The halo mass function in clustering dark energy models as a tool versus the σ_8 tension

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Main observables

- Two different sets of observables: late and early times
- Early times: CMB (linear physics, very well understood, precise measurements)
- Late times: clusters and galaxy clusters (non-linear physics, baryonic effects, many uncertainties)

CMB

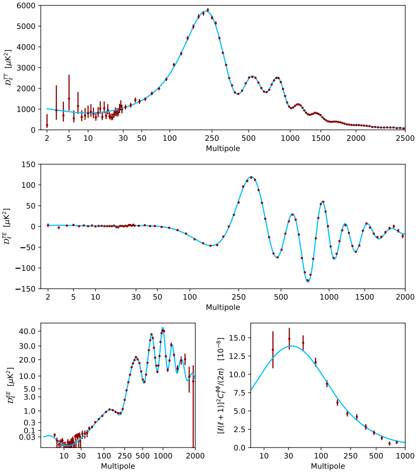
Cosmological parameters

⇓

Very accurate theoretical model and predictions

⇓

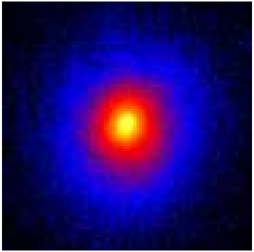
Parameter constraints

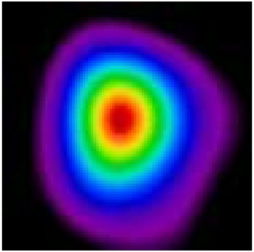


Courtesy of https://www.cosmos.esa.int, Planck2018 results

Cosmology from clusters

- Largest gravitationally bound objects in the Universe
- Highly sensitive to cosmology
- Strong dependence on $\Omega_{\rm m}$ and σ_8
- Look for them with SZ effect, X-ray emission, Optical
- Two key ingredients: mass and mass function (based on *N*-body simulations)
- Mass is tricky (scaling relations, bias, halo shape, . . .)
- Relatively high uncertainties with the mass function

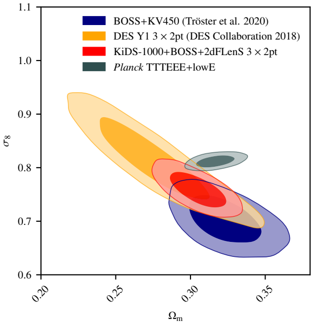




Allen et al., 2011

Anomalies & Tensions

- H_0 with local measurements
- S_8 (σ_8) with cosmic shear data ←
- $A_{\rm lens}$
- $\Omega_K \neq 0$



Heymans et al., 2021

The σ_8 tension

$S_8 = \sqrt{\Omega_{\rm m}/0.3}$

- 3σ discrepancy between Planck and SZ number counts
- Confirmed by many other SZ experiments
- It amounts to a factor of two in the number counts of very massive objects
- $S_8 = 0.789 \pm 0.012$ vs $S_8 = 0.834 \pm 0.016$ (Clusters vs Planck)

Proposed solutions to the σ_8 tension

- Correlation between S_8 and H_0 $\rightarrow$ need to solve them both
- Early-time solutions
  - Axion monodromy
  - (New) Early dark energy
  - Vary N_{eff}
  - Modified Recombination history
  - ...
- Late-time solutions
  - Bulk viscosity
  - Various dark energy models
  - Modified gravity models
  - **Clustering dark energy** $\leftarrow$

The halo mass function

- Number of halos per unit mass and volume at a given time
- Very sensitive to cosmology in the high-mass tail
- But there are strong uncertainties in its theoretical formulation
- Baryons usually neglected, but they are very important
- Its determination from observations is model dependent → we need local measurements
- Accurate mass determination is very important

Cosmology dependence on the halo mass function

ST HMF

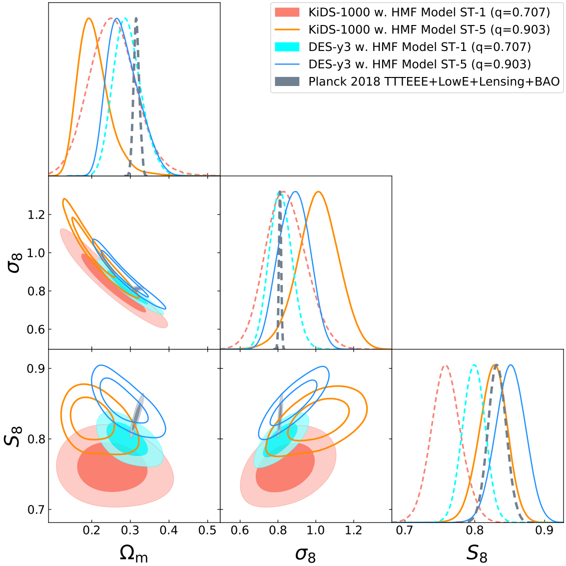
$$\frac{dn}{dM} = -\sqrt{\frac{2\tilde{a}}{\pi}} A \left[1 + \left(\tilde{a}\nu^2\right)^{-p}\right] \frac{\bar{\rho}_{\mathrm{m}}}{M^2} \nu \frac{d \ln \sigma_M}{d \ln M} \exp\left(-\frac{1}{2}\nu^2\right)$$

