Towards a possible solution to the 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

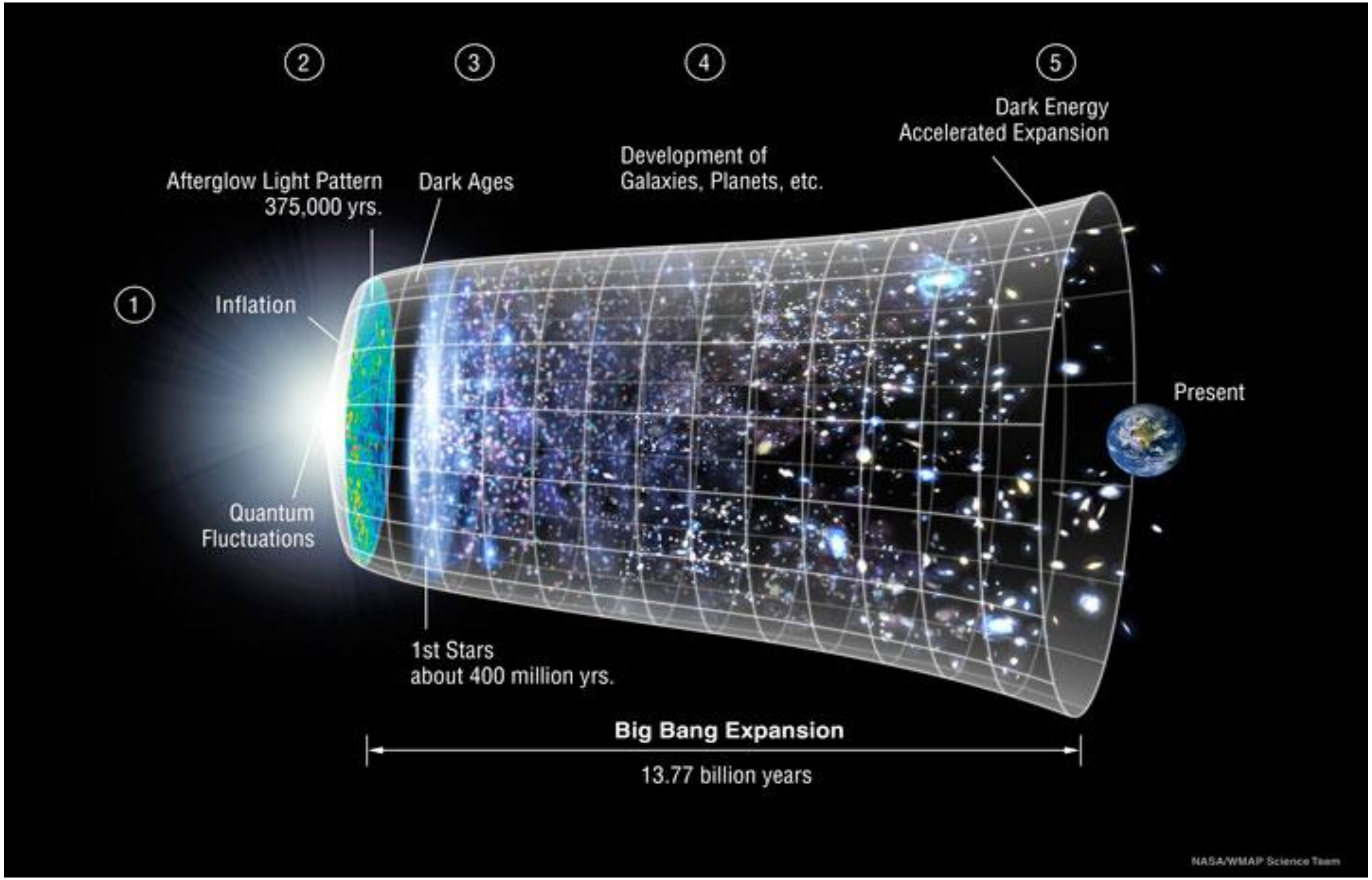


Image Credit: NASA/ LAMBDA Archive / WMAP Science Team

Present understanding of the universe: ΛCDM model

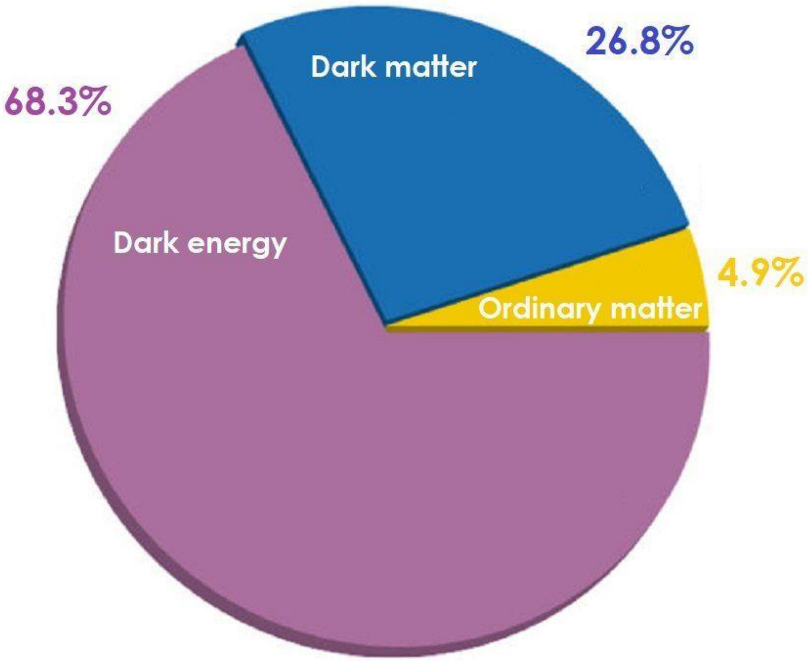
Cosmological Principle + General Relativity

↓

$$ds^2 = -dt^2 + a(t)^2 d\bar{x}^2 \qquad R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

↓

Friedmann Equation ⟵ $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$ ⟶ Total energy density



