Model-independent Cosmology: summary talk

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16/05/2024

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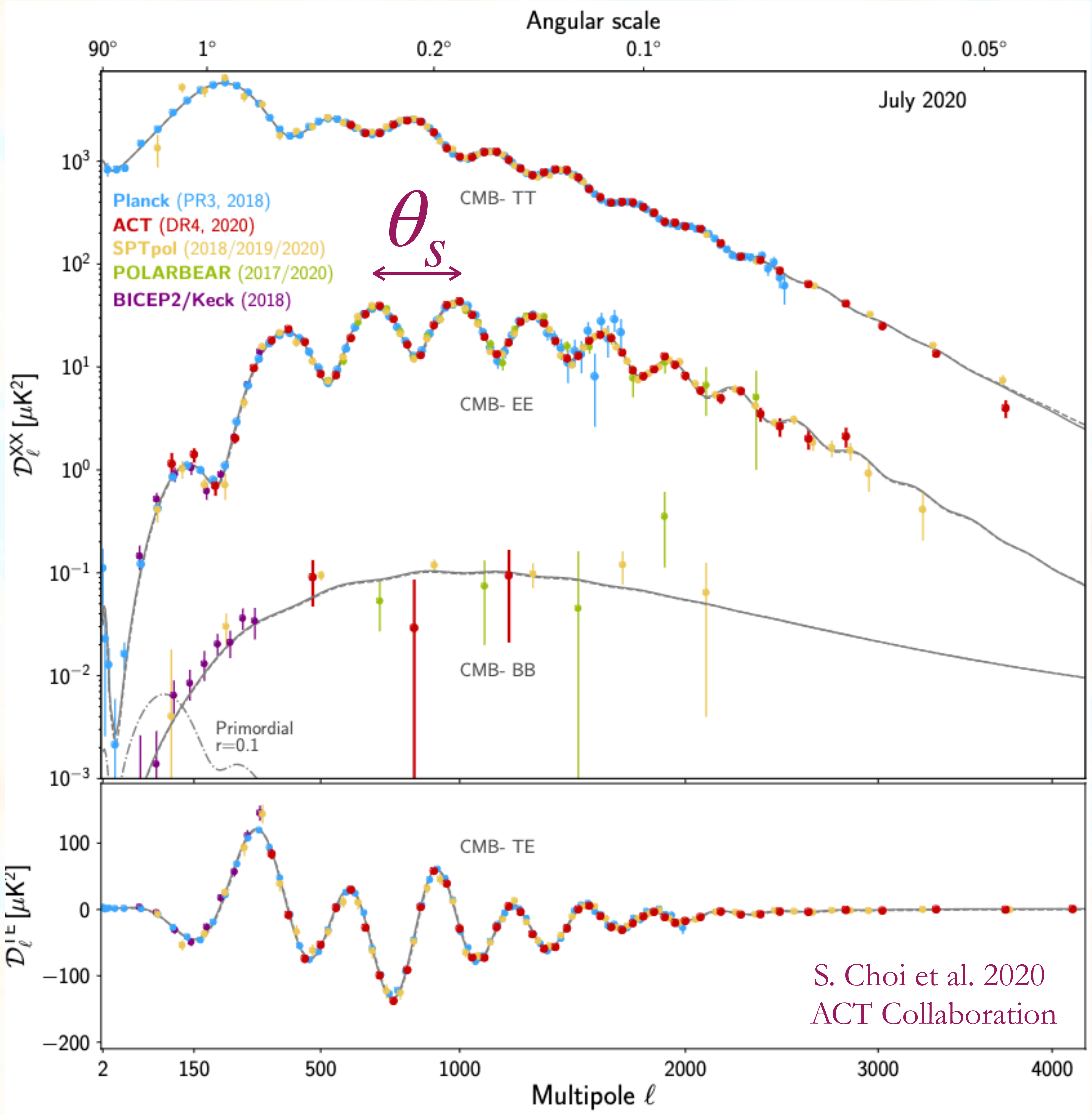
Status of Modern Cosmology



ΛCDM : **Remarkably accurate** description of CMB anisotropies

+ many more

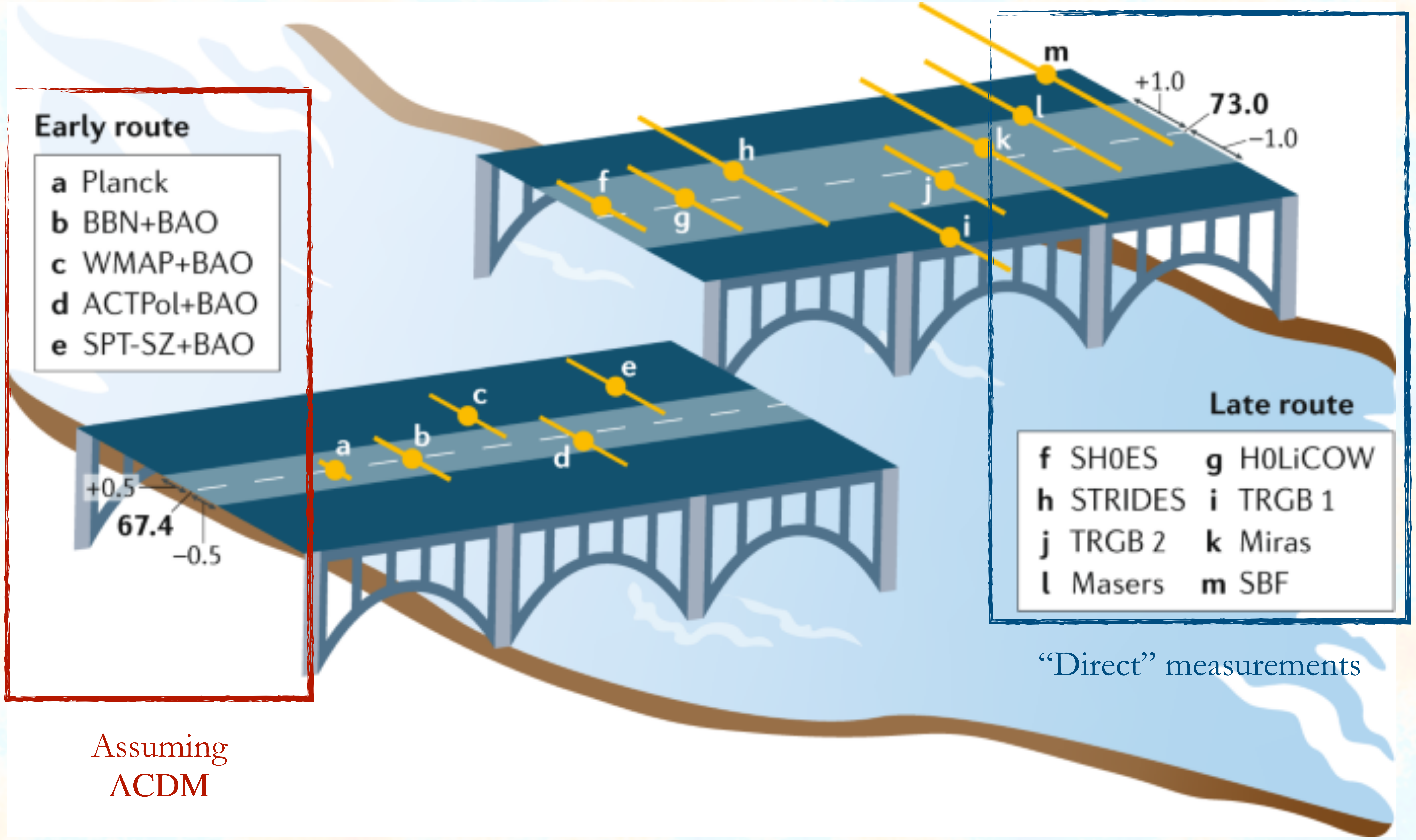
$\{\theta_s, \omega_c, \omega_b, \tau\}$ **Energy Content**

$\{n_s, A_s\}$ **Initial Conditions**

Although successful, still **phenomenological**

- Collection of (reasonable) assumptions:
  - Flat FLRW : (Isotropy + Homogeneity)
  - Gravity = GR
  - Dark Energy = Λ
  - (Cold) Dark Matter
  - Nearly Adiabatic / Scale-invariant fluctuations spectrum

The H_0 tension



Assuming
ΛCDM

Riess, Nat. Rev. Phys. 2 (2020) 10

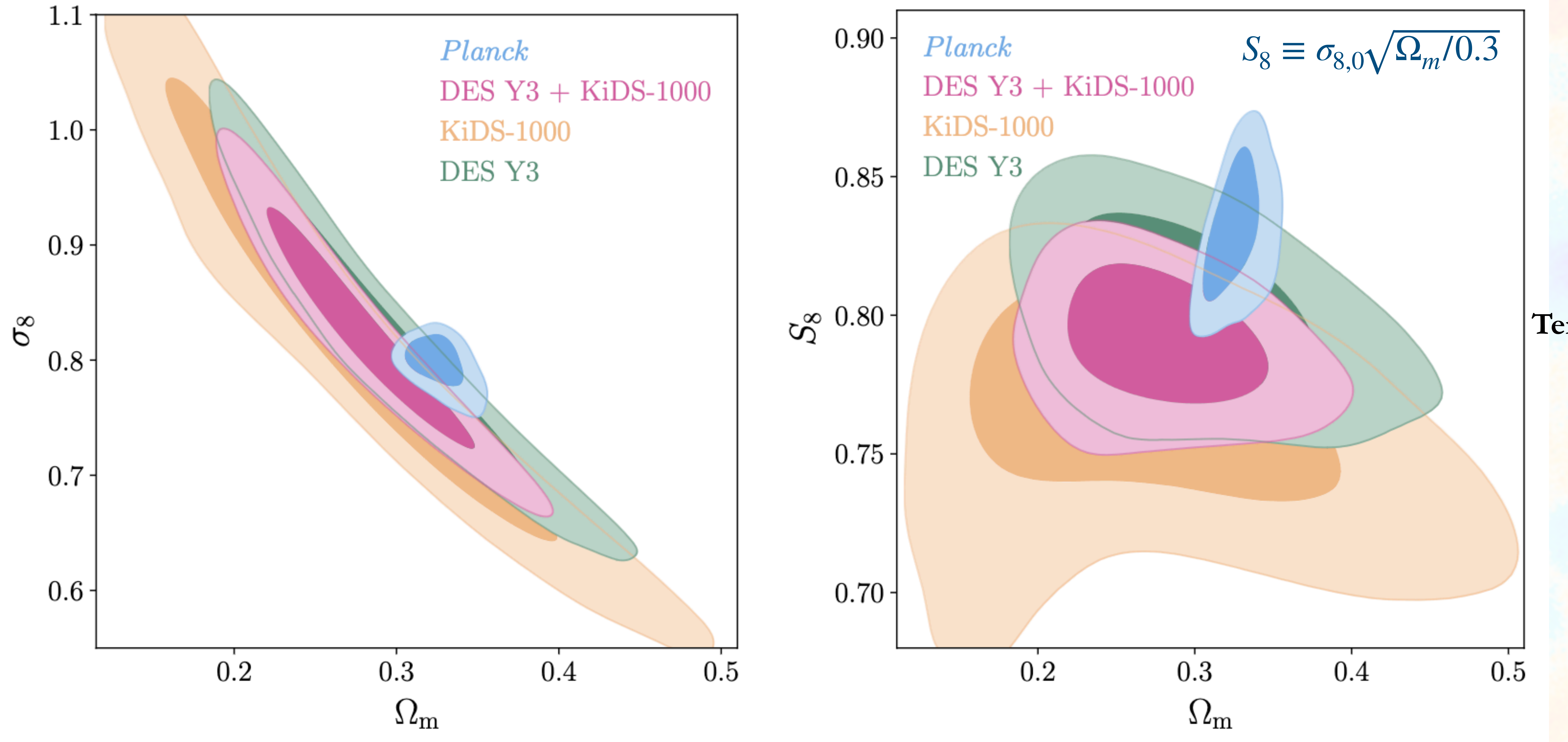
Indirect

- Model-dependent: Acoustic scale $\theta_s = \frac{r_s}{d_A}$
- Relies on well-understood (linear) physics

Direct

- Model-independent
- Relies on astrophysics

The S_8 anomaly



$\sim 2 - 3\sigma$

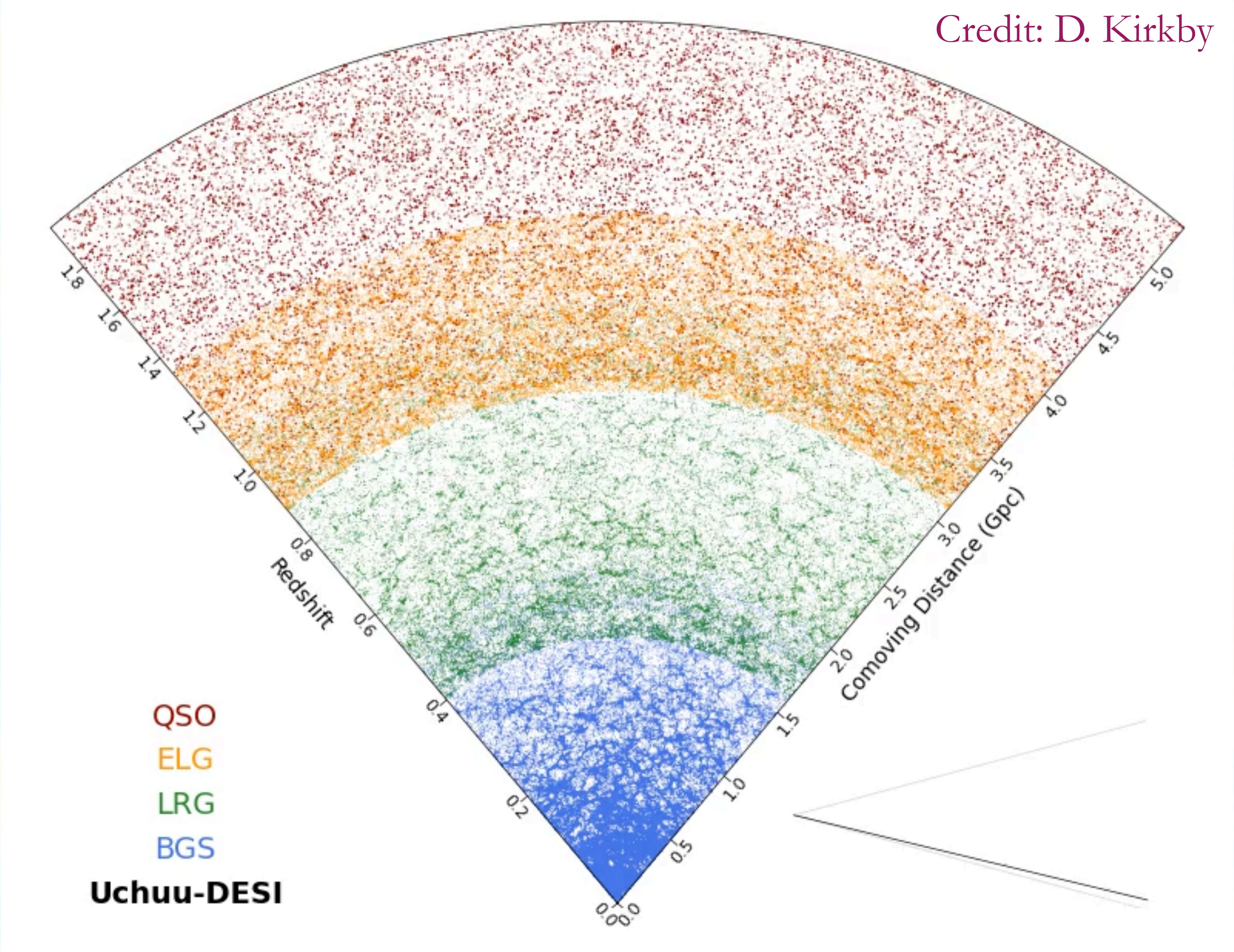
Tension/Agreement with CMB

DES Y3+KiDS-1000 [2305.17173]

Part I: DESI

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



DESI: Mayall 4m Telescope @ Kitt-peak (Arizona)

- 30 Million Galaxies ~ 5000 Spectra with each exposure !
- Accurate z-estimates
- $(z, \phi, \theta) \rightarrow$ Compute n-point statistics
- Derive constraints on your favorite cosmological model !

