Probing alternative theories of gravity with Planck

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based on

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

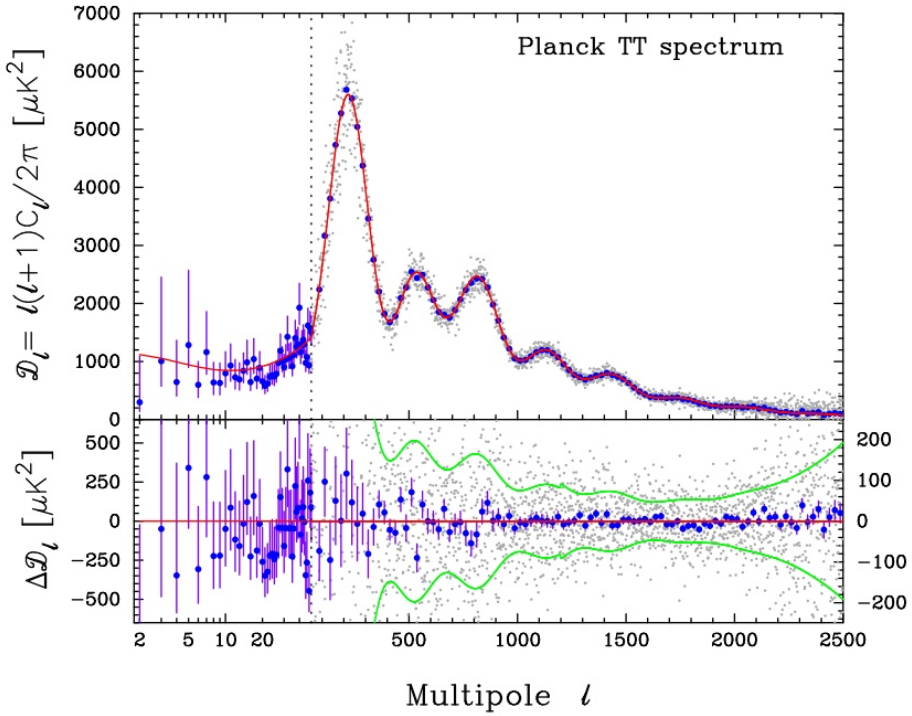
In collaboration with V. Salvatelli

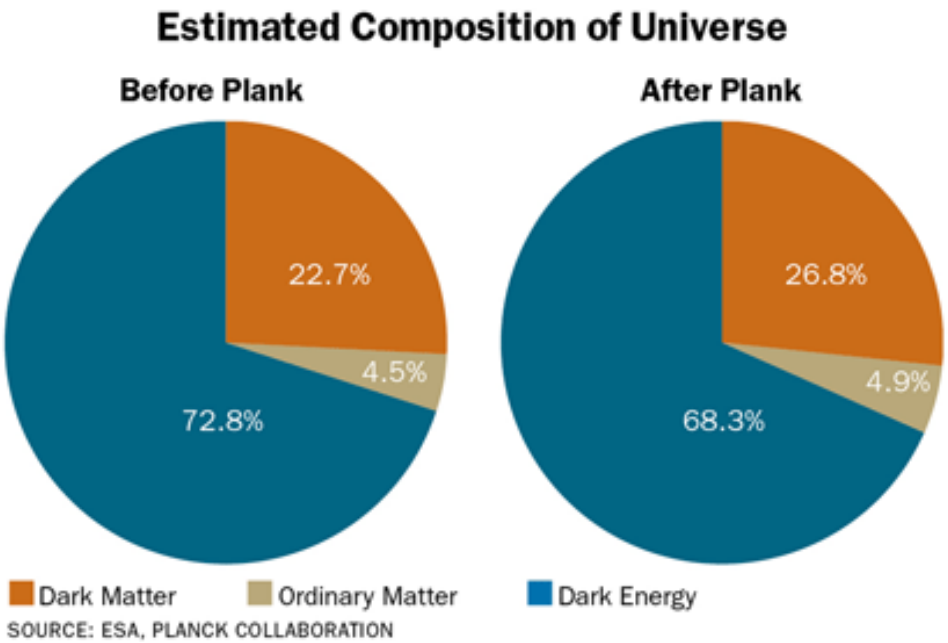
January 16, 2014

Cosmology on the Beach 2014

Planck results

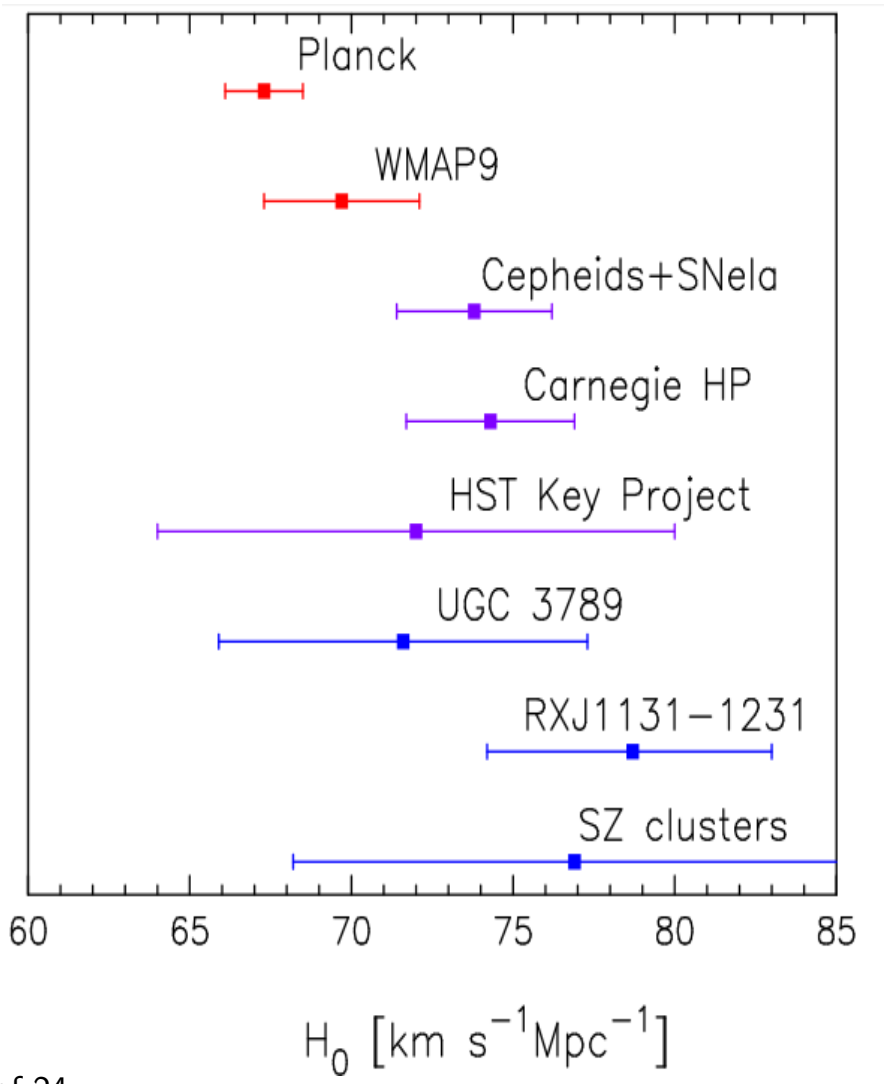
