Implications for cosmological expansion models from the final Dark Energy Survey BAO and SN data

Juan Mena-Fernández - LPSC (Grenoble, France)

On behalf of the Dark Energy Survey collaboration.

The Dark Energy Survey

The Dark Energy Survey

- Photometric galaxy survey

The Dark Energy Survey

- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

The Dark Energy Survey

- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

DES Wide survey

The Dark Energy Survey

- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

DES Wide survey

- 6 years (2013-2019)

The Dark Energy Survey

- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

DES Wide survey

- 6 years (2013-2019)
- 5000 deg^2 with depth *i=23.8*

The Dark Energy Survey

- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

DES Wide survey

- 6 years (2013-2019)
- 5000 deg^2 with depth *i=23.8*
- >100 million galaxies with shapes and photo-z up to z~1.4

The Dark Energy Survey

- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

DES Wide survey

- 6 years (2013-2019)
- 5000 deg^2 with depth *i=23.8*
- >100 million galaxies with shapes and photo-z up to z~1.4

DES Supernova survey:

The Dark Energy Survey

- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

DES Wide survey

- 6 years (2013-2019)
- 5000 deg^2 with depth *i=23.8*
- >100 million galaxies with shapes and photo-z up to z~1.4

DES Supernova survey:

- 5 years (6-month seasons)

The Dark Energy Survey

- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

DES Wide survey

- 6 years (2013-2019)
- 5000 deg^2 with depth *i=23.8*
- >100 million galaxies with shapes and photo-z up to z~1.4

DES Supernova survey:

- 5 years (6-month seasons)
- 10 fields (total 30 deg^2)

The Dark Energy Survey

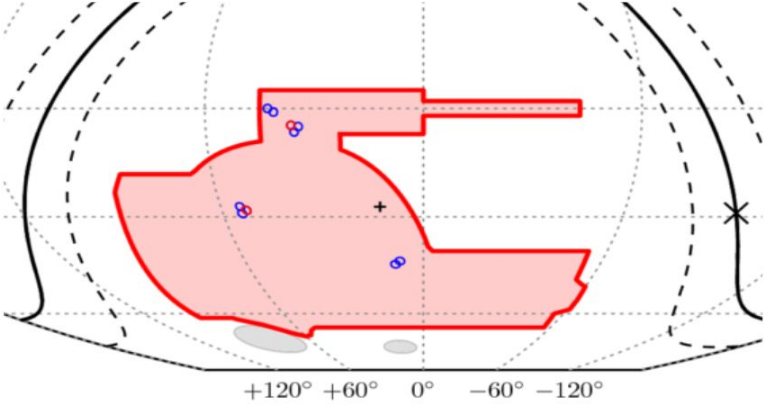
- Photometric galaxy survey
- 5 bands: g, r, i, z, Y

DES Wide survey

- 6 years (2013-2019)
- 5000 deg^2 with depth *i=23.8*
- >100 million galaxies with shapes and photo-z up to z~1.4

DES Supernova survey:

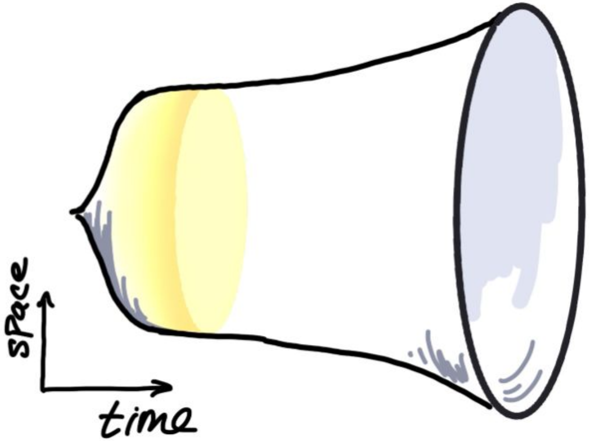
- 5 years (6-month seasons)
- 10 fields (total 30 deg^2)



