

<u>Towards a possible solution to the</u> Hubble tension with Horndeski gravity



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Outline

- The Standard Model of Cosmology
- Hubble Tension
- Resolution: Dynamical Dark Energy
- Hints of dynamical dark energy : DESI
- Dark Energy in Horndeski gravity
- Constraints from Observations
- Conclusion and Future Prospects

Present understanding of the universe



Image Credit: NASA/ LAMBDA Archive / WMAP Science Team

Present understanding of the universe: Λ CDM model





Lambda Cold Dark Matter (ACDM) Model : Simplest Scenario

$$H(z) = H_0 \sqrt{\Omega_{r0}(1+z)^4 + \Omega_{m0}(1+z)^3 + \Omega_\Lambda}$$

Here it is assumed that universe is spatially flat i.e. $\Omega_k=0$. Thanks to inflation!

High Precision Measures of H_0



CMB with Planck

Balkenhol et al. (2021), Planck 2018+SPT+ACT : 67.49 ± 0.53 -Aghanim et al. (2020), Planck 2018: 67.27 ± 0.60 -Aghanim et al. (2020), Planck 2018+CMB lensing: 67.36 ± 0.54 -

CMB without Planck -

Dutcher et al. (2021), SPT: 68.8 ± 1.5 – Aiola et al. (2020), ACT: 67.9 ± 1.5 – Aiola et al. (2020), WMAP9+ACT: 67.6 ± 1.1 – Zhang, Huang (2019), WMAP9+BAO: 68.36 ± 0.53

No CMB, with BBN

Colas et al. (2020), BOSS DR12+BBN: 68.7 ± 1.5 Philcox et al. (2020), P_{ℓ} +BAO+BBN: 68.6 ± 1.1 Ivanov et al. (2020), BOSS+BBN: 67.9 ± 1.1 Alam et al. (2020), BOSS+eBOSS+BBN: 67.35 ± 0.97

Cepheids – SNIa

Riess et al. (2020), R20: 73.2 ± 1.3 Breuval et al. (2020): 72.8 ± 2.7 Riess et al. (2019), R19: 74.0 ± 1.4 Camarena, Marra (2019): 75.4 ± 1.7 Burns et al. (2018): 73.2 ± 2.3 Follin, Knox (2017): 73.3 ± 1.7 Feeney, Mortlock, Dalmasso (2017): 73.2 ± 1.8 Riess et al. (2016), R16: 73.2 ± 1.7 Cardona, Kunz, Pettorino (2016): 73.8 ± 2.1 Freedman et al. (2012): 74.3 ± 2.1

TRGB - SNIa

Soltis, Casertano, Riess (2020): 72.1 ± 2.0 -Freedman et al. (2020): 69.6 ± 1.9 -Reid, Pesce, Riess (2019), SH0ES: 71.1 ± 1.9 -Freedman et al. (2019): 69.8 ± 1.9 -Yuan et al. (2019): 72.4 ± 2.0 -Jang, Lee (2017): 71.2 ± 2.5 -

Masers

Pesce et al. (2020): 73.9 ± 3.0

Tully – Fisher Relation (TFR) Kourkchi et al. (2020): 76.0 ± 2.6

Schombert, McGaugh, Lelli (2020): 75.0 ± 2.6

Surface Brightness Fluctuations

Blakeslee et al. (2021) IR-SBF w/ HST: 73.3 ± 2.5

Lensing related, mass model – dependent

Yang, Birrer, Hu (2020): $H_0 = 73.65^{+1.95}_{-226}$ Millon et al. (2020), TDCOSMO: 74.2 ± 1.6 Qi et al. (2020): 73.6^{+1.8}_{-1.6} Liao et al. (2020): 72.2 ± 2.1 Shajib et al. (2019), STRIDES: 74.2^{+2.7}_{-2.7} Wong et al. (2019), HOLICOW 2019: 73.3^{+2.7}_{-2.6} Birrer et al. (2018), HOLICOW 2018: 72.5^{+2.3}_{-2.7}_{-3.0} Bonvin et al. (2016), HOLICOW 2016: 71.9^{+2.3}_{-3.0}

