Neutrino Mass Constraints Beyond Linear Order: Cosmology Dependence and Systematic Biases

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Motivation

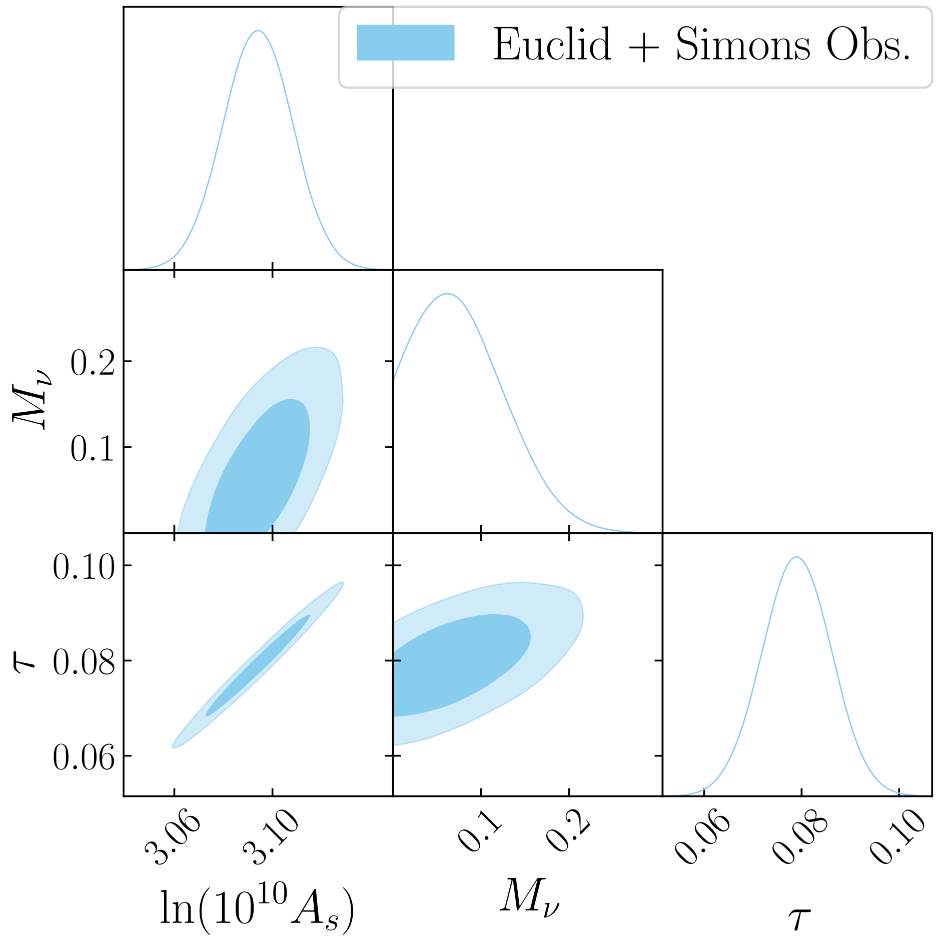
Deconstruction of M_ν constraints from galaxy clustering

- Distance information e.g. BAOs, AP test
- RSDs
- Suppression of power on small scales.
- …

Cosmology dependence of constraints

Cosmology	M_ν (eV)
ΛCDM+M_ν	0.12
$+\,w_0$	0.19
$+\,w_0 w_a$	0.25
$+\,\Omega_k$	0.15

Table shows Planck upper bounds in extended cosmologies (Choudhury & Hannestad 2020)



Significant degeneracies: e.g. $M_\nu - \tau$

Euclid 1-loop galaxy power spectrum and Simons Observatory CMB lensing

Extending to NLO

Desjacques, Jeong & Schmidt, 2018 (1806.04015)

