Towards a possible solution to the Hubble tension with Horndeski gravity

(Based on arXiv: 2301.09382)

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20th January, 2024

Weekly online meeting on Cosmology, IIT Madras

Outline

- Present Understanding of the Universe
- The ΛCDM Model
- Hubble Tension
- Understanding Tension
- Directions of resolution
- Hints of dynamical dark energy
- Horndeski gravity: a plausible approach
- Dark Energy in Horndeski gravity
- Constraints from Observations
- Conclusion and Future Prospects

Present understanding of the universe

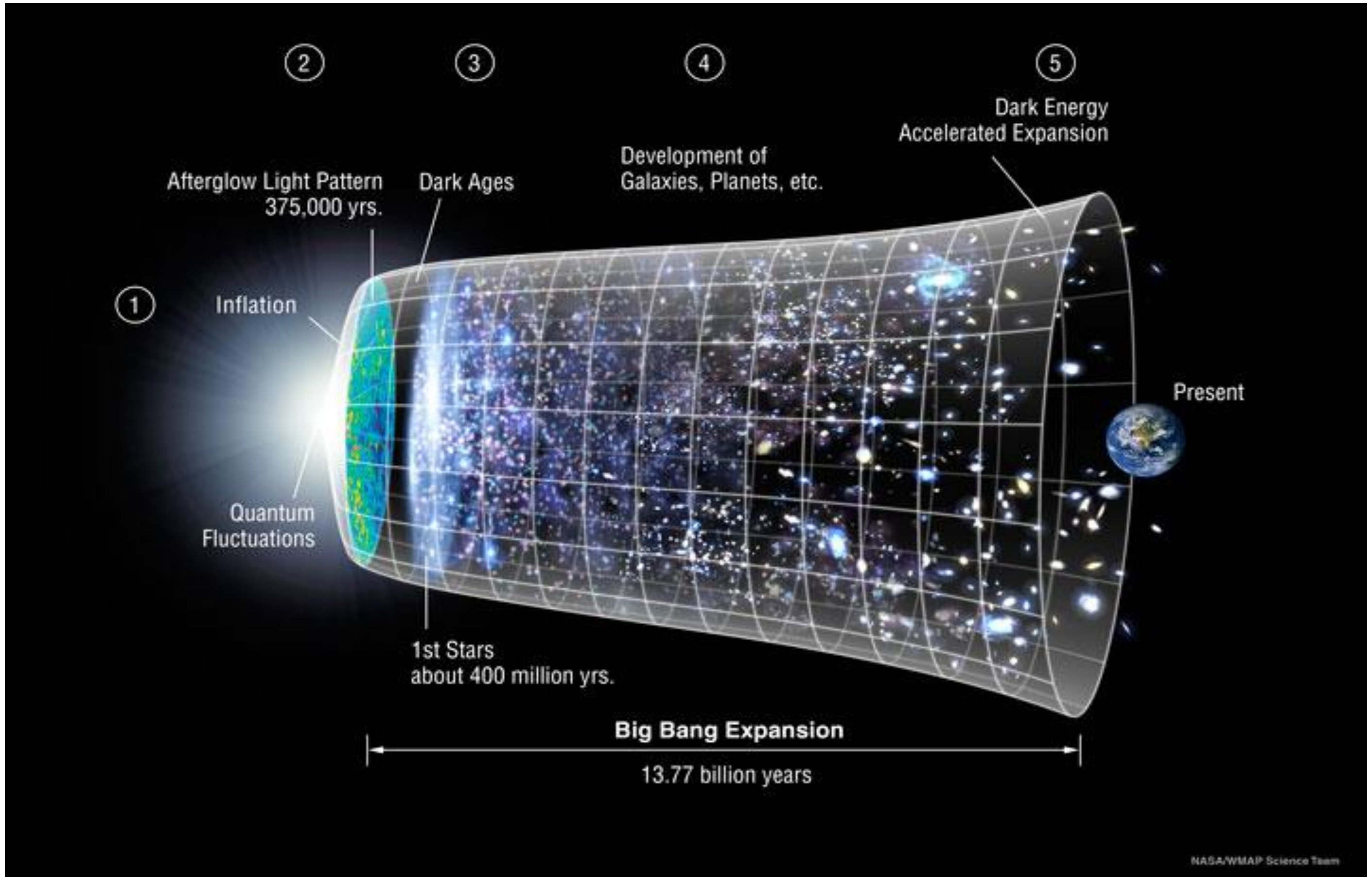


Image Credit: NASA/ LAMBDA Archive / WMAP Science Team

Cosmological Probes

- Cosmic microwave background
- Baryon acoustic oscillations
- Large scale structures
- Supernovae and Cepheids Standard Candles
- Tip of Red Giant Branch
- Weak Lensing

Present understanding of the universe: ΛCDM model

Cosmological Principle + General Relativity

↓

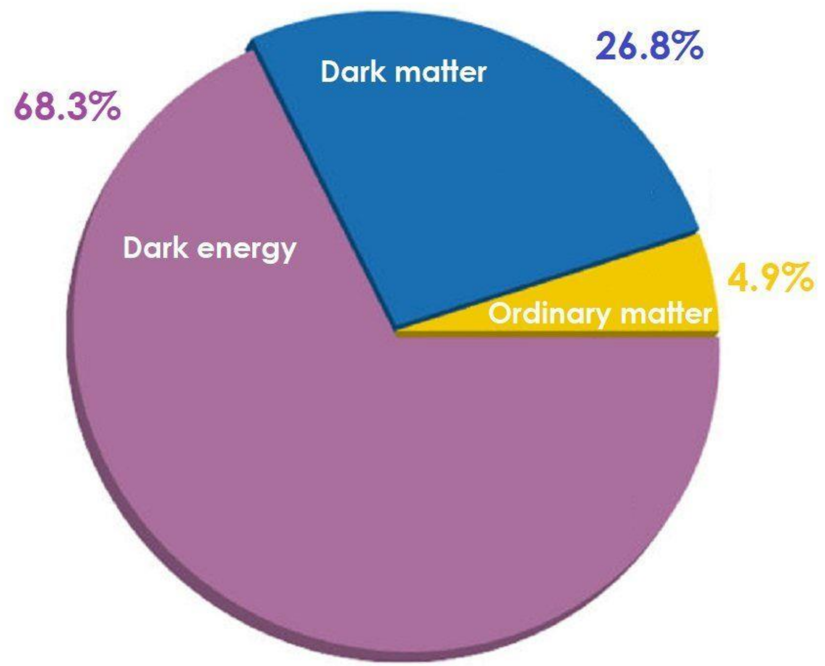
$$ds^2 = -dt^2 + a(t)^2 d\bar{x}^2 \qquad R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

↓

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

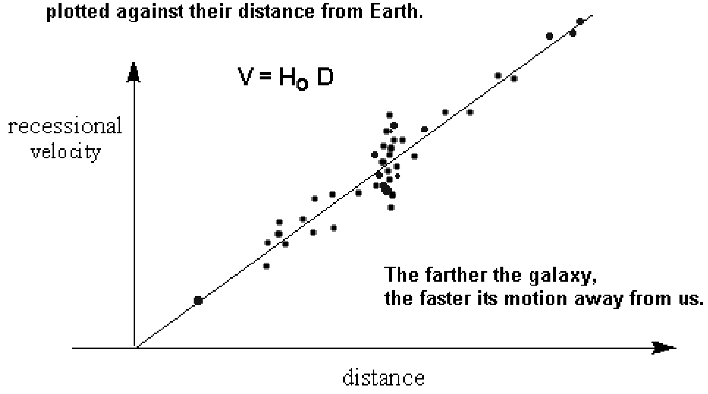
$$H(z) = H_0 \sqrt{\Omega_{r0}(1+z)^4 + \Omega_{m0}(1+z)^3 + \Omega_\Lambda}$$

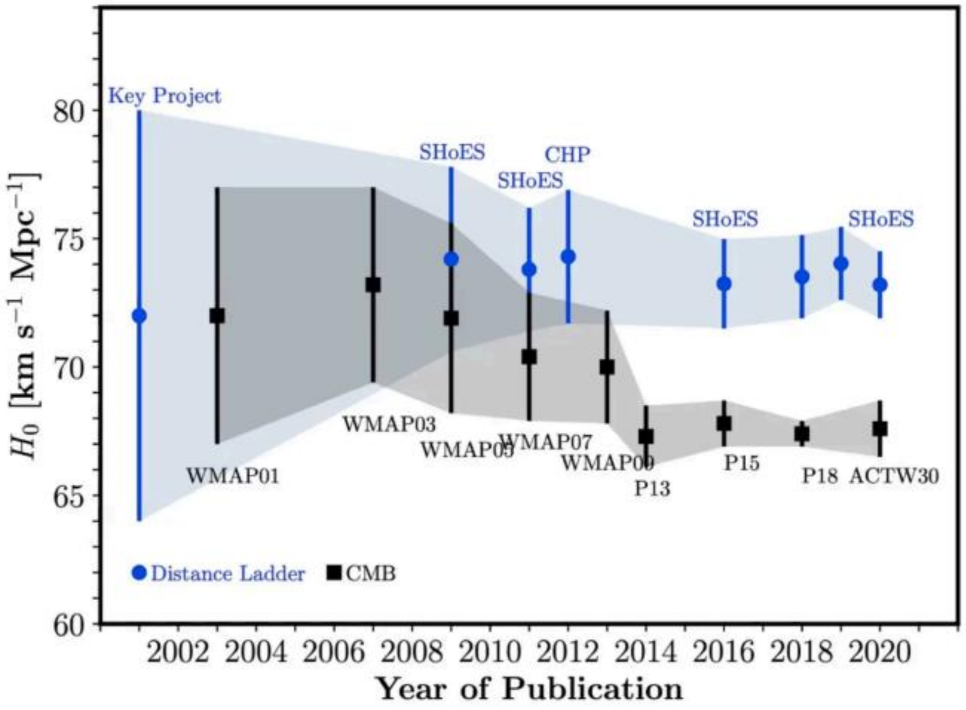


Here it is assumed that universe is spatially flat i.e. Ω_k=0. Thanks to inflation!

The Hubble Constant H_0

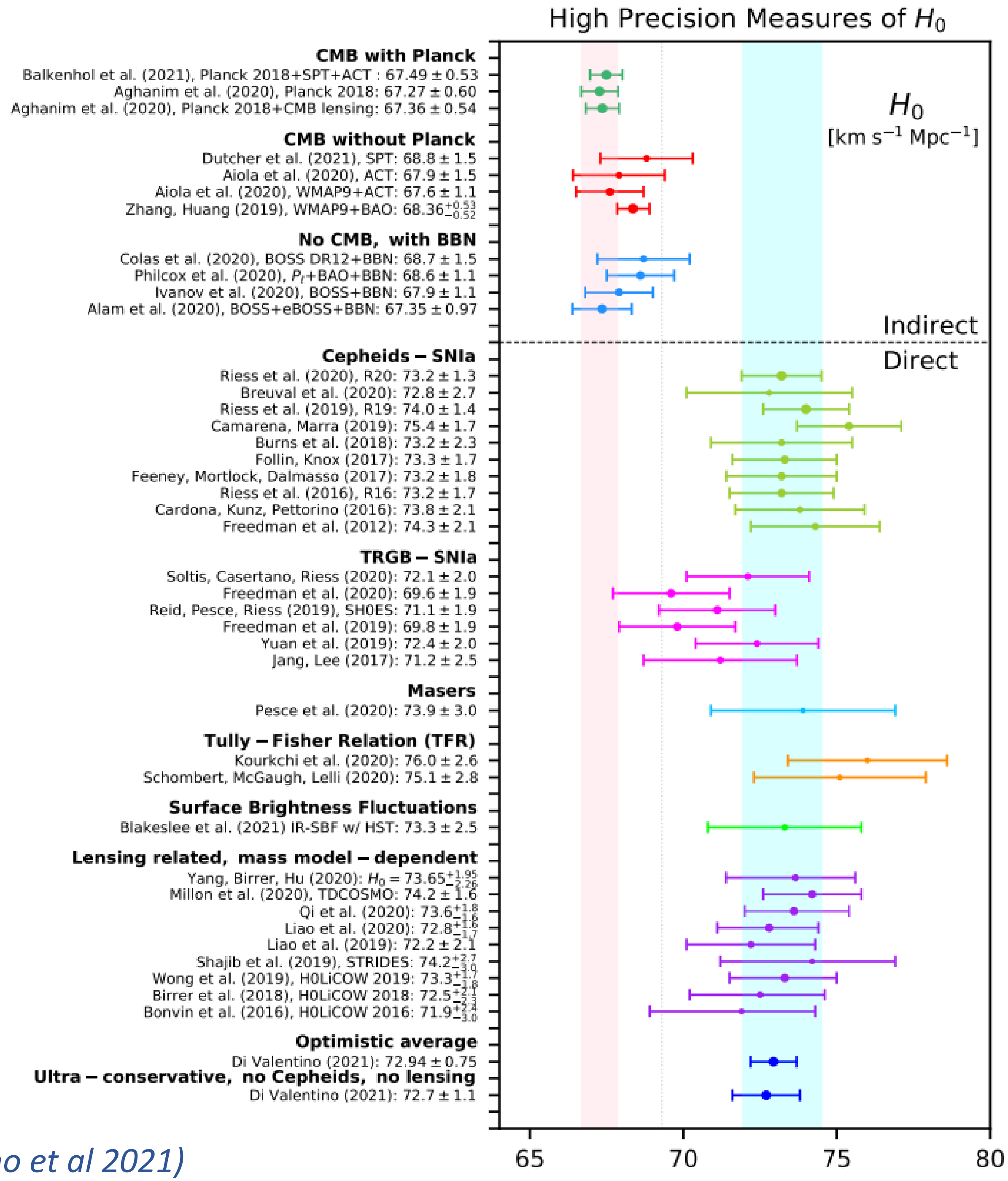
- The rate of expansion of universe at present.
- A crucial cosmological parameter.
- It has been a challenge to correctly measure the value of H_0.





