DECONSTRUCTING THE NEUTRINO MASS CONSTRAINTS FROM GALAXY REDSHIFT SURVEYS

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MOTIVATION

- The standard model of particle physics is incomplete.
- The upper limit on the sum of the neutrino masses still comes from cosmology.
  - Where exactly does the constraining power come from?
  - How do the constraints change if we allow deviation from the standard $\Lambda CDM + M_\nu$ model?
- For our constraints to be convincing, it is crucial that they are **independent of the cosmological model assumed.**

CURRENT STATUS

- Particle physics: $M_\nu = \Sigma m_\nu \geq 0.06$ eV
- Cosmology (optimistic): $M_\nu < 0.12$ eV; 95% CL (Vagnozzi +, 2017)

  → Planck: TT data, τ measurements (high frequency), cluster counts from thermal SZ effect, high-l polarisation data (may have systematic issues)

  → Local H_0 measurements

  → **BAO measurements from BOSS, 6dFGs, WiggleZ**

  → **Galaxy power spectrum from BOSS**

CURRENT STATUS

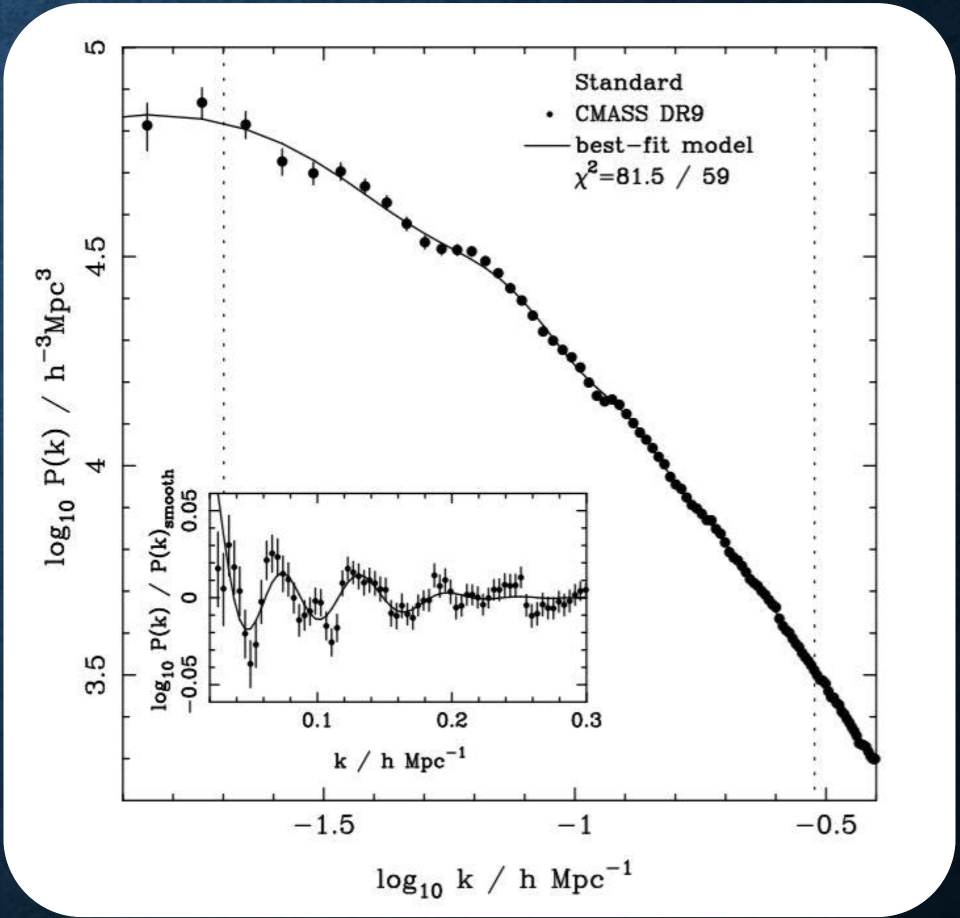
- Particle physics: $M_\nu = \Sigma m_\nu \geq 0.06$ eV
- Cosmology (optimistic): $M_\nu < 0.15$ eV; 95% CL (Vagnozzi +, 2017)

  → Assumes ΛCDM! $(+M_\nu)$
- Future surveys (PFS, DESI, Euclid…) predict constraints on $\sigma M_\nu \ll 0.1$ eV → could allow us to exclude the inverted neutrino mass hierarchy.

HOW DOES $P_{gg}(k,\mu)$ HELP CONSTRAIN M_ν?

Effects can be divided into two main categories:

- Geometric information
- Structure growth information

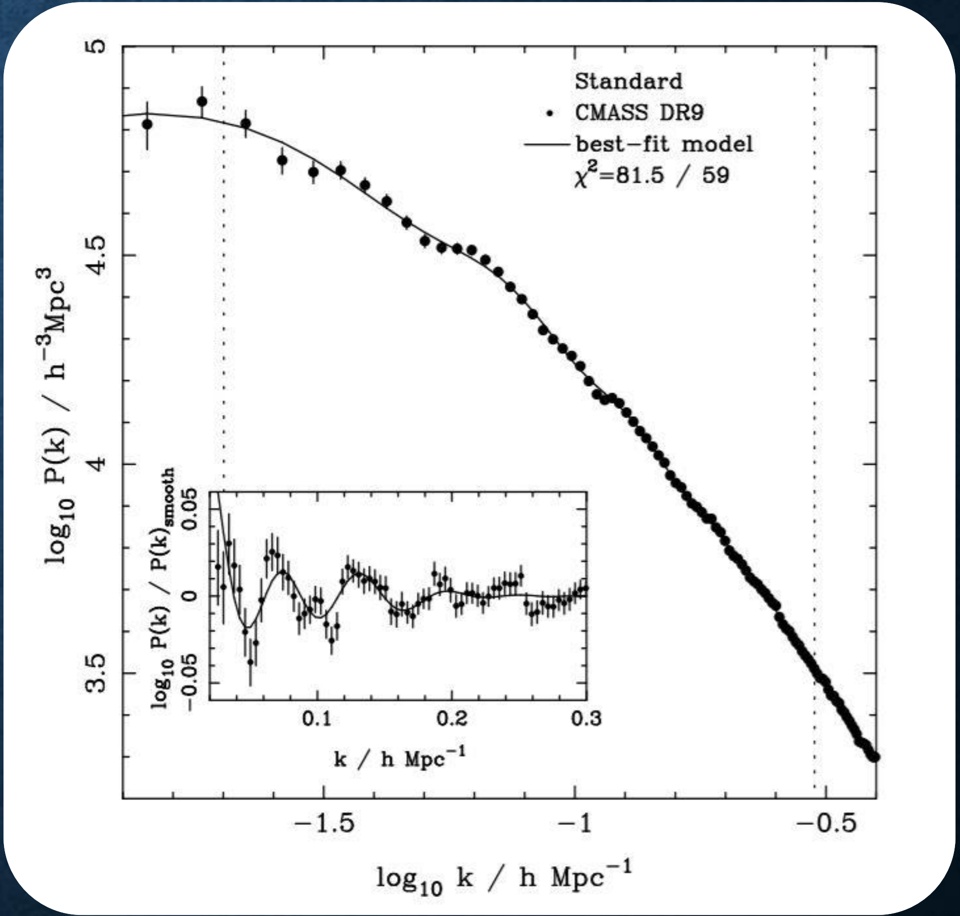


SDSS DR9 Galaxy Power Spectrum: L. Anderson *et al.* (2012)

HOW DOES $P_{gg}(k, \mu)$ HELP CONSTRAIN M_ν?

Geometric Information

- Constrains cosmology through measurements of $D_A(z)$ and therefore $H(z)$.
- Includes BAOs.
- Also other characteristic scales (matter-radiation equality, Silk damping scale) and the Alcock-Paczynski test.

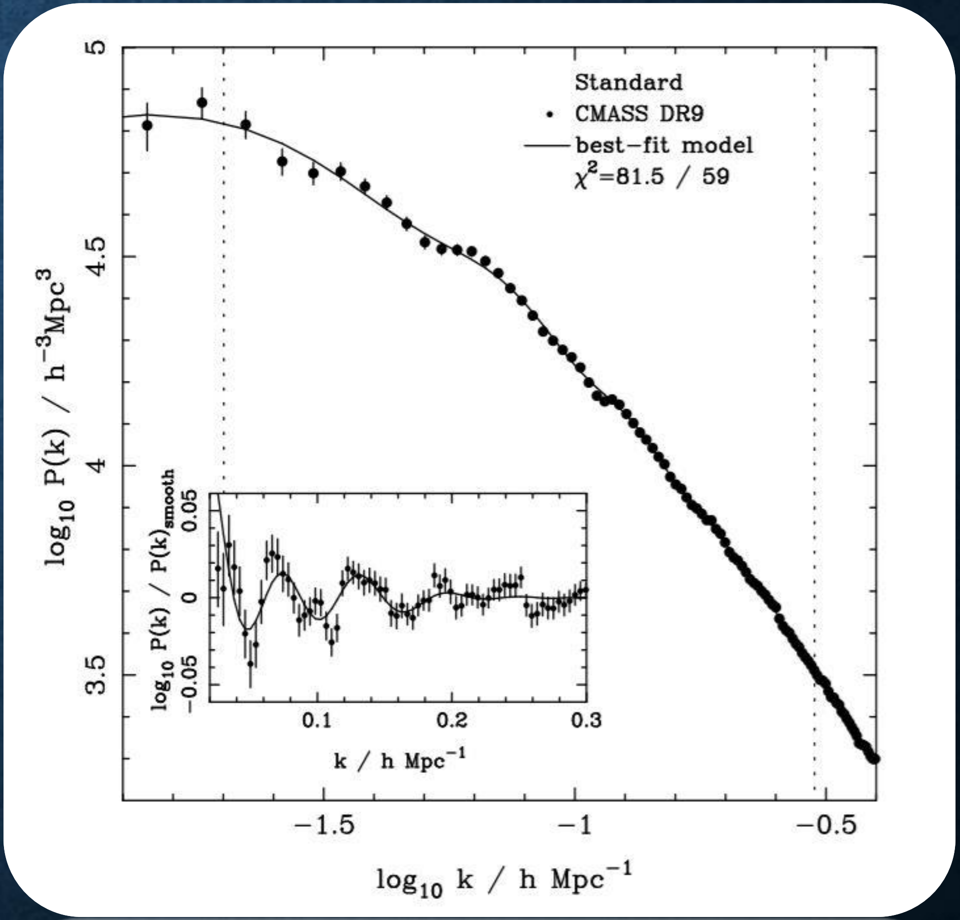


SDSS DR9 Galaxy Power Spectrum: L. Anderson *et al.* (2012)

HOW DOES $P_{gg}(k,\mu)$ HELP CONSTRAIN M_ν?

<u>Structure Growth Information</u>

- Redshift-space distortions (RSDs) probe the structure growth rate $f(z)$.
- The shape and amplitude of $P_{gg}(k,\mu)$ provide information on the underlying matter power spectrum, $P_{mm}(k)$.



SDSS DR9 Galaxy Power Spectrum: L. Anderson *et al.* (2012)

OUR ANALYSIS: FORECASTING CONSTRAINTS

Fisher Matrix:

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

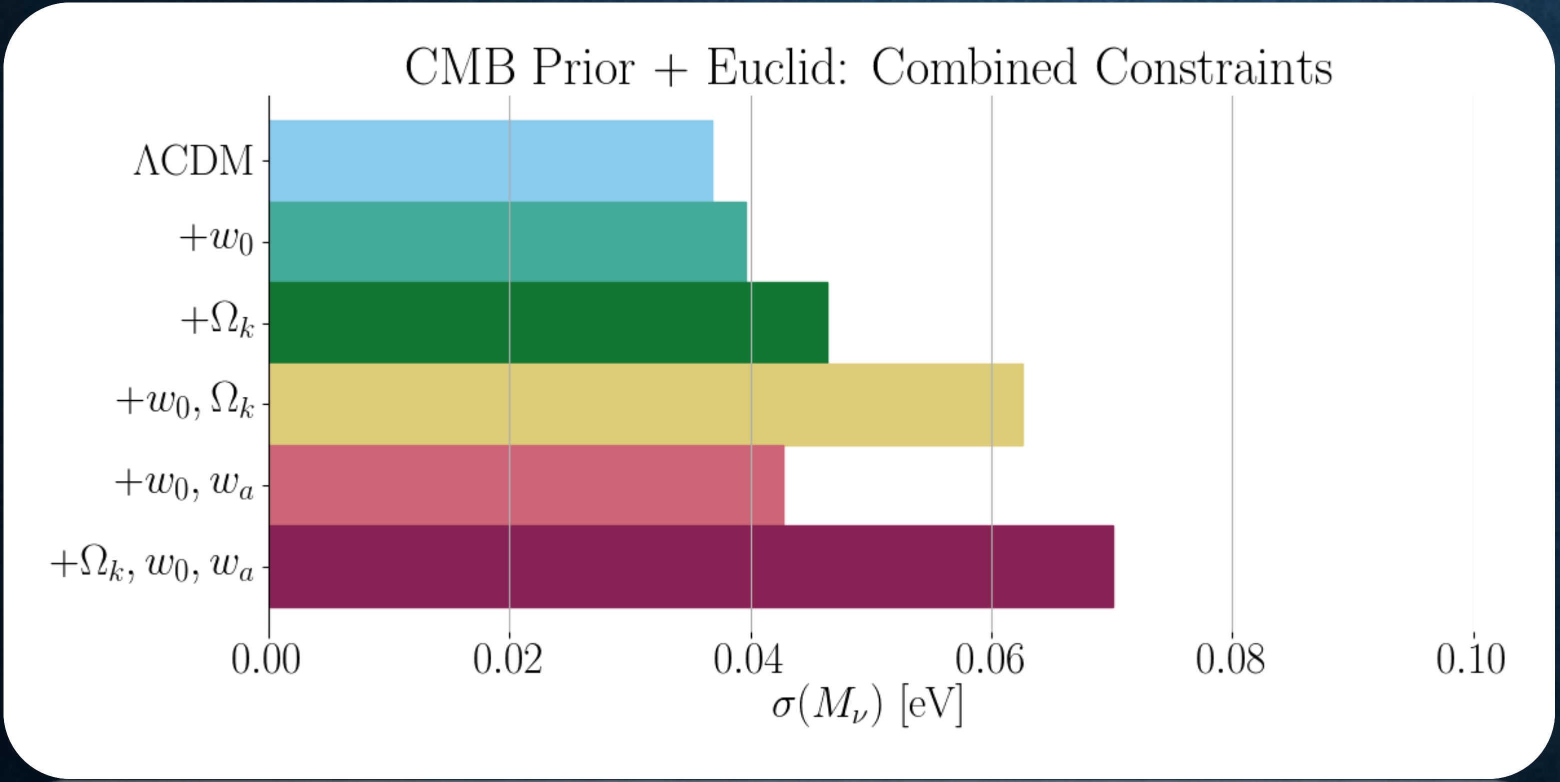
Free parameters:

- M_ν
- ΛCDM parameters: θ_s*, A_s, n_s*, ω_b*, ω_c, τ
- Extensions: Ω_k, w_0, w_a

* A conservative CMB prior ('compressed likelihood') from Planck is included on these parameters.

COMBINED CONSTRAINTS (MOST OPTIMISTIC)

Constraints achievable from fitting entire galaxy power spectrum → combines geometric and structure growth information.

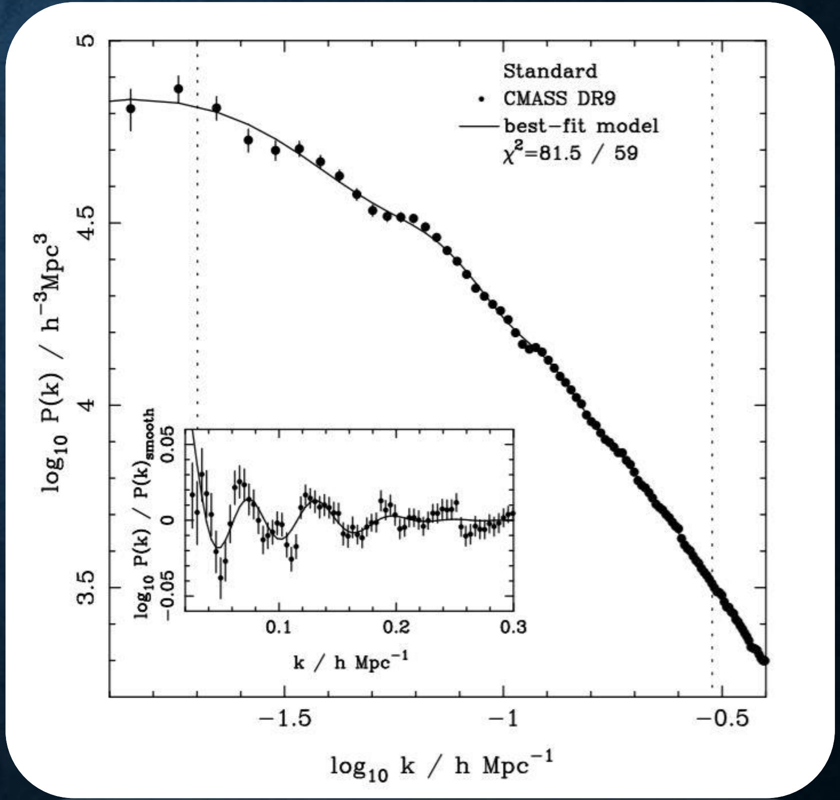


Depend heavily on assumed cosmology!

EXAMPLE: ISOLATING CONSTRAINTS FROM BAOS

- $P_{gg}(k,\mu) = (b + f\mu^2)^2 P_{mm}(k) + n_g^{-1}$
- $P_{mm}(k) = P_{BB}(k) + P_{BAO}(k)$
- Do a 2-step Fisher matrix calculation:
  - Constrain $H(z), D_A(z)$ by replacing derivatives with $\frac{\partial P_{BAO}}{\partial H(z)}, \frac{\partial P_{BAO}}{\partial D_A(z)}$.
  - Constrain θs using $\frac{\partial H(z)}{\partial \theta}, \frac{\partial D_A(z)}{\partial \theta}$.
  - Marginalise over P_{BB}, RSD term, etc.

