Implications for cosmological expansion models from the final DES BAO and SNe

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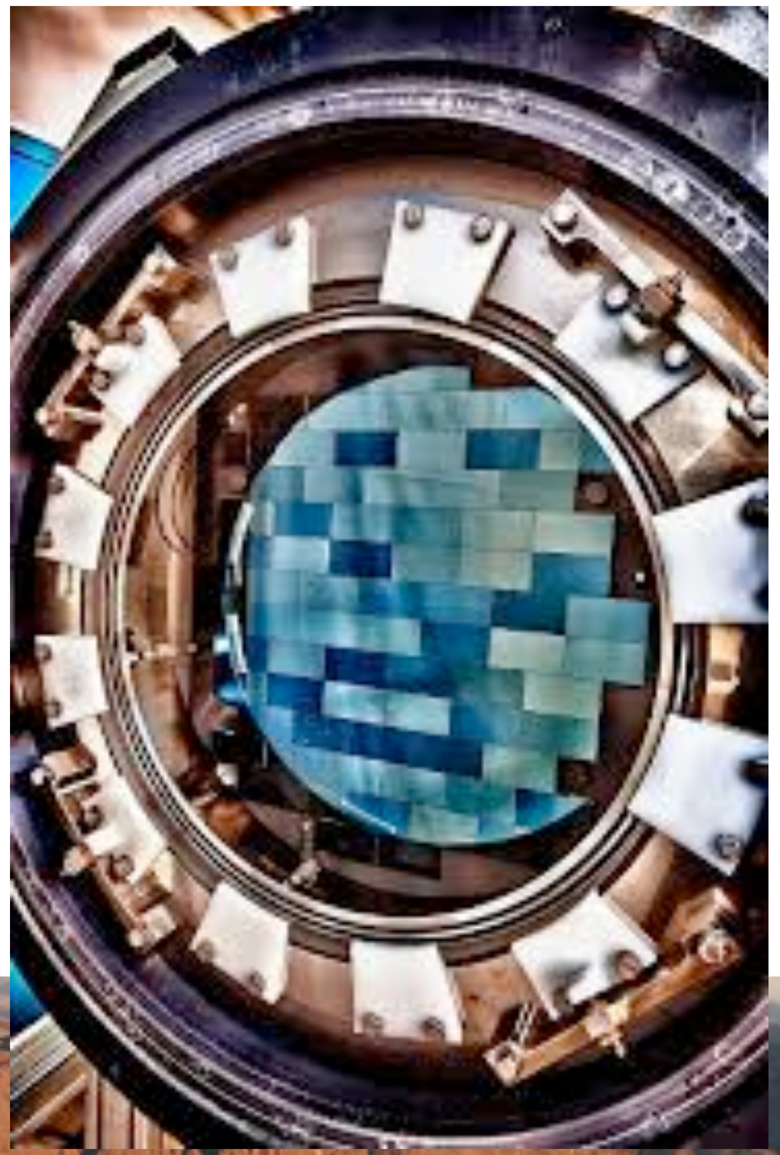
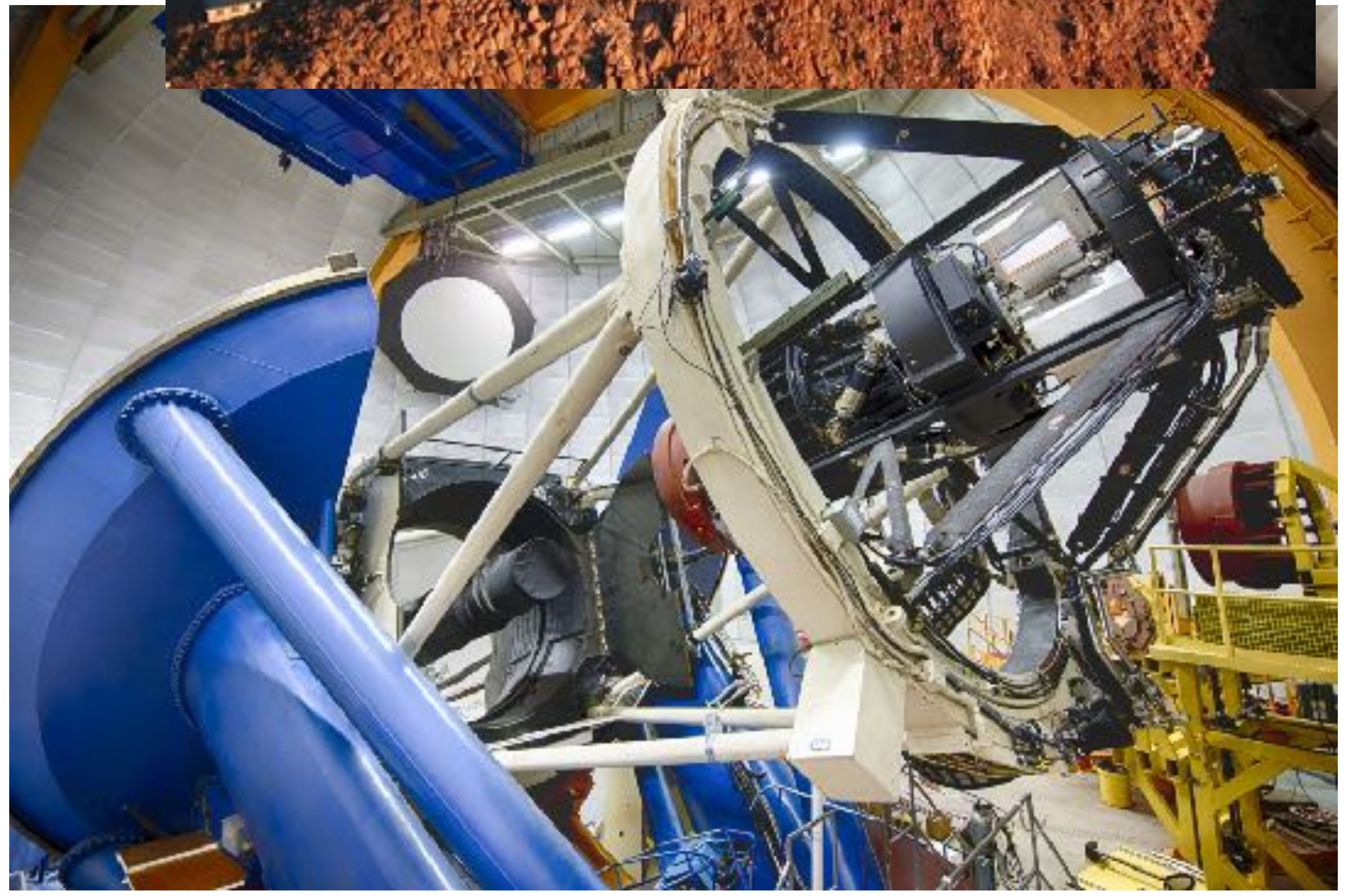
On behalf of the Dark Energy Survey collaboration

Rencontres du Vietnam: Cosmology
Quy Nhon, 13 Aug 2025

Dark Energy Survey (DES)

- Dark Energy Survey (DES) is an ongoing photometric survey.
- Use blanco 4-meter telescope at Cerro Tololo Inter-American Observatory in Chile
- Dark Energy Camera, Field of view: 3 sq deg, 570-megapixels CCD

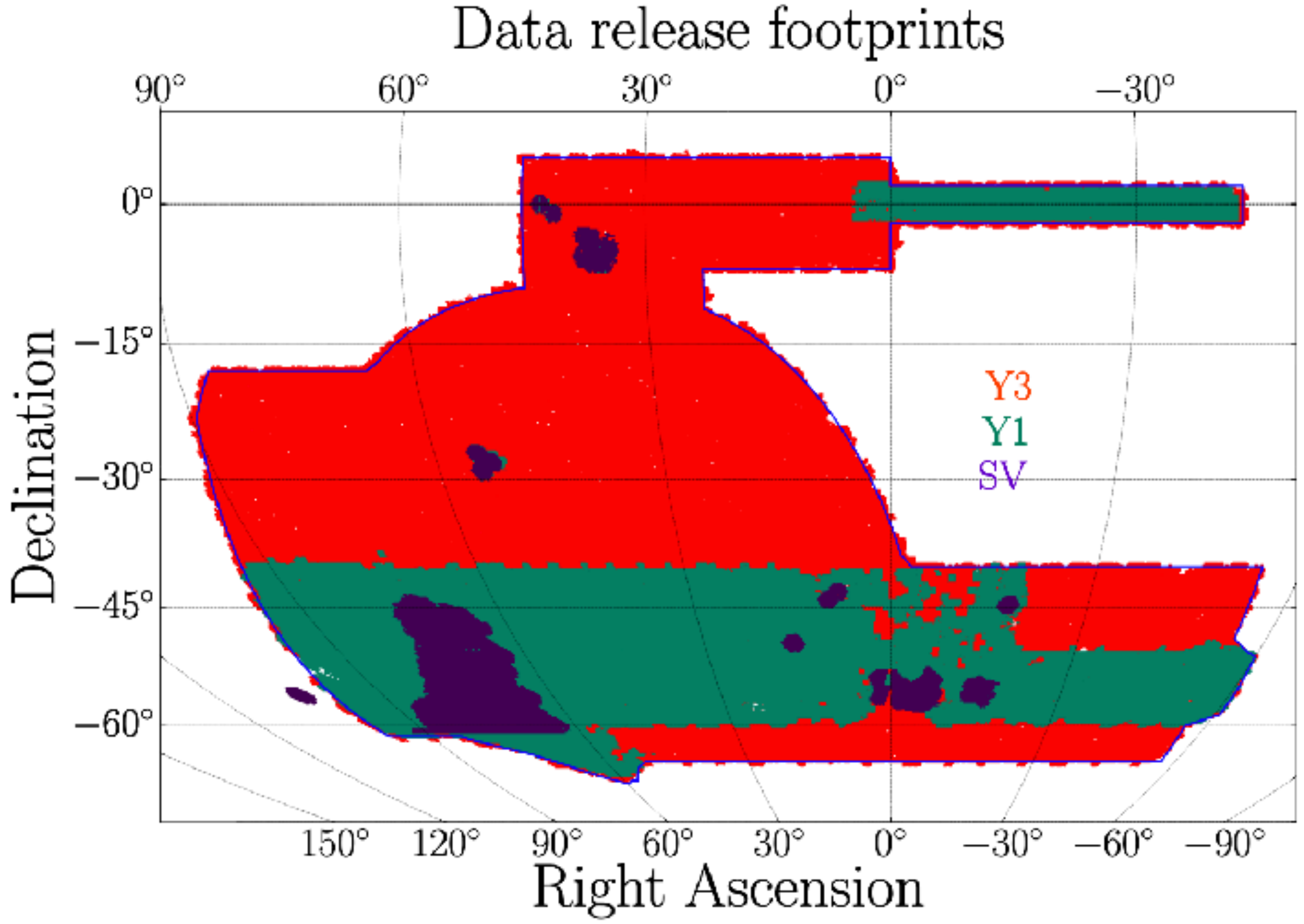




DES data releases

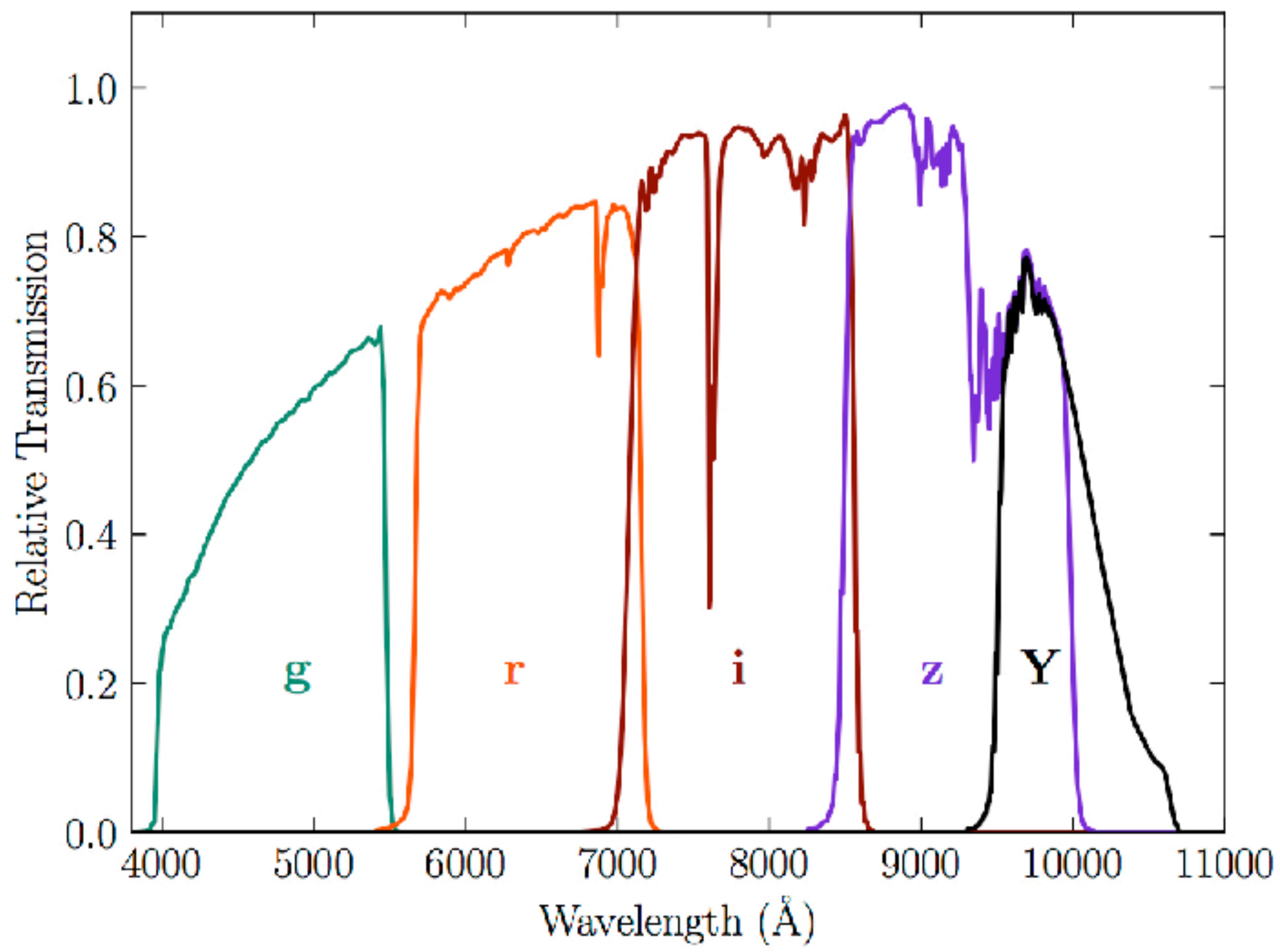
- DES major release: SV, Y1, Y3, and (Y5) Y6.
- Y6 is the last official analysis, data taken from Aug 2013 to Jan 2019, 760 nights

Y3 and Y6 cover 5000 sq deg



Sevilla-Noarbe +, 2011.03407

grizY bands



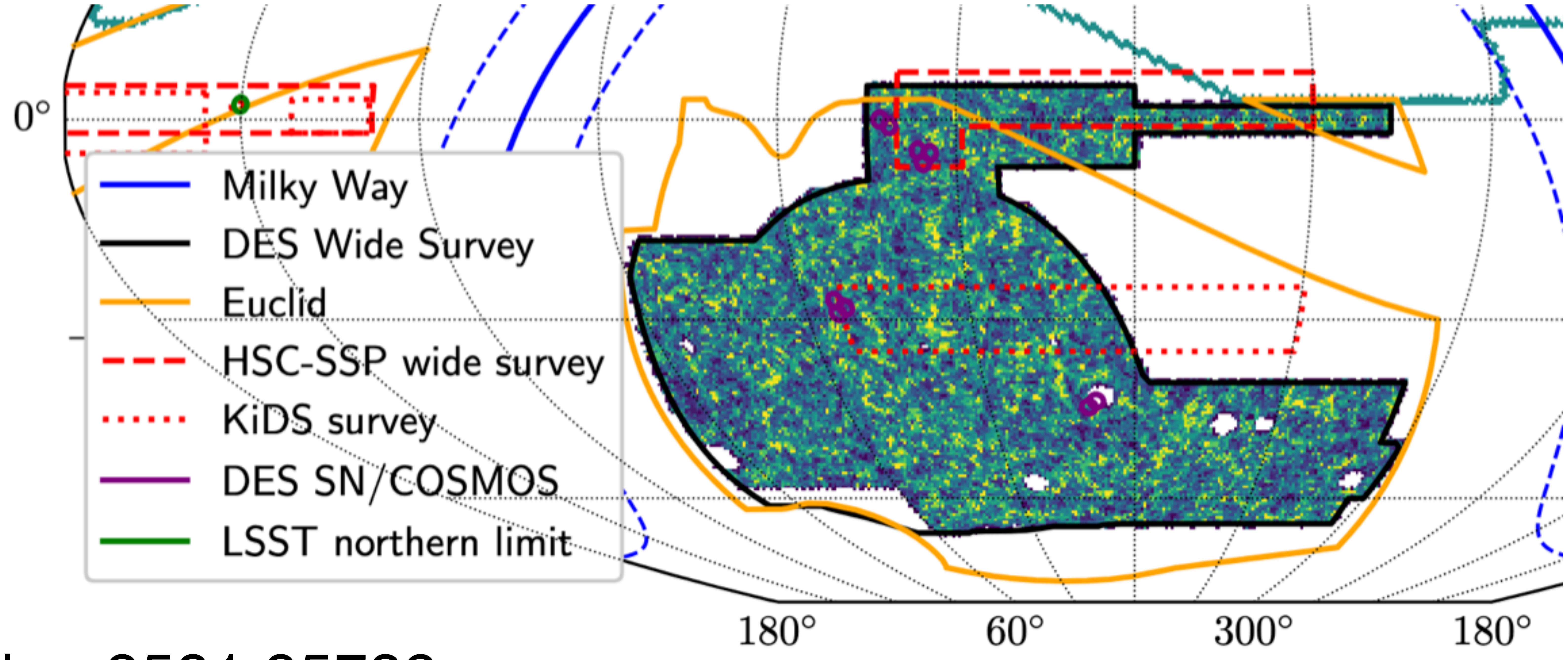
Key probes of DES

- Probe the properties of DE in 4 key probes
- Weak lensing — light distortion by gravity, geometry, structure
- Galaxy clustering especially BAO — Standard ruler, structure
- SNe — Standard candles, geometry
- Cluster/halo abundance — Growth of (collapsed) structure
- Complementary in systematics and cosmological parameter degeneracy control

Survey modes

- Wide field survey: ~5000 sq. deg, grizY bands, optimized for weak gravitational lensing, galaxy clustering, and galaxy clusters.

- Supernova survey: 10 SNe fields, ~3 sq. deg each, griz bands, optimized for SNe search



Bechtol +, 2501.05739

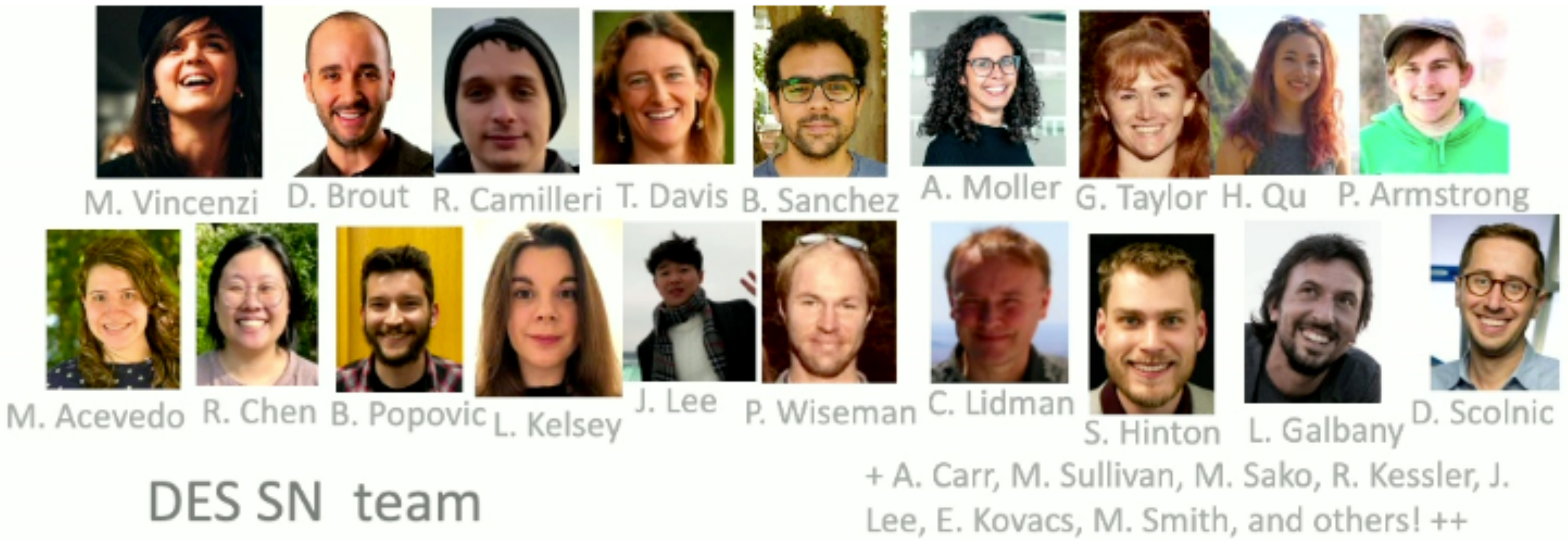
Y6 BAO + Y5 SNe on expansion model, 2402.10696

Dark Energy Survey: implications for cosmological expansion models from the final DES Baryon Acoustic Oscillation and Supernova data

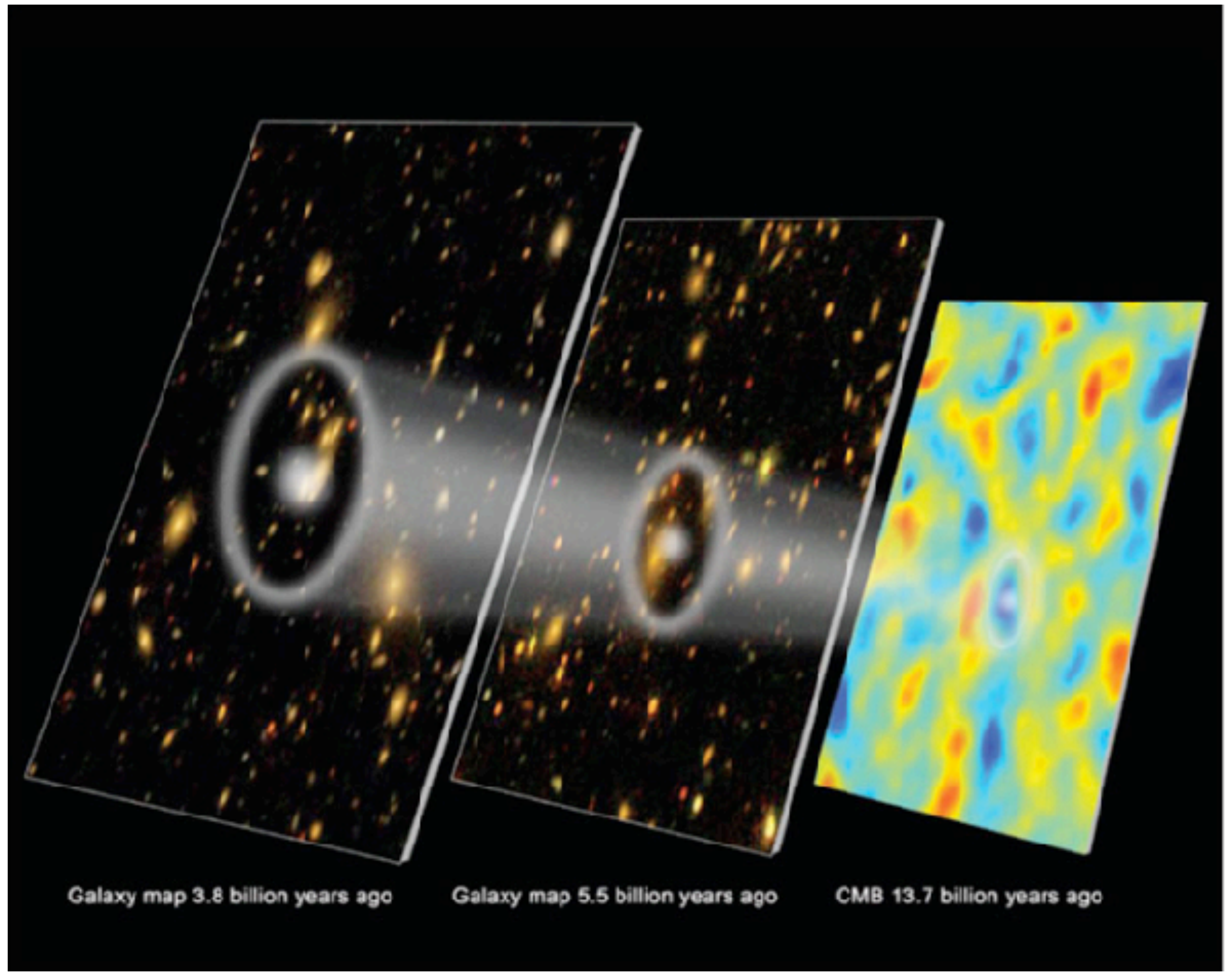
Y6 BAO, 2402.10696

Dark Energy Survey: A 2.1% measurement of the angular Baryonic Acoustic Oscillation scale at redshift $z_{\rm eff} = 0.85$ from the final dataset

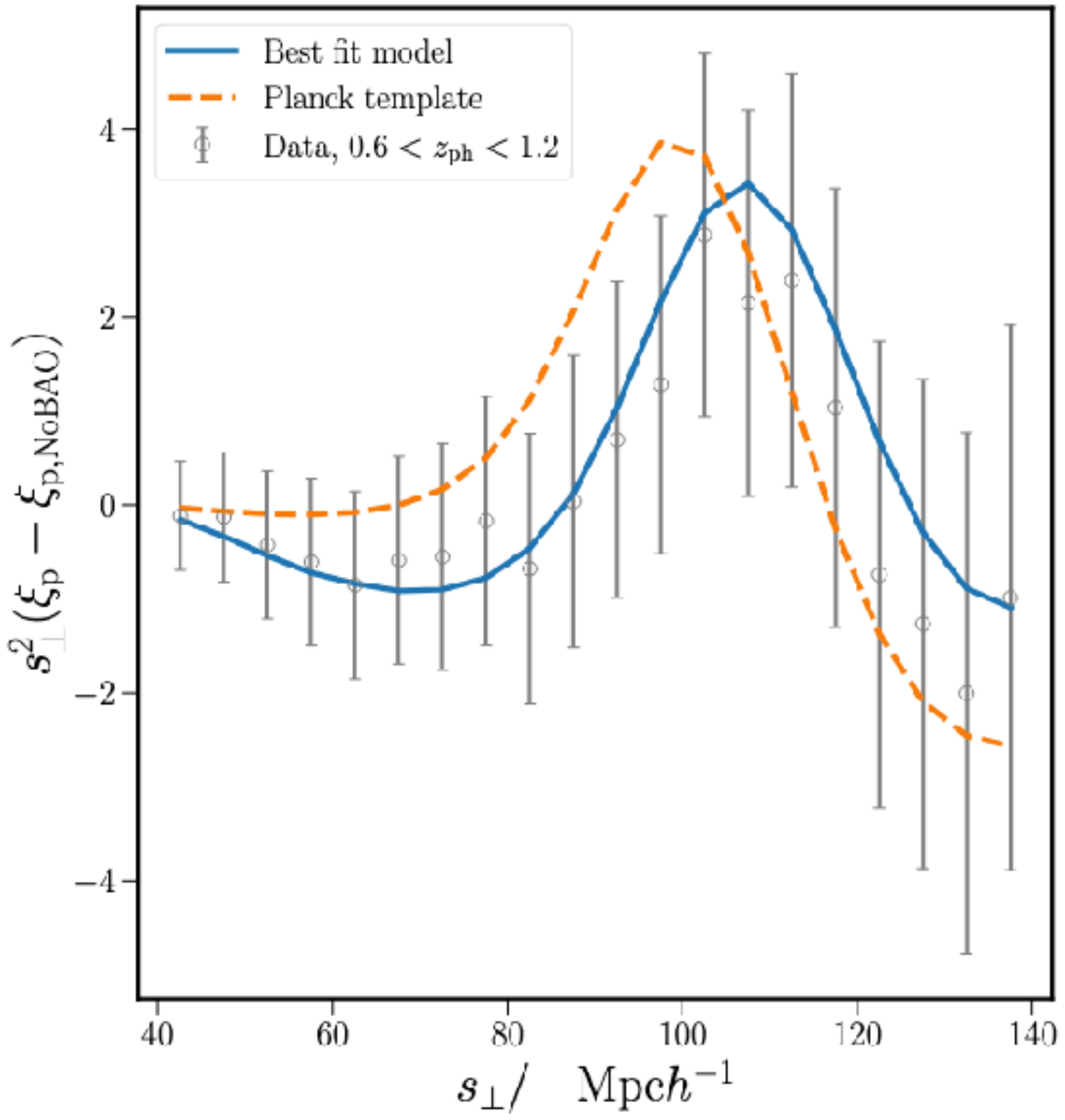
Y5 SNe, 2401.02929



The Dark Energy Survey: Cosmology Results With ~1500 New High-redshift Type Ia Supernovae Using The Full 5-year Dataset



