Credit: NASA

Impact of nonlinear prescriptions and baryonic effects on future weak lensing analyses

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ICE INSTITUT DE CIÈNCIES DE L'ESPAI

CSIC Consejo Superior de Investigaciones Científicas

IEEC

Contents

Euclid: impact of nonlinear prescriptions on cosmological parameter estimation from weak lensing cosmic shear*

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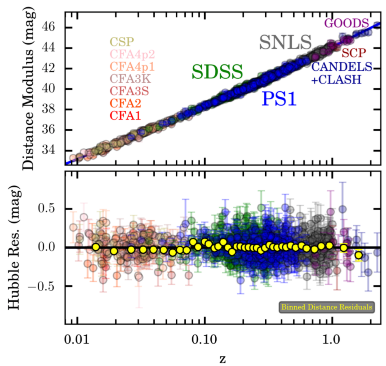
(Affiliations can be found after the references)

arXiv:2010.12382

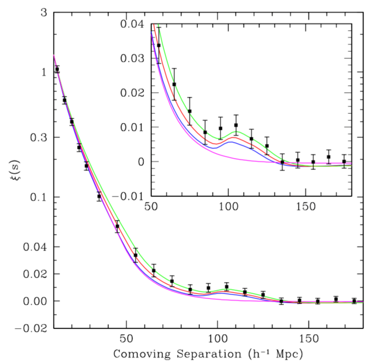
Action Dark Energy **Introduction**

- LCDM has become the concordance model thanks to its ability to fit (and predict) many different cosmological data sets:

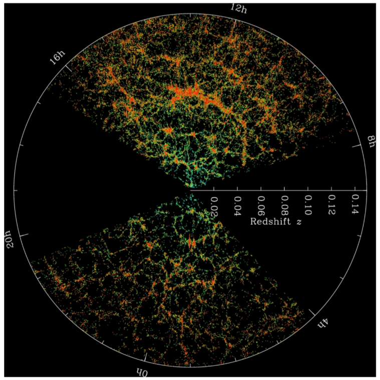
Type Ia supernovae



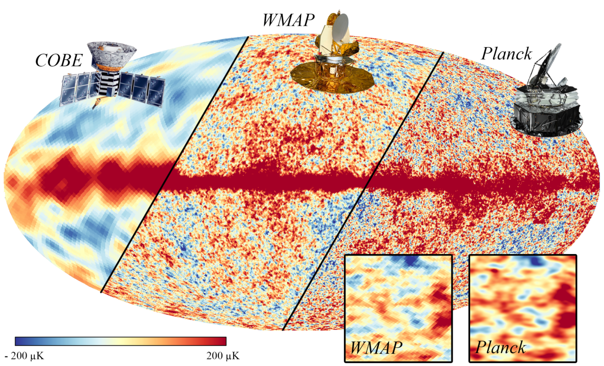
Baryon acoustic oscillations



Galaxy clustering



Cosmic microwave background



Weak lensing

I. Tutusaus | 11th March 2021

[Credit: Scolnic, Gudmundsson, Blanton, Eisenstein, Richard, SDSS, NASA, ESA]

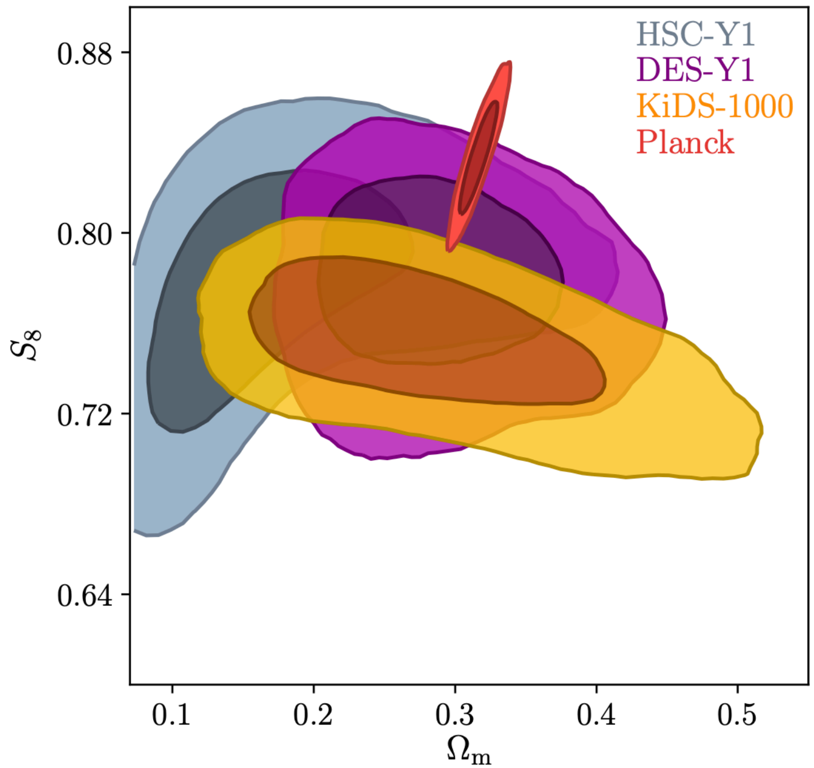
- LCDM has become the concordance model thanks to its ability to fit (and predict) many different cosmological data sets:
  - Combining probes (BAO+CMB):

Parameter	Symbol	Value
Physical baryon density	$\Omega_b h^2$	0.02242 ± 0.00014
Physical cold dark matter density	$\Omega_{cdm} h^2$	0.11933 ± 0.00091
Dimensionless Hubble constant	h	0.6766 ± 0.0042
Power spectrum amplitude	$\ln(10^{10} A_s)$	3.047 ± 0.014
Power spectrum slope	n_s	0.9665 ± 0.0038
Re-ionization optical depth	τ	0.0561 ± 0.0071
CMB temperature	T_{CMB} [K]	2.72548 ± 0.00057

[Planck Collaboration 2018]