Part I: DESI

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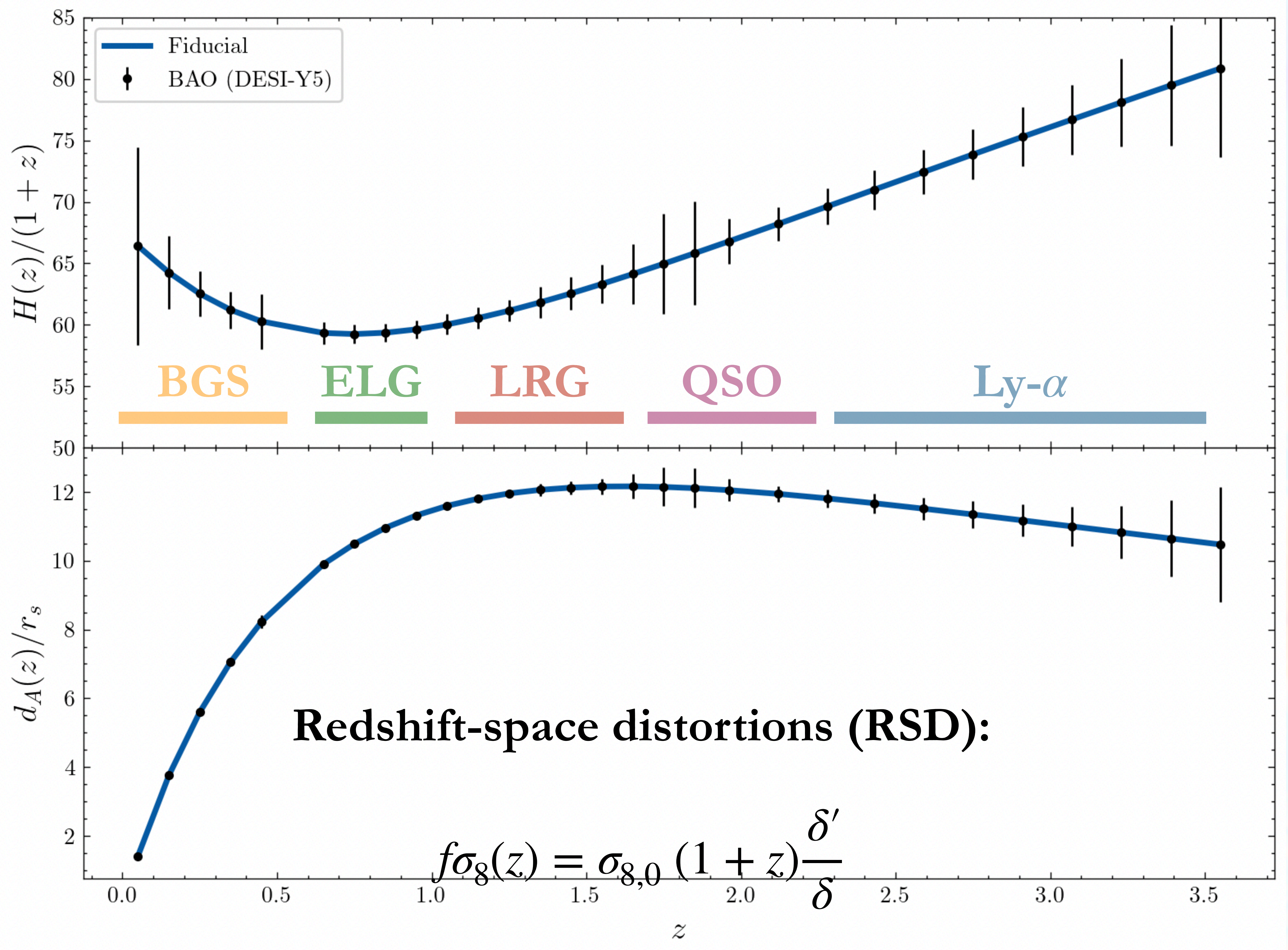

Redshift-space distortions (RSD):

$$f\sigma_8(z) = \sigma_{8,0}\,(1+z)\frac{\delta'}{\delta}$$

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Sensitive to new physics in mainly two ways:

Modified Expansion

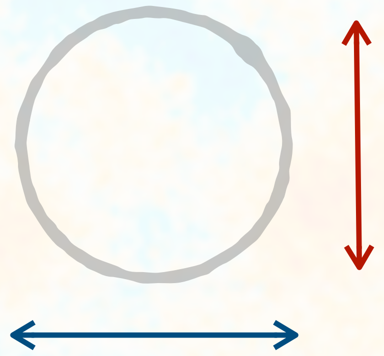
$$\frac{H^2(z)}{H_0^2} = \Omega_m a^{-3} + (1 - \Omega_m)$$

Modified Growth

$$f' + \left(f + 2 + \frac{h'}{h}\right) f = \frac{3}{2}\Omega_m(z)$$

Clustering measurements :

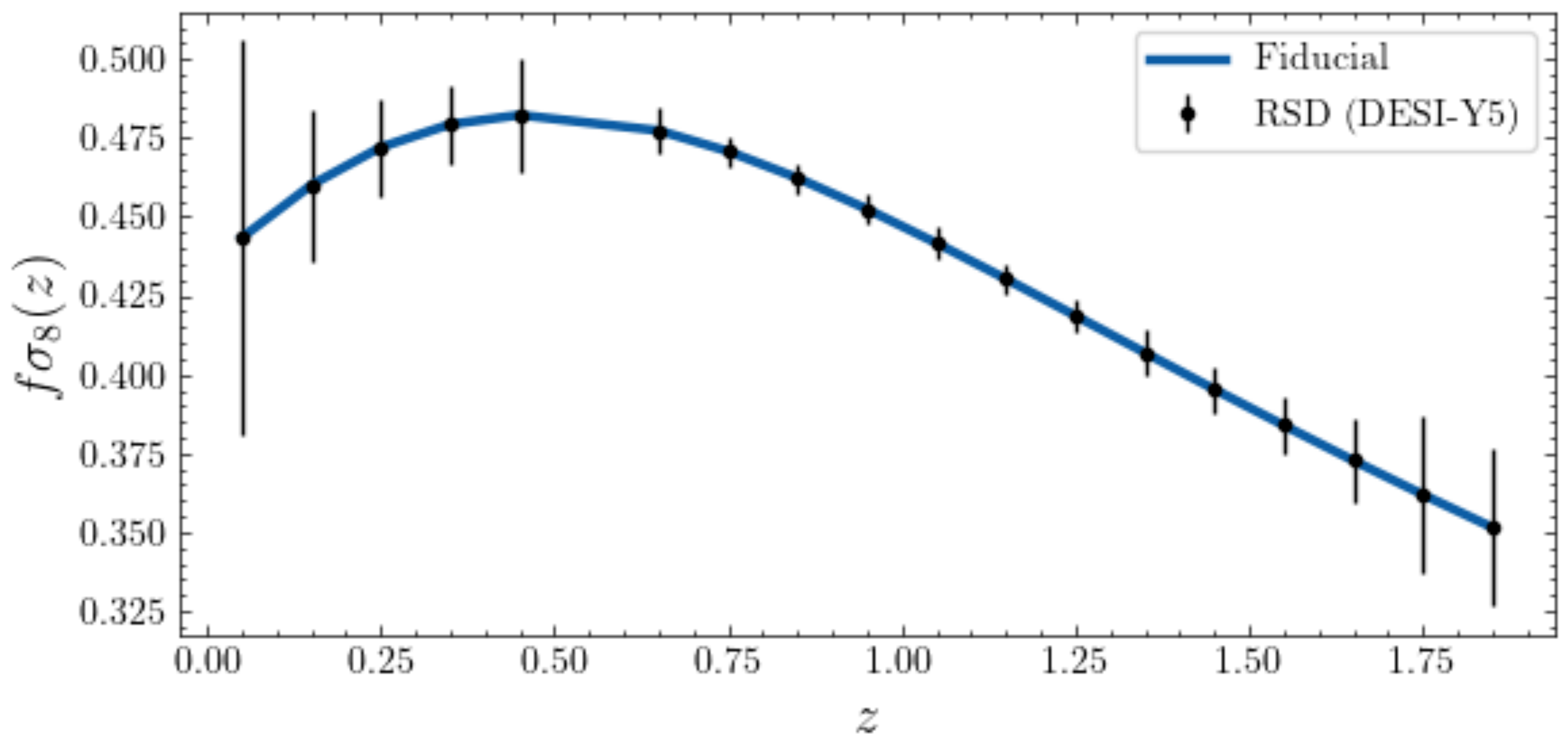
- Transversal $d_A(z)/r_s$
- Radial $H(z)\ r_s$



Part I: DESI

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science



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Modified Expansion

$$\frac{H^2(z)}{H_0^2} = \Omega_m a^{-3} + (1-\Omega_m)\, f_{\rm DE}(z)$$

Modified Growth

$$f' + \left(f + 2 + \frac{h'}{h}\right) f = \frac{3}{2}\Omega_m(z)\,\mu(z)$$

Clustering measurements :

- Transversal $d_A(z)/r_s$
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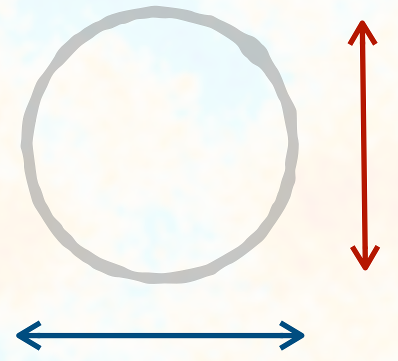
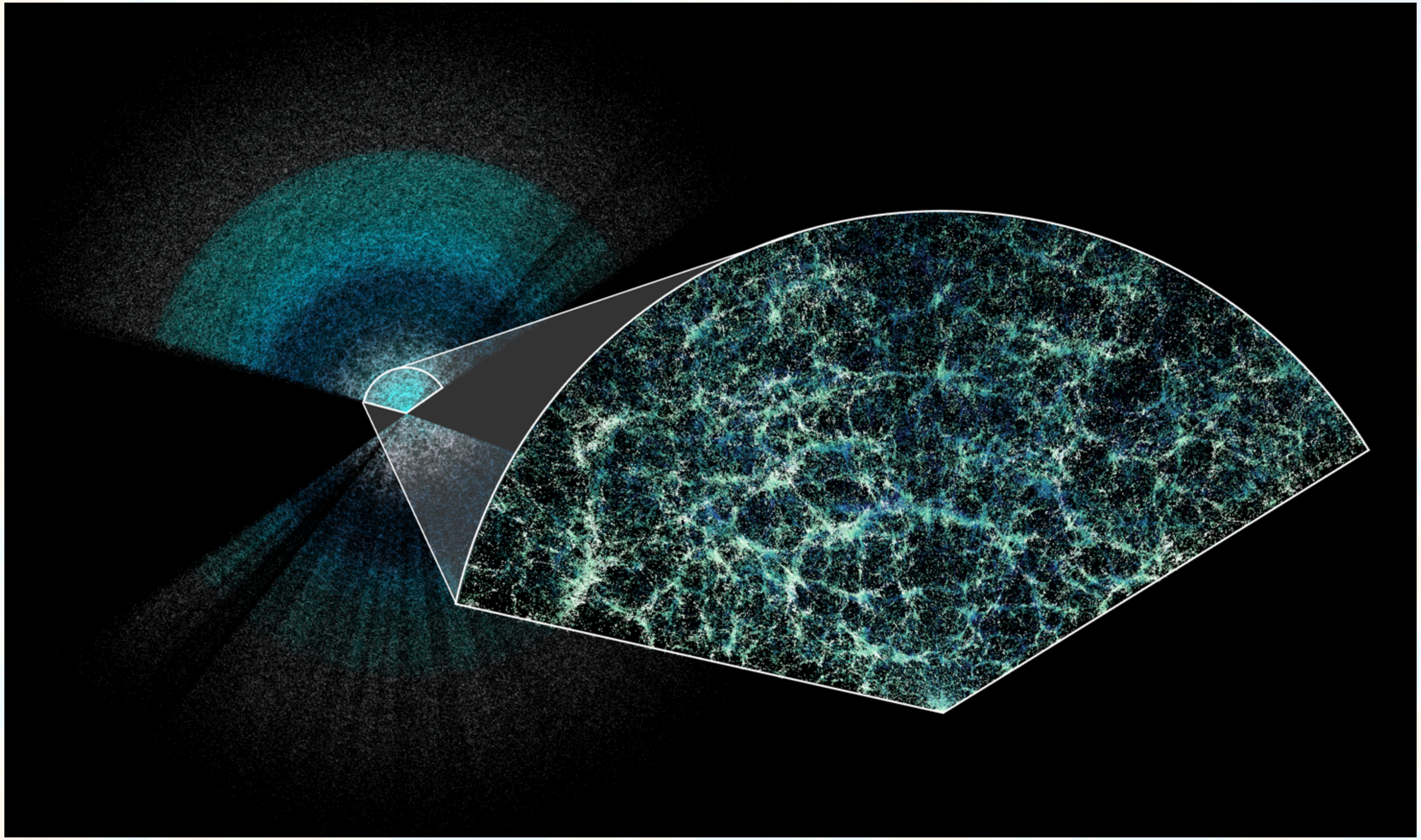
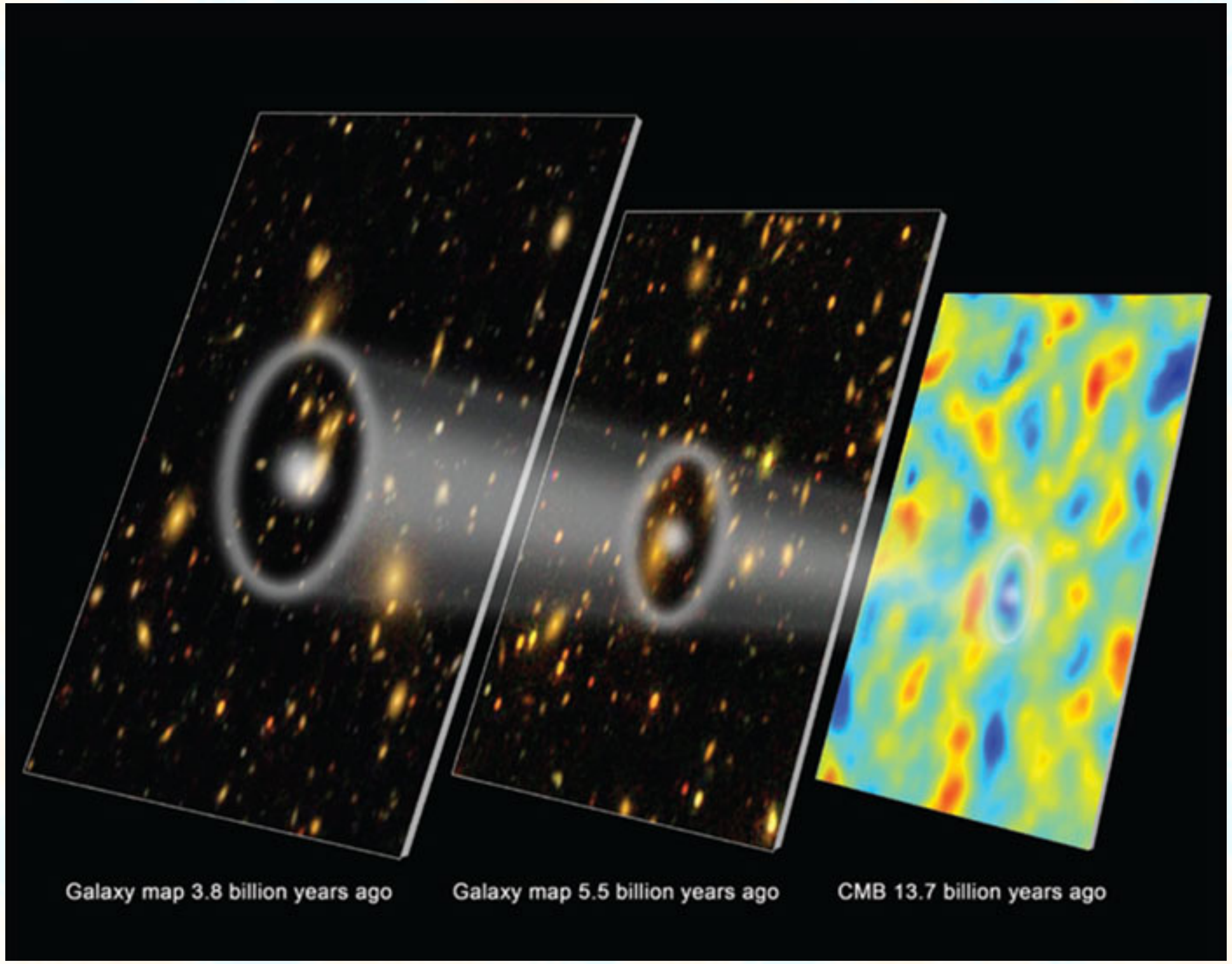


