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Do cosmological observations allow a negative Λ?

Centre for Strings, Gravitation and Cosmology
IIT Madras
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Outline

- Expanding Universe
- H_0 from Planck
- Distance Ladder and Local Measurement of H_0
- Hubble Tension
- Early Universe Solution
- Late Time Solution
- Presence of a -ve Λ
- Conclusion

Expanding Universe: Friedmann Robertson Walker (FRW) Spacetime

Space is Homogeneous and Isotropic:

$$ds^2 = dt^2 - a^2(t)[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)]$$

+

Gravity is determined by GR

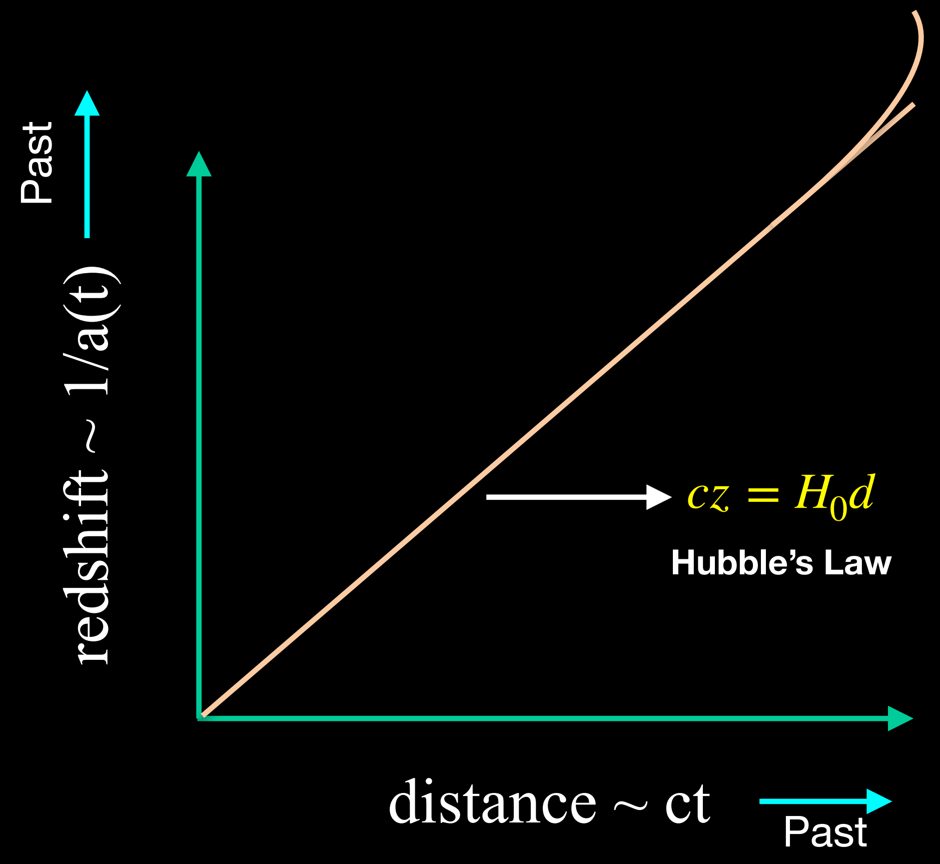
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Equation for the scale factor a(t):

$$3(\frac{\dot{a}}{a})^2 = 8\pi G(\rho_m + \Lambda) - \frac{3k}{a^2}$$ Friedmann equation

$$3\frac{\ddot{a}}{a} = -4\pi G(\rho_t + 3p_t)$$ Raychaudhuri Equation

$$H_0 = \frac{\dot{a}}{a}|_{z=0} \qquad q_0 = -\frac{(\ddot{a}/a)}{(\dot{a}/a)^2}|_{z=0}$$



Expanding FRW Universe

Three Numbers:

H_0 = Expansion Rate ⟶ age, size of the universe

q_0 = Acceleration Rate ⟶ nature of gravity, origin, fate of the universe

k = Spatial Curvature ⟶ Inflation is true ⟶ 0

Spatially Flat Universe:

Negligible at late times

$$H^2(z) = H_0^2[\underbrace{(\Omega_{cdm0} + \Omega_{b0})}_{\Omega_{m0}}(1+z)^3 + \Omega_{rad0}(1+z)^4 + \Omega_{\Lambda 0}(1+z)^{3(1+w)}]$$

$$q_0 = \frac{1}{2}[\Omega_{m0} + (1+3w)\Omega_{\Lambda 0}]$$

$$\Omega_{m0} + \Omega_{\Lambda 0} = 1$$

$$\Omega_{i0} = \frac{\rho_{i0}}{3H_0^2/8\pi G}$$ Dimension-less Density Parameters

$$w = \frac{p_\Lambda}{\rho_\Lambda}$$ Equation of state of dark energy

= -1 for Cosmological Constant

Around 1990's, H_0 = 60-80 km/s/Mpc

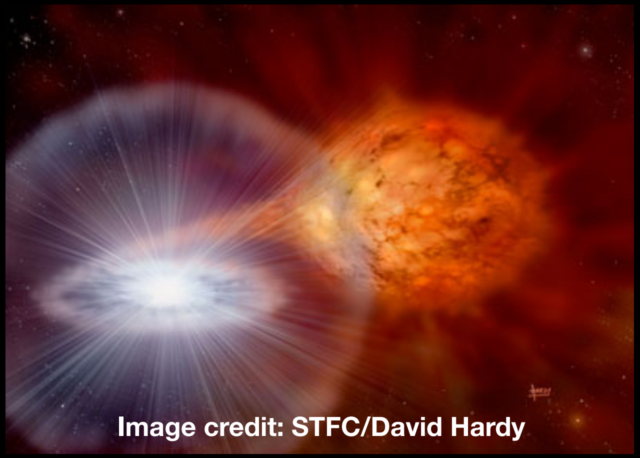
Ω_{m0} = 1, $\Omega_{\Lambda 0}$ = 0

q_0 = Ω_{m0} / 2

Standard Candles: Type-Ia Supernova and Cepheids

Basic Principle of Standard candles: **Brightness = Luminosity/Distance²**

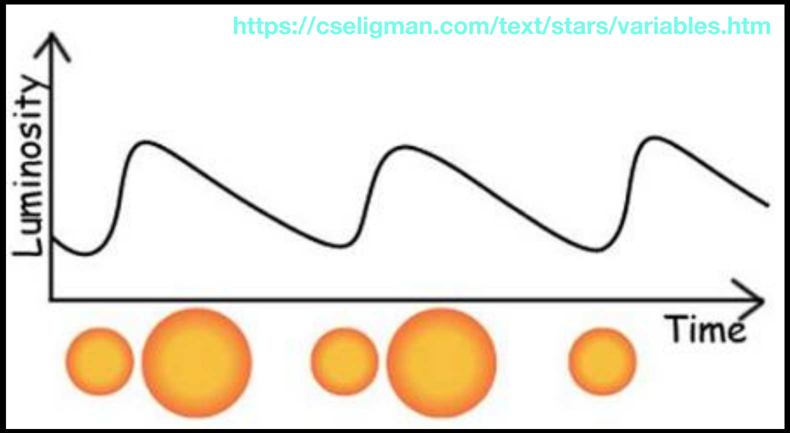
Type-Ia Supernova



Thermonuclear explosion of a White-Dwarf star reaching the Chandrasekhar Mass limit

Luminosity = $10^9 L_\odot$

Cepheid Stars



Massive Pulsating Stars having correlation between their Time-period and luminosity.

Luminosity = $10^5 L_\odot$

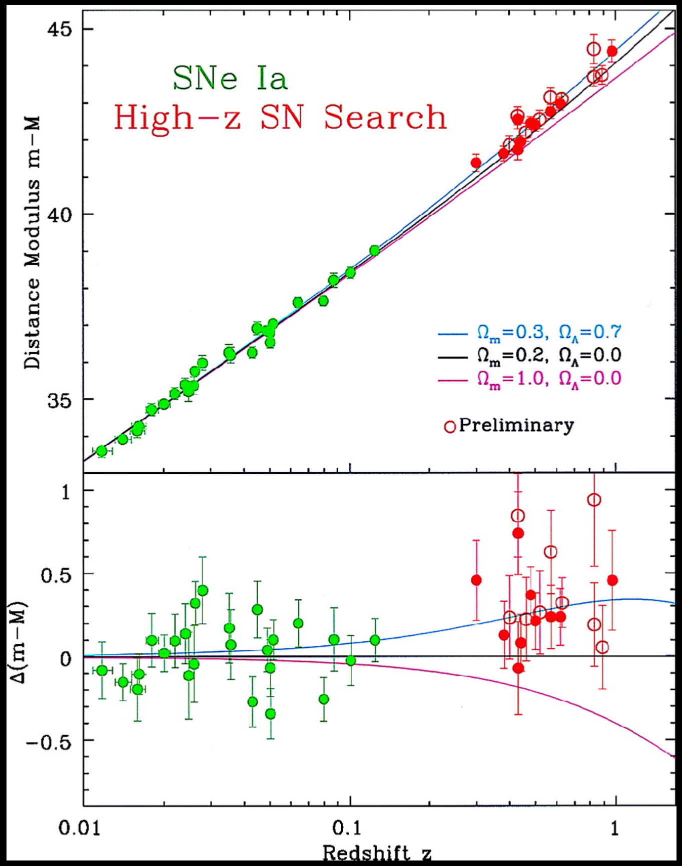
Integral part of Cosmic Distance Ladder to measure distances

Accelerating Universe and Dark Energy

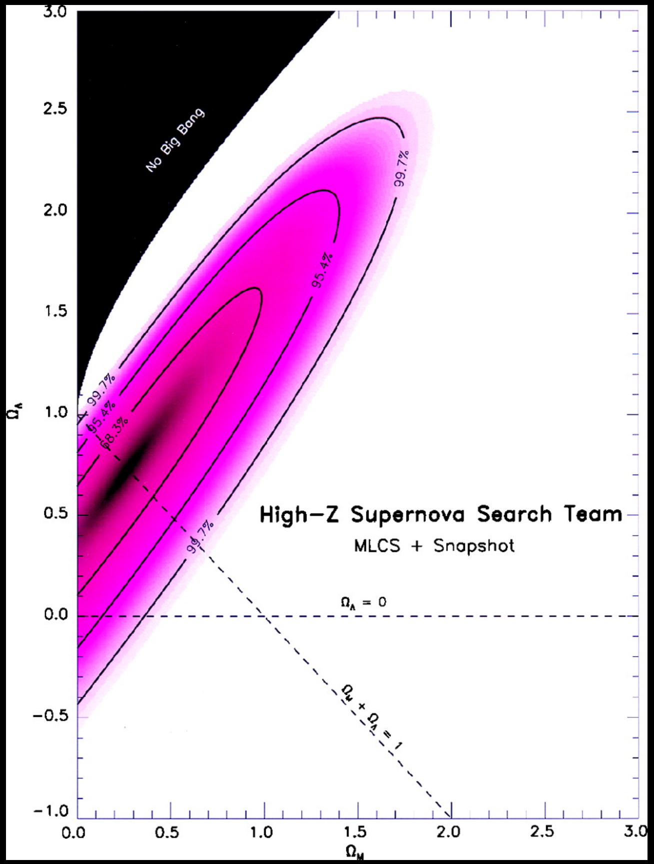
Two Teams: Supernova Cosmology Project, High-z Supernova Search Team

Distance Modulus: $\mu = m - M = H_0(\frac{d_L(z)}{10Mpc}) + 25$

Luminosity Distance: $d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{H(z)/H_0}$



