Deconstructing the Neutrino Mass Constraints from Galaxy Redshift Surveys

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Background

- Galaxy surveys are key to deriving the current upper limit on the sum of neutrino masses, M_ν.
- However, our work shows that the constraints predicted for future surveys are heavily dependent on the measurement method and the cosmological model assumed.
- We identify cosmological signatures of massive neutrinos that could be used to constrain their mass independently of the cosmological model. This will be key in providing convincing results to the particle physics community in the future.

Calculation Details

The Fisher matrix is used to calculate the best possible constraints on a theoretical model for a planned experiment. Errors on the observables are propagated into errors on a set of model parameters.

$$F_{\alpha\beta} = \frac{\partial P_{gg}}{\partial \theta_\alpha} C^{-1} \frac{\partial P_{gg}}{\partial \theta_\beta}$$

C is the covariance matrix of observables, in our case, galaxy power spectra $P_{gg}(z, \vec{k})$. θ are the model parameters, which define the chosen cosmological model. The final matrix F is the inverse covariance matrix for the model parameters.

We begin with the standard ΛCDM + M_ν model, which assumes a flat Universe and a constant dark energy equation of state (EOS). We then check the effects of adding extensions to the model on our forecasted constraints.

θ: ΛCDM + M_ν	
θ_s*	Sound horizon size
A_s	Primordial power spectrum amplitude
n_s*	Primordial power spectrum tilt
ω_b*	Baryon density today
ω_c	Cold dark matter density today
τ	Optical depth to the CMB
M_ν	Neutrino mass

θ: Extensions	
Ω_k	Curvature
w_0	Time-independent dark energy EOS
w_a	Time-dependent dark energy EOS factor

*We include a very conservative CMB prior from Planck on these parameters.
We also marginalise over a linear galaxy bias parameter.

Galaxy Surveys

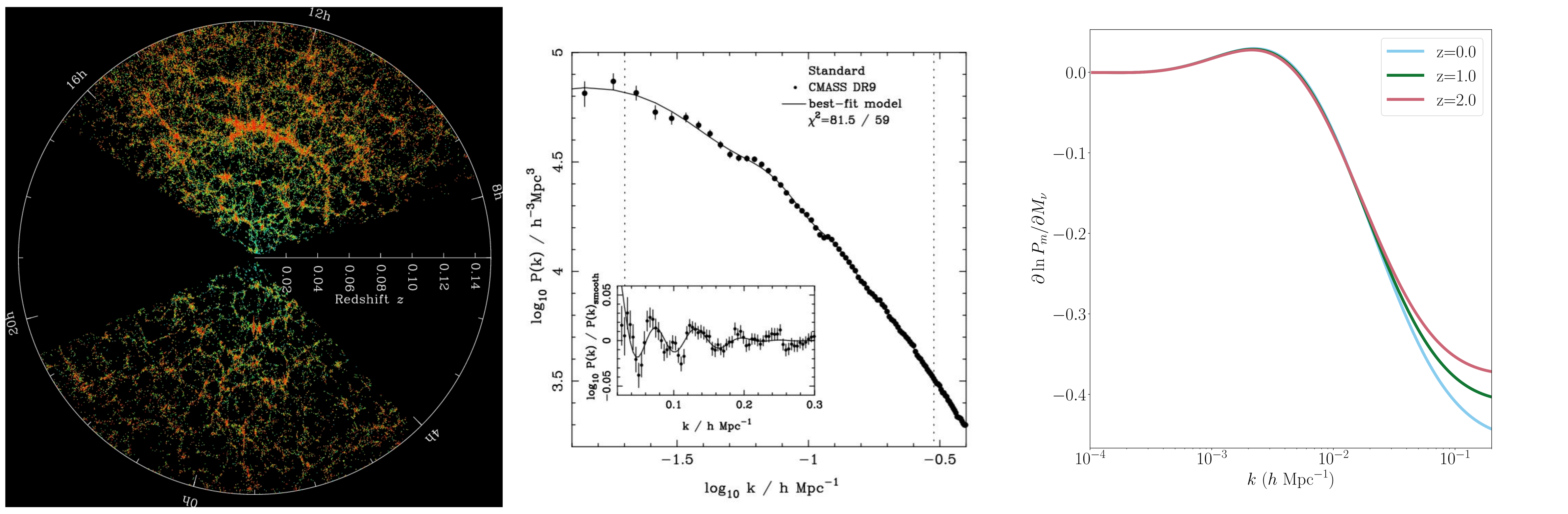

Figure 1: Left: SDSS galaxy map (M. Blanton / SDSS); Centre: SDSS DR9 galaxy power spectrum [1]; Right: The derivative of the matter power spectrum with respect to M_ν, with the change in the overall amplitude normalised. The reduction in the power on small scales caused by the free-streaming of massive neutrinos is clearly seen.

