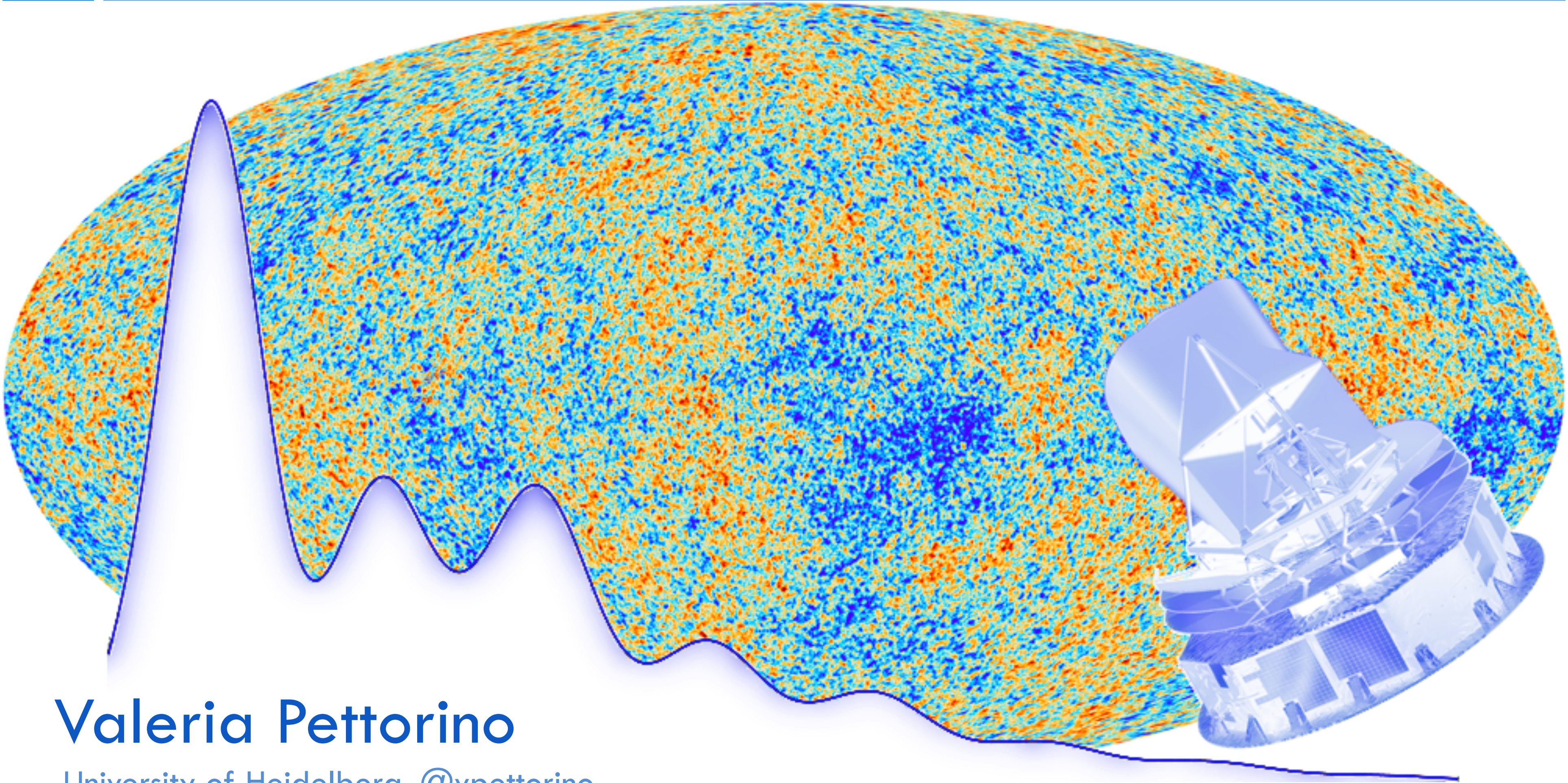
Planck 2014 results:
Dark Energy and Modified Gravity



Valeria Pettorino
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on behalf of the Planck collaboration

CMB as a probe for DE and MG

Even if background is LCDM, perturbations can be different.
CMB is a clean probe, important to test DE and MG models:

- Expansion and distance to last scattering
- Damping tail
- Ratio between 1^{st} and 3^{rd} peak
- Lensing potential
- Polarization and B modes

We present the state of the art after Planck.
Natural continuation of the parameter paper.

