Accounting for theoretical uncertainties in LSS analyses

Thejs Brinckmann

Paris-Saclay Astroparticle Symposium 2022

Based on

Parameter inference with non-linear galaxy clustering: accounting for theoretical uncertainties
Knabenhans, **TB**, Stadel, Schneider, Teyssier 2110.01448

Cosmology in the era of Euclid and the Square Kilometre Array
Sprenger, Archidiacono, **TB**, Clesse, Lesgourgues 1801.08331

Università degli Studi di Ferrara

Overview

A ton of models of interest, as seen by the talk by Julien yesterday

- Full simulation grids are too costly
- We need fast non-linear approaches

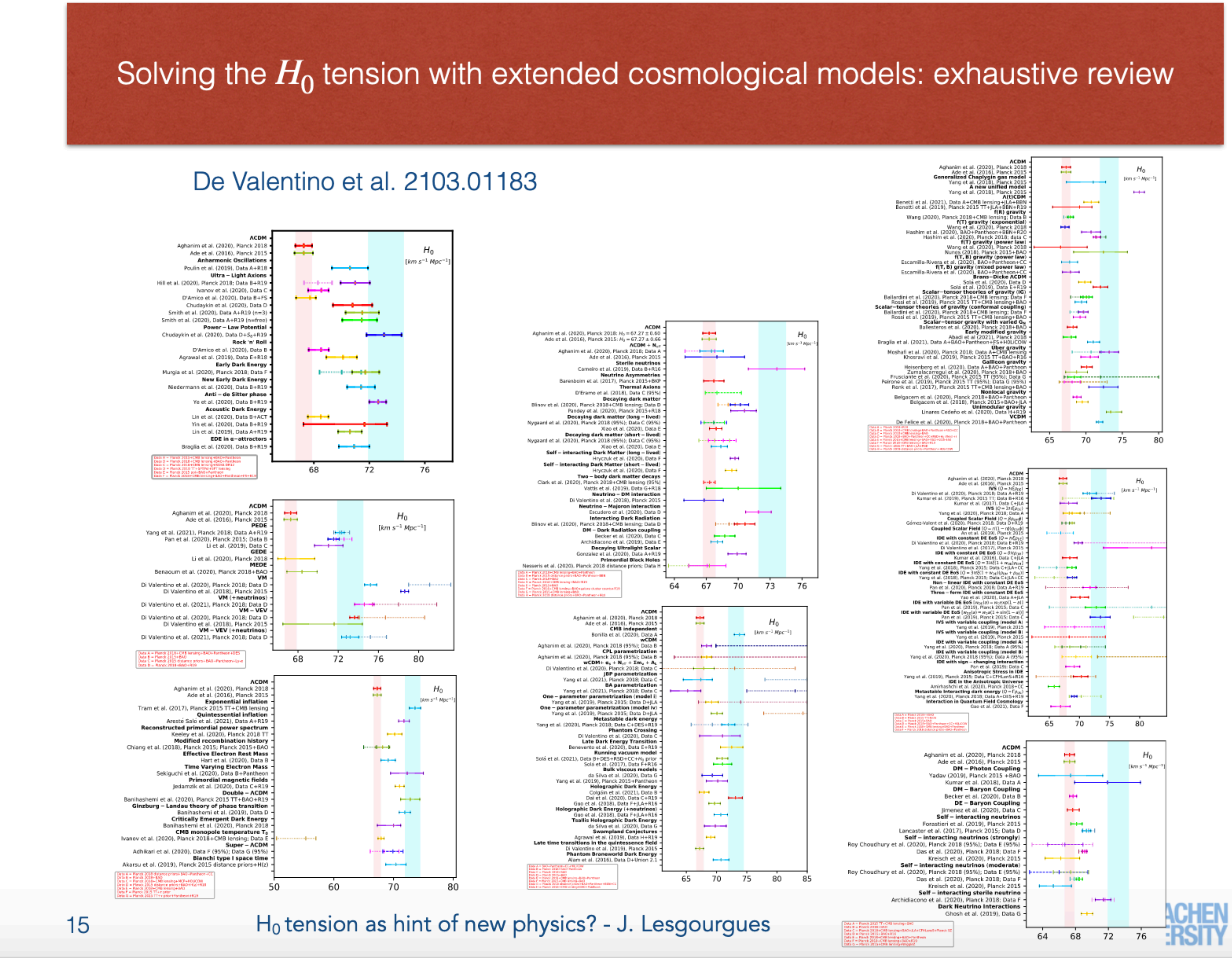
Emulators / halo model approaches

- Fast, extended models, linear effects captured
- Useful if non-linear structure formation not altered w.r.t. valid models

Considering here

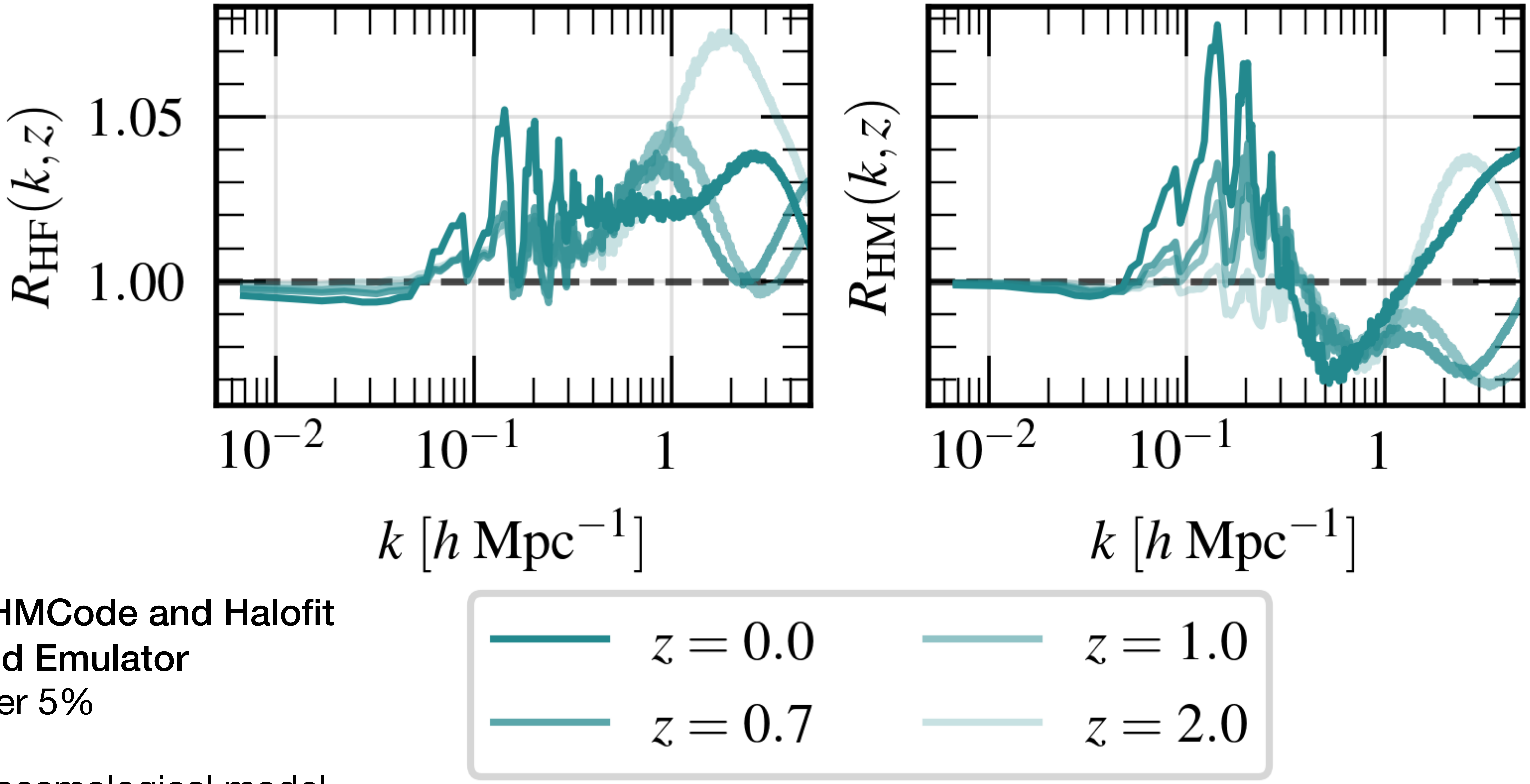
- Euclid Emulator
- Halofit
- HMCode

Also interesting: other emulators, EFTofLSS (but limited to not so non-linear scales)



