PHYSICS

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Testing the Standard Cosmological Model with DESI

Cosmology Seminar
IIT Hyderabad
30th June 2026

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2nd Year PhD Student
Advisor: Dragan Huterer

The Big Questions

- What is the Universe made up of?
- How did it evolve?
- What is its ultimate fate?

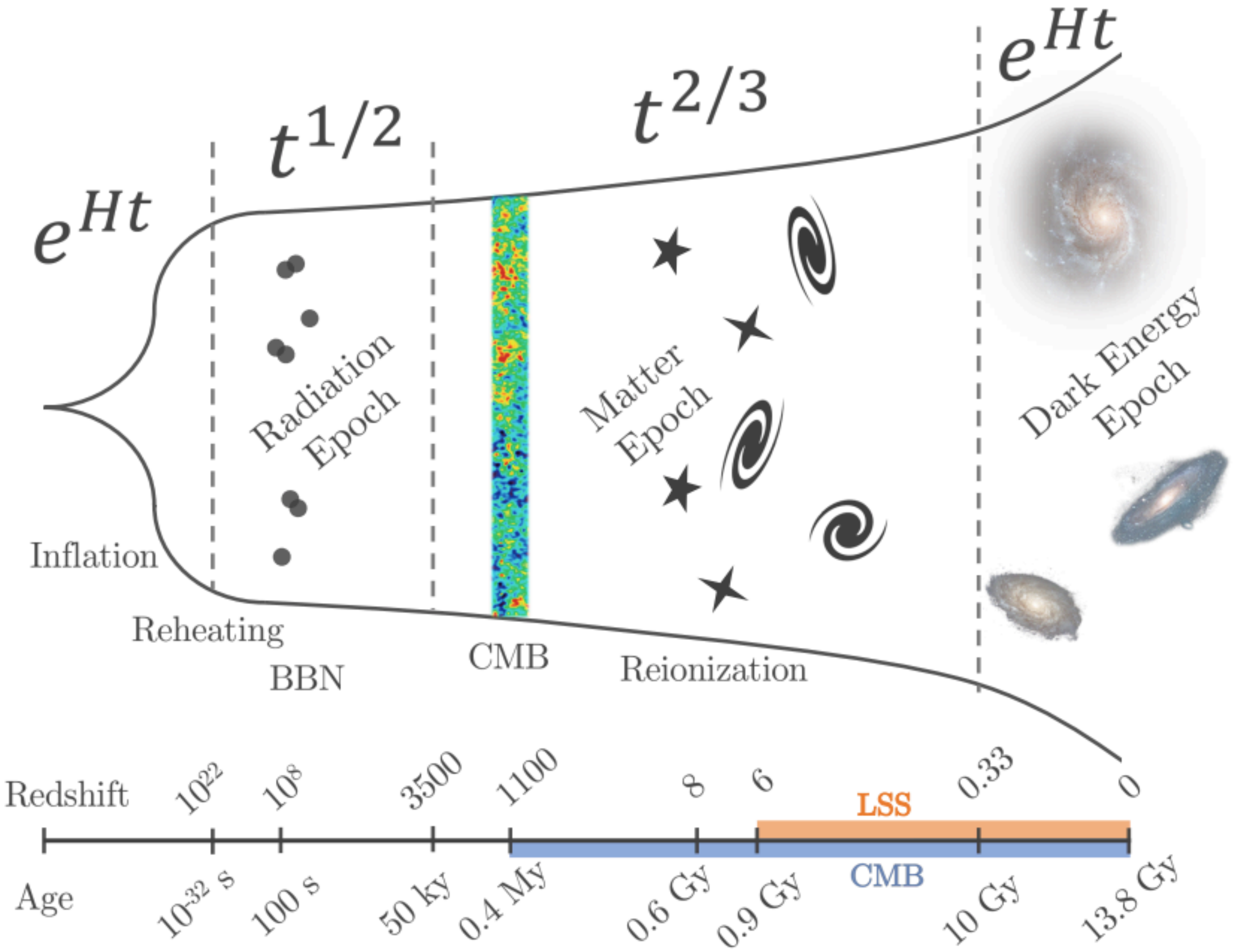
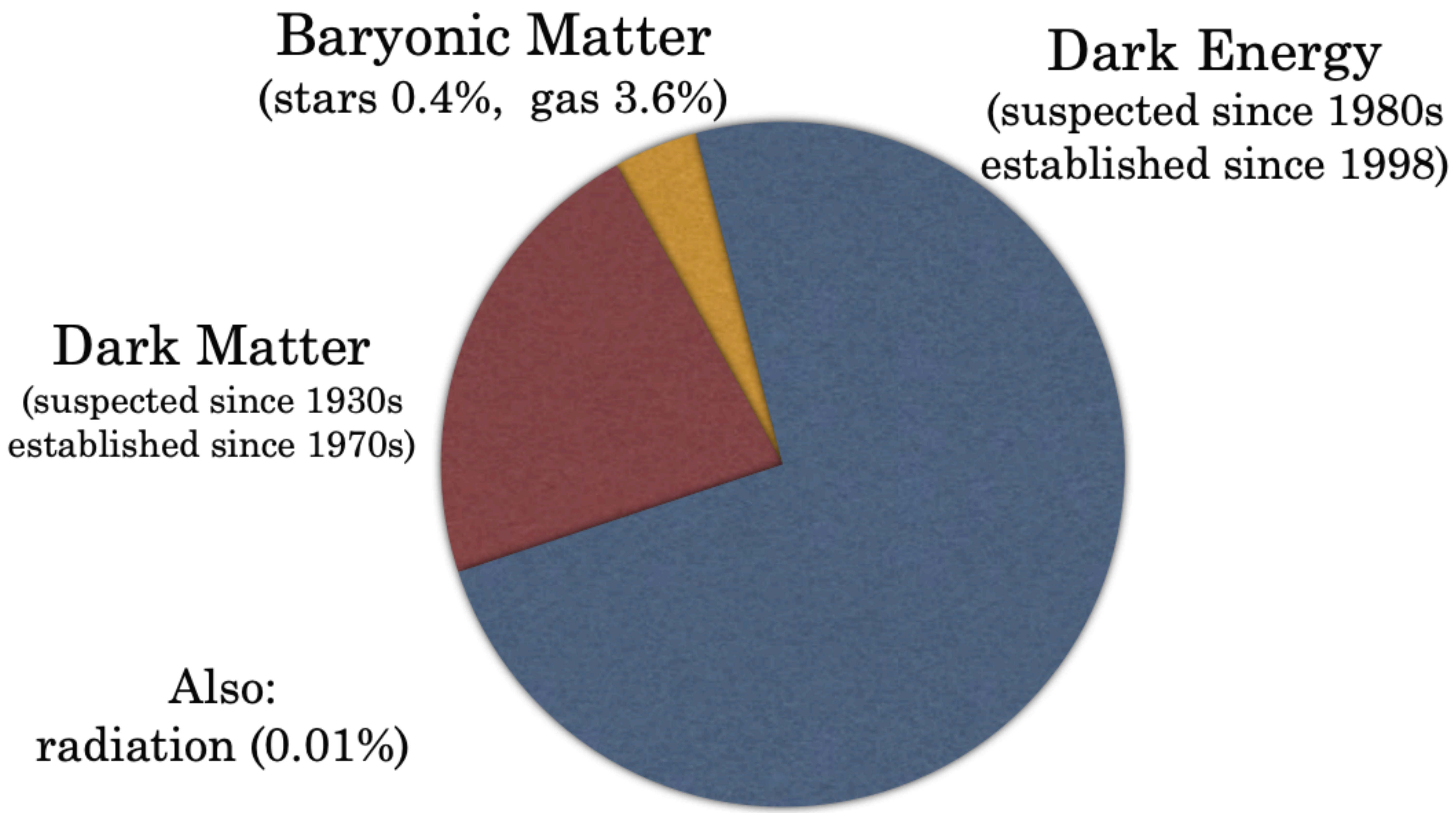


Fig. Credits: Noah Weaverdyck

The Standard Model of Cosmology: ΛCDM

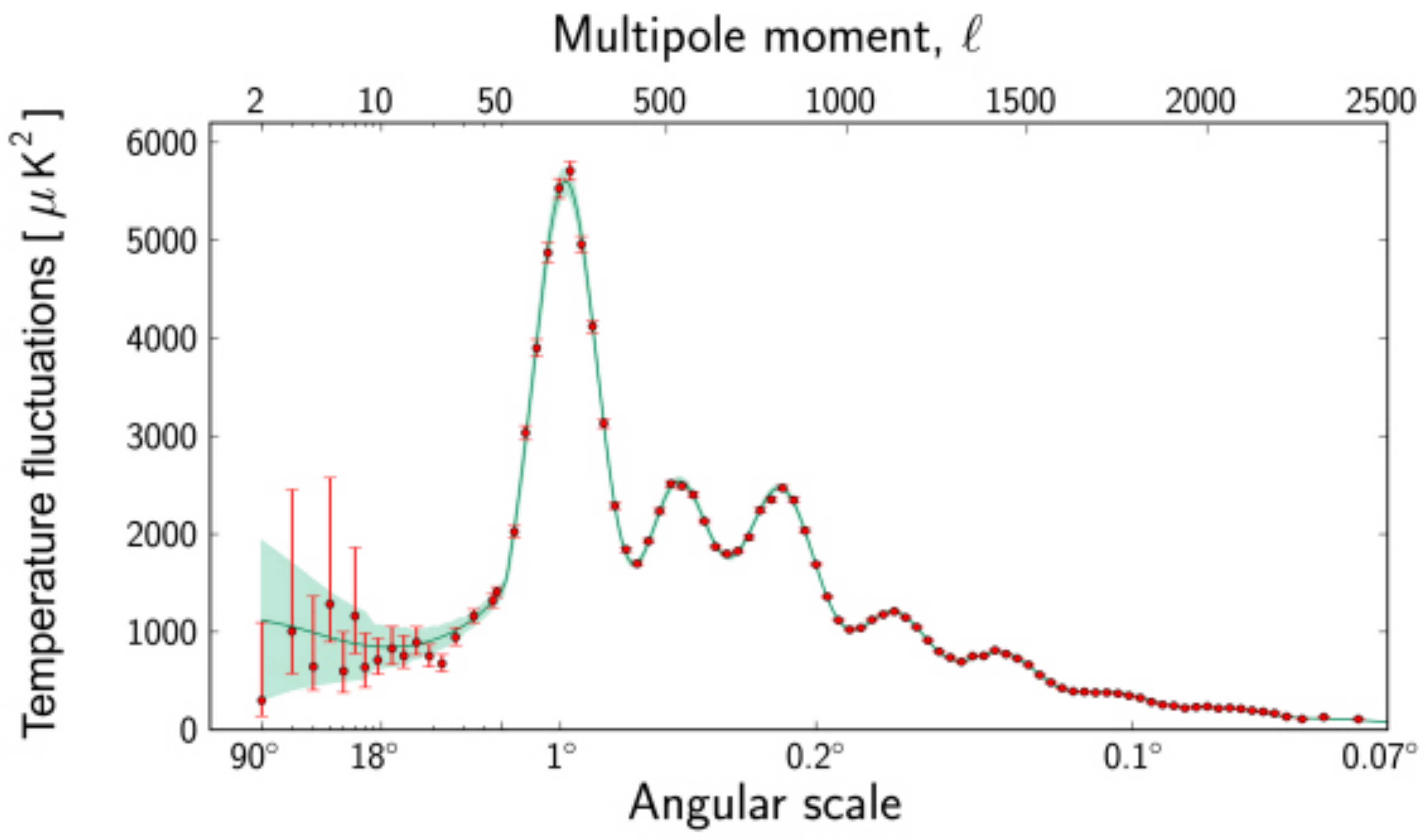


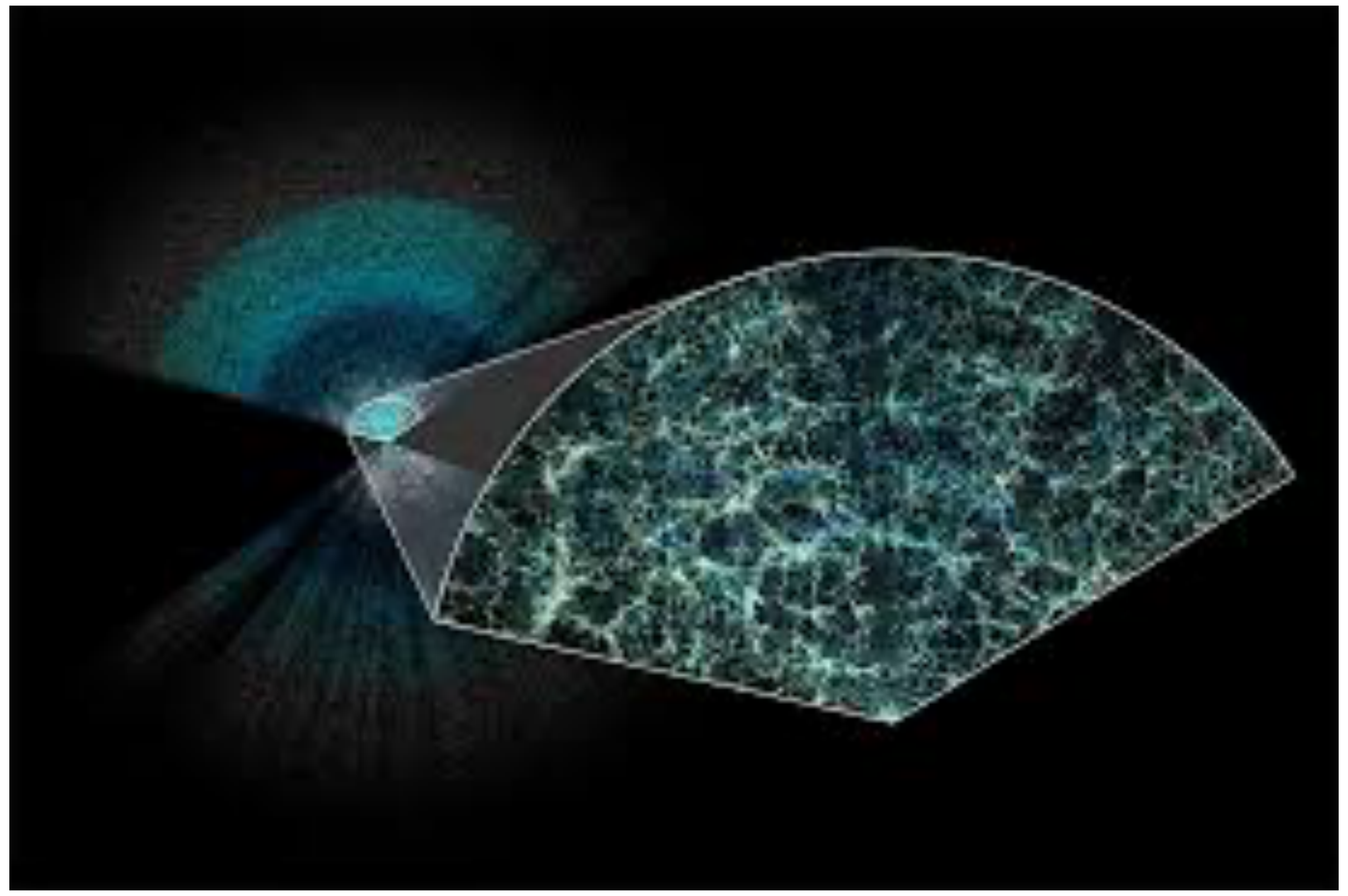
Incredibly simple model
with just 6 parameters

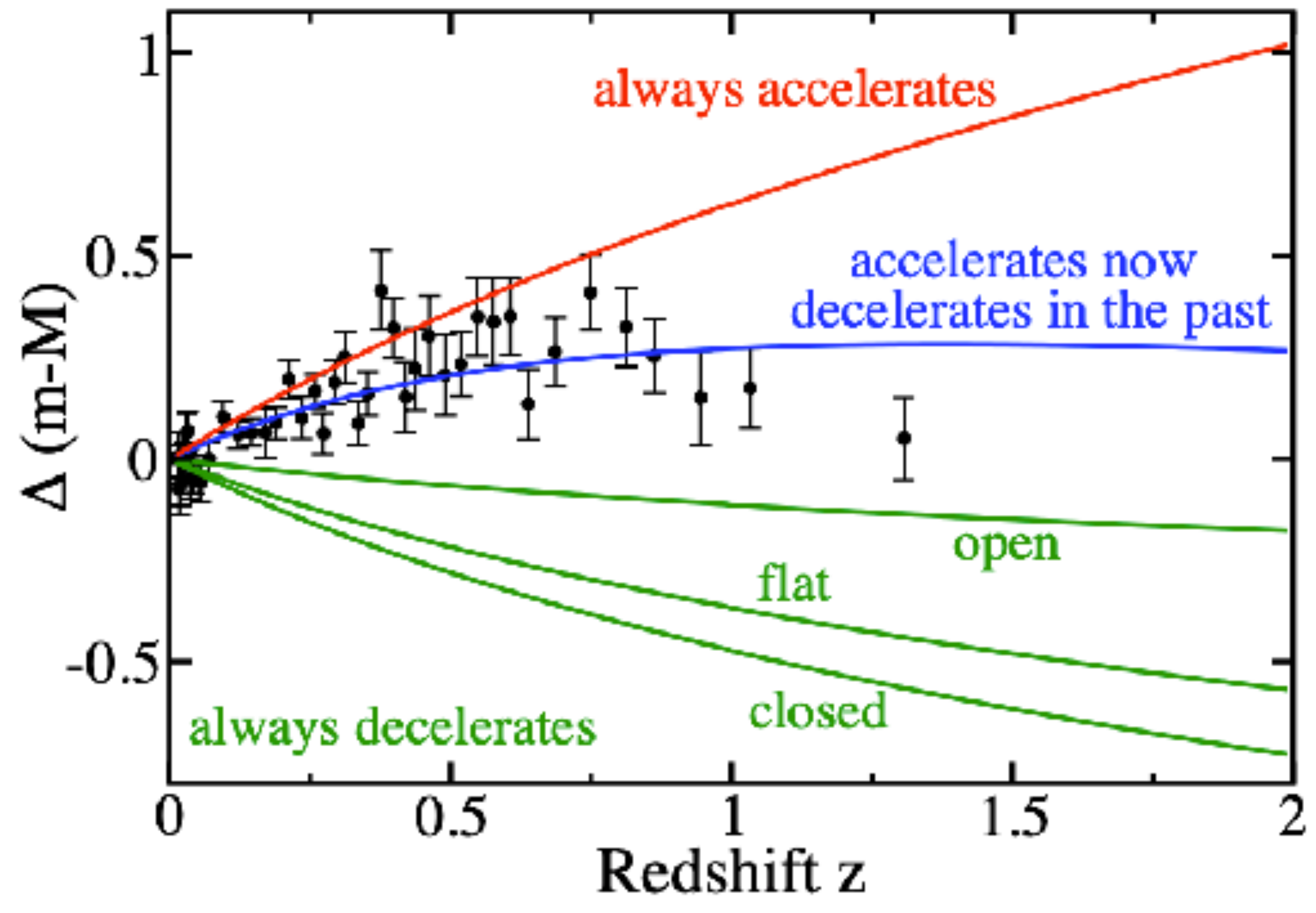
Fig. Credits: Dragan Huterer

Why should we believe ΛCDM?