- The Planck experiment has provided new and precise measurements of CMB anisotropy.
  - Angular scales covered up to multipole $\ell \sim 2500$.
  - The new data are in full agreement with the ΛCDM model...
  - ...with some differences in the content of the Universe.





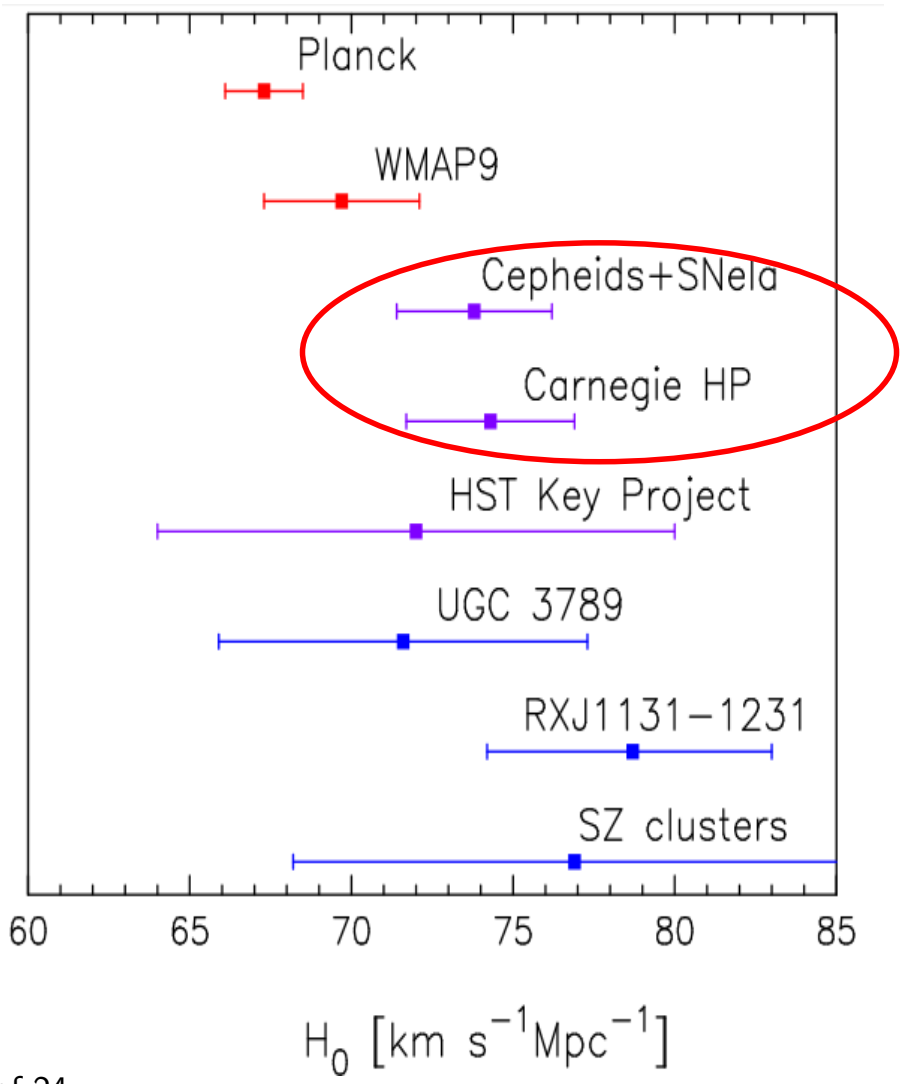
P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5062 [astro-ph.CO].