Talk yesterday by Julien Lesgourgues

Euclid Emulator vs Halofit, HMCode

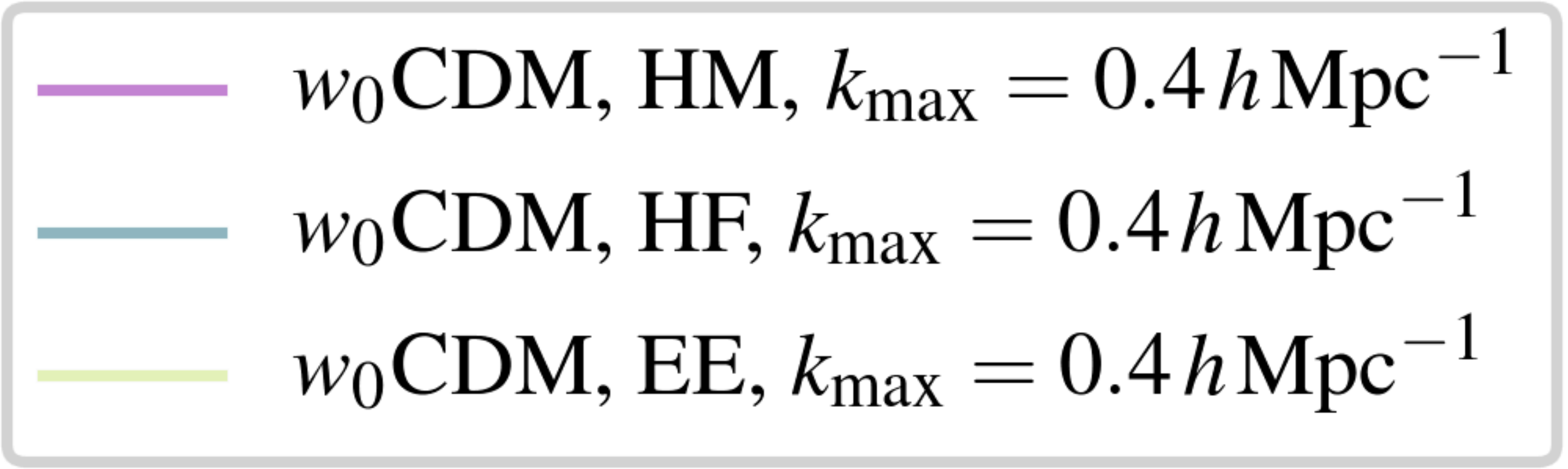


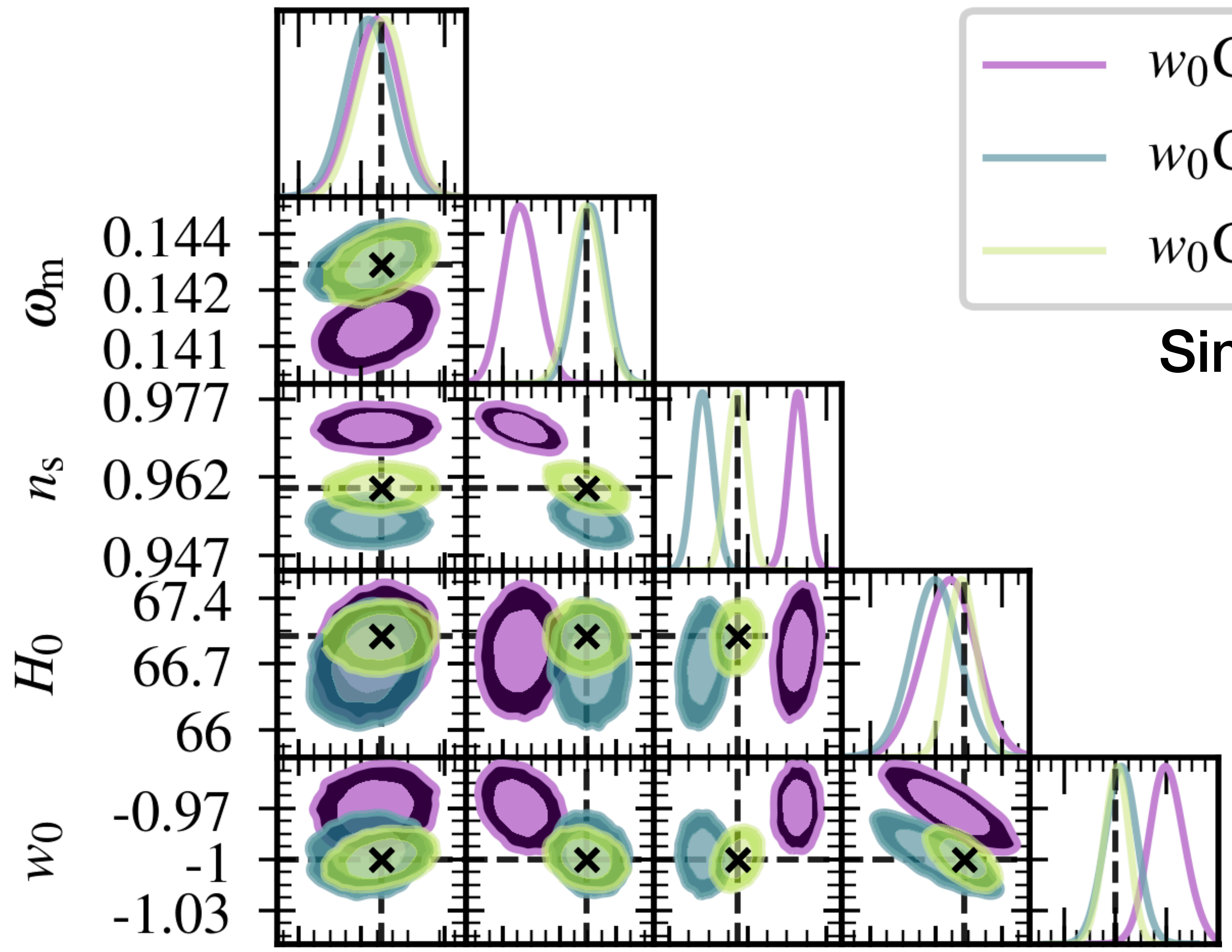
Differences between HMCode and Halofit compared to the Euclid Emulator

- Disagreement of order 5%
- Depends on redshift
- Depends weakly on cosmological model

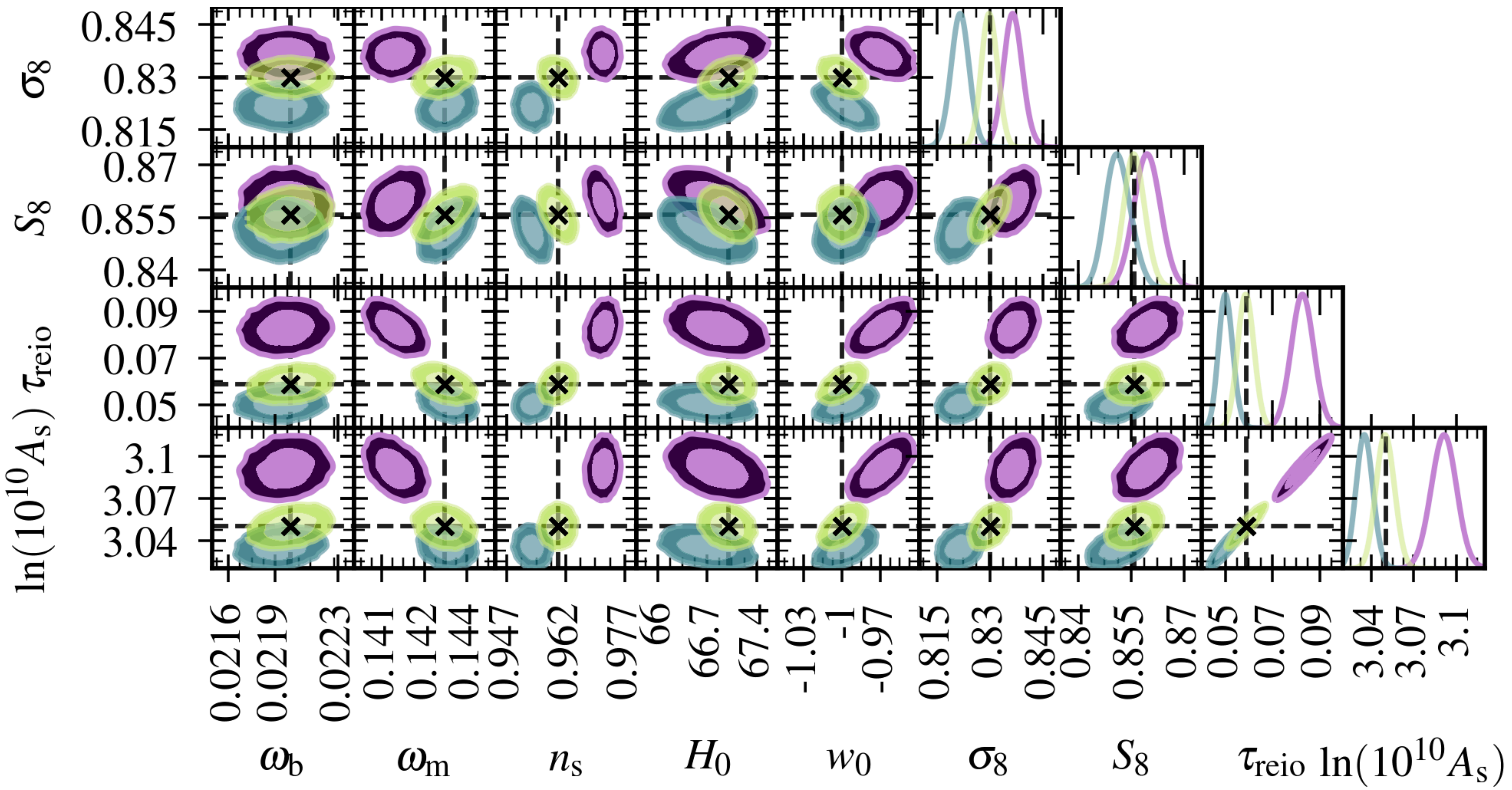
$$R_{\mathrm{model}}(k, z; p) \equiv \frac{P_{\mathrm{model}}(k, z; p)}{P_{\mathrm{EE}}(k, z; p)}$$

Euclid Emulator vs Halofit, HMCode





Similar bias for LCDM



Differences lead to significant biases in parameter estimation

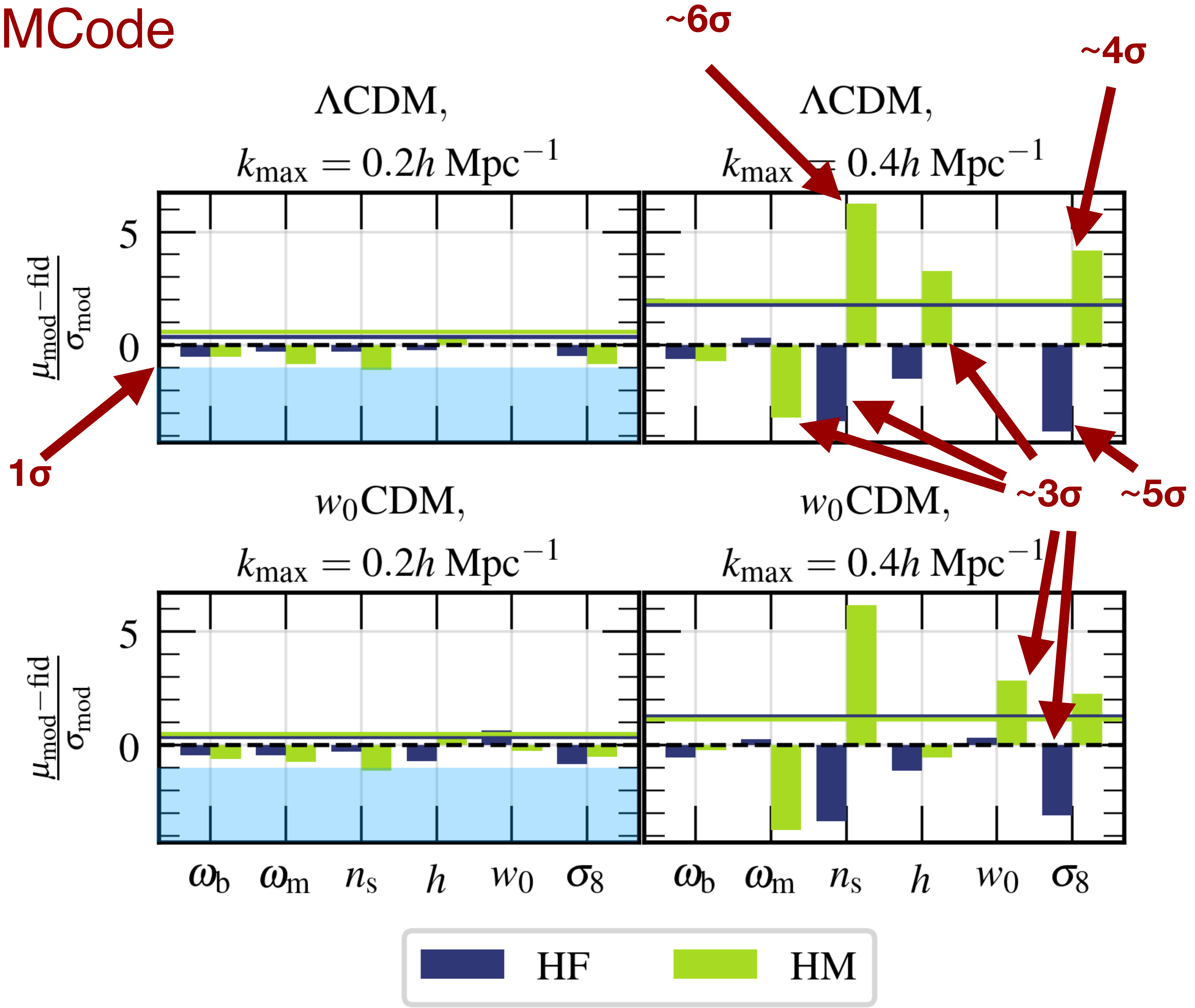
Euclid Emulator vs Halofit, HMCode

Unsurprisingly, much smaller bias for aggressive non-linear cut-off

- But about **~1σ** for several parameters

Going to more non-linear scales results in large biases

- Bias of order **3σ** to **6σ** in parameters
- We need to be careful
- This is where theoretical uncertainties come in!

