Probing new physics in the dark sector with Planck

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based on

`New constraints on Coupled Dark Energy from Planck`: PRD88(2),023531

`Updated constraints from the Planck experiment on modified gravity`:PRD88,027502

In collaboration with V. Salvatelli, O. Mena, L. Lopez Honorez

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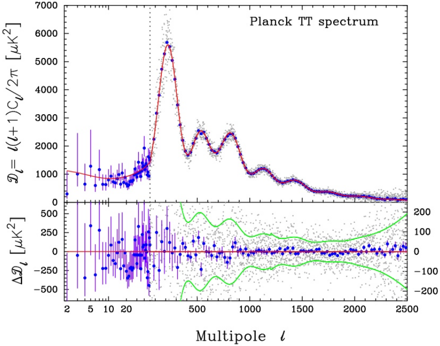
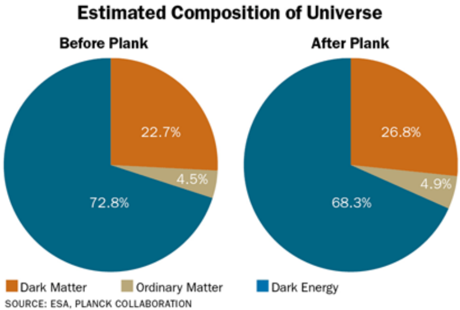
Planck results

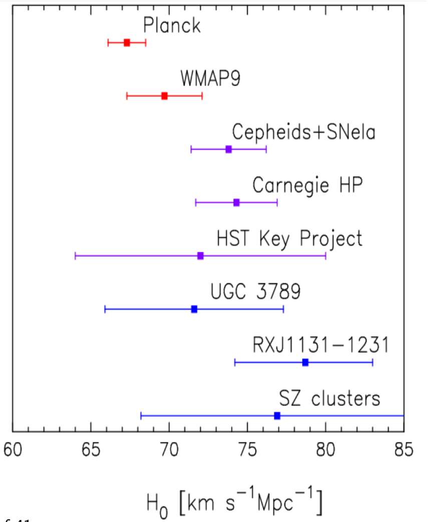
- The Planck experiment has provided new and precise measurements of CMB anisotropy.
    - Angular scales covered up to multipole $\ell \sim 2500$.
    - The new data are in full agreement with the ΛCDM model...
    - ...with some differences in the content of the Universe.





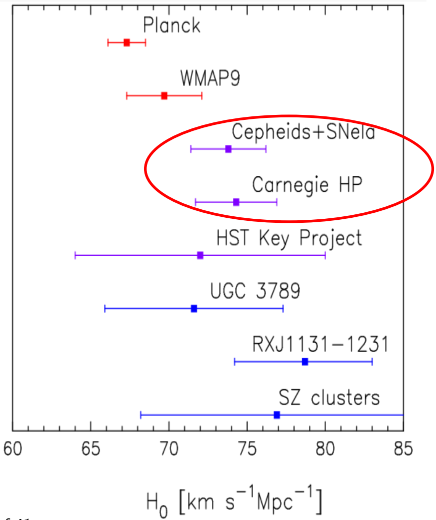
P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5062 [astro-ph.CO].

Tension with H_0 astrophysical measurements



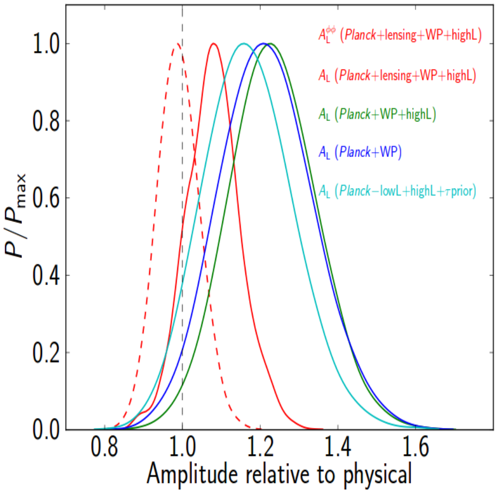
- Discrepancy between H_0 measured by Planck compared with the values measured by independent cosmological probes.
- While systematics can be present, the discrepancy can be explained including new physical phenomena.
- **The Planck determination of H_0 is model dependent.**

Tension with H_0 astrophysical measurements



- Discrepancy between H_0 measured by Planck compared with the values measured by independent cosmological probes.
- While systematics can be present, the discrepancy can be explained including new physical phenomena.
- **The Planck determination of H_0 is model dependent.**

Anomalous lensing signal



- $A_L^{\phi\phi}$ rescales the trispectrum while A_L rescales the power spectra for the lensing effect.
- In ΛCDM we expect $A_L^{\phi\phi} = A_L = 1$.
- From Planck $A_L^{\phi\phi}$ is in excellent agreement with the standard value while there is an evidence for $A_L > 1$.

New Physics in the Dark Sector?

- How can we interpret the tensions?
- Systematic effects.
- Signature of New Physics.

New Physics in the Dark Sector?

- How can we interpret the tensions?
- Systematic effects.
- Signature of New Physics.

