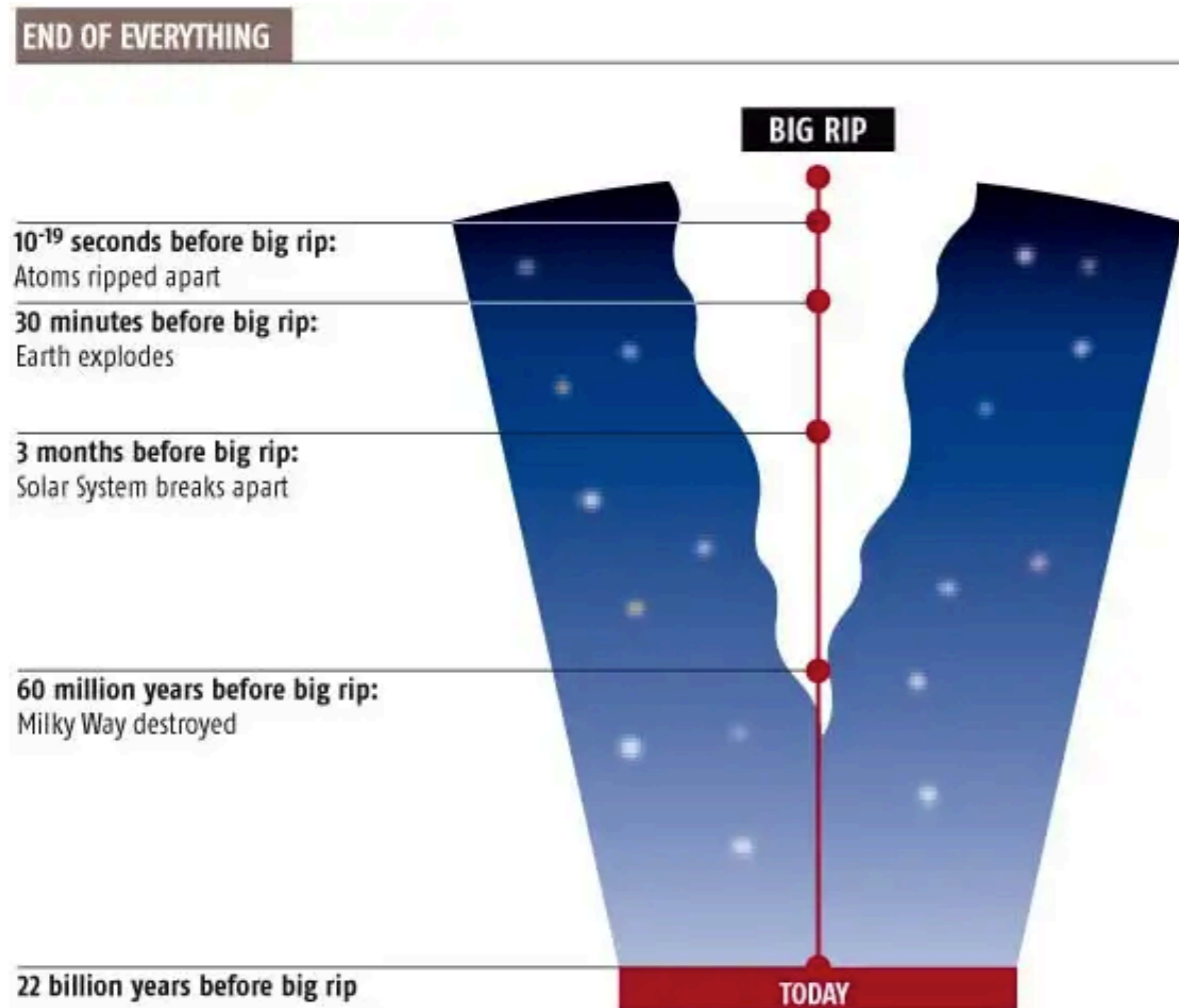
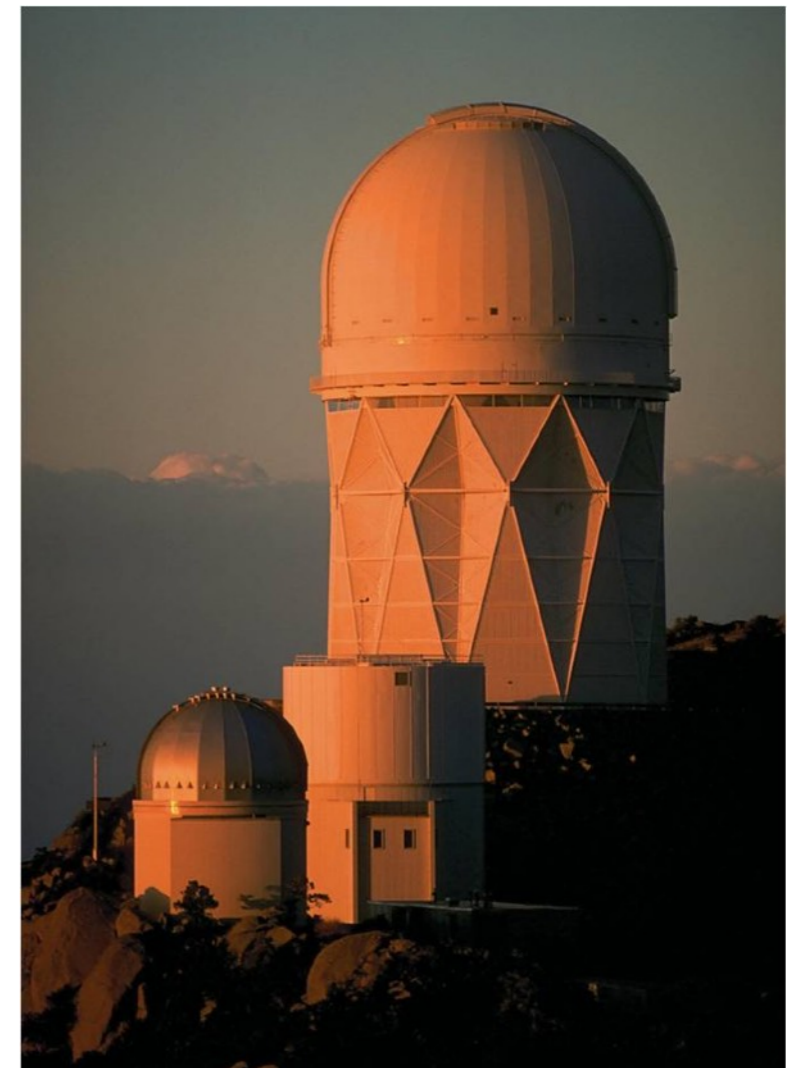


Phantom dark energy ~~22~~ 26 years later

Dragan Huterer
University of Michigan



VS.



Plan of talk

1. Two essential papers from ~ 25 years ago
2. DESI DR2++ constraints on dark energy
3. Where do the hints for departure from LCDM come from? What does it imply for the Hubble tension?

A Phantom Menace?

Cosmological Consequences of a Dark Energy Component

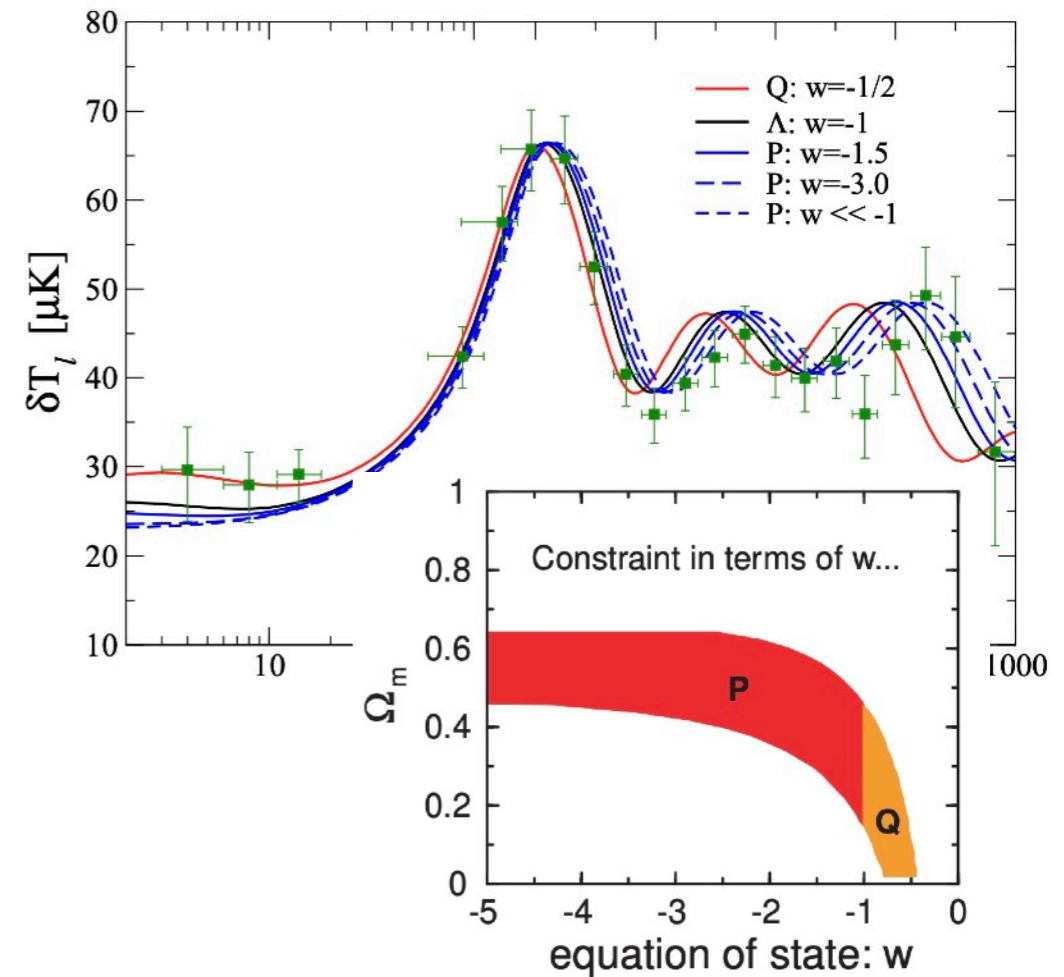
with Super-Negative Equation of State

R. R. Caldwell¹

Department of Physics & Astronomy, Dartmouth College, Hanover, NH 03755

Abstract

It is extraordinary that a number of observations indicate that we live in a spatially flat, low matter density Universe, which is currently undergoing a period of accelerating expansion. The effort to explain this current state has focused attention on cosmological models in which the dominant component of the cosmic energy density has negative pressure, with an equation of state $w \geq -1$. Remarking that most observations are consistent with models right up to the $w = -1$ or cosmological constant (Λ) limit, it is natural to ask what lies on the other side, at $w < -1$. In this regard, we construct a toy model of a “phantom” energy component which possesses an equation of state $w < -1$. Such a component is found to be compatible with most classical tests of cosmology based on current data, including the recent type 1a SNe data as well as the cosmic microwave background anisotropy and mass power spectrum. If the future observations continue to allow $w < -1$, then barring unanticipated systematic effects, the dominant component of the cosmic energy density may be stranger than anything expected.



PLB 545 (2002) 23-29;
3277 citations on INSPIRE

Phantom Energy and Cosmic Doomsday

Robert R. Caldwell,¹ Marc Kamionkowski,² and Nevin N. Weinberg²

¹*Department of Physics & Astronomy, Dartmouth College, 6127 Wilder Laboratory, Hanover, NH 03755*

²*Mail Code 130-33, California Institute of Technology, Pasadena, CA 91125*

Cosmologists have long wondered whether the Universe will eventually re-collapse and end with a Big Crunch, or expand forever, becoming increasingly cold and empty. Recent evidence for a flat Universe, possibly with a cosmological constant or some other sort of negative-pressure dark energy, has suggested that our fate is the latter. However, the data may actually be pointing toward an astonishingly different cosmic end game. Here, we explore the consequences that follow if the dark energy is phantom energy, in which the sum of the pressure and energy density is negative. The positive phantom-energy density becomes infinite in finite time, overcoming all other forms of matter, such that the gravitational repulsion rapidly brings our brief epoch of cosmic structure to a close. The phantom energy rips apart the Milky Way, solar system, Earth, and ultimately the molecules, atoms, nuclei, and nucleons of which we are composed, before the death of the Universe in a “Big Rip”.

PRL 91 (2003) 071301;
2178 citations on INSPIRE

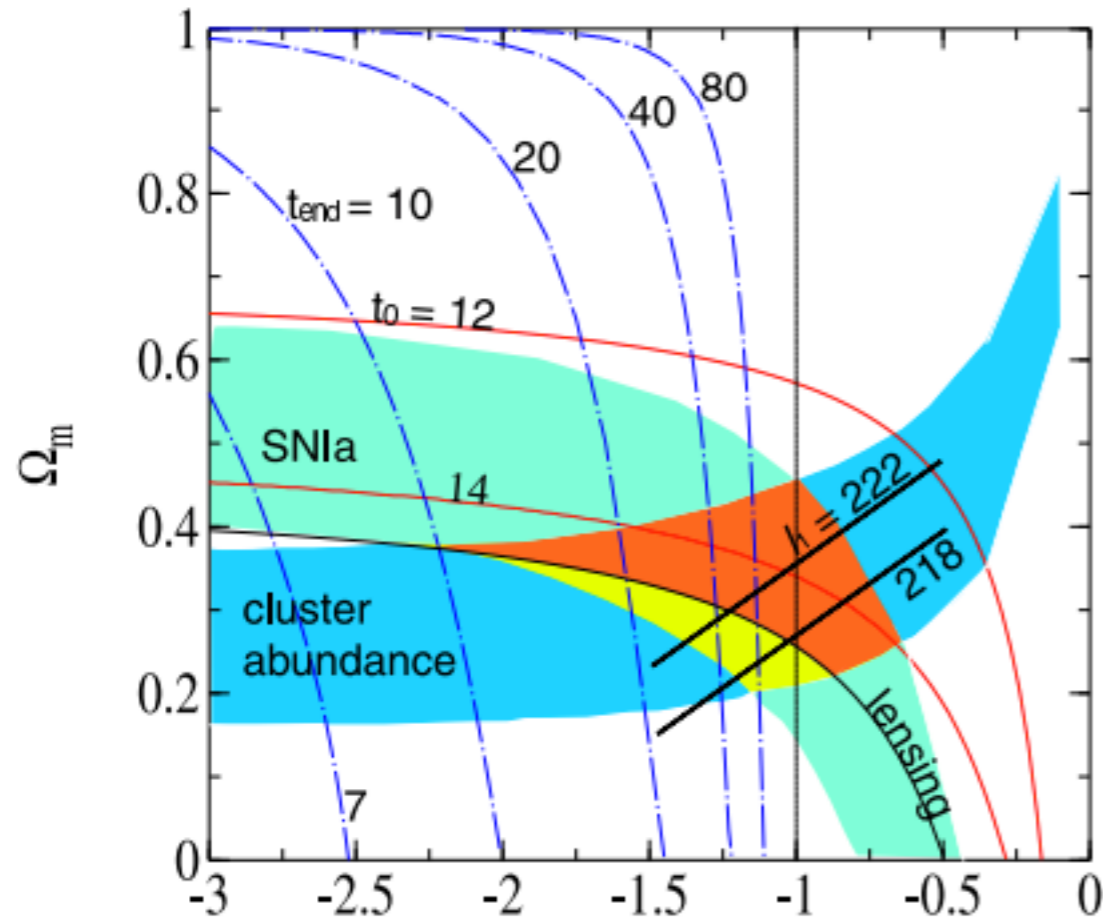


TABLE I: The history and future of the Universe with $w = -3/2$ phantom energy.