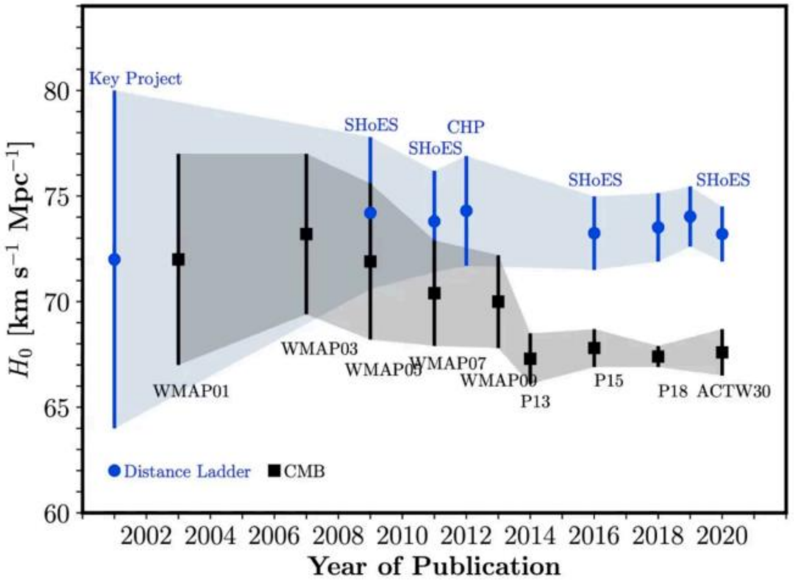
Lambda Cold Dark Matter (ΛCDM) Model : Simplest Scenario

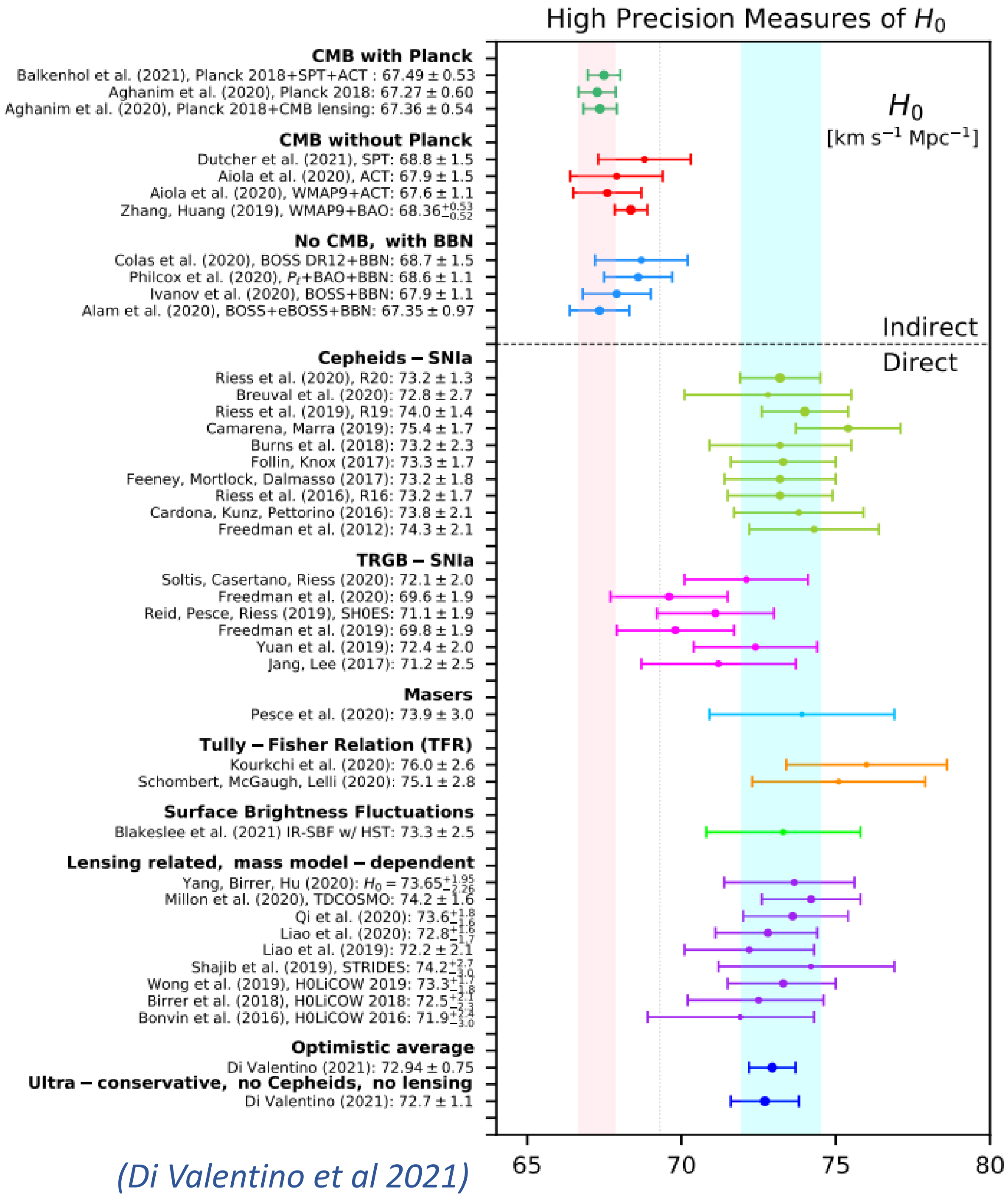
$$H(z) = H_0 \sqrt{\Omega_{r0}(1+z)^4 + \Omega_{m0}(1+z)^3 + \Omega_\Lambda}$$

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

The Hubble Trouble

5σ tension
at present!