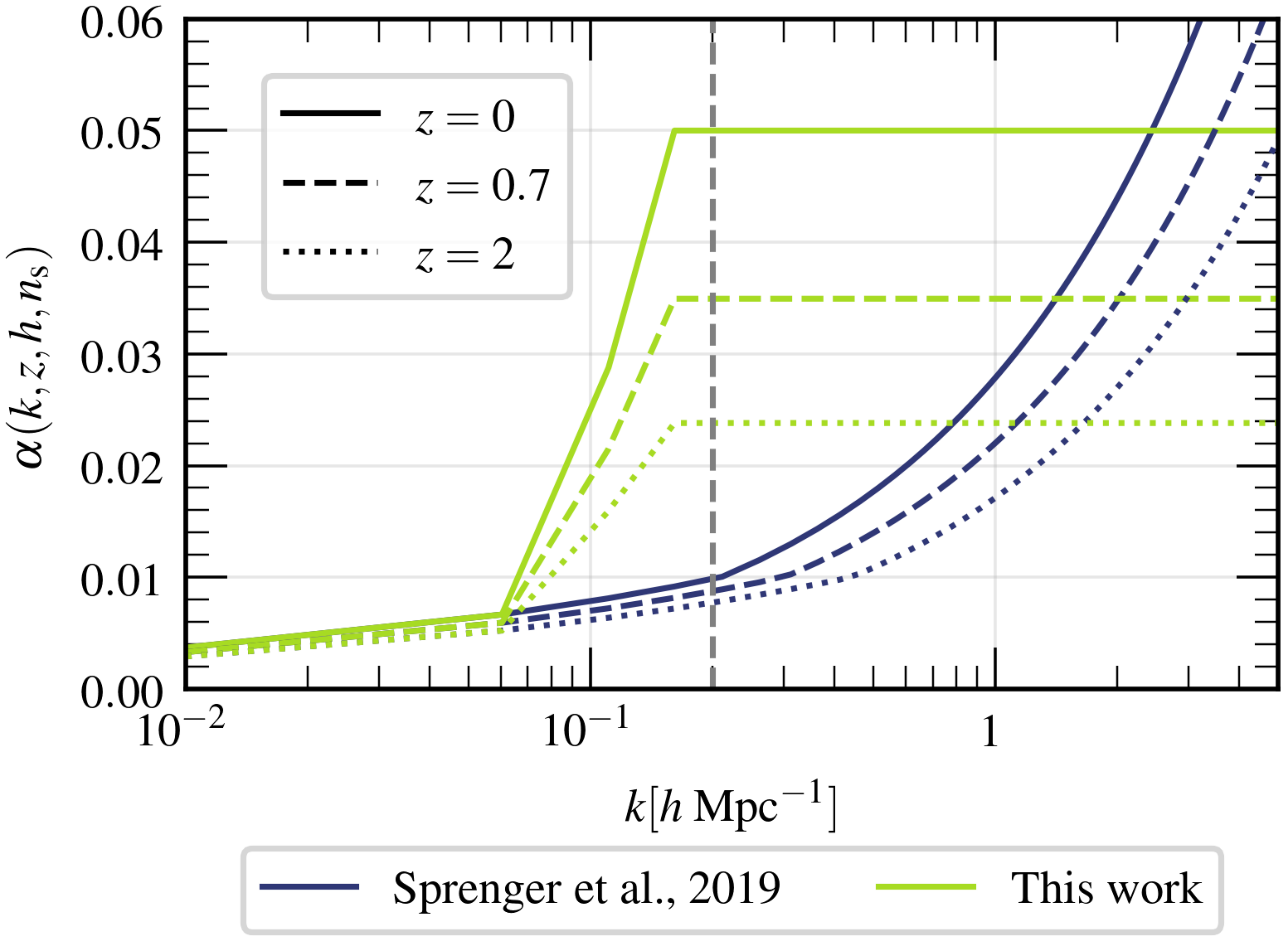


Theoretical uncertainty

We already used a theoretical uncertainty

Sprenger et al.
1801.08331
(previous slides)

The envelope of the error increases gradually with wavenumber
fixed to 0.33% below k = 0.01 h/Mpc
increasing to 1% at k = 0.2 h/Mpc
and to 10% at k = 10 h/Mpc
(at z=0, shifted to larger k at larger z)



New proof-of-concept theoretical uncertainty from Knabenhans, TB, et al. 2110.01488
- Increases on BAO scales where the fast non-linear approaches disagree significantly

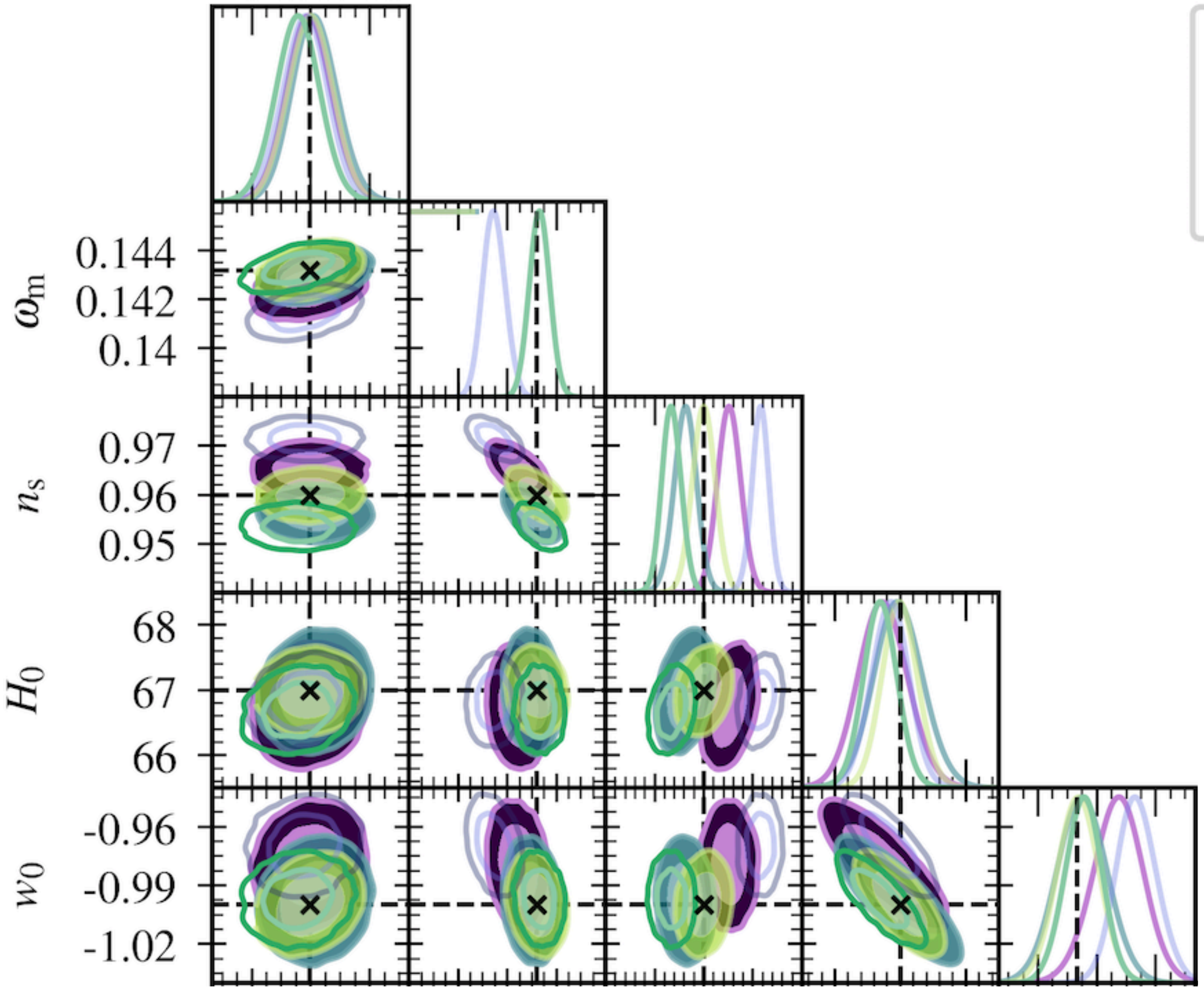
Knabenhans,
TB, et al.

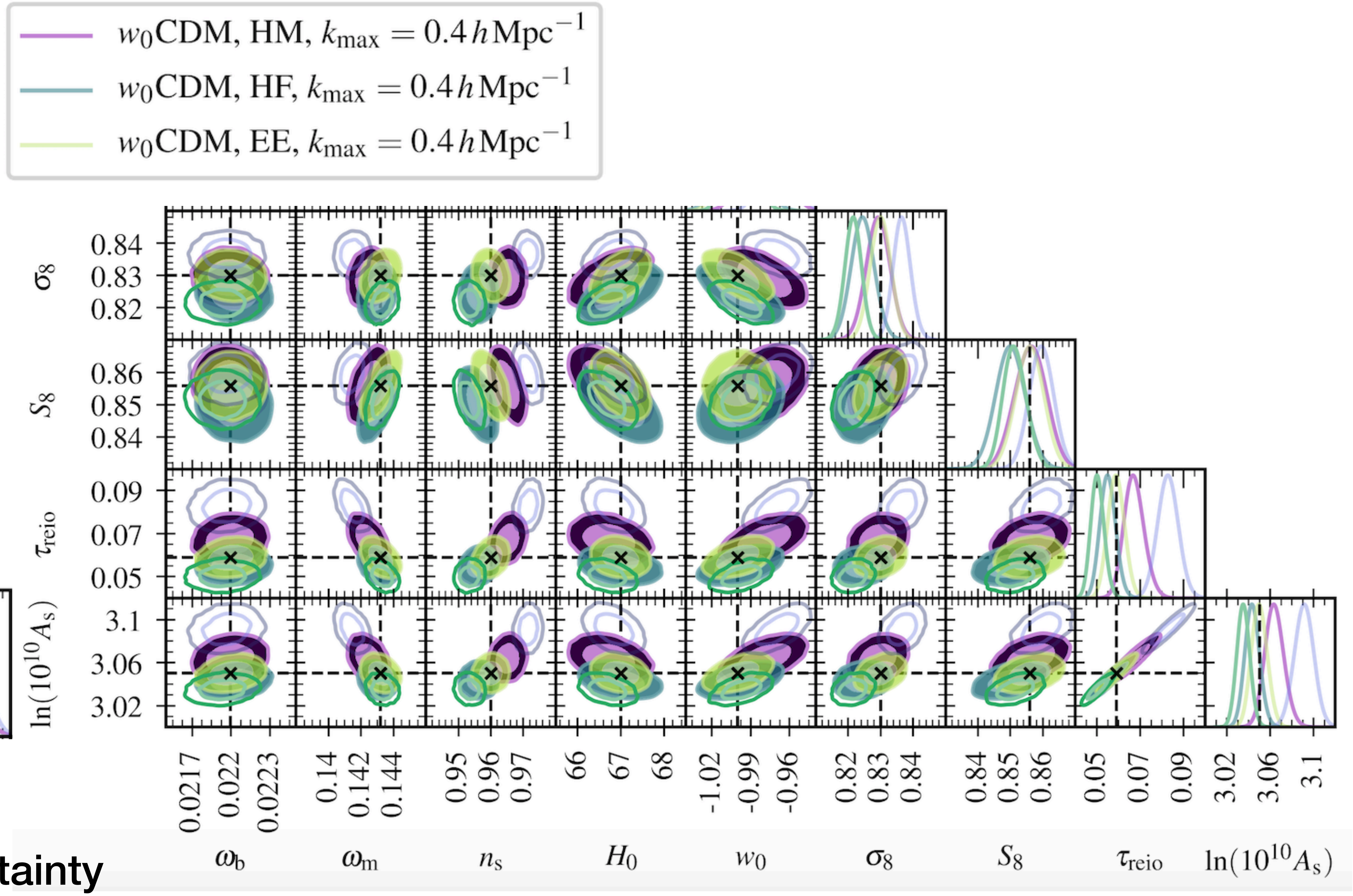
The envelope of the error increases suddenly on BAO scales
Same as Sprenger et al. until k = 0.05 h/Mpc
increasing exponentially to 5% at k = 0.15 h/Mpc
flat at 5% above k = 0.15 h/Mpc

