The Gravity of the Trouble with H_0 and its Possible Origin

Fabio Finelli

INAF OAS Bologna

INFN Bologna

INAF OAS BOLOGNA

VI Jose Plinio Baptista of Cosmology, Pedra Azul, Sept. 19-23, 2022

INFN Istituto Nazionale di Fisica Nucleare

Outline

Preamble: cosmological constraints on Newton's constant

The trouble with H_0

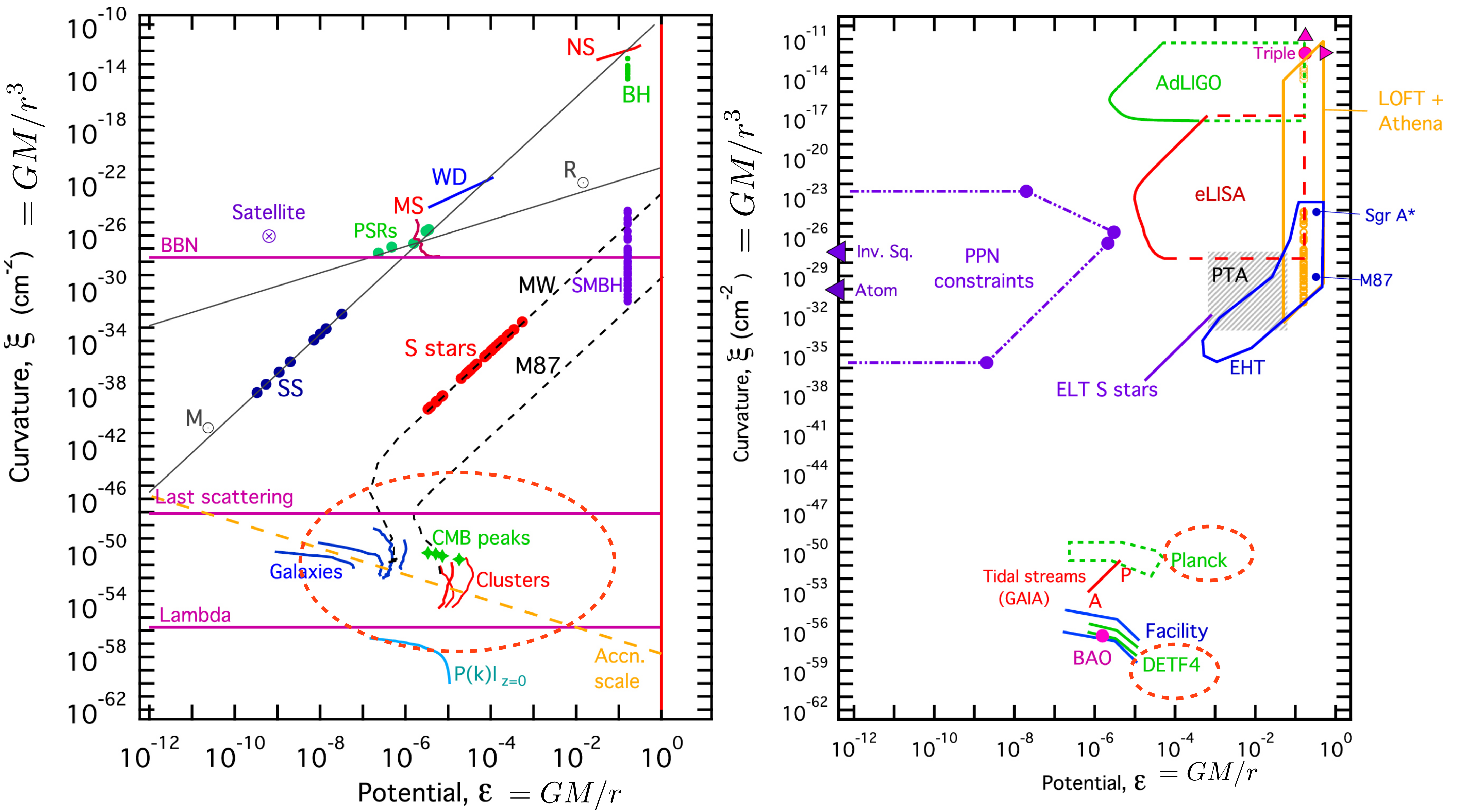
Scalar-tensor gravity and the trouble with H_0

What can we expect from future observations?

How did the gravity of the trouble with H_0 originate?

Summary

Cosmological and astrophysical constraints on gravity



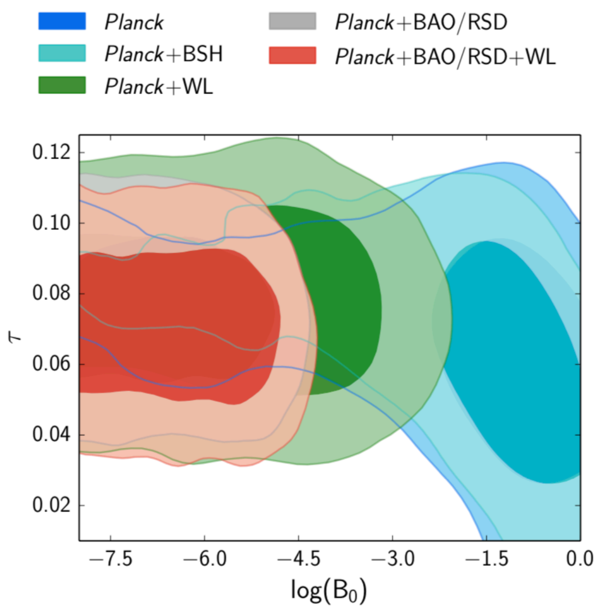
Baker, Psaltis and Skordis (2015)

Cosmological and astrophysical constraints on gravity

Advance in CMB experiments and in galaxy surveys.

CMB can constrain alternative theories of gravity

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}(R + f(R)) + \int d^4x\,\mathcal{L}_{\mathrm{M}}(\chi_i, g_{\mu\nu})$$



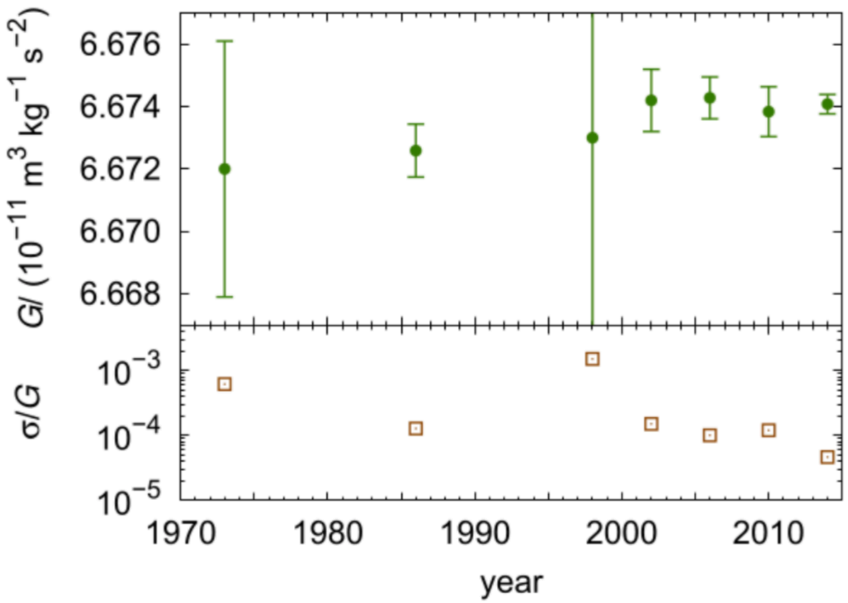
$$B(z) = \frac{f_{RR}}{1+f_R}\frac{H\dot{R}}{\dot{H} - H^2}$$

$$B_0 = B(z=0)$$

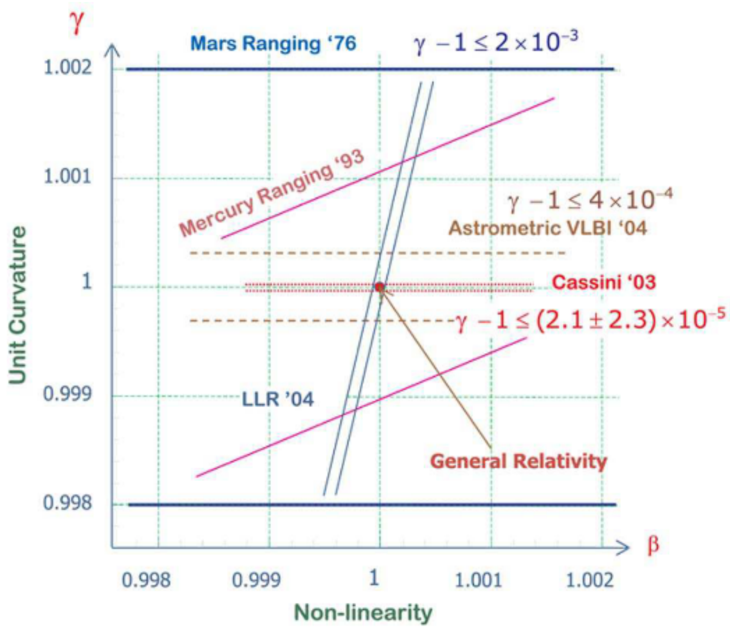
Planck 2015 results. XIV. Dark Energy and Modified Gravity

Laboratory and astrophysical constraints on gravity

Cosmology can constrain the variation of fundamental constants



Rothleitner & Schlamminger 2017

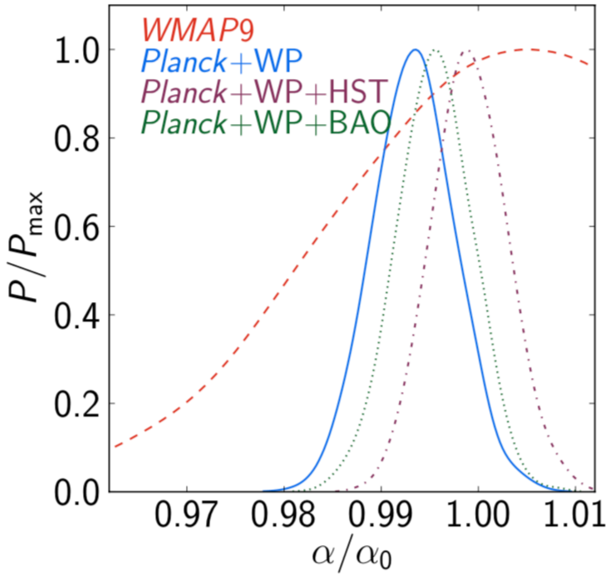


The typical uncertainty from CMB you expect on the value of G is definitely the closest to laboratory limits among the different constant of nature.

Cosmological constraints on fundamental constants

Cosmology can constrain the variation of fundamental constants

$$\alpha_0 = \frac{e^2}{2\epsilon_0 hc}$$



Planck Int. Results. XXIV.

Experimental tests on QED provide an error of 81 part per trillion (Morel et al. 2020).

An archetypal model for Scalar-Tensor gravity (eJBD/IG gravity)

The simplest choice is extended Jordan-Brans-Dicke (eJBD) theory of gravity with a non-vanishing potential:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi}\left(\phi R - \frac{\omega_{\rm BD}}{\phi}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right) - \tilde{V}(\phi) + \mathcal{L}_m\right]$$

which by a field redefinition can be recast in form of Induced Gravity (IG):

$$\gamma\sigma^2 = \frac{\phi}{8\pi} \qquad\qquad \gamma = \frac{1}{4\omega_{\rm BD}}$$

$$S = \int d^4x\sqrt{-g}\left[\frac{\gamma\sigma^2 R}{2} - \frac{g^{\mu\nu}}{2}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma) + \mathcal{L}_m\right] \qquad V(\sigma) \propto \sigma^n \qquad n > 0$$

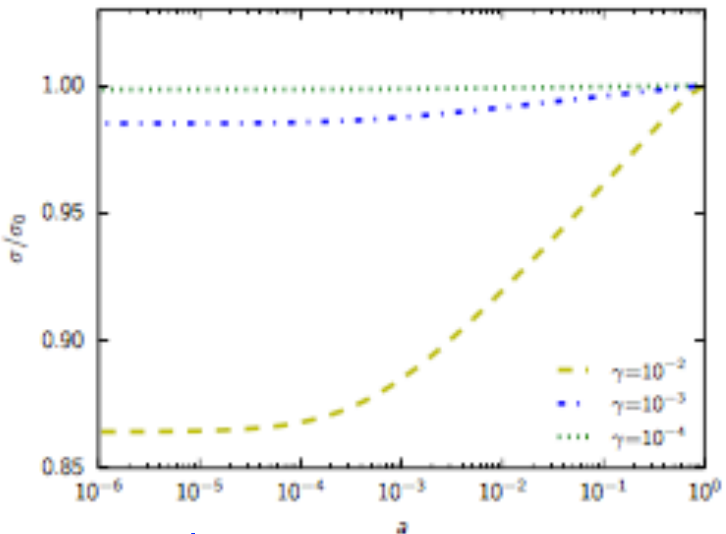
This class of models leads to:

$$\gamma_{\rm PN} - 1 = -\frac{4\gamma}{1+8\gamma} < 0$$

$$\beta_{\rm PN} = 0$$

Background dynamics

Example of background evolution



Umiltà, Ballardini, Finelli, Paoletti (2015)

$$V(\sigma) \propto \sigma^4$$

Zee 1981; Cooper, Venturi 1981; Wetterich 1988; Finelli, Tronconi, Venturi 2007

$$\ddot{\sigma} + 3H\dot{\sigma} + \frac{\dot{\sigma}^2}{\sigma} + \frac{1}{(1+6\gamma)}\left(V_{,\sigma} - \frac{4V}{\sigma}\right) = \frac{1}{(1+6\gamma)}\frac{\sum_i(\rho_i - 3p_i)}{\sigma}$$

$$a(\tau) = \sqrt{\frac{\rho_{r0}}{3\gamma\sigma_I^2}}\tau\left[1 + \frac{\omega}{4}\tau - \frac{5}{16\gamma}\omega^2\tau^2 + \mathcal{O}(\tau^3)\right]$$

$$\sigma(\tau) = \sigma_i\left[1 + \frac{3}{2}\gamma\omega\tau + \mathcal{O}(\tau^2)\right] \qquad \omega = \frac{\rho_{m0}}{\sqrt{3\gamma\rho_{r0}}\sigma_i(1+6\gamma)}$$

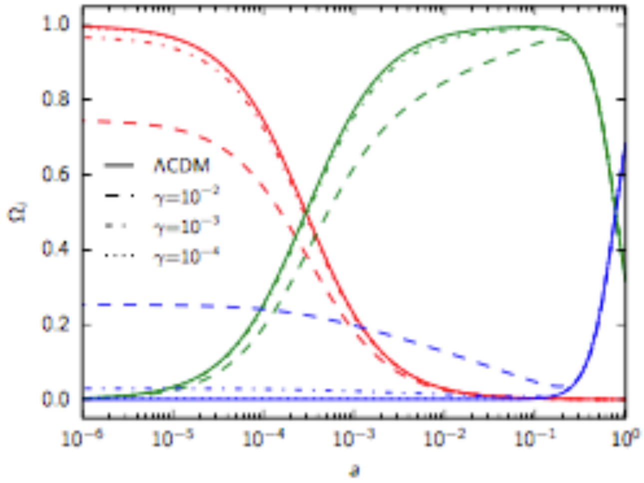
We consider the present value for the scalar field value consistent with the gravitational constant G = 6.67 10^{-8} cm^3 g^{-1} s^{-2} measured in laboratory Cavendish-type:

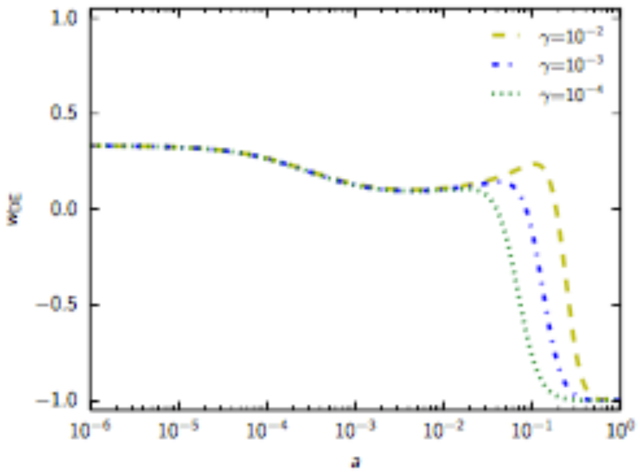
$$G_{\rm eff}(z=0) = G$$

$$\gamma\sigma_0^2 = \frac{1}{8\pi G}\frac{1+8\gamma}{1+6\gamma}$$

Background dynamics

Example of background evolution (example with $V(\sigma) \propto \sigma^4$)





$$\Omega_i = \frac{\rho_i}{3\gamma\sigma_0^2} \qquad i = m\,, r\,, \mathrm{DE} \qquad\qquad w_{\mathrm{DE}} = \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}}$$

$$\rho_{\mathrm{DE}} = \frac{\sigma_0^2}{\sigma^2}\rho_\sigma + (\rho_m + \rho_r)\left(\frac{\sigma_0^2}{\sigma^2} - 1\right) \qquad \rho_\sigma = \frac{\dot{\sigma}^2}{2} + V(\sigma) - 6H\gamma\sigma\dot{\sigma}$$

$$p_{\mathrm{DE}} = \frac{\sigma_0^2}{\sigma^2}p_\sigma + p_r\left(\frac{\sigma_0^2}{\sigma^2} - 1\right) \qquad p_\sigma = \frac{\dot{\sigma}^2}{2} + V(\sigma) + 2\gamma\sigma\ddot{\sigma} + 2\gamma\dot{\sigma}^2 + 4H\sigma\dot{\sigma}$$

Boisseau, Esposito-Farese, Polarski, Starobinsky (2000)

Cosmological Perturbations

For the glory details of the treatment of cosmological perturbations see Umilta' et al. JCAP 08 (2015) 017; Ballardini et al. JCAP 05 (2016) 067.