Dark energy probes in DES

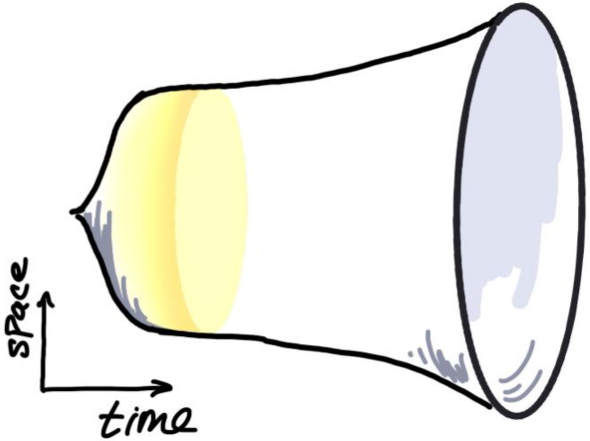
Dark energy probes in DES

1. Expansion history



Dark energy probes in DES

1. Expansion history

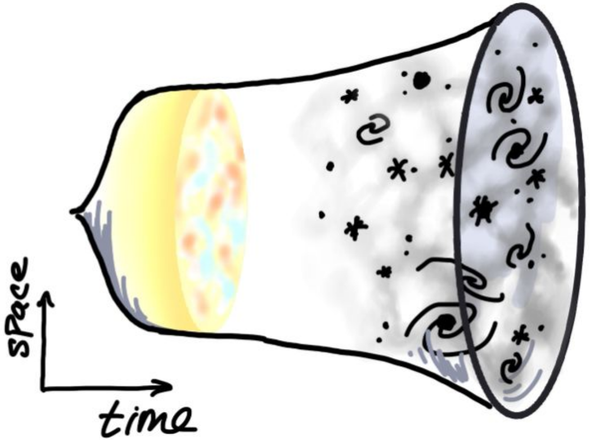


Galaxy clustering

Supernovae

Dark energy probes in DES

1. Expansion history



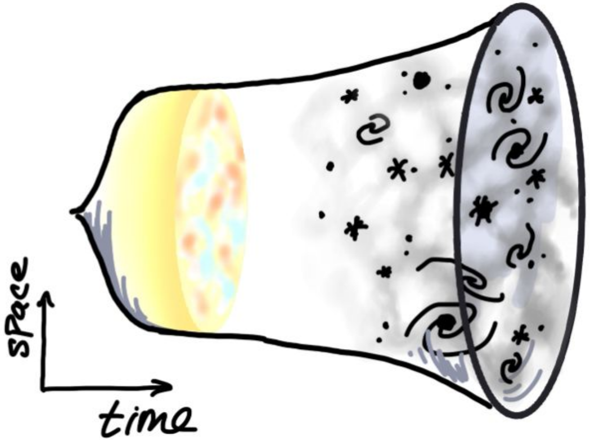
2. Structure growth

Galaxy clustering

Supernovae

Dark energy probes in DES

1. Expansion history



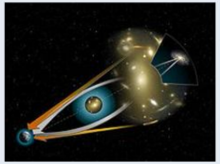
2. Structure growth

Galaxy clustering

Supernovae

Galaxy clustering

Weak lensing

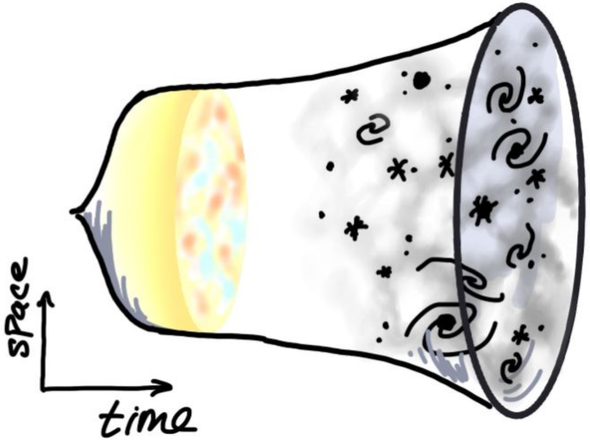


Galaxy clusters

Dark energy probes in DES

Focus of this talk!

1. Expansion history



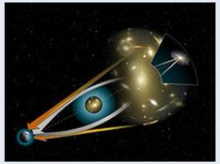
Galaxy clustering

Supernovae

2. Structure growth

Galaxy clustering

Weak lensing

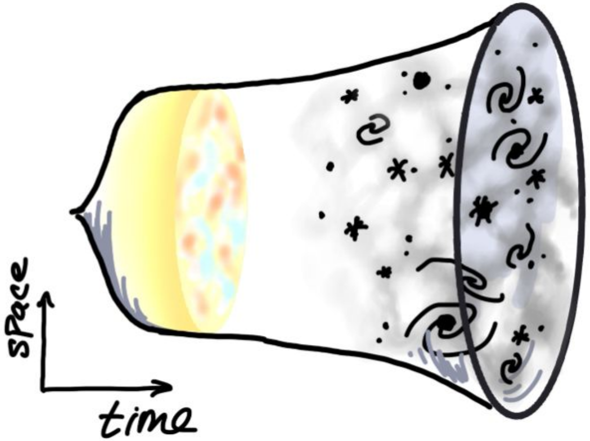


Galaxy clusters

Dark energy probes in DES

Focus of this talk!