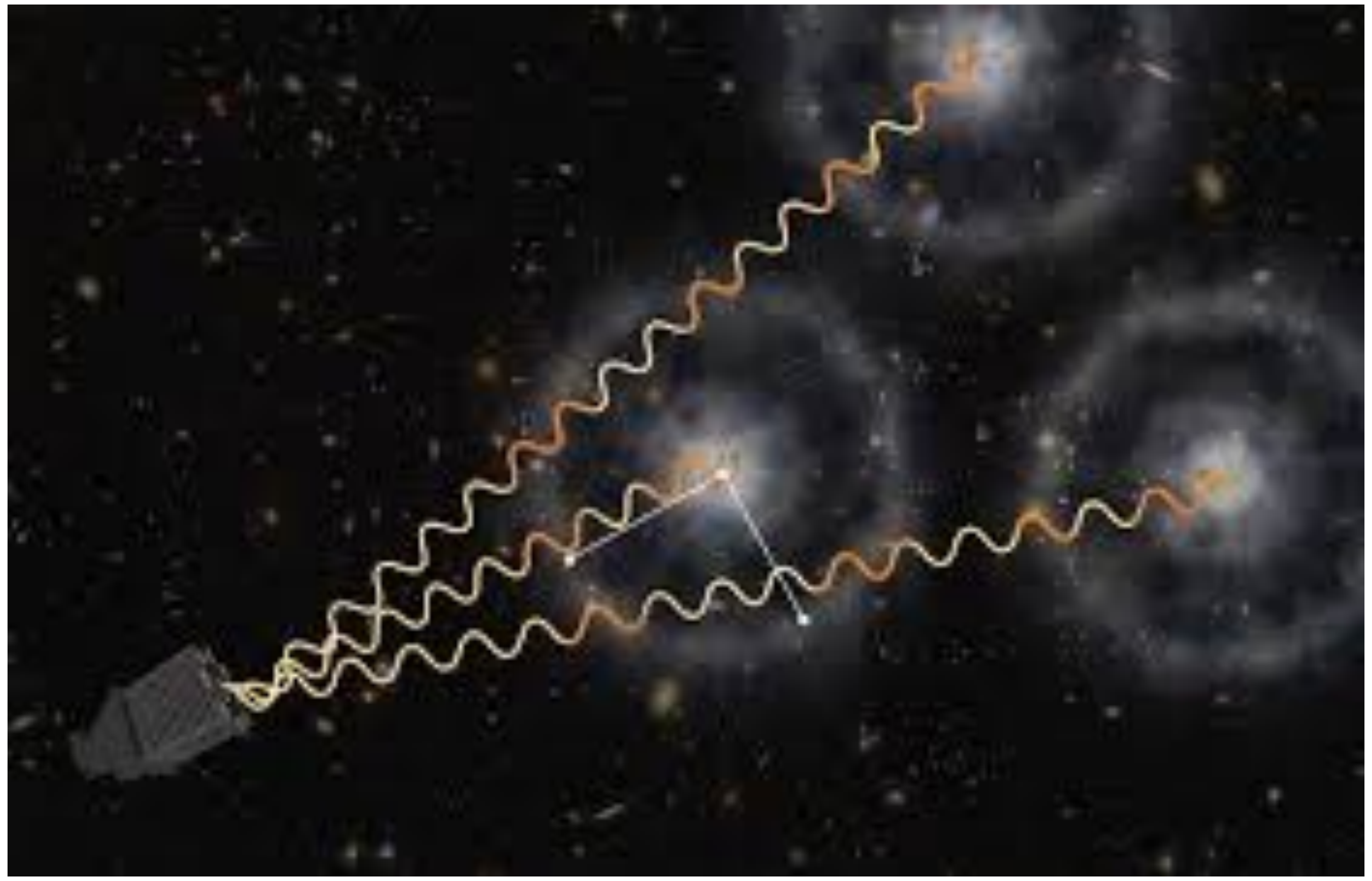
Y6 BAO

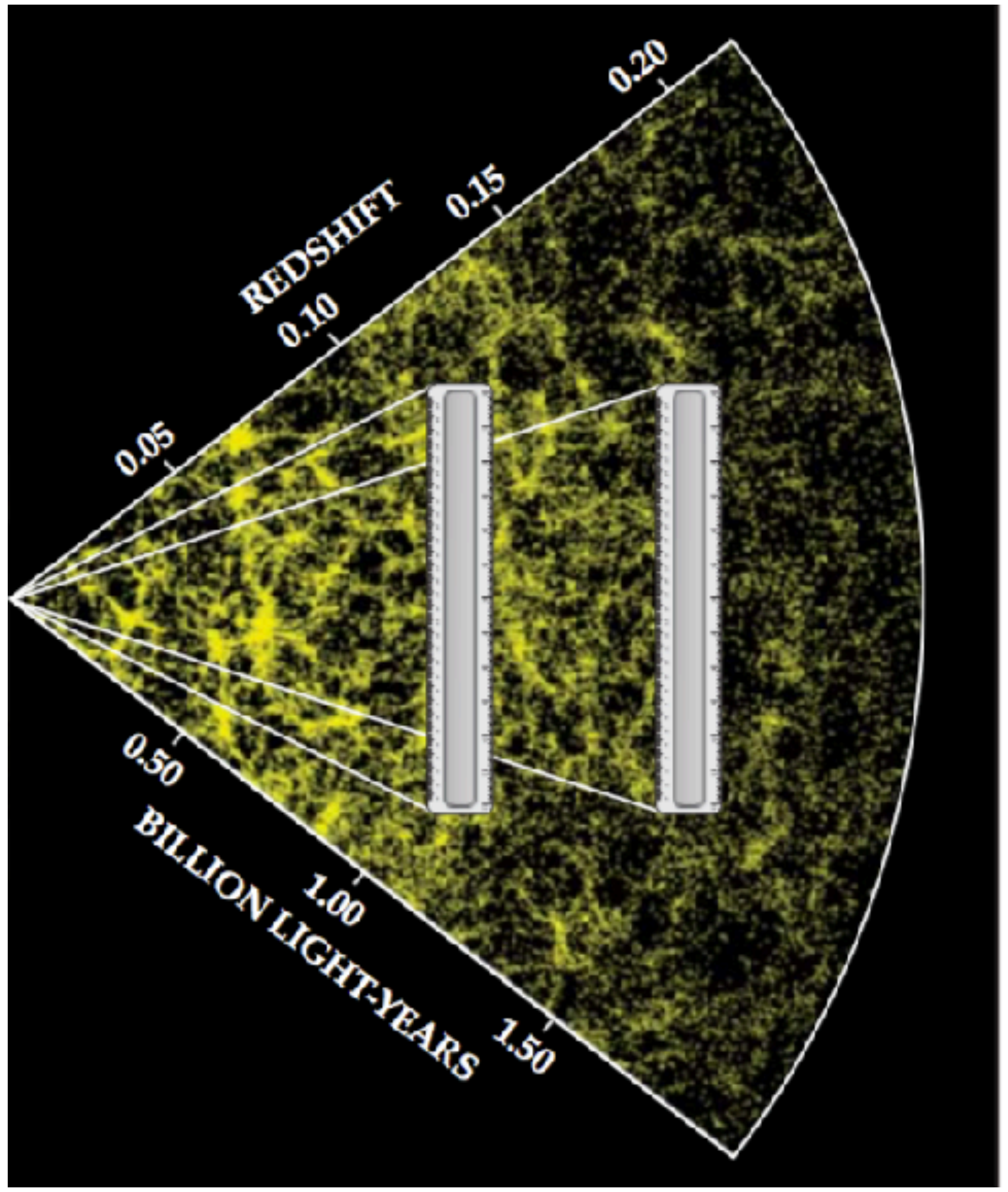


arXiv:2402.10696

Baryonic Acoustic Oscillations (BAO)

- Arised from acoustic oscillations in primordial plasma
- Imprint preserved in the LSS distribution
- A standard ruler in the late universe, ~150 Mpc
- Measured in numerous analyses, mostly spectroscopic



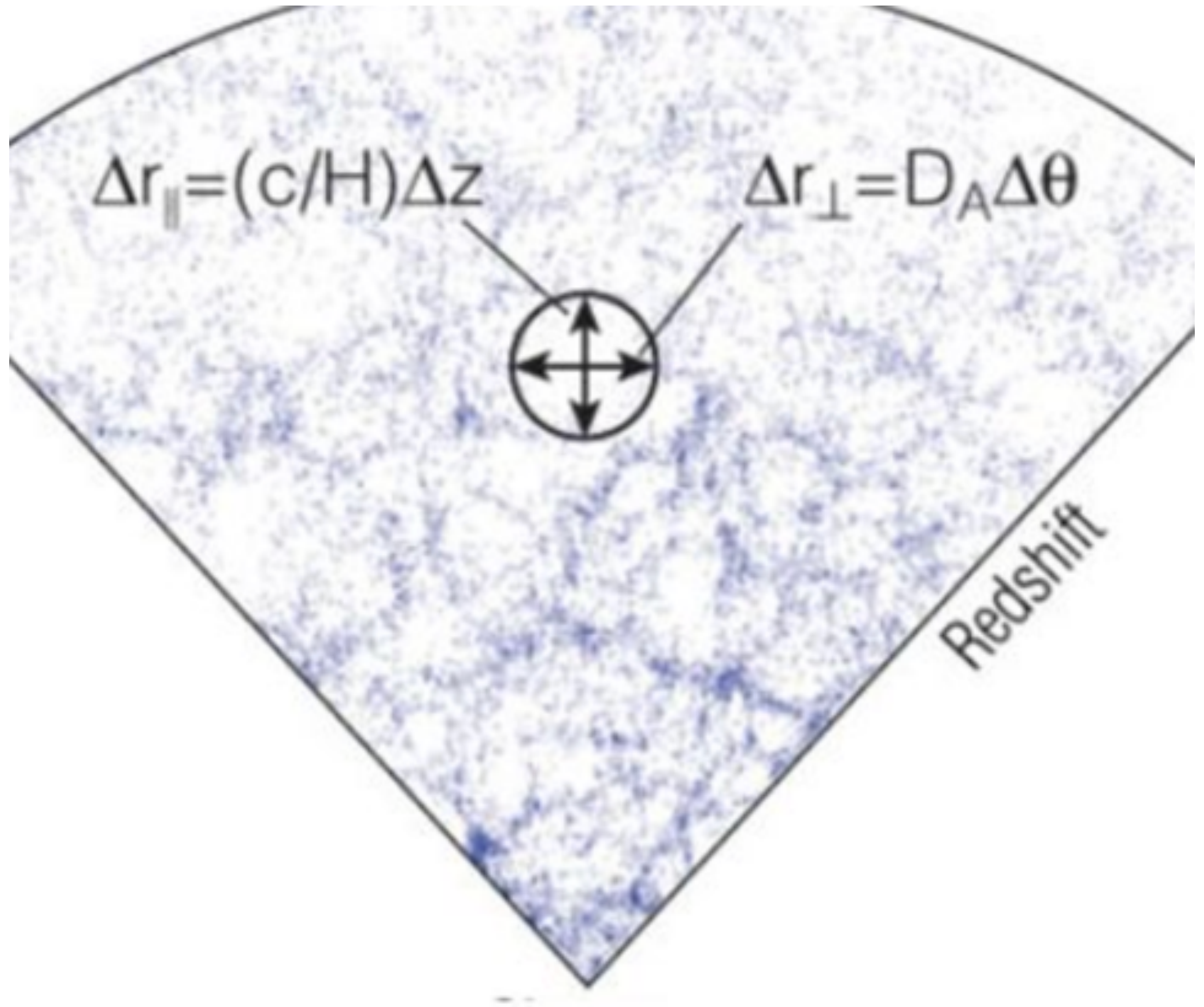


Physical constraint from BAO

- Spec-z surveys can constrain H and D_M
- Photometric surveys, imprecise redshift, only constrain D_M
- BAO measurements require large volume
- Photometric surveys can survey large volume with deep magnitude quickly

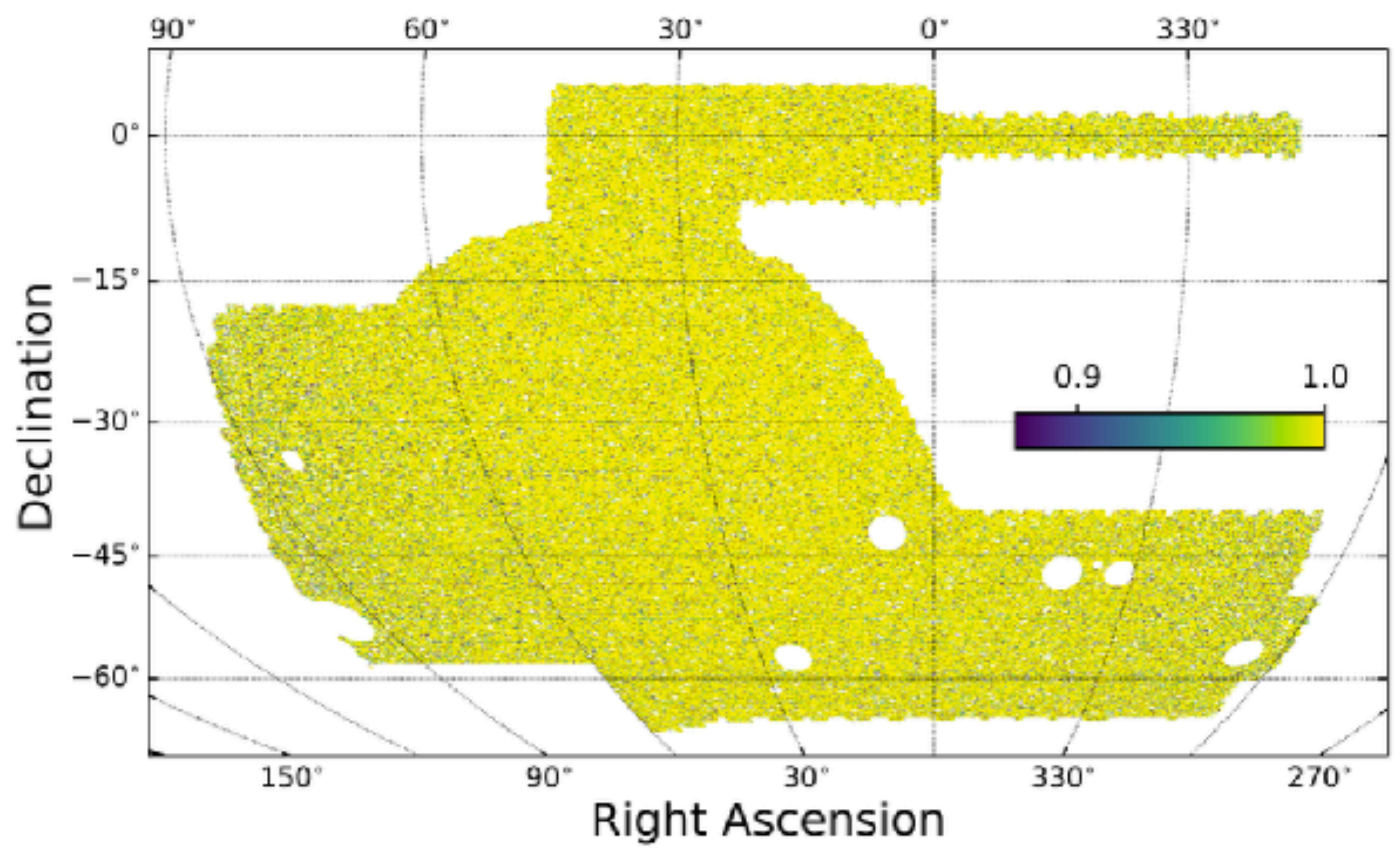
Radial BAO $\longrightarrow H$

Transverse BAO $\longrightarrow D_M$



Y6 BAO sample overview

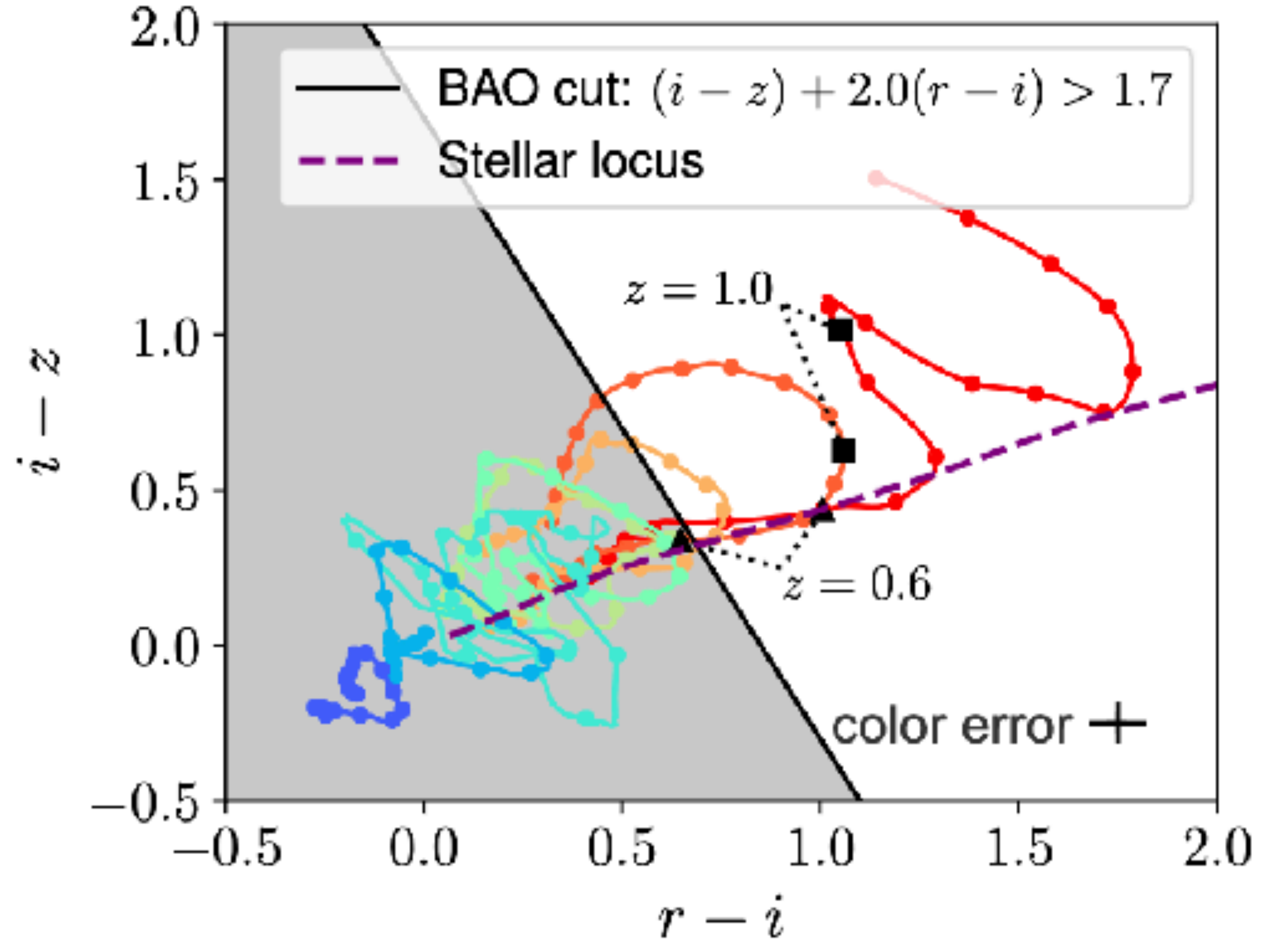
- Gold sample ➜ BAO sample
- Area: 4273 sq. deg
- Redshift range: [0.6,1.2], divided into 6 tomographic bins, each of width 0.1
- Number of gals: 15 937 556, x 2 wrt Y3



$$1.7 < i - z + 2(r - i),$$
$$17.5 < i < a + b z_{\rm ph},$$
$$i < 22.5,$$
$$0.6 < z_{\rm ph} < 1.2.$$

Red galaxy selection

Maximizing the BAO constraint



J. Mena-Fernández +, 2402.10697

Crocce +, 1712.06211

Y6 sample properties

Y6

Bin	$\langle z_{ph} \rangle$	N_{gal}	σ_{68}
$0.6 < z_{ph} < 0.7$	0.654	2,854,542	0.0232
$0.7 < z_{ph} < 0.8$	0.752	3,266,097	0.0254
$0.8 < z_{ph} < 0.9$	0.844	3,898,672	0.0292
$0.9 < z_{ph} < 1.0$	0.929	3,404,744	0.0358
$1.0 < z_{ph} < 1.1$	1.013	1,752,169	0.0403
$1.1 < z_{ph} < 1.2$	1.107	761,332	0.0415

$z_{\rm eff} = 0.867, A = 4273.42 \rm deg^2$

Y3

N_{gal}	σ_{68} (*)
1,478,178	0.0246
1,632,805	0.0279
1,727,646	0.0298
1,315,604	0.0363
877,760	0.0455

$z_{\rm eff} = 0.835, A = 4108.47 \rm deg^2$

- Double in sample size, better photo-z and one more redshift bin

Photo-z

- DNF Photo-z, trained using grizY on a large of set spec-z data

- Redshift uncertainty is ~0.03(1+z)

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$0.6 < z_{ph} < 0.7$	2,854,542	0.0232
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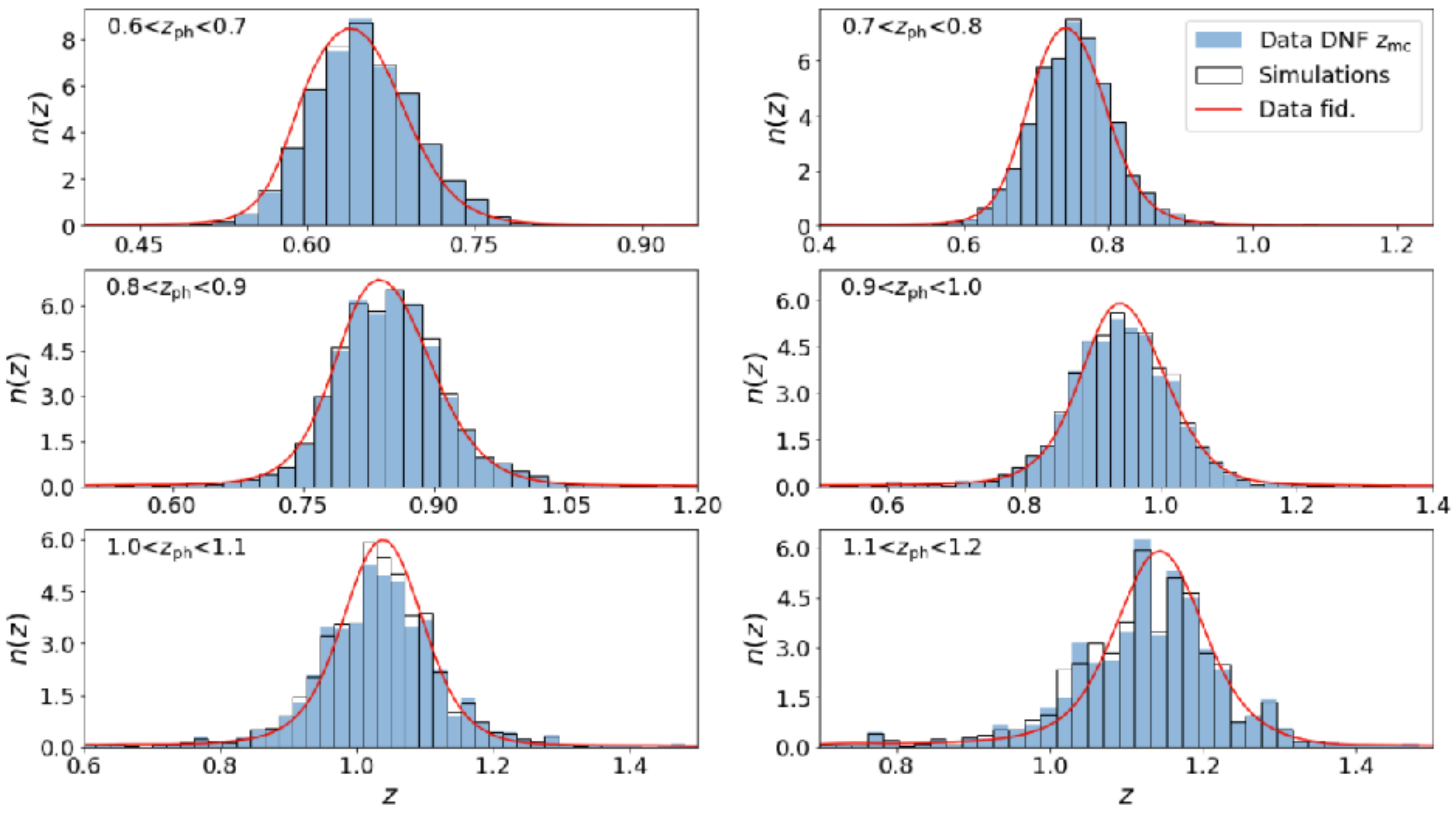
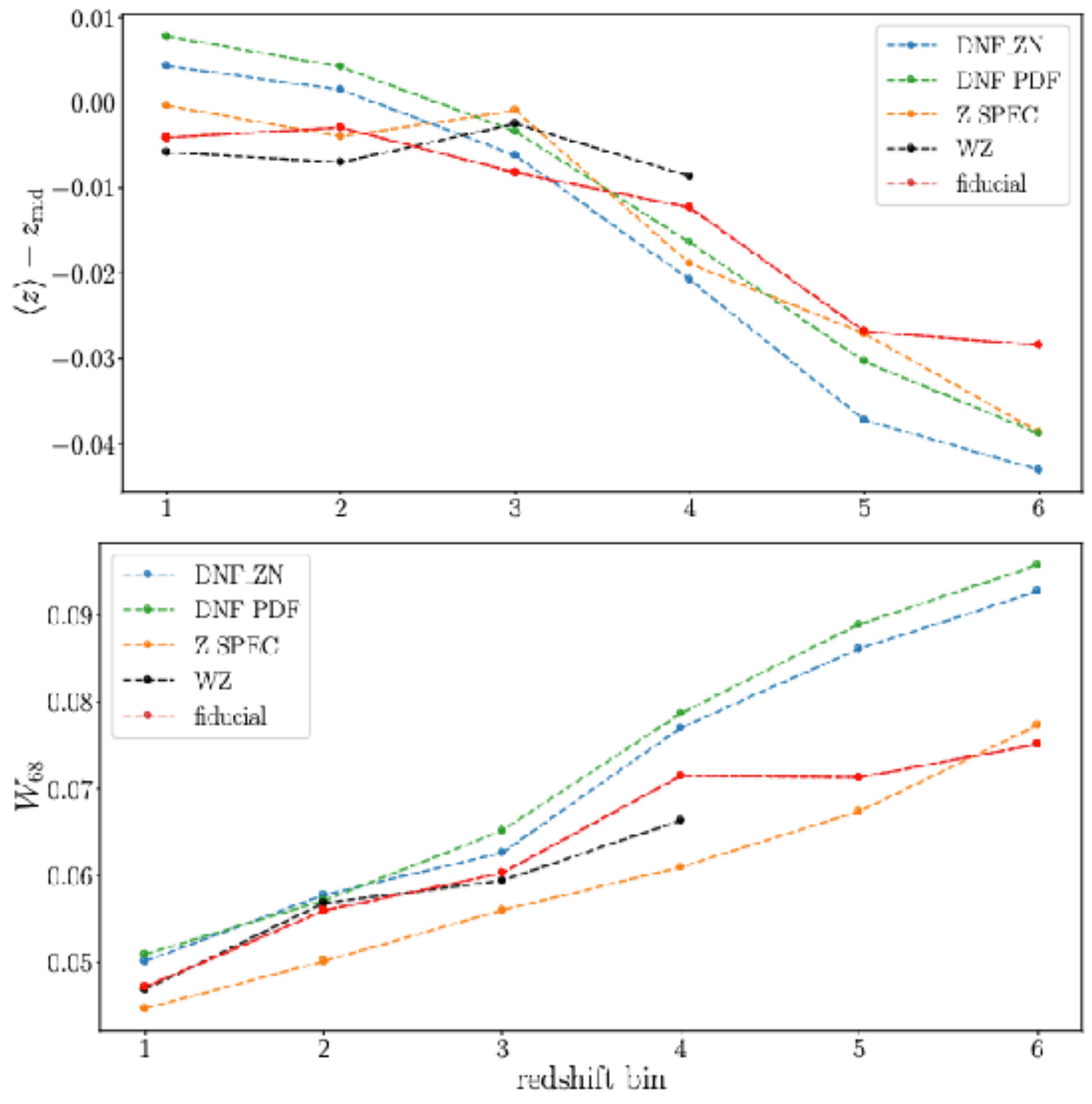
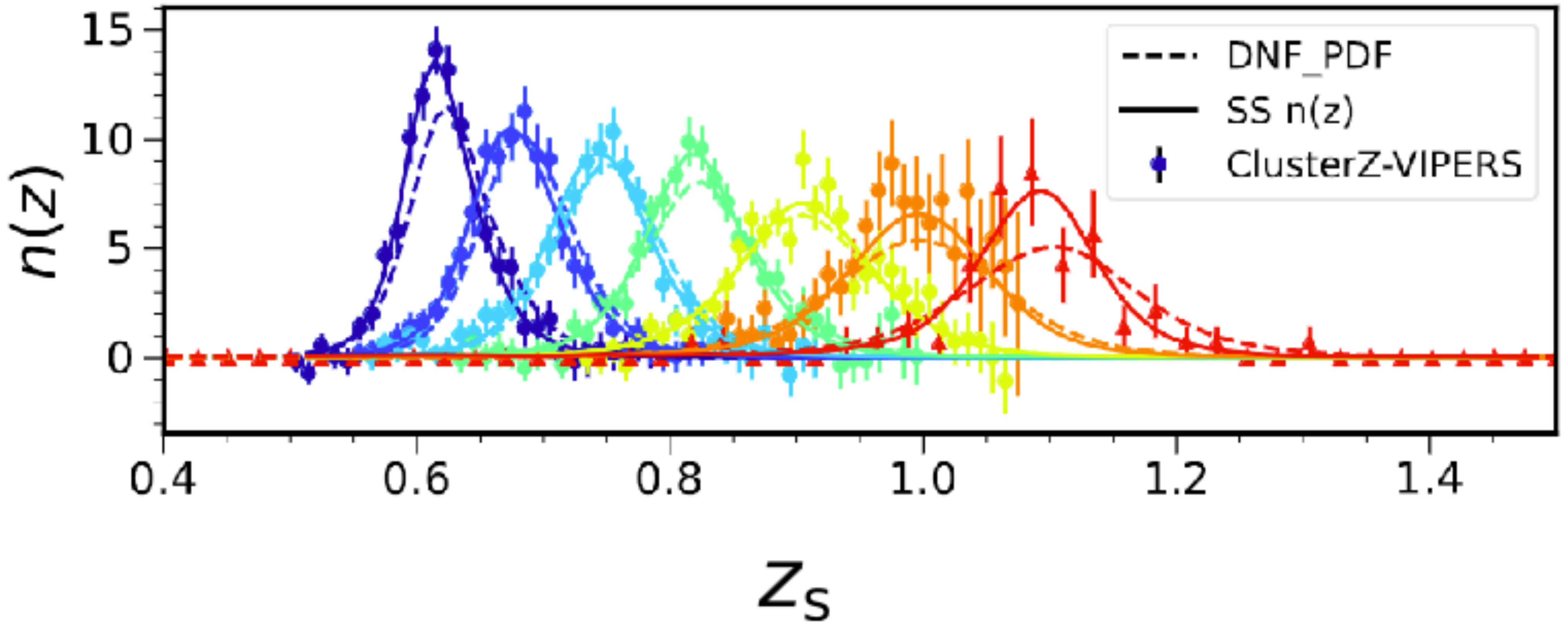
$$\sigma_{68} \approx \frac{z_p - z_s}{1 + z_s}$$