Mass determination

$$M(R < 1.5\,\mathrm{Mpc}/h) \propto \kappa_\Delta T_X/(1+z)$$

$$\nu = \frac{\delta_{\mathrm{c}}}{D_+ \sigma_8} \qquad \kappa_\Delta = \kappa_\Delta(\Delta_{\mathrm{Vir}}) \qquad p = 0.3\,, \quad q = 0.707$$

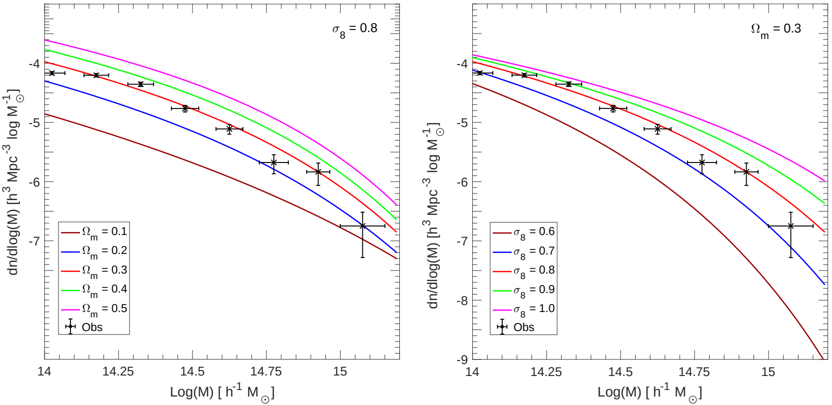
Are the ΛCDM HMF parameters not correct?



Gu et al., 2302.00780

Or is it just calibration?

$\Omega_m = 0.31$, $\sigma_8 = 0.81$ for Tinker 08



Abdullah et al., 2020

Clustering Dark Energy

- Dark energy can cluster at all scales
- Clustering dictated by the sound speed
- For fully clustering DE ($c_s^2 = 0$) $\delta_{\rm de} = \frac{1+w_{\rm de}}{1-3w_{\rm de}}\delta_{\rm m}$
- In this case, $\delta_{\rm de}$ contributes substantially to the gravitational potential
- $\delta = \delta_{\rm m} + \frac{\Omega_{\rm de}}{\Omega_{\rm m}}\delta_{\rm de}$

The equations for $c_s^2 = 0$

Continuity equation

$$\delta'_{\rm de} - 3w_{\rm de}\delta_{\rm de} + (1 + w_{\rm de} + \delta_{\rm de})\tilde{\theta} = 0$$

Euler equation

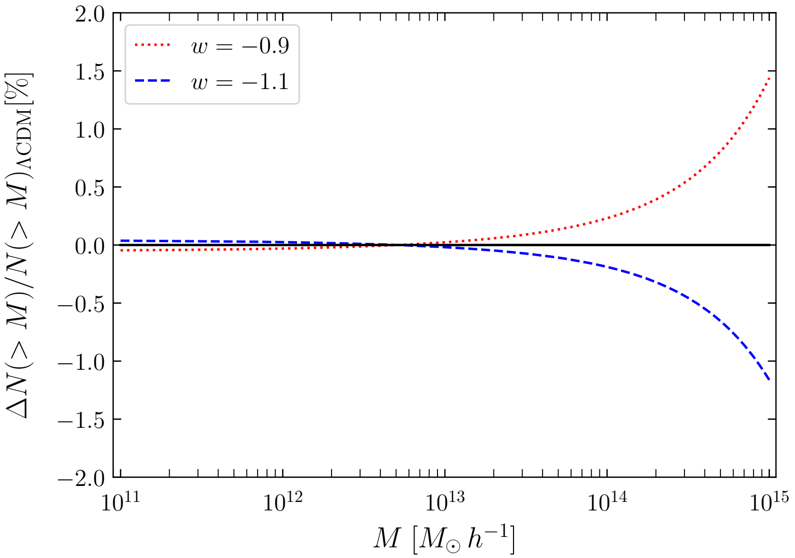
$$\tilde{\theta}' + \left(2 + \frac{H'}{H}\right)\tilde{\theta} + \frac{\tilde{\theta}^2}{3} + \frac{\nabla^2\Phi}{H^2} = 0$$