$$\delta_g(x,\tau) = \sum b_O(\tau) O(x,\tau) + \epsilon$$

Local bias expansion: $b_1\delta + \frac{1}{2}\boldsymbol{b_2}\delta^2 + \dots$

Higher derivative bias: $\boldsymbol{b_{\nabla^2\delta}}\nabla^2\delta$

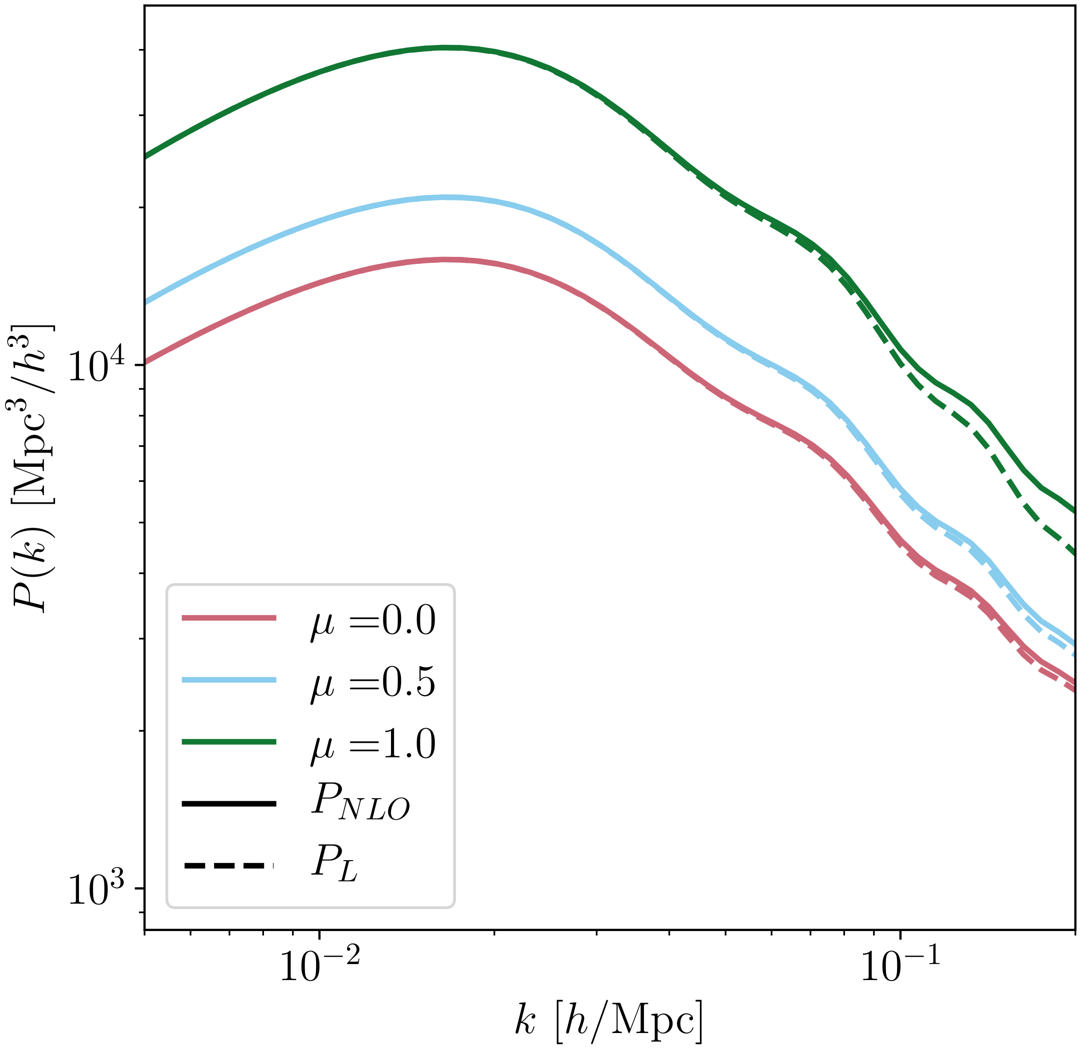
Tidal bias: $\boldsymbol{b_{K^2}}K^2 \rightarrow K^2 = K_{ij}K^{ij}$

$$\boldsymbol{b_{td}}O_{td} \rightarrow O_{td} = \frac{8}{21}K_{ij}D^{ij}\left(\delta_m^2 - \frac{3}{2}K^2\right)$$

Velocity bias: $\boldsymbol{b_{\nabla^2 v}}\nabla^2 v$

Stochastic parameters: $P_\epsilon^{\{0\}}, \boldsymbol{P_\epsilon^{\{2\}}}, \boldsymbol{P_{\epsilon\varepsilon_\eta}^{\{2\}}}$