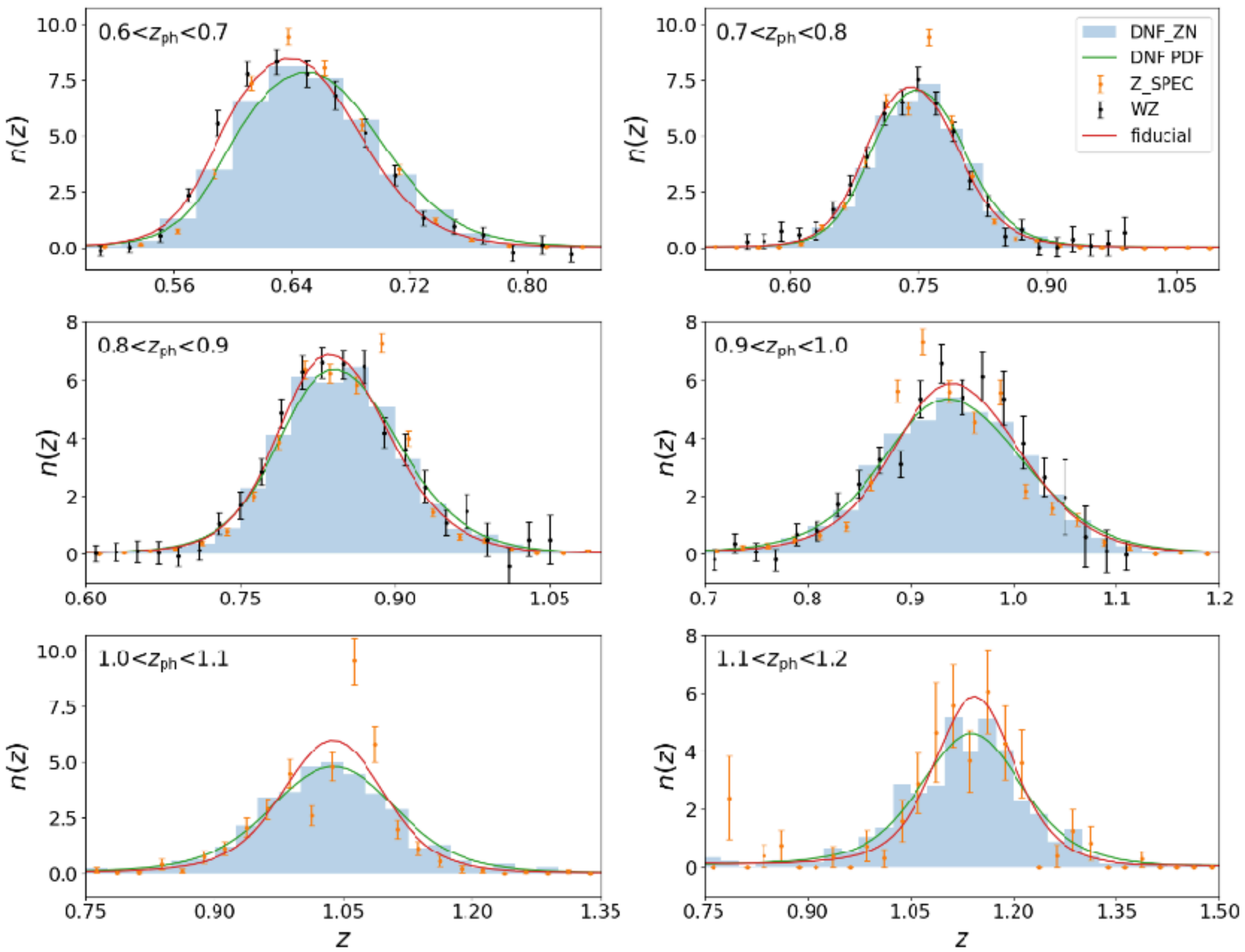




True-z distribution calibration

- Use DNF PDF as proxy
- Corrected by Shift & Stretched using Clustering-z (z<1) and VIPERS spec-z (z>1)
- Shift in mean and stretch in the spread



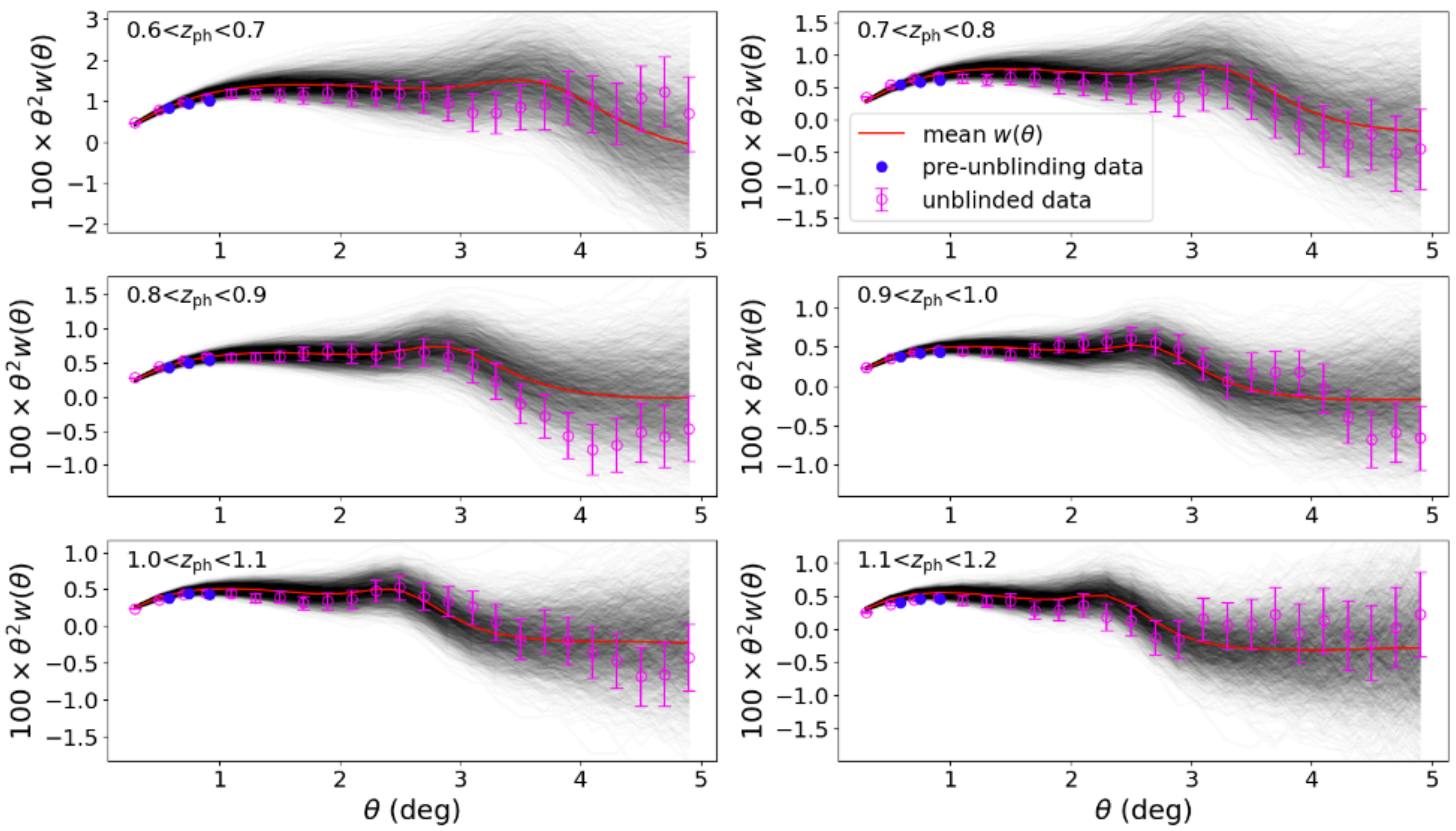


ICE-COLA mock catalog

- ICE-COLA mocks are used for pipeline testing

- 1952 mocks, match to Y6 properties

Ferrero +, 2107.04602



Three clustering statistics

- Angular correlation function (ACF): w

  KCC +, 1801.04390

- Angular power spectrum (APS): C_ℓ

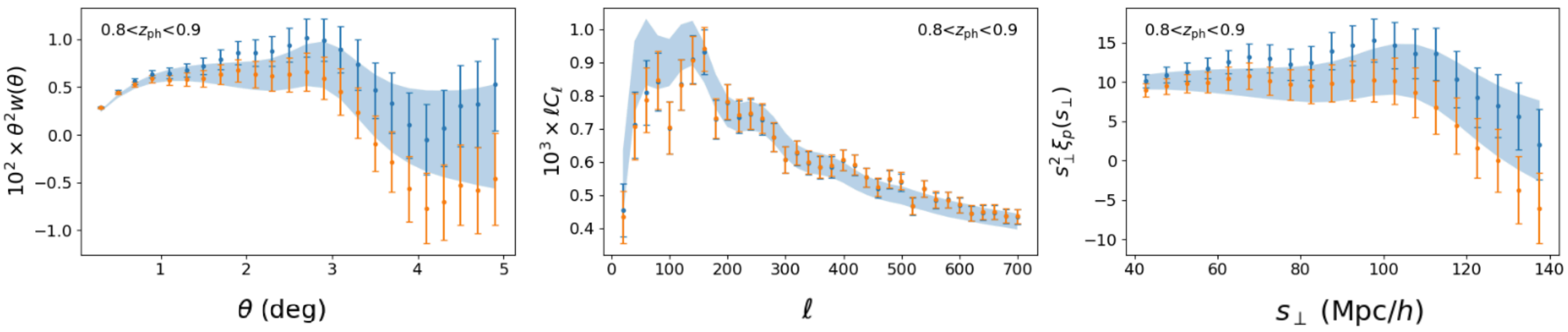
  Camacho +, 1807.10163

- Projective correlation function (PCF): ξ_p

  Ross +, 1705.05442, KCC+, 2110.13332, 2210.05057

$$\text{AVG} = w_1\text{ACF} + w_2\text{APS} + w_3\text{PCF}$$

Consensus measurements



BAO model fitting

$$P(k,\mu) = (b+\mu^2 f)^2 \left[(P_{\rm lin} - P_{\rm nw})e^{-k^2\Sigma^2} + P_{\rm nw}\right]$$

P(*k*) model

Clustering statistics template *T*
: w, C_ℓ, $\xi_{\rm p}$

+

$$M(x) = BT_{\mathrm{BAO},\alpha}(x') + A(x)$$

Nuisance para + $\alpha = \left.\frac{D_{\rm M}}{r_{\rm s}}\frac{r_{\rm s}}{D_{\rm M}}\right|_{\rm fid}$

+

Covariance

+

Data measurement

χ^2 minimization

α or $\frac{D_{\rm M}}{r_{\rm s}}$

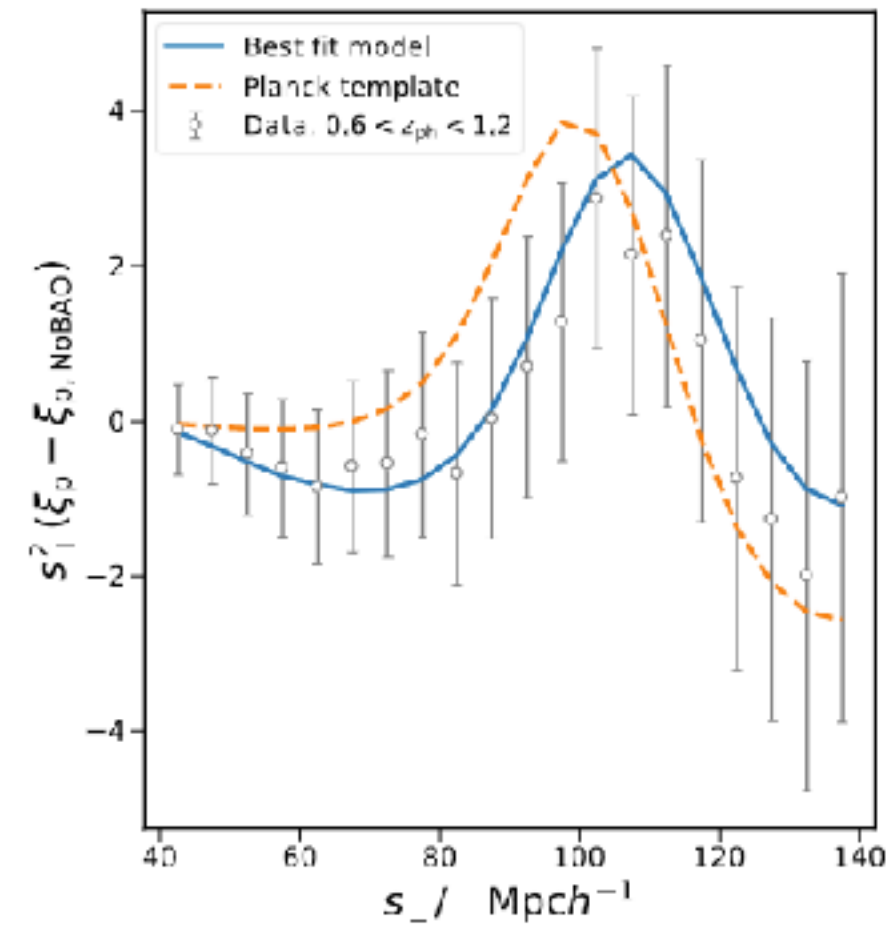
Parameter α is introduced to match the BAO scale in the data to that in the template

Y6 BAO measurements

- Different statistics are consistent with each other
- 3.5 σ detection of BAO

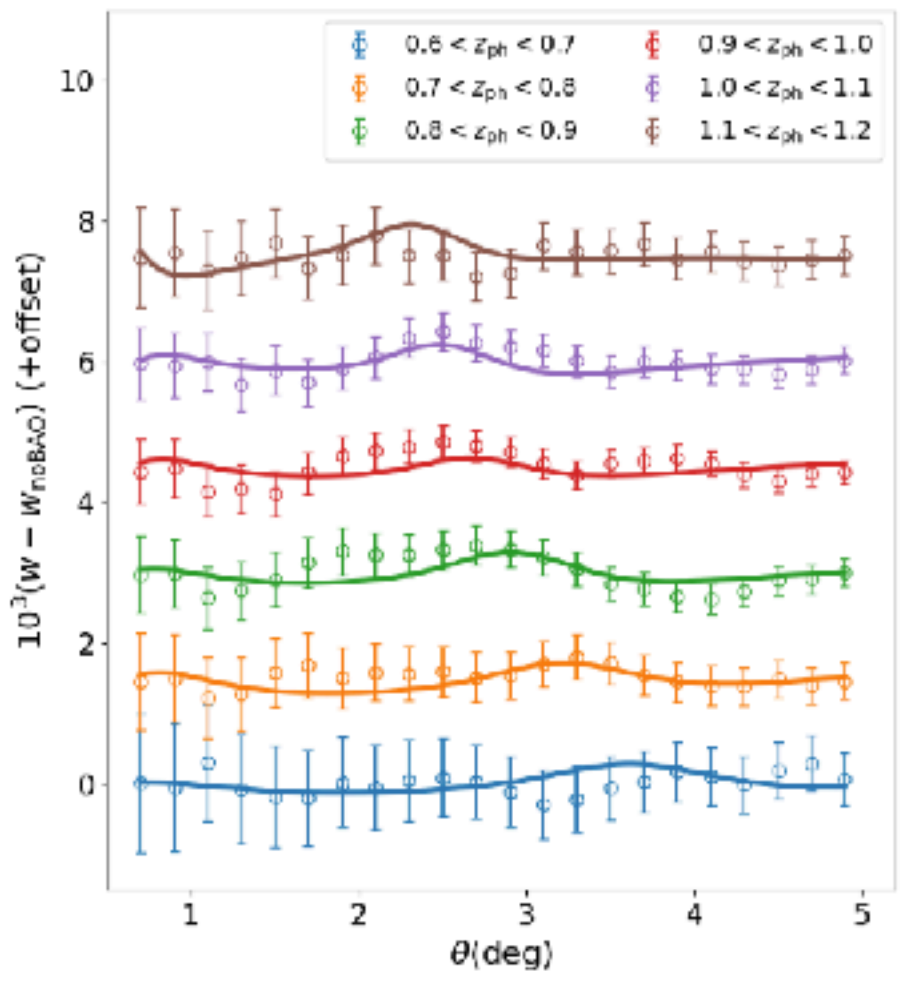
fiducial Planck

$$\alpha = 0.9571 \pm 0.0196\ [\text{stat.}], \pm 0.0041\ [\text{sys.}],$$
$$\alpha = 0.9571 \pm 0.0201\ [\text{tot.}].$$



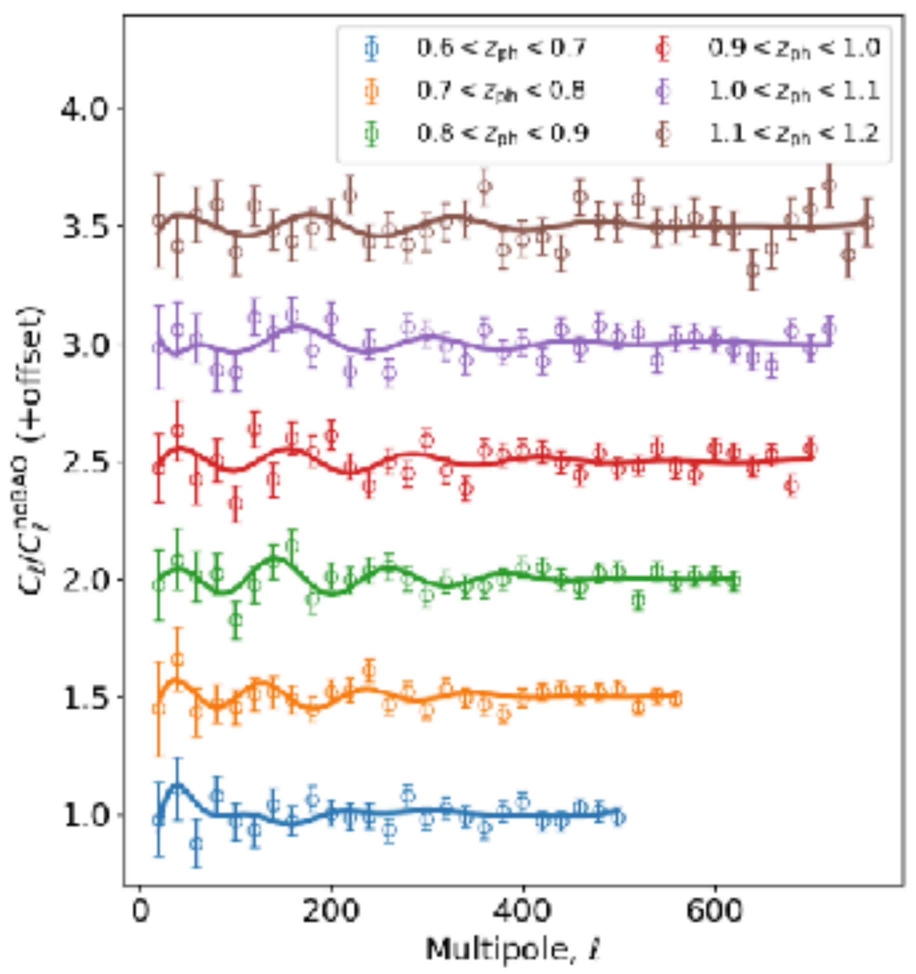
ACF, w

$\alpha = 0.9517 \pm 0.0227$



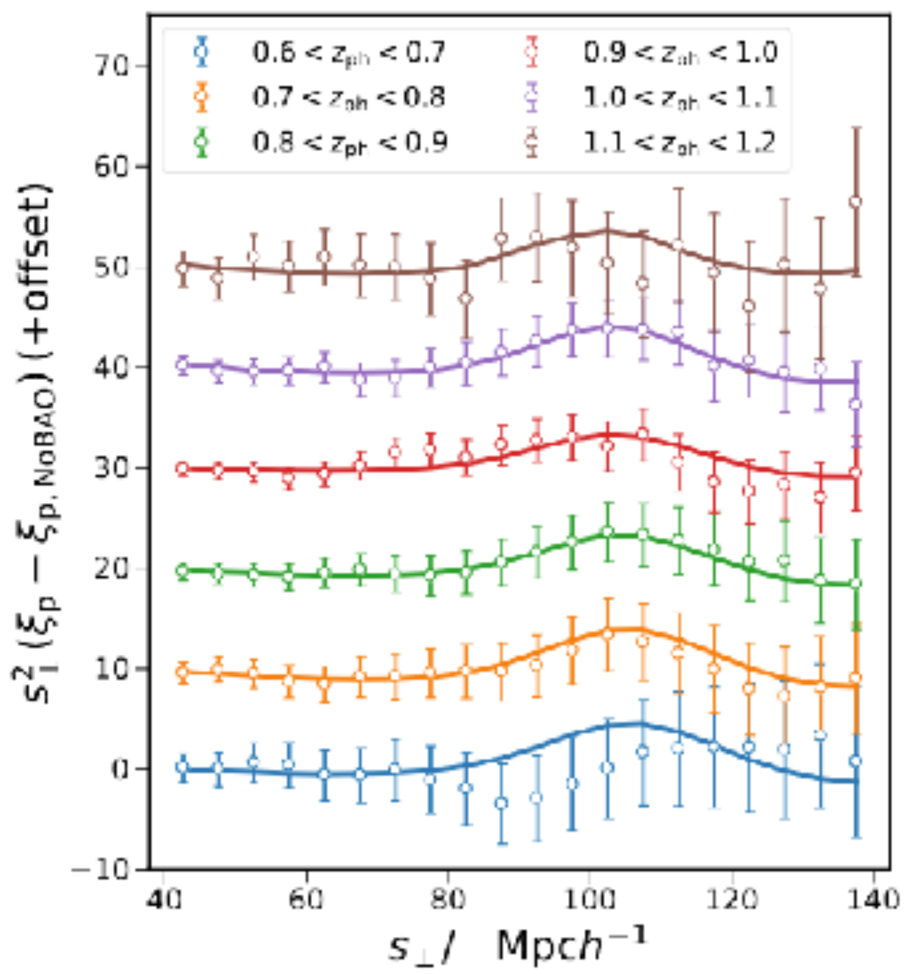
APS, C_ℓ

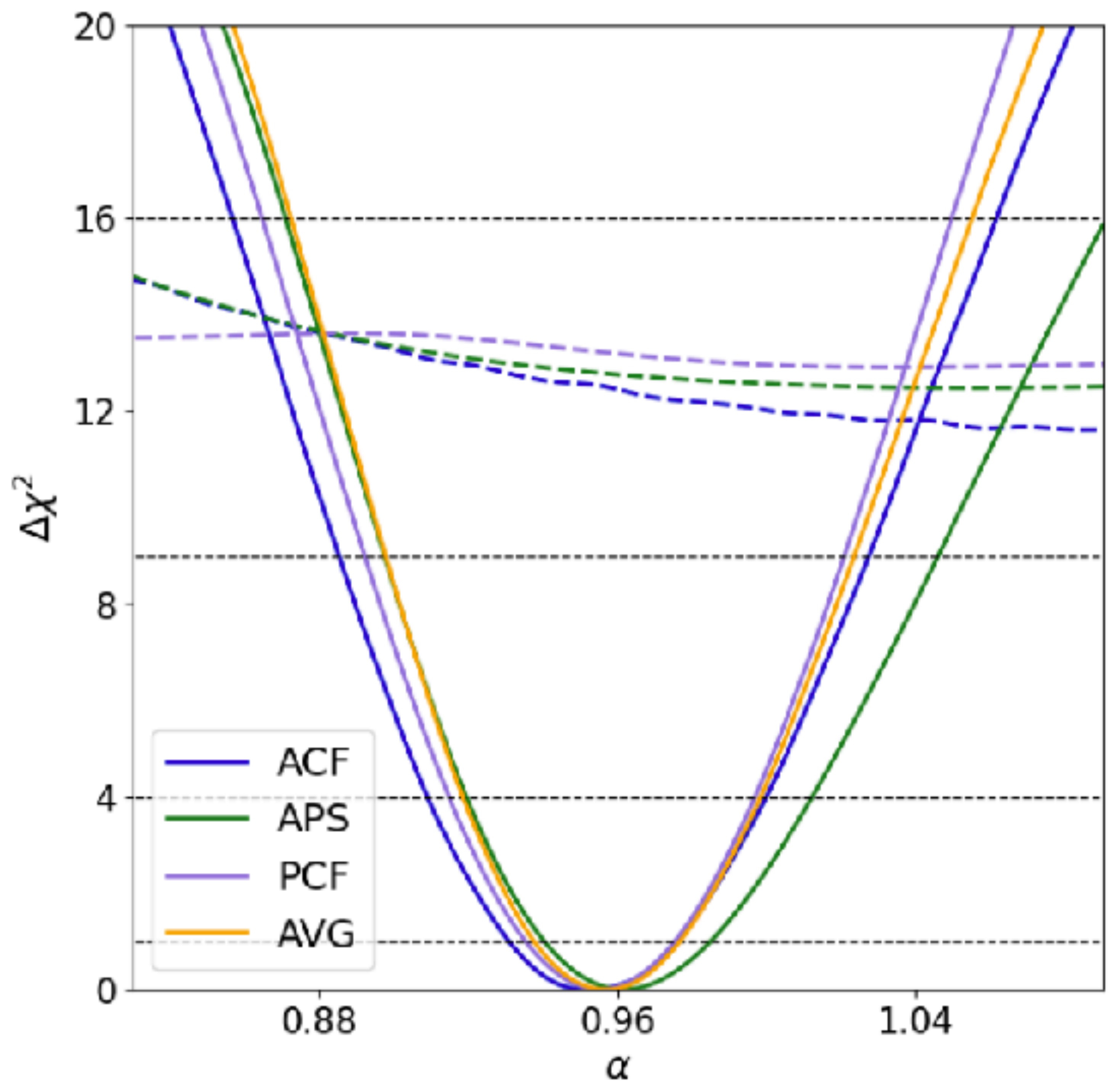
$\alpha = 0.9617 \pm 0.0224$



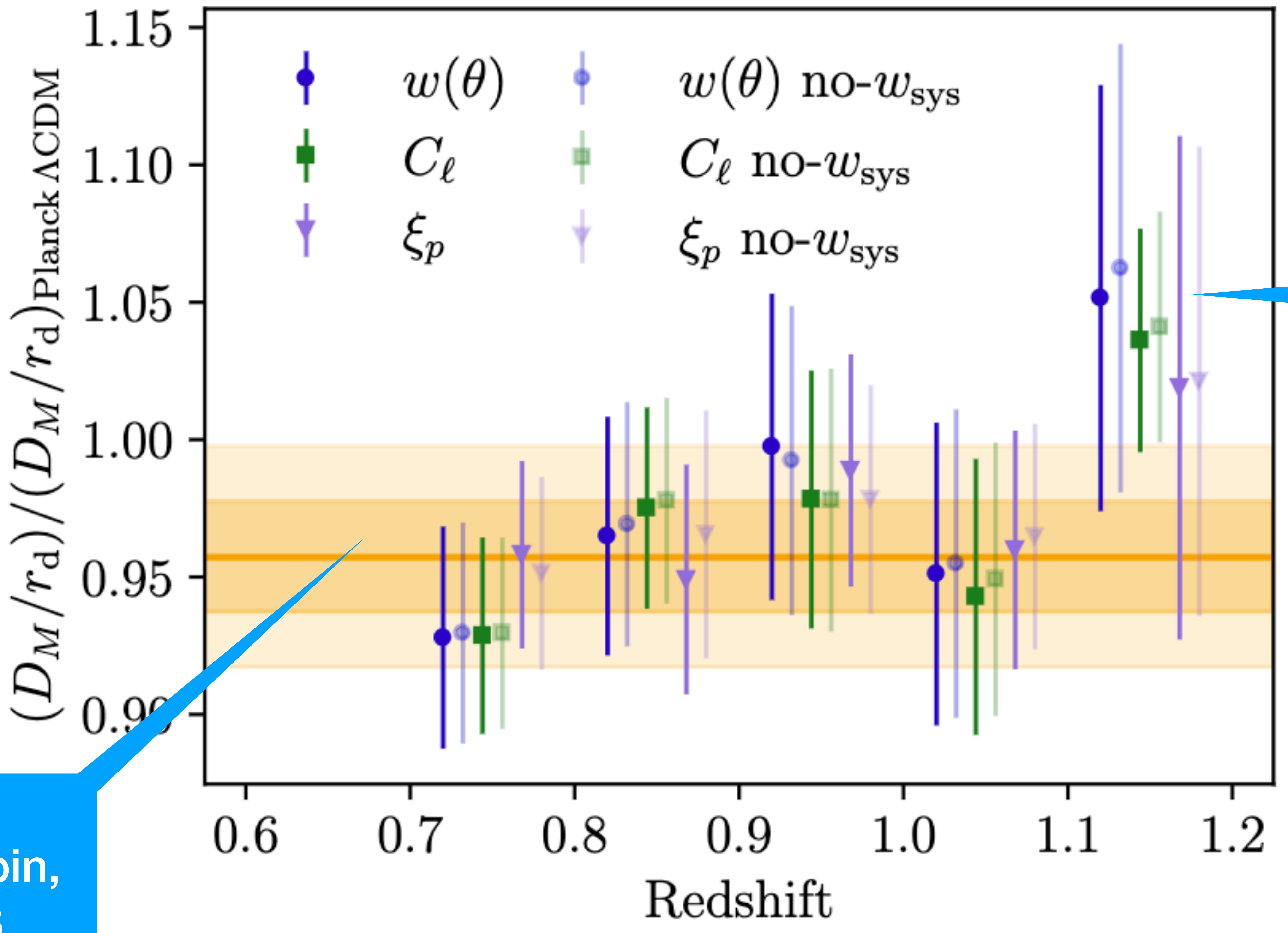
PCF, ξ_p

$\alpha = 0.9553 \pm 0.0201$





Individual bin measurements

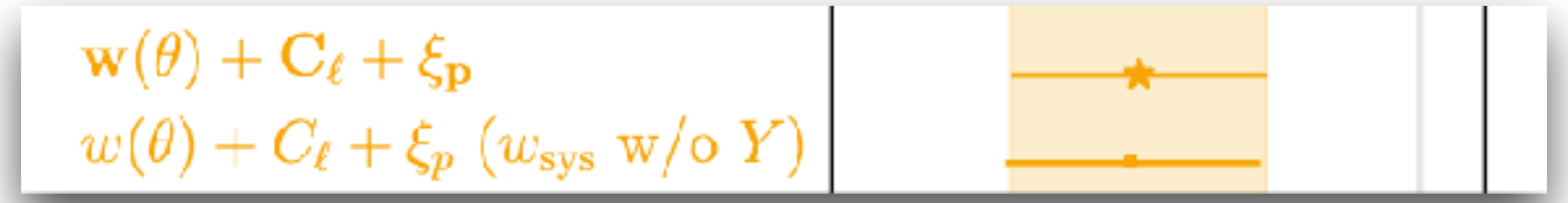


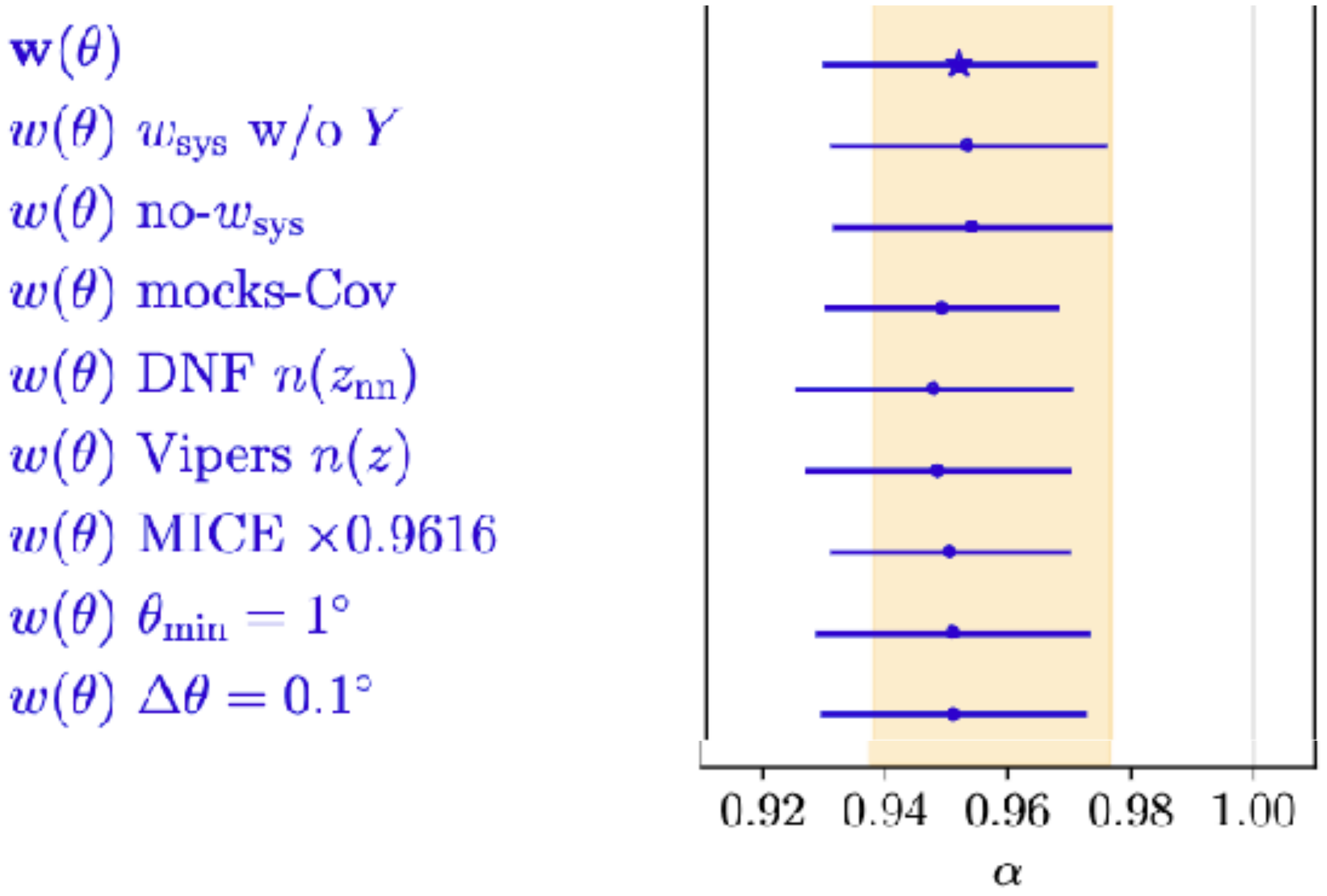
Highest redshift bin shows the largest deviation from the low bins, but its contribution to final constraint is weak

