Thawing Gravity and The Cosmological Tensions

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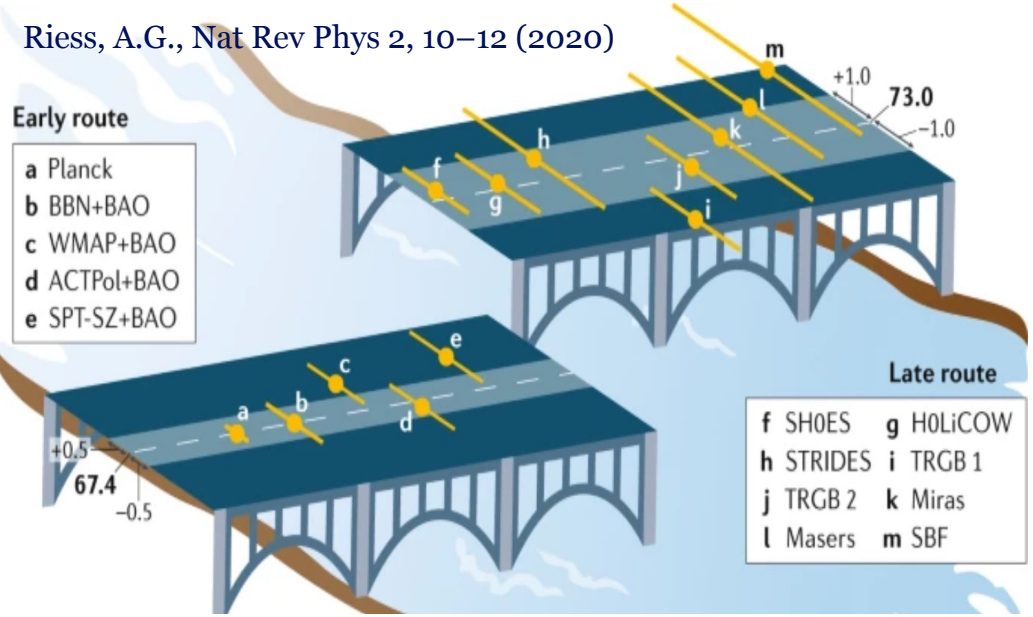
GY, M.Martinelli, B.Hu, A. Silvestri, arXiv:2407.15832
GY, arXiv:2411.11743

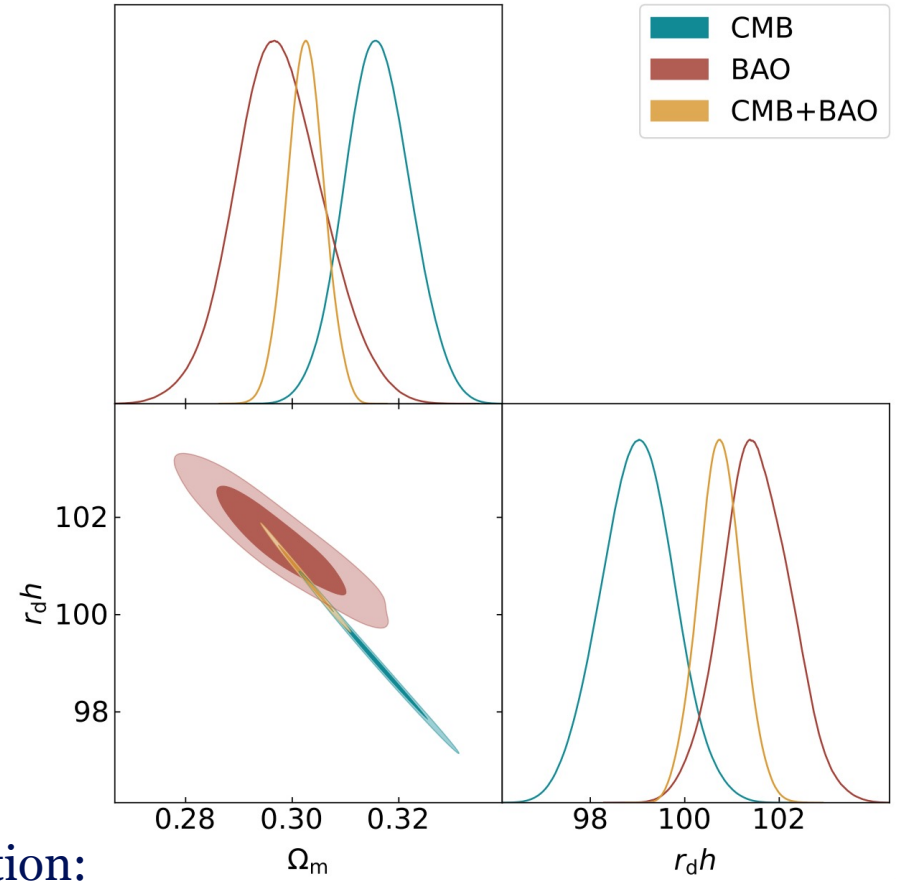
Cosmological tensions

Riess, A.G., Nat Rev Phys 2, 10–12 (2020)



Hubble tension ($> 5\sigma$)

BAO v.s. CMB tension from DESI?



CMB, BAO common assumption:
Post-recombination background parametrized by $\Omega_m = 1 - \Omega_\Lambda, H_0$

2σ inconstentcy

(**GY**, SJL, 2505.02207)

