Planck 2015 results on Dark Energy and Modified Gravity

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Outline

Minimal ΛCDM model

Since the '90s and the discovery of the late accelerated expansion of the Universe, the standard cosmological model has been the most efficient in describing our observations.

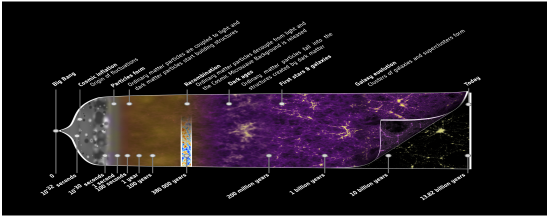
This model relies on a Cold Dark Matter component to describe the evolution of cosmic structures and on a cosmological constant Λ to account for the accelerated expansion phase.

The ΛCDM gives predictions for cosmological observables in terms of 6 standard parameters

$$\{\Omega_b,\ \Omega_{cdm},\ n_s,\ A_s,\ H_0,\ \tau\}$$

The Cosmic Microwave Background

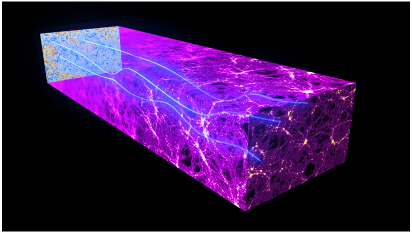
The minimal ΛCDM model explains quite efficiently cosmological observables, including the most primordial available: the Cosmic Microwave Background



This relic radiation from the Big Bang carries information on the density distribution and the primordial phases of the Universe

CMB and the late time Universe

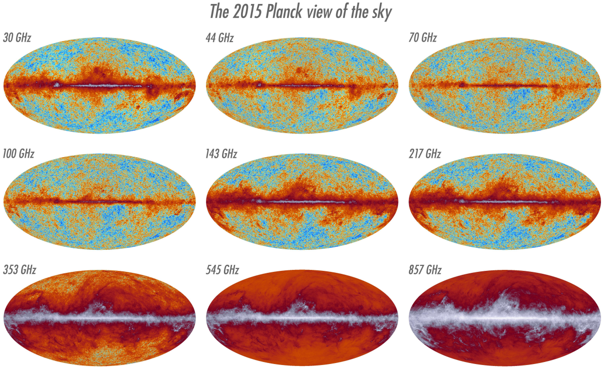
CMB photons travel through the more recent Universe and are therefore affected also by more recent physical mechanisms, e.g. CMB lensing and ISW effect.



CMB photons contain also informations on the more recent phases of the Universe and can be used to test cosmological models on a wide time range.

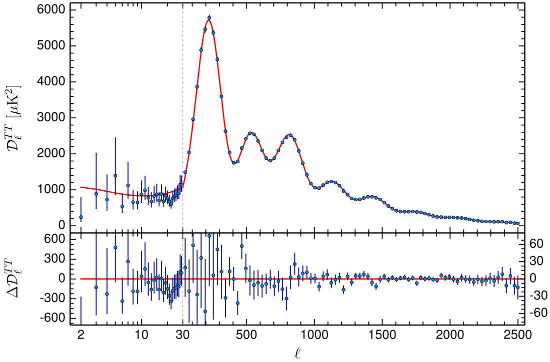
The Planck Satellite

Early in 2015, the ESA Planck satellite released the most up to date CMB data.
Accurate foreground control and extreme sensitivity.



Planck 2015

Temperature and polarization spectra extracted from CMB maps are in very good agreement with the predictions of the minimal 6-parameters ΛCDM model



Planck 2015 results. XIII. Cosmological parameters

Testing Λ

ΛCDM is a good fit to CMB data and within this framework accurate constraints on cosmological parameters can be obtained.

CMB allows to test the assumption of a Cosmological Constant (Λ) as the responsible for the late time acceleration.

Abandoning this paradigm impacts the evolution of the Universe through changes of

- background expansion
- evolution of cosmological perturbations

CMB power spectra are affected by these modifications

What to test for?