The Hubble Tension

5σ tension at present

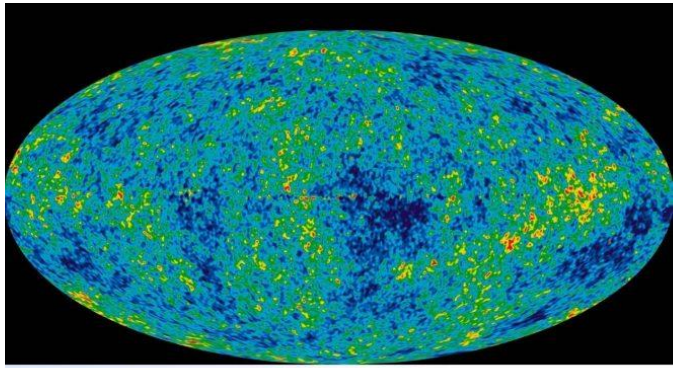


(Di Valentino et al 2021)

Understanding Hubble Tension

Early measurements

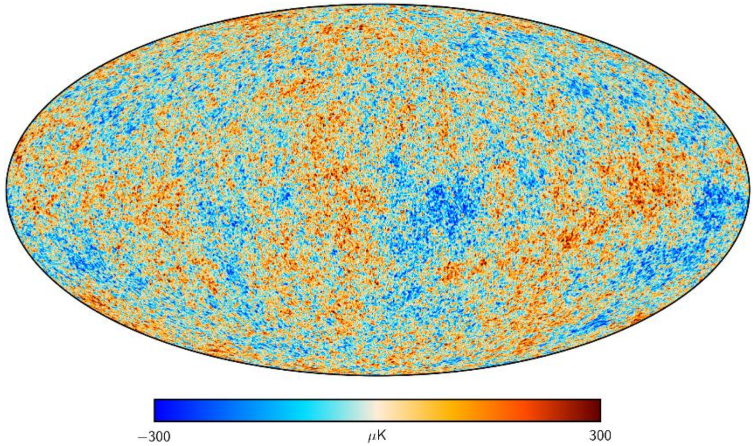
- Based on observations of cosmic microwave background coming from last scattering surface (redshift $\sim$ 1100, 13.76 Gyr back).
- Assumes ΛCDM model to calculate H_0.
- Planck, WMAP

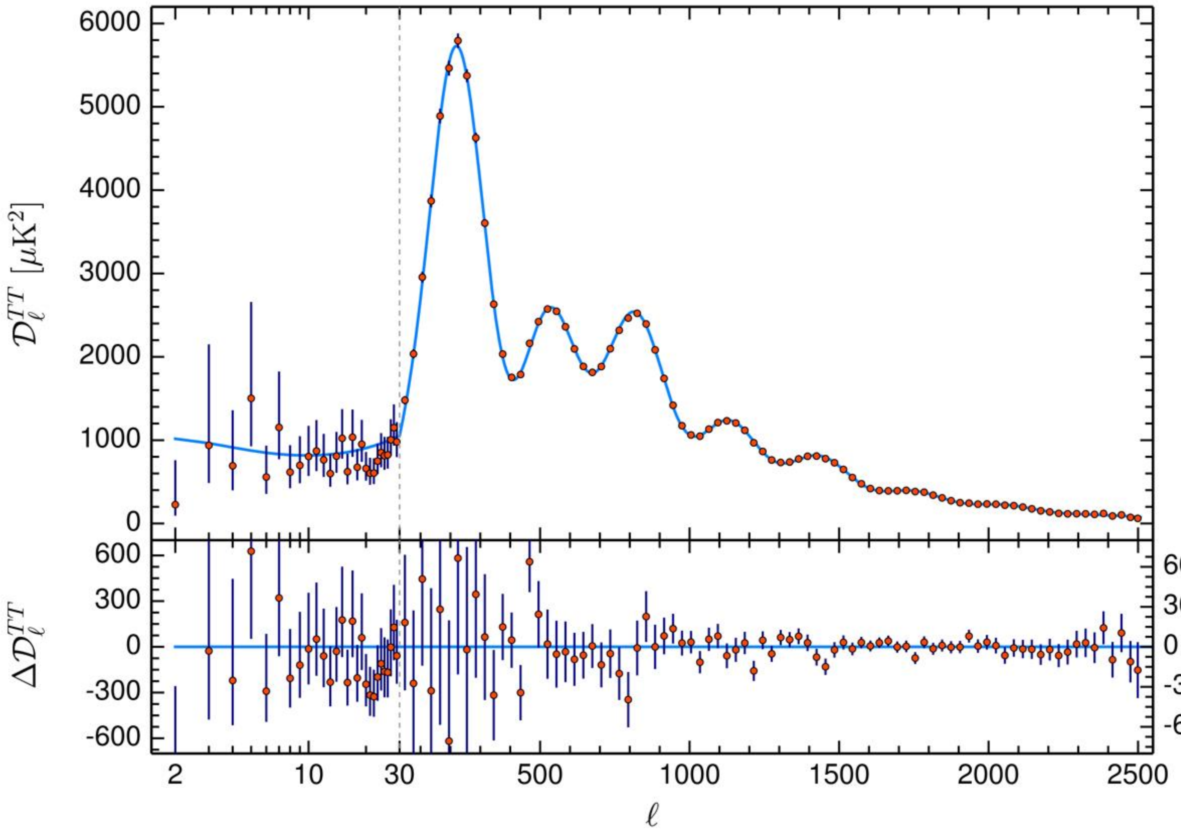


Late measurements

- Based on astrophysics of stars: observing standard candles in the nearby universe.
- Model independent measurement.
- SH0ES, CHP

Measurement of H_0 from early Universe





six independent parameters of **LCDM** model.

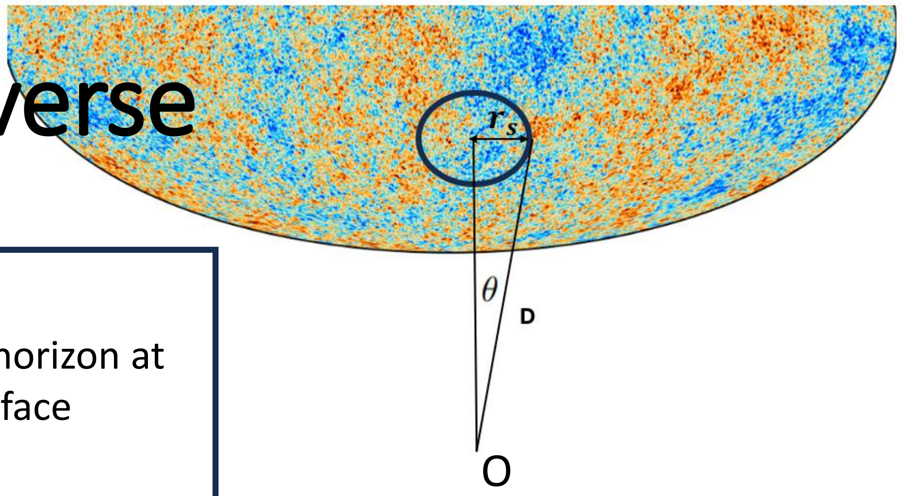
Derived parameters

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 $\boldsymbol{H_0}$ from early Universe



Angular size of sound horizon at last scattering surface: **precisely determined from the peaks in CMB (0.03 % Precision)** ← $\theta = \dfrac{r_s}{D}$

r_s → comoving sound horizon at last scattering surface

D → comoving distance to the last scattering surface.

$$r_s = \int_{z_L}^{\infty} \frac{c_s(z')}{H(z')} dz'$$

$$c_s = \frac{1}{\sqrt{3(1+3\Omega_b/\Omega_r)}}$$

Based on pre-recombination physics or **early universe physics**.

$$z_L = 1100$$

→ Redshift of recombination or last scattering surface

$$D(z_L) = \int_0^{z_L} \frac{dz}{H(z)}$$

$$H(z) = H_0 \times E(z)$$

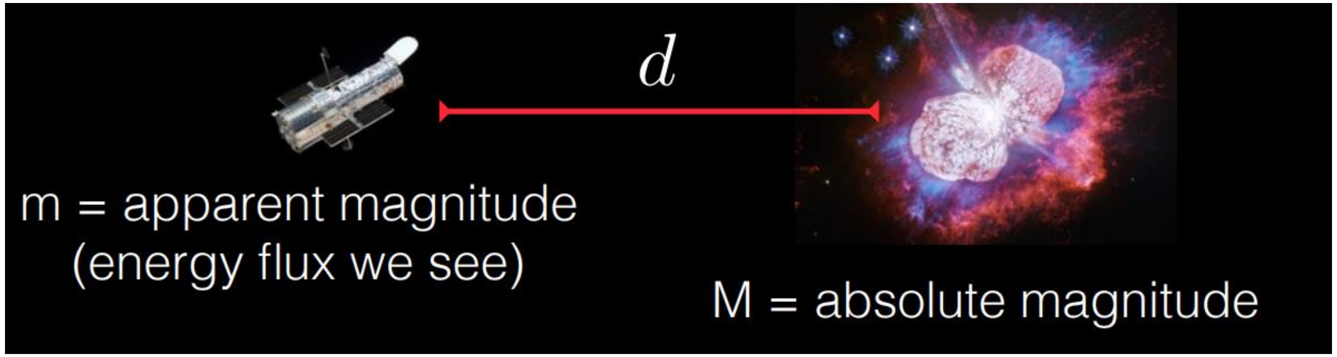
This involves **late universe physics**, depending on dark energy model i.e. H(z) or E(z).

H_0 can be extrapolated for a given model at H(z=0).

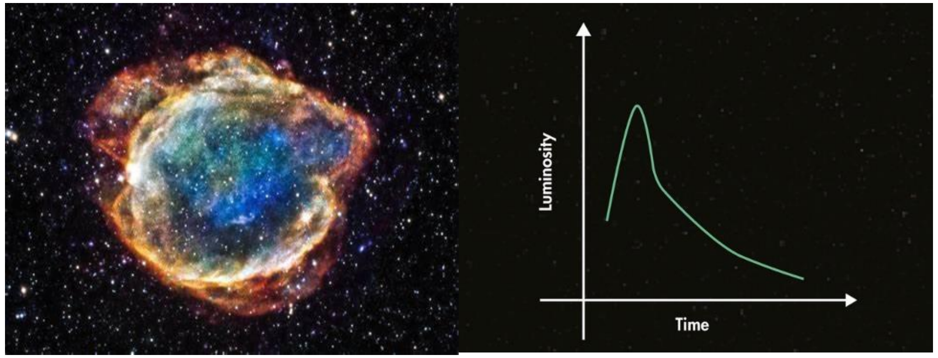
$$E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$$

→ For LCDM model

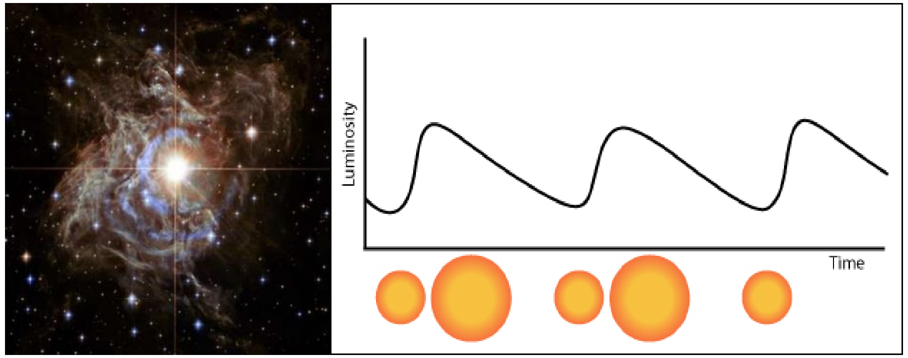
Measurement of H_0 from Late Universe



Observing standard candles to calibrate distances to galaxies and using Hubble's law to calculate H_0.



Type 1a Supernovae: Thermonuclear explosion of white dwarf stars reaching Chandrasekhar mass Limit.



Cepheid variables: Pulsating stars with a definite period luminosity relation

Measurement of H_0 from Late Universe

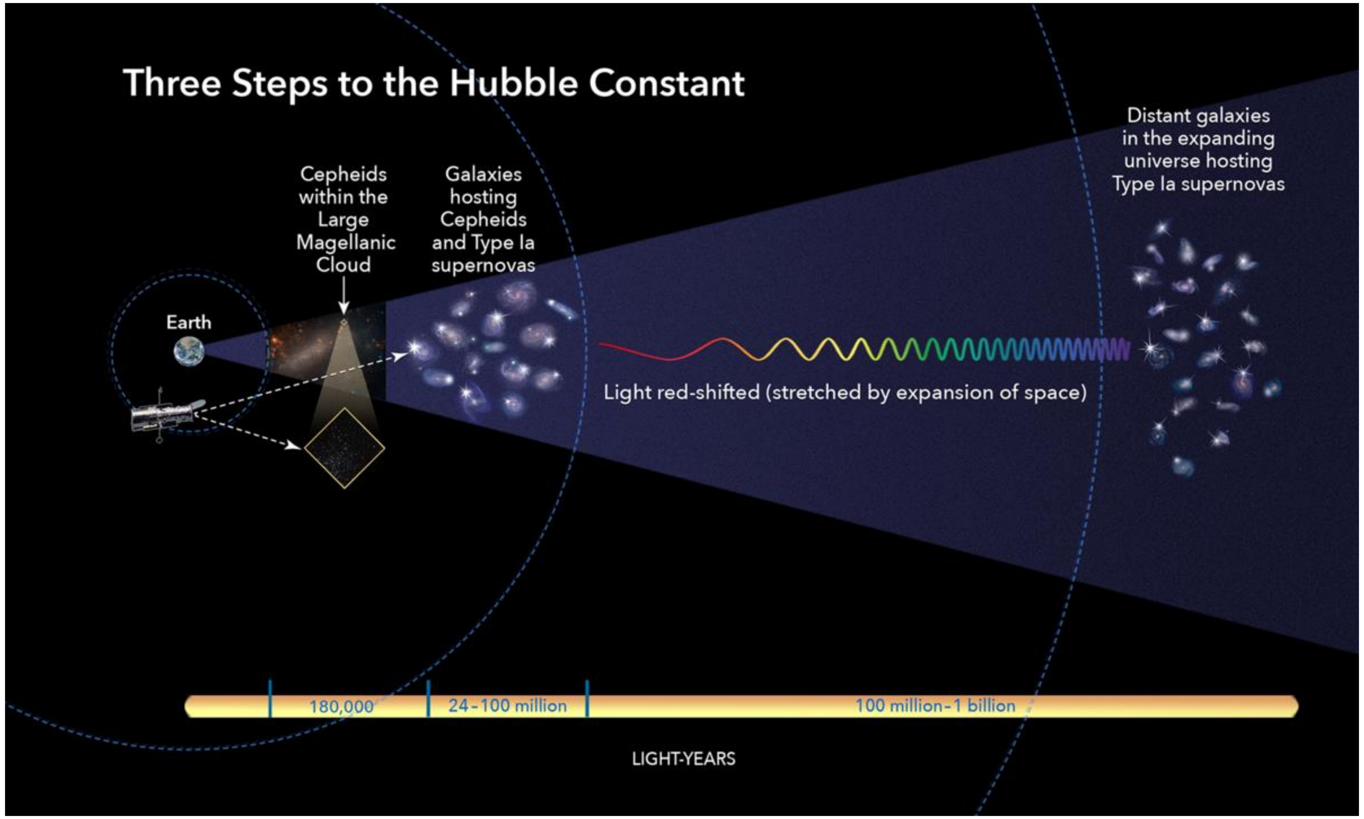


Image Credit: NASA

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

- The **SH0ES** Program (Supernovae and H_0 for the Equation of State of dark energy) measured $\boldsymbol{H_0} = \mathbf{73.3 \pm 1.04}$ km/sec/Mpc *(Riess et al 2022)*.
- This drives the H_0 tension $\sim 5\sigma$
- In fact various other local measurements, apart from SH0ES also give $H_0 > 70$ km/sec/Mpc, indicating tension with the Planck (LCDM) value *(Freedman 2021, Anand et al 2021, Shajib et al 2023, Pesce et al 2020 …)*.