Poisson equation

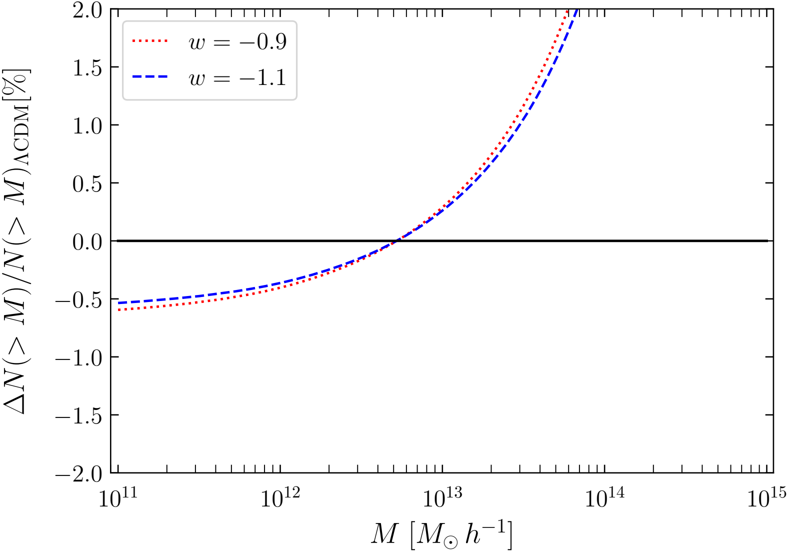
$$\nabla^2\Phi = \frac{3}{2}H^2\left(\Omega_{\rm m}\delta_{\rm m} + \Omega_{\rm de}\delta_{\rm de}\right)$$

HMF for smooth DE models

Same σ_8 of ΛCDM



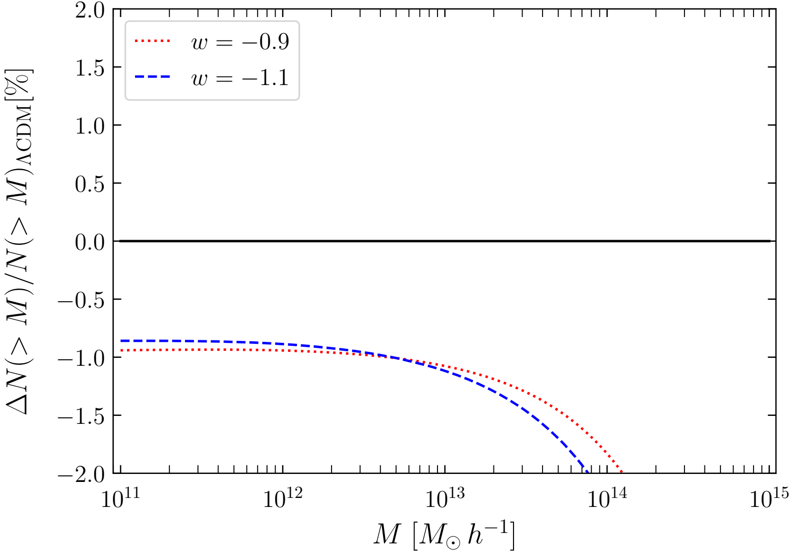
HMF for clustering DE models



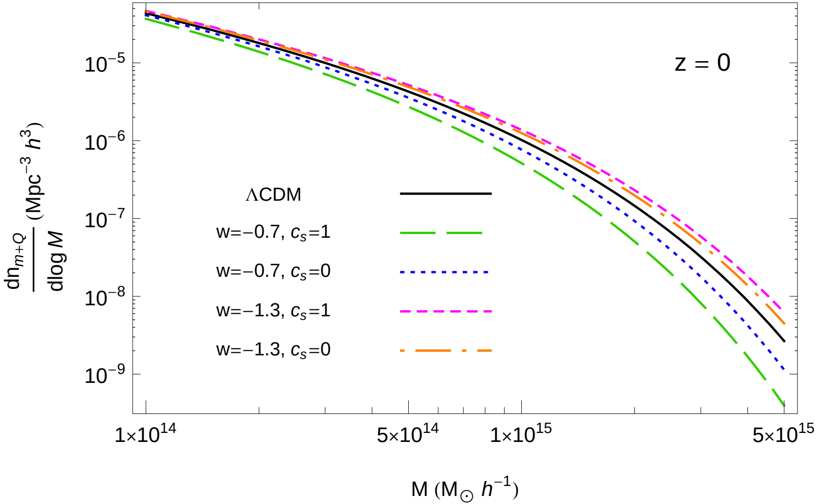
Which mass?