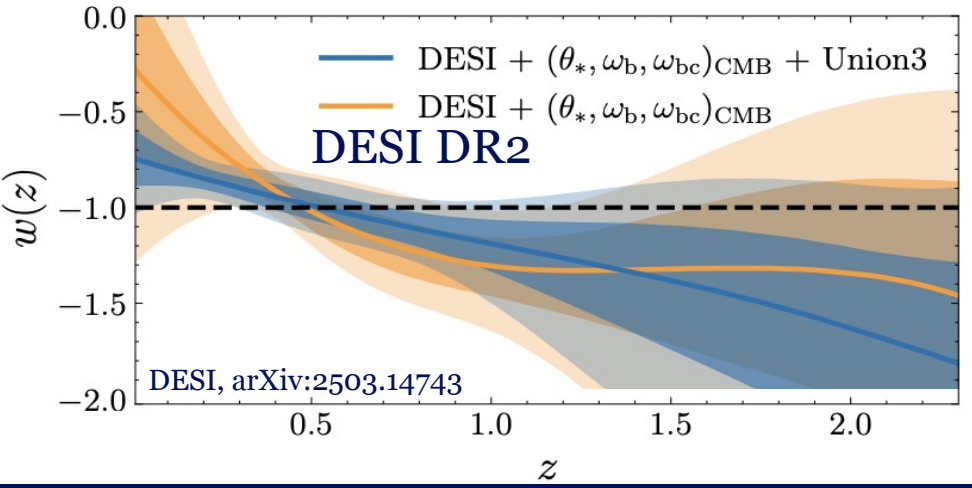
Phantom Crossing in DESI BAO

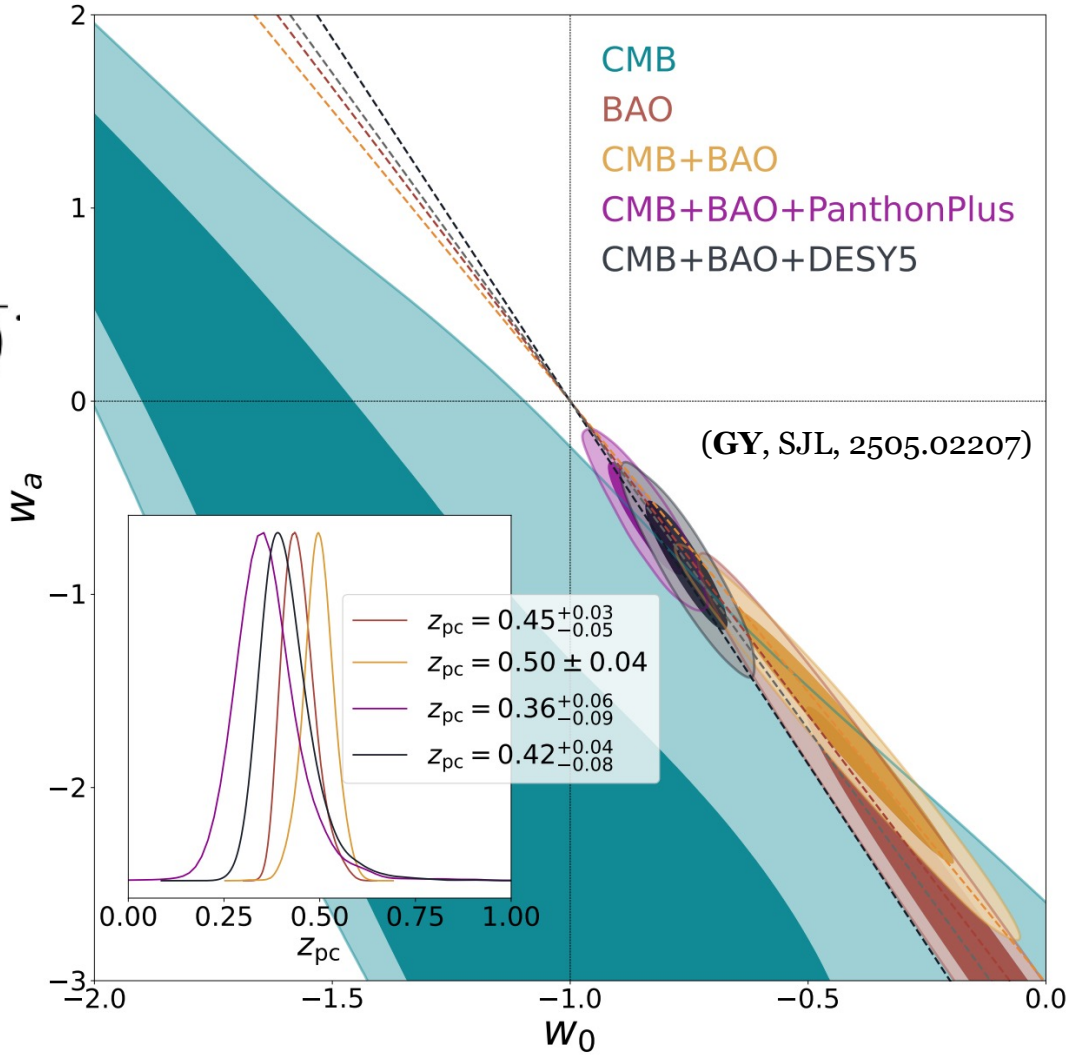
- Dynamical DE
- DE phantom crossing
  - Rule out quintessence DE due to theoretical instability

$$w_{DE} = w_0 + w_a \frac{z}{1+z} = -1$$

$$z_{\rm pc} = -\frac{w_0 + 1}{w_a + (w_0 + 1)}.$$

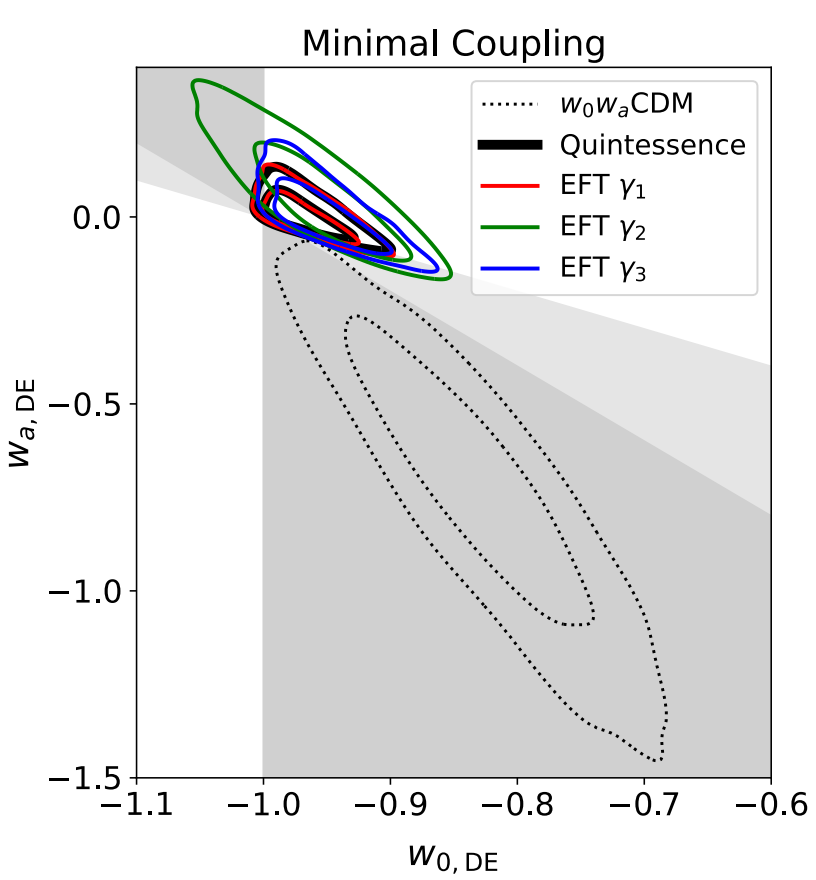
Non-parametric Reconstruction of w_{DE}





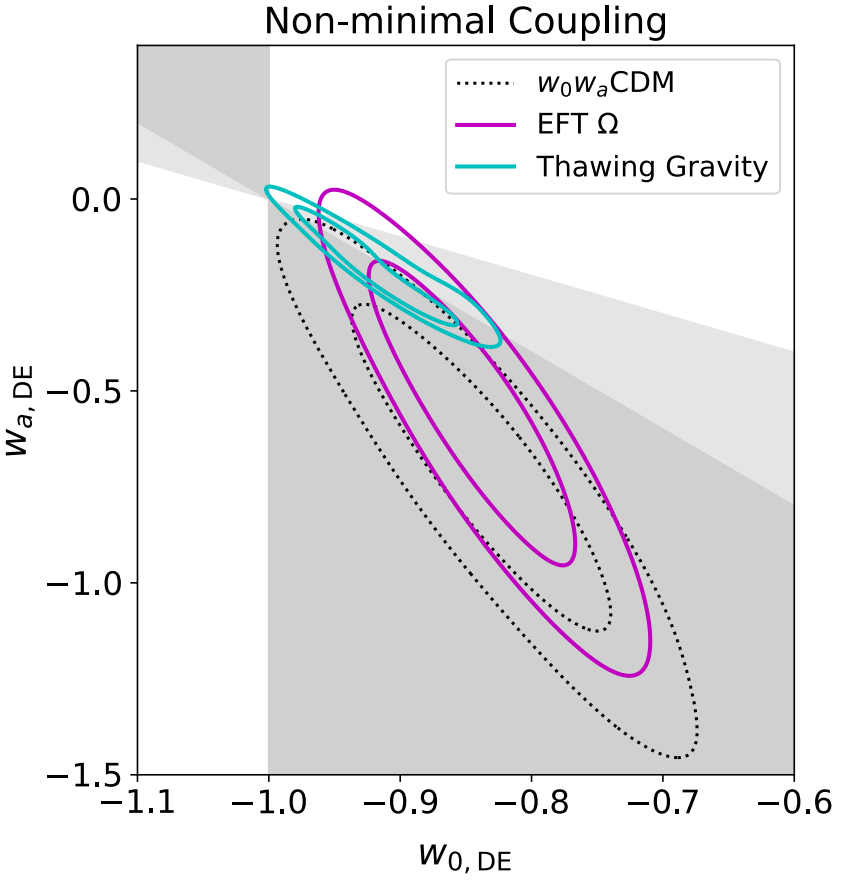
Hint of Modified Gravity in DESI DR1

$$\mathcal{S}=\int d^4x\sqrt{-g}\Big\{\frac{M_p^2}{2}(1+\Omega(\tau))R+\Lambda(\tau)-c(\tau)\,a^2\delta g^{00}+\frac{M_p^2H_0^2\gamma_1(\tau)}{2}\left(a^2\delta g^{00}\right)^2$$
$$-\frac{M_p^2H_0\gamma_2(\tau)}{2}\,a^2\delta g^{00}\,\delta K_\mu^\mu-\frac{M_p^2\gamma_3(\tau)}{2}\left[\left(\delta K_\mu^\mu\right)^2-\delta K_\nu^\mu\,\delta K_\mu^\nu-\frac{a^2}{2}\delta g^{00}\,\delta\mathcal{R}\right]\Big\}+S_m[g_{\mu\nu},\chi_m]$$