Theoretical uncertainty

New proof-of-concept theoretical uncertainty from Knabenhans, TB, et al. 2110.01488

- Significantly decreases bias with only a relatively small loss in sensitivity





Open contours: Sprenger et al. uncertainty
Filled contours: Knabenhans, TB et al. uncertainty

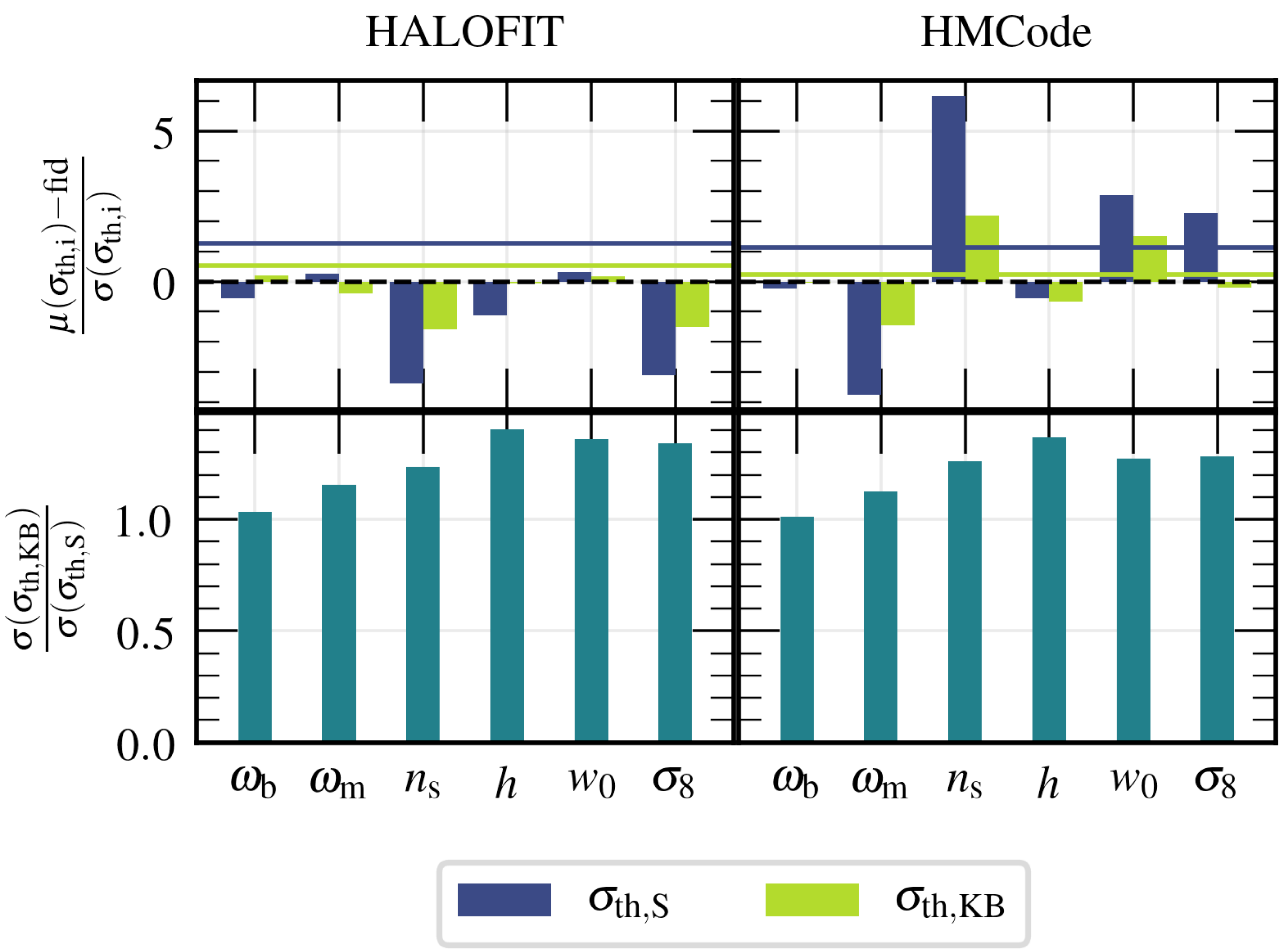
Theoretical uncertainty

New proof-of-concept theoretical uncertainty from Knabenhans, TB, et al. 2110.01488

- Significantly decreases bias with only a modest loss in sensitivity

Next steps

- Can obviously do a lot better with a more sophisticated uncertainty
- Should repeat analysis with EFT, other emulators on the market, new HMCode
  - Biases are likely to be smaller and more manageable
  - But we should be honest that our methods are not perfect



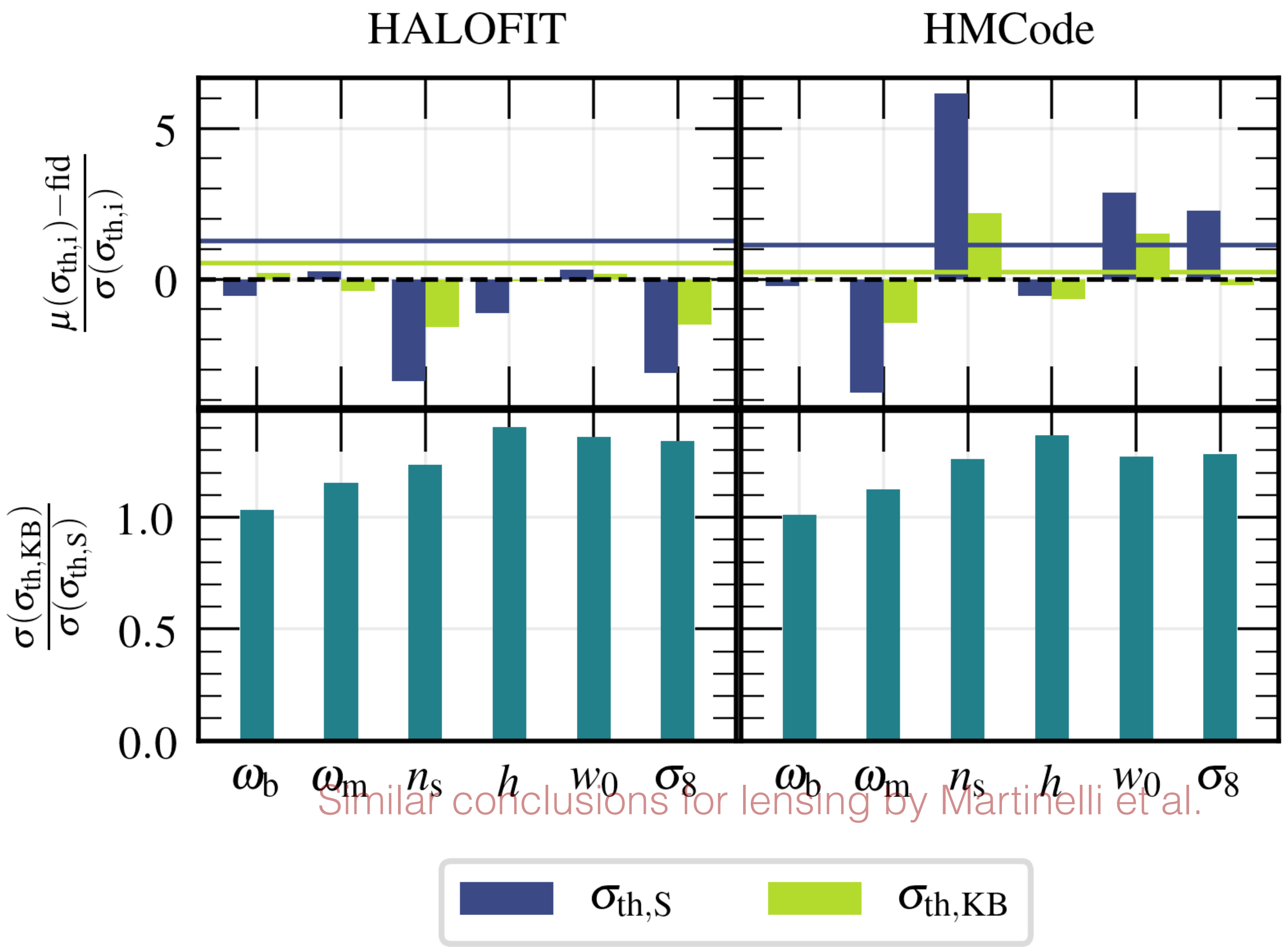
Summary and conclusions

We need fast methods for accounting for non-linear structure formation in upcoming large-scale structure analyses (e.g. galaxy clustering, cosmic shear, intensity mapping, CMB lensing) in order to study a wide array of models — simulations approach not feasible beyond a smaller number of baseline models.

Current non-linear estimation methods introduce a bias of up to 6 σ (in blue) in the estimation of cosmological parameters from a galaxy clustering analysis with a Euclid-like survey **unless care is taken to mitigate this with a theoretical uncertainty.**

We introduced a proof of concept theoretical uncertainty (in green), which improves on this with a modest loss in sensitivity.

Need to improve with a more realistic theoretical uncertainty envelope to minimize bias while maximizing sensitivity.