Robert P. Kirshner PNAS 1999



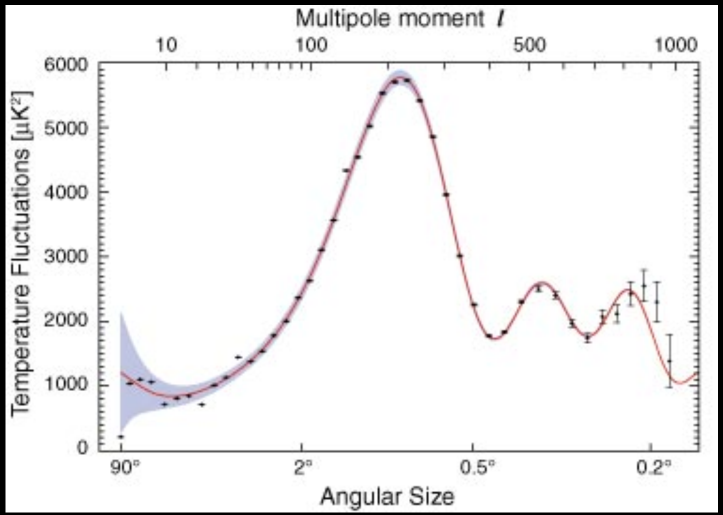
Robert P. Kirshner PNAS 1999

$\Omega_{m0} = 0.3$ $\Omega_{\Lambda 0} = 0.7$ Assuming w = -1, Cosmological Constant

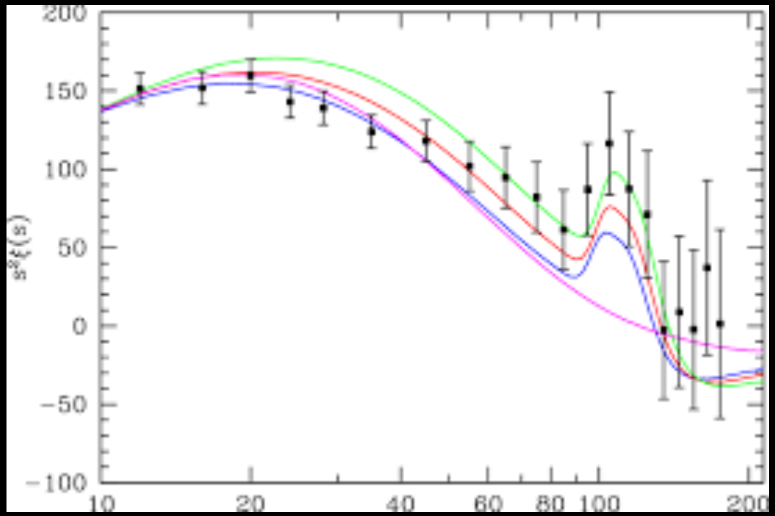
$q_0 < 0$ ⟶ Accelerating Universe !!

Accelerating Universe and Dark Energy

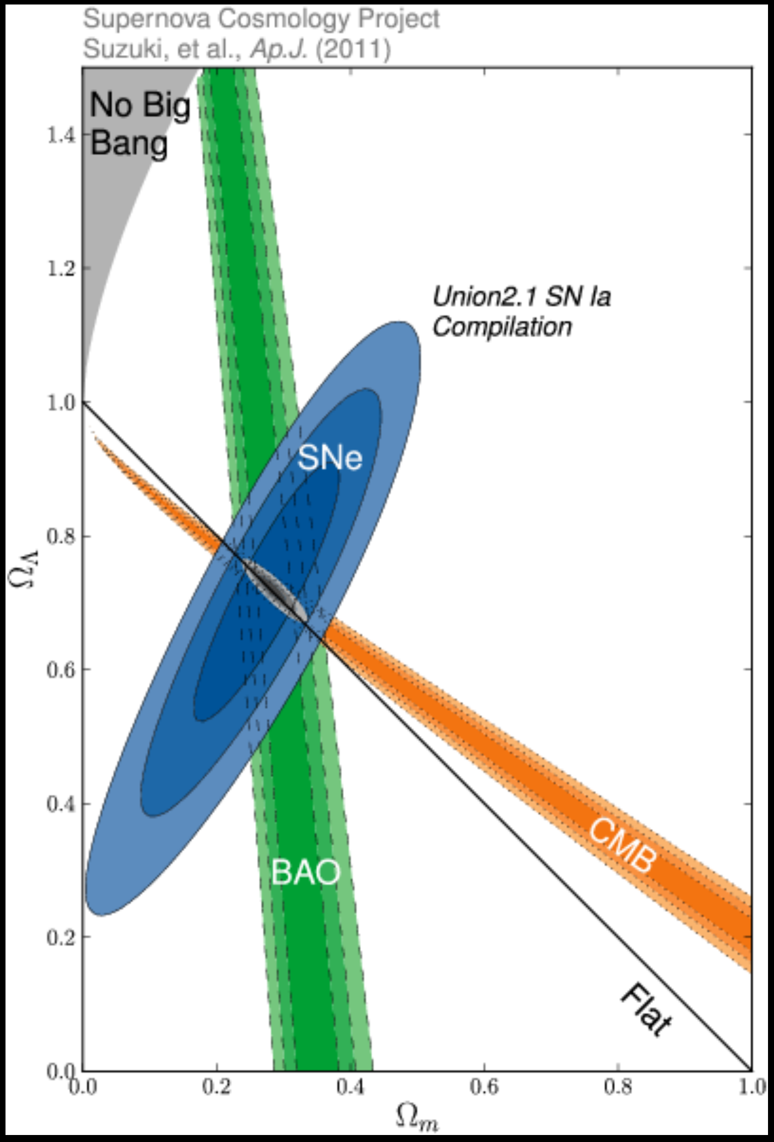
Add Other Cosmological Observation:



WMAP(Credit: NASA)



SDSS (credit: Eisenstein et al. (2005)



Cause of Acceleration

$$q_0 = \frac{1}{2}[\Omega_{m0} + (1+3w)\Omega_{\Lambda 0}]$$

$q_0 < 0 \rightarrow w < -1/2$ (with $\Omega_{\Lambda 0} = 0.7$)

Possible Source:

1) Cosmological Constant or Vacuum Energy: w = -1

Fine Tuning Problem, cosmic coincidence problem

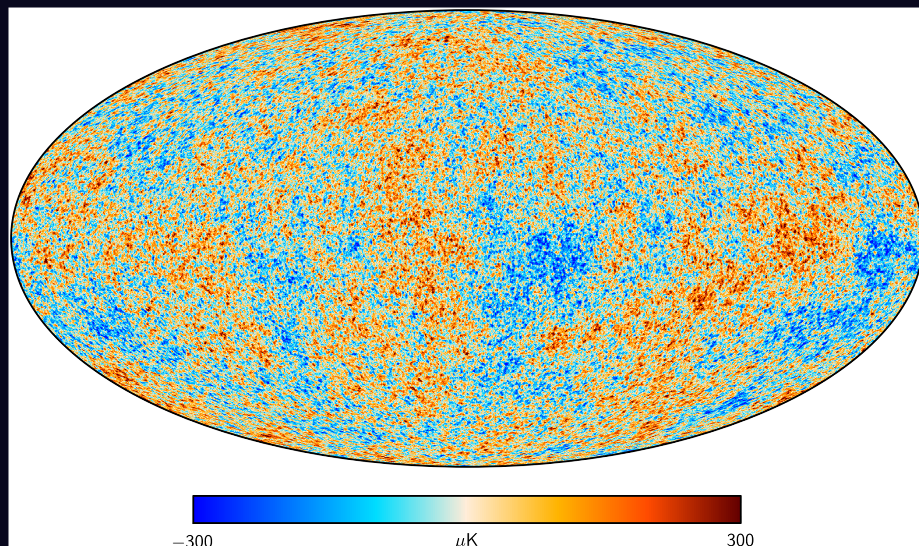
2) Evolving Dark Energy, scalar field slowly rolling over a potential: $w \neq -1$, $\frac{dw}{dt} \neq 0$

Fine Tuning Problem, Fifth Force Problem, no such scalar field from particle physics

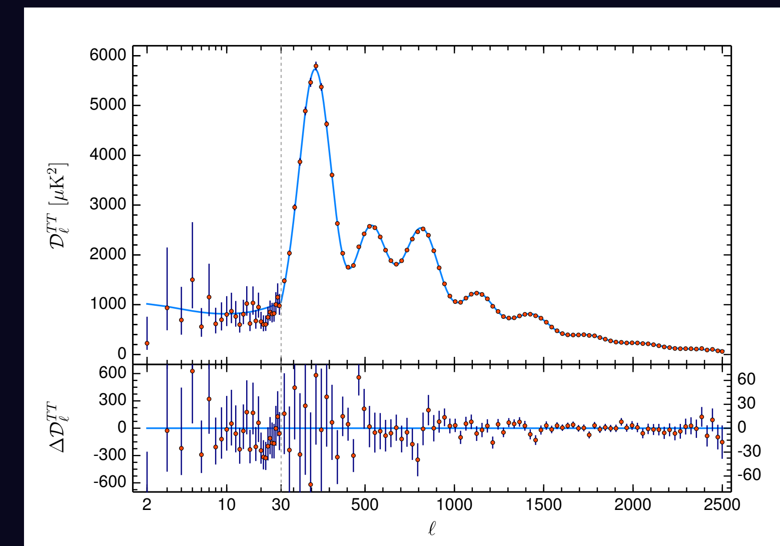
3) Modified Gravity Models: Modification of GR at Large Cosmological Scales

Tightly constrained by recent Gravitational Wave measurements by LIGO
Severely Constrained by Local Measurements, e.g Solar System Constraints

Universe After Planck-2018



Aghanim et al, 1807.06209



Six Parameter Concordance ΛCDM model is exceptionally good fit to the Planck data.

CMB+BAO+SnIA

Six Parameters

$$\Omega_b h^2 = 0.02233 \pm 0.00015$$

$$\Omega_c h^2 = 0.1198 \pm 0.0012$$

$$100\theta_{MC} = 1.04089 \pm 0.00031$$

$$\tau = 0.0540 \pm 0.0074$$

$$\ln(10^{10} A_s) = 3.043 \pm 0.014$$

$$n_s = 0.9652 \pm 0.0042$$

Derived Parameters

$$\Omega_m = 0.3147 \pm 0.0074$$

$$H_0 = 67.37 \pm 0.54 \ \ Km/sec/Mpc$$

$$\sigma_8 = 0.8101 \pm 0.0061$$

$$r_{drag} = 147.26 \pm 0.29 \ \ Mpc$$

$$z_{re} = 7.64 \pm 0.74$$

$$\Lambda = (2.846 \pm 0.076) \times 10^{-122} \ m_{pl}^2$$

No evidence for dark energy models beyond Cosmological Constant!!

How CMB Measures H_0 ?

Three Steps Process:

1) Calculate the Sound Horizon of Last Scattering surface of CMB:

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

z^* = Redshift for recombination epoch

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

Depends on pre-recombination physics only

2) Infer the angular size of the sound horizon from the peak spacing in CMB:

$$\theta = \pi/\Delta l$$

3)Calculate the Angular Diameter Distance for the Sound Horizon and infer H(z) :

$$D_A = \frac{r_s}{\theta} = \frac{1}{(1+z*)} \int_0^{z*} \frac{dz}{H(z)}$$

→ Extrapolate H(z) to z=0 and get H_0

In this step, one needs a late time model and Planck uses ΛCDM

How Local Measurements Determine H_0

Hubble already told us: $cz = H_0 d$ + peculiar velocity

Redshift measurements are dominated by peculiar velocities.

To get rid of peculiar velocity effect, one needs go far away.

Distance measurements are more reliable for nearby astrophysical objects.