Time	Event
$\sim 10^{-43}$ s	Planck era
$\sim 10^{-36}$ s	Inflation
First Three Minutes	Light Elements Formed
$\sim 10^5$ yr	Atoms Formed
~ 1 Gyr	First Galaxies Formed
~ 15 Gyr	<i>Today</i>
$t_{rip} - 1$ Gyr	Erase Galaxy Clusters
$t_{rip} - 60$ Myr	Destroy Milky Way
$t_{rip} - 3$ months	Unbind Solar System
$t_{rip} - 30$ minutes	Earth Explodes
$t_{rip} - 10^{-19}$ s	Dissociate Atoms
$t_{rip} = 35$ Gyrs	Big Rip

Big Rip as a homework problem!

12.5 The Big Rip.

value — the so-universe's fate i turns out that tl so-called Big Rip Assume the cosm of state $w < -1$. parameter, that flat-universe for Demonstrate th the Big Rip star $w = -1.5$, and v

386

Dark energy

Friedmann I equation reads

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \Omega_{\text{DE}} a^{3\alpha}.$$

Solving this equation:

$$\begin{aligned}\frac{da}{a^{1+3\alpha/2}} &= H_0 \Omega_{\text{DE}}^{1/2} dt \\ -\frac{2}{3\alpha} a^{-3\alpha/2} \Big|_{a_0}^{a_{\text{rip}}} &= H_0 \Omega_{\text{DE}}^{1/2} \Delta t \\ \frac{2}{3\alpha} \left(\frac{1}{a_0^{3\alpha/2}} - \frac{1}{a_{\text{rip}}^{3\alpha/2}} \right) &= H_0 \Omega_{\text{DE}}^{1/2} \Delta t\end{aligned}$$

$$a_{\text{rip}} = \frac{1}{[1 - (3\alpha/2)H_0 \Omega_{\text{DE}}^{1/2} \Delta t]^{2/3\alpha}},$$

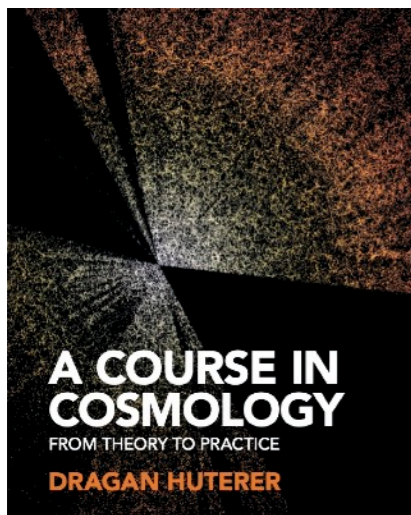
which demonstrates that the scale factor indeed blows up, in finite time given by

$$\Delta t_{\text{rip}} = \frac{2}{3|1+w|H_0 \Omega_{\text{DE}}^{1/2}}.$$

For the two values of w , this evaluates to

$$\Delta t_{\text{rip}} = \begin{cases} 22 \text{ Gyr} & (w = -1.5) \\ 220 \text{ Gyr} & (w = -1.05), \end{cases}$$

where we used $H_0^{-1} \simeq 14 \text{ Gyr}$.



Dark Energy Spectroscopic Instrument (DESI)

- on 4m Mayall telescope at Kitt Peak (AZ)
- international collaboration ~900 scientists, 72 institutions
- 5000 spectra at once (system built at Michigan - Tarlé group)
- operating extremely well: up to 100,000 spectra per night!
- world's leading spectroscopic survey

key DESI
science:

1. dark energy
2. neutrino mass
3. primordial non-Gaussianity



student
Prakhar Bansal
(cosmo analysis)



student
Jiaming Pan
(cosmo analysis)

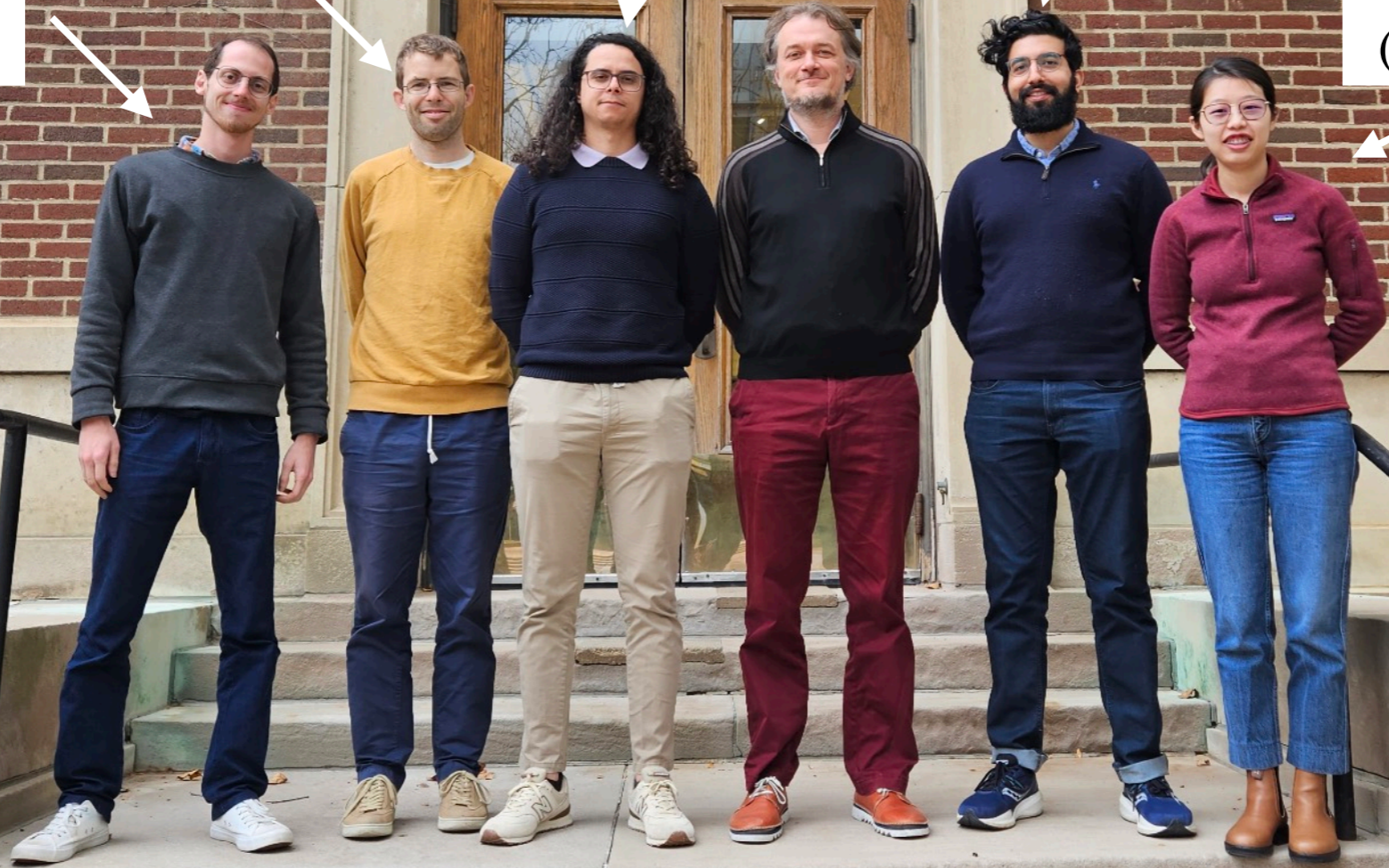
postdoc
Uendert Andrade
(blinding); **DR2
BAO coord.**

postdoc (now prof)
Johannes Lange
(DESI x lensing)

student
Sikandar Hanif
(fiber assignment)

student
Otavio Alves
(covariance)

student
Tianke Zhuang
(cosmo analysis)



Huterer group at UMich: DESI effort

DESI DR2 sample

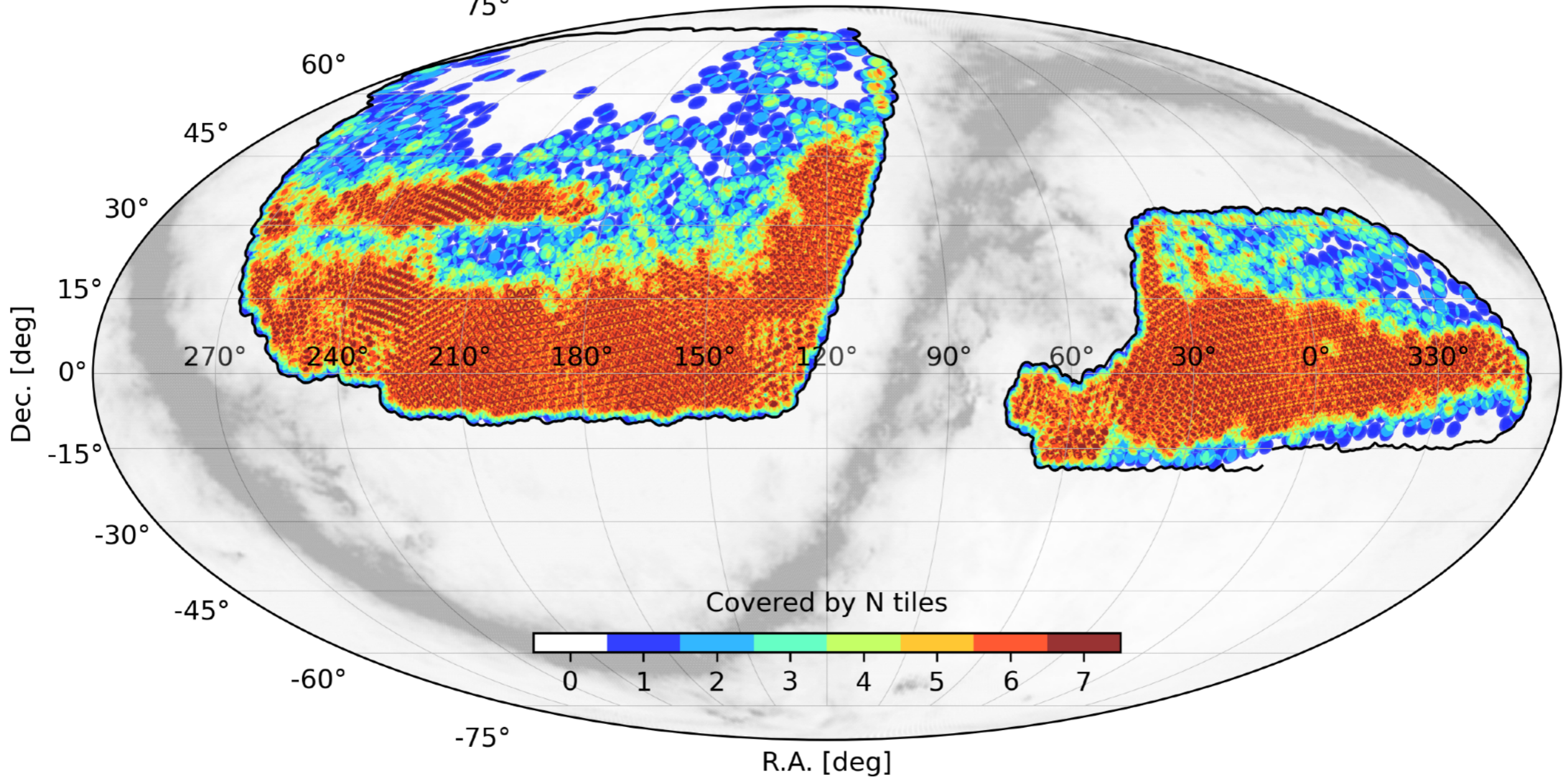
- Over 30M galaxy and quasar redshifts in **3 years of operation**, ~14M of which are used in this analysis.
- Compared to DR1 (~6M redshifts), DR2 represents a factor of **~2.4 improvement** in data volume.

Redshifts for the BAO analysis

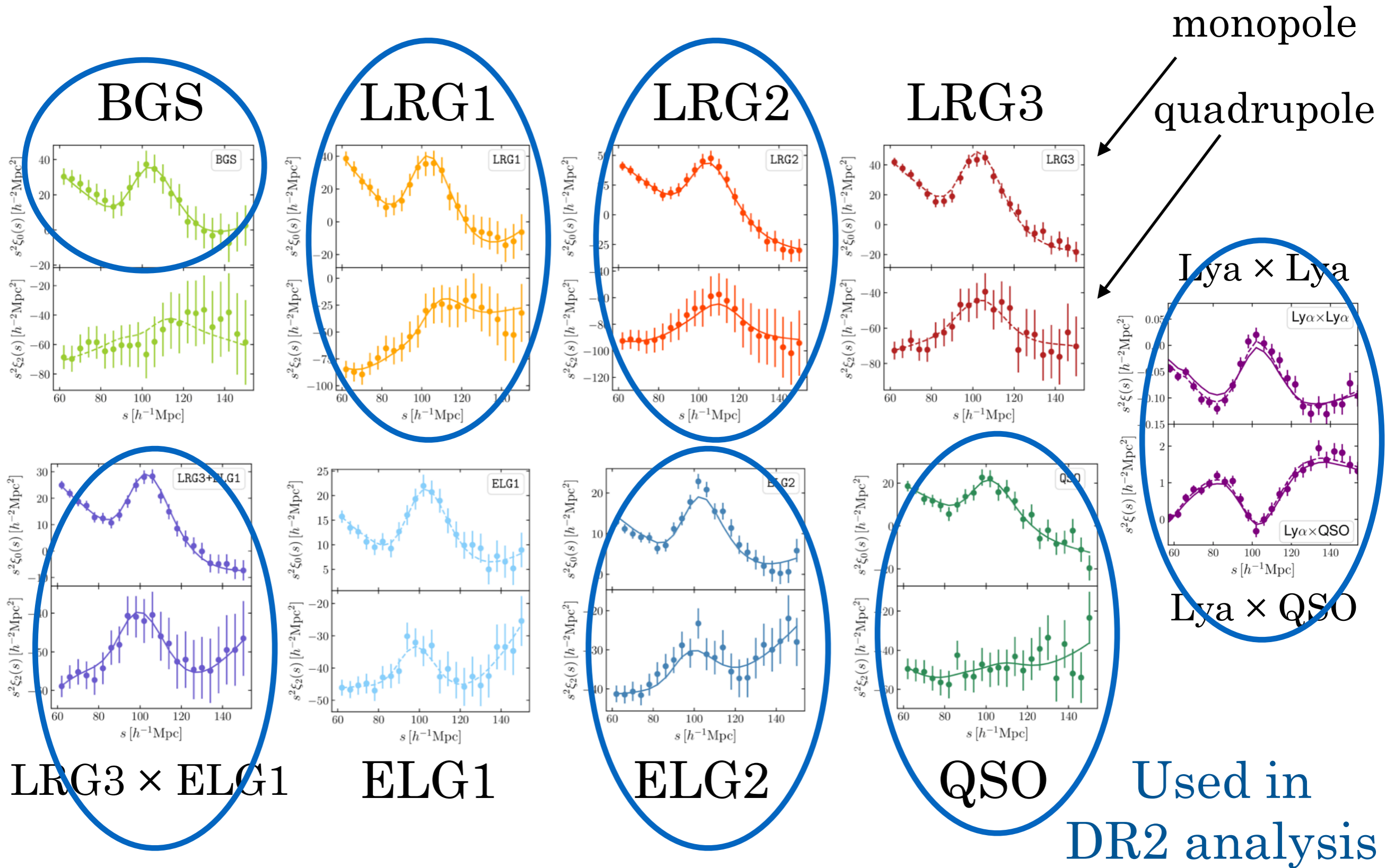
Tracer	DR1	DR2
BGS	300,043	1,188,526
LRG	2,138,627	4,468,483
ELG	2,432,072	6,534,844
QSO	1,223,391	2,062,839
Total	6,094,133	14,254,692