- The solution of the Planck tension could arise from New Physics in the Dark Sector. We focus on:

Interacting dark energy models

Modified gravity models

Interacting dark energy

ΛCDM

- Dark energy and dark matter are uncoupled components.
- Separately conserved energy-momentum balances:
  - $\nabla_\mu T^{\mu}_{(\mathrm{de})\nu} = 0$
  - $\nabla_\mu T^{\mu}_{(\mathrm{dm})\nu} = 0$

- Only total energy-momentum conservation is required by Einstein equations.

- Relaxing the hypothesis of separately conservation in the dark sector we can build interacting dark energy models.

Interacting dark energy

- The total energy-momentum tensor has a perfect fluid structure and is conserved.
- We split it in two components that are still perfect fluids:
  - $\mathbf{T}^{\mu\nu} = \mathbf{T}^{\mu\nu}_{\mathbf{(de)}} + \mathbf{T}^{\mu\nu}_{\mathbf{(dm)}} \qquad \boldsymbol{\nabla}_{\mu}\mathbf{T}^{\mu\nu} = \mathbf{0}$
- The energy-momentum tensor of each dark component is not conserved.
- The interaction can be described respecting the total energy-momentum conservation as

$$\nabla_\mu T^{\mu}_{(\mathrm{de})\nu} = -Q_\nu \qquad \nabla_\mu T^{\mu}_{(\mathrm{dm})\nu} = Q_\nu$$

$\Rightarrow Q_\nu$ governs the energy-momentum transfer

- Two families of models depending on the form of Q_ν.

Two families for Q_ν

- Momentum exchange parallel to dark energy (**DEvel**) or dark matter (**DMvel**) four-velocity.

DEvel

$$Q_\nu = Q u_\nu^{(\mathrm{de})}/a$$

- $Q \propto \rho_{\mathrm{dm}}$: coupled quintessence.
- No momentum transfer to DE frame, momentum conserved in DM frame.
- Increase/decrease in the DM peculiar velocity equal and opposite to the change in ρ_{dm}.
- Extra source of acceleration for the DM (effectively "modified gravity").

DMvel

$$Q_\nu = Q u_\nu^{(\mathrm{dm})}/a$$

- Both momentum and energy density are transferred from the DM system to DE one.
- No apparent fifth force.

Background evolution

Background equations

$$\dot{\rho}_{\rm de}+3\mathcal{H}\rho_{\rm de}(1+w) = -Q \qquad \dot{\rho}_{\rm dm}+3\mathcal{H}\rho_{\rm dm} = Q$$

- For $Q > 0$ the energy flows from the DE system to DM one (reversed situation for $Q < 0$).
- Q changes DM and DE energy density redshift dependence.
- It is convenient to introduce two effective equations of state:
  - $w_{\rm de}^{\rm eff} = w + \frac{Q}{3\mathcal{H}\rho_{\rm de}}$ $\qquad w_{\rm dm}^{\rm eff} = -\frac{Q}{3\mathcal{H}\rho_{\rm dm}}$

Background evolution

Effective background equations

$\dot{\rho}_{\rm de}+3\mathcal{H}\rho_{\rm de}(1+w_{\rm de}^{\rm eff})=0$ $\qquad$ $\dot{\rho}_{\rm dm}+3\mathcal{H}\rho_{\rm dm}(1+w_{\rm dm}^{\rm eff})=0$

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  - $w_{\rm de}^{\rm eff}=w+\frac{Q}{3\mathcal{H}\rho_{\rm de}}$ $\qquad$ $w_{\rm dm}^{\rm eff}=-\frac{Q}{3\mathcal{H}\rho_{\rm dm}}$
- Regardless the coupling we need $w<-\frac{1}{3}$ for an accelerated expansion.

Linear perturbations: baryons

- Linear perturbations theory in the conformal Newtonian gauge.

- In this gauge FLRW metric and the four-velocity of the fluids are:
$\mathbf{ds^2 = a^2[-(1+2\Psi)d\tau^2 + (1-2\Phi)dx_i dx^i]}$
$\mathbf{u_\nu = a(-(1+\Psi), v_i)}$

- Baryons do not interact with DE.

- The continuity and Euler equations after the decoupling are the same of ΛCDM:

$$\begin{aligned} \dot{\delta}_{\rm b} &= -\theta_{\rm b} + 3\dot{\Phi} \\ \dot{\theta}_{\rm b} &= -\mathcal{H}\theta_{\rm b} + k^2\Psi \end{aligned}$$