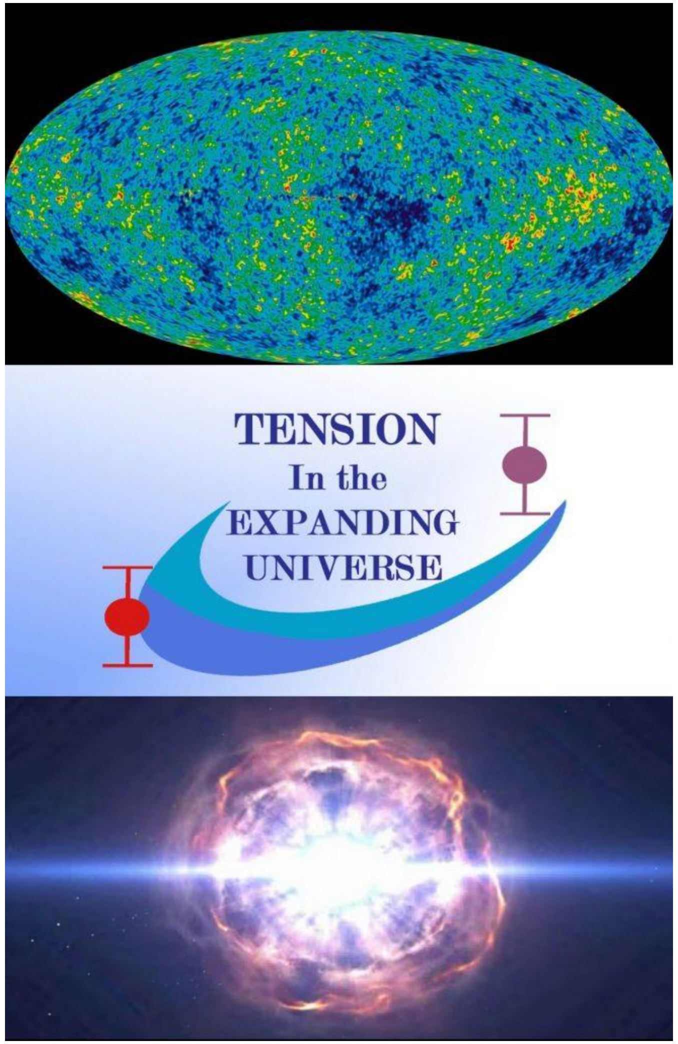


(Di Valentino et al 2021)

Understanding Hubble Tension

Early measurements

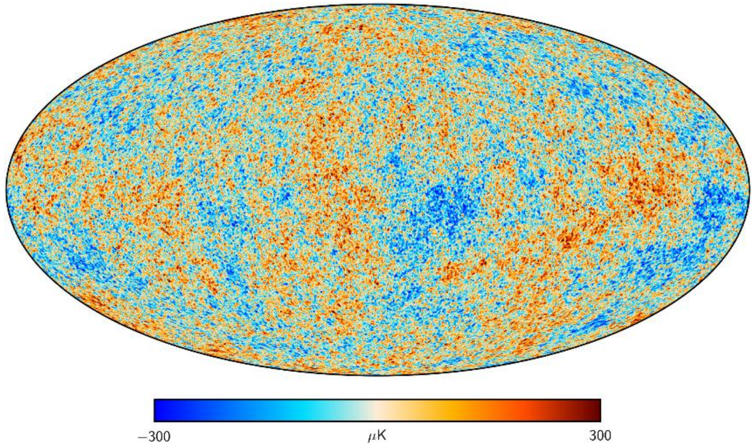
- Based on observations of cosmic microwave background coming from last scattering surface (redshift ~ 1100, 13.76 Gyr back).
- Assumes ΛCDM model to calculate H_0.
- Planck, WMAP
- $H_0 = 67.37 \pm 0.54$ km/sec/Mpc



Late measurements

- Based on astrophysics of stars: observing standard candles in the nearby universe.
- Model independent measurement.
- SH0ES, CHP
- $H_0 = 73.3 \pm 1.04$ km/sec/Mpc

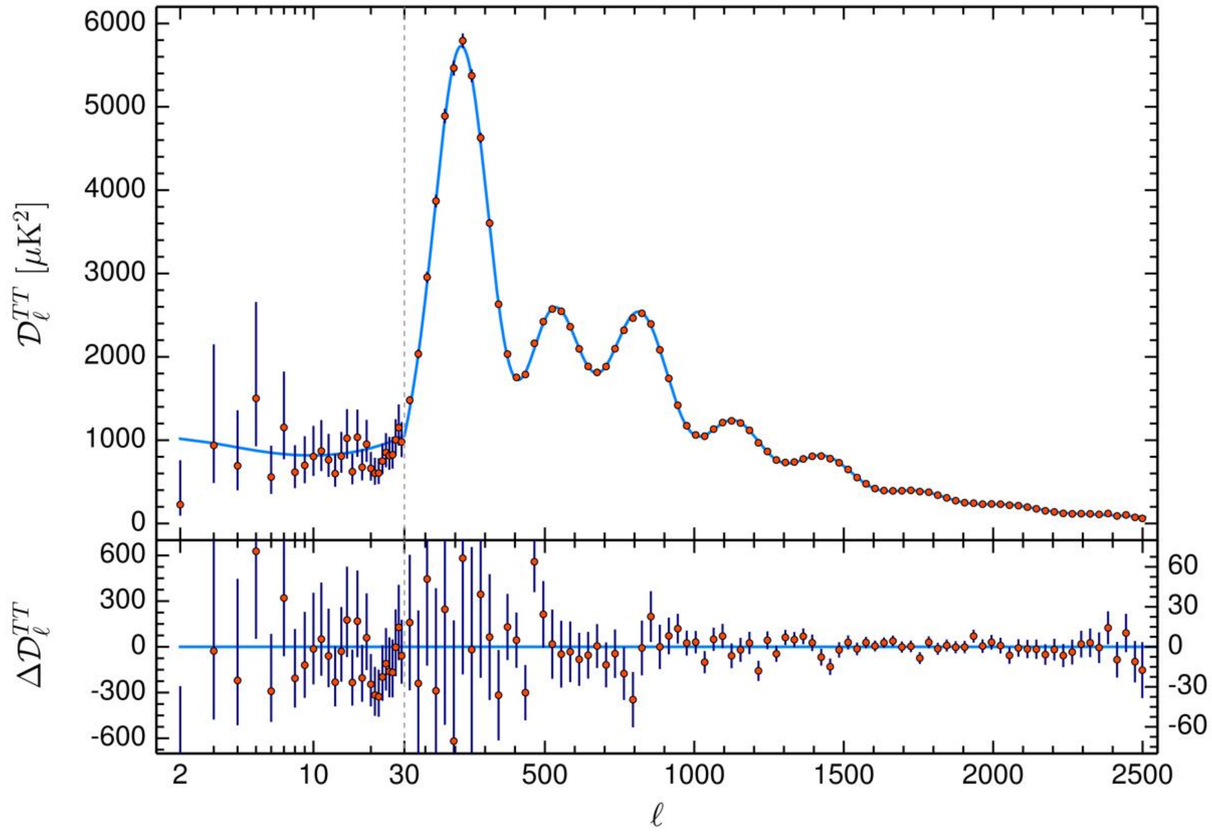
Measurement of H_0 from early Universe



six independent parameters of **LCDM** model.