Galaxy surveys allow us to map the 3D distribution of galaxies. The statistical information on how these galaxies cluster is usually presented in the form of a galaxy power spectrum. Figure 1 shows such a map and power spectrum from the Sloan Digital Sky Survey (SDSS). The galaxy power spectrum provides a wide range of constraining information. Two of the most popular probes are:

- **Baryon Acoustic Oscillations (BAOs)**: Characteristic wiggles in the power spectrum (see the subplot of the power spectrum in Figure 1). The scales at which these wiggles occur are very well constrained from observations of the CMB. Using their apparent scale in the observed power spectrum, we can measure the distance to the redshift we are looking at. This in turn allows us to constrain the Universe's expansion rate as a function of redshift, $H(z)$, which is sensitive to M_ν.
- **Redshift Space Distortions (RSDs)**: Anisotropies in the galaxy power spectrum that appear because of peculiar velocities along the line of sight, which alter the measured redshifts. These peculiar velocities can be caused by structure formation, and can therefore be used to constrain the rate of structure growth as a function of redshift, $f(z, k)$, which is also sensitive to M_ν.

BAOs and RSDs are two of the most popular probes of cosmological parameters that can be extracted from the galaxy power spectrum. However, the effects of massive neutrinos on the expansion rate (measured by BAOs) and the structure growth rate (measured by RSDs) are not unique. Therefore, the constraints extracted can depend heavily on the assumed cosmology. This is seen clearly in Figure 2.
Is there a cosmology-insensitive probe of M_ν contained in the galaxy power spectrum?

- **Free-streaming effects**: Massive neutrinos have one unique effect on the power spectrum that is not mimicked by changes in other cosmological parameters. Because massive neutrinos are relativistic at early times, they free-stream out of perturbations below a characteristic size, causing a suppression in the rate of structure growth on small scales (see the right panel of Figure 1). This effect is manifested in both the underlying matter power spectrum, which can be extracted from the galaxy power spectrum, and in the structure growth rate, as measured using RSDs. The relative level of suppression is proportional to M_ν.

[1] L. Anderson *et al.*, 2012, MNRAS, 427, 3435, arXiv: 1203.6594.