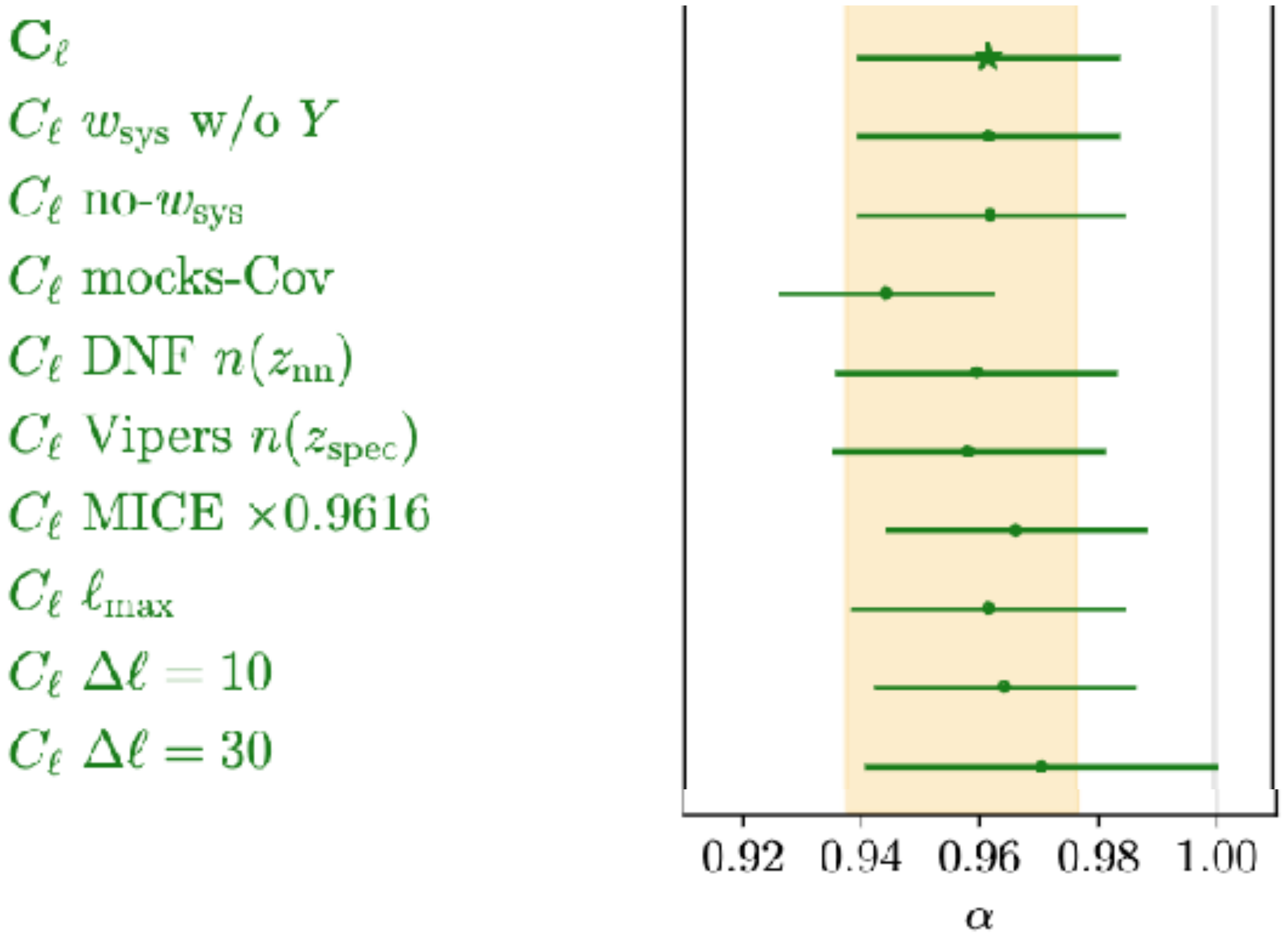
No detection in first bin, same in Y1 and Y3

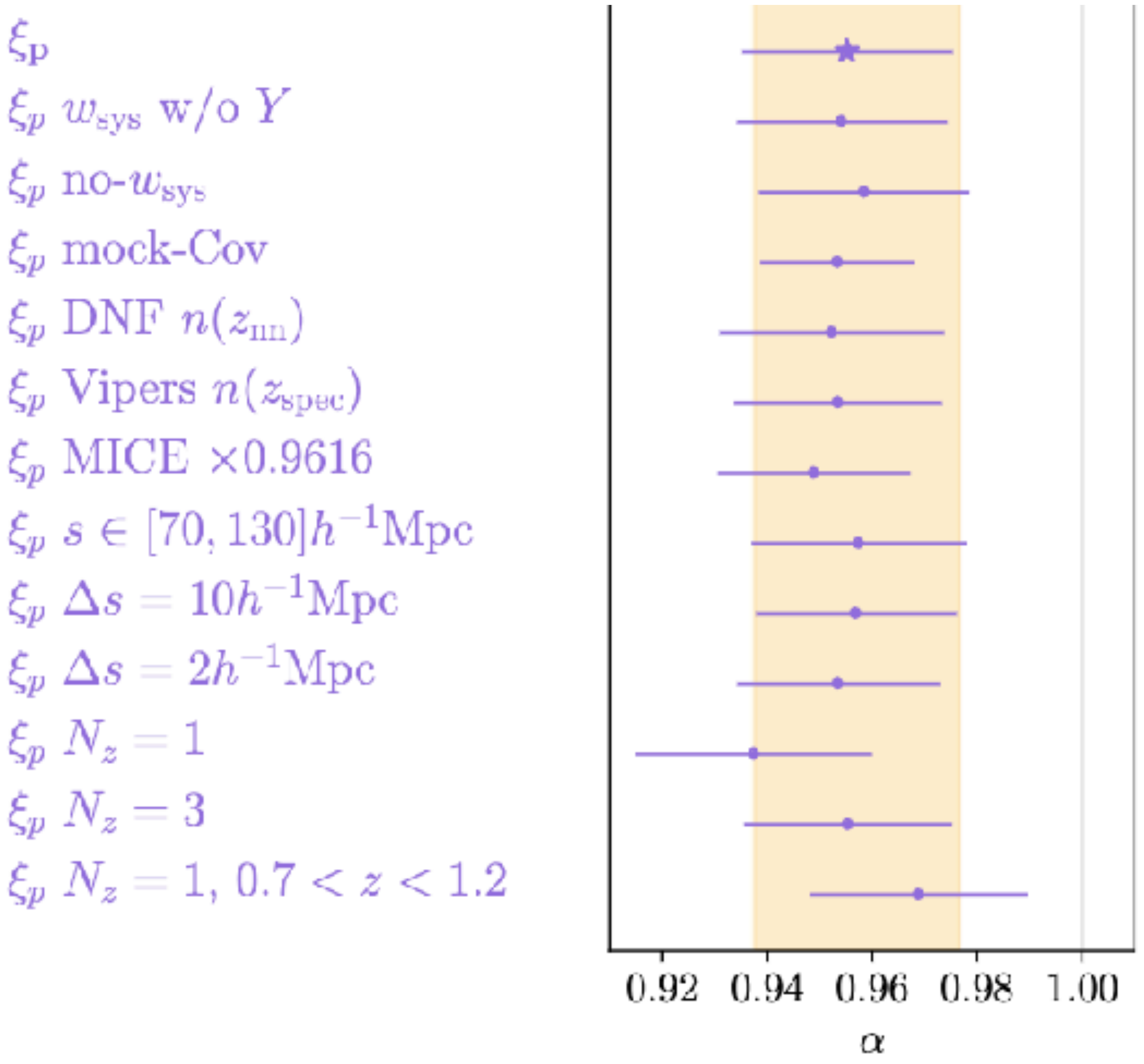
Robustness tests

- Change in the best fit α is within 1σ







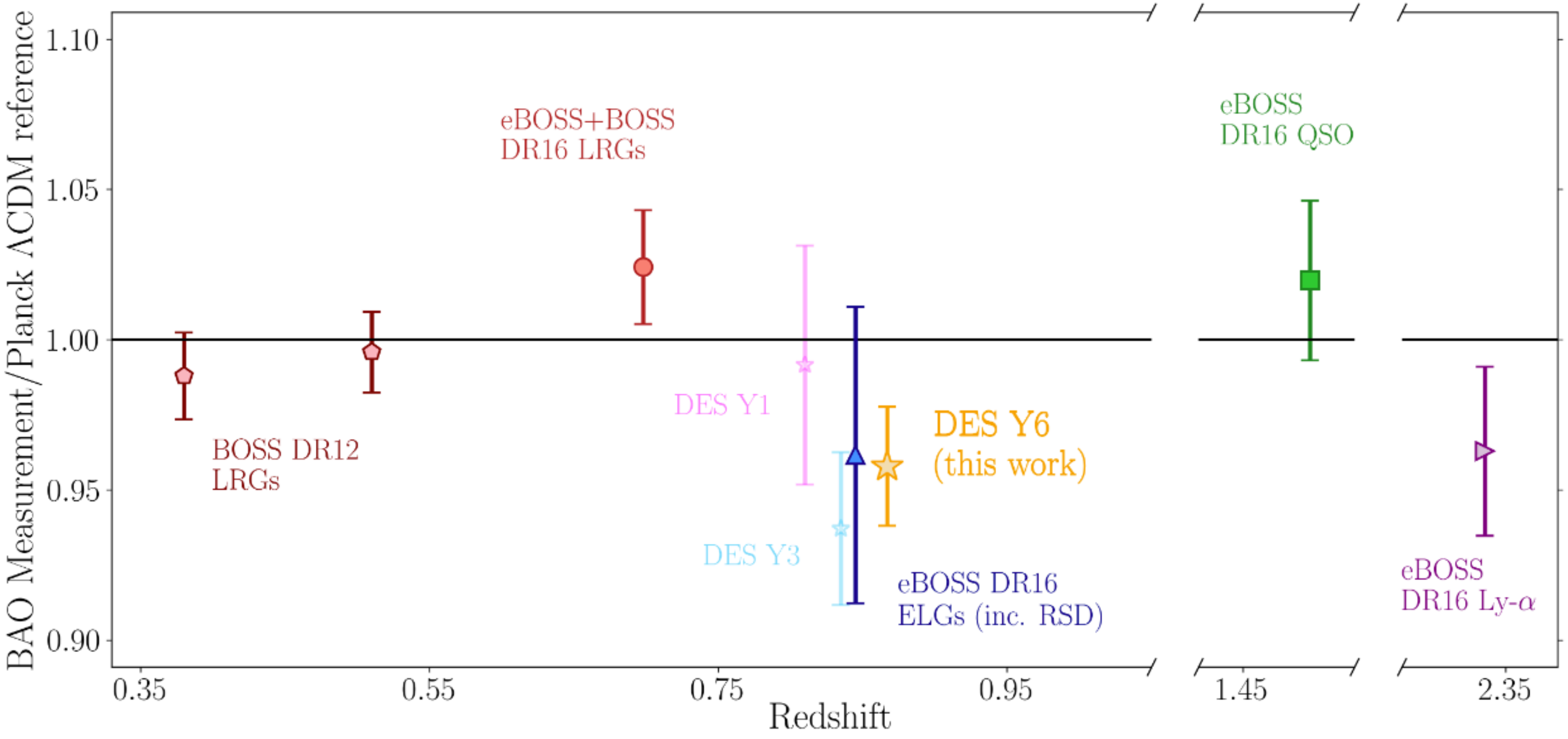


Y6 BAO measurement

- Y6 is the most precise photometric BAO measurement
- Most precise transverse BAO measurement at z ~ 0.8, at least before DESI

The physical quantity directly constrained by transverse BAO

$$\frac{D_M}{r_s}$$

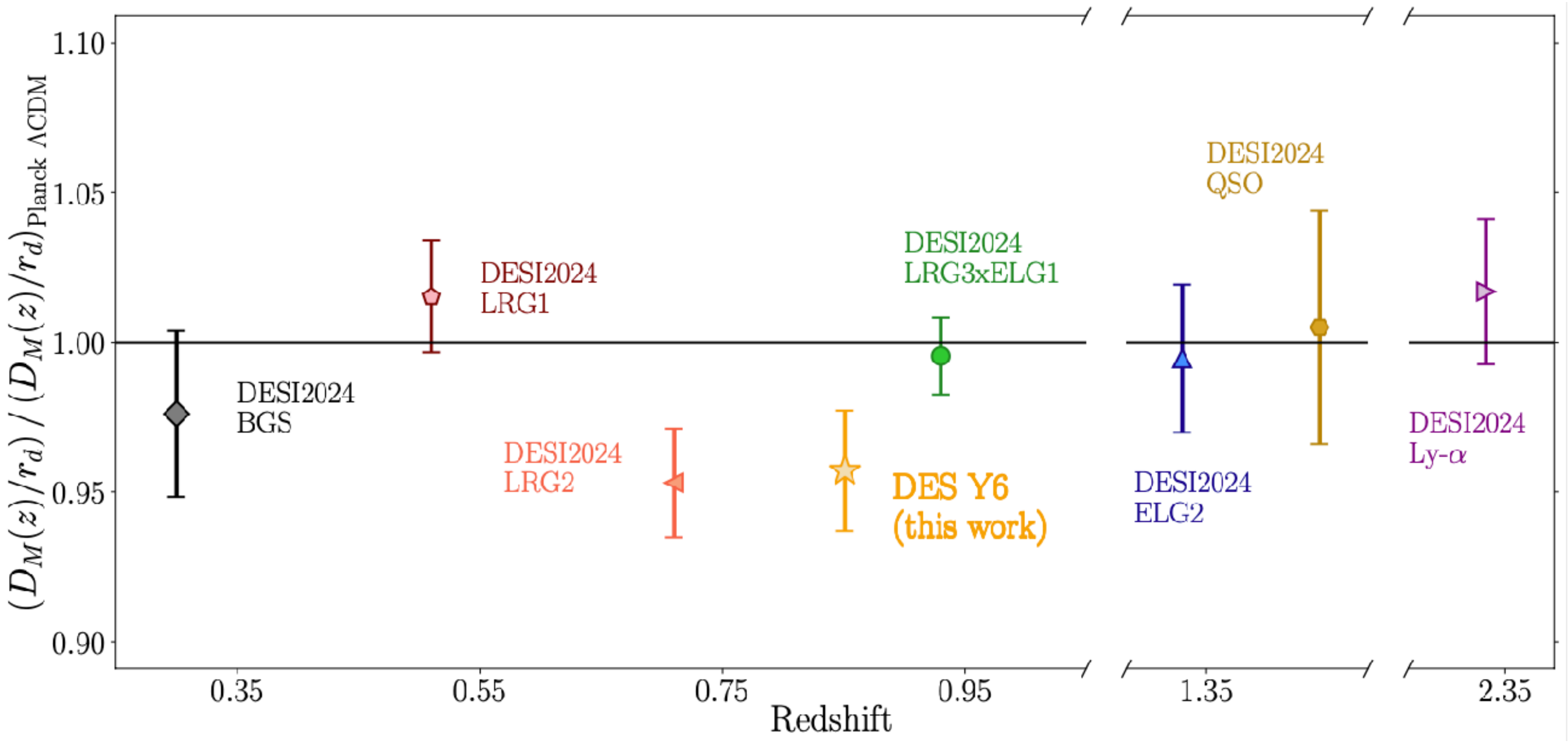


Y6 BAO measurement

- Even after DESI, still competitive

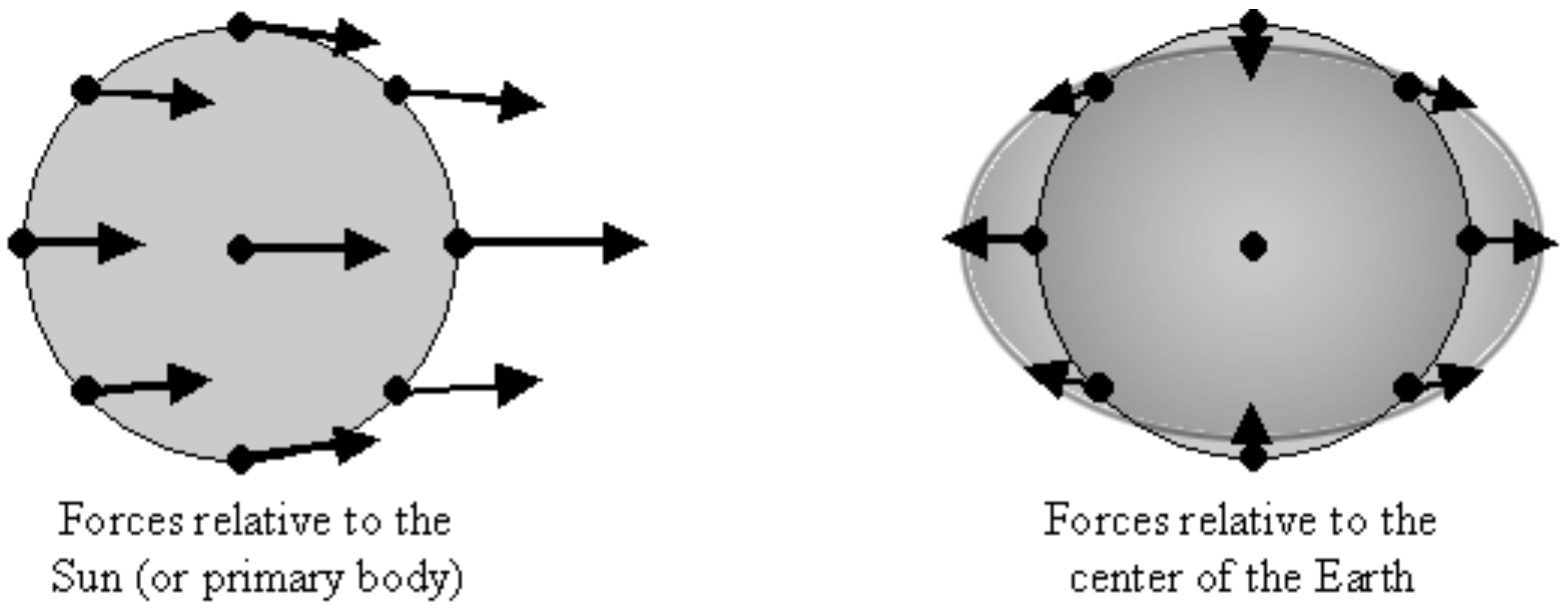
The physical quantity directly constrained by transverse BAO

$$\frac{D_M}{r_s}$$



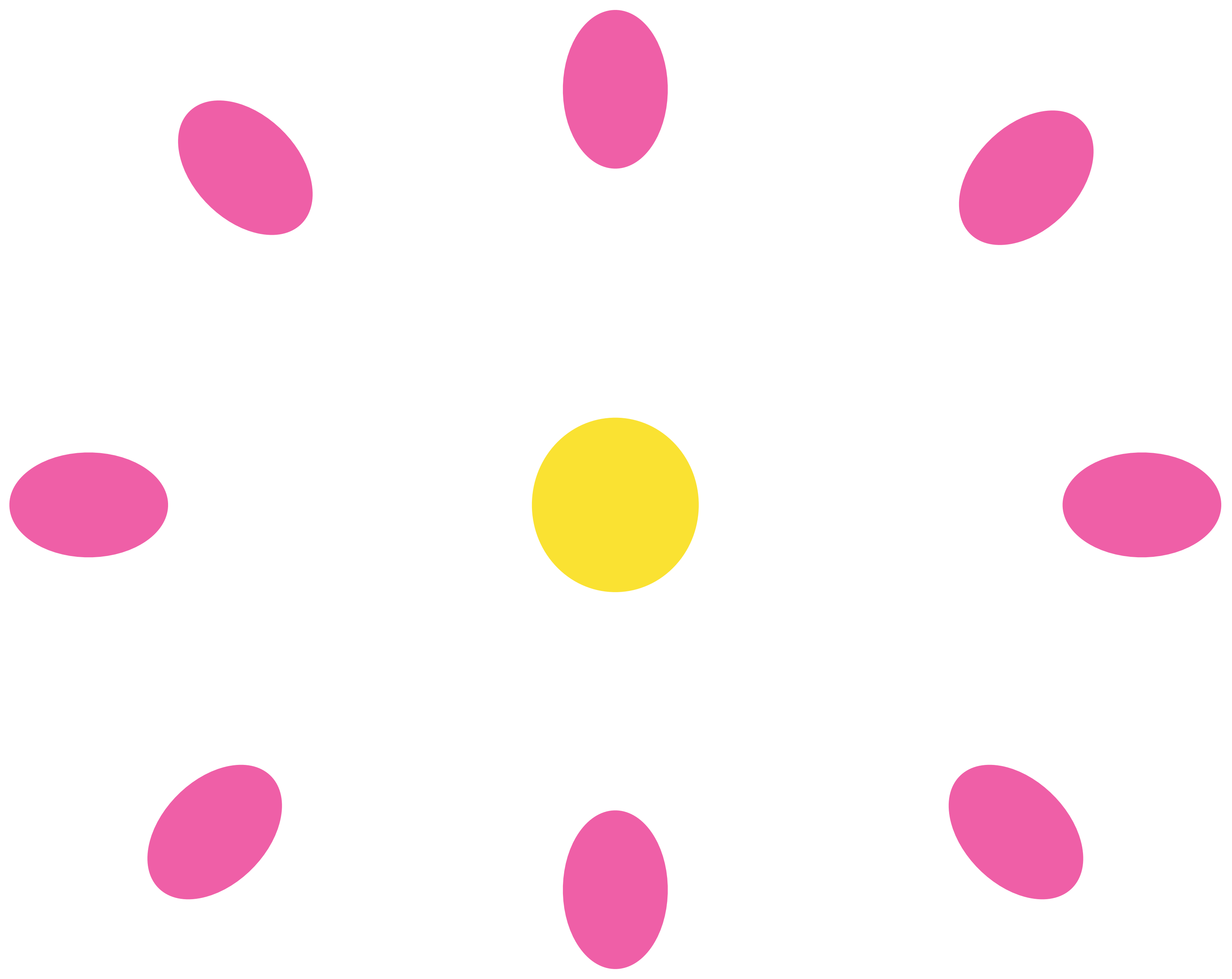
Linear tidal alignment

- Tidal field causes tides on earth
- Can also distort galaxy shape



- Linear alignment model

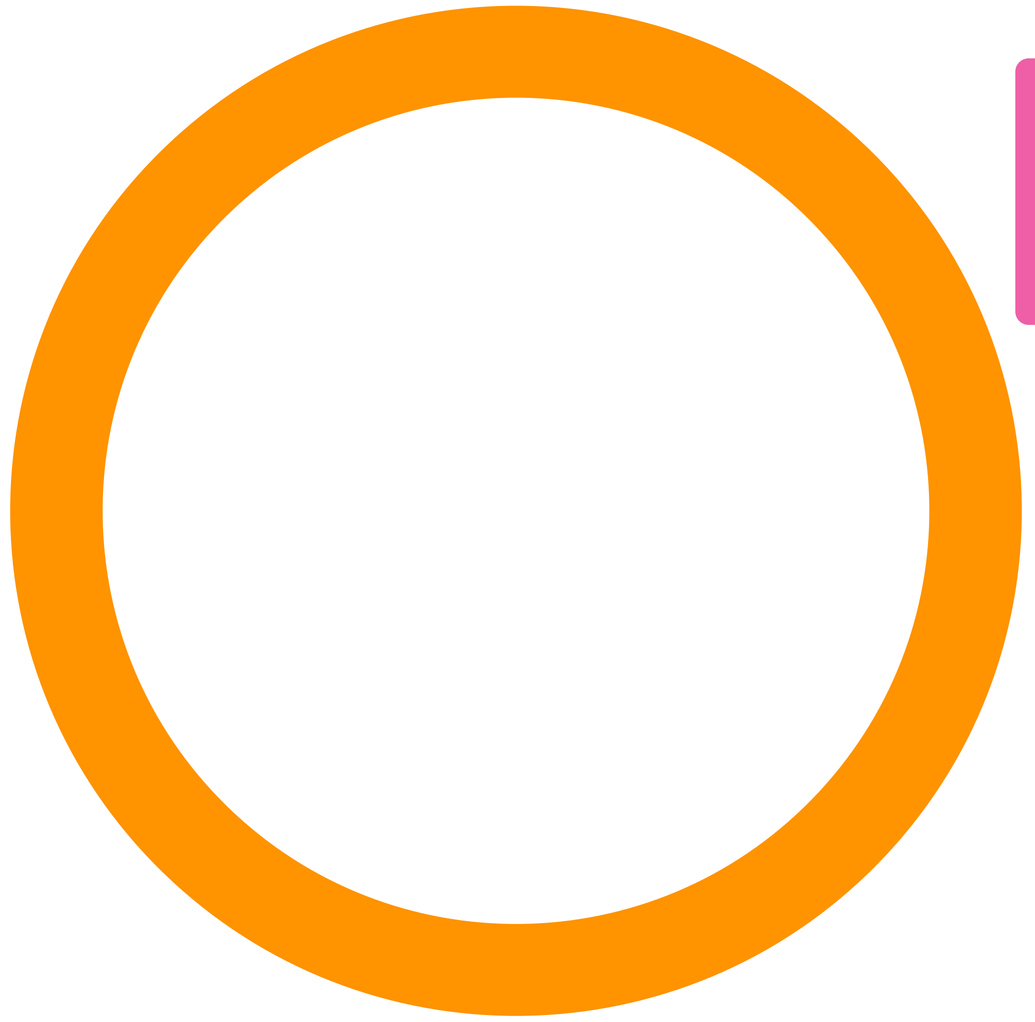
$$\gamma(\boldsymbol{x}, z) = -\frac{C_1 \bar{\rho}_{\mathrm{m}0}}{D}(\partial_{xx} - \partial_{yy}, 2\partial_{xy})\nabla^{-2}\delta$$