The DESI DR2 sample

DESI Y3 DARK : 6671/9929 observed tiles up to 20240409 (=67%)

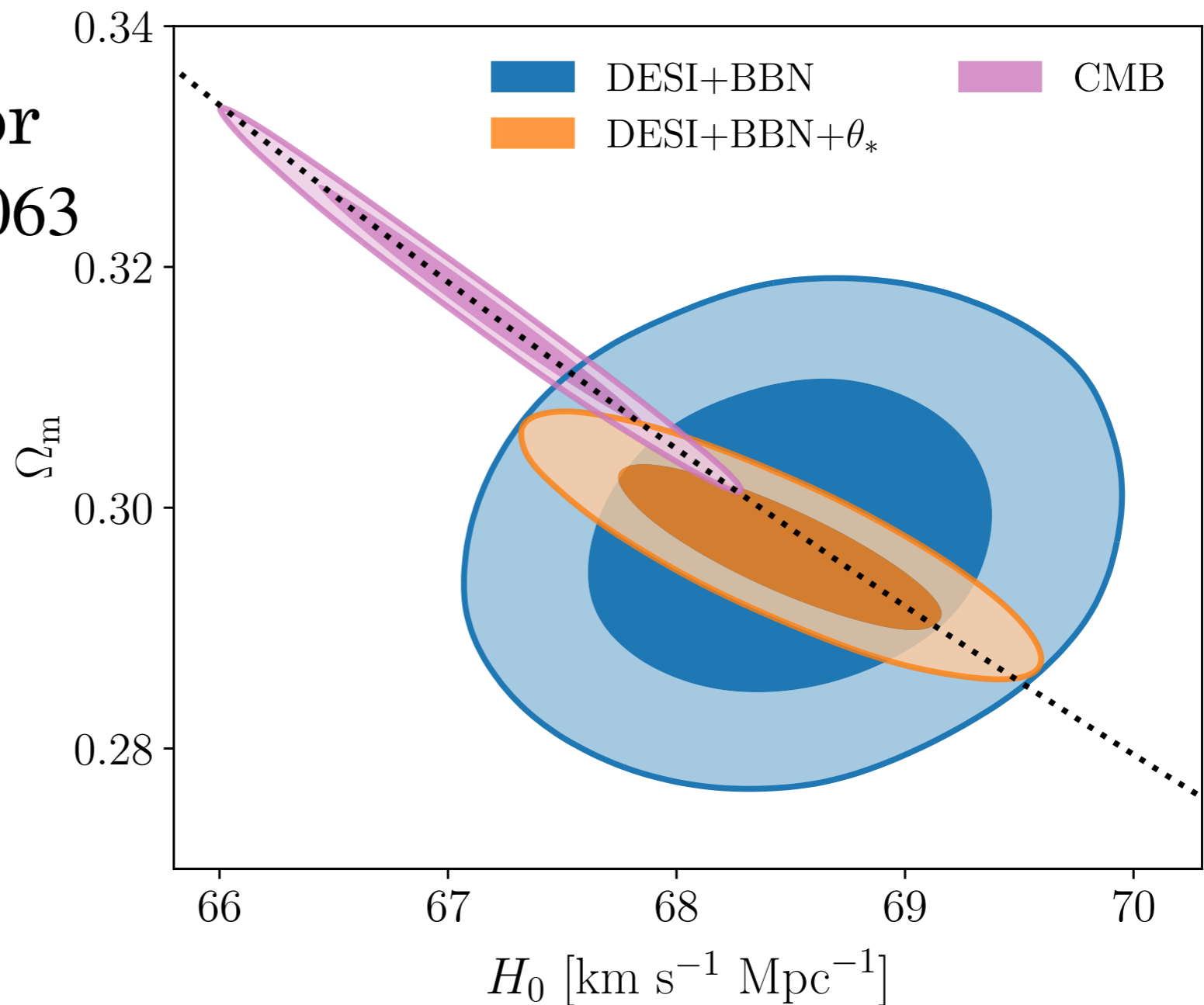


DESI DR2 Clustering Measurements



Hubble constant (in LCDM)

Requires BBN prior
 $\Omega_b h^2 = 0.02196 \pm 0.00063$
(Schöneberg 2024)



$$H_0 = (68.51 \pm 0.58) \text{ km/s/Mpc} \quad (\text{DESI} + \text{BBN})$$

28% more precise than in DR1;
4.5 σ away from SH0ES (without CMB!)

Dark energy - (w_0, w_a)

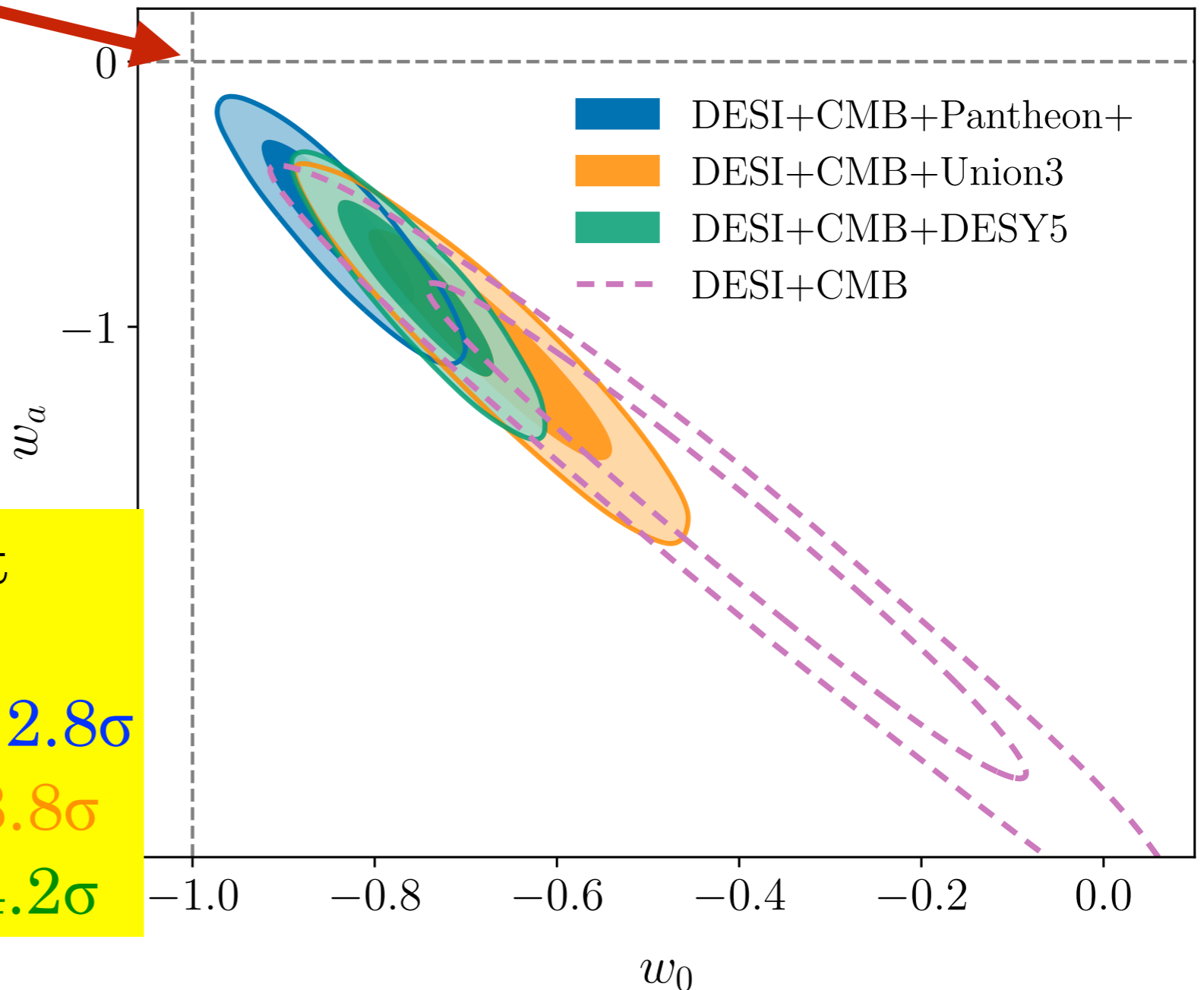
$$w(a) = w_0 + w_a(1 - a)$$

a is scale factor
 $a=0$: Big Bang
 $a=1$: today

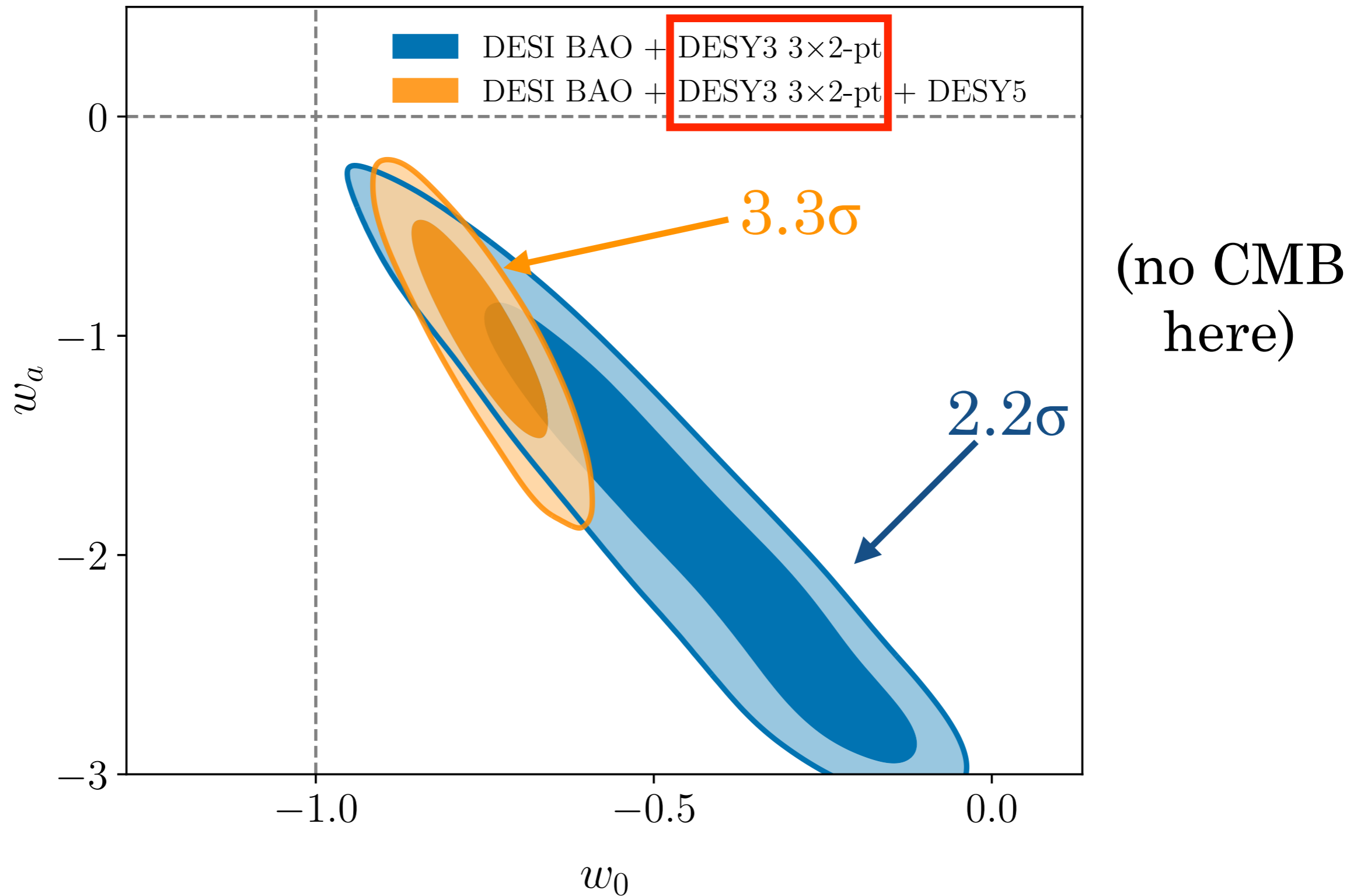
Λ CDM
(standard model)

DESII shows
preference for
 $w_0 > -1, w_a < 0$

Significance against
LCDM:
DESII+CMB+Pantheon: 2.8σ
DESII+CMB+Union3: 3.8σ
DESII+CMB+DESY5: 4.2σ