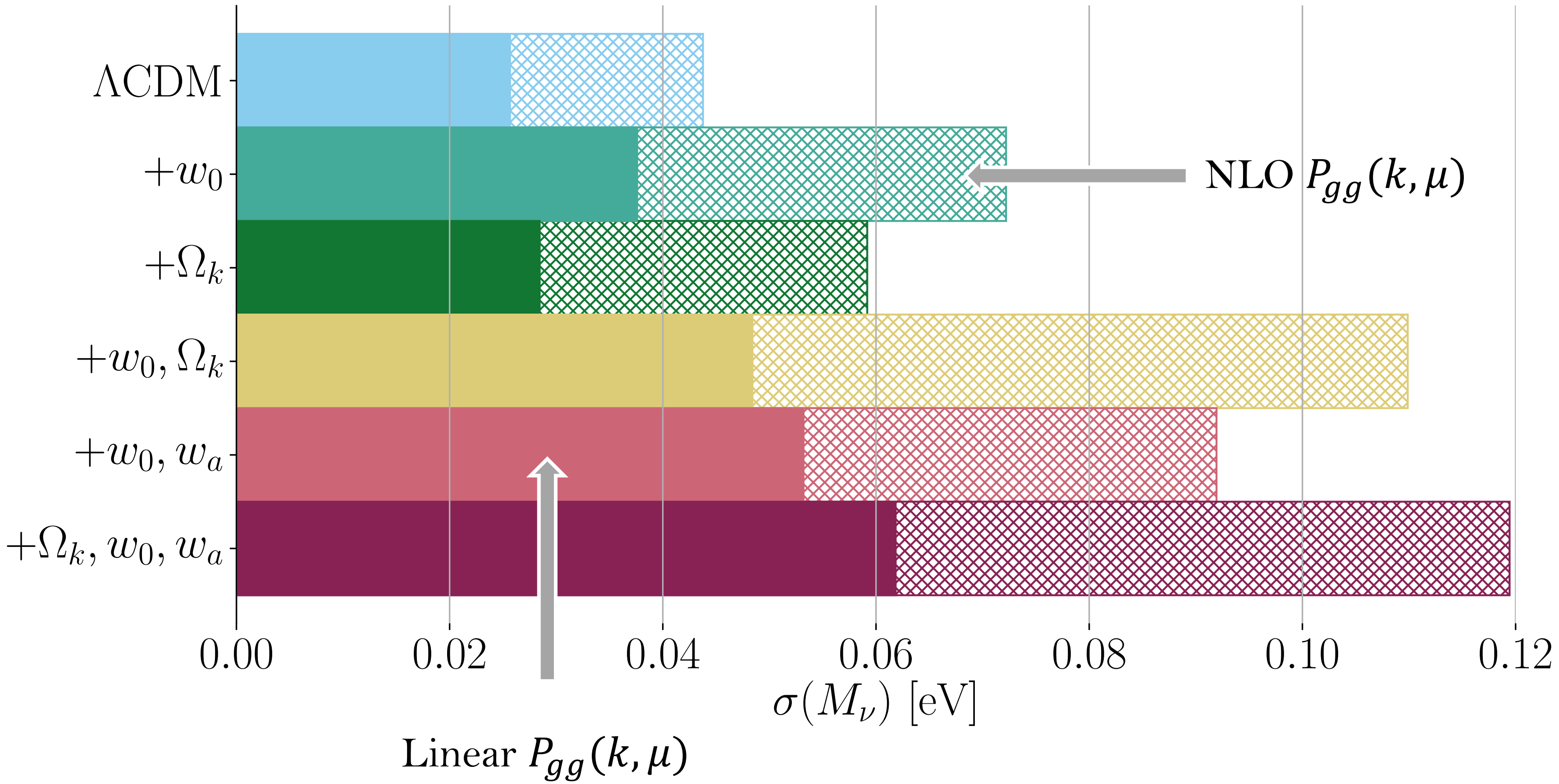
Many of these parameters change the galaxy power spectrum in a scale-dependent way.



Change in the galaxy power spectrum at z=1.35.