Linear perturbations: dark sector

$$
\begin{aligned}
\dot{\delta}_{\rm dm} &= -(\theta_{\rm dm} - 3\dot{\Phi}) + \frac{Q}{\rho_{\rm dm}}\left(\frac{\delta Q}{Q} - \delta_{\rm dm} + \Psi\right) \\
\dot{\theta}_{\rm dm} &= -\mathcal{H}\theta_{\rm dm} + (1-\mathbf{b})\frac{Q}{\rho_{\rm dm}}(\theta_{\rm de} - \theta_{\rm dm}) + k^2\Psi \\
\dot{\delta}_{\rm de} &= -(1+w)(\theta_{\rm de} - 3\dot{\Phi}) - \frac{Q}{\rho_{\rm de}}\left(\frac{\delta Q}{Q} - \delta_{\rm de} + \Psi\right) + \\
&\quad -3\mathcal{H}\left(\hat{c}^2_{s\,\rm de} - w\right)\left[\delta_{\rm de} + \mathcal{H}\left(3(1+w) + \frac{Q}{\rho_{\rm de}}\right)\frac{\theta_{\rm de}}{k^2}\right] \\
\dot{\theta}_{\rm de} &= -\mathcal{H}\left(1 - 3\hat{c}^2_{s\,\rm de} - \frac{\hat{c}^2_{s\,\rm de} + \mathbf{b}}{1+w}\frac{Q}{\mathcal{H}\rho_{\rm de}}\right)\theta_{\rm de} + \frac{k^2}{1+w}\hat{c}^2_{s\,\rm de}\delta_{\rm de} + \\
&\quad + k^2\Psi - \mathbf{b}\,\frac{Q}{\rho_{\rm de}}\frac{\theta_{\rm dm}}{1+w}\,.
\end{aligned}
$$

Fifth force

- The Euler equations for the matter are

$$\dot{\theta}_{\rm b} = -\mathcal{H}\theta_{\rm b} + k^2\Psi$$

BARYONS

$$\dot{\theta}_{\rm dm} = -\mathcal{H}\theta_{\rm dm} + k^2\Psi$$

DARK MATTER (DMvel)

$$\dot{\theta}_{\rm dm} = -\mathcal{H}\theta_{\rm dm} + k^2\Psi + \boxed{\frac{Q}{\rho_{\rm dm}}(\theta_{\rm de} - \theta_{\rm dm})}$$

DARK MATTER (DEvel)

- The equation for DM is different from the baryons equation only in DEvel models.
- Violation of weak equivalence principle in these models.

Instabilities

- Generic form of the second order differential equations for DM and DE

$$
\begin{aligned}
\delta''_{dm} &= A_m \frac{\delta_{dm}}{a^2} + B_m \frac{\delta'_{dm}}{a} + \mathcal{F}(\rho_i, \delta_i, \delta'_i; i \neq dm) \\
\delta''_{de} &= A_e \frac{\delta_{de}}{a^2} + B_e \frac{\delta'_{de}}{a} + \mathcal{G}(\rho_i, \delta_i, \delta'_i; i \neq de)
\end{aligned}
$$

- Positive A
  - Negative B: damped growth of perturbations.
  - Positive B: unstable exponentially growing regime.
- Negative A
  - Negative B: damped oscillations (third term could be the leading one).
  - Positive B: antidamped oscillations.

We have to find a model free from instabilities.

The analyzed model

- The instabilities depend on:
  - The form of the coupling Q.
  - The dark energy equation of state w.
  - The Q_ν four-velocity dependence.

$Q = \xi \mathcal{H} \rho_{\rm de}$ $\qquad Q_\nu \propto u_\nu^{(\rm dm)}$

$$\dot{\rho}_{dm} + 3\mathcal{H}\rho_{dm} = \xi\mathcal{H}\rho_{de}$$
$$\dot{\rho}_{de} + 3\mathcal{H}\rho_{de}(1 + w_{de}) = -\xi\mathcal{H}\rho_{de}$$
$$w_{dm}^{eff} = -\frac{\xi}{3}\frac{\rho_{de}}{\rho_{dm}}, \; w_{de}^{eff} = w + \frac{\xi}{3}$$

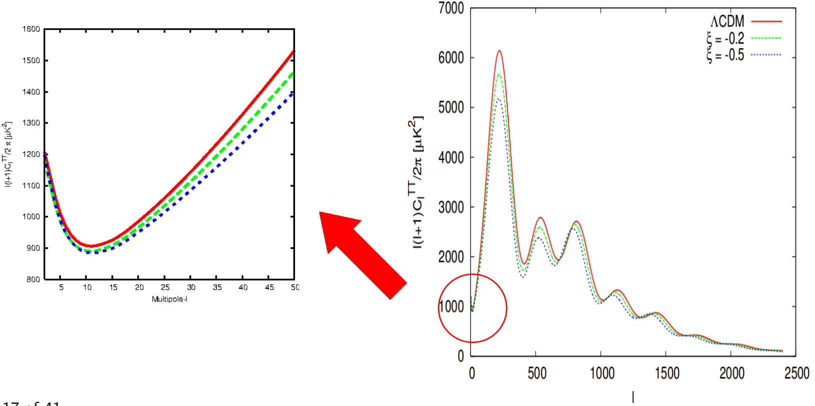
$$\rho_{dm} = \rho_{dm}^{(0)} a^{-3} + \rho_{de}^{(0)} \frac{\xi}{3w_{de}^{eff}} (1 - a^{-3w_{de}^{eff}}) a^{-3}$$
$$\rho_{de} = \rho_{de}^{(0)} a^{-3(1+w_{de}^{eff})}$$

- Constant w: w_{dm}^{eff} is redshift dependent and w_{de}^{eff} is constant.
- For a model in agreement with the cosmological constraints and free form instabilities we choose $\xi < 0$ and $w > -1$.