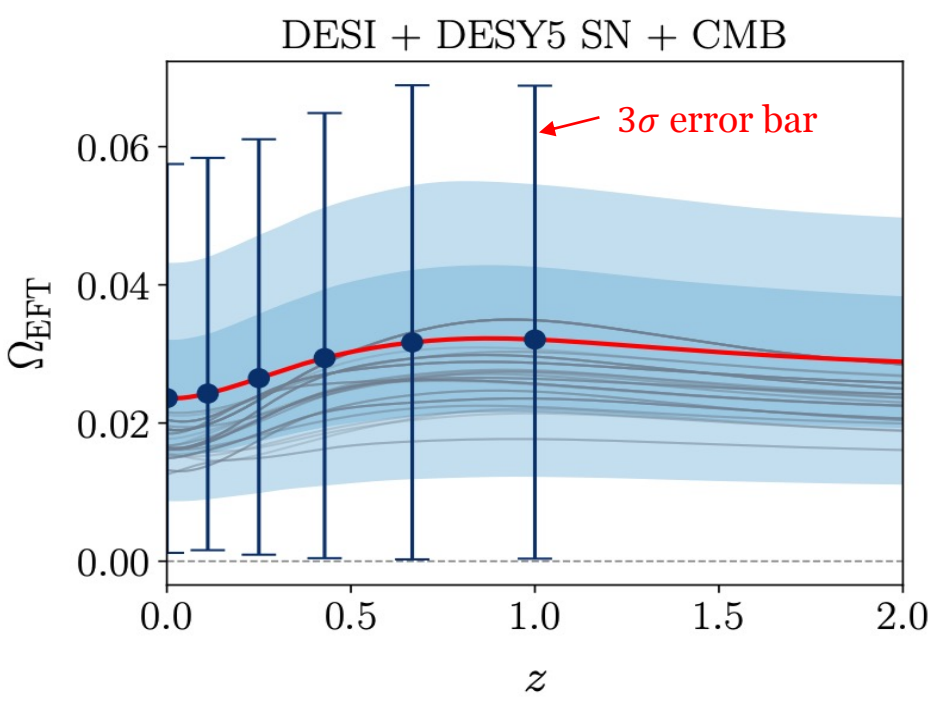


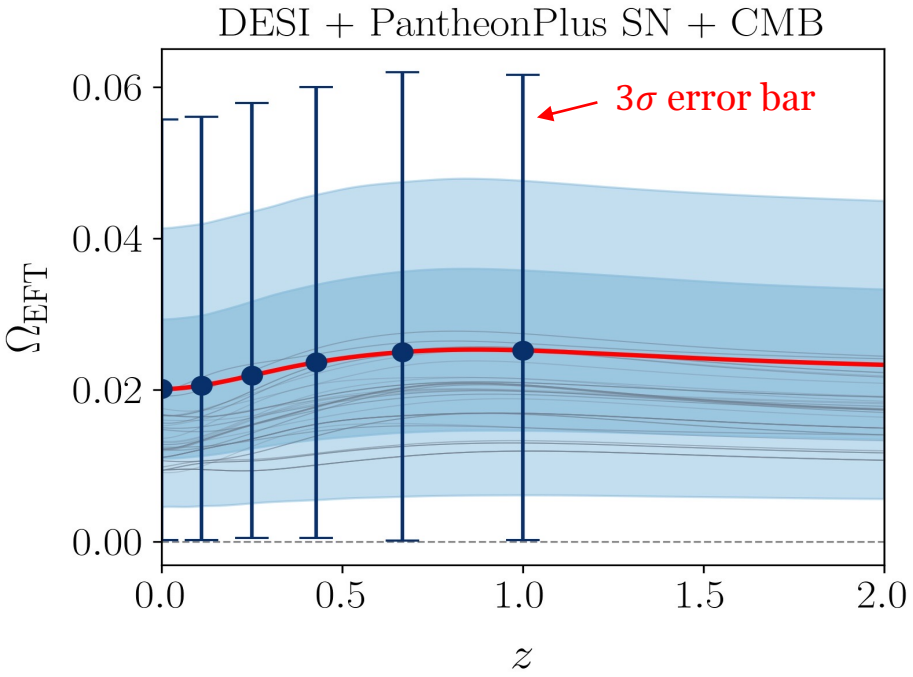
Physical interpretation of MG effect:

- Ω: non-minimal coupling (NMC) between gravity and matter
- γ_1: non-canonical kineticity, e.g. $P(X)$
- γ_2: Kinetic mixing between metric and DE, e.g. $X\Box\phi$
- γ_3: Modified GW speed



More hint of Modified Gravity in DESI DR2





3σ preference for NMC function $\Omega > 0$

Thawing Gravity (TG)

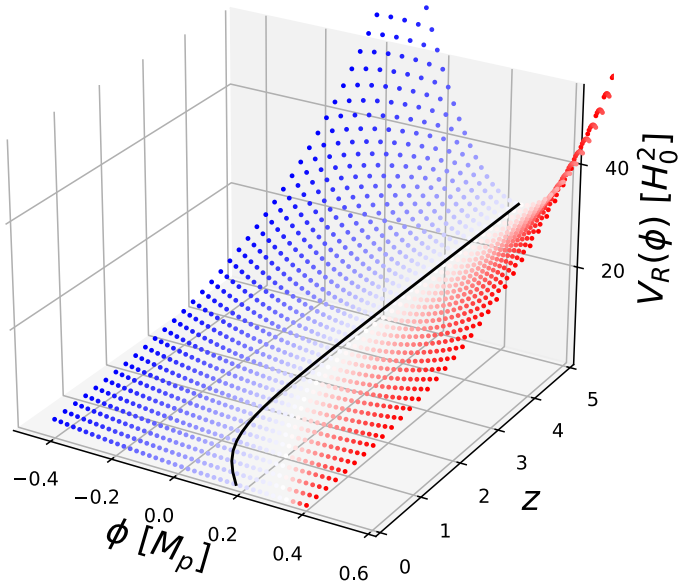
$$\mathcal{S} = \int dx^4\sqrt{-g}\left[\frac{M_p^2}{2}f(\phi)R + X - V(\phi)\right] + \mathcal{S}_m[g_{\mu\nu}]$$