Part II: Baryon Acoustic Oscillations

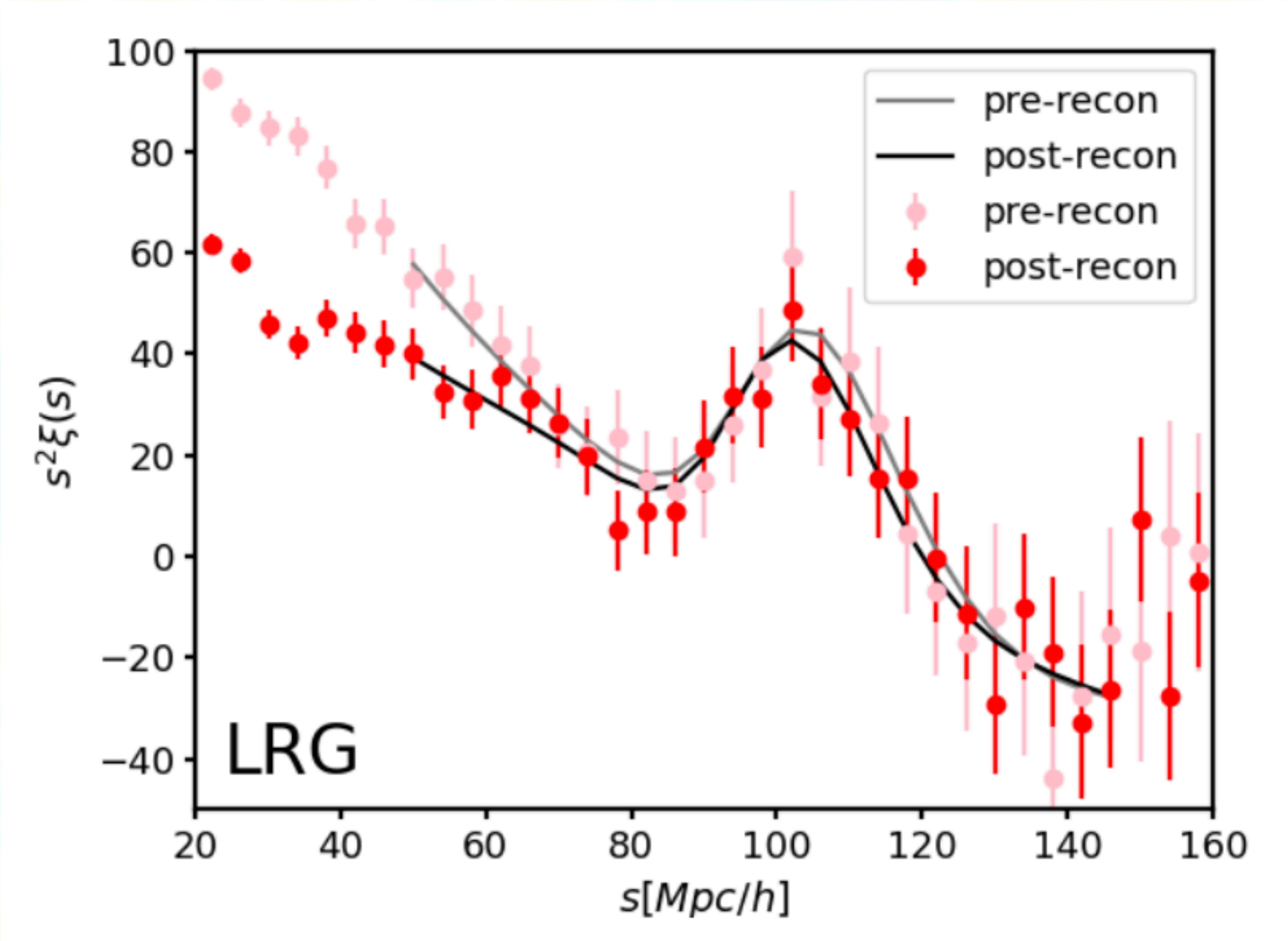
From the distribution of galaxies & quasars, to cosmological constraints



Baryon Acoustic Oscillations

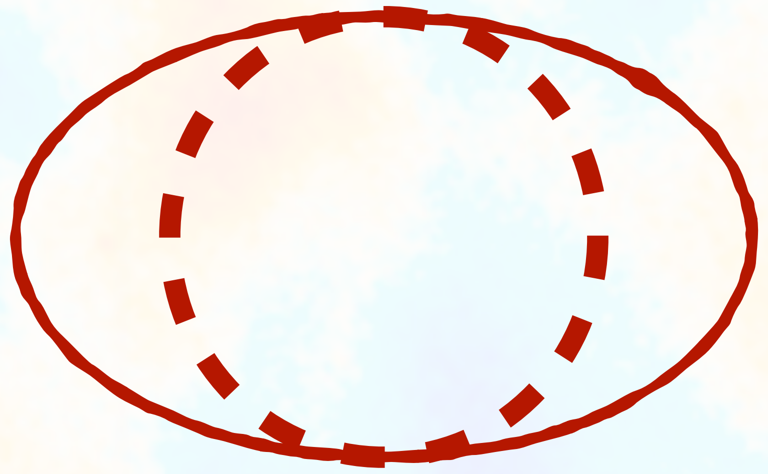


Credit: E. M. Huff & SPT team



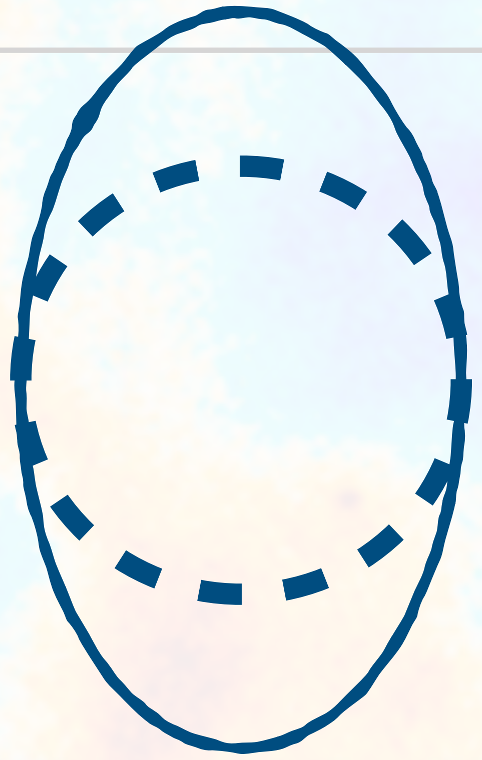
J. Moon et al. (2023) - First Detection of the BAO Signal from Early DESI Data

"Compressed Parameters"



Transverse direction

"Alcock-Paczyński"
Parameters

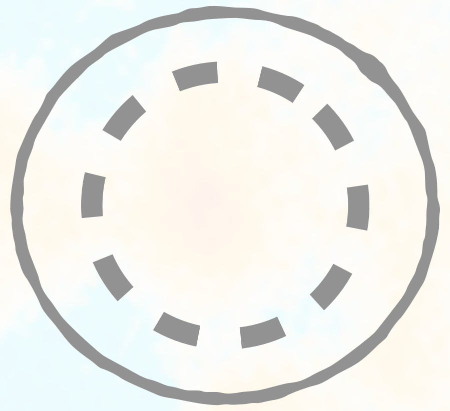


Line of sight direction

$$\frac{D_M}{r_d} = \alpha_\perp \frac{D_M^{\rm fid}}{r_d^{\rm fid}} \qquad D_M(z) \propto \int \frac{dz}{H(z)}$$

$$\frac{D_H}{r_d} = \alpha_{||} \frac{D_H^{\rm fid}}{r_d^{\rm fid}} \qquad D_H(z) \propto \frac{1}{H(z)}$$

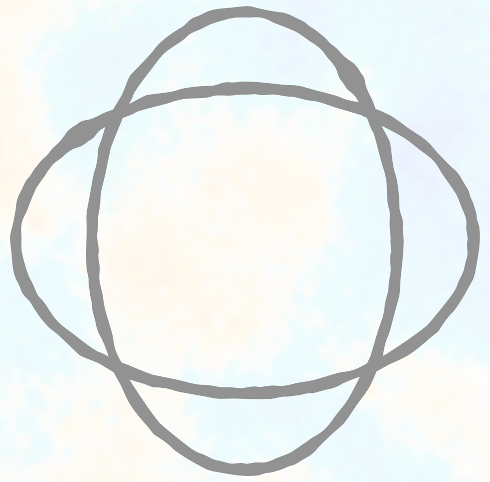
Alternatively,



Isotropic scaling
of the BAO

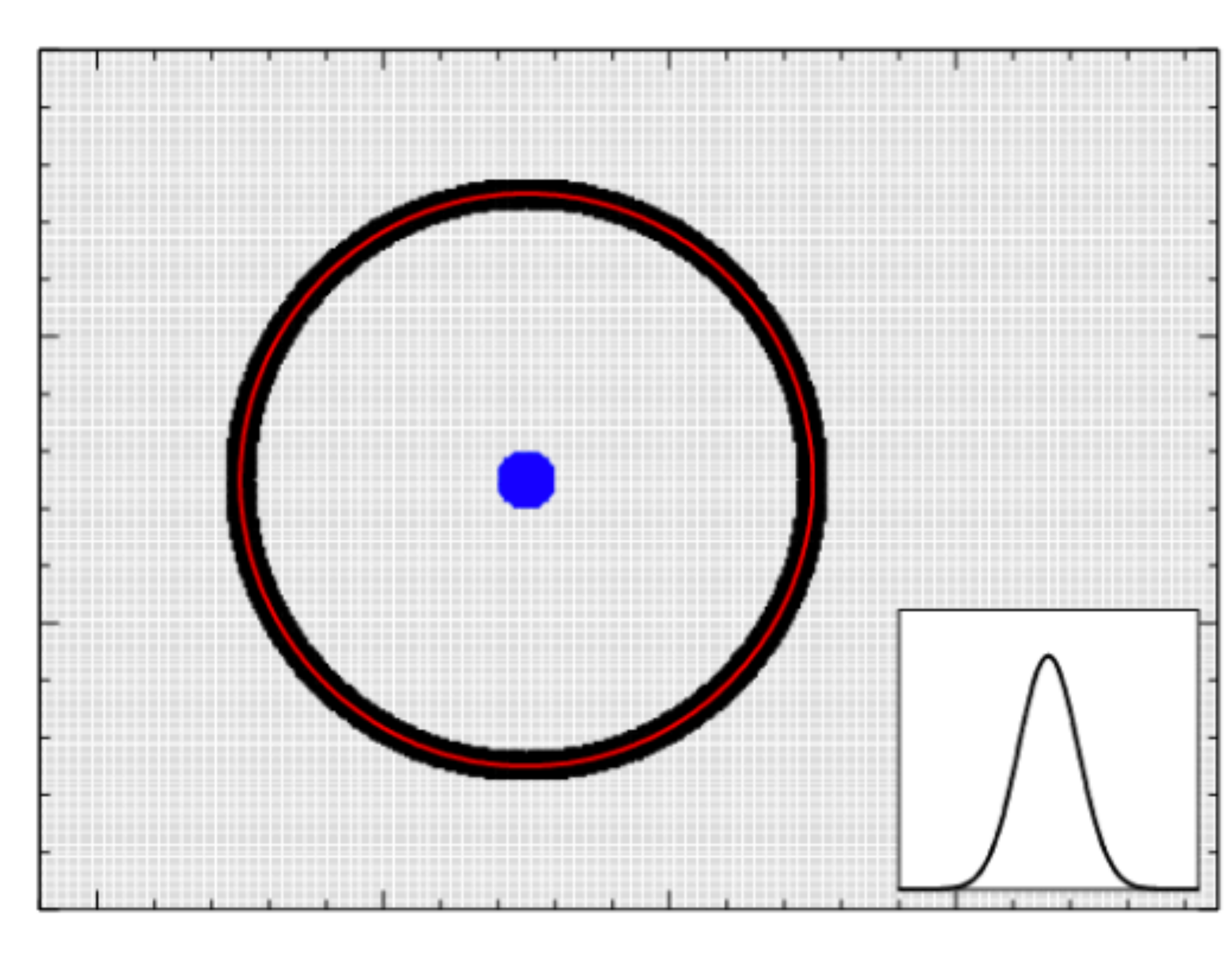
$$\alpha_{\rm iso} = (\alpha_\perp^2 \alpha_{||})^{1/3}$$

$$\alpha_{\rm AP} = \frac{\alpha_{||}}{\alpha_\perp} = \frac{D_H}{D_M}\frac{D_M^{\rm fid}}{D_H^{\rm fid}}$$



Anisotropy
of the BAO

Baryon Acoustic Oscillations



Padmanabhan et al. (2012) MNRAS

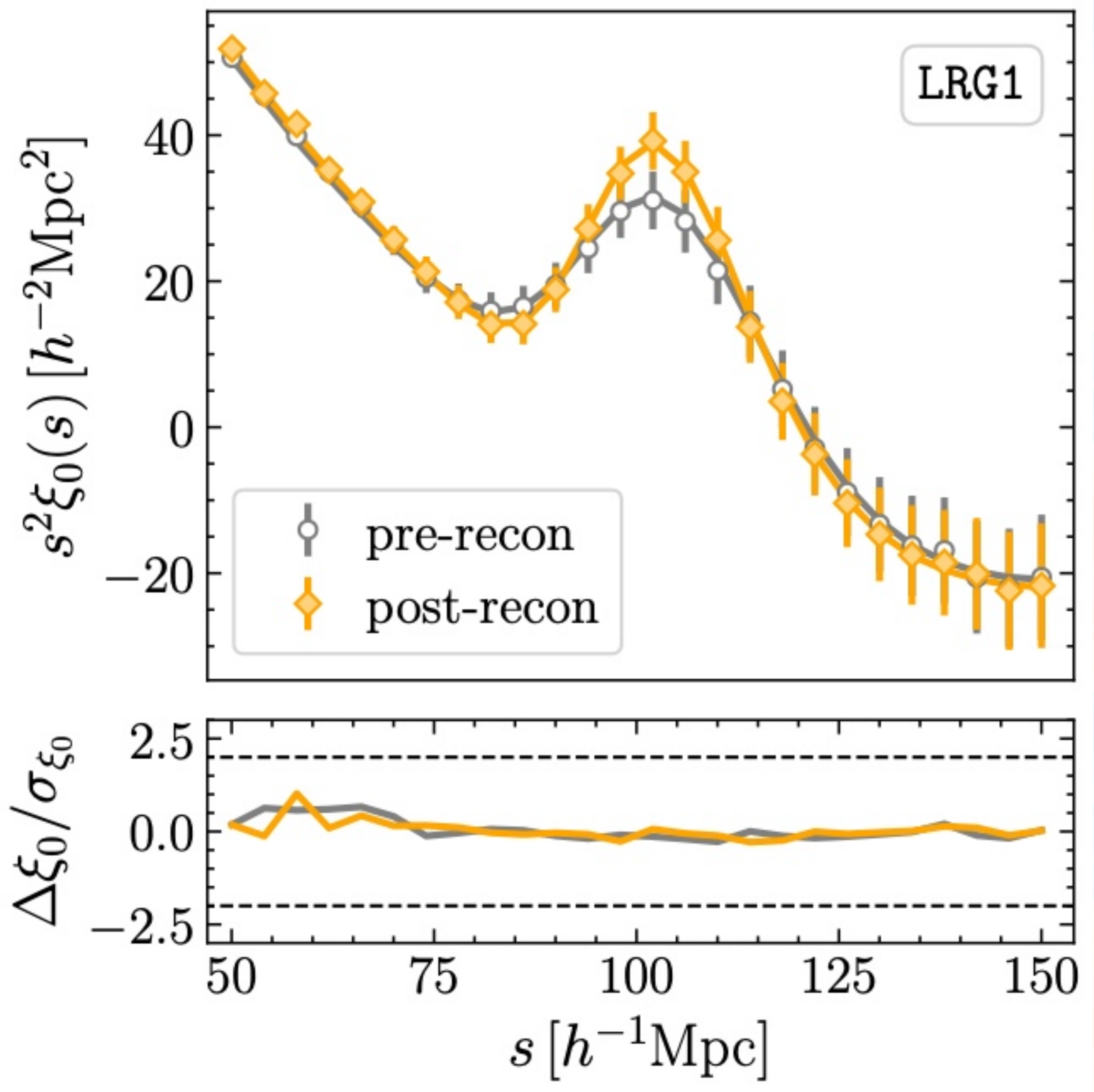
- The BAO feature is expected to be **isotropic** !
- Non-linear **gravitational evolution** introduce **anisotropies** along longitudinal/transversal directions