M. B. Gavela et al., JCAP0907 (2009) 034 [Erratum-ibid. 1005 (2010) E01] [arXiv:0901.1611 [astro-ph.CO]].

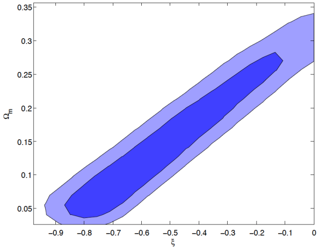
Effect on CMB

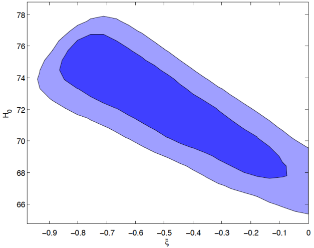
- Low multipoles: a non-zero coupling contributes to the late integrated Sachs-Wolfe effect.
- High multipoles: shifting the position of the acoustic peaks.



Constraints from Planck

Parameters	PLANCK + ΛCDM 68% limit	PLANCK+ ξ 68% limit
$\Omega_b h^2$	0.02205 ± 0.00028	0.02200 ± 0.00027
$\Omega_c h^2$	0.1199 ± 0.0027	< 0.074
100θ	1.04131 ± 0.00063	1.0456 ± 0.0026
τ	$0.089^{+0.012}_{-0.014}$	$0.087^{+0.012}_{-0.014}$
n_s	0.9603 ± 0.0073	0.9580 ± 0.0071
$\log(10^{10} A_s)$	$3.089^{+0.024}_{-0.027}$	$3.083^{+0.023}_{-0.025}$
ξ	——	$-0.49^{+0.19}_{-0.31}$
$\Omega_{\rm m}$	$0.315^{+0.016}_{-0.018}$	$0.155^{+0.050}_{-0.11}$
Ω_Λ	$0.685^{+0.018}_{-0.016}$	$0.845^{+0.11}_{-0.050}$
z_{re}	11.1 ± 1.1	10.9 ± 1.1
$H_0[{\rm km/s/Mpc}]$	67.3 ± 1.2	$72.1^{+3.2}_{-2.3}$
Age/Gyr	13.817 ± 0.048	$13.733^{+0.062}_{-0.065}$
$\chi^2_{\rm min}/2$	4902.95	4902.45



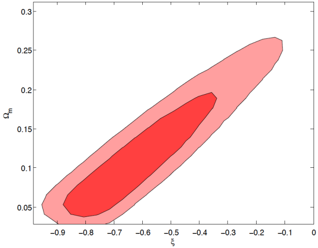


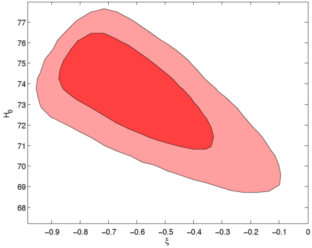
- Dark coupling is weakly constrained and compatible with Planck.
- The model with the dark interaction gives a lower matter density.
- The model with the dark interaction gives a larger Hubble parameter.

Constraints from Planck + HST

Parameters	PLANCK + ΛCDM 68% limit	PLANCK+ HST+ ξ 68% limit
$\Omega_b h^2$	0.02205 ± 0.00028	0.02203 ± 0.00027
$\Omega_c h^2$	0.1199 ± 0.0027	< 0.056
100θ	1.04131 ± 0.00063	1.0466 ± 0.0021
τ	$0.089^{+0.012}_{-0.014}$	$0.088\ ^{+0.017}_{-0.014}$
n_s	0.9603 ± 0.0073	0.9589 ± 0.0070
$\log(10^{10} A_s)$	$3.089^{+0.024}_{-0.027}$	$3.084^{+0.024}_{-0.027}$
ξ	——	$-0.58^{+0.090}_{-0.22}$
Ω_m	$0.315^{+0.016}_{-0.018}$	$0.122^{+0.033}_{-0.070}$
Ω_Λ	$0.685^{+0.018}_{-0.016}$	$0.878^{+0.070}_{-0.033}$
z_{re}	11.1 ± 1.1	10.9 ± 1.1
H_0[km/s/Mpc]	67.3 ± 1.2	$73.3^{+2.0}_{-1.6}$
Age/Gyr	13.817 ± 0.048	$13.711^{+0.051}_{-0.046}$
$\chi^2_{\mathrm{min}}/2$	4902.95	4902.52

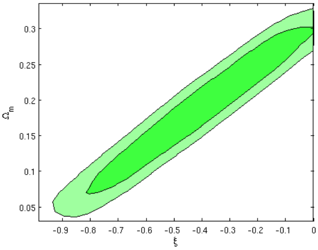
- The combined Planck + HST constraint excludes a zero value of the coupling parameter at more than 2 sigma.
- The model with the dark interaction gives as expected an even larger Hubble parameter.