Modified version of the public Einstein-Boltzmann CLASS code - dubbed CLASSig - including perturbations and solutions for the corresponding initial conditions deep in the radiation era as a Taylor series in conformal time - as for GR.

Necessity to go beyond the so-called quasi-static approximation, which is only valid for small scales deep in the matter dominated regime:

$$ds^2 = -dt^2[1+2\Psi(t,\mathbf{x})] + a^2(t)[1-2\Phi(t,\mathbf{x})]dx^i dx_i$$

$\mu = 1$ for GR

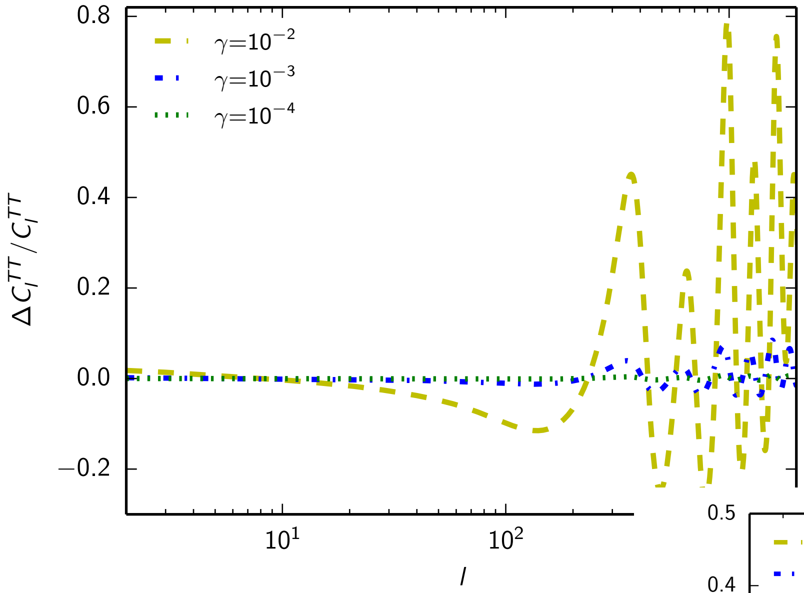
$$k^2\Psi = -4\pi G a^2 \mu(k,a)\,[\Delta + 3(\rho+p)\bar{\sigma}]$$

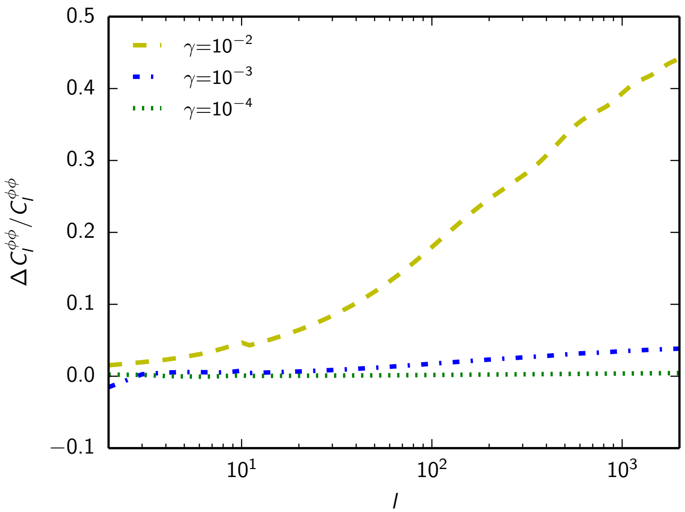
$$k^2[\Phi - \delta(k,a)\Psi] = 12\pi G a^2 \mu(k,a)(\rho+p)\bar{\sigma}$$

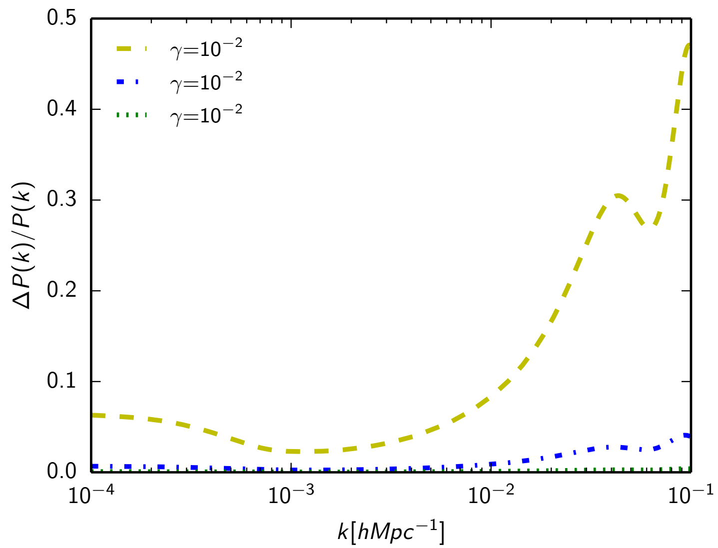
$\delta = 1$ for GR

since we need accurate theoretical predictions both for CMB.

CMB & LSS predictions







Umiltà, Ballardini, Finelli, Paoletti (2015)

CMB predictions for JBD pioneered by *Chen & Kamionkowski (1999), Perrotta, Baccigalupi, Matarrese (1999)*

Cosmological constraints circa 2013

Markov Chain Monte Carlo (MCMC) exploration by MontePython with just only one extra parameter wtr to the Λ CDM model. We chose to sample with flat priors on

	PLANCK 2013 + BAO ΛCDM	PLANCK 2013 + BAO
$10^5\Omega_b h^2$	2215^{+24}_{-25}	2203 ± 25
$10^4\Omega_c h^2$	1187^{+13}_{-14}	1207^{+18}_{-22}
H_0 [km s^{-1} Mpc^{-1}]	$68.4^{+0.6}_{-0.7}$	$69.5^{+0.9}_{-1.2}$
τ	$0.091^{+0.012}_{-0.014}$	$0.088^{+0.012}_{-0.013}$
$\ln(10^{10} A_s)$	$3.089^{+0.024}_{-0.027}$	$3.090^{+0.024}_{-0.026}$
n_s	0.9626 ± 0.0053	0.9611 ± 0.0053
ζ	...	< 0.0047 (95% CL)
$10^3\gamma$	...	< 1.2 (95% CL)
γ_{PN}	...	> 0.9953 (95% CL)
Ω_m	0.301 ± 0.008	0.295 ± 0.009
$\delta G_N/G_N$	...	$-0.015^{+0.013}_{-0.006}$
$10^{13}\dot{G}_N(z=0)/G_N$ [yr^{-1}]	...	$-0.61^{+0.55}_{-0.25}$
$10^{23}\ddot{G}_N(z=0)/G_N$ [yr^{-2}]	...	$0.86^{+0.33}_{-0.78}$

Table 1. Constraints on main and derived parameters (at 68% CL if not otherwise stated).

Umiltà, Ballardini, Finelli, Paoletti (2015)

$$\frac{\delta G_N}{G_N} = \frac{\sigma_i^2 - \sigma_0^2}{\sigma_0^2} \qquad \frac{\dot{G}_N}{G_N} = -2\frac{\dot{\sigma}_0}{\sigma_0}$$

Tightest constraints at the Solar System scale:

$$\gamma_{PN} - 1 = (2.1 \pm 2.3) \times 10^{-5} \; (68\% \text{ CL})$$

Bertotti et al., 2005

Cosmological parameters compatible with those of the LambdaCDM model

eJBD is not required by current data (the improvement in the fit is *O*(1), with one extra parameter)

A larger value for H_0 than in LambdaCDM.

Agreement with Chen et al. 2013, who also compared eJBD with a different potential with Planck DR1 data. The comparison with Avilez & Skordis 2013 (and Acquaviva, Baccigalupi et al. 2001 for pre-Planck data) is more complicate because of different priors.

Combination with H_0 local measurements

The combination with local measurement has been studied with two different estimates for H_0:

$$H_0^* = 73.8 \pm 2.4 \text{ km/s Mpc}$$ Riess et al. (2011)

$$H_0^+ = 70.6 \pm 3.0 \text{ km/s Mpc}$$ Efstathiou (2014)

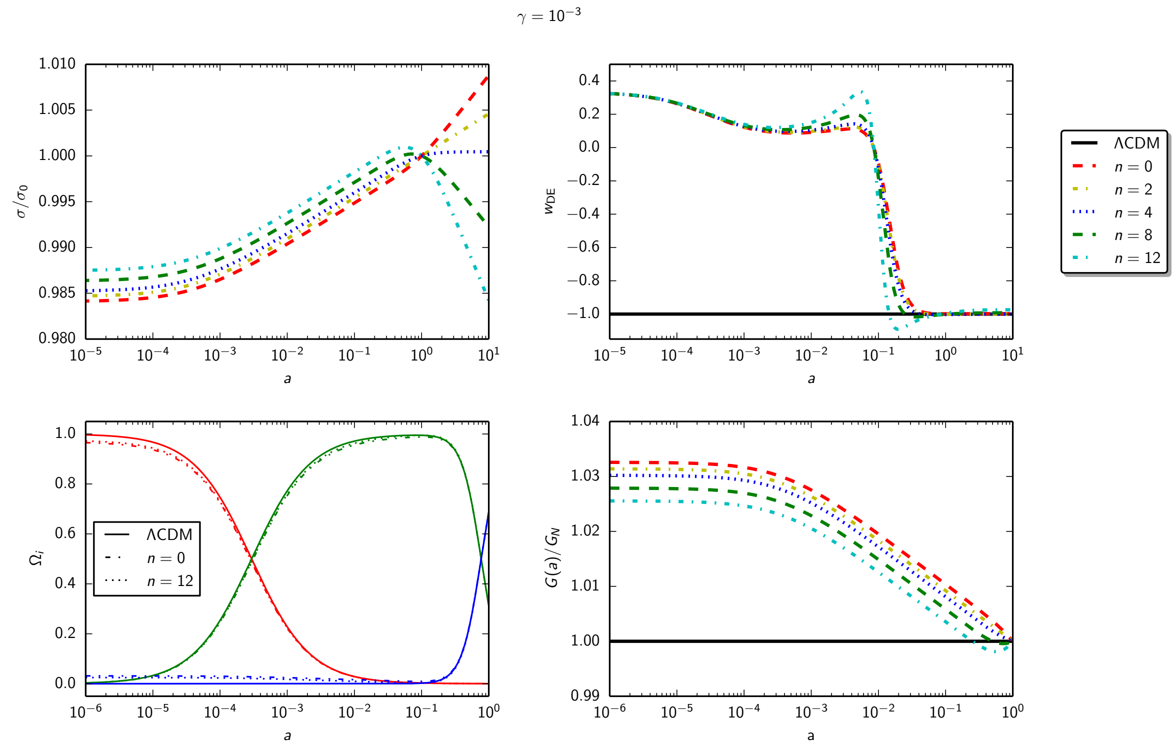
For a fixed potential, the model is so rigid that a high H_0 estimate allows higher values for γ :

$$H_0 = 74.1^{+2.3}_{-2.4} \text{ km/s/Mpc}$$
$$\gamma = 0.0014 \pm 0.0006$$

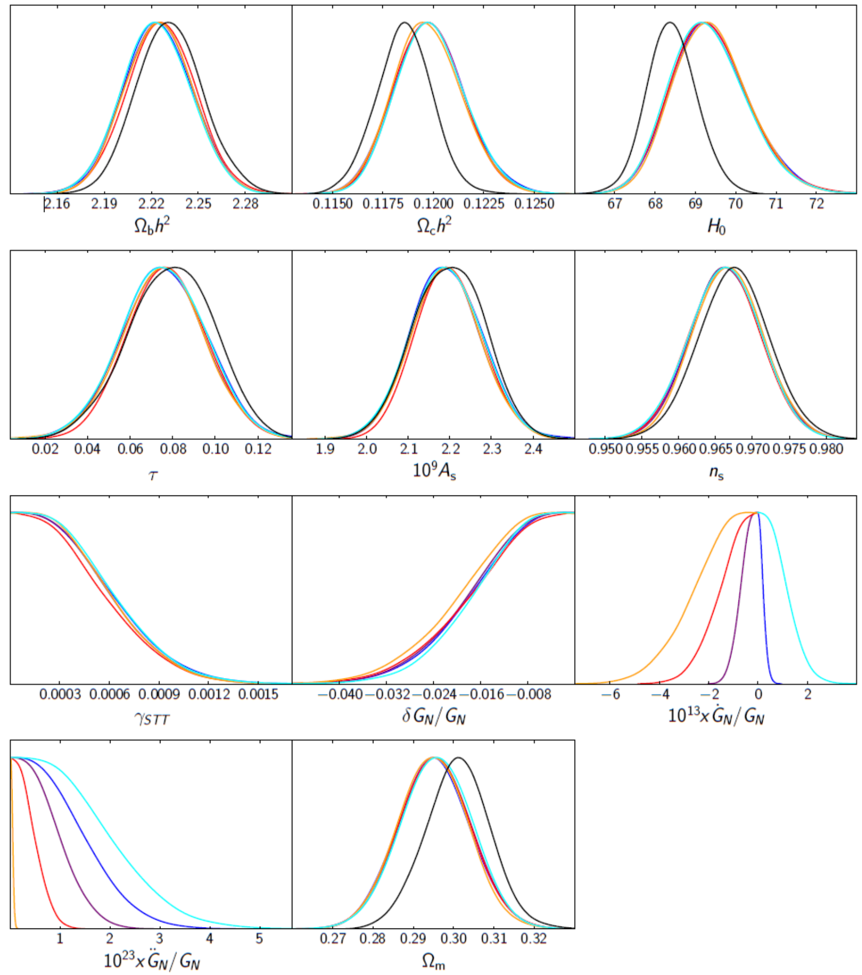
For an estimate of H_0 more compatible with CMB, the pull on γ is much smaller:

$$H_0 = 72.1^{+2.2}_{-3.1} \text{ km/s/Mpc}$$
$$\gamma < 0.0021 (95\,\% \text{ CL})$$

Generalisation to other potentials



Ballardini, Finelli, Umilta', Paoletti (2015)



$$V(\sigma) \propto \sigma^n$$

Very different mechanism from a late transition

of the gravitational constant at $z < 0.1$ (Marra, Perivolaropoulos 2021)

Outline

Preamble: CMB (o cosmological constraints) constraints on Newton's constant

The trouble with H_0

Scalar-tensor gravity and the H_0 trouble

What can we expect from future observations?

How did the gravity of the trouble with H_0 originate?