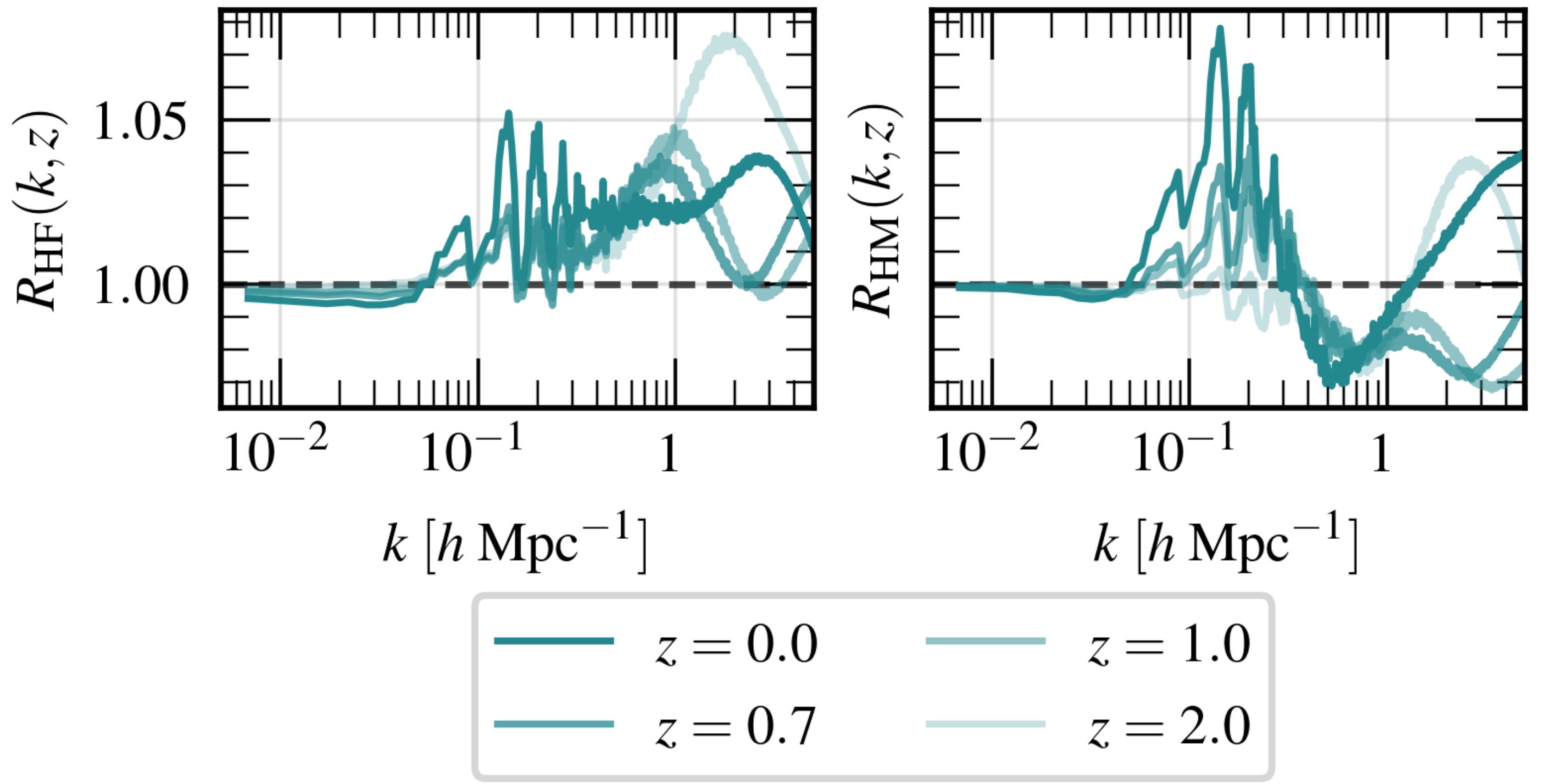
Similar conclusions for lensing by Martinelli et al.

Check out the paper!

Parameter inference with non-linear galaxy clustering: accounting for theoretical uncertainties
Knabenhans, **TB**, Stadel, Schneider, Teyssier 2110.01448

Also see
Martinelli et al. 2010.12382
for weak lensing analogy

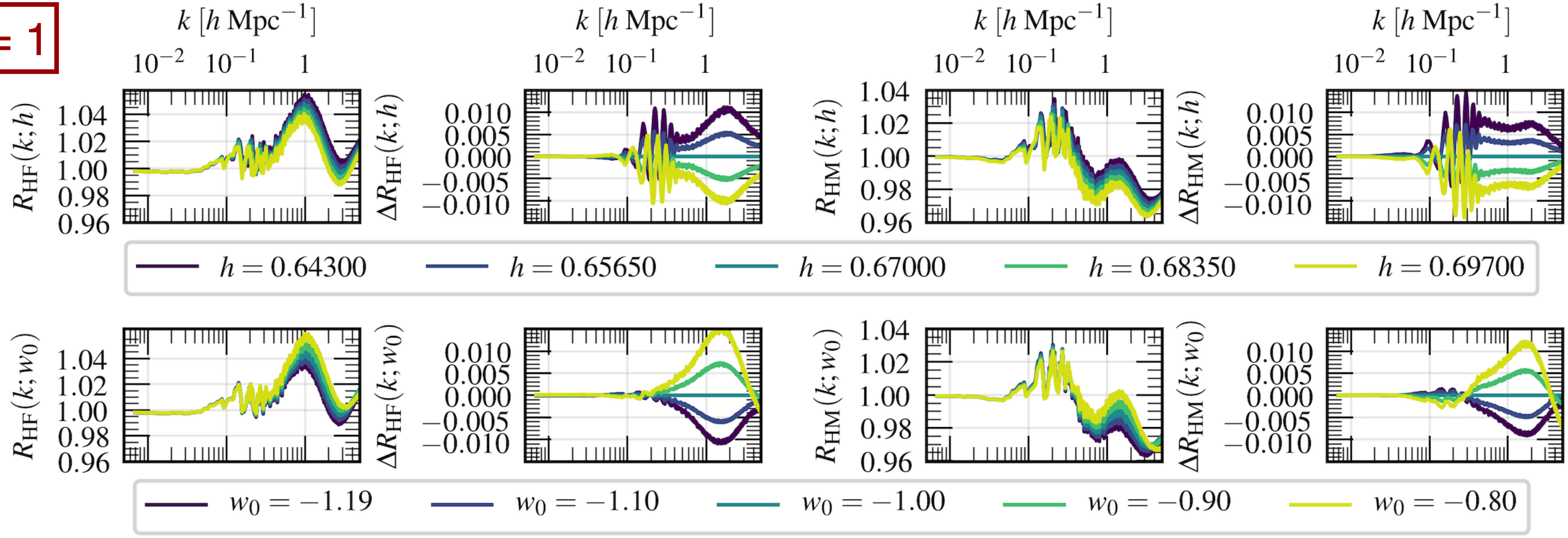
Backup slides



Significant differences between non-linear approaches

- Depends on redshift, but order ~5%
- Depends weakly on cosmological model
  - Worst for equation of state of dark energy
  - Up to ~1% at Planck 2σ for the Hubble parameter (less for others)