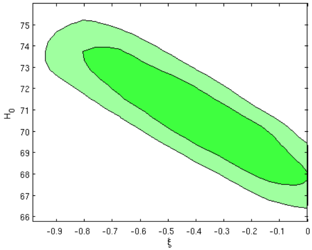


Constraints from Planck + BAO

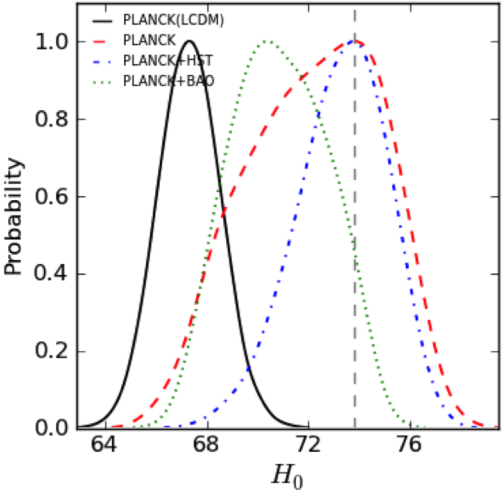
	PLANCK + ΛCDM	PLANCK+ BAO+ ξ
Parameters	68% limit	68%
$\Omega_b h^2$	0.02205 ± 0.00028	0.02192 ± 0.00025
$\Omega_c h^2$	0.1199 ± 0.0027	$0.0.069^{+0.040}_{-0.022}$
100θ	1.04131 ± 0.00063	1.0445 ± 0.0021
τ	$0.089^{+0.012}_{-0.014}$	$0.085^{+0.012}_{-0.013}$
n_s	0.9603 ± 0.0073	0.9556 ± 0.0060
$\log(10^{10} A_s)$	$3.089^{+0.024}_{-0.027}$	$3.082^{+0.023}_{-0.026}$
ξ	——	$-0.42^{+0.29}_{-0.21}$
$\Omega_{\rm m}$	$0.315^{+0.016}_{-0.018}$	$0.187^{+0.085}_{-0.063}$
Ω_Λ	$0.685^{+0.018}_{-0.016}$	$0.813^{+0.063}_{-0,085}$
z_{re}	11.1 ± 1.1	10.7 ± 1.1
$H_0 [\rm km/s/Mpc]$	67.3 ± 1.2	$70.8^{+1.9}_{-2.1}$
Age/Gyr	13.817 ± 0.048	13.765 ± 0.044
$\chi^2_{\rm min}/2$	4902.95	4902.71



- Adding the BAO measurements we can observe that a zero coupling it is admitted but not favored.
- The Hubble parameter tension is still alleviated, but non strongly as in the Planck alone case.



H_0 tension solved



The modern theory of gravitation

General relativity is the theory of gravity

"The theory of gravitational fields, constructed on the basis of theory of relativity, is called *general relativity*. It was established by Einstein (and finally formulated by him 1915), and represents probably the most beautiful of all existing physical theories."

Landau & Lifshits. The classical theory of fields. Vol. 2.

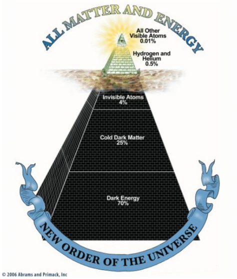
- GR has been tested directly in the Solar System in the weak-field limit.
- Indirect test in the same regime outside the Solar System from binary pulsar.
- **Strong regime tests are missing and gravity is tested very poorly at the large scales.**

Cosmology and general relativity

- Can the success of ΛCDM be advocated as a clear confirmation that GR works properly at large scales?

Cosmology and general relativity

- Can the success of ΛCDM be advocated as a clear confirmation that GR works properly at large scales? **NO**
- Almost all theories of gravity admit the FLRW as solution of their field equations.
- Indeed cosmology could indicates that gravity is not exactly described by GR.



To explain the cosmic acceleration within the context of GR, one needs to introduce the dark energy, which is very exotic, comprises approximately 70% of the energy content of the universe, and is not detected in the laboratory.

Modified gravity: $f(\mathrm{R})$ models

- Generalization of the Einstein-Hilbert action by making it more general function of the Ricci scalar.
- This choice leads to fourth-order field equations.
- Possible explanation for the observed late-time accelerating expansion of the Universe.

General relativity

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{2\kappa} + \mathcal{L}_m(\psi, g_{\mu\nu})\right)$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa T_{\mu\nu}$$

$$3H^2 = \kappa\left(\rho_{\mathrm{m}} + \rho_{\mathrm{rad}}\right)$$

$$-2\dot{H} = \kappa\left(\rho_{\mathrm{m}} + \frac{4}{3}\rho_{\mathrm{rad}}\right)$$

Modified gravity: $f(\mathrm{R})$ models

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- This choice leads to fourth-order field equations.
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$f(\mathrm{R})$ theories

$$S = \int d^4x \sqrt{-g} \left(\frac{f(R)}{2\kappa} + \mathcal{L}_m(\psi, g_{\mu\nu}) \right)$$
$$f_R(R) R_{\mu\nu} - \frac{1}{2} f(R) g_{\mu\nu} + (g_{\mu\nu}\Box - \nabla_\mu \nabla_\nu) f_R(R) = \kappa T_{\mu\nu}$$

$$3 f_R(R) H^2 = \kappa \left(\rho_{\mathrm{m}} + \rho_{\mathrm{rad}}\right) + \frac{1}{2}(f_R(R) R - f(R)) - 3H \dot{f}_R(R)$$
$$-2 f_R(R) \dot{H} = \kappa \left(\rho_{\mathrm{m}} + \frac{4}{3}\rho_{\mathrm{rad}}\right) + \ddot{f}_R(R) - H \dot{f}_R(R)$$

Conformal transformation

- We can perform the conformal transformation $g_{\mu\nu} = e^{2\beta\sqrt{\kappa}\phi} g^{\mathrm{E}}_{\mu\nu}$.
- We can recast $f(\mathrm{R})$ theories as GR with a scalar field coupled to the matter sector.