The trouble with H_0

The (model dependent) determination of H_0 by Planck 2018 was in 3.6σ tension with the most recent local measurement by Riess et al. 2018

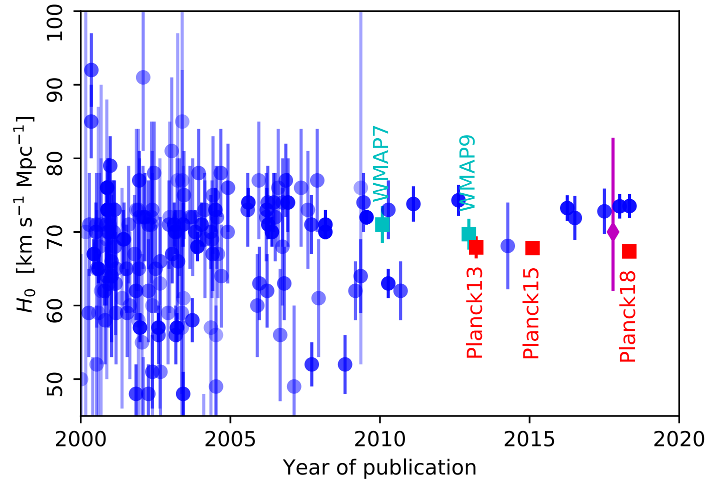
H_0 [km s^{-1} Mpc^{-1}]= 73.5 ± 1.6 at 68 % CL

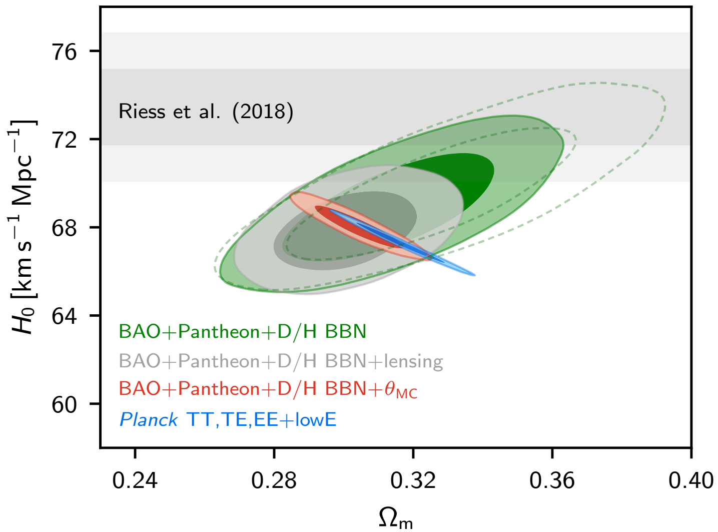
This is NOT a tension with Planck data only: WMAP 9 yr + BAO also determines a value of H_0 which is 2.9σ lower than Riess et al. 2018.

A lower value of H_0 is also found without using the information in the CMB power spectra at all (DES Coll. 2017, Planck Coll. 2018).

This tension is now at 5σ with the most recent Riess et al. 2021 result:

H_0 [km s^{-1} Mpc^{-1}]= 73.1 ± 1.1 at 68 % CL





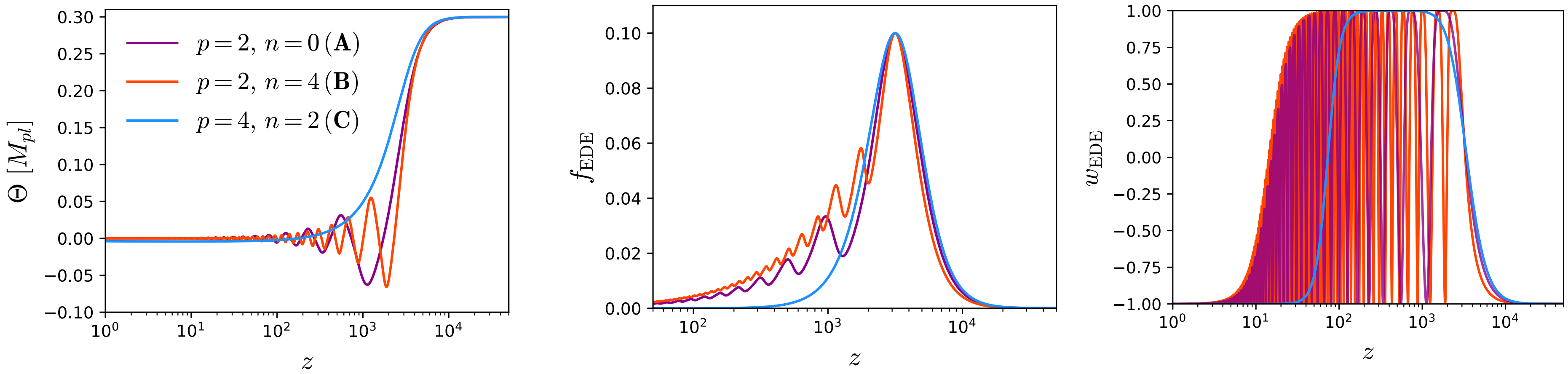
The trouble with H_0

Late time solutions: these models are very constrained by BAO and P(k).

Early time solutions: N_{eff} , eJBD, Early Dark Energy (EDE), …

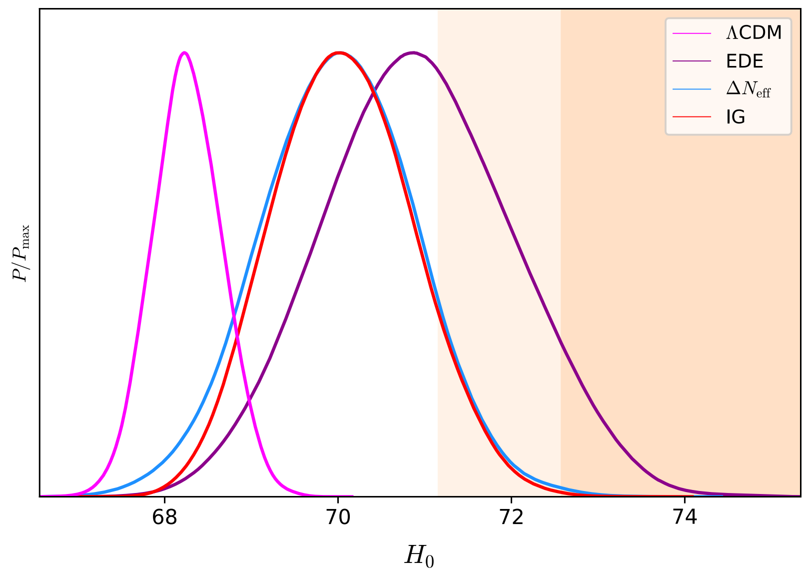
EDE $$V(\sigma) = V_0\left[1-\cos\left(\frac{\sigma}{f}\right)\right]^n$$ *Poulin, Smith, Karwal, Kamionkowski 2018*

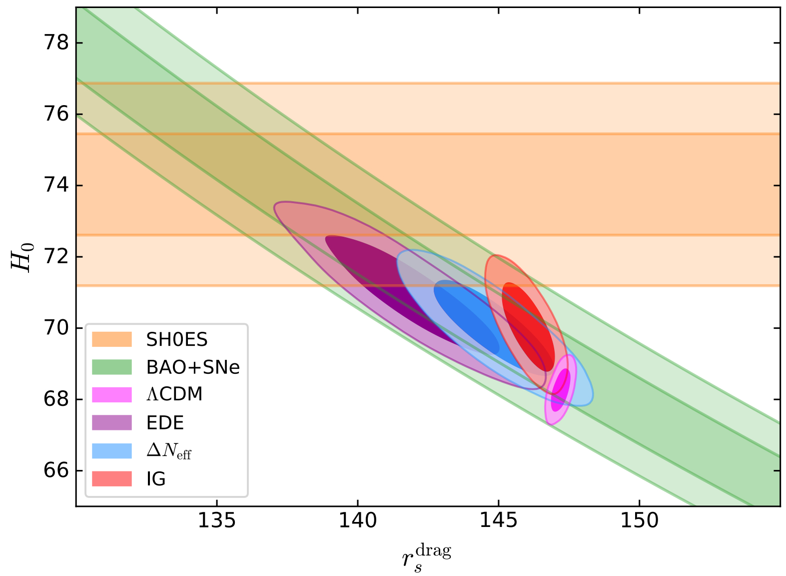
See also: $$V(\sigma) = \frac{\lambda\sigma^4}{4}$$ *Agrawal, Cyr-Racine, Pinner, Randall 2019*



Other potentials are possible, such as α attractor like potentials, see e.g. Braglia, Emond, Finelli, Gumrukcuoglu, Koyama (2020)

The trouble with H_0





M. Braglia, Ph. D. Thesis (2020)

Outline

Preamble: CMB (o cosmological constraints) constraints on Newton's constant

The trouble with H_0

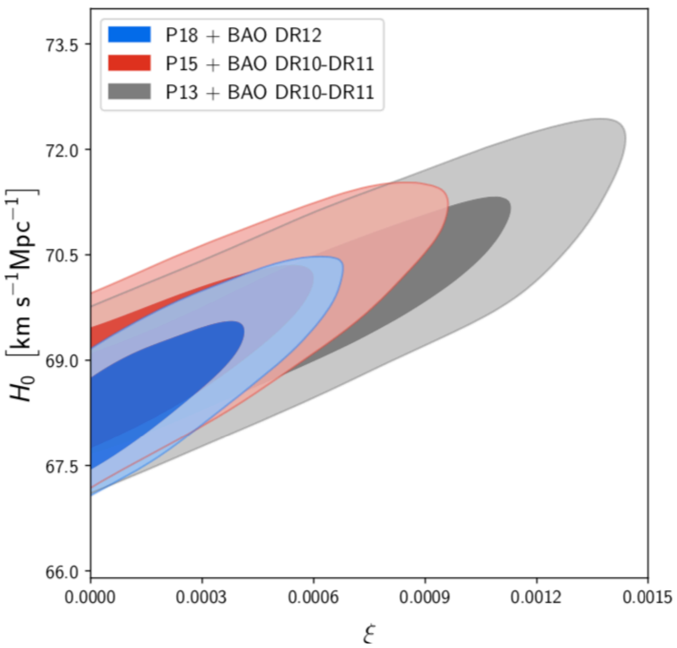
Scalar-tensor gravity and the trouble with H_0

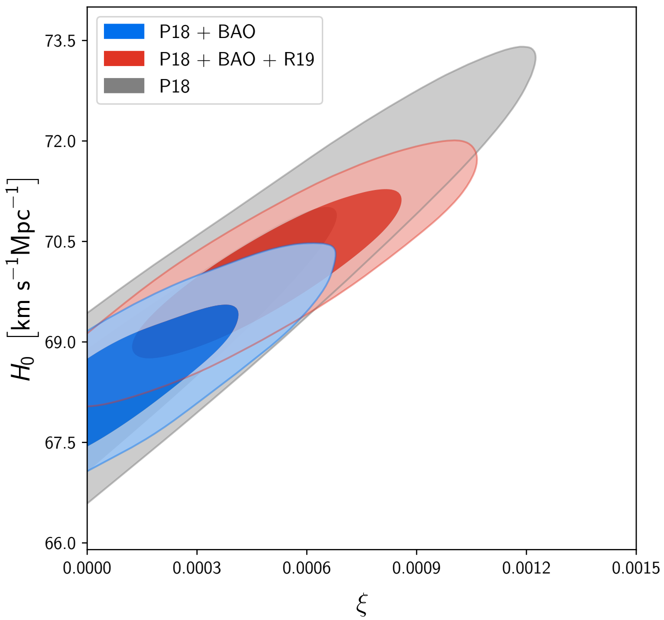
What can we expect from future observations?

How did the gravity of the trouble with H_0 originate?

Scalar-tensor gravity and H_0

Planck polarisation kicks in





Note the change in notation:
γ is now ξ

Scalar-tensor gravity

This is the simplest extension of GR explaining the acceleration of the Universe among the most general Horndeski action:

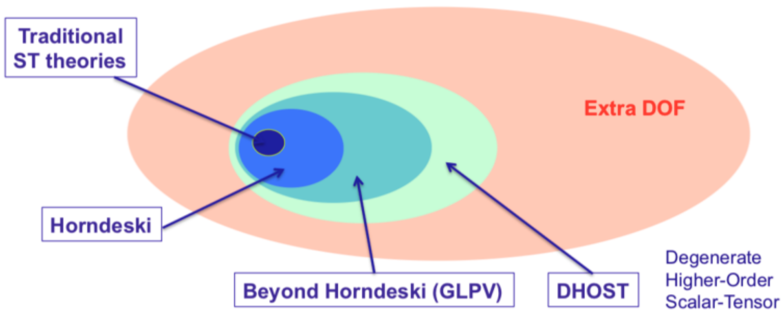
$$S = \int d^4x\sqrt{-g}\left[\sum_{i=2}^{5} L_i^\sigma + \mathcal{L}_m\right]$$

$$L_2^\sigma \equiv G_2(\sigma,\chi)\,, \qquad G_2(\chi,\sigma) = \chi - V(\sigma) \qquad \chi = -\frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma$$

$$L_3^\sigma \equiv G_3(\sigma,\chi)\Box\sigma\,,$$

$$L_4^\sigma \equiv G_4(\sigma,\chi)^{(4)}R + G_{4,\chi}(\sigma,\chi)\left((\Box\sigma)^2 - \sigma^{;\mu\nu}\sigma_{;\mu\nu}\right)\,,$$

$$L_5^\sigma \equiv G_5(\sigma,\chi)^{(4)}G_{\mu\nu}\sigma^{;\mu\nu} - \frac{1}{6}G_{5,\sigma}(\sigma,\chi)\left((\Box\sigma)^3 - 3\sigma_{;\mu\nu}\phi^{;\mu\nu}\Box\sigma + 2\sigma_{;\mu\nu}\sigma^{;\nu\rho}\sigma^{;\mu}{}_{\rho}\right)\,.$$



	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence Traditional ST/$f(R)$ Kinetic Gravity Braiding	quartic/quintic Galileons Fab Four de Sitter Horndeski $G_{\mu\nu}\phi^\mu\phi^\nu$, $f(\phi)$·Gauss-Bonnet
beyond H.	Derivative Conformal Disformal Tuning quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV quadratic DHOST with $A_1 \neq 0$ cubic DHOST
	Viable after GW170817	Non-viable after GW170817

Minimal scalar-tensor gravity

Traditional scalar-tensor theories

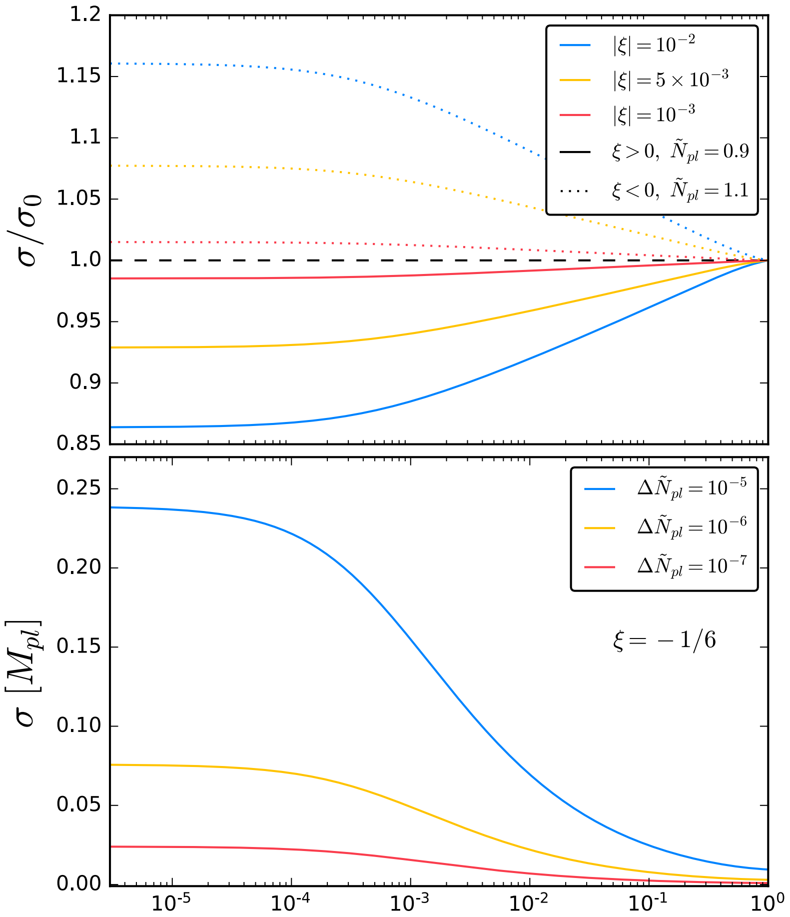
$$S = \int d^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R - \frac{g^{\mu\nu}}{2}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma) + \mathcal{L}_m\right]. \qquad F(\sigma) = N_{\rm pl}^2 + \xi\sigma^2$$

$$\gamma_{\rm PN} = 1 - \frac{F_{,\sigma}^2}{F + 2F_{,\sigma}^2}$$

$$\beta_{\rm PN} = 1 + \frac{F\,F_{,\sigma}}{8F + 12F_{,\sigma}^2}\frac{d\gamma_{\rm PN}}{d\sigma}$$