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



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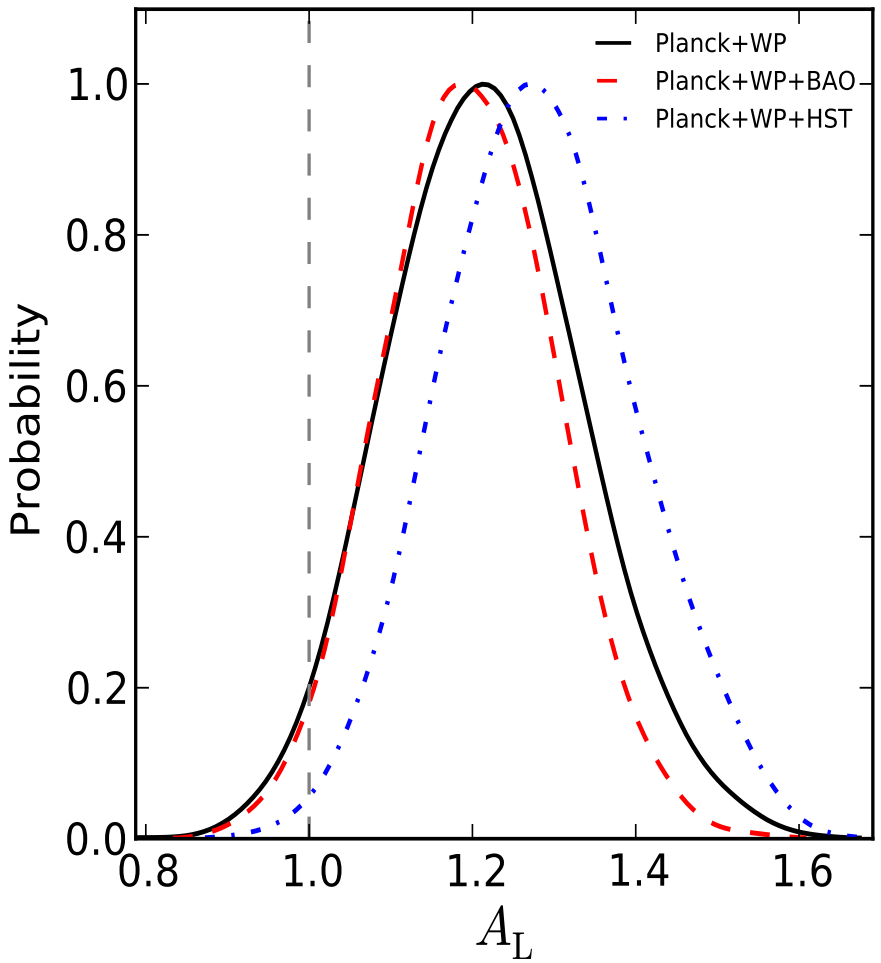
Anomalous lensing signal



- $A_{\rm L}$ scales the lensing power spectrum and modulates the lensing effect in the temperature power spectrum.
- We expect $A_{\rm L} = 1$.
- **There is an evidence for $\mathbf{A_L > 1}$.**

$A_{\rm L} = 1.22^{+0.25}_{-0.22}$ @ 95% c.l.

$A_{\rm L} = 1.20^{+0.21}_{-0.20}$ @ 95% c.l.

$A_{\rm L} = 1.28^{+0.24}_{-0.22}$ @ 95% c.l.

Hints of New Physics?