If we want to test Λ we have to describe departures from it:

- parametrized deviations
  find peculiar properties of your model and parametrise them (e.g. $w(z) = -1$)
- specific alternative models
  assume a specific model and test whether or not it better fits the data

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Both approaches can be applied to the two broad classes of alternatives to Λ

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

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Modified Gravity
modifications to GR lagrangian

Dark Energy
additional energy components

Planck models and parametrizations

Planck collaboration tried to investigate deviations from ΛCDM moving between these approaches

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Model	Section
ΛCDM	Planck Collaboration XIII (2015)
Background parameterizations:	
w	Planck Collaboration XIII (2015)
w_0, w_a	Sect. 5.1.1: Figs. 3, 4, 5
w higher order expansion	Sect. 5.1.1
1-parameter $w(a)$	Sect. 5.1.2: Fig. 6
w PCA	Sect. 5.1.3: Fig. 7
ϵ_s, ζ_s, ϵ_∞	Sect. 5.1.4: Figs. 8, 9
Early DE	Sect. 5.1.5: Figs. 10, 11
Perturbation parameterizations:	
EFT exponential	Sect. 5.2.1: Fig. 12
EFT linear	Sect. 5.2.1: Fig. 13
μ, η scale-independent:	
DE-related	Sect. 5.2.2: Figs. 1, 14, 15, 16, 17
time related	Sect. 5.2.2: Figs. 14, 16
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Other particular examples:	
DE sound speed and k-essence . .	Sect. 5.3.1
Equation of state approach:	
Lorentz-violating massive gravity	Sect. 5.3.2
Generalized scalar fields	Sect. 5.3.2
$f(R)$	Sect. 5.3.3: Figs. 19, 20
Coupled DE	Sect. 5.3.4: Figs. 21, 22

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Data combinations

These parametrizations are investigated combining Planck with additional observations

- **Planck baseline**: Planck TT + low-ℓ polarization
- **background probes**:
  - BAO: SDSS (Ross et al 2014), BOSS (Anderson et al. 2014), 6dFGS (Beutler et al. 2011)
  - SN: JLA (Betoule et al. 2013)
  - H_0 conservative prior (Efstathiou 2014)
- **perturbation probes**:
  - RSD (BOSS DR11, Samushia et al. 2014)
  - WL (CFHTLens, Kilbinger et al. 2013, Heymans et al. 2013), with an ultra conservative cut of non linear scales

Equation of State

Assuming the background expansion deviates from the standard ΛCDM, the EoS parameter can depart from the constant -1

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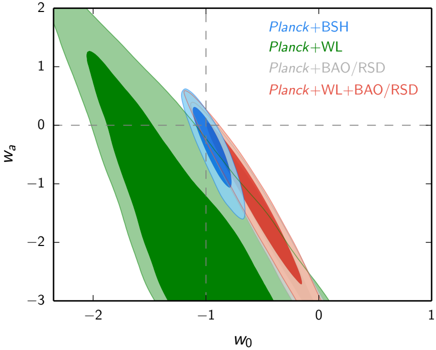

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Modified perturbations evolution

Focusing on perturbations evolution, Planck analysis exploited two different parametrizations of departure from standard ΛCDM driven behaviour:

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Top-down approach

Bottom-up approach

Modified perturbations evolution

- Top-down approach$\rightarrow$parametrize your theory

Modified perturbations evolution

- Top-down approach→parametrize your theory
  Action for scalar tensor theories with only one extra dynamical field, preserving background isotropy and homogeneity

$$S = \int d^4x\sqrt{-g}\{\frac{m_0^2}{2}\left[1+\Omega(\tau)\right]R+\Lambda(\tau)+ f(c,\hat{M}^2,\bar{M}_1^3,\bar{M}_2^4,\bar{M}_3^2,m_2^2)\}$$

  Planck analysed the case where $\Omega(\tau)$ is the only free function (non minimally coupled K-essence)

  EFTCAMB (Hu, Raveri, Silvestri, Frusciante 2014)

Modified perturbations evolution

- Top-down approach→parametrize your theory

$$\Omega(a) = e^{\frac{\alpha_{M0}}{\beta} a^{\beta}} - 1 \quad \Omega(a) = \alpha_{M0} a$$

