Scalar-tensor theories to tackle cosmological tensions

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Outline

1. non-minimally coupled scalar-tensor theory
   - Hubble tension
   - S_8 tension

2. beyond simplest models
   - unconstrained JBD
   - Early modified gravity (EMG)
   - Brans-Dicke Galileon (BDG)

Scalar-tensor gravity (e.g. extended Jordan-Brans-Dicke)

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

$$G_{\mathrm{eff}} = \frac{1}{8\pi F} \frac{ZF + 2F_\sigma^2}{ZF + \frac{3}{2}F_\sigma^2}$$

- effective Planck mass [Umiltà, **MB**, Finelli, Paoletti, JCAP 08, 2015; Rossi, **MB**, Braglia, Finelli, Paoletti, Starobinsky, Umiltà, PRD 100, 2019]

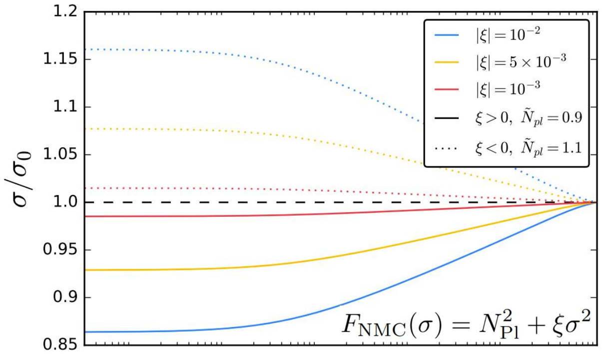
$$F_{\mathrm{IG}}(\sigma) = \xi\sigma^2$$
$$F_{\mathrm{NMC}}(\sigma) = N_{\mathrm{Pl}}^2 + \xi\sigma^2$$

- simple potential is mostly important in the late-time dynamics, it can be a constant or be proportional to the scalar field [**MB**, Umiltà, Finelli, Paoletti, JCAP 05, 2016] (nealy massless theory)
- *Z* can be set to ±1 by a redefinition of the scalar field [**MB**, Ferrari, Finelli, JCAP 04, 2023]
- $\frac{G_{\mathrm{eff}}(z=0)}{G} = 1$

Scalar-tensor gravity (e.g. extended Jordan-Brans-Dicke)

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{|g|}\left[\frac{F(\sigma)R}{2} - \frac{Z(\sigma)}{2}(\partial\sigma)^2 - V(\sigma) + \mathcal{L}_m\right] \qquad G_{\rm eff} = \frac{1}{8\pi F}\frac{ZF + 2F_\sigma^2}{ZF + \frac{3}{2}F_\sigma^2}$$

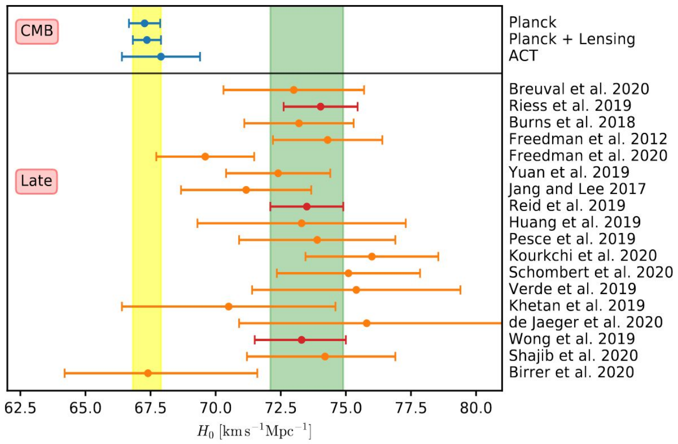
$$\Box\sigma - V_\sigma + F_\sigma R = 0$$



The scalar is effectively massless during the radiation and most of the matter era:

- it is at rest deep in the radiation dominated epoch due to Hubble friction, since an initial non-vanishing time derivative would be rapidly dissipated;
- it starts evolving due to the presence of non-relativistic matter like $\sigma \sim a^{2Z\xi}$.