Full Power Spectrum Constraints

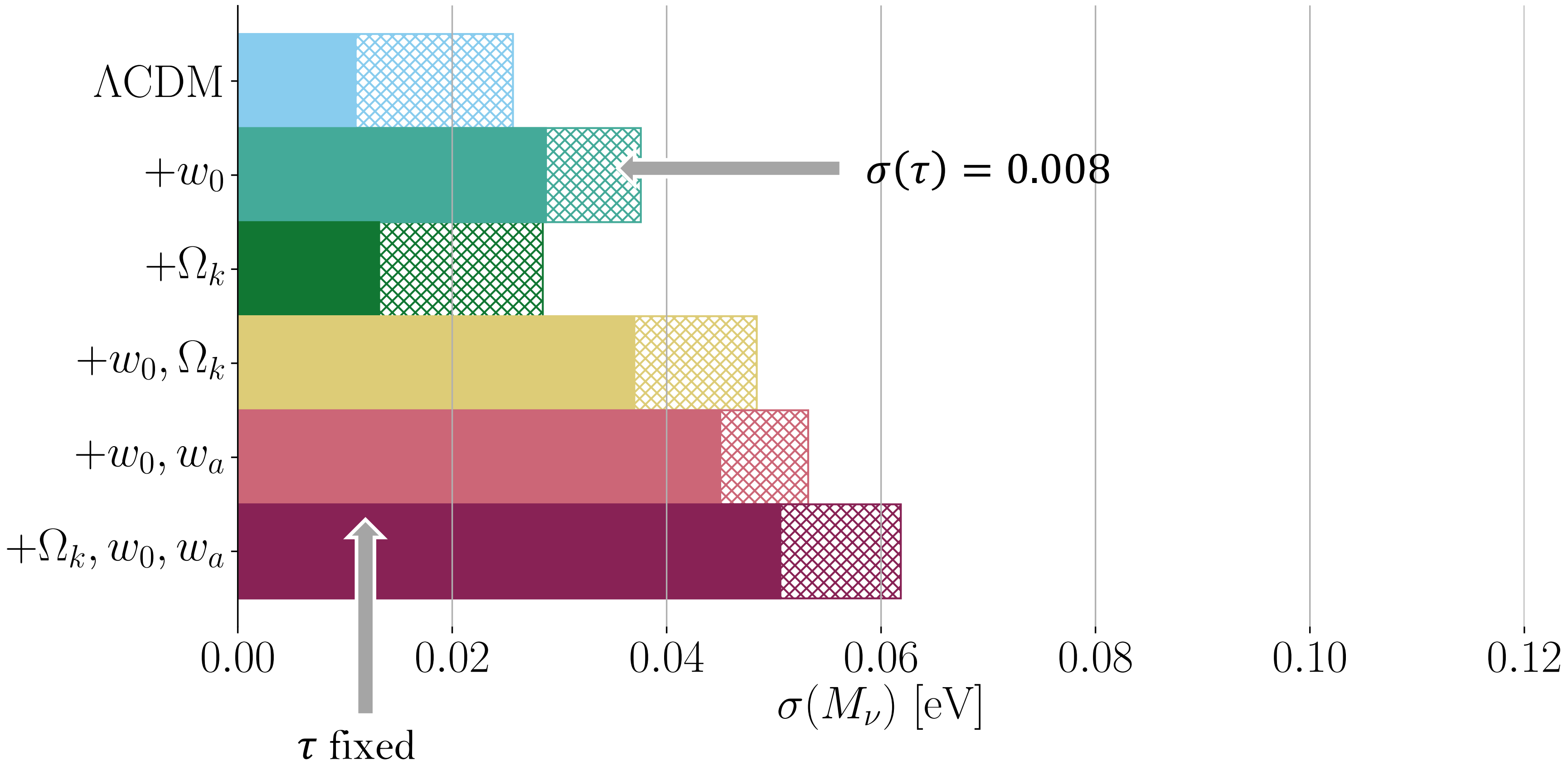
Planck TT, Simons Observatory EE/TE, $\sigma(\tau) = 0.008$, Euclid $P_{gg}(k,\mu) \rightarrow 0.2\ h$/Mpc.



- New parameters degrade constraints significantly.
- Strong cosmology dependence.

$M_\nu - \tau$ Degeneracy (Linear Case)

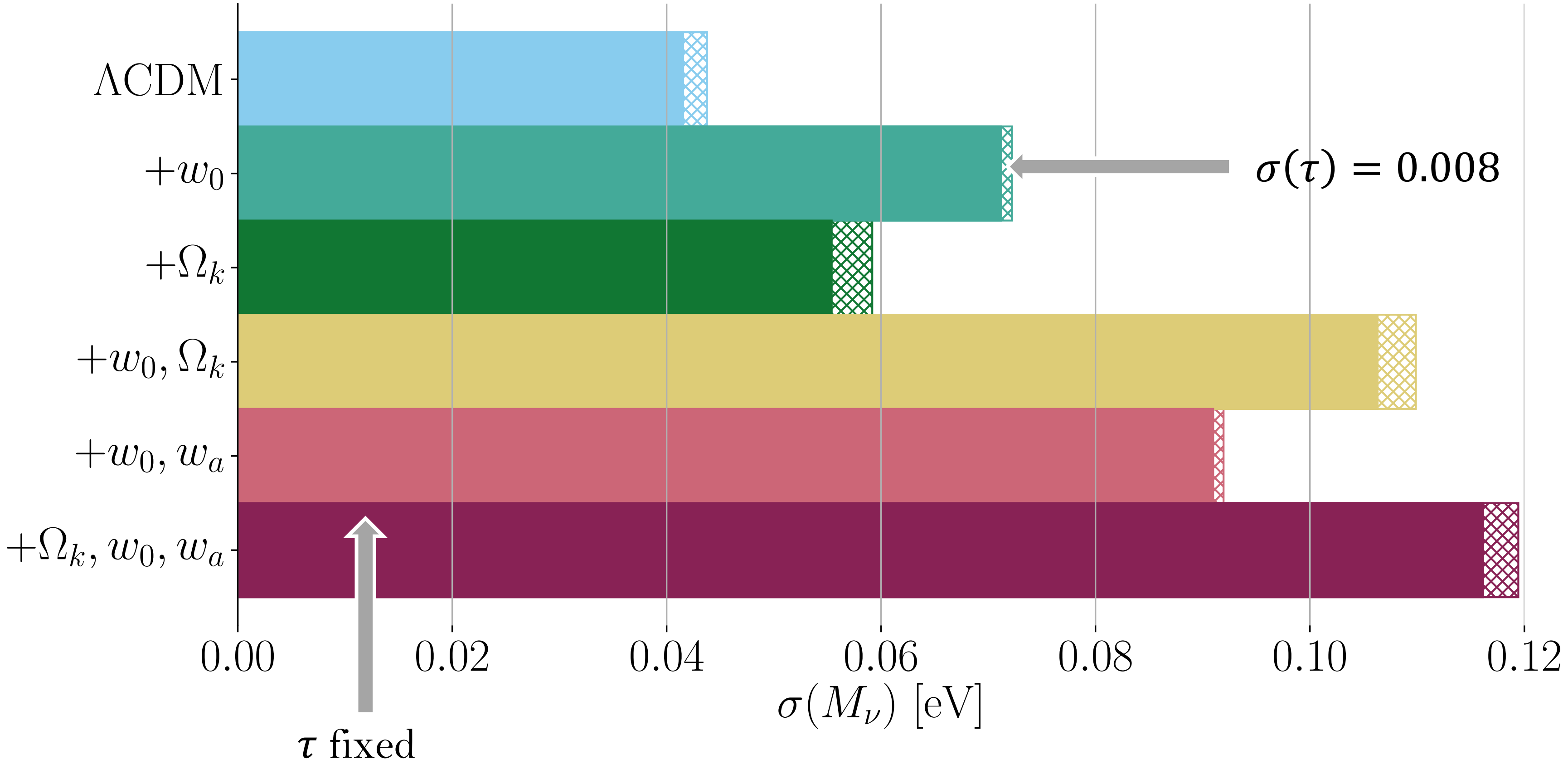
Planck TT, Simons Observatory EE/TE, $\sigma(\tau) = 0.008$/Fixed, Euclid $P_{gg}(k,\mu) \rightarrow 0.2\ h$/Mpc.