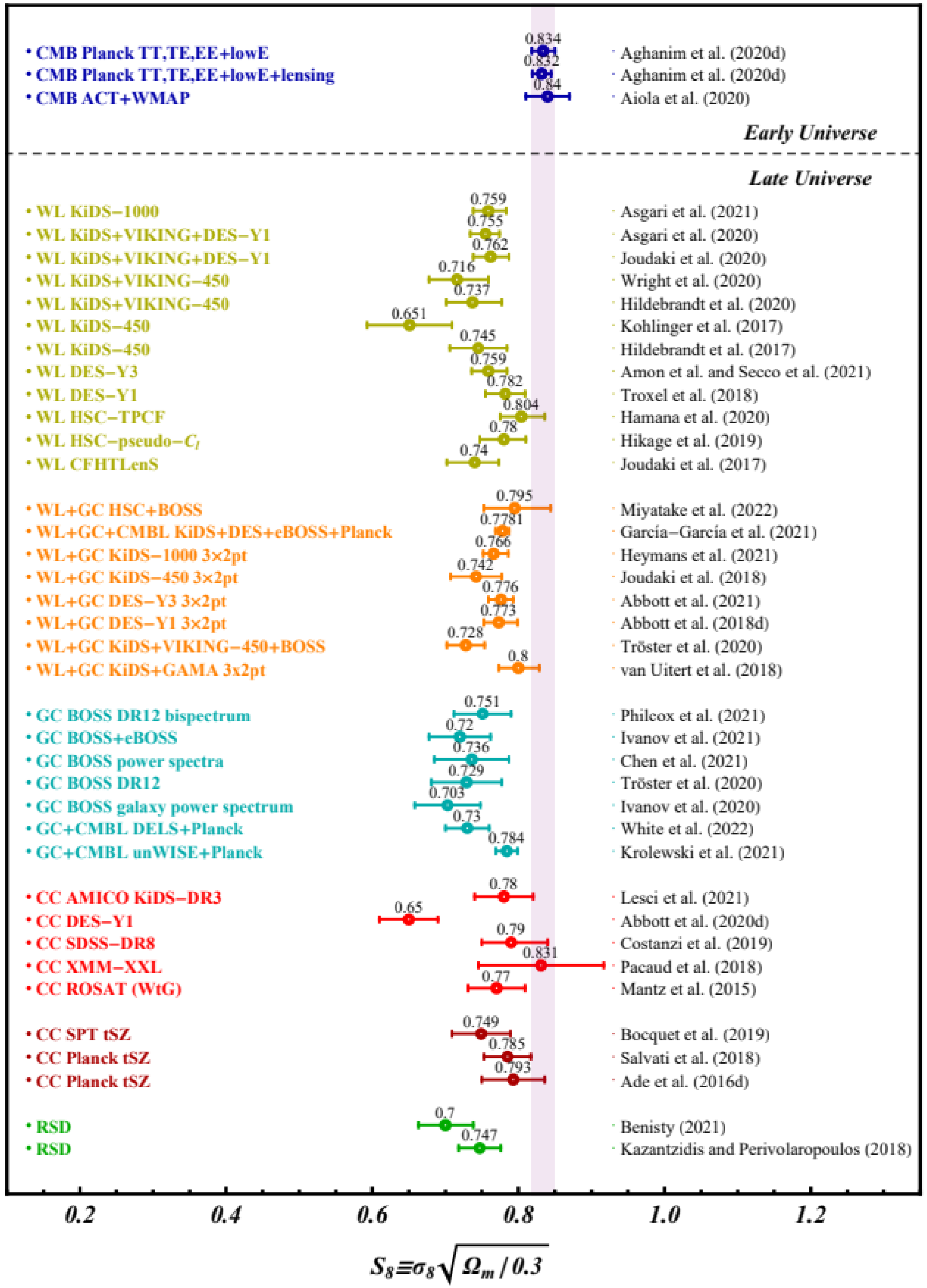
S_8 Tension

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

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



(Abdalla et al 2022)

How to address Hubble Tension?

Review of solutions

arXiv > astro-ph > arXiv:2103.01183

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 1 Mar 2021 (v1), last revised 5 Jun 2021 (this version, v3)]

In the Realm of the Hubble tension — a Review of Solutions

Eleonora Di Valentino, Olga Mena, Supriya Pan, Luca Visinelli, Weiqiang Yang, Alessandro Melchiorri, David F. Mota, Adam G. Riess, Joseph Silk

arXiv > astro-ph > arXiv:2107.10291

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 21 Jul 2021 (v1), last revised 15 Oct 2021 (this version, v2)]

The H_0 Olympics: A fair ranking of proposed models

Nils Schöneberg, Guillermo Franco Abellán, Andrea Pérez Sánchez, Samuel J. Witte, Vivian Poulin, Julien Lesgourgues

arXiv > astro-ph > arXiv:2203.06142

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 11 Mar 2022 (v1), last revised 24 Apr 2022 (this version, v3)]

Cosmology Intertwined: A Review of the Particle Physics, Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies

Elcio Abdalla, Guillermo Franco Abellán, Amin Aboubrahim, Adriano Agnello, Ozgur Akarsu, Yashar Akrami, George Alestas, Daniel Aloni, Luca Amendola, Luis A. Anchordoqui, Richard I. Anderson, Nikki Arendse, Marika Asgari, Mario Ballardini, Vernon Barger, Spyros Basilakos, Ronaldo C. Batista, Elia S. Battistelli, Richard Battye, Micol Benetti, David Benisty, Asher Berlin, Paolo de Bernardis, Emanuele Berti, Bohdan Bidenko, Simon Birrer, John P. Blakeslee, Kimberly K. Boddy, Clecio R. Bom,

Possible Resolutions to Hubble Tension

Aim: Modifying the LCDM picture without disturbing the well constrained peaks of CMB.

Fixed by CMB $\longleftarrow$ $$\theta = \frac{r_s}{\int_0^{z_L} \frac{dz'}{H(z')}} = \frac{H_0 r_s}{\int_0^{z_L} \frac{dz'}{E(z')}}$$

Modifying early universe

- Decreasing sound horizon r_s (changing pre-recombination physics).
- H_0 is increased in order to fix θ , without changing late universe physics.

Modifying late universe

- Modifying H(z) or E(z) (with non-trivial dark energy models), keeping comoving distance to last scattering surface unchanged.
- Pre-recombination physics is not disturbed.

Early universe solutions

- Reducing the comoving sound horizon

$$r_s = \int_{z_L}^{\infty} \frac{c_s(z)}{H(z)} dz$$

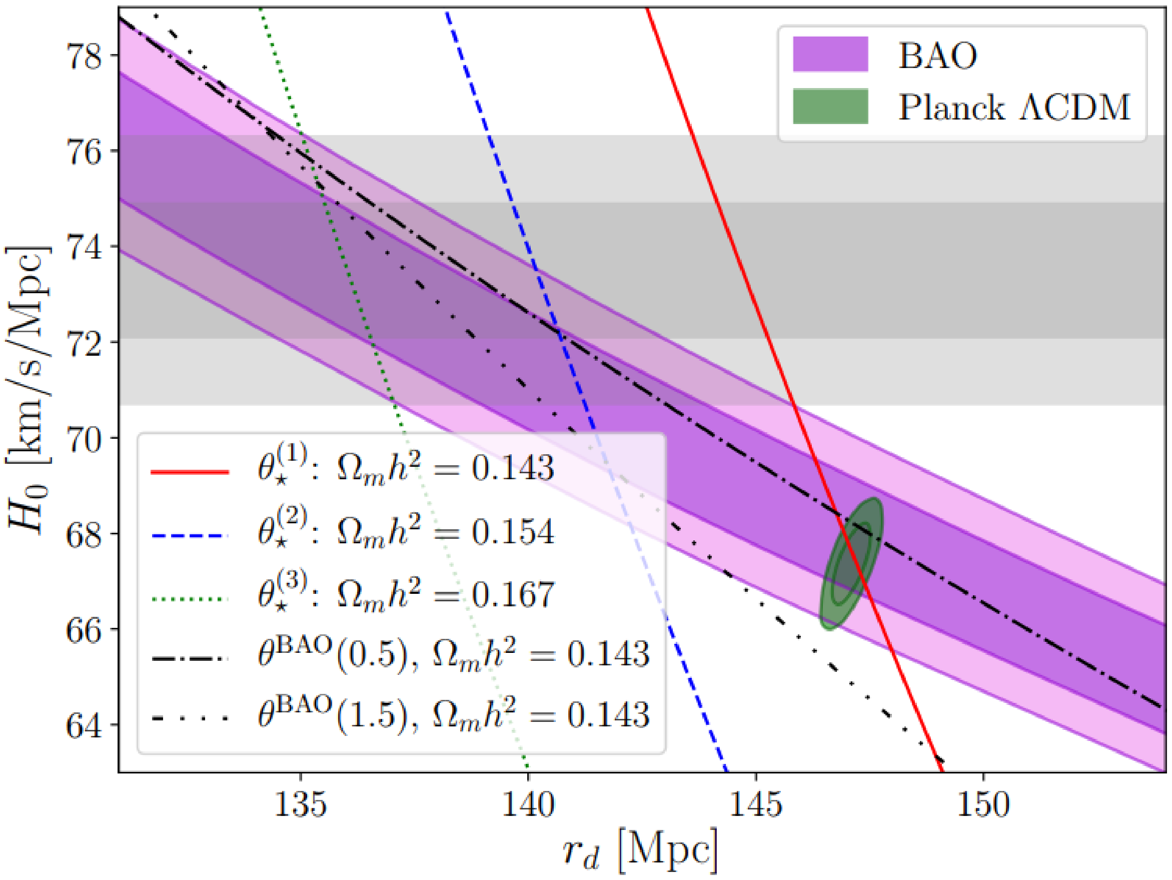
Altering recombination history

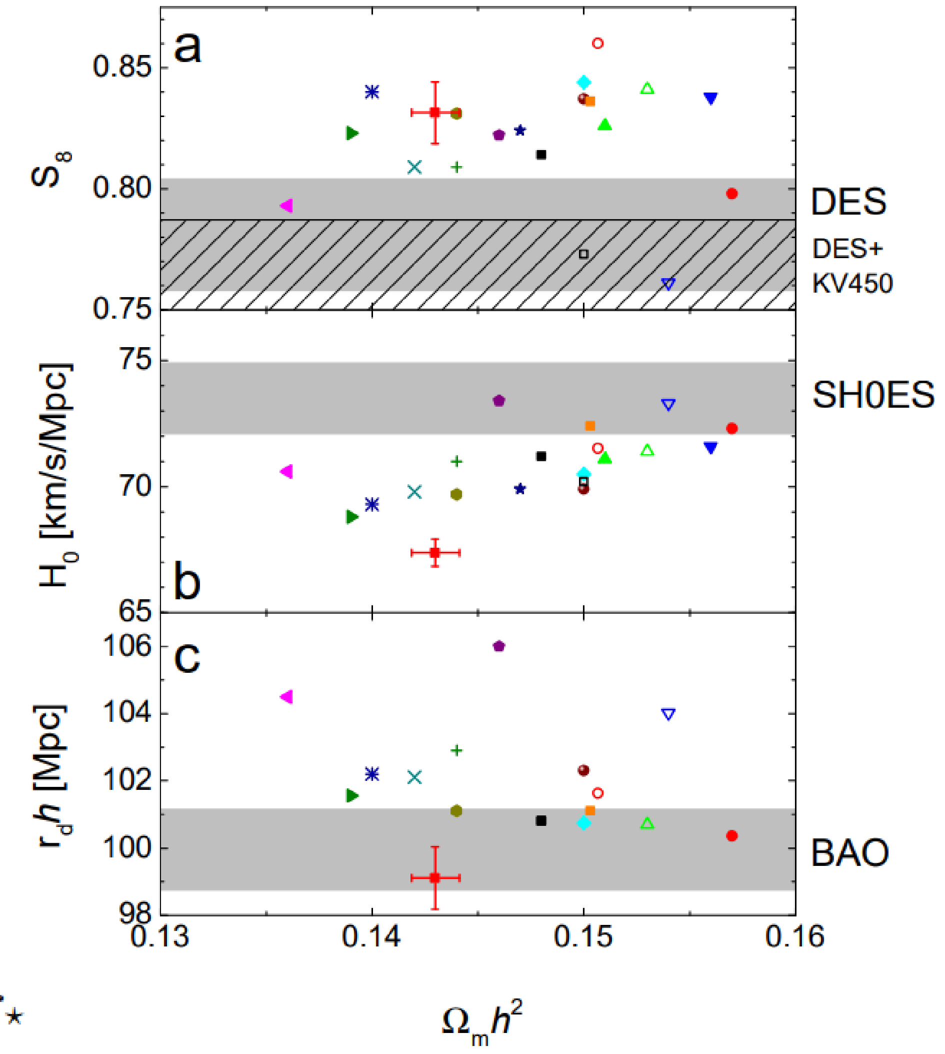
- Primordial magnetic fields
  (Jedamzik et al 2020)
- Non-standard recombination
  (Chiang et al 2018)
- Varying fundamental constant
  (Sekiguchi et al 2020, Hart et al 2020)

$\uparrow H(z) \implies \uparrow \rho(z)$ since $H(z) \propto \sqrt{\rho(z)}$

- Extra radiation (N_{eff})
  (Kreisch et al 2019, Sakstein et al 2019,Archidiacono et al 2020, Anchordoqui et al 2019,Gonzalez et al 2020….)
- Energy injection around matter radiation equality: Early Dark Energy (EDE), Early Modified Gravity (EMG)
  (Karwal et al 2016, Poulin et al 2018, Braglia et al 2021)

But there exist some issues *(Based on Jedamzik et al 2020)*





$$\theta_\star \equiv \frac{r_\star}{D(z_\star)} \qquad \theta_\perp^{\rm BAO}(z_{\rm obs}) \equiv \frac{r_{\rm d}}{D(z_{\rm obs})} \qquad r_{\rm d} = 1.0184 r_\star$$

So early universe solutions **alone** cannot resolve the H_0 tension!

Opinion

Seven Hints That Early-Time New Physics Alone Is Not Sufficient to Solve the Hubble Tension

Sunny Vagnozzi

Special Issue

Modified Gravity Approaches to the Tensions of ΛCDM

Edited by

Dr. Eleonora Di Valentino, Prof. Dr. Leandros Perivolaropoulos and Dr. Jackson Levi Said

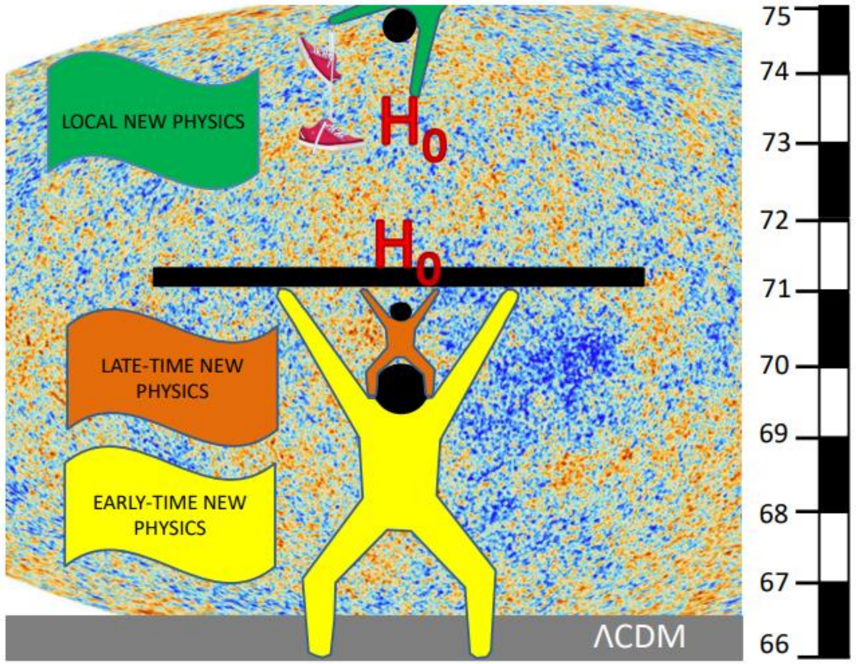


Image Credit: Cristina Ghirardini

For more details read the following

Late universe solutions

Modifying late time expansion history without disturbing comoving distance to LSS.

$$D(z_L) = \int_0^{z_L} \frac{dz}{H(z)}$$

Expansion rate in late universe: crucial dependence on dark energy model

Simplest solution: an extension of LCDM model with a dark energy component (equation of state w)

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

To resolve Hubble tension, $\uparrow H_0 \implies (1+w) < 0$

Phantom dark energy

But simplest phantom models are now ruled out by observations as they worsen σ_8/S_8 tension.

Need for a non-trivial dynamical dark energy?

