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The Low Redshifts-High Redshifts Tensions in Cosmological Observations and Its Possible Implications

XXIII DAE-BRNS-HEP Symposium

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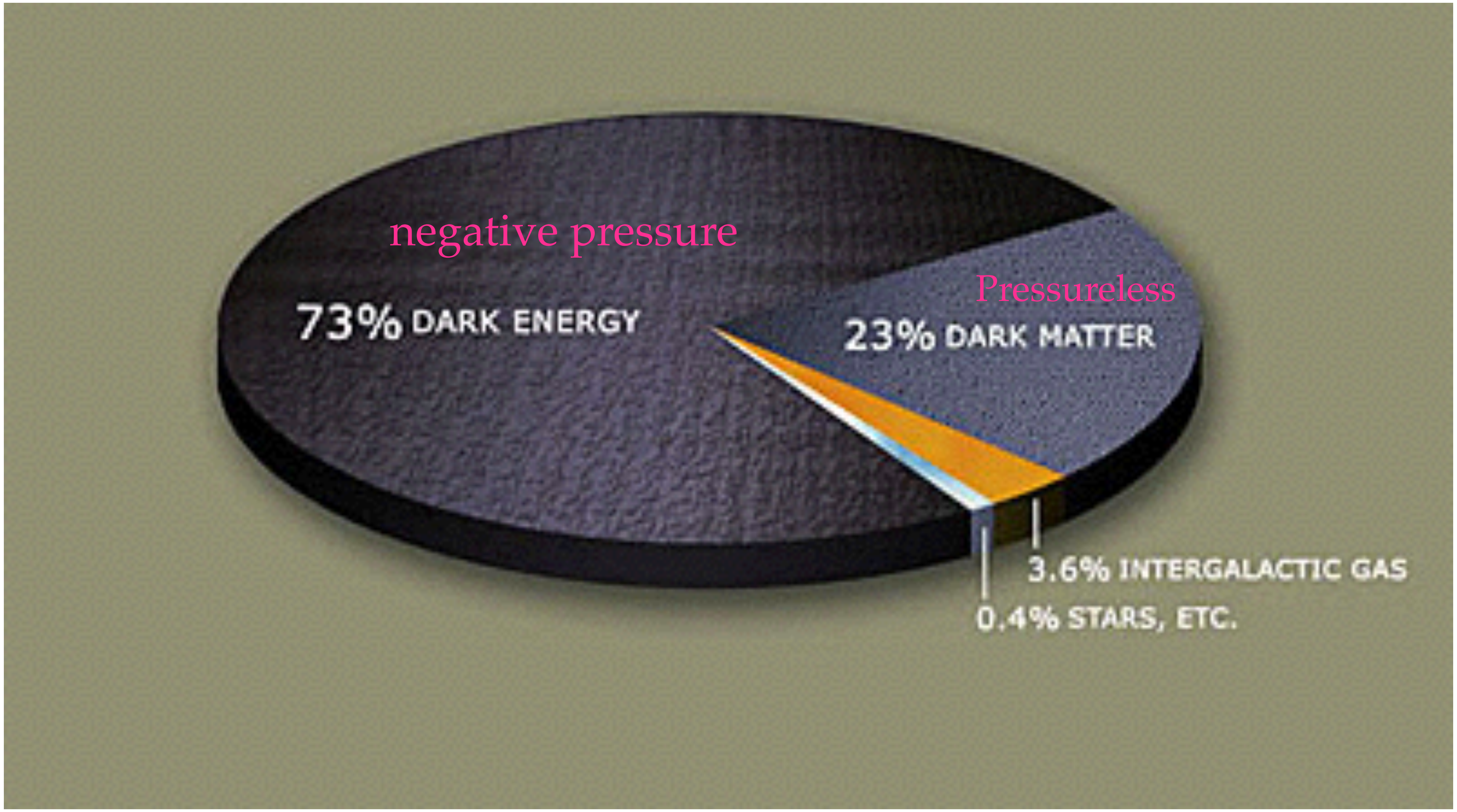
Plan

- Brief introduction on current tension between low-redshift and high-redshift observations.
- Model independent constraint on background evolution and dark energy evolution.
- Possible dark energy behaviour.
- Incorporating Planck results from CMB on background evolution.
- Effects on dark energy evolution.
- Conclusions

Universe Composition



Cosmology after Planck-2018

Concordance ΛCDM model (Aghanim et al. ArXiv: 1807.06209):

6-parameters model

- $\Omega_b h^2 = 0.02233 \pm 0.00015$
- $\Omega_c h^2 = 0.1198 \pm 0.0012$
- $100\theta_{MC} = 1.04089 \pm 0.00031$
- $\tau = 0.0540 \pm 0.0074$
- $\ln(10^{10} A_s) = 3.043 \pm 0.014$
- $n_s = 0.9652 \pm 0.0042$

Other Parameters

$\Omega_m = 0.3147 \pm 0.0074$

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

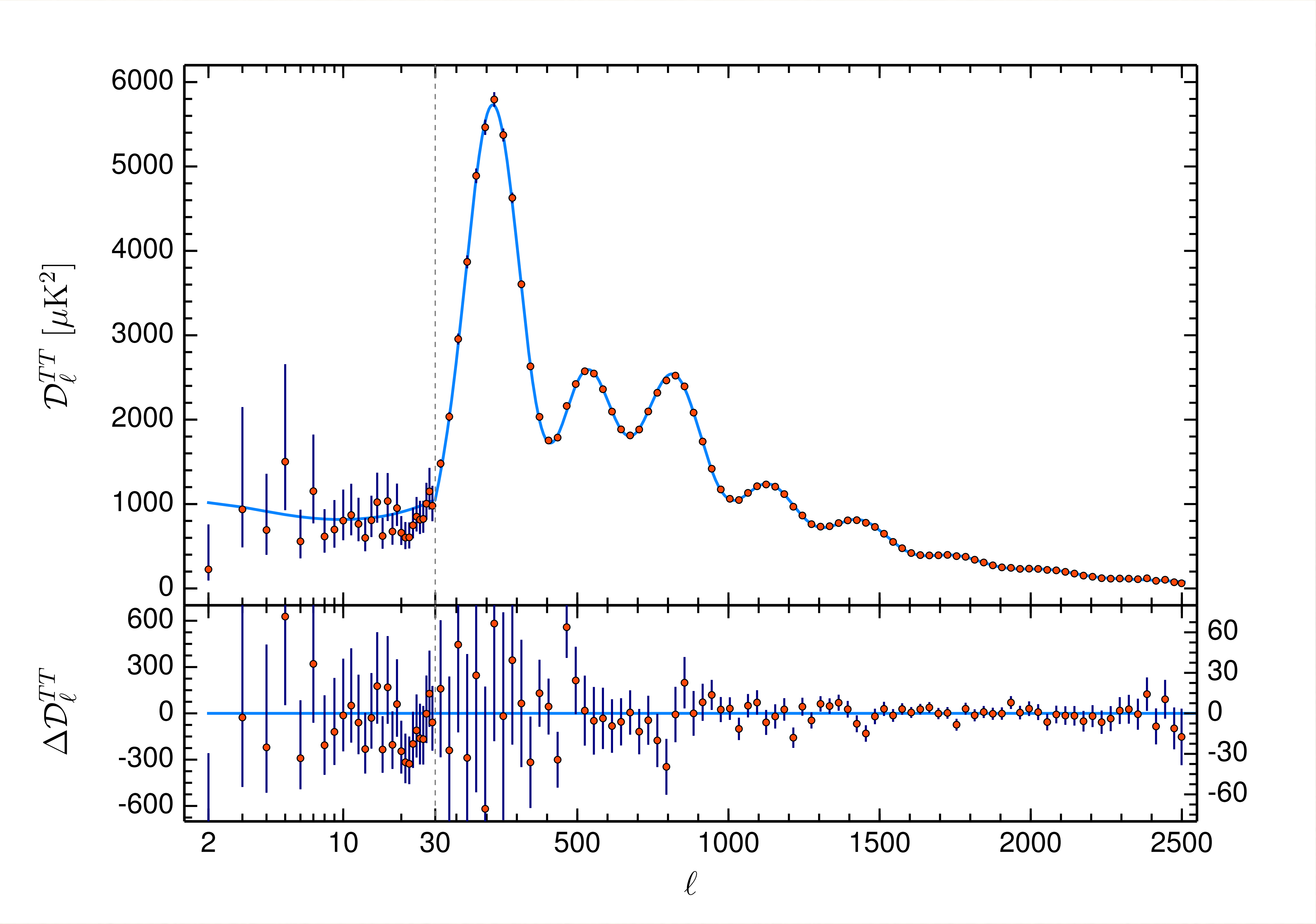
$\sigma_8 = 0.8101 \pm 0.0061$

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

$z_{re} = 7.64 \pm 0.74$

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

Planck Result 2018



Cosmology with Planck

- Going beyond ΛCDM, evolving dark energy with

$$w(z) = p(z)/\rho(z) = w_0 + w_a \frac{z}{1+z}$$ (CPL Parametrisation)

$$w(z) = -1 \; for \; \Lambda \; (w_0 = -1, w_a = 0)$$

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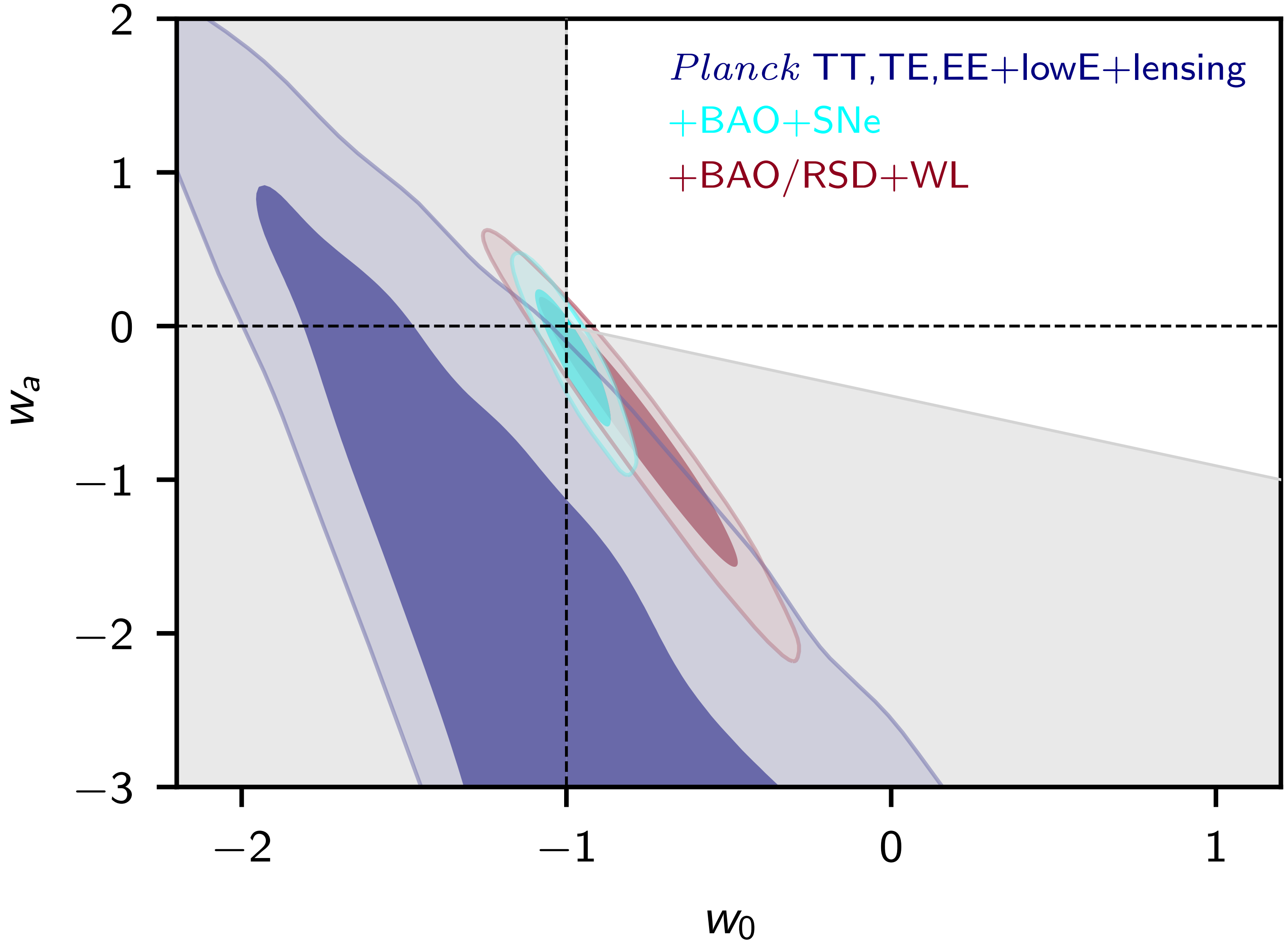

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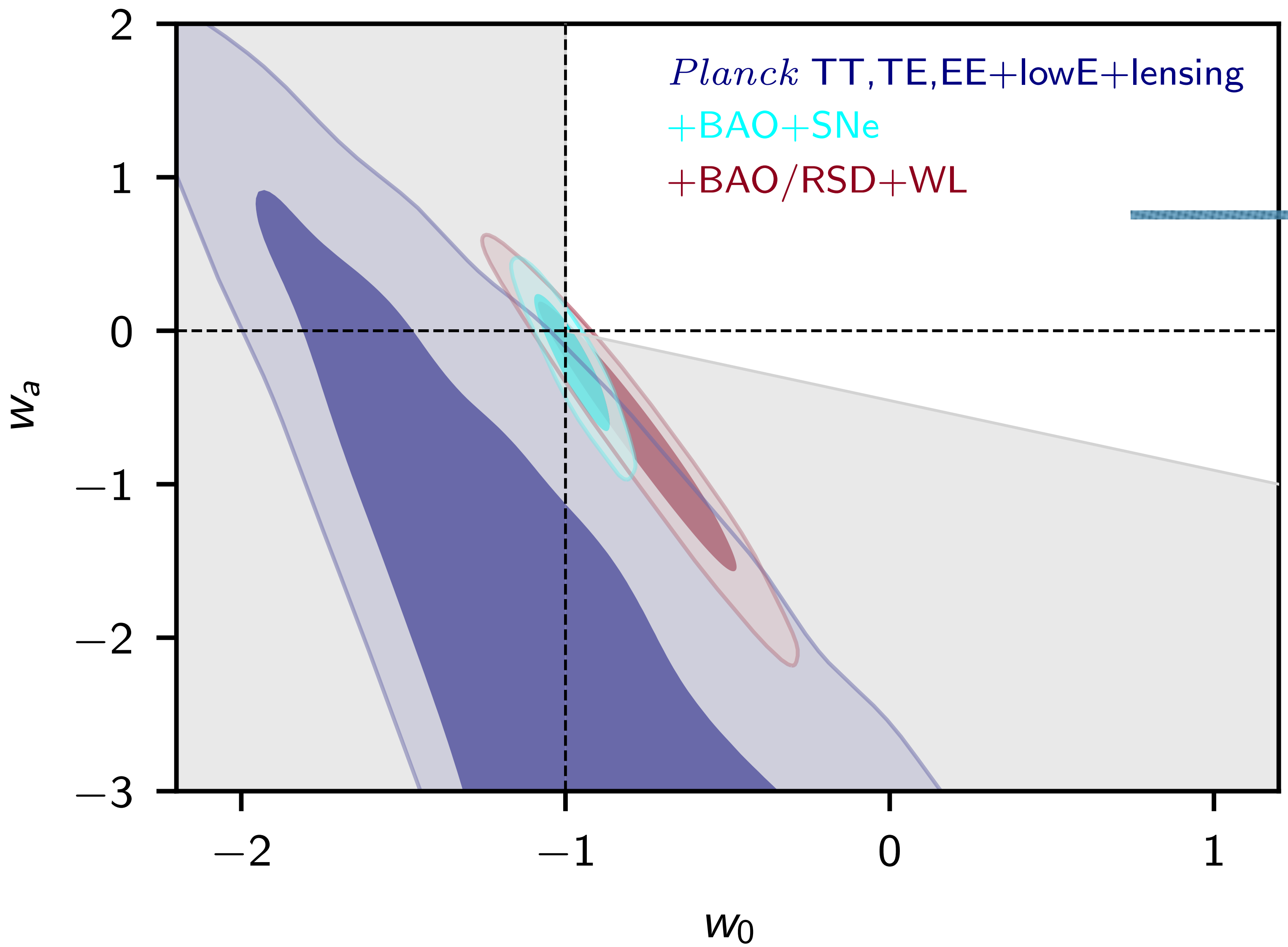