- τ degeneracy very significant.

$M_\nu - \tau$ Degeneracy (NLO Case)

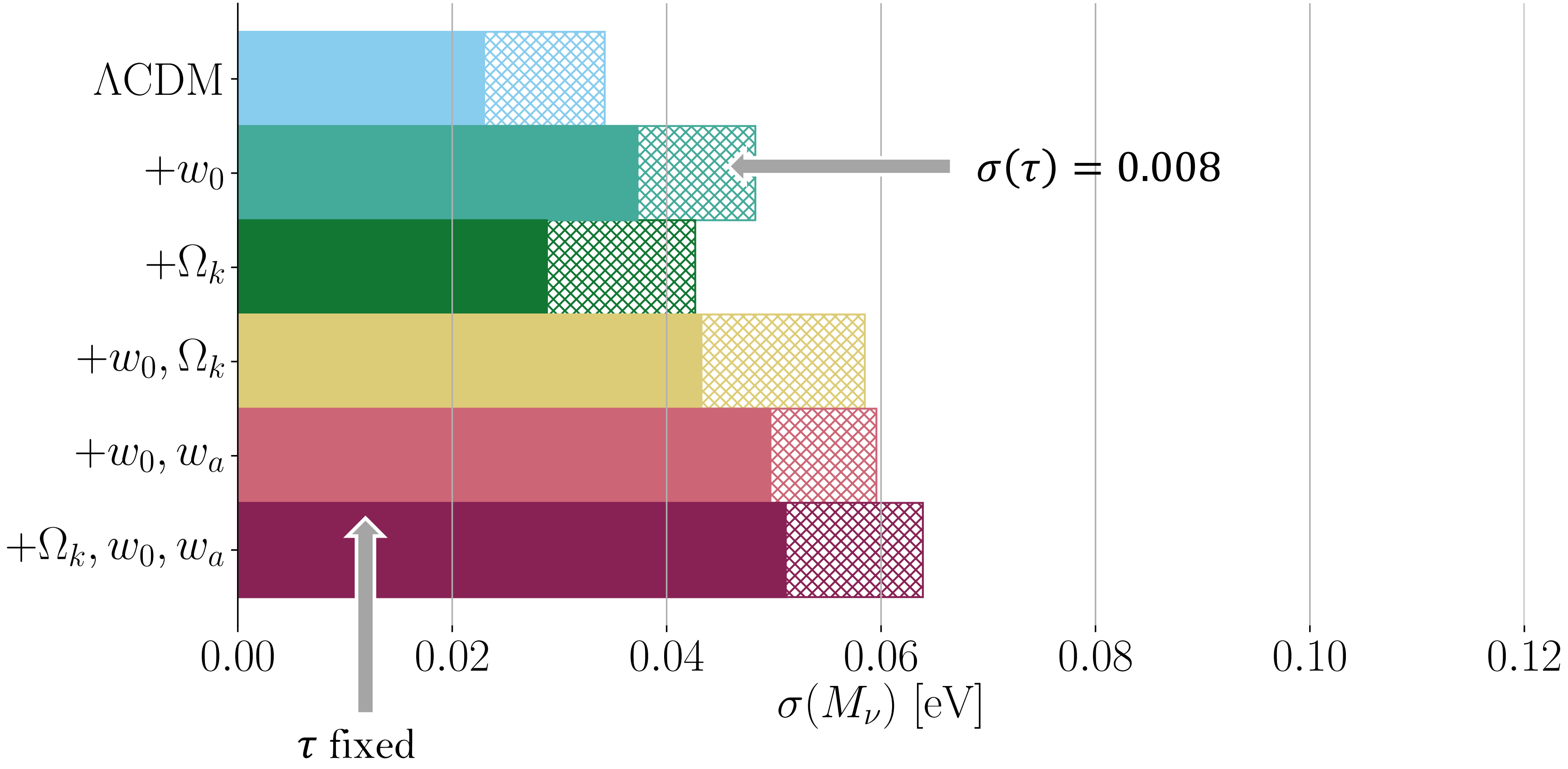
Planck TT, Simons Observatory EE/TE, $\sigma(\tau) = 0.008$/Fixed, Euclid $P_{gg}(k,\mu) \rightarrow 0.2\ h$/Mpc.