Derived parameters

Parameter	Combined
$\Omega_b h^2$	0.02233 ± 0.00015
$\Omega_c h^2$	0.1198 ± 0.0012
$100\theta_{MC}$	1.04089 ± 0.00031
τ	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.043 ± 0.014
n_s	0.9652 ± 0.0042
$\Omega_m h^2$	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.37 ± 0.54
Ω_m	0.3147 ± 0.0074
Age [Gyr]	13.801 ± 0.024
σ_8	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.830 ± 0.013
z_{re}	7.64 ± 0.74
$100\theta_*$	1.04108 ± 0.00031
r_{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

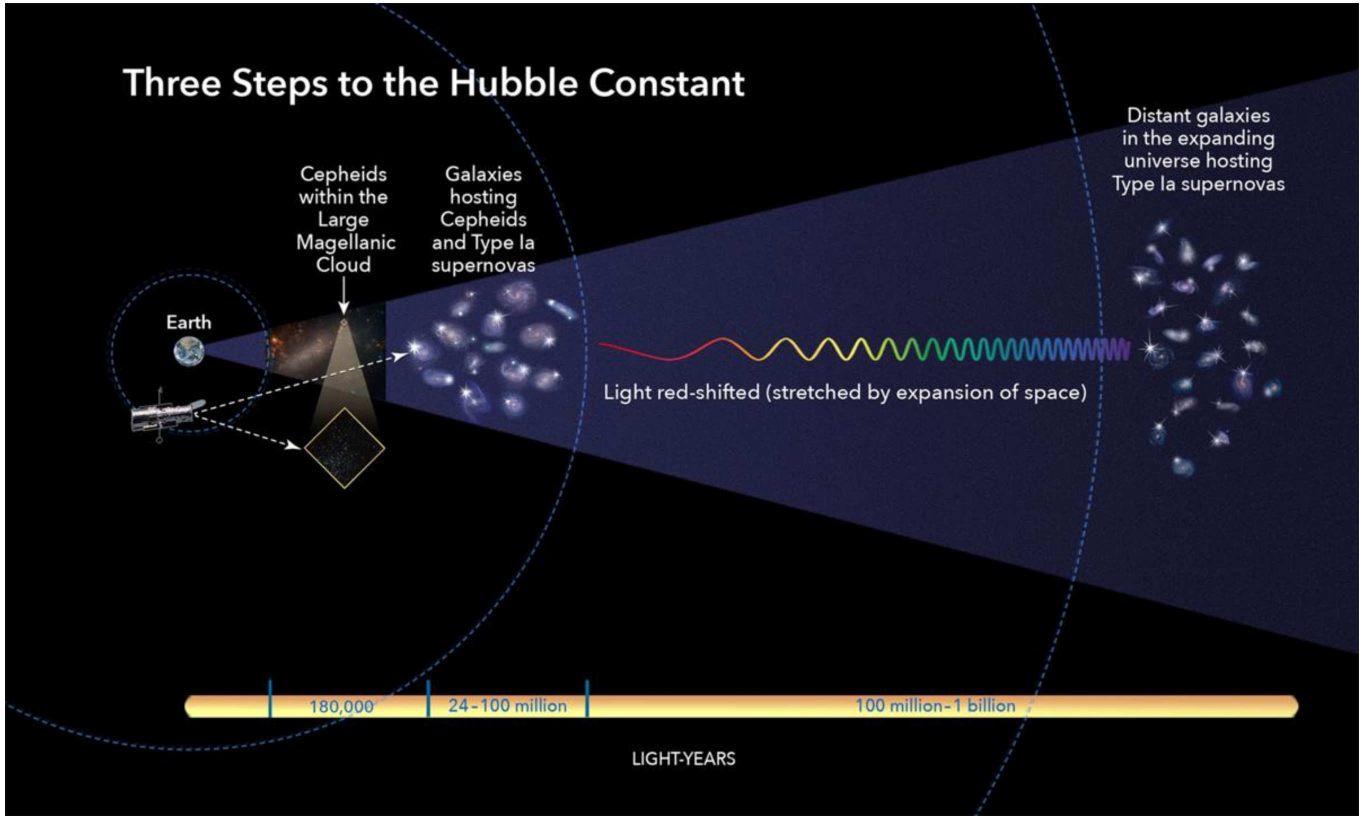


Image Credit: NASA

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 H_0.
- The **SH0ES** Program (Supernovae and H_0 for the Equation of State of dark energy) measured $\boldsymbol{H_0 = 73.3 \pm 1.04}$ km/sec/Mpc *(Riess et al 2022)*.
- This drives the H_0 tension $\sim 5\sigma$

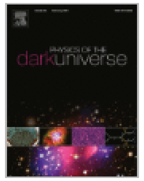
Resolving Hubble Tension with a dynamical dark energy

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

ELSEVIER

Physics of the Dark Universe

Volume 39, February 2023, 101163



Simultaneously solving the H_0 and σ_8 tensions with late dark energy

Lavinia Heisenberg [a b], Hector Villarrubia-Rojo [b], Jann Zosso [b]

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

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

Phantom equation of state: $w < -1$ ⇒ Violation of Strong Energy Condition

Hints of dynamical dark energy from DESI

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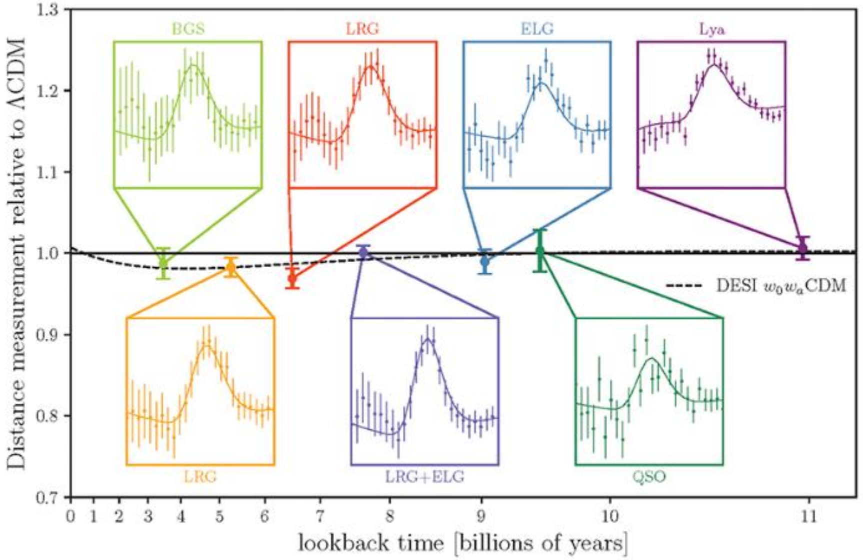
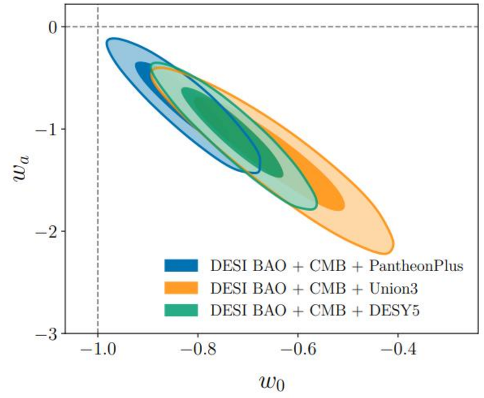
PREPARED FOR SUBMISSION TO JCAP