Warnings

General difficulties encountered:

1. Theoretical models: no agreement on a well defined set of theories yet in the community
2. Numerical codes: no agreement yet on well tested set of codes in the Dark Energy community
3. Data: need to be careful about possible systematics or impact of non-linear physics, for which we don't know how the theory behaves.

Dark Energy is not in the era of precision cosmology yet!

Models and parametrizations

Includes:

Background parametrizations

a. w expansion and PCA
b. Early Dark Energy
c. Generic potentials

Perturbation parametrizations

a. Effective Field Theory (EFT)
b. Gravitational potentials

Examples of particular models

a. Universal couplings
b. Non universal couplings

Data

Planck baseline: Planck TT + low-ℓ Polarization

Data

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Planck
Planck + BSH

Useful to test the background:

BSH: BAO + SNe + H_0

BAO:
- SDSS Main Galaxy Sample (Ross et al 2014)
- BOSS Lowz and CMASS samples (Anderson et al 2014)
- 6dFGS (Beutler etal 2011)

SNe:
- Joint Light-curve Analysis, JLA (Betoule et al 2013)

H_0:
- Conservative prior (70.6 ±3.3 km/s/Mpc) Efstathiou 2014

Data

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Useful to test the background:
BSH: BAO + SNe + H_0

Useful to test perturbations:
RSD: Redshift Space Distortions (BOSS DR11, Samushia etal 2014)
WL: Weak Lensing (CFHTLens, Kilbinger etal 2013, Heymans etal 2013 + ultraconservative cut of non-linear scales)

Planck
Planck + BSH
Planck + WL
Planck + RSD
Planck + WL + RSD

Data

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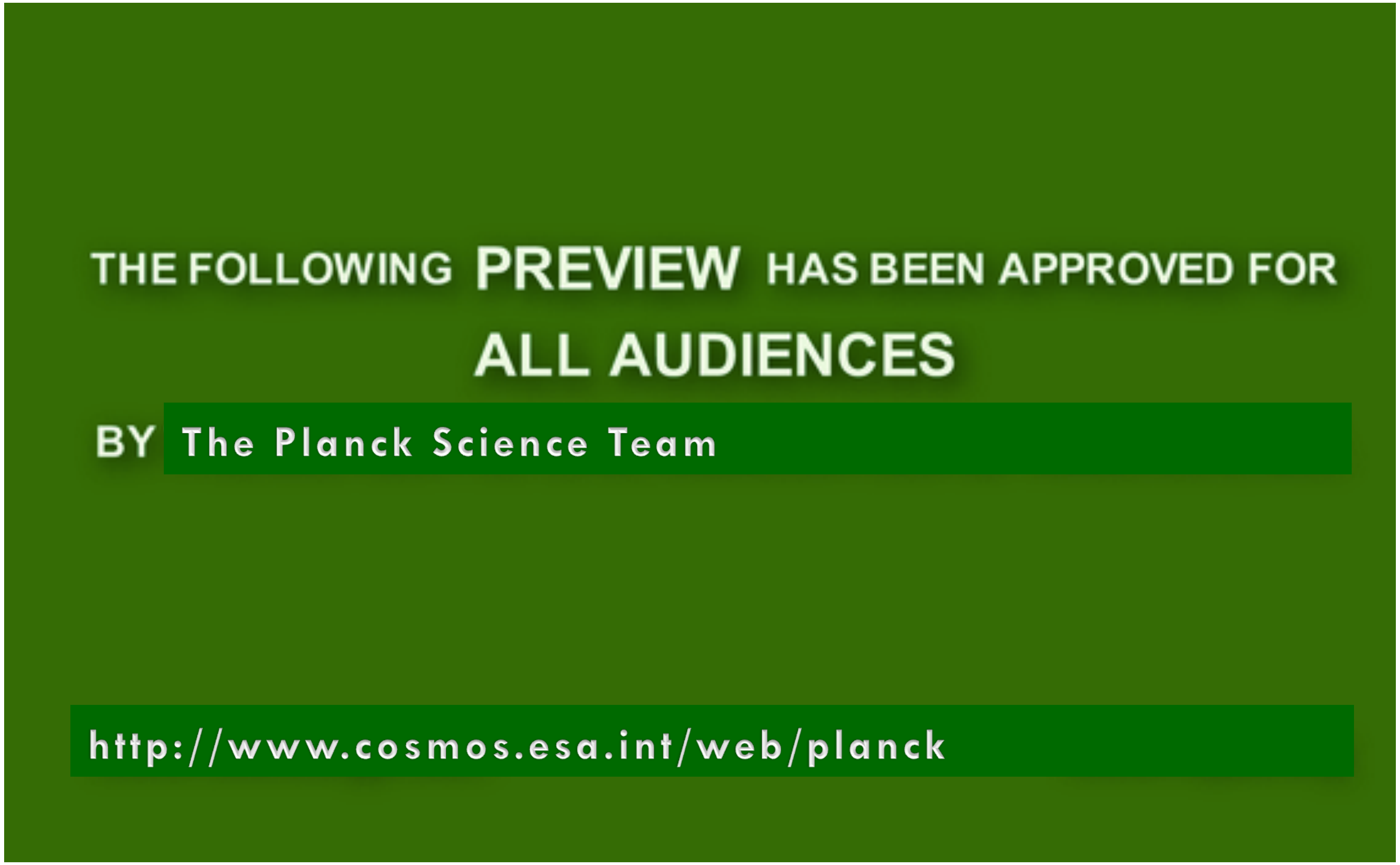
CMB lensing and TT TE EE polarization