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

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- Systematic effects.
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- The solution of the Planck tensions could arise from New Physics effects. We focus on:

Alternative theories of gravity

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.

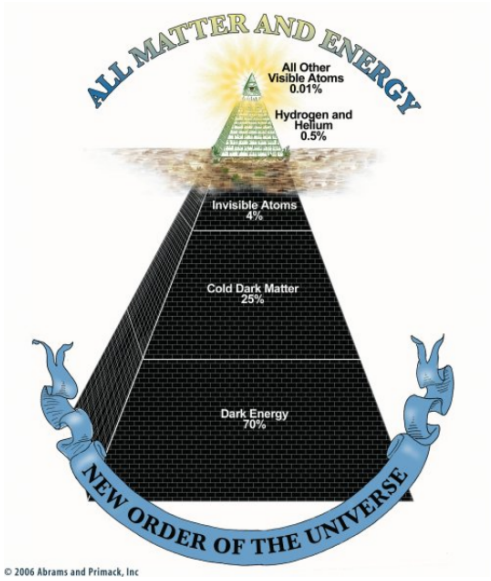
- GR has been tested directly in the Solar System in the weak-field limit.
- Indirect test in the same regime outside the Solar System from binary pulsar.
- **Strong regime tests are missing and gravity is tested very poorly at the large scales.**

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.

Alternative theories of 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

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

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

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

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

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$f(\mathrm{R})$ theories

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

$$f_R(R)R_{\mu\nu} - \frac{1}{2}f(R)g_{\mu\nu} + (g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu)f_R(R) = \kappa T_{\mu\nu}$$