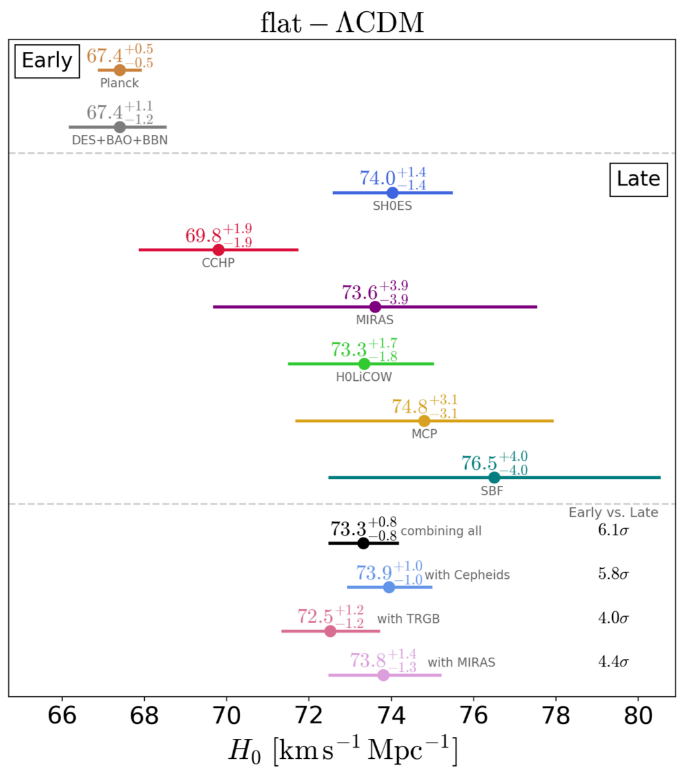
- However, some tensions start to appear between different data sets within the LCDM framework:
  - Tension on σ_8 from CMB and WL measurements

$$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$$



[Asgari et al. 2020]

- However, some tensions start to appear between different data sets within the LCDM framework:
  - Tension on H_0 from direct and derived measurements.



[Verde et al. 2019]

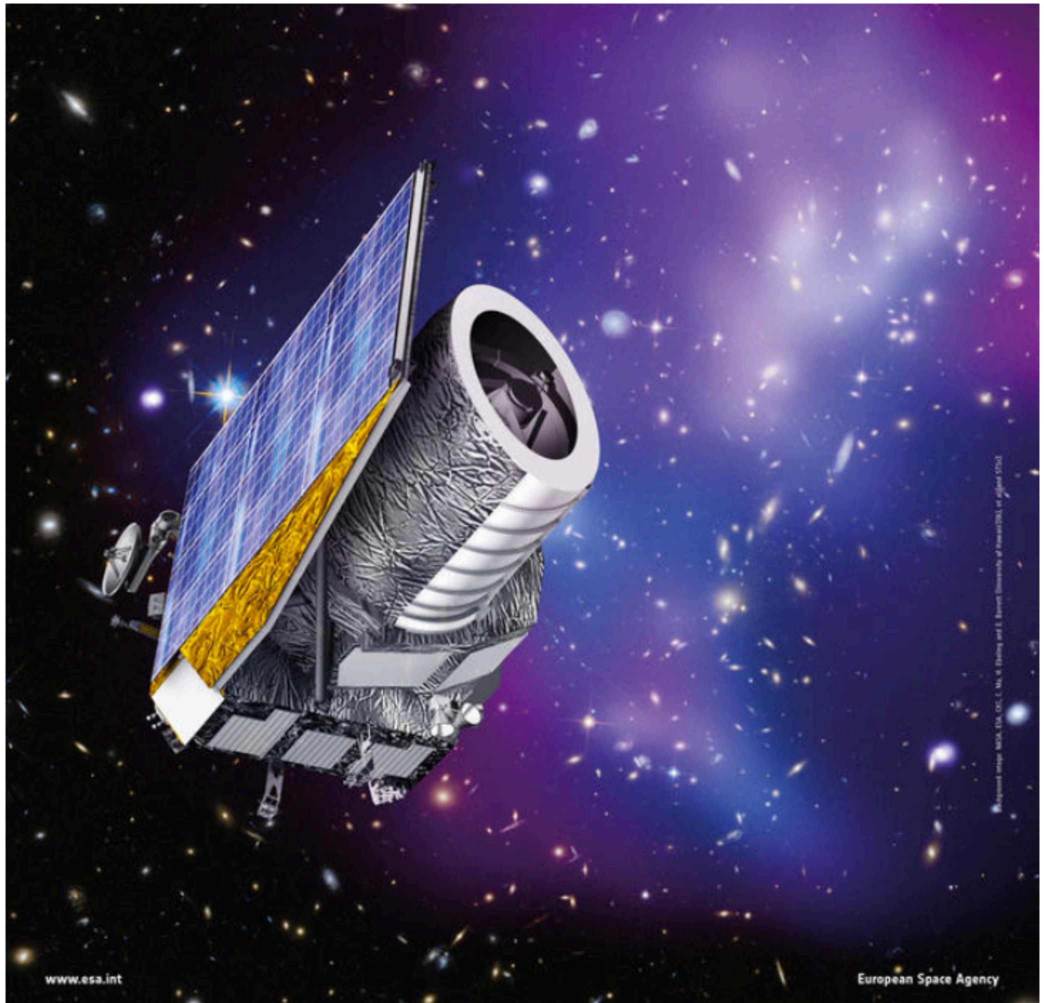
- And the nature of ~95% of the energy content of the Universe remains still unknown.