$w > -1 \; non-phantom$

Planck-2018 Result:

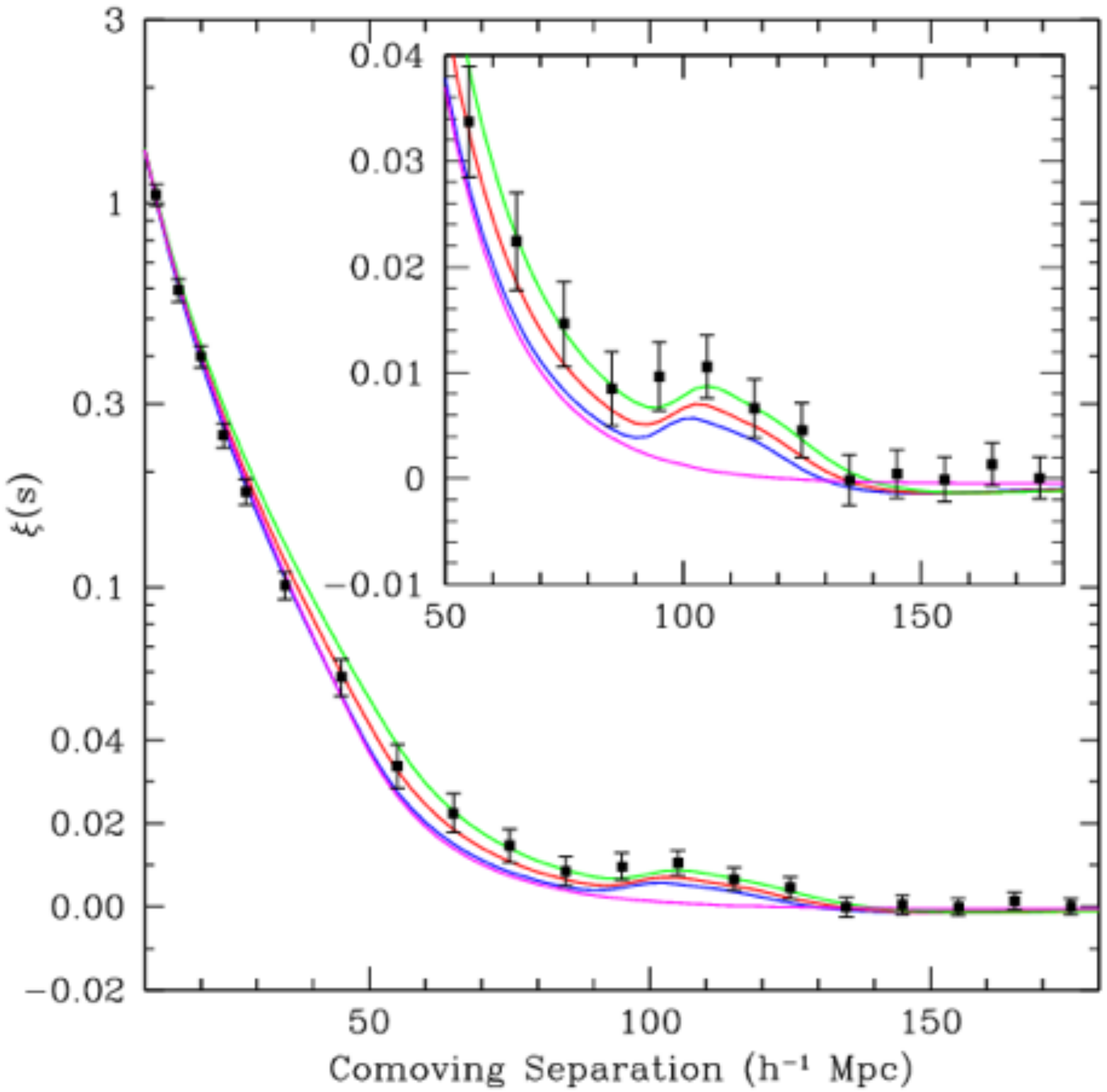
Aghanim et al. ArXiv: 1807.06209

Baryon Acoustic Oscillations

$$c_s = 1/\sqrt{3(1+R)}$$

$$R = 3\frac{\rho_b}{\rho_r}$$

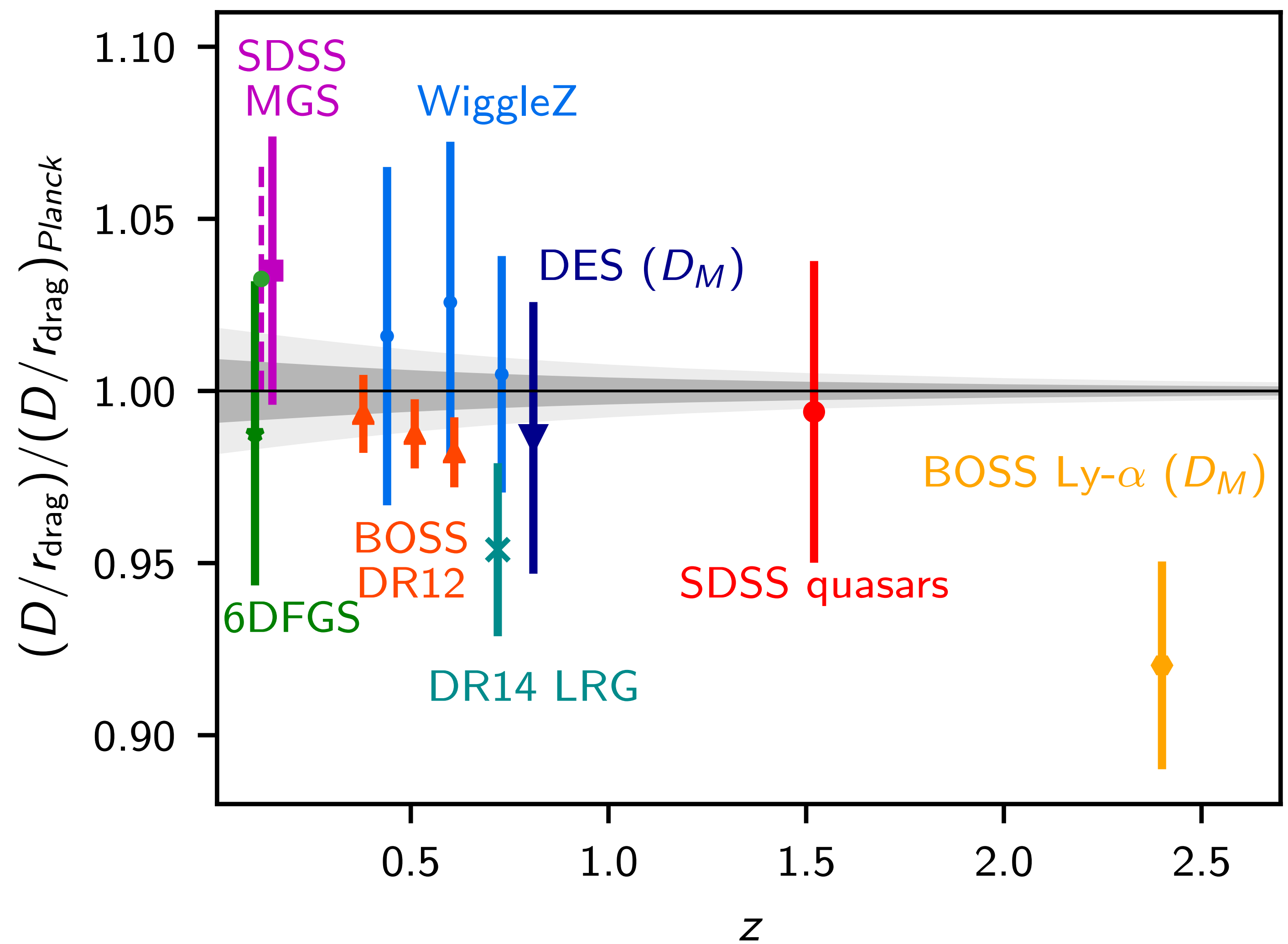
$$r_d = \int_0^{t(z_d)} c_s(1+z)dt$$



Eisenstein et al 2005

Tension with BAO

$$D(z) = \left[D_M^2 \frac{cz}{H(z)} \right]^{1/3}$$



Planck-2018 Result:

Aghanim et al. ArXiv: 1807.06209

Tensions in H_0 Measurements

H_0 Measurements

- The Planck-2018 measurement of Hubble parameter for ΛCDM: (Aghanim et al 2018):

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

- The local Measurement of Hubble Parameter BY HST (R18): (Riess et al. 2018, SHOES project)

$$H_0 = 73.45 \pm 1.66 \ Km/s/Mpc$$

This is 3.5σ higher than the Planck-2018 measurement.

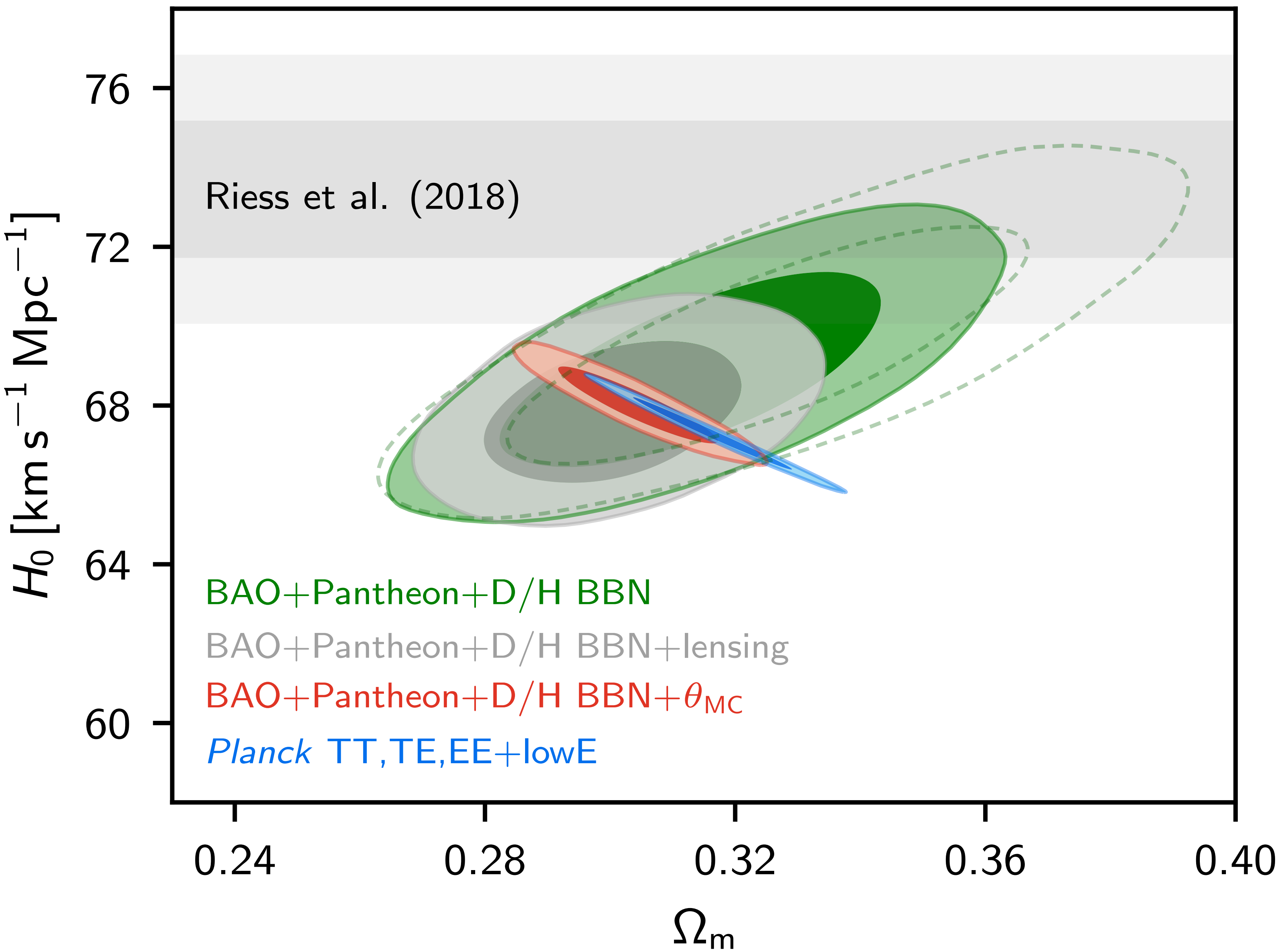
- Latest result by GAIA using Cepheids in Milky Way (Riess et al 2018):

$$H_0 = 73.52 \pm 1.62 km/s/Mpc$$

- Independent measurement by HoliCOW using Time-Delay Strong Lensing Probe for ΛCDM:

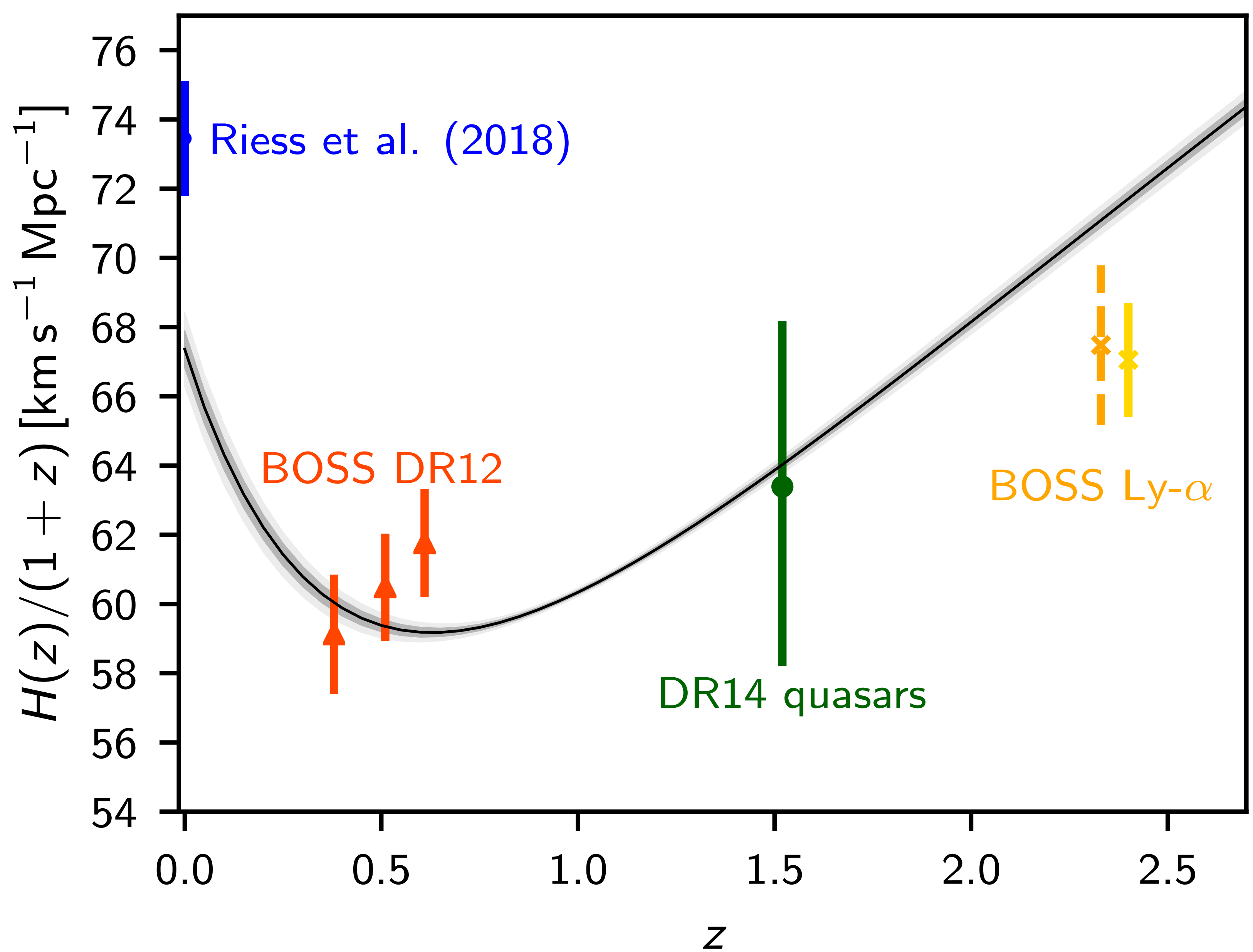
$H_0 = 71.9^{+2.4}_{-3.0} \ Km/s/Mpc$ (Bonvin et al 2017) $H_0 = 72.5^{+2.3}_{-2.1} \ km/s/Mpc$ (Birrer et al 2018)

Tensions in H_0 measurements



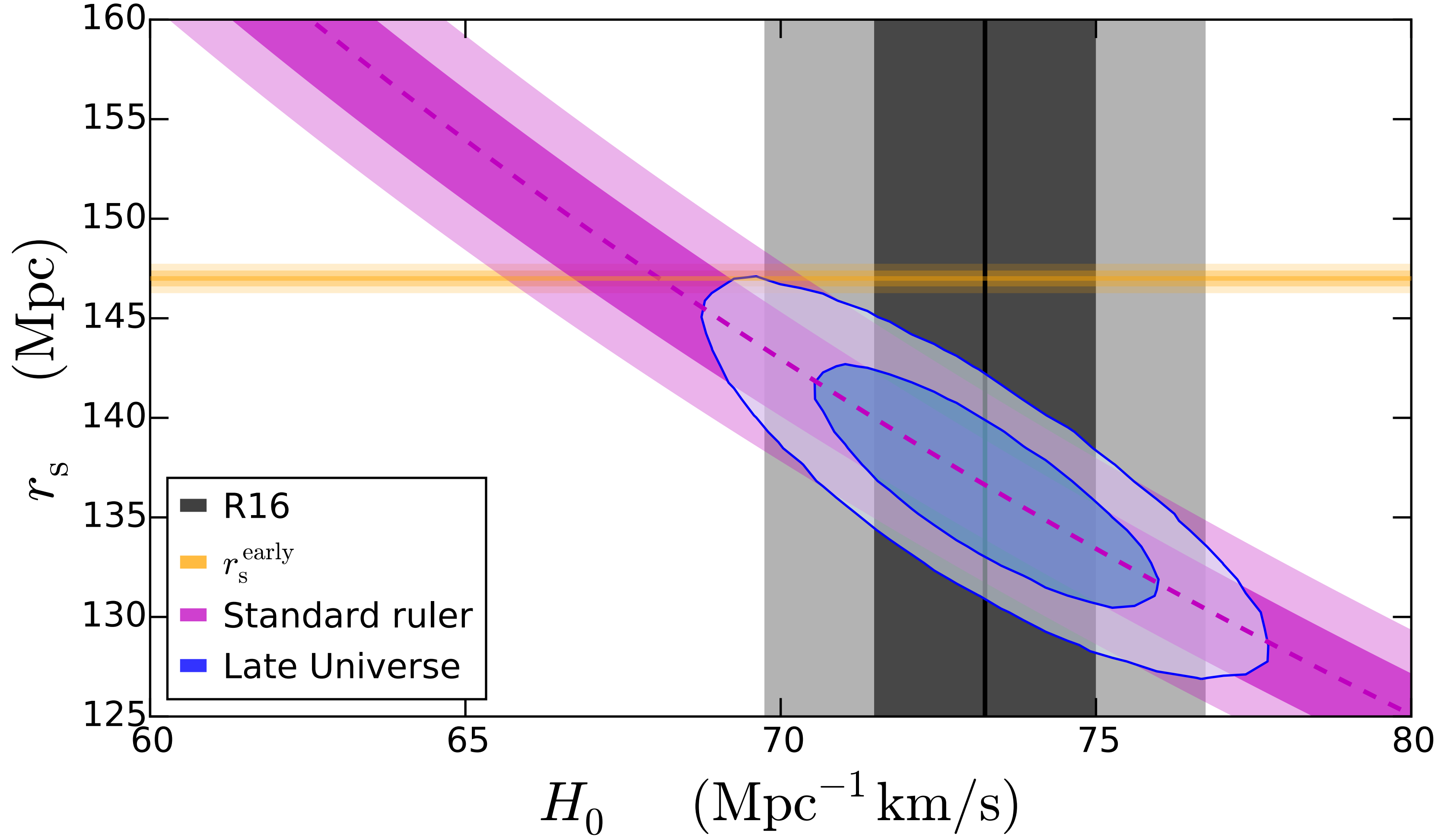
Tensions in H(z) measurements

Planck-2018, arXiv: 1807.06209



Tension with Sound Horizon at Drag Epoch

Bernal, Verde, Riess, JCAP 2016



Same is also confirmed by Evslin, AAS, Ruchika, PRD 2017

Implications Of These Tensions in Dark Energy Behaviour

How to Infer about Dark Energy

Einstein Equation: $$3H^2 = 8\pi G\left(\rho_m + \rho_{de}\right)$$

$$\rho_m \propto a^{-3} \; or \; (1+z)^3$$

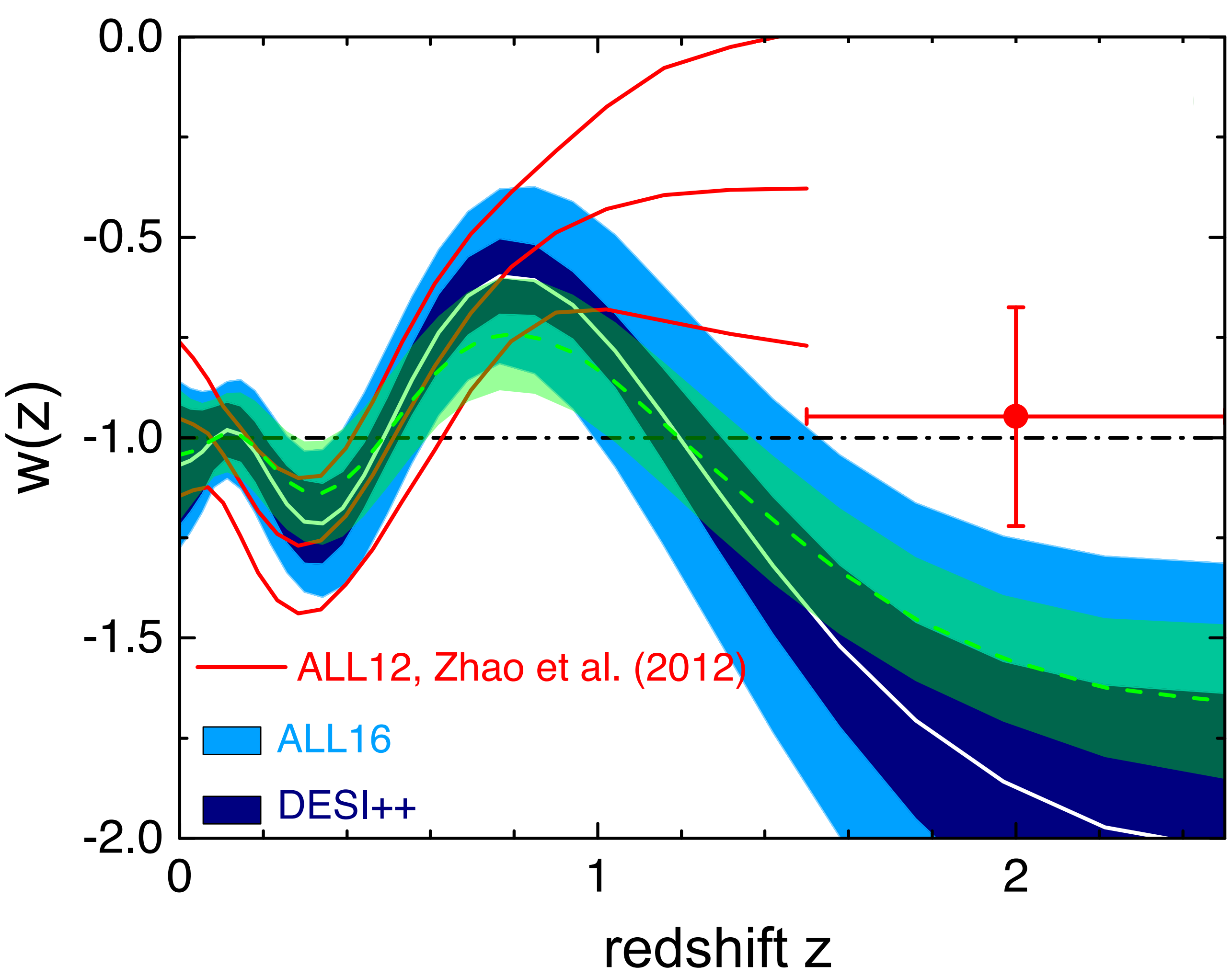
For dark energy, two possibilities:

1) Assume: $\rho_{de} > 0 \rightarrow \rho_{de} \propto \exp\left[3\int \frac{1+w(z)}{1+z}dz\right]$

2) Directly constrain ρ_{de} without assuming that it has to be > 0.

Case 1: Evidence for varying dark energy

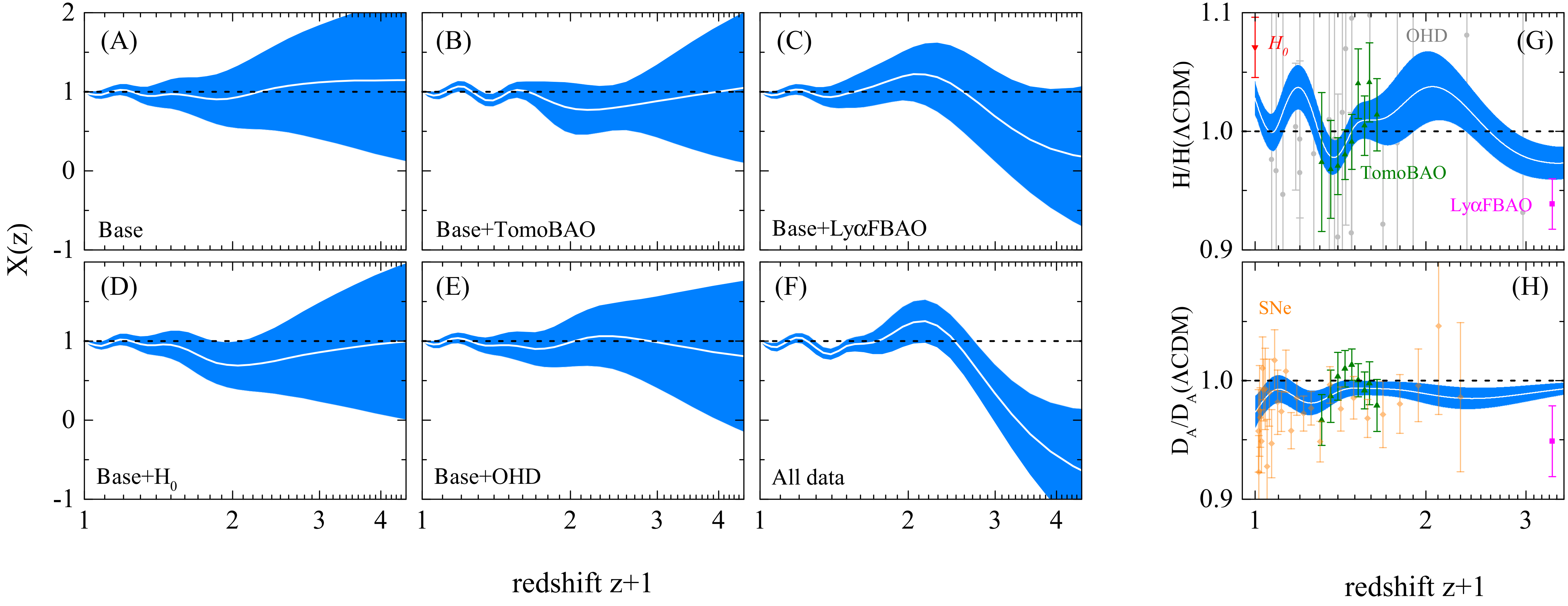
- **Zhao et al., Nature Astronomy, 1, 627-632, (2017)**



This assumes that the late time acceleration is driven by a non-interacting minimally coupled dark energy, with $\rho_{de} > 0$