$$G_{\rm eff} = \frac{1}{8\pi F}\left(\frac{2F + 4F_{,\sigma}^2}{2F + 3F_{,\sigma}^2}\right)$$

$$G_{\rm eff}(z=0) = G$$



$$V(\sigma) \propto F^2(\sigma)$$

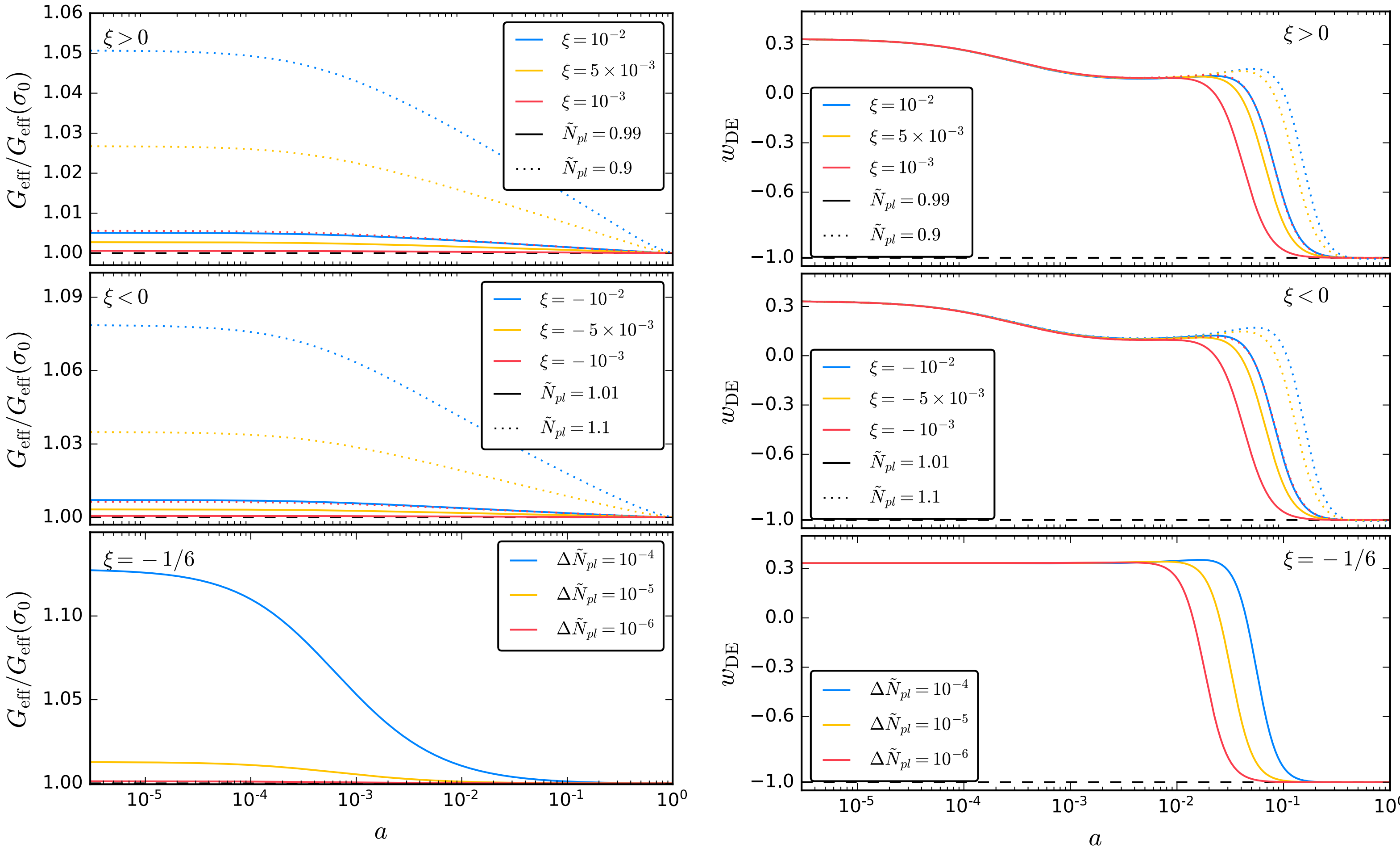
Rossi, Ballardini, Braglia, Finelli, Paoletti, Starobinsky, Umilta' 2019

Minimal scalar-tensor gravity

Traditional scalar-tensor theories

$$S = \int d^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R - \frac{g^{\mu\nu}}{2}\partial_\mu\sigma\partial_\nu\sigma - V(\sigma) + \mathcal{L}_m\right]$$

Rossi, Ballardini, Braglia, Finelli, Paoletti, Starobinsky, Umilta' 2019



$$F(\sigma) = N_{\rm pl}^2 + \xi\sigma^2$$

$$V(\sigma) \propto F^2(\sigma)$$

Amendola, 1999

INAF OAS BOLOGNA

INFN Istituto Nazionale di Fisica Nucleare

Minimal scalar-tensor gravity

	P18	P18 + BAO	P18 + BAO + R19
ω_b	0.02244 ± 0.00015	0.02241 ± 0.00013	0.0250 ± 0.0013
ω_c	0.1197 ± 0.0012	0.11990 ± 0.00094	0.1195 ± 0.0010
H_0 [km s^{-1}Mpc^{-1}]	$69.0^{+0.7}_{-1.2}$ (3.2σ)	$68.62^{+0.47}_{-0.66}$ (3.6σ)	$69.64^{+0.65}_{-0.73}$ (2.8σ)
τ	$0.0554^{+0.0064}_{-0.0081}$	$0.0551^{+0.0058}_{-0.0076}$	$0.0562^{+0.0066}_{-0.0077}$
$\ln(10^{10} A_s)$	$3.048^{+0.013}_{-0.016}$	$3.047^{+0.011}_{-0.015}$	$3.050^{+0.013}_{-0.015}$
n_s	0.9684 ± 0.0047	0.9668 ± 0.0039	0.9707 ± 0.0040
N_{pl} [M$_{pl}$]	< 1.000028 (95% CL)	< 1.000018 (95% CL)	< 1.000031 (95% CL)
γ_{PN}	> 0.999972 (95% CL)	> 0.999982 (95% CL)	> 0.999969 (95% CL)
β_{PN}	< 1.0000023 (95% CL)	< 1.0000015 (95% CL)	< 1.0000025 (95% CL)
$\delta G_N/G_N$	> -0.026 (95% CL)	> -0.017 (95% CL)	> -0.029 (95% CL)
$10^{13}\dot{G}_N/G_N$ [yr^{-1}]	$> -3.8 \times 10^{-9}$ (95% CL)	$> -2.5 \times 10^{-9}$ (95% CL)	$> -4.2 \times 10^{-9}$ (95% CL)
G_N/G	> 0.999986 (95% CL)	> 0.999991 (95% CL)	> 0.999985 (95% CL)
Ω_m	$0.299^{+0.011}_{-0.009}$	0.3023 ± 0.0061	0.2928 ± 0.0064
σ_8	$0.832^{+0.011}_{-0.007}$	$0.8299^{+0.0060}_{-0.0088}$	$0.8364^{+0.0089}_{-0.011}$
r_s [Mpc]	$146.71^{+0.46}_{-0.33}$	$146.82^{+0.37}_{-0.28}$	$146.53^{+0.51}_{-0.42}$
$\Delta\chi^2$	2.2	0.8	−1.7

$$\xi = -1/6$$

$$G_{\rm eff}(z=0) = G$$

$$H_0 = 70.20 \pm 0.83 \ [\mathrm{km/s/Mpc}]$$ *Planck 15 + BAO + H₀*

$$H_0 = 69.64^{+0.65}_{-0.73} \ [\mathrm{km/s/Mpc}]$$ *Planck 18 + BAO + H₀*

$$0 < 1 - \gamma_{\rm PN} \lesssim 4 \times 10^{-5}$$

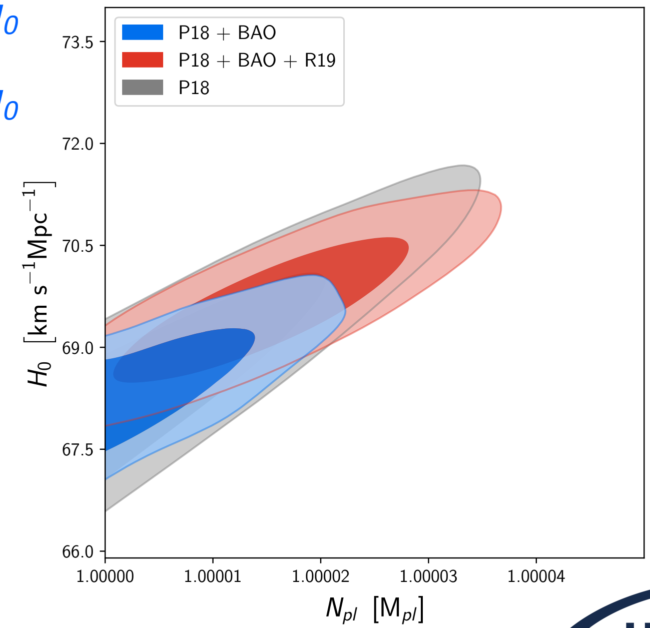
$$0 < \beta_{\rm PN} - 1 \lesssim 3 \times 10^{-6}$$

Rossi, Ballardini, Braglia, Finelli, Paoletti, Starobinsky, Umilta' 2019

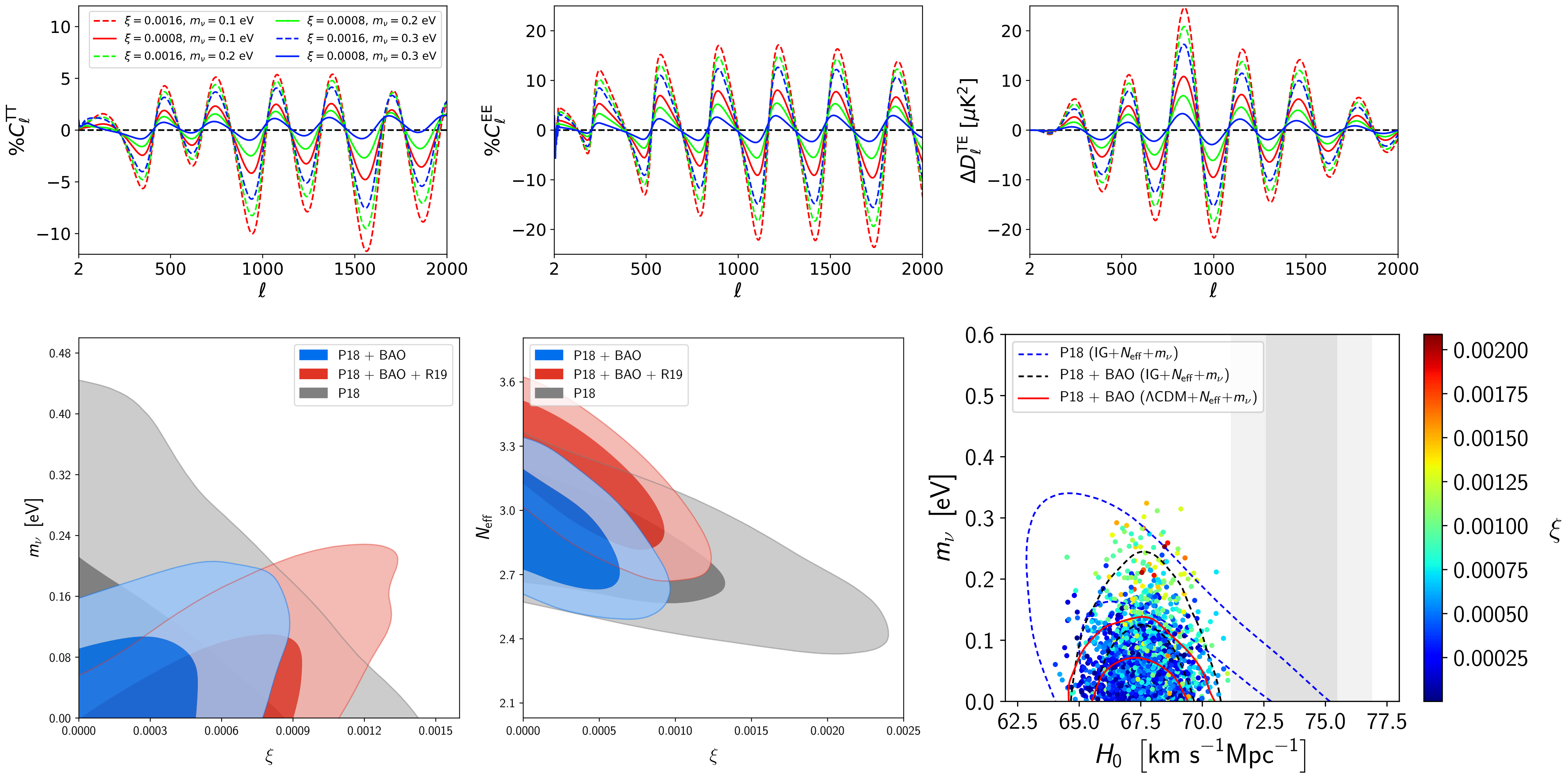
Ballardini, Braglia, Finelli, Paoletti, Starobinsky, Umilta' 2020

$$\gamma_{\rm PN} - 1 = (2.1 \pm 2.3) \times 10^{-5}$$ *Bertotti et al., 2005*

$$\beta_{\rm PN} - 1 = (4.1 \pm 7.8) \times 10^{-5}$$ *Will et al., 2014*



Minimal scalar-tensor gravity and neutrinos



Ballardini, Braglia, Finelli, Paoletti, Starobinsky, Umilta' 2020

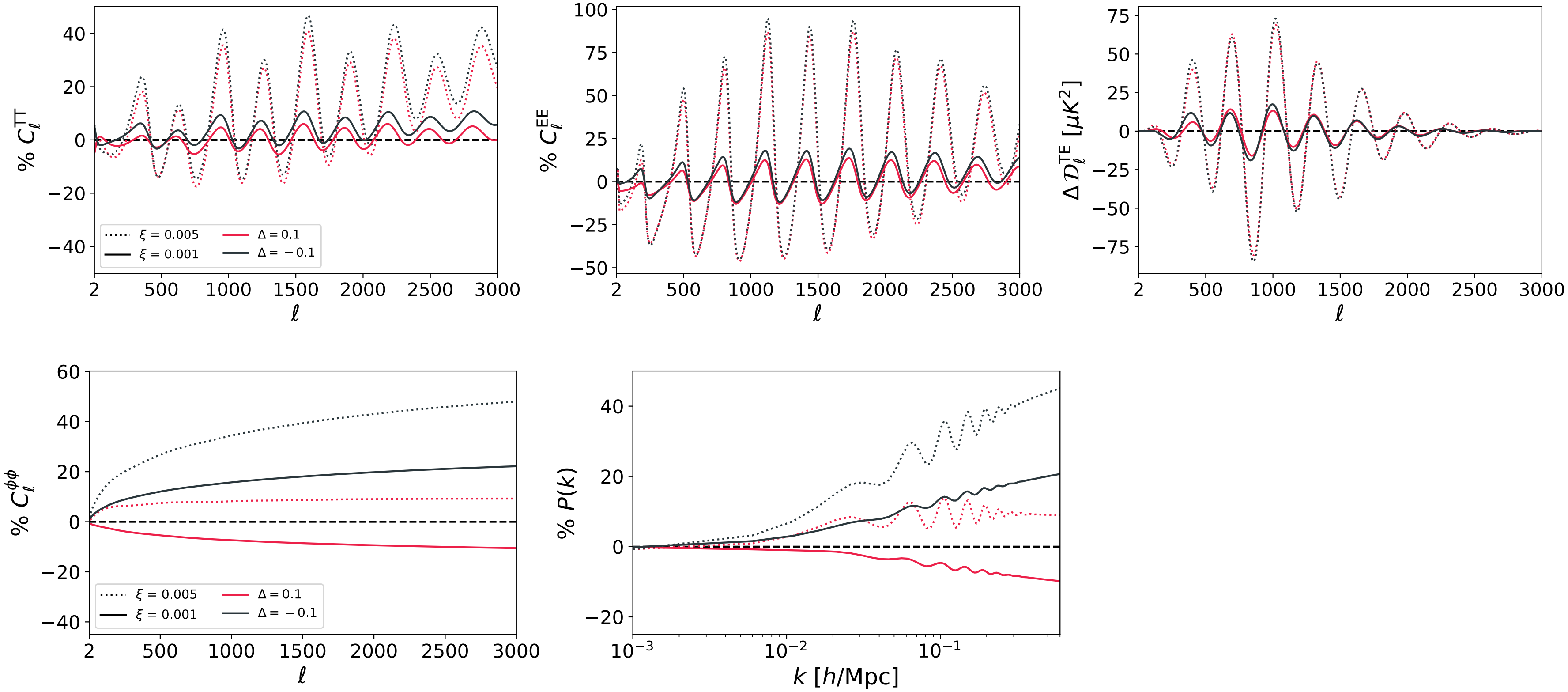
Minimal scalar-tensor gravity

In order to consider the most general and conservative constraints we have also analysed the case