Planck
Planck + BSH
Planck + WL
Planck + RSD
Planck + WL + RSD

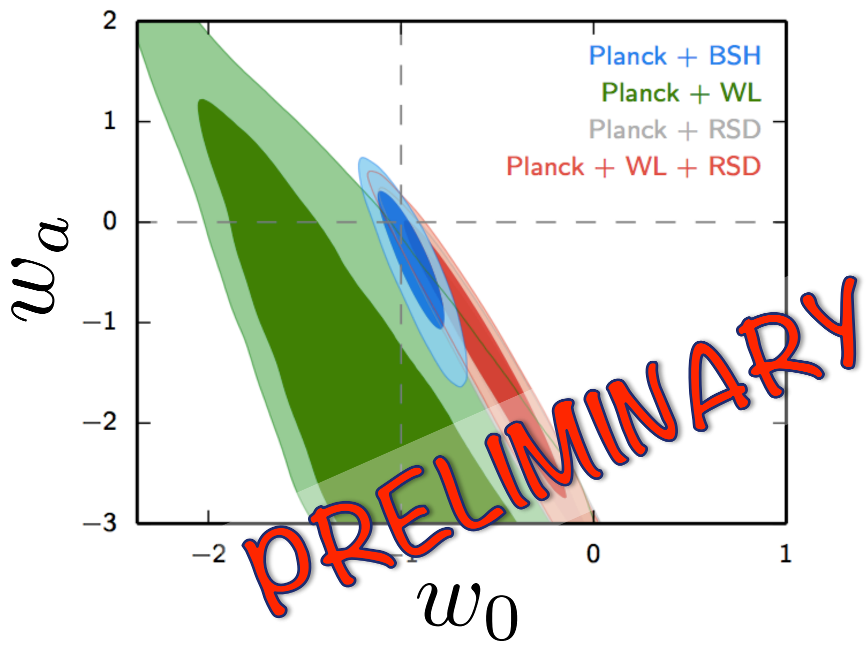
Trailer of the results



Results: equation of state

$$w(a) = w_0 + (1 - a)w_a$$

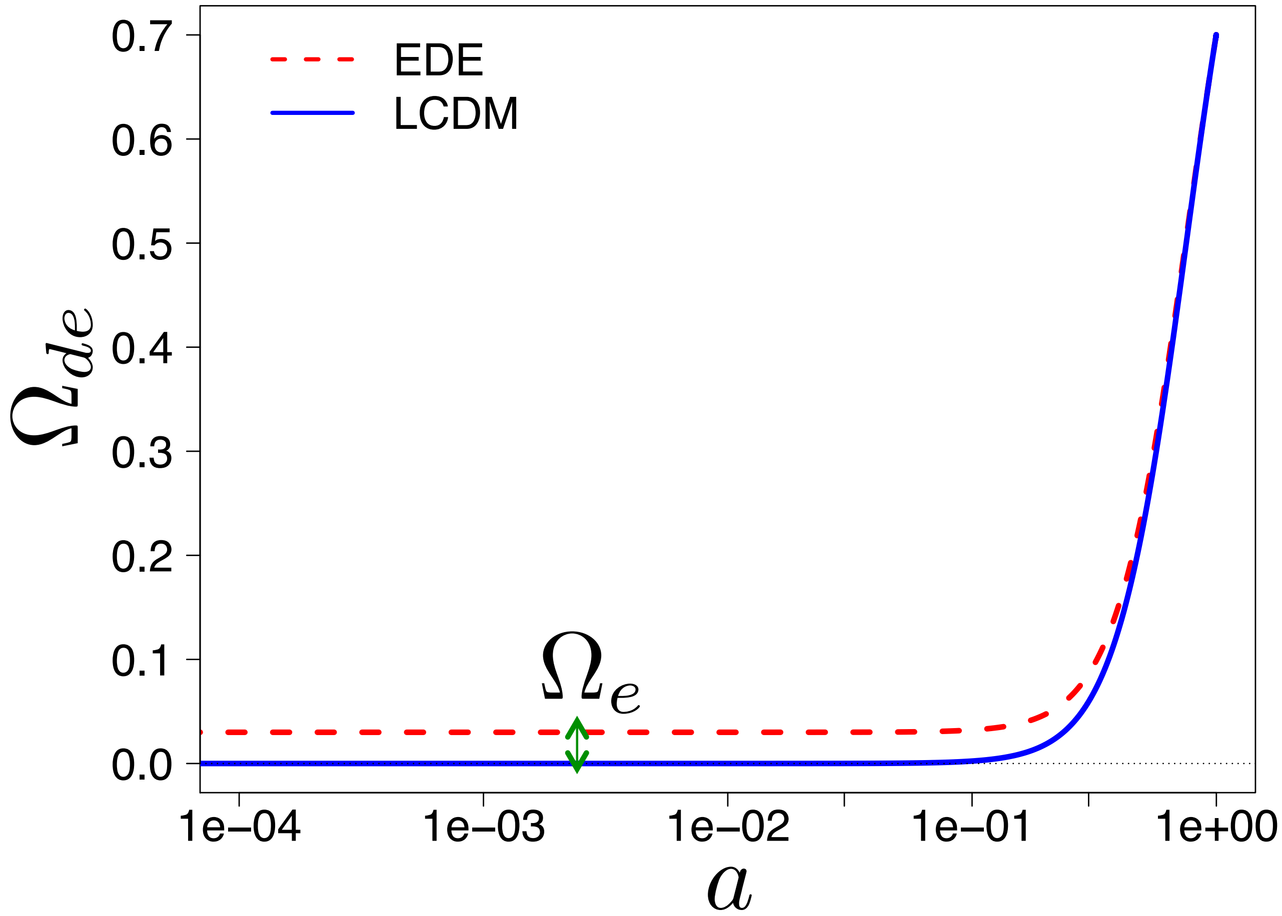
Planck, BSH and RSD are in agreement with LCDM.
Marginal tension when adding the (ultraconservative) WL data



WL data would prefer lower matter abundance and higher expansion parameter.