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

arXiv > astro-ph > arXiv:2201.11623

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 27 Jan 2022]

Simultaneously solving the H_0 and σ_8 tensions with late dark energy

Lavinia Heisenberg, Hector Villarrubia-Rojo, Jann Zosso

According to *Heisenberg et al 2022*, late dark energy models must exhibit **PHANTOM DIVIDE** behavior to simultaneously alleviate H_0 and S_8 tension.

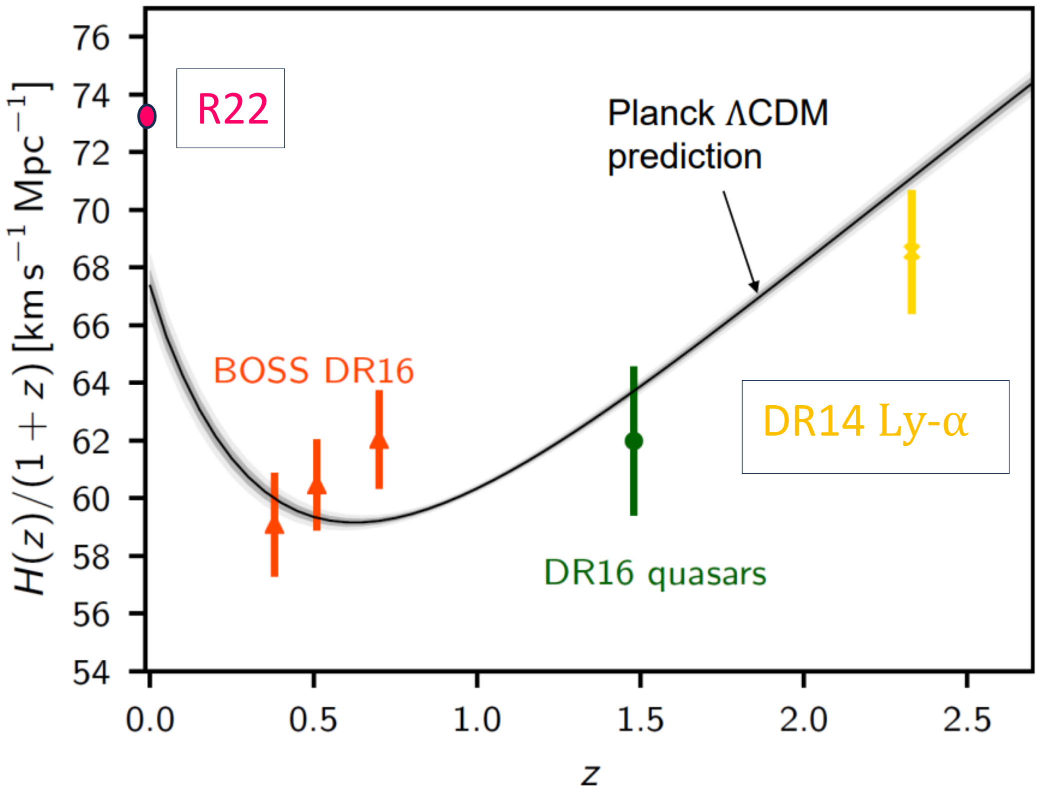
A dynamics which can give rise to a phantom divide behavior?

↓

One way to achieve this is to have a **negative dark energy density** during some epoch **at high redshifts**

Are there any signatures of negative dark energy density in observational data?

Hints for negative Dark energy? BAO Ly-α Anomaly



A&A 629, A85 (2019)

Baryon acoustic oscillations at $z = 2.34$ from the correlations of Lyα absorption in eBOSS DR14

Victoria de Sainte Agathe[1], Christophe Balland[1], Hélion du Mas des Bourboux[2], Nicolás G. Busca[1], Michael

A&A 629, A86 (2019)

Baryon acoustic oscillations from the cross-correlation of Lyα absorption and quasars in eBOSS DR14

Michael Blomqvist[1], Hélion du Mas des Bourboux[2], Nicolás G. Busca[3], Victoria de Sainte Agathe[3], James

~ 2σ tension in the measurement of H(z) at z~2.3 from prediction of LCDM.

Hints for negative Dark energy? BAO Ly-α Anomaly

LETTERS

MODEL-INDEPENDENT EVIDENCE FOR DARK ENERGY EVOLUTION FROM BARYON ACOUSTIC OSCILLATIONS

V. Sahni[1], A. Shafieloo[2,3], and A. A. Starobinsky[4,5]

Published 2014 September 19 •

[The Astrophysical Journal Letters](), [Volume 793](), [Number 2]()

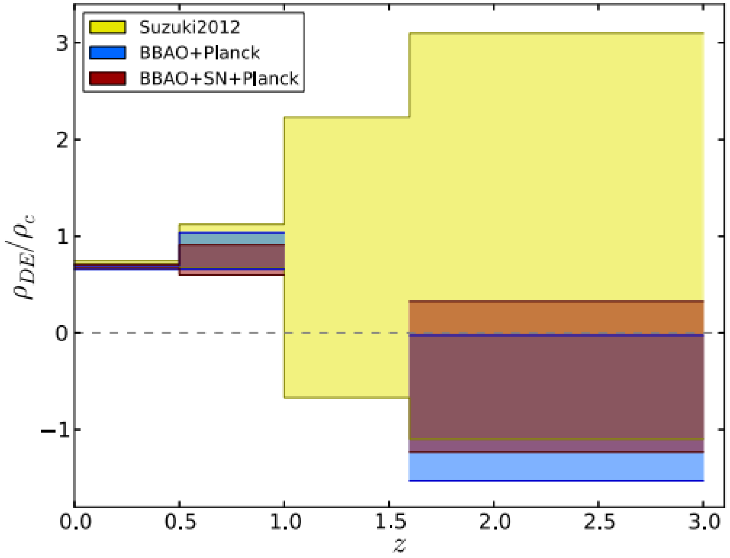
Citation V. Sahni *et al* 2014 *ApJL* **793** L40

DOI 10.1088/2041-8205/793/2/L40

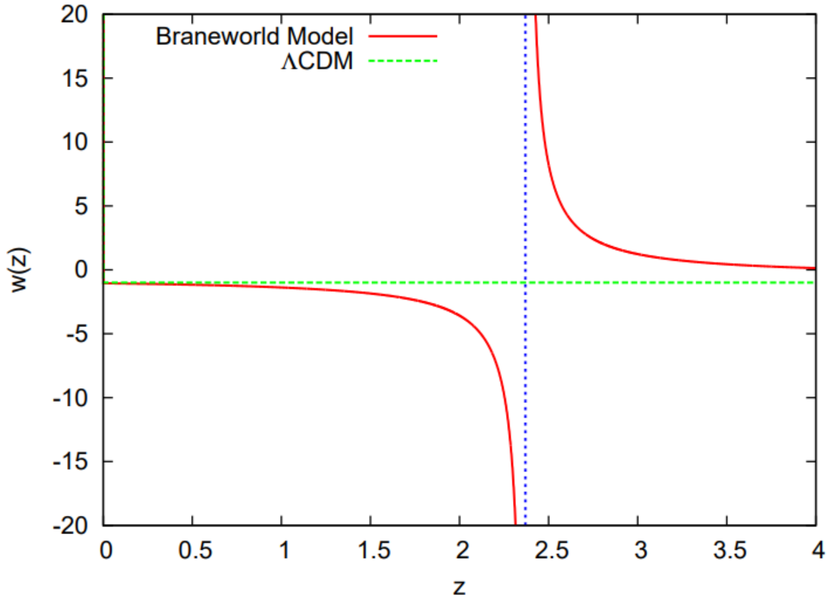
Cosmological implications of baryon acoustic oscillation measurements

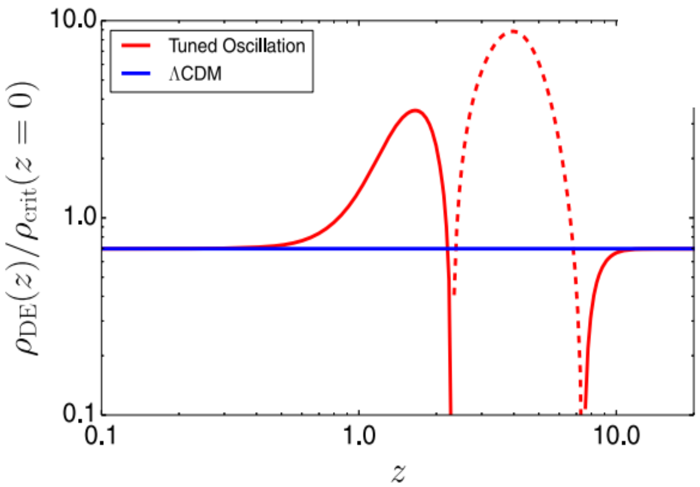
Éric Aubourg *et al.* (BOSS Collaboration)

Phys. Rev. D **92**, 123516 – Published 14 December 2015



Negative energy density at high redshifts (z>2) can explain the feature.

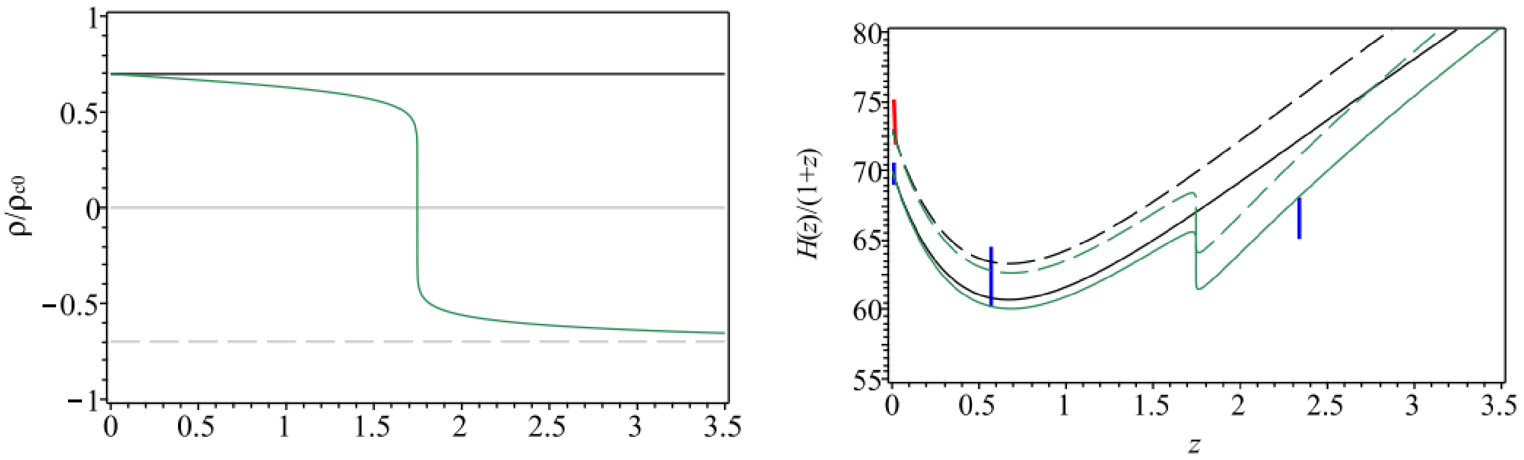




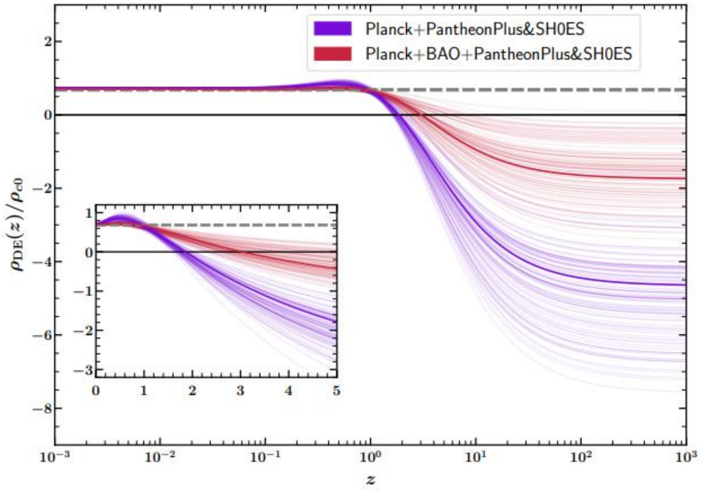
Hints for negative Dark energy?

Dark energy models with a negative energy density feature at high redshifts, give a good fit to observation data (BAO, SN, H0, Planck)

- Graduated dark energy *(Akarsu et al 2020)*
- Negative cosmological constant (plus extra component) *(Calderon et al 2021, Sen et al 2021)*
- Sign switching cosmological constant *(Akarsu et al 2021, Akarsu et al 2023,)*
- Omnipotent dark energy *(Adil et al 2023)*



(arXiv:1912.08751)



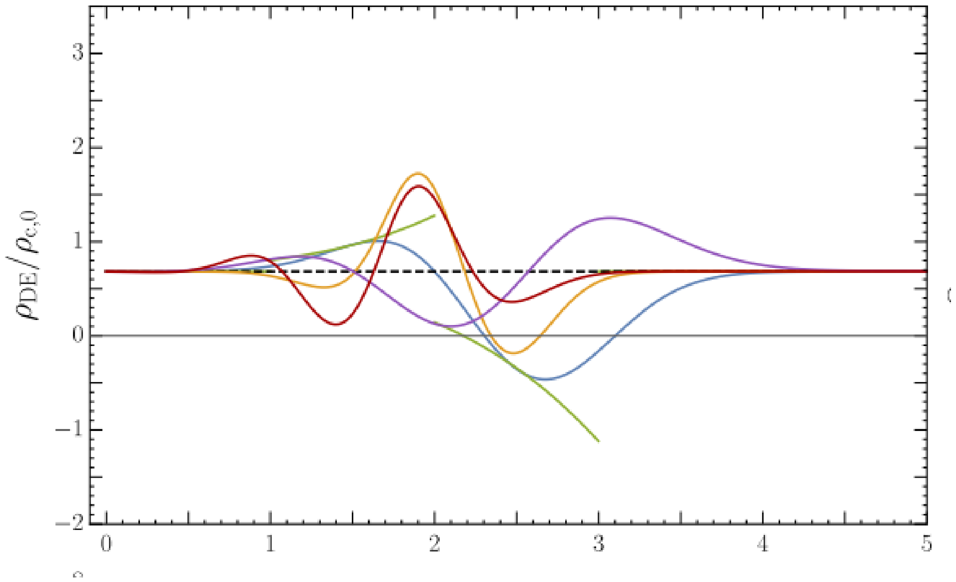
(arXiv:2306.08046)

Hints for negative Dark energy?