ΛCDM is able to explain a majority of wildy different observations







CMB

Galaxy Clustering

SNIa

As the observations are getting better, cosmology is increasingly becoming a precision science

Fig. Credits: Planck Collab, Berkeley Lab, Dragan Huterer

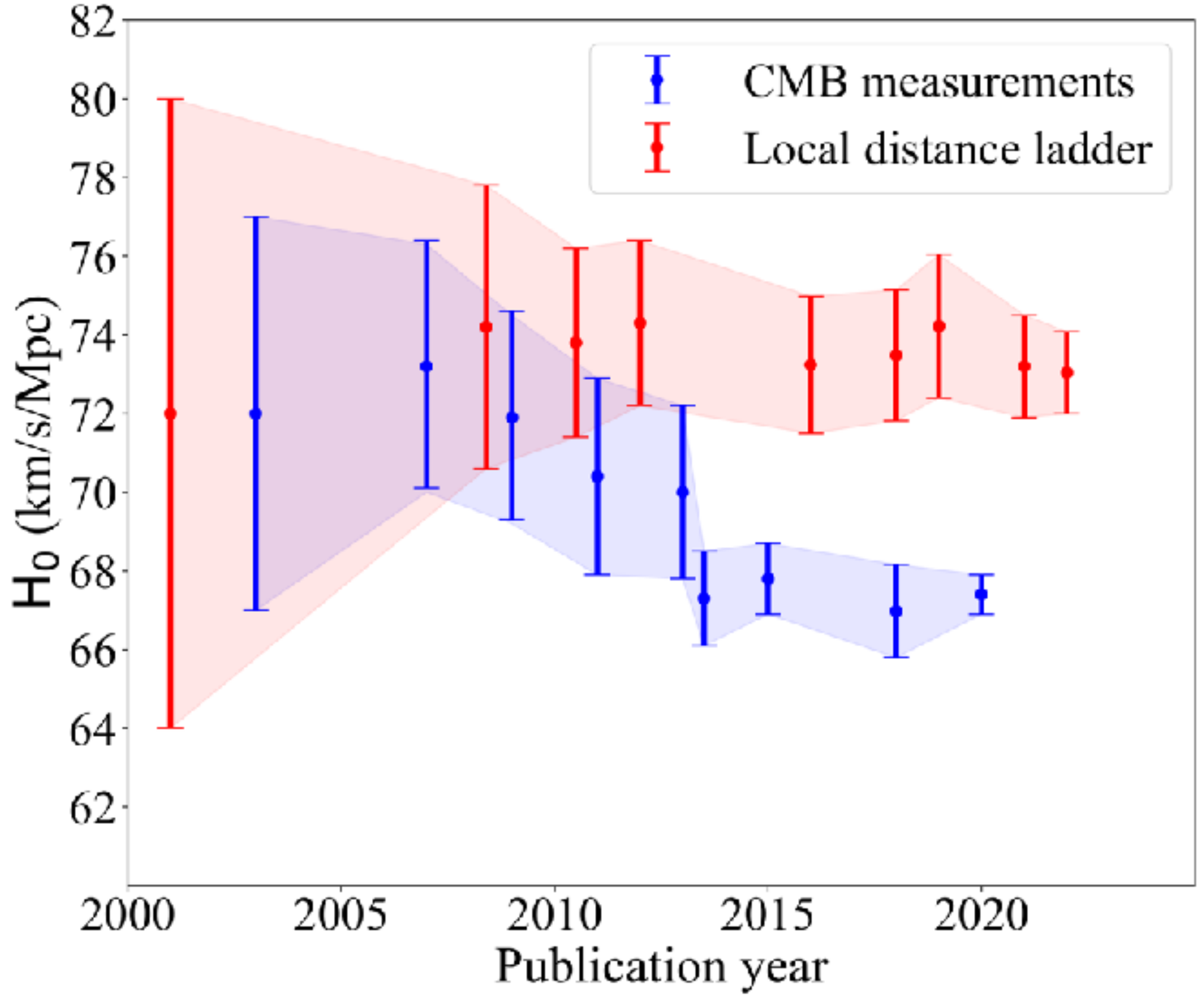
But precision reveals cracks

- Hubble Tension
- Dynamical Dark Energy
- Neutrino Mass
- ....

Fig. Credits: Claire Lamman

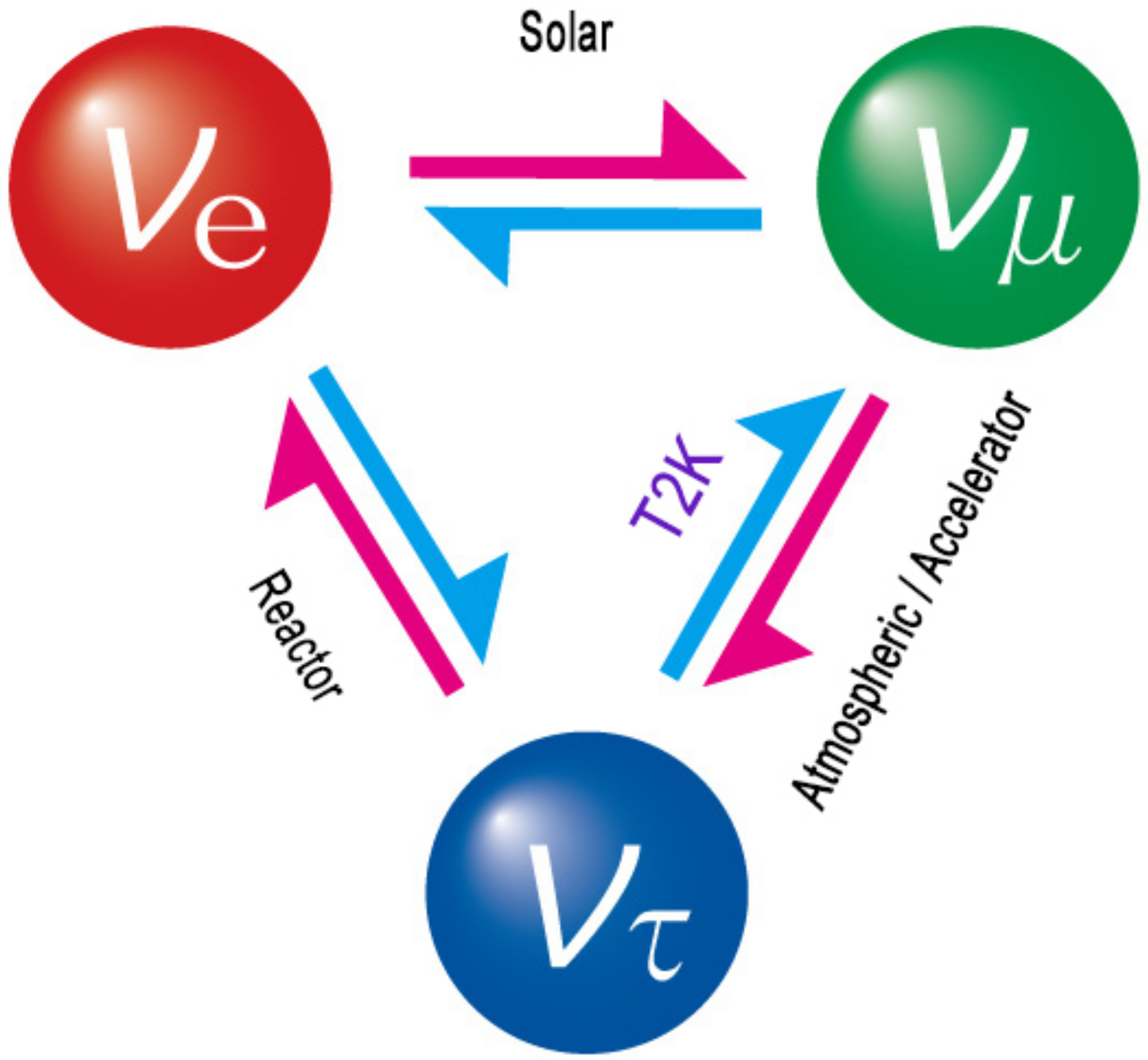
The Hubble Tension

H_0 : The Hubble Constant (~ 70 km s^{-1} Mpc^{-1})
(Measure of the expansion rate of the Universe today)



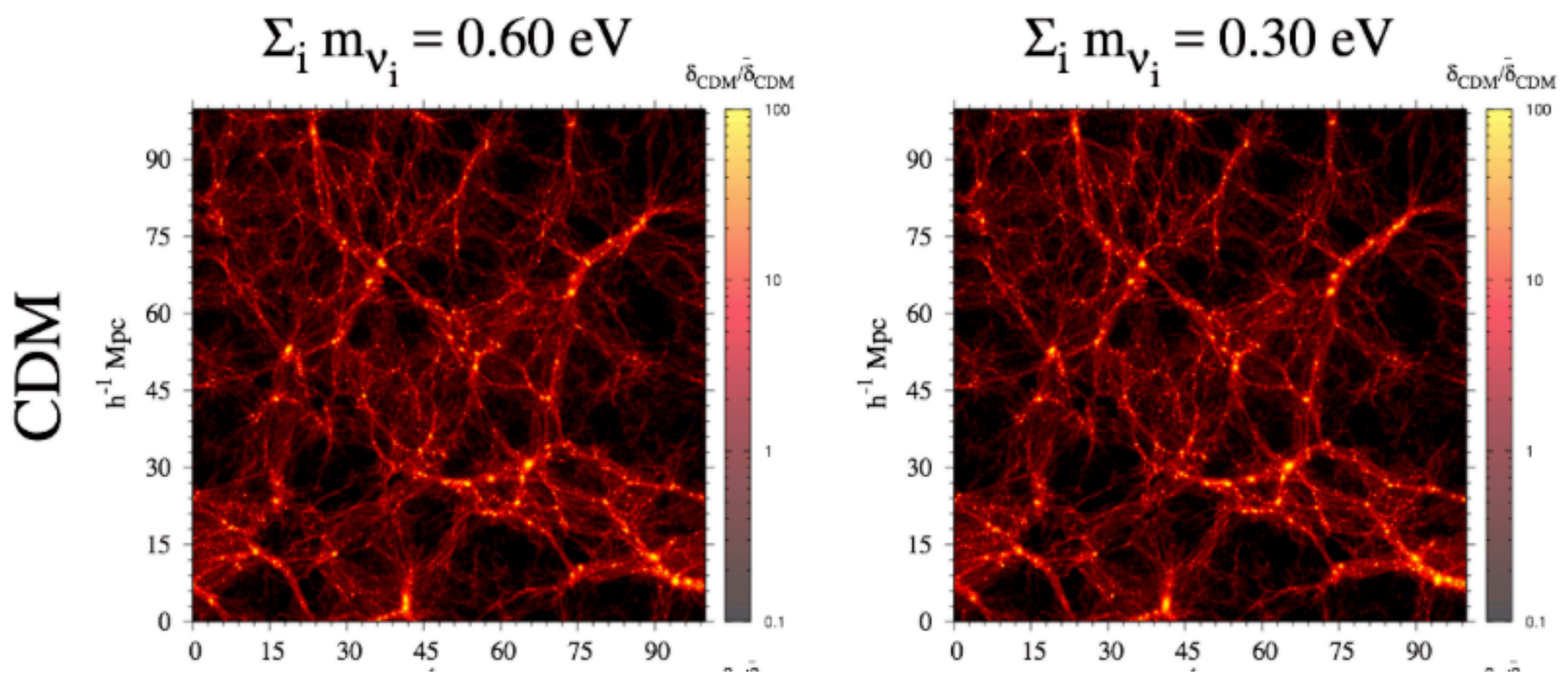
Hu & Wang 2023

Neutrino Mass



Neutrino oscillation between three generations

Massive neutrinos suppress the growth of structure



$$\Sigma m_\nu \gtrsim 0.06\,\mathbf{eV}$$

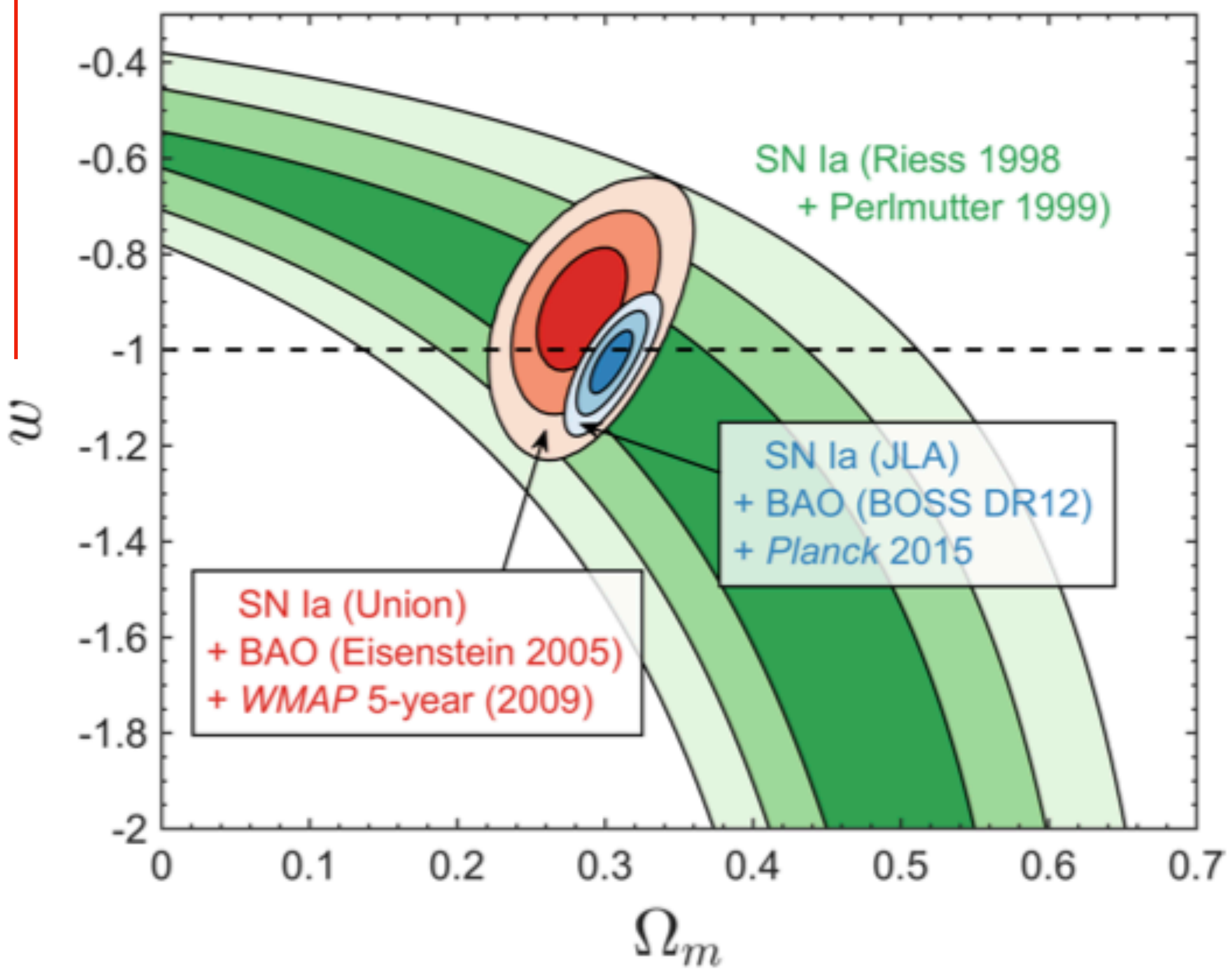
$$\Sigma m_\nu \lesssim 0.06\,\mathbf{eV}$$

Fig. Credits: EWT, Francisco Navarro

Dark Energy

- The Universe's expansion is accelerating!!
  Reason: Dark Energy
- Confirmed in 1998. Nobel Prize in 2011!
- Experiments so far have revealed
  - DE makes up ~70% of the energy budget of the Universe
  - A constant energy density (ΛCDM) DE model ($w \simeq -1$)
  - But recent experiments are providing increasing evidence of a time-varying dark energy

EOS Parameter for DE



$$\dot{\rho} \propto (1 + w)\rho$$

Huterer & Shafer 2018 Riess+1998

How can we test these cracks?