Results: DE at early times

Wetterich 2004
Doran & Robbers 2006

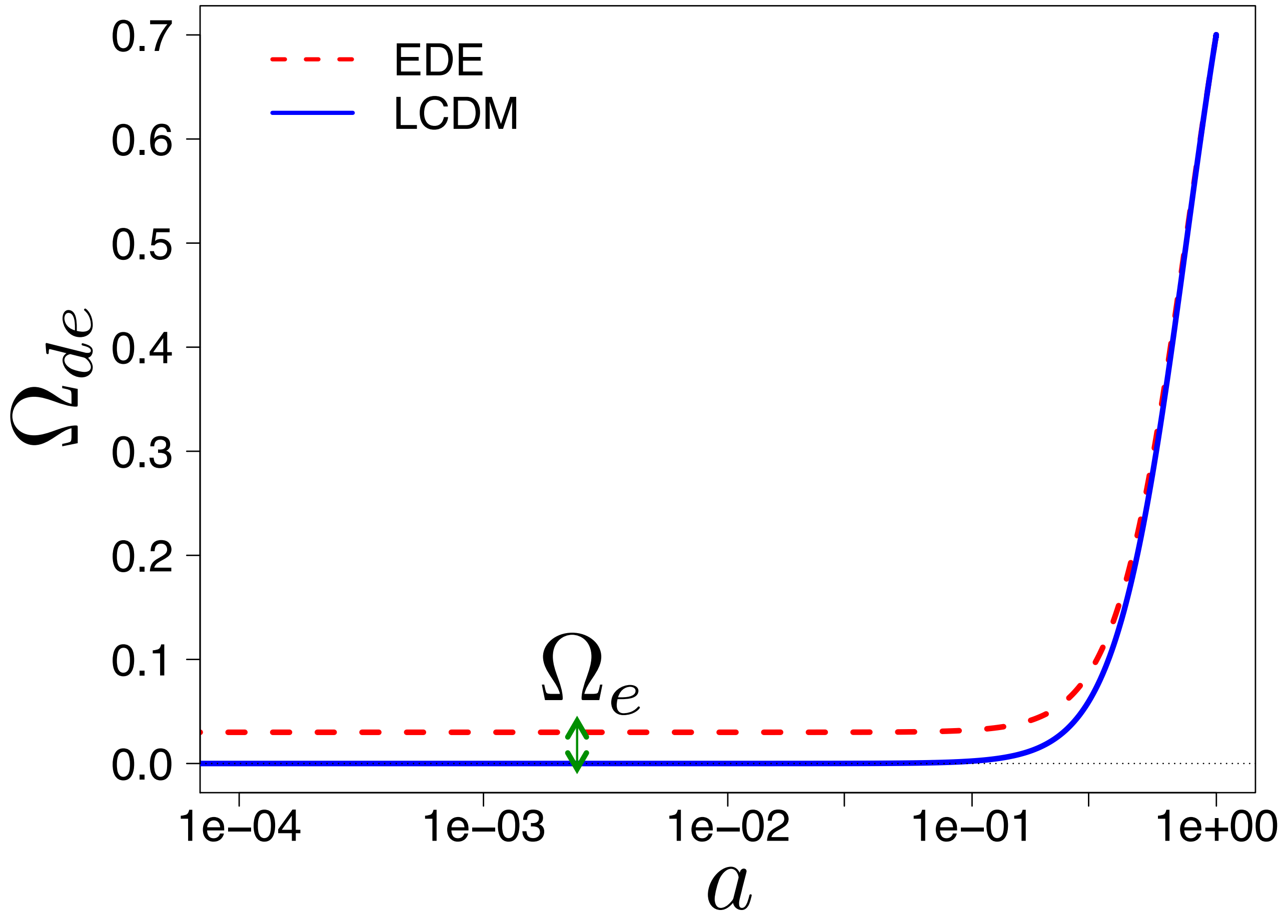


Results: DE at early times

Wetterich 2004
Doran & Robbers 2006

$$\Omega_e \lesssim 0.007$$

Planck + BSH, 95% C.L.