- τ degeneracy no longer relevant.
- Error supported by other degeneracies.
- The bias and stochastic parameters are primarily *all somewhat degenerate with each other*.

+ CMB Lensing (NLO Case)

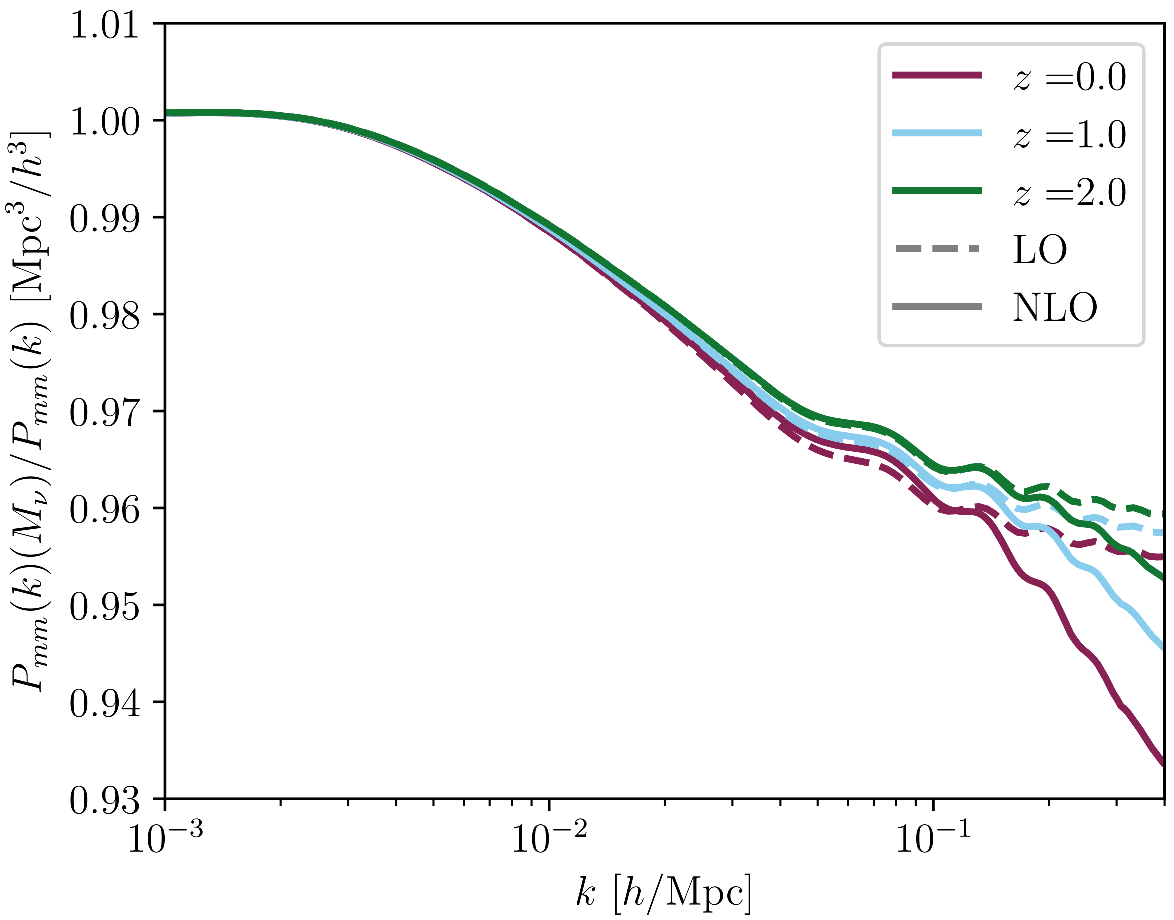
Planck TT, Simons Observatory EE/TE, $\sigma(\tau) = 0.008$, Euclid $P_{gg}(k,\mu) \rightarrow 0.2\ h$/Mpc, Simons Observatory CMB Lensing



- CMB lensing significantly improves constraints.
- Keeps degeneracies with new bias parameters under control → τ degeneracy becomes important again.