Case 2: Model Independent Result

Wang, Pogosian, Zhao and Zucca arXiv: 1807.03772



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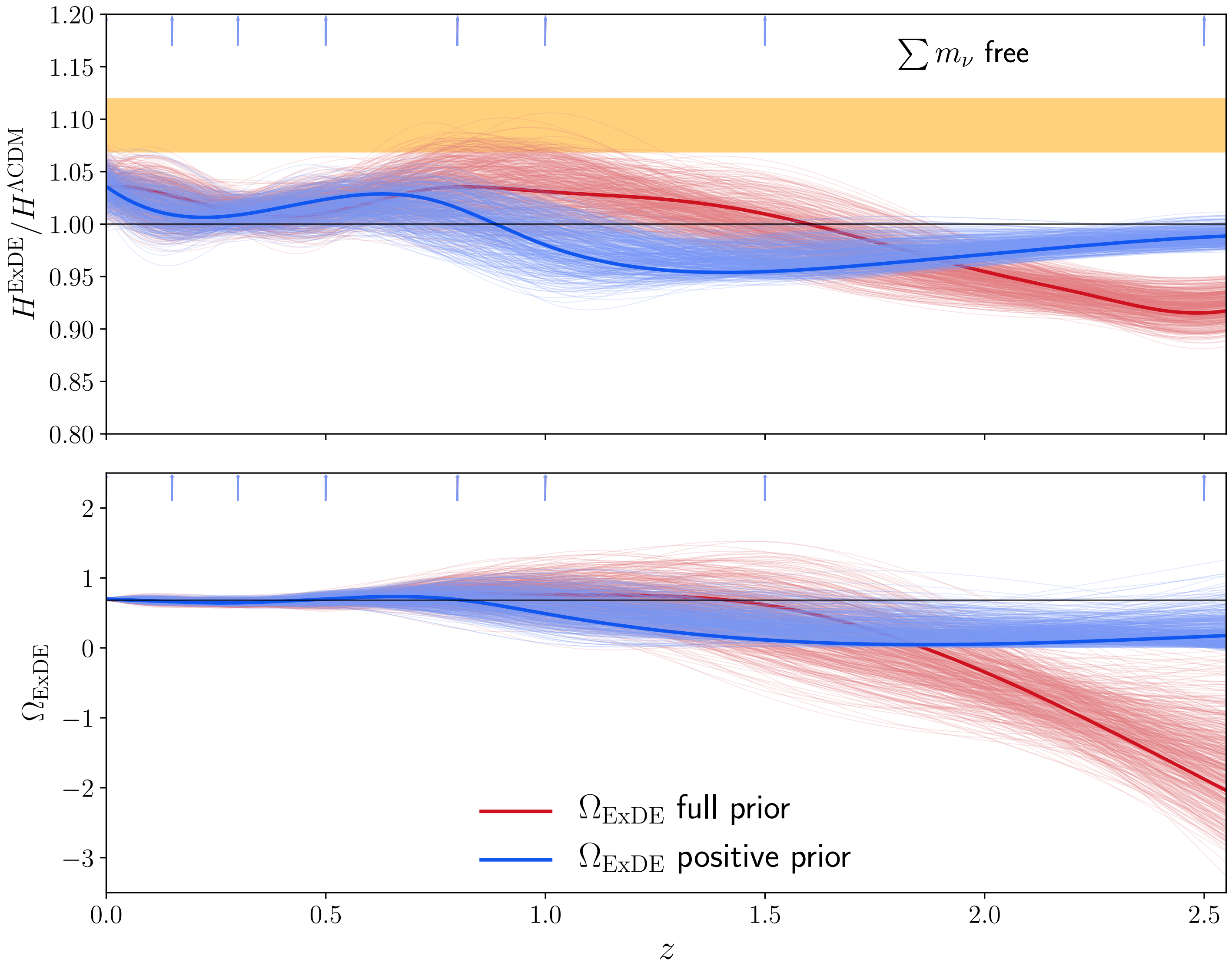
Poulin, Boddy, Bird, Kaminkowski, Phys. Rev. D 2018



Same result also confirmed by Sahni, Shafieloo, Starobinsky APJL, 2014.

Also by Delubac et al. [BOSS Collaboration], Astron. Astrophys. 2015

Modelling $\varrho_{de} < 0$

- Assume Brans-Dicke Lagrangian:

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[\frac{F(\phi)R}{16\pi G} - \frac{1}{2}\partial^\mu \phi \partial_\mu \phi - V(\phi) + \mathcal{L}_m \right]$$

- This gives:

$$G_{\mu\nu} = 8\pi G \left[\rho_m + \rho_{de}^{eff} \right]$$

- where

$$\rho_{de}^{eff} = F^{-1} \left[\frac{1}{2}\dot{\phi}^2 + V(\phi) - 3H\dot{F} + (1-F)\rho_m \right]$$

$$p_{de}^{eff} = F^{-1} \left[\frac{1}{2}\dot{\phi}^2 - V(\phi) + 2H\dot{F} + \ddot{F} \right]$$

Problem with $\varrho_{de} < 0$

CMB tells us that the **Universe is Spatially flat**

$$\Omega_m + \Omega_{DE} = 1$$

But if $\varrho_{de} < 0$, and also unbounded from below, then **$\Omega_m > 1$ and will grow very quickly with redshifts**.

This will completely destroy the large scale structure formation in the Universe as there will be much structures in the universe than what is observed.

So **we need to have a lower bound** for $\varrho_{de} < 0$.

We Ask the following questions:

- How robust are these dark energy behaviours?
- To answer this, we reconstruct the evolution of the background universe using low redshift data without any assumption about the underlying model for dark energy / modified gravity.
- Then we study what kind of dark energy behaviour can give rise to such background evolution.

Capozziello, Ruchika, AAS, arXiv:1806.03943

Dutta, Ruchika, Roy, Sen Sheikh-Jabbari arXiv:1808.06623

The Observables

- $$D_H(z) = \frac{c}{H(z)}$$

- $$D_A(z) = \frac{c}{1+z}\int_0^z \frac{dz'}{H(z')}$$

- $$D_V(z) = \left((1+z)D_A(z)\right)^{2/3}\left(zD_H(z)\right)^{1/3}$$

- $$D_{\Delta t}(z_d, z_s) = c\frac{\int_0^{z_d}\frac{dz'}{H(z')}\int_0^{z_s}\frac{dz'}{H(z')}}{\int_{z_d}^{z_s}\frac{dz'}{H(z')}}$$

- $$D_L(z) = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

The Observables

- $$D_H(z) = \frac{c}{H(z)}$$

So it is better to reconstruct the H(z) directly using existing data.

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$$q(t) = -\frac{1}{a}\frac{d^2a}{dt^2}\left[\frac{1}{a}\frac{da}{dt}\right]^{-2}; j(t) = -\frac{1}{a}\frac{d^3a}{dt^3}\left[\frac{1}{a}\frac{da}{dt}\right]^{-3}$$

→ **j = 1 for ΛCDM**

$$s(t) = -\frac{1}{a}\frac{d^4a}{dt^4}\left[\frac{1}{a}\frac{da}{dt}\right]^{-4}; l(t) = -\frac{1}{a}\frac{d^5a}{dt^5}\left[\frac{1}{a}\frac{da}{dt}\right]^{-5}$$

$$H(z) = H_0 + H_{10}z + \frac{H_{20}}{2}z^2 + ...$$

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$$H(z) = H_0 + H_{10}z + \frac{H_{20}}{2}z^2 + \ldots$$

$$H_1 = H_{10}/H_0 = 1 + q_0,$$
$$H_2 = H_{20}/H_0 = -q_0^2 + j_0,$$
$$H_3 = H_{30}/H_0 = 3q_0^2(1+q_0) - j_0(3+4q_0) - s_0)$$
$$H_4 = H_{40}/H_0 = -3q_0^2(4+8q_0+5q_0^2) + j_0(12+32q_0+25q_0^2-4j_0) + s_0(8+7q_0) + l_0$$

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But with this, for $z > 1$, the series does not converge.
So taking observations from $z > 1$, this is not useful.

Pade Approximation

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$$R(x) = \frac{A_n(x)}{B_m(x)}$$

$$A_n(z) = A_0 + A_1 x + A_2 x^2 + ... + A_n x^n$$

$$B_m(z) = 1 + b_1 x + b_2 x^2 + ... + b_m x^m$$

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- such that

$$f(0) = R(0)$$

$$f'(0) = R'(0)$$

$$f''(0) = R''(0)$$

$$\dots\dots\dots\dots\dots\dots$$

$$f^{(n+m)}(0) = R^{(n+m)}(0)$$

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$$f'(0) = R'(0)$$
$$f''(0) = R''(0)$$
$$........................$$
$$f^{(n+m)}(0) = R^{(n+m)}(0)$$

The Padé approximant often gives better approximation of the function than truncating its Taylor series, and it may still work where the Taylor series does not converge.

Pade Approximation

- We use $P_{22}(z)$ to approximate H(z):

$$E(z) = H(z)/H_0 = \frac{1 + P_1 z + P_2 z^2}{1 + Q_1 z + Q_2 z^2}$$

- The different parameters are related to cosmographic parameters as:

$$P_1 = H_1 + Q_1,$$

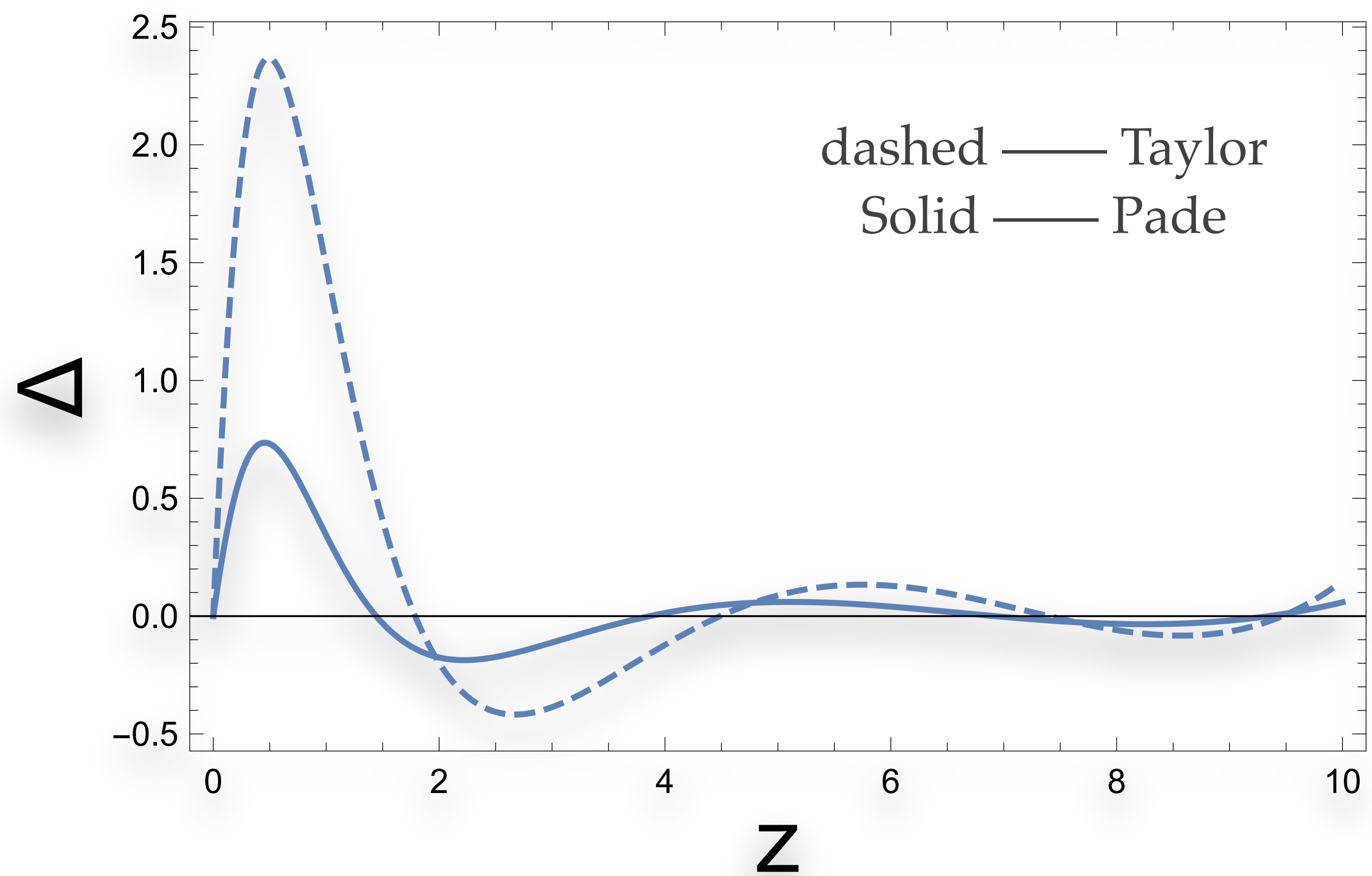
$$P_2 = \frac{H_2}{2} + Q_1 H_1 + Q_2$$

$$Q_1 = \frac{-6H_1H_4 + 12H_2H_3}{24H_1H_3 - 36H_2^2},$$

$$Q_2 = \frac{3H_2H_4 - 4H_3^2}{24H_1H_3 - 36H_2^2}.$$

Pade Approximation

- To show that it fits better the H(z) behaviour than Taylor expanding H(z) upto 4th order, we assume a ΛCDM model and fit both the Taylor expanded H(z) and the Pade Approximated H(z).



Data Used

- The SnIa data from latest Pantheon results.
- The H(z) data from different Cosmic Chronometer measurements.
- Different BAO and MegaMaser measurements
- Strong Lensing data from H0LiCow experiment
- H_0 measurement by Riess et al (R16).

68% CL for Parameters

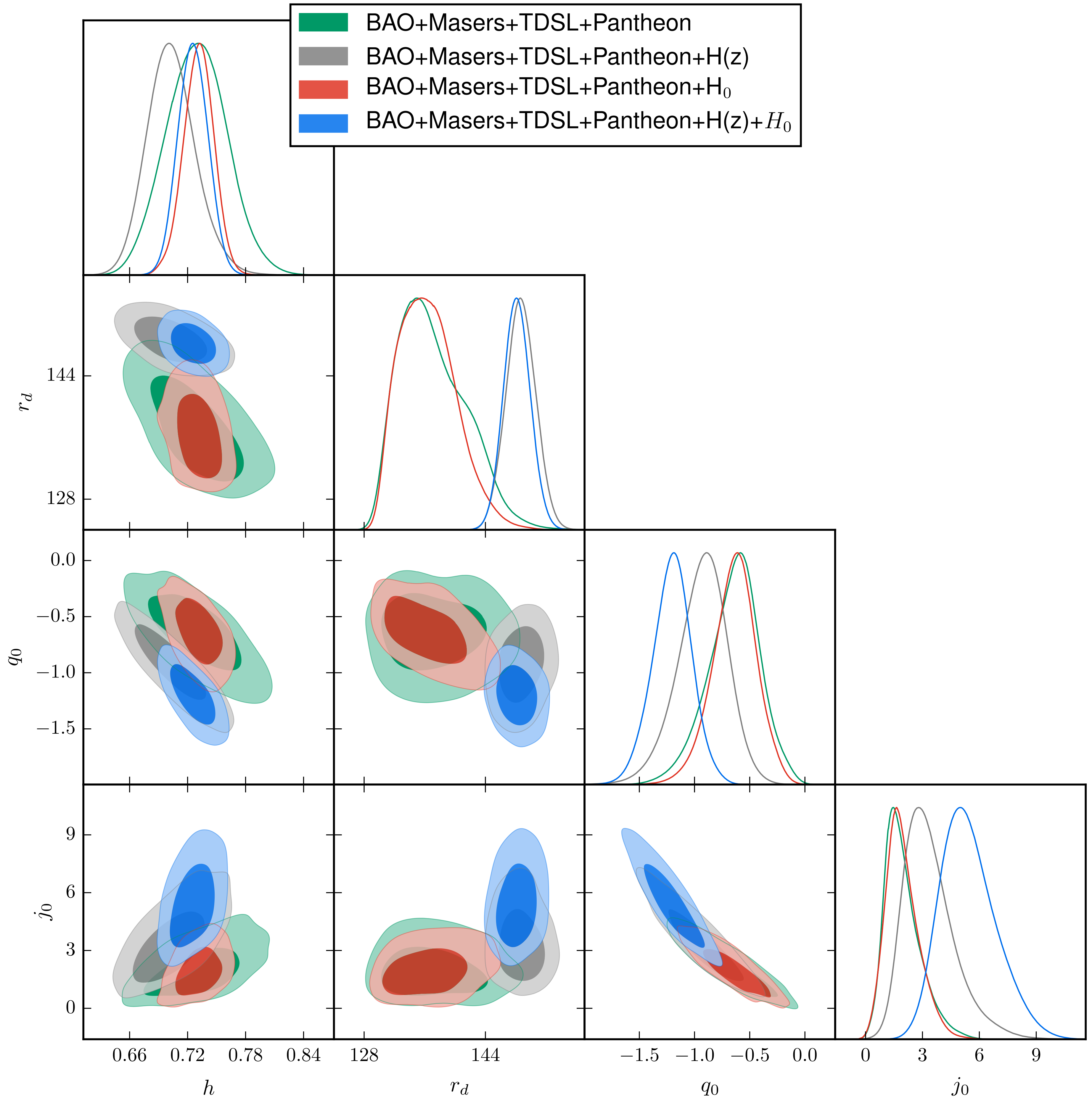
$H_0 = 100$ h km/sec/Mpc

	$Bao + Mas + SL + SN(1)$	$(1) + H_0$	$(1) + H(z)$	All
h	0.7293 ± 0.031	0.7313 ± 0.015	0.7034 ± 0.024	0.7256 ± 0.015
r_d	137.06 ± 4.58	136.41 ± 3.82	148.67 ± 1.93	148.16 ± 1.74
q_0	-0.644 ± 0.223	-0.6401 ± 0.187	-0.930 ± 0.218	-1.2037 ± 0.175
j_0	$1.961^{+0.926}_{-0.884}$	$1.9461^{+0.871}_{-0.816}$	$3.369^{+1.270}_{-1.294}$	$5.423^{+1.497}_{-1.443}$