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

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

Parametrization

- Poisson and anisotropy equations for ΛCDM

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

Parametrization

- Poisson and anisotropy equation for alternative theories of gravity

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

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

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

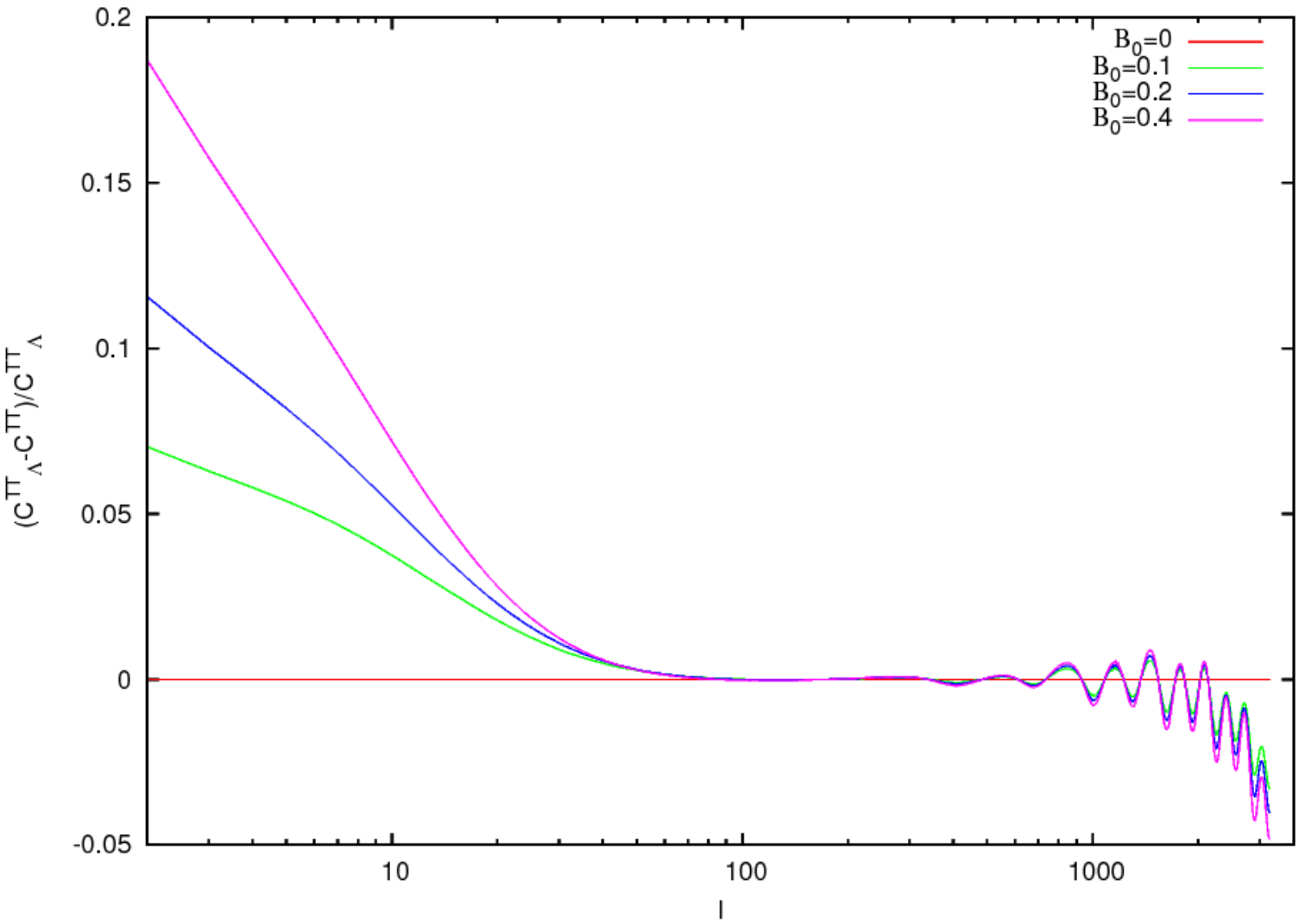
Bertschinger-Zukin parametrization

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

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

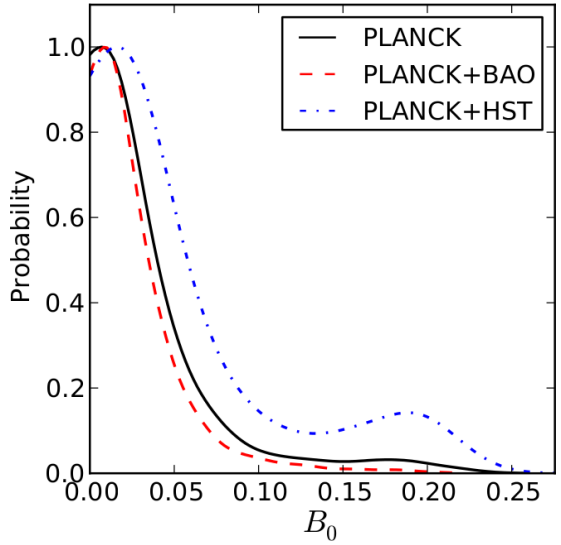
- The only free parameter for $f(\mathrm{R})$ is λ_1^2.
- Usually it is expressed as the present length-scale in units of the horizon scale: $B_0 = 2\lambda_1^2 H_0^2/c^2$.

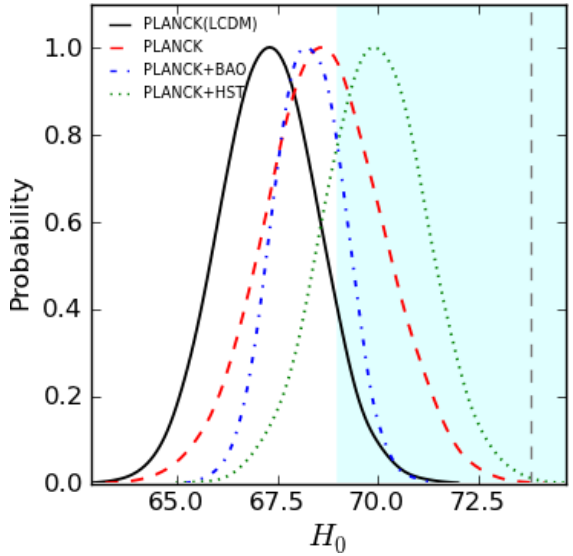
Effect on the Cosmic Microwave Background



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.)	$< \mathbf{0.085}$ **(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