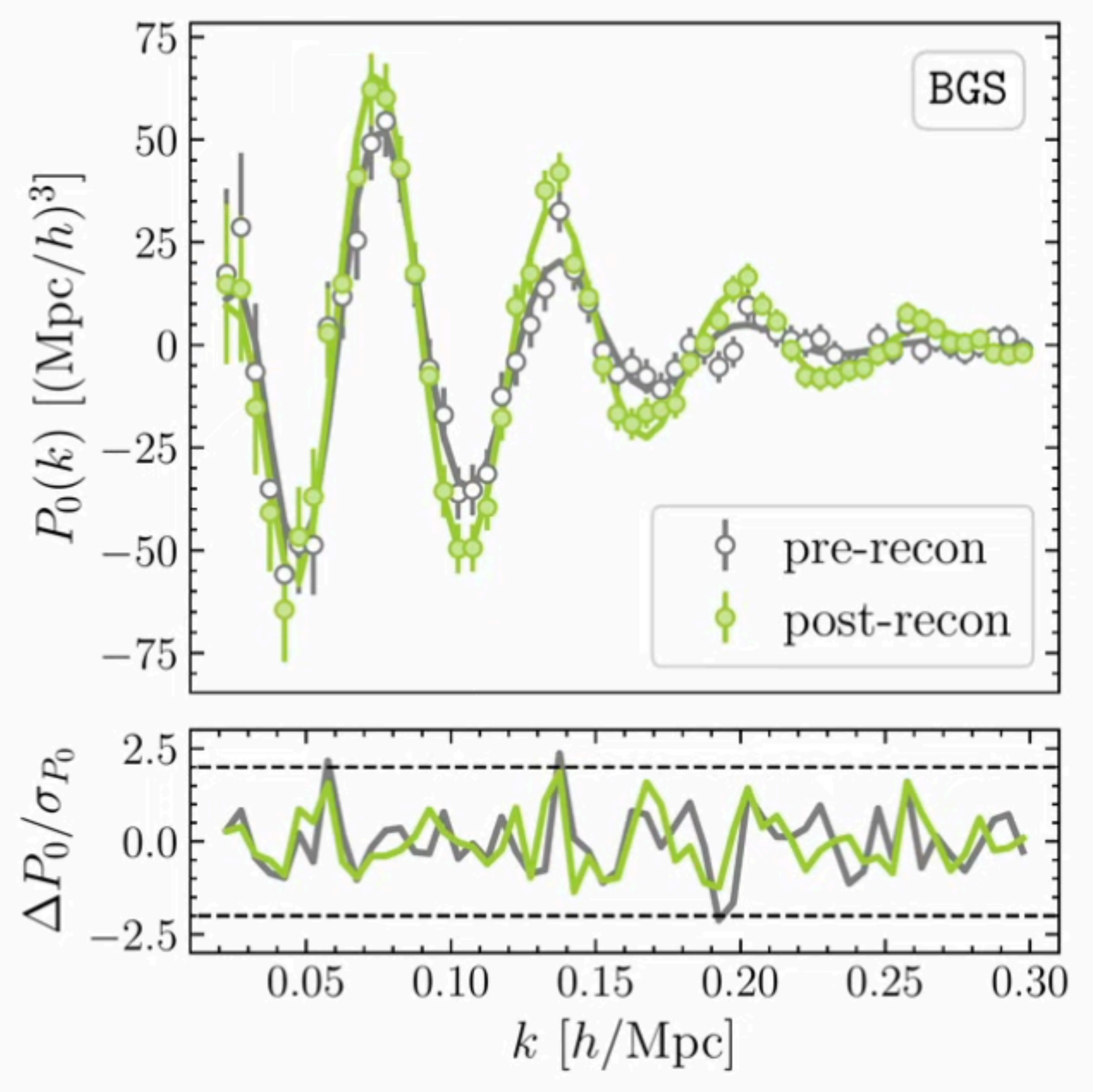
  → Broadening of the BAO peak in 2pt correlation function

- By reconstructing the velocity field, we can "**undo**" the effect of gravity/non-linearities.

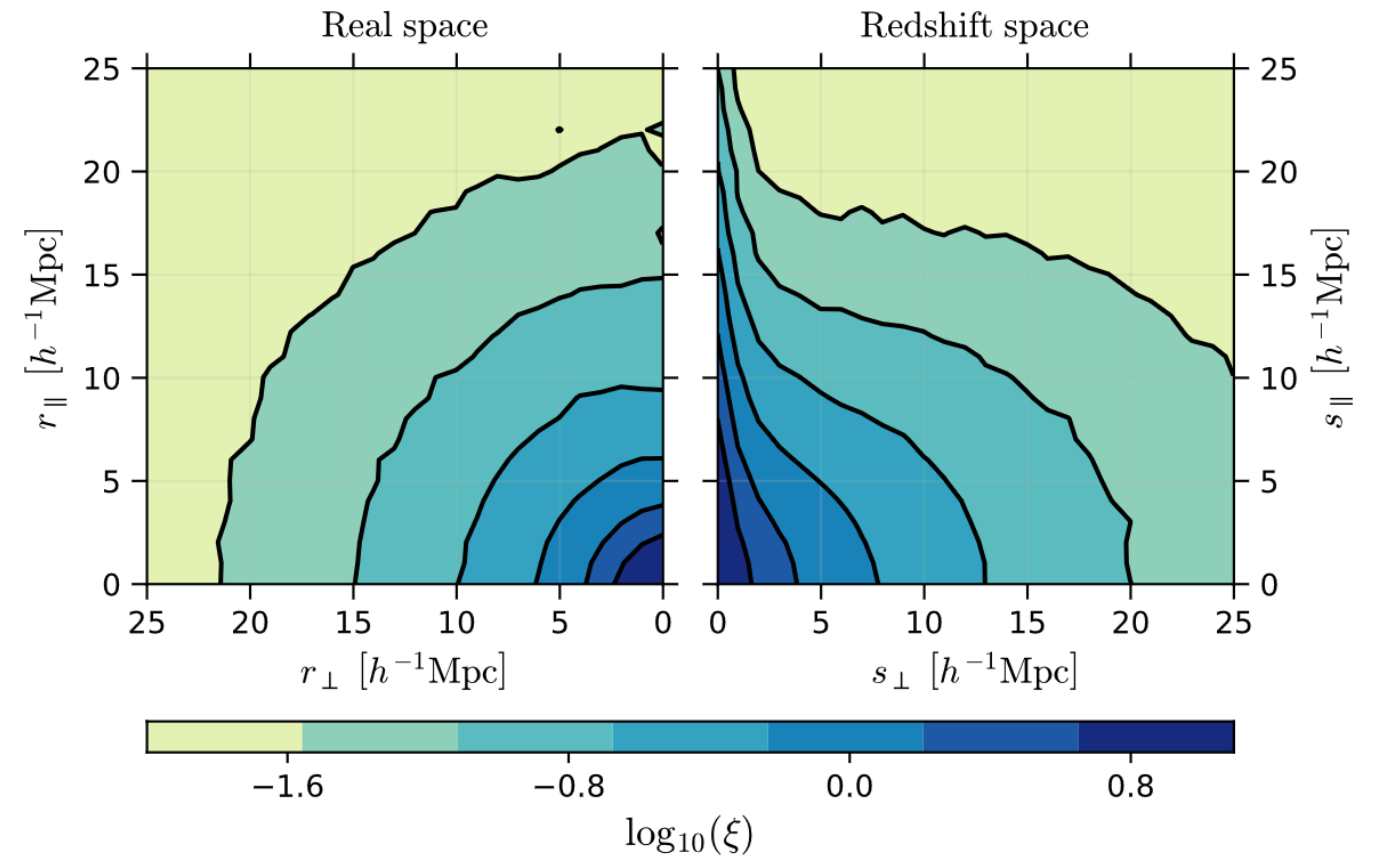
  → Increase significance of the detection !

Pre vs post-reconstruction



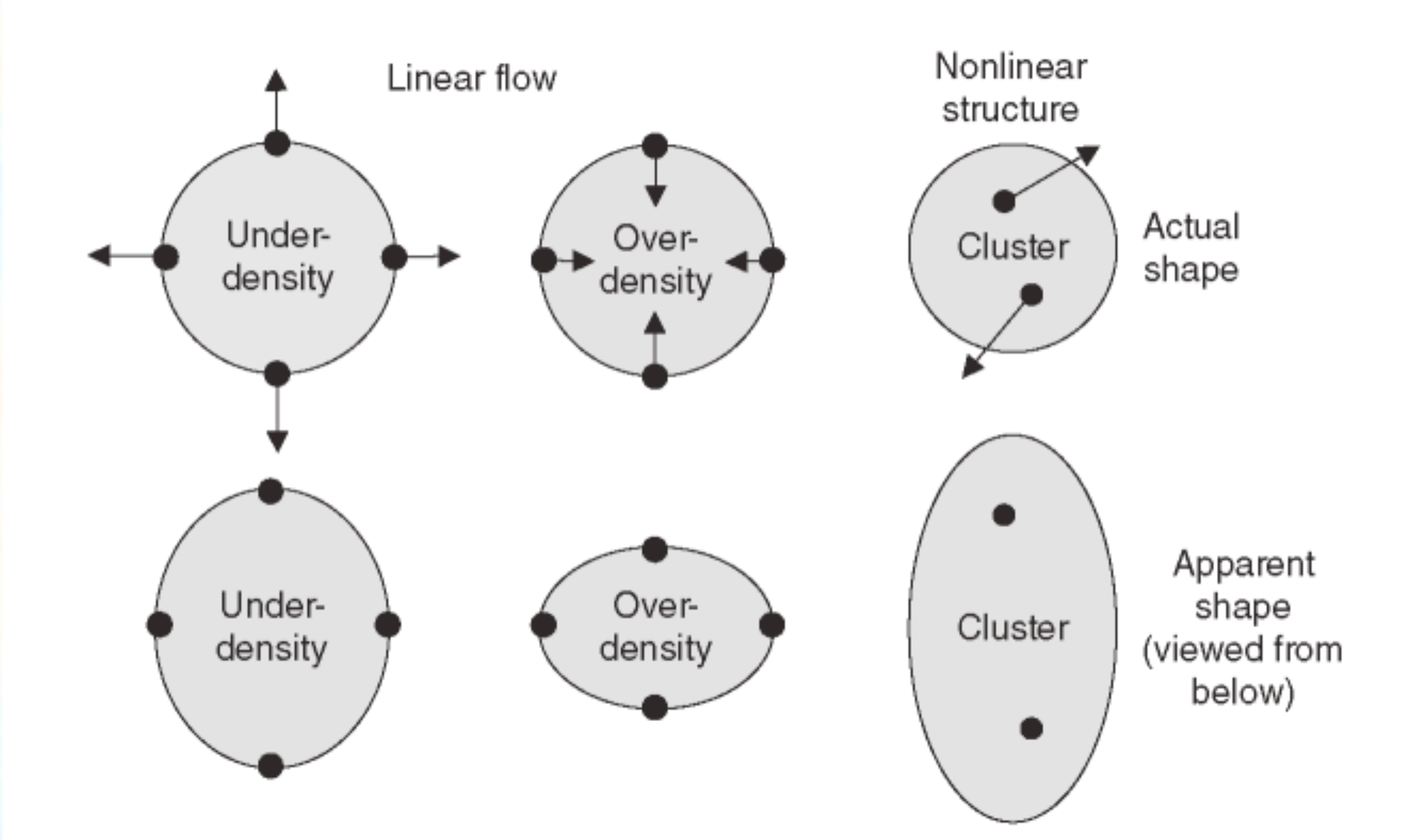


Redshift Space Distortions



J. Kuruvilla, C. Porciani - MNRAS (2018)

- Observations are done in **redshift-space**



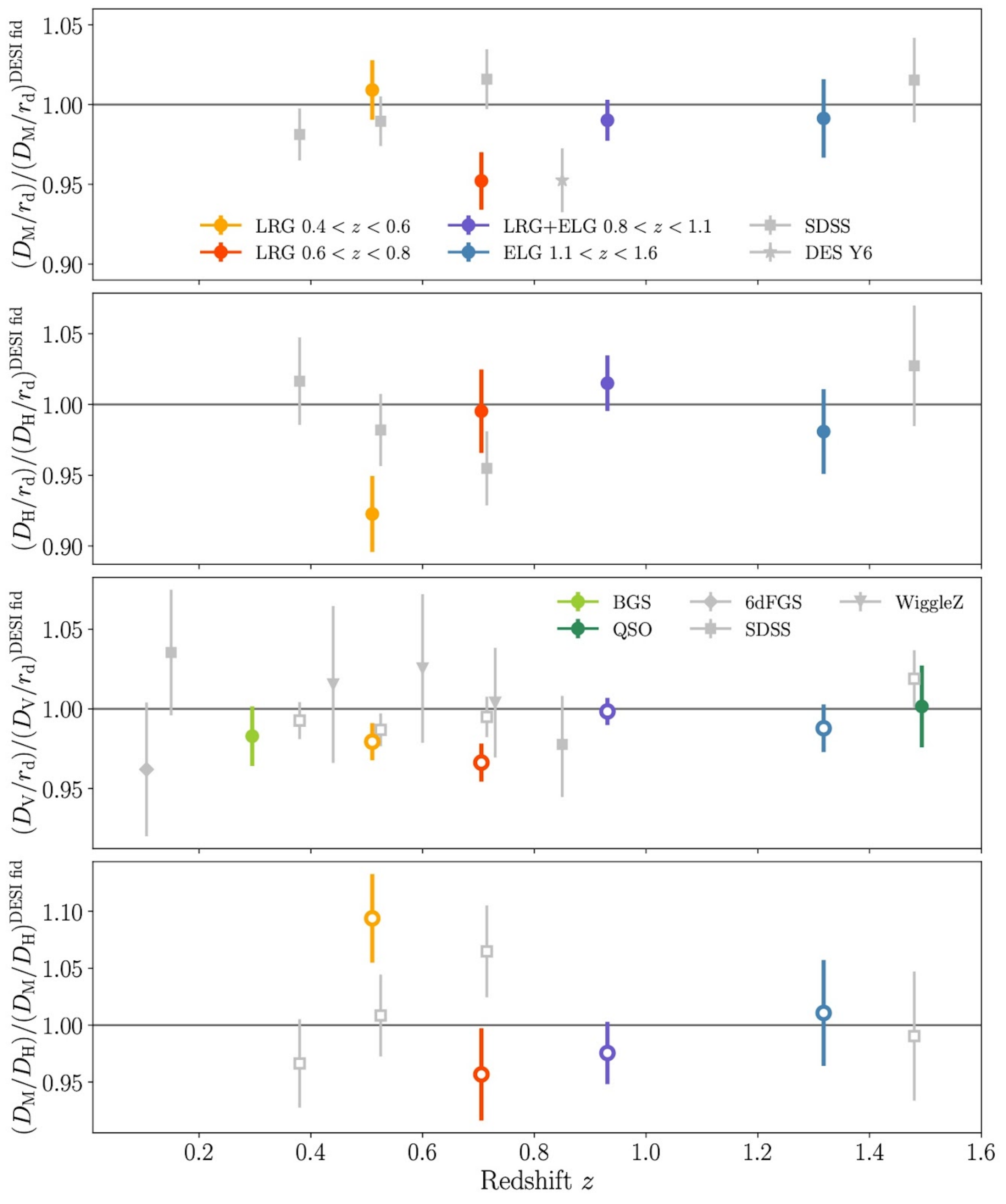
- Introduce additional **anisotropies** in 2PCF

  → Large-scales: "Kaiser" effect
  → Small-scales : "Finger-of-god" effect

- Can be used a probe of gravity !

  → Measurements of growth: $f\sigma_8(z)$

DESI vs SDSS



Already the largest BAO dataset ever !