- Need precise expansion history
- Need precise structure growth

Galaxy Surveys!

DESI: Dark Energy Spectroscopic Instrument

- 4th Generation Spectroscopic Survey
- 4M Mayall Telescope at Kitt Peak (Tucson, AZ)
- International Collaboration ~900 Scientists, ~70 institutions
- Mapping the distribution of the galaxies in the Universe by precisely measuring their redshifts

But how does this map of galaxies help??

This map helps us study some patterns in clustering of galaxies governed by the laws of Physics

Fig. Credits: NOIR LAB

1. Baryon Acoustic Oscillations

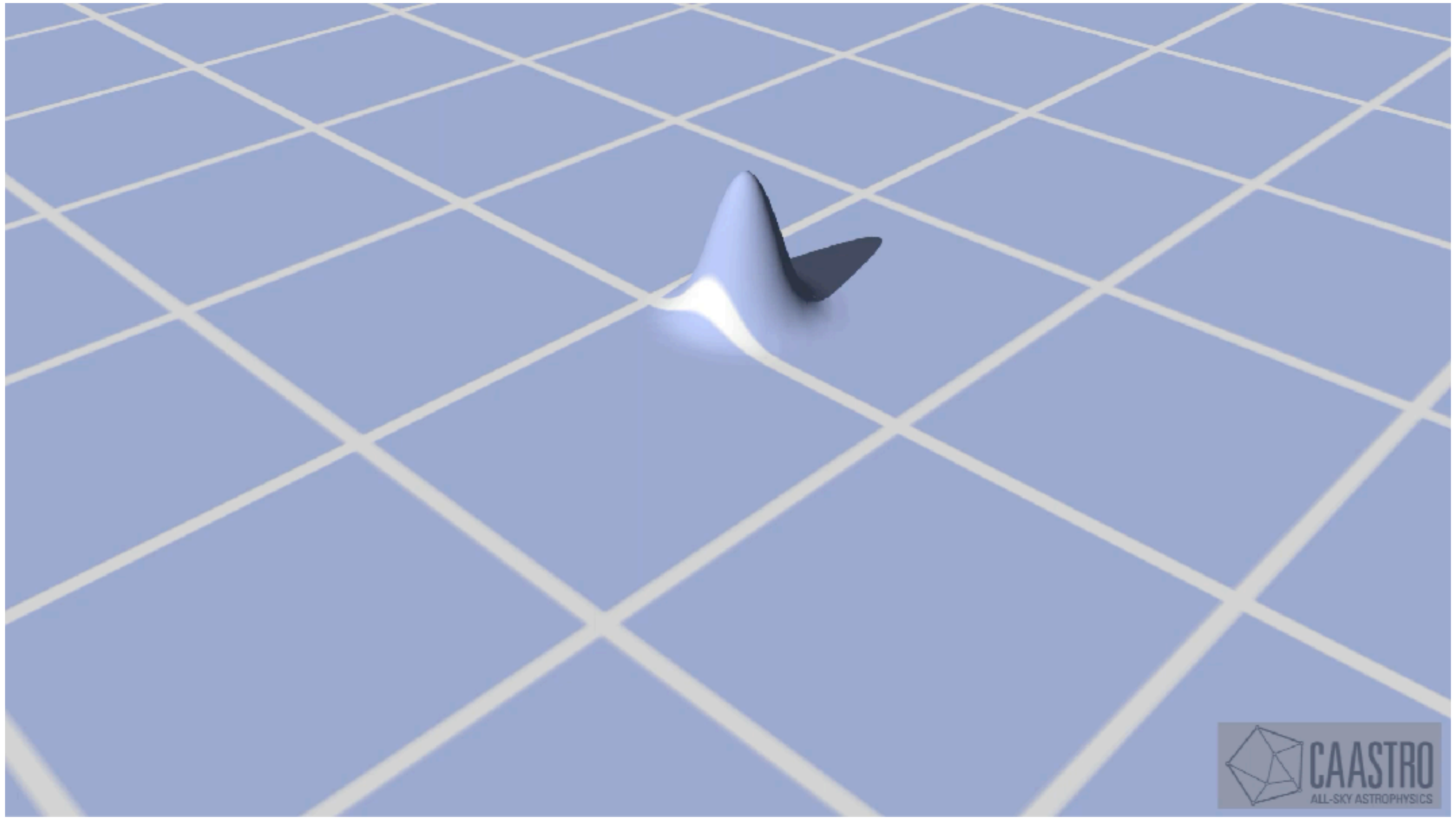
- Tightly coupled photons & baryons act as a single fluid plasma

- Overdensity $\longrightarrow$ Collapse

  $\downarrow$

  Outwards travelling pressure wave

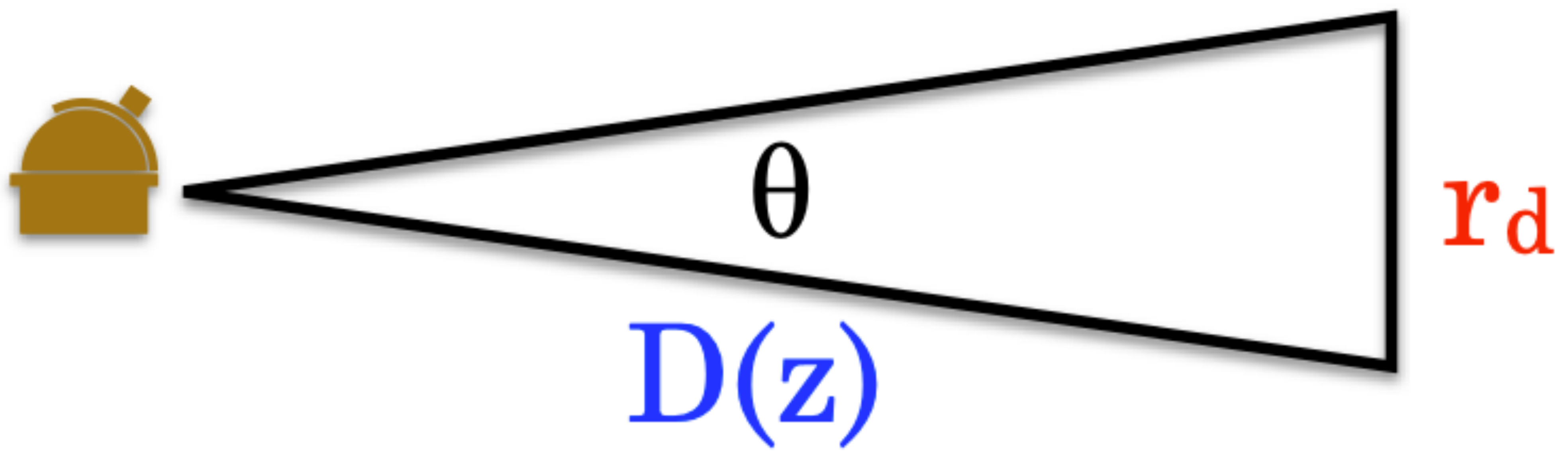
- At decoupling, $z_d \sim 1060$, the pressure wave stops and the distance this pressure wave travels from big bang ($r_d \sim 150$ Mpc) gets locked in



Movie Credits: CAASTRO

How does the BAO feature help understand DE?

- Due to this feature, two galaxies have a preferential probability of being separated by a distance r_d
- Excessive clustering at a preferred scale - "Standard Ruler"
- What we actually observe is the angle to the Standard Ruler

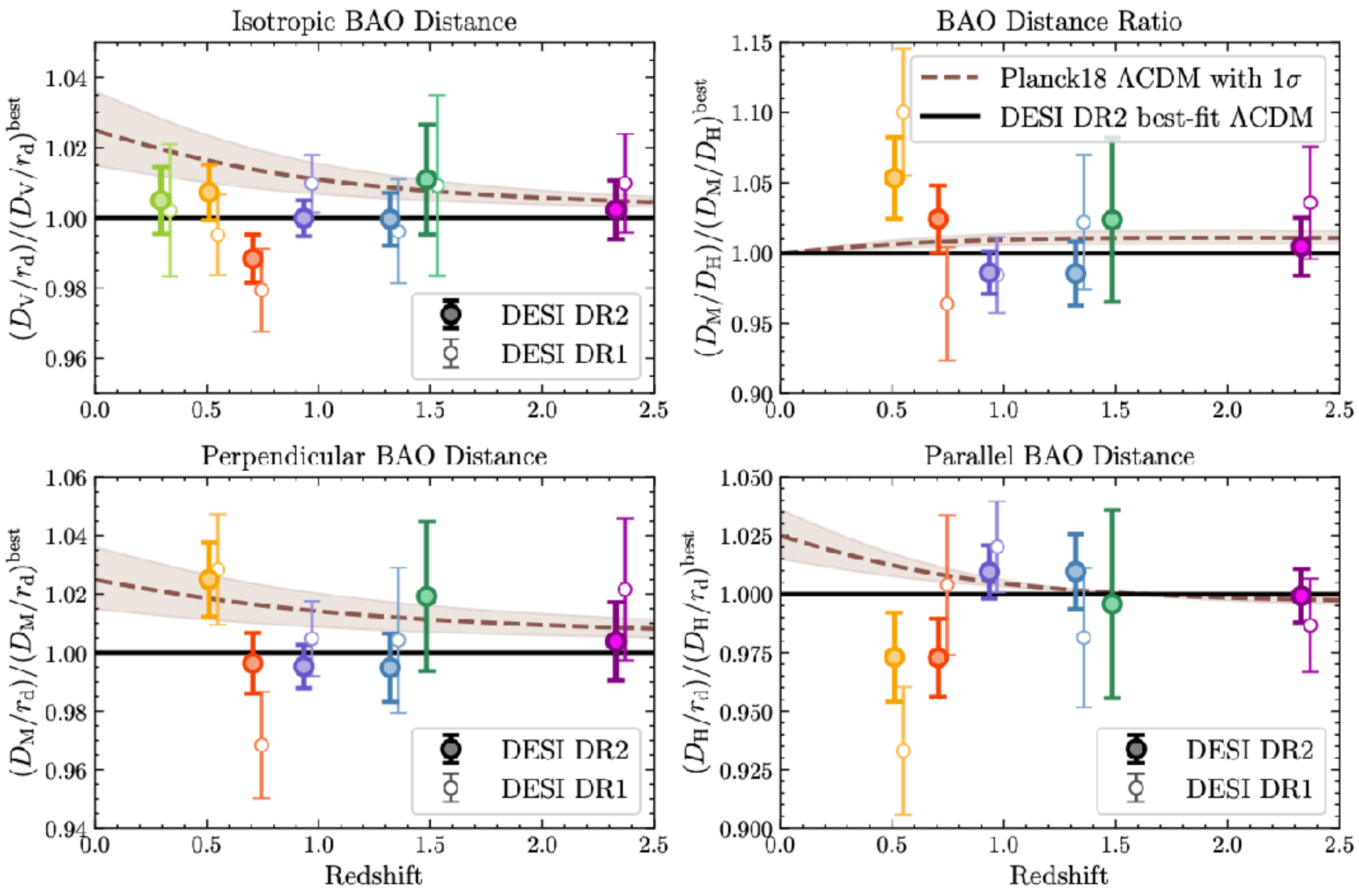


$$\theta = r_d / D$$

Sensitive to DE equation of state & energy density

Fig. Credits: Dragan Huterer

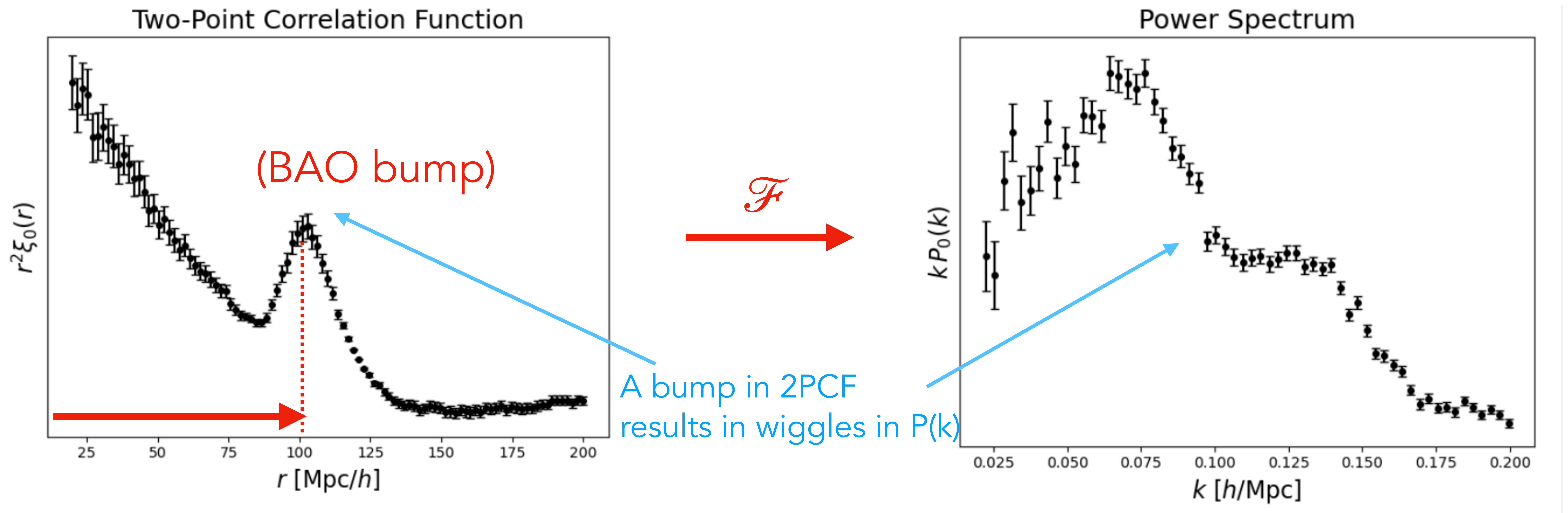
How does the BAO feature help understand DE?



DESI Collab (Phys. Rev. D 112, 083515)

2. Full Shape Analysis

- BAO measurement is the most important measurement of DESI for cosmology
- But it's not the only measurement!



DESI DE Results (DR1 BAO)

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

- Came out in April 2024
- > 400 unique articles!!