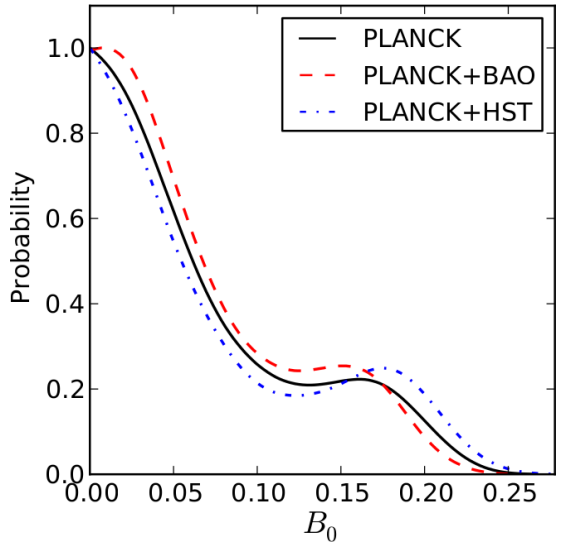


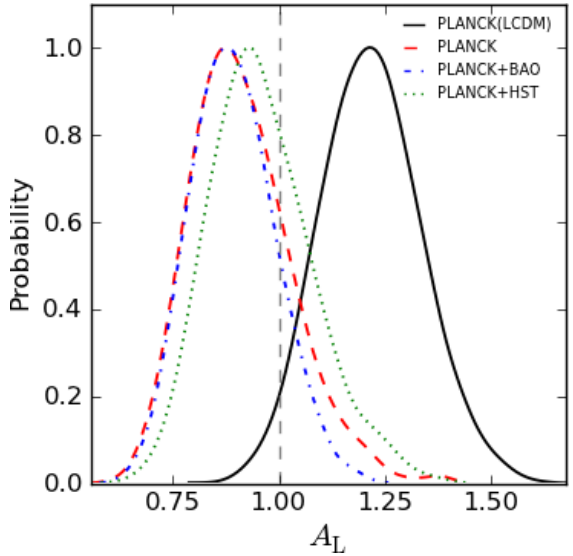


- $f(\mathrm{R})$ models are not favored but we obtain an upper limit on B_0.
- $f(\mathrm{R})$ theories alleviate the H_0 tension between Planck and HST.

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.

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.
- $f(\mathrm{R})$ theories are compatible but not favored and we obtain a tight upper limit on the length-scale B_0.
- In this scenario the tensions are alleviated indicating that new physics can be a proper explanation.

Thank
You

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.

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

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

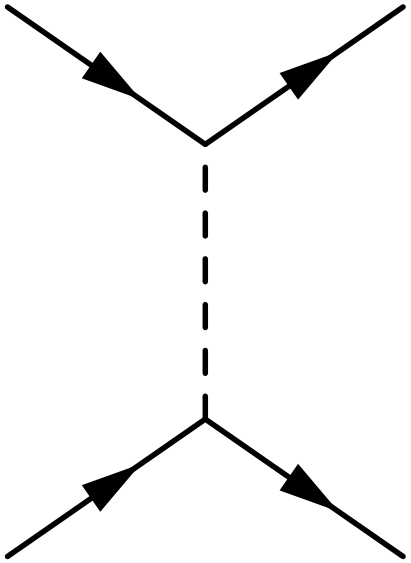
$$V(\phi) = \frac{R f_R(R) - f(R)}{2\kappa f_R^2(R)}$$

- 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 $m_0 \sim H_0 \sim 10^{-43} Gev$.

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



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

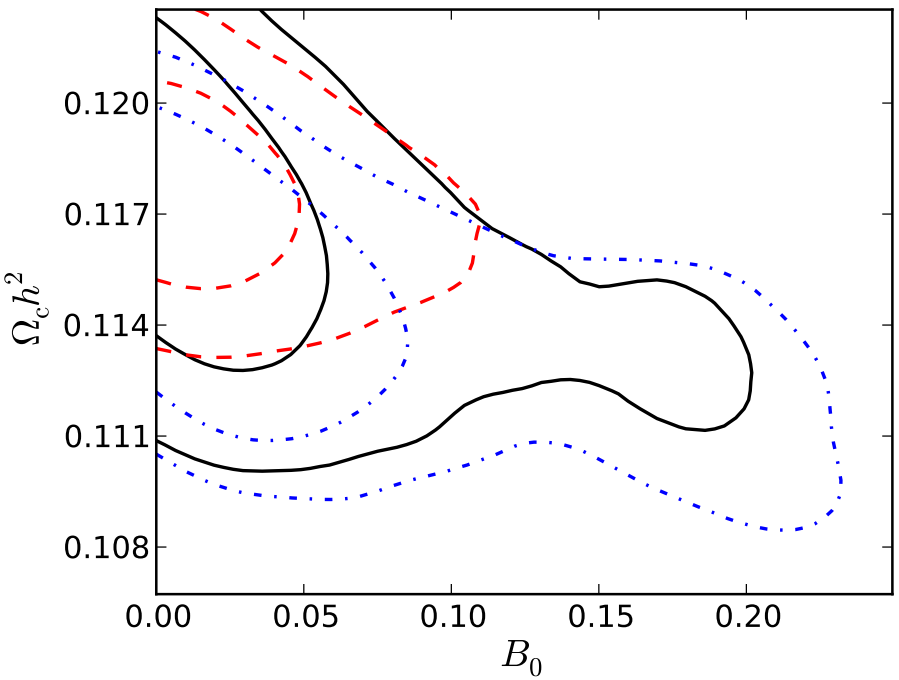
- Constrained by Cassini measurements: $\beta^2 \leq 10^{-5}$.