- General local structure of non-minimal coupling :

$$f(\phi) = 1 - \xi\left(\frac{\phi}{M_p}\right)^2, \qquad \xi \geq 0$$

  - GR can be a local attractor [T.Damour, K.Nordtvedt, PRL 1993]
  - $\xi = 1/6$ conformally coupled

$$V_{eff} = \frac{1}{2}\xi R\phi^2 + V_0 e^{-\lambda\phi/M_p}$$

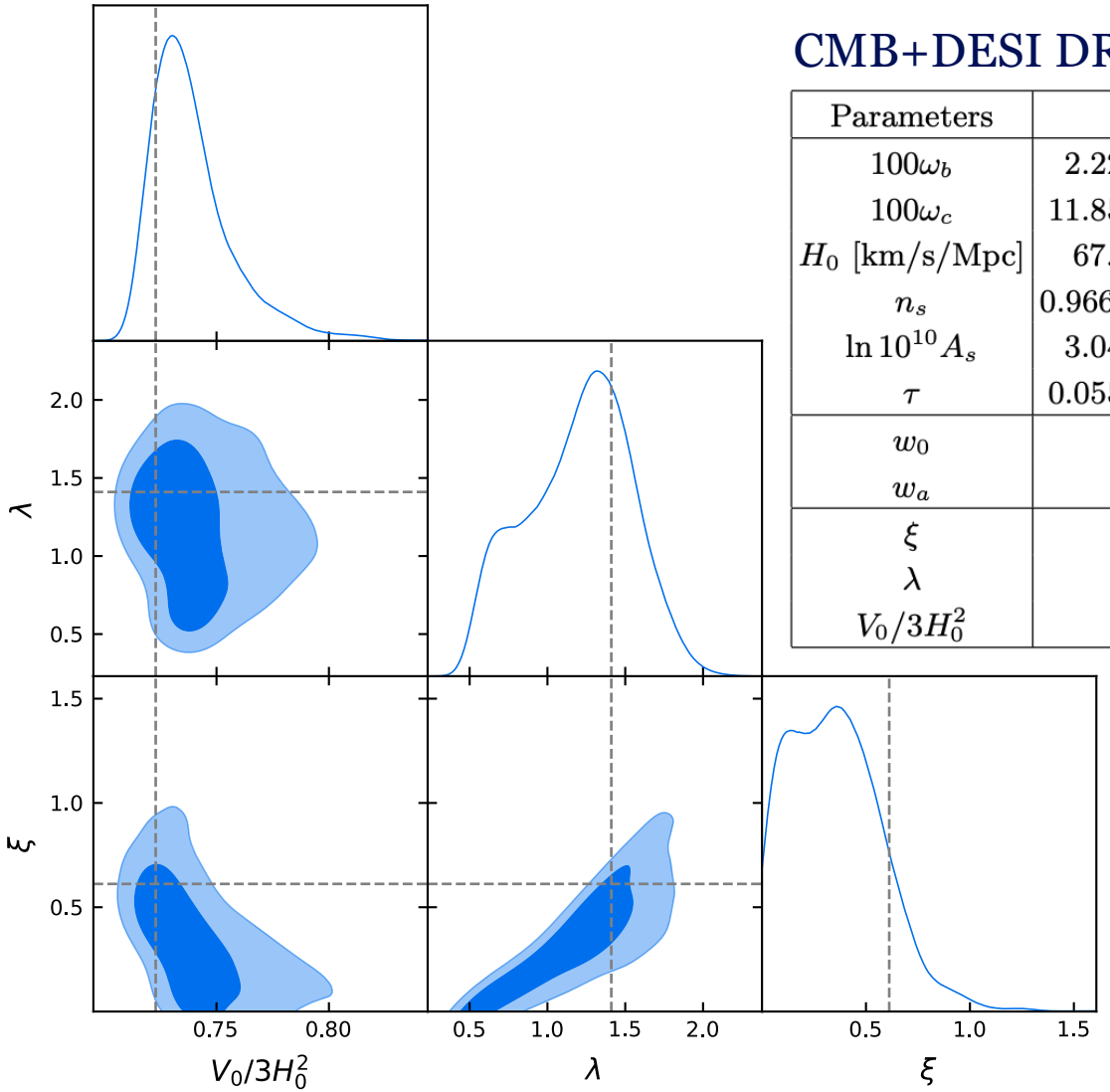


- Typical DE potential:

$$V(\phi) = V_0 e^{-\lambda\phi/M_p}$$

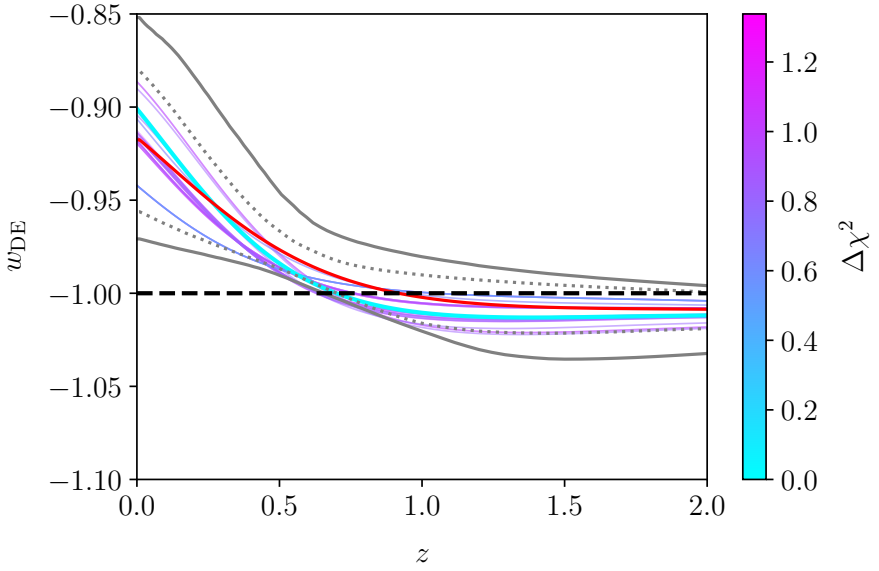
  - Support accelerated expansion
  - No strong constraint on shape from observations
  - Thawing quintessence potential might fit better [W.Wolf, P.G.Ferreira, C.Garcia-Garcia, arXiv:2409.17019]

TG limited to the late Universe

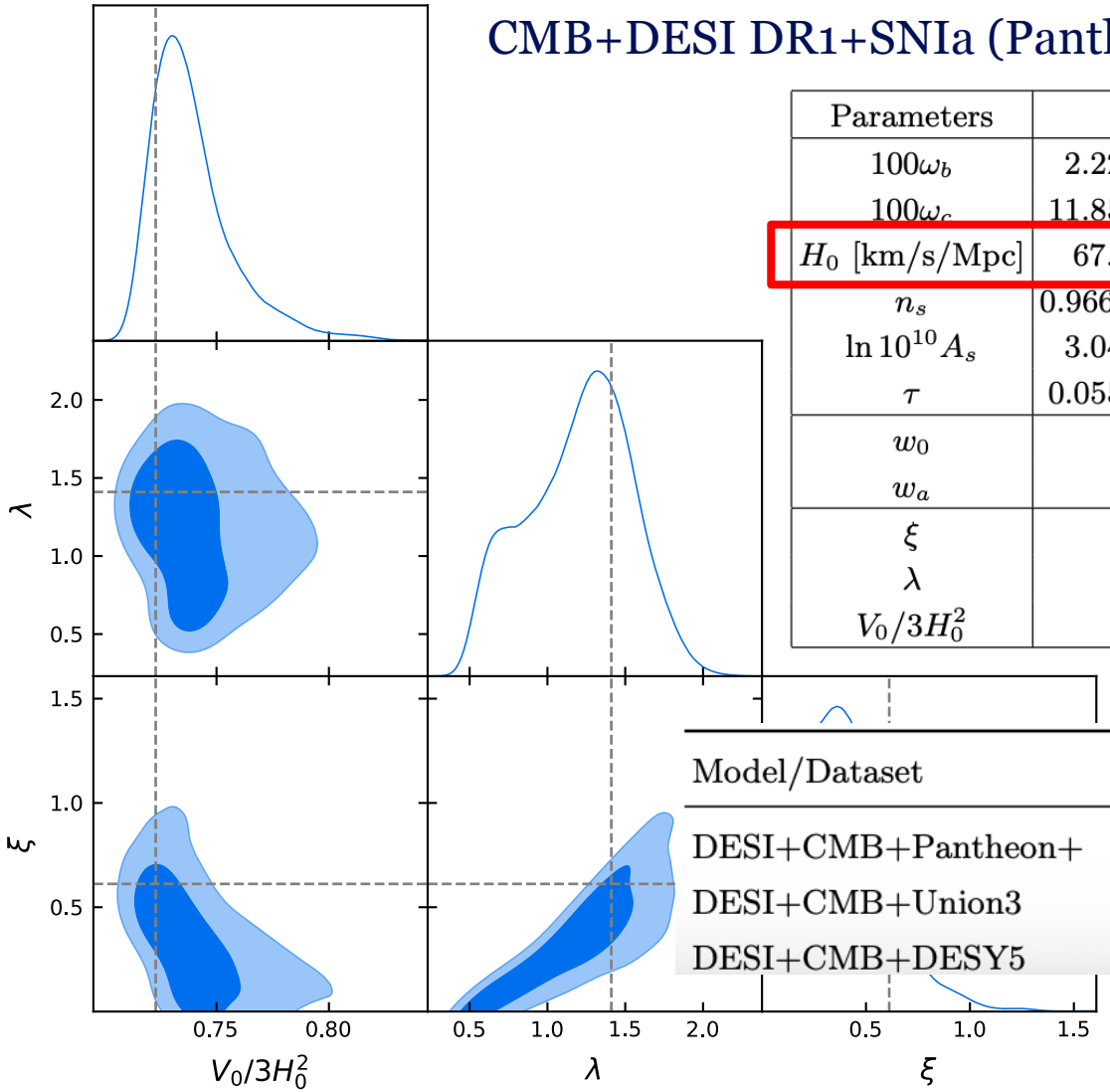


CMB+DESI DR1+SNIa (PantheonPlus)