- We need more precise measurements to test models beyond LCDM:
  - Simple example: parametrize dark energy with an effective fluid with equation of state:

$$p = w\rho \quad \Rightarrow \quad w(z) = w_0 + w_a \frac{z}{1+z}$$

[Chevallier & Polarski 2001; Linder 2003]

Action Dark Energy The Euclid mission



Action Dark Energy The Euclid mission

Phot. clustering (GCp)
1.5×10^9 gal.
$z \in [0, 2.5]$

Weak lensing (WL)
1.5×10^9 gal.
$z \in [0, 2.5]$

Spec. clustering (GCs)
5×10^7 gal.
$z \in [0.9, 1.8]$

The Euclid Mission: baseline and options Euclid Consortium

SURVEYS In ~5.5 years

	Area (deg2)	Description
Wide Survey	**15,000 deg²**	Step and stare with 4 dither pointings per step.
Deep Survey	**40 deg²**	In at least 2 patches of > 10 deg² 2 magnitudes deeper than wide survey

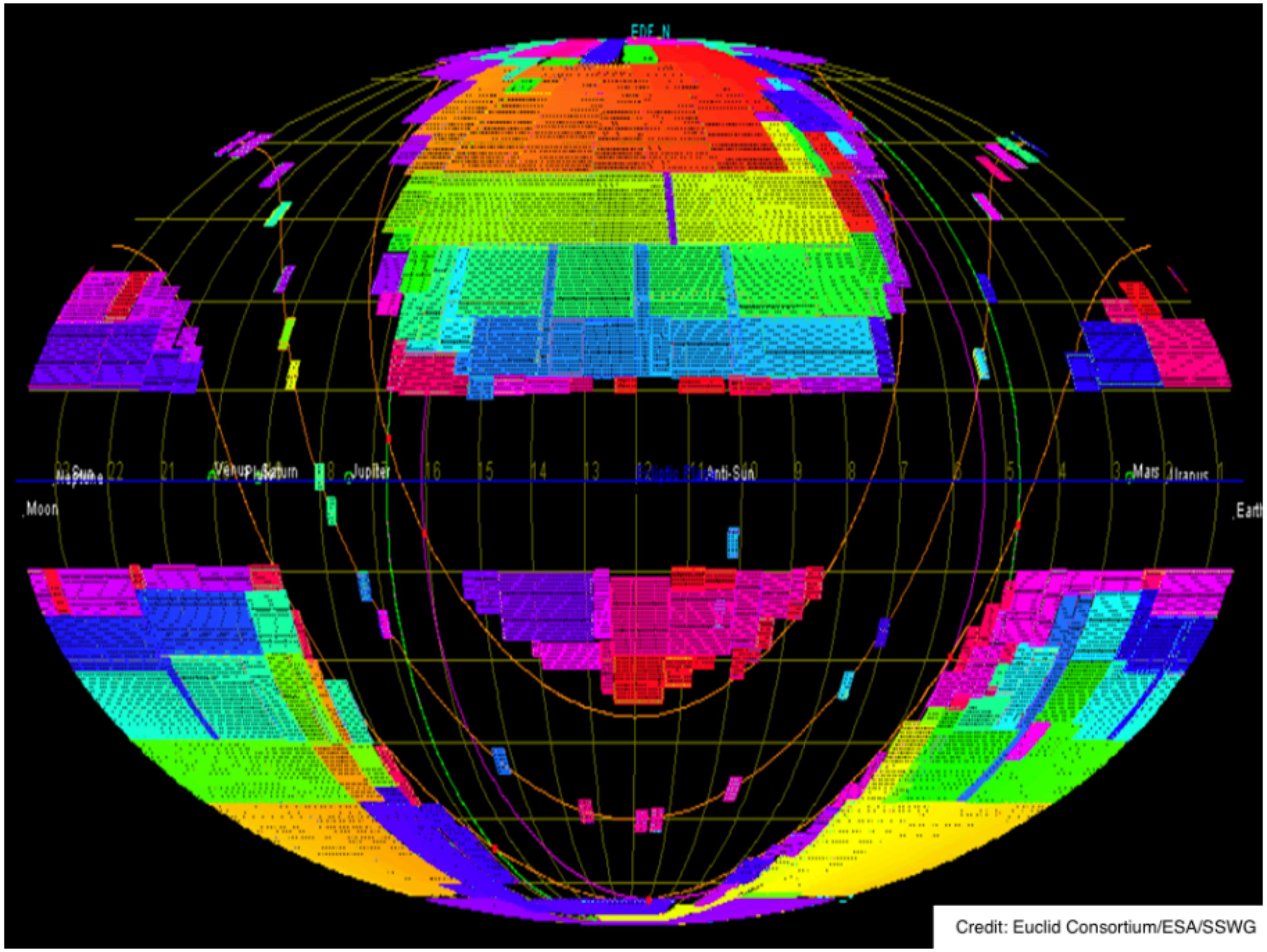
PAYLOAD

Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg²	0.763×0.722 deg²			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	3 10^{-16} erg cm-2 s-1 3.5σ unresolved line flux
	Shapes + Photo-z of $n = 1.5 \times 10^9$ galaxies				z of $n=5 \times 10^7$ galaxies
Detector Technology	36 arrays 4k×4k CCD	16 arrays 2k×2k NIR sensitive HgCdTe detectors			
Pixel Size Spectral resolution	0.1 arcsec	0.3 arcsec			0.3 arcsec R=250

Possibility other surveys: SN and/or µ-lens surveys, Milky Way ?

Ref: Euclid RB arXiv:1110.3193

The Euclid mission

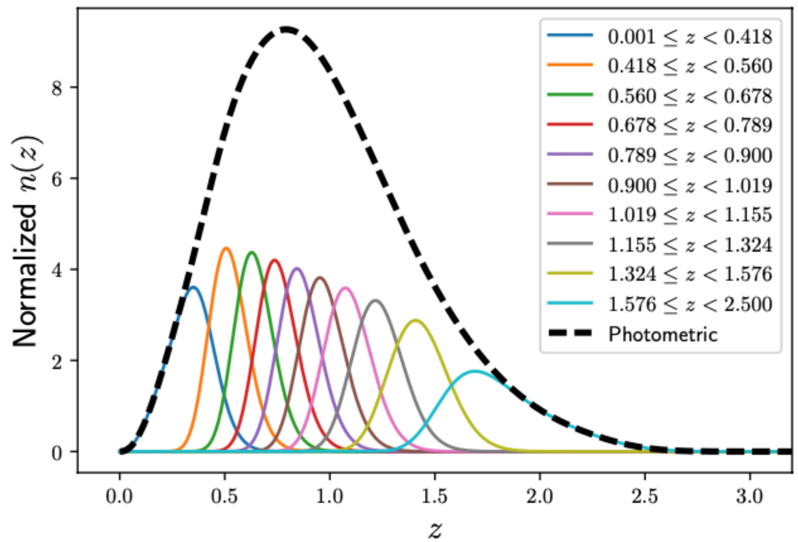


Credit: Euclid Consortium/ESA/SSWG

The Euclid mission

- Euclid will probe **scales** and **redshifts** currently inaccessible.
- However, we need an **accurate modeling** of the large-scale structure of the Universe in order **not to bias** our cosmological analyses.
- **Question**: Given our current knowledge on the modeling, how significant could be the changes in the results for Euclid cosmic shear analyses?