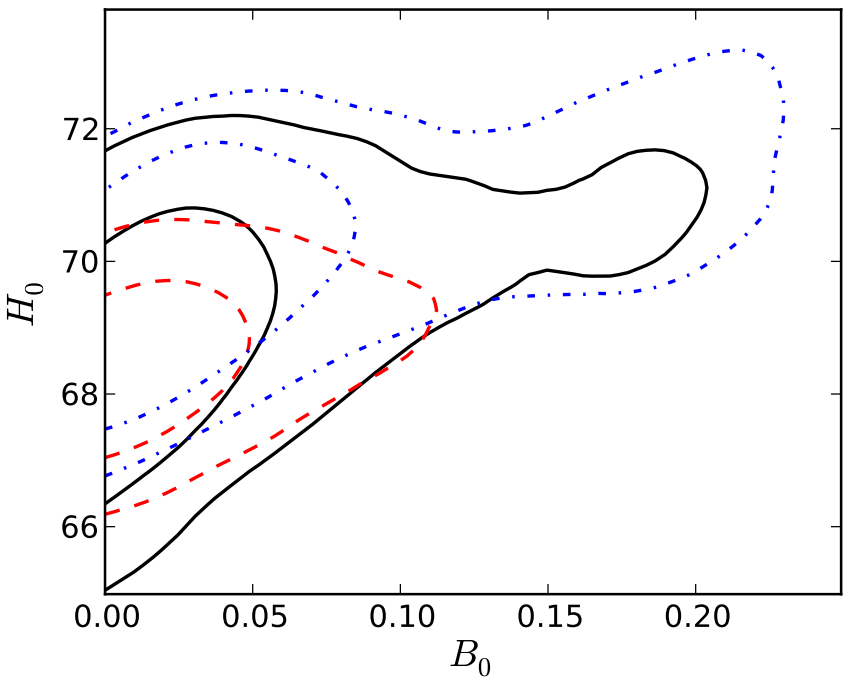
  (B. Bertotti, L. Iess, and P. Tortora, Nature 425 (2003) 374)