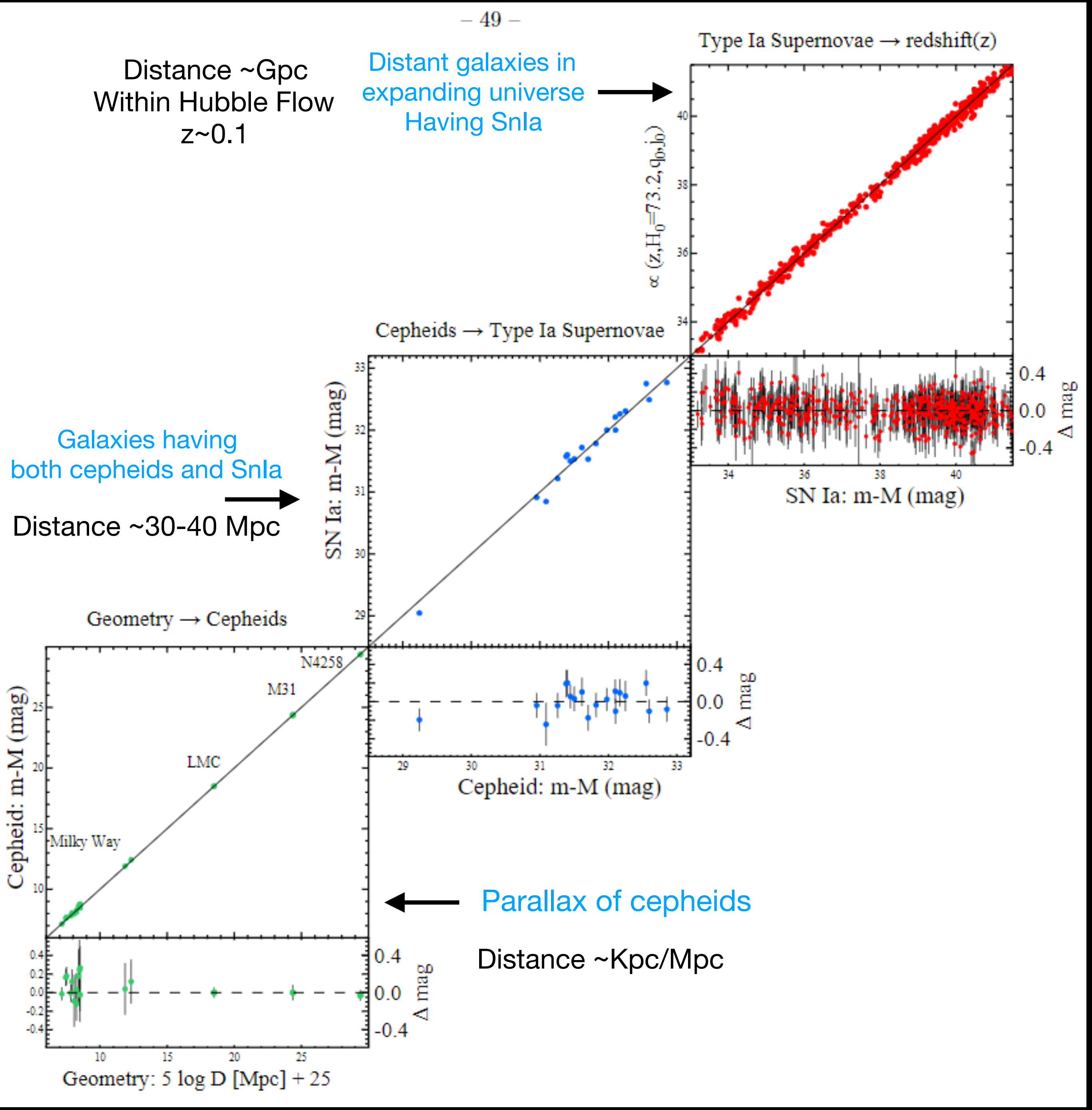
One needs to connect the two

Cosmic Distance Ladder

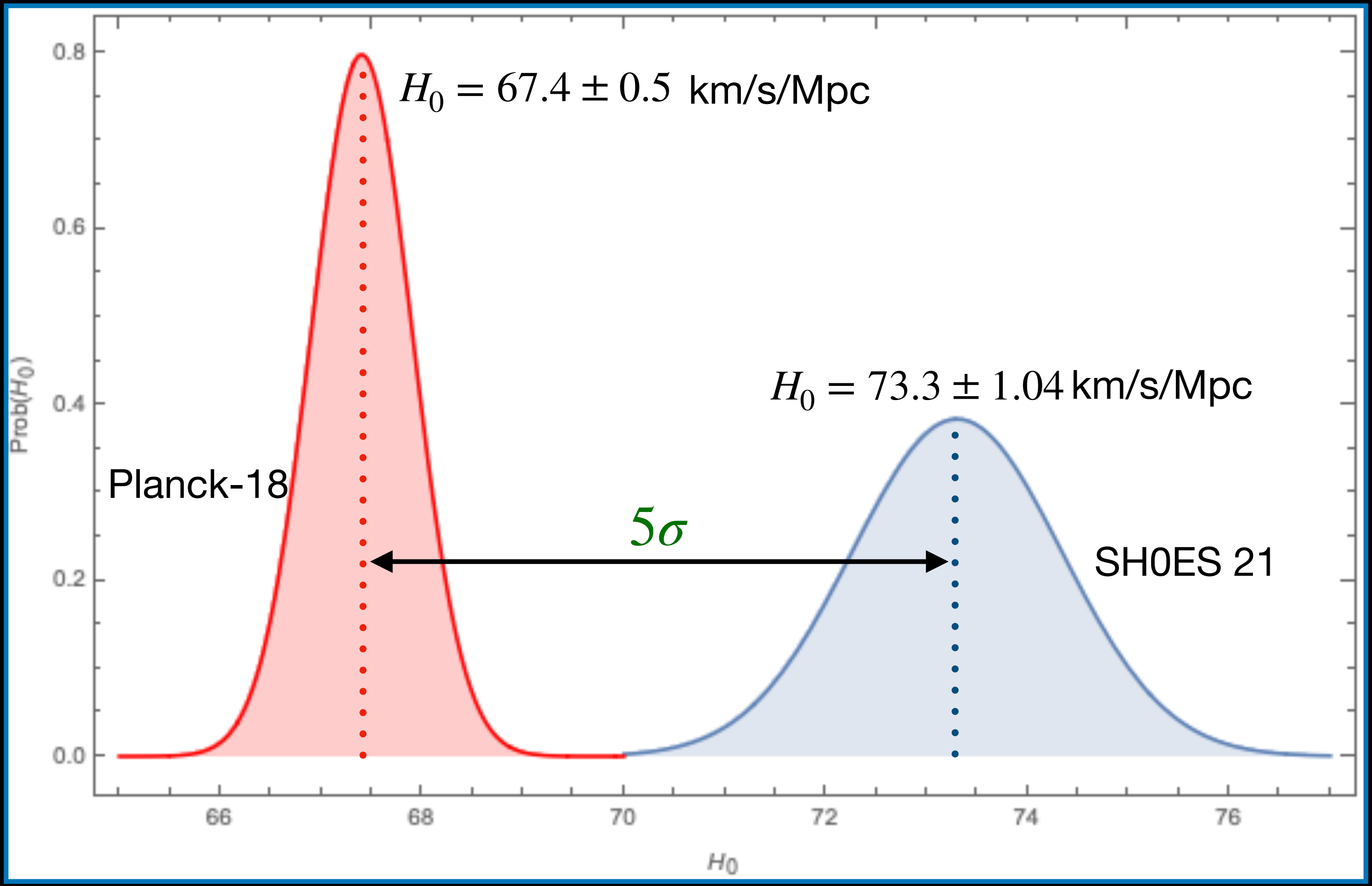
$H_0 = 73.30 \pm 1.04 Km/s/Mpc$

Riess et al: 2112.04510

SH0ES:1604.01424



Hubble Tension



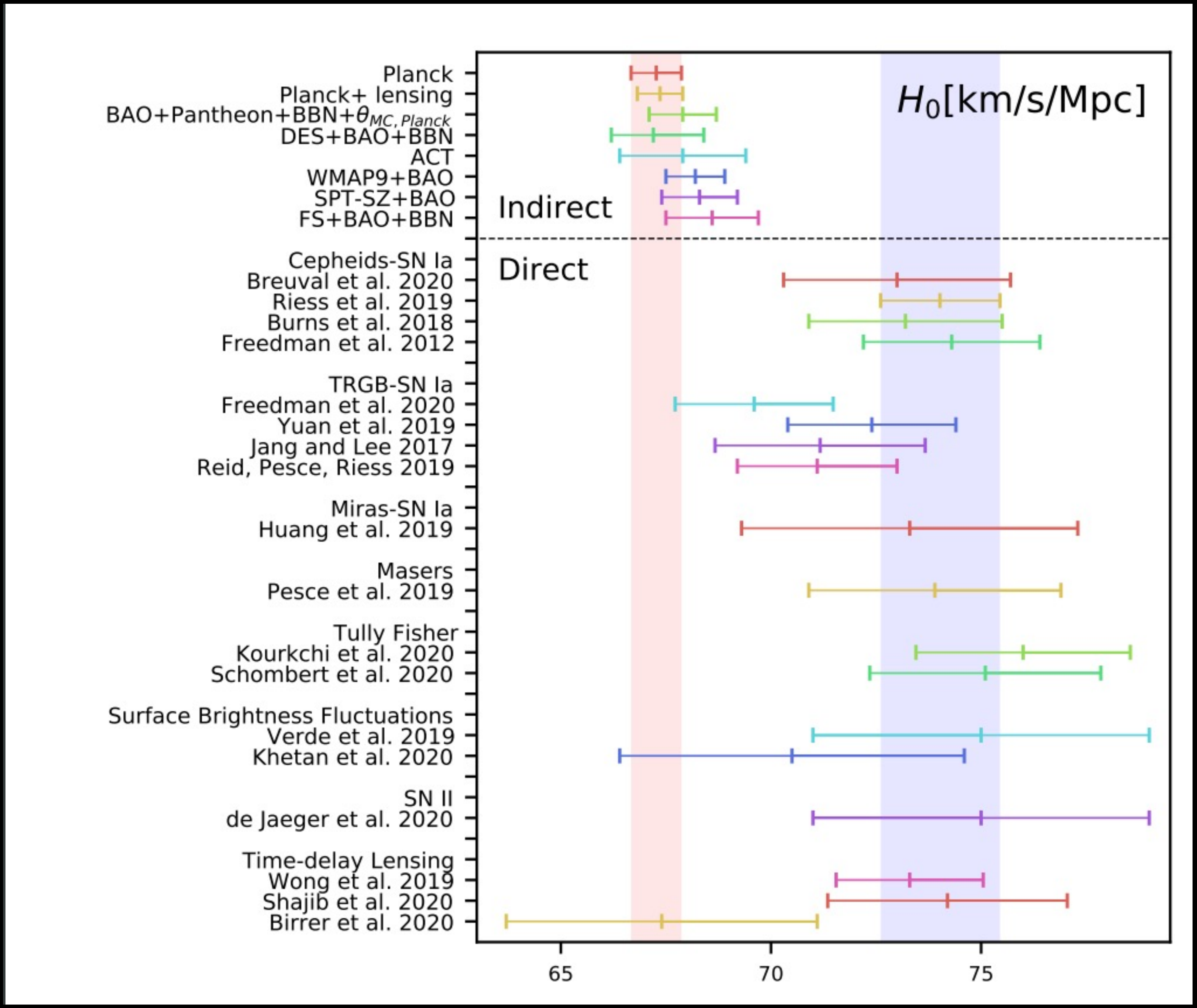
Note: Planck measurement of H_0 is bases on Physics of Early Universe

SH0ES measurement of H_0 is bases on Astrophysics of Stars

Two are separated by 13.4 Gyr.

Still two measurements agree within 10% which is remarkable!!