- Euclid cosmic shear forecasts:
  - Fisher matrix (and MCMC) forecasts based on Euclid Collaboration: Blanchard et al. 2020 recipe.
  - Redshift distribution of sources: $n(z) \propto \left(\frac{z}{z_0}\right)^2 \exp\left[-\left(\frac{z}{z_0}\right)^{3/2}\right]$
  - convolved with 2 Gaussian distributions for photo-zs.
  - 10 tomographic bins between z=0 and 2.5. 30 gal/arcmin^2.



- Euclid cosmic shear forecasts:
  - Observable:

$$C_{ij}^{\epsilon\epsilon}(\ell) = c \int \mathrm{d}z \, \frac{W_i^{\epsilon}(z) W_j^{\epsilon}(z)}{H(z) r^2(z)} P_{\delta\delta} \left[\frac{\ell + 1/2}{r(z)}, z \right]$$

  - with IA given by:

$$W_i^{\epsilon}(z) = W_i^{\gamma}(z) - \frac{\mathcal{A}_{\rm IA} \mathcal{C}_{\rm IA} \Omega_{\rm m,0} \mathcal{F}_{\rm IA}(z) H(z) n_i(z)}{D(z) c}, \qquad \mathcal{F}_{\rm IA}(z) = (1+z)^{\eta_{\rm IA}} \left[\langle L \rangle (z) / L_\star(z) \right]^{\beta_{\rm IA}}$$

  - and a Gaussian covariance:

$$\begin{aligned} \mathrm{Cov}(C_{ij}^{\rm AB}(\ell), C_{kl}^{\rm A'B'}(\ell')) = & \frac{\delta^{\rm K}_{\ell\ell'}}{(2\ell+1) f_{\rm sky} \Delta\ell} \times \\ & \times \left[\left(C_{ik}^{\rm AA'}(\ell) + N_{ik}^{\rm AA'}(\ell) \right) \cdot \left(C_{jl}^{\rm BB'}(\ell) + N_{jl}^{\rm BB'}(\ell) \right) \right. \\ & \left. + \left(C_{il}^{\rm AB'}(\ell) + N_{il}^{\rm AB'}(\ell) \right) \cdot \left(C_{jk}^{\rm BA'}(\ell) + N_{jk}^{\rm BA'}(\ell) \right) \right] \end{aligned}$$

Modeling of matter

- Much of the cosmic shear constraining power comes from small scales (k~7 h/Mpc).
- Matter density field perturbations are no longer small, so we cannot use linear theory to predict the large-scale structure.
- Option 1: Extend the linear theory (e.g. perturbation theory).
  - It works until $k < 0.3$ h/Mpc (mildly nonlinear regime). OK for GC analyses. Not enough for WL.
- Option 2: Use N-body simulations (highly nonlinear regime). OK for WL. Not precise enough for GC.
  - N-body simulations + fitting function.
  - N-body simulations + emulators.

Modeling of matter

- N-body simulations + fitting function:
  - Run several N-body simulations (large volume and low particle mass) in different points of the parameter space.
  - Compute the power spectrum of matter for each simulation.
  - Fit a fitting function with several free parameters to match the spectra.
  - E.g. Halofit, Halofit+PKEqual, HMCode.

Modeling of matter

- N-body simulations + fitting function:
  - Halofit:
    - One of the first widely used [Smith et al. 2003].
    - Fitting function based on the halo model [Peacock & Smith 2000; Seljak 2000; Ma & Fry 2000] — density field described by isolated dark matter haloes:

$$P_{\rm NL}(k) = P_{\rm Q}(k) + P_{\rm H}(k)\,,$$

    - Proposal [Seljak 2000; Ma & Fry 2000; Scoccimarro et al. 2001]:

$$P_{\rm Q}(k) = P_{\rm L}(k)\left[\frac{1}{\bar{\rho}}\int {\rm d}M\, b_{\rm H}(M) n(M) \tilde{\rho}(k,M)\right]^2\,,$$

halo bias — halo distribution — halo density profile

Modeling of matter

- N-body simulations + fitting function:
  - Halofit:
    - Simpler approach [Peacock & Smith 2000; Smith et al. 2003]:

$$\Delta^2(k) \equiv \frac{k^3}{2\pi^2} P(k)\,, \qquad \Delta_{\mathrm{Q}}^2(k) = \Delta_{\mathrm{L}}^2(k) \frac{[1+\Delta_{\mathrm{L}}^2(k)]^{\beta_n}}{1+\alpha_n \Delta_{\mathrm{L}}^2(k)}\, \mathrm{e}^{-f(y)}\,,$$

    - 1-halo term:

$$P_{\mathrm{H}}(k) = \frac{1}{\bar{\rho}^2 (2\pi)^3} \int \mathrm{d}M\, n(M) |\tilde{\rho}(k, M)|^2$$

    - Modeled as shot-noise at large scales and vanishing at small scales [Smith et al. 2003]:

$$\Delta_{\mathrm{H}}^2(k) = \frac{\Delta_{\mathrm{H}}^{2\,\prime}(k)}{1+\mu_n y^{-1} + \nu_n y^{-2}}$$

    - But the simulations used did not include massive neutrinos.

Modeling of matter

- N-body simulations + fitting function:
  - Halofit with Bird and Takahashi corrections:
    - One of the most used nowadays [Smith et al. 2003; Bird et al. 2012; Takahashi et al. 2012].
    - Bird: corrections to the fitting function to include massive neutrinos.
    - Takahashi: update of the fitting function parameters with new (and better) simulations.
    - But the simulations used did not include evolving dark energy (only w0).
    - I will refer to this model as Halofit in the following.