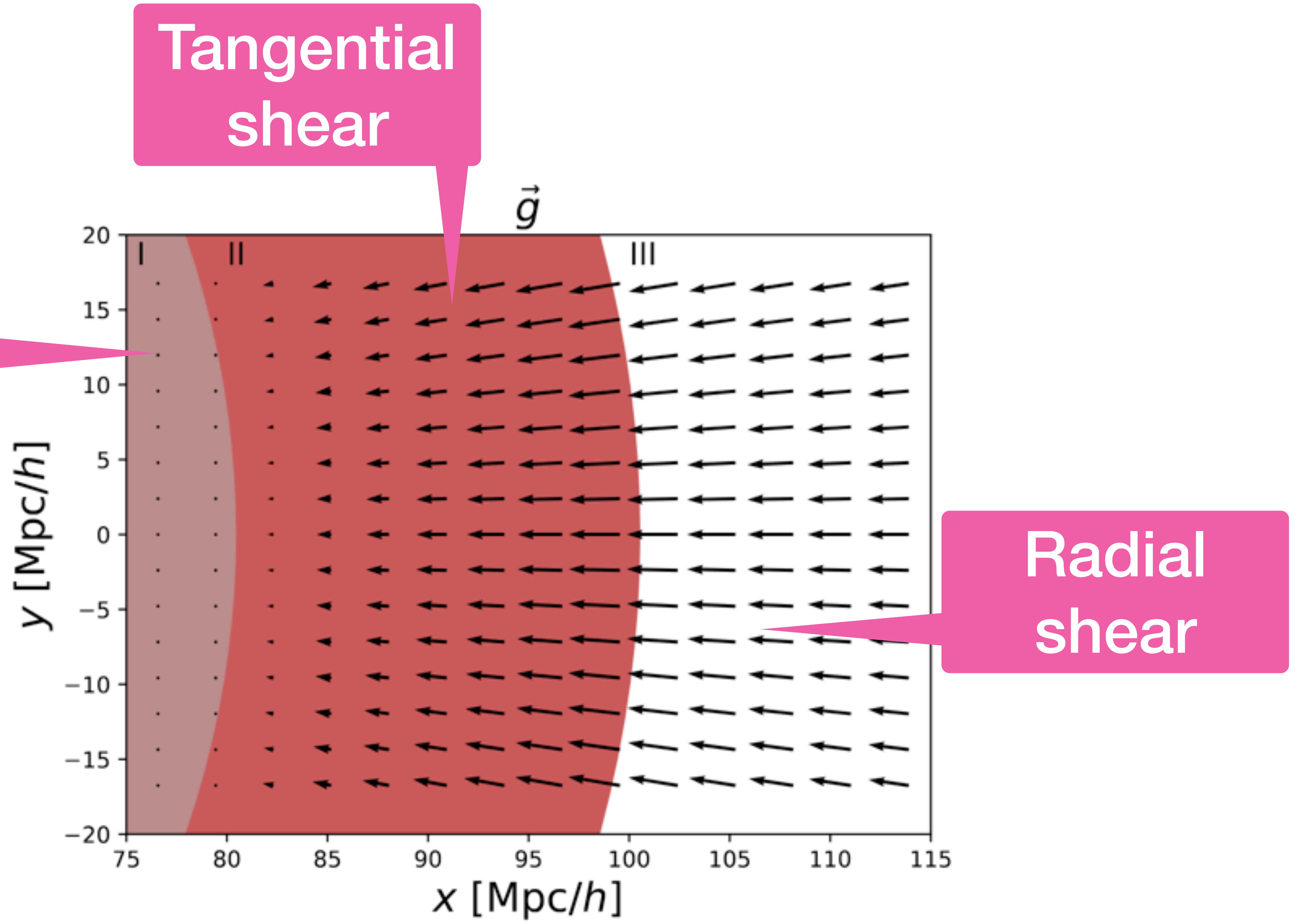


Intrinsic alignment: Tidal field causes radial shear in nearby galaxies, a contamination in weak lensing

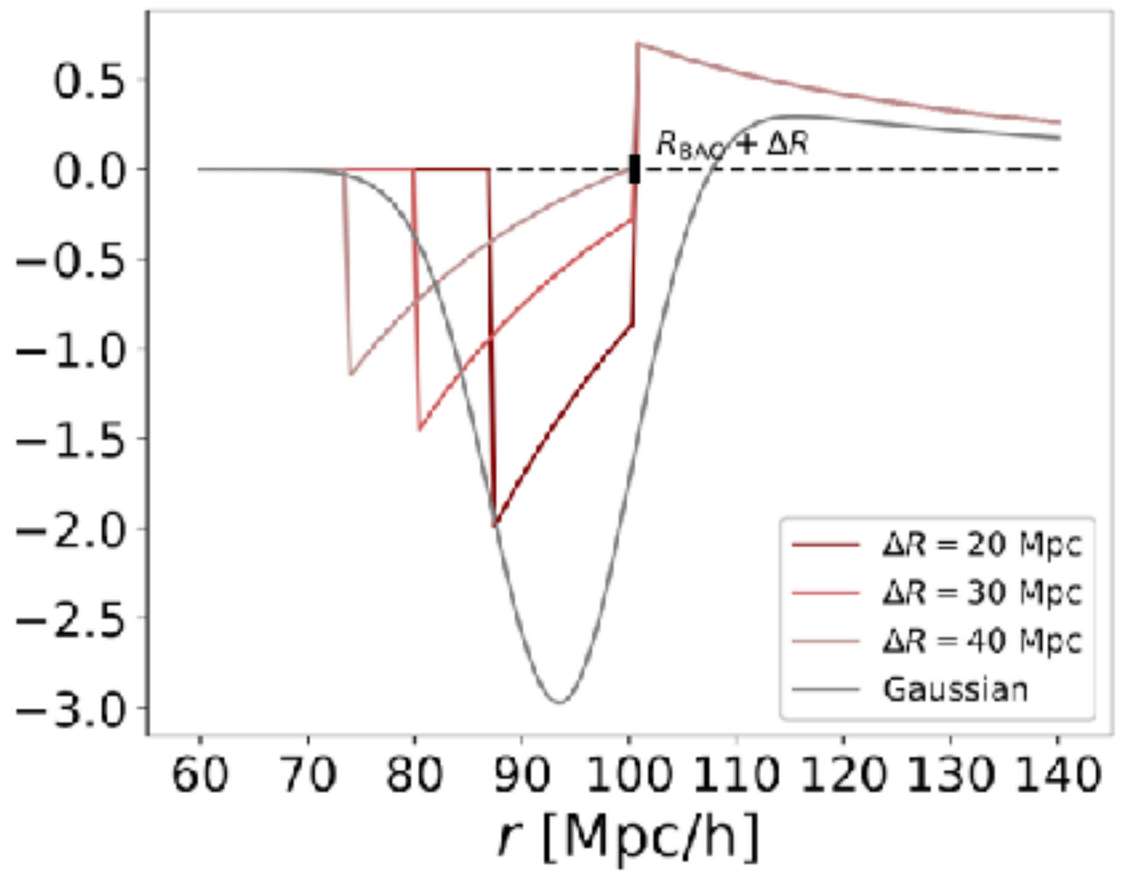
Tidal effect of the BAO galaxies

- The presence of the BAO matter is the difference from the no-BAO universe, suffice to consider the tidal effect of the BAO matter





Radial shear



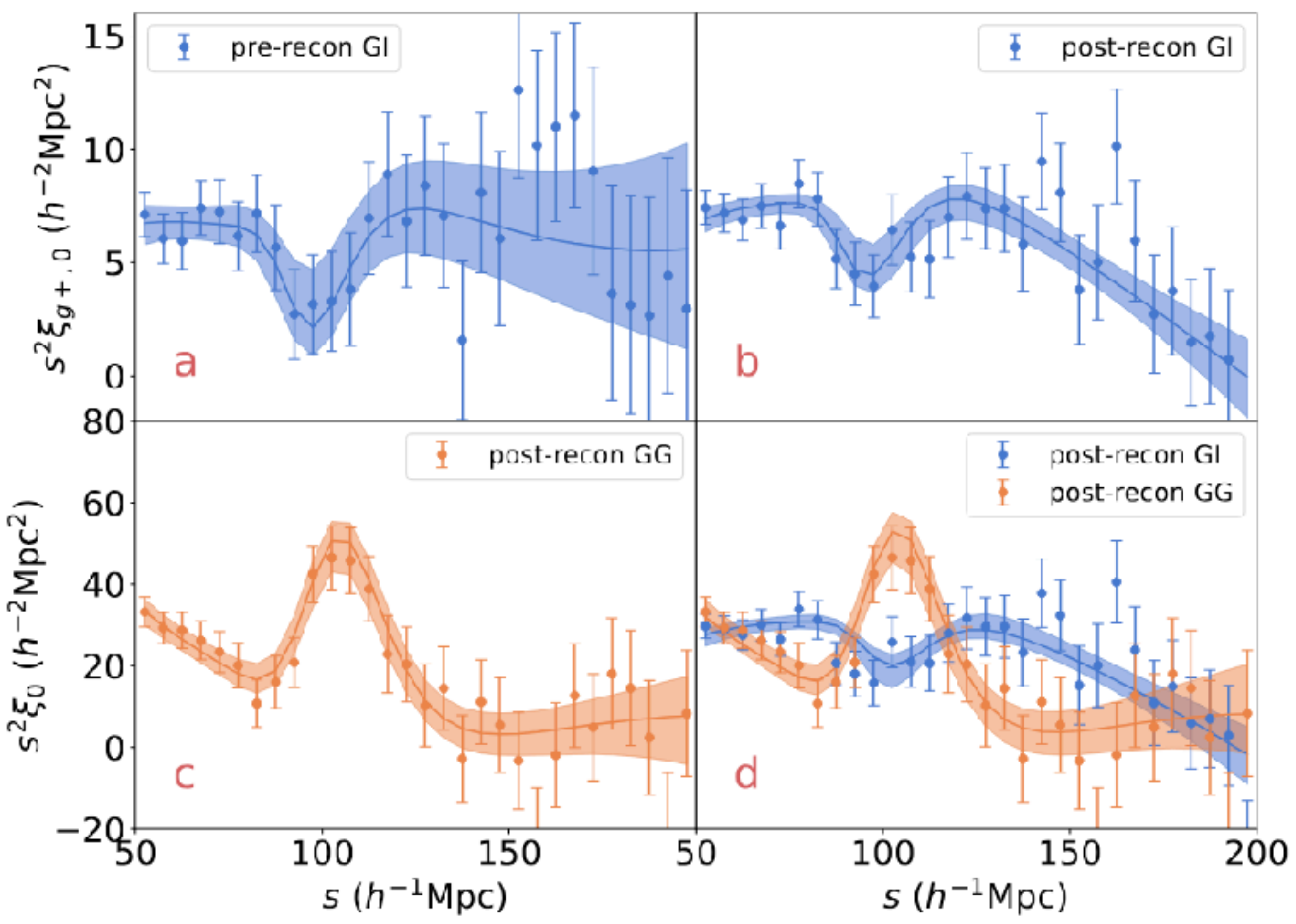
van Dompsele +, 2301.04649

Gravitational acceleration due to BAO galaxies

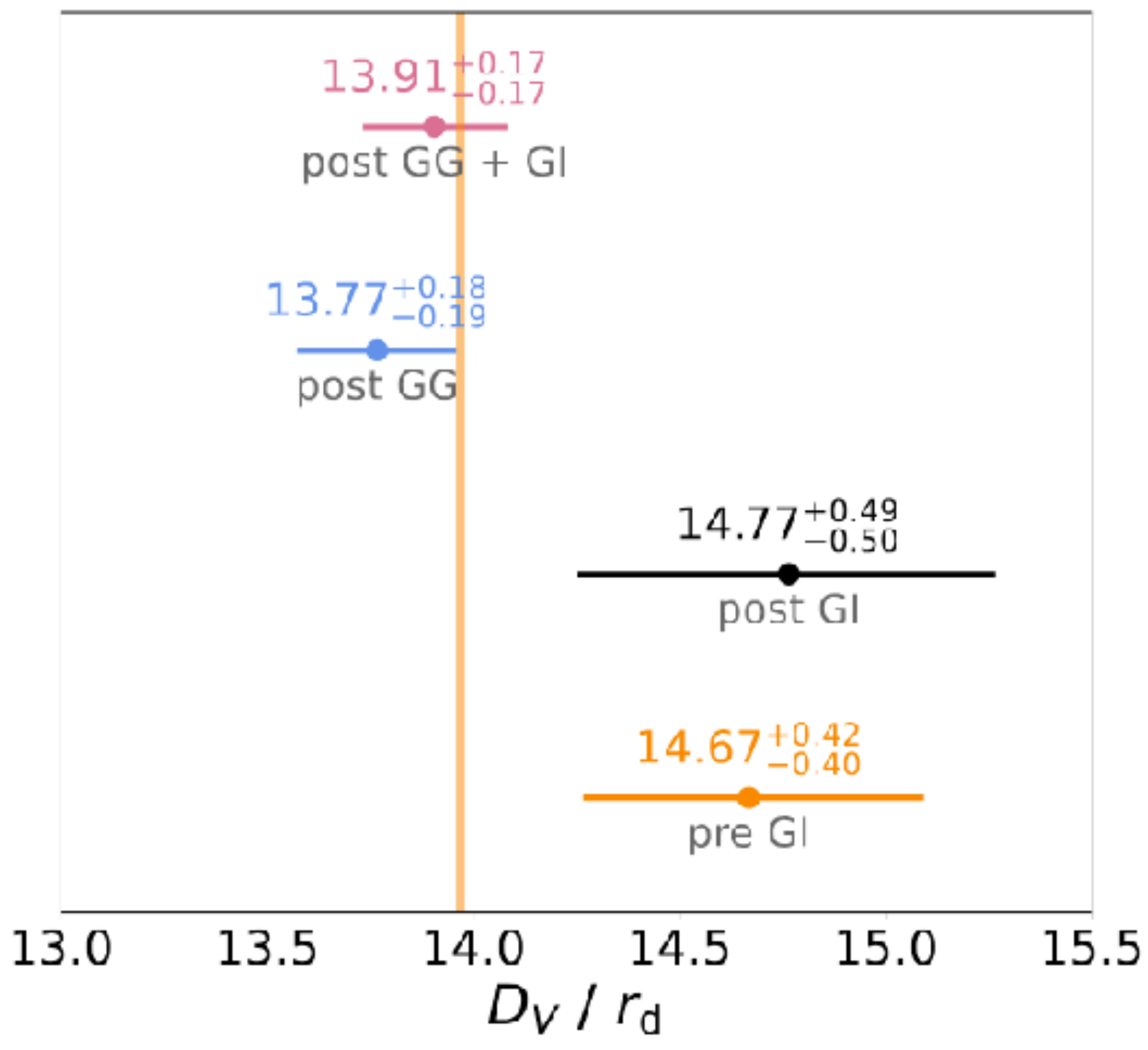
- **Vanish in region I**
- **In region II, radially inward with magnitude increasing with distance from center**
- **Radially inward, with magnitude decreasing with distance in region III**

GI BAO signal in galaxy-ellipticity correlation

- First GI measurement obtained by cross correlating CMASS galaxies (0.43M, 0.43<z<0.7) with DESCaLS ellipticity (cross matching to CMASS gal)



$$\xi_{g+,0}(r) = \frac{2}{3}\widetilde{C}_1 b_g \int_0^\infty \frac{k^2 dk}{2\pi^2} P_{\delta\delta}(k) j_2(kr)$$



More than 3σ detection, but the constraint is ~2σ from GG-only constraint

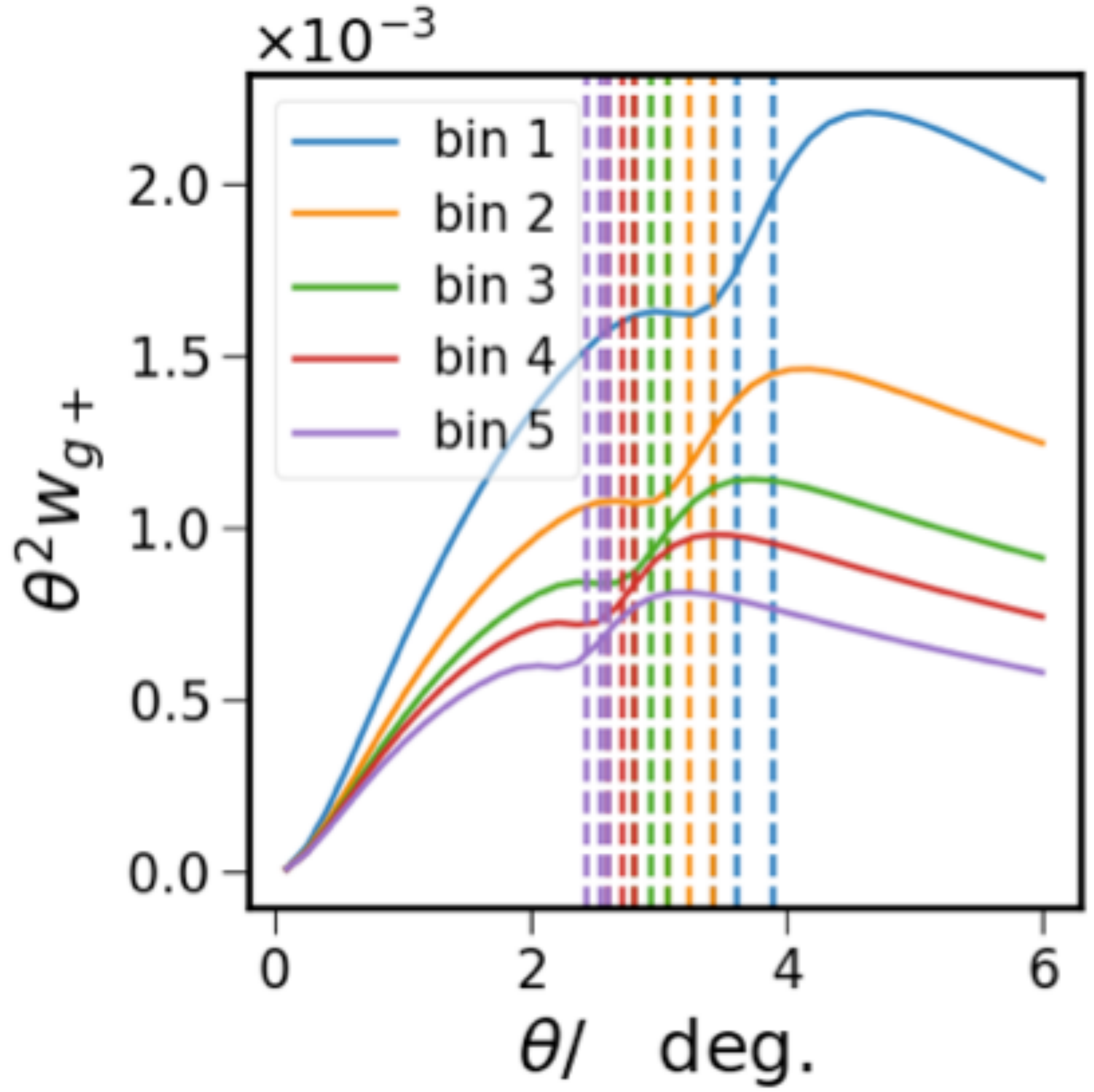
Xu + , Nature Astronomy, 2023

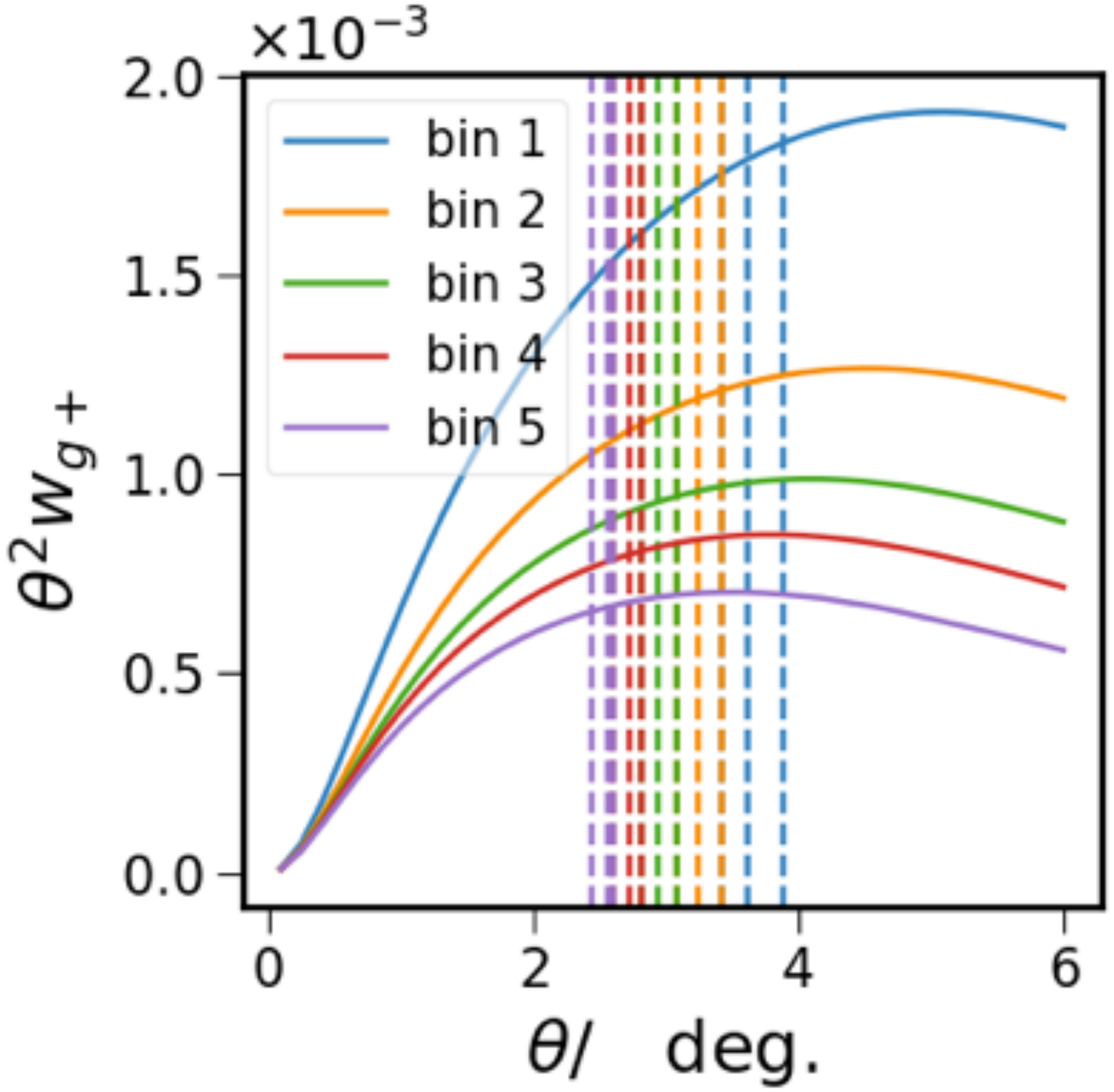
Transverse GI BAO

- With DES data, similar to GG BAO, can only measure transverse GI BAO

$$w_{\rm gt}(\theta) = \int \frac{dk}{2\pi} kP(k)F(k\theta)$$

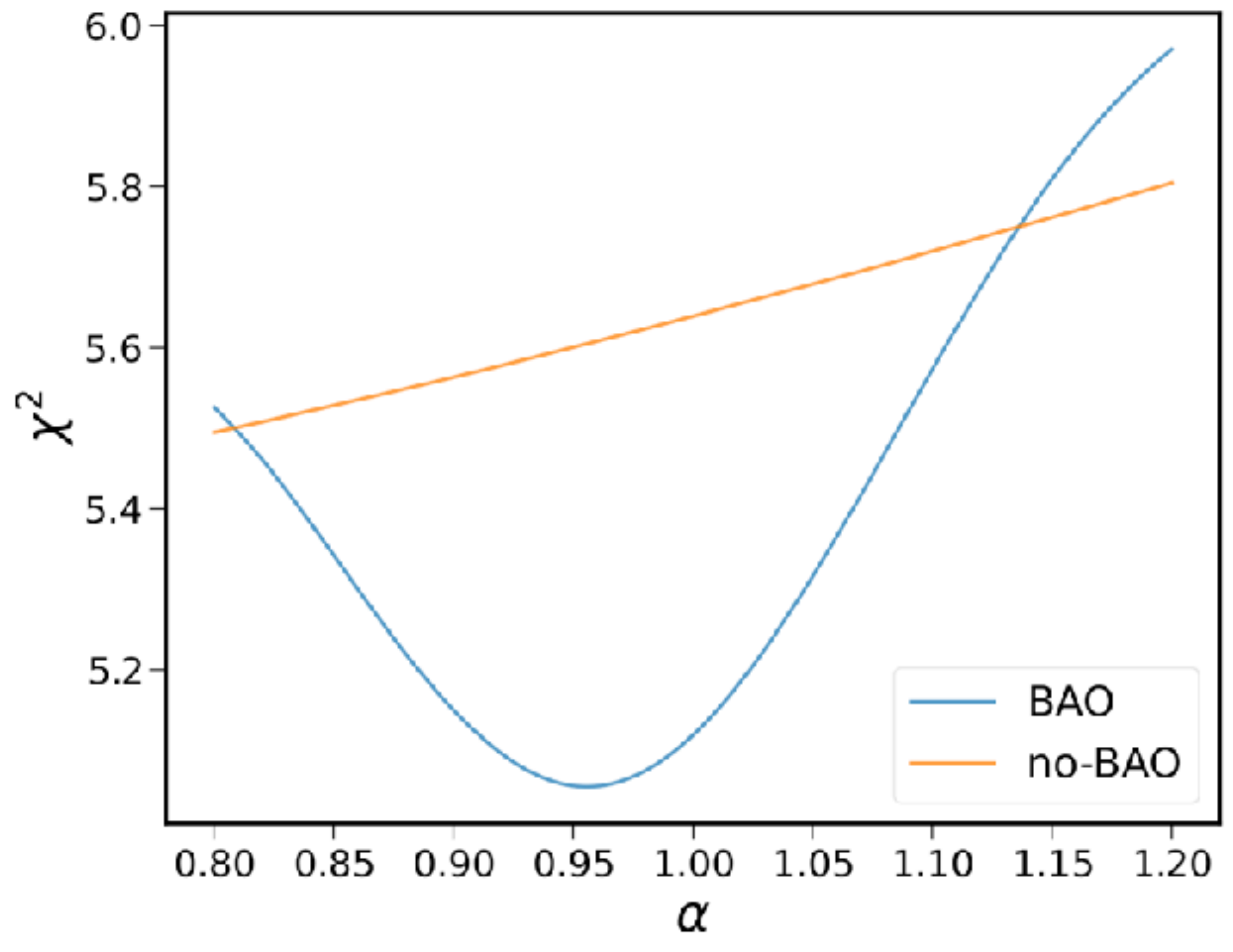
$$F(k\theta) = b_{\rm g} \int d\chi W_{\rm g}(\chi) W_\gamma(\chi) C_1' D(\chi) J_2(k\theta\chi)$$



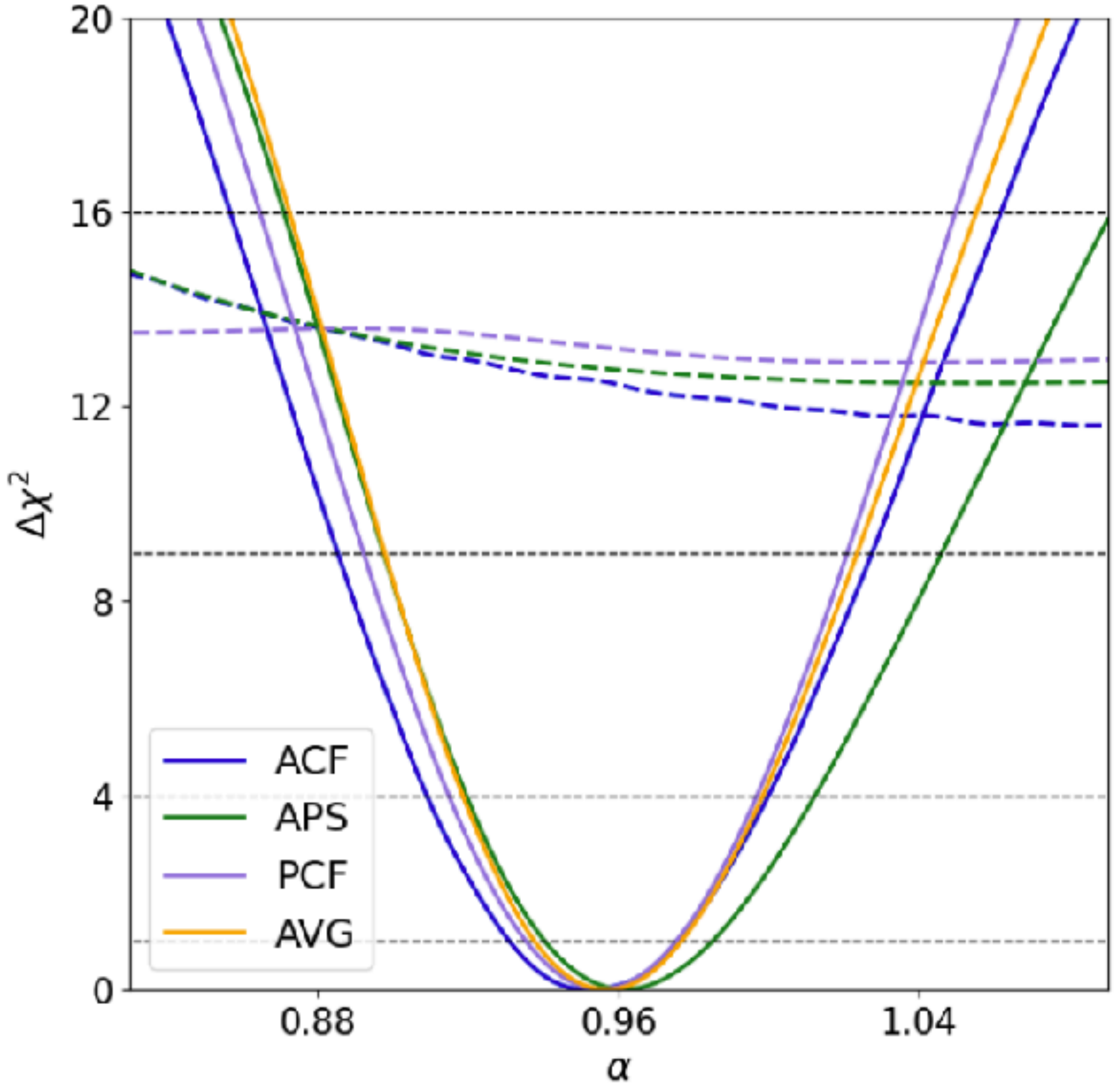


GI BAO from DES data

- DES Y6 BAO galaxy sample (0.6<z<0.9) cross correlating with the cross-matched Y3 shear sample