A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

DESI DE Results (DR1 BAO)

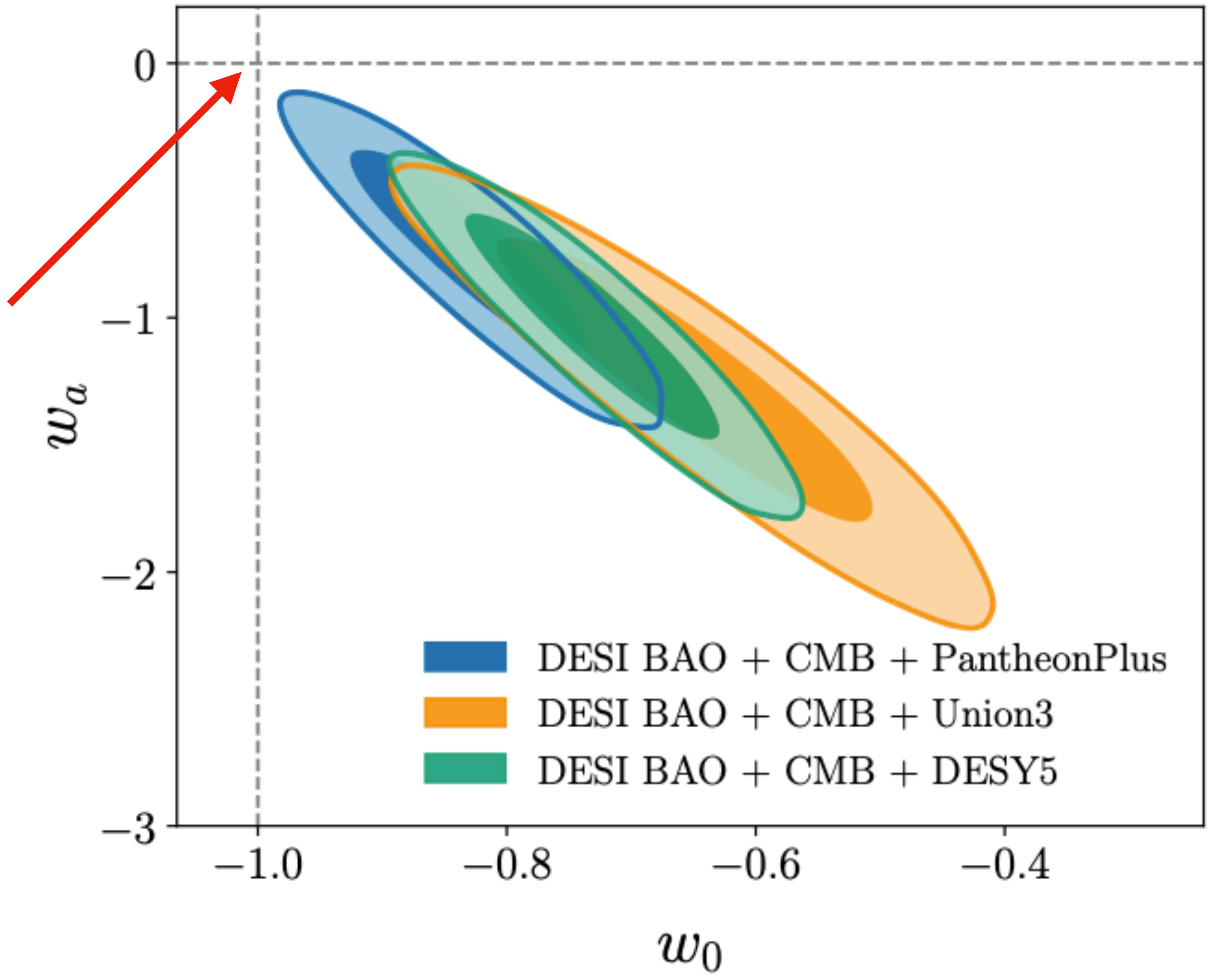
$w_0 w_a$ Parametrization

$$w = \frac{p_{\text{DE}}}{\rho_{\text{DE}}} = w_0 + (1 - a) w_a$$

As $w_0 \to -1, w_a \to 0$

ΛCDM is recovered

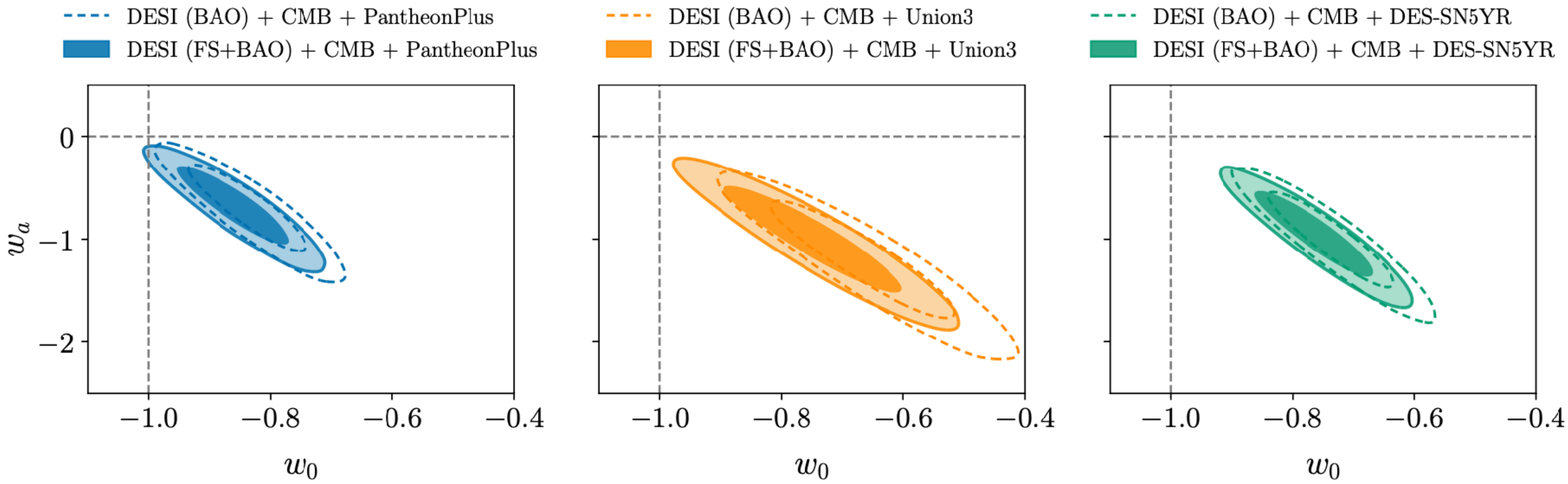
ΛCDM Point



2.5σ, 3.5σ, 3.9σ deviation from ΛCDM!

DESI VI: 2024

DESI DE Results (DR1 Full Shape)



Contours shrink by ~ 20% on adding FS information

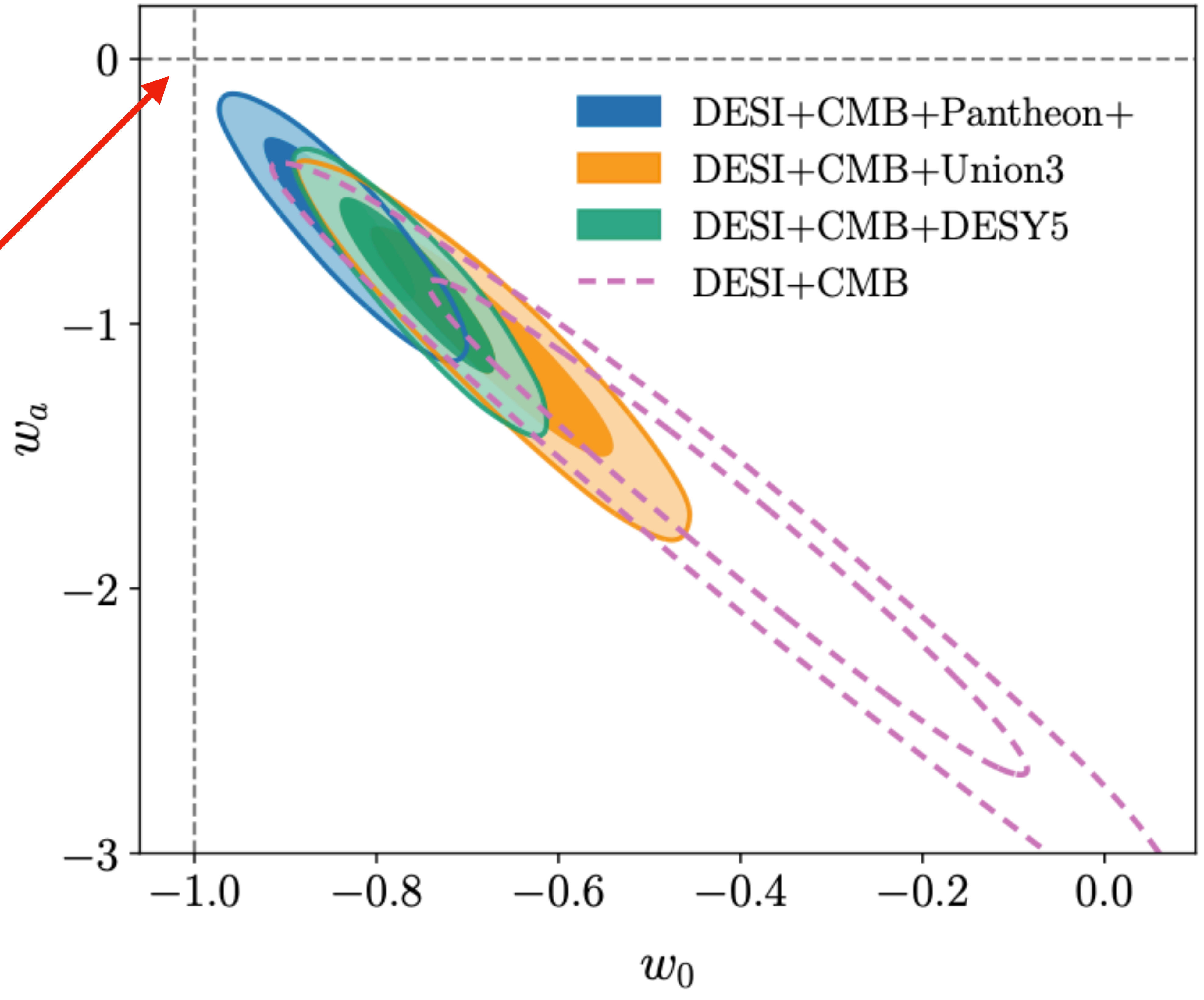
In total 42 Nuisance Parameters!

2.5σ, 3.4σ, 3.8σ deviation from ΛCDM!!

DESI VII: 2024

DESI DE Results (DR2 BAO)

ΛCDM
Point



- Came out in March 2025
- 2.4x more galaxies than DR1
- ~20 - 40% improvement in the BAO distances

3.1σ, 2.8σ, 3.8σ, 4.2σ deviation from ΛCDM

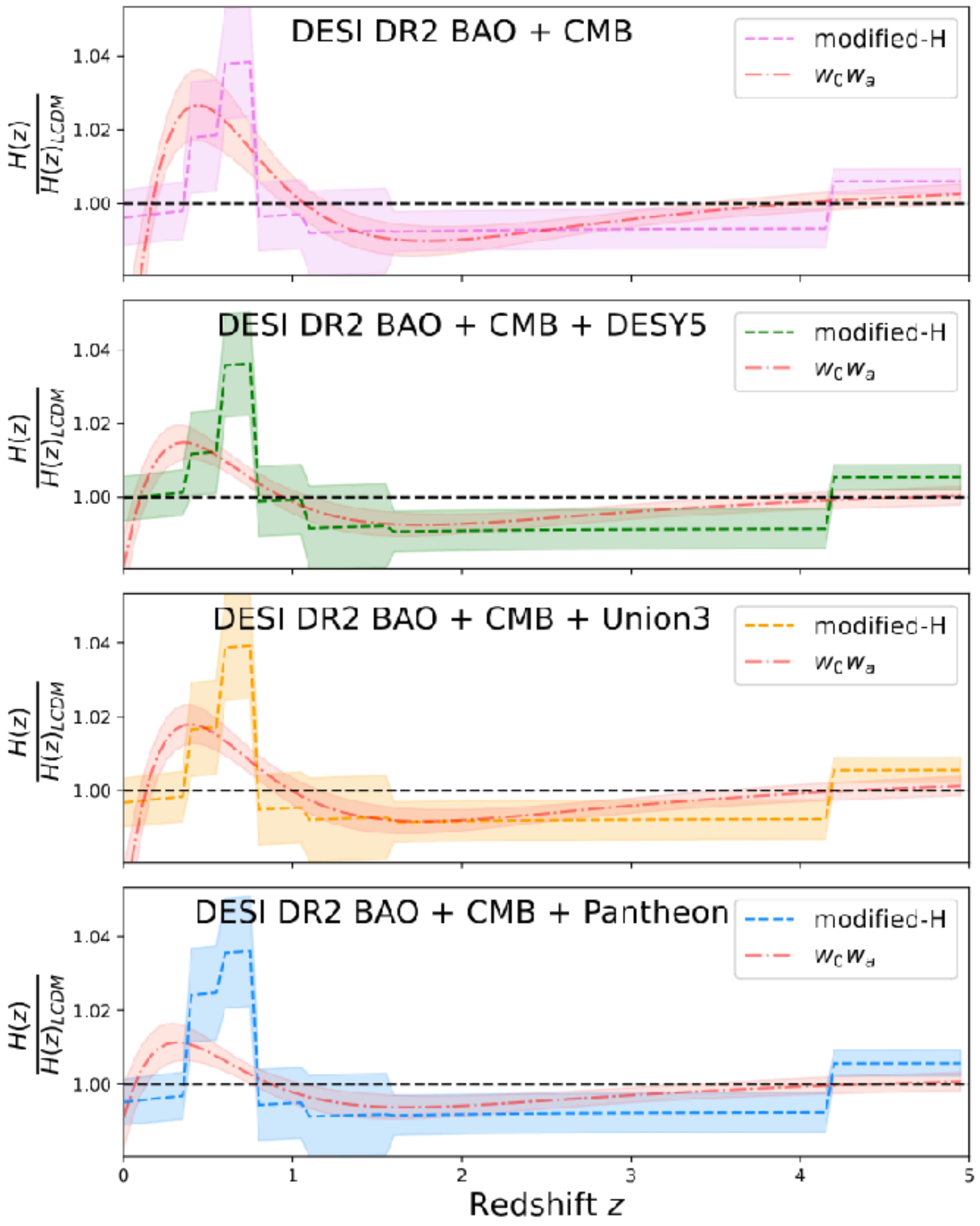
Upcoming: DR2 Full Shape!

DESI DR2: 2025

1. Expansion History Preferences of DESI DR2 and external data

Phys. Rev. D 112, 023528

Results



Modified-H Model

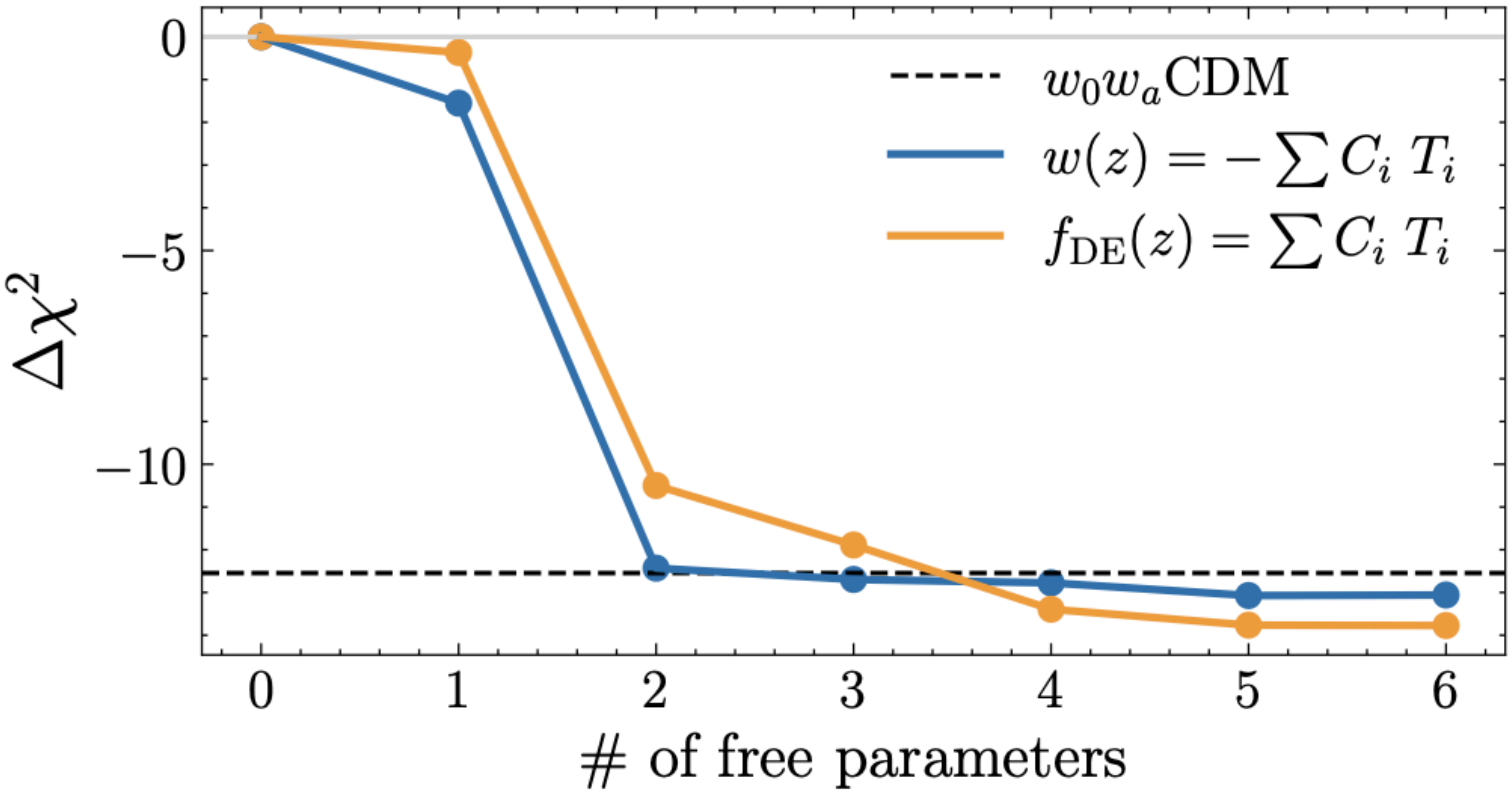
$$H(z) = H(z)^{LCDM}(1 + \alpha_i)$$

6 free parameters
(as opposed to 2 in $w_0 w_A$)

$w_0 w_a$ parametrization is flexible enough to model the DESI data favoured expansion history!!