Action in the Einstein frame

$$S = \int d^4x \sqrt{-g^{\mathrm{E}}} \left(\frac{R^{\mathrm{E}}}{2\kappa} - \frac{3}{\beta^2} g^{\mathrm{E}}_{\mu\nu} \partial^\mu \phi \partial^\nu \phi - V(\phi) + \mathcal{L}_m(\psi, e^{2\beta\sqrt{\kappa}\phi} g^{\mathrm{E}}_{\mu\nu}) \right)$$

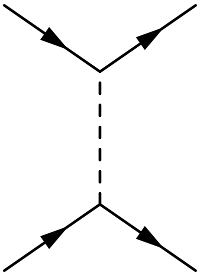
$$V(\phi) = \frac{R f_R(R) - f(R)}{2\kappa f_R^2(R)}$$

- The theory is well-defined as long as $V(\phi)$ is bounded from below.
- The scalar field is defined as $\phi \equiv -\frac{1}{2\beta\sqrt{\kappa}} \ln f_R(R)$.
- The coupling for $f(\mathrm{R})$ theories is $\beta = \frac{1}{\sqrt{6}}$ to obtain a canonical kinetic term (in general $f_{\mathrm{R}}(\mathrm{R}) > 0$ to avoid ghost).

Coupling with matter

- The mass of the scalar for viable model is $m_0 \sim H_0 \sim 10^{-43} Gev$.

$$\mathcal{L} = \sqrt{\kappa}\beta\phi m_{\psi 0}\bar{\psi}\psi \Rightarrow$$



$$\Rightarrow \delta\Phi_N = -2\beta^2 \frac{G_N m_{\psi 0}^2}{r}$$

- Constrained by Cassini measurements: $\beta^2 \leq 10^{-5}$.

(B. Bertotti, L. Iess, and P. Tortora, Nature 425 (2003) 374)

- $f(\mathrm{R})$ theories violate this condition.
- Screening mechanisms: chameleons, dilatons, symmetrons , ...

What can we measure cosmologically?

Perturbed metric

$$ds^2 = a^2[-(1+2\Psi)d\tau^2 + (1-2\Phi)dx_i dx^i]$$

- From the perturbed metric:
  - **a**: expansion history.
  - $\boldsymbol{\Psi}$: non-relativistic dynamics (growth of structure).
  - $\boldsymbol{\Psi + \Phi}$: relativistic dynamics (weak lensing, Sachs–Wolfe effect).

- Poisson equation and anisotropy equation

$$k^2\Psi = -4\pi G a^2\{\rho\Delta + 3(\rho+P)\sigma\}$$
$$\mathrm{k}^2[\Phi - \Psi] = 12\pi G a^2(\rho+P)\sigma$$

Parametrization

- We can parametrize the effect of modified gravity as:

$$k^2\Psi = -\mu(a,k)\,4\pi G a^2\{\rho\Delta + 3(\rho+P)\sigma\}$$

$$k^2[\Phi - \gamma(a,k)\,\Psi] = \mu(a,k)\,12\pi G a^2(\rho+P)\sigma$$

- The background evolution is fixed to ΛCDM but the evolution of matter perturbations can be different.

Bertschinger-Zukin parametrization

$$\mu(a,k) = \frac{1+\beta_1\lambda_1^2\,k^2a^s}{1+\lambda_1^2\,k^2a^s},\ \gamma(a,k) = \frac{1+\beta_2\lambda_2^2\,k^2a^s}{1+\lambda_2^2\,k^2a^s}$$

(B. & Z., PRD **78**, 024015, 2008)

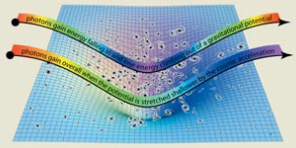
- The only free parameter for $f(\mathrm{R})$ is λ_1^2.
- Usually it is expressed as the present length-scale in units of the horizon scale: $B_0 = 2\lambda_1^2H_0^2/c^2$.

Effect on the Cosmic Microwave Background

- The CMB power spectrum depends on the Ψ and Φ potentials.

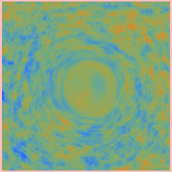
Integrated Sachs-Wolfe effect

$$\left(\frac{\Delta T}{T}\right)_{ISW} = \int d\tau \left[\dot{\Psi}(\tau, \vec{x}) - \dot{\Phi}(\tau, \vec{x})\right]$$