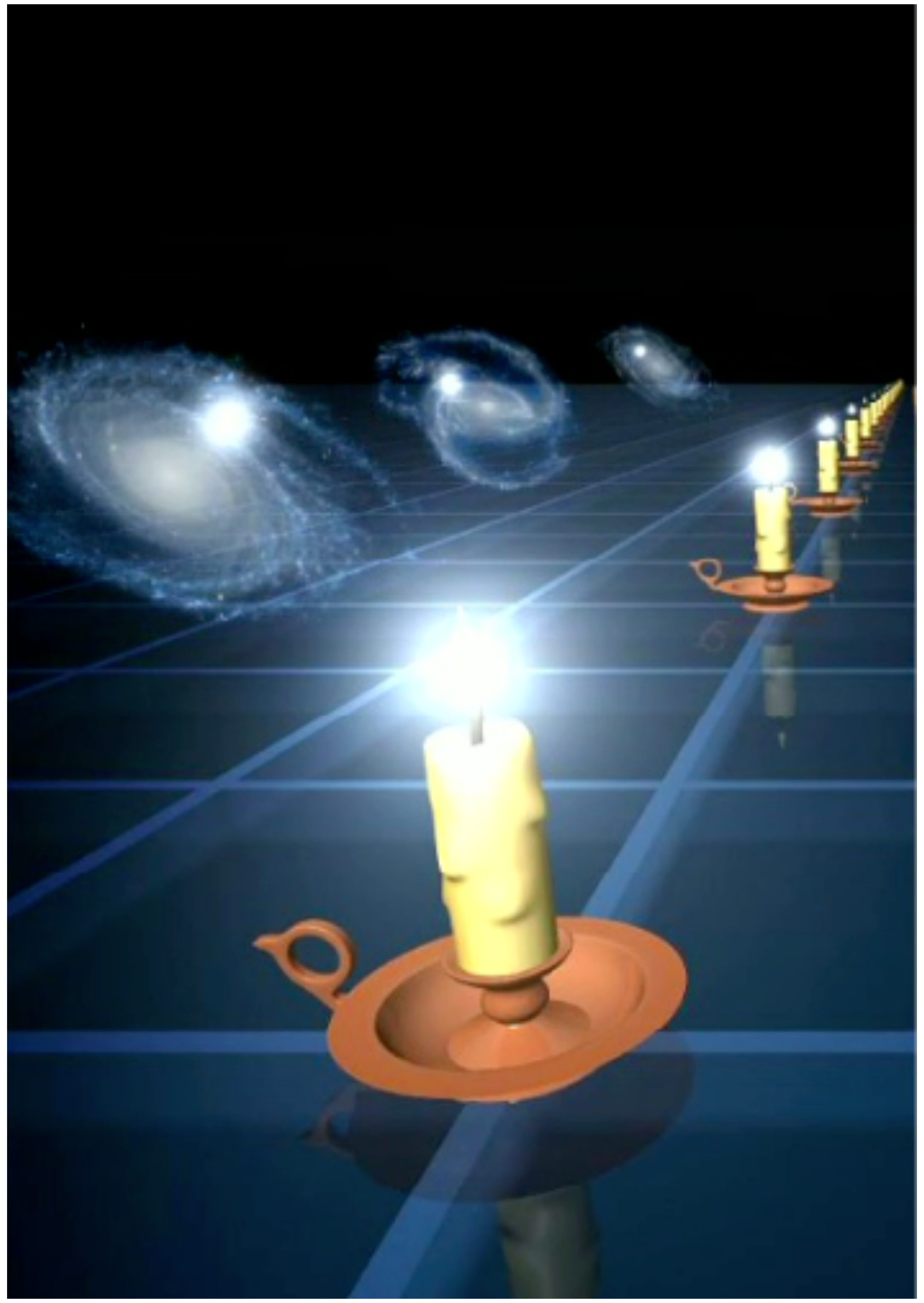


KCC +, in preparation

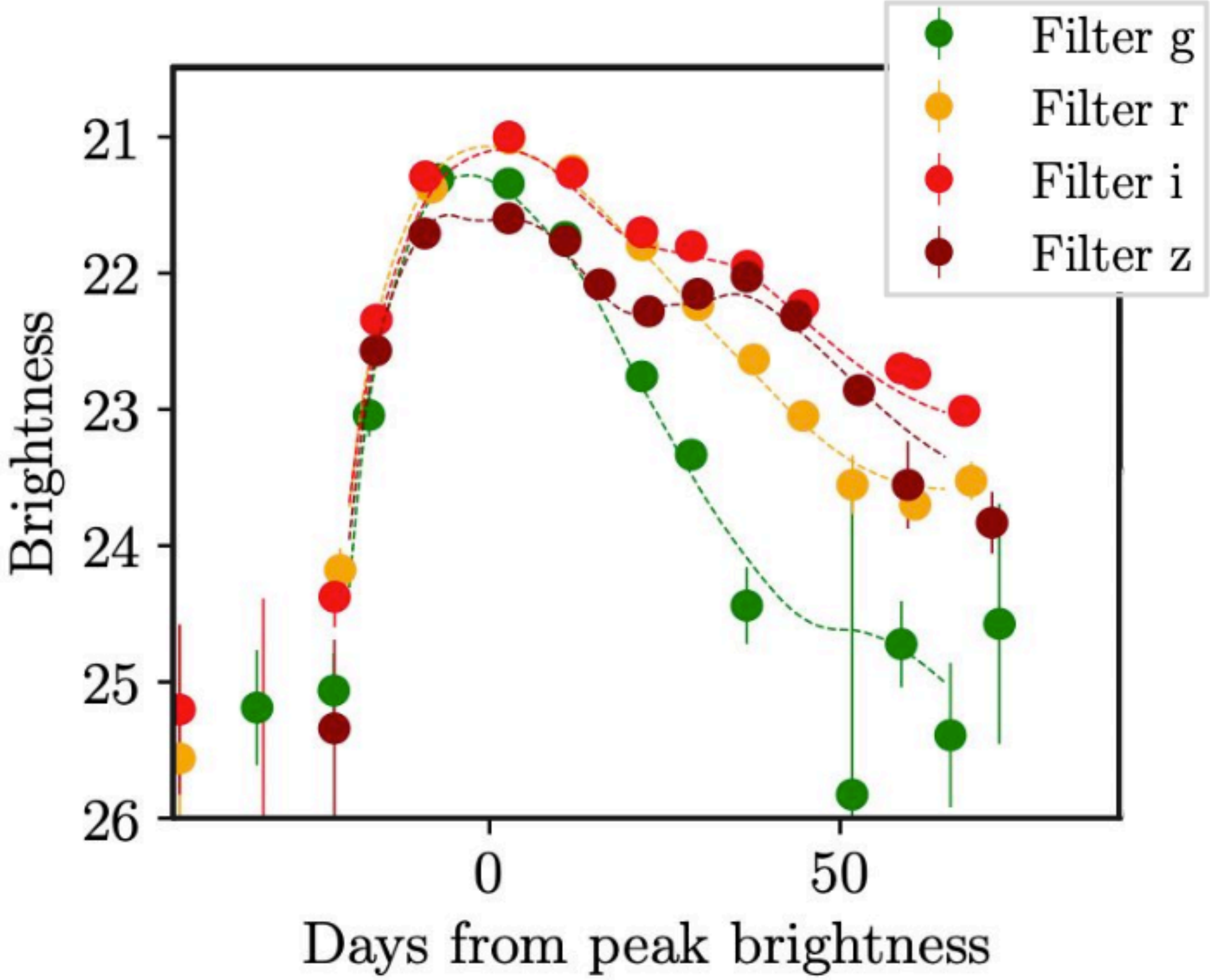


DES Y6 BAO

The GI BAO detection is only ~0.5σ,
but it is consistent with GG BAO measurement



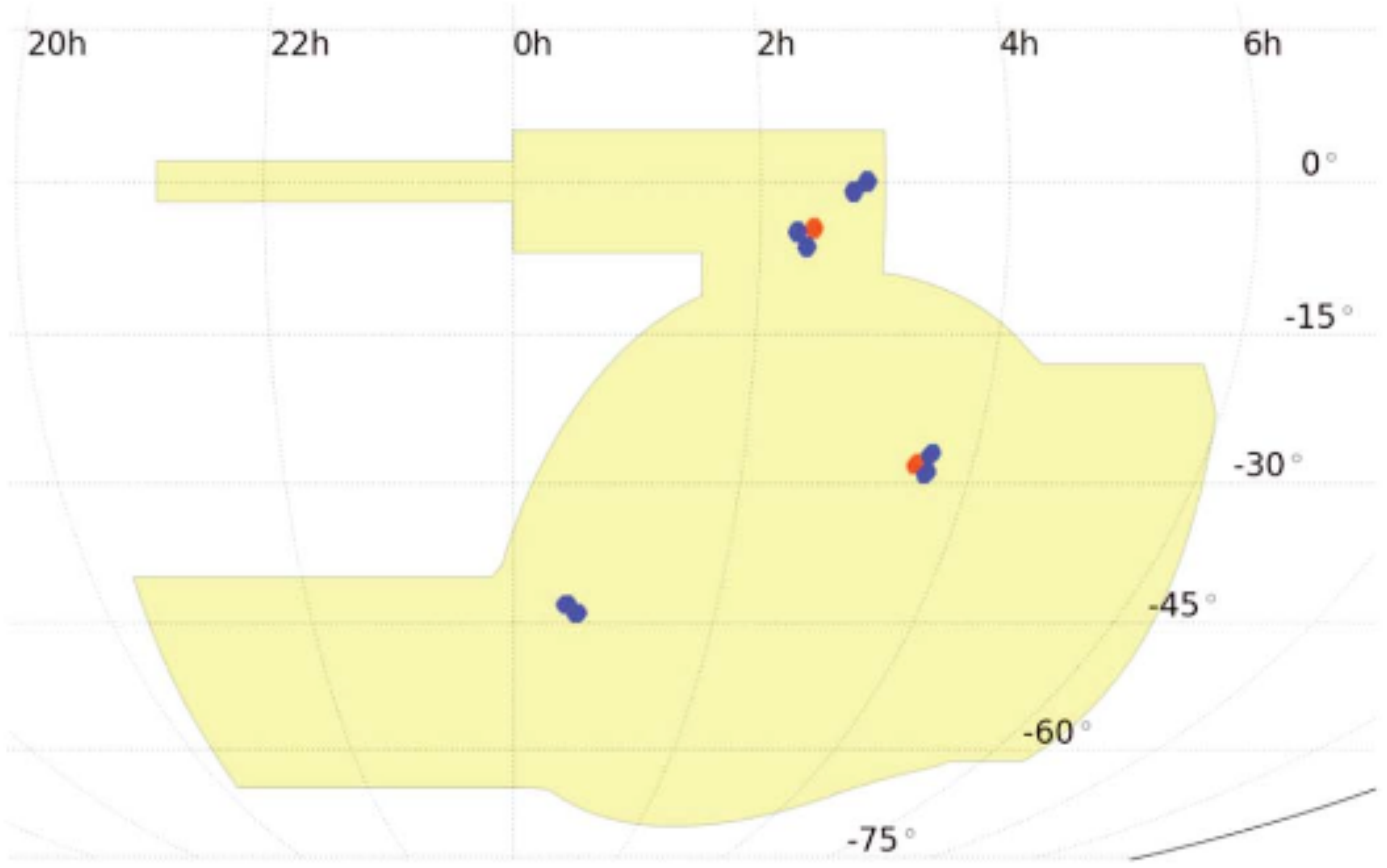
Y5 SNe

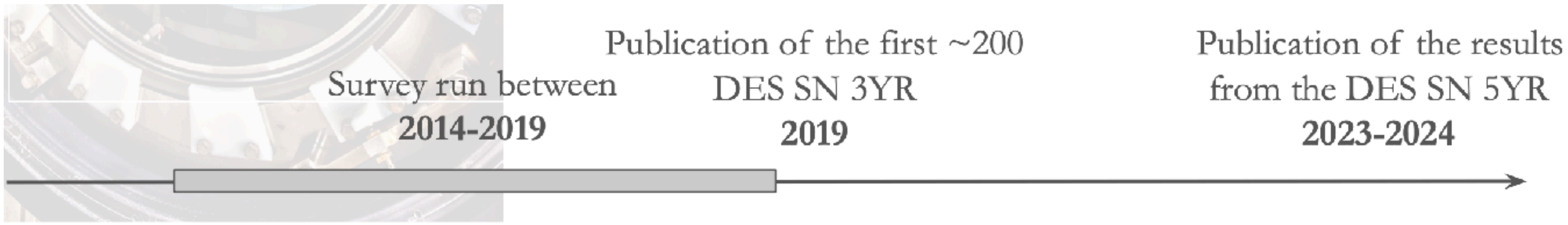


Filter g
Filter r
Filter i
Filter z
Brightness
21
22
23
24
25
26
0
50
Days from peak brightness

DES SNe observations

- Observed in 5 Yr period
- 10 fields, 8 shallow, 2 deep, covering 27 sq. deg
- Detection of transients using Difference Image Analysis
- Spectroscopic follow-up of the host in OzDES survey





DES SNe workflow

The DES-5YR analysis keys:

1. **Building the Data Set**: find SNe, **measure** and **calibrate** their **photometry**, find the SN **host galaxy**;
2. **Simulating** DES-SN samples that look like the *observed* sample;
3. Classification to get a **pure** sample of SNe Ia
4. Modelling SN **dust extinction, SN progenitor physics**
5. **Error budget: Systematic uncertainties > Statistical uncertainties**

$$\mu_{\rm obs} = m_x - M + [\text{calib.}]$$

- $\mu_{\rm obs}$: Calibrated distance modulus
- m_x: Measured magnitude
- M: SN intrinsic mag. (degenerate with H_0)
- [calib.]: Depends on SN color, stretch, host galaxy mass, sample selection, (calib. w simulations)

DES-SN5YR analysis overview

Data:
- Calibration (Burke et al. 2018, Brout et al. 2022, Rykoff et al. 2023)
- SN photometry (Brout et al. 2019, Sanchez et al. 2024)
- SN spectroscopy (Smith et al. 2020a)
- DCR and chrom (Lasker et al. 2018, Lee&Acevedo et al. 2023)
- Host galaxy redshifts and properties (Lidman et al. 2020, Carr et al. 2021, Wiseman et al. 2020/2021, Kelsey et al. 2023)

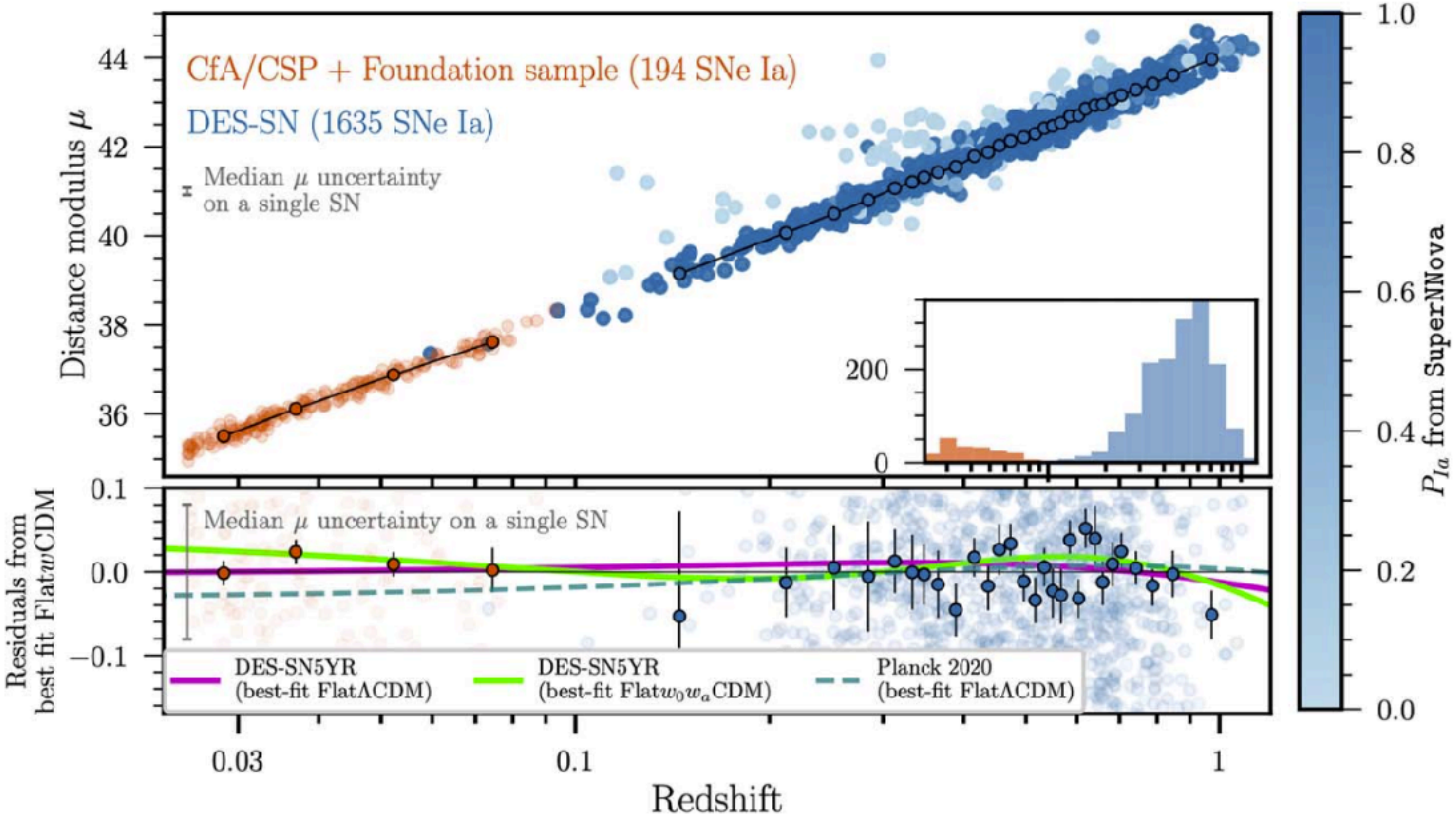
Simulations:
- Survey selection effects (Kessler et al. 2019a, Vincenzi et al. 2020)
- SN Ia intrinsic and dust properties (Brout&Scolnic 2021, Popovic et al. 2021a/b, Wiseman et al. 2022) and rates (Wiseman et al. 2021)
- Contamination (Vincenzi et al. 2019/2020, Kessler et al. 2019b)

Analysis:
Pipeline and Overview (Hinton et al. 2020, Vincenzi et al. 2024)
- Light-curve fitting (Taylor et al. 2023)
- SN classification (Möller & de Boissière 2020, Qu et al. 2021, Vincenzi et al. 2021, Moller et al. 2022)
- "BEAMS" and bias corrections (Kessler & Scolnic 2017), unbinning the SN Hubble diagram (Brout et al. 2020, Kessler et al. 2023)
- Effects of host galaxy mismatch (Qu et al. 2023)
- Cosmological contour validation (Armstrong et al. 2023)

Cosmological results: DES Collaboration 2024
Testing non-standard cosmological models (Camilleri et al. 2024)

5 Yr SNe sample

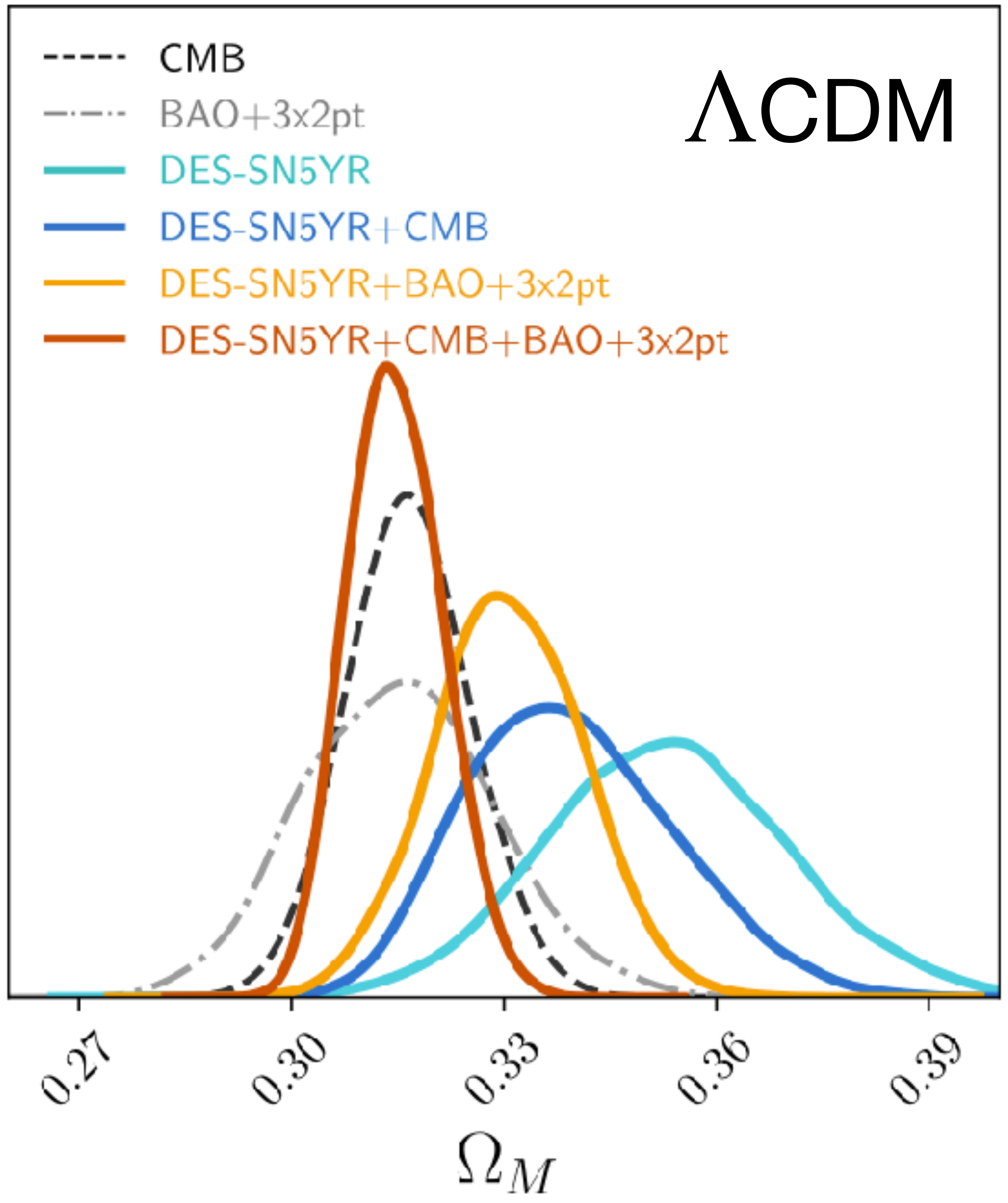
- Classified as SNe Ia based on photometry info using machine-learning method
- Host galaxy redshift confirmed spectroscopically
- 1635 DES SNe in 0.10< z <1.13, largest and deepest high-z SN sample from a single telescope ever compiled
- Combine with 194 SNe Ia at low z, 0.025<z<0.10 from external catalogs



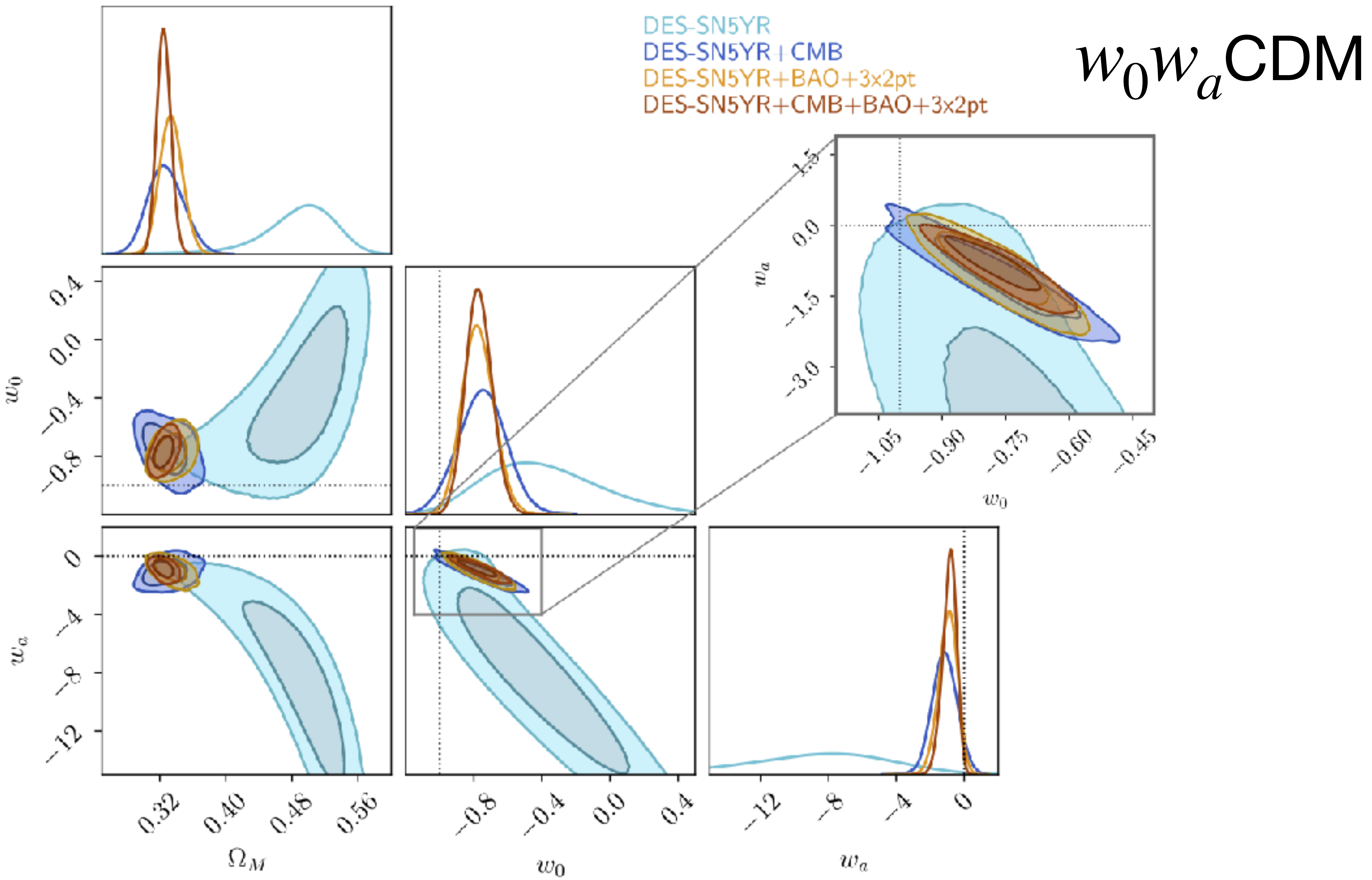
DES collaboration, arXiv:2401.02929

DES SNe constraint

Ω_m value reflects tension btw DES SNe other datasets in ΛCDM

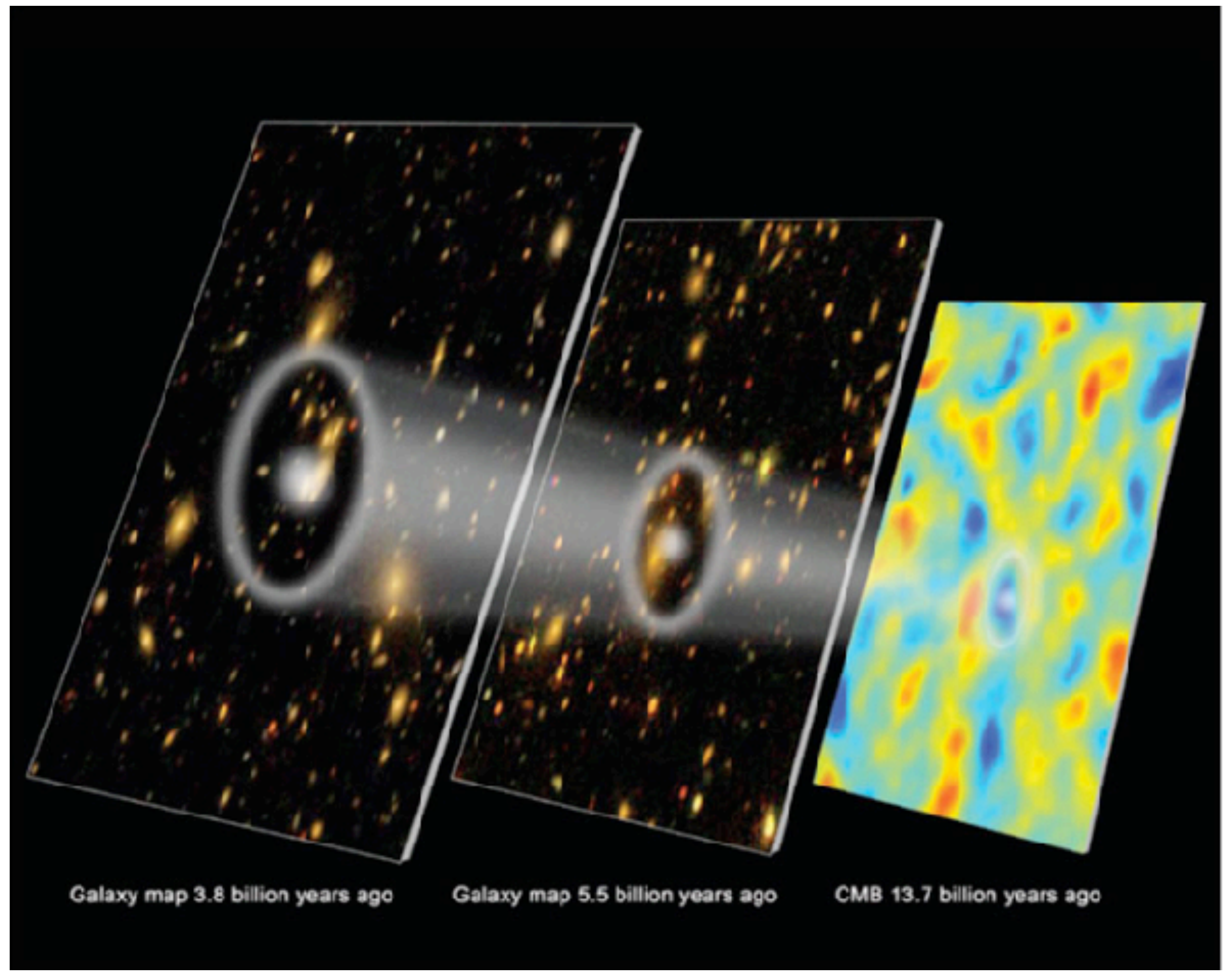


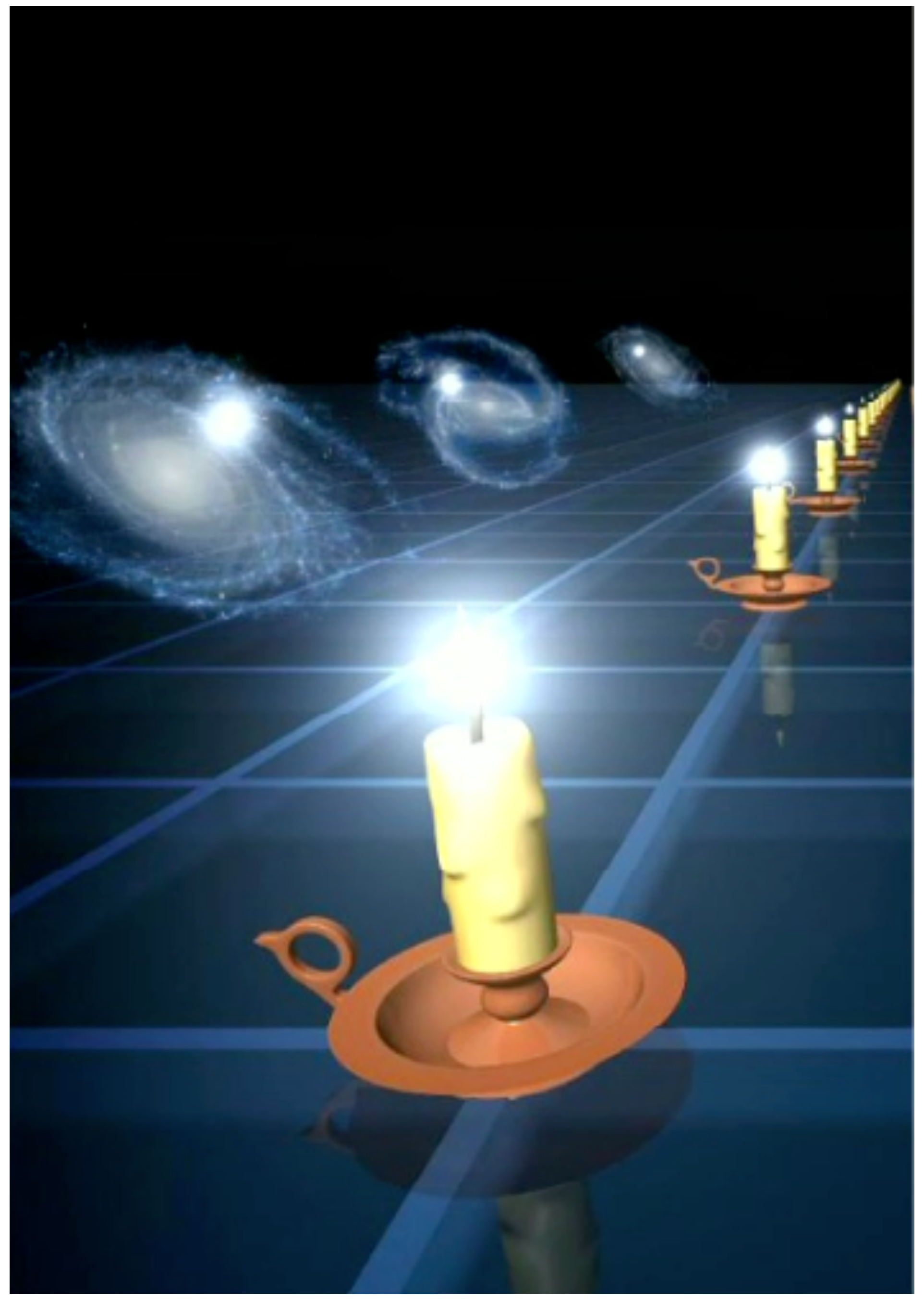
DES SNe favors evolving DE, but the constraint is weak