Bansal & Huterer, Phys. Rev. D 112, 023528

…Later confirmed by independent studies

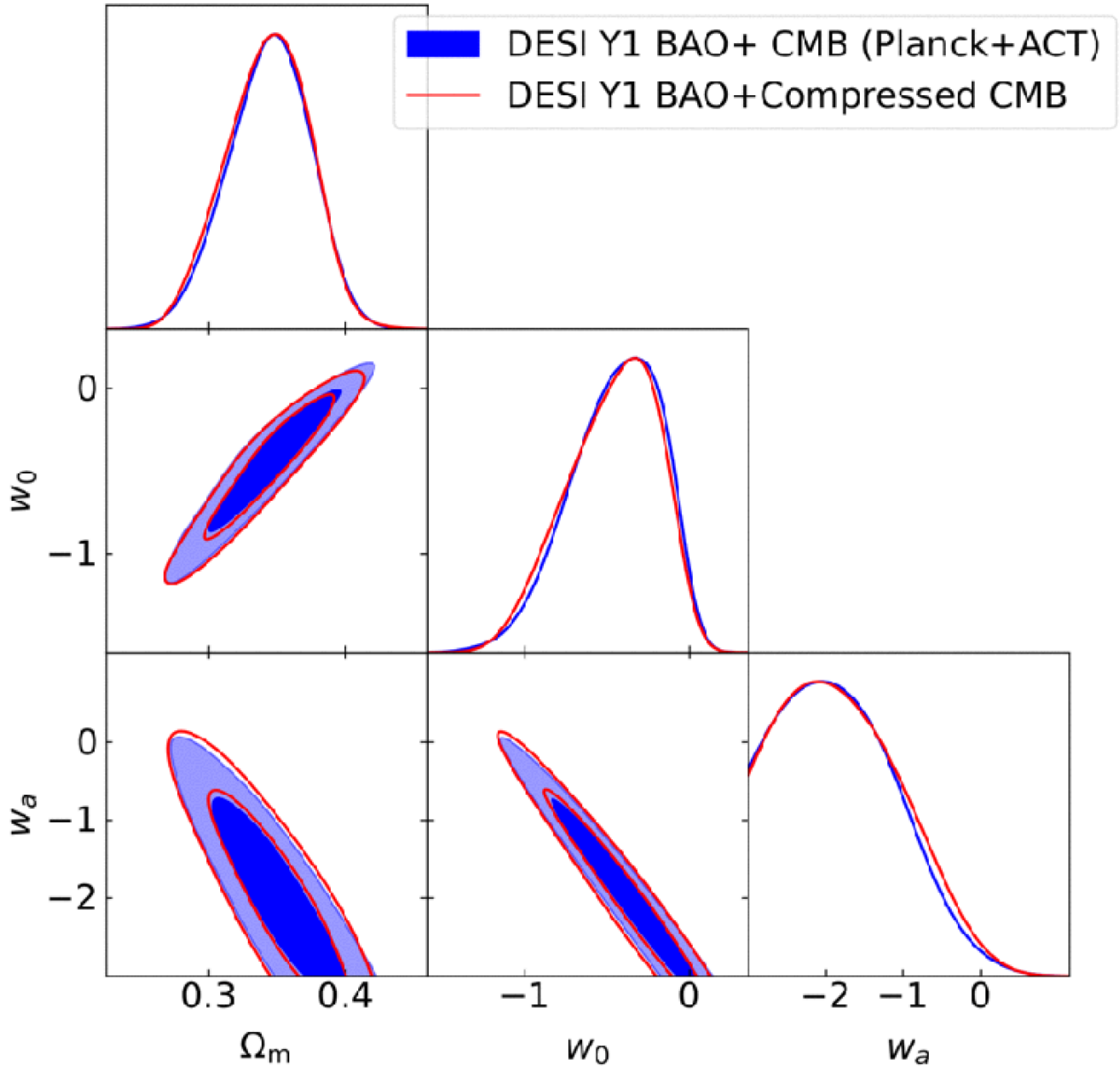


Lodha++, Phys. Rev. D 112, 083511

Corollary: CMB Compression

- Full CMB likelihood: ~7K data points
- Compressed CMB: 3 data points
- Run time goes from ~ 6-7 hours to 3-4 minutes

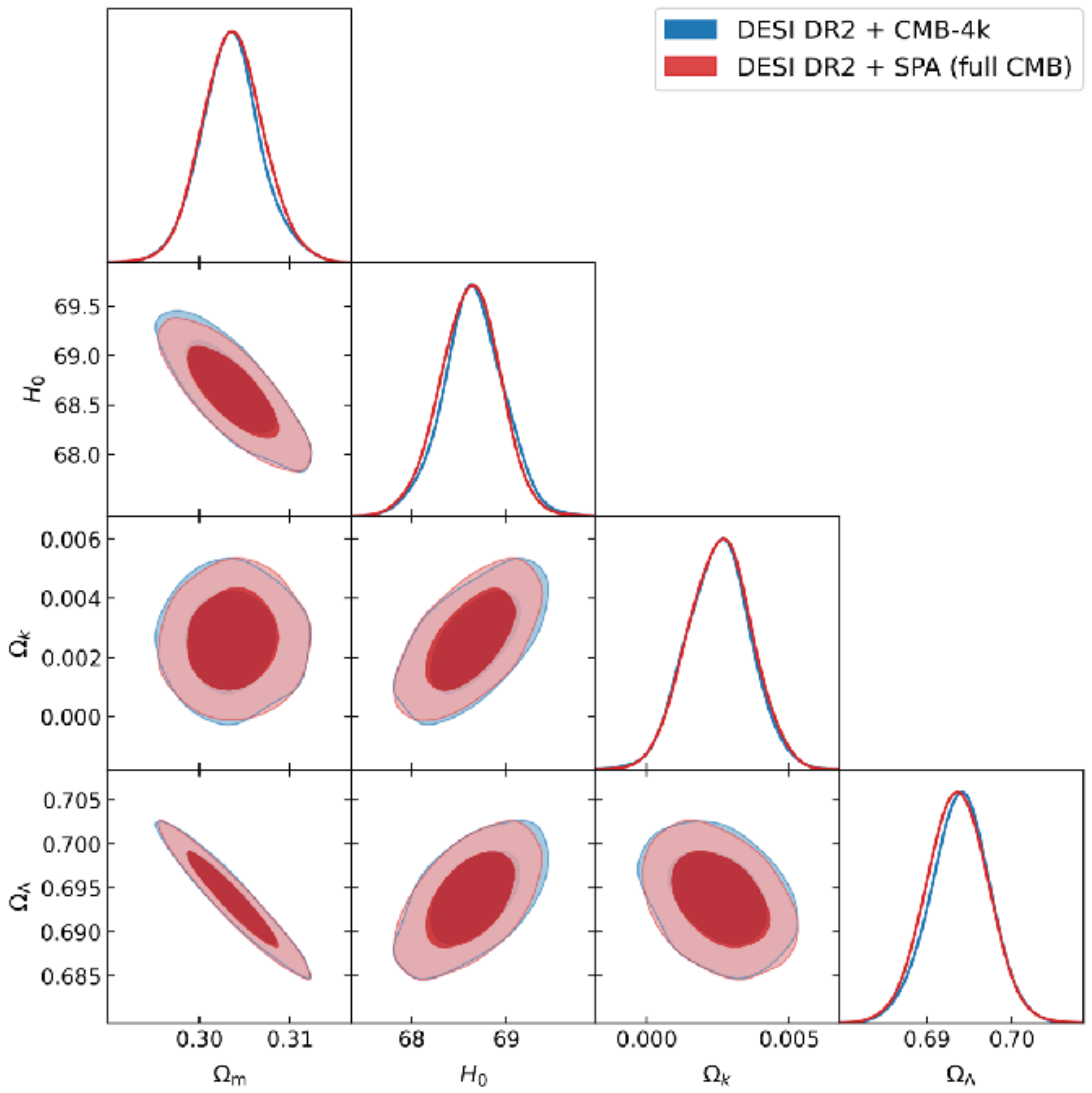
$$\mathbf{v}_{\mathrm{CMB}} \equiv (R, \ell_a, \Omega_b h^2)$$

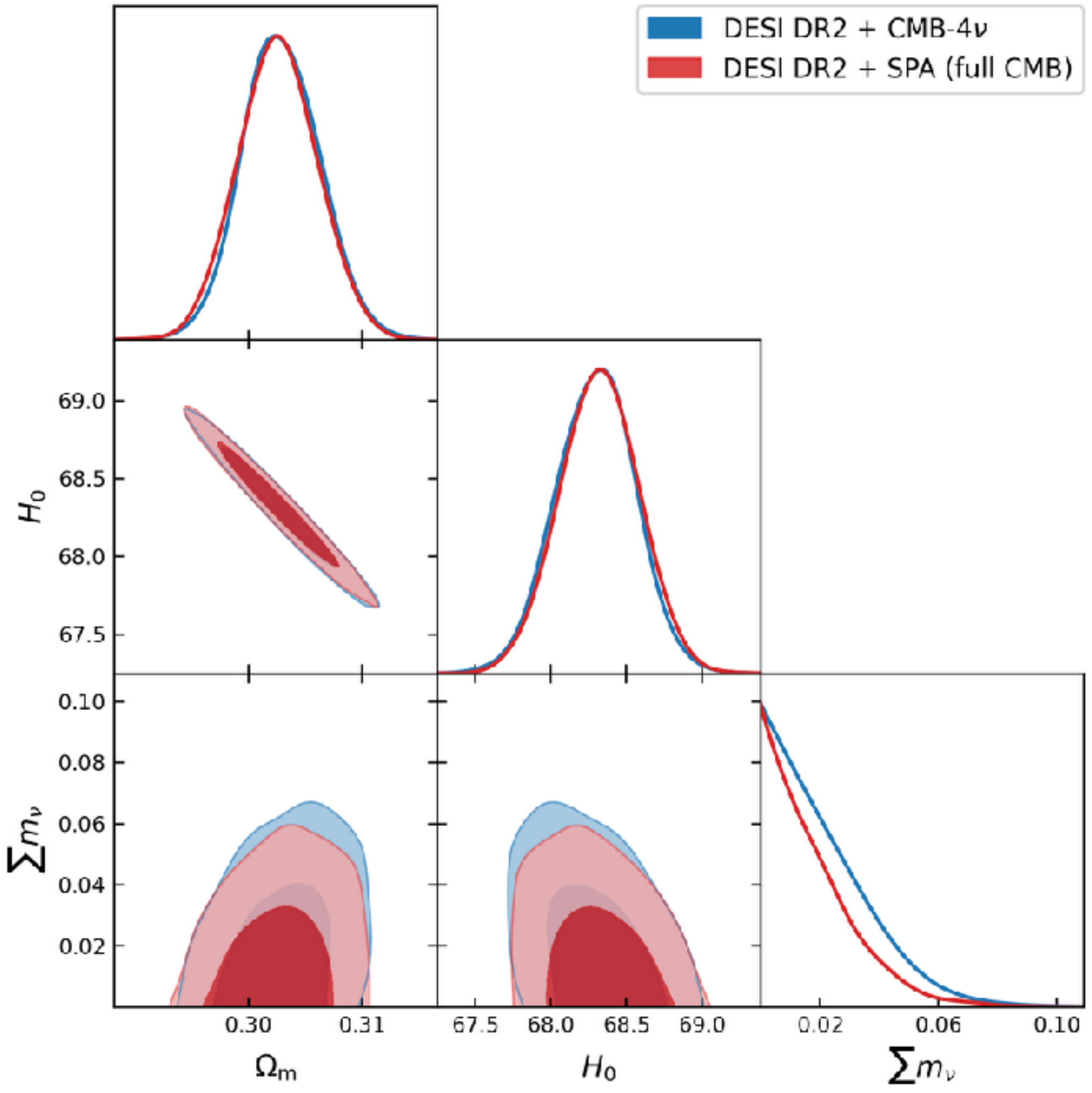


One of the most accurate compressions as of now!!
Also adopted in DESI DR2 BAO Key Paper*

Bansal & Huterer, Phys. Rev. D 112, 023528

Follow-up: CMB Compressions for Ω_K and m_ν





A simple user-friendly suite of fast CMB likelihoods!

Srivastav et. al. (arXiv: 2606.18455)

2. Difficulties with Late-Time Solutions for the Hubble Tension

Phys. Rev. D 113, 103539

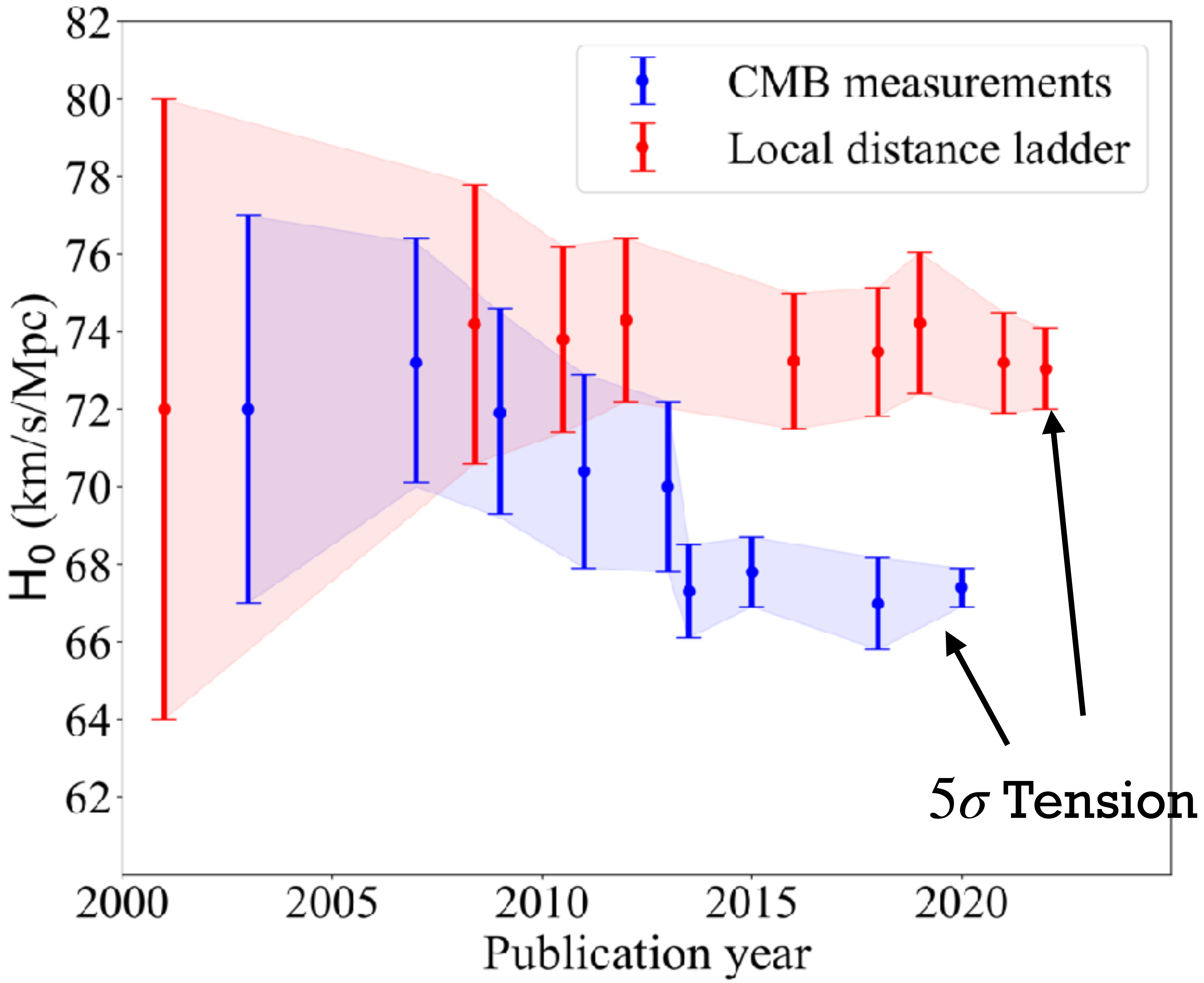
The Hubble Tension

H_0

Hubble Constant: Measure of the expansion rate today

Two ways to measure H_0

- CMB: Early Time Probe (z~ 1100)
- SNIa Distance Ladder: Late Time Probe (z~0.001-0.15)

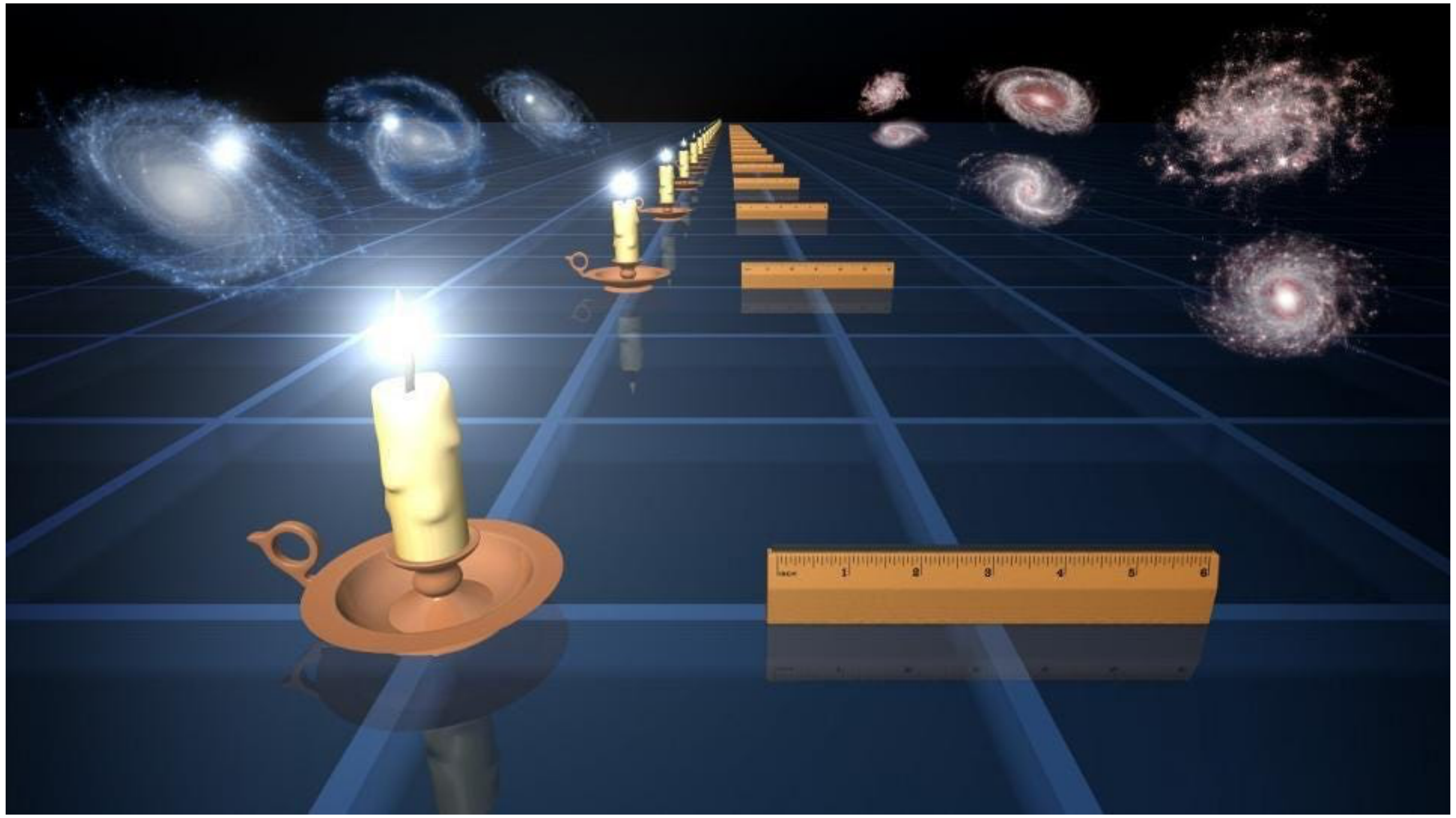


It might be tempting to think of a solution, in which the Universe went through a phase of exotic expansion at late times!!