Hubble Tension



Di Valentino et al: arXiv:2103.01183

Tension Related To LSS

Constraints on strength of Clustering of Matter

This tension is quantified using the parameter S_8:

$$S_8 = \sigma_8[(\Omega_{m0}/0.3)]^{1/2}$$

For ΛCDM:

$S_8 = 0.832 \pm 0.013$ **Planck-2018+CMB-Lensing**

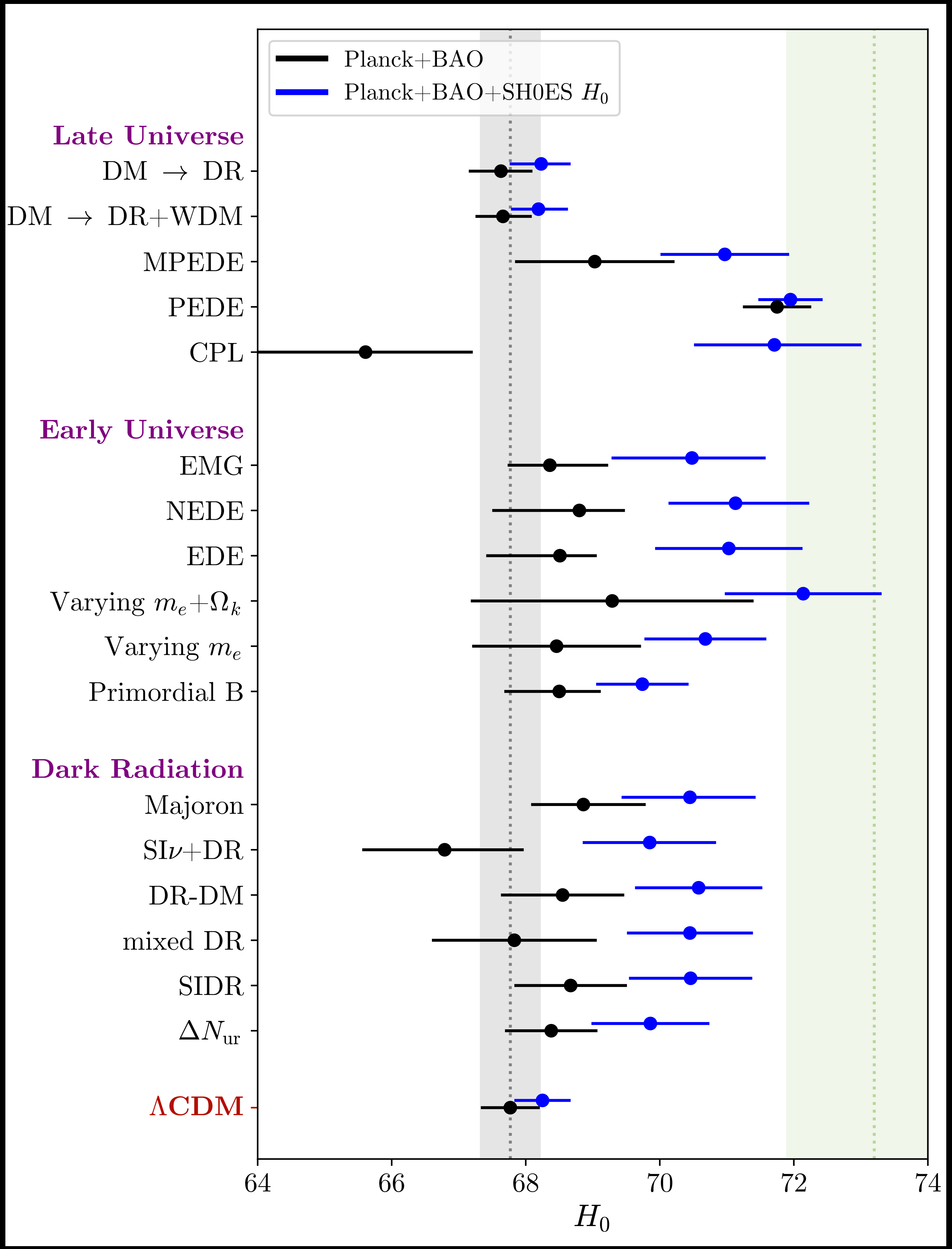
$S_8 = 0.759^{+0.024}_{-0.021}$ **Weak Lensing by KiDS-1000**

Asgari et al arXiv:2007.15633

~ 3σ Tension!!

Possible Solution

Schoneberg et al
arXiv:2107.10291



Possible Solution

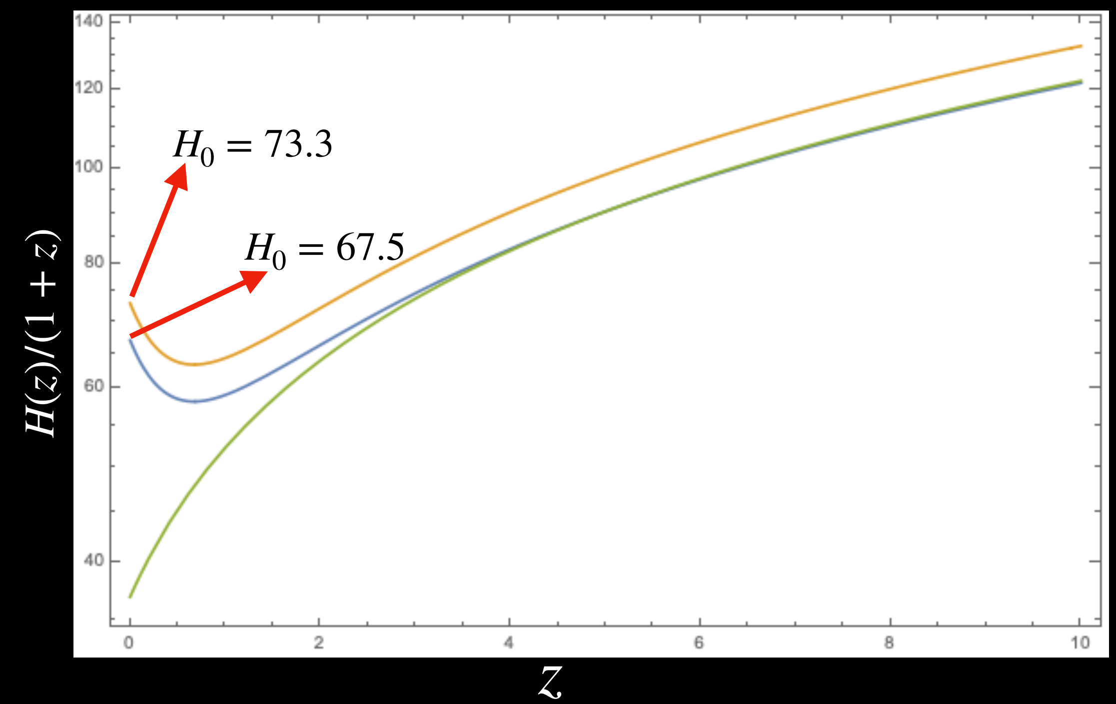
$H(z) = H_0 E(z)$ ⟶ Late time DE model

$$E(z) = \sqrt{\Omega_{m0}(1+z)^3 + f(z)}$$

$$D_A(z^*) = \frac{1}{(1+z^*)}\int_0^{z^*}\frac{dz}{H(z)} = \frac{1}{(1+z^*)}\frac{1}{H_0}\int_0^{z^*}\frac{dz}{E(z)}$$

$$r_s = \int_{z^*}^{\infty}\frac{dz}{H(z)}c_s(z) \qquad c_s = \frac{1}{\sqrt{3(1+3\Omega_b/\Omega_r)}}$$

⟶ Pre-Recombination Physics



$$\theta = \frac{r_s}{D_A}$$ ⟶ Fixed

Early Time Solution (no change in late time physics) : E(z) remains same

H_0 increases —> D_A decreases —> r_s decreases —> ***pre-recombination period H(z) increases***

Early Dark Energy Solution

- Poulin et al [1811.04083]

H_0 increases —> D_A decreases —> r_s decreases —> ***pre-recombination period H(z) increases***

Introducing an Early Dark Energy before recombination which decays quickly later

Model: Dissipated Axion Field

$$V(\phi) = V_0(1 - cos\phi)^n$$

$$\ddot{\phi} + (3H + \Gamma(z))\dot{\phi} + V'(\phi) = 0$$

$$\dot{\rho_{rad}} + 4H\rho_{rad} = \Gamma\dot{\phi}^2$$

Disadvantages:

Highly Fine-Tuned
Not consistent with LSS data

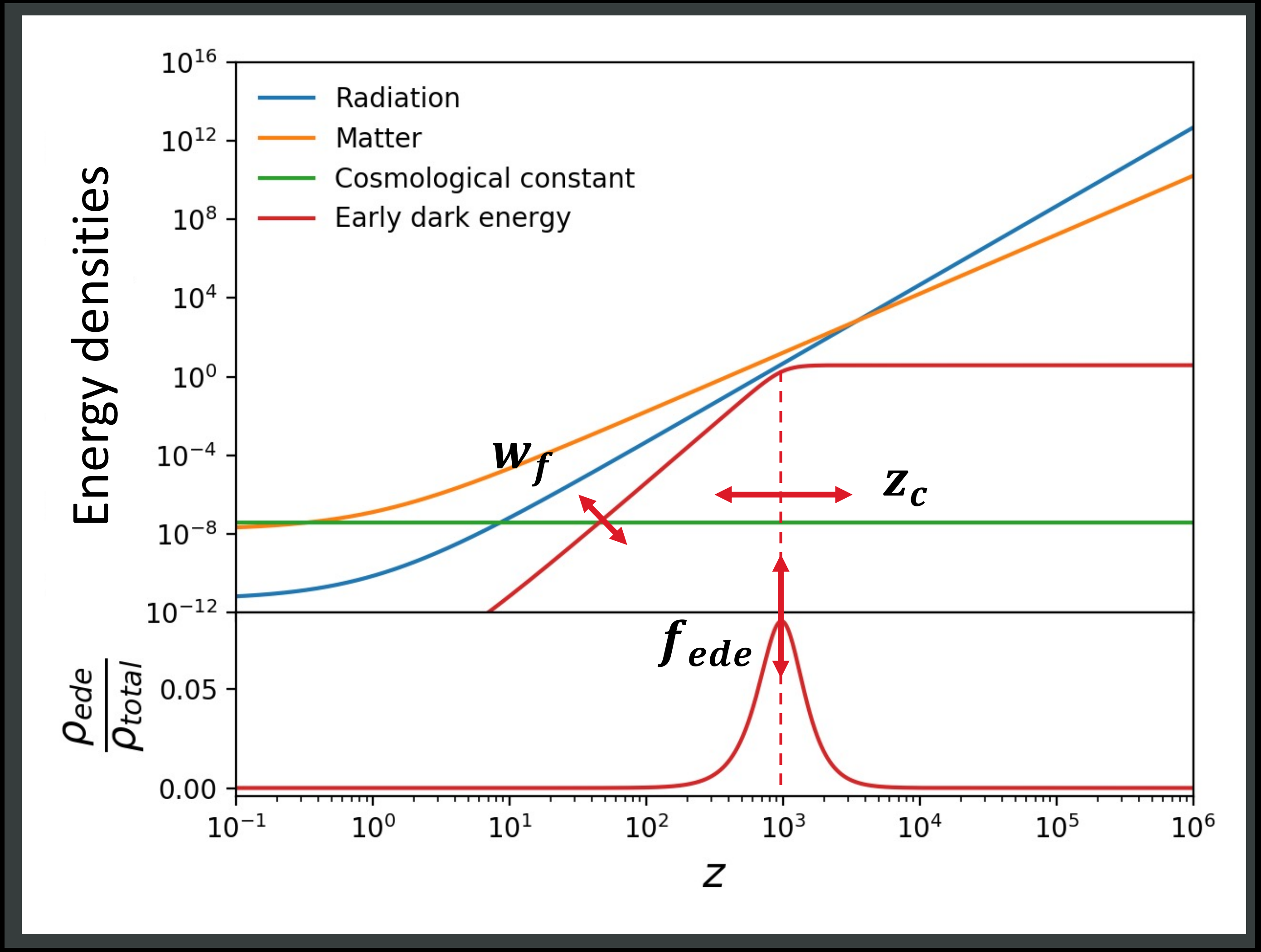


Image Credit: T. Karwal

Possible Solution

Late Time Solution (no change in pre-recombination physics) : r_s remains same ⟶ D_A should not change