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



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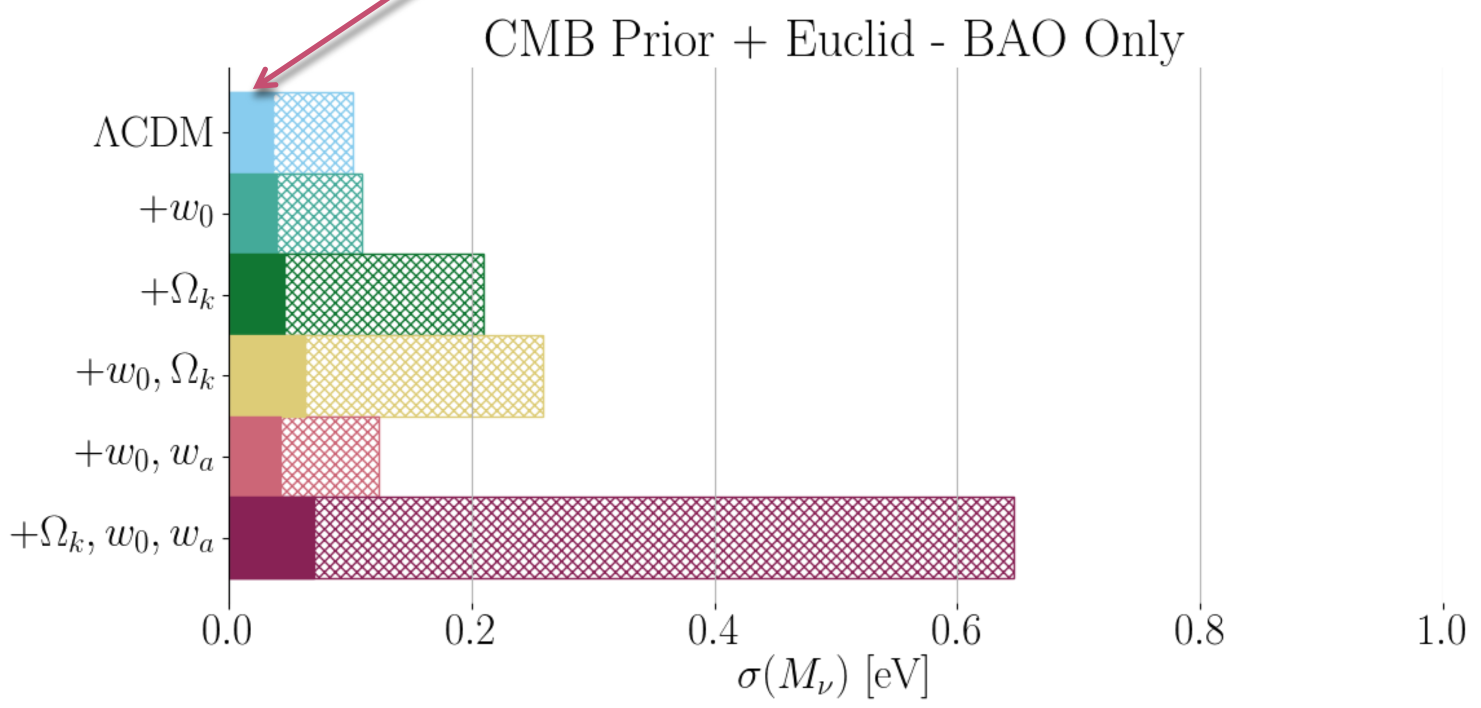
BAO-ONLY CONSTRAINTS

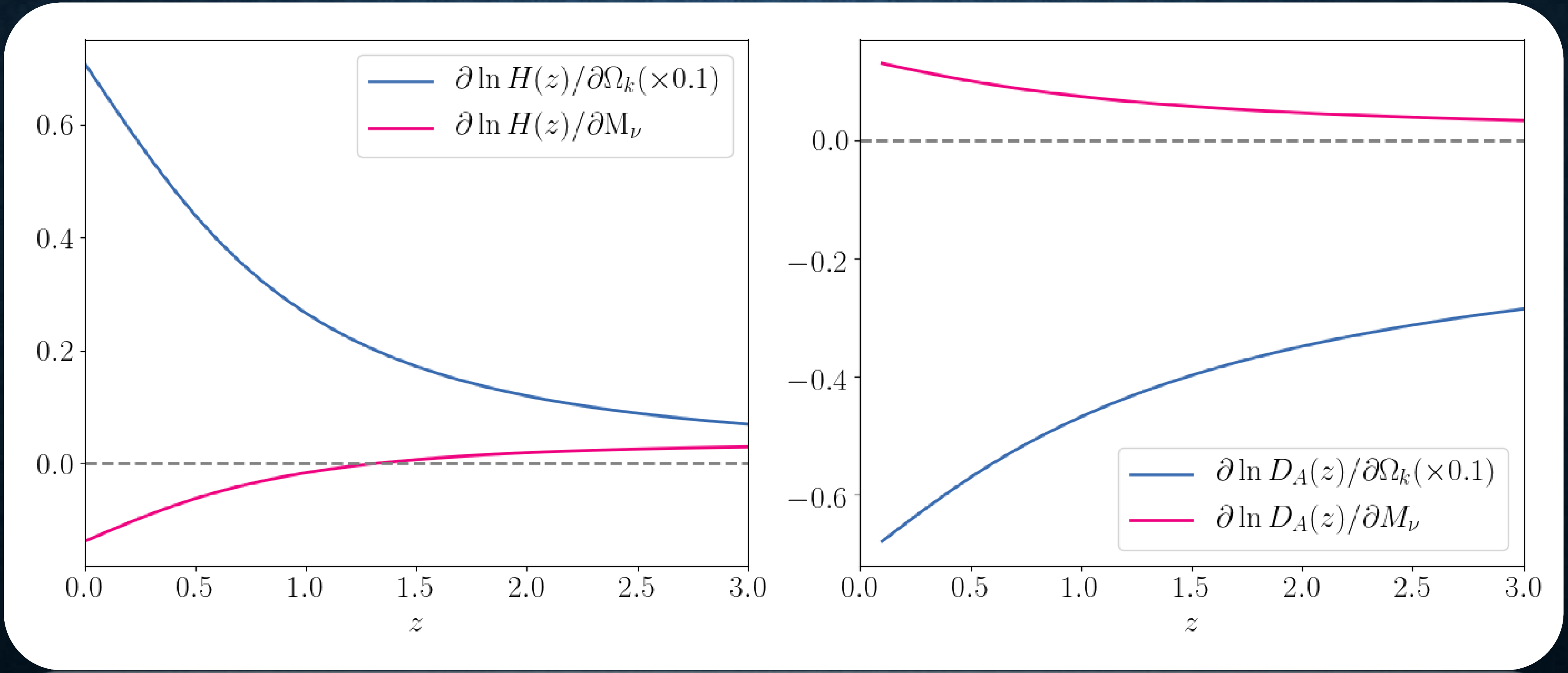
Combined constraints for comparison



Extreme reduction in constraining power if non-zero curvature allowed.