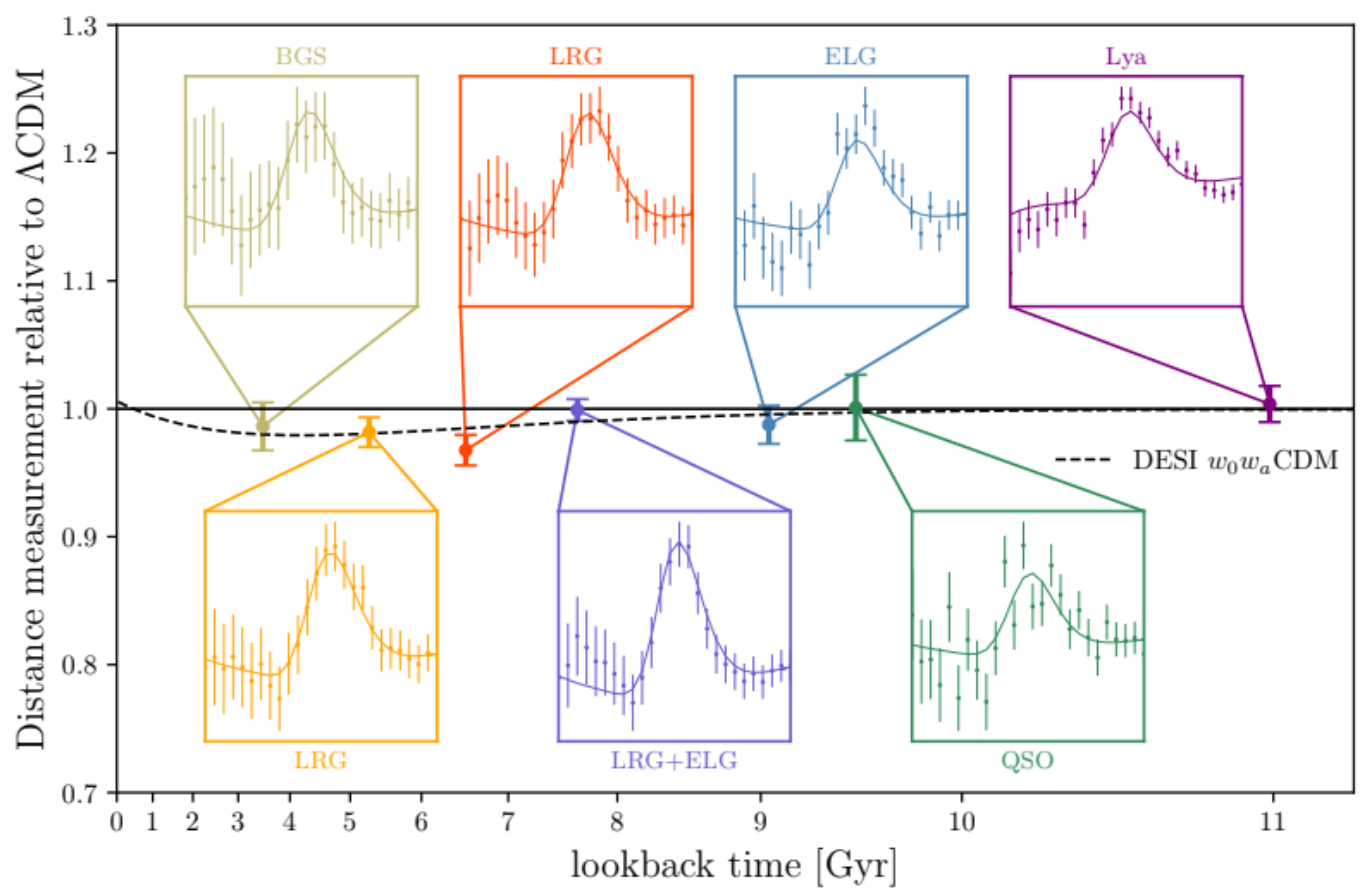
- **5.7 Million** individual redshifts
- Effective cosmic volume $V_{\text{eff}} = 18\ \text{Gpc}^3$
- ~**3x bigger** than SDSS

Merely first year of data

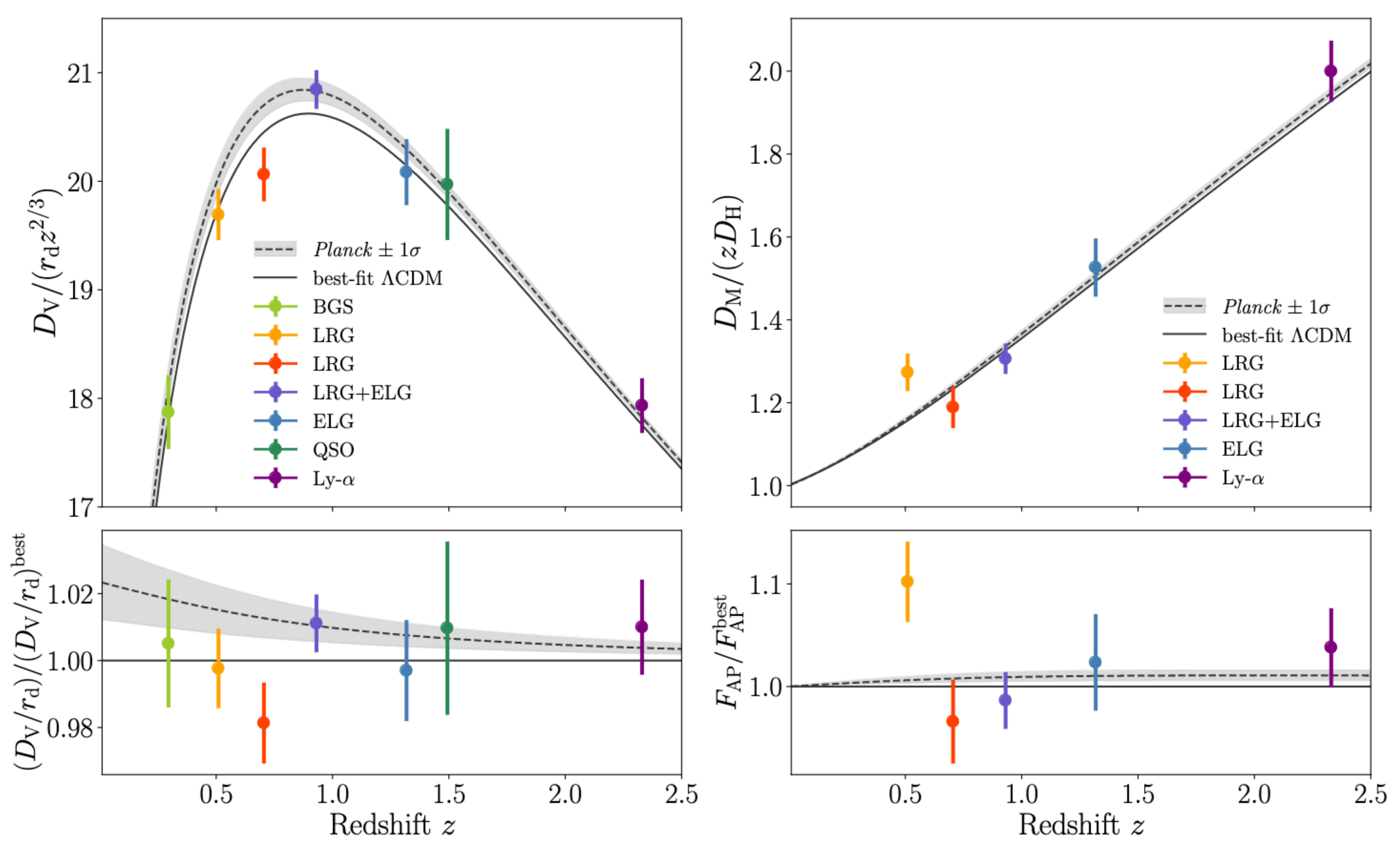
First blind analysis !

(At the catalogue level)

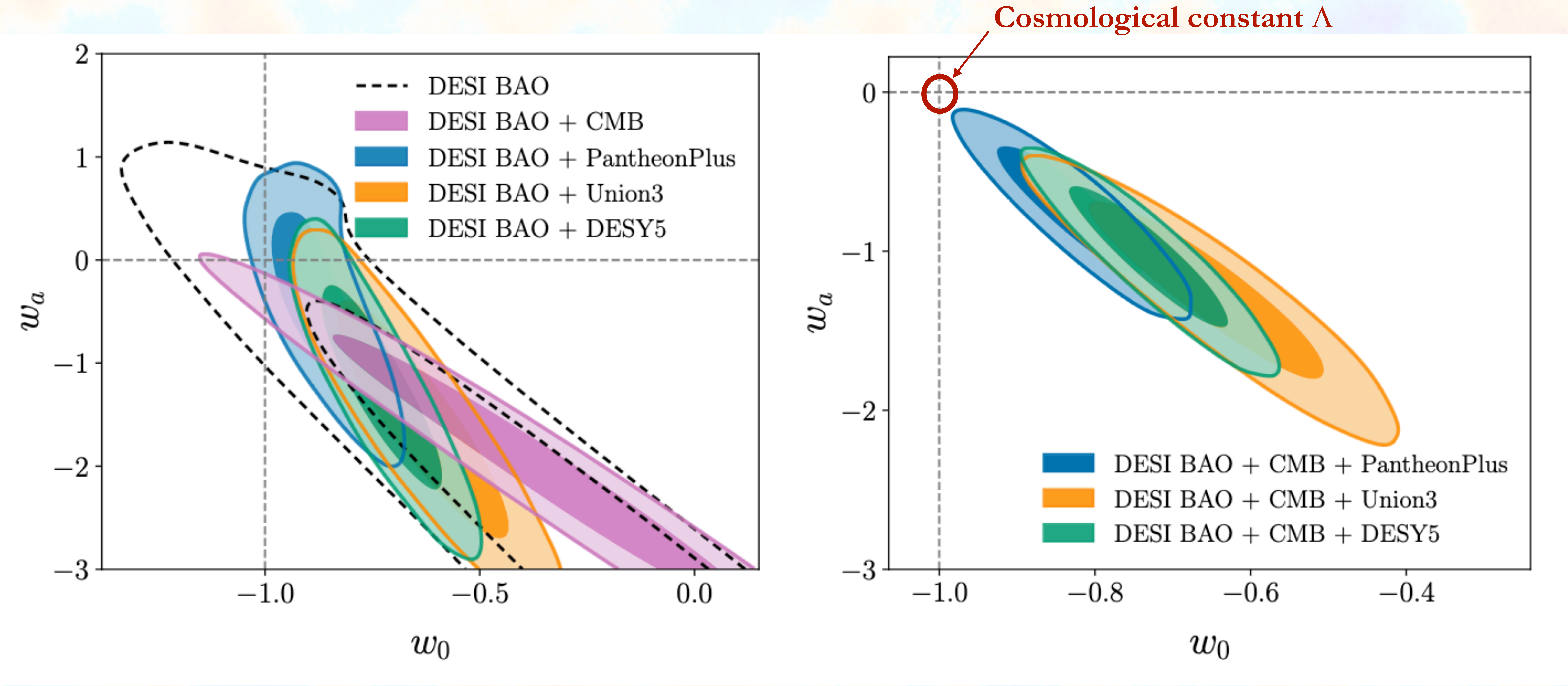
Part III: Cosmological Implications



Distance measurements



Varying equation of state $w(a) = w_0 + w_a(1 - a)$



2.5σ **DESI+CMB+PantheonPlus** 3.5σ **DESI+CMB+Union3** 3.9σ **DESI+CMB+DESY5**

Part IV: Beyond $w_0 w_a$CDM

DESI 2024: Reconstructing Dark Energy using Crossing Statistics with DESI DR1 BAO data

R. Calderon,[1] K. Lodha,[1,2] A. Shafieloo,[1,2] E. Linder,[3,4,5] W. Sohn,[1] A. de Mattia,[6] J. L. Cervantes-Cota,[7] R. Crittenden,[8] T. M. Davis,[9] M. Ishak,[10] A. G. Kim,[3] W. Matthewson,[1] G. Niz,[11,12] S. Park,[1,2] J. Aguilar,[3] S. Ahlen,[13] S. Allen,[14,15] D. Brooks,[16] T. Claybaugh,[3] A. de la Macorra,[17] A. Dey,[18] B. Dey,[19] P. Doel,[16] J. E. Forero-Romero,[20,21] E. Gaztañaga,[22,8,23] S. Gontcho A Gontcho,[3] K. Honscheid,[24,25,26] C. Howlett,[9] S. Juneau,[18] A. Kremin,[3] M. Landriau,[3] L. Le Guillou,[27] M. E. Levi,[3] M. Manera,[28,29] R. Miquel,[30,29] J. Moustakas,[31] J. A. Newman,[19] N. Palanque-Delabrouille,[6,3] W. J. Percival,[32,33,34] C. Poppett,[3,4,5] F. Prada,[35] M. Rezaie,[36] G. Rossi,[37] V. Ruhlmann-Kleider,[6] E. Sanchez,[38] D. Schlegel,[3] M. Schubnell,[39,40] H. Seo,[41] D. Sprayberry,[18] G. Tarlé,[40] P. Taylor,[26] M. Vargas-Magaña,[17] B. A. Weaver,[18] P. Zarrouk,[27] H. Zou,[42]

Affiliations are in Appendix F

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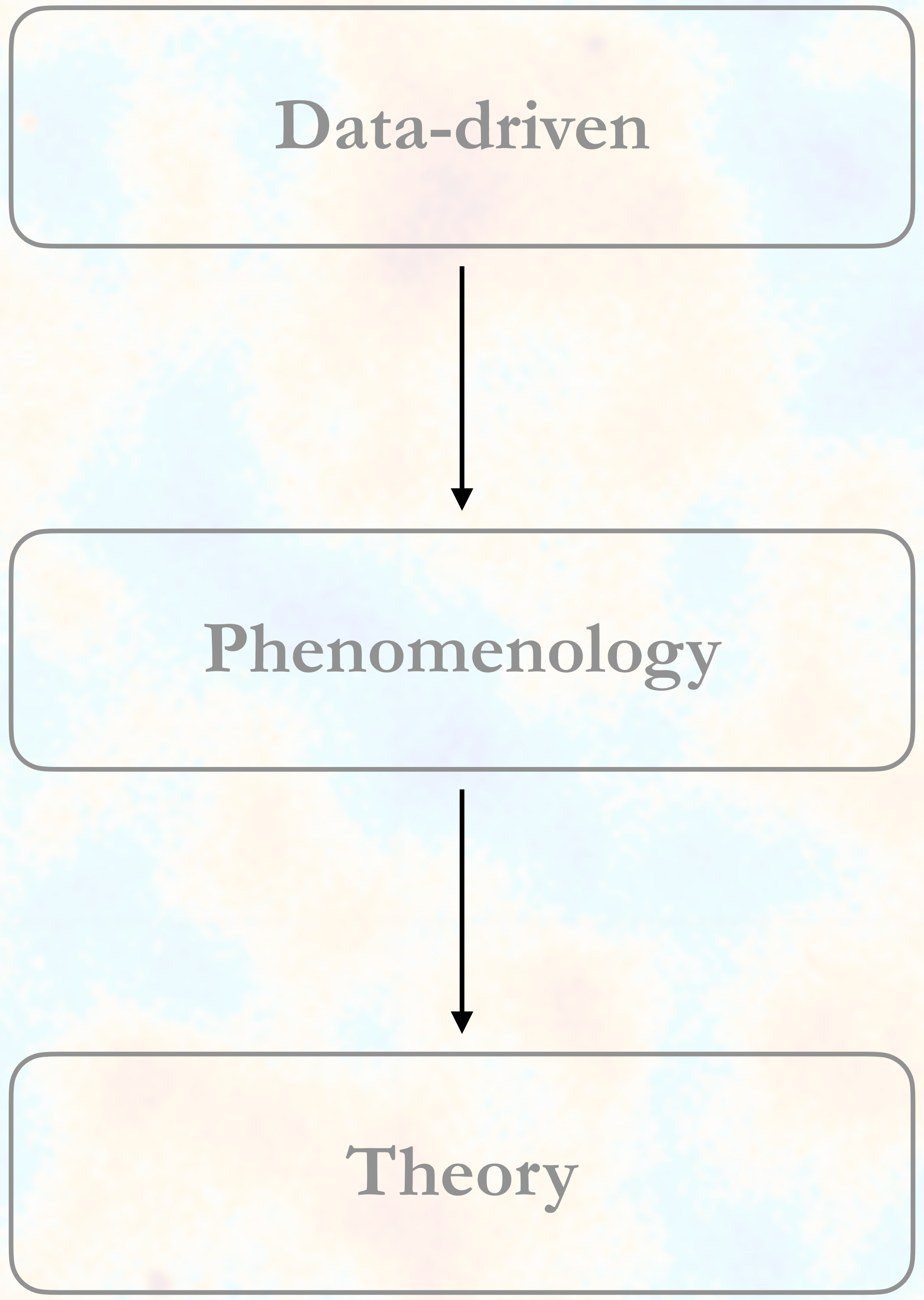