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

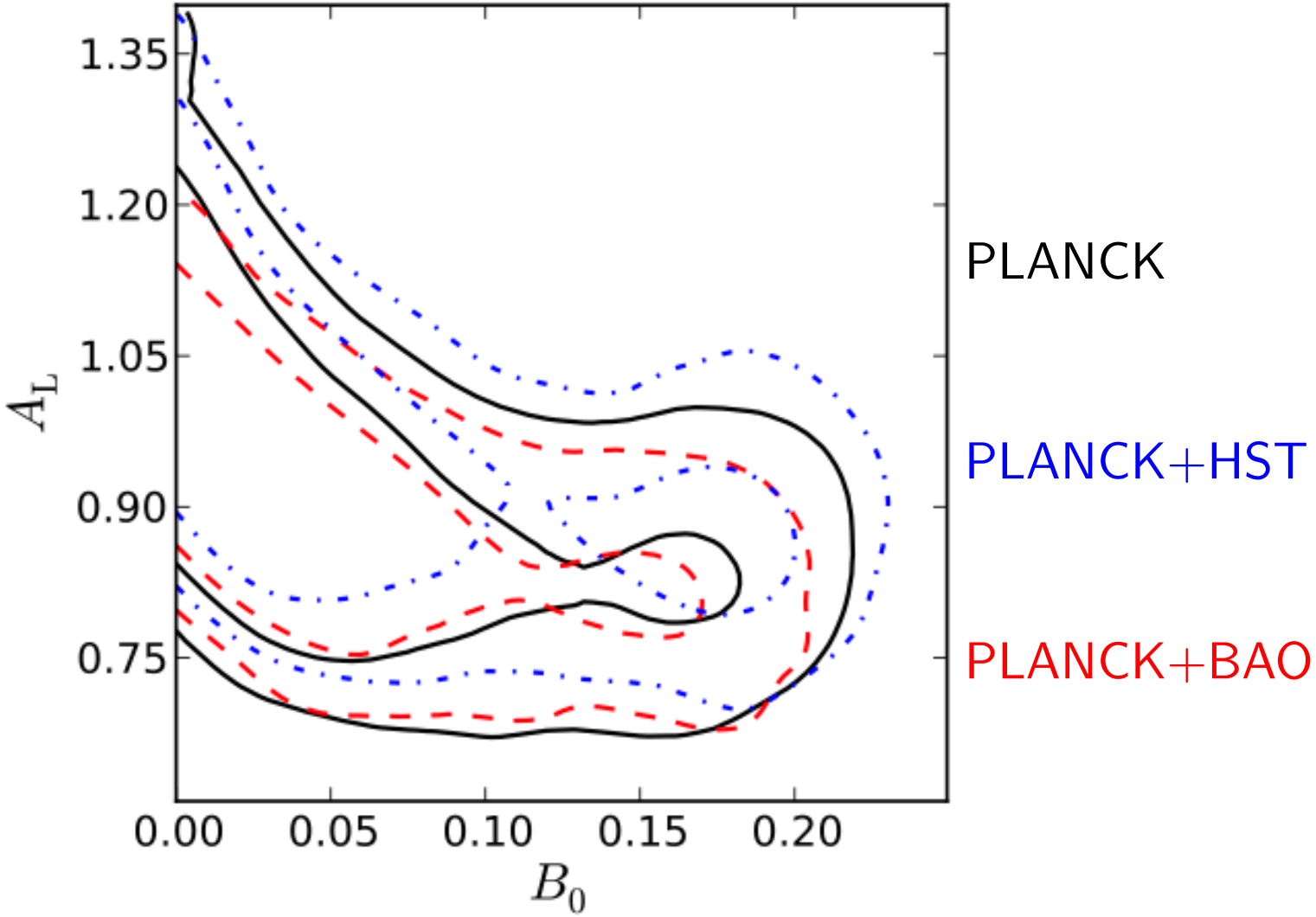
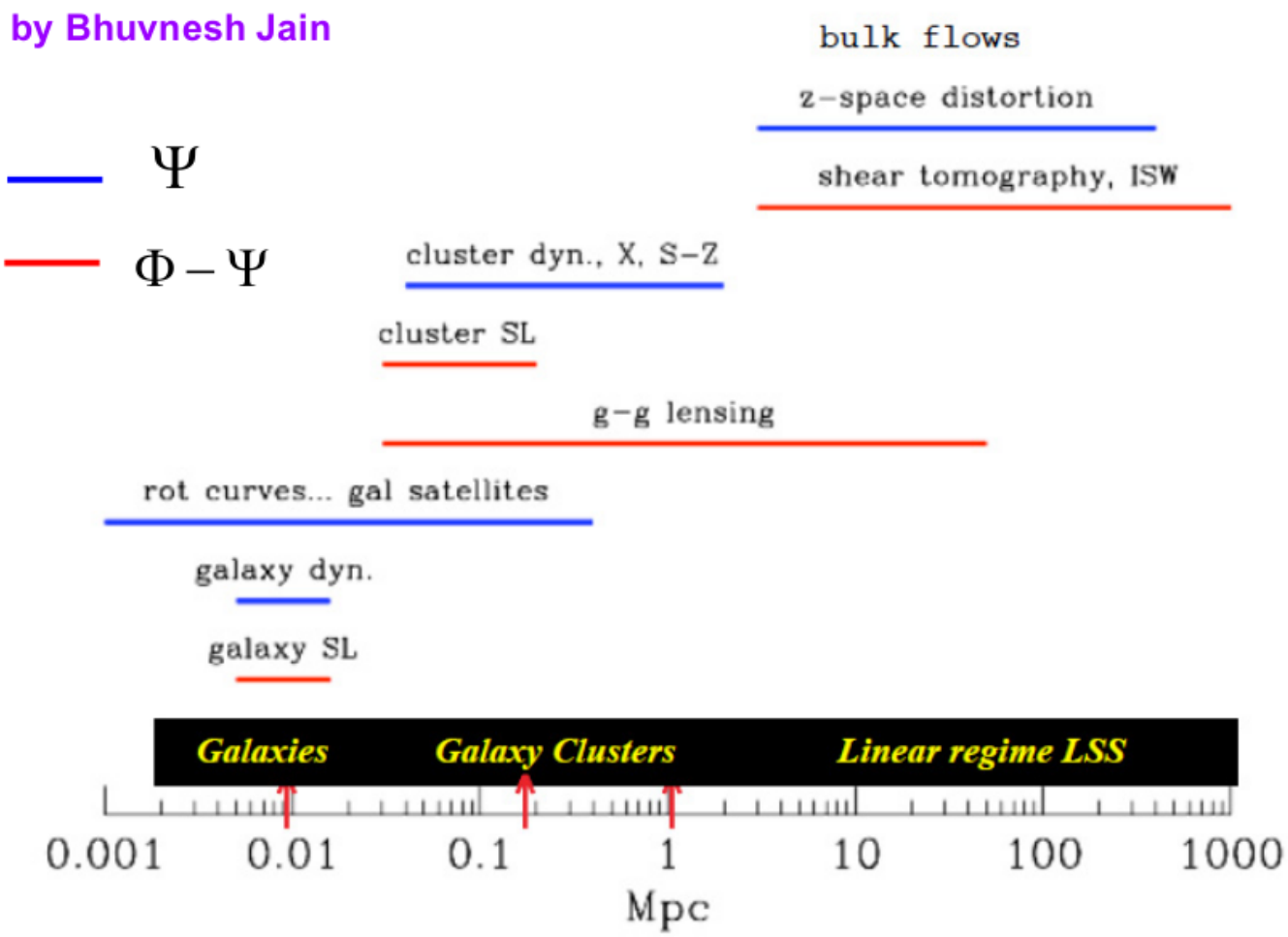
B_0 vs $\Omega_c h^2$ and B_0 vs H_0

PLANCK PLANCK+HST PLANCK+BAO





B_0 vs A_{L}



Effect of the potentials