Late time solutions

Hu & Wang 2023

SNIa distance ladder



$$f = \frac{L}{4\pi d^2}$$

$$m_{app} = \mu + M_{abs}$$

What we measure

Can be determined for nearby SNIa

Cosmological Information
(What we want to determine)

$$\underbrace{}_{H_0}$$

SNIa: Standard Candles
(All SNIa are *believed* to have same Luminosity (absolute magnitude)

Fig. Credits: Medium

How does a typical SNIa likelihood work?

$$\mu = 5\log_{10}(d_L) + 25$$

$$m_{app} = \mu + M_{abs}$$

$$m_{app} = 5\log_{10}(d_L) + 25 + M_{abs}$$

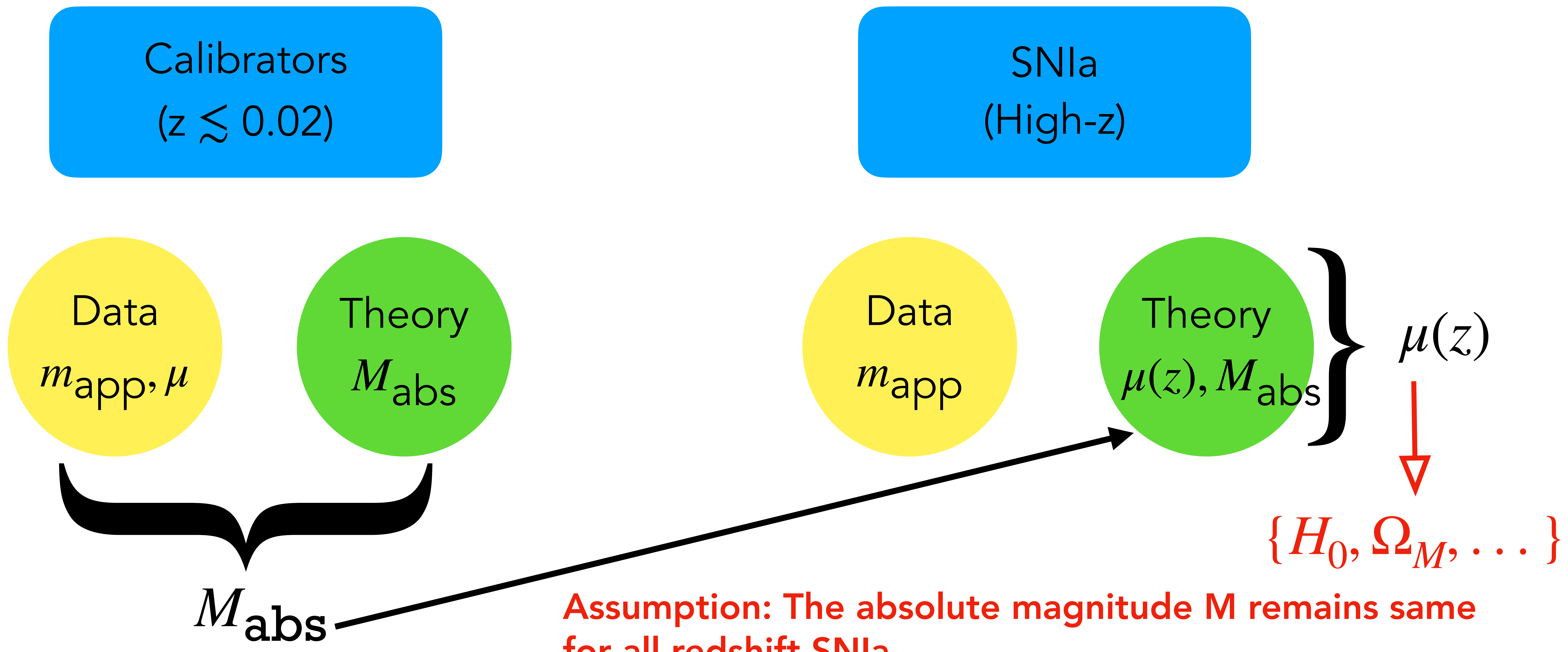
$$m_{app} = 5\log_{10}(H_0 d_L) - 5\log_{10} H_0 + 25 + M_{abs}$$

$$m_{app} = 5\log \underbrace{H_0 d_L}_{\{\Omega_M,\, \Omega_K,\, w_0,\, w_a \ldots\}} + \underbrace{\mathscr{M}}_{\{\text{SN Properties},\, H_0\}}$$

Marginalized over in std analyses

How does a typical (Calib.) SNIa likelihood work?

$$m_{app} = \mu + M_{abs}$$



Assumption: The absolute magnitude M remains same for all redshift SNIa

Hubble Tension as “M” tension

Fixing M to SHOES Best-fit value

Hubble Tension as "M" tension

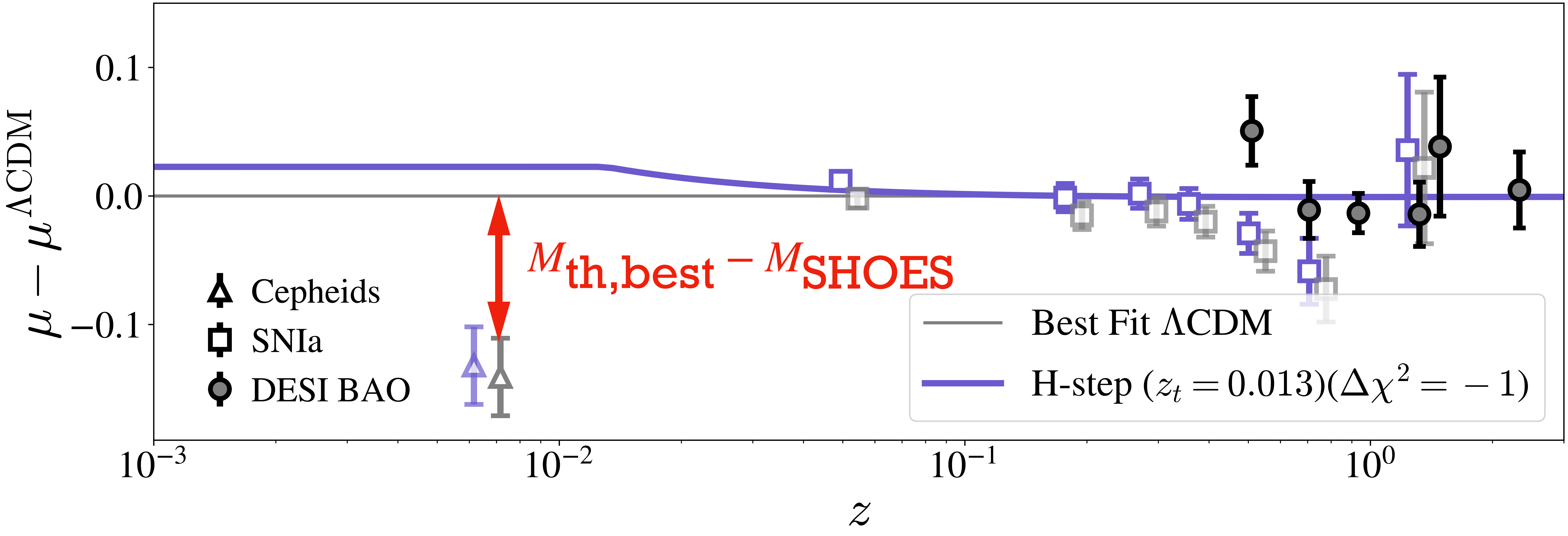
Allowing M to be a free parameter

Hubble Tension as “M” tension

Thus, a model which **solves** Hubble Tension would give a best-fit absolute magnitude M (in the combined fit to BAO+CMB+SNIa data) which is consistent with the best-fit value preferred by SHOES Cepheids (-19.25 ± 0. 027)

A simple expansion history modification cannot resolve this tension!

$$H(z) = \begin{cases} H_0 E(z), & \text{if } z \le z_\mathrm{t} \\ H_0^\mathrm{E} E(z), & \text{if } z > z_\mathrm{t} \end{cases}$$



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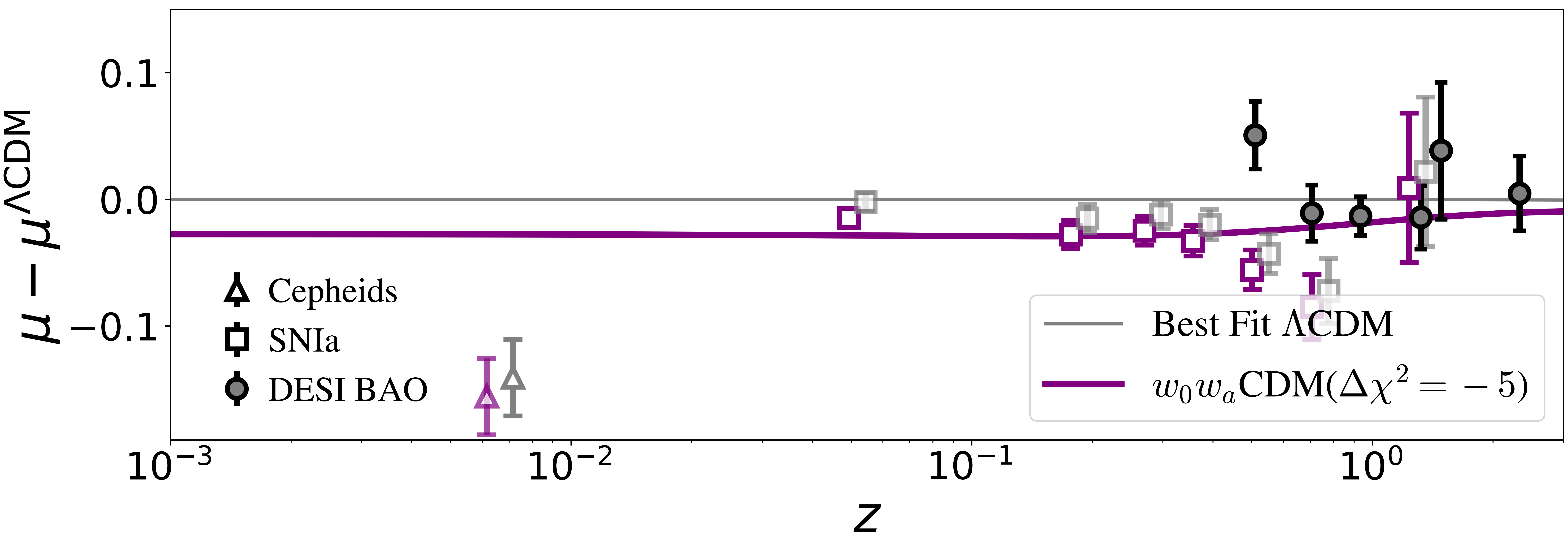
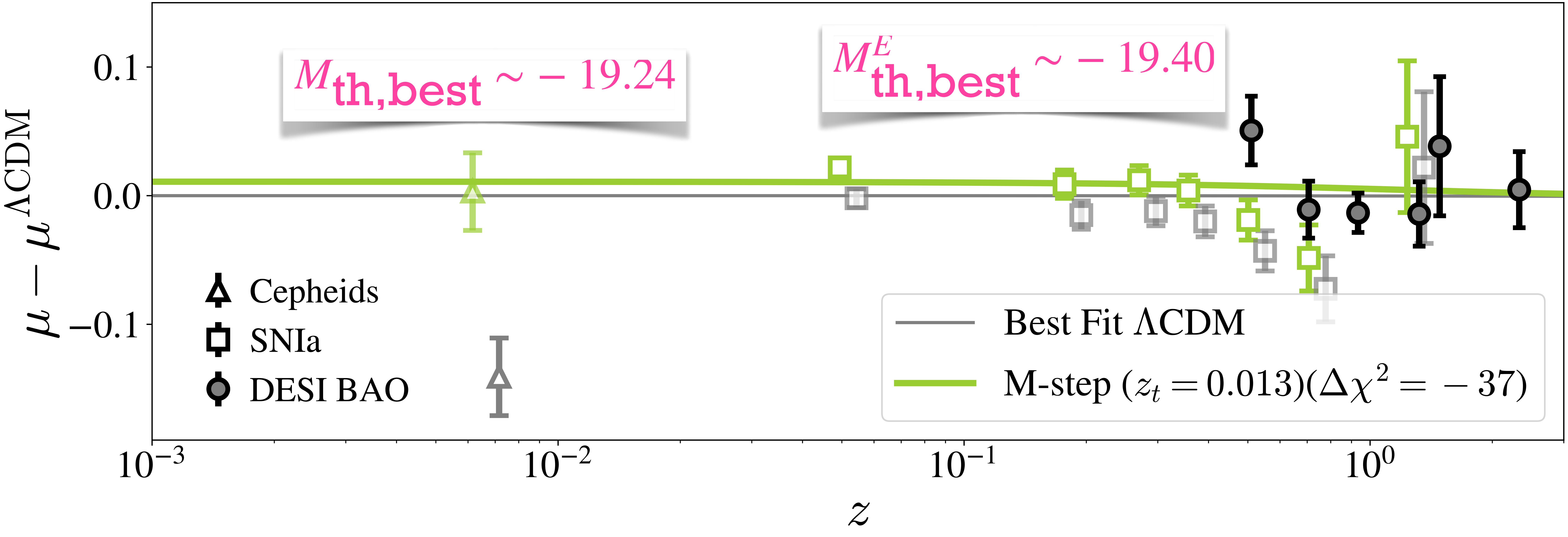


So what type of solutions can work?