z = 1

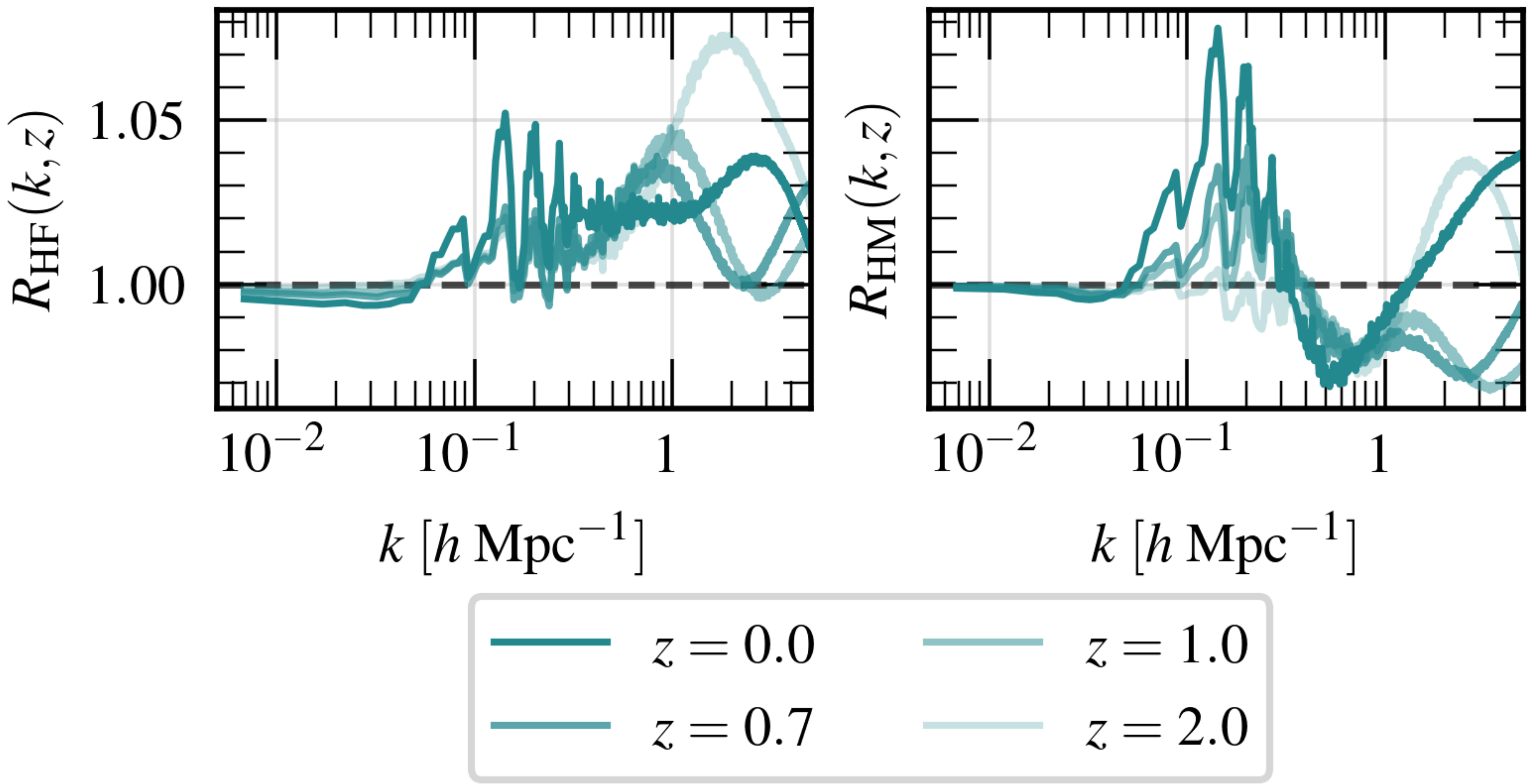


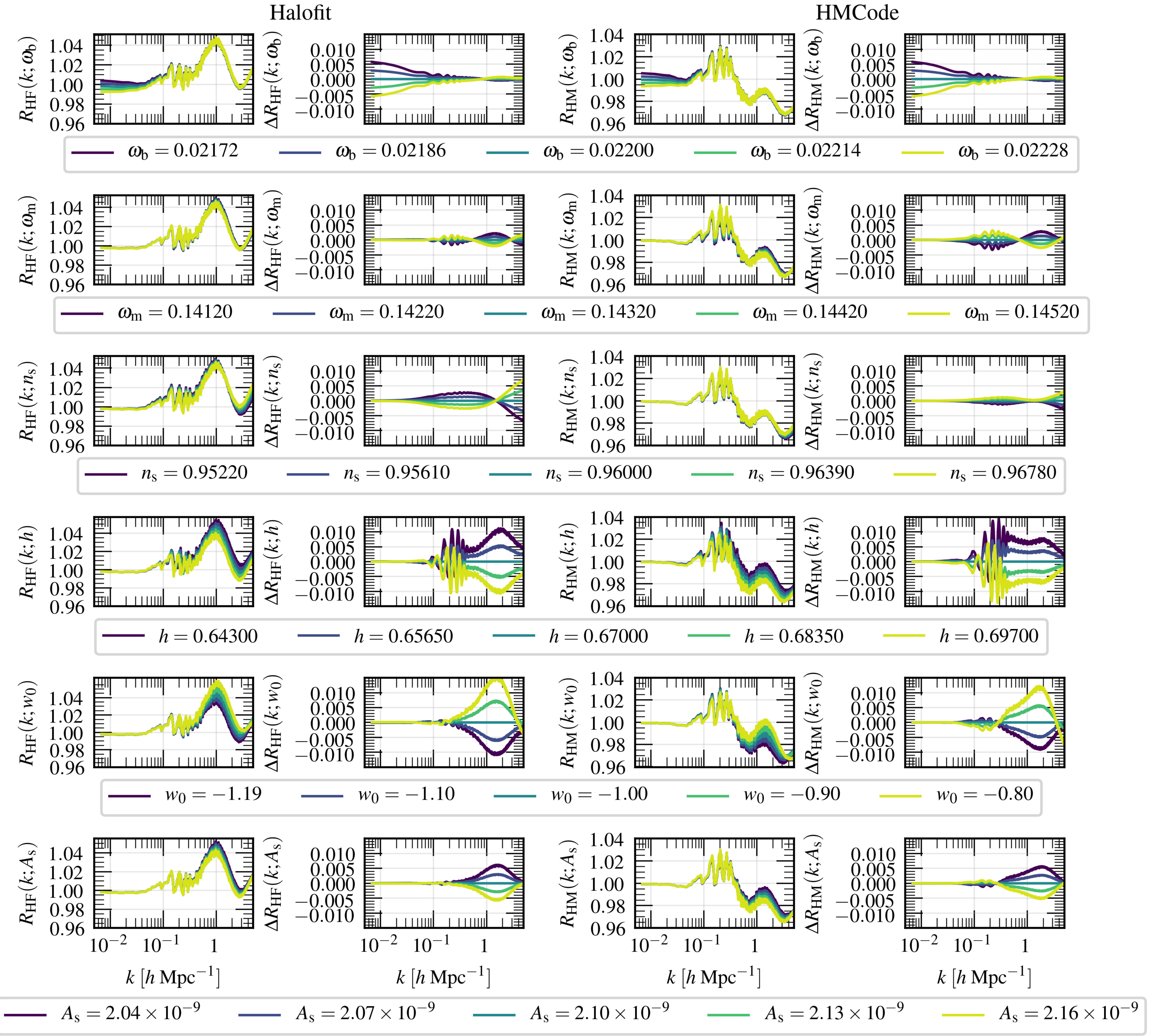
Backup slides

z = 1

$$R_{\mathrm{model}}(k, z; p) \equiv \frac{P_{\mathrm{model}}(k, z; p)}{P_{\mathrm{EE}}(k, z; p)}$$

$$\Delta R_{\mathrm{model}}(k, z; p) = R_{\mathrm{model}}(k, z; p) - R_{\mathrm{model}}(k, z; p_{\mathrm{ref}})$$





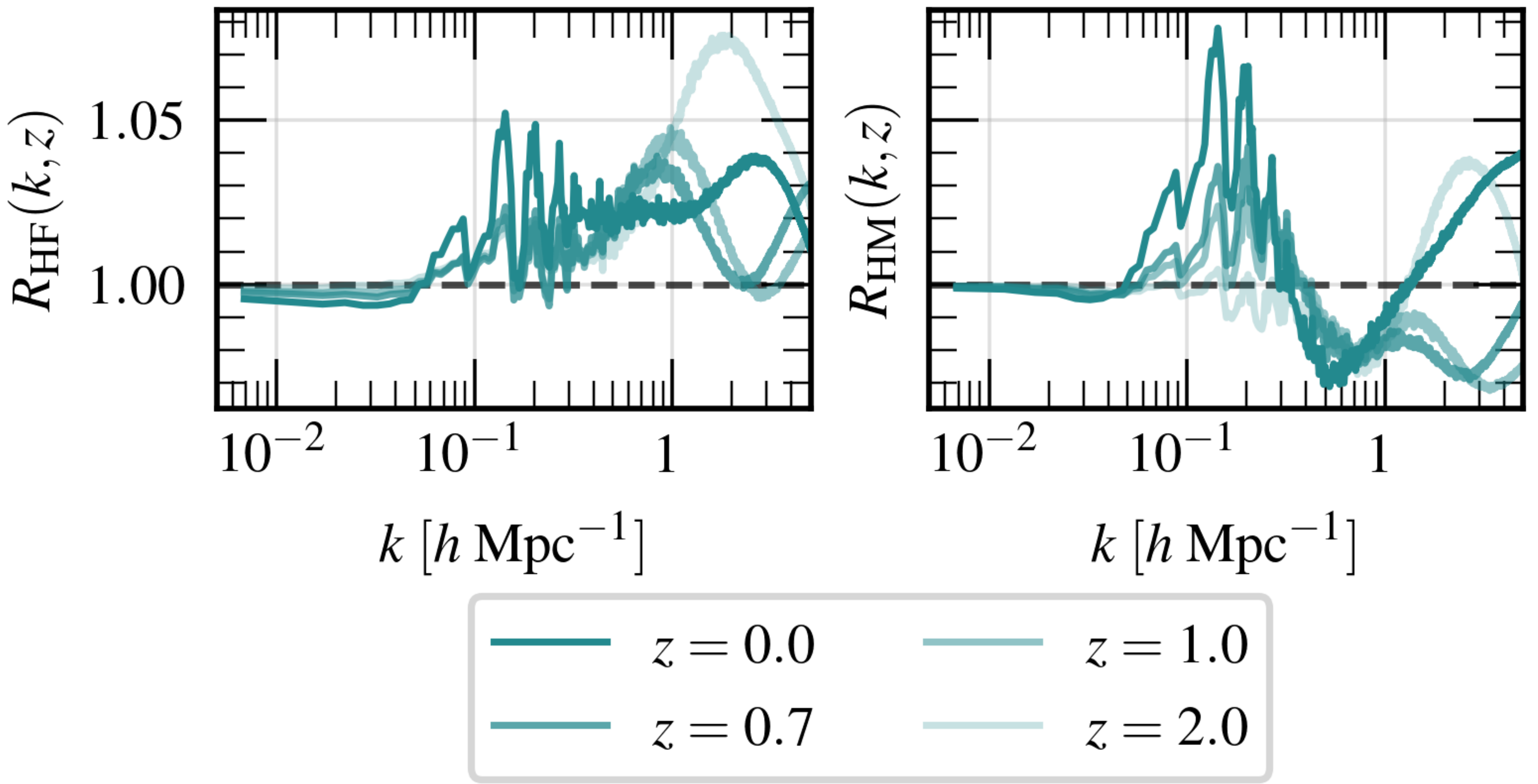
Backup slides

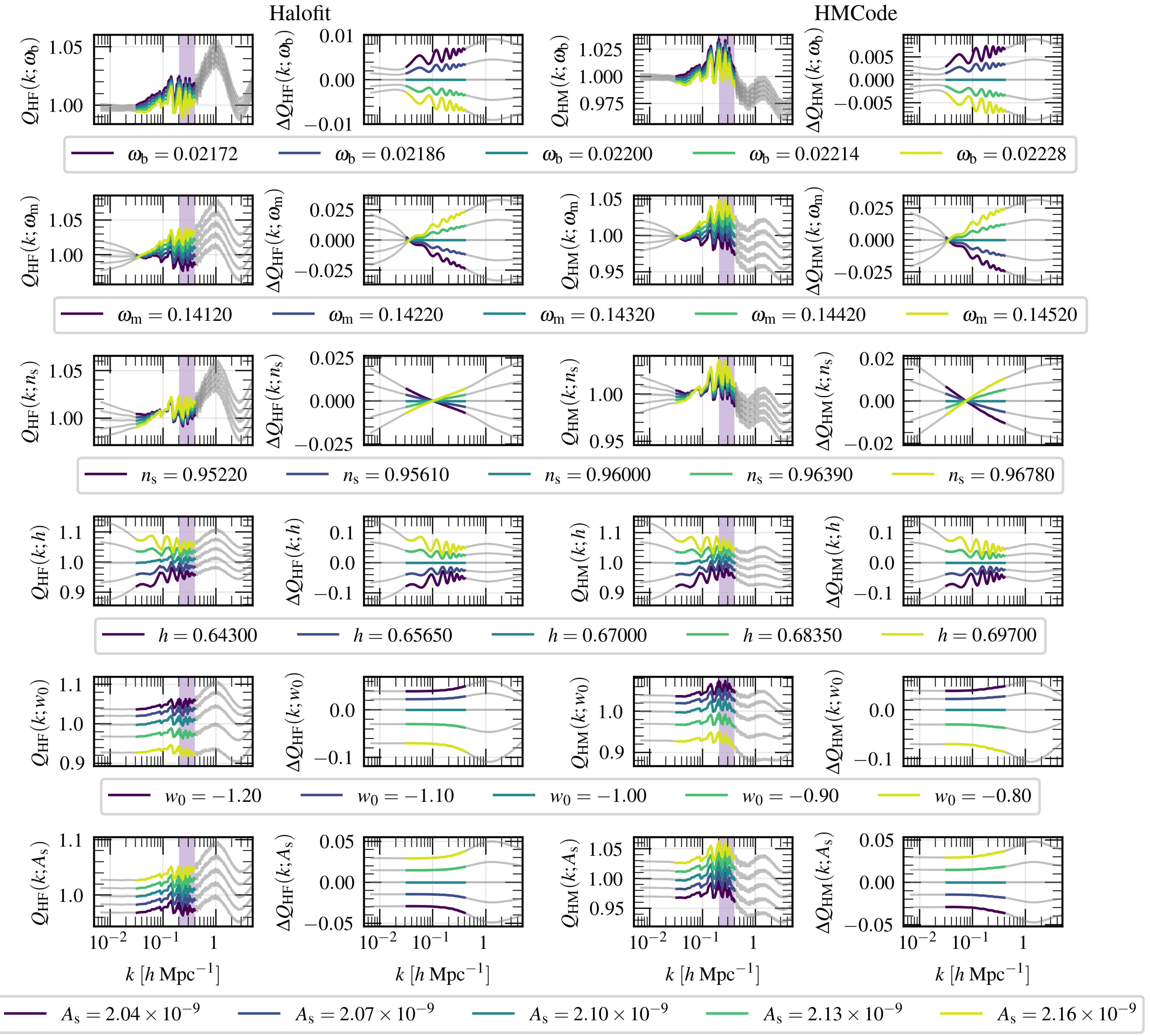
z = 1

$$Q_{\rm mod}(k;p) \equiv \frac{P_{\rm mod}(k;p)}{P_{\rm EE}(k;p_{\rm fid})}\,,$$

and

$$\Delta Q_{\rm mod}(k;p) \equiv Q_{\rm mod}(k;p) - Q_{\rm mod}(k;p_{\rm fid})\,,$$