1. Expansion history



2. Structure growth

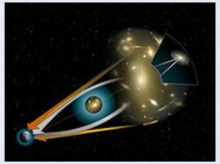
Credits: J. Muir

Galaxy clustering

Supernovae

Galaxy clustering

Weak lensing



Galaxy clusters

Distance probes

Distance probes

Type Ia Supernovae

Distance probes

Type Ia Supernovae

Uniform luminosity at peak → used as
“standardizable candles”

Distance probes

Type Ia Supernovae

Uniform luminosity at peak → used as
“standardizable candles”

Luminosity distance vs **redshift**, $D_L(z)$.
Depends on cosmology $H(z)$

$$D_L(z) = (1+z)c\, S_k\left[\int \frac{dz}{H(z)}\right]$$

with $S_{k=0}(x) = x,\ S_{k>0}(x) = \sinh(x),\ S_{k<0}(x) = \sin(x)$

Distance probes

Type Ia Supernovae

Uniform luminosity at peak → used as **"standardizable candles"**

Luminosity distance vs **redshift**, $D_L(z)$.
Depends on cosmology $H(z)$

$$D_L(z) = (1+z)c\, S_k\left[\int \frac{dz}{H(z)}\right]$$

with $S_{k=0}(x) = x,\ S_{k>0}(x) = \sinh(x),\ S_{k<0}(x) = \sin(x)$

Baryonic Acoustic Oscillations

Distance probes

Type Ia Supernovae

Uniform luminosity at peak → used as **“standardizable candles”**

↓

Luminosity distance vs **redshift**, $D_L(z)$.
Depends on cosmology $H(z)$

$$D_L(z) = (1+z)c\, S_k\left[\int \frac{dz}{H(z)}\right]$$

with $S_{k=0}(x) = x,\ S_{k>0}(x) = \sinh(x),\ S_{k<0}(x) = \sin(x)$

Baryonic Acoustic Oscillations

Sound horizon ‘imprinted’ in our Universe at recombination → used as a **“standard ruler”**

Distance probes

Type Ia Supernovae

Uniform luminosity at peak → used as **"standardizable candles"**

↓

Luminosity distance vs **redshift**, $D_L(z)$. Depends on cosmology $H(z)$

$$D_L(z) = (1+z)c\, S_k\left[\int \frac{dz}{H(z)}\right]$$

with $S_{k=0}(x) = x,\ S_{k>0}(x) = \sinh(x),\ S_{k<0}(x) = \sin(x)$

Baryonic Acoustic Oscillations

Sound horizon 'imprinted' in our Universe at recombination → used as a **"standard ruler"**

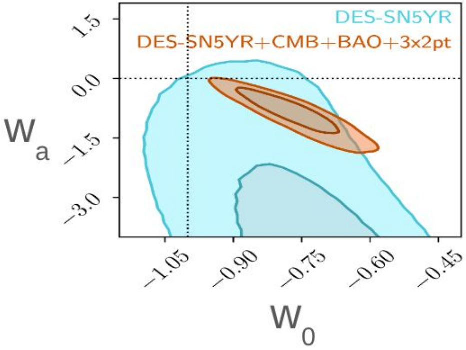
↓

Angular distance vs **redshift**, $D_M(z)$. Depends on cosmology $H(z)$

$$D_M(z) = c\, S_k\left[\int \frac{dz}{H(z)}\right]$$

2024: Λ’s annus horribilis

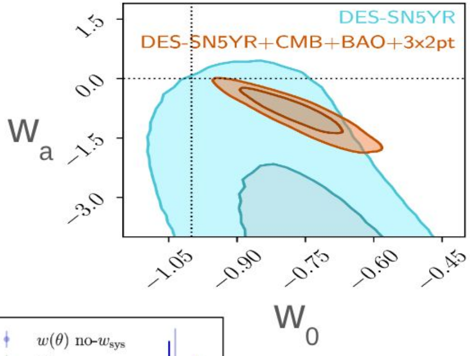
2024: Λ's annus horribilis

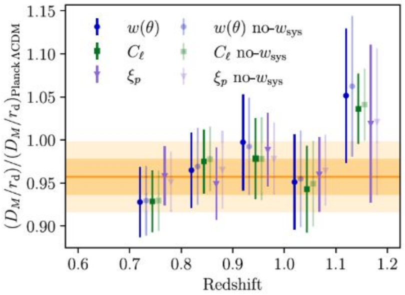


- January 2024: **DES-SN**. **~2σ** preference for w_0w_aCDM (arXiv:2401.02929).