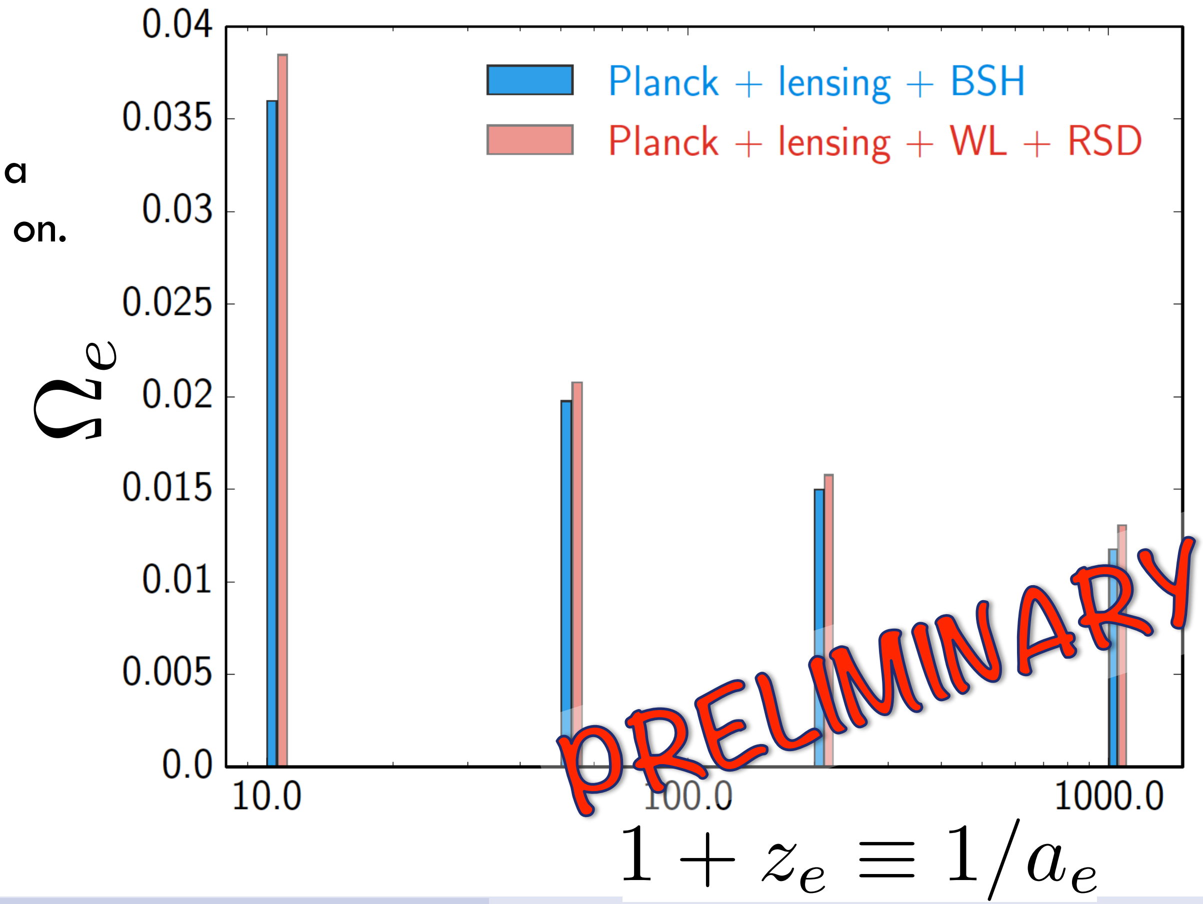


Results: how early is early?

Using Pettorino etal 2013

Tight constraints even if Dark Energy starts to play a role only from a redshift z_e on.