Parameters	ΛCDM	w_0w_aCDM	Quintessence	Thawing Gravity
$100\omega_b$	$2.226(2.227) \pm 0.013$	$2.222(2.221) \pm 0.013$	$22.30(22.34) \pm 0.013$	$2.230(2.222) \pm 0.012$
$100\omega_c$	$11.857(11.830) \pm 0.081$	$11.924(11.913) \pm 0.091$	$11.809(11.862) \pm 0.012$	$11.810(11.759) \pm 0.077$
H_0 [km/s/Mpc]	$67.74(67.85) \pm 0.36$	$67.93(68.06) \pm 0.73$	$66.94(66.95)^{+0.58}_{-0.49}$	$66.81(66.89)^{+0.54}_{-0.41}$
n_s	$0.9662(0.9668) \pm 0.0036$	$0.9648(0.9648) \pm 0.0037$	$0.9677(0.9673) \pm 0.0037$	$0.9674(0.9672) \pm 0.0035$
$\ln 10^{10} A_s$	$3.042(3.044) \pm 0.014$	$3.035(3.030) \pm 0.014$	$3.046(3.045) \pm 0.014$	$3.044(3.058) \pm 0.013$
τ	$0.0558(0.573) \pm 0.0069$	$0.0519(0.0491) \pm 0.0071$	$0.0582(0.0506) \pm 0.0073$	$0.0571(0.0569) \pm 0.068$
w_0	N.A.	$-0.83(-0.83) \pm 0.06$	$-0.968(-0.970)^{+0.011}_{-0.030}$	$-0.92(-0.89)^{+0.03}_{-0.05}$
w_a	N.A.	$-0.71(-0.73)^{+0.29}_{-0.25}$	$0.006(-0.006)^{+0.033}_{-0.048}$	$-0.19(-0.27)^{+0.13}_{-0.12}$
ξ	N.A.	N.A.	N.A.	$< 0.74(0.61)$
λ	N.A.	N.A.	N.A.	$1.19(1.41)^{+0.42}_{-0.30}$
$V_0/3H_0^2$	N			$0.723(0.723)^{+0.008}_{-0.021}$



TG limited to the late Universe



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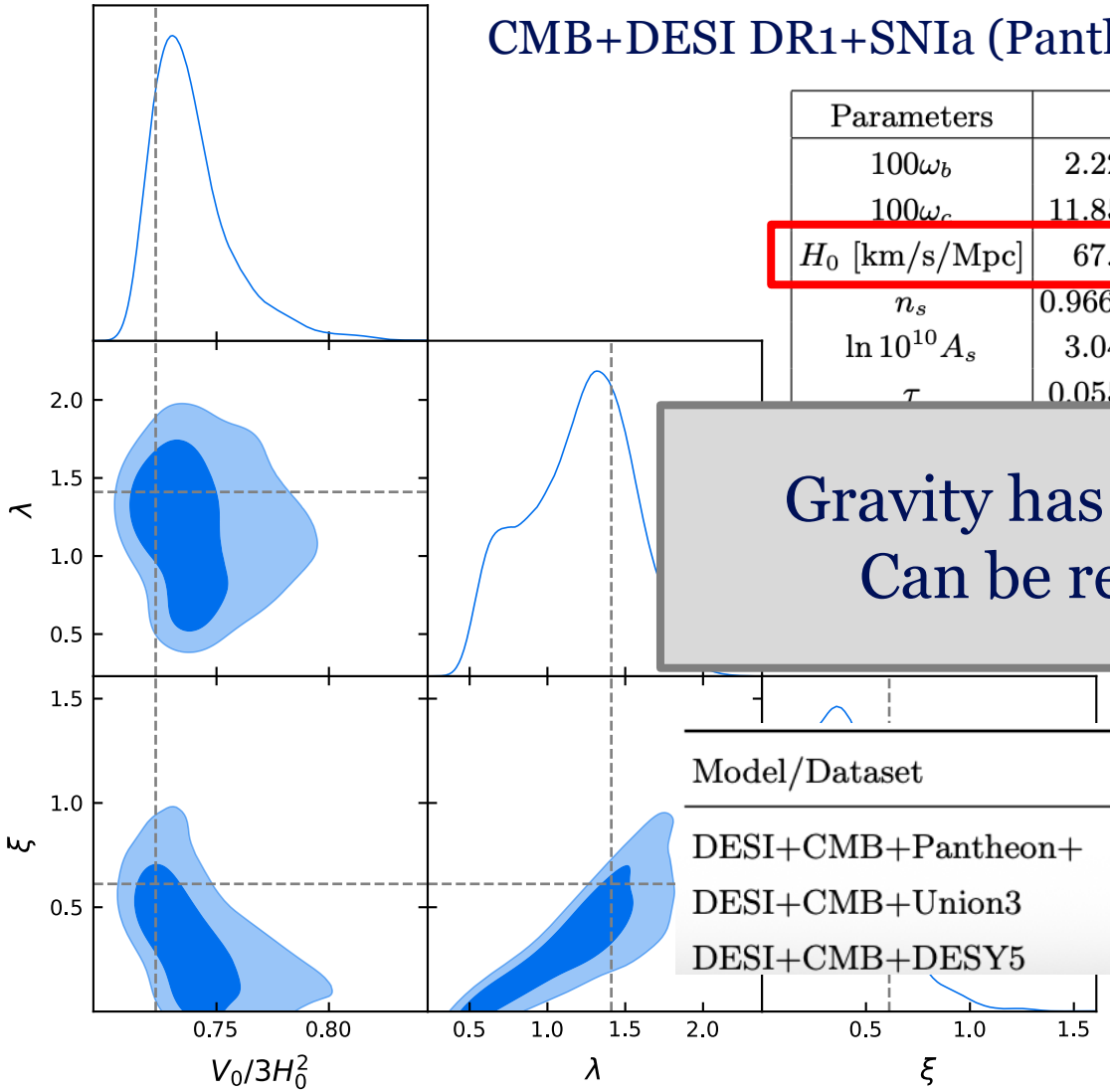
$V_0/3H_0^2$	N.A.	N.A.	N.A.	$0.723(0.723)^{+0.008}_{-0.021}$

Model/Dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_K$	w or w_0	w_a
DESI+CMB+Pantheon+	0.3114 ± 0.0057	67.51 ± 0.59	—	-0.838 ± 0.055	$-0.62^{+0.22}_{-0.19}$
DESI+CMB+Union3	0.3275 ± 0.0086	65.91 ± 0.84	—	-0.667 ± 0.088	$-1.09^{+0.31}_{-0.27}$
DESI+CMB+DESY5	0.3191 ± 0.0056	66.74 ± 0.56	—	-0.752 ± 0.057	$-0.86^{+0.23}_{-0.20}$

DESI, 2503.14738

TG limited to the late Universe



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			N.A.	$< 0.74(0.61)$
			N.A.	$1.19(1.41)^{+0.42}_{-0.30}$
			N.A.	$0.723(0.723)^{+0.008}_{-0.021}$