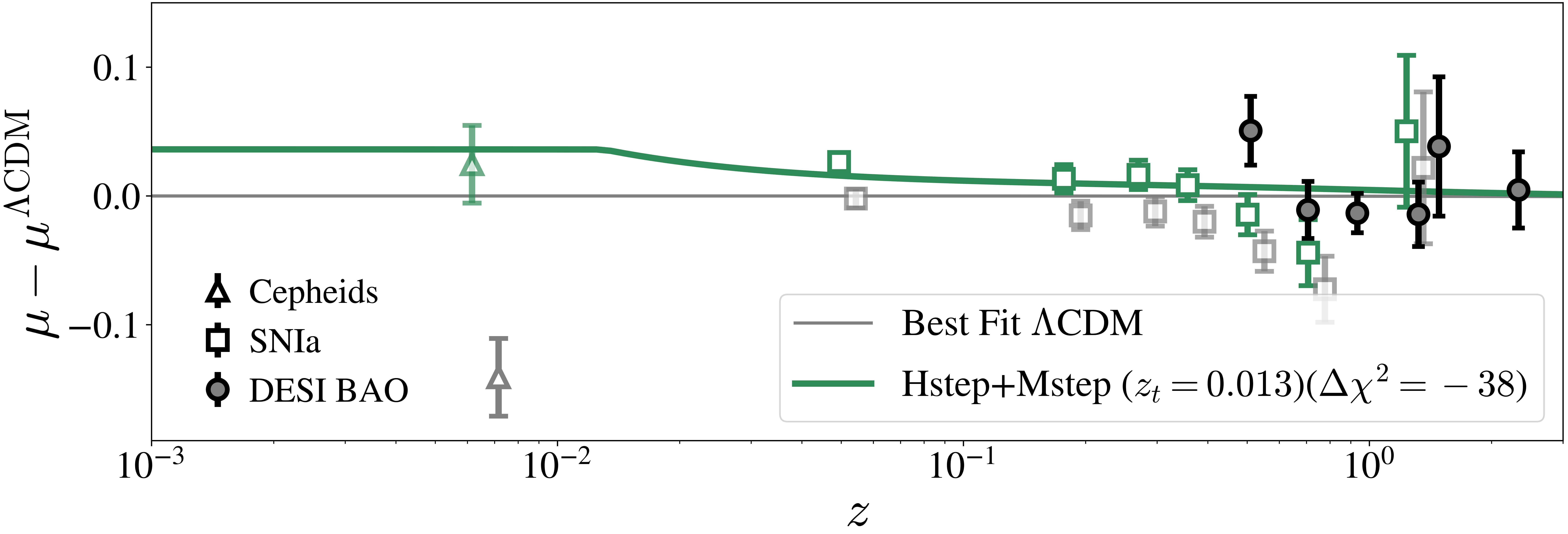
1. Allowing for a break in SNIa absolute magnitude significantly improves the $\Delta\chi^2$

$$m(z) = \begin{cases} \mu(z) + M, & \text{if } z \leq z_t \\ \mu(z) + M^E, & \text{if } z > z_t \end{cases}$$



2. A break in absolute magnitude along with a modified expansion history also works

$$m(z) = \begin{cases} \mu(z) + M, & \text{if } z \leq z_\mathrm{t} \\ \mu(z) + M^\mathrm{E}, & \text{if } z > z_\mathrm{t} \end{cases} \qquad H(z) = \begin{cases} H_0 E(z), & \text{if } z \leq z_\mathrm{t} \\ H_0^\mathrm{E} E(z), & \text{if } z > z_\mathrm{t} \end{cases}$$



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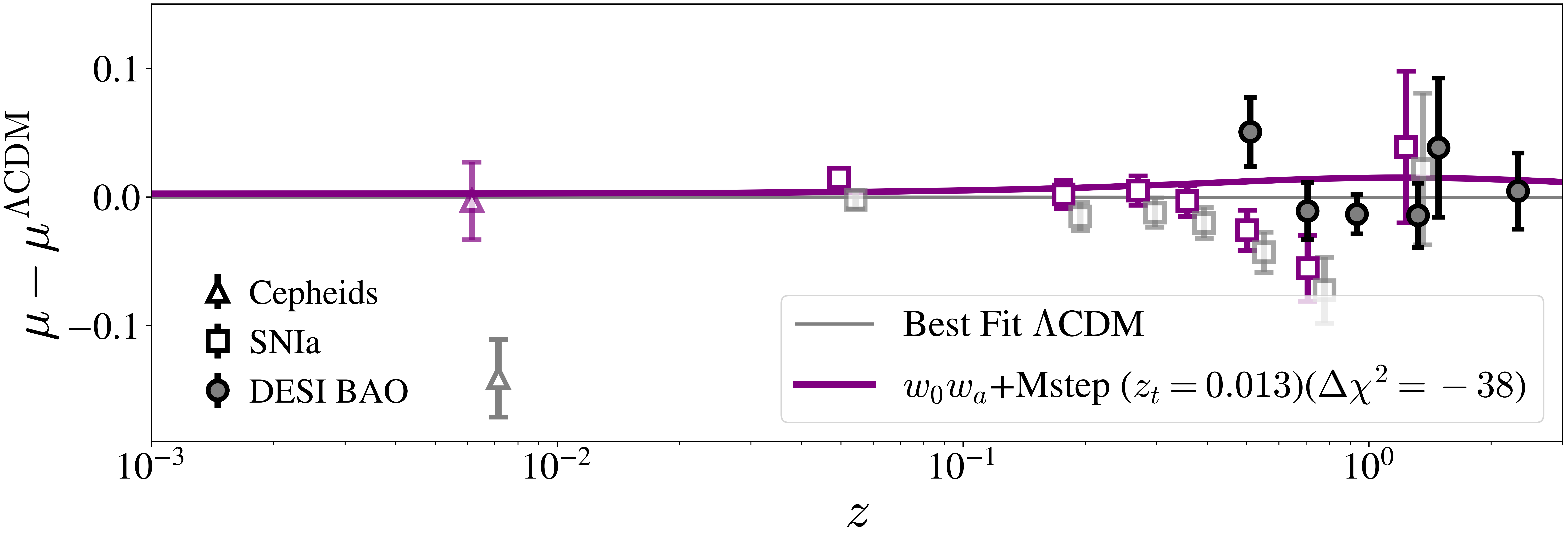
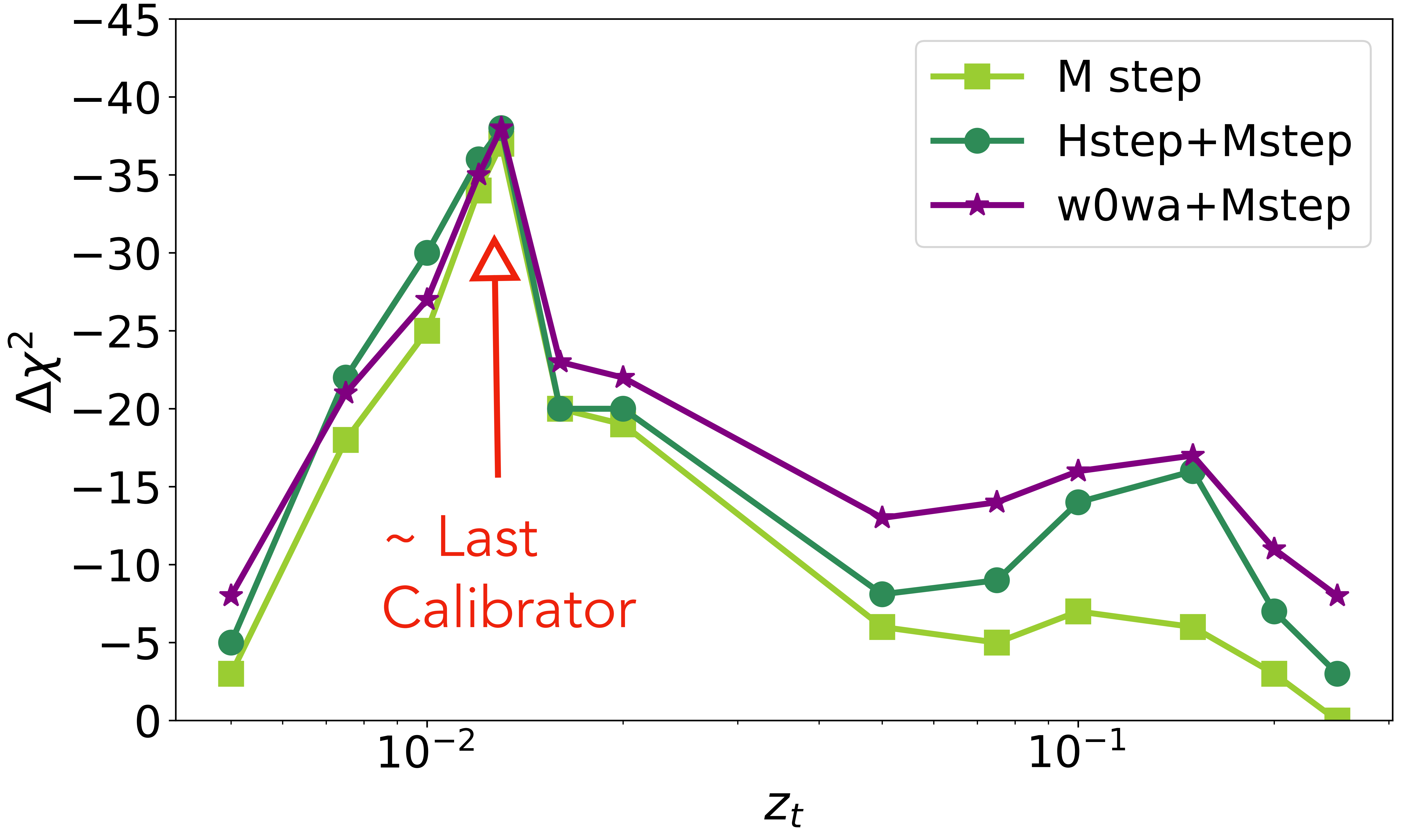


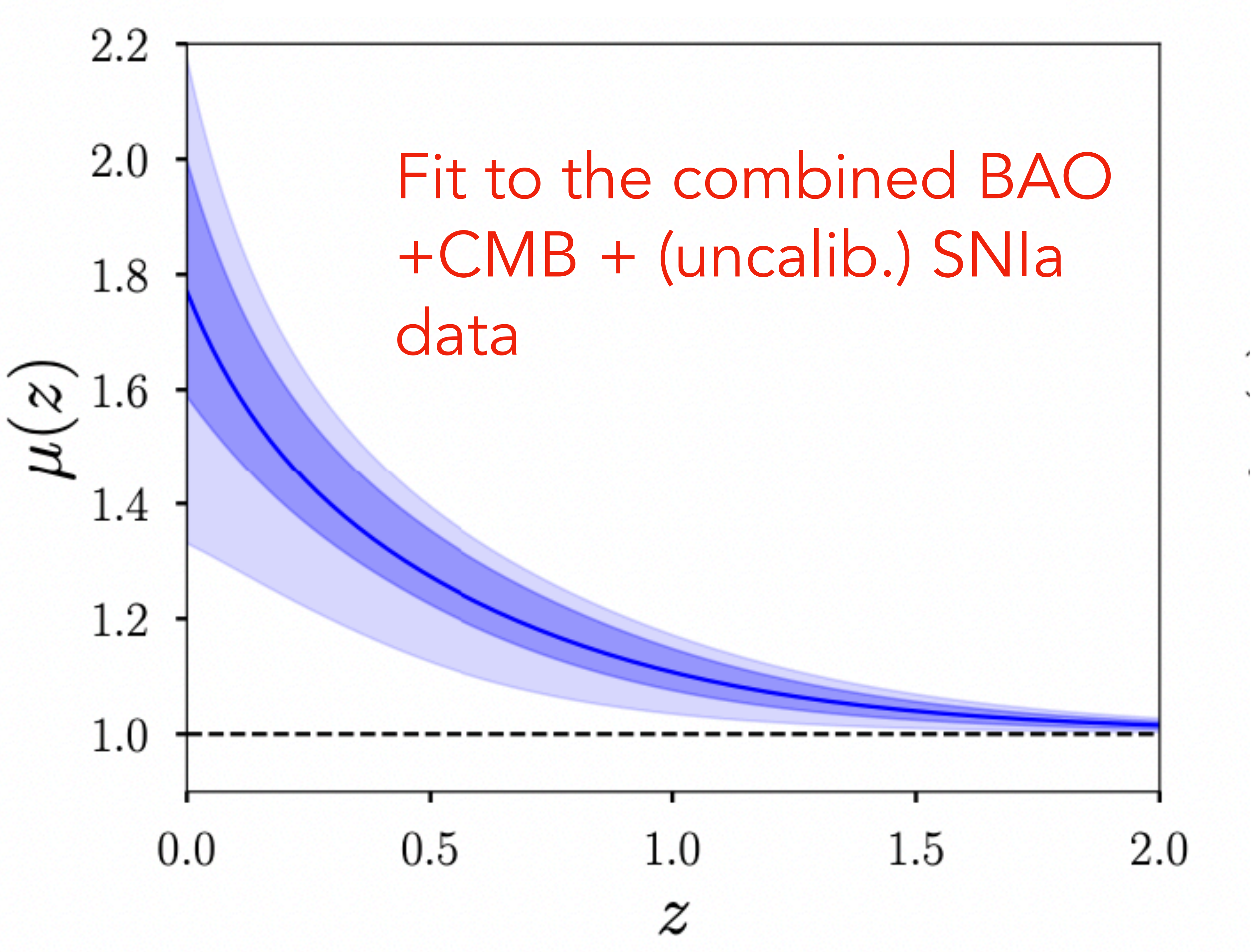
Does the redshift of this step in magnitude also matter?



Is there any "physical" way to achieve this magnitude transition?

A "tweaked" non-minimally coupled scalar field

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm Pl}^2}{2} F(\varphi) R \quad \ldots\ldots\ldots \right. \Longrightarrow G_{\mathbf{eff}}(t) \Longrightarrow M_{\mathbf{ch}}(t)$$



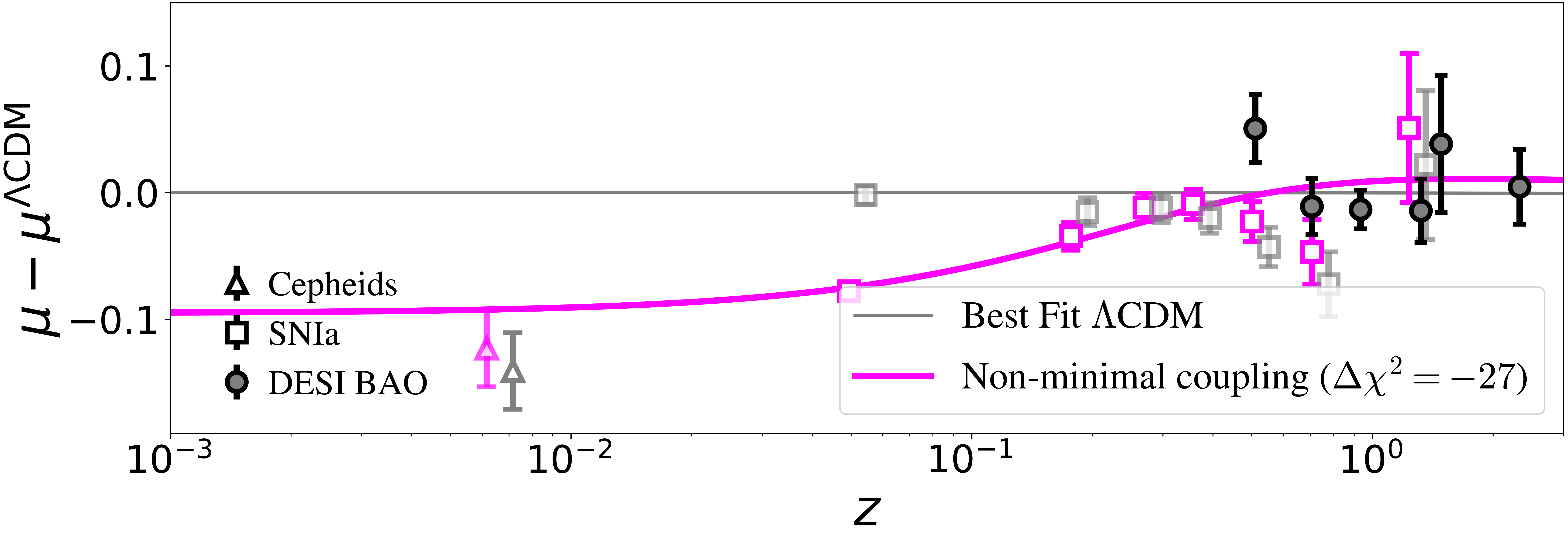
$$\nabla^2\Phi = 4\pi G\mu_{MG}\rho$$

Assuming, a power law variation of Chandrashekhar mass, and hence peak SNIa luminosity,

$$M(z) = M^E + n\log[\mu_{MG}(z)]$$

Wolf *et.al. Phys. Rev. Lett. 135, 081001*

Is there any “physical” way to achieve this magnitude transition?