Results 1

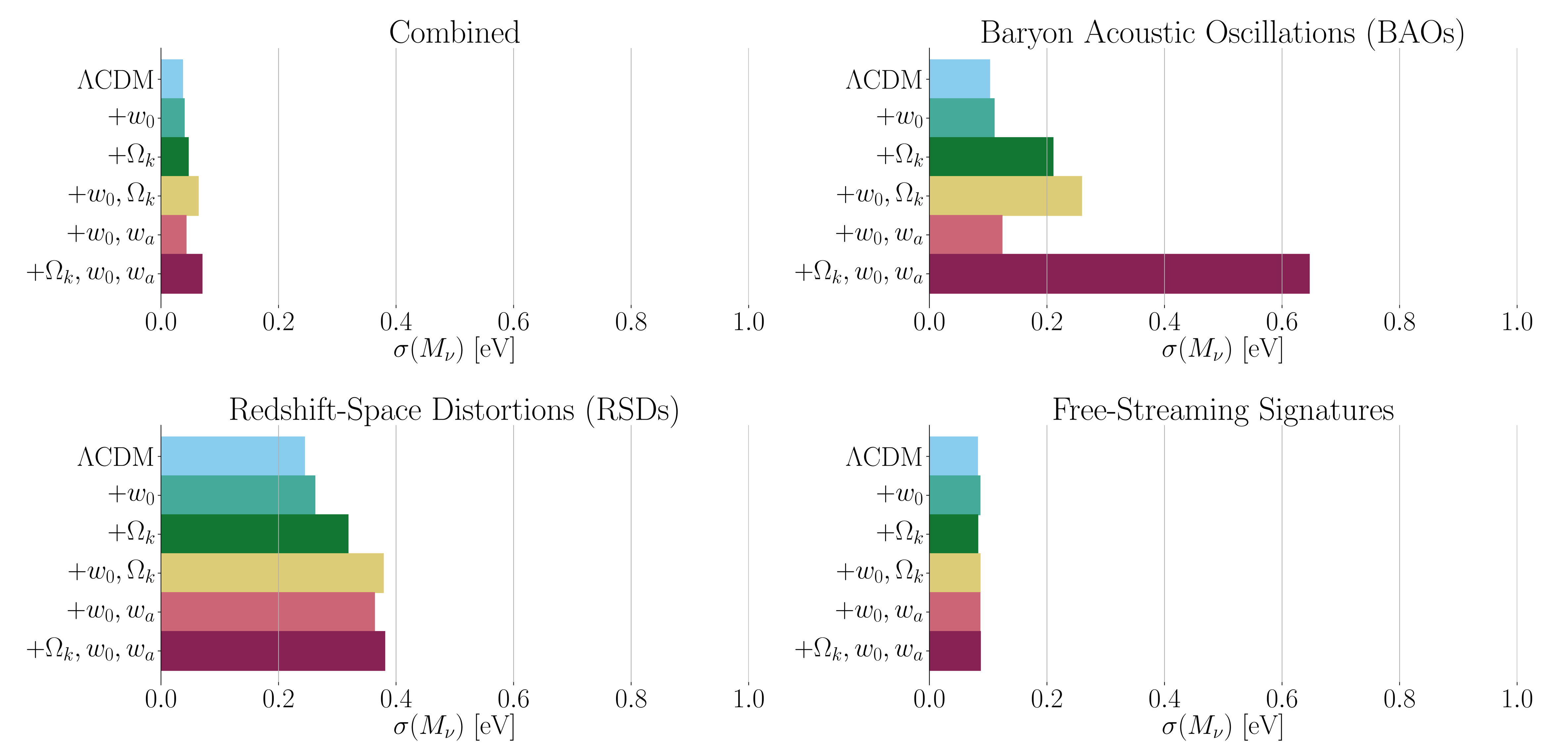

Figure 2: A summary of our forecasts for Euclid combined with a very conservative CMB prior. The x-axes show the 1σ neutrino mass constraints for the different cosmological models labelled on the y-axis. The first panel shows the forecasted constraints using the full observed galaxy power spectrum. The second and third panels show the constraints from BAOs and RSDs only, respectively. We see that all of these constraints are very model-dependent. The final panel shows the forecasted constraints using only the scale-dependence of clustering as measured in the shape of the underlying power spectrum and the structure growth rate measured from redshift space distortions. The constraints in this case are insensitive to changes in the cosmological assumptions.

Results 2

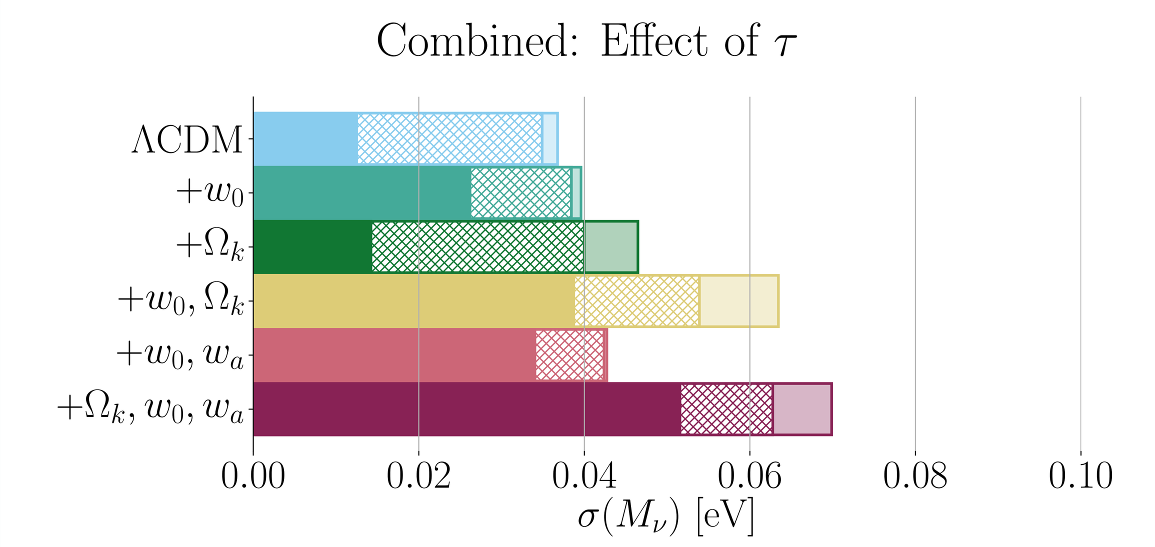

Figure 3: The same as the first panel of Figure 2, but this time with the x-axis expanded scale reduced by a factor of 10. The various bars show the constraints with different priors on τ. The longest bars correspond to Figure 2, with no prior on τ. The cross-hatched bars show the same constraints if a prior on τ from the Planck survey is assumed. The shortest bars show how the constraints would look if τ was known perfectly. It is clear that τ and M_ν are heavily degenerate, and that improving constraints on τ would provide significant gains. With the strong constraints predicted for Euclid, the weakness of the constraint on τ becomes the limiting factor.

This degeneracy arises because τ is heavily degenerate with A_s in the CMB data (the combination $A_s \exp(-2\tau)$ is what is actually measured). Meanwhile, A_s and M_ν are highly degenerate in the galaxy power spectrum, as both affect the amplitude. This leads to a strong degeneracy between M_ν and τ when the two are combined.

Conclusions and Future Work

Conclusions

- The current and forecasted constraints on the neutrino mass from galaxy surveys are heavily dependent on the assumed cosmology.
- Isolating the signatures of neutrino free-streaming in the power spectrum and structure growth rate gives the most robust constraints, because this effect is difficult to mimic with changes in other cosmological parameters. These constraints are very competitive with BAO-only and RSD-only constraints.
- In the case of the combined constraints, the weak constraints on τ become the limiting factor. This suggests that a more efficient way to reduce the error bars on M_ν could be to invest in reionisation surveys and enhanced CMB polarisation measurements, rather than increasingly powerful galaxy surveys.

Future Work

- The inclusion of more comprehensive CMB priors.
- The addition of lensing information. Lensing probes the matter power spectrum directly and is therefore particularly useful.
- An examination of the effects of a more complex treatment of galaxy bias.