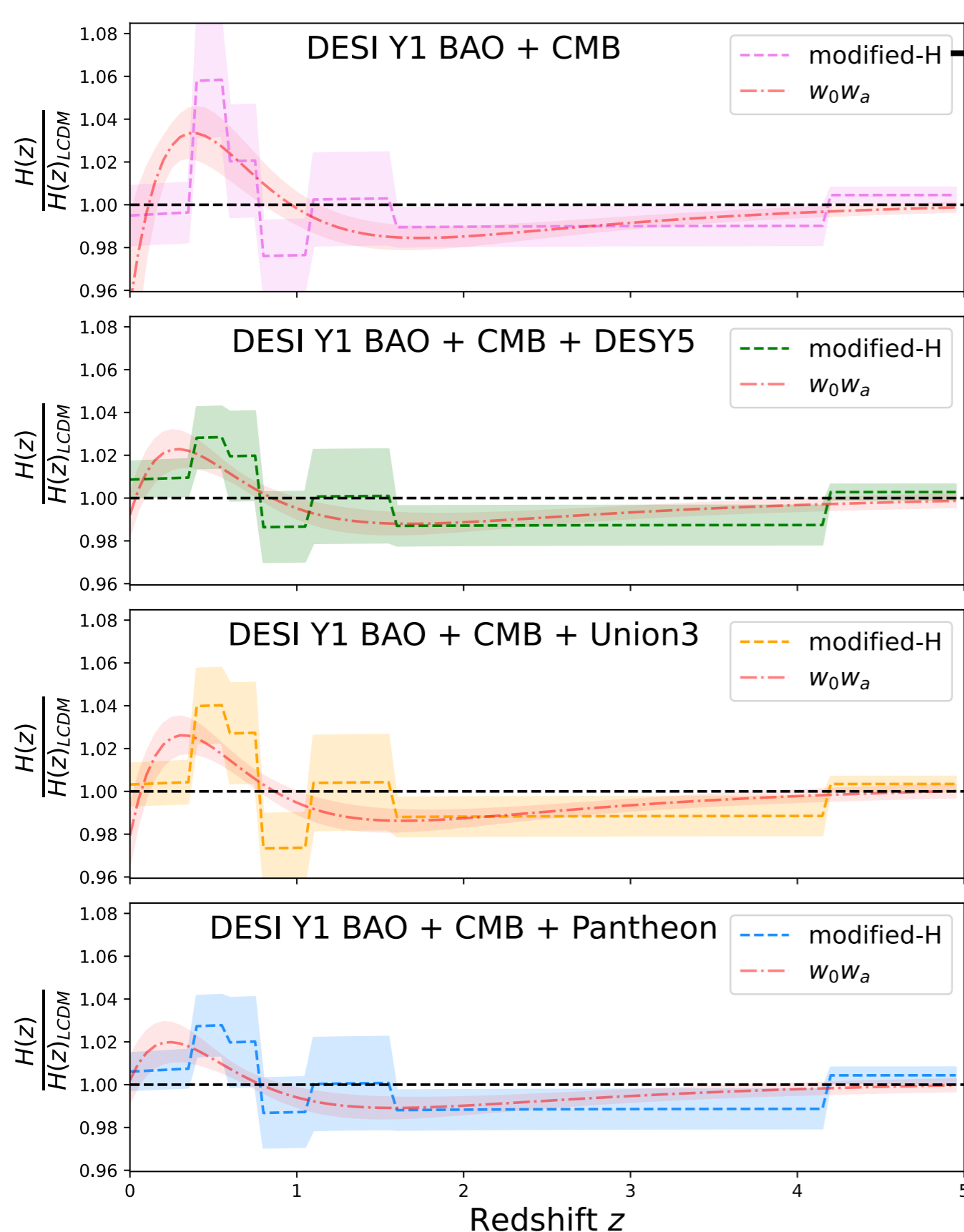


Low- z probes alone hint for ~~LCDM~~



Therefore: tantalizing hints of departure from LCDM

Attempt to understand this DE tension



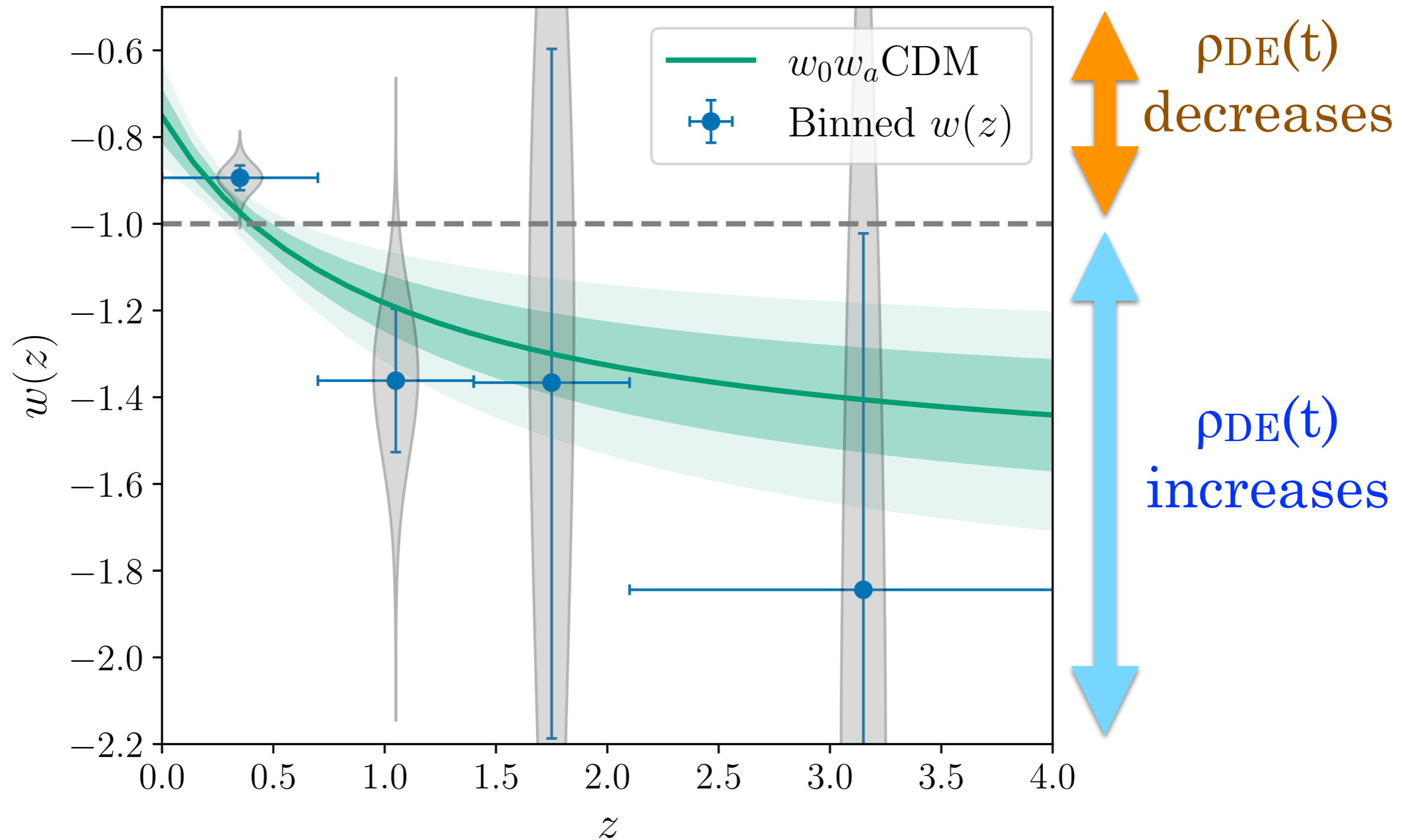
new model with lots of $H(z)$ freedom

We find: a more general expansion history agrees very well with best-fit w_0w_a

(so e.g. goodness of fit only marginally better with several more parameters)

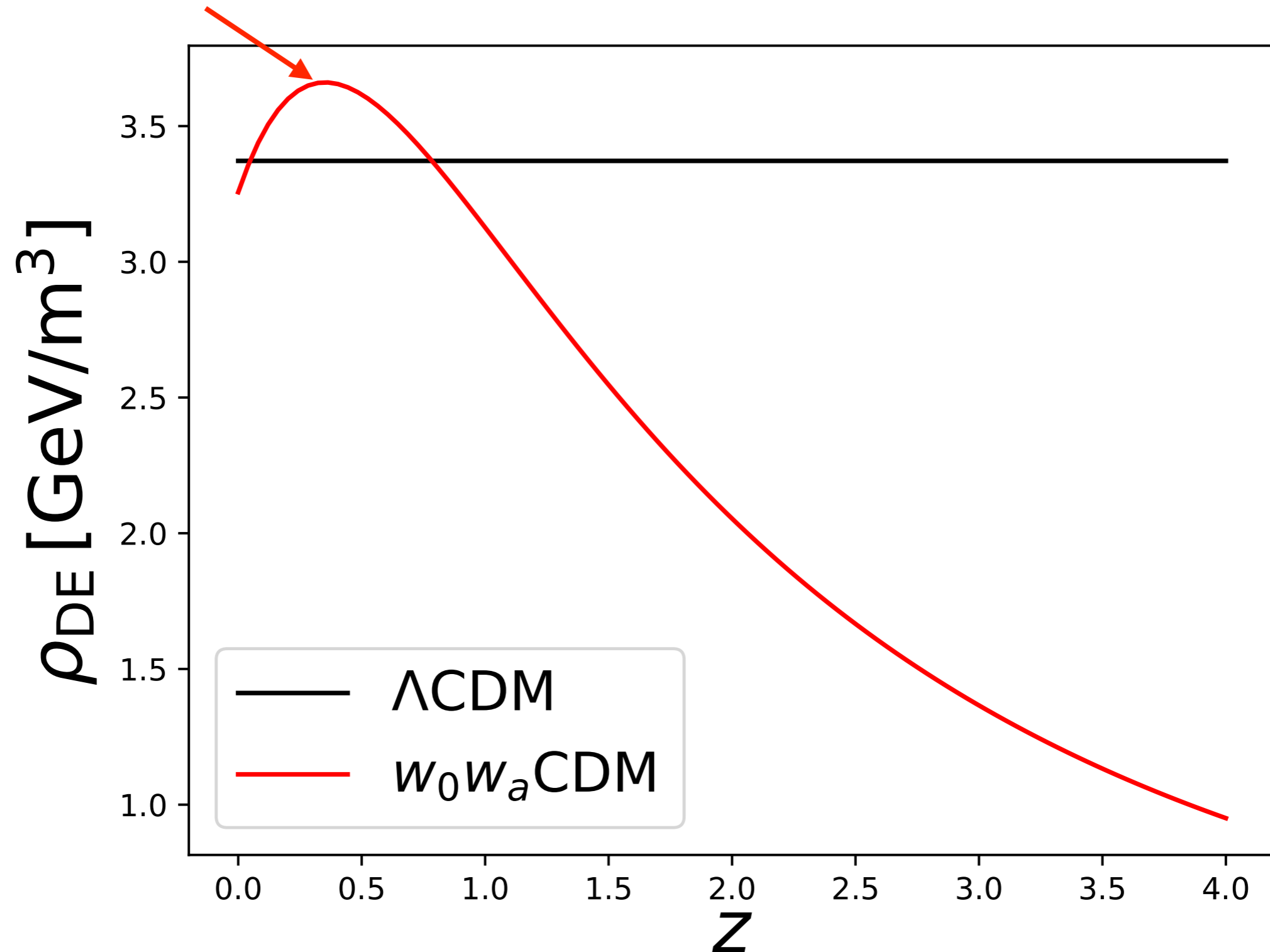


Robustness confirmed by alternative analyses



in other words

Best-fit w_0w_a model
from DESI+CMB+SNIa



DESI DR2 Frequently Asked Questions!

★ Are the datasets that you are combining in conflict/tension?

➔ No. For example, DESI BAO and DESY5 SNIa are consistent in $w_0wa\Lambda\text{CDM}$.

★ Is DESI DR2 BAO data in tension with SDSS BAO?

➔ No, even at level of individual data pts

(e.g. $z=0.71$ data pt that was in 3-sigma difference is now <2 sigma)

★ Is conflict w ΛCDM due to specific data point XYZ (e.g. $z=0.51$ BAO)?

➔ No - we checked!

★ Isn't it an "unsettling" coincidence that we find $w(z) \simeq -1$ at z_{pivot} ?

➔ No:

1) it's a coincidence, nothing unsettling;

2) in fact $w(z_p)$ is away from -1 (DESI BAO + SNIa + CMB gives -0.954 ± 0.024);

3) it also wouldn't be unexpected in models where CMB distance prior is satisfied (as explained in E. Linder's "mirage of $w = -1$ " 2007 paper)

Five facts about hints for dynamical dark energy (and Hubble tension)

Fact #1:

- The preference for $w_0wa\Lambda\text{CDM}$ model does not come from a single cosmological probe

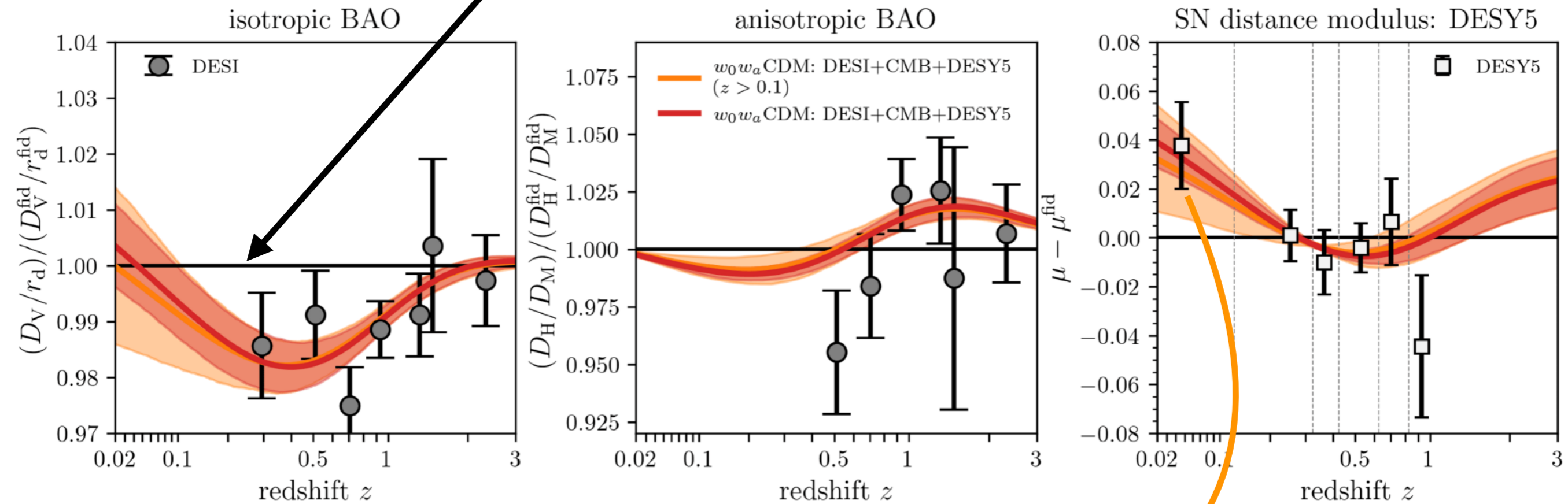
Datasets	$\Delta\chi_{\text{MAP}}^2$	Significance	$\Delta(\text{DIC})$
DESI	-4.7	1.7σ	-0.8
DESI+ $(\theta_*, \omega_b, \omega_{bc})_{\text{CMB}}$	-8.0	2.4σ	-4.4
DESI+CMB (no lensing)	-9.7	2.7σ	-5.9
DESI+CMB	-12.5	3.1σ	-8.7
DESI+Pantheon+	-4.9	1.7σ	-0.7
DESI+Union3	-10.1	2.7σ	-6.0
DESI+DESY5	-13.6	3.3σ	-9.3
DESI+DESY3 ($3\times 2\text{pt}$)	-7.3	2.2σ	-2.8
DESI+DESY3 ($3\times 2\text{pt}$)+DESY5	-13.8	3.3σ	-9.1
DESI+CMB+Pantheon+	-10.7	2.8σ	-6.8
DESI+CMB+Union3	-17.4	3.8σ	-13.5
DESI+CMB+DESY5	-21.0	4.2σ	-17.2