Gravity has no preferred scale ⇒
Can be relevant at all times

Model/Dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_K$	w or w_0	w_a
DESI+CMB+Pantheon+	0.3114 ± 0.0057	67.51 ± 0.59	—	-0.838 ± 0.055	$-0.62^{+0.22}_{-0.19}$
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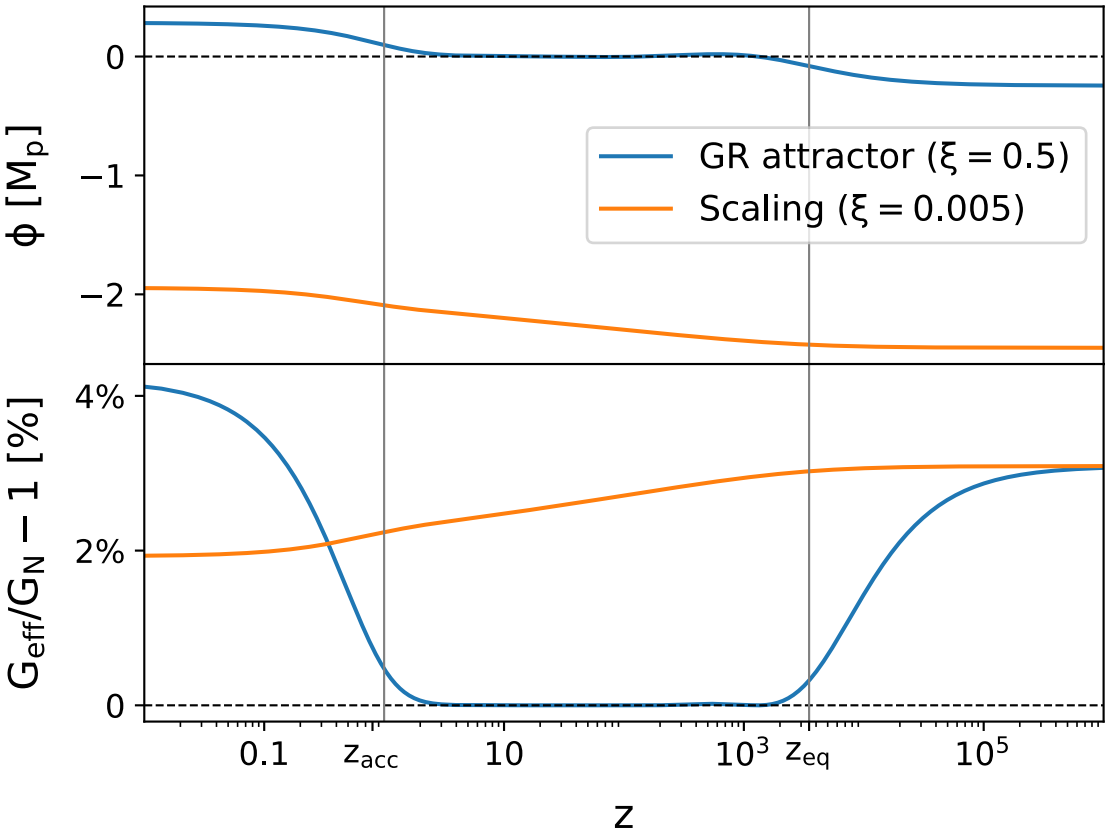
DESI, 2503.14738

Full TG: 2 thawing

$$L = \frac{M_p^2}{2}\left[1 - \xi(\phi/M_p)^2\right] R + X - V_0 e^{-\lambda\phi/M_p},$$

Gravity has no preferred scale ⇒ Thawing whenever evolution of R changes

- 1st thawing: $z = z_{eq}$
  - Transition: $R \ll H^2 \rightarrow R \sim O(H^2)$
  - $\phi \simeq \phi_i$ frozen → ϕ rolling (EDE like)
- 2nd thawing: $z = z_{acc}$
  - Transition: deceleration→ acceleration
  - Matter dominance → ϕ dominance (DE/MG)



Full TG: 2 scenarios

$$L = \frac{M_p^2}{2}\left[1 - \xi(\phi/M_p)^2\right] R + X - V_0 e^{-\lambda\phi/M_p},$$

- Approximate solution

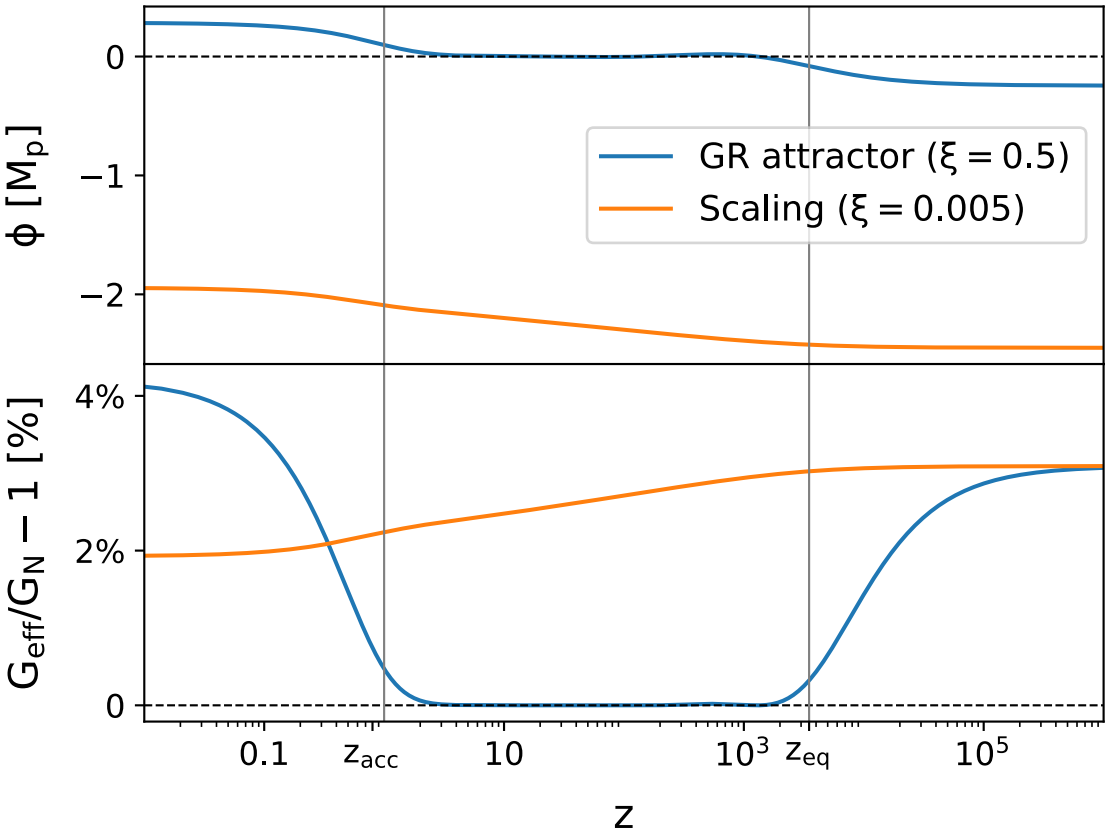
$$\phi \simeq \begin{cases} \phi_{\rm ini} & \text{RD}, \\ \phi_{\rm ini} \exp\left[\dfrac{-3 \pm \sqrt{9 - 48\xi}}{4}(N - N_i)\right] & \text{MD}, \end{cases} \qquad N = \ln\frac{a}{a_0}$$

- GR attractor $\xi > \frac{3}{16}$

  damped oscillation around $\phi \simeq 0$

- Scaling $\xi < \frac{3}{16}$

  scales with scale factor $\phi \propto a^\gamma, 0 < \gamma < 3$



Full TG: Bayes Evidence

	w_0w_aCDM	EDE	TG
CMB+BAO+SNIa	-1.4	-0.6	$+1.5$
CMB+BAO+SNIa+H_0	$+4.6$	$+9.5$	$+11.8$

→ DESI BAO tension

→ Hubble tension

Bayes Factor $\ln B = \ln Z_{model} - \ln Z_{\Lambda CDM}$

Jeffreys' scale:

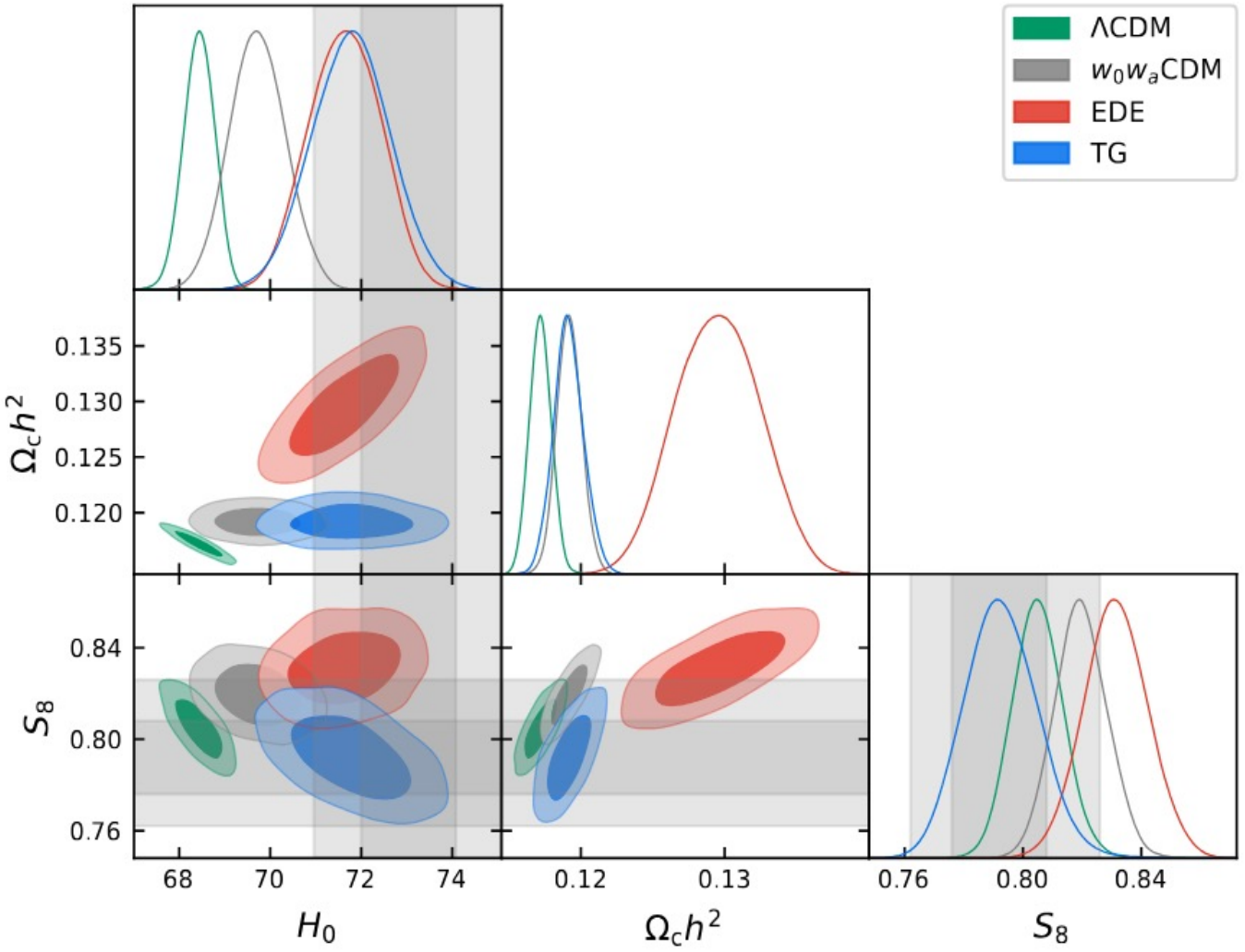
- Weak $\leftrightarrow$ $\ln B < +1 \leftrightarrow < 2.1\sigma$
- Moderate $\leftrightarrow$ $\ln B < +2.5 \leftrightarrow < 2.7\sigma$
- Strong $\leftrightarrow$ $\ln B < +5 \leftrightarrow < 3.6\sigma$
- $\ln B = 11 \leftrightarrow 5\sigma$

Nested Sampling:

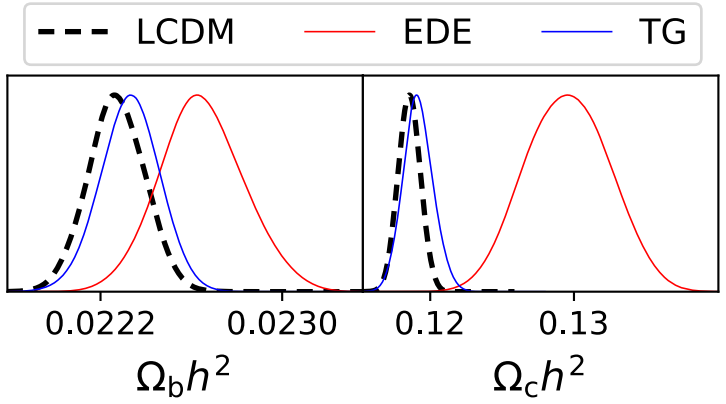
- Better performance with non-Gaussian posterior
- Bayes evidence and model comparison

- CMB: Planck PR4 TTTEEE, low l TTEE, PR4 lensing
- BAO: DESI DR1
- SNIa: Pantheon+
- H_0: SH0ES calibrated Pantheon+
- Baseline = CMB+DESI BAO+SNIa