Bellini, Sawicki 2014

Modified perturbations evolution

- Top-down approach→parametrize your theory

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Bellini, Sawicki 2014

- Bottom-up approach→parametrize your "observables"

$$k^2\Psi = 4\pi G a^2 \mu(a,k)\rho\Delta$$

$$\frac{\Phi}{\Psi} = \eta(a,k)$$

MGCAMB (Hojjati, Pogosian, Zhao 2011)

Modified perturbations evolution

- Top-down approach$\rightarrow$parametrize your theory

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Bellini, Sawicki 2014

- Bottom-up approach$\rightarrow$parametrize your "observables"

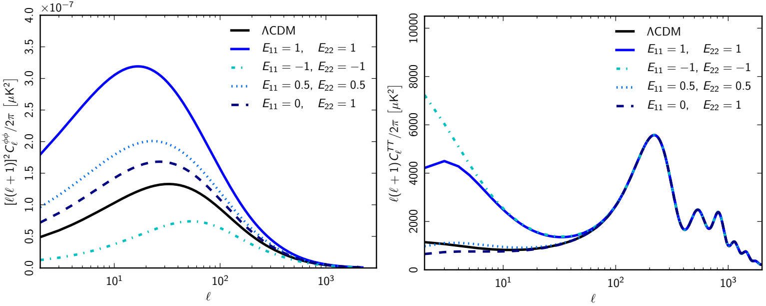
$$\mu(z,k) = 1 + E_{11}\Omega_{DE}(z)\frac{1 + c_1(\lambda H/k)^2}{1 + (\lambda H/k)^2}$$

$$\eta(z,k) = 1 + E_{22}\Omega_{DE}(z)\frac{1 + c_2(\lambda H/k)^2}{1 + (\lambda H/k)^2}$$

Effects on CMB

While testing for deviations from the standard perturbations evolution, background expansion of ΛCDM is assumed.

CMB is affected by the late modified evolution of cosmological perturbations: ISW effect and CMB lensing



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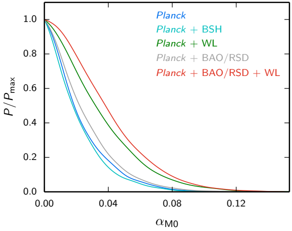
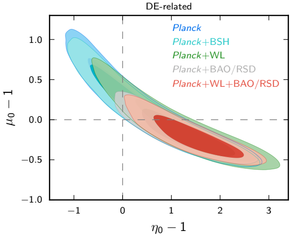
(some) Planck results

Top-down approach

- ΛCDM limit in agreement with all data combinations
- possible hint of tensions between the datasets





Bottom-up approach

- Mild tension with ΛCDM ($\approx 2\sigma$)
- Tension enhanced including perturbation probes (RSD and WL)

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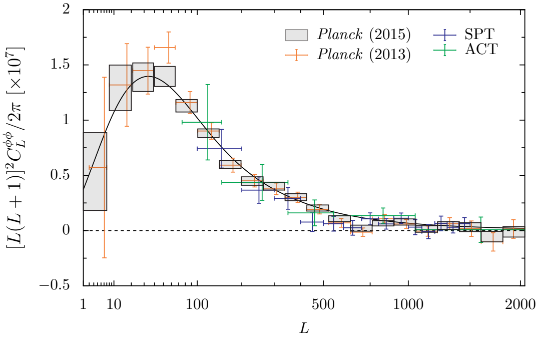
Lensing reconstruction

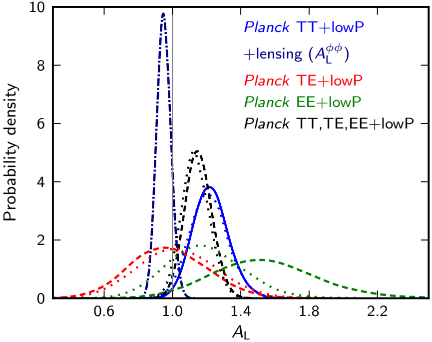
From Planck CMB maps it's possible to reconstruct the CMB lensing potential power spectrum through quadratic estimators