BAO-ONLY CONSTRAINTS

Effects of changes in Ω_k and M_ν on $H(z)$ and $D_A(z)$ are degenerate!



COSMOLOGY-INDEPENDENT CONSTRAINTS

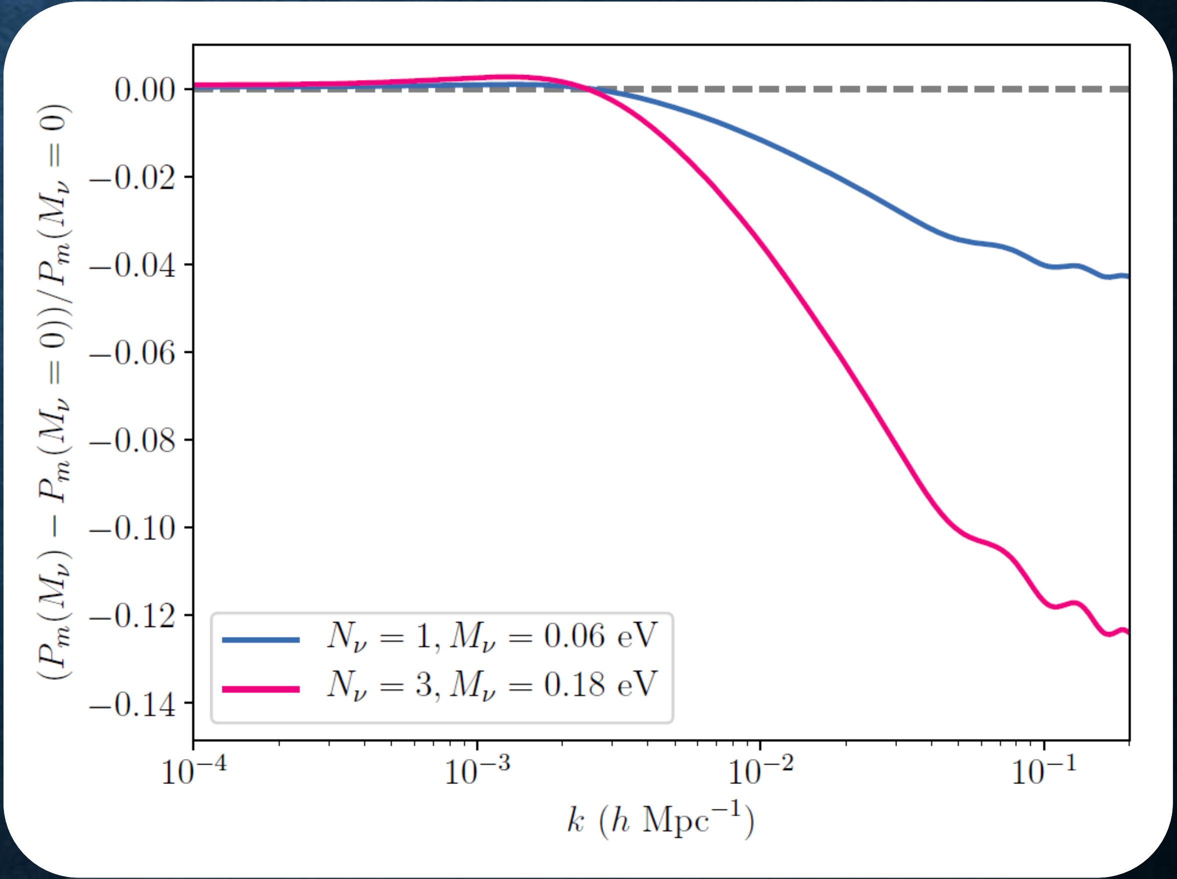
- Our paper also provides isolated M_ν constraints for RSDs, the AP test, etc.
- Recurring problem: Constraints are heavily **cosmology-dependent**.
- How can we extract more robust neutrino mass constraints?
- We require a distinct, mass-sensitive signature of massive neutrinos that is not mimicked by other cosmological parameters.

COSMOLOGY-INDEPENDENT CONSTRAINTS

Neutrino Free-Streaming

- Massive neutrinos are relativistic at early times and become non-relativistic over time.
- Neutrinos free-stream out of small perturbations while still relativistic, causing a relative suppression in the power spectrum on small scales.

Ω_m held constant:



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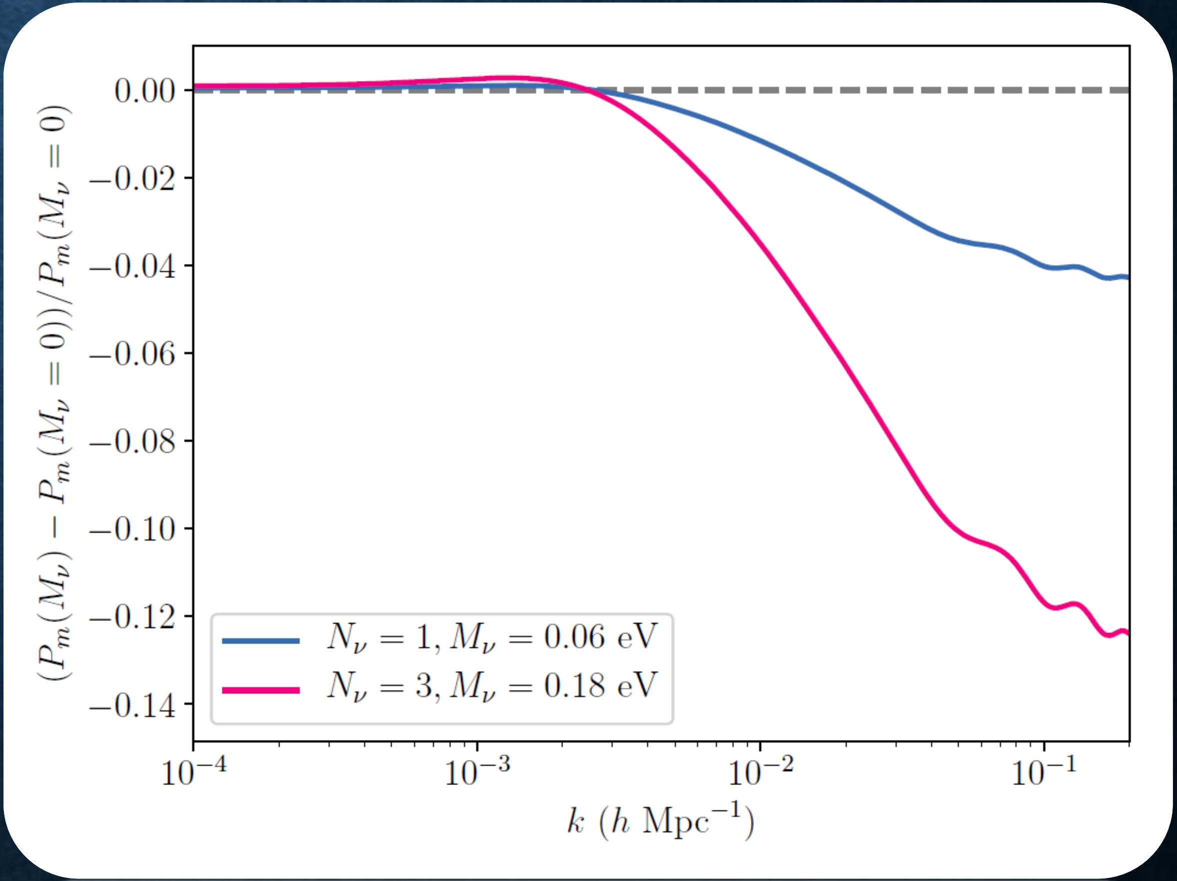
COSMOLOGY-INDEPENDENT CONSTRAINTS

Neutrino Free-Streaming

This effect can be measured in two independent ways:

- In P_{mm} (right), constrained from P_{gg}.
- In the structure growth rate $f(k)$, constrained using RSDs.

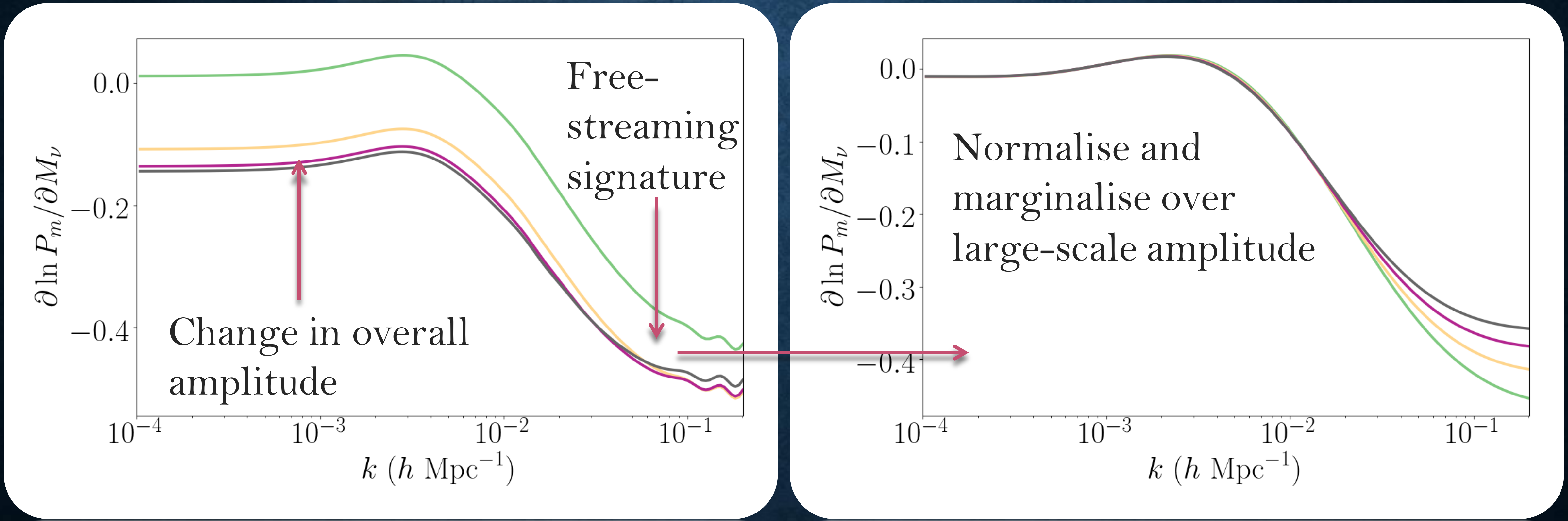
Ω_m held constant:



COSMOLOGY-INDEPENDENT CONSTRAINTS

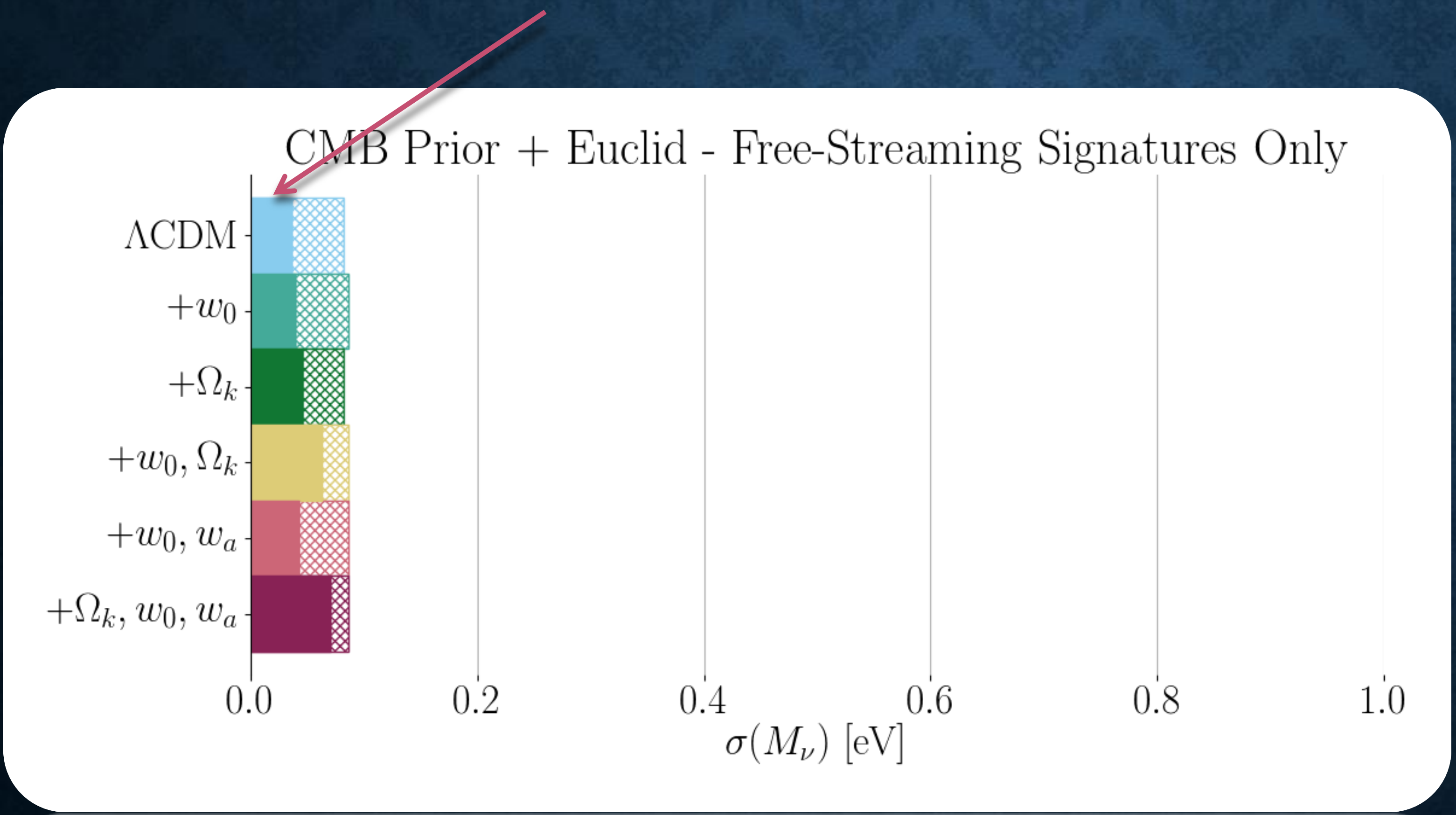
Redshift (z):

0.0	2.0
1.0	3.0



COSMOLOGY-INDEPENDENT CONSTRAINTS

Combined constraints for comparison



Independent of assumed cosmology!