Modeling of matter

- N-body simulations + fitting function:
  - Halofit with PKequal [Casarini et al. 2016]:
    - To account for an evolving dark energy equation of state we can run more simulations or map the nonlinear spectra of constant dark energy models to those with evolving dark energy.
    - PKequal does this mapping imposing the equivalence of the distance to the CMB and requiring that the density fluctuation amplitudes are the same. For each w0, wa, and z there is a unique w_eq and sigma8_eq.

Modeling of matter

- N-body simulations + fitting function:
  - HMCode [Mead et al. 2015; 2016; 2020]:
    - Physically-motivated free parameters into the halo model formalism.
    - New simulations.
    - Can account for baryonic effects (not considered in the following).
    - Accounts for massive neutrinos and evolving dark energy (2016; 2020).
    - One of the most used nowadays.

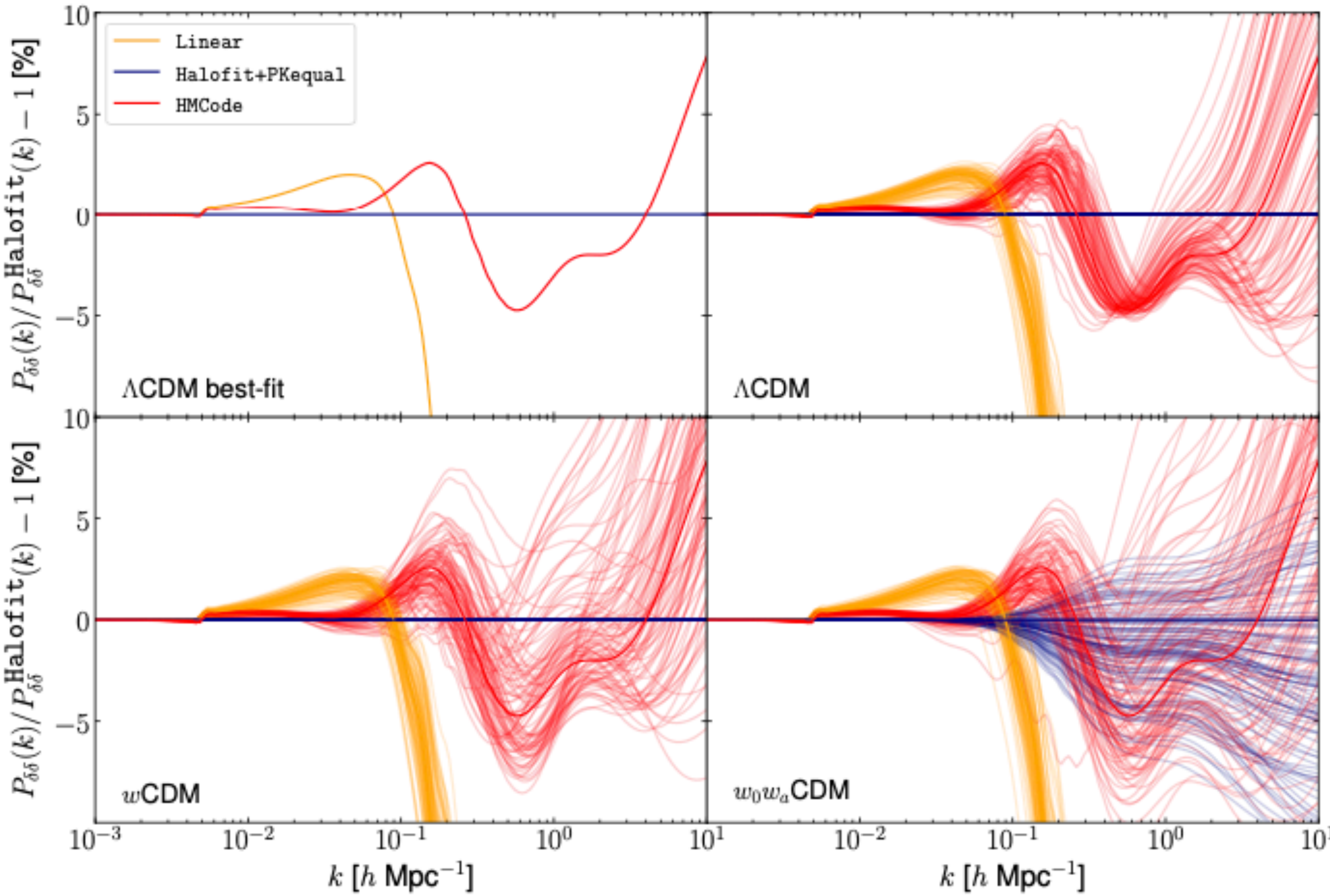
Modeling of matter

- N-body simulations + fitting function

- N-body simulations + emulators:
  - Run several N-body simulations (large volume and low particle mass) in different points of the parameter space.
  - Compute the power spectrum of matter for each simulation.
  - Interpolate the different spectra.
  - It does not degrade the accuracy of the corrections over the parameter space, nor the redshift and scale ranges.
  - E.g. Coyote [Heitmann et al. 2009; 2010; 2014; Lawrence et al. 2010], Euclid Emulator [Knabenhans et al. 2019; 2020], BACCO [Angulo et al. 2020]

Action Dark Energy Modeling of matter

- Nonlinear matter prescriptions considered:



Action Dark Energy **Modeling of matter**

- Impact of nonlinear corrections on forecast constraints:
  - Fisher matrix analyses for Euclid WL following Euclid Collaboration: Blanchard et al. 2020
  - Figure-of-merit:

$$\mathrm{FoM} = \sqrt{\det \tilde{\mathrm{F}}_{w_0 w_a}},$$

pessimistic

optimistic

$\ell_{\rm max}$	Halofit	HMCode	Halofit+PKequal
1500	23	14	19
5000	44	34	36

  - Up to 60% change in constraining power because of the nonlinear matter modeling.