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

$$E(z) = \sqrt{\Omega_{m0}(1+z)^3 + f(z)}$$

$$D_A(z) = \frac{1}{(1+z^*)}\int_0^{z^*}\frac{dz}{H(z)} = \frac{1}{(1+z^*)}\frac{1}{H_0}\int_0^{z^*}\frac{dz}{E(z)} \longrightarrow A(z)$$

H_0 increases —> D_A remains the same —> A(z) increases —> ***Modification in late-time evolution***

For a Constant DE EOS $\quad f(z) \propto (1+z)^{3(1+w)}$

E(z) decreases —> (1+w) < 0 —> Phantom DE

Another Interesting Late-Time Modification

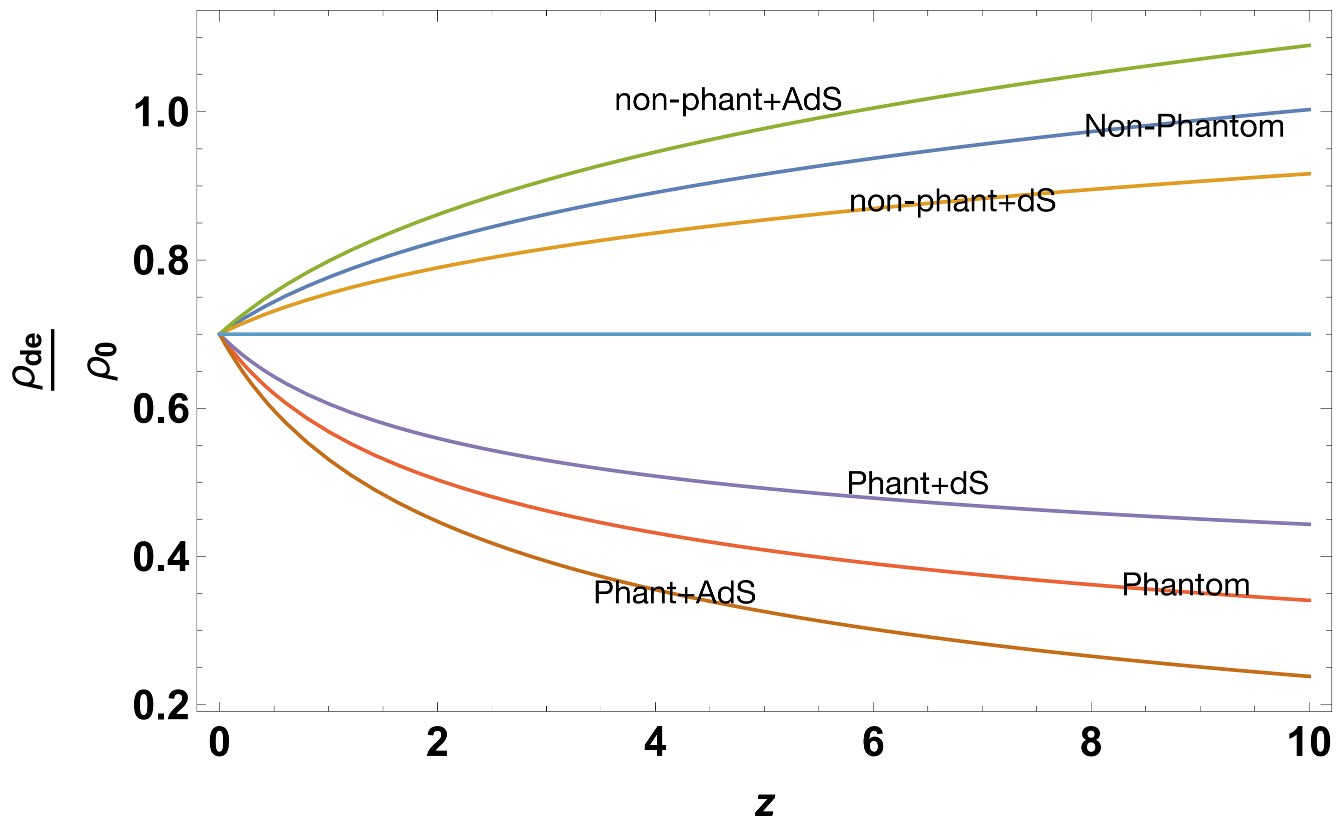
Let's Add An Extra Cosmological Constant in Energy Budget:

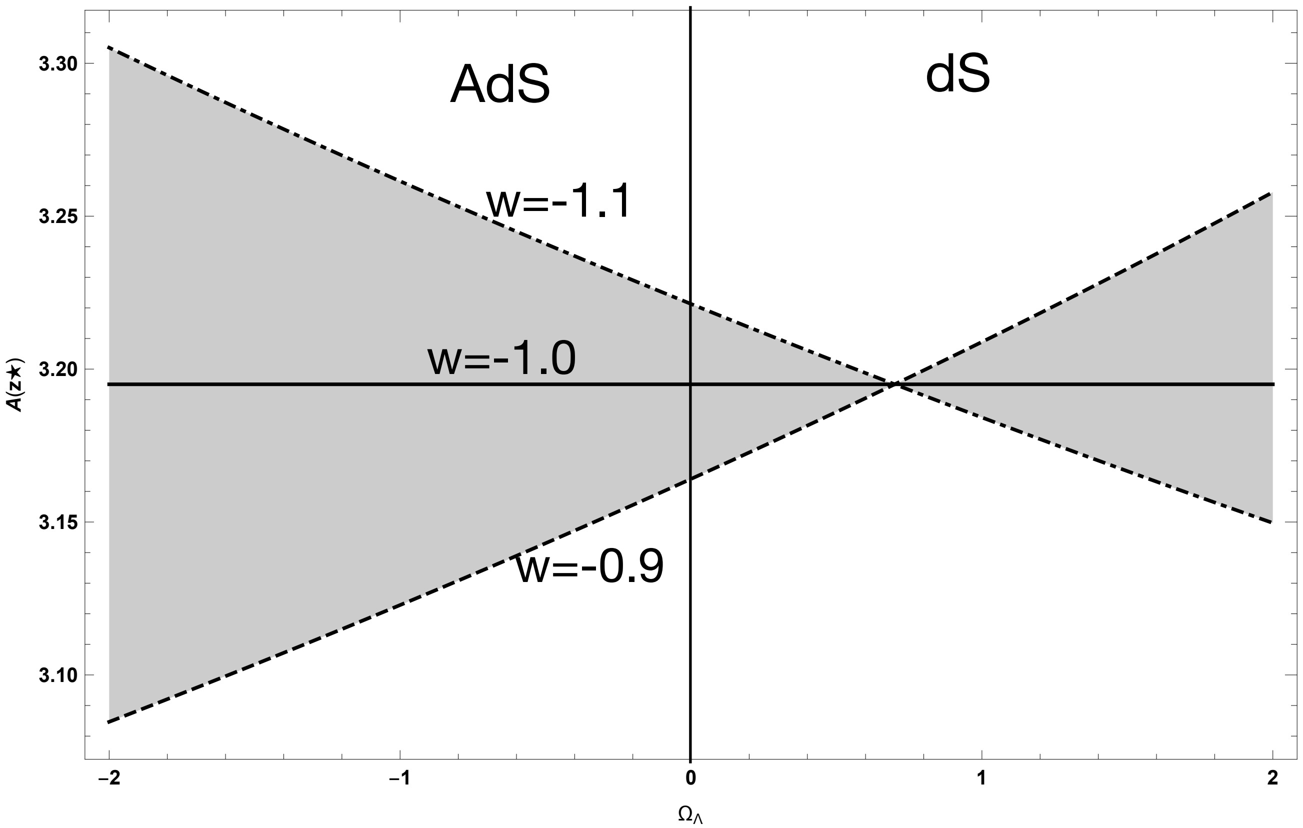
$$E(z) = [\Omega_{m0}(1+z)^3 + (1-\Omega_{m0}-\Omega_{\Lambda 0})(1+z)^{3(1+w)} + \Omega_{\Lambda 0}]^{1/2}$$

This is same as adding a non-zero cosmological constant for the Scalar field potential:

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

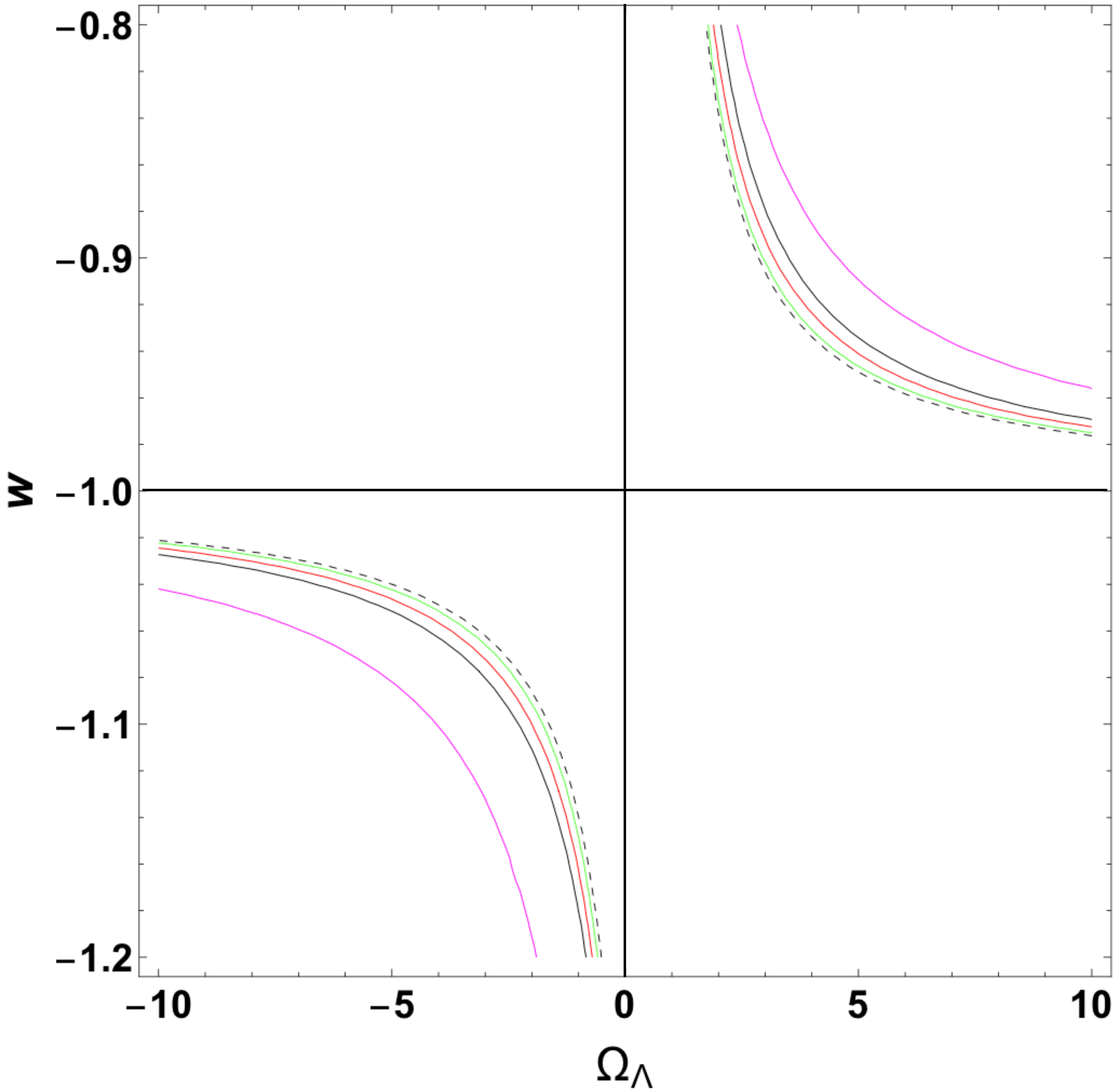
V_0 can be both positive (dS) or negative (AdS)





Another Interesting Late-Time Modification

Find out what is the possible combinations for (w-Ω_Λ) that give identical BAO/CMB/SnIa measurements as ΛCDM by Planck but with H_0 = 72 km/s/Mpc.