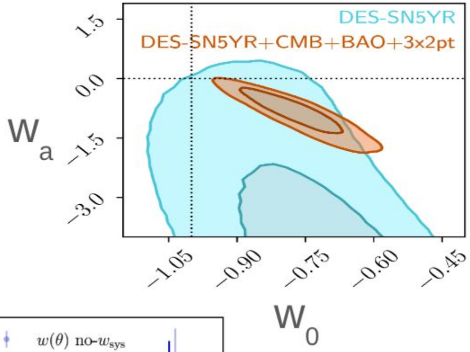
2024: Λ's annus horribilis

- January 2024: **DES-SN**. **~2σ** preference for w_0w_aCDM (arXiv:2401.02929).
- February 2024: **DES-BAO**. **~2.1σ** deviation from Planck-ΛCDM (arXiv:2402.10696).

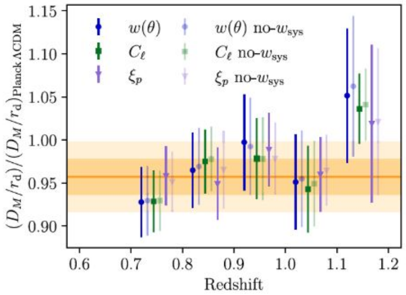




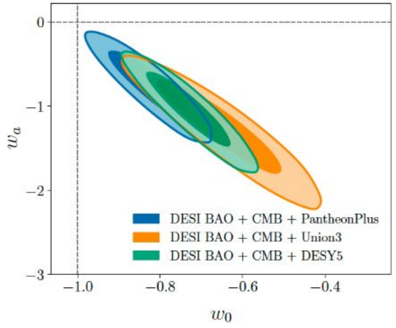
2024: Λ's annus horribilis



- January 2024: **DES-SN**. **~2σ** preference for w_0w_aCDM (arXiv:2401.02929).

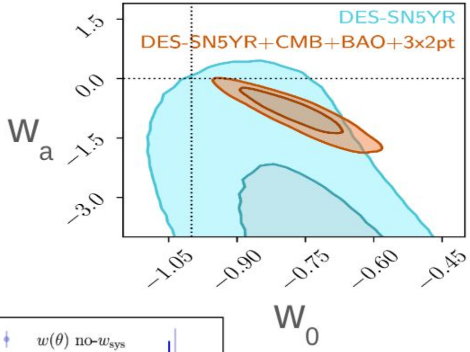


- February 2024: **DES-BAO**. **~2.1σ** deviation from Planck-ΛCDM (arXiv:2402.10696).

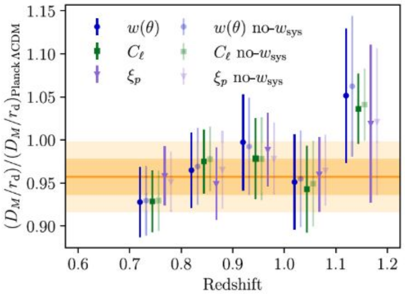


- April 2024: **DESI-BAO**. **~3.9σ** preference for w_0w_aCDM when combined with CMB + DES SN (arXiv:2404.03002).

2024: Λ's annus horribilis

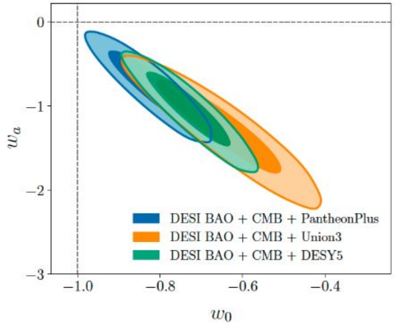


- January 2024: **DES-SN**. **~2σ** preference for w_0w_aCDM (arXiv:2401.02929).
- February 2024: **DES-BAO**. **~2.1σ** deviation from Planck-ΛCDM (arXiv:2402.10696).



Focus of this talk: combined analysis of DES BAO and SN!

- April 2024: **DESI-BAO**. **~3.9σ** preference for w_0w_aCDM when combined with CMB + DES SN (arXiv:2404.03002).