$$G_{\rm eff}(z=0) = (1+\Delta)^2 G$$

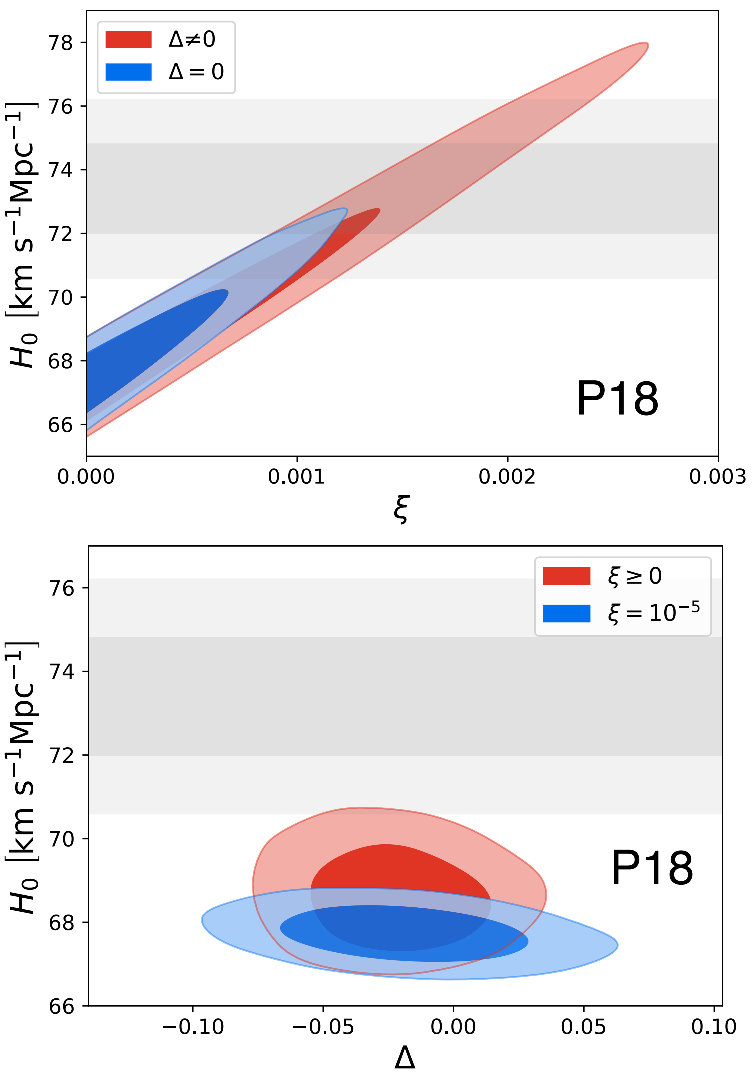
jointly with the coupling to the curvature.

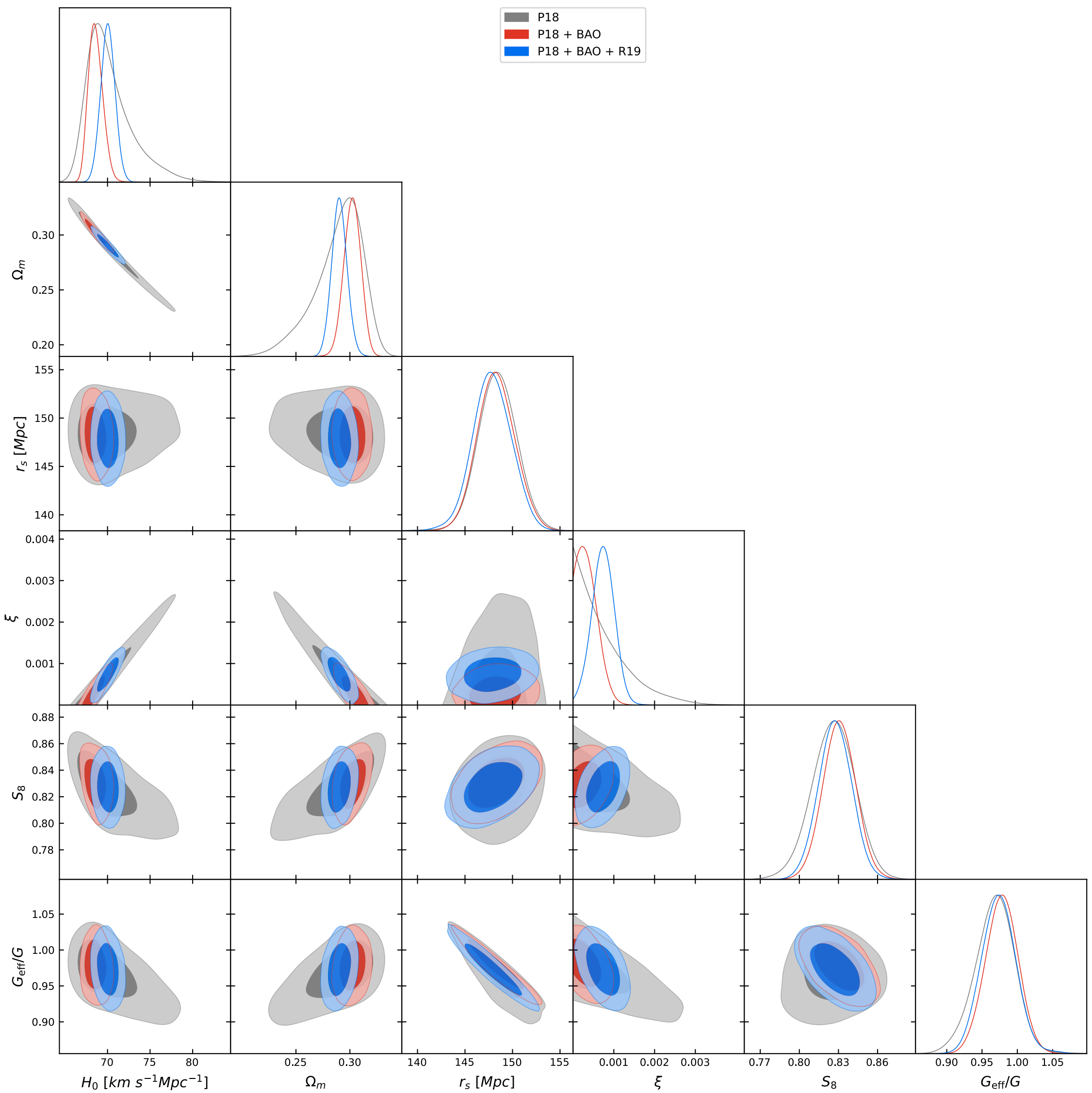
Studies done for IG/eJBD, NMC with $N_{pl} = M_{pl}$. Results shown only for IG/eJBD.



Ballardini, Finelli, Sapone, "Cosmological constraints on Newton's constant", arXiv:2111.xhywz (2021)

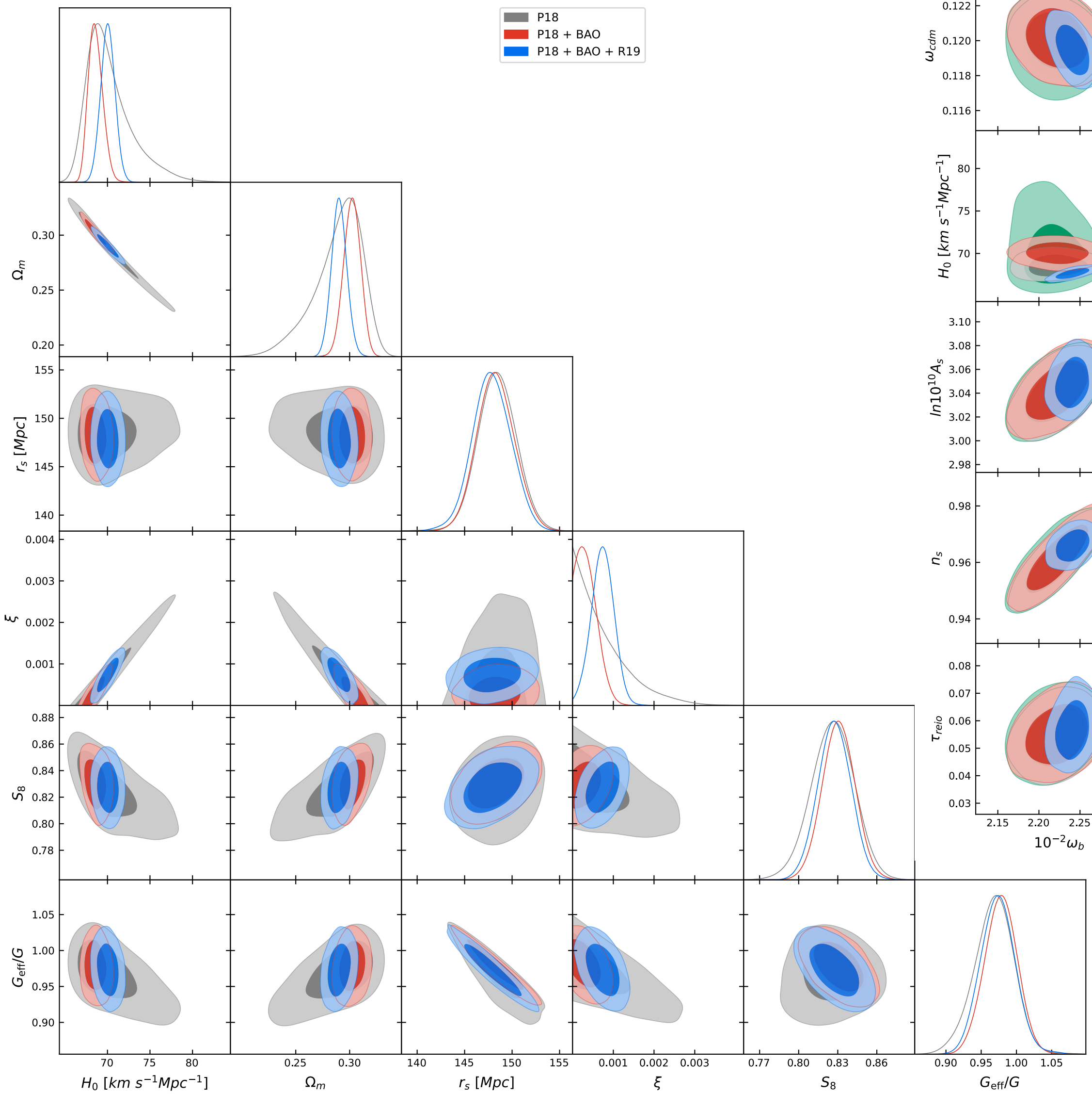
Minimal scalar-tensor gravity

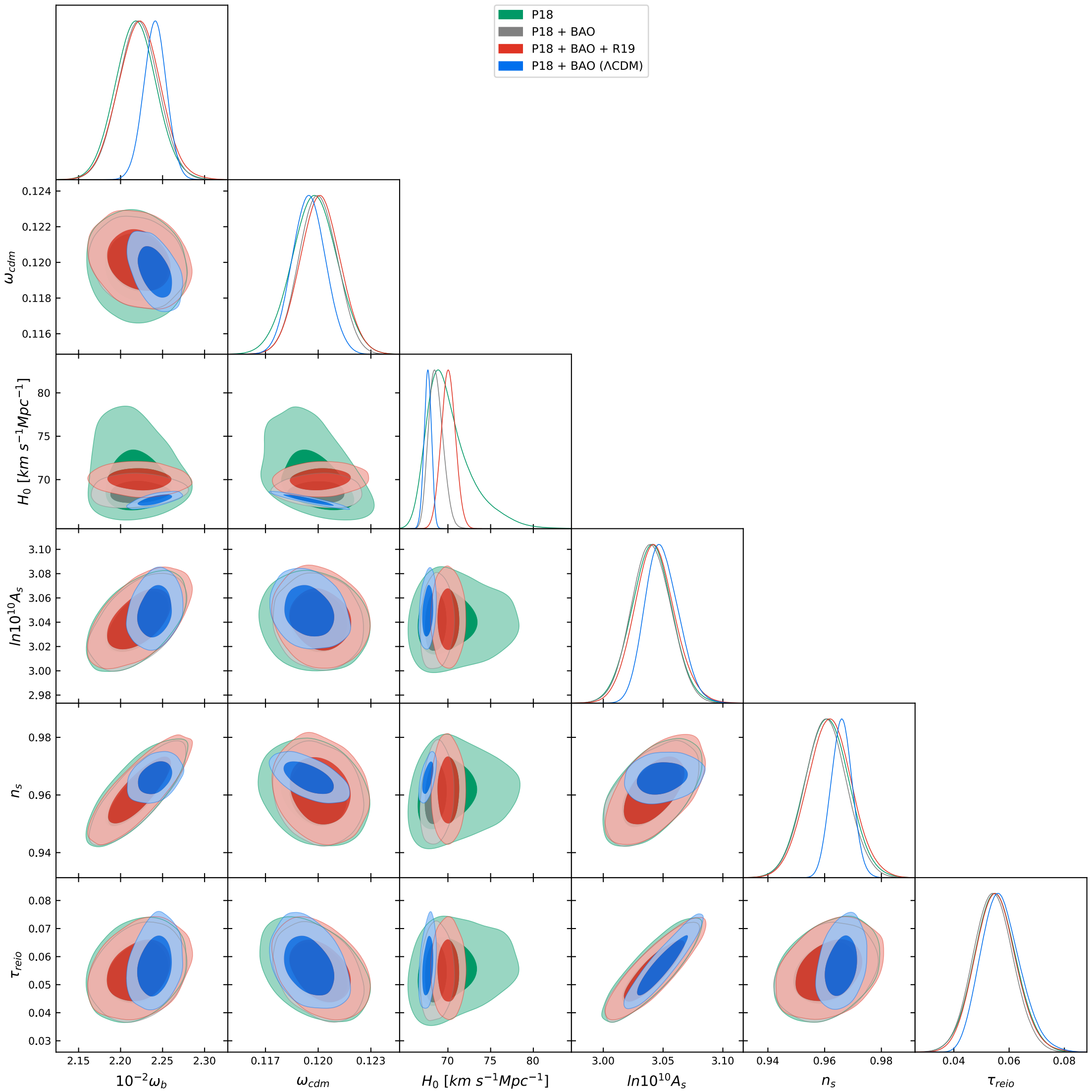




Ballardini, Finelli, Sapone, "Cosmological constraints on Newton's constant", arXiv:2111.xhywz (2021)

Minimal scalar-tensor gravity





Ballardini, Finelli, Sapone, "Cosmological constraints on Newton's constant", arXiv:2111.xhywz (2021)

Quantifying minimal scalar-tensor gravity as H0 solution

Braglia, Ballardini, Edmond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

Braglia, Ballardini, Finelli, Koyama 2020

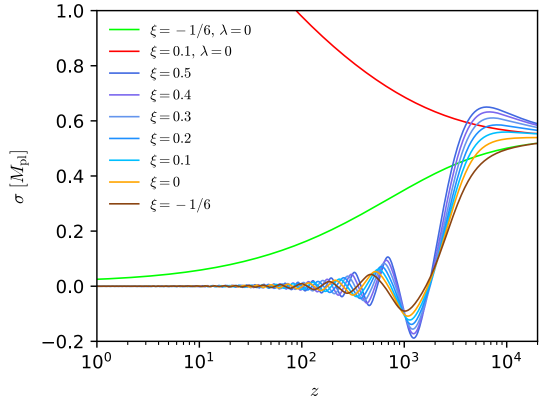
1. $F(\sigma) = M_{\rm pl}^2 \left[1 + \xi (\sigma/M_{\rm pl})^n\right] \qquad n = 2\,, 4$ $\qquad\qquad F(\sigma) = M_{\rm pl}^2 + \xi\sigma^2$