Black,Red, Green —> D_A from BOSSDR12 (z=0.38,0.51,0.61)
Pink —> D_A from CMB Last Scattering Surface (z=1100)
Dashed —> D_L From SnIa (z=0.5)

Do Observations give hint for -Λ?

Consider the relevant cosmological data (AAS, Adil, Sen, arXiv:2112.10641, To Appear in MNRAS)

CMB by Planck
BAO data from LSS
SnIa data Pantheon
SH0ES data for H_0

Which one is preferred: DE with dS or AdS ground state or ΛCDM?

Evolving Dark Energy: **Scalar Field rolling over a potential**

→ with dS/AdS minimum

$\rho_{de} = \rho_\phi + \Lambda$ ($\Lambda > 0$ or $\Lambda < 0$)

Instead of any particular scalar field potential, we use two most popular parameterisations for the scalar field equation of states for ρ_ϕ :

w_ϕ = constant → wCDMCC

$w_\phi = w_0 + (1 - a)w_a$ → cplCDMCC

Do Observations give hint for -Λ?

For wCDMCC

Parameters	CMB	CMB+BAO	CMB+BAO+H_0
Ω_m	(0.215) $0.200^{+0.049}_{-0.068}$	(0.2956)0.304 ± 0.012	(0.2793)0.2791 ± 0.0065
H_0(km/s/Mpc)	(81.43)$87.2^{+9.6}_{-16}$	(69.6) $68.5^{+1.3}_{-1.5}$	(71.62)71.66 ± 0.85
r_d	(147.2) 147.20 ± 0.38	(147)147.17 ± 0.22	(147)147.01 ± 0.22
σ_8	(0.936)$0.970^{+0.085}_{-0.11}$	(0.8335)0.818 ± 0.015	(0.8525)0.853 ± 0.011
τ_{re}	(0.05548)0.0550 ± 0.0025	(0.05494)0.0549 ± 0.0026	(0.05492)0.0541 ± 0.0026
Ω_ϕ	(6.63) $2.80^{+0.17}_{-2.3}$	(1.584)$1.86^{+0.46}_{-1.3}$	(1.539)$1.58^{+0.16}_{-0.87}$
w_0	(−1.035) −1.47 ± 0.51	(−1.034)$-1.017^{+0.030}_{-0.015}$	(−1.061)$-1.072^{+0.037}_{-0.015}$
Ω_Λ	(−5.845)$-2.00^{+2.5}_{-0.18}$	(−0.8801) $-1.17^{+1.3}_{-0.46}$	(−0.8182)$-0.86^{+0.87}_{-0.16}$
Ω_{de}	(0.7849)$0.7999^{+0.068}_{-0.049}$	(0.7043) $0.6959^{+0.012}_{-0.012}$	(0.7206)$0.7208^{+0.0065}_{-0.0065}$

CMB+BAO+H_0

Model	χ^2	AIC	$ln\,(z)$	ΔAIC	$\Delta ln\,(z)$
ΛCDM	2803.04	2869.04	-1427.829	0	0
wCDMCC	2782.40	2852.40	-1420.259	-16.64	7.561

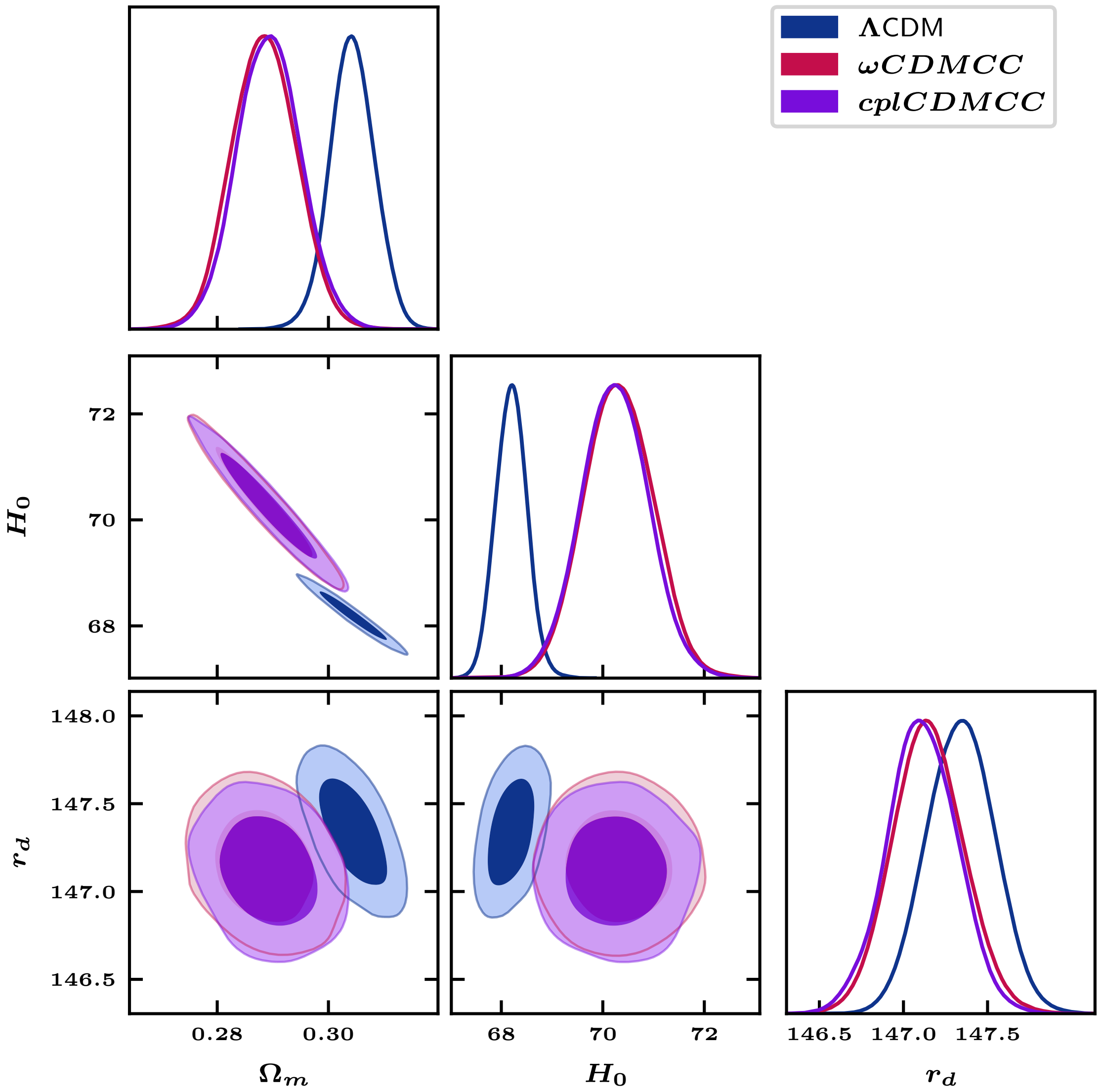
Does SH0ES result give hint for -Λ?

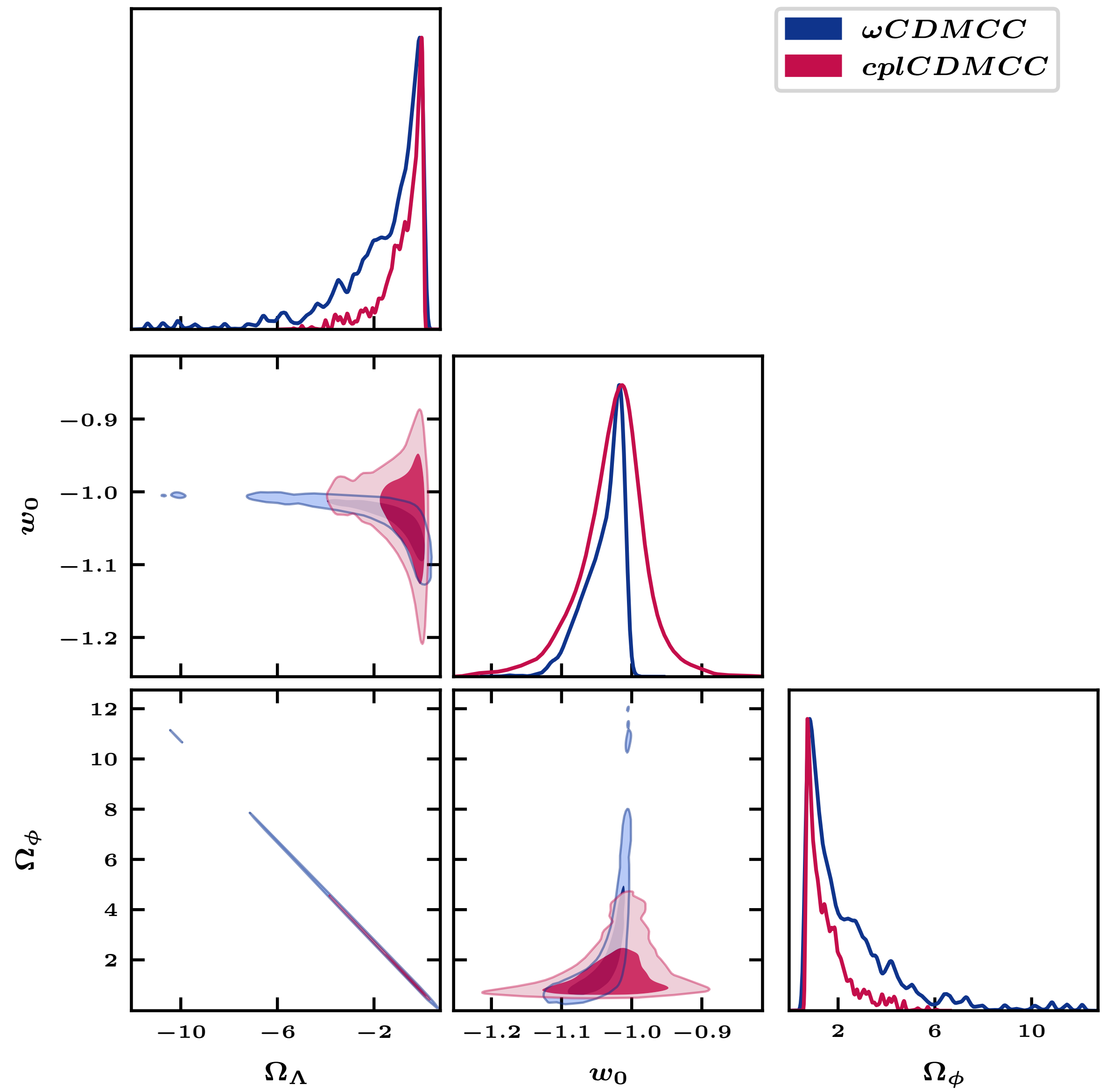
Parameters	ΛCDM	wCDMCC	cplCDMCC
Ω_m	$(0.303)0.304^{+0.0039}_{-0.0042}$	$(0.287)0.288^{+0.0063}_{-0.0071}$	$(0.292)0.289^{+0.0055}_{-0.0061}$
$H_0(km/s/Mpc)$	$(68.32)68.2^{+0.31}_{-0.32}$	$(70.34)70.32^{+0.82}_{-0.77}$	$(69.89)70.25^{+0.67}_{-0.69}$
r_d	$(147.2)147.3^{+0.2}_{-0.22}$	$(147.3)147.1^{+0.21}_{-0.22}$	$(147.2)147.1^{+0.2}_{-0.21}$
σ_8	$(0.804)0.805^{+0.0026}_{-0.0026}$	$(0.833)0.834^{+0.0096}_{-0.0097}$	$(0.835)0.835^{+0.0086}_{-0.0088}$
τ_{re}	$(0.0548)0.0556^{+0.0025}_{-0.0026}$	$(0.0554)0.0547^{+0.0028}_{-0.0025}$	$(0.0542)0.0547^{+0.0026}_{-0.0027}$
Ω_ϕ	–	$(3.191)\ 2.504^{+0.28}_{-1.9}$	$(1.206)\ 1.492^{+0.025}_{-0.84}$
Ω_Λ	–	$(-2.479)-1.792^{+1.90}_{-0.29}$	$(-0.498)-0.781^{+0.85}_{-0.03}$
w_0	-	$(-1.02)-1.04^{+0.035}_{-0.013}$	$(-1.02)-1.03^{+0.051}_{-0.039}$
w_a	-	-	$(-0.12)-0.10^{+0.20}_{-0.14}$