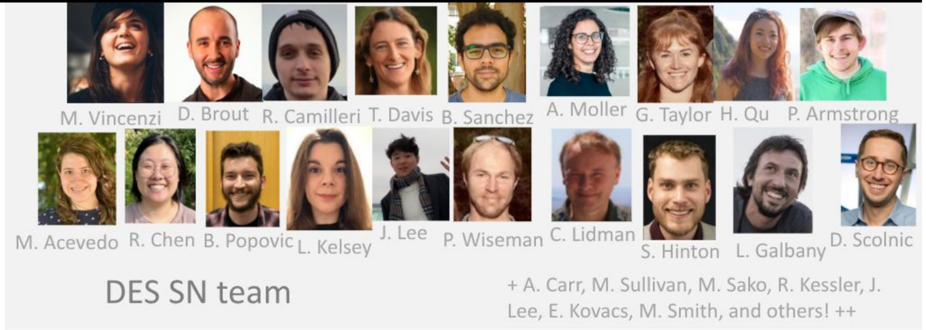


DES Y5 SNe

DES Collaboration 2024, arXiv:2401.02929

DES Y5 SNe

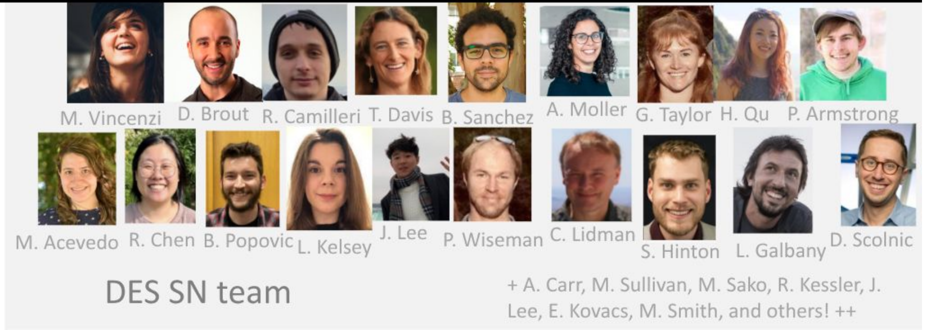
DES Collaboration 2024, arXiv:2401.02929



DES Y5 SNe

DES Collaboration 2024, arXiv:2401.02929

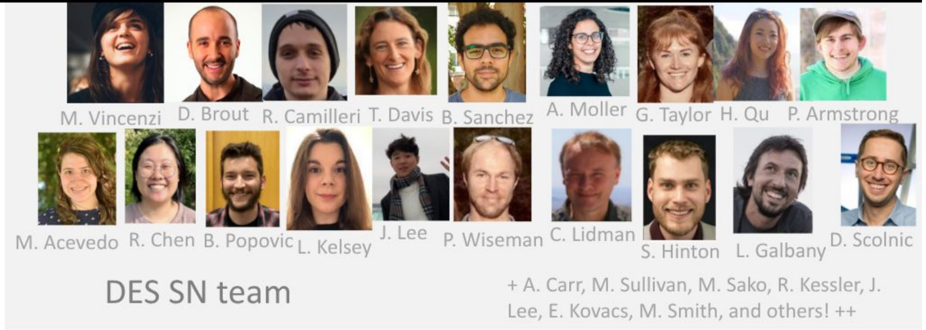
- Largest and deepest SN sample from a single telescope ever.



DES Y5 SNe

DES Collaboration 2024, arXiv:2401.02929

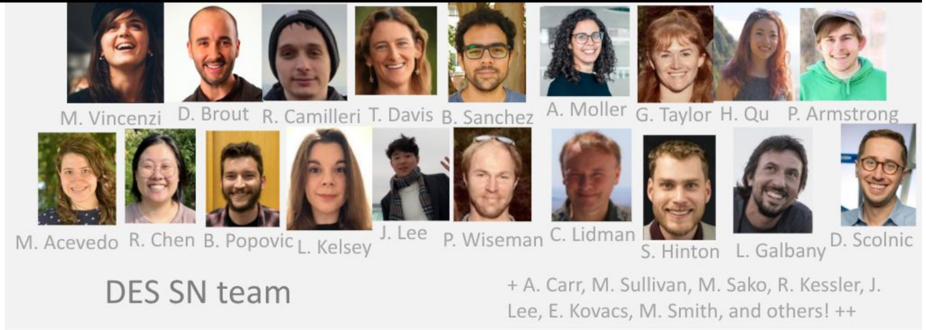
- Largest and deepest SN sample from a single telescope ever.
- 1635 photometrically classified SNe Ia



DES Y5 SNe

DES Collaboration 2024, arXiv:2401.02929

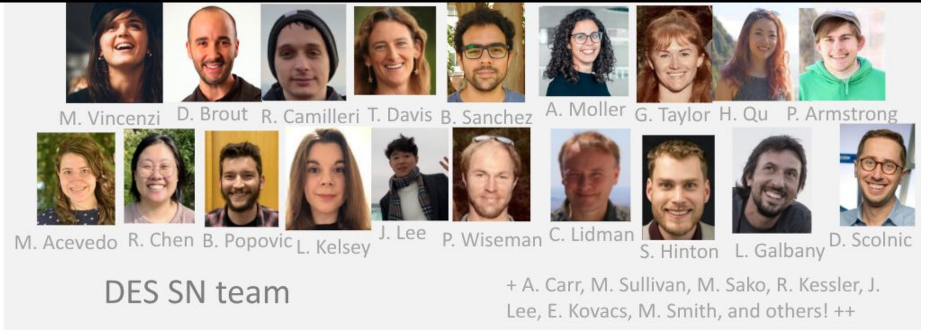
- Largest and deepest SN sample from a single telescope ever.
- 1635 photometrically classified SNe Ia
  - calibrated to 5 mmag accuracy.