For other two parameters:

$$s_0 = 19.97^{+11.57}_{-10.84}$$

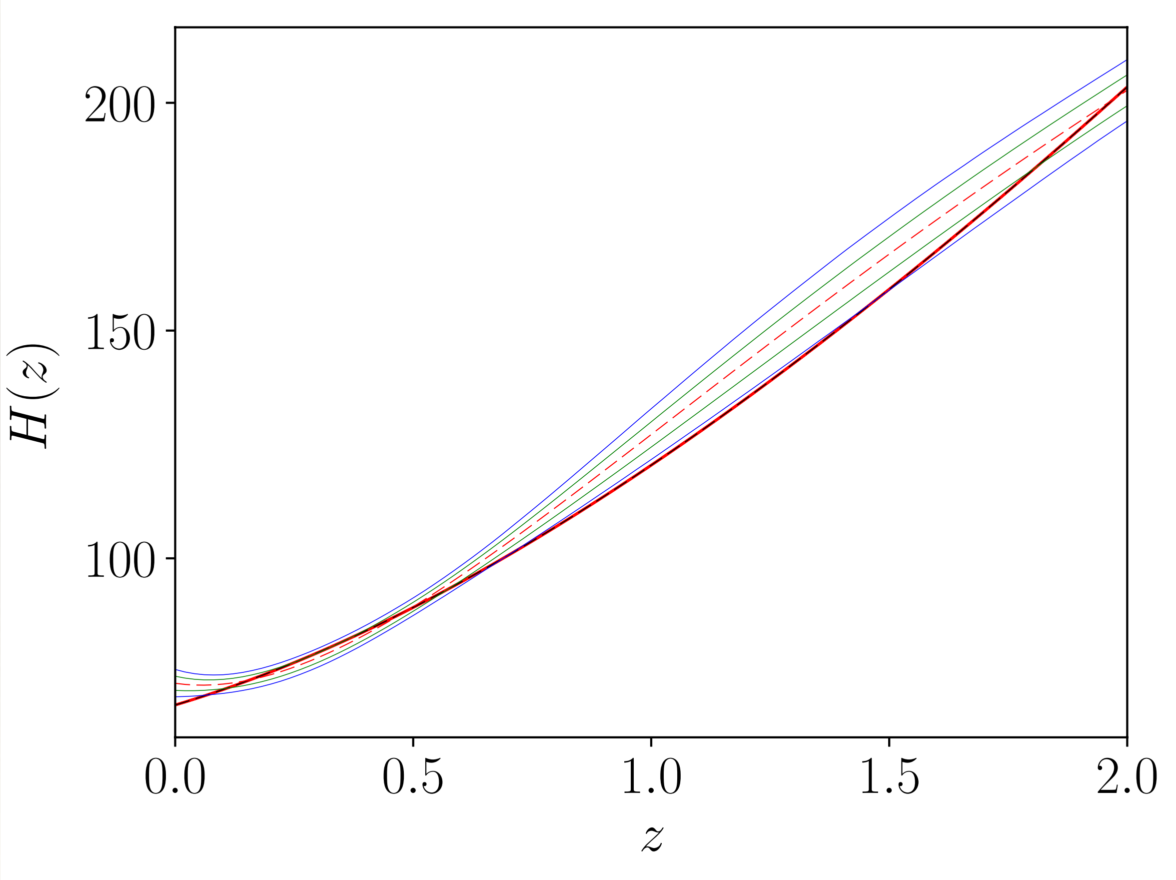
$$l_0 = 121.41^{+91.94}_{-83.56}$$

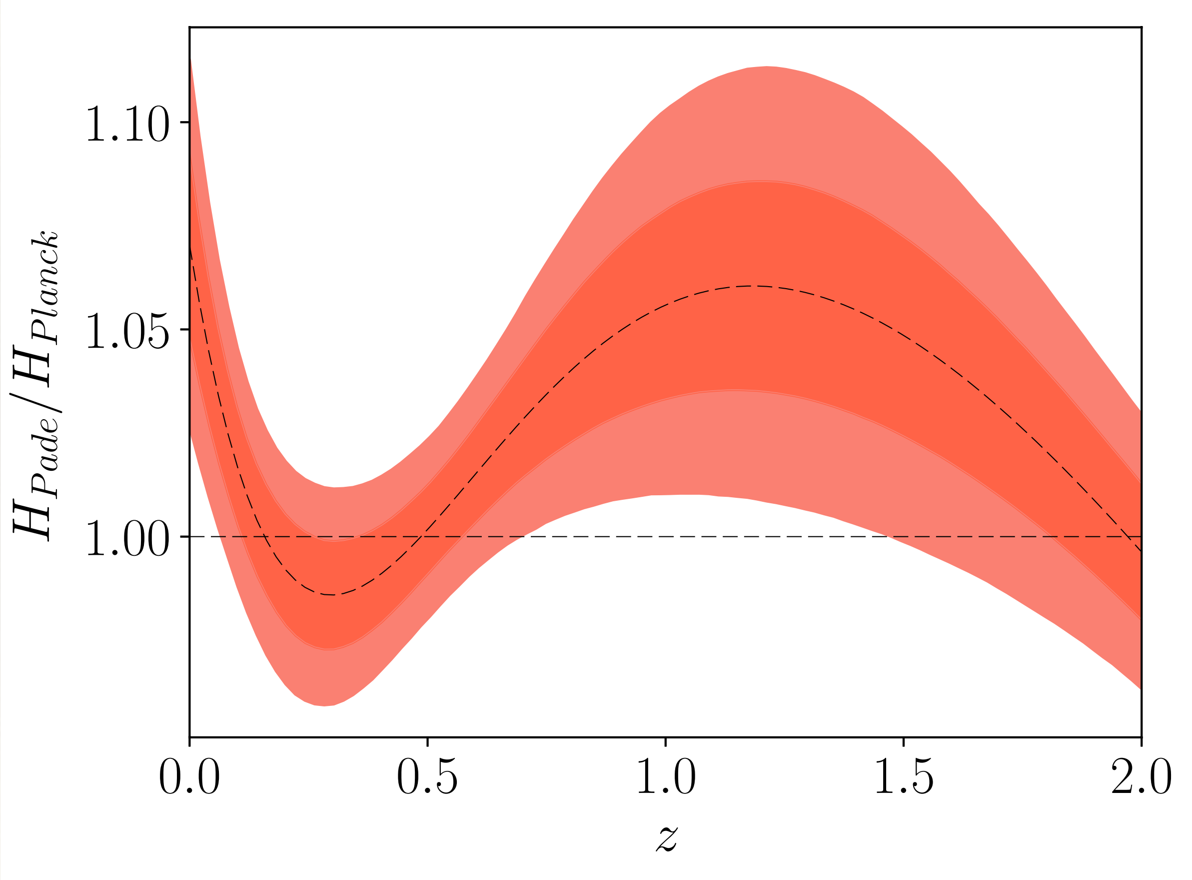


BAO+Masers+TDSL+Pantheon
BAO+Masers+TDSL+Pantheon+H(z)
BAO+Masers+TDSL+Pantheon+H_0
BAO+Masers+TDSL+Pantheon+H(z)+H_0
r_d
q_0
j_0
h
144
128
0.0
−0.5
−1.0
−1.5
9
6
3
0
0.66
0.72
0.78
0.84
−1.5
−1.0
−0.5
0.0

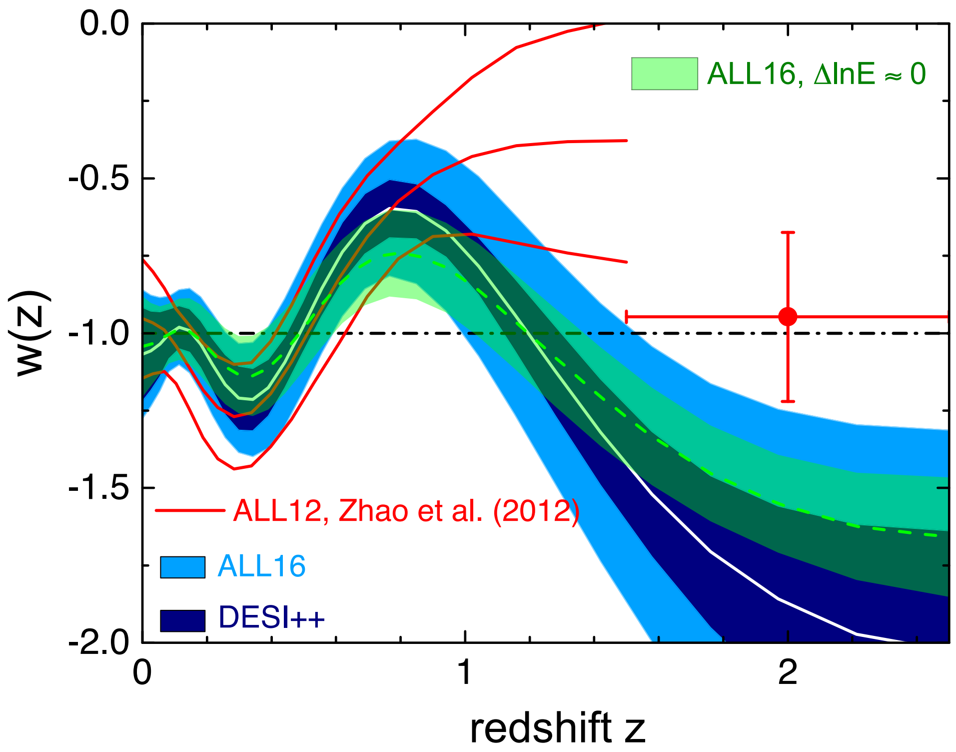
Model Independent Behaviour

Hubble parameter H(z)