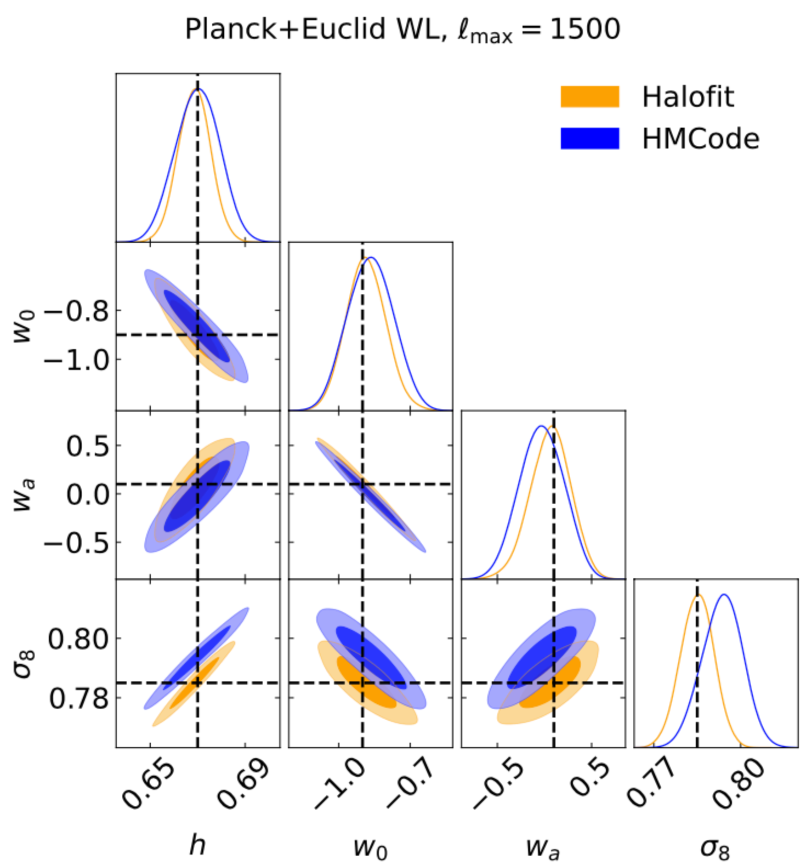
Modeling of matter

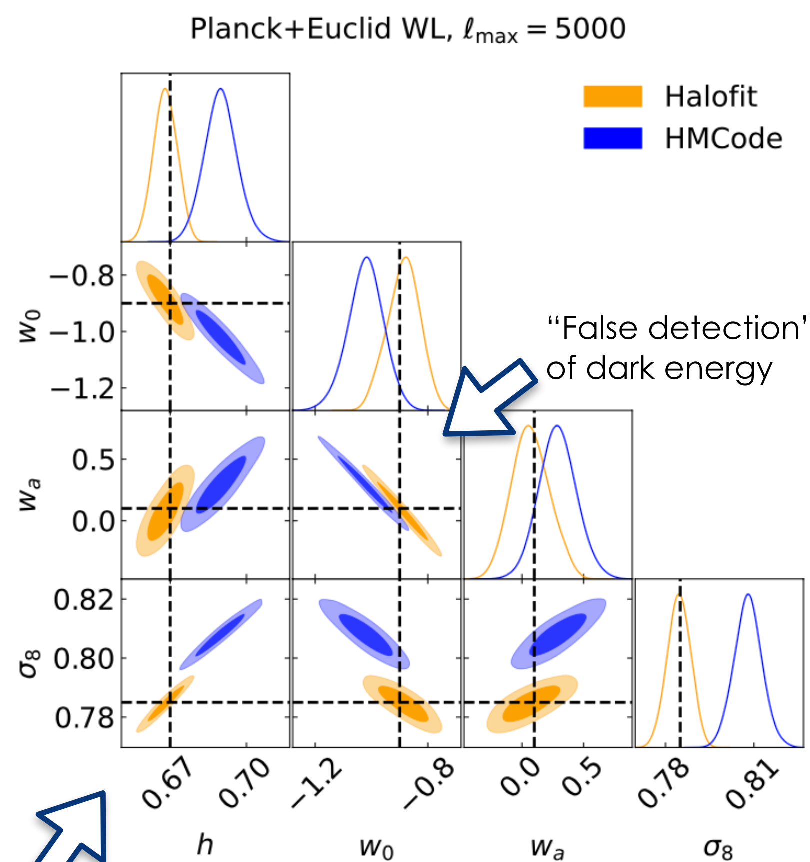
- What happens if the Universe does not follow our exact model?
  - Assume the true Universe is given by Halofit+PKequal.
  - Perform our cosmological analyses (MCMC parameter estimation) with other models.
  - Fiducial cosmology not LCDM.
  - Add the TT, TE, EE, and lensing data from a mock Planck likelihood.
  - Compute the biases on cosmological parameters with respect to the fiducial cosmology:

$$B(\theta) = \frac{|\theta^{\star} - \theta^{\rm fid}|}{\sigma},$$

Action Dark Energy **Modeling of matter**

- What happens if the Universe does not follow our exact model?





"False detection" of dark energy

H0 and S8 tensions

Action Dark Energy Modeling of matter

- What happens if the Universe does not follow our exact model?

θ	ℓ_{max}	Halofit $\theta^\star$	Halofit σ	Halofit B	HMCode $\theta^\star$	HMCode σ	HMCode B
$\omega_{b,0}$	1500	0.02244	0.00011	0.08	0.02240	0.00012	0.43
	5000	0.02243	0.00012	0.15	0.02246	0.00012	0.05
$\omega_{c,0}$	1500	0.12056	0.00036	0	0.12101	0.00039	1.16
	5000	0.12054	0.00038	0.053	0.12112	0.00036	1.57
h	1500	0.6689	0.0069	0.16	0.6702	0.0096	0.02
	5000	0.6683	0.0048	0.36	0.6899	0.0066	3.02
$\ln(10^{10}A_s)$	1500	3.0591	0.0086	0.09	3.0657	0.0088	0.84
	5000	3.0593	0.0090	0.10	3.0656	0.0086	0.85
n_s	1500	0.9602	0.0025	0.06	0.9615	0.0027	0.57
	5000	0.9604	0.0023	0.18	0.9556	0.0023	1.90
w_0	1500	−0.888	0.085	0.14	−0.869	0.099	0.31
	5000	−0.888	0.060	0.21	−1.021	0.064	1.88
w_a	1500	0.07	0.21	0.14	−0.02	0.25	0.50
	5000	0.07	0.16	0.16	0.29	0.16	1.22
$\Omega_{m,0}$	1500	0.3212	0.0065	0.18	0.3209	0.0090	0.10
	5000	0.32164	0.0046	0.36	0.3031	0.0057	2.96
σ_8	1500	0.7852	0.0058	0.14	0.7938	0.0071	1.09
	5000	0.7847	0.0041	0.30	0.8080	0.0048	4.62
$\Delta\chi^2$	1500		0.60			32.04	
	5000		1.06			62.34	