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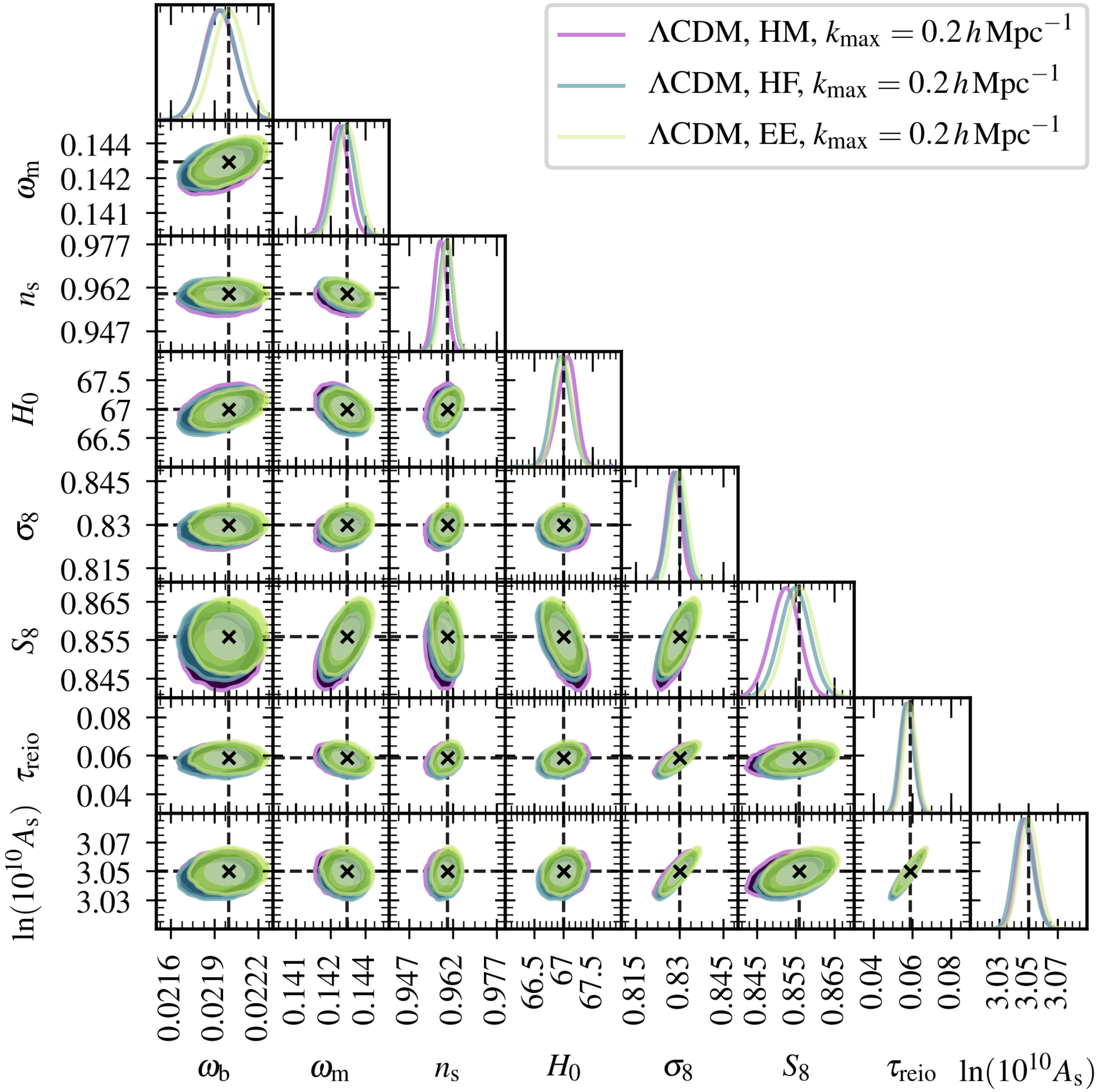