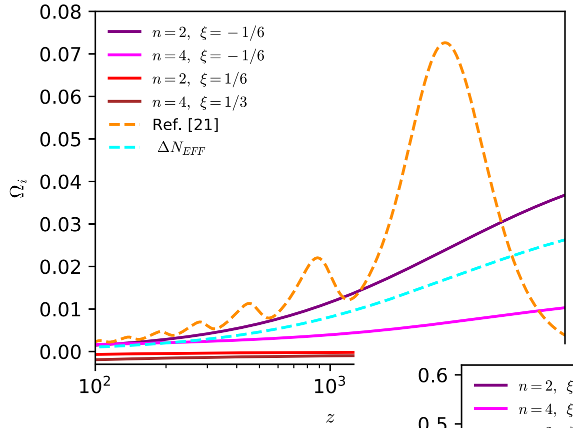
2. $G_{\rm eff}$ not fixed

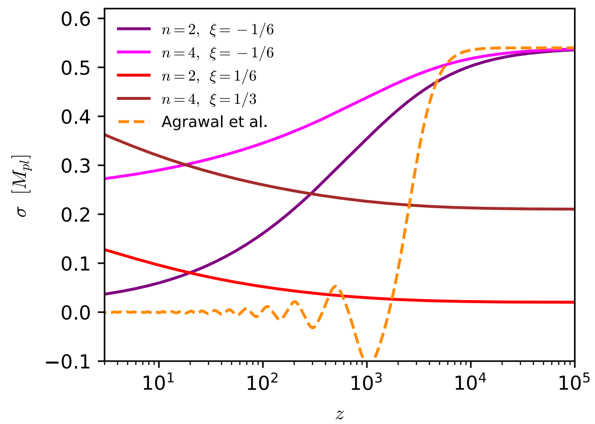
3. To avoid the exploration of a large parameter space $N_{\rm pl} = M_{\rm pl}$

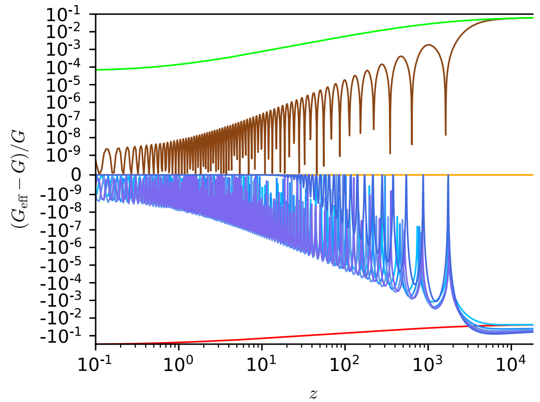
4. $V(\sigma) = \Lambda$ $\qquad\qquad V(\sigma) = \Lambda + \dfrac{\lambda\sigma^4}{4}$

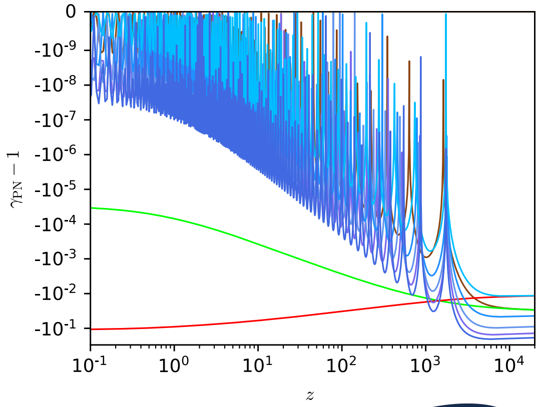
See also Ballesteros, Notari, Rompineve (2020)





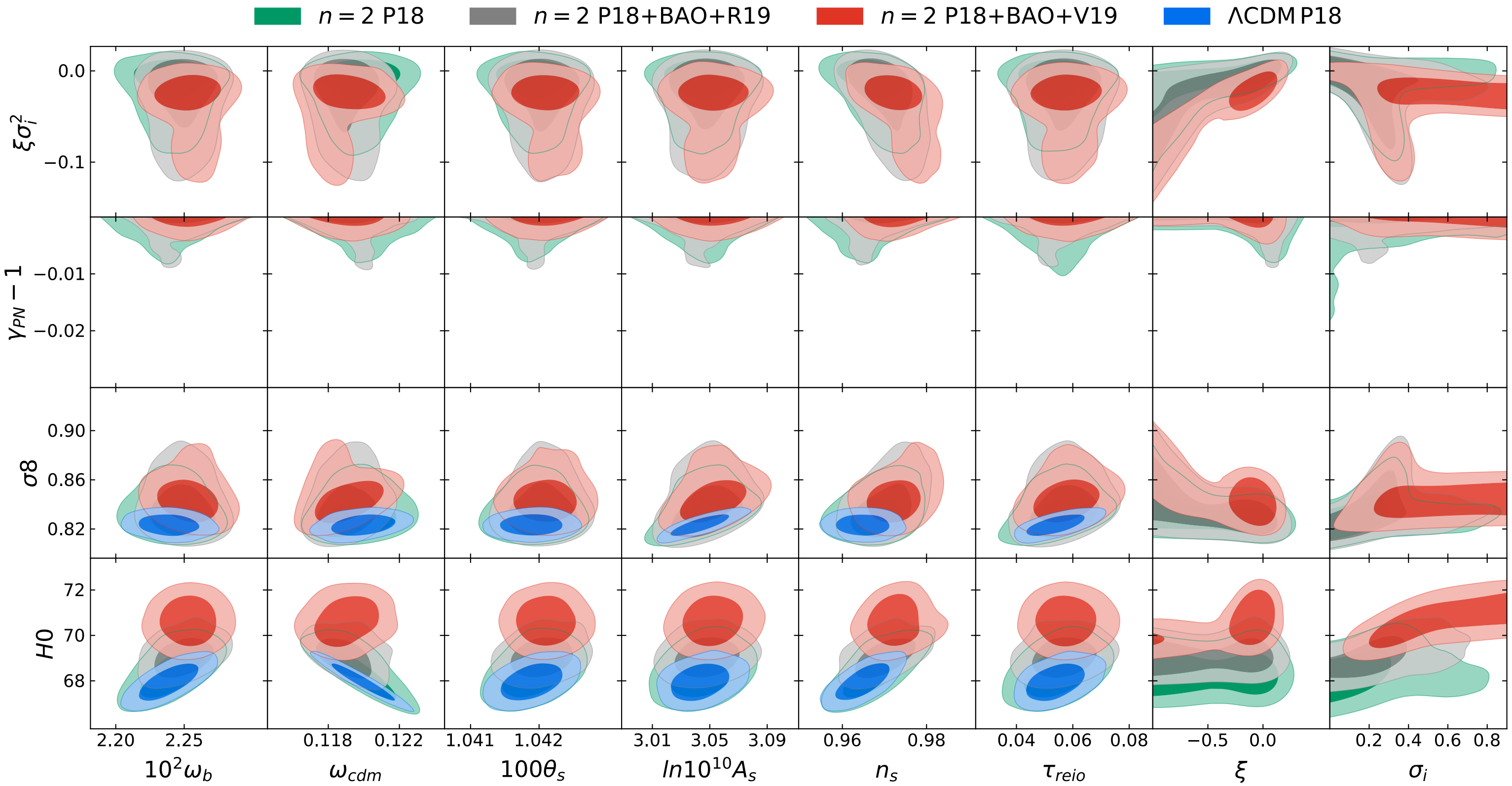






Quantifying minimal scalar-tensor gravity as H0 solution

Braglia, Ballardini, Edmond, Finelli,
Gumrukcuoglu, Koyama, Paoletti 2020



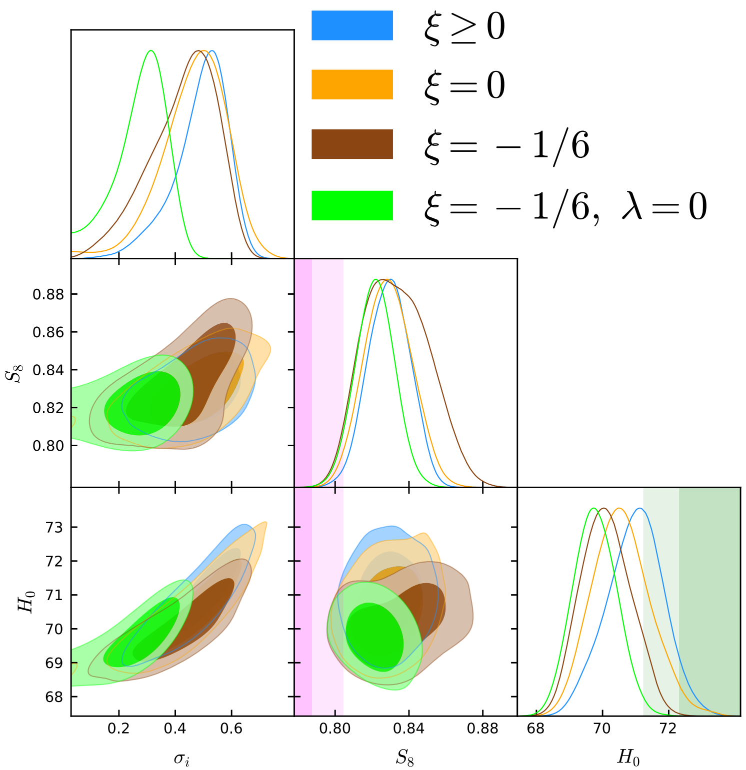
Results consistent with previous analysis (V19 indicates a tighter prior on H_0 based on the combination of different observations as in Verde et al.).

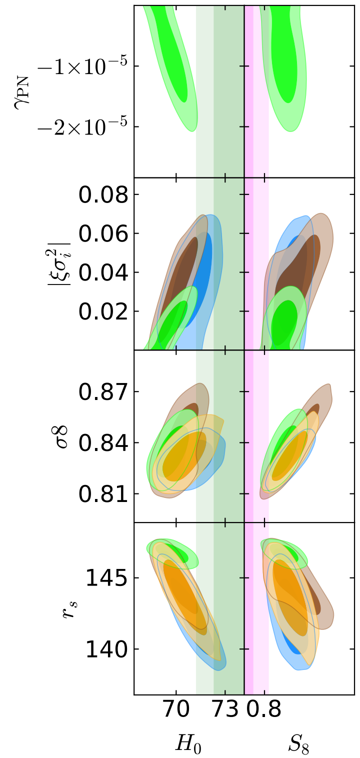
In this paper we also discussed in more depth the goodness of fit.

For n=2 we obtain $\Delta\chi^2 \sim$ -5 (-6.8) for $\xi = -1/6$ (ξ allowed to vary) for P18+BAO+R19.

Quantifying minimal scalar-tensor gravity as H0 solution

Here we consider the combination of Riess et al. 2019 (SH0ES team) and Wong et al. 2019 (H0LiCOW team): $H_0 = 73.4 \pm 1.1$ [km/s/Mpc]
In this model we can also include the BOSS DR 12 full shape P(K) which has been recently used in the context of EDE.





Braglia, Ballardini, Finelli, Koyama 2020

For P18+BAO+FS+SN+H0 we obtain $\Delta\chi^2 \sim$ -16 (-9.3) when ξ is allowed to vary (set to 0).

The trouble with S_8 is barely affected.

Quantifying minimal scalar-tensor gravity as H0 solution

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓ 3
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ 2
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓ 3
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ 1
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ 1
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ 2
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ 2
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓ 2
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	✗	-4.94	-0.94	✗	✗
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	✗	✗
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	✗	-0.45	1.55	✗	✗
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	✗	-0.19	3.81	✗	✗
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	✗	-0.53	3.47	✗	✗

Table 1: Test of the models based on dataset $\mathcal{D}_{\rm baseline}$ (Planck 2018 + BAO + Pantheon), using the direct measurement of M_b by SH0ES for the quantification of the tension (3rd column) or the computation of the AIC (5th column). Eight models pass at least one of these three tests at the 3σ level.

N. Schoneberg et al. "The H0 Olympics: A fair ranking of proposed models", arXiv:2107.10291

Outline

Preamble: cosmological constraints on Newton's constant

The trouble with H_0

Scalar-tensor gravity and the trouble with H_0

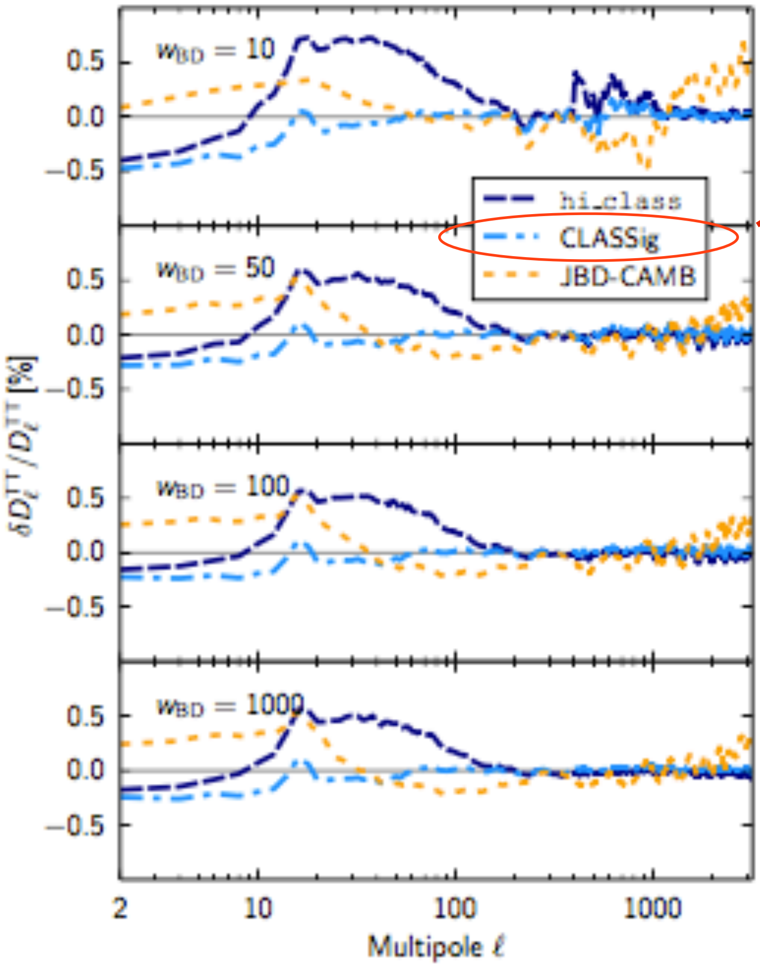
What can we expect from future observations?

How did the gravity of the trouble with H_0 originate?

Summary and conclusions

Are we ready for the precision of future cosmological observations?

The predictions for CMB anisotropies and matter power spectra by different independent codes now agree at the subpercent level for JBD gravity (and other theories beyond GR). Tests up to values of the coupling to curvature which are smaller han the precision required by the current observations.



We named our code CLASSig. The relative differences with respect to the public EFTcamb are reported.