Threshold < 0.1

Baryonic effects

- But WL probes the very small scales (highly nonlinear):
  - Baryons collapse into the dark matter halos to form stars, or are heated up, or expelled into the intergalactic medium.
  - Baryonic processes modify the matter power spectrum at small scales: suppression due to AGN feedback (k = 3 - 13 h/Mpc) and boost due to stars (k > 15 h/Mpc).
- Approach: modify the nonlinear matter power spectrum with a correction factor accounting for baryons:

$$P_{\mathrm{c+b}}(k,z) = P_{\delta\delta}(k,z)\mathcal{B}(k,z)\,,$$

  - Can be estimated from hydrodynamical simulations including baryons.
  - No clear way (yet) to incorporate baryonic effects into cosmological simulations from first principles. It leads to several baryonic corrections depending on the baryonic recipe used.

Baryonic effects

- Approach: modify the nonlinear matter power spectrum with a correction factor accounting for baryons:

$$P_{\mathrm{c+b}}(k,z) = P_{\delta\delta}(k,z)\mathcal{B}(k,z)\,,$$

- Examples: Harnois-Déraps et al. 2015 — HD15
  - Based on 3 scenarios of the Over-Whelmingly Large hydrodynamical simulations [Schaye et al. 2010]
  - Accuracy better than 2% for k < 1h/Mpc and z < 1.5

$$\mathcal{B}(k,z) = 1 - A_{\mathrm{HD15}}(z)\,\exp\left\{\left[B_{\mathrm{HD15}}(z)\,x(k) - C_{\mathrm{HD15}}(z)\right]^3\right\} + D_{\mathrm{HD15}}(z)\,x(k)\,\exp\left[E_{\mathrm{HD15}}(z)\,x(k)\right]\,,$$

  - with $x(k) \equiv \log_{10}(k/[h\,\mathrm{Mpc}^{-1}])$ and $X_{\mathrm{HD15}}(z)$ are polynomials.

Action Dark Energy **Baryonic effects**

- Approach: modify the nonlinear matter power spectrum with a correction factor accounting for baryons:

$$P_{\mathrm{c+b}}(k,z) = P_{\delta\delta}(k,z)\mathcal{B}(k,z)\,,$$

  - Examples: Schneider & Teyssier 2015 — ST15
    - DM-only N-body simulations with density field modifications to mimic a baryonic feedback recipe.
    - Explicitly modeling halos, hot gas in hydrostatic equilibrium, ejected gas and stars.
    - Model parameters set to resemble SZ and X-ray observations.

$$\mathcal{B}(k,z) = \frac{1+(k/k_{\mathrm{s}})^2}{[1+k/k_{\mathrm{g}}(z)]^3}\mathcal{G}(z) + \left[1+(k/k_{\mathrm{s}})^2\right]\left[1-\mathcal{G}(z)\right],$$

    - Model parameters updated to the best fitting values obtained with the more recent Horizon-AGN simulations [Chisari et al. 2018].

Baryonic effects

- Approach: modify the nonlinear matter power spectrum with a correction factor accounting for baryons:

$$P_{\mathrm{c+b}}(k,z) = P_{\delta\delta}(k,z)\mathcal{B}(k,z)\,,$$

  - Examples: Chisari et al. 2018 — CH18
    - ST15 performs well at low redshift, but its accuracy degrades at high redshift.
    - New proposal fitting the Horizon-AGN simulations:

$$\mathcal{B}(k,z) = \frac{[1 + k/k_{\mathrm{s}}(z)]^2}{[1 + k/k_{\mathrm{s}}(z)]^{1.39}}$$

Baryonic effects

- Impact of baryonic corrections on forecast constraints:

  - Fisher matrix analyses for Euclid WL following Euclid Collaboration: Blanchard et al. 2020
  - Figure-of-merit:

$$\mathrm{FoM} = \sqrt{\det \tilde{\mathsf{F}}_{w_0 w_a}},$$

pessimistic → 1500; optimistic → 5000

$\ell_{\max}$	Halofit	HD15	ST15	Ch18
1500	23	22	21	22
5000	44	37	41	41

  - No significant change in constraining power because of the baryonic correction.