Modeling of $w(z)$

Chebychev Polynomial expansion

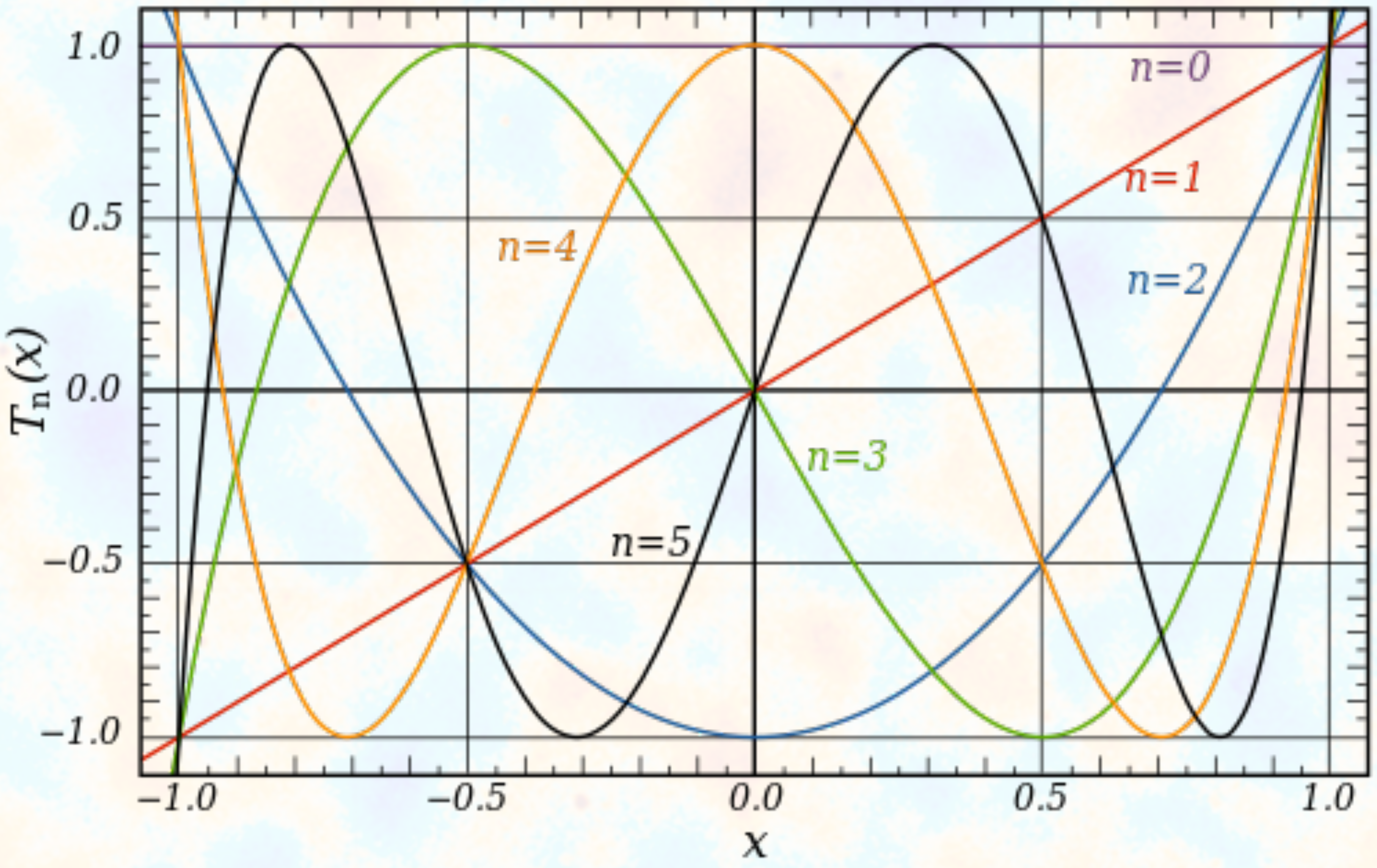
$$w(z) \equiv -\sum_{n=0}^{N} C_n\, T_n(x)$$

Form an (orthogonal) basis spanning the space of functions

$$x \equiv 2\frac{z}{z_{\max}} - 1 \in [-1,1]$$

$$T_0 = 1\ ,\ T_1 = x$$

$$T_2 = 2x^2 - 1\ ,\ T_3 = 4x^3 - 3x$$



Modeling of $w(z)$

R. Calderon, K. Lodha, A. Shafieloo, E. Linder et al - arXiv: 2405.04216

Chebychev Polynomial expansion

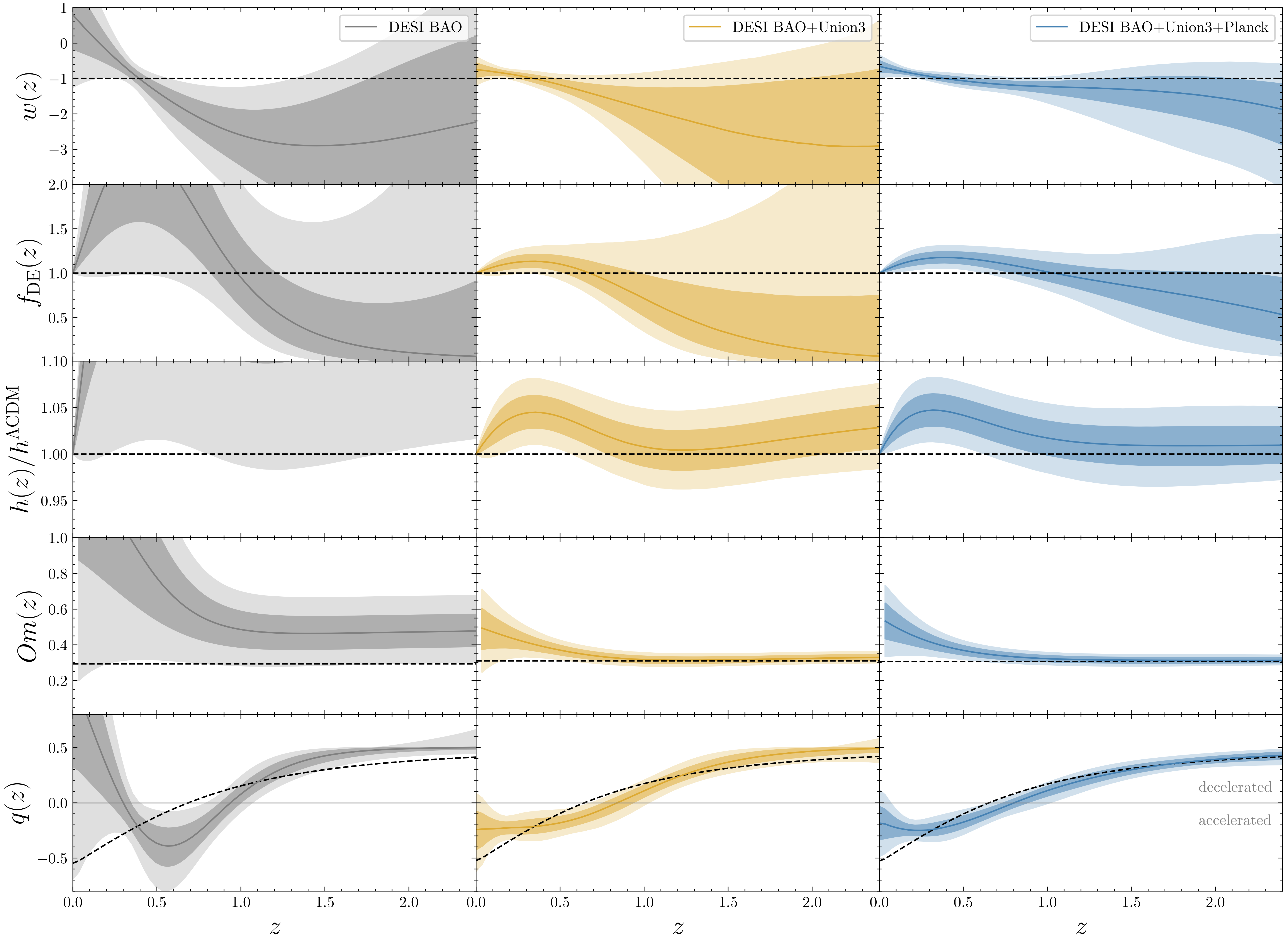
$$w(z) \equiv -\sum_{i=0}^{N=3} C_i\, T_i(x)$$

$$f_{DE}(z) \equiv \exp\left(\int_0^z 3[1 + w(z')]d\ln(1+z')\right)$$

V. Sahni, A. Shafieloo and A. A. Starobinsky (2008)

$$Om(z) \equiv \frac{h^2(z) - 1}{(1+z)^3 - 1}$$

$$q(z) \equiv -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\dot{H}}{H^2} - 1 = \frac{d\ln H}{d\ln(1+z)} - 1$$



Modeling of $f_{\rm DE}(z) \equiv \rho_{\rm DE}(z)/\rho_{\rm DE,0}$

R. Calderon, K. Lodha, A. Shafieloo, E. Linder et al - arXiv: 2405.04216

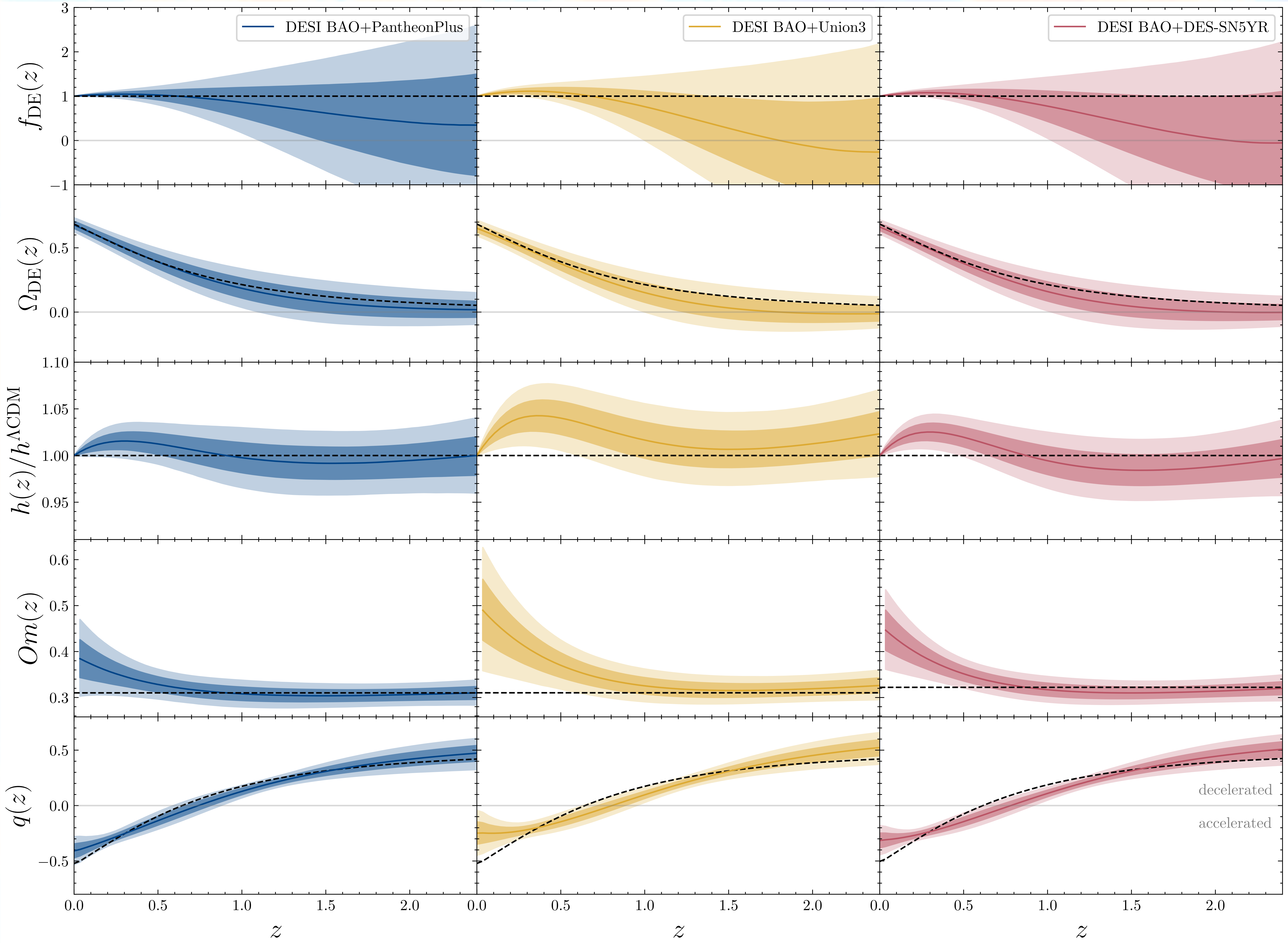
Chebychev Polynomial expansion

$$f_{\rm DE}(z) \equiv \sum_{i=0}^{N} C_i \; T_i(x)$$

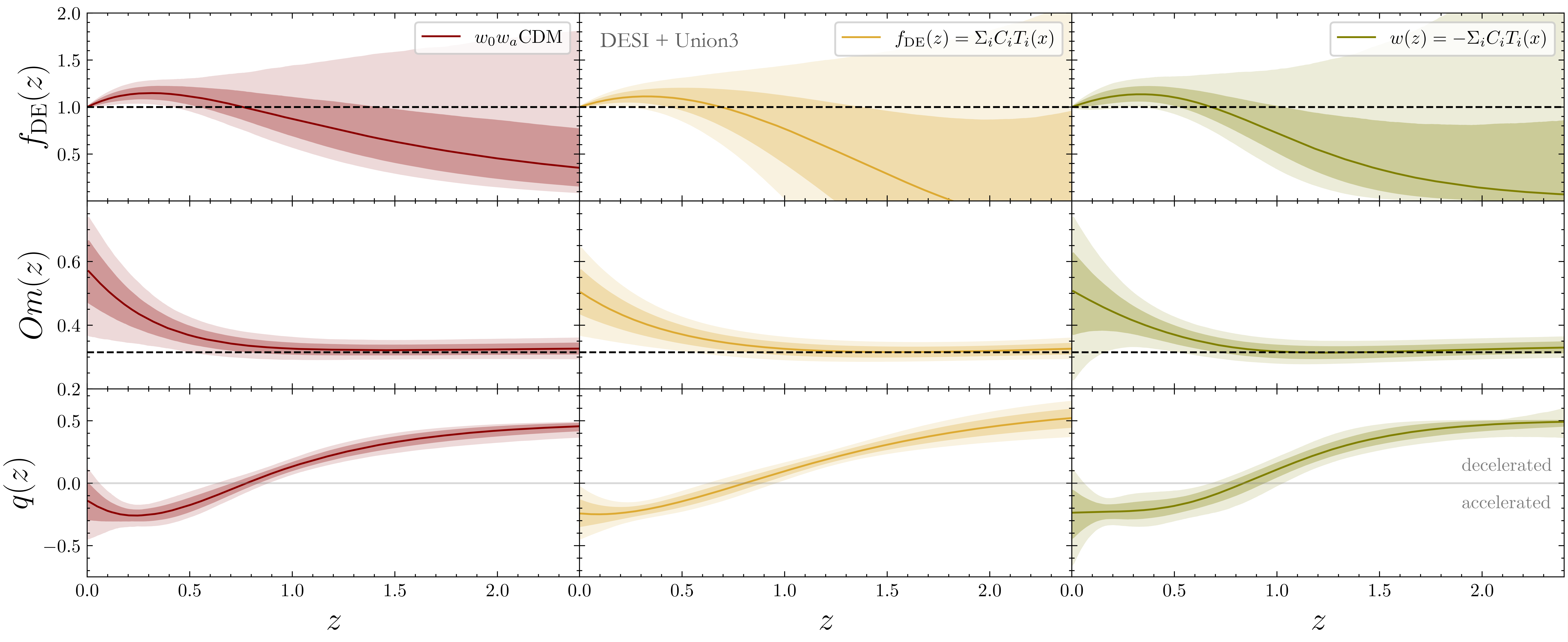
$$C_0 = 1 - \sum_{i=1}^{N=3} C_i \; T_i(x = -1)$$

$$= 1 - \sum_{i=1}^{N=3} C_i \times (-1)^i$$

$$q(z) \equiv -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\dot{H}}{H^2} - 1 = \frac{d \ln H}{d \ln(1+z)} - 1$$