STG for a higher H_0 value



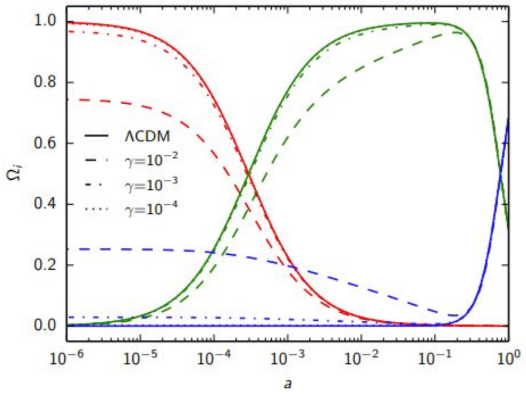
Cosmological background evolution

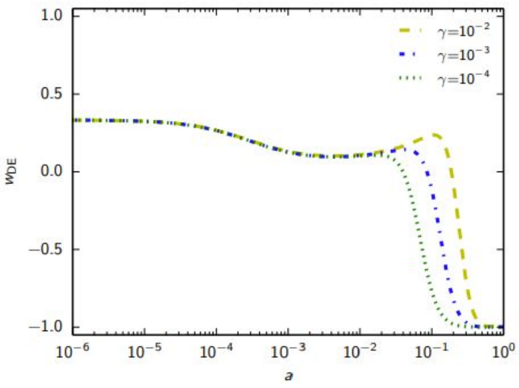
In a (flat) ΛCDM:

- the current value of the CDM density is “fixed” by the amplitude of the first acoustic peak of the CMB temperature anisotropies;
- the current value of the baryon density is “fixed” by the relative amplitude of the second and third peaks w.r.t. the first one;
- small margin to play with the cosmological constant density in order to explain the precise location of the CMB peaks.

In ST theory, we can change the value of H_0 for a fixed amount of standard constituents. This means that differences in the Hubble function can be induced by an evolving scalar field.

$$3FH^2 = \rho + V + \frac{Z\dot{\sigma}^2}{2} - 3H\dot{F}$$





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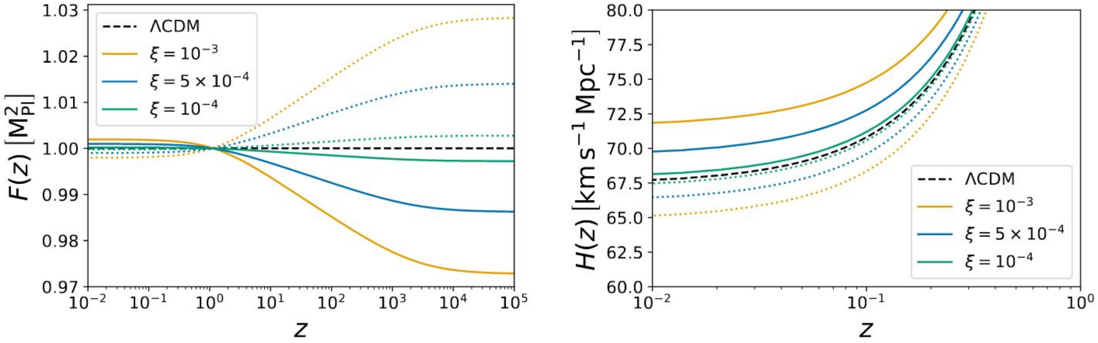
In ST theory, we can change the value of H_0 for a fixed amount of standard constituents. This means that differences in the Hubble function can be induced by an evolving scalar field.

$$3FH^2 = \rho + V + \frac{Z\dot{\sigma}^2}{2} - 3H\dot{F}$$

$$\frac{H(\xi \neq 0)}{H(\xi = 0)} \approx \frac{1}{F(\sigma)}$$



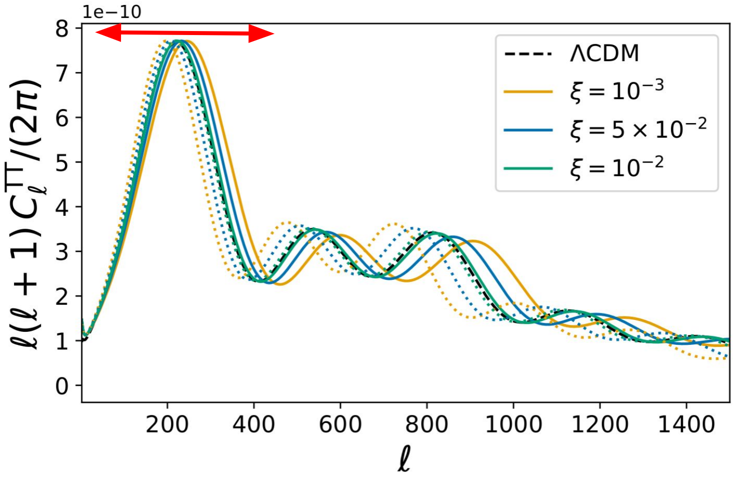
At early times, reducing the Planck mass F(σ) w.r.t. the GR prediction increases the expansion rate and consequently reduces the comoving sound horizon at recombination. A phantom, i.e. Z = -1, non-minimally coupled scalar field (dotted lines) behaves in the opposite way.