Down to

$$\gamma = 2.5 \cdot 10^{-4}$$

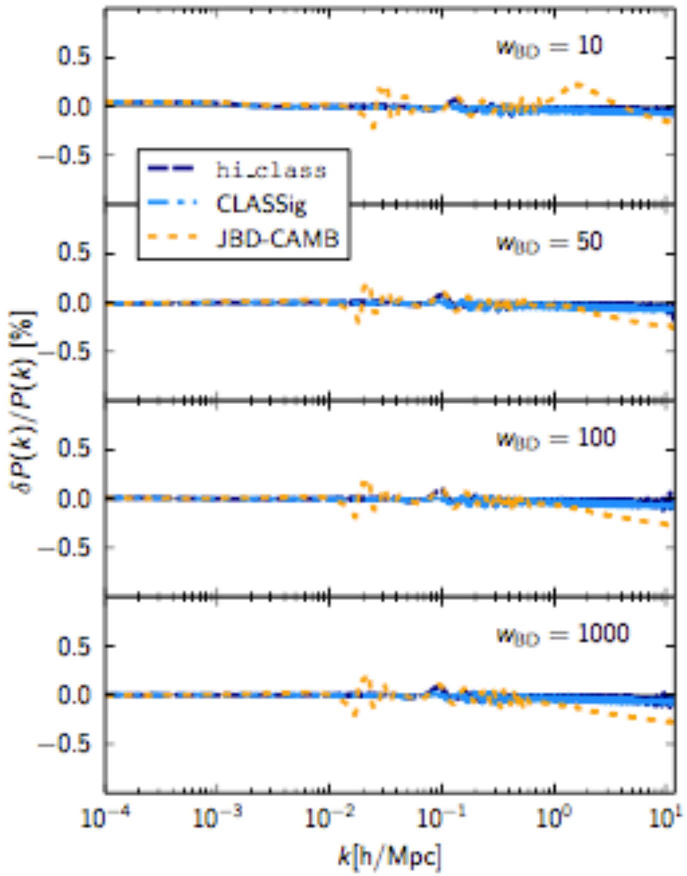
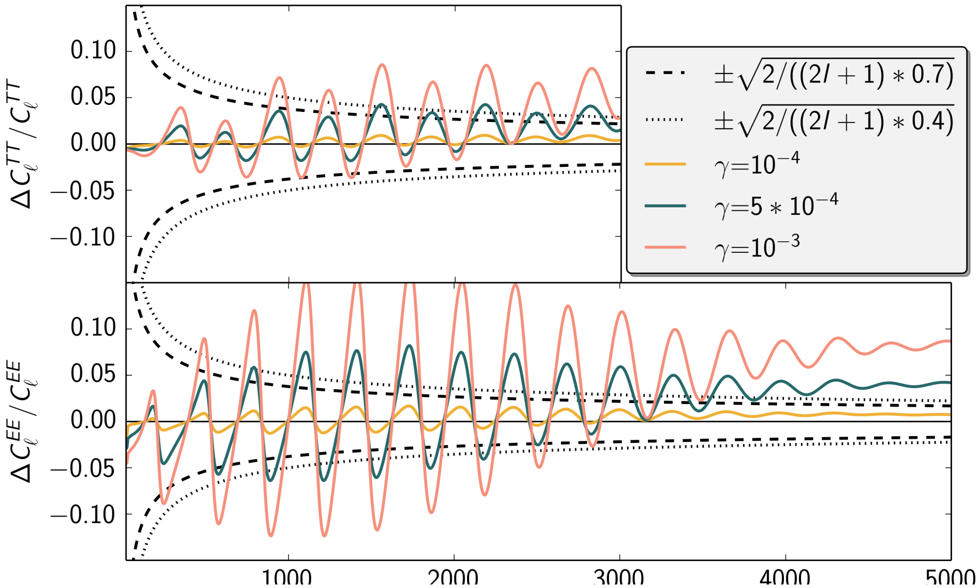


FIG. 3. Top figure: The relative difference of the TT angular powerspectra of the CMB for the same models showed in Fig. 2. Every panel correspond to a model and the comparison of each code in the legend has been done w.r.t. EFTCAMB. Bottom figure: The same as in the top figure but for the matter power spectrum.

Bellini et al. (incl. Ballardini, Finelli, Paoletti, Umilta'), "A comparison of Einstein-Boltzmann solvers for testing General Relativity", Phys. Rev.D 97 (2018) 2, 023520

Forecasts for future cosmological observations

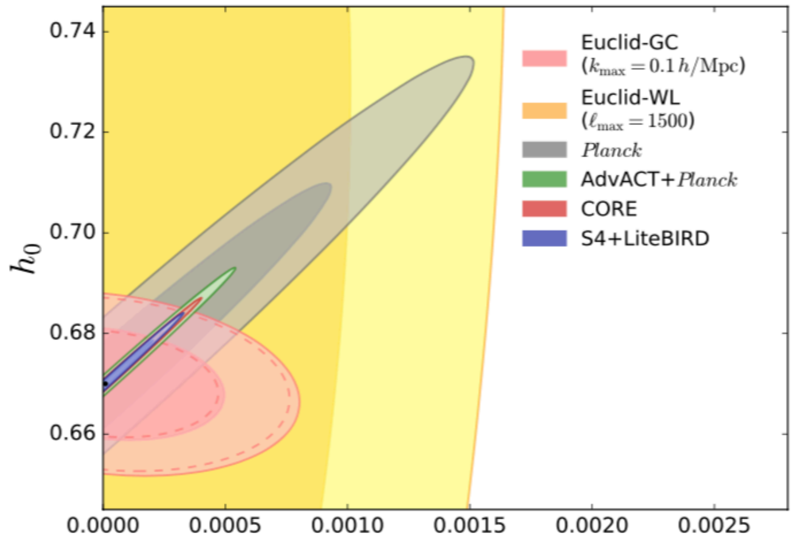


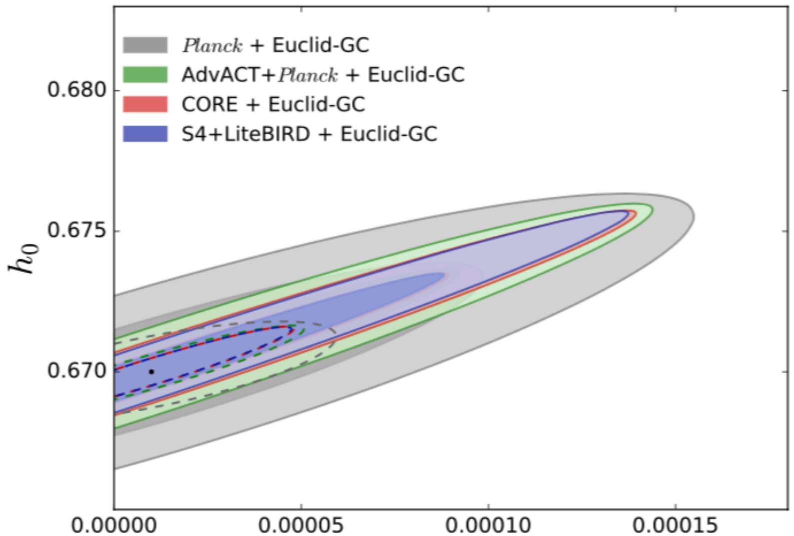
Forecasts for current (e.g. Planck-like) and future CMB surveys in combination with future galaxy surveys, e.g. Euclid, for eJBD theory

$$\sigma\left(|\gamma_{\rm PN}-1|\right) \sim 9.2\times 10^{-5}$$

(k_{max}=0.1 h/Mpc for GC and l_{max}=1500 for WL)

$$\gamma_{\rm PN}-1=(2.1\pm 2.3)\times 10^{-5}$$ *Bertotti et al., 2005*





Ballardini, Sapone, Umilta', Finelli, Paoletti, "Testing eJBD theories with future cosmological observations", JCAP 05 (2019) 049

Forecasts for future cosmological observations

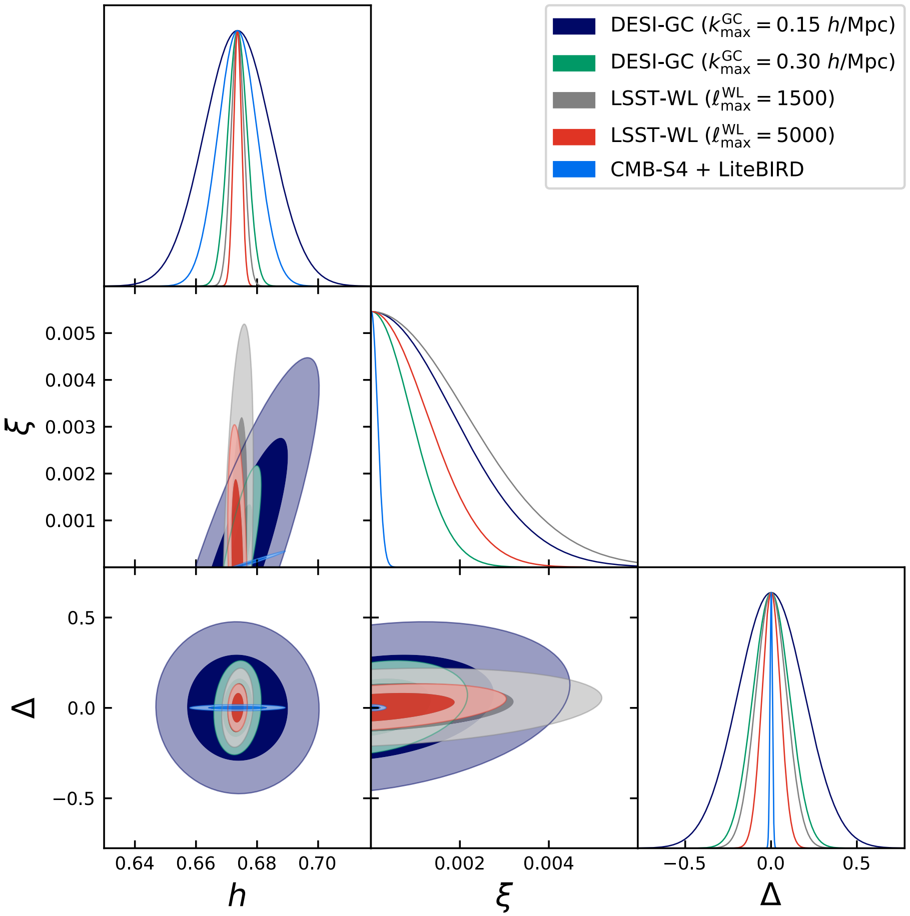
Joint constraints for (Delta, xi) with future CMB surveys (LiteBIRD + CMB-S4) in combination with future galaxy surveys, e.g. DESI or LSST

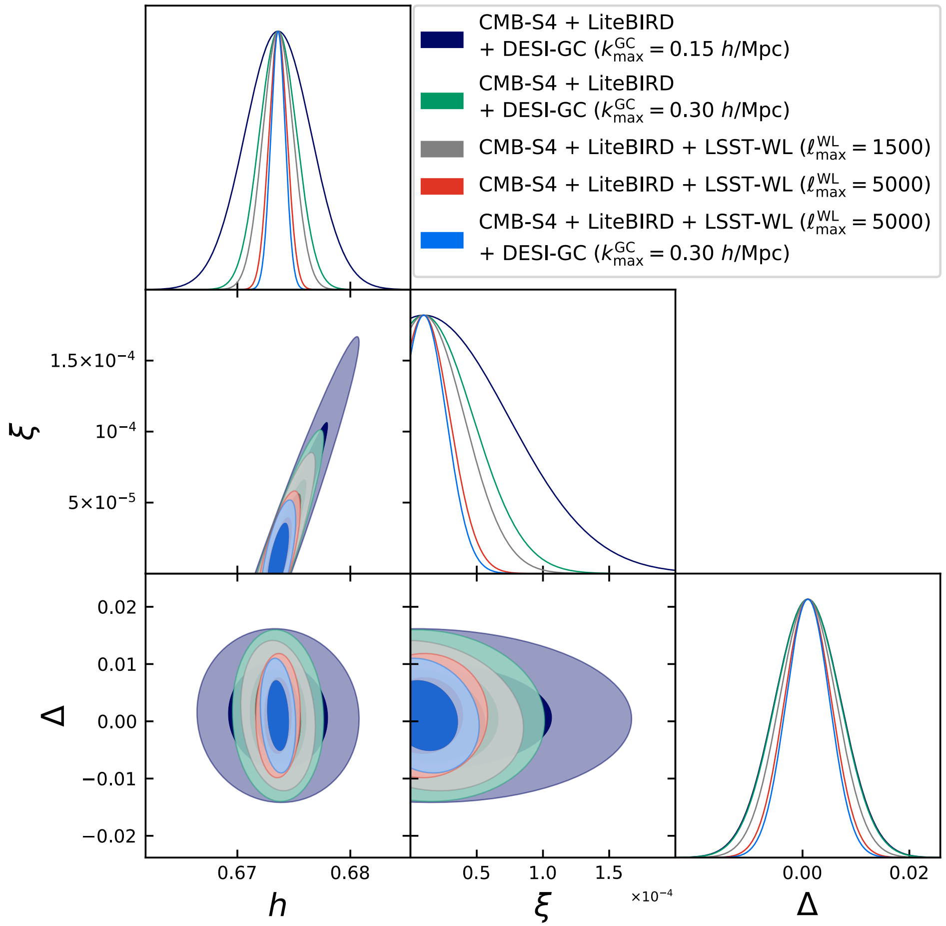
$$\sigma\left(|\gamma_{\rm PN}-1|\right) \sim 9.2\times10^{-5}$$

Constraints on the coupling compatible with the previous investigation

$$\sigma(\Delta) \simeq 0.004$$

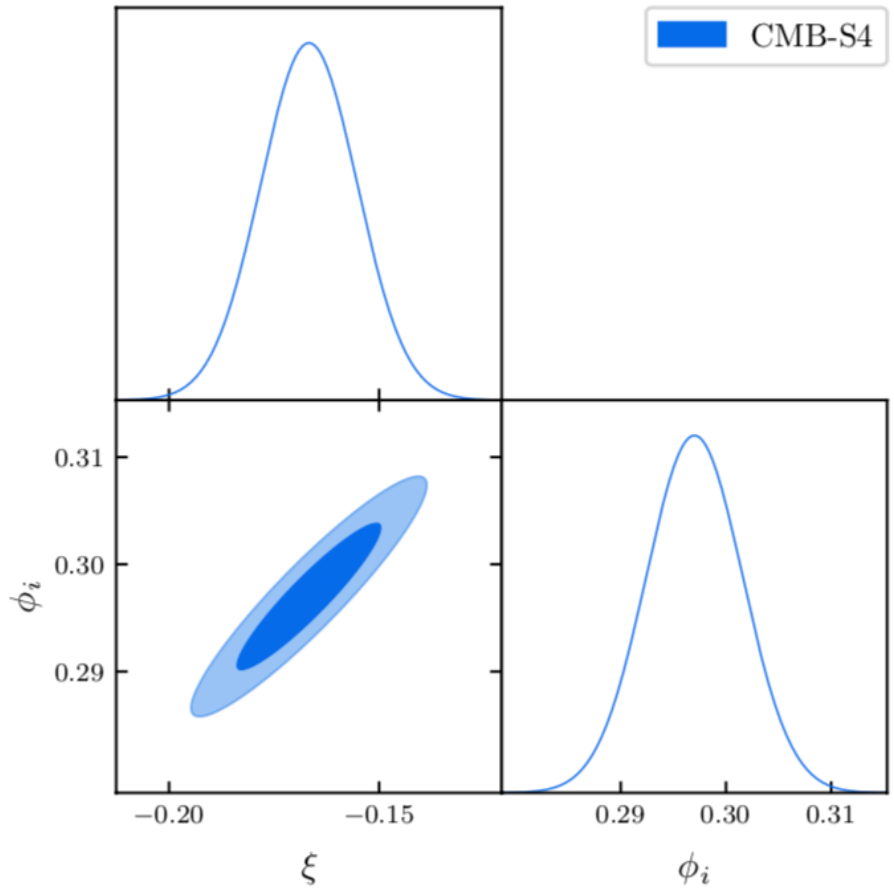
$$\sigma(G_{\rm eff}(z=0)/G) \simeq 0.008$$





Ballardini, Finelli, Sapone, "Cosmological constraints on Newton's constant", arXiv:2111.xhywz (2021)

Forecasts for future cosmological observations



Forecasts for CMB-S4 for the massless case with V = Lambda for $\xi = -1/6$

Abadi, Kovetz, "Can Conformally Coupled Modified Gravity Solve the Hubble Tension?", arXiv:2011.13853 (2020)

Outline

Preamble: cosmological constraints on Newton’s constant

The trouble with H_0

Scalar-tensor gravity and the trouble with H_0

What can we expect from future observations?

How did the gravity of the trouble with H_0 originate?

Summary and conclusions

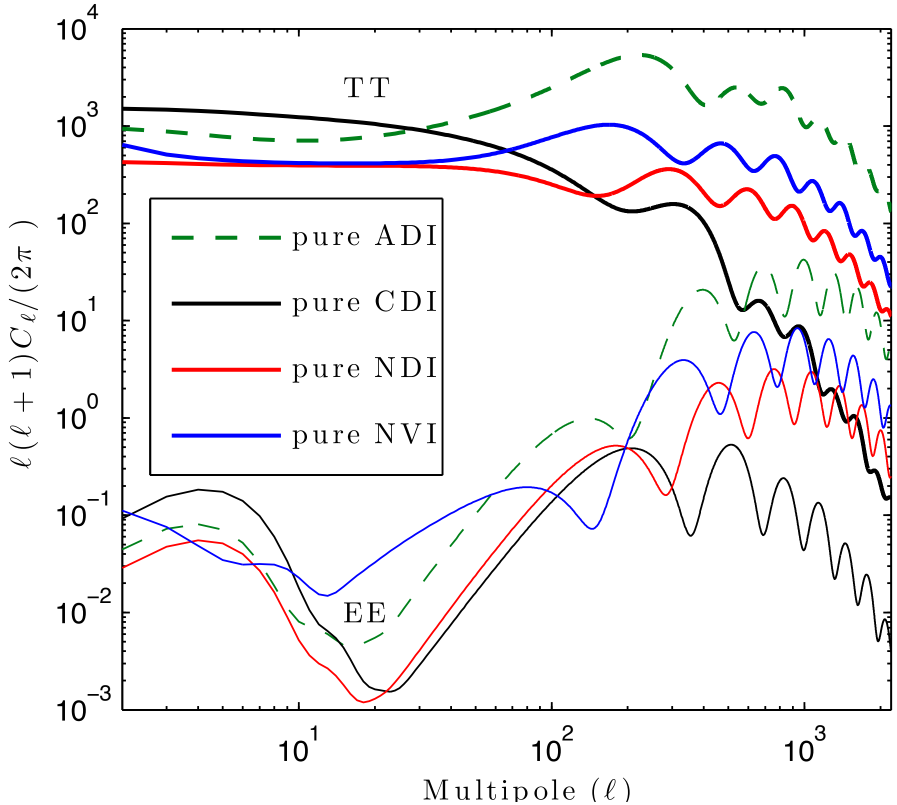
How did the gravity of the H_0 trouble originate?

