distinct n_s value in the Lyman-α and CMB likelihood.

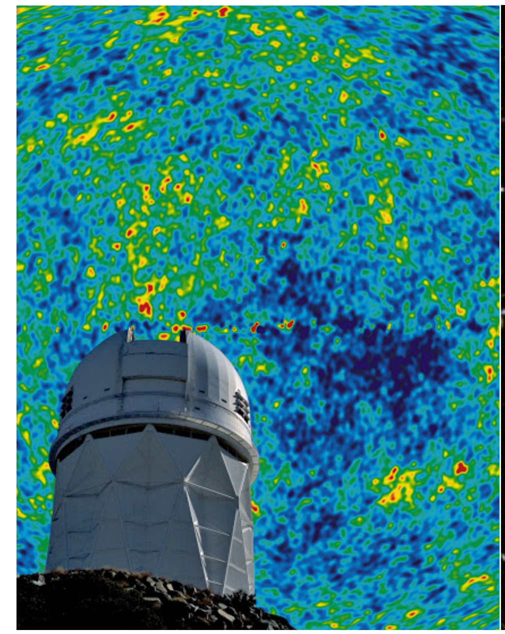
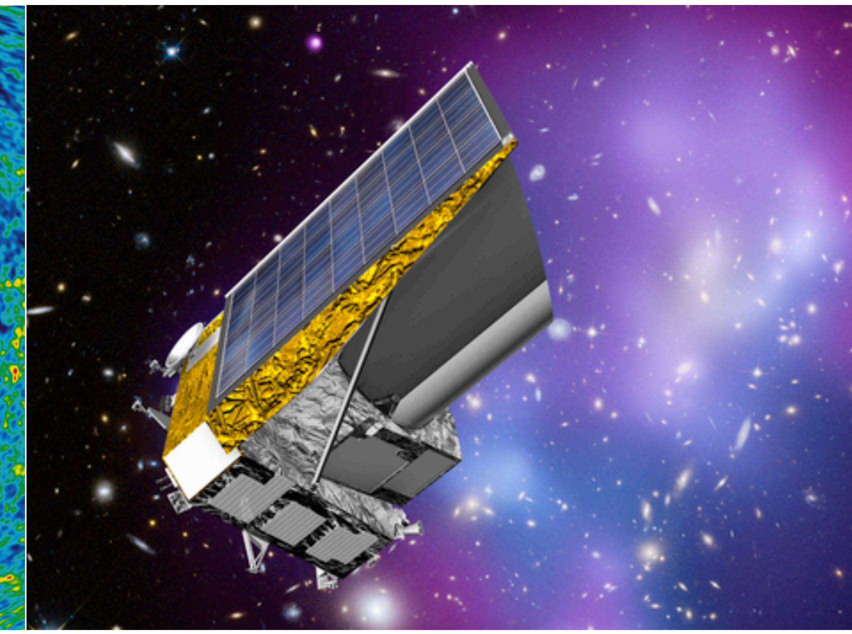
Near Future (2020-?) neutrino mass ~~limits~~ Sensitivities

KATRIN	DESI	EUCLID
		
$\sigma(m_{\nu e}) \sim 0.20$eV (90%CL) 5 years	$\sigma(M_\nu) \sim 0.02$eV	$\sigma(M_\nu) \sim 0.03$eV
Drexlin et al. (2005)	*Font-Ribera et al. (2014)*	*Audren et al. (2013)*

Even in the case of neutrino mass **normal hierarchy ($M_\nu>0.059$eV)**,
Large scale surveys in cosmology might show the
1st detection of neutrino masses well before laboratory experiments do!

And if they don't detect anything, they will have **strong implications** on neutrino physics

Near Future (2020-?) neutrino mass ~~limits~~ Sensitivities

KATRIN	DESI	EUCLID
		
Today (KNM1, 4weeks of data) *1.1eV (Frequentist); 0.9eV (Bayesian) 90%CL* *arXiv:1909.06048 + arXiv:2101.05253*	Started in 2020 (Now in re-commissioning)	Launch in 2022?

Even in the case of neutrino mass **normal hierarchy (M_ν>0.059eV)**,
Large scale surveys in cosmology might show the
1st detection of neutrino masses well before laboratory experiments do!