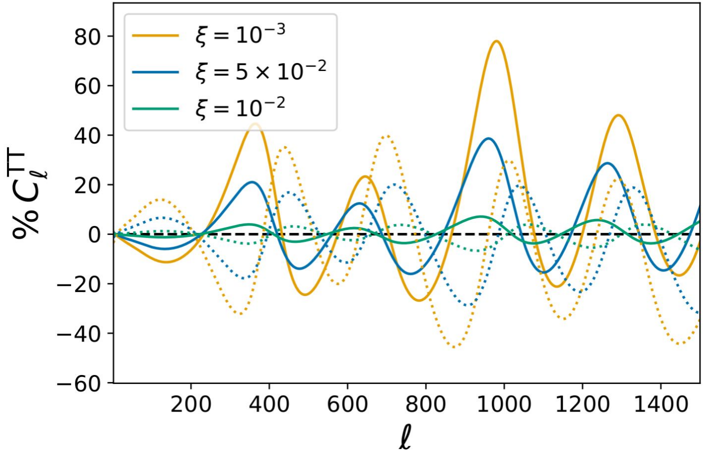
CMB peaks

$$r_s = \int_{z_d}^{\infty} \frac{c_s \mathrm{d}z'}{H(z')} \quad D_\mathrm{M}(z) = \int_0^z \frac{\mathrm{d}z'}{H(z')}$$

The modified expansion history, producing a change in the value of the Hubble function and of the cosmological distances, induces shifts on the position of the CMB acoustic peaks (that can be compensated by small changes in the baryon and CDM density parameters).

$$\theta_* = \frac{r_s}{D_\mathrm{M}(z_*)}$$





BAO distance and SN

$$\frac{D_V(z)}{r_s} = \frac{1}{r_s}\left[D_M^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

Small effect on BAO due to cancellation. However, BAO data provide constraints on the total matter density parameter.

Correction to the SN distance modulus due to the redshift dependence of the Chandrasekhar mass:

$$\mu_{\rm th}(z) = 5\log_{10} d_L(z) + 25 + \frac{15}{4}\log_{10}\frac{G_{\rm eff}(z)}{G}$$

Weak constraints from SN data alone but they improve the constraints once combined with CMB data [**MB**, Finelli, PRD 106, 2022]:

$$\xi < \begin{cases} 0.0095 & \text{SNe} \\ 0.00096 & \text{P18} \\ 0.00080 & \text{P18 + SNe} \\ 0.00068 & \text{P18 + BAO} \\ 0.00063 & \text{P18 + BAO + SNe} \end{cases}$$

$$F_{\rm IG}(\sigma) = \xi\sigma^2$$

Results for eJBD

[**MB**, Braglia, Finelli, Paoletti, Starobinsky, Umiltà, JCAP 10, 2020; **MB**, Finelli, PRD 106, 2022]