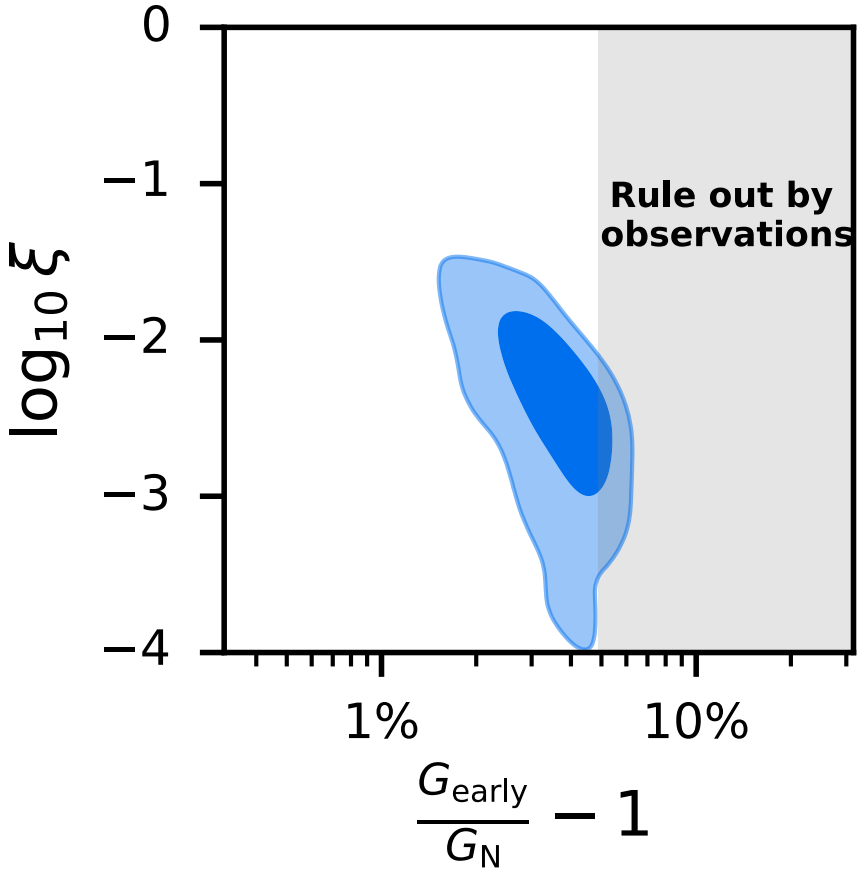
Full TG: Cosmological parameters



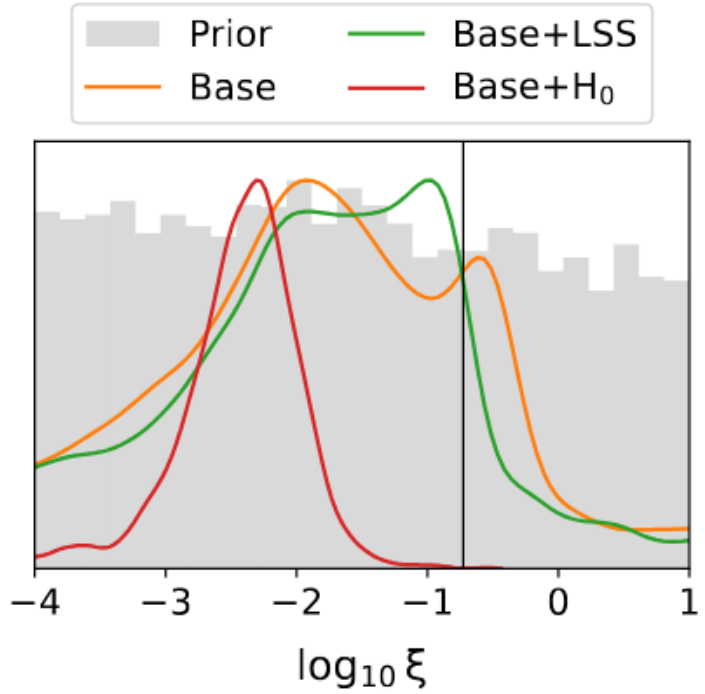
- Pre-recombination NMC important
  - $H_0 = 66.8 \pm 0.5 \Rightarrow H_0 = 71.8 \pm 0.9$
  - Stronger gravity in CMB negates the need to increase $\omega_{c,b}$
- Post-recombination NMC important
  - BAO no longer fixes Ω_m, thus compatibility does require $\Omega_m h^2$ increasing with H_0
  - Address DESI BAO inconsistency with CMB



Full TG: Modified Gravity Prediction



Baseline+SHoES:
$> 4\sigma$ detection of **stronger gravity** $\frac{G_{CMB}}{G_N} = 1.04 \pm 0.01$ at CMB



- Double peak in CMB+BAO+SNIa
- Local Hubble measurement picks out the scaling case $\xi < 3/16$

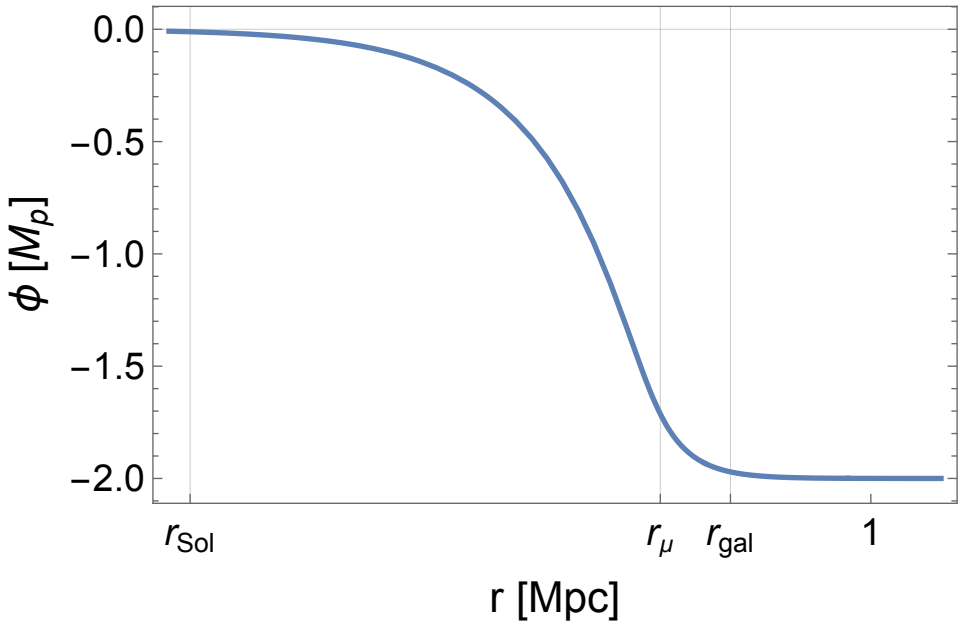
Consistent with BBN constraint $\frac{G_{BBN}}{G_N} = 0.99^{+0.06}_{-0.05}$ [J.Alvey et al. 2019]

Full TG: Screening?

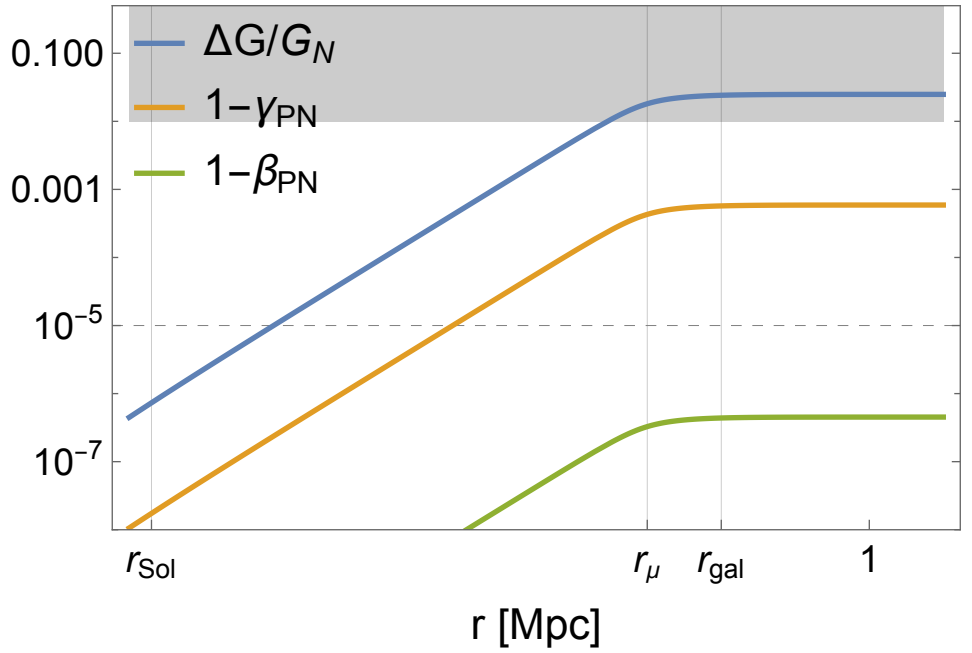
TG as an EFT of gravity on cosmological scales, screening can happen for new operators appearing on small scales.

- Example:

$$\mathcal{L} = \frac{M_p^2}{2}\left[1-\xi(\phi/M_p)^2\right]R + X - \frac{1}{M_p^2\mu^2}X^2 - V_0\exp(-\lambda\phi/M_p)$$



$$r_\mu = \mu^{-1} = 1\ \text{kpc}$$



Summary

• Thawing Gravity:

- Restore consistency between DESI BAO and CMB
- Stably explain the potential DE phantom crossing indicated by DESI BAO

- Relevant in all epochs of Universe evolution
- Two natural “thawing points” z_{eq} and z_{acc} when curvature R changes behavior
- Restore concordance with local Hubble measurement

- Possibility to screen MG effects on small scales

Thank You!

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	ΛCDM	w_0w_aCDM	Quintessence	Thawing Gravity
CMB	10972.6	10970	10972.9	10970.8
DESI BAO	15.8	12.4	18.6	13.7
SNIa	1404.8	1403.4	1402.8	1402.9
Total	12393.2	12385.8	12394.3	12387.4