Fact #2:

Preference for dynamical dark energy comes about because data prefer “curvature” in distance(z)

(but why *that* is, I/we don't know)

LCDM



Arnaud de Mattia

orange contours:
same result even when
dropping $z < 0.1$ data

Fact #3:

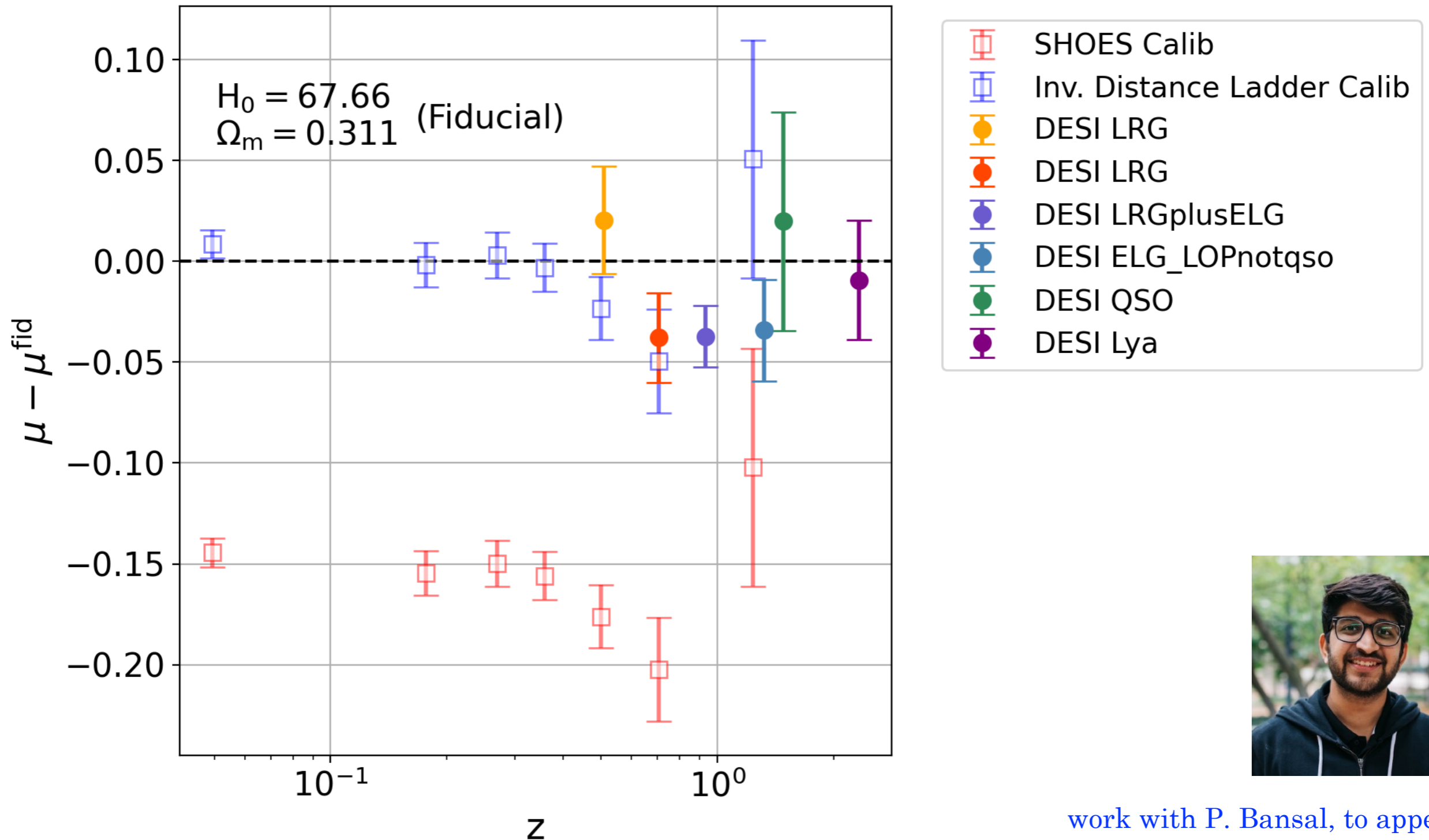
LCDM tension and Hubble tension are different!

- No apparent relationship (afaik)
- Also Hubble tension gets worse in w_0w_a CDM:

$$H_0^{w_a w_a \text{CDM}} \simeq (63 - 67) \text{ km/s/Mpc}$$

Fact #4:

It is near impossible to relax both Hubble tension and evidence for dynamical DE with a low-z model - even w/ model with a sharp jump in $H(z)$



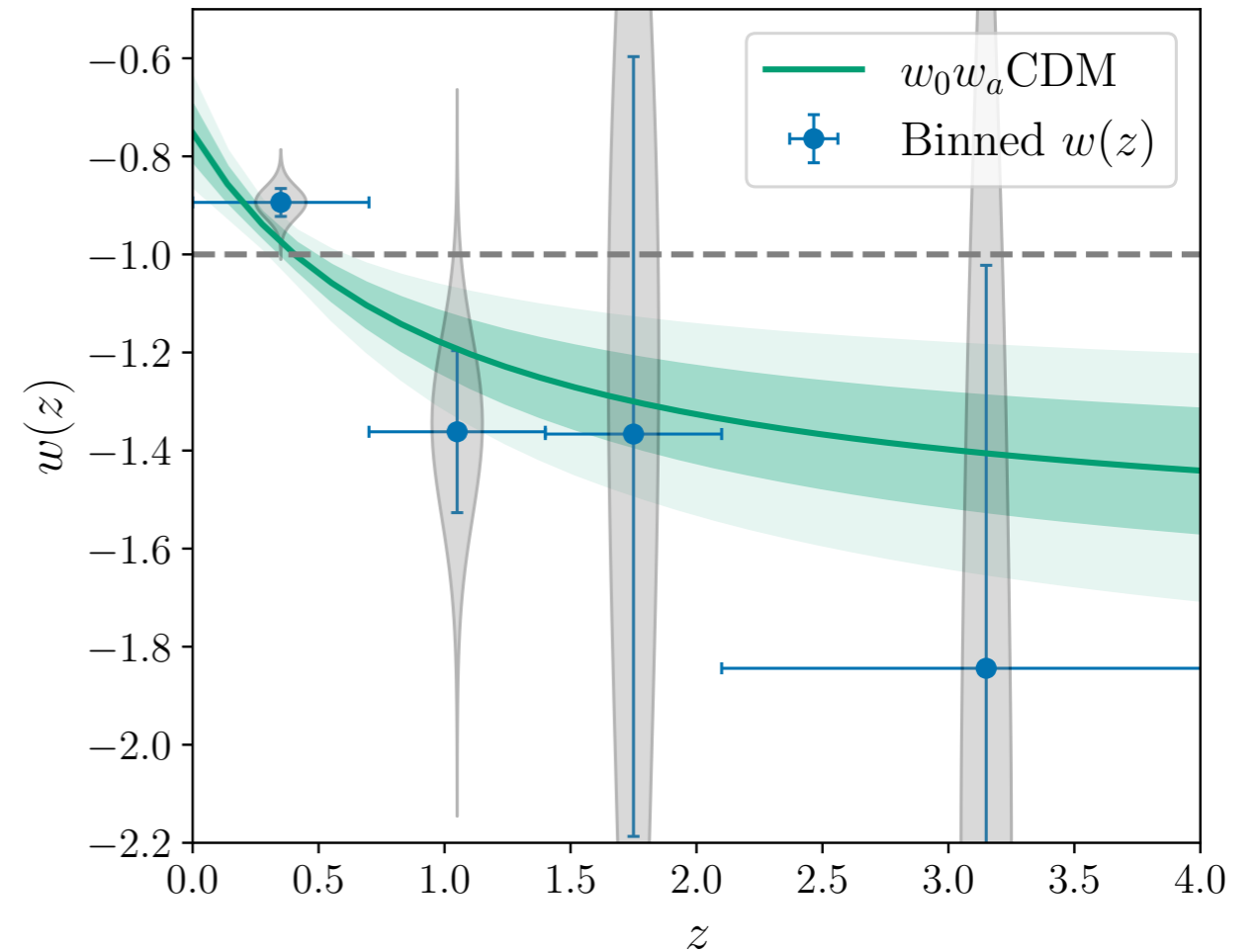
work with P. Bansal, to appear

Fact #5:

Finally, is there convincing evidence in the data for

- phantom dark energy, or
- phantom crossing, or
- “slowdown” of DE ($w > -1$)?

No (for either).



- The strongest statistical hints are for departure from LCDM, in particular in w_0w_a CDM model.
- We have not tested the above aspects alone, but statistical evidence for them would be necessarily weaker.

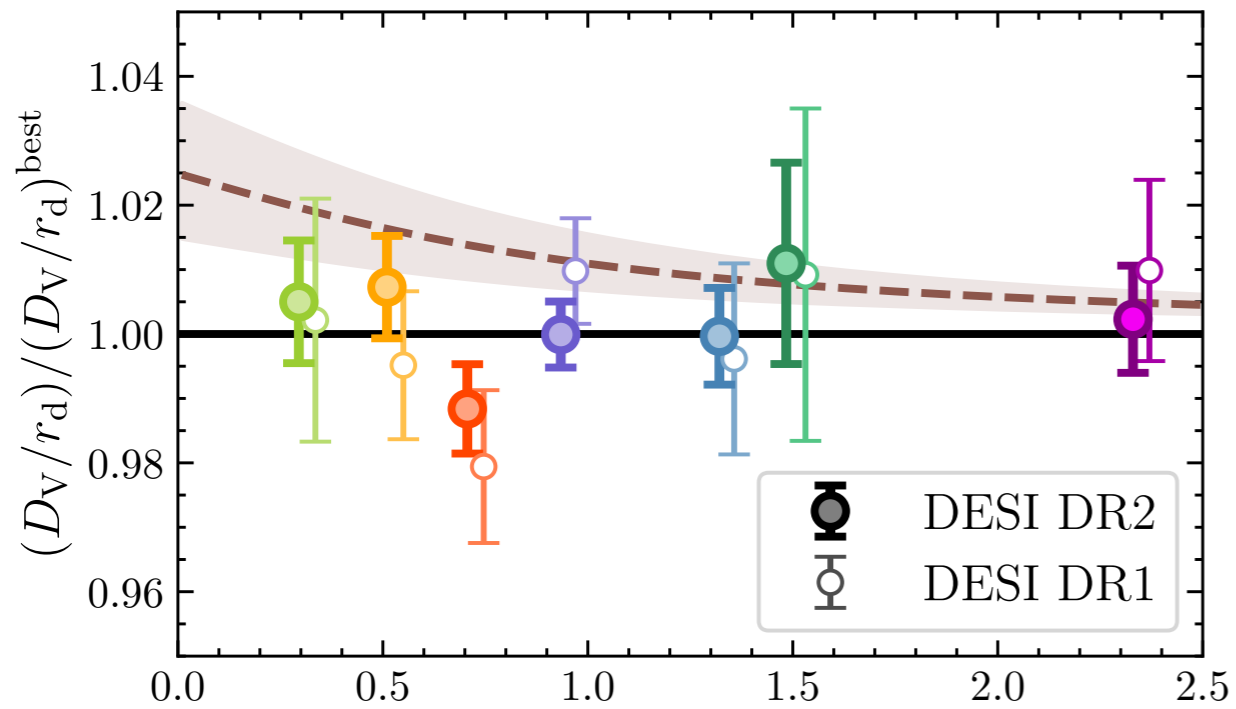
Conclusions

- Hints for departure from LCDM model are independent from (albeit statistically weaker than) the Hubble tension
- There is no one simple explanation (in the data) for the preference for w_0w_a CDM
- These hints are exciting, but to claim evidence for departure from the standard LCDM model should require a **very high bar**
- It will be exciting to see what forthcoming data show
- Phantom dark energy is definitely in play (though no firm evidence for it in current data)