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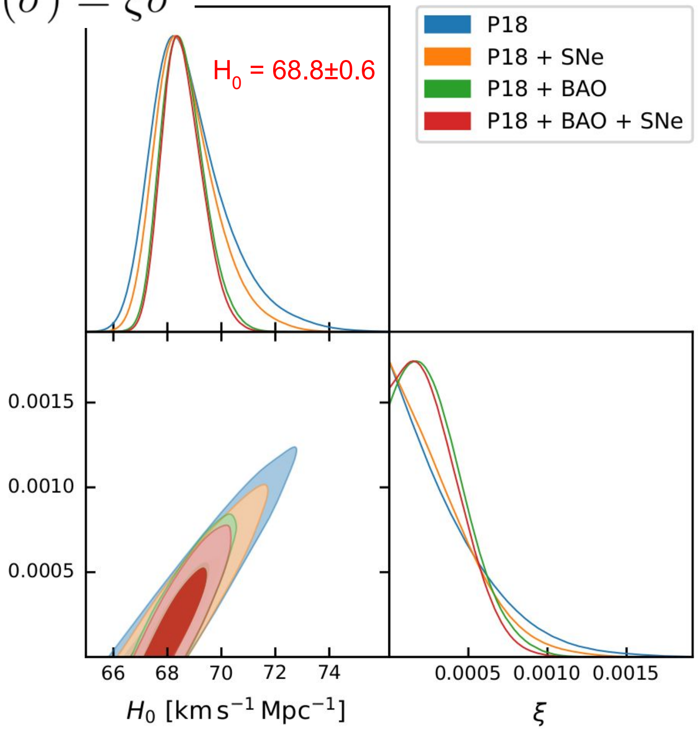
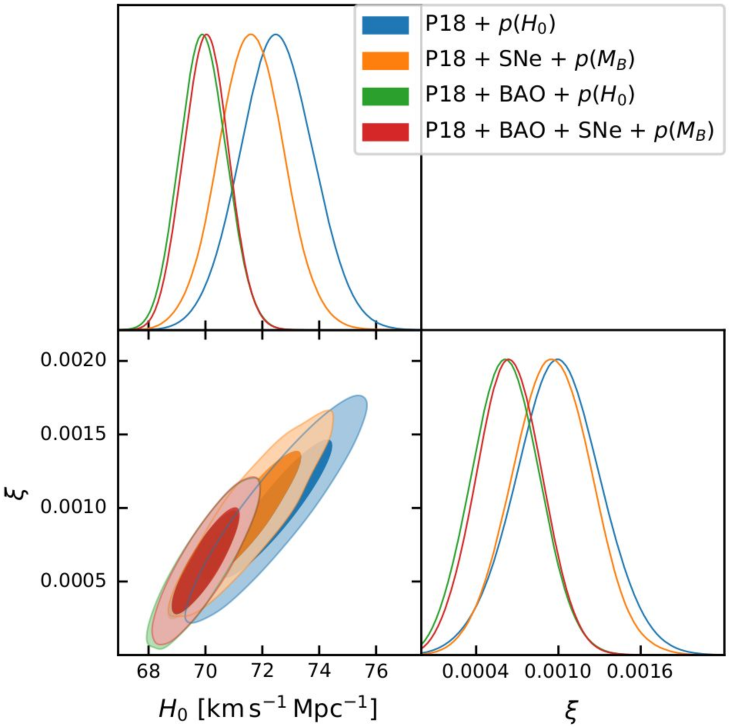
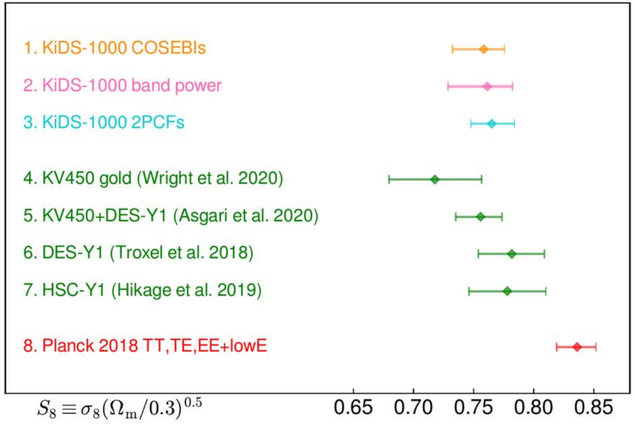


H_0 = 70.1±0.8 Planck+BAO+Pan+M_b



STG for a lower S_8 (or σ_8) value



Matter perturbations in STG

We start from the late-time solution of the perturbation equation for the matter density contrast in the linear regime, on sub-horizon scales (derivatives w.r.t. scale factor)

$$\delta_{\rm m}'' + \left(\frac{3}{a} + \frac{H'}{H}\right)\delta_{\rm m}' - \frac{G_{\rm eff}}{2GH^2}\frac{\rho_{\rm m}}{a^2}\delta_{\rm m} \simeq 0$$

where the effective gravitational constant comes from a generalization of Poisson's equation

$$\nabla^2\phi \approx 4\pi G_{\rm eff}\rho_m\delta_m$$

also called μ or $G_{\rm matter}$

Matter perturbations in eJBD

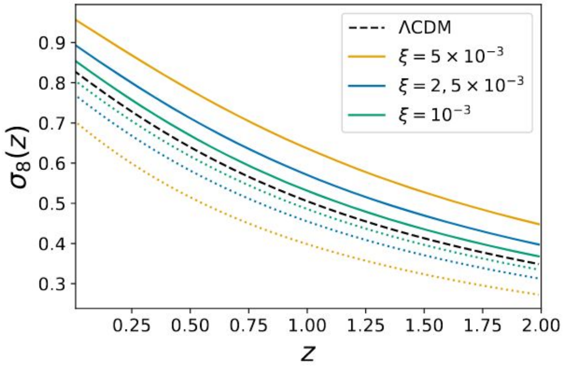
For IG, assuming weak coupling, we have:

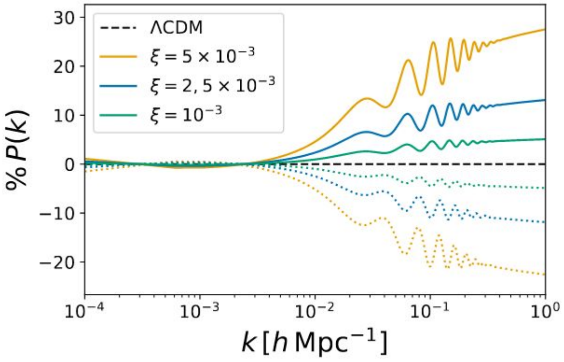
$$F_{\mathrm{IG}}(\sigma) = \xi\sigma^2$$

$$\delta''_{\mathrm{m}} + \frac{3}{2a}\left(1 - \frac{4Z\xi}{3}\right)\delta'_{\mathrm{m}} - \frac{3}{2a^2}\left(1 + \frac{16Z\xi}{3}\right)\delta_{\mathrm{m}} \simeq 0$$

The leading-order growing solution goes as:

$$\delta_{\mathrm{m}} \sim a^{1+4Z\xi}$$





Summary

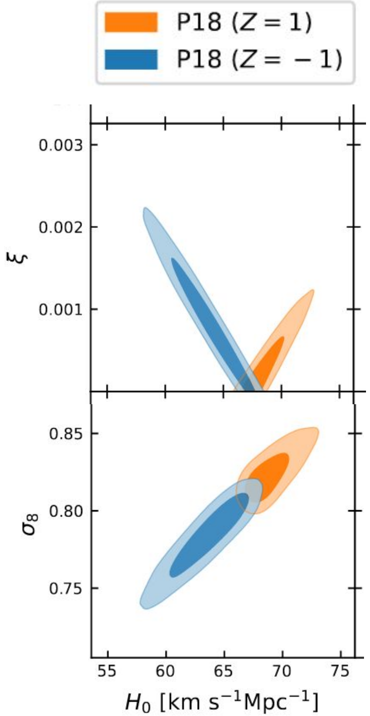
Simple ST models, described by

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

$$F_{\mathrm{IG}}(\sigma) = \xi\sigma^2$$
$$F_{\mathrm{NMC}}(\sigma) = N_{\mathrm{Pl}}^2 + \xi\sigma^2$$

+ $$\frac{G_{\mathrm{eff}}(z=0)}{G} = 1$$

$Z = +1$	$F(\sigma) < M_{\mathrm{Pl}}^2$	$\frac{G_{\mathrm{eff}}(z)}{G} \geq 1$	$H_0^{\mathrm{ST}} > H_0^{\Lambda\mathrm{CDM}}$
$Z = -1$	$F(\sigma) > M_{\mathrm{Pl}}^2$	$\frac{G_{\mathrm{eff}}(z)}{G} \leq 1$	$\sigma_8^{\mathrm{ST}} < \sigma_8^{\Lambda\mathrm{CDM}}$



Going beyond the simplest models

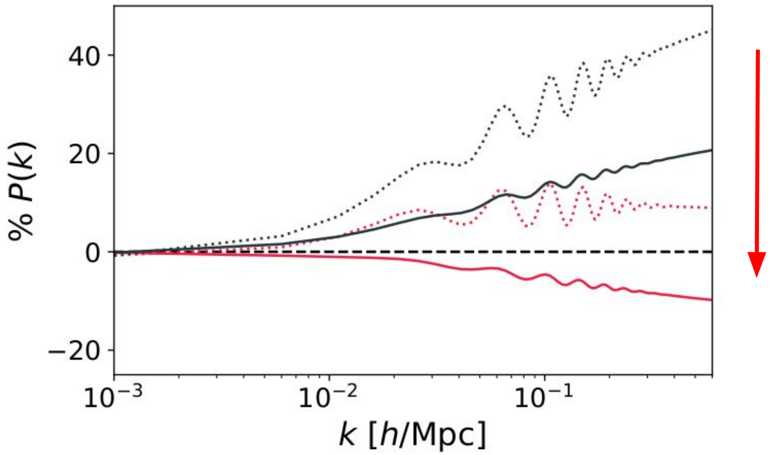
Cosmological constraints on G

[**MB**, Finelli, Sapone, JCAP 06, 2022]