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

DESI Collaboration: A. G. Adame,[1] J. Aguilar,[2] S. Ahlen,[3]



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



Our Approach

Towards a possible solution to the Hubble tension with Horndeski gravity

Yashi Tiwari, Basundhara Ghosh, Rajeev Kumar Jain

Eur. Phys. J. C (2024) 84:220
https://doi.org/10.1140/epjc/s10052-024-12577-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Towards a possible solution to the Hubble tension with Horndeski gravity

Yashi Tiwari[1,a], **Basundhara Ghosh**[2,b], **Rajeev Kumar Jain**[2,c]

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[2] Department of Physics, Indian Institute of Science, CV Raman Road, Bengaluru, Karnataka 560012, India

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

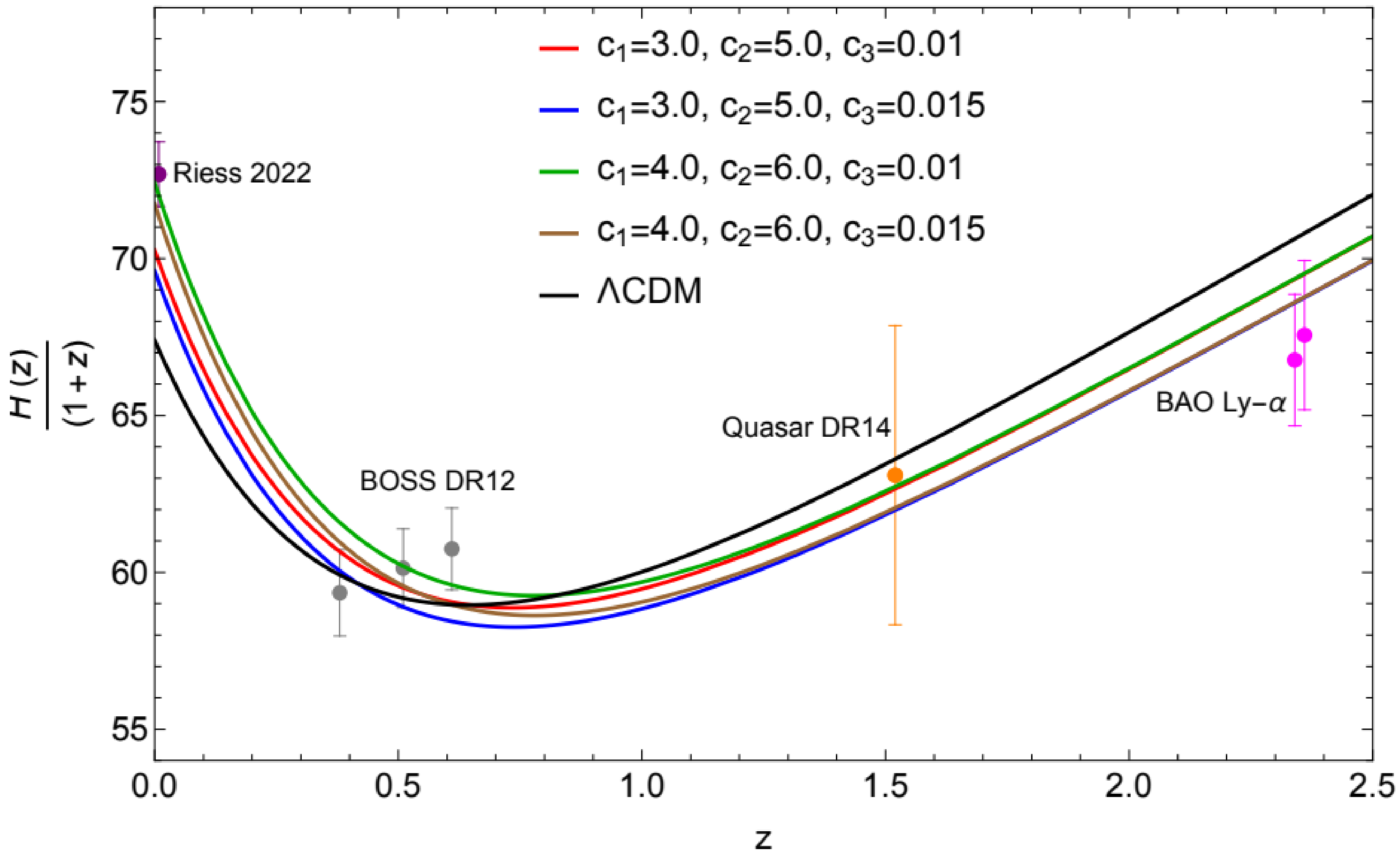
$$\begin{aligned}
\mathcal{L}_2 &= G_2(\phi, X),\\
\mathcal{L}_3 &= -G_3(\phi, X)\Box\phi,\\
\mathcal{L}_4 &= G_4(\phi, X)R + G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right],\\
\mathcal{L}_5 &= G_5(\phi, X)G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\nabla_\mu\nabla_\nu\phi)^2 + 2(\nabla_\mu\nabla_\nu\phi)^3\right],
\end{aligned}$$

$$G_{i,Y} = \partial G_i/\partial Y$$

$$X = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi$$

(Kobayashi et al 2011, Kobayashi 2019)