CMB+BAO+SN+H_0

Model	χ^2	AIC	$ln(z)$	ΔAIC	$\Delta ln(z)$
ΛCDM	3835.73	3901.73	-1944.75	0	0
wCDMCC	3823.58	3893.58	-1940.96	-8.15	+3.79
cplCDMCC	3824.29	3896.29	-1942.82	-5.44	+1.93

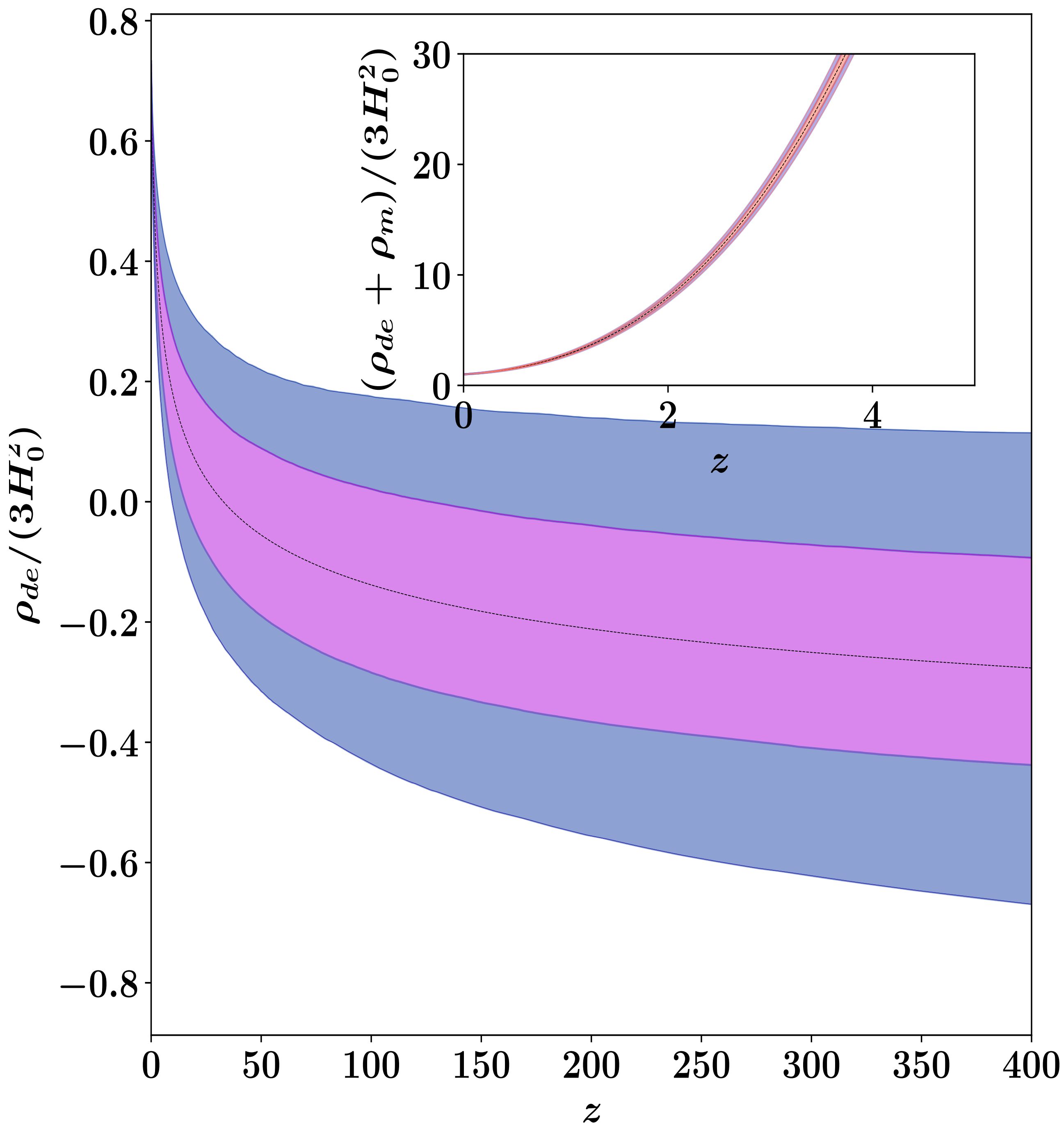
Does SH0ES result give hint for -Λ?





CMB+BAO+SN+H_0

Does SH0ES result give hint for -Λ?



$$\frac{d\rho_{de}}{dz} < 0$$

Energy Conservation eqn:

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

$$\rho_{de} < 0 \rightarrow (1+w_{de}) > 0$$

$$\rho_{de} > 0 \rightarrow (1+w_{de}) < 0$$

Phantom Crossing !!

What Happens When We Take A Scalar Field?

One Possible Scalar field model from Axion:

$$V(\phi) = V_0[1 + pCos(\frac{\phi}{f})]$$

Cicoli et al (2019)

p > 1 ⟶ AdS minimum

p < 1 ⟶ dS minimum

But the EOS is always non-phantom: w > -1

Ruchika, Adil, Dutta, Mukherjee, AAS, ArXiv:2005.08813

CMB by Planck (Compressed Likelihood involving Shift Parameter and Acoustic Scale)
BAO data from LSS
SnIa data Pantheon
Cosmic Chronometer data for H(z)
SH0ES data for H_0
Growth Data ($f\sigma_8$)
H0LiCOW data for Strong Lensing

What Happens When We Take A Scalar Field?

	Model	χ^2
	P <1	80.10
All Data - H_0 -CMB	P >1	80.34
	ΛCDM	88.93

	Model	χ^2
	P <1	81.29
All Data - H_0	P >1	81.59
	ΛCDM	90.58

No. Of Parameters for ΛCDM = 5
No of Parameters for P <1, P >1 = 8

	Model	χ^2
	P <1	84.69
All Data - CMB	P >1	84.63
	ΛCDM	98.49

	Model	χ^2
	P <1	86.33
All Data	P >1	86.32
	ΛCDM	104.87

What Happens When We Take A Scalar Field?

	Model	χ^2	No. Of parameters	AIC	ΔAIC	Ln Z	ΔLn Z
	P <1	86.33	8	102.33	-12.56	-64.95	2.6
All Data	P >1	86.32	8	102.32	-12.55	-64.81	2.7
	ΛCDM	104.87	5	114.87	— —	-67.54	— —

For Both P <1 and P >1

$H_0 = 71.3 \pm 0.0039$ km/s/Mpc

$\sigma_8 = 0.75 \pm 0.022$

$\Omega_{m0} = 0.298 \pm 0.007$

Consequence of -Λ?

End of Expansion

Andrei, Ijjas and Steinhardt

arXiv: 2201:07704

If dark energy is a form of quintessence driven by a scalar field ϕ evolving down a monotonically decreasing potential $V(\phi)$ that passes sufficiently below zero, the universe is destined to undergo a series of smooth transitions: the currently observed accelerated expansion will cease; soon thereafter, expansion will come to end altogether; and the universe will pass into a phase of slow contraction. In this paper, we consider how short the remaining period of expansion can be given current observational constraints on dark energy. We also discuss how this scenario fits naturally with cyclic cosmologies and recent conjectures about quantum gravity.

Conclusion

1) **The ΛCDM seems to be in Serious Trouble:** Now the tension between Local measurement and CMB measurement has reached 5σ.

2) Beyond ΛCDM model is certainly needed if Hubble tension is indeed valid.

3) Whether the new physics is at E**arly Universe (Pre-Recombination) or at Late Universe?**

4) Both are exciting but still not fully understood

5) Need to reconcile with the other data like LSS

6) May be a **Combination of Two** is the best possible solution, but still no work in that direction

7) Till now, ΛCDM is the best possible scenario. For scalar fields, potentials with zero minimum (no extra Λ) is considered.

8) But allowing a dS/AdS minima can change the situation drastically.

9) With the inclusion of Local Measurement for H_0, it seems fields with AdS minima may be a viable option for DE.

10) If the existence of negative Λ is confirmed, that will be truly exciting from both theoretical and observational point of view.

Thank You

Phantom Crossing Model

Phenomenological Phantom Crossing DE model: Valentino, Mukherjee, AAS arXiv:2005.12587

$$\rho_{de}(z) = \rho_0[1 + \alpha(a - a_m)^2 + \beta(a - a_m)^3]$$

$a = a_m$ there is an extrema

Drawback:
S_8 not consistent with LSS

Parameters	CMB+Lensing	CMB+R19	CMB+BAO	CMB+Pantheon	CMB+All
a_m	< 0.276	> 0.830	0.859 ± 0.064	$0.917^{+0.054}_{-0.029}$	$0.851^{+0.048}_{-0.031}$
α	< 17.7	< 8.62	7.3 ± 3.9	< 5.10	< 3.32
β	< 16.7	16.0 ± 7.5	16.1 ± 7.8	$10.6^{+4.4}_{-7.9}$	$7.7^{+2.2}_{-4.7}$
$\Omega_c h^2$	0.1194 ± 0.0014	0.1196 ± 0.0014	0.1201 ± 0.0013	0.1198 ± 0.0014	0.1198 ± 0.0011
$\Omega_b h^2$	0.02243 ± 0.00014	0.02243 ± 0.00016	0.02238 ± 0.00014	0.02240 ± 0.00015	0.02240 ± 0.00014
$100\theta_{MC}$	1.04097 ± 0.00031	1.04096 ± 0.00032	1.04092 ± 0.00030	1.04095 ± 0.00032	1.04093 ± 0.00030
τ	0.0521 ± 0.0076	0.0532 ± 0.0080	$0.0539^{+0.0070}_{-0.0080}$	0.0529 ± 0.0076	0.0521 ± 0.0075
n_s	0.9667 ± 0.0042	0.9665 ± 0.0045	0.9652 ± 0.0043	0.9659 ± 0.0045	0.9655 ± 0.0038
$\ln(10^{10} A_s)$	3.038 ± 0.015	3.041 ± 0.016	3.044 ± 0.016	3.041 ± 0.016	3.039 ± 0.015
H_0[km/s/Mpc]	> 92.8	74.2 ± 1.4	$71.0^{+2.9}_{-3.8}$	$71.7^{+2.2}_{-3.1}$	70.25 ± 0.78
σ_8	$1.012^{+0.051}_{-0.009}$	0.881 ± 0.018	$0.848^{+0.027}_{-0.034}$	$0.860^{+0.026}_{-0.033}$	0.838 ± 0.011
S_8	$0.752^{+0.009}_{-0.025}$	0.818 ± 0.016	0.826 ± 0.019	0.828 ± 0.016	0.823 ± 0.011
r_{drag}	$147.19^{+0.28}_{-0.26}$	147.14 ± 0.30	147.06 ± 0.29	147.10 ± 0.30	147.10 ± 0.25