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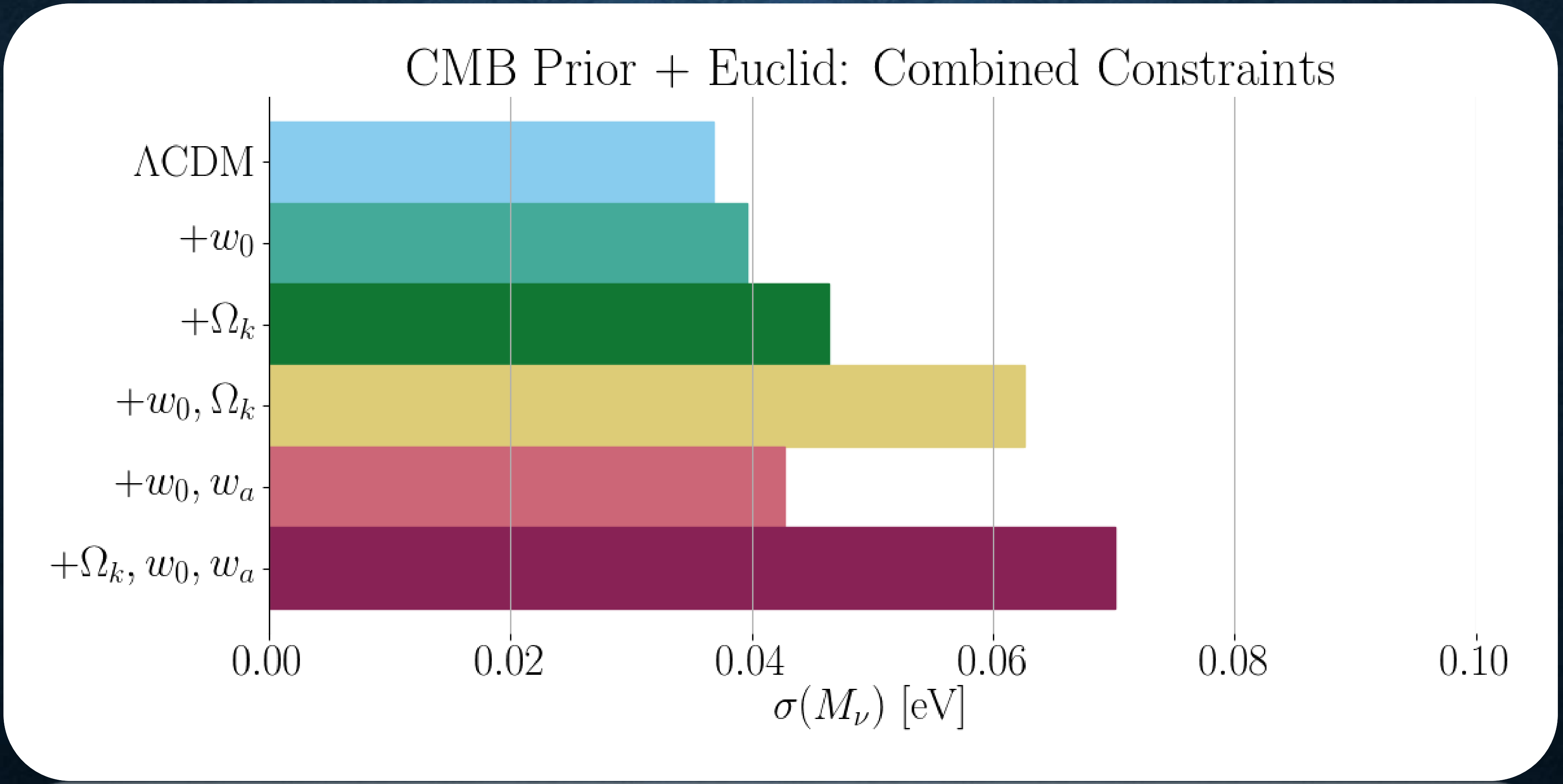
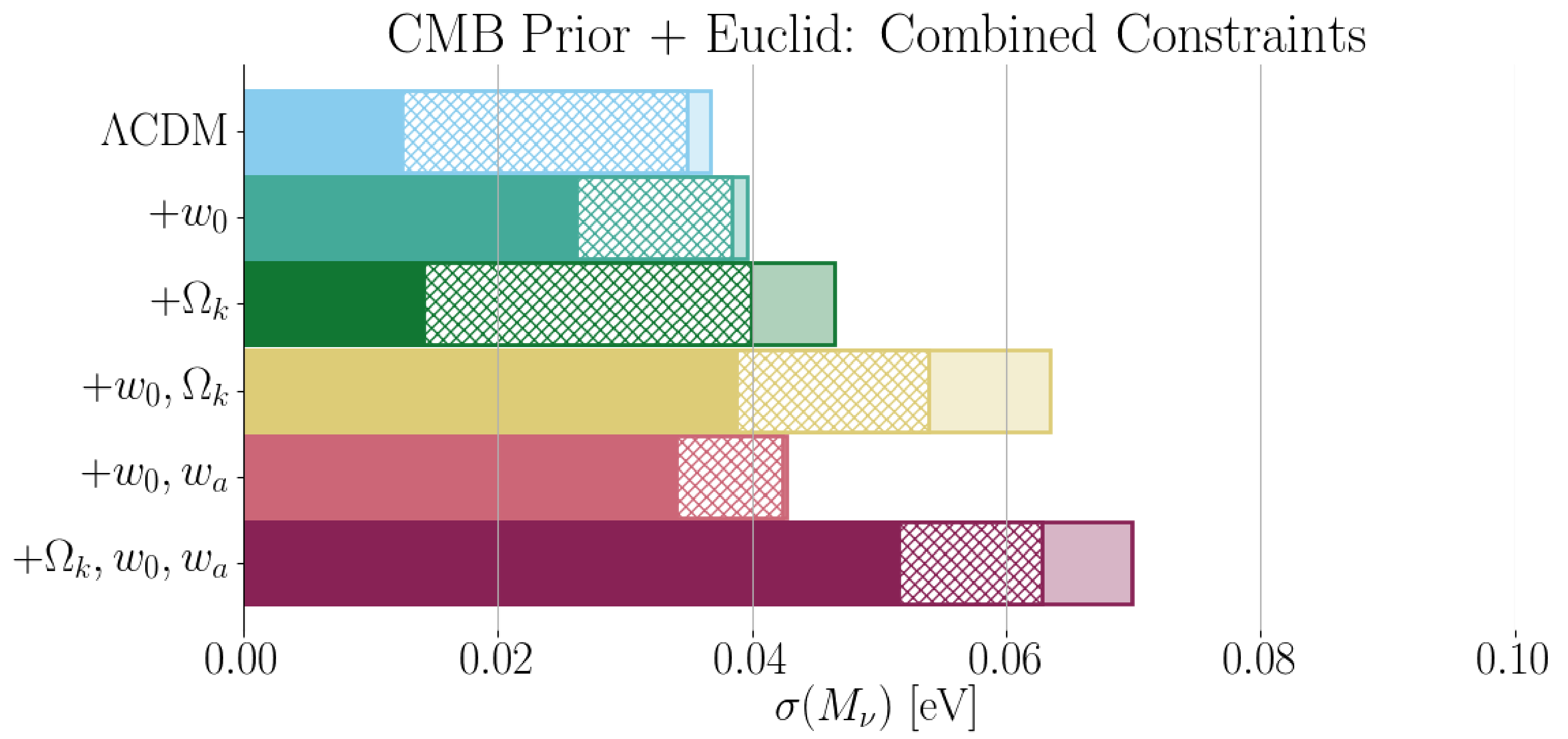
COMBINED CONSTRAINTS AGAIN…



IMPORTANCE OF τ DATA

Constraints on M_ν heavily dependent on constraints on τ.

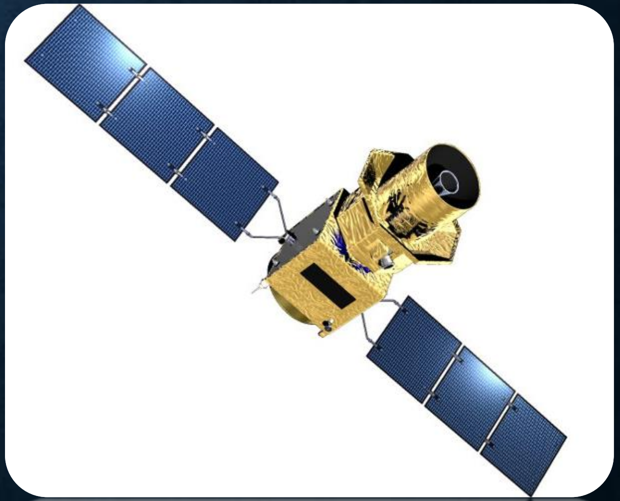


No constraint on τ / τ constraint from Planck / τ known perfectly

IMPORTANCE OF τ DATA

- In combination of CMB and galaxy survey information, M_ν and τ strongly correlated.
- τ currently very weakly constrained by CMB polarisation.
- Improved CMB polarisation measurements / reionisation surveys will improve τ constraints.
- Free-streaming constraints do not suffer from this effect.

The LiteBIRD satellite:



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SUMMARY AND CONCLUSIONS

- Current/forecasted constraints on M_ν heavily dependent on ΛCDM assumption.
- Isolating the signatures of neutrino free-streaming gives much more robust constraints.
- Even if we take the most optimistic (combined) constraints, we are ultimately limited by the accuracy to which τ is known.

TO BE CONTINUED…

Upcoming implementations:

- More comprehensive CMB priors.
- CMB lensing and galaxy-CMB lensing.
- Non-linear bias.