Observational Reconstructions hint towards negative energy density at high redshifts

Inevitable manifestation of wiggles in the expansion of the late Universe

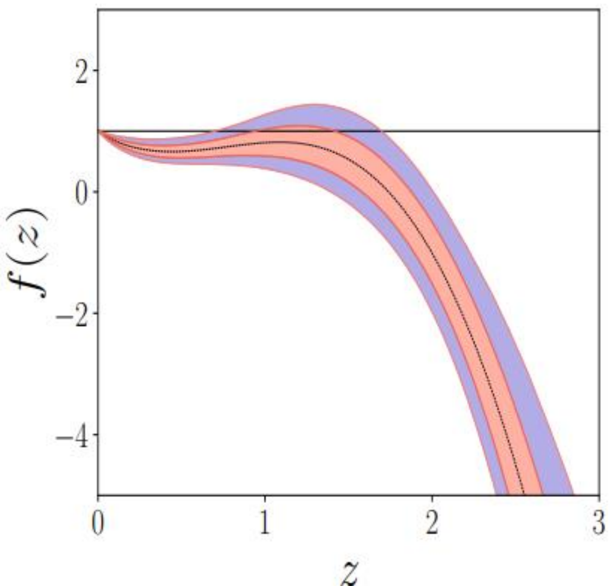
Özgür Akarsu, Eoin Ó Colgáin, Emre Özülker, Somyadip Thakur, and Lu Yin
Phys. Rev. D **107**, 123526 – Published 20 June 2023



Beyond ΛCDM with low and high redshift data: implications for dark energy

Koushik Dutta (Saha Inst.), Ruchika (Jamia Millia Islamia), Anirban Roy (SISSA, Trieste), Anjan A. Sen (Jamia Millia Islamia), M.M. Sheikh-Jabbari (IPM, Tehran)
Aug 20, 2018

10 pages
Published in: *Gen.Rel.Grav.* 52 (2020) 2, 15



$$3H^2(z) = \rho_m + \rho_{\rm DE} = \rho_{m0}(1+z)^3 + \rho_{\rm DE0} f(z)$$

Our Approach

Towards a possible solution to the Hubble tension with Horndeski gravity

Yashi Tiwari, Basundhara Ghosh, Rajeev Kumar Jain

arXiv: 2301.09382

Motivation

- A late universe solution to address Hubble tension
- Dynamical dark energy which can exhibit interesting features like negative dark energy, phantom crossing.
- To motivate the model from a **Lagrangian perspective** in the framework of generalized scalar-tensor theories.
- But lets first talk a bit about **Horndeski theory.**

Horndeski theory

- The Lagrangian constructed out of metric tensor and scalar field, such that **equations of motion are second order**.

(Kobayashi et al 2011, Kobayashi 2019)

$$\mathcal{L} = \sum_{i=2}^{5} \mathcal{L}_i \,,$$

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

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

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

$G_4 = \frac{M_{Pl}^2}{2}$ $\Rightarrow$ Einstein-Hilbert action

$G_2 = X - V(\phi), G_4 = \frac{M_{Pl}^2}{2}$ $\Rightarrow$ Single-field inflation or Quintessence dark energy

Other subclasses: non-minimal coupling, Galileons, derivative couplings …

Applications: Primordial black-hole formation, Black-hole physics, CMB anomalies, non-trivial dark energy models...

Horndeski theory (Background equations)

(Matsumoto et al 2017)

$$3H^2 = \kappa^2(\rho_\phi + \rho_M)$$
$$-3H^2 - 2\dot{H} = \kappa^2(p_\phi + p_M)$$

Friedmann Equations

$$\frac{1}{a^3}\frac{d}{dt}(a^3\mathcal{J}) = \mathcal{P}_\phi \longrightarrow$$

Evolution of scalar field

$$\rho_\phi = 2XG_{2,X} - G_2 + 6X\dot{\phi}HG_{3,X} - 2XG_{3,\phi} - 6H^2G_4 + 24H^2X(G_{4,X} + XG_{4,XX} - 12HX\dot{\phi}G_{4,\phi X}$$
$$-6H\dot{\phi}G_{4,\phi} + 2H^3X\dot{\phi}(5G_{5,X} + 2XG_{5,XX}) - 6H^2X(3G_{5,\phi} + 2XG_{5,\phi X}) + \frac{3H^2}{\kappa^2}$$

$$\mathcal{J} = \dot{\phi}G_{2,X} + 6HXG_{3,X} - 2\dot{\phi}G_{3,\phi} + 6H^2\dot{\phi}(G_{4,X} + 2XG_{4,XX}) - 12HXG_{4,\phi X}$$
$$+2H^3X(3G_{5,X} + 2XG_{5,XX}) - 6H^2\dot{\phi}(G_{5,\phi} + XG_{5,\phi X}),$$

$$\boxed{\kappa^2 = 1/M_{\rm Pl}^2}$$

$$\mathcal{P}_\phi = G_{2,\phi} - 2X(G_{3,\phi\phi} + \ddot{\phi}G_{3,\phi X}) + 6(2H^2 + \dot{H})G_{4,\phi} + 6H(\dot{X} + 2HX)G_{4,\phi X}$$
$$-6H^2XG_{5,\phi\phi} + 2H^3X\dot{\phi}G_{5,\phi X}.$$

Horndeski theory (Perturbations)

$$\mathcal{S}_2 = \int \mathrm{d}t\mathrm{d}^3x a^3 \left[Q_S \left(\underbrace{\dot{\mathcal{R}}^2 - \frac{c_S^2}{a^2}(\partial_i \mathcal{R})^2}_{\text{scalar}} \right) + Q_T \left(\underbrace{\dot{h}_{ij}^2 - \frac{c_T^2}{a^2}(\partial_k h_{ij})^2}_{\text{tensor}} \right) \right],$$

(Felice et al 2011, Bellini et al 2014)

Stability Conditions (for a consistent theory)

$c_S^2 > 0$

$c_T^2 > 0$

To avoid gradient instability

$Q_S > 0$

$Q_T > 0$

To avoid ghost instability

where $c_S, Q_S, c_T, Q_T = \mathcal{F}(G_i, G_{i,Y}, \phi, \dot{\phi})$

An example !!

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

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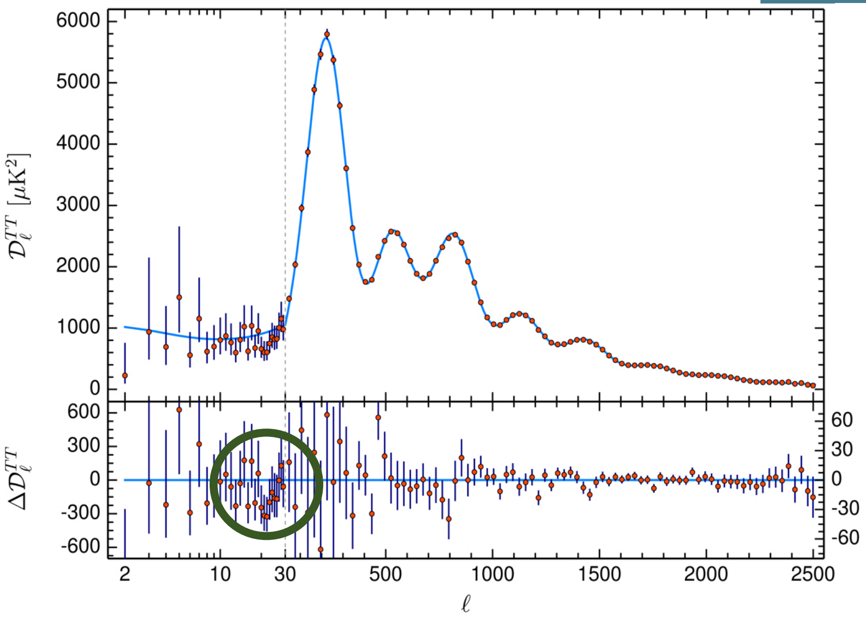

Understanding large scale CMB anomalies with the generalized nonminimal derivative coupling during inflation

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GNMDC

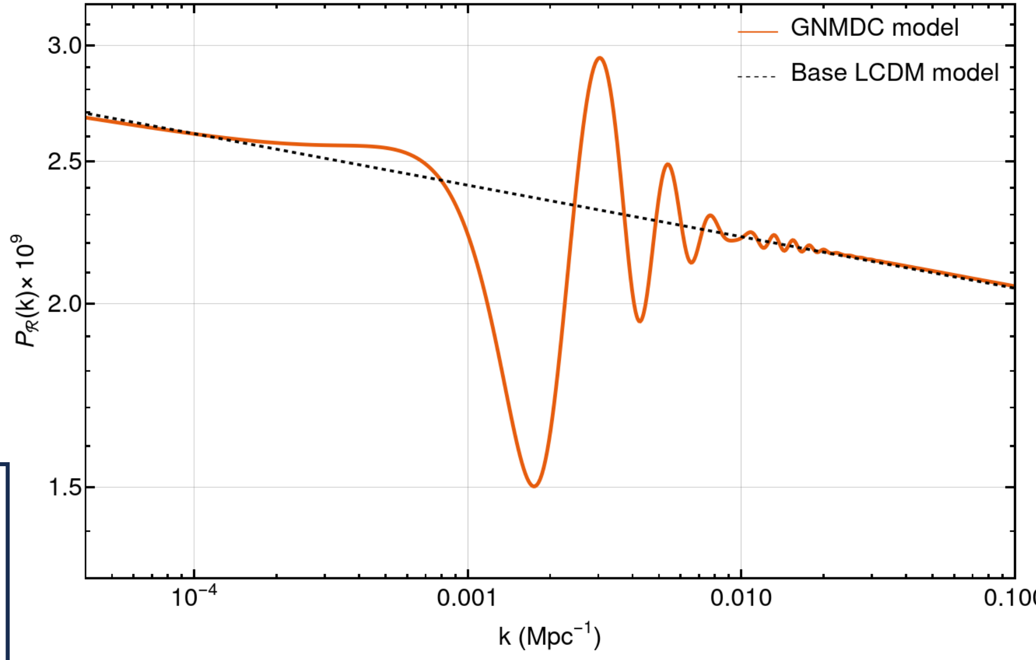
$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}\Big(g^{\mu\nu} - \overbrace{\theta(\phi)G^{\mu\nu}}^{\text{GNMDC}}\Big)\partial_\mu\phi\partial_\nu\phi - V(\phi)\right],$$

This can be obtained from **Horndeski Lagrangian** using

$$G_2 = X - V(\phi), G_4 = \frac{M_{Pl}^2}{2}, G_5 = G_5(\phi)$$

$$\theta(\phi) = -2G_{5,\phi}$$

Primordial power spectrum



(Similar features as studied by Jain et al. 2008, Hazra et al. 2010)

Building a dark energy model in the framework of Horndeski gravity

Model Specifications

- A dynamical scalar field as dark energy (No cosmological constant).

$$\mathcal{L}_\phi = \underbrace{G_4(\phi)\mathcal{R}}_{\text{Non-minimal coupling (NMC)}} - \underbrace{G_3(\phi, X)\Box\phi}_{\text{Self-interaction (SI) (Galileon)}} - \underbrace{\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}_{\text{kinetic term (K)}} - \underbrace{V(\phi)}_{\text{Scalar field potential}}$$

$$\mathcal{S} = \int d^4x\sqrt{-g}\left(\mathcal{L}_\phi + \mathcal{L}_M\right) \longrightarrow \text{Total action}$$

Background equations are solved giving initial conditions on $\phi, \dot{\phi}, H$ **at high redshift.**
The case with $c_1 = c_2 = c_3 = 0$ corresponds to Quintessence .

We choose

$$ds^2 = -dt^2 + a(t)^2 d\bar{x}^2,$$

$$G_3(\phi, X) = c_1\phi + c_2 X$$

$$G_4(\phi) = \frac{1}{2} + c_3\phi$$

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

$$V(\phi) = V_0\phi$$

V_0 → Kept fixed

$$\kappa^2 = 1$$

$$G_5 = 0$$

c_1, c_2 and c_3 are the free parameters, controlling strengths of coupling terms.

Model Specifications

Effective energy density of dark energy field

$$\rho_\phi = \underbrace{\frac{1}{2}\dot{\phi}^2 + V(\phi)}_{\text{Canonical kinetic + potential}} \underbrace{- 6c_3\phi H^2 - 6c_3 H\dot{\phi}}_{\text{Due to NMC, leads to negative energy density in past : phantom crossing (for } c_3 > 0)} \underbrace{- c_1\dot{\phi}^2 + 3c_2 H\dot{\phi}^3}_{\text{Due to Self interactions}}$$

pressure

$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) + 6c_3\phi H^2 + 4c_3\phi\dot{H} + 2c_3\ddot{\phi} + 4c_3 H\dot{\phi} - c_1\dot{\phi}^2 - c_2\ddot{\phi}\dot{\phi}^2$$

It will be shown later that **both** nonminimal coupling and self interactions are needed to appropriately address the H_0 tension.

$$G_3(\phi, X) = c_1\phi + c_2 X$$

$$G_4(\phi) = \frac{1}{2} + c_3\phi$$

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

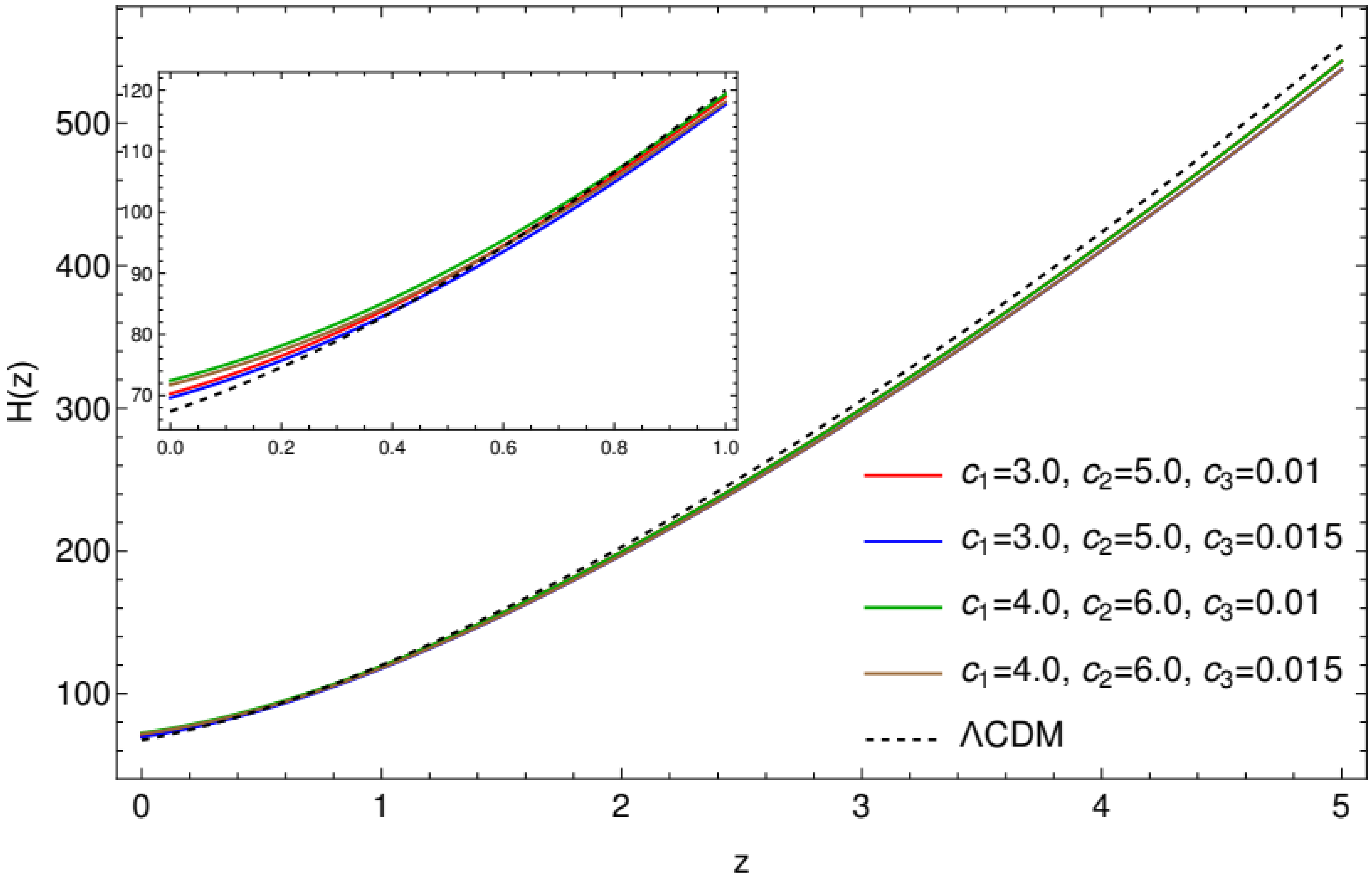
$$V(\phi) = V_0\phi$$

$$w_\phi = \frac{p_\phi}{\rho_\phi}$$

Equation of state

$$\frac{d\rho_\phi}{dz} = \frac{3(1+w_\phi)\rho_\phi}{1+z}$$

Distinct Features



- At high redshifts

  $H(z) < H_{LCDM}$(z)