- When dark energy clusters, the halo mass might need to be redefined
- Usually, $M_{\rm tot} = \rho_{\rm m} + \delta\rho_{\rm de}$
- $M_{\rm tot}$ is not constant in the perturbation formalism
- Defined in analogy to the ΛCDM model
- If the mass changes, also the mass function needs to be corrected
- A couple of corrections proposed

Corrected mass in the HMF



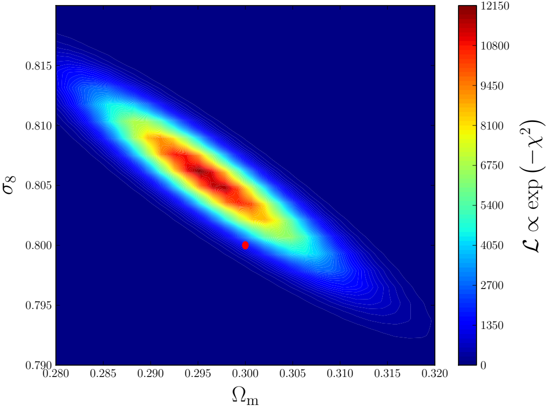
Corrected HMF



Creminelli et al. 2010

Is that all?

Fitting to a wrong theoretical model induces biases on the cosmological parameters



Reische, FP et al., 2016

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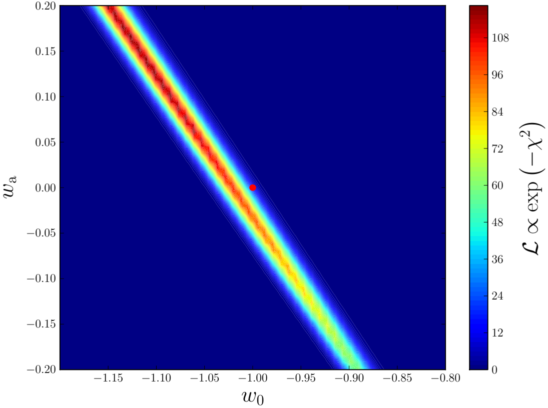
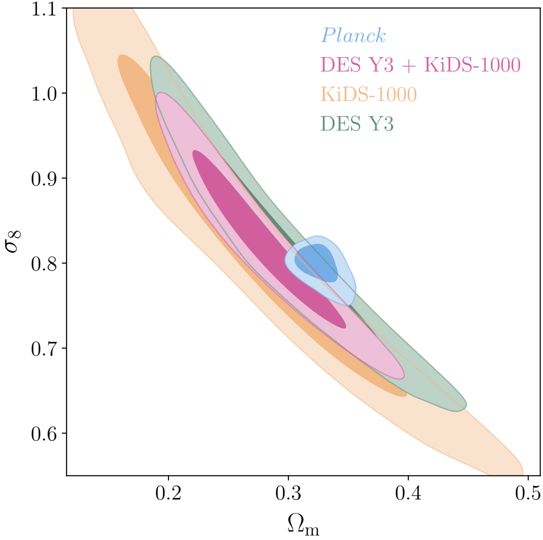


Reische, FP et al., 2016

But at the end there might no be any tension



DES Y3 + KIDS-1000, 2305.17173

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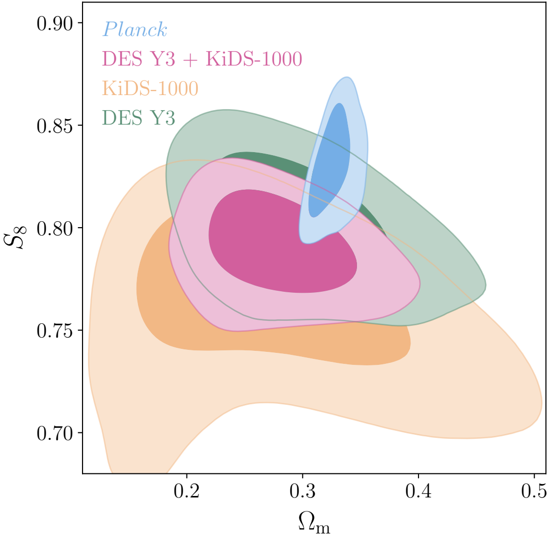

DES Y3 + KIDS-1000, 2305.17173

Conclusions and outlook

- The HMF is a very valuable cosmological tool
- It can shade light on dark energy and on tensions
- Still large error bars and theoretical uncertainties
- Care is required when used for cosmological predictions
- Need to compare and test theoretical predictions with future *N*-body simulations of clustering dark energy
- Code validation for the spherical collapse model