We can relax the boundary condition on the present value of the effective gravitational constant:

$$\frac{G_{\rm eff}(z=0)}{G} \neq 1$$

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



and accomodate for a lower value of σ_8.
[Joudaki, Ferreira, Lima, Winther PRD 105, 2022;
MB, Finelli, Sapone, JCAP 06, 2022]

It requires however a screening mechanism to justify the imbalance and it does not improve to fit larger values of H_0.

Early modified gravity (EMG)

[Braglia, **MB**, Finelli, Koyama, PRD 103, 2021]

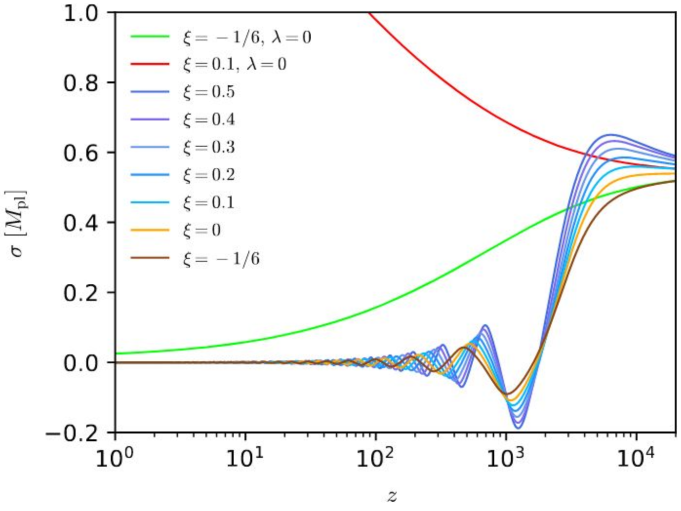
The rolling of the field towards the minimum of the potential suppresses the modification to gravity at late times, recovering a good agreement with the laboratory experiments and Solar System tests with General Relativity, and avoiding the enhancement of growth.

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

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

$$V(\sigma) = \lambda\sigma^4/4$$

$$\lambda \sim \mathcal{O}(\mathrm{eV}^4/M_{\mathrm{pl}}^4)$$



Comparison with the Rock'n'Roll EDE model

[Abellan, Braglia, **MB**, Finelli, Poulin, 2308.12345, 2023]

EMG successfully address the Hubble tension with a detection of 3σ of the initial value of the non-minimal coupling $\xi\sigma^2$ = 0.033±0.014.

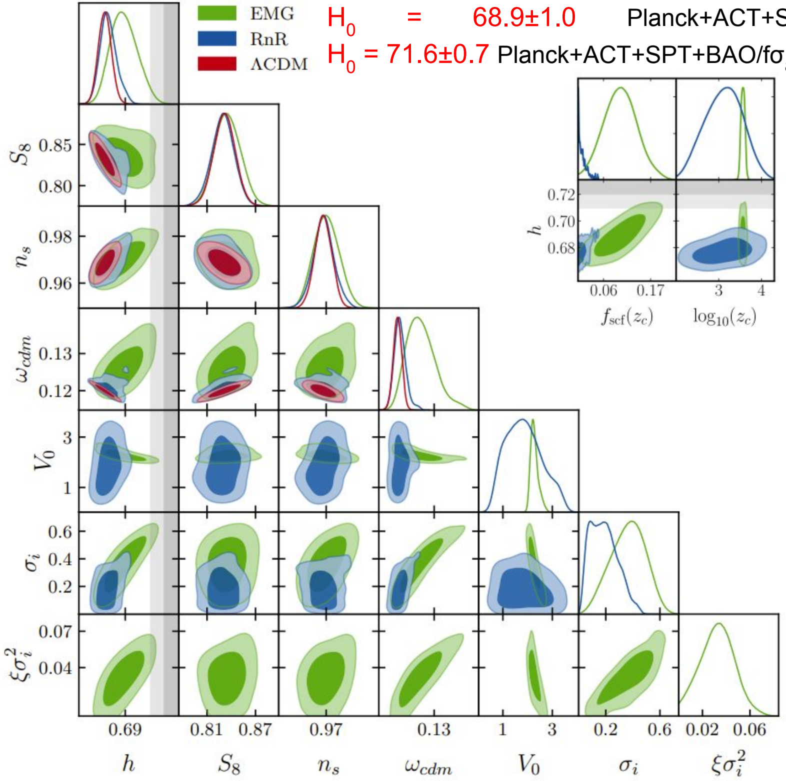
The residual Hubble tension is 3.3σ, strongly decreased from 6.4σ in ΛCDM (for the same data combination), but not fully alleviated.