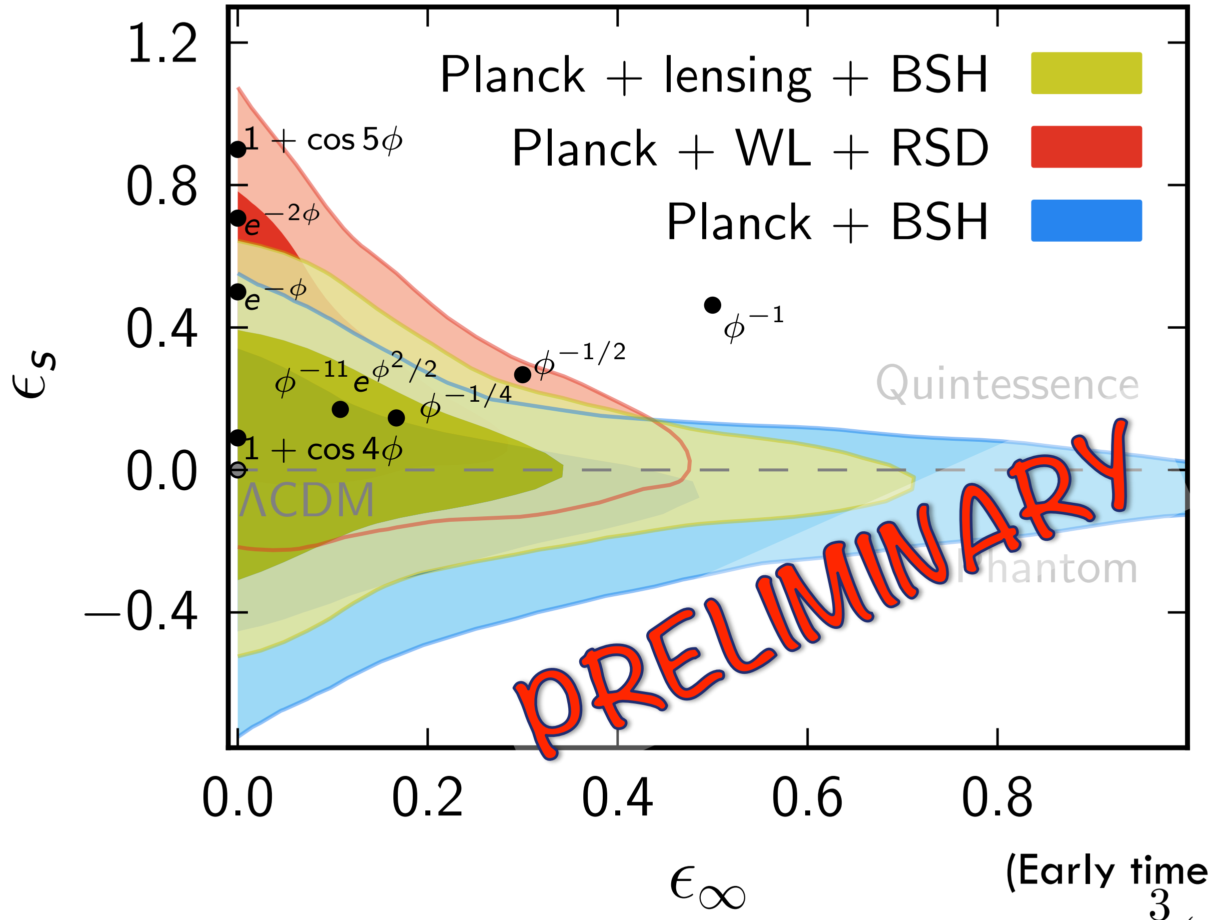
$$\Omega_e(z_e \sim 50) \lesssim 0.02$$



Results: generic DE potential

Based on
Huang et al 2011

(Late time evolution related to the slope of the potential)



(Early time evolution)

$$\epsilon_\infty = \frac{3}{2}(1 + w_{\rm early})$$

Modifying Perturbations

1. Top down approach → Start from theory and a very generic action

2. Bottom up approach → Start from observations and parametrize two independent functions of the gravitational potentials

1. Effective Field Theories (EFT)

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_0^2}{2}[1 + \Omega(\tau)]R + \Lambda(\tau) - a^2 c(\tau)\delta g^{00} \right.$$
$$+ \frac{M_2^4(\tau)}{2}(a^2\delta g^{00})^2 - \bar{M}_1^3(\tau)2a^2\delta g^{00}\delta K_\mu^\mu$$
$$- \frac{\bar{M}_2^2(\tau)}{2}(\delta K_\mu^\mu)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta K_\nu^\mu \delta K_\mu^\nu + \frac{a^2\hat{M}^2(\tau)}{2}\delta g^{00}\delta R^{(3)}$$
$$\left. + m_2^2(\tau)(g^{\mu\nu} + n^\mu n^\nu)\partial_\mu(a^2 g^{00})\partial_\nu(a^2 g^{00}) \right\} + S_m[\chi_i, g_{\mu\nu}].$$

Gubitosi etal 2012

In general there are 9 functions of time that include majority of Modified Gravity models (with both anisotropic stress and generic sound speed)

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Example: select Horndeski models
(stable ST theories with second order eom in the fields)
with varying α_M (Bellini & Sawicki 2014)
i.e. non minimal coupling, changing lensing
(and also tensor modes – Amendola etal 2014)

EFTCAMB (Hu, Raveri, Silvestri, Frusciante 2014)