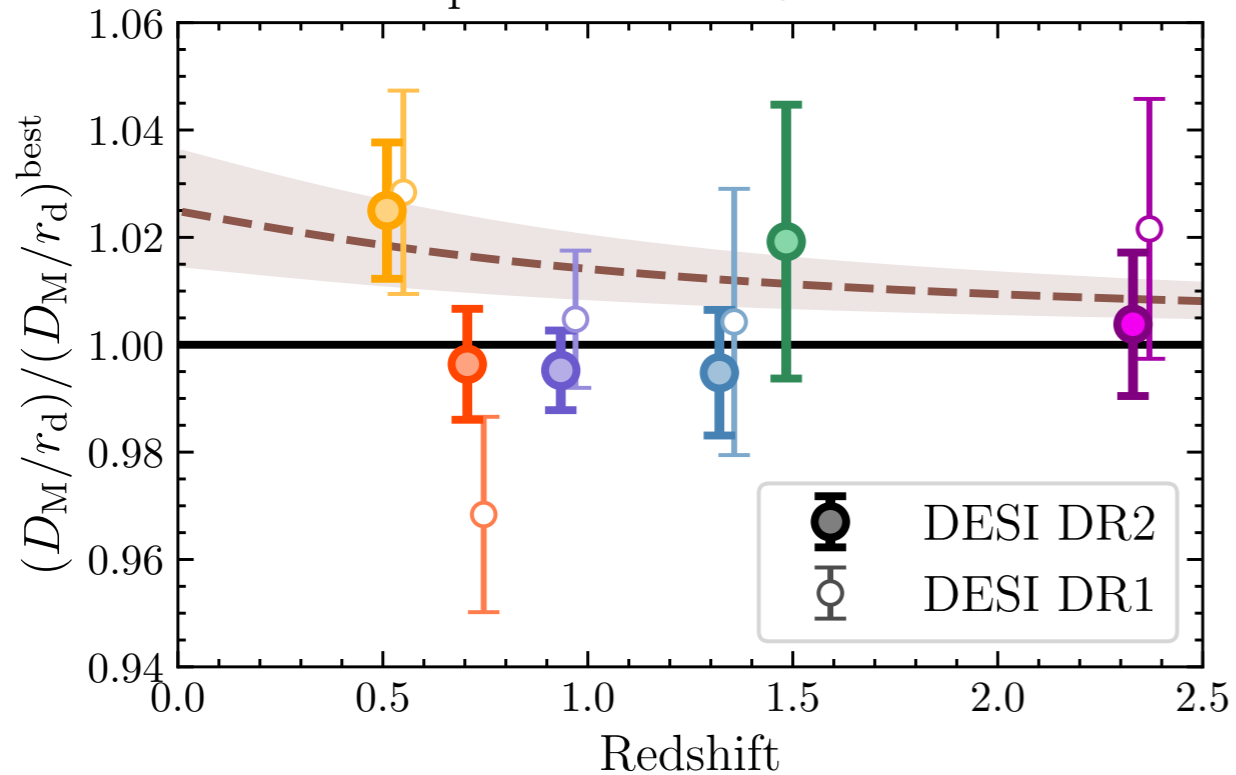
Extra slides

DR2 Distance Measurements

Isotropic BAO Distance



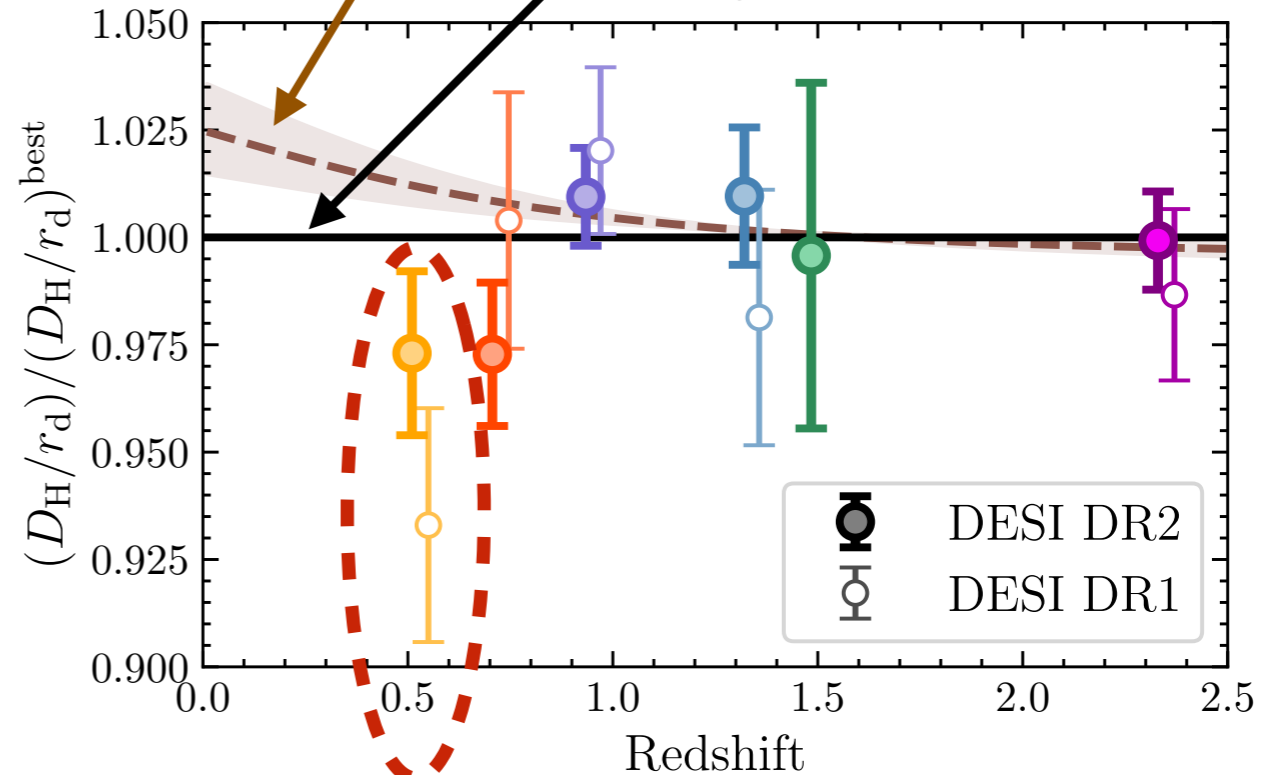
Perpendicular BAO Distance

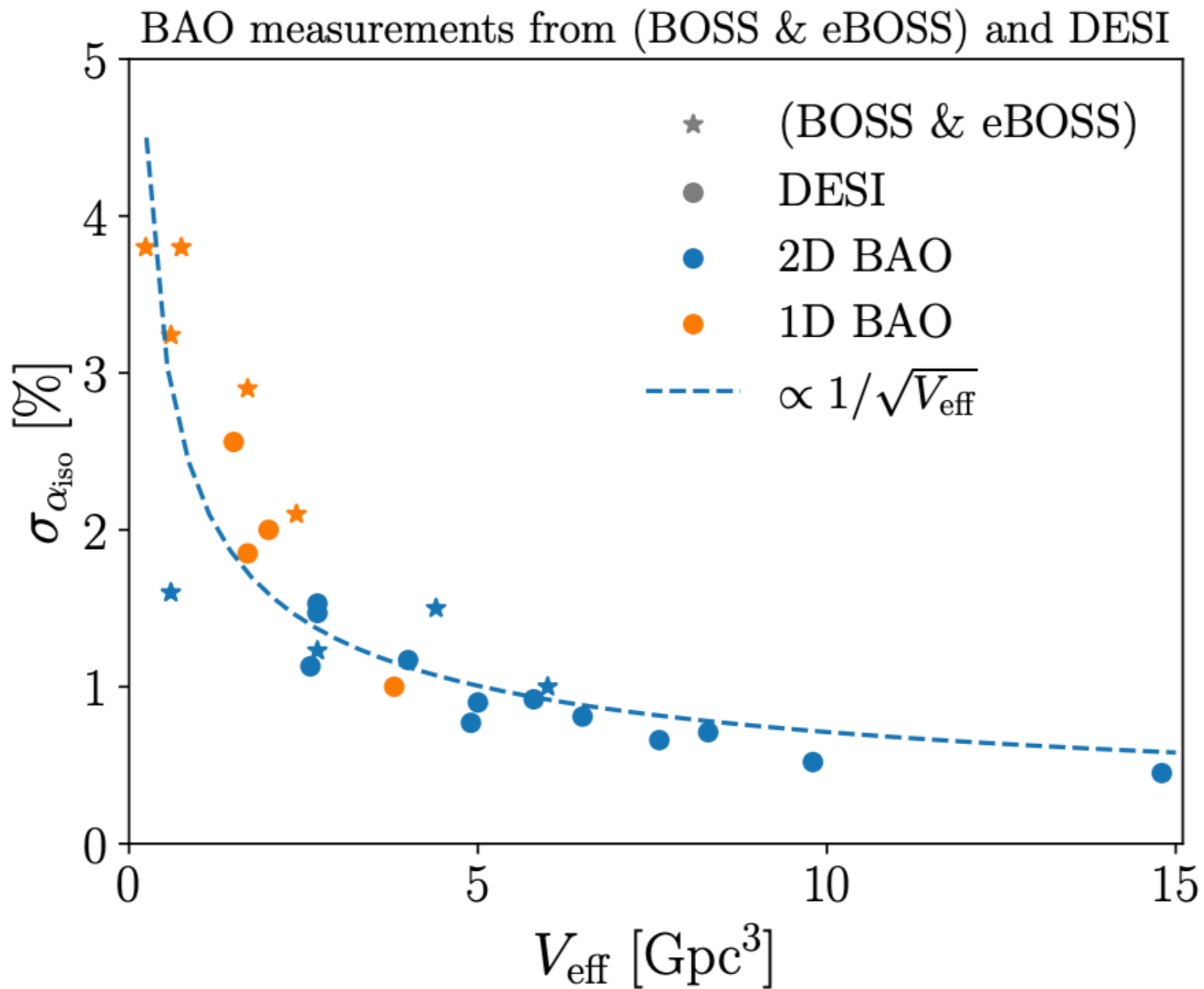


Planck18 LCDM

DESI best fit

Parallel BAO Distance

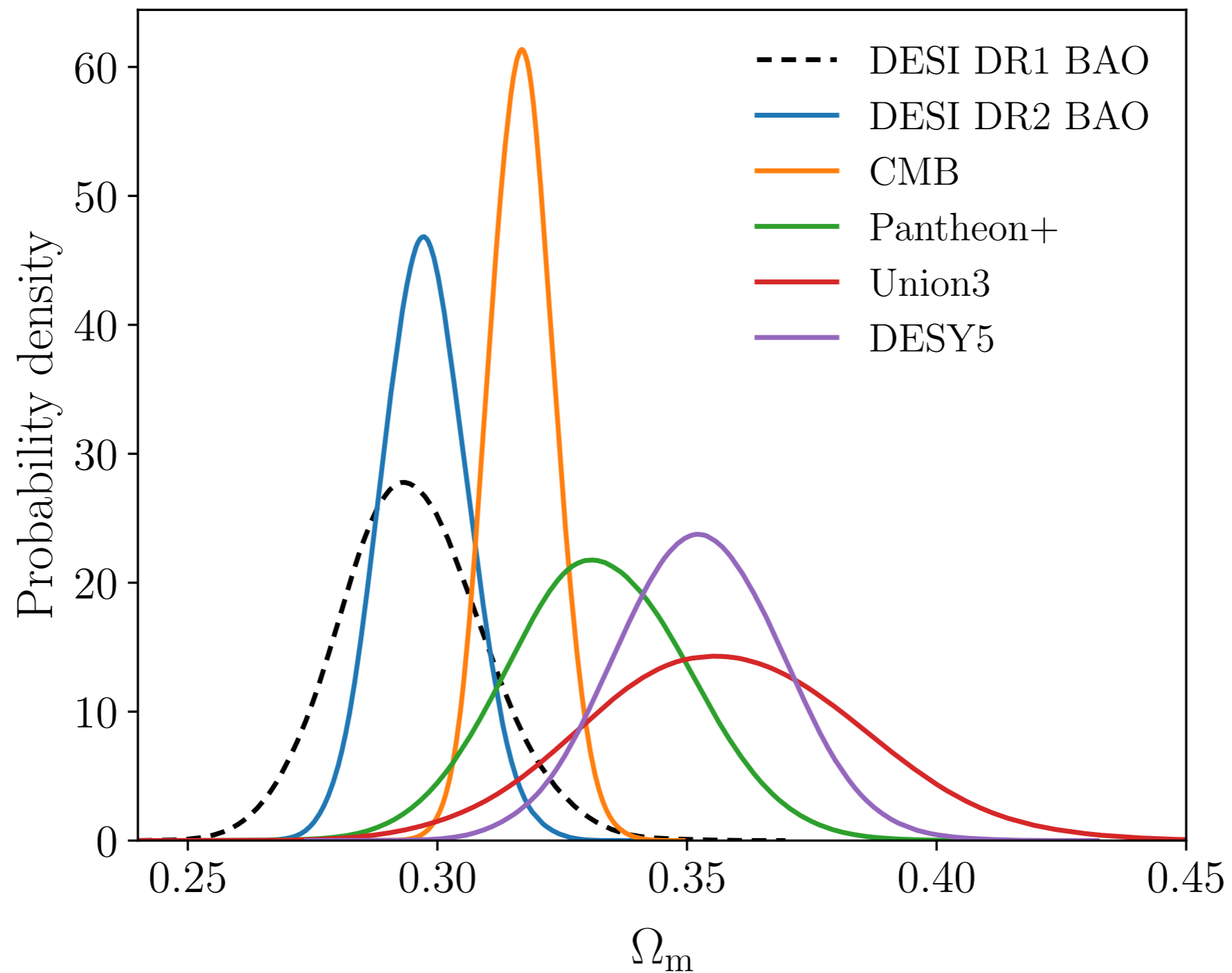




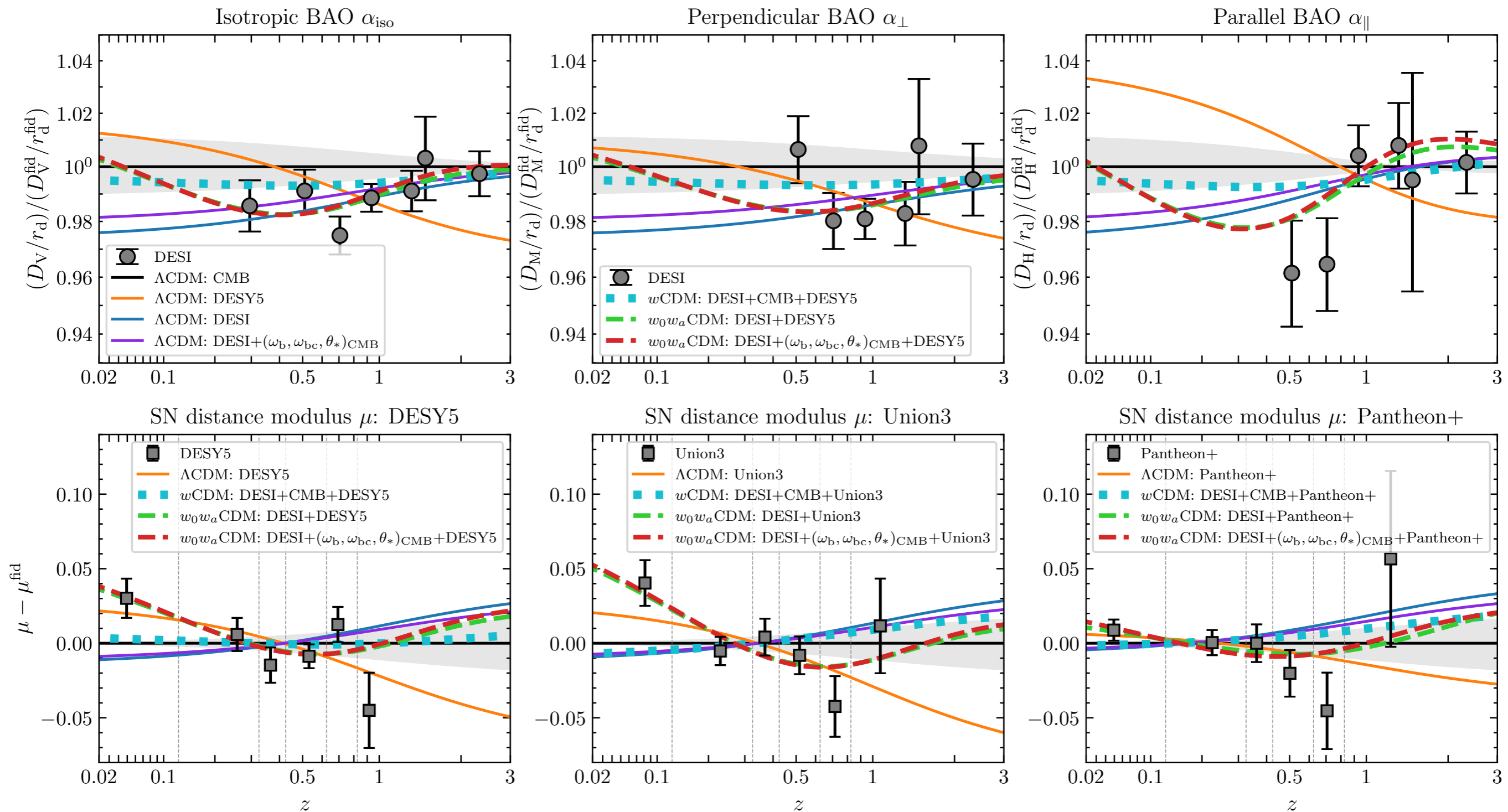
Significances of w_0w_a vs LCDM

Datasets	$\Delta\chi_{\text{MAP}}^2$	Significance	$\Delta(\text{DIC})$
DESI	-4.7	1.7σ	-0.8
DESI+ $(\theta_*, \omega_b, \omega_{bc})_{\text{CMB}}$	-8.0	2.4σ	-4.4
DESI+CMB (no lensing)	-9.7	2.7σ	-5.9
DESI+CMB	-12.5	3.1σ	-8.7
DESI+Pantheon+	-4.9	1.7σ	-0.7
DESI+Union3	-10.1	2.7σ	-6.0
DESI+DESY5	-13.6	3.3σ	-9.3
DESI+DESY3 ($3\times 2\text{pt}$)	-7.3	2.2σ	-2.8
DESI+DESY3 ($3\times 2\text{pt}$)+DESY5	-13.8	3.3σ	-9.1
DESI+CMB+Pantheon+	-10.7	2.8σ	-6.8
DESI+CMB+Union3	-17.4	3.8σ	-13.5
DESI+CMB+DESY5	-21.0	4.2σ	-17.2