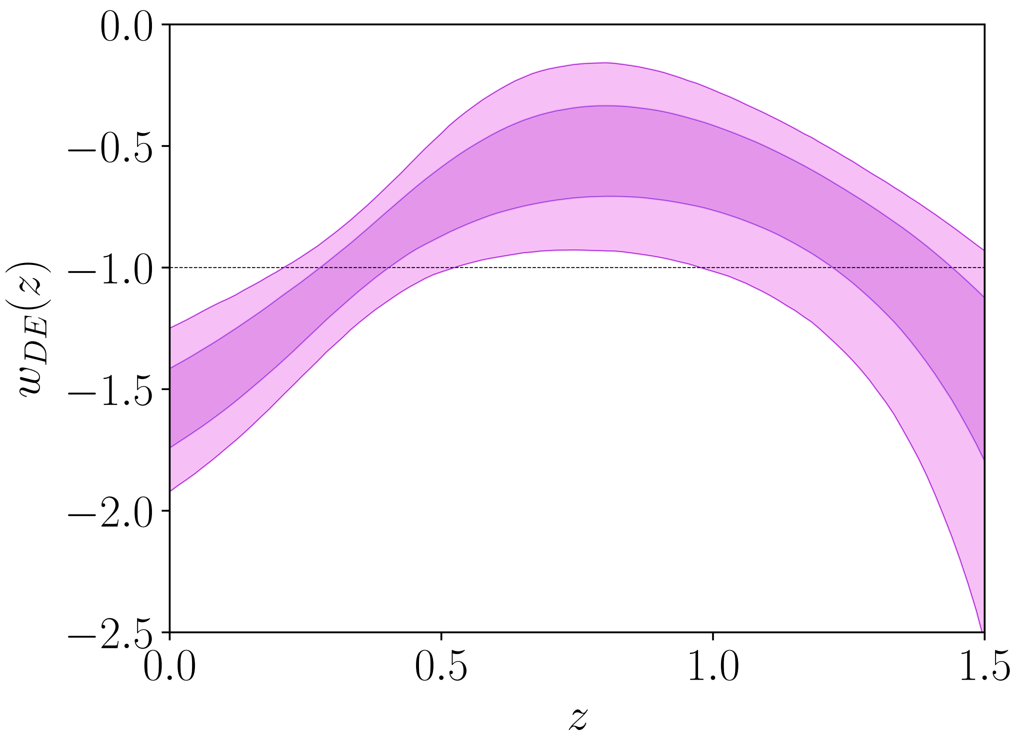




Compare with Other Model Independent Results



Zhou et al., 2017

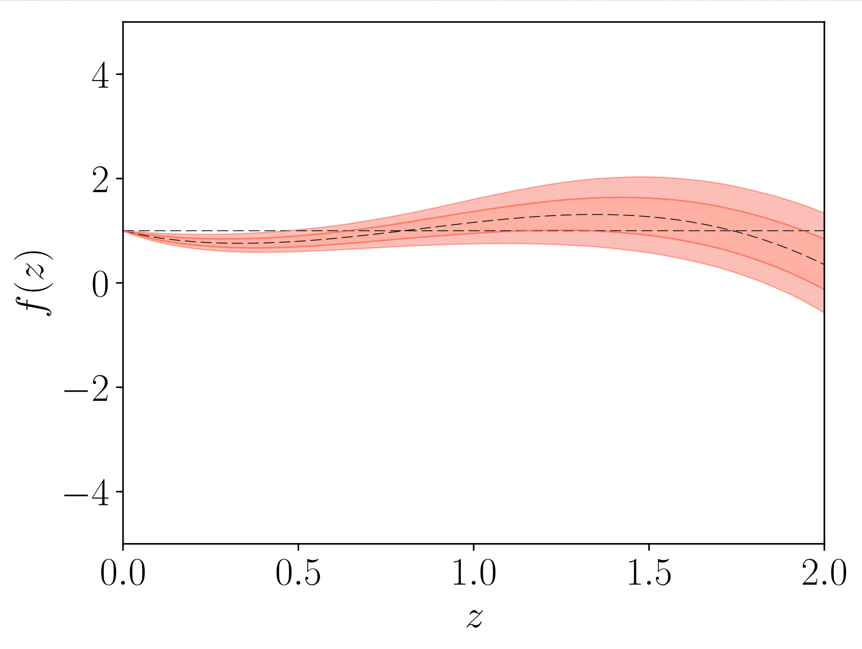


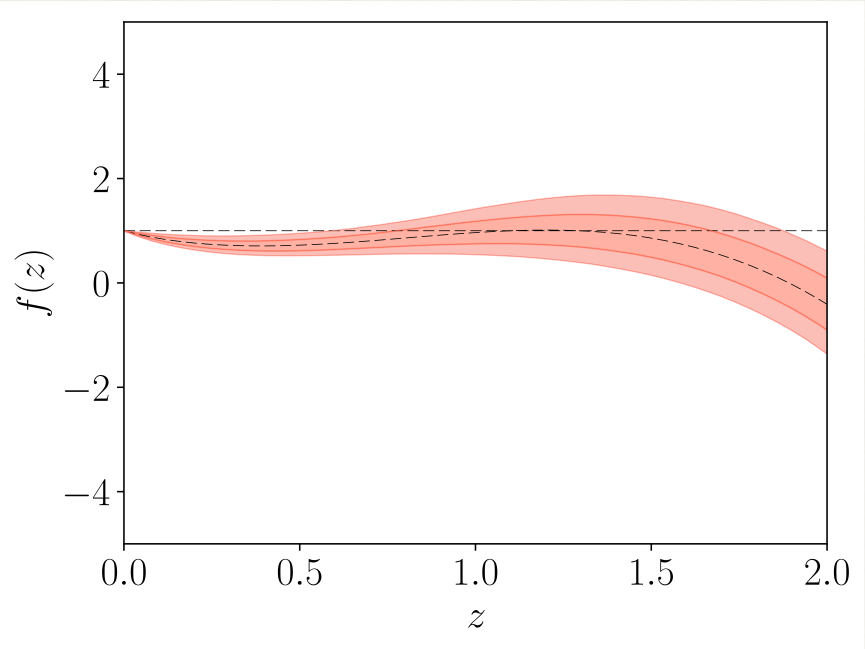
Our Result

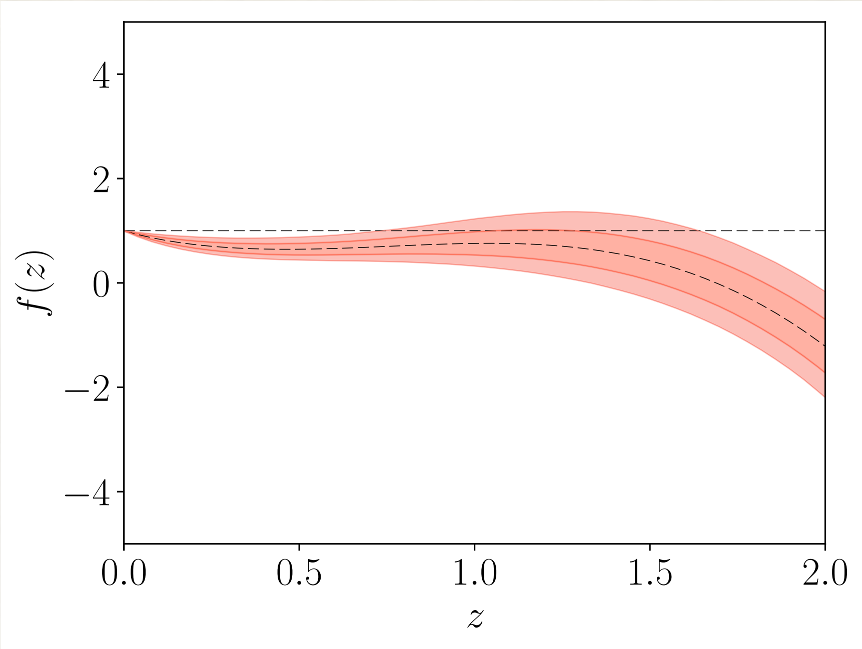
Model Independent Behaviour

Assuming Flat Universe: $3H^2 = \rho_m + \rho_{de} = \rho_{m0}(1+z)^3 + \rho_{de0} f(z)$

$$\frac{H^2}{H_0^2} = \Omega_{m0}(1+z)^3 + (1-\Omega_{m0}) f(z)$$







$\Omega_{m0} = 0.28$

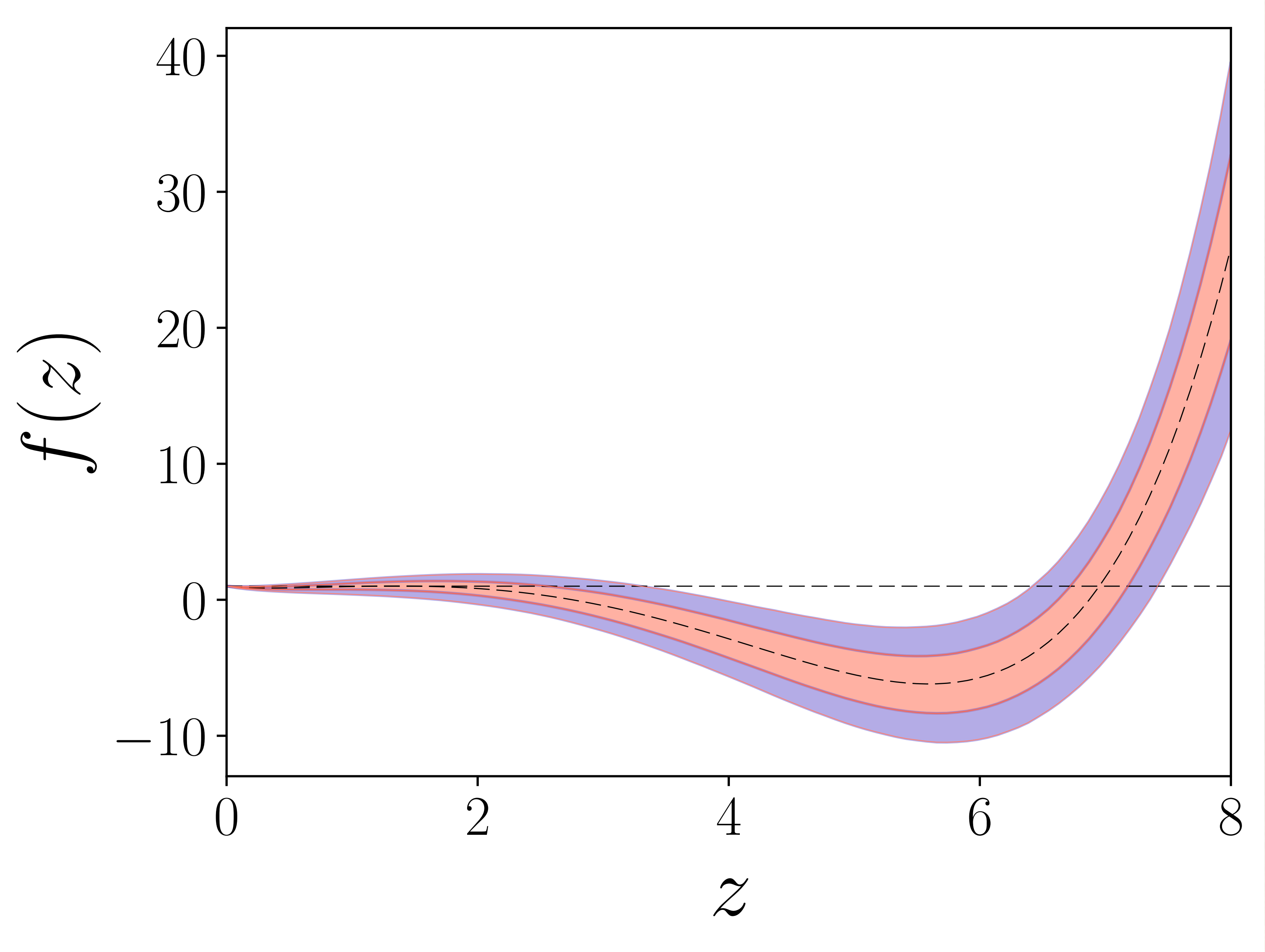
$\Omega_{m0} = 0.30$

$\Omega_{m0} = 0.32$

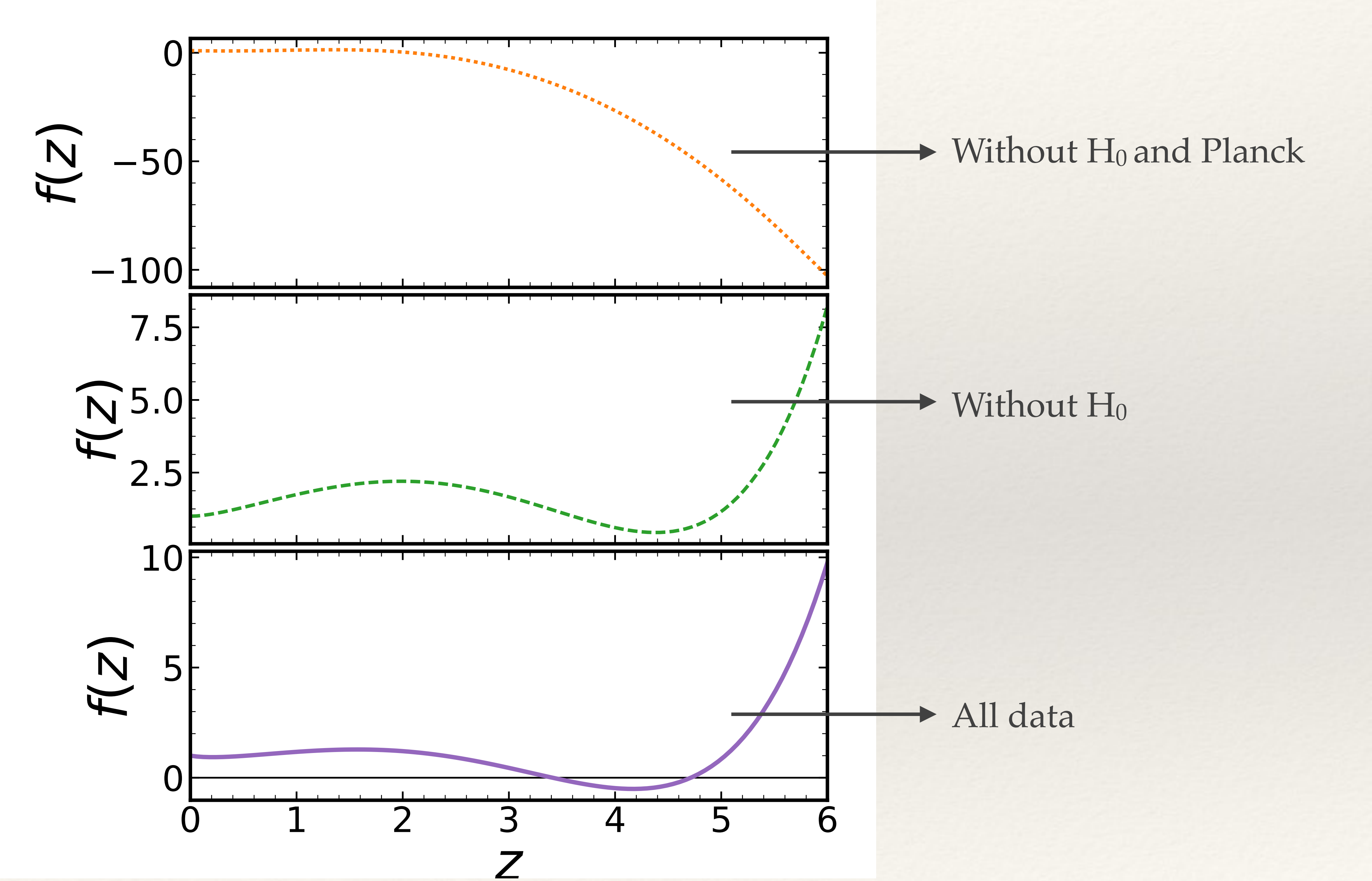
To Incorporate Matter Domination

- At higher redshifts, all models should reproduce the same matter dominated period.
- Therefore, we assume that our model independent behaviour for $H(z)$ should reproduce $H(z)$ as constrained by Planck for ΛCDM model at some appropriate higher redshifts.
- We assume three specific choices of the redshifts, $z = 4, 5, 6$.

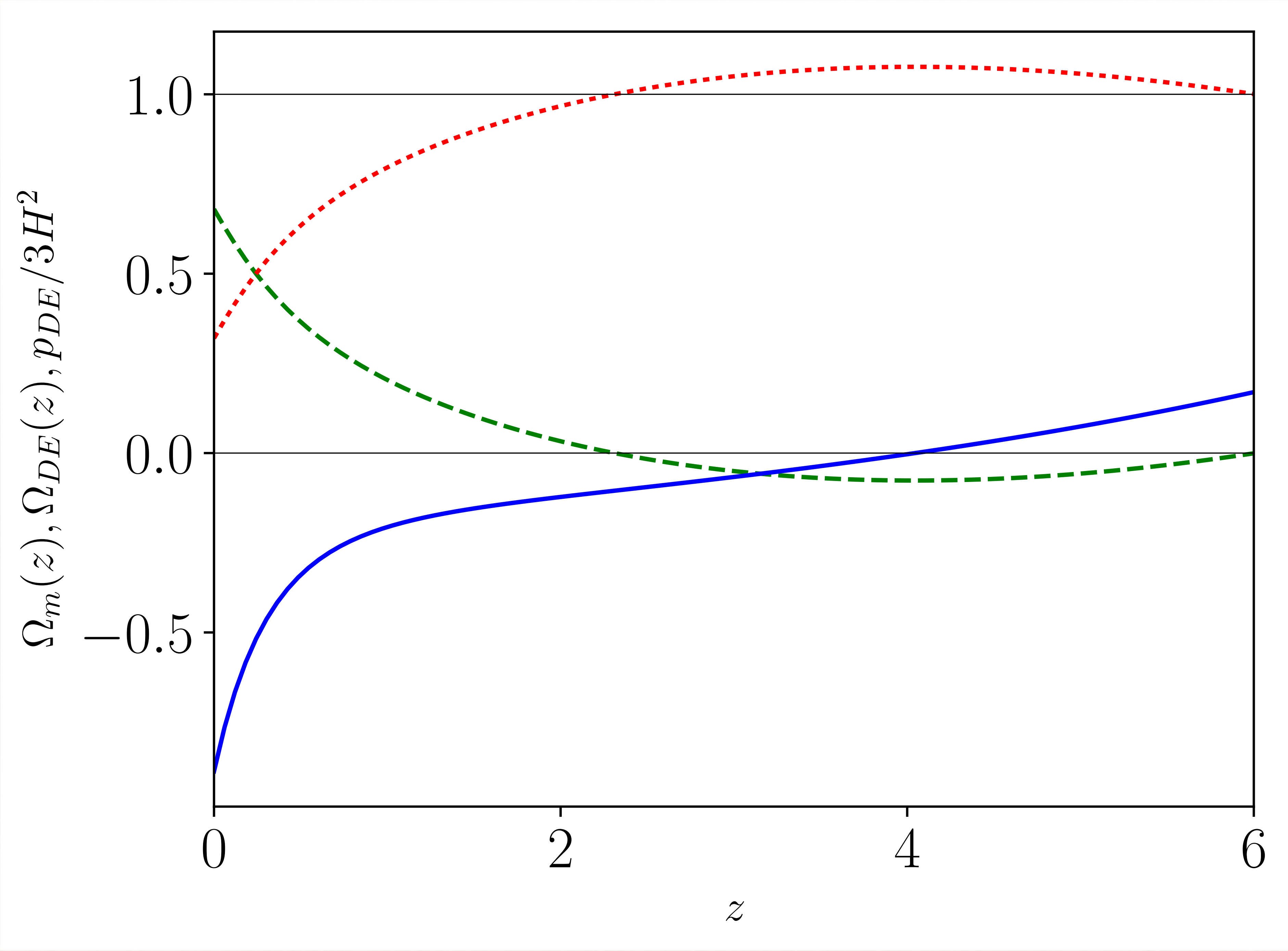
Results with Planck Constraint on H(z)