ΛCDM	CMB+Lensing	CMB+R19	CMB+BAO	CMB+Pantheon	CMB+All
$\chi^2_{bf,tot}$	2782.040	2791.838	2779.712	3807.500	3840.406
$\chi^2_{bf,CMB}$	2778.122	2768.113	2770.060	2767.697	2779.508
$\chi^2_{bf,lensing}$	8.981	–	–	–	9.510
$\chi^2_{bf,R19}$	–	18.117	–	–	16.414
$\chi^2_{bf,BAO}$	–	–	6.514	–	5.271
$\chi^2_{bf,Pantheon}$	–	–	–	1035.268	1034.768
Phantom Crossing	**CMB+Lensing**	**CMB+R19**	**CMB+BAO**	**CMB+Pantheon**	**CMB+All**
$\chi^2_{bf,tot}$	2776.610	2765.556	2775.204	3805.278	3828.424
$\chi^2_{bf,CMB}$	2770.124	2762.965	2763.945	2765.943	2775.585
$\chi^2_{bf,lensing}$	8.145	–	–	–	8.702
$\chi^2_{bf,R19}$	–	0.307	–	–	8.275
$\chi^2_{bf,BAO}$	–	–	5.321	–	5.702
$\chi^2_{bf,Pantheon}$	–	–	–	1036.603	1035.971

Phantom Crossing Model

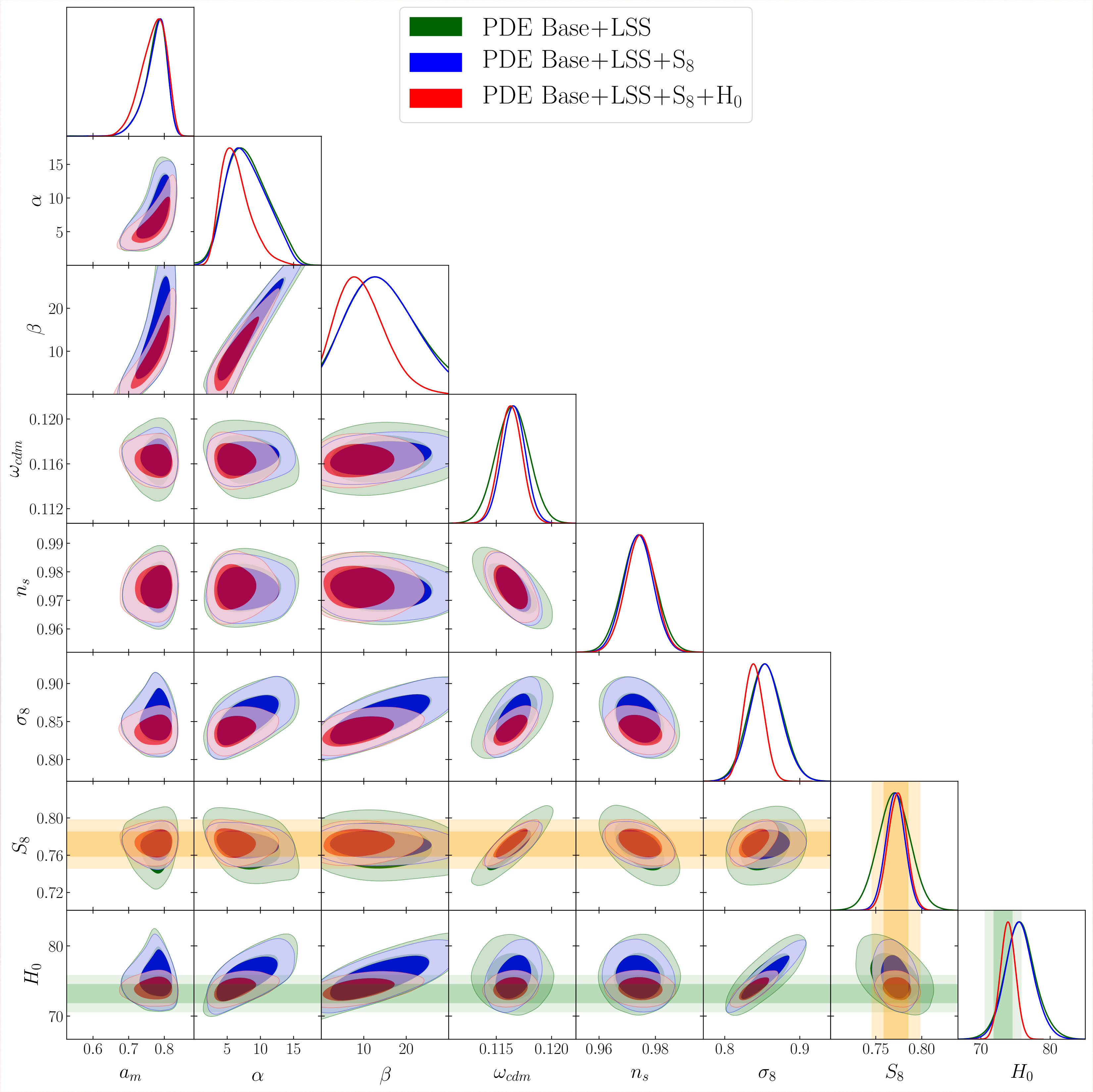
Updated Result with inclusion of
SPT-3G ($300 < l < 3000$) data
SPTPol measurement of $c_l^{\phi\phi}$ ($100 < l < 2000$)

	Phantom-crossing Dark Energy (PDE)		
Parameter	Base + LSS	Base + LSS + S_8	Base + LSS + S_8 + H_0
a_m	$0.774^{+0.037}_{-0.020}$	$0.774^{+0.038}_{-0.020}$	$0.773^{+0.044}_{-0.025}$
α	$8.2^{+2.6}_{-3.7}$	$8.0^{+2.5}_{-3.6}$	$6.5^{+1.6}_{-2.8}$
β	$14.2^{+6.7}_{-8.7}$	$14.1^{+6.8}_{-8.4}$	$10.2^{+4.5}_{-6.9}$
$100\,\omega_b$	2.246 ± 0.019	2.245 ± 0.018	2.246 ± 0.018
$10\,\omega_{cdm}$	1.165 ± 0.015	1.166 ± 0.011	1.163 ± 0.010
H_0	$75.70^{+2.05}_{-2.32}$	$75.60^{+1.93}_{-2.12}$	73.92 ± 1.09
τ	0.057 ± 0.005	0.057 ± 0.005	0.057 ± 0.005
$\ln(10^{10}A_s)$	3.038 ± 0.012	3.038 ± 0.011	3.037 ± 0.011
n_s	0.974 ± 0.006	0.974 ± 0.005	0.975 ± 0.005
$r_{\rm drag}$	$147. \pm 0.38$	147.91 ± 0.31	147.97 ± 0.30
Ω_m	0.244 ± 0.015	0.245 ± 0.013	0.255 ± 0.007
σ_8	0.854 ± 0.022	0.855 ± 0.021	0.839 ± 0.013
S_8	0.770 ± 0.017	0.771 ± 0.010	0.774 ± 0.010

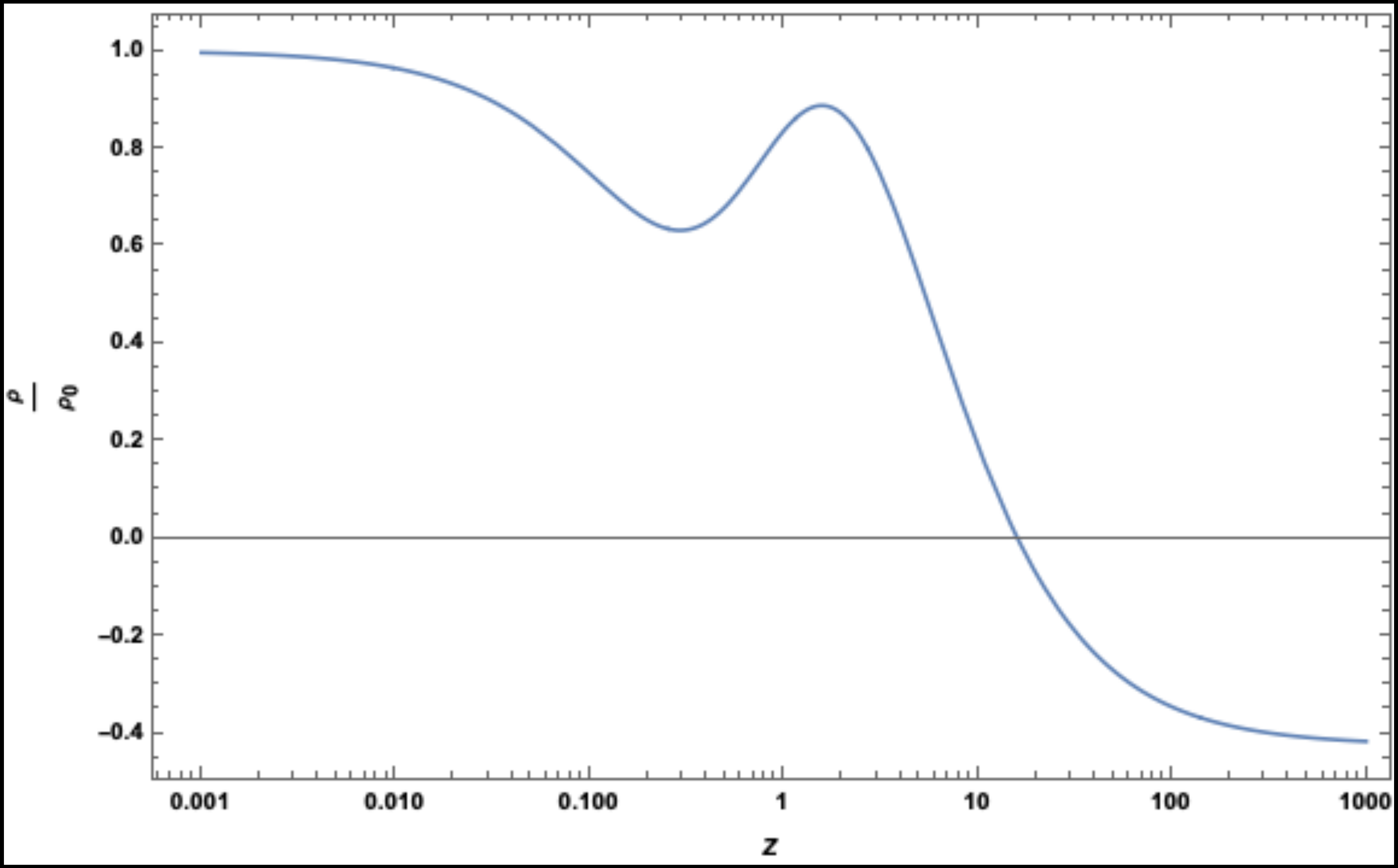
Both H_0 and S_8 Problems Solved in a Single Model Having Phantom Crossing.
Phantom Crossing Detected at 5σ (nonzero a_m parameter).

Chudaykin, Gorbunova and Nedelko : arXiv:2203.03666

Phantom Crossing Model



Phantom Crossing Model



The DE is surely have an AdS component