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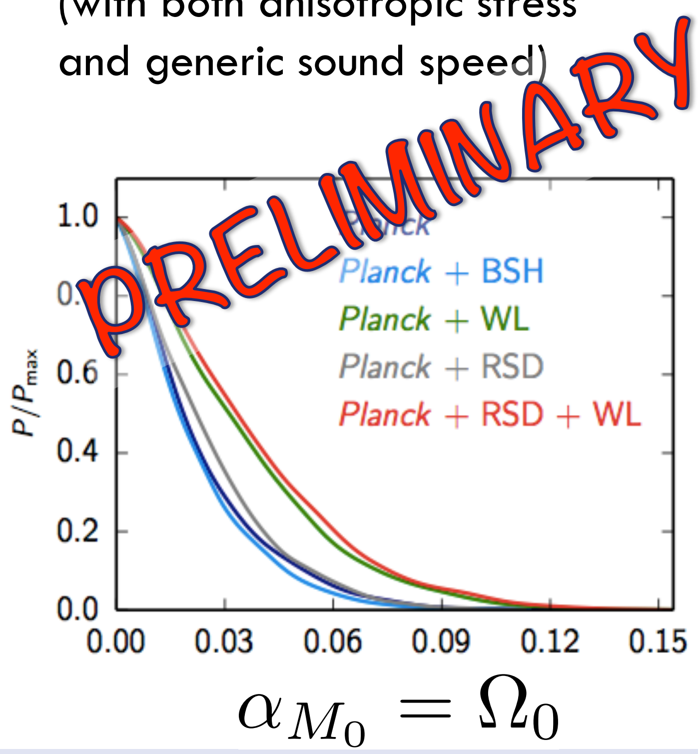


2. Parametrizing observables

2 functions of scale and time:

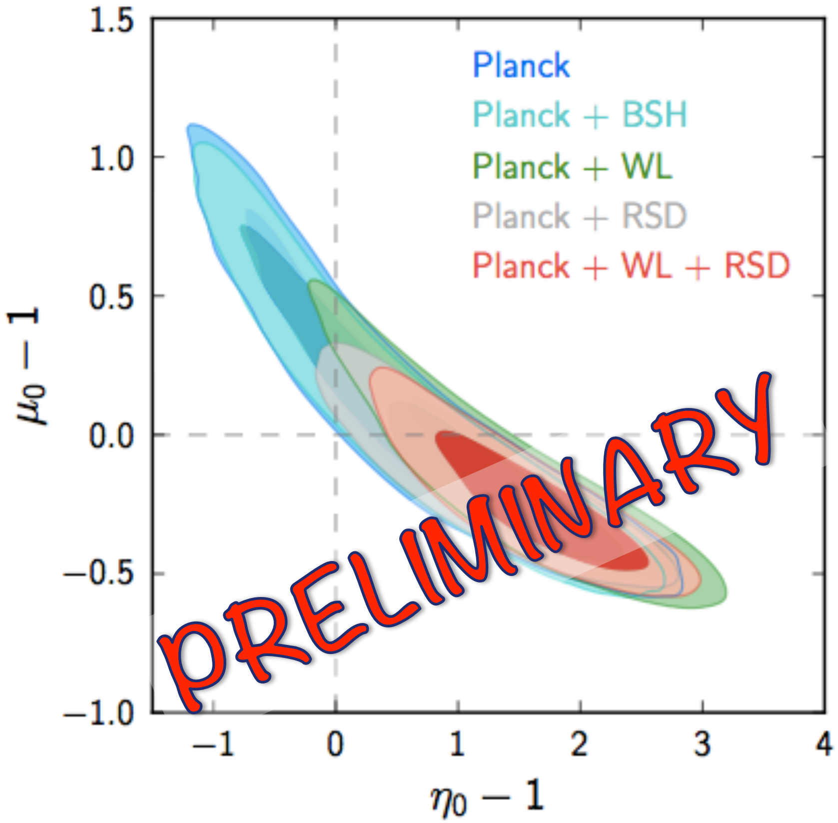
μ modifies the Poisson equation

η is the ratio of the gravitational potentials

Marginal tension with LCDM

- Planck alone lies at the 2 sigma limit
- driven by external datasets (WL)
- degenerate with optical depth and A_L
- WL+RSD will help to tighten constraints

(Simpson et al 2012)



$\Delta\chi^2 \sim -4$ for Planck alone (but 2 extra parameters, not significant)

Conclusions

- Overall agreement between Planck and LCDM.
- In all cases, we improve current bounds both on background and on perturbation parametrizations.
- Marginal tensions ($\approx 2\ \sigma$).

AND

MUCH

MORE

…coming soon on the Arxiv.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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