Effects of different data combinations



Results with Planck Constraint on H(z)



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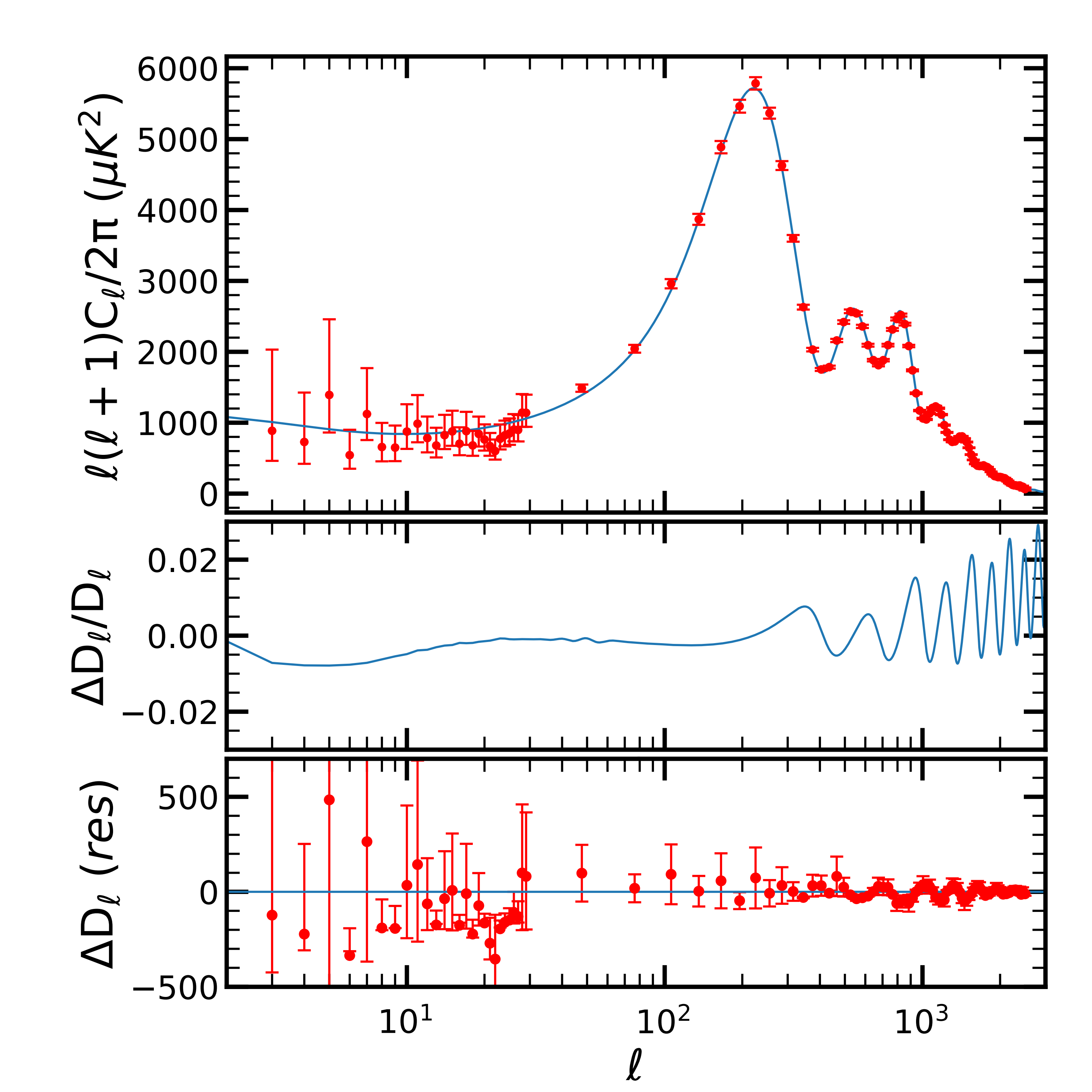


Interpretation of the result

- Without the Planck constraints on H(z) for matter era, energy density of the dark energy ϱ(z) becomes negative at high redshifts.
- Putting Planck's constraints on H(z) at redshifts z=4 and beyond, ϱ(z) gets a negative minimum.
- Continuity equation: $\frac{d}{dz}\rho_{de} - 3(\rho_{de} + p_{de})/(1+z) = 0$
- Minimum for ϱ(z) ⟶ $\rho_{de} + p_{de} = 0 \rightarrow \rho_{de} = -p_{de} \rightarrow Cosm.Const.$
- But at the minimum, $\varrho(z) < 0$, hence **there is a presence of -ve CC**.

Negative Λ !!!!

The Model

- If one take out the matter part from the total energy density, then $\rho_{total} - \rho_m$ can be written as

$$\rho_{de} + (-ve\ \Lambda)$$

This initially decreases with expansion as non-phantom field, but later increases like a phantom field to give higher H_0 at present. So it has a non-phantom to phantom transition.

This has a tiny negative value and helps to avoid the energy density is going unbounded in -ve direction and also plays role to enter the matter domination at high redshifts. **It does not play any role for late time acceleration.**

Possible effects in Structure Formation

- Due to the **presence of -ve Λ** and due to spatial flatness, the $\Omega_m > 1$ for certain redshift range. This results more growth of structures due to deeper gravitational potential and the nonlinear regime may start earlier than ΛCDM Universe and there will be more massive galaxies at high redshifts than ΛCDM.

- **These are definite prediction and can be verified by upcoming large scale surveys.**

Conclusions

- After Planck-2018 results, ΛCDM model is the simplest model that is consistent with data.
- But several low-redshift observations including H_0 measurements by Riess et al., BAO measurements using Lyman-Alpha as well as the low-redshift measurements of sound horizon at drag epoch (r_d) using BAO, has shown **significant tensions** with ΛCDM model as constrained by Planck-2018 using CMB.
- This opens possibility for new physics for both at early universe as well as late universe involving the dark energy behaviour.
- Several Model independent reconstruction for dark energy behaviour have shown either phantom-nonphantom crossing in dark energy equation of state or negative dark energy density at higher redshifts.
- We confirm these results in our model independent reconstruction using Pade Series Approximation for H(z).

Conclusions

- While incorporating the H(z) behaviour as constrained by Planck for matter dominated era,**we showed that ρ_{de} has a small negative minimum at $z > 4$.**
- One can associate this negative minimum with the existence of a **tiny negative cosmological constant.**
- The actual dark energy density is not positive cosmological constant, but **an evolving one which evolves from a non-phantom era to a phantom one.**
- The presence of tiny negative Cosmological Constant does not affect late time expansion.
- But due to its presence, the Ω_m becomes more than 1 for a certain redshift range and this has interesting implications on large scale structure formation that can be probed using near future galaxy surveys.

Thank You

Is there really any evidence for dark energy evolution?

- ***Bayesian Evidence*** of a model with a parameter space dimensionality D is given by:

$$\mathcal{Z} = \int \mathcal{L}(\Theta)\pi(\Theta)d^D\Theta$$

Likelihood — $\mathcal{L}(\Theta)$; Prior — $\pi(\Theta)$

- To compare two models, one uses the Jeffrey's Scale:

Δlog(z)	Conclusion	
0 ---- 1	No evidence	→ Blue
1------2.5	Significant Evidence	→ Orange
2.5-----5	Strong Evidence	→ Green
> 5	Decisive Evidence	→ Red

- The calculations have been done using PyMultinest.

Dark Energy Models

- **Scalar field models:**
  - Canonical Scalar field:

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)$$

  - Non-Canonical Scalar fields:

$$\mathcal{L} = V(\phi)\sqrt{1 - \partial^\mu\phi\partial_\mu\phi}$$

  - Scalar fields with higher derivative terms:

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi(1 + \frac{\alpha}{M^3}\Box\phi) - V(\phi)$$

EOM is still second order

Dark Energy Models

- Constant equation of state w
- Varying w as a function of redshift z: (Different parametrisation)

thawer

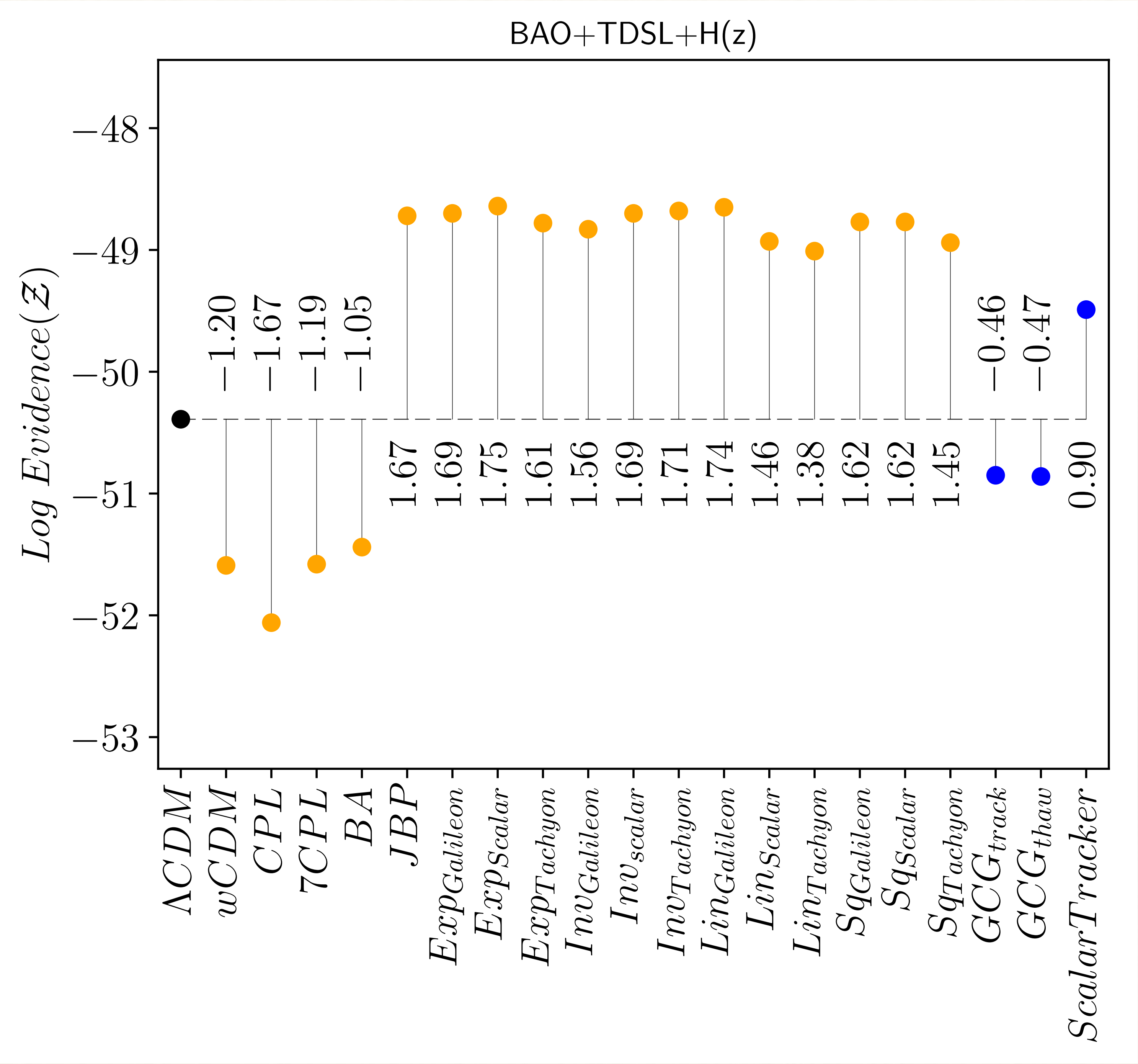
Freezer

- $w(z) = w_0 + w_a \frac{z}{1+z}$ CPL (Chevallier & Polarski 2001, Linder 2003)
- $w(z) = w_0 + w_a (\frac{z}{1+z})^7$ 7CPL (Pantazis et al, 2016)
- $w(z) = -\frac{w_0}{w_0 + (1-w_0)(1+z)^{3(1+w_a)}}$ GCG (Thakur, Nautiyal, Sen, Seshadri, 2012)
- $w(z) = w_0 + w_a \frac{z(1+z)}{1+z^2}$ BA (Barboza & Alcaniz, 2012)
- $w(z) = w_0 + w_a \frac{z}{(1+z)^2}$ JBP (Jassal, Bagla, Padmanabhan, 2005)