Planck 2015 results. XV. Gravitational lensing

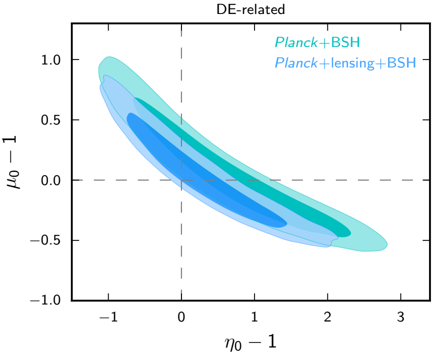
The amplitude of lensing potential

Planck collaboration measured how much the amplitude of the CMB lensing potential power spectrum deviates from the ΛCDM prediction ($C_\ell = A_L C_\ell^{\Lambda CDM}$), both through temperature and polarization spectra and through the extraction of the lensing potential from CMB maps.



The importance of being lensed

Results obtained from lensing extraction seem “more in agreement” with ΛCDM.
This feature affects significantly the slight tension with the standard model found with the MGCAMB approach



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Conclusions

- Overall agreement betwen Planck and the ΛCDM model
- "Agnostic" analysis, based on several parametrizations and approaches
- Improvement of previous bounds on both background and perturbation parametrizations
- Planck+external datasets results show some marginal tensions with ΛCDM

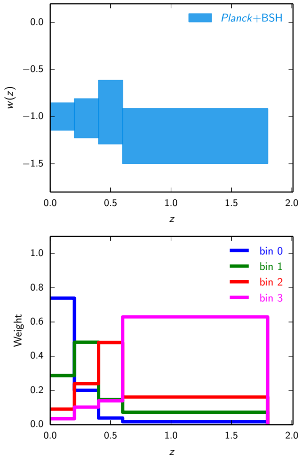
Planck Collaboration

EoS PCA

The PCA approach allows to avoid any assumptions on the behaviour of the EoS.

The value of $w(z)$ is free to vary in different redshift bins.

Model independent, but larger errors.



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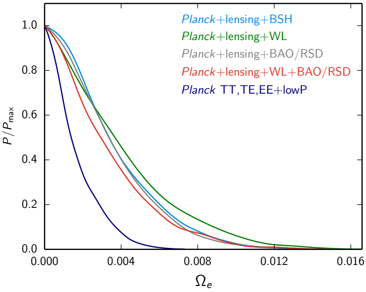
Early Dark Energy

This kind of models account for a time evolving DE with non vanishing density at early times

$$\Omega_{de}(a) = \frac{\Omega_{de}^0 - \Omega_{\rm e}(1 - a^{-3w_0})}{\Omega_{de}^0 + \Omega_m^0 a^{3w_0}} + \Omega_{\rm e}(1 - a^{-3w_0})$$



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Effective Field Theory for DE/MG

In general there are 9 functions of time that include majority of Modified Gravity models

$$S = \int d^4x \sqrt{-g} \{ \frac{m_0^2}{2}[1+\Omega(\tau)]R + \Lambda(\tau) - a^2 c(\tau)\delta g^{00}$$

$$+ \frac{M_2^4(\tau)}{2}(a^2\delta g^{00})^2 - \bar{M}_1^3(\tau) 2a^2 \delta g^{00} \delta K_\mu^\mu$$

$$- \frac{\bar{M}_2^2(\tau)}{2}(\delta K_\mu^\mu)^2 - \frac{\bar{M}_3^2(\tau)}{2}\delta K_\nu^\mu \delta K_\mu^\nu + \frac{a^2 \hat{M}^2(\tau)}{2}\delta g^{00}\delta R^{(3)}$$

$$+ m_2^2(\tau)(g^{\mu\nu} + n^\mu n^\nu)\partial_\mu(a^2 g^{00})\partial_\nu(a^2 g^{00}) \} + S_m[\chi_i, g_{\mu\nu}]$$

Describes scalar tensor theories with one extra dynamical d.o.f.

Gubitosi et al. 2012