DES Y5 SNe

DES Collaboration 2024, arXiv:2401.02929

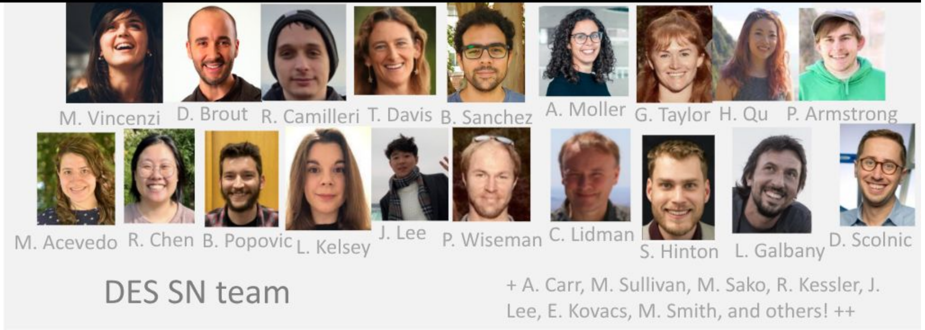
- Largest and deepest SN sample from a single telescope ever.
- 1635 photometrically classified SNe Ia
  - calibrated to 5 mmag accuracy.
  - spectra for host galaxy redshifts.



DES Y5 SNe

DES Collaboration 2024, arXiv:2401.02929

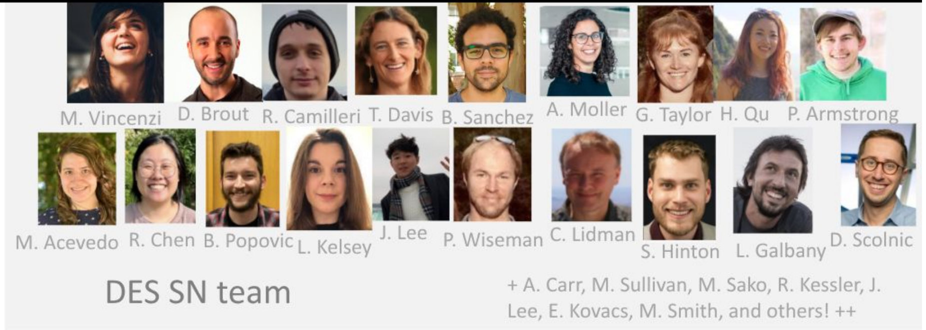
- Largest and deepest SN sample from a single telescope ever.
- 1635 photometrically classified SNe Ia
  - calibrated to 5 mmag accuracy.
  - spectra for host galaxy redshifts.
- For cosmology, combined with data from 194 low-z SN from other samples.



DES Y5 SNe

DES Collaboration 2024, arXiv:2401.02929

- Largest and deepest SN sample from a single telescope ever.
- 1635 photometrically classified SNe Ia
  - calibrated to 5 mmag accuracy.
  - spectra for host galaxy redshifts.
- For cosmology, combined with data from 194 low-z SN from other samples.



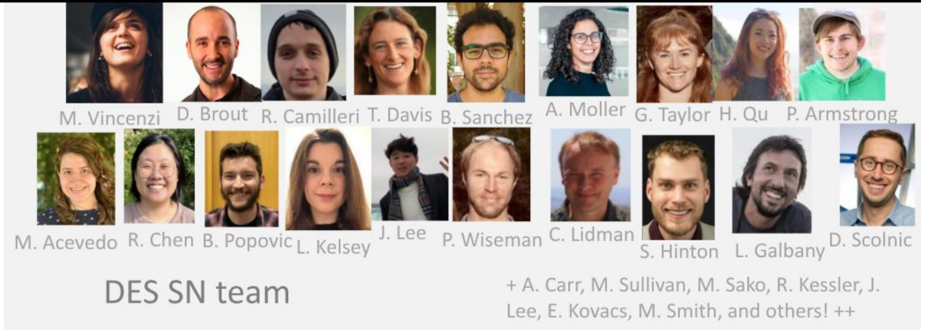
$$\mu_{\rm obs} = m_x - M + [\text{calib.}] \quad \propto \log_{10}\left[\frac{D_L(z)}{10\text{pc}}\right]$$