Background: Previous results



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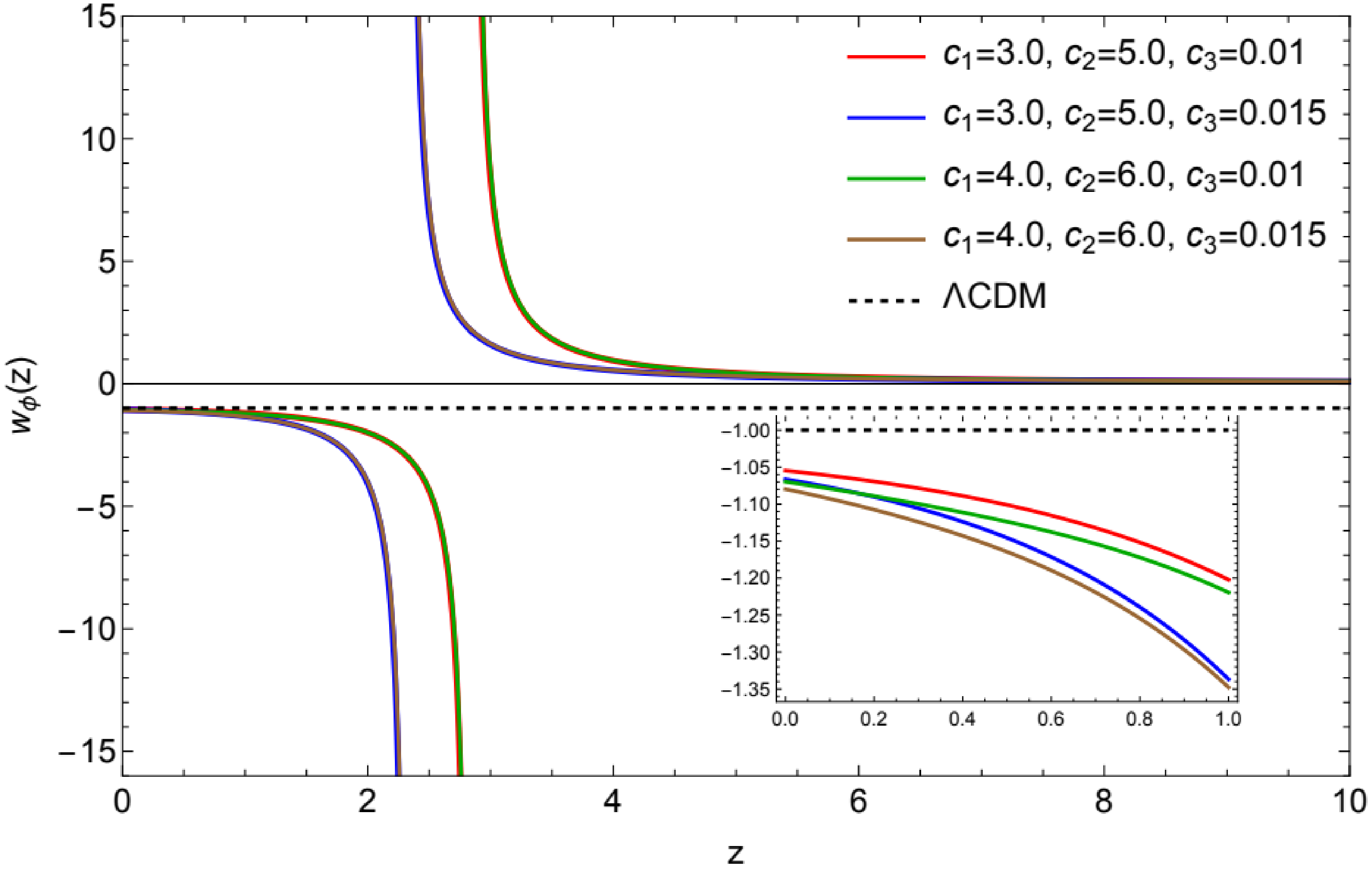
Background: Previous results



The model exhibits phantom divide

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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

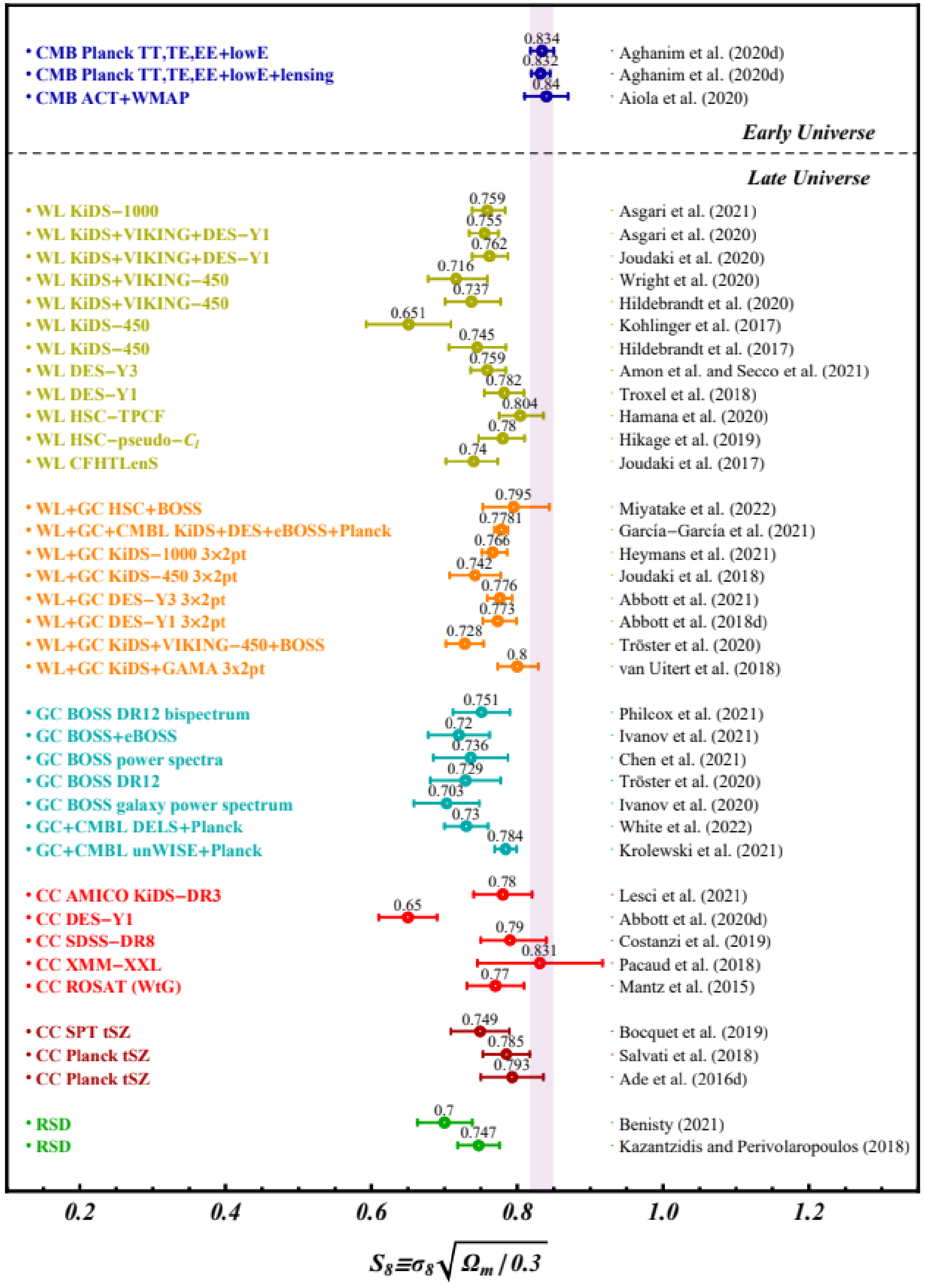
$$S_8 = \sigma_8 \left(\frac{\Omega_M}{0.3}\right)^{0.5}$$