We have always considered a nearly massless scalar field for σ, therefore generation during inflation is unavoidable.

The field σ survives until now and rules the gravitational strength.

Were initial conditions in this field in G adiabatic?

Isocurvature initial conditions in Einstein gravity have been classified



$\mathcal{R} \approx C(k\tau)^\alpha \quad \text{for} \quad k\tau << 1$

$\alpha = 0 \quad$ Curvature

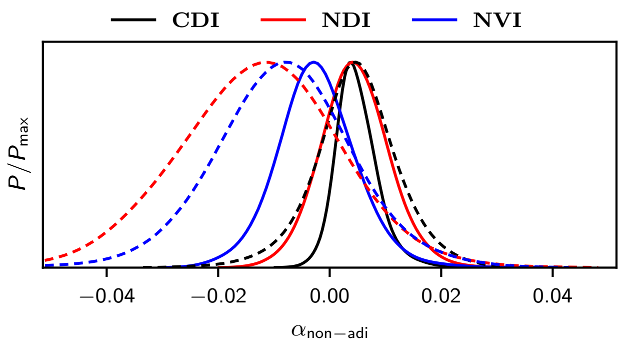
$\alpha = 1 \quad C \approx \Omega_c(\Omega_b) \quad$ CDI(BI)

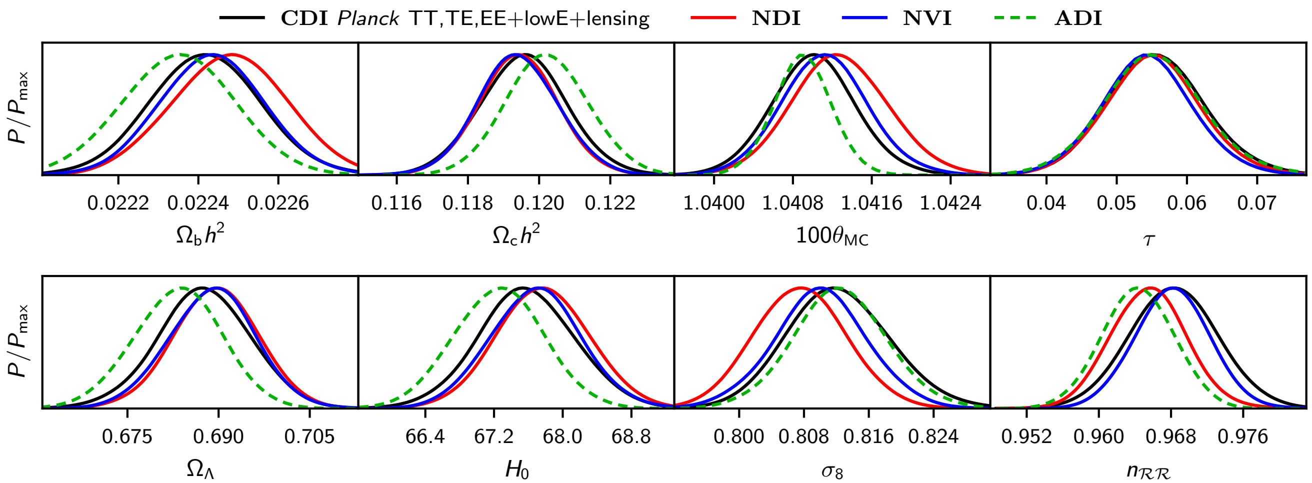
$\alpha = 1 \quad$ NVI

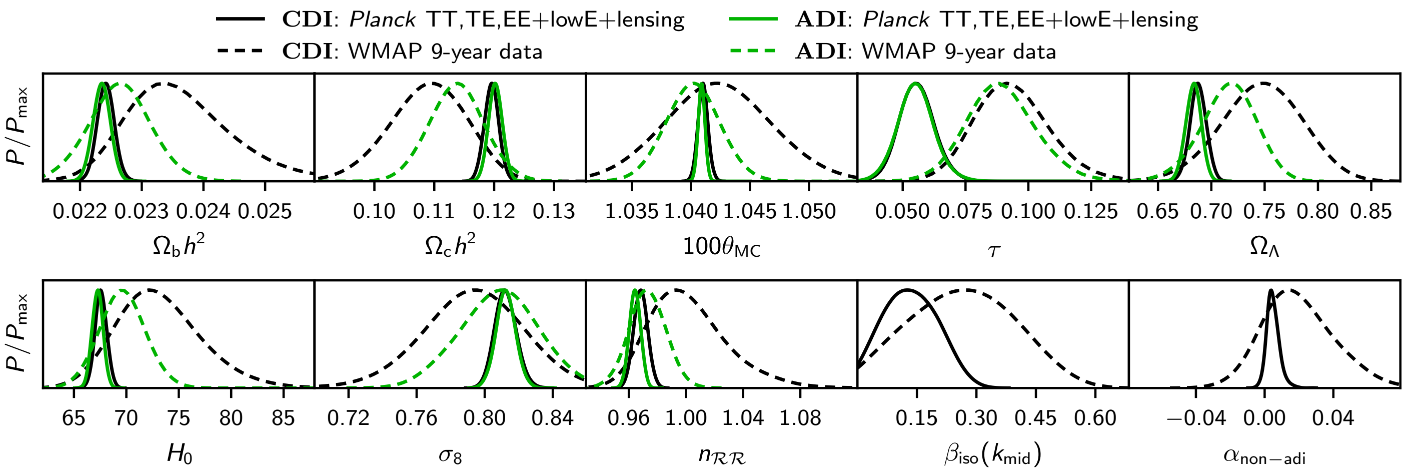
$\alpha = 2 \quad$ NDI

How did the gravity of the H_0 trouble originate?

Planck has been a fantastic test for adiabatic initial conditions in Einstein gravity!







Isocurvature fluctuations in the effective Newton's constant

$$\delta_\gamma = \delta_\nu = C\left[-\frac{2}{3}k^2\tau^2 + \frac{2\omega}{15}k^2\tau^3\right] + D\Big[-1 - \frac{2\omega}{3}\tau + \frac{3(15\xi+2)\omega^2 + 4k^2}{24}\tau^2\Big],$$

$$\theta_\gamma = C\Big[-\frac{k^4\tau^3}{36} + \frac{\omega(5(1+6\xi)R_b + R_\gamma)}{240R_\gamma}k^4\tau^4\Big] + D\Big[-\frac{k^2}{4}\tau + \frac{\omega}{48}\left(\frac{9(1+6\xi)R_b}{R_\gamma} - 4\right)k^2\tau^2\Big],$$

$$\delta_b = C\Big[-\frac{k^2}{2}\tau^2 + \frac{\omega}{10}k^2\tau^3\Big] + D\Big[-\frac{\omega}{2}\tau + \frac{1}{8}\left(\frac{3(15\xi+2)\omega^2}{4k} + k\right)k\tau^2\Big],$$

$$\delta_c = C\Big[-\frac{k^2}{2}\tau^2 + \frac{\omega}{10}k^2\tau^3\Big] + D\Big[-\frac{1}{2}\omega\tau + \frac{3}{32}(15\xi+2)\omega^2\tau^2\Big],$$

$$\delta_\nu = C\Big[-\frac{2}{3}k^2\tau^2 + \frac{2}{15}k^2\tau^3\omega\Big] + D\Big[-1 - \frac{2\omega}{3}\tau + \frac{3(15\xi+2)\omega^2 + 4k^2}{24}\tau^2\Big],$$

$$\sigma_\nu = C\Big[\frac{4k^2\tau^2}{3(4R_\nu+15)} + \frac{(1+6\xi)(4R_\nu-5)\omega k^2\tau^3}{3(4R_\nu+15)(2R_\nu+15)}\Big] + D\Big[\frac{k^2\tau^2}{6(4R_\nu+15)} - \frac{2\omega(1+6\xi)(R_\nu+5)k^2\tau^3}{3(2R_\nu+15)(4R_\nu+15)}\Big],$$

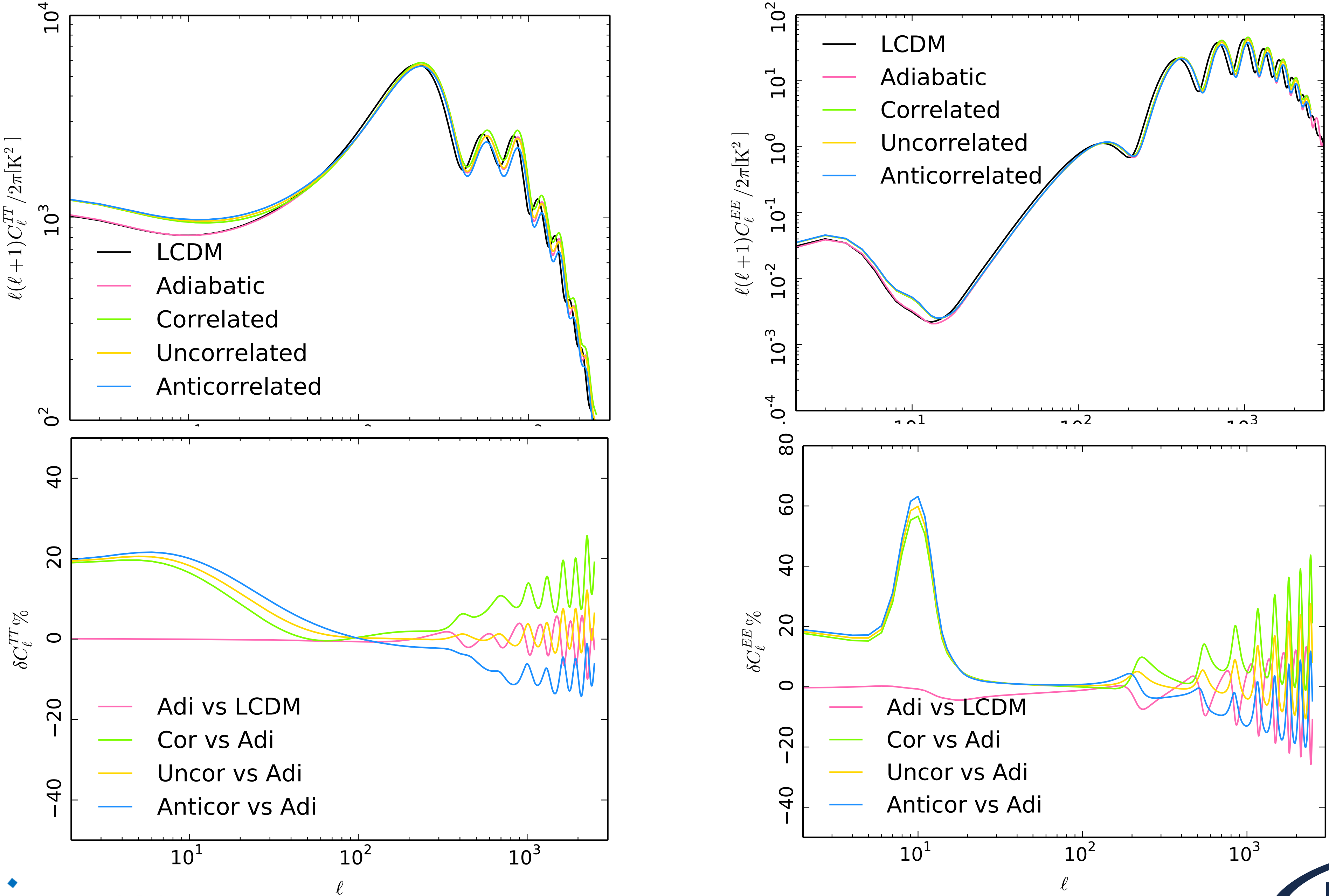
$$h = C\left[k^2\tau^2 - \frac{1}{5}\omega k^2\tau^3\right] + D\left[\omega\tau - \frac{3}{16}(15\xi+2)\omega^2\tau^2\right],$$

$$\eta = C\left[2 - \frac{(4R_\nu+5)}{6(4R_\nu+15)}k^2\tau^2\right] + D\Big[-\frac{\omega}{6}\tau + \frac{16k^2(R_\nu+5) + 3(15\xi+2)(4R_\nu+15)\omega^2}{96(4R_\nu+15)}\tau^2\Big]$$

$$\frac{\delta\sigma}{\sigma_i} = C\Big[-\frac{1}{4}\xi\omega k^2\tau^3 + \frac{\xi\omega^2}{40}(4+15\xi)k^2\tau^4\Big] + D\Big[-\frac{1}{2} + \frac{3}{4}\xi\omega\tau\Big]$$

Paoletti, Braglia, Finelli, Ballardini, Umilta', "Isocurvature fluctuations in the effective Newton's constant" (2018)

Isocurvature fluctuations in the effective Newton's constant



Isocurvature fluctuations in the effective Newton's constant

Planck 2015 constraints

$$f_{\rm iso}^{\rm FC} < 0.07$$
$$f_{\rm iso}^{\rm UC} < 0.31 \qquad (95\,\%{\rm CL}\,,\,{\rm Planck\,2015\,TT + lowP + lensing})$$
$$f_{\rm iso}^{\rm AC} < 0.12$$

obtained with ξ fixed to 0.0005, $n_{iso}=n_{ad}$ with PlikLite.

Results confirmed for fully and uncorrelated fraction with full P18 likelihood allowing ξ to vary as well (thanks to the solution of the problem in the deallocation).

Summary

We have shown how simple models of scalar-tensor theories consistent with the most recent constraints from GW can alleviate the existing tension between H0 inferred by Planck (and other complementary observations such galaxy surveys and Supernovae Ia) and those obtained by the SH0ES and H0LiCOW teams.

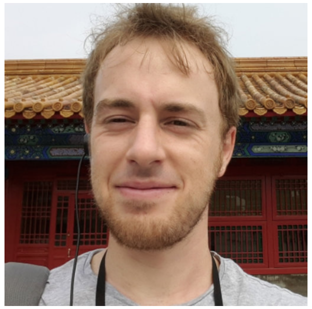
The solution is mainly due to the motion of the scalar field which regulates the gravitational strength as driven by the trace of the energy momentum tensor after radiation-matter equality. Starting from this effect which is present even in the workhorse model for testing gravity in cosmology, i.e. the eJBD/IG model, you can already have models which cope with laboratory and SS tests with scalar fields with a quadratic coupling to gravity massless or with a small effective potential. These results are robust to our ignorance in the neutrino sector.

These theoretically motivated models of fundamental physics effect allow to study an imbalance in the value of G in time and space across redshifts at the accuracy required by current and future observations. Future experiments might push the precision of cosmology closer to the one of current tests of gravity in laboratories and in the Solar System.

This scalar field persists until now and its mass is definitely light compared the Hubble rate during inflation and therefore its connection with the Early Universe need to be studied. We have worked out the new growing solution connected to the isocurvature mode in scalar-tensor theories. The fraction of this new iso mode is comparable or larger wtr to other modes. More work in this direction is in progress.

The Gravity of the Trouble with H_0 and its Possible Origin

Umiltà, Ballardini, Finelli, Paoletti (2015)
Ballardini, Finelli, Umiltà, Paoletti (2016)
Paoletti, Braglia, Finelli, Ballardini, Umiltà (2018)
Ballardini, Sapone, Umiltà, Finelli, Paoletti (2019)
Rossi, Ballardini, Finelli, Paoletti, Starobinsky, Umiltà (2019)
Braglia, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti (2020)
Ballardini, Braglia, Finelli, Paoletti, Starobinsky, Umiltà (2020)
Braglia, Ballardini, Finelli, Koyama (2020)
Ballardini, Finelli, Sapone (2021)



M. Ballardini

A. A. Starobinsky

M. Braglia

K. Koyama

D. Paoletti

D. Sapone

C. Umiltà

E. Gumrukcuoglu