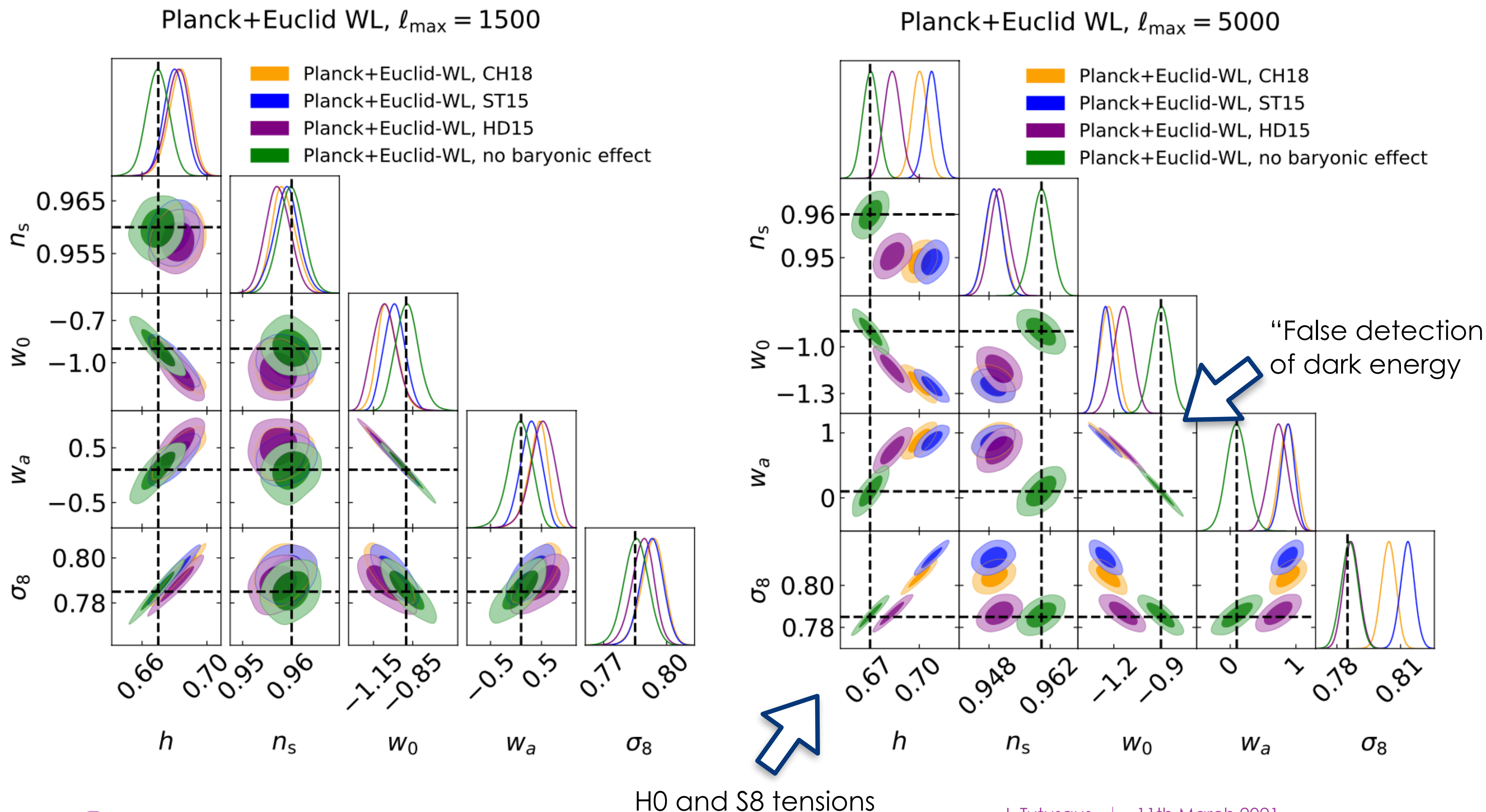
Baryonic effects

- What happens if baryons do not follow our exact model? Or if we do not include them?
  - Assume the true Universe have no baryons.
  - Perform our cosmological analyses (MCMC parameter estimation) with different baryonic models.
  - Fiducial cosmology not LCDM.
  - Add the TT, TE, EE, and lensing data from a mock Planck likelihood.
  - Compute the biases on cosmological parameters with respect to the fiducial cosmology:

$$B(\theta) = \frac{|\theta^{\star} - \theta^{\rm fid}|}{\sigma},$$

Action Dark Energy **Baryonic effects**

- What happens with baryons?



Action Dark Energy **Baryonic effects**

- What happens with baryons?

Threshold < 0.1

θ	$\ell_{\rm max}$	CH18 $\theta^\star$	CH18 σ	CH18 B	ST15 $\theta^\star$	ST15 σ	ST15 B	HD15 $\theta^\star$	HD15 σ	HD15 B
$\omega_{\rm b,0}$	1500	0.2246	0.00011	0.09	0.2245	0.00012	0.00	0.02249	0.00012	0.34
	5000	0.02251	0.00012	0.51	0.02252	0.00012	0.64	0.02252	0.00012	0.56
$\omega_{\rm c,0}$	1500	0.12061	0.00035	0.15	0.12059	0.00036	0.08	0.12044	0.00040	0.30
	5000	0.12109	0.00036	1.49	0.12110	0.00037	1.46	0.12083	0.00036	0.76
h	1500	0.6833	0.0069	1.92	0.6799	0.0065	1.52	0.6819	0.0069	1.73
	5000	0.6990	0.0041	7.15	0.7069	0.0041	9.11	0.6835	0.0045	2.99
$\ln(10^{10}A_{\rm s})$	1500	3.0571	0.0087	0.14	3.0590	0.0083	0.07	3.0578	0.0084	0.07
	5000	3.0644	0.0083	0.73	3.0679	0.0087	1.10	3.0592	0.0083	0.10
$n_{\rm s}$	1500	0.9583	0.0024	0.68	0.9589	0.0025	0.42	0.9572	0.0025	1.11
	5000	0.9489	0.0020	5.49	0.9488	0.0021	5.44	0.9503	0.0021	4.69
w_0	1500	−1.040	0.078	1.79	−0.990	0.078	1.16	−1.063	0.092	1.77
	5000	−1.220	0.039	8.22	−1.240	0.040	8.43	−1.142	0.053	4.55
w_a	1500	0.43	0.19	1.68	0.30	0.20	0.98	0.51	0.23	1.78
	5000	0.84	0.09	8.27	0.84	0.10	7.70	0.73	0.13	5.04
$\Delta\chi^2$	1500		6.35			3.94			11.54	
	5000		63.61			107.32			45.05	

Action Dark Energy **Conclusions**

- LCDM provides an excellent fit to the data, but some tensions start to appear and the nature of its components remains unknown.
- We need to test other models with new data, but it requires a proper modeling of the small scales.
- Given the scales we would like to probe with Euclid, and the discrepancies between the current nonlinear matter models, we expect significant changes in the results.
- Neglecting baryonic effects in Euclid will not change significantly the constraining power, but it will severely bias the results.
- A wrong model of nonlinearities can influence the H0 and S8 tensions and could lead us to a false detection of dark energy!
- Significant effort will be needed to properly model the scales Euclid will probe.