A measure of amplitude of matter clustering in late universe

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

2-3σ tension at present

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

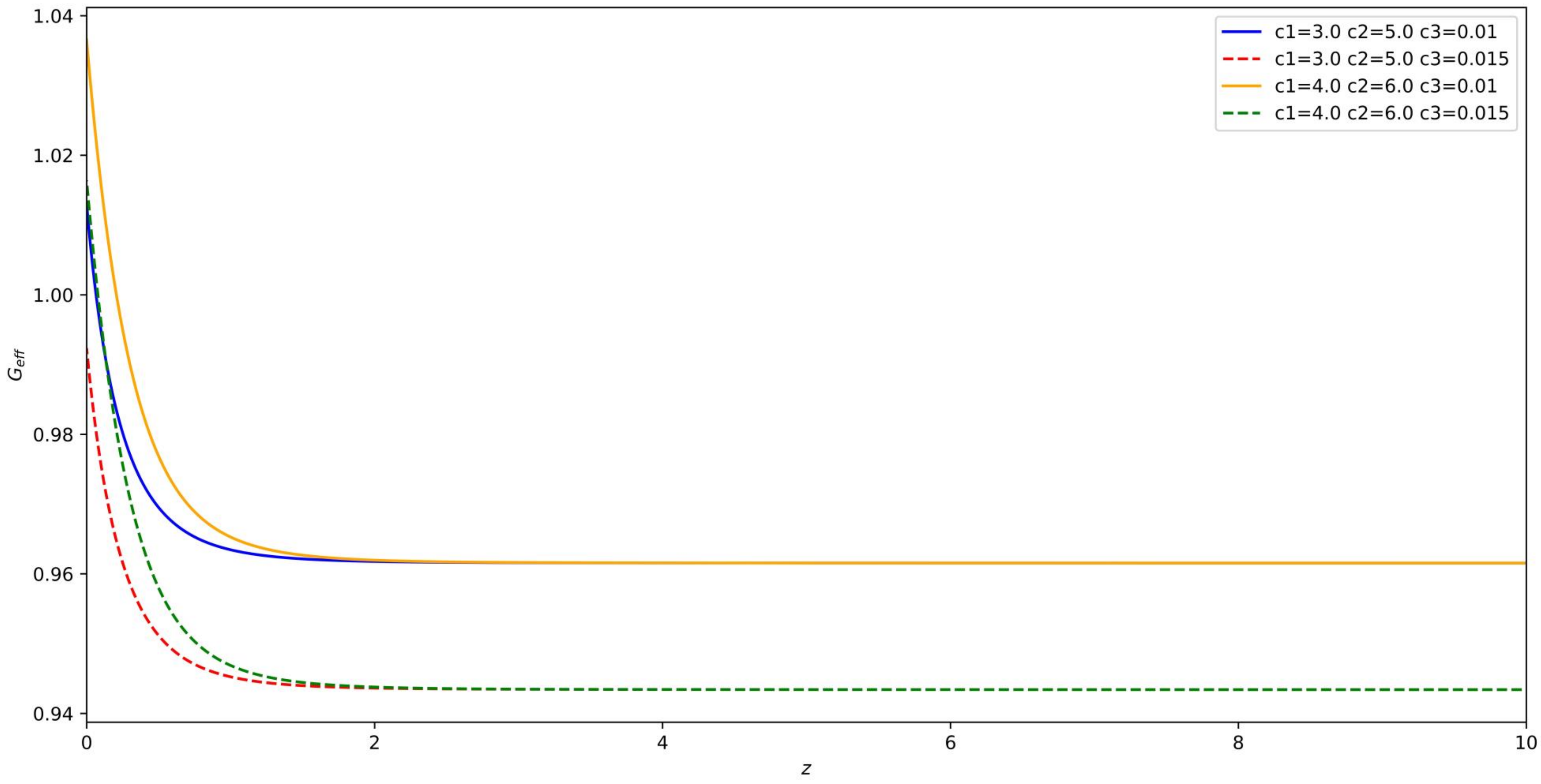
In **quasistatic limit** within sub horizon scales the evolution of matter density perturbation follows,

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G_{\text{eff}}\rho_m\delta \approx 0,$$