EMG can be compared with popular 'axion-like' EDE models [Karwal, Kamionkowski, PRD 94, 2016; Poulin, Smith, Karwal, Kamionkowski, PRL 122, 2019; Agrawal, Cry-Racine, Pinner, Randal, 2019], which show hint of a detection at ~3σ only when removing high-ℓ Planck temperature data, but it is compatible with ΛCDM at 1σ with the full data (Planck+ACTPol).

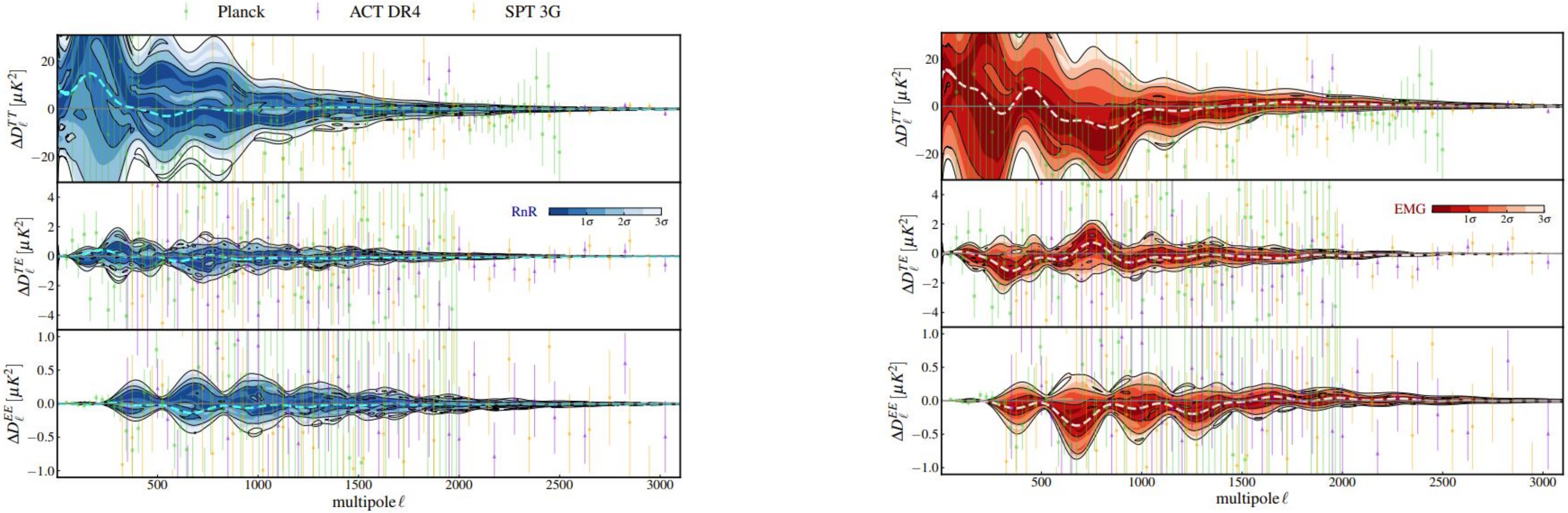
EMG model is fitting CMB data significantly better than the axion-like EDE model.

H_0 = 68.9±1.0 Planck+ACT+SPT+BAO/fσ_8+PanPlus

H_0 = 71.6±0.7 Planck+ACT+SPT+BAO/fσ_8+PanPlus+M_b



Comparison with the Rock’n’Roll EDE model



EMG can attain a larger H_0 compared to the RnR while fitting the dip seen around ℓ~750 in temperature.