And if they don't detect anything, they will have **strong implications** on neutrino physics

CONCLUSIONS

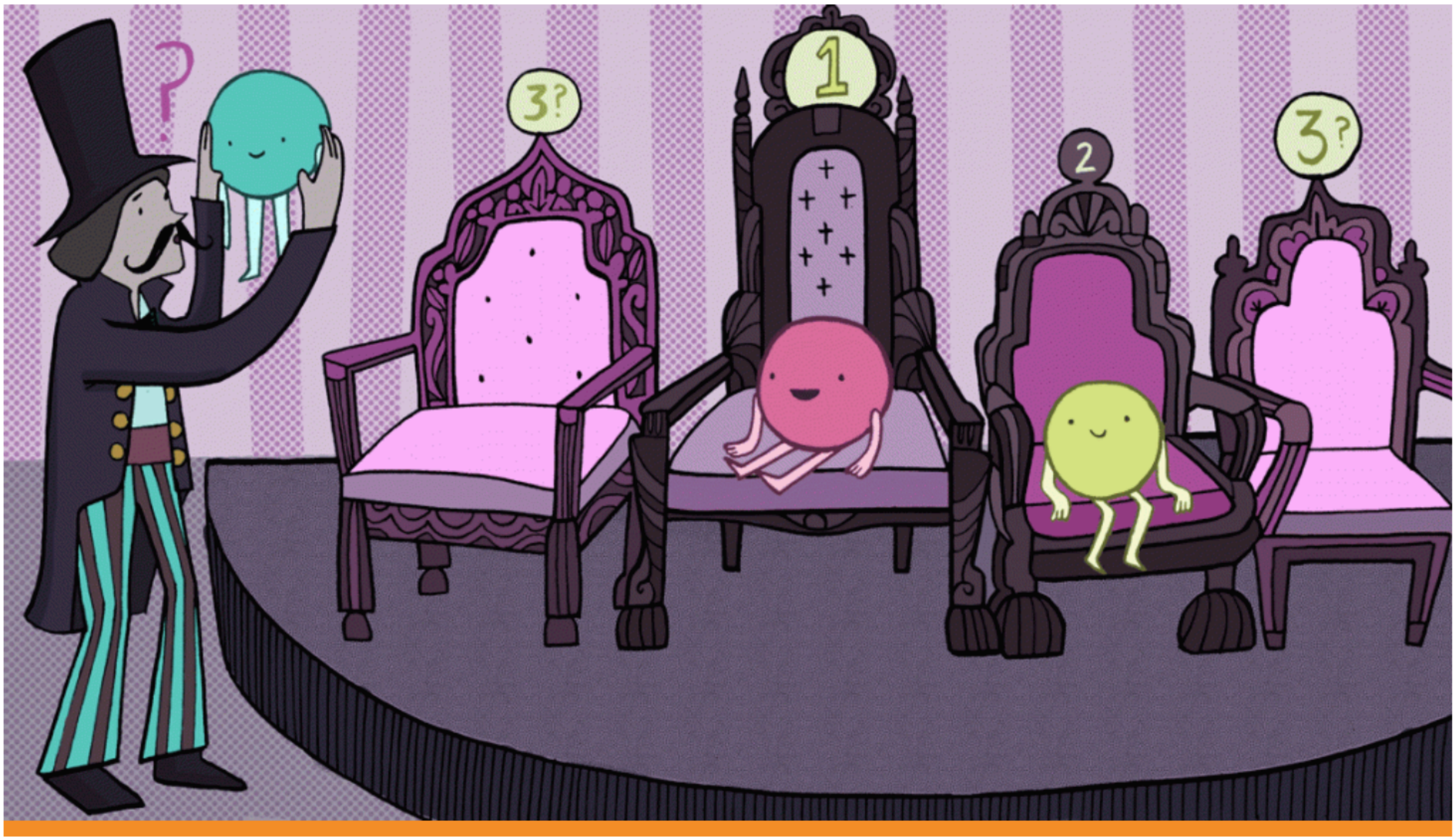
- *If the ΛCDM model is correct,* **Planck CMB** measurements are already placing a **strong bound** on neutrino masses **m_ν<0.24eV**

- *Galaxy surveys measure BAO and P(k)*, which **combined with CMB** break degeneracies with evolution of background & perturbation providing **stronger constraints,** even in beyond-ΛCDM cosmologies

- *Surveys also measure Lyα, and CMB+Lyα* has reached a mass limit **below m_ν<0.09eV**, starting to put pressure in the inverted ordering

- *Next-generation galaxy surveys* **can detect** a signal of neutrino mass or **alternatively rule out** the neutrino **inverted mass ordering,** provided that cosmological **tensions** (**H_0** & **σ_8**) are addressed

Thanks for your attention (email: ajcuesta@uco.es)



Credit: Symmetry Magazine / Sandbox Studio, Chicago