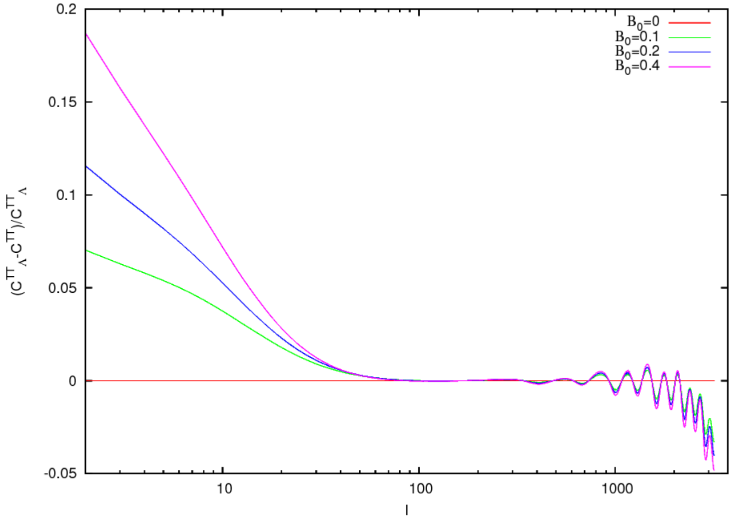


CMB lensing

$$\Delta T(\hat{n}) \rightarrow \Delta T(\hat{n} + d(\hat{n}))$$
$$d(\hat{n}) = \nabla\psi(\hat{n}, \Psi, \Phi)$$

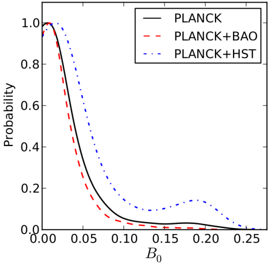


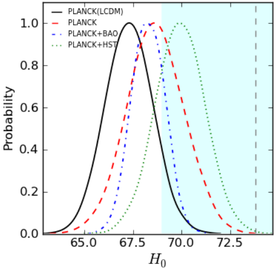
Effect on the Cosmic Microwave Background



Constraints

	PLANCK	PLANCK+BAO	PLANCK+HST
Parameters	68% limit	68% limit	68% limit
$\Omega_b h^2$	0.02253 ± 0.00032	0.02245 ± 0.00026	0.02274 ± 0.00030
$\Omega_c h^2$	0.1165 ± 0.0027	0.1174 ± 0.0017	0.1143 ± 0.0024
100θ	1.04189 ± 0.00066	1.04173 ± 0.00058	1.04220 ± 0.00062
τ	0.087 ± 0.013	0.085 ± 0.012	0.090 ± 0.013
n_s	0.9697 ± 0.0076	0.9671 ± 0.0056	0.9748 ± 0.0071
$\log(10^{10} A_s)$	3.078 ± 0.025	3.077 ± 0.025	3.079 ± 0.025
B_0	< 0.134 (95% c.l.)	**< 0.085 (95% c.l.)**	< 0.195 (95% c.l.)
Ω_m	0.293 ± 0.016	0.299 ± 0.010	0.280 ± 0.013
Ω_Λ	0.707 ± 0.016	0.701 ± 0.010	0.720 ± 0.013
z_{re}	10.6 ± 1.1	10.5 ± 1.1	10.8 ± 1.1
H_0[km/s/Mpc]	69.1 ± 1.3	68.61 ± 0.79	70.2 ± 1.1
Age/Gyr	13.736 ± 0.054	13.753 ± 0.039	13.696 ± 0.049

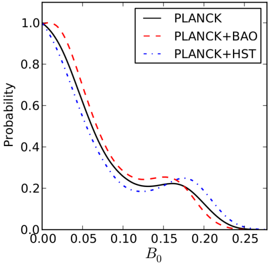


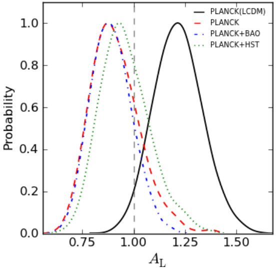


- $f(\mathrm{R})$ models are not favored but we obtain an upper limit on B_0.
- **BAO better constrain the growth of structures at low redshift.**
- $f(\mathrm{R})$ theories alleviate the H_0 tension between Planck and HST.

Constraints: varying the lensing amplitude

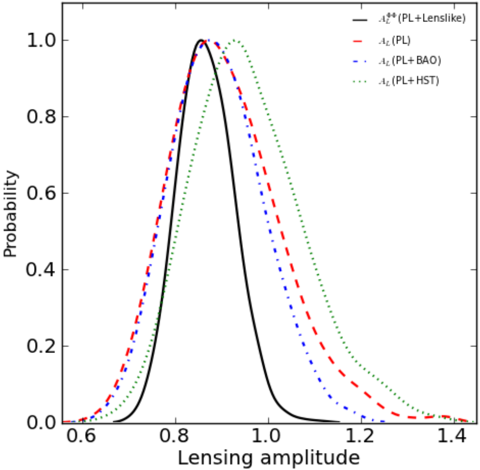
	PLANCK	PLANCK+BAO	PLANCK+HST
Parameters	68% limit	68% limit	68% limit
$\Omega_b h^2$	0.02241 ± 0.00035	0.02234 ± 0.00029	0.02265 ± 0.00033
$\Omega_c h^2$	0.1172 ± 0.0030	0.1180 ± 0.0017	0.1147 ± 0.0026
100θ	1.04172 ± 0.00069	1.04159 ± 0.00057	1.04215 ± 0.00065
τ	0.088 ± 0.012	0.088 ± 0.012	0.091 ± 0.013
n_s	0.9675 ± 0.0086	0.9655 ± 0.0060	0.9740 ± 0.0078
$\log(10^{10} A_s)$	3.082 ± 0.026	3.082 ± 0.024	3.082 ± 0.026
B_0	< 0.185 (95% c.l.)	< 0.175 (95% c.l.)	< 0.198 (95% c.l.)
A_L	$0.91^{+0.10}_{-0.14}$	$0.89^{+0.092}_{-0.11}$	$0.96^{+0.10}_{-0.14}$
Ω_m	0.298 ± 0.018	0.303 ± 0.011	0.283 ± 0.015
Ω_Λ	0.702 ± 0.018	0.697 ± 0.011	0.717 ± 0.015
z_{re}	10.8 ± 1.1	10.8 ± 1.1	10.9 ± 1.1
H_0[km/s/Mpc]	68.7 ± 1.4	68.28 ± 0.85	69.9 ± 1.3
Age/Gyr	13.757 ± 0.060	13.771 ± 0.043	13.708 ± 0.055