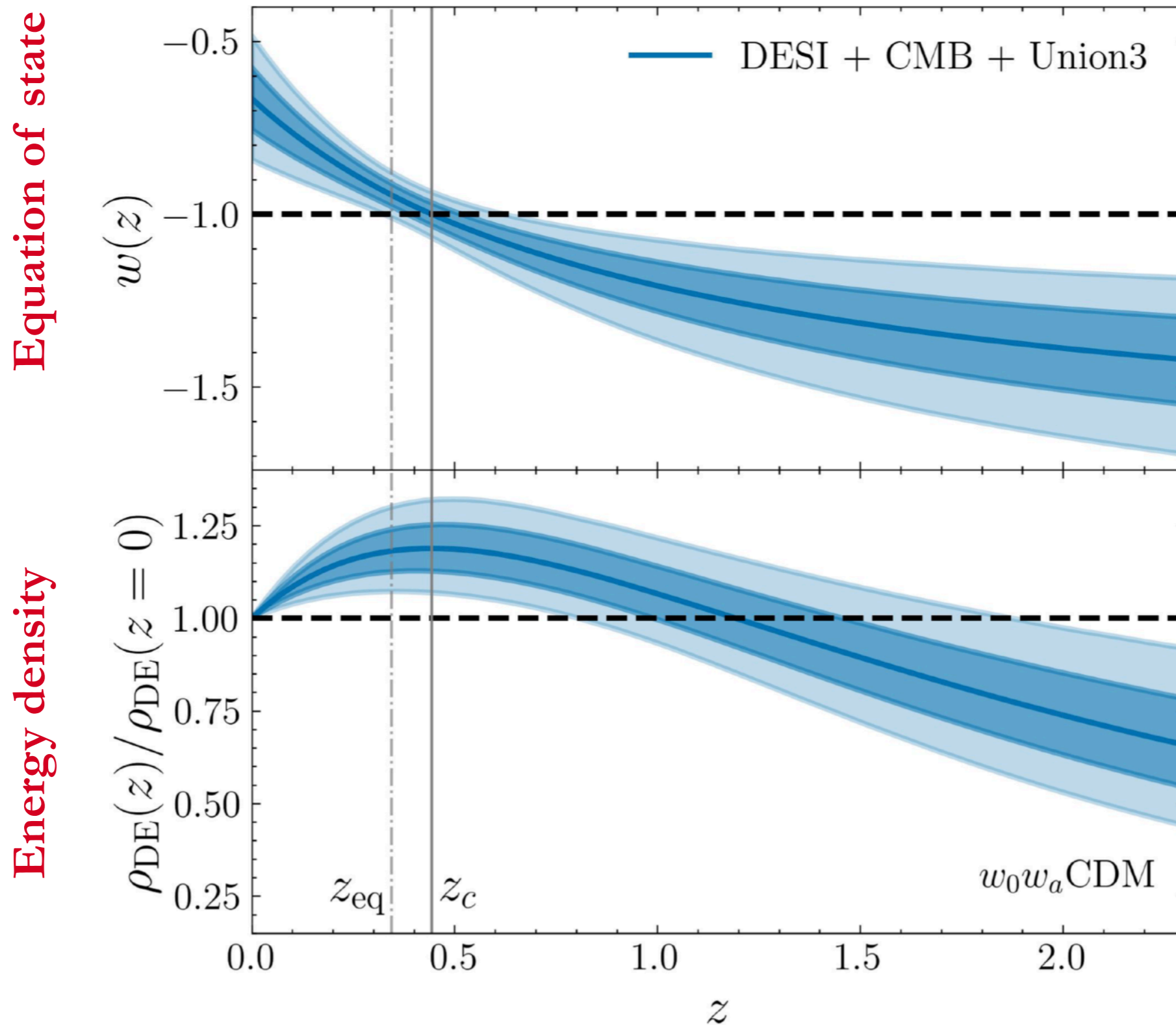
Ω_m constraints in LCDM



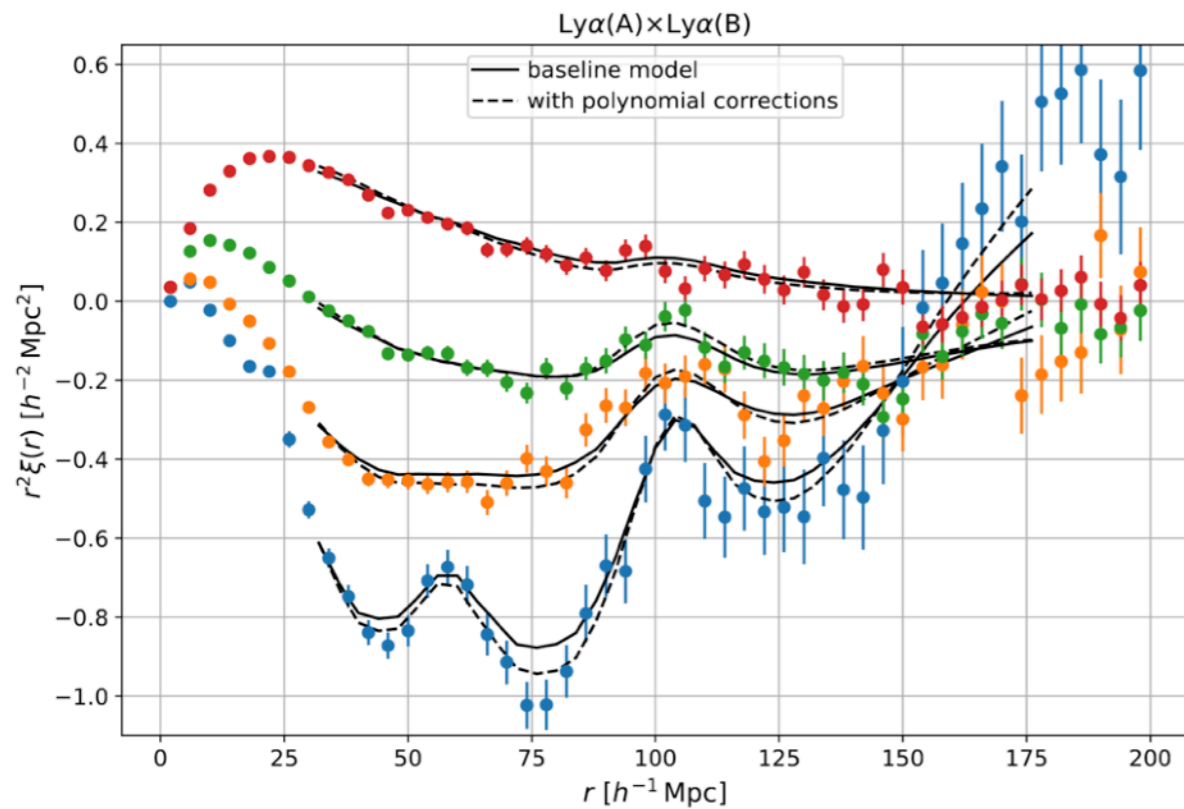
Why preference for w_0w_a (from DR2 key paper)



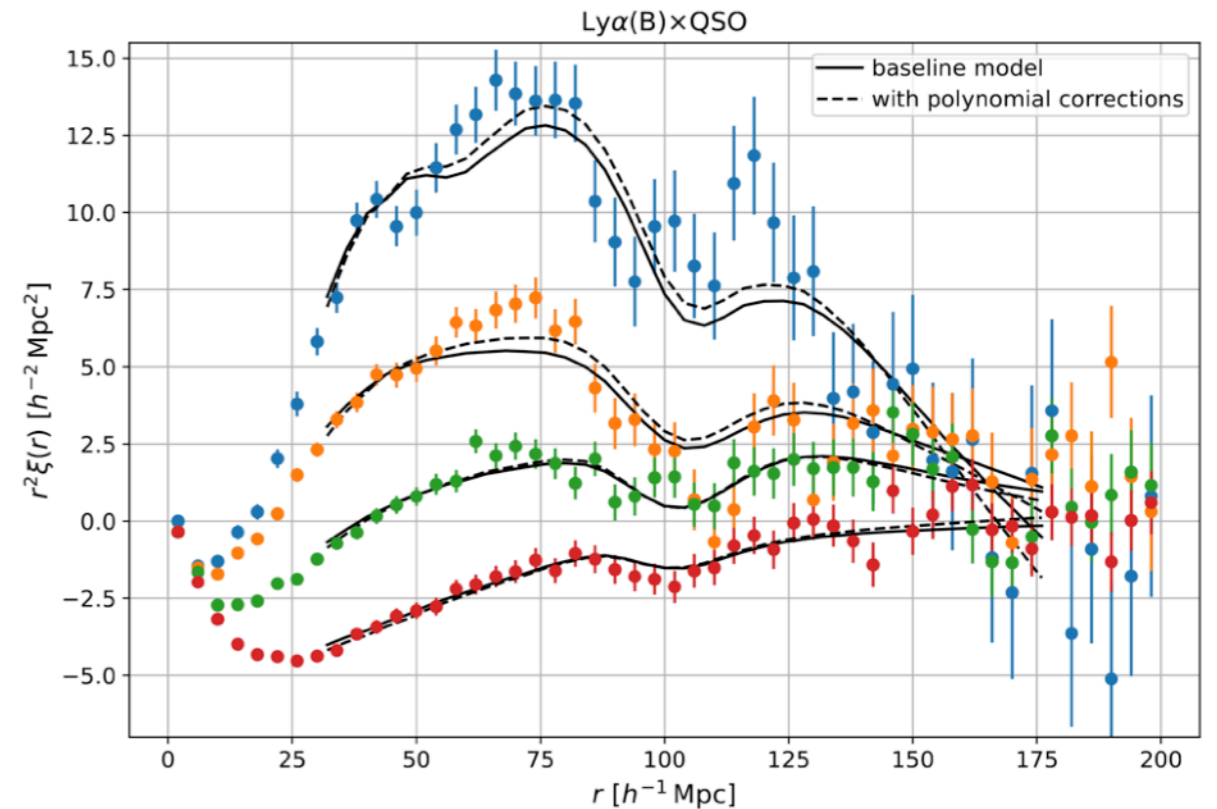
What best-fit w_0w_a model predicts



Lyman α Forest Correlations

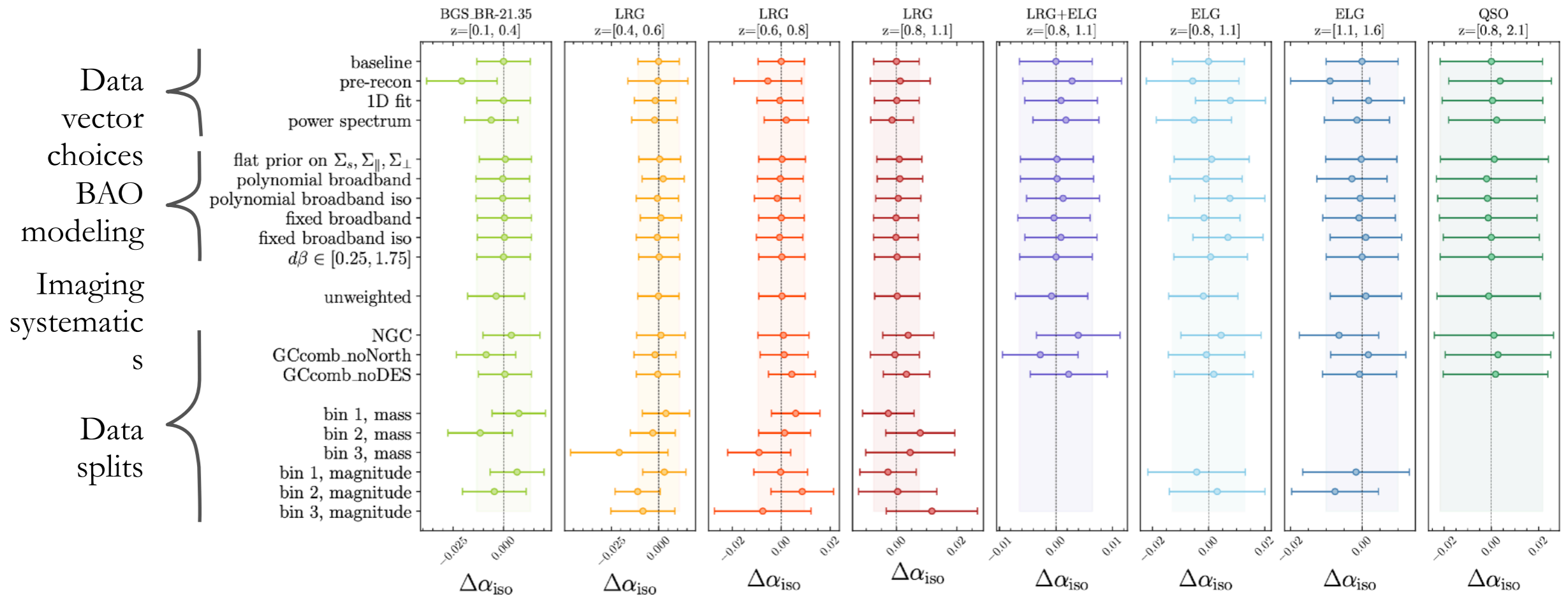


Ly α forest autocorrelation
 $\xi(r) = \langle \delta_F(x) \delta_F(x+r) \rangle$