DES collaboration, arXiv:2401.02929

Joint Y6 BAO & Y5 SNe analysis





arXiv:2503.06712

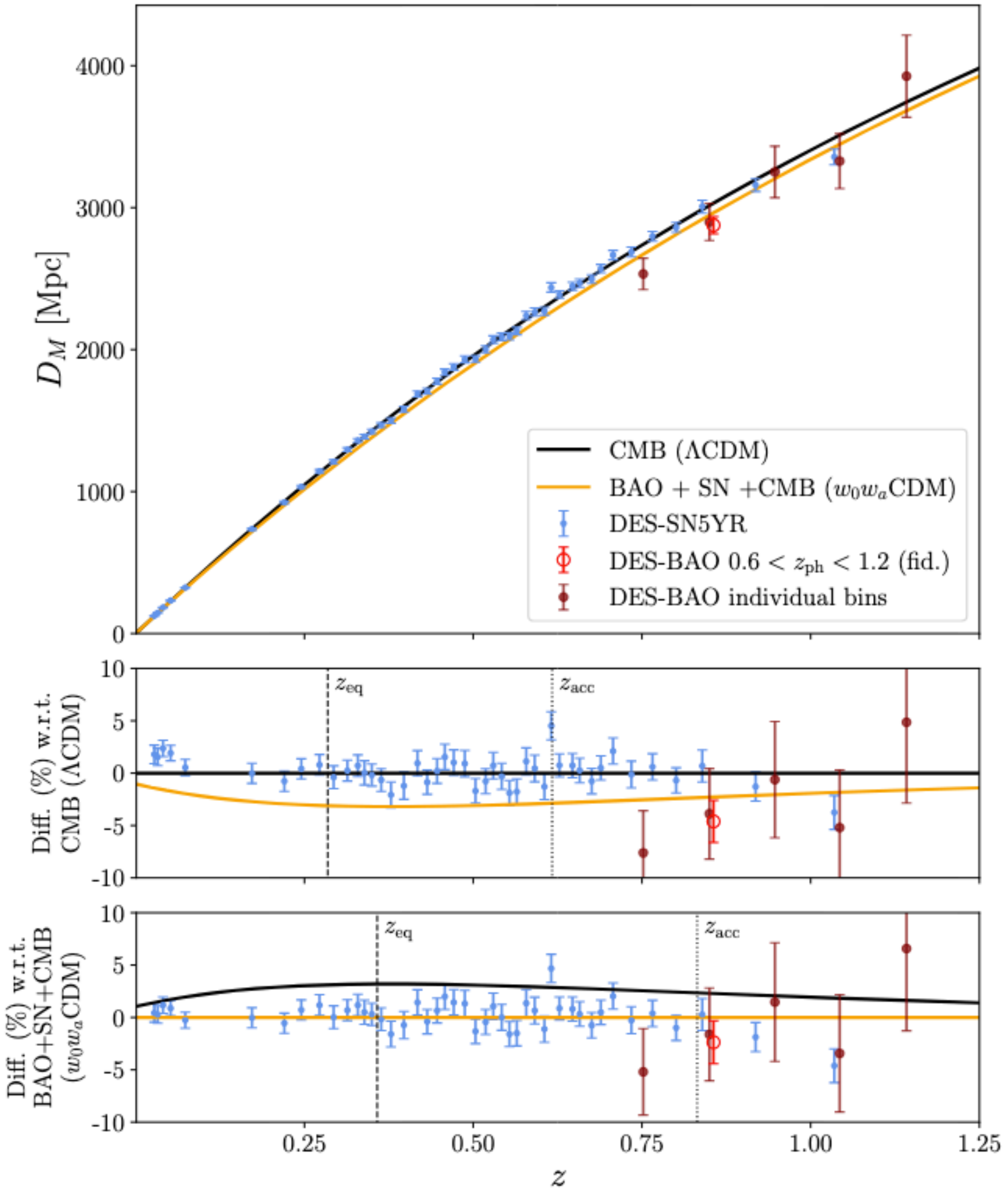
See also Notari +, arXiv: 2411.11685

How much cosmological constraint can we get from the DES BAO and SNe?

- Can we get a DES-only constraint?
- Are BAO and SNe consistent with each other? If so, in what model?
- How much constraint from these probes and their combination with others such as CMB?

DES BAO + SNe data

- DES BAO, 5 tomographic bin data from z=0.6 to 1.2, 17M galaxies
- 1829 SNe: 1635 DES SNe + 194 low-z SNe from external samples
- Complementary redshift range

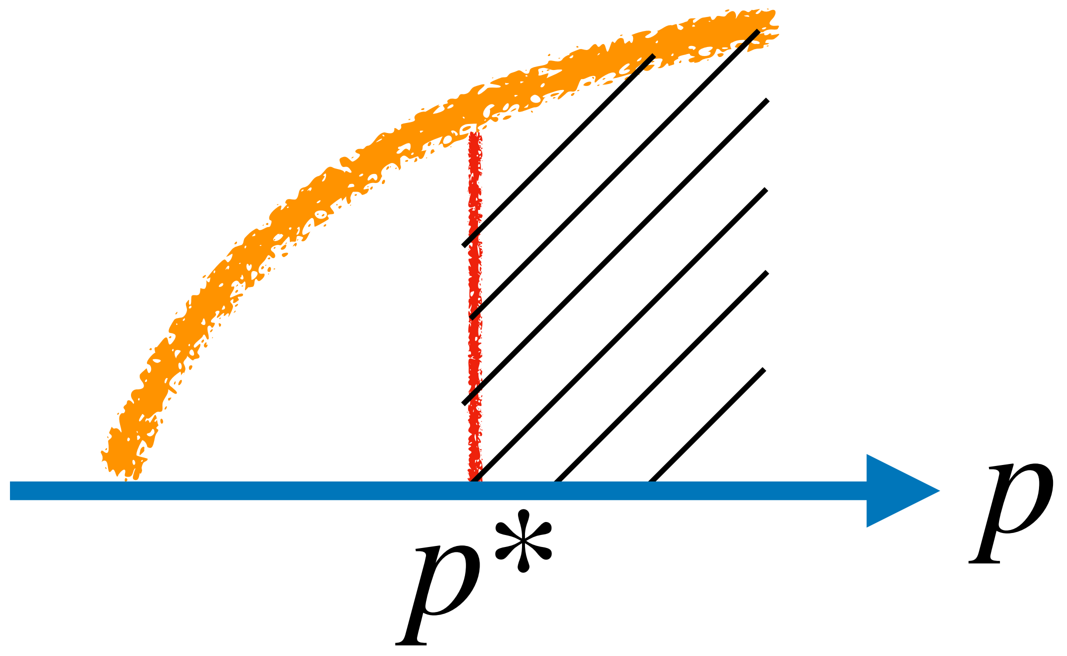


External datasets

- Planck CMB, temperature and polarization
- Angular scale of the acoustic peak θ_*
- Comoving scale of the acoustic peak $r_{\rm d}$
- Age of the universe from globular clusters
- Big Bang Neosynthesis on $\Omega_{\rm b}h^2$

Tension metrics

- Compute how much probability mass that the new model is favored relative to the reference one



$$\Delta(D, M) \equiv \int_{P(\mathbf{p} \mid D,M) > P(\mathbf{p}^* \mid D,M)} P(\mathbf{p} \mid D, M) \mathrm{d}\mathbf{p}$$

Phrase the results in terms of sigma as if it is Gaussian distributed

	Deviations from ΛCDM (σ)		
Dataset	$k\Lambda$CDM	wCDM	w_0w_aCDM
BAO + SN + BBN	1.4	1.4	1.8
BAO + SN + BBN + t_U	–	–	2.0 (2.7)
BAO + SN + $\theta_\star$	2.5	2.7	2.3
BAO + SN + $\theta_\star$ + BBN	2.8	3.1	2.8
BAO + SN + $\theta_\star$ + BBN + t_U	–	–	2.9 (2.8)
SN	1.3	1.6	2.0
CMB	3.0	1.7	2.5
SN + CMB	2.9	2.0	2.2
BAO + CMB	0.6	2.8	3.4
BAO + SN + CMB	1.2	1.8	**3.2**

Consistency of the datasets

- Check if the datasets are consistent with each other under a given model

The joint probability distribution of two independent datasets

$$P(\mathbf{p}_1, \mathbf{p}_2 | d_1, d_2) = P_1(\mathbf{p}_1 | d_1) P_2(\mathbf{p}_2 | d_2)$$

$$\Delta \mathbf{p} \equiv \mathbf{p}_1 - \mathbf{p}_2$$

$$P(\Delta \mathbf{p}) = \int P_1(\mathbf{p}) P_2(\mathbf{p} - \Delta \mathbf{p}) d\mathbf{p}$$

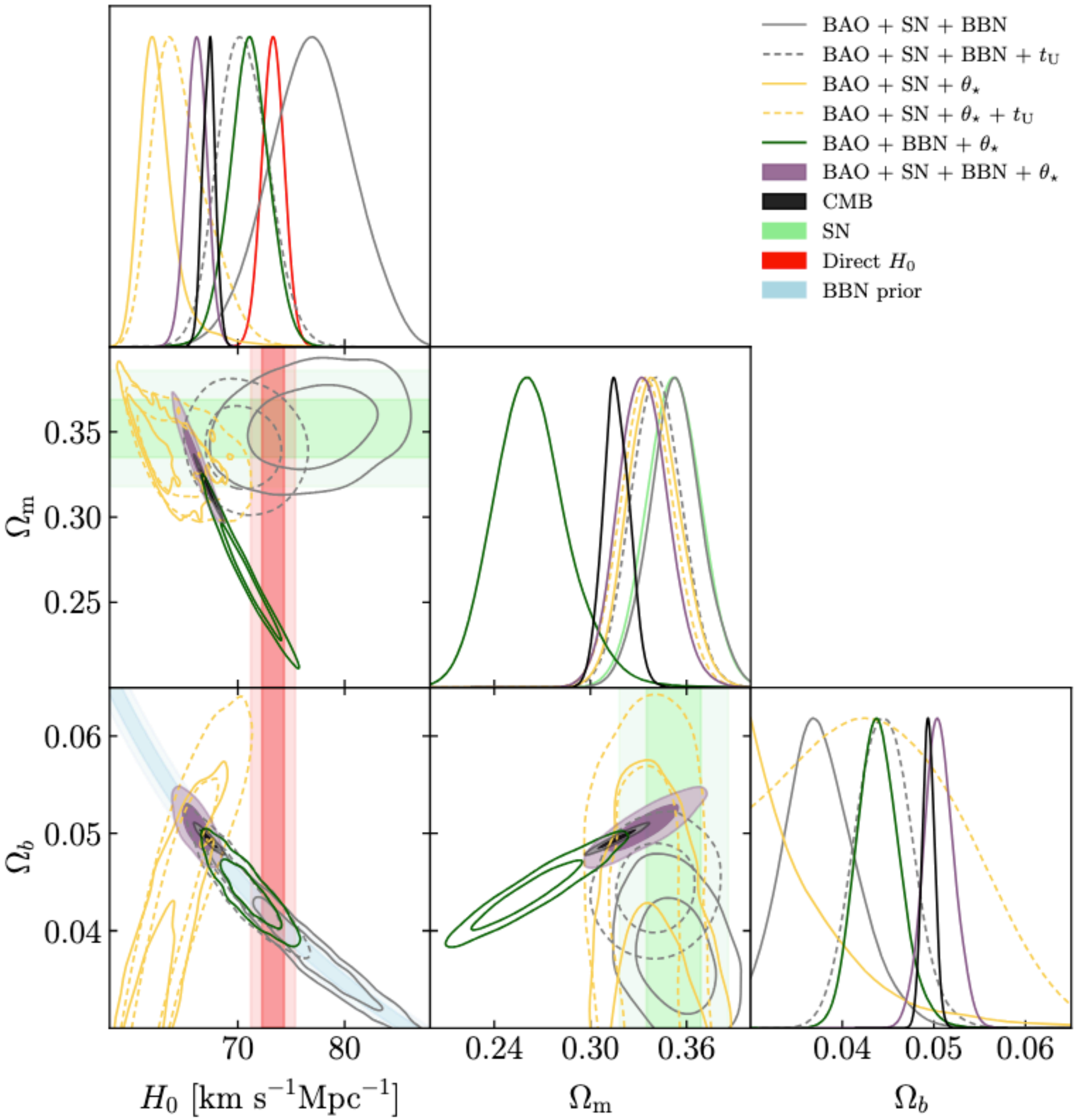
No significant tension among datasets

$$\Delta \equiv \int_{P(\Delta \mathbf{p}) > P(0)} P(\Delta \mathbf{p})\, d\Delta \mathbf{p}$$

	Tension (σ)				
Datasets	ΛCDM	$k\Lambda$CDM	wCDM	w_0w_aCDM	$\nu\Lambda$CDM
BAO vs SN	0.5	0.0	0.0	0.3	0.2
CMB vs SN	1.7	1.5	1.3	1.1	1.2
CMB vs BAO	2.0	3.2	0.6	0.1	2.0
SN vs BAO + $\theta_\star$	2.4	-	-	-	-
CMB vs BAO + SN + BBN	2.2	3.3	2.2	1.2	-
SN vs BAO + BBN	0.4	-	-	-	-
SN vs BAO + BBN + $\theta_\star$	2.9	0.5	0.0	0.9	2.6
BAO + CMB vs SN	2.1	1.5	2.5	1.6	2.1
CMB vs BAO + SN + BBN + t_U	1.5 (0.8)	-	-	0.9 (0.9)	-

Tension in ΛCDM

- BAO + θ_*: $\Omega_\mathrm{m} = 0.255^{+0.021}_{-0.035}$
- CMB: $\Omega_\mathrm{m} = 0.305^{+0.008}_{-0.009}$
- SNe: $\Omega_\mathrm{m} = 0.353 \pm 0.017$
- These datasets give inconsistent constraints on parameters such as Ω_m



Tension in kCDM

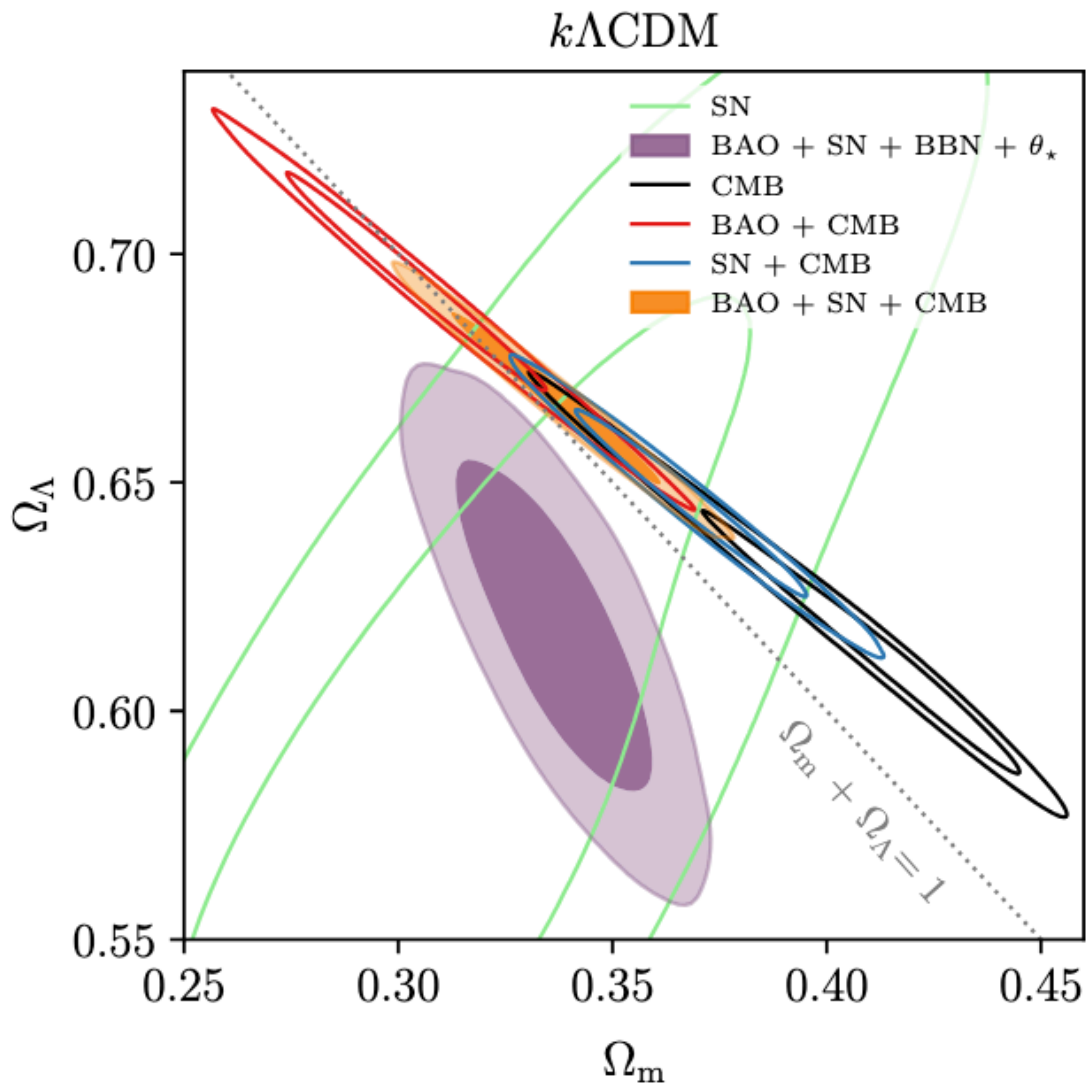
- Curvature model, spatial curvature is allowed

- CMB:
$\Omega_k = -23.6^{+4.2}_{-7.9} \times 10^{-3}$

- BAO + SN + BBN + θ_* :
$\Omega_k = 45^{+15}_{-15} \times 10^{-3}$

- Inconsistent curvature constraint

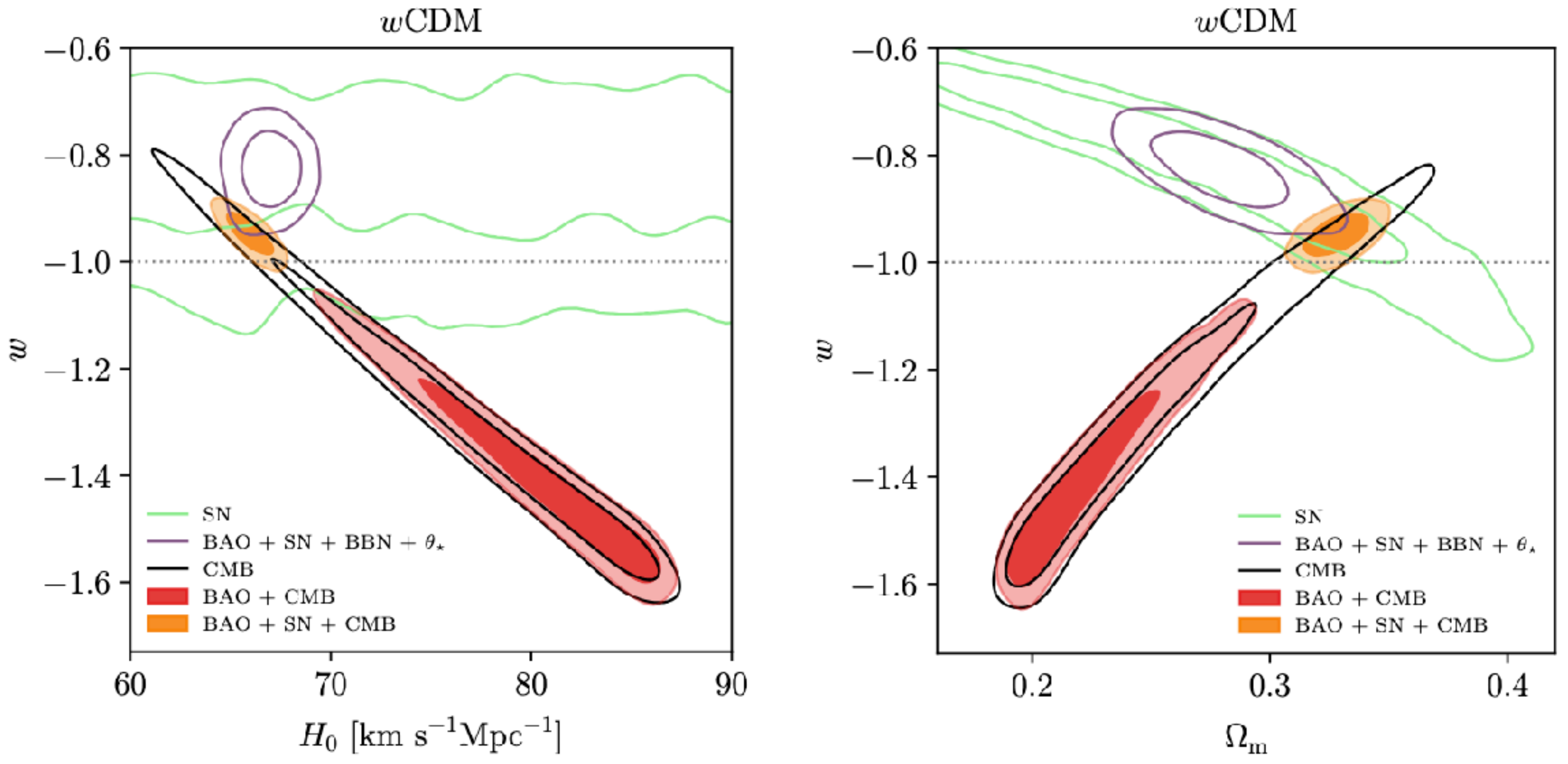
$$\Omega_k = 1 - \Omega_m - \Omega_\Lambda$$



Tension in wCDM

- CMB: weak constraint, $w = -1.32^{+0.12}_{-0.25}$
- SN prefers $w = -0.82^{+0.15}_{-0.11}$
- BAO + SN + θ_*: $w = -0.826^{+0.062}_{-0.047}$
- Inconsistent constraint on H_0 and Ω_m

w for DE is constant, but not necessarily -1



Consistent results in $w_0 w_a$CDM

- Consistent constraint across various dataset combinations

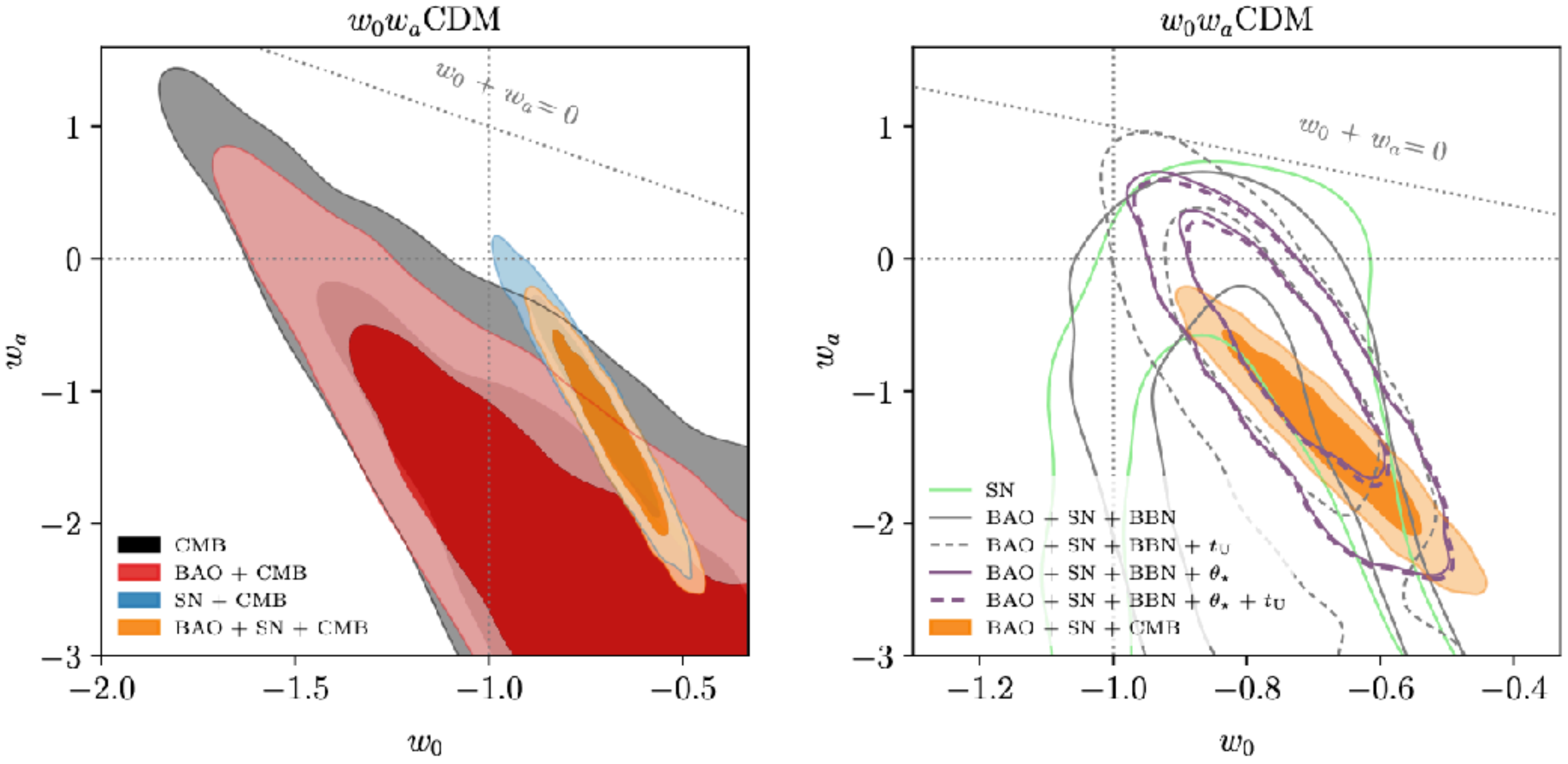
Time evolving DE, parametrized in CPL form

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

$$\left.\begin{aligned} w_0 &= -0.673^{+0.098}_{-0.097} \\ w_a &= -1.37^{+0.51}_{-0.50} \end{aligned}\right\} \text{BAO + SN + CMB}$$

$$\left.\begin{aligned} w_0 &= -0.76 \pm 0.11 \\ w_a &= -0.79^{+0.87}_{-0.67} \end{aligned}\right\} \text{BAO + SN + BBN} + t_U$$

$$\left.\begin{aligned} w_0 &= -0.74^{+0.09}_{-0.10} \\ w_a &= -0.78^{+0.75}_{-0.54} \end{aligned}\right\} \text{BAO + SN + BBN} + \theta_\star + t_U.$$

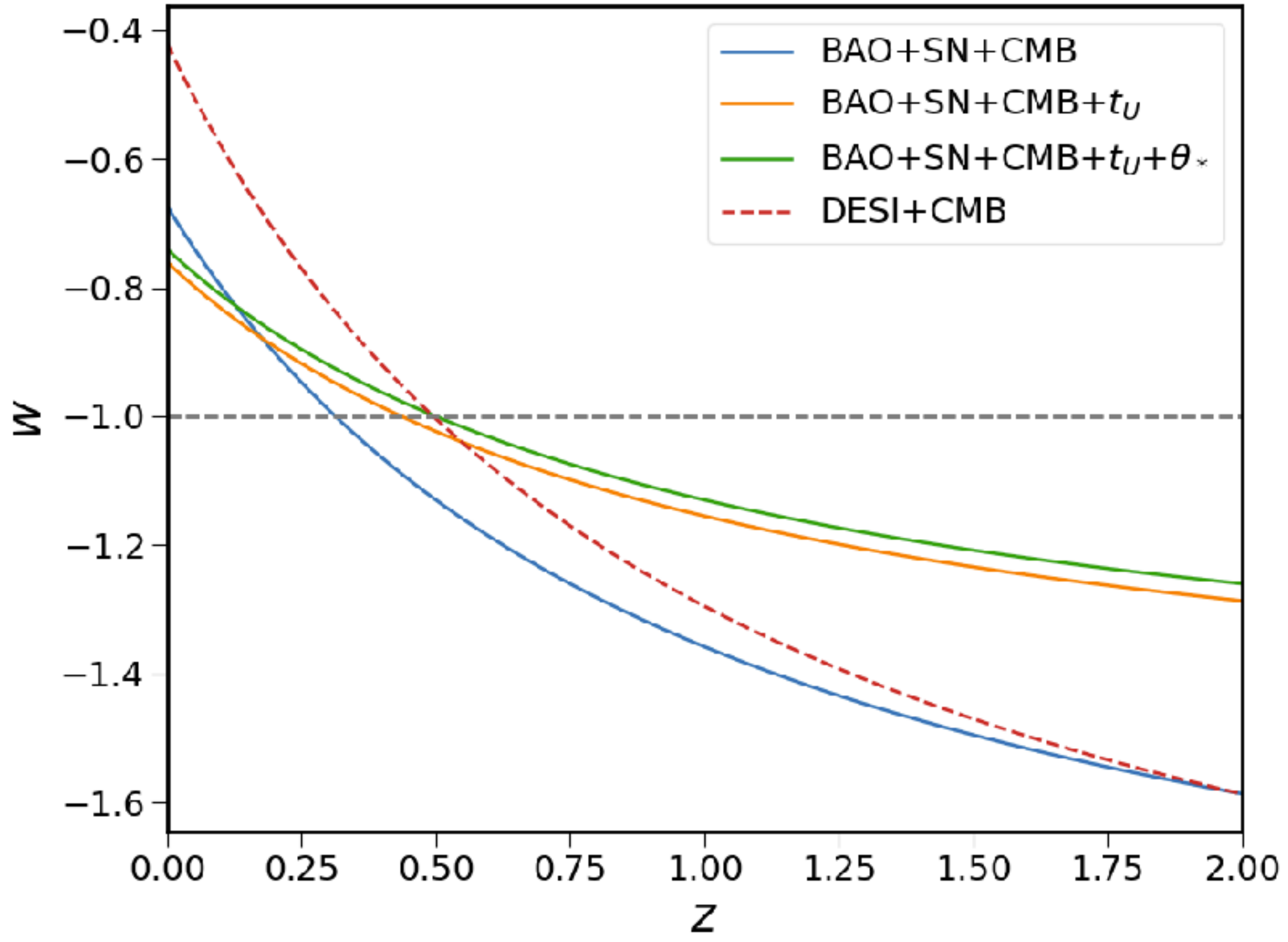


Evidence for time-evolving w

- The best fit indicates phantom crossing at z ~ 0.5, a trend that is in agreement with DESI.