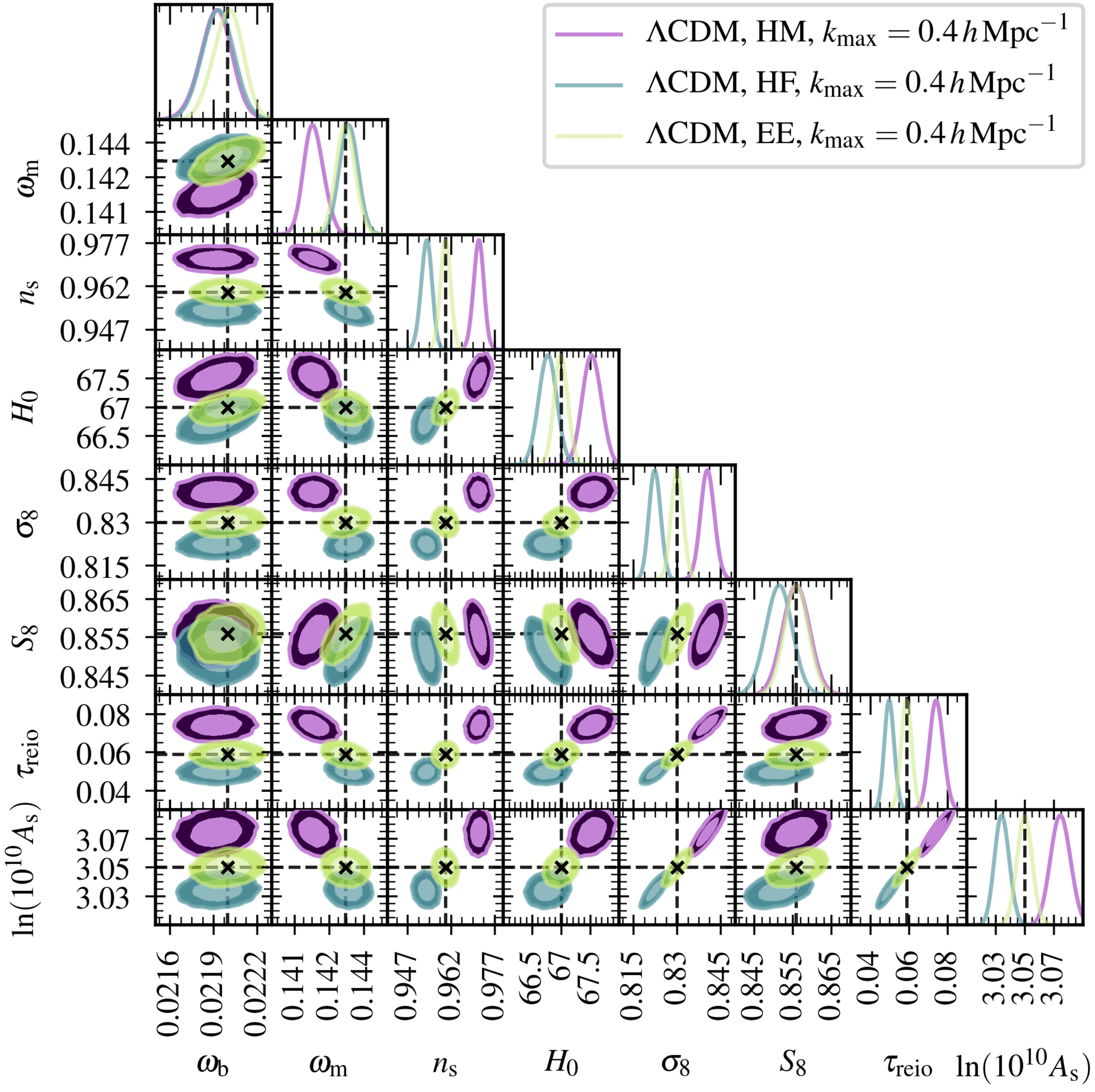

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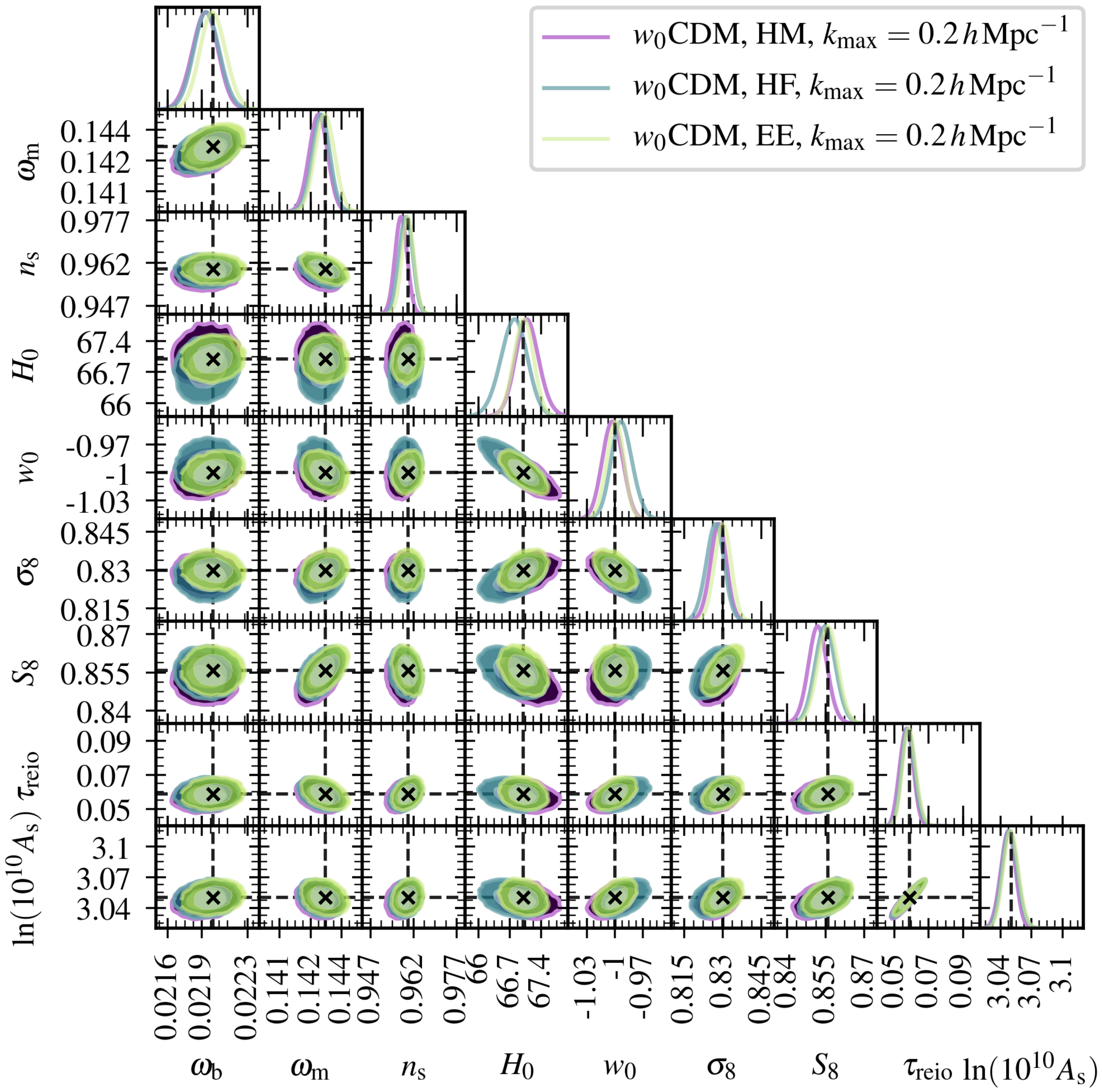
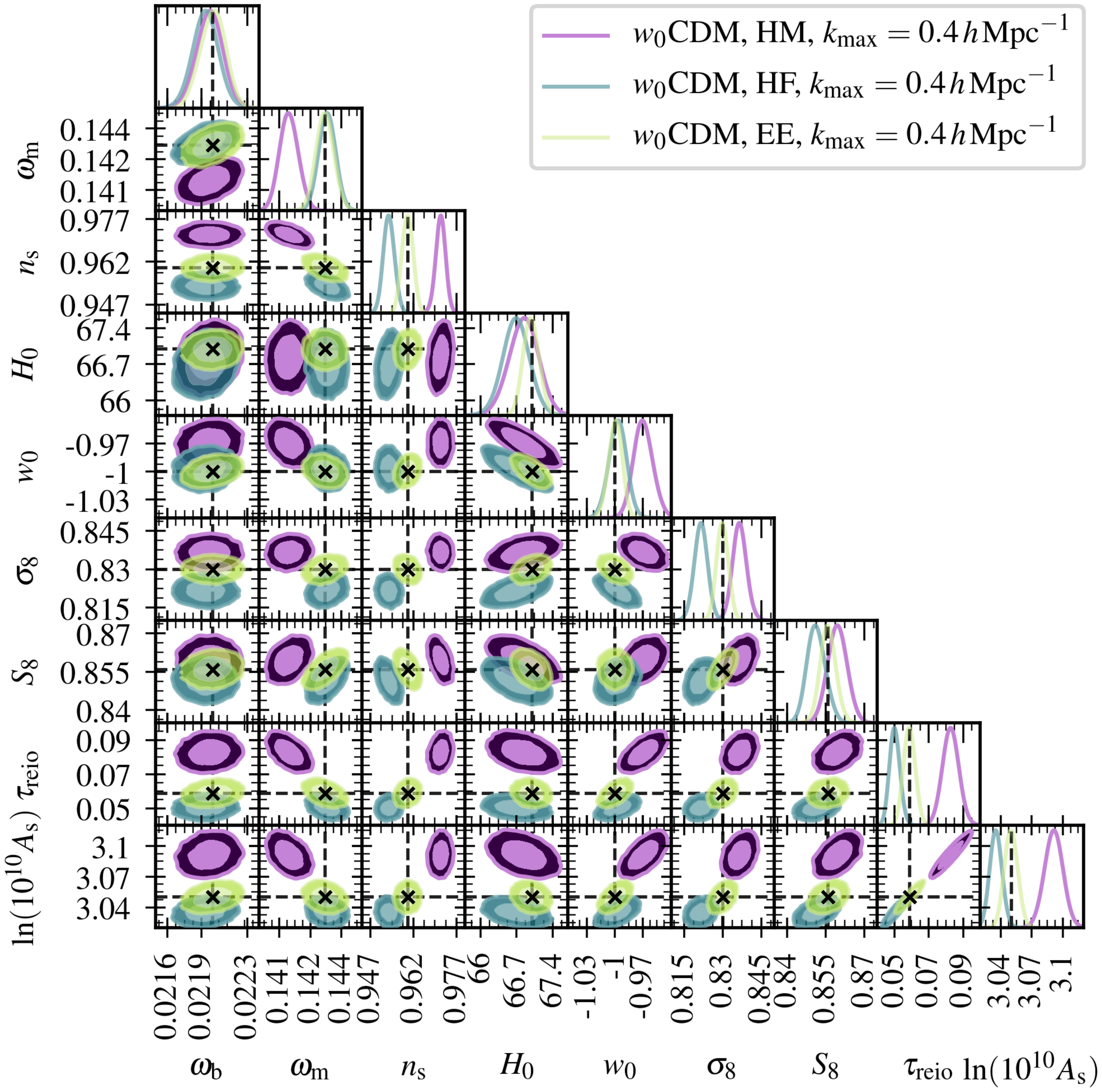
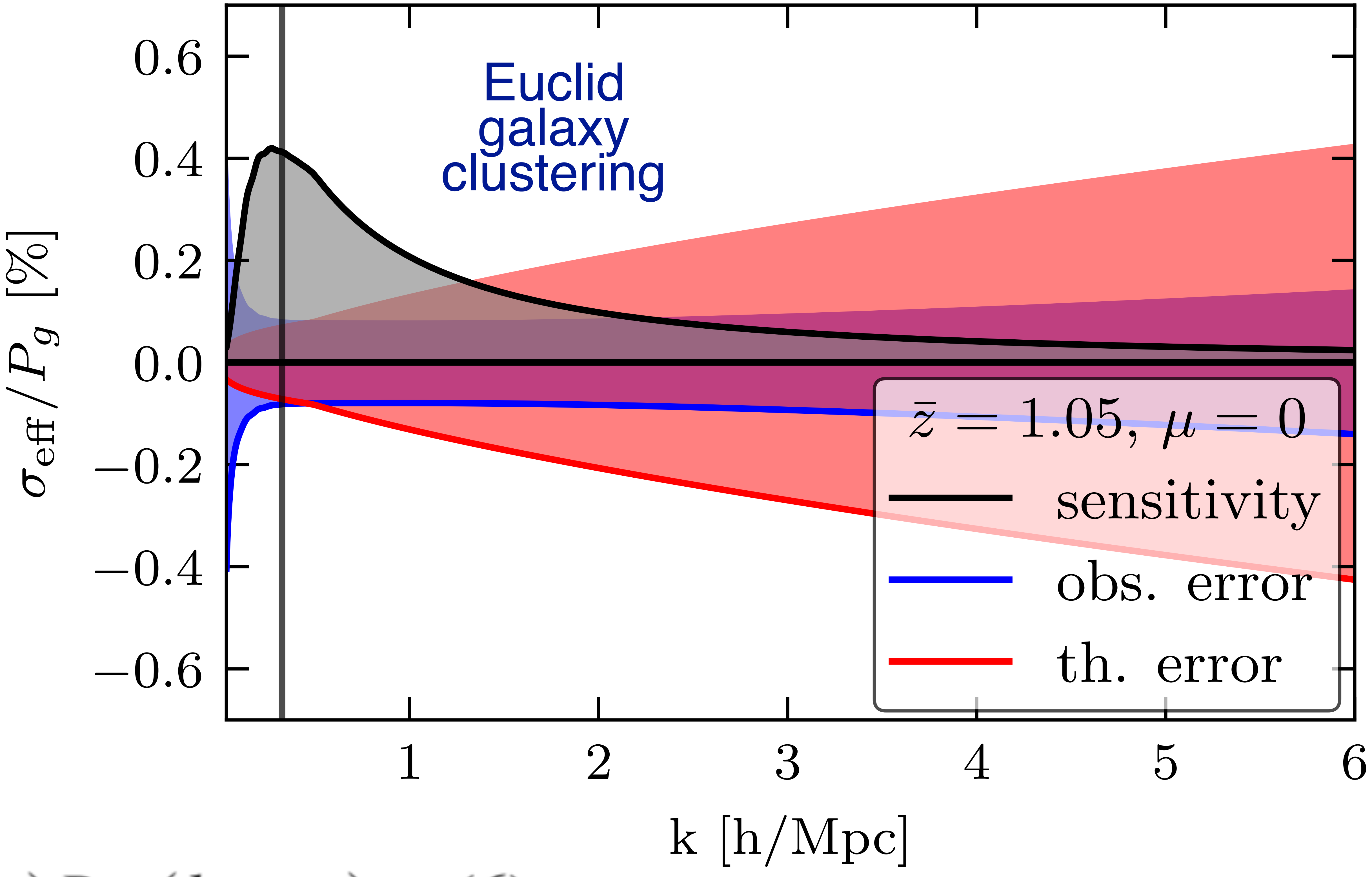




Backup slides

Theoretical uncertainty from Sprenger et al. 2018.08331
- Increases on small scales where hydrodynamical simulations increasingly disagree between different codes and implementations



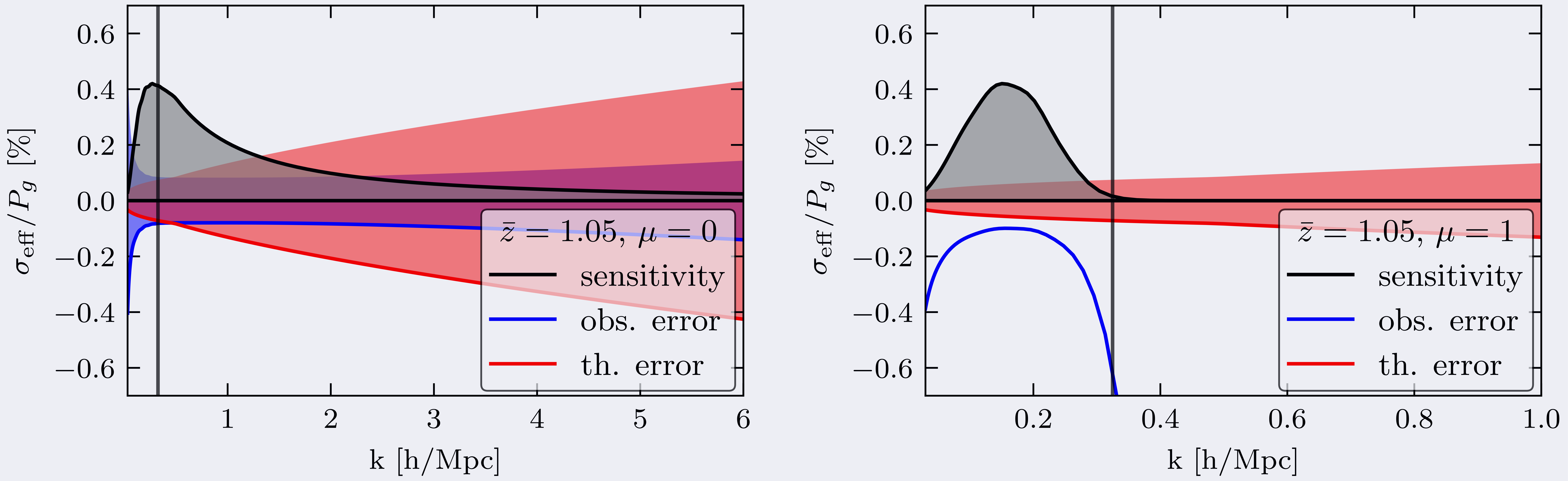
$$\sigma_{\rm th}(k,\mu,z) = \left[\frac{V_r(z)}{2(2\pi)^2}k^2\Delta k\Delta\mu\frac{\Delta z}{\Delta\bar{z}}\right]^{1/2}\alpha(k,\mu,z)P_{\rm gg}(k,\mu,z) \qquad (6)$$

$$\alpha(k,z) = \begin{cases} a_1 \exp c_1 \log_{10}\left[\frac{k}{k_{1\,h\,{\rm Mpc}^{-1}}(z)}\right], & \frac{k}{k_{1\,h\,{\rm Mpc}^{-1}}(z)} < 0.3 \\ a_2 \exp c_2 \log_{10}\left[\frac{k}{k_{1\,h\,{\rm Mpc}^{-1}}(z)}\right], & \frac{k}{k_{1\,h\,{\rm Mpc}^{-1}}(z)} > 0.3 \end{cases}$$

The envelope of the error increases gradually with wavenumber
fixed to 0.33% below k = 0.01 h/Mpc, increasing to 1% at k = 0.3 h/Mpc, and to 10% at k = 10 h/Mpc (at z=0, shifted to larger k at larger z)

Backup slides

Euclid
galaxy
clustering



Common non-linear approach:
Non-linear cut-off e.g. k_{max} = 0.2 h/Mpc

Our non-linear method:
Theoretical uncertainty due to non-linear modelling

The envelope of the error increases gradually with wavenumber
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