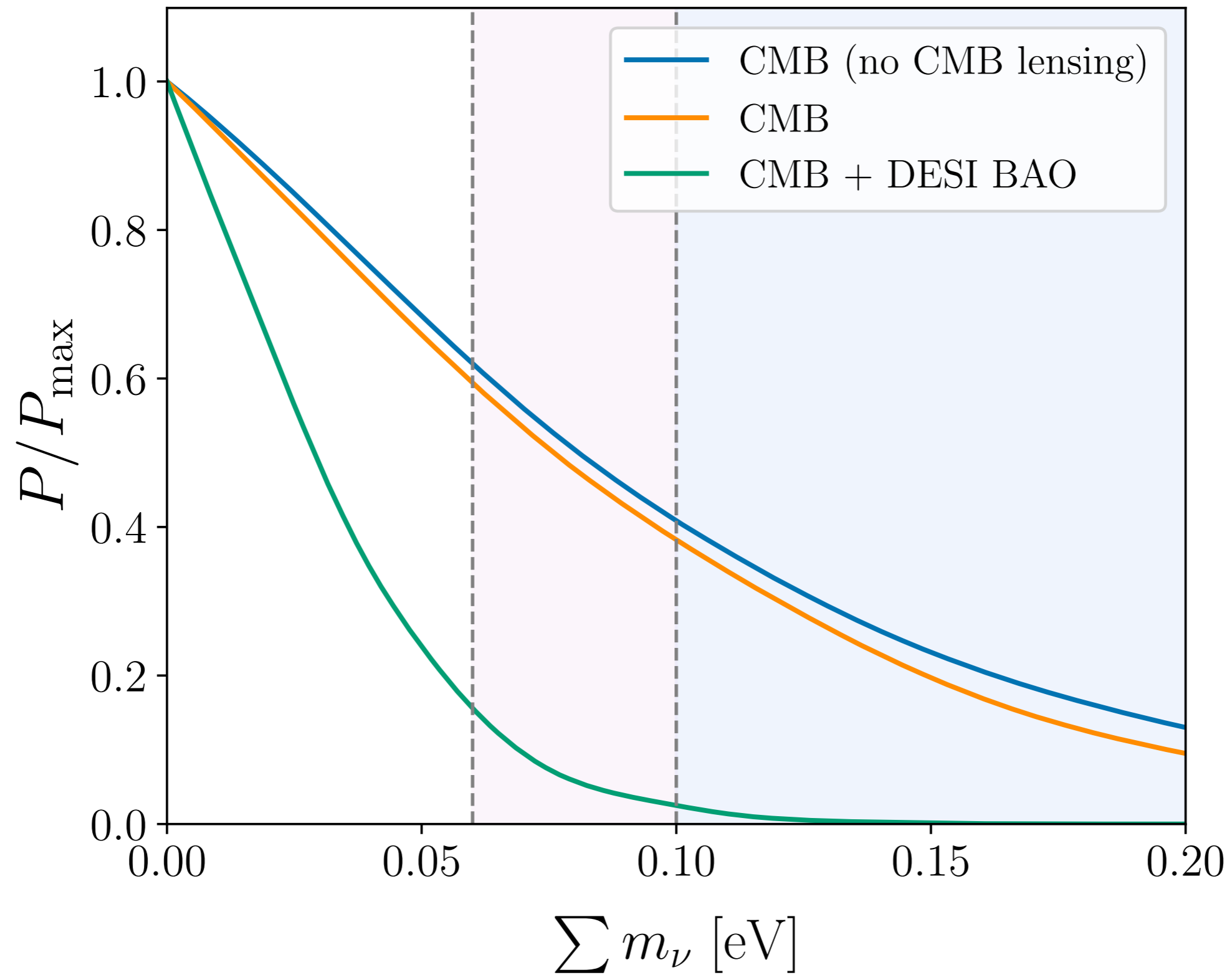
Ly α -QSO cross-correlation
 $\xi(r) = \langle \delta_F(x) Q(x+r) \rangle$

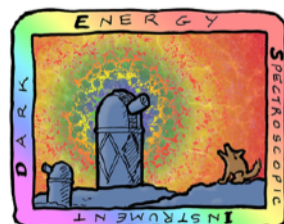
DR2 BAO is robust against different pipeline choices



Differences in the isotropic BAO dilation

Sum of neutrino masses

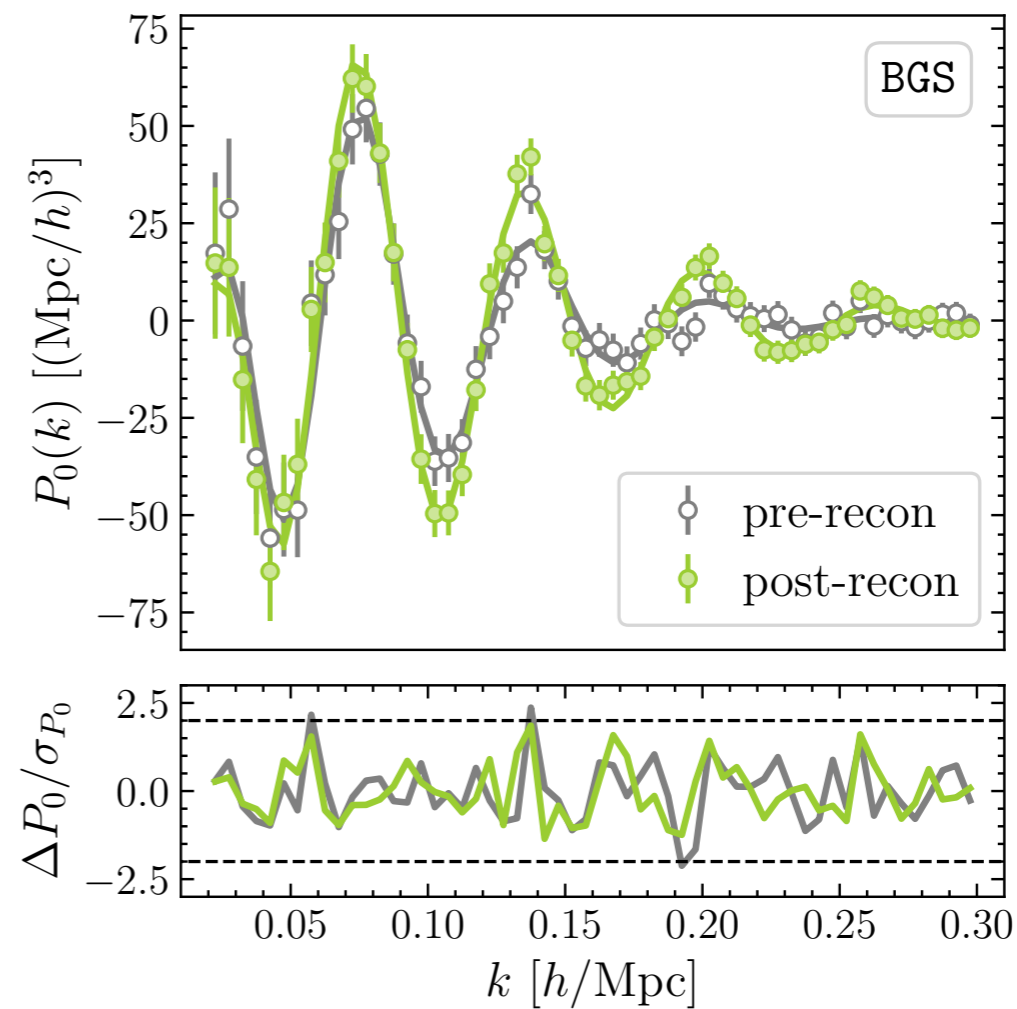
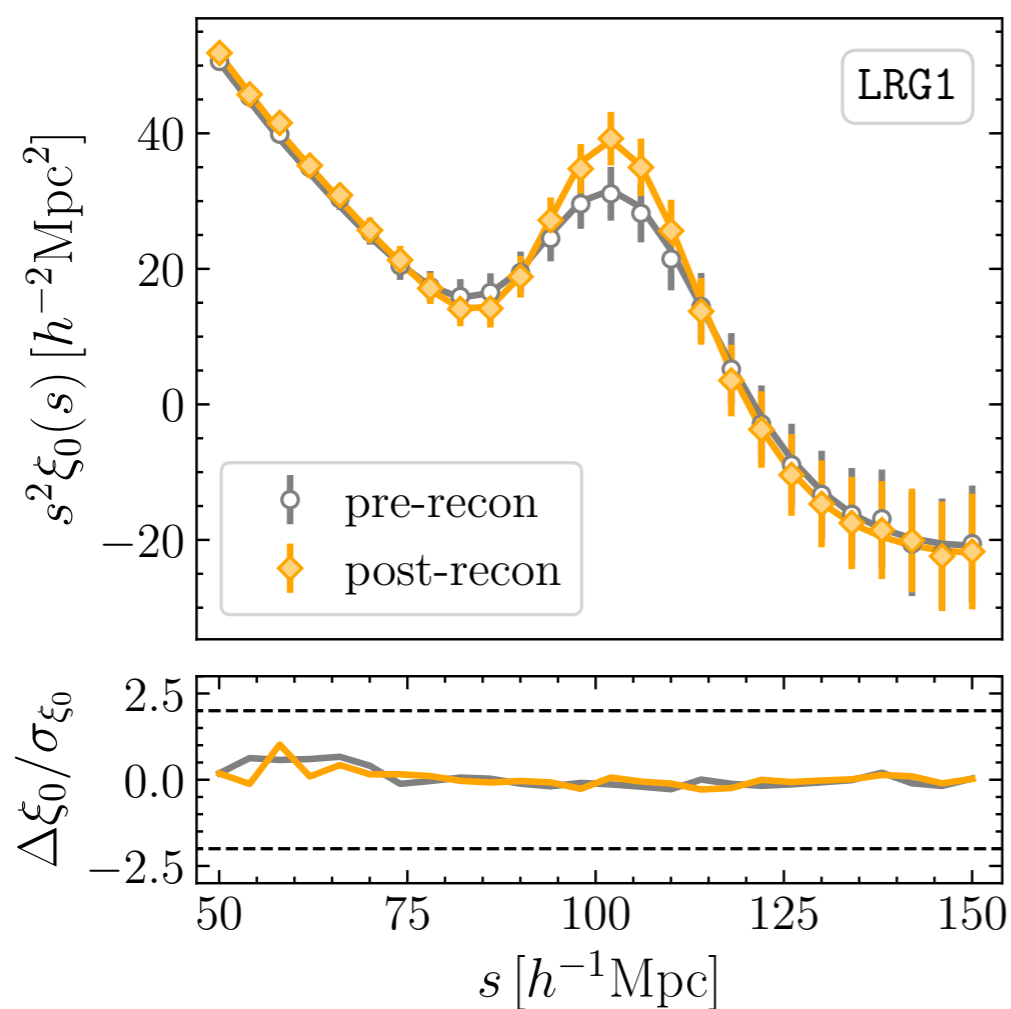




DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

Density field reconstruction



Refurbishes the ruler – **improves both precision and accuracy**

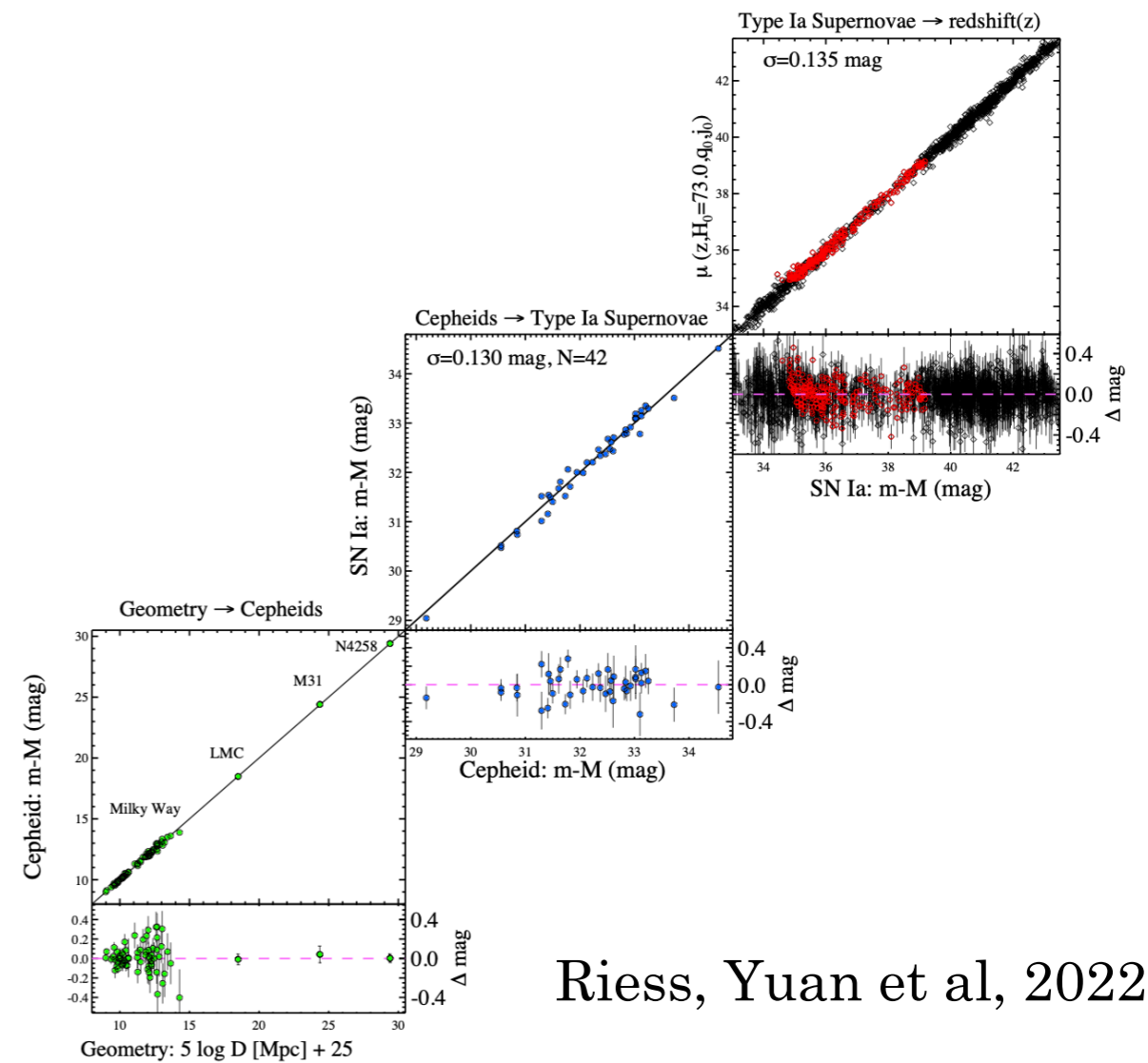
Distance-ladder measurements of H_0

starting with

$$m - M = 5 \log_{10} \left(\frac{d_L}{10\text{pc}} \right)$$

we get

$$m = 5 \log_{10}(H_0 d_L) + \mathcal{M}, \quad \text{where} \quad \mathcal{M} \equiv M - 5 \log_{10}(H_0 \cdot 1\text{Mpc}) + 25$$



Riess, Yuan et al, 2022

Because SNIa measure relative distances, to get at H_0 they need to be “anchored” by absolute distances from e.g. Cepheids