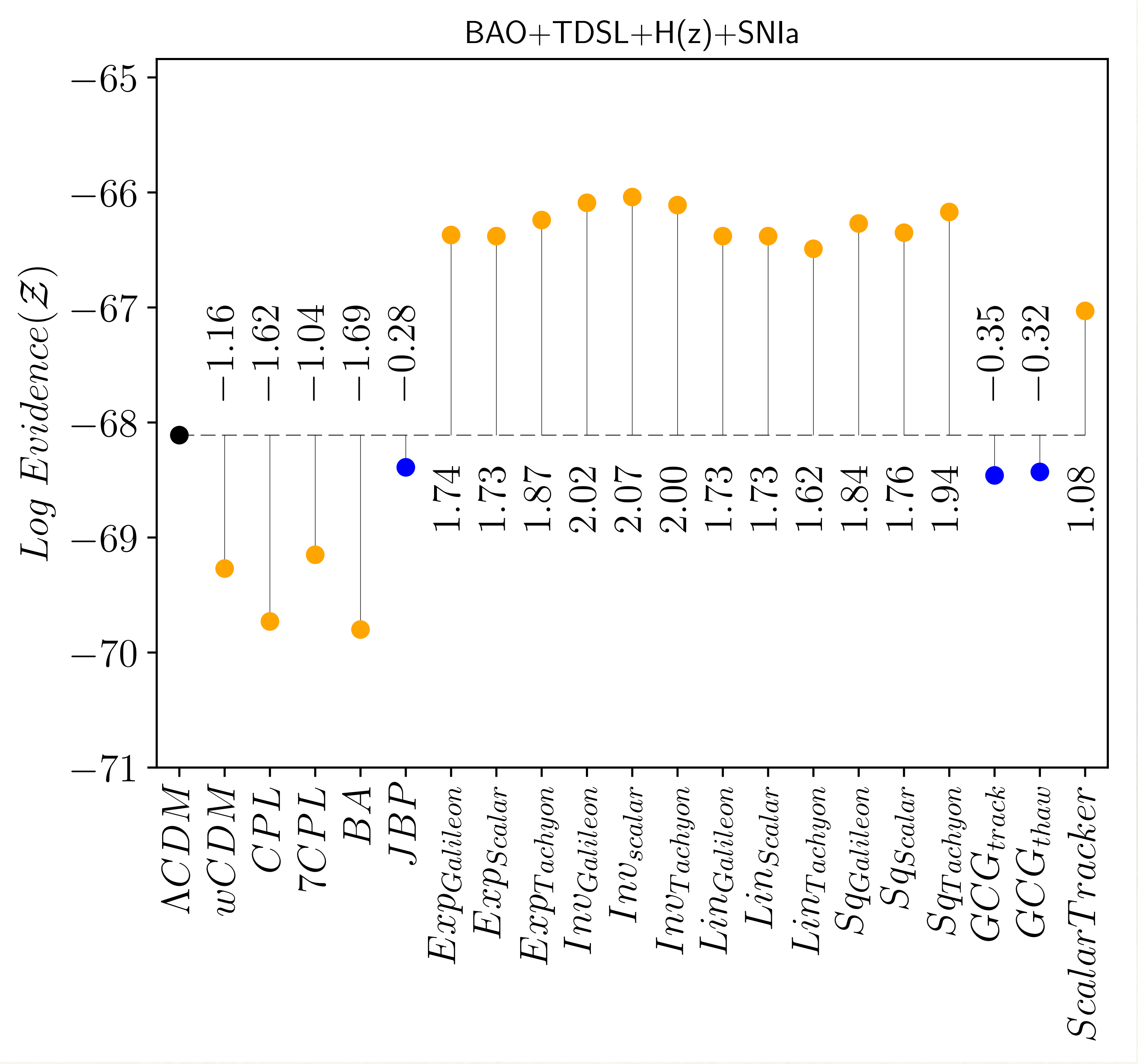
thawer/freezer

Thawer

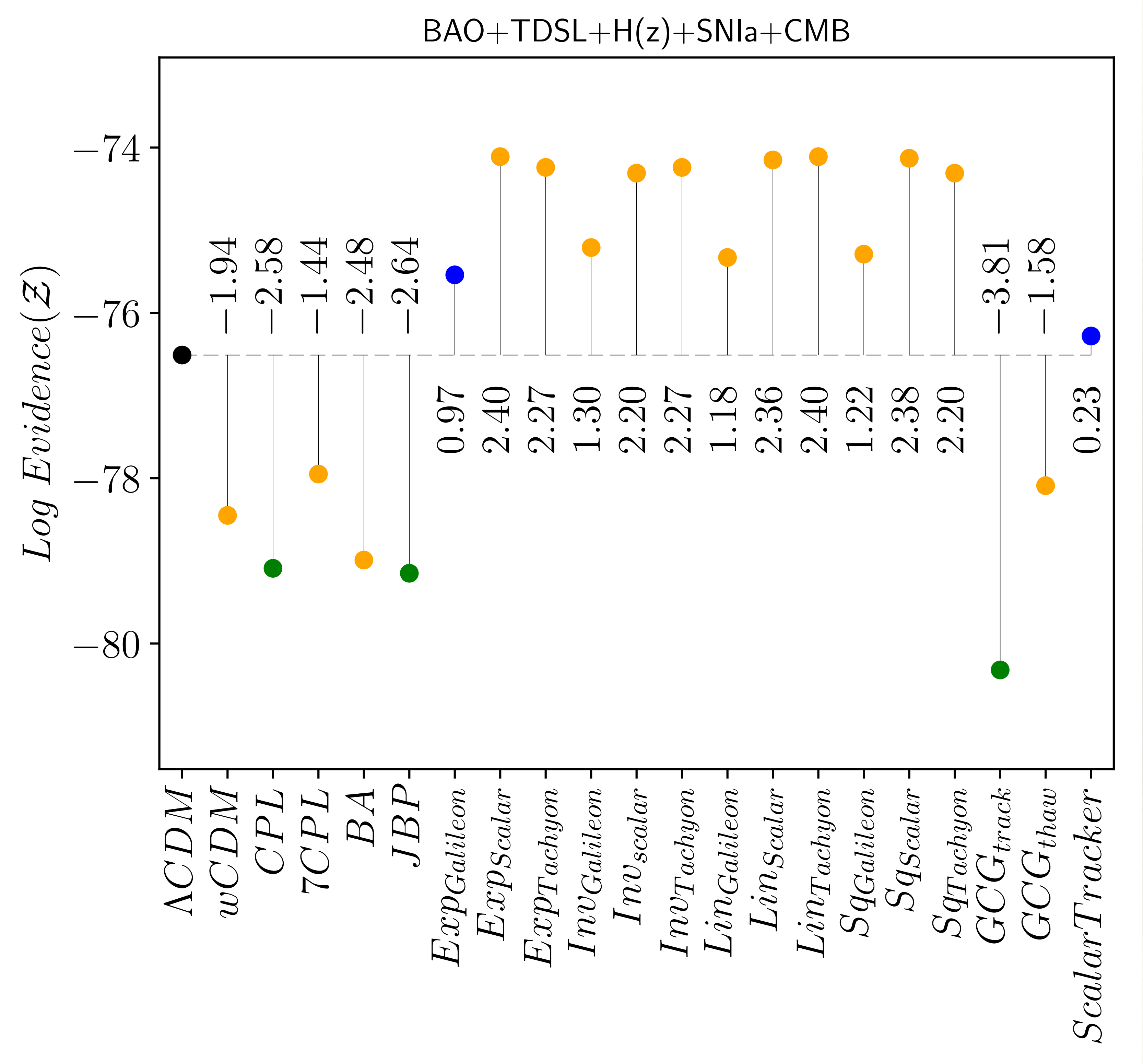
BAO+TDSL+H(z)


BAO+TDSL+H(z)
Log Evidence(Z)
−48
−49
−50
−51
−52
−53
−1.20
−1.67
−1.19
−1.05
1.67
1.69
1.75
1.61
1.56
1.69
1.71
1.74
1.46
1.38
1.62
1.62
1.45
−0.46
−0.47
0.90
ΛCDM
wCDM
CPL
7CPL
BA
JBP
Exp_Galileon
Exp_Scalar
Exp_Tachyon
Inv_Galileon
Inv_scalar
Inv_Tachyon
Lin_Galileon
Lin_Scalar
Lin_Tachyon
Sq_Galileon
Sq_Scalar
Sq_Tachyon
GCG_track
GCG_thaw
ScalarTracker

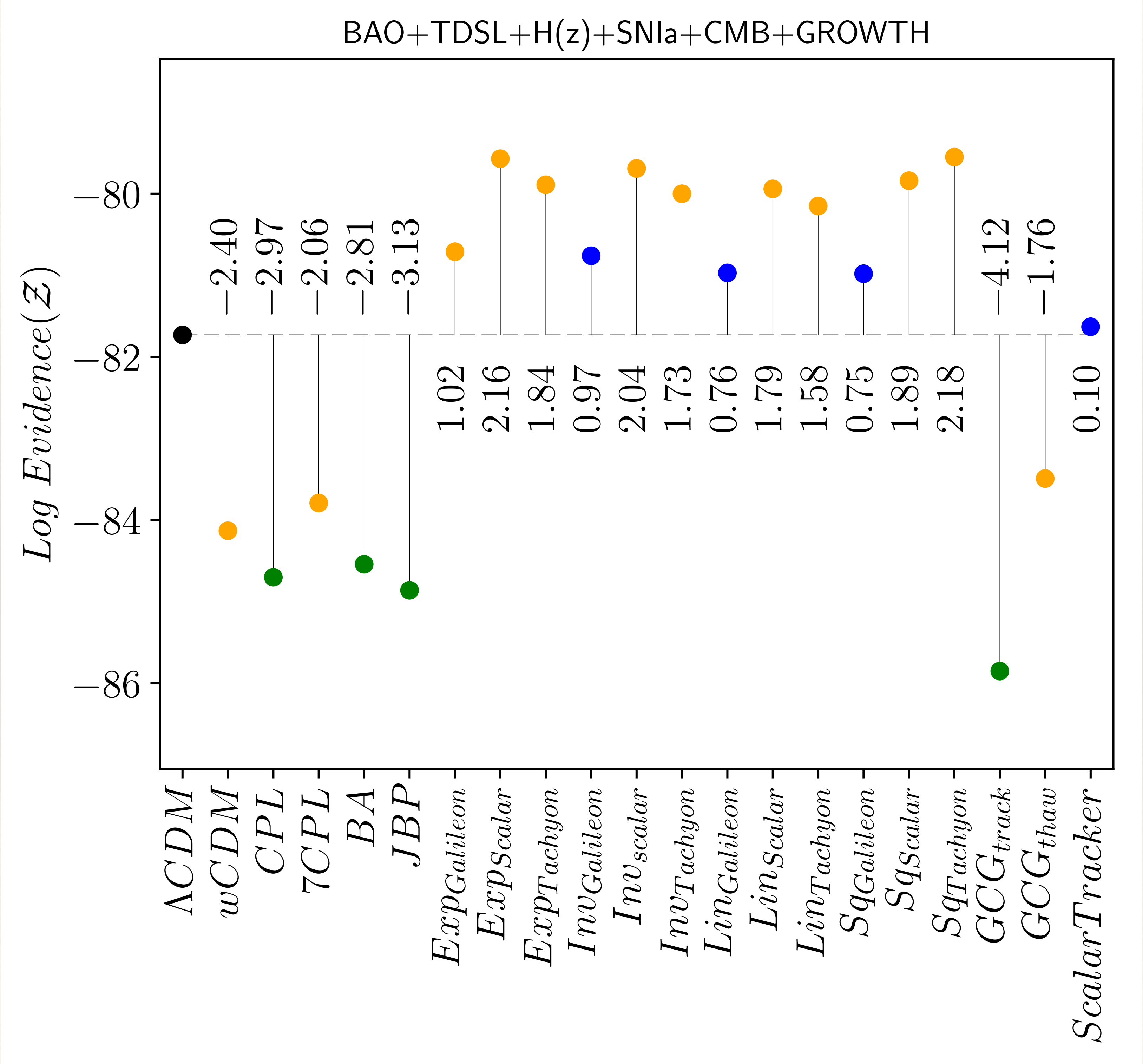
BAO+TDSL+H(z)+SnIa



BAO+TDSL+H(z)+SnIa+CMB



BAO+TDSL+H(z)+SnIa+CMB+Growth



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- Considering 21 different dark energy models including different scalar fields and different parametrisation for DE eos, we showed there is **significant but not strong evidence** for dark energy evolution compared to ΛCDM.
- Interestingly the CPL parametrisation which is a universal parametrisation used for DE constraint, is shown to be pretty inferior compared to actual scalar field models.

Thank You

Tensions in ΛCDM

H_0 $Measurements$

- The Planck-2015 measurement of Hubble parameter for ΛCDM: (Ade et al 2016):

$$H_0 = 66.93 \pm 0.62 \; Km/s/Mpc$$

- The local Measurement of Hubble Parameter BY HST (R16): (Riess et al. 2016)

$$H_0 = 73.24 \pm 1.24 \; Km/s/Mpc$$

This is 3.4σ higher than the Planck-2015 measurement.

- Latest local measurement of Hubble parameter: (Riess et al 2018):

$$H_0 = 73.45 \pm 1.66 \; Km/s/Mpc$$

This is 3.7σ higher than the Planck-2015 measurement.

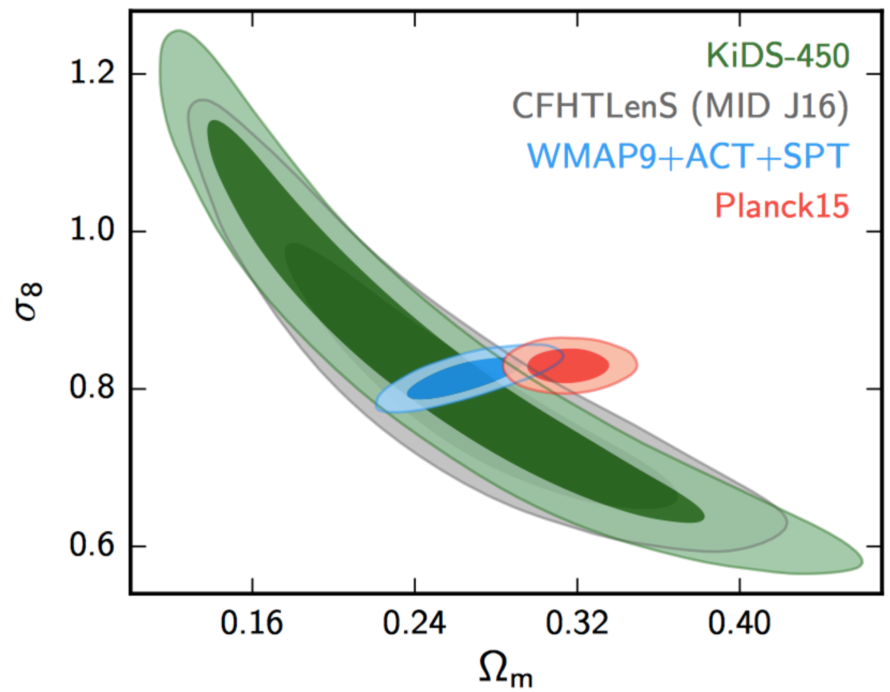
- Local measurements are also consistent with independent measurement by HoliCOW using Time-Delay Strong Lensing Probe for ΛCDM:(Bonvin et al 2017)

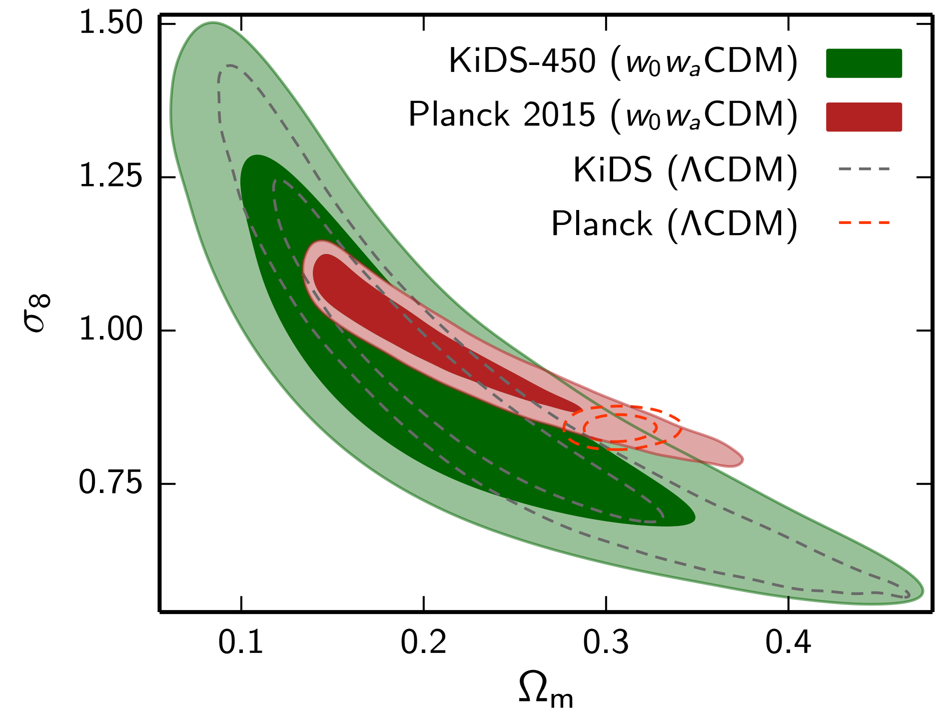
$$H_0 = 71.9^{+2.4}_{-3.0} \; Km/s/Mpc$$

Tensions in ΛCDM

Measurement by Weak Lensing by KiDS survey:

- The amplitude of the cosmic shear scales as $S_8^{2.5}$ $where\ S_8 = \sigma_8\sqrt{\Omega_m/0.3}$





Joudaki et al. arXiv:1610.04606

Tensions in ΛCDM

- KiDS measured $S_8 = 0.745 \pm 0.039$ for ΛCDM.
- Tension with Planck-2015:

Model	$T(S_8)$
ΛCDM	2.1σ
DE (const. w)	0.89σ
DE $(w_0 - w_a)$	0.91σ

Joudaki et al, arXiv:1610.04606