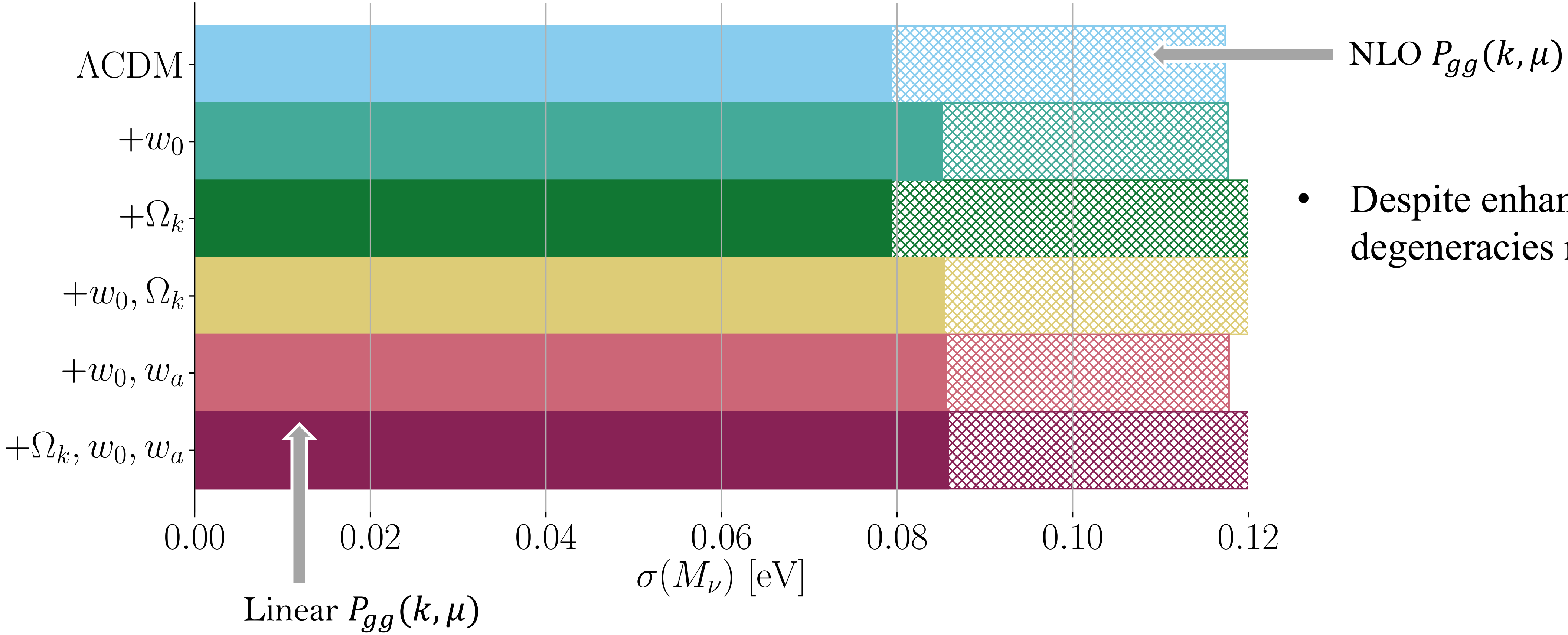
Cosmology-Independent Constraints

- Isolating the relative suppression in the power spectrum caused by massive neutrinos provides a cosmology-independent measurement of M_ν.
- This suppression is actually enhanced in the NLO case.
- The suppression affects the underlying matter power spectrum, the structure growth rate (probed by RSDs), and the CMB lensing power spectrum.