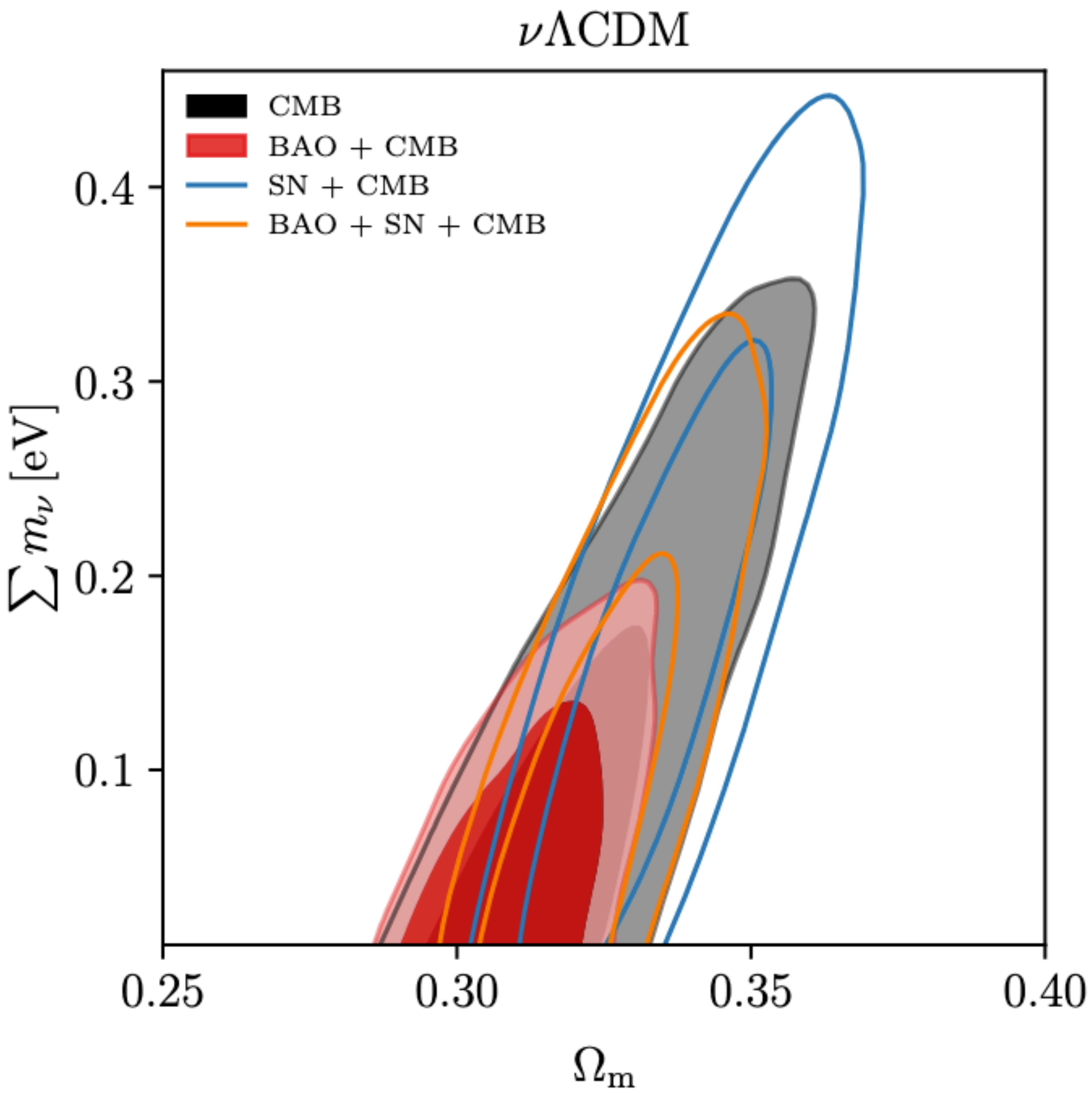
DES BAO and SNe also give evidence for evolving DE

BAO+SN+CMB disfavors ΛCDM model by 3.2σ

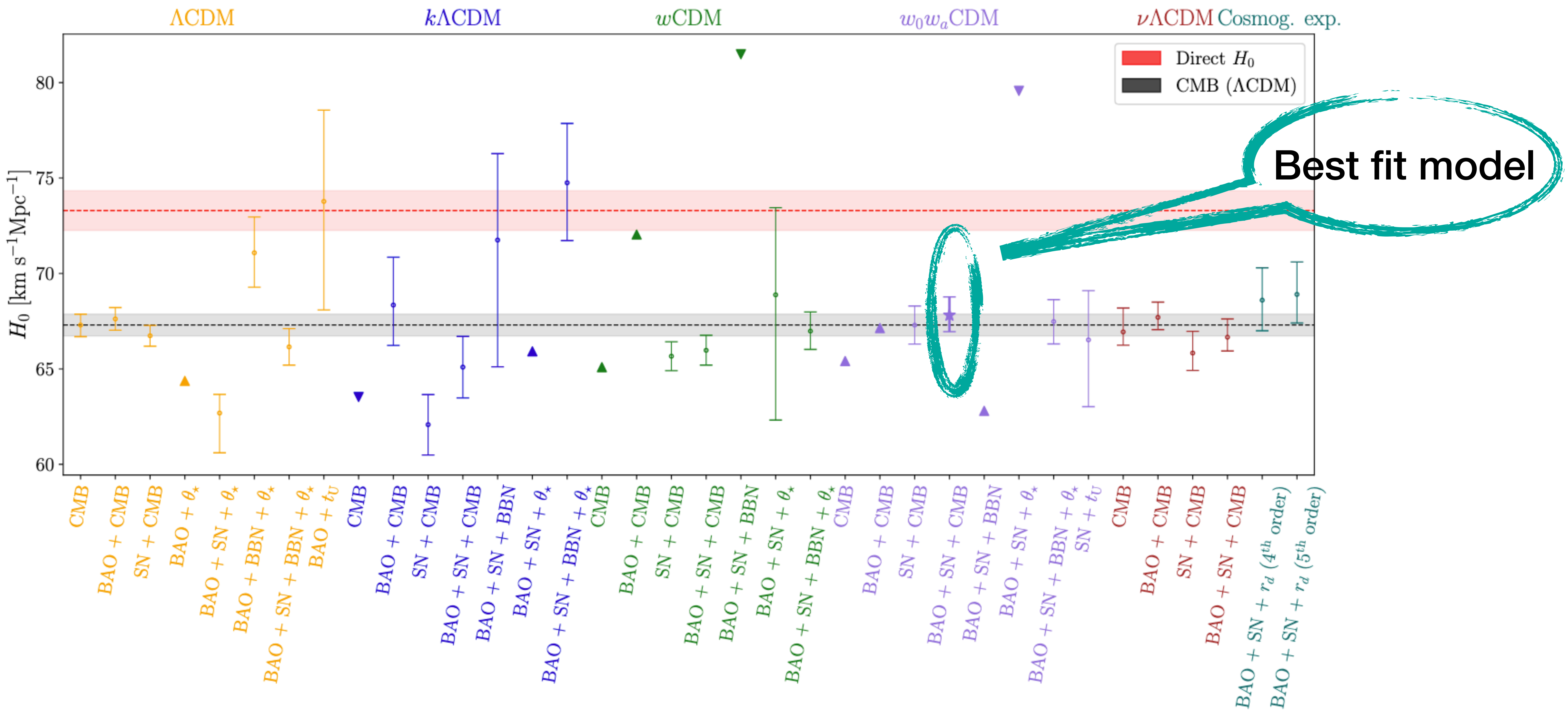


Tension in νCDM

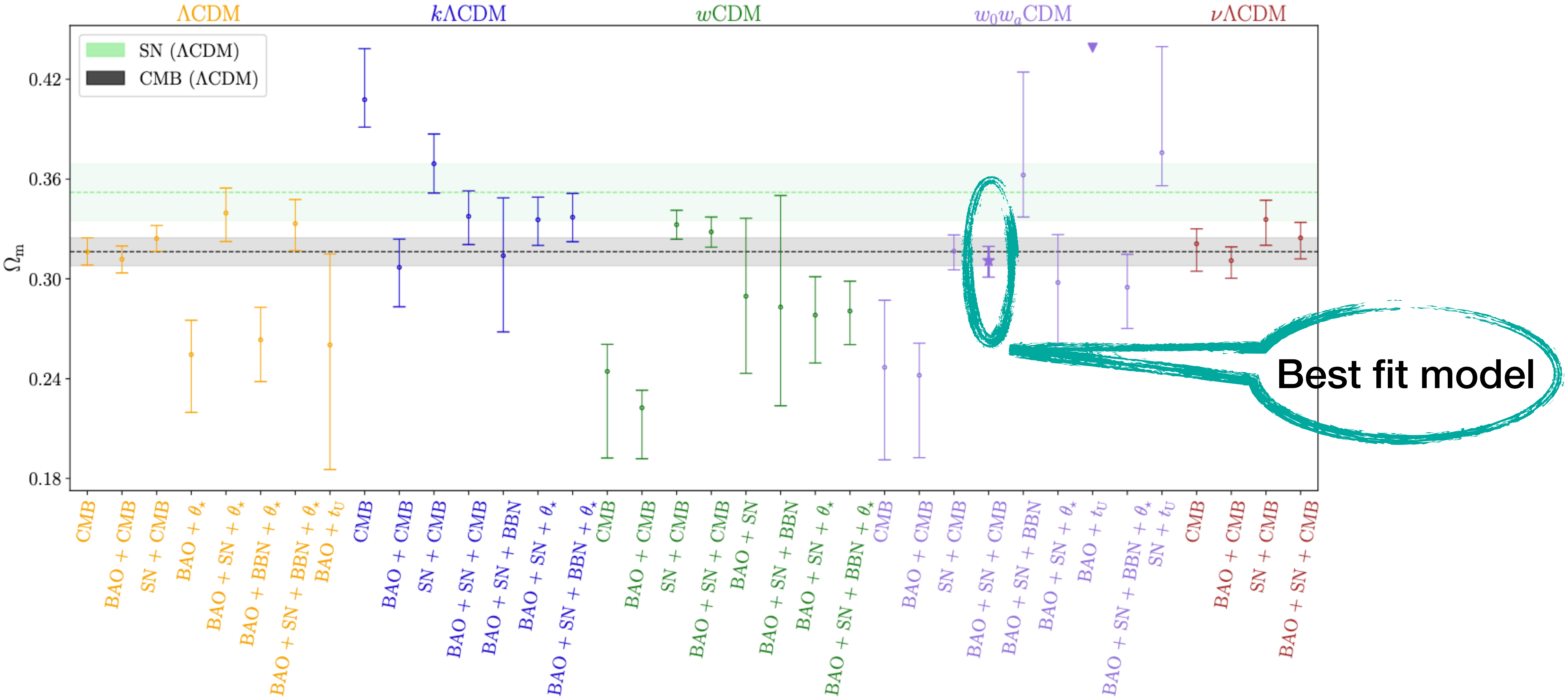
- Rather than fixing $\sum m_\nu = 0.06\,\mathrm{eV}$, allow it to be a free parameter
- Tension btw different datasets persists
- The lower bound on neutrino mass hits zero boundary



Hubble parameter across models



Matter density parameter across models



Chinese Space Station Survey Telescope (CSST)

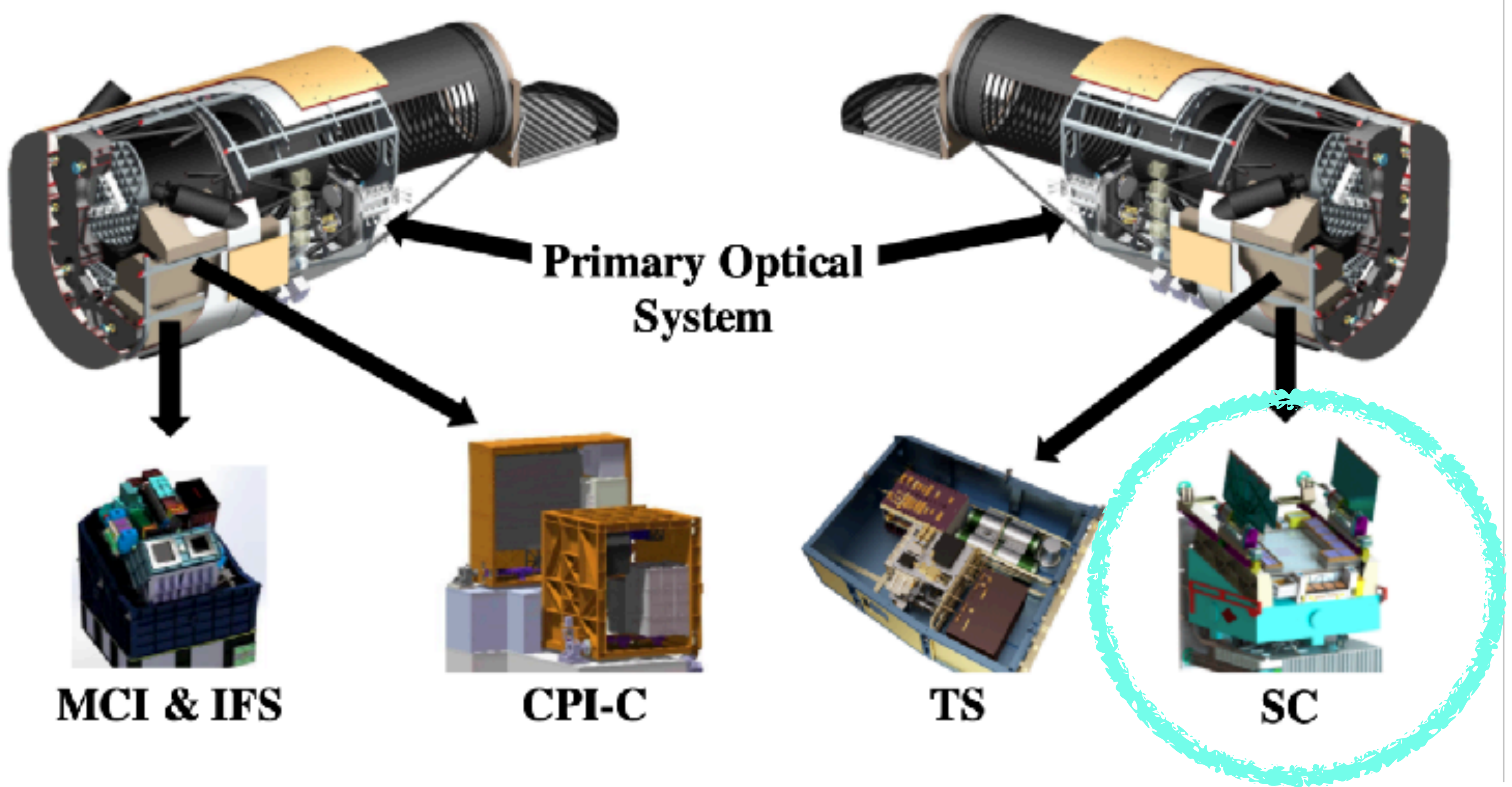
- Stage IV cosmological survey

  Satellite survey equipped with a 2m telescope

- Orbiting in tandem with the Chinese Space Station

  To be launched in 2027, operate for 10 years

  Multi-band Imaging and Slitless Spectroscopy Survey Camera (SC) Multi-Channel Imager (MCI), Integral Field Spectrograph (IFS), Cool Planet Imaging Coronagraph (CPI-C), and THz Spectrometer (TS)



CSST cosmological survey

- Wide field 17500 sq. deg, g band reach 26 mag

- Billion galaxies, hundreds of million of spectra

- 400 sq. deg of deep field

- 7 years of survey observation over a 10 year period

  7 photometric bands, NUV, u , g, r, i, z, y

  3 slitless bands, GU, GV, GI, resolution ≥ 200

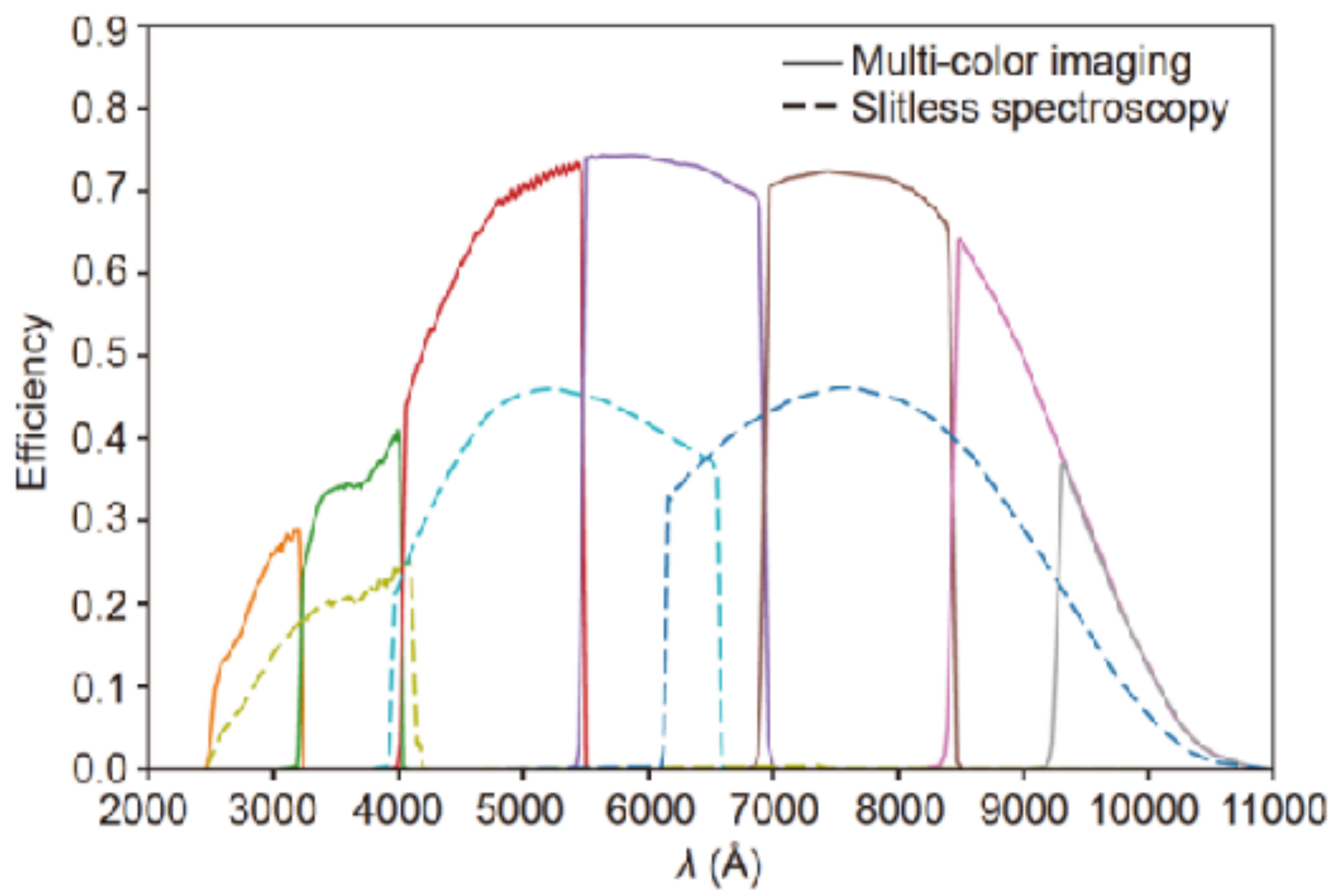
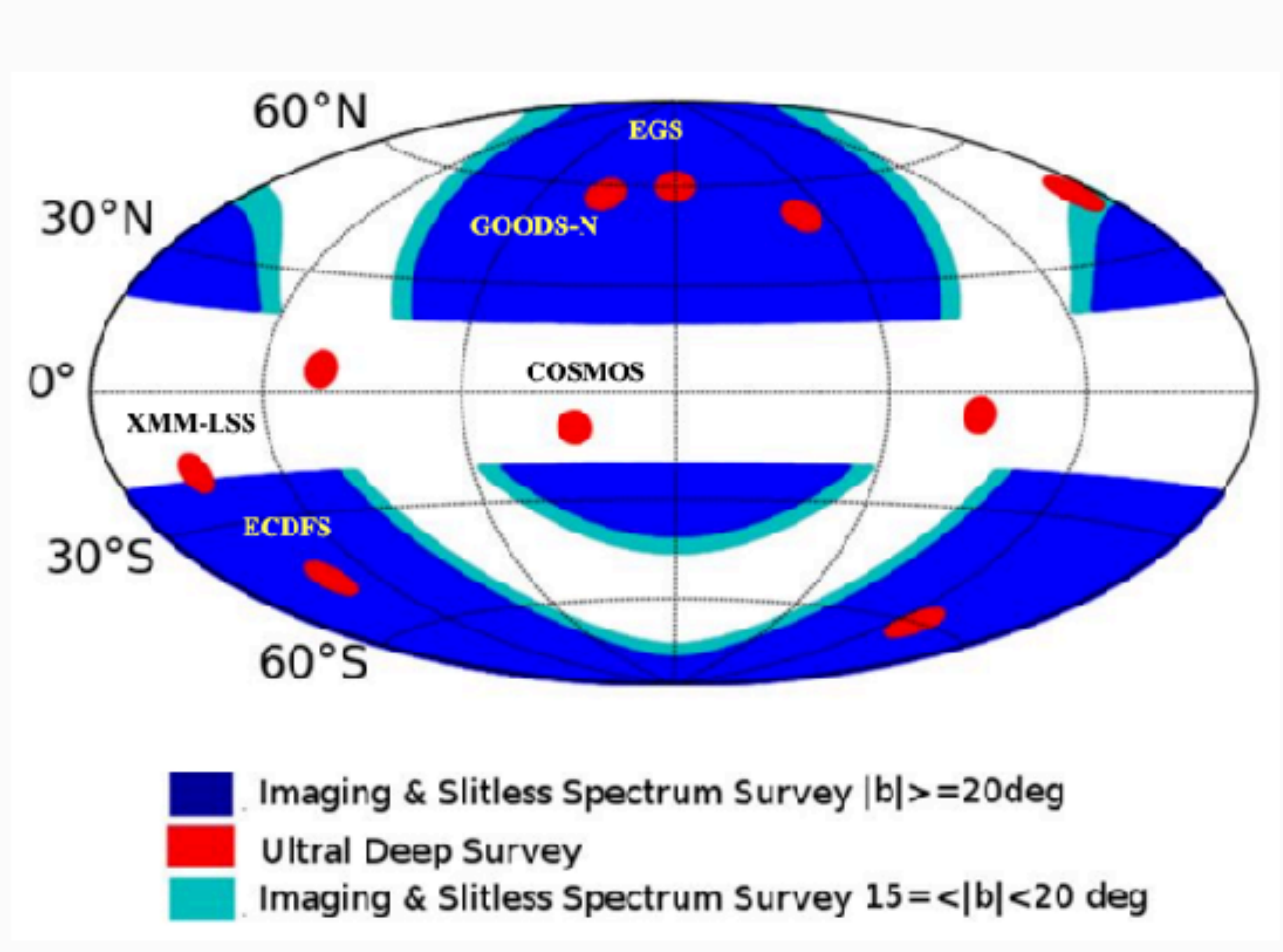


Figure 3 The transmission curves of the seven photometric imaging bands, i.e. *NUV*, *u*, *g*, *r*, *i*, *z*, and *y* (solid curves), and three slitless spectroscopic bands, i.e. *GU*, *GV*, and *GI* (dashed curves) for the CSST-SC [13].

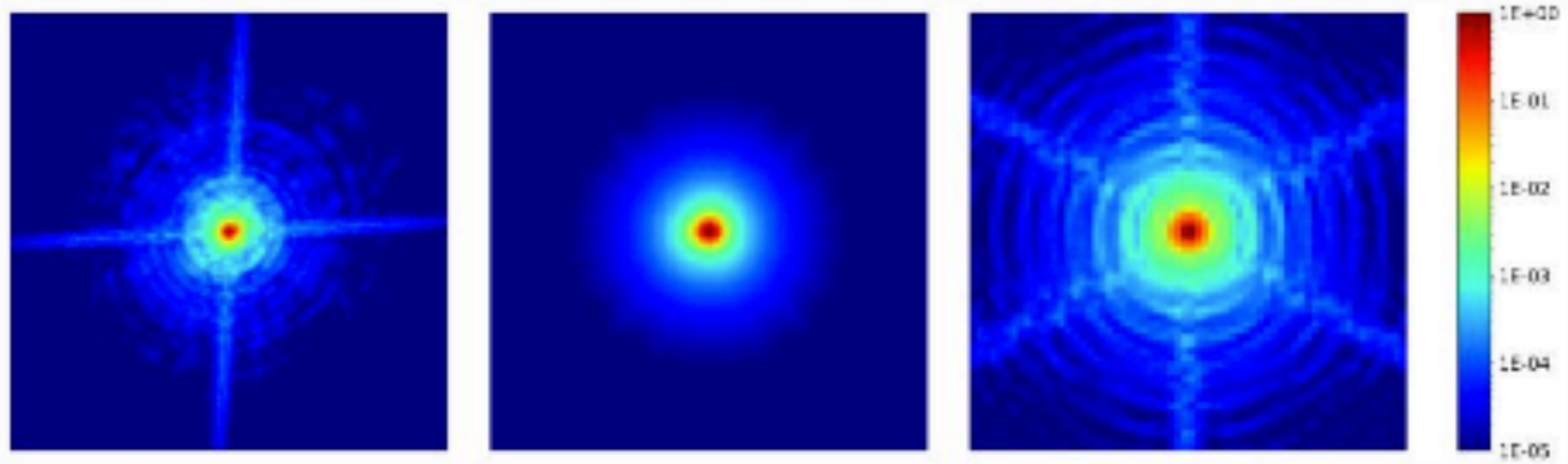


Comparison with surveys

	Project	Site/ orbit	Launch /op	FoV	R_{EE80}	Num pixels	Area	Wavelength	Num Filters	Spect
				deg^2	"	10^9	deg^2	nm		
2 m	CSST	LEO	2027	1.1	0.15 0.074/pix	2.5	17500	255—1000	7	yes
1.2 m	Euclid	L2	2023	0.56 0.55	>0.2 pix lmt	0.6 0.07	15000	550—920 1000—2000	1 3	no yes
2.4 m	Roman	L2	~2026	0.28	>0.2	0.3	~2000	927—2000	4	yes
8.4 m	Rubin	Chile	2025	9.6	~0.54	3.2	18000	320—1050	6	no

R_{EE80}: radius encircling 80% energy

	CSST	HST/ACS WFC	Euclid VIS	WFIRST J
R_{EE50}	0.1"	0.06"	0.13"	0.12"
R_{EE80}	0.15"	0.12"	~0.23"	~0.24"



HST CSST Euclid

Slide from Hu Zhan

CSST Science
Slide from Hu Zhan
Cosmology：DE & DM
暗物质地图
暗能量模型
弱透镜效应（椭率）
暗物质相互作用
极小质量暗晕
Cosmology：LSS
Galaxy & AGN
total model
bar model
中国空间站巡天空间望远镜2025年度科学年会暨早期科学研讨会
2025年7月26日-30日
云南·昆明
Illustrating str. and evo. of Milky way & nearby galaxies; Studying stellar physics
Improving astrometry accuracy; Detecting SSSBs & transient objects
Probing and studying Exoplanets
27

Conclusions

- Y6 BAO gives the tightest BAO constraint from photometric survey, ~2σ deviation from Planck

- Signature of GI BAO is detected in DES samples

- Y5 SNe quintuples the number of SNe at z>0.5, give ~1500 new high redshift SNes

- Y6 BAO + Y5 SNe are consistent with each other in w_0w_aCDM model, giving further evidence to evolving DE. Do justice to its name!