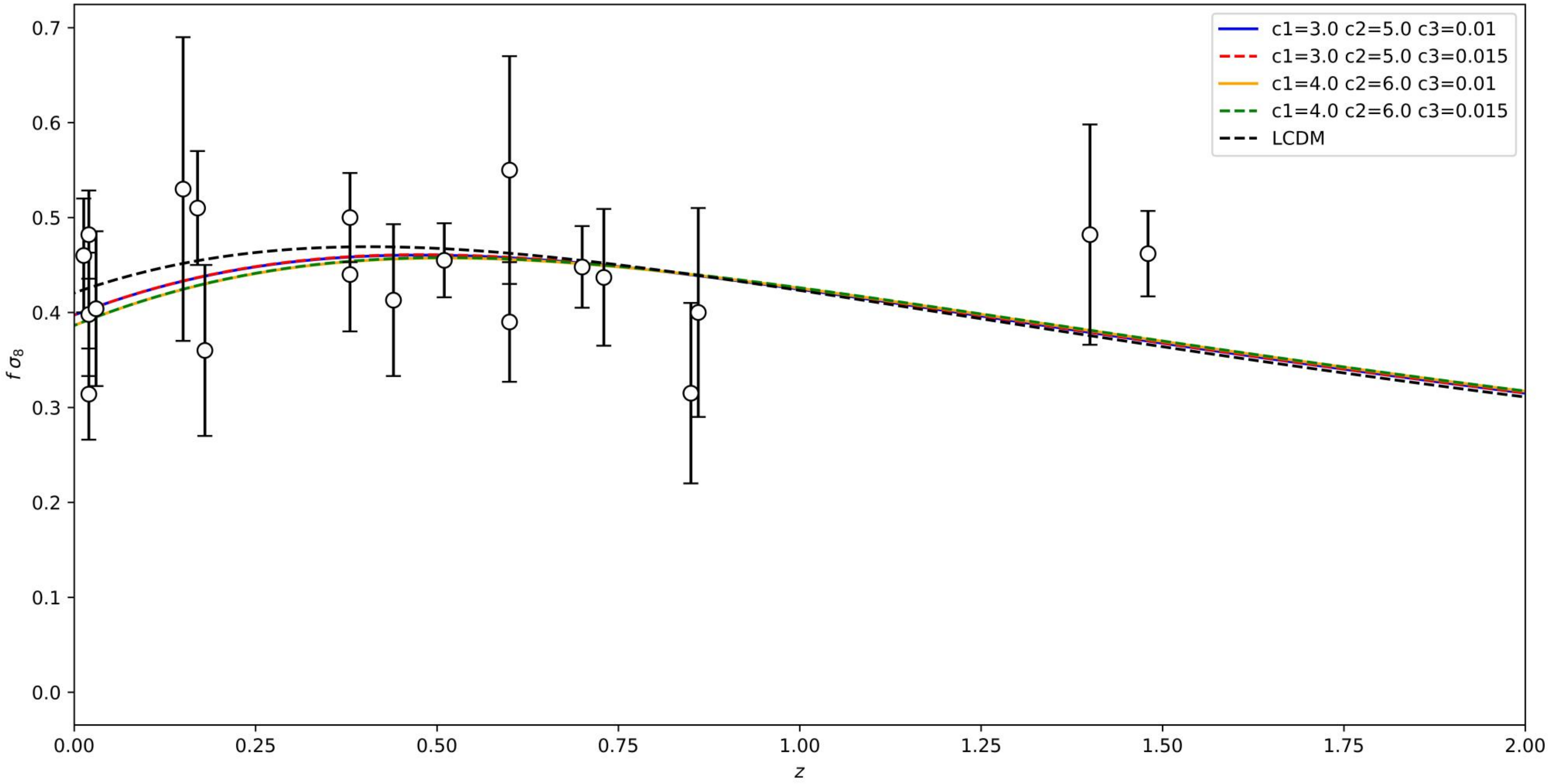
In General Relativity
$G_{eff} = G_N$

In Modified Gravity like Horndeski
$G_{eff} = F(t)$

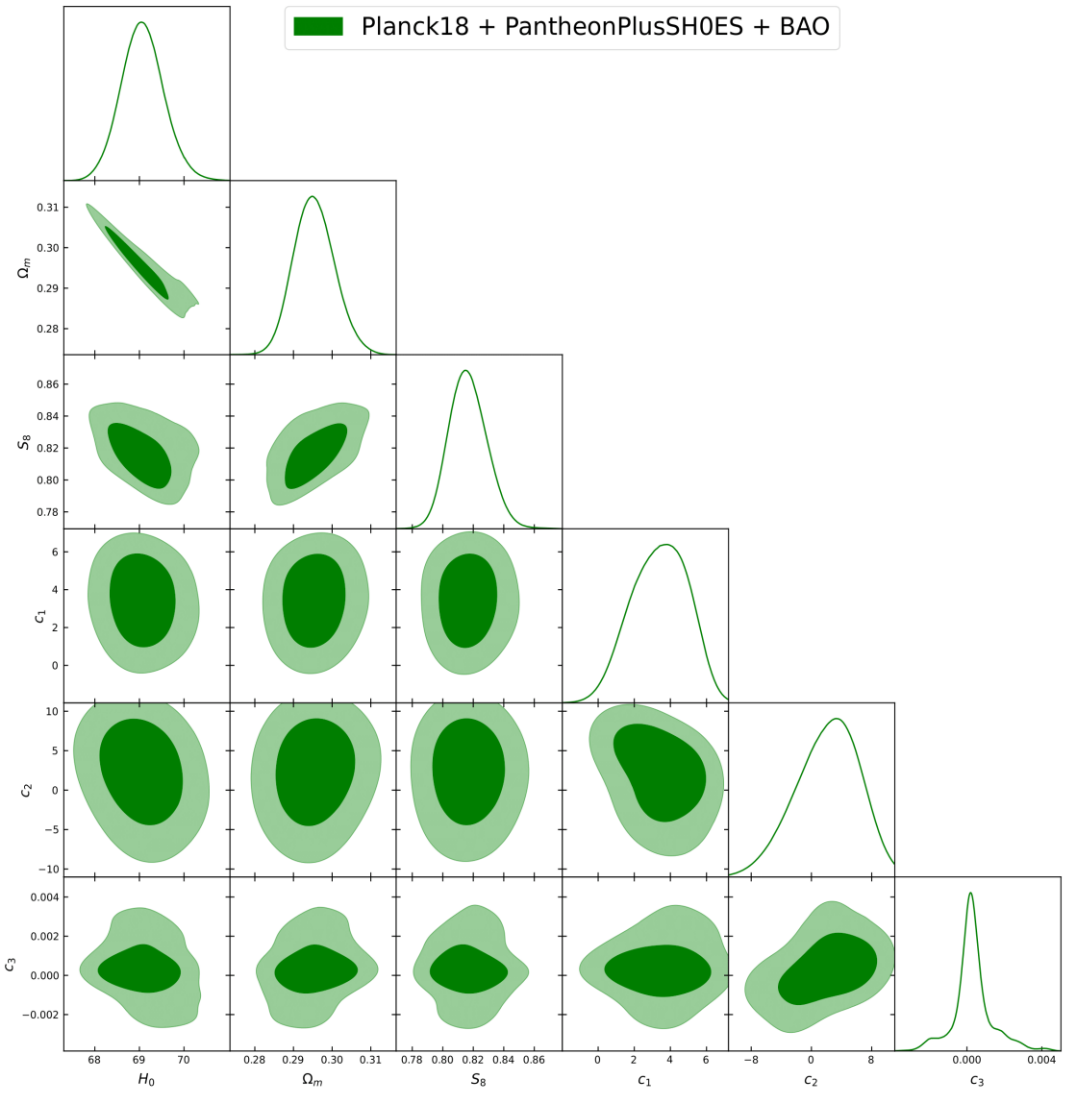
Some preliminary results: G_{eff}



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 SH0ES 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.

Thank you