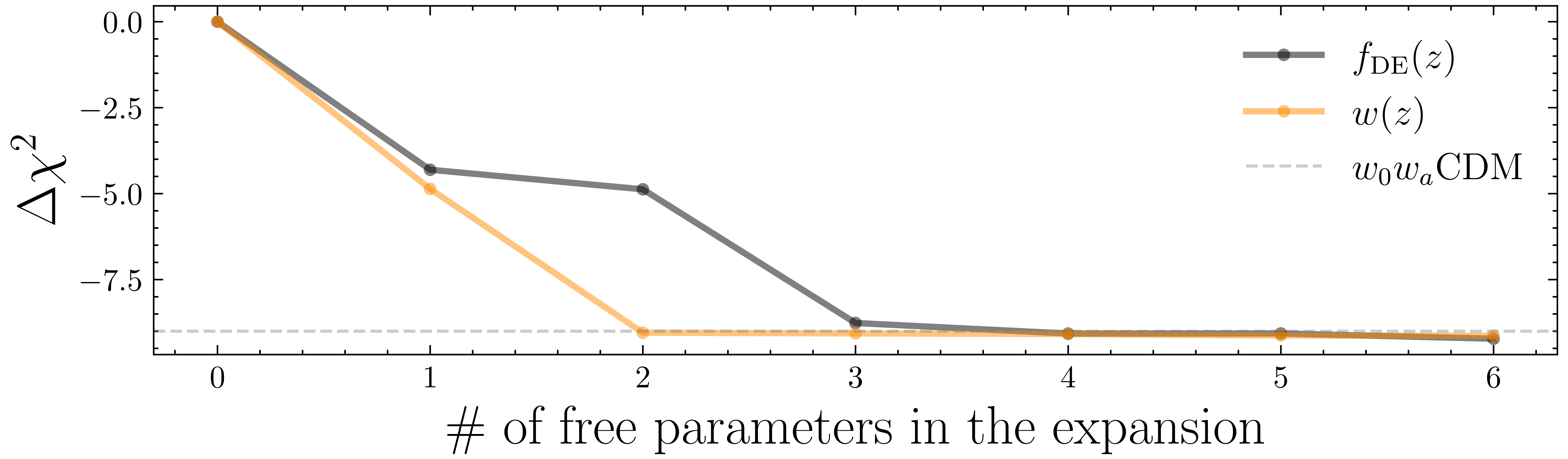
Comparison with w_0w_aCDM



R. Calderon, K. Lodha, A. Shafieloo, E. Linder et al - arXiv: 2405.04216

Seems $w_0 w_a$CDM is good enough

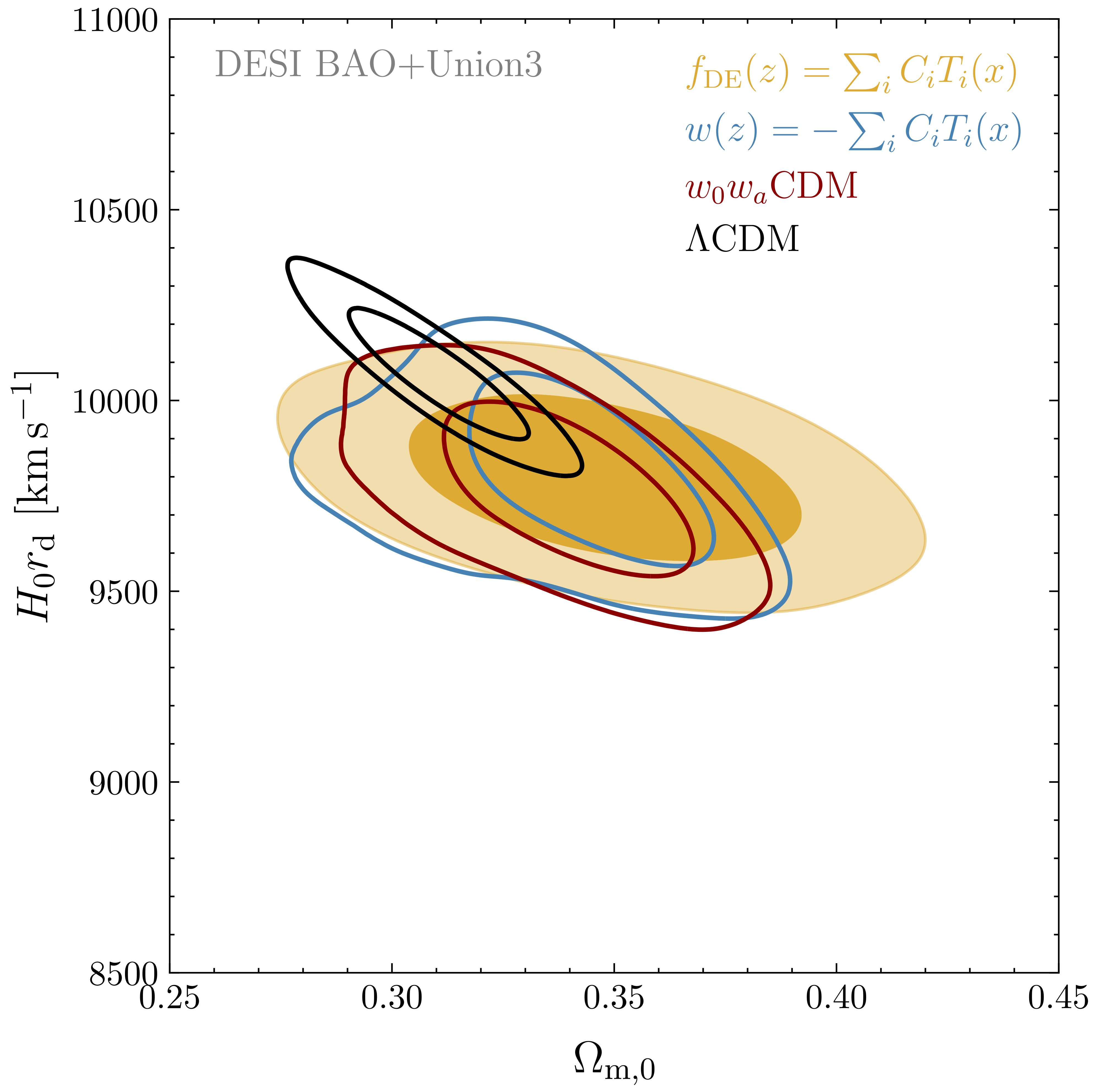
DESI + Union3

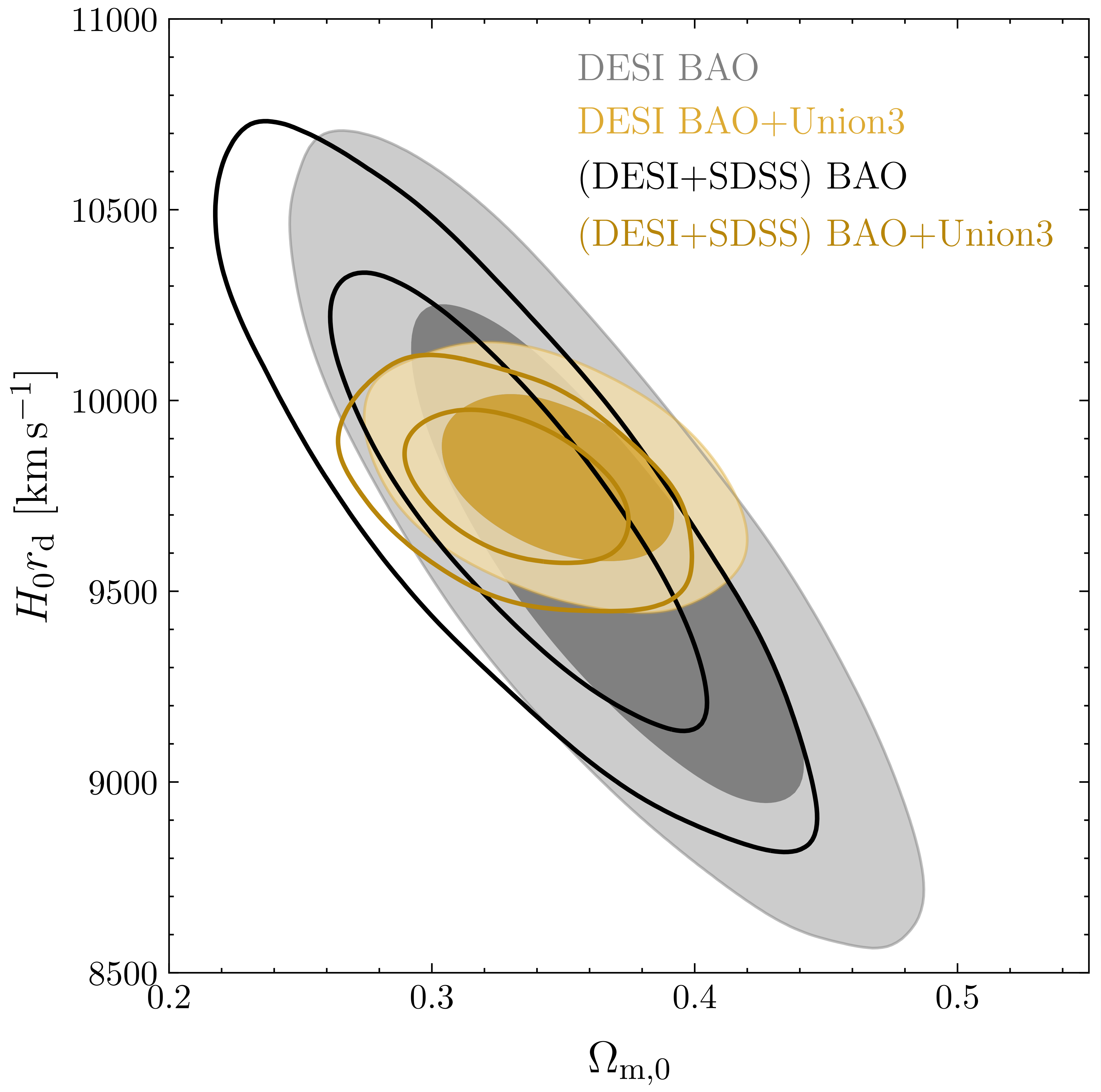


R. Calderon, K. Lodha, A. Shafieloo, E. Linder et al - arXiv: 2405.04216

χ^2 "saturates" at 2 d.o.f

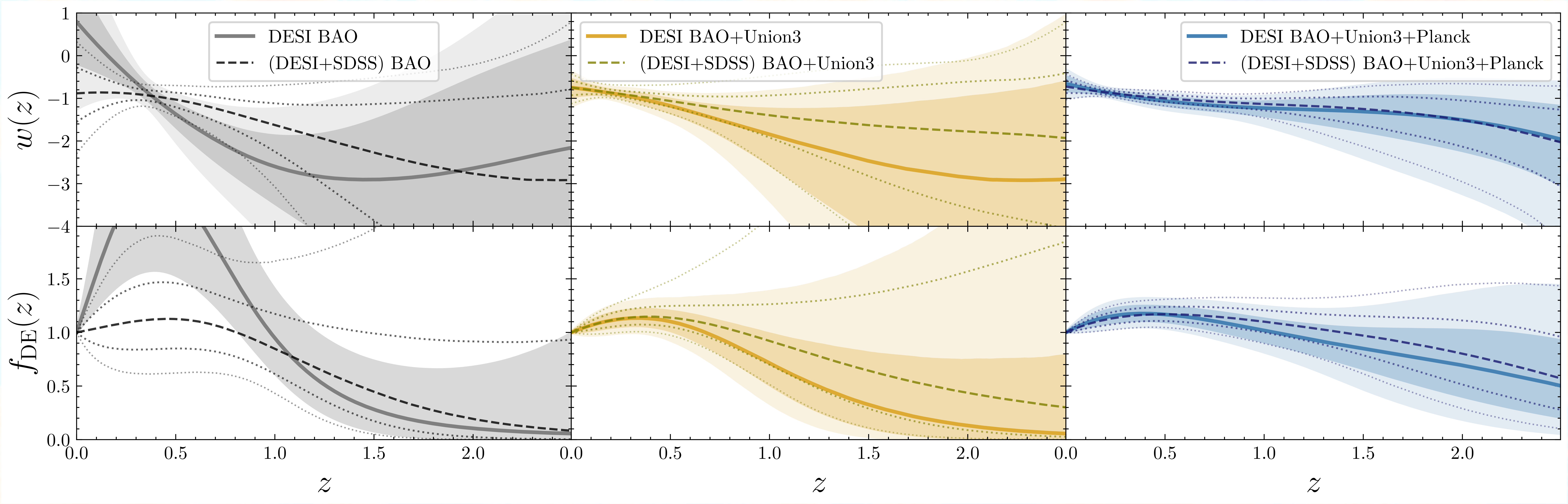
Constraints on $H_0 r_d$





R. Calderon, K. Lodha, A. Shafieloo, E. Linder et al - arXiv: 2405.04216

Comparison with (SDSS+DESI) BAO

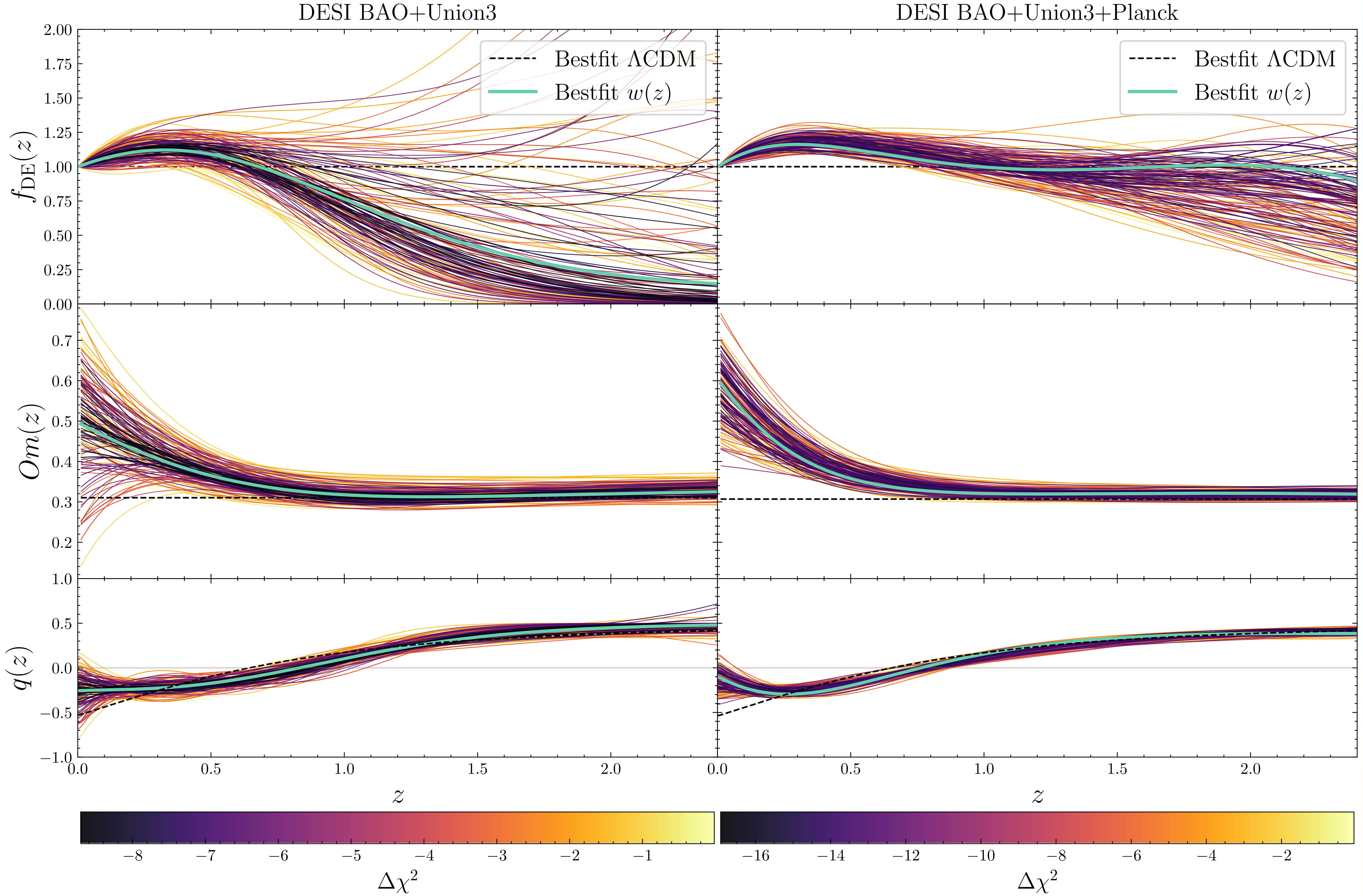


R. Calderon, K. Lodha, A. Shafieloo, E. Linder et al - arXiv: 2405.04216

Overall trends remain !
In particular +Planck

Improvement in fit

R. Calderon, K. Lodha, A. Shafieloo, E. Linder et al - arXiv: 2405.04216



Individual expansion histories Improving over ΛCDM

$$\Delta\chi^2 \equiv \Delta\chi^2_{w(z)} - \Delta\chi^2_{\Lambda\rm CDM}$$

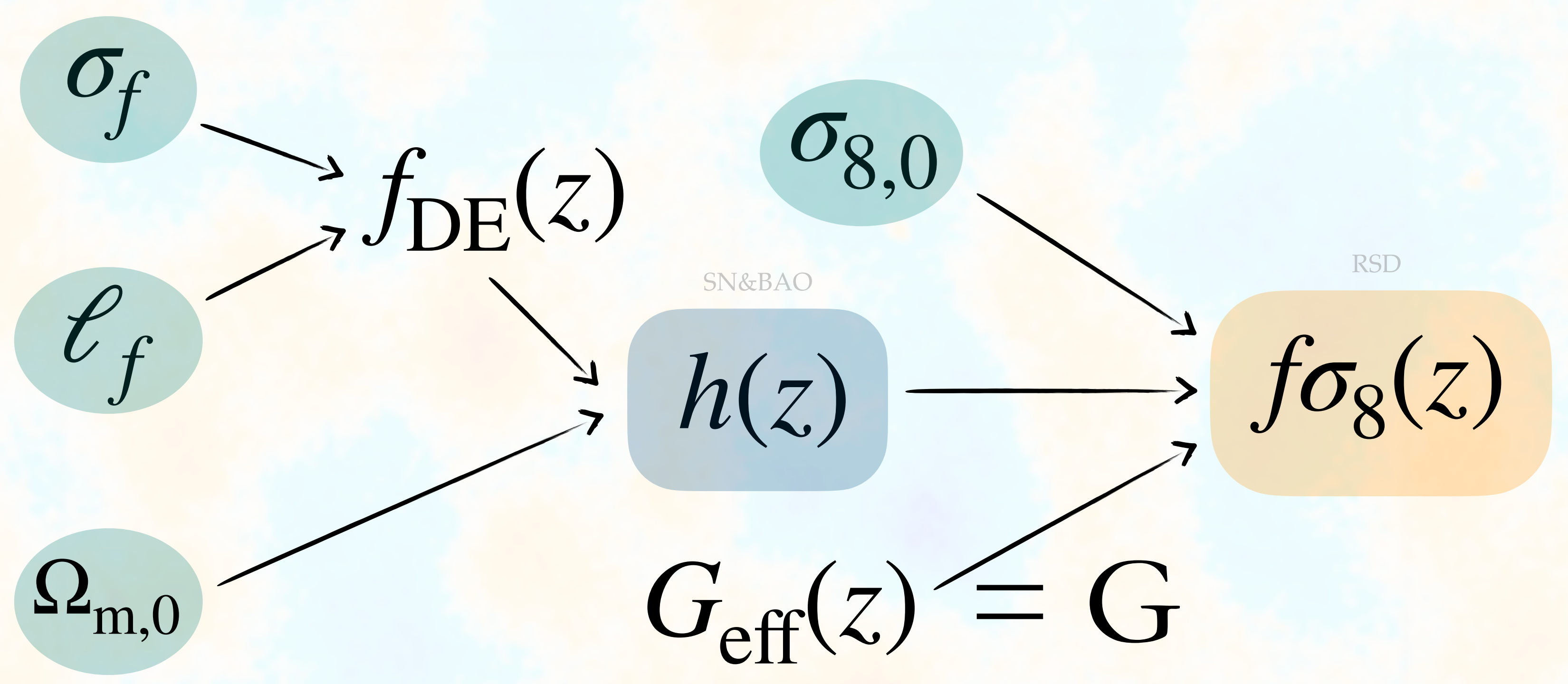
Expansion History (GR)

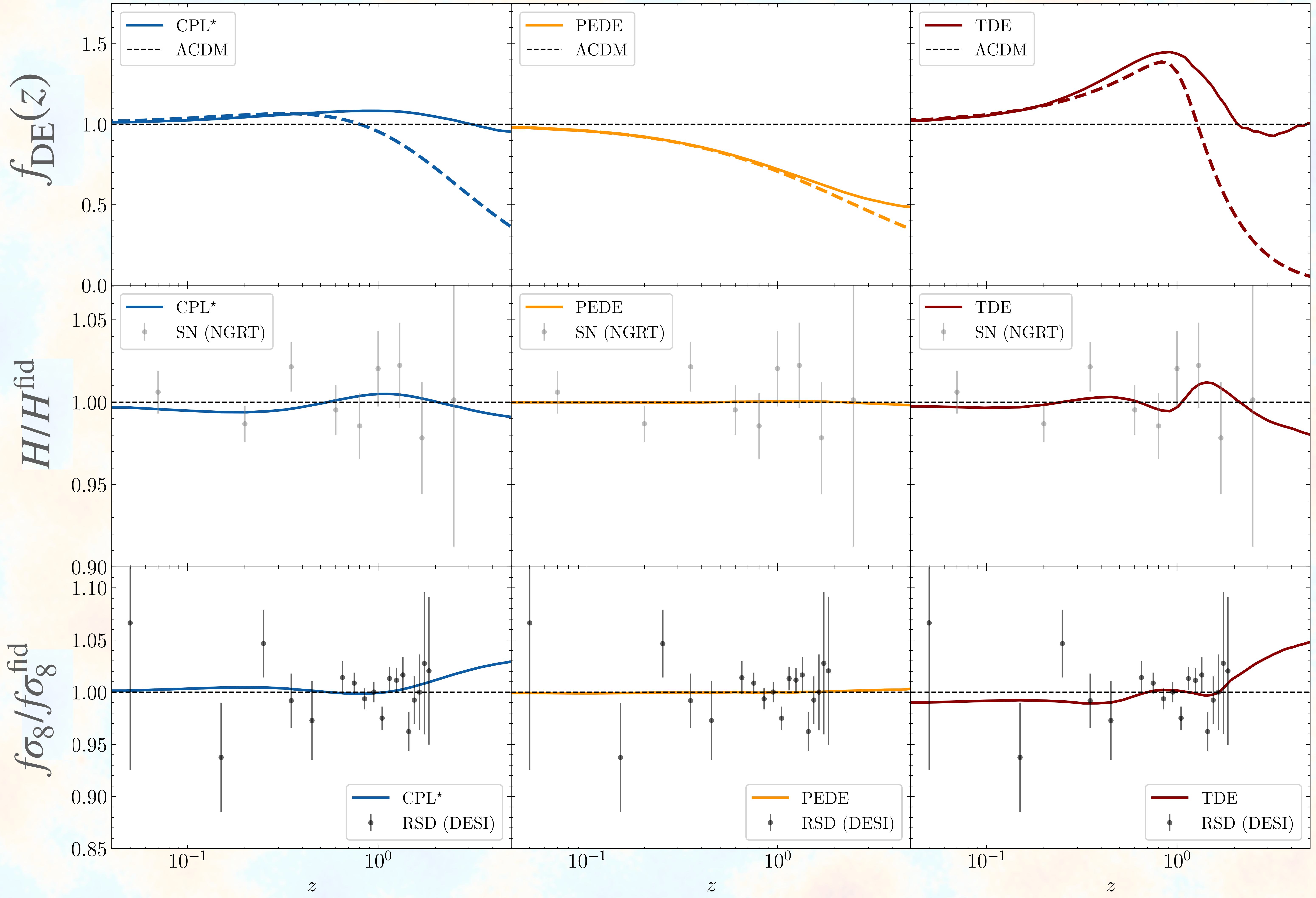
$$f_{\rm DE}(z) \equiv \frac{\rho_{\rm DE}(z)}{\rho_{\rm DE,0}} \sim \mathcal{N}\left(\bar{f} = 1, K = k(\sigma_f, \ell_f)\right)$$

$$\frac{H^2(z)}{H_0^2} = \Omega_m a^{-3} + (1 - \Omega_m)\, f_{\rm DE}(z)$$

Captures any additional (unknown) component!

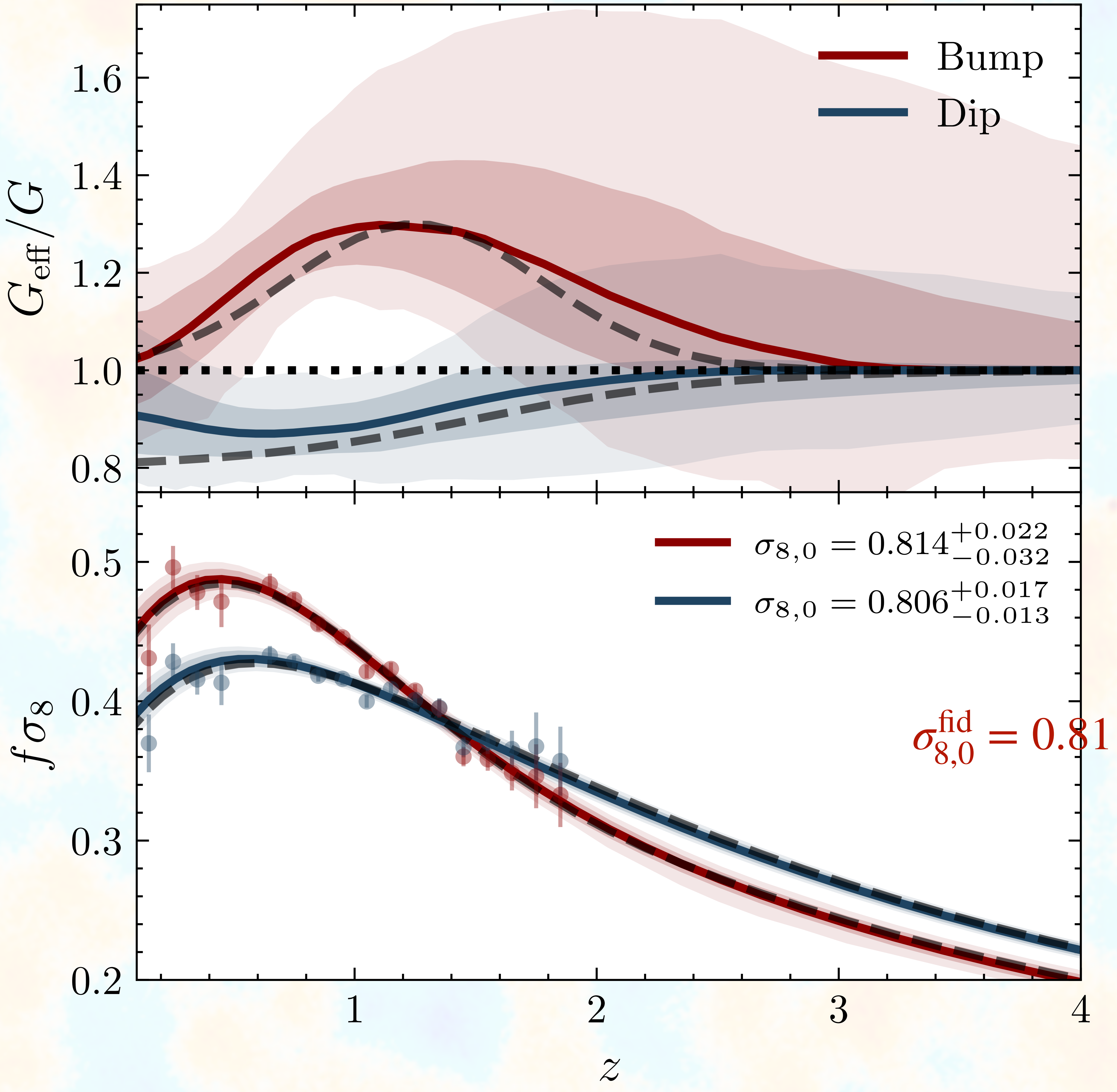
$f_{\rm DE} \neq 1 \Rightarrow$ **New physics** beyond ΛCDM





Calderón, L'Huillier, Polarski, Shafieloo & Starobinsky - Phys. Rev .D 106 (2022) 8, 083513

Modified Growth



Calderón, L'Huillier, Polarski, Shafieloo & Starobinsky - Phys. Rev. D 108, 023504

Modified Poisson Equation

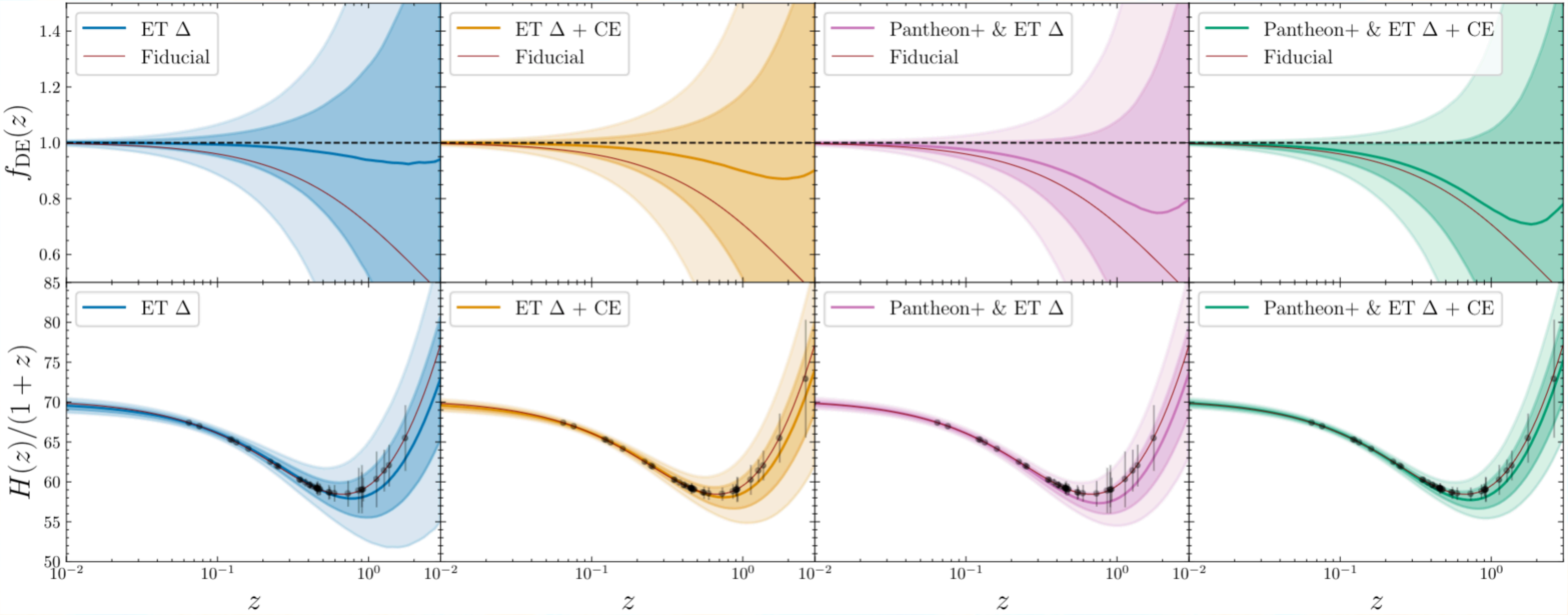
$$-\frac{k^2}{a^2}\phi = 4\pi G_{\rm eff}(z)\rho_m\delta_m$$

$$\mu(z;\sigma_f,\ell_f,z_c) \sim \mathcal{N}\left(\bar{f}=1,\, k(\sigma_f,\ell_f)\right)$$