- $\mu_{\rm obs}$: 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 Y5 SNe

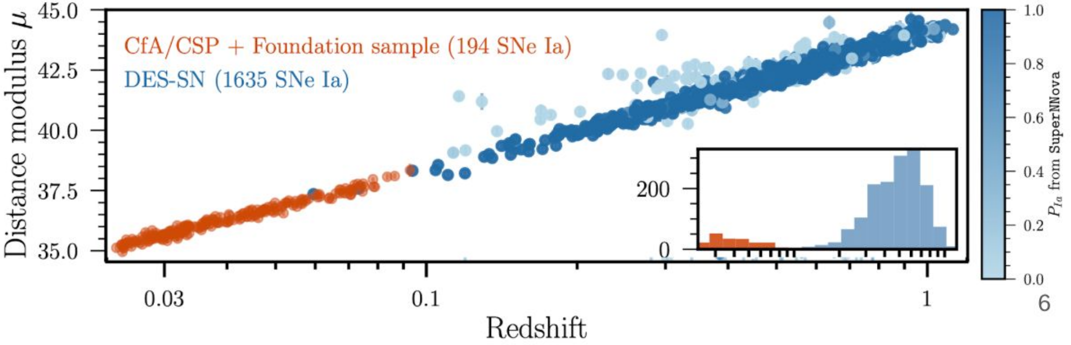
DES Collaboration 2024, arXiv:2401.02929

- Largest and deepest SN sample from a single telescope ever.
- 1635 photometrically classified SNe Ia
  - calibrated to 5 mmag accuracy.
  - spectra for host galaxy redshifts.
- For cosmology, combined with data from 194 low-z SN from other samples.



$$\mu_{\rm obs} = m_x - M + [\text{calib.}] \quad \propto \log_{10}\left[\frac{D_L(z)}{10\text{pc}}\right]$$

- $\mu_{\rm obs}$: 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)

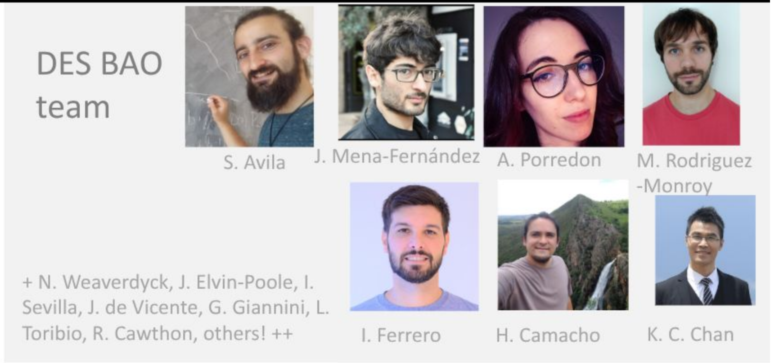


DES Y6 BAO

DES Collaboration 2024, arXiv:2401.02929

DES Y6 BAO

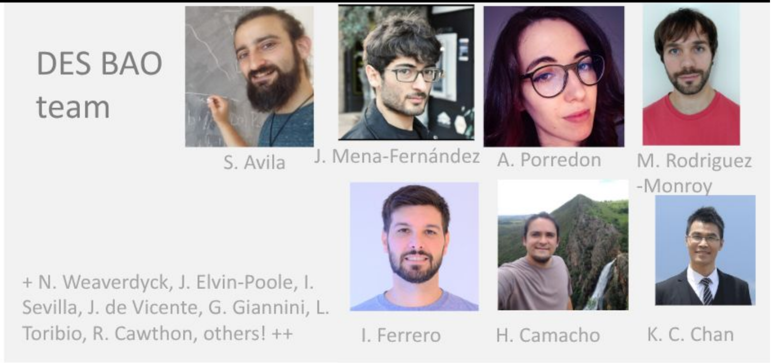
DES Collaboration 2024, arXiv:2401.02929



DES Y6 BAO

DES Collaboration 2024, arXiv:2401.02929

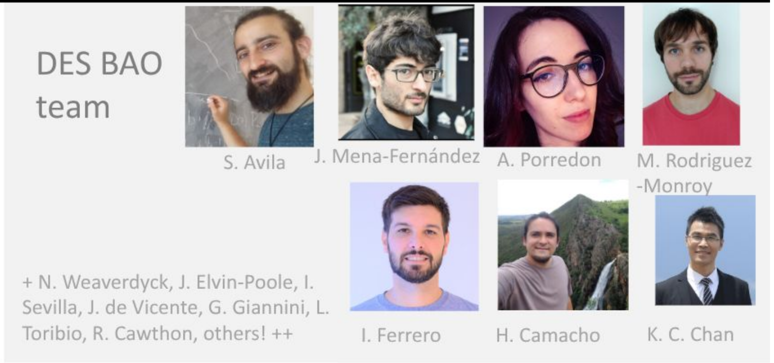
- DES BAO optimized sample of 16M red bright galaxies over 4,273 deg^2 in 6 tomographic bins $0.6<z_{ph}<1.2$.