- The bimodal behavior of the B_0 posterior distribution appears for all the data sets combinations.
- In $f(\mathrm{R})$ models A_L is in much better agreement with one than in ΛCDM.

Consistency between A_{L} and $A_{\mathrm{L}}^{\phi\phi}$



$$A_{\mathrm{L}}^{\phi\phi} = 0.868^{+0.132}_{-0.113} \text{ @ } 95\% \text{ c.l.}$$

Why the bimodality?

Why the bimodality?

- Varying A_{L} has the same effect of varying B_0 at the high multipoles.
- At low multipoles instead increasing B_0 lowers the integrated Sachs-Wolfe effect plateau, contrary to the effect of an increased H_0 value.
- This favors the match between theory and data even in presence of large H_0 values.
- The competition between these effects creates the local maximum in the posterior distribution.

Conclusions

- Some tensions can arise comparing Planck results with others independent astrophysical probes.

- While the systematic effects can be important it is worth to investigate if this discrepancy can be explained by new physics.

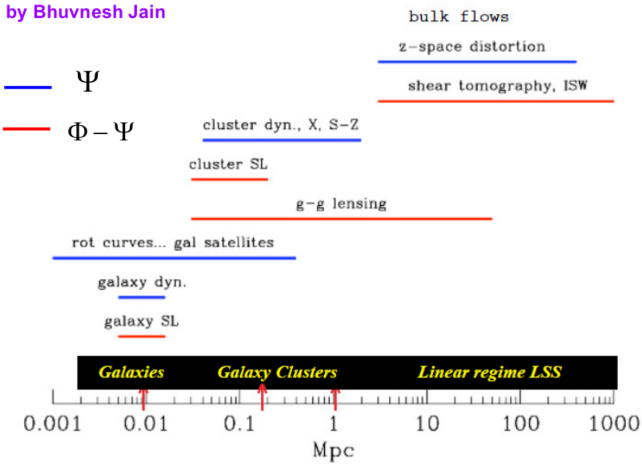
- An interacting dark energy model is compatible with CMB data and even favored when we combine Planck with HST.

- Also $f(\mathrm{R})$ theories are compatible but not favored and we obtain a tight upper limit on the length-scale B_0.

- In both these scenarios the tensions are solved or alleviated indicating that new physics can be a proper explanation to them.

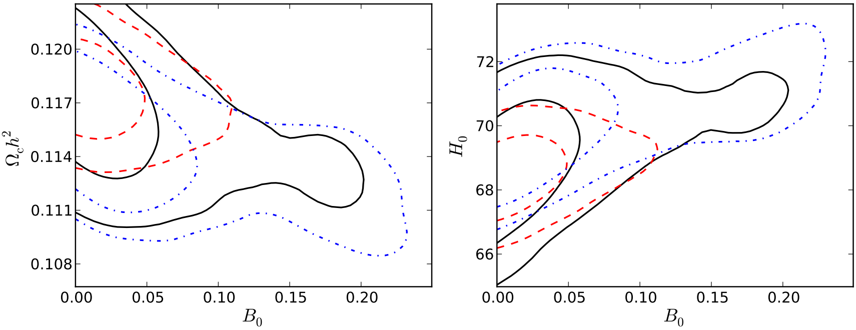

Thank
You

Effect of the potentials

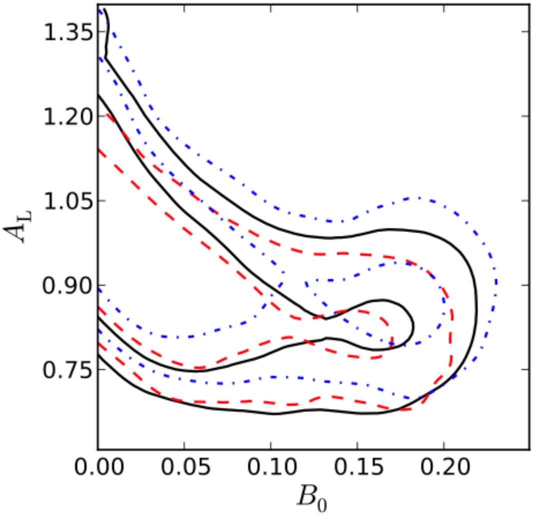


B_0 vs $\Omega_c h^2$ and B_0 vs H_0

PLANCK PLANCK+HST PLANCK+BAO



B_0 vs A_{L}



PLANCK

PLANCK+HST

PLANCK+BAO