Optimistic average

Di Valentino (2021): 72.94 ± 0.75 Ultra – conservative, no Cepheids, no lensing Di Valentino (2021): 72.7 ± 1.1

The Hubble Trouble





(Di Valentino et al 2021)

Understanding Hubble Tension

Early measurements

- Based on observations of cosmic microwave background coming from last scattering surface (redshift ~ 1100, 13.76 Gyr back).
- > Assumes Λ CDM model to calculate H_0 .
- Planck, WMAP
- $H_0 = 67.37 \pm 0.54 \text{ km/sec/Mpc}$





Late measurements

- Based on astrophysics of stars: observing standard candles in the nearby universe.
- Model independent measurement.
- ➢ SHOES, CHP
- $> H_0 = 73.3 \pm 1.04 \text{ km/sec/Mpc}$

Measurement of H_0 from early Universe



six independent parameters of **LCDM** model.

Derived parameters

Parameter	Combined
$\overline{\Omega_{\rm b}h^2}$	0.02233 ± 0.00015
$\Omega_{\rm c}h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10}A_{\rm s})$	3.043 ± 0.014
<i>n</i> _s	0.9652 ± 0.0042
$\Omega_{-}h^{2}$	0.1428 ± 0.0011
H_0^{-1} [km s ⁻¹ Mpc ⁻¹]	67.37 ± 0.54
36m	0.3147 ± 0.0074 12 801 + 0.024
Age [Gyr]	15.801 ± 0.024
σ_8	0.8101 ± 0.0061
$S_8 \equiv \sigma_8 (\Omega_{\rm m}/0.3)^{0.5} . .$	0.830 ± 0.013
Zre	7.64 ± 0.74
1000.	1.04108 ± 0.00031
<i>r</i> _{drag} [Mpc]	147.18 ± 0.29



Planck 2018 measurements assuming LCDM model give, $H_0 = 67.37 \pm 0.54$ km/sec/Mpc

Reference: Planck Collaboration (2018)

Measurement of H_0 from Late Universe



Image Credit: NASA

Cosmic Distance Ladder : calibrating distances to galaxies farther away upto redshift ~ 0.1

- Observing standard candles (Supernovae and Cepheids) to calibrate distances to galaxies and using Hubble's law to calculate H₀.
- The **SHOES** Program (Supernovae and H_0 for the Equation of State of dark energy) measured $H_0 = 73.3 \pm 1.04$ km/sec/Mpc (*Riess et al 2022*).
- \succ This drives the H_0 tension $\sim 5\sigma$

Resolving Hubble Tension with a dynamical dark energy

A dark energy field whose equation of state evolves with time w(z): But what else?



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Conditions which can resolve cosmological tensions without disturbing the CMB observations:

- Phantom crossing
- Variation in Gravitational coupling constant G_{eff}

Simultaneously solving the H_0 and σ_8 tensions with late dark energy

Lavinia Heisenberg ^{a b} 🝳 🖂 , Hector Villarrubia-Rojo ^b 🖂 , Jann Zosso ^b 🖂

Phantom equation of state: w < -1 \longrightarrow Violation of Strong Energy Condition

Hints of dynamical dark energy from DESI

FERMILAB-PUB-24-0154-PPD

PREPARED FOR SUBMISSION TO JCAP

DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations

DESI Collaboration: A. G. Adame,¹ J. Aguilar,² S. Ahlen⁰,³

- DESI BAO favors a dynamical dark energy over cosmological constant.
- Signatures of phantom crossing in DESI.