- At low redshifts,

  $H(z) > H_{LCDM}$(z)

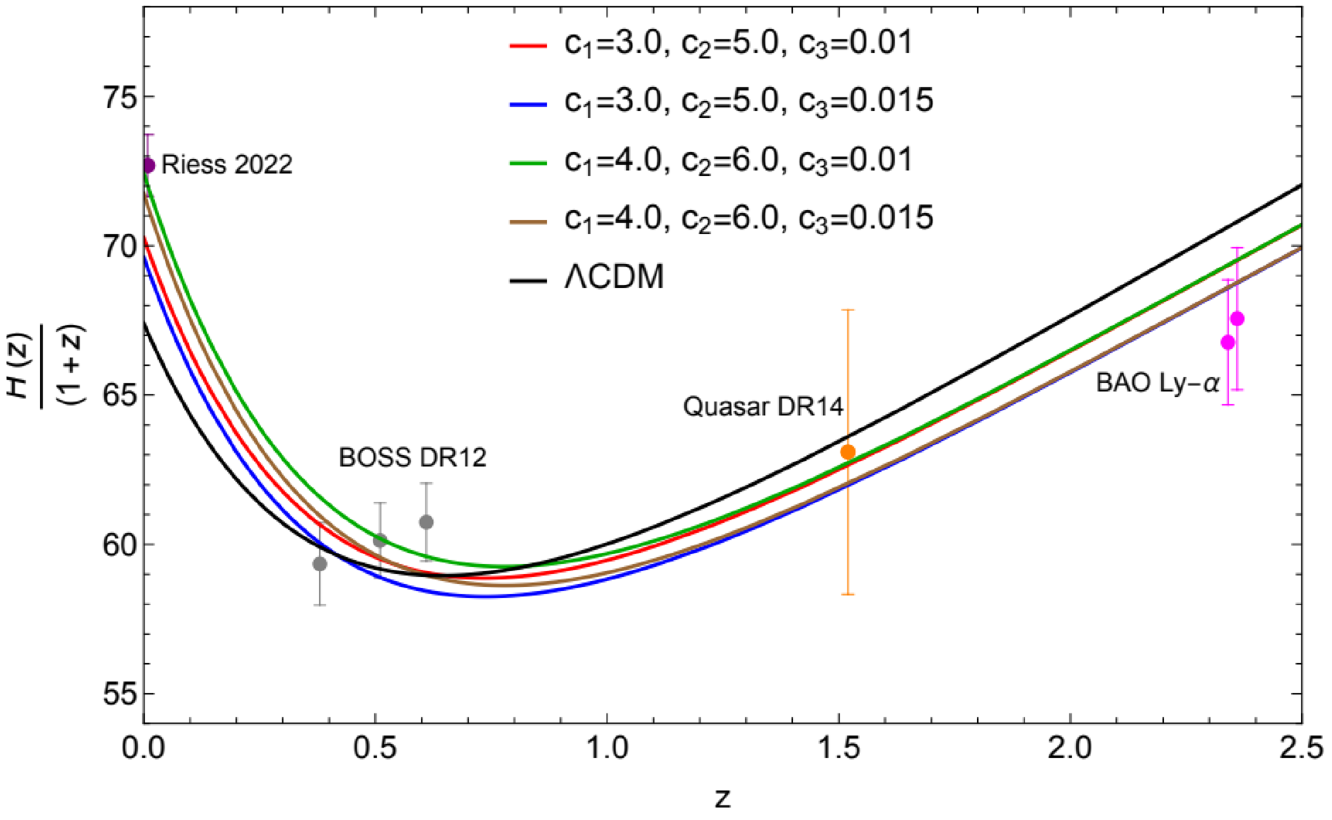
Necessary for D to remains undisturbed

$$D(z_L) = \int_0^{z_L} \frac{dz}{H(z)}$$

i.e. to ensure CMB peaks remain undisturbed

(Refer: Adil et al 2023)

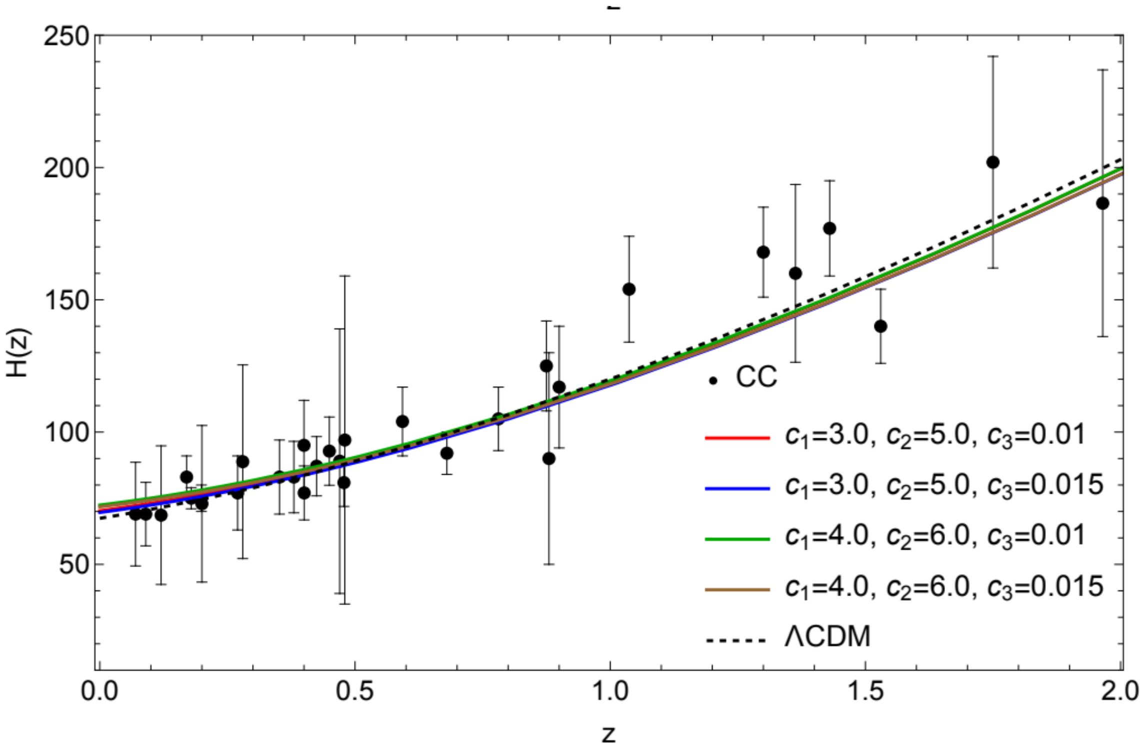
Distinct Features



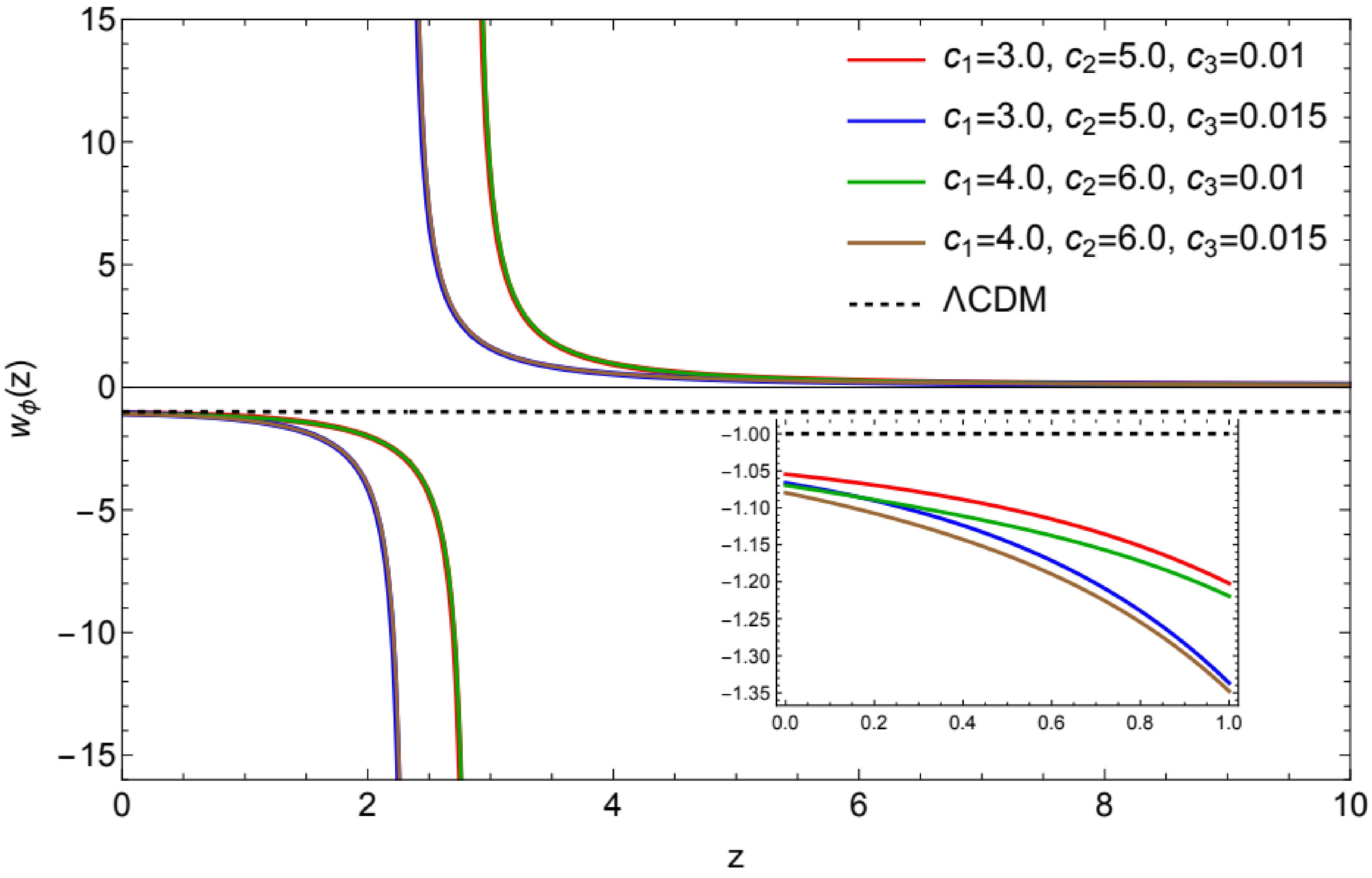
Negative energy density ($c_3 > 0$) can explain the BAO Lyman-alpha anomalous H(z) measurement at $z \sim 2.3$.

(Aubourg et al 2014, Sahni et al 2014, Poulin et al 2018, Adil et al 2023)

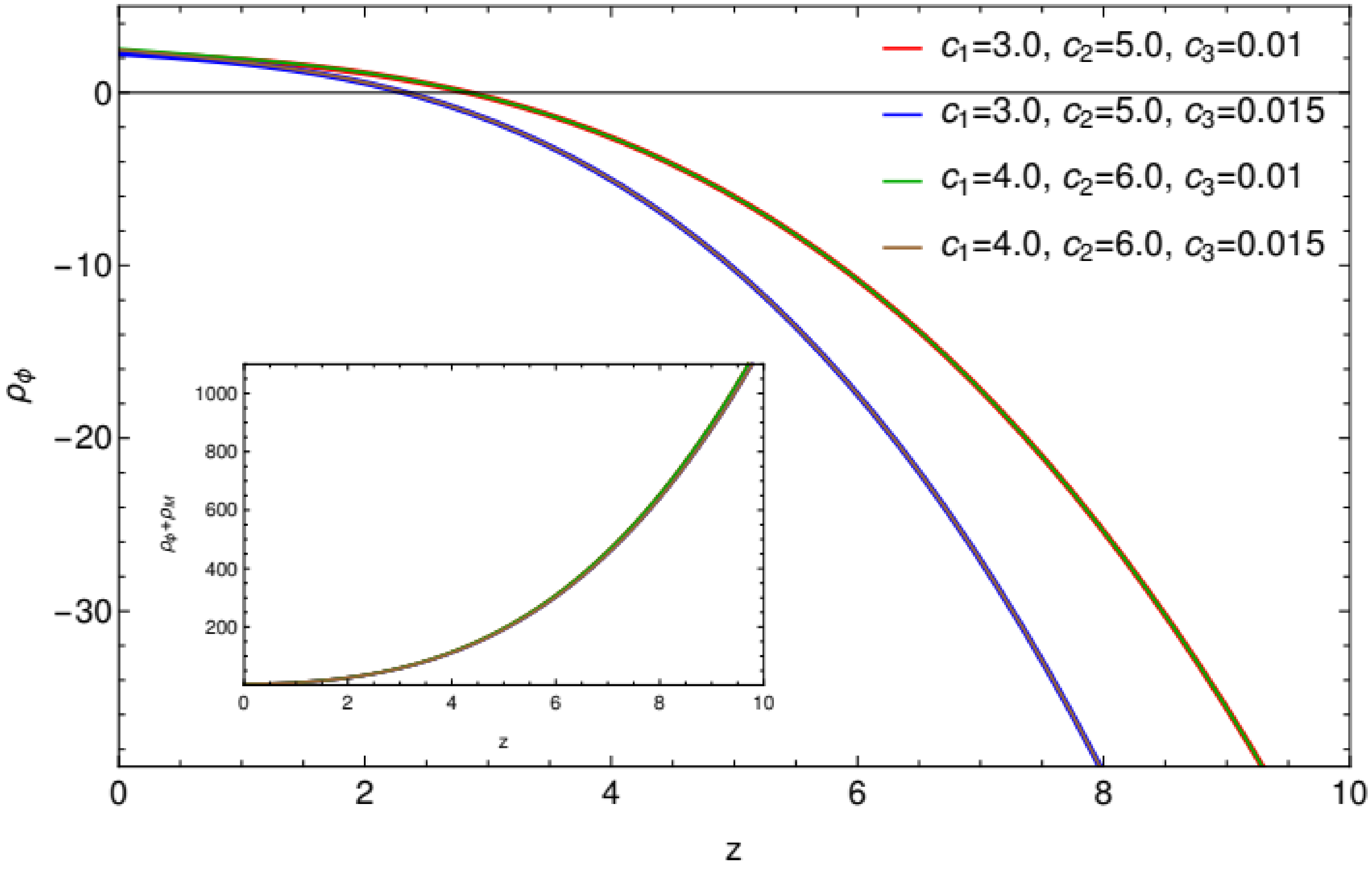
Evolution of H(z) with 33 Cosmic chronometer (CC) data