The NMC can provide a sharper energy injection and a different evolution of scalar perturbation for modes entering the Hubble radius before the energy injection (suppressing differences for the Weyl potential dynamics).

Scalar-Tensor Gravity

Horndeski theory can accommodate for wider phenomenology, in particular for different evolution of the effective gravitational constant [De Felice, Kobayashi, Tsujikawa PLB 706, 2011; Gannouji, Perivolaropoulos, Polarski, Skara PRD 103, 2021].

$$L = \sum_{i=2}^{5} L_i^\sigma$$

$$L_2^\sigma \equiv G_2(\sigma, \chi)$$

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

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

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

after the detection of the gravitational wave signal GW170817 accompanied by the gamma-ray burst event GRB170817A [Baker, Bellini, Ferreira, Lagos, Noller PRL 119, 2017; Creminelli, Vernizzi PRL 119, 2017; Sakstein, Jain PRL 119, 2017; Ezquiaga, Zumalacárregui PRL 119, 2017; Amendola, Kunz, Saltas, Sawicki PRL 120, 2018].

Brans-Dicke Galileon

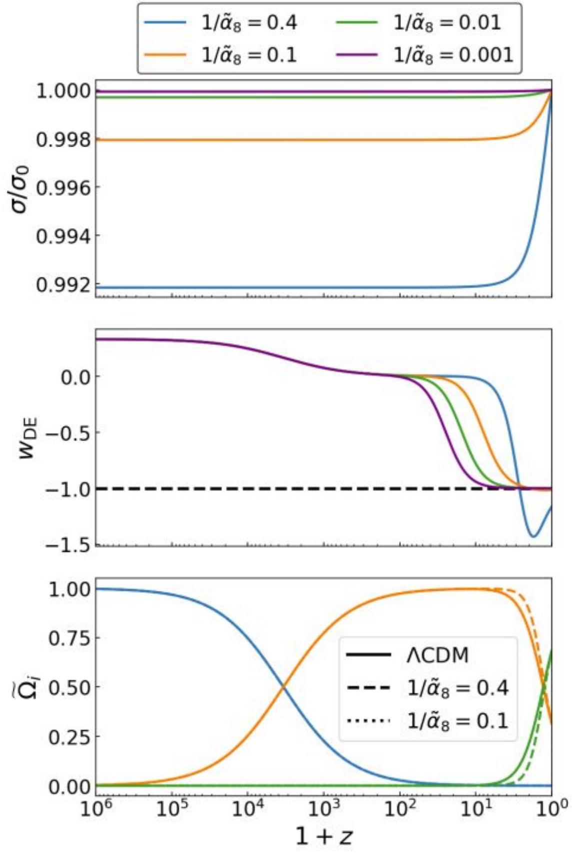
[Ferrari, **MB**, Finelli, PRD, 2023]

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{|g|}\,[G_4(\sigma)R + G_2(\sigma, X) + G_3(\sigma, X)\Box\sigma + \mathcal{L}_\mathrm{M}]$$

$$G_4 = \gamma\sigma^2/2$$
$$G_3 = -2g(\sigma)X$$
$$G_2 = ZX - V(\sigma) + 4\zeta(\sigma)X^2$$
$$g(\sigma) = \alpha\sigma^{-1}$$

Brans-Dicke Galileon in the phantom branch (BDGph) can:

1. provides a Vainshtein radius of ~ 100 pc for a solar mass;
2. avoids the instabilities in the phantom branch;
3. raises the value of H_0 reducing the Hubble tension.
   H_0 = 70.6±1.0 Planck+Pan+M_b



Conclusions

Scalar-tensor theories of gravity can naturally reduce the evidence for cosmological tensions:

1. simple models for which the scalar field is effectively massless predict a higher expansion rate in the standard branch while a slower growth of structure in the phantom branch;

2. leaving some of the minimal assumptions, such as varying the present value of the effective gravitational constant on cosmological scales, including a self-interaction in the scalar field potential (early modified gravity) or adding a Galileon term, it is possible to reduce the tensions even further. In particular, in EMG it is possible to ease the Hubble tension without exacerbating the S_8 tension and providing a good fit to all the current CMB experiments.

The interest in scalar-tensor gravity goes beyond the game of cosmological tensions:

- explain the late-time accelerating expansion of the Universe;
- test of gravity on cosmological scales.