Summary

- We first show that simple late time modifications of the expansion history cannot resolve Hubble Tension
- What works instead is letting go of the standard candle assumption and allowing for an evolution in the SNIa absolute magnitude
- We also show a particular (somewhat fine tuned) modifed gravity model can achieve such a transition

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

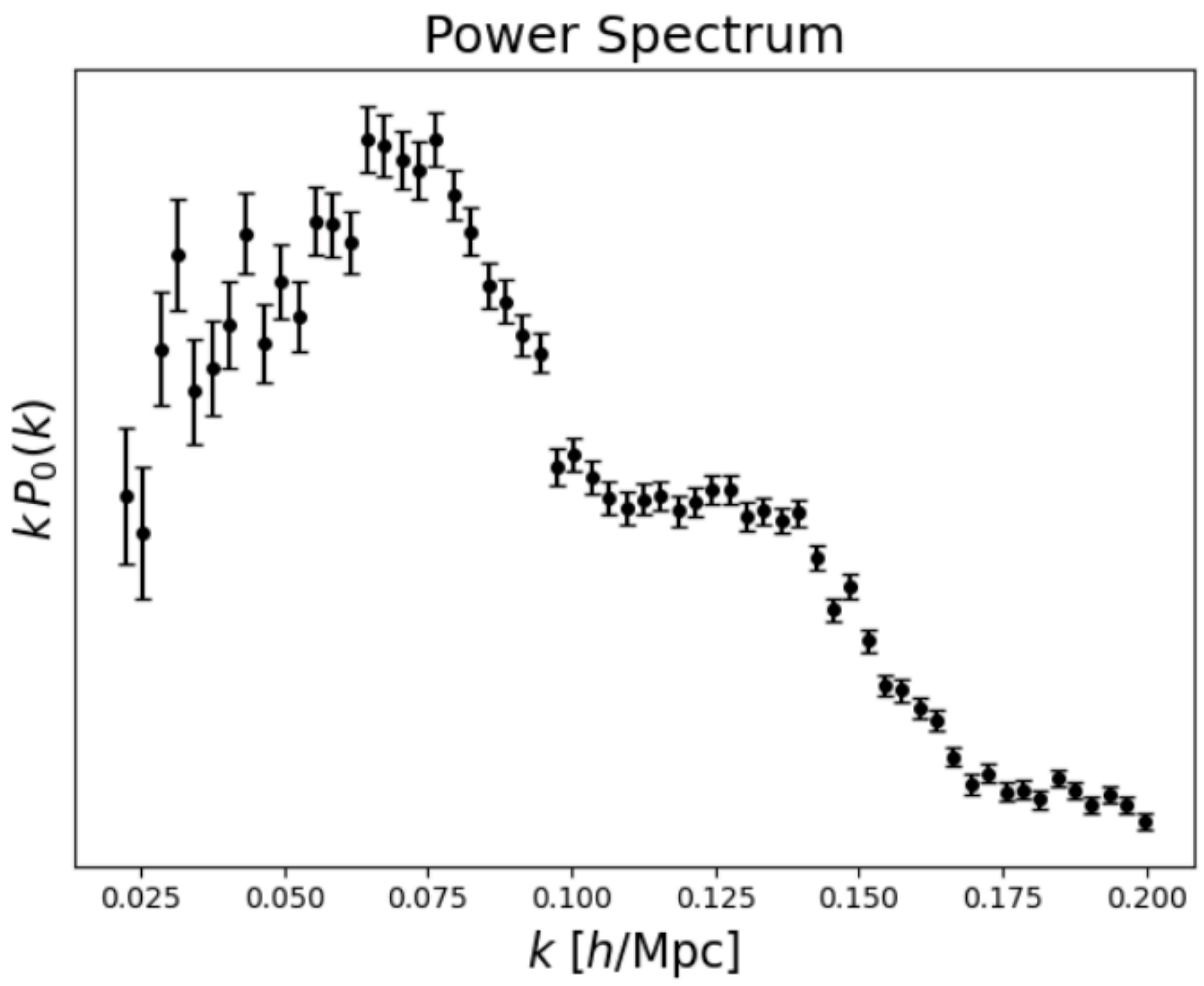
3. FolpsD: combining EFT and phenomenological approaches for joint power spectrum and bispectrum analyses

arXiv: 2604.08895

https://github.com/cosmodesi/FolpsD/tree/main

(With Alejandro Aviles, Hernan Noriega, Isaac Garzon…..)

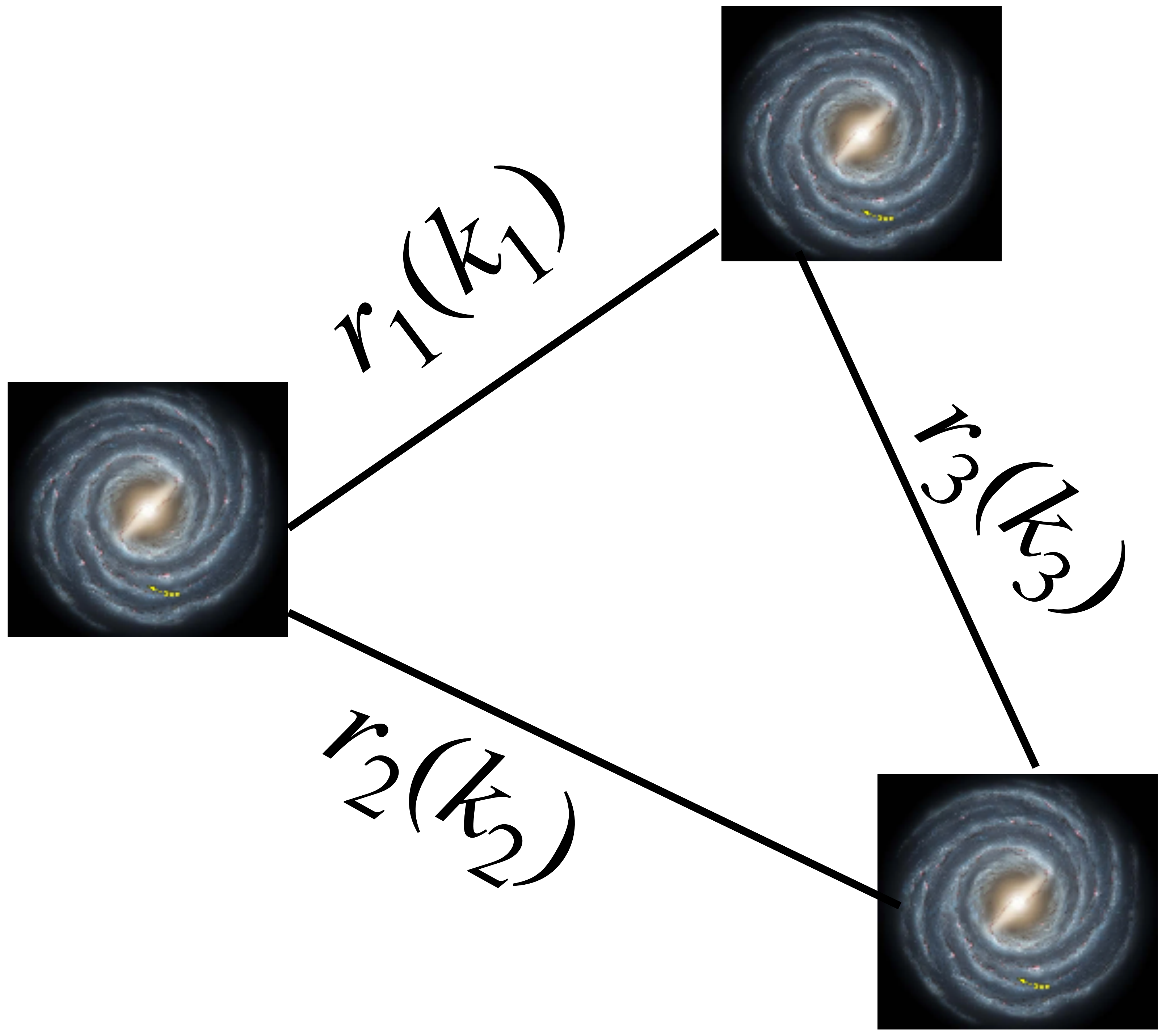
Power Spectrum



Fourier analogue of 2PCF

$P(k)$

Bispectrum



Fourier analogue of 3PCF

$B(k_1, k_2, k_3)$

EFT vs FOLPS-D

FolpsD = Damping($k_{||}$) x Folps

$$P(k,\mu) = \mathscr{D}(k^2\mu^2)\Big[P_K(k,\mu) + P_{\text{1-loop}}(k,\mu)\Big] + P^{\text{LO}}_{\text{ctr}}(k,\mu) + P_{\text{shot}}(k,\mu)\,.$$

$$\mathscr{D}(x^2) = \frac{1}{1+x^2},$$

$$x^2 = (X_{\text{FoG,p}}\, f\sigma_v k\mu)^2,$$

This damping term allows us to model the small scale non-linear modes ($k>0.20\ h\ \text{Mpc}^{-1}$) and thus derive extra information from the PS

FOLPS

[Submitted on 4 Aug 2022 (v1), last revised 19 Nov 2022 (this version, v2)]

Fast computation of non-linear power spectrum in cosmologies with massive neutrinos

Hernán E. Noriega, Alejandro Aviles, Sebastien Fromenteau, Mariana Vargas-Magaña

- EFT based code
- Massive ν and Modified gravity models
- Computationally very fast (~ 0.2s/ PS)

FOLPSD

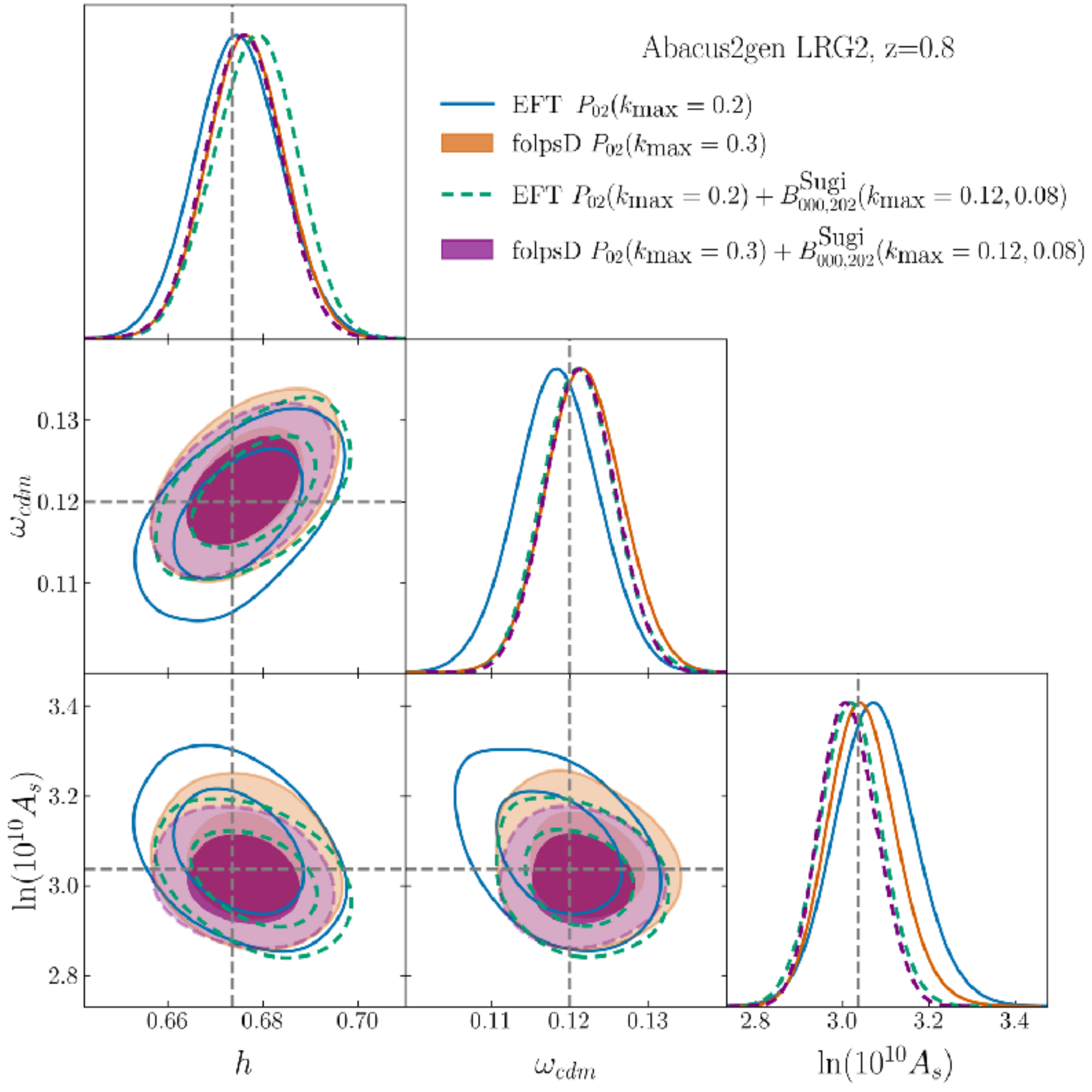
[Submitted on 10 Apr 2026]

FolpsD: combining EFT and phenomenological approaches for joint power spectrum and bispectrum analyses

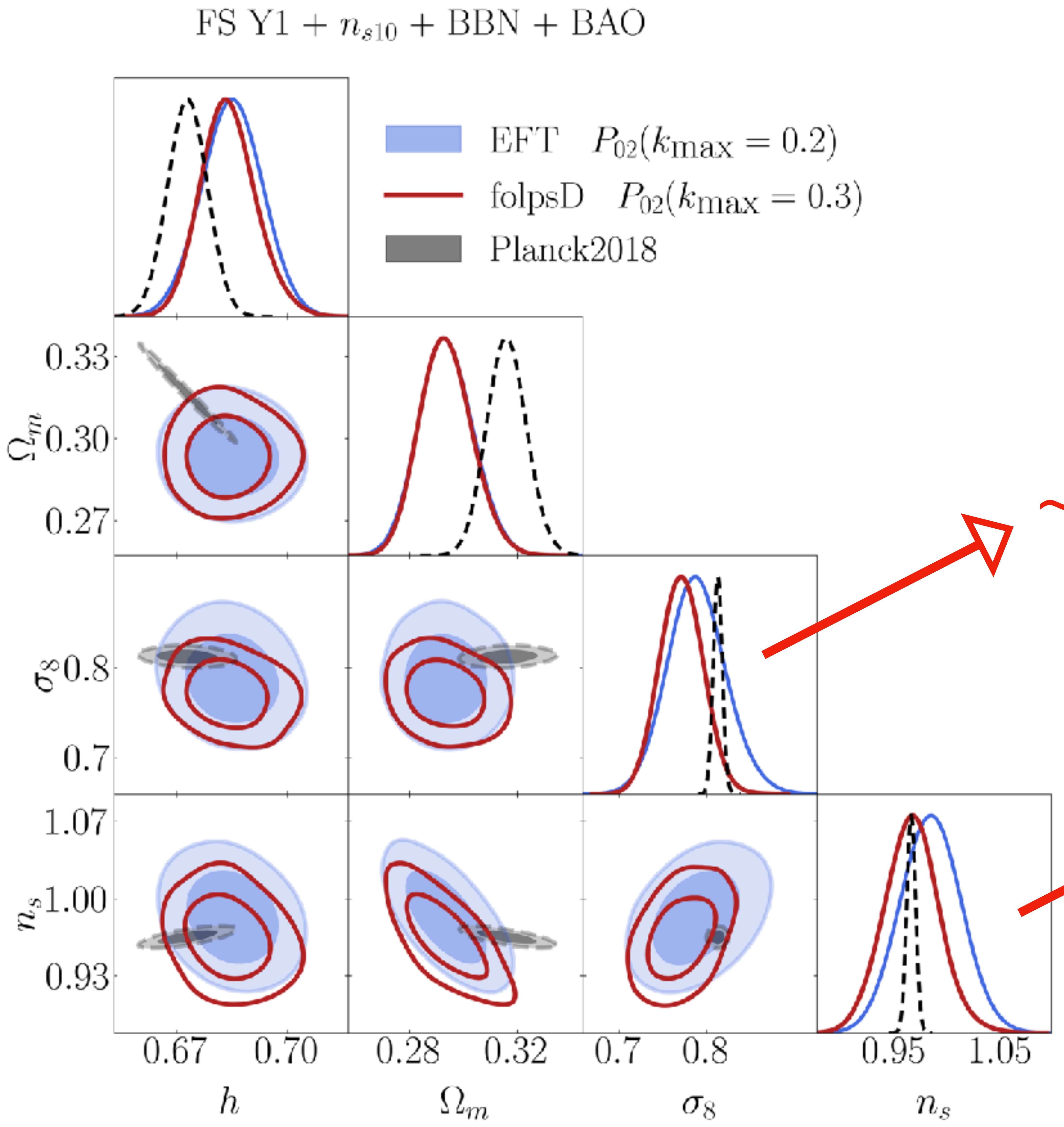
P. Bansal, A. Aviles, H. E. Noriega, C. Guandalin, I. Garzon, G. Niz, M. S. Wang, U. Andrade, F. Beutler, A. de Mattia, D. Gonzalez, J. Hou, D. Huterer, E. Paillas, M. Pellejero Ibanez, J. Aguilar, S. Ahlen, D. Bianchi, D. Brooks, T. Claybaugh, A. Cuceu, A. de la Macorra, B. Dey, P. Doel, S. Ferraro, A. Font-Ribera, J. E. Forero-Romero, E. Gaztañaga, S. Gontcho A Gontcho, G. Gutierrez, C. Hahn, H. K. Herrera-Alcantar, K. Honscheid, C. Howlett, M. Ishak, R. Joyce, S. Juneau, D. Kirkby, A. Kremin, M. Landriau, L. Le Guillou, M. Manera, A. Meisner, R. Miquel, S. Nadathur, W. J. Percival, F. Prada, I. Pérez-Ràfols, G. Rossi, L. Samushia, E. Sanchez, D. Schlegel, M. Schubnell, H. Seo, J. Silber, G. Tarlé, B. A. Weaver, P. Zarrouk, R. Zhou

- Bispectrum included
- EFT + a phenomenological damping term
- Even faster (~ 0.1s/ PS, 0.02s/ BS)
- To be used as the official code for DESI DR2 FS analysis

FolpsD vs EFT (Abacus2gen Mocks LRG2 z0.800)



FolpsD vs EFT (DESI Y1 Full Shape + BAO)



This improved modelling can help us derive more stringent constrains for quantities of interest ($w_0, w_a, \Sigma m_\nu \ldots$) without waiting years for additional data

~25 % improvement in σ_8

~8 % improvement in n_s

Summary

1. The standard cosmological model remains remarkably succesful
   - A simple six-parameter model explains observations from the CMB to galaxy clustering
2. Important cracks and open questions remain
   - DESI continues to find intriguing hints for evolving dark energy and a small neutrino mass
   - Late time expansions history modifications cannot resolve the Hubble Tension
3. New analysis and modelling techniques are crucial
   - Joint power spectrum + bispectrum analyses allow us to extract significantly more information from existing data.

Looking Ahead: DESI DR2 Full Shape Analysis!

Fig. Credits: NOIR LAB