- Successful reconstruction of 2 **phenomenological** profiles for $\mu(z) \equiv \frac{G_{\rm eff}(z)}{G}$
- Unbiased estimation of $\sigma_{8,0}$!
- Posteriors of the hyperparameters contains **valuable information**

$\mu \neq 1 \Rightarrow$ **New physics!**

Applications to bright sirens



Cozzumbo, Dupletsa, Calderón, Murgia+, in prep.

Some possible research directions

- **Late-time reconstruction of the expansion history**
  Bright & Dark Sirens x LSS (HI-IM)
  Robust model-independent determination of H_0

- **Early-Universe changes to the expansion (& growth) history**
  Implications for the Hubble and S_8 tensions
  Physics prior to recombination
  Testing non-standard inflationary scenarios with EFTofLSS

- **Gravitational Waves**
  Population studies/Modeling Mass-distributions
  Testing the (an)isotropy of the Universe
  Model-independent tests of gravity

$$h_p'' + (2 + \alpha_M)\mathscr{H} h_p' + (1 + \alpha_T)k^2 h_p = \Pi_p \longrightarrow d_L^{\mathrm{GW}}(z) = d_L^{\mathrm{EM}}(z)\ \exp\left(\frac{1}{2}\int_0^z \alpha_M(\tilde{z})\ d\ln(1+\tilde{z})\right)$$

Summary & prospects

- More **constraining power** demands more **careful** analyses:
  Scrutiny for systematics and confirmation biases

- **BAO** is one of the **most mature probes** of modern cosmology
  Distance measurements that can be used to test alternative cosmological models
  Direct-fit/Full-shape power spectrum analysis on the way (RSD)!

- Tantalizing hints of an **evolving dark energy** component:
  $\sim 2.5 - 4\sigma$ deviation from $(w_0 = -1,\, w_a = 0)$

- Year 3 data acquisition complete. Analysis on the way!

Distance measurements that can be used to test alternative cosmological models

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