Cosmology-Independent Constraints

Planck TT, Simons Observatory EE/TE, $\sigma(\tau) = 0.008$, Euclid P_{gg} (shape only) → 0.2 h/Mpc, Simons Observatory CMB Lensing (shape only)



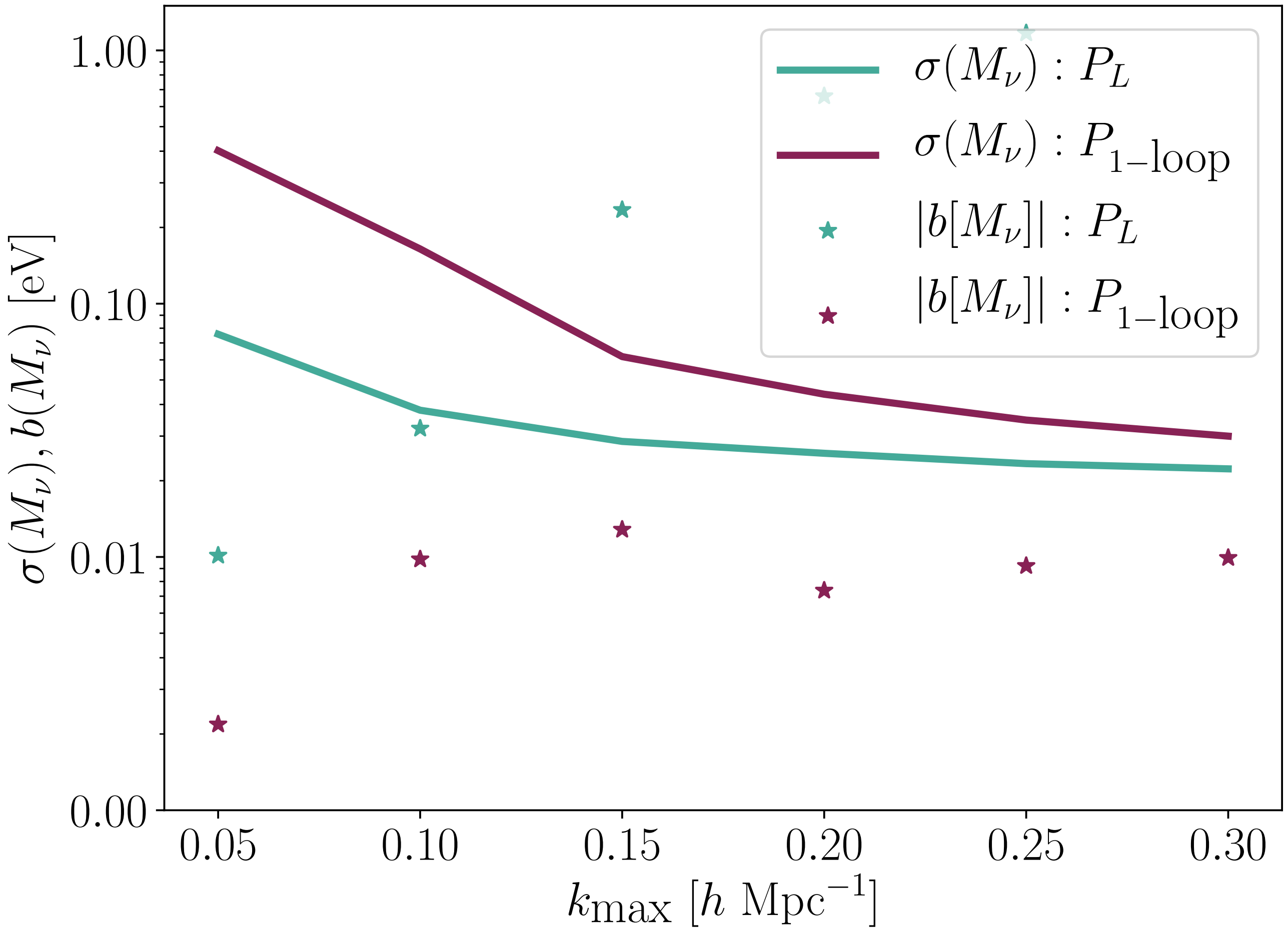
- Despite enhanced suppression, degeneracies reduce

Fisher Bias

$$b[\theta_i] = \langle \theta_{\text{sys},i} \rangle - \langle \bar{\theta}_i \rangle$$

$$= \sum_j (F^{-1})_{ij} \sum_x \frac{O^{\text{sys}}(x)}{Var[\hat{O}(x)]} \frac{\partial O^{\text{theory}}(x)}{\partial \theta_j}$$

- Linear bias: exceeds constraint from $k_{max} = 0.1\ h$/Mpc.
- 1-loop bias (estimate): bias approximately 20% of constraint at $k_{max} = 0.2\ h$/Mpc.



Conclusions

Considering the 1-loop power spectrum has a significant qualitative and quantitative impact on neutrino mass constraints.

- 7 new free parameters → constraints degrade considerably. **Realistic constraints, even up to k=0.2 h/Mpc, should include these parameters.**
- CMB lensing can play a significant role in keeping effects of degeneracies with additional nuisance parameters under control.
- Free-streaming constraints remain cosmology-independent, though weaker.
- The 1-loop power spectrum seems reasonably unbiased compared to the linear power spectrum.

Neutrino mass constraints (apart from the free-streaming only constraints we developed) are strongly cosmology dependent.