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Our Approach

Towards a possible solution to the Hubble tension with Horndeski gravity

Yashi Tiwari, Basundhara Ghosh, Rajeev Kumar Jain

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Regular Article - Theoretical Physics

Towards a possible solution to the Hubble tension with Horndeski gravity



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Our Model: A subclass of Horndeski theory

$$\mathcal{L}_{\phi} = \frac{R}{2} \left[1 + 2c_{3}\phi \right] + \frac{1}{2}\partial_{\mu}\phi\partial^{\mu}\phi - V(\phi) - \left[c_{1}\phi + \frac{1}{2}c_{2}\partial_{\mu}\phi\partial^{\mu}\phi \right] \partial_{\mu}\partial^{\mu}\phi,$$

Non-minimal coupling

Self-interaction (Galileon)

 $\mathcal{L} = \sum_{i=2}^{5} \mathcal{L}_{i},$ Horndeski gravity: A generalized scalar tensor theory in 4D with second order equations o motion $\mathcal{L}_{2} = G_{2}(\phi, X),$ $\mathcal{L}_{3} = -G_{3}(\phi, X)\Box\phi,$ $\mathcal{L}_{4} = G_{4}(\phi, X)R + G_{4,X}(\phi, X) \left[(\Box\phi)^{2} - (\nabla_{\mu}\nabla_{\nu}\phi)^{2} \right],$ $\mathcal{L}_{5} = G_{5}(\phi, X)G_{\mu\nu}\nabla^{\mu}\nabla^{\nu}\phi - \frac{1}{6}G_{5,X}(\phi, X) \left[(\Box\phi)^{3} - 3\Box\phi(\nabla_{\mu}\nabla_{\nu}\phi)^{2} + 2(\nabla_{\mu}\nabla_{\nu}\phi)^{3} \right],$ (Kobayashi et al 2011, Kobayashi 2019)

Background: Previous results

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- c₁=3.0, c₂=5.0, c₃=0.01 75 - c₁=3.0, c₂=5.0, c₃=0.015 - c₁=4.0, c₂=6.0, c₃=0.01 Riess 2022 - c₁=4.0, c₂=6.0, c₃=0.015 70 — ACDM H (Z) (1 + Z) BAO Ly-α 65 Quasar DR14 BOSS DR12 60 55 0.0 0.5 1.0 1.5 2.0 2.5 z

Eur.Phys.J.C 84 (2024) 3, 220

Background: Previous results



Eur.Phys.J.C 84 (2024) 3, 220

Work in progress

Towards a Simultaneous Alleviation of H0 and S8 tension with Horndeski gravity

Yashi Tiwari, Ujjwal Upadhyay, Rajeev Kumar Jain



S_8 Tension

$$S_8 = \sigma_8 \left(\frac{\Omega_M}{0.3}\right)^{0.5}$$

A measure of amplitude of matter clustering in late universe

 σ_8 is the variance of density field smoothed over $8h^{-1}$ Mpc



Most of the proposed solutions which resolve Hubble Tension, actually worsen S_8 tension !!!



⁽Abdalla et al 2022)

Perturbations: Growth of structures

$$ds^{2} = -(1+2\Psi)dt^{2} + a^{2}(1-2\Phi)d\mathbf{x}^{2} -$$

Perturbed metric in Newtonian gauge

In quasistatic limit within sub horizon scales the evolution of matter density perturbation follows,



Some preliminary results: *G*_{eff}



Some preliminary results: Growth Rate



Cosmological Parameter Estimation



Parameters	68% limits
H_0	69.06 ± 0.47
Ω_m	0.2953 ± 0.0052
S_8	0.8165 ± 0.0124
c_1	3.4275 ± 1.5290
c_2	2.1895 ± 3.9560
c_3	0.0003 ± 0.0006

Conclusion and Future Prospects

- We exploit the phenomenology of Horndeski theory to build dark energy model to resolve cosmological tensions.
- Interesting features like phantom crossing, variation in gravitational coupling constant etc., can be obtained in such a setup.
- > Constrains are obtained on parameter space by Supernovae, Planck, BAO and SHOES data.
- > We are working on including new DESI data in the analysis.
- We further plan to constrain such MG theories (particularly with nonminimal couplings) with GWs and their cross correlations with galaxy surveys, in a model independent way.