Distinct Features : Equation of state



Distinct Features : Energy density of scalar field



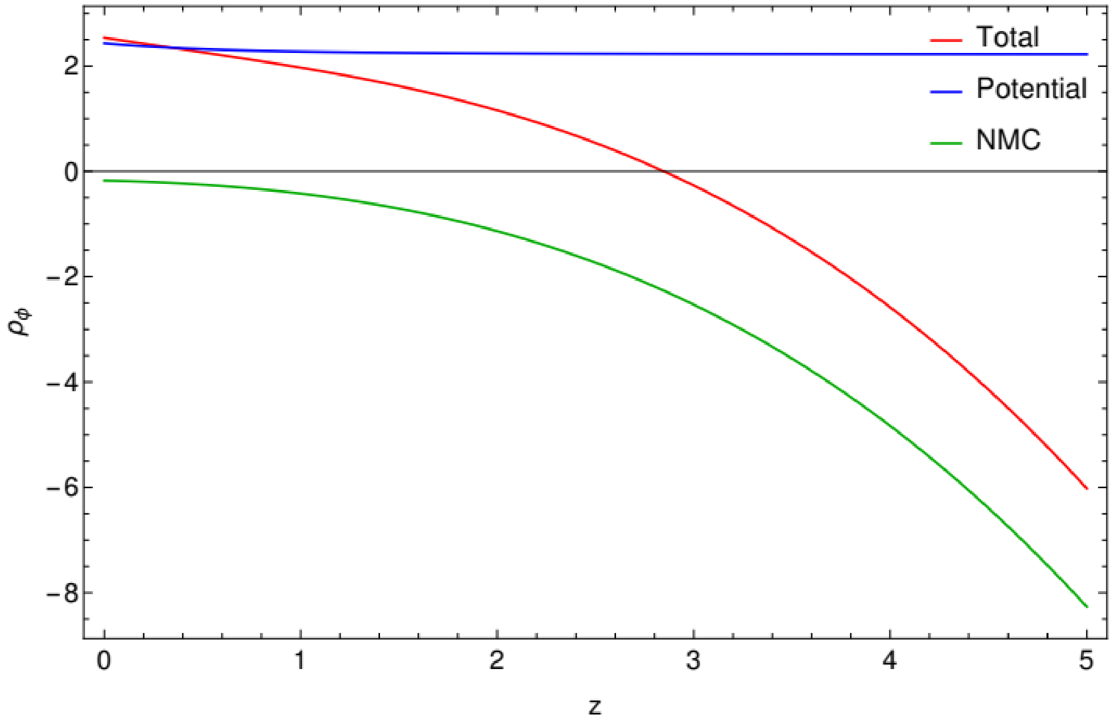
- Energy density of the scalar field is negative at high redshifts.
- The **total** energy density of universe is always **positive.**

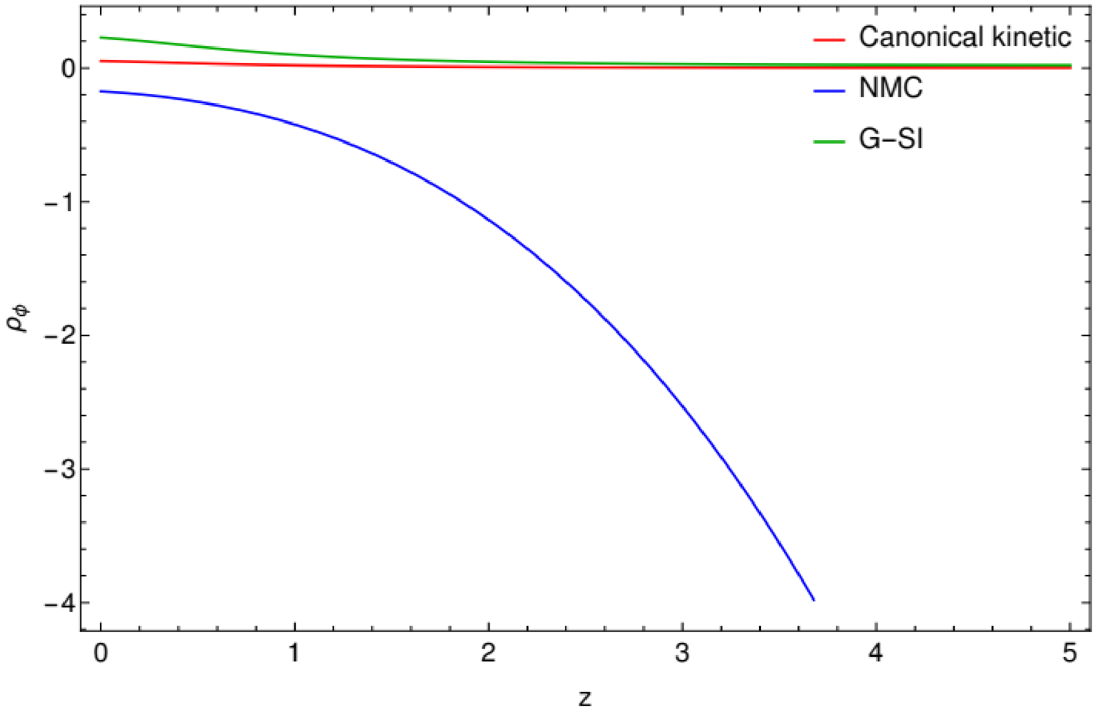
Distinct Features : Energy density of scalar field

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \underbrace{- 6c_3\phi H^2 - 6c_3 H\dot{\phi}}_{\text{Dominates at high z as H}\uparrow\text{ as z}\uparrow\text{.}}^{\text{(NMC)}} \overbrace{- c_1\dot{\phi}^2 + 3c_2 H\dot{\phi}^3}^{\text{Dominates at low z as }\dot{\phi}\text{ increases.}}_{\text{(G-SI)}}$$

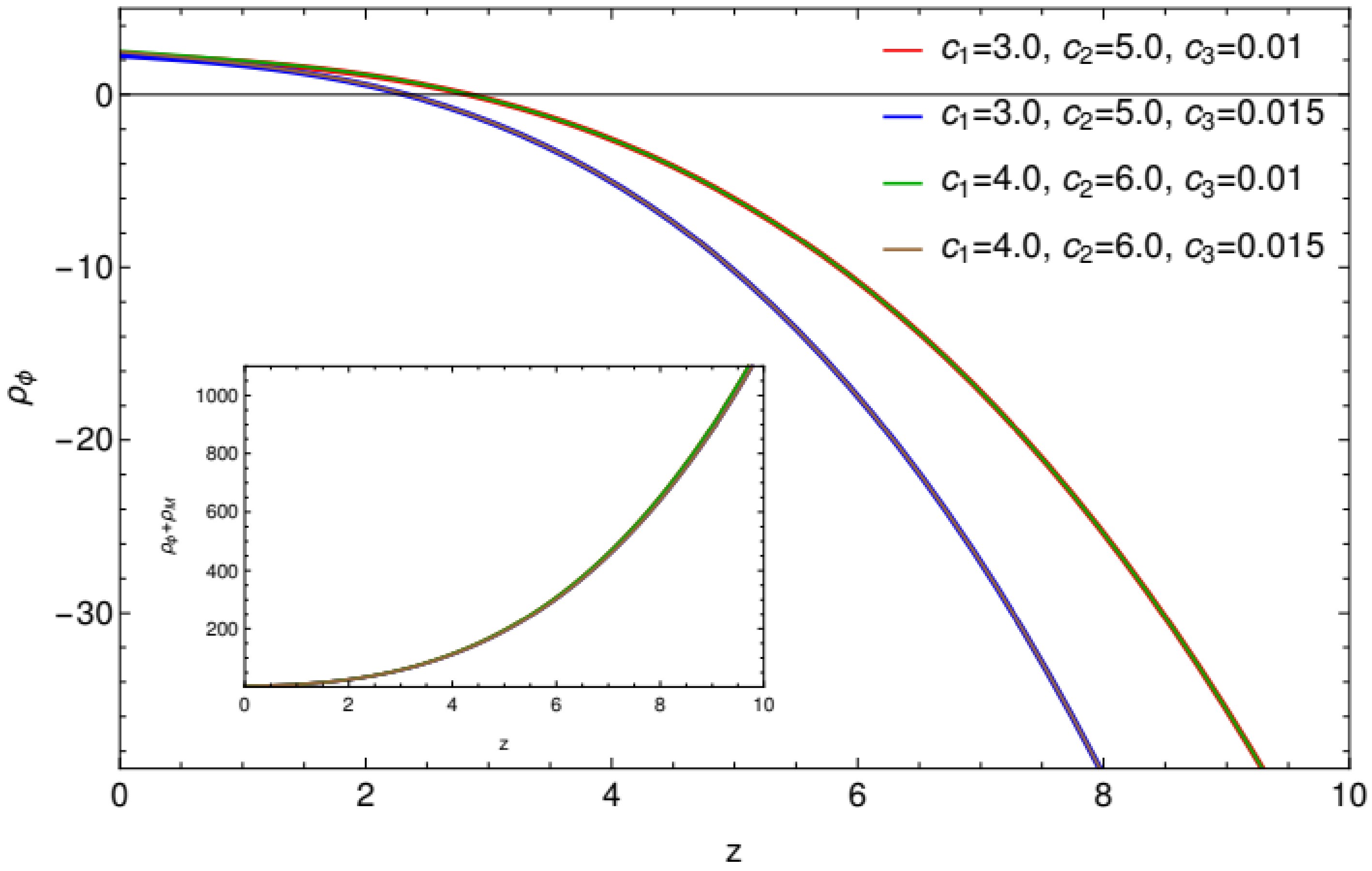
$$G_3(\phi, X) = c_1\phi + c_2 X$$

$$G_4(\phi) = \frac{1}{2} + c_3\phi$$





Distinct Features : Phantom Crossing



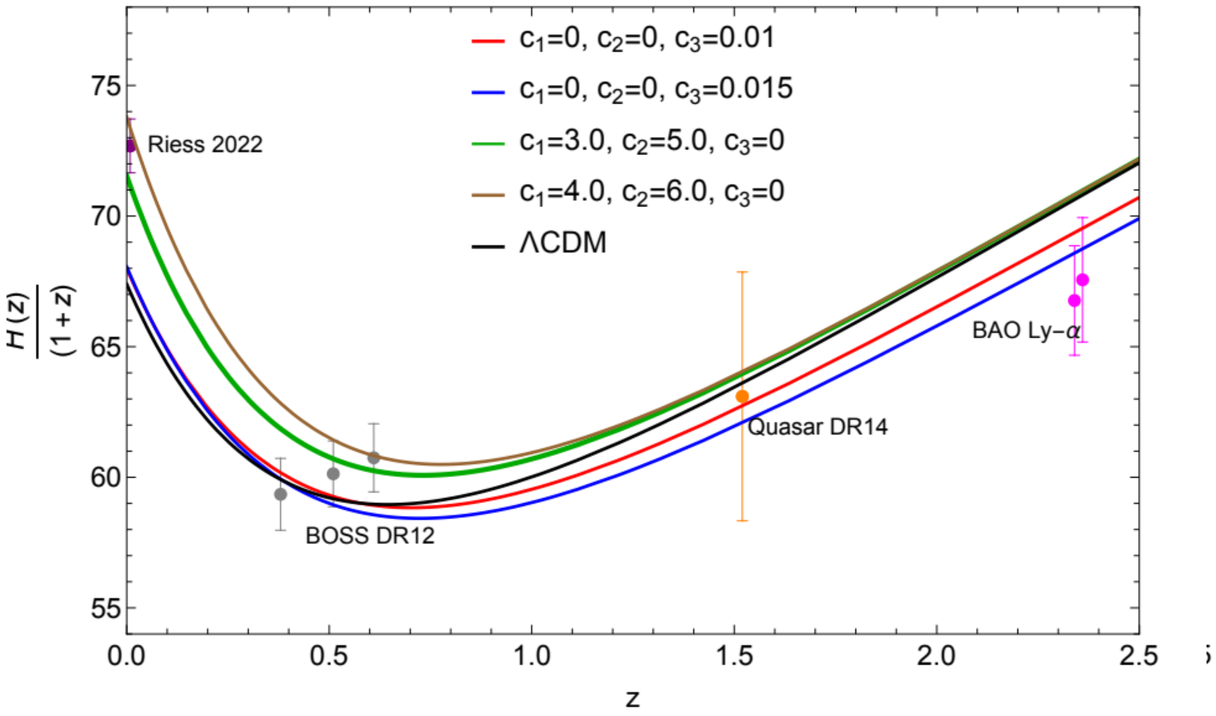
The evolution of energy density of scalar field from negative to positive values leads to **a phantom crossing**. This can be understood as follows,

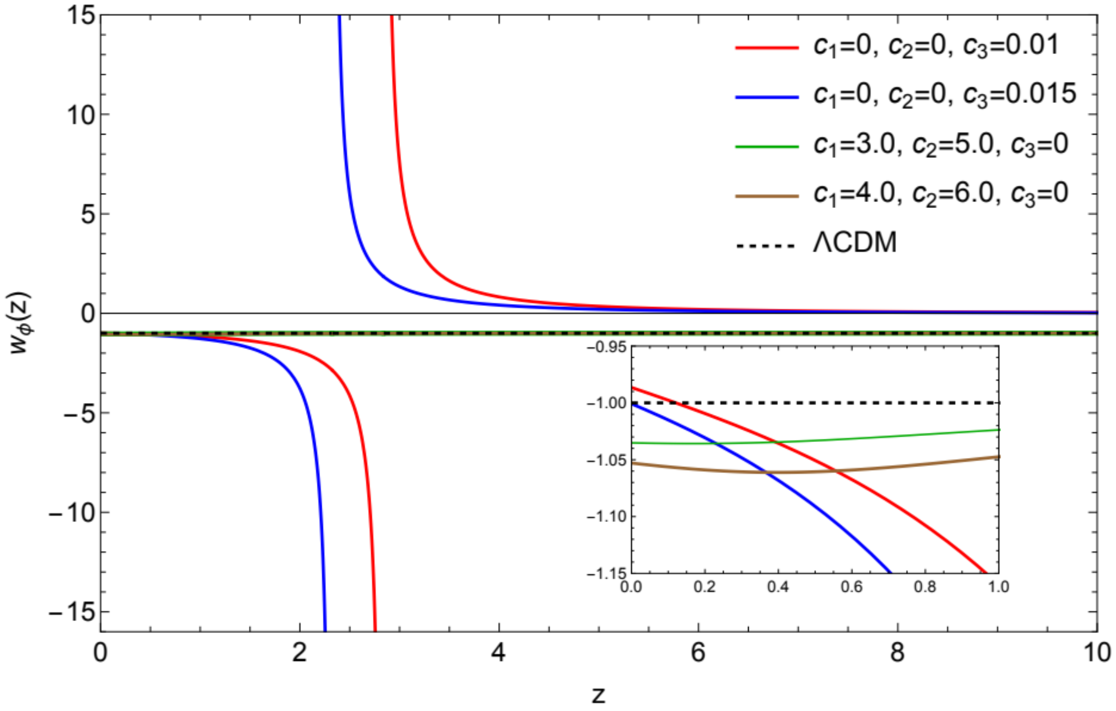
$$\frac{d\rho_\phi}{dz} = \frac{3(1+w_\phi)\rho_\phi}{1+z}$$

As $\frac{d\rho_\phi}{dz} < 0,\quad \rho_\phi < 0 \Rightarrow w_\phi > -1$

$\rho_\phi > 0 \Rightarrow w_\phi < -1$

Effect of interactions on dynamics (Separately)





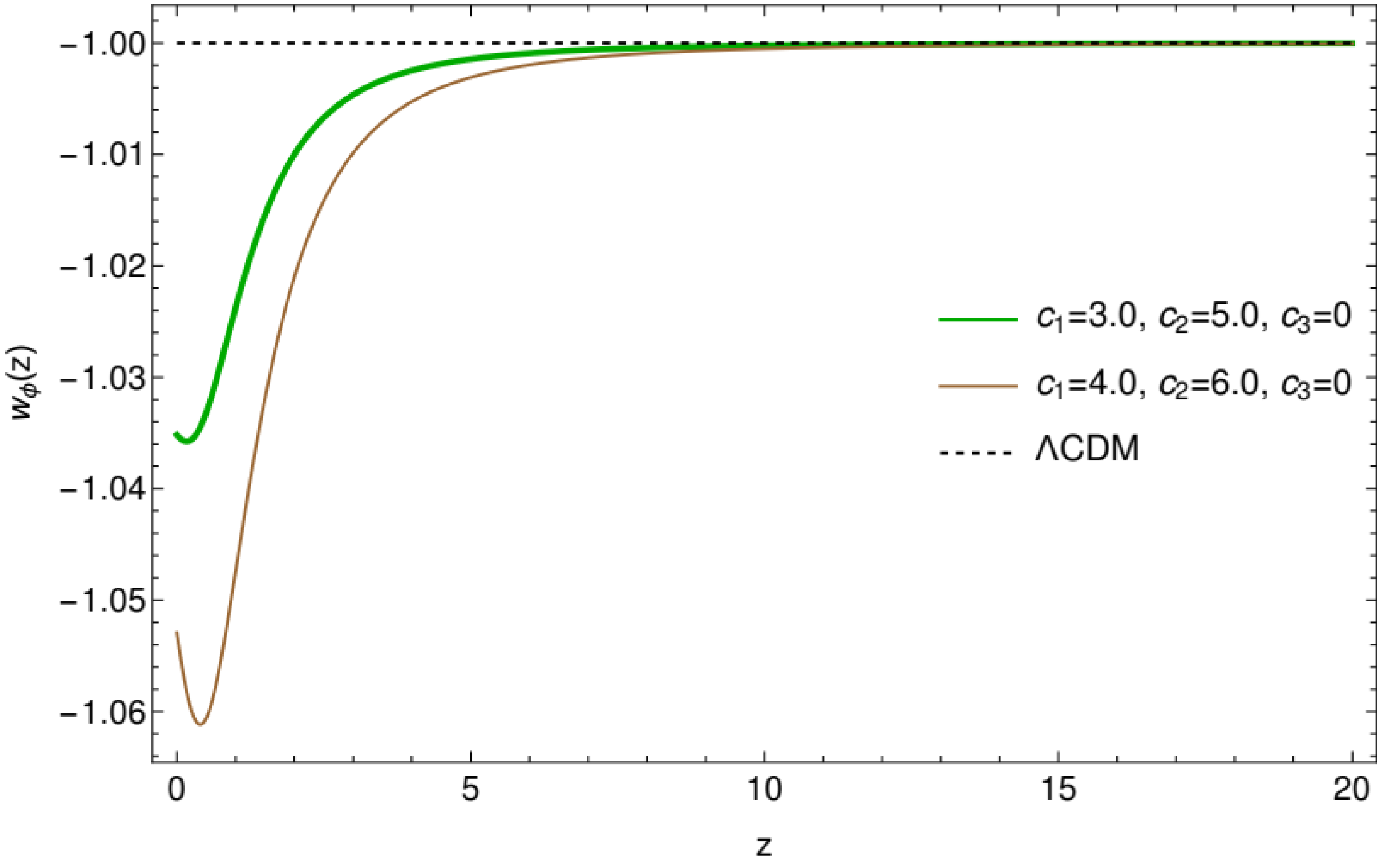
Case : $\boldsymbol{G_3(\phi, X)}$ **=0;** $\boldsymbol{G_4 = \frac{1}{2} + c_3 \phi}$

$$G_3(\phi, X) = c_1\phi + c_2 X$$

$$G_4(\phi) = \frac{1}{2} + c_3\phi$$

- Only non-minimal coupling
- Negative energy density at high redshifts.
- Phantom crossing (a necessary condition!)
- May not achieve very large H_0.

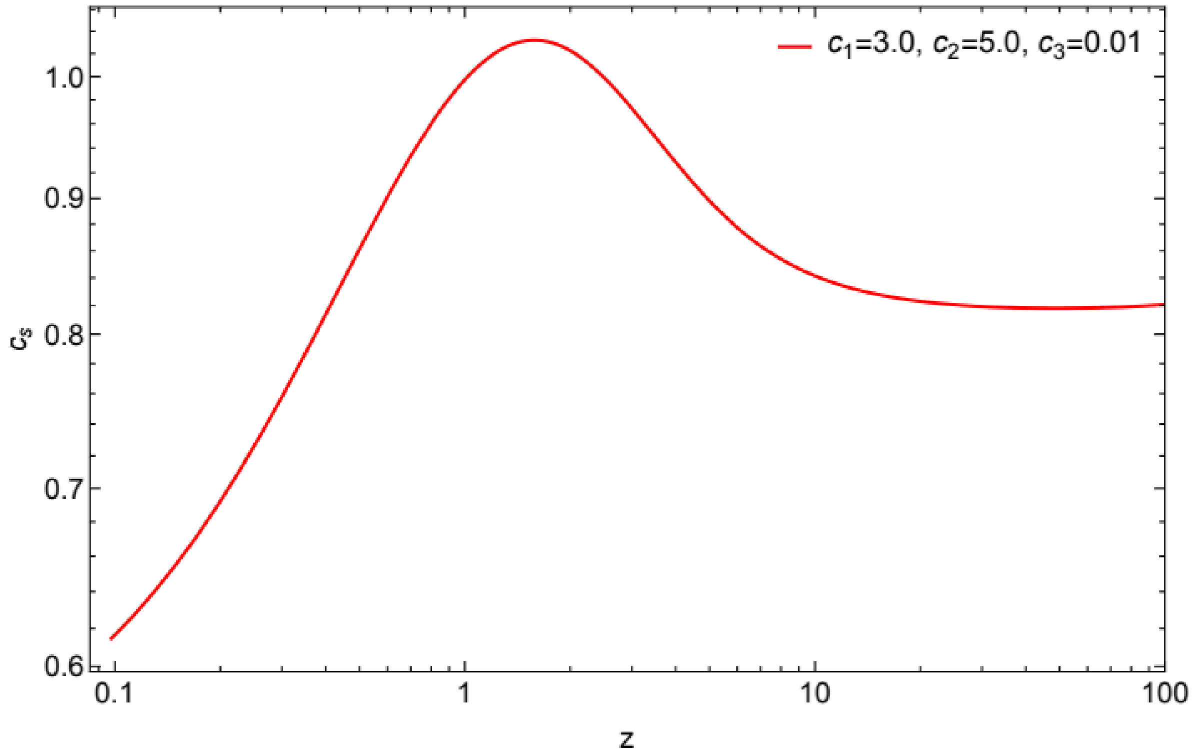
Effect of interactions on dynamics (Separately)



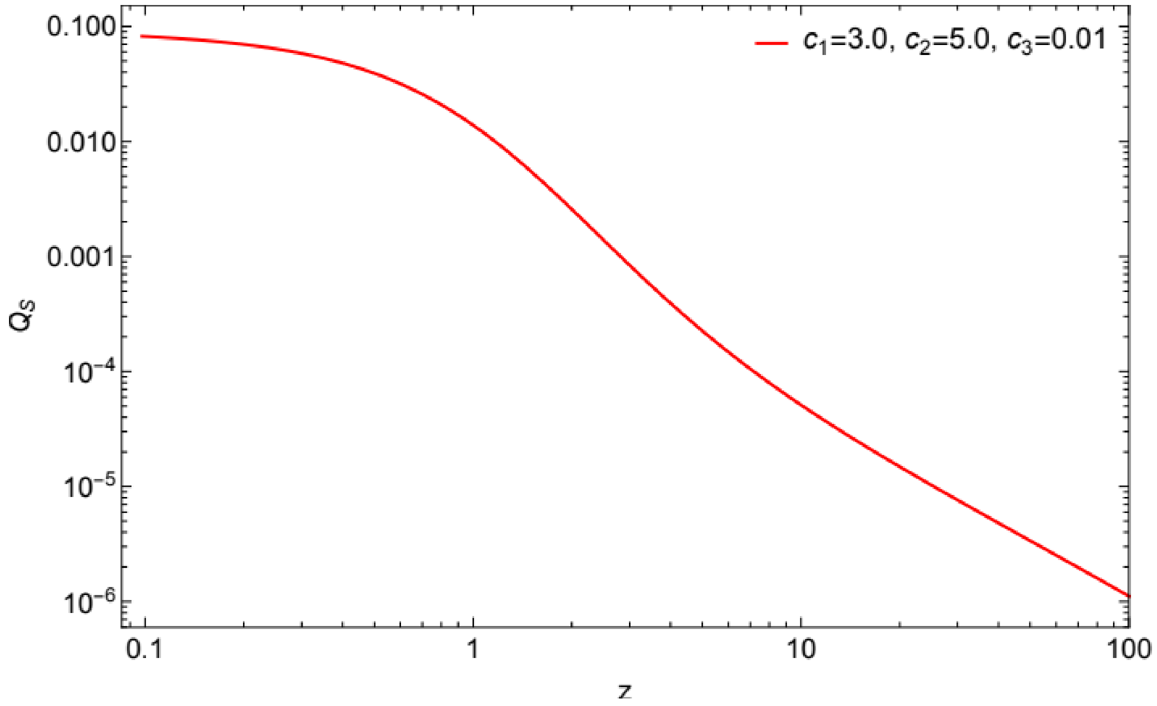
Case : $\boldsymbol{G_3(\phi, X) = c_1\phi + c_2X;\ \ G_4 = \frac{1}{2}; c_3 = 0}$

- Only self interactions.
- Phantom switch at low redshifts.
- Energy density is always positive.
- Large values of H_0 can be attained by tuning c_1, c_2.
- No Phantom crossing
- Behaves like hockey-stick model (Not preferred by observations)

Stability Conditions: Towards consistent model building



No gradient instability



Ghost free theory

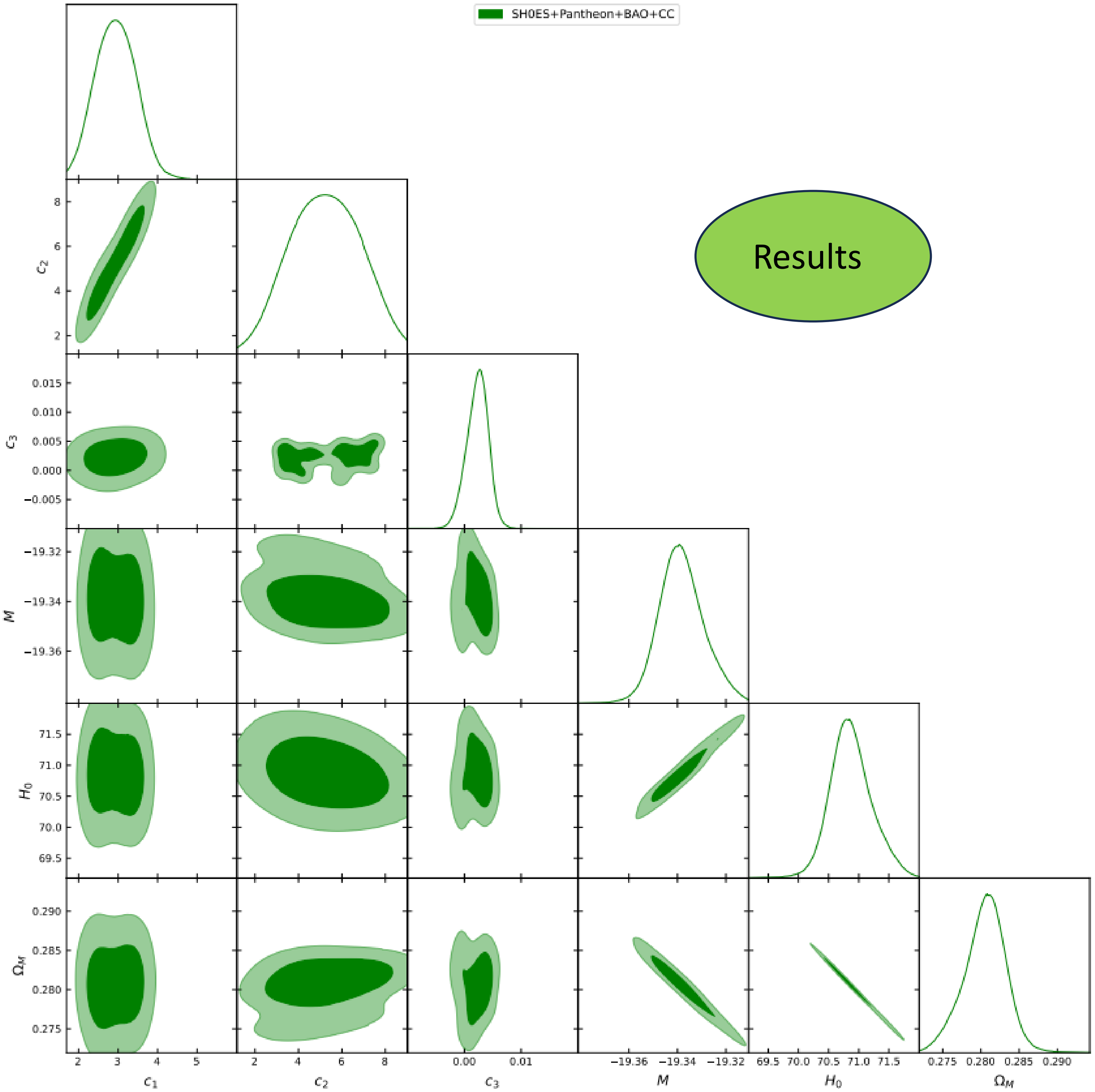
Constraints on Parameter space from Observations

- We employ Markov Chain Monte Carlo technique to obtain constraints on the parameter space.
- Uniform priors are provided on three model parameters and on absolute magnitude of Supernovae (M).
- We use the following observation data for our analysis:

Parameters	Priors
c_1	[2.0,8.0]
c_2	[2.0,10.0]
c_3	[-0.02,0.02]
M	[-19.5,-19.0]

1. SH0ES: Modelled with a Gaussian likelihood on M = -19.2435$\pm$0.0373 *(Riess et al 2021, Camarena et al 2021)*
2. 1048 SNIa Pantheon Sample in redshift range $0.01 < z < 2.3$. *(Scolnic et al 2017)*
3. Six H(z) measurement from BAO. *(Alam et al 2020, also compiled in Table I of Tiwari et al 2023)*
4. 33 Cosmic chronometer (CC) measurement of H(z). *(as compiled in Table III of Gomez-Valent et al 2023, using covariance matrix method as discussed in Moresco et al 2020)*

For more details visit: arXiv 2301.09382



Results

Parameter	68% limits
$\boldsymbol{c_1}$	2.93 ± 0.45
$\boldsymbol{c_2}$	5.2 ± 1.5
$\boldsymbol{c_3}$	$0.0023^{+0.0021}_{-0.0017}$
$\boldsymbol{M}$	$-19.3383^{+0.0081}_{-0.010}$
$\boldsymbol{H_0}$	$70.87^{+0.29}_{-0.37}$
$\boldsymbol{\Omega_M}$	$0.2805^{+0.0029}_{-0.0024}$

- Data prefers a positive c_3 (1σ) which indicates a preference of negative dark energy at high redshifts.
- Inclusion of CMB data will tighten the constraints on the parameter space.
- As of now the present model reduces the tension with SH0ES measurement to $\sim 2\sigma$.

Conclusion and Future Prospects

- We exploit the phenomenology of Horndeski theory to build dark energy model in order to address Hubble Tension.

- Interesting features like negative energy density at high redshifts, phantom crossing, etc can be obtained in such a setup.

- Constrains are obtained on parameter space by Supernovae, BAO and CC data.

- Next step is to study the perturbation theory for such Horndeski models: obtaining power spectra and confronting with CMB data. *(in progress)*

- Studying the implications of such models towards resolution of other cosmological tensions like **growth tension**. *(in progress)*

Thank you