DES Y6 BAO

DES Collaboration 2024, arXiv:2401.02929

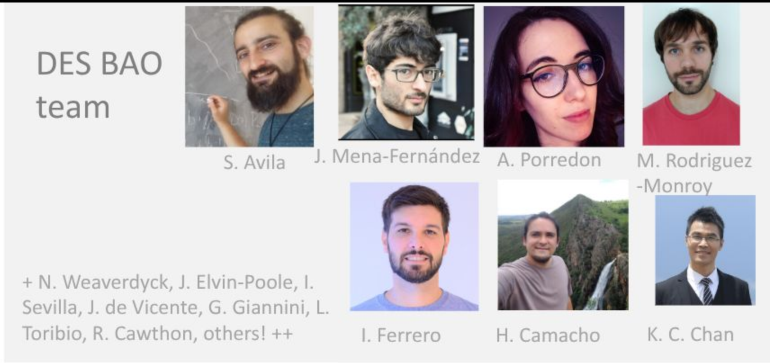
- DES BAO optimized sample of 16M red bright galaxies over 4,273 deg^2 in 6 tomographic bins $0.6<z_{ph}<1.2$.
- BAO signal meas. with 3 clustering statistics.



DES Y6 BAO

DES Collaboration 2024, arXiv:2401.02929

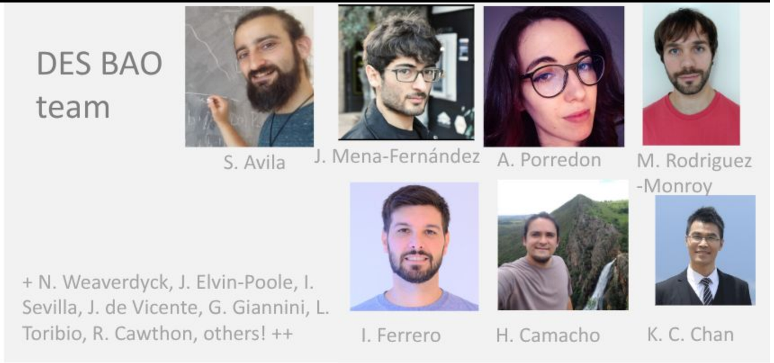
- DES BAO optimized sample of 16M red bright galaxies over 4,273 deg^2 in 6 tomographic bins $0.6<z_{ph}<1.2$.
- BAO signal meas. with 3 clustering statistics.
- 3.5σ significance detection of the BAO peak.



DES Y6 BAO

DES Collaboration 2024, arXiv:2401.02929

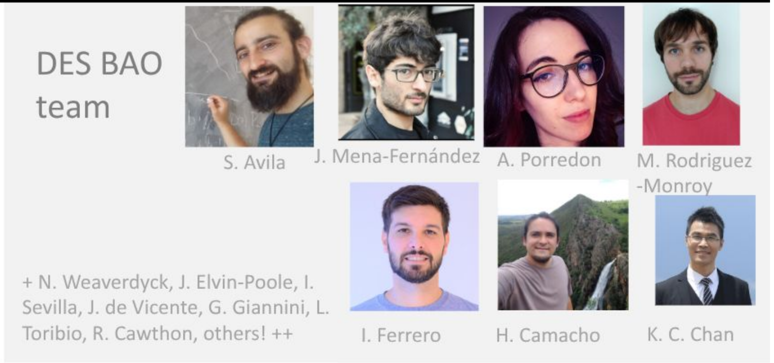
- DES BAO optimized sample of 16M red bright galaxies over 4,273 deg^2 in 6 tomographic bins $0.6<z_{ph}<1.2$.
- BAO signal meas. with 3 clustering statistics.
- 3.5σ significance detection of the BAO peak.
- Template-based BAO fit, validated using ~2000 mock catalogs, lots of robustness checks and pre-unblinding tests.



DES Y6 BAO

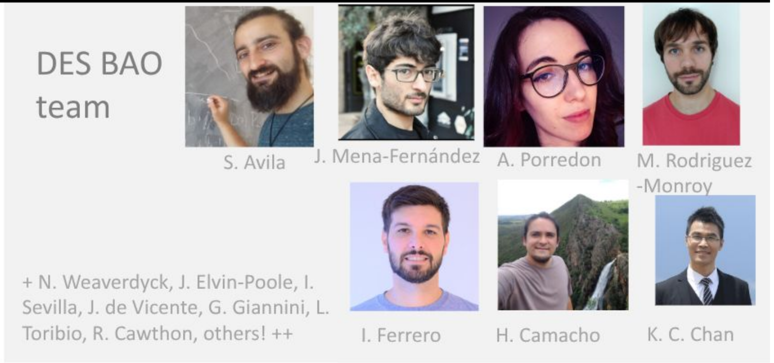
DES Collaboration 2024, arXiv:2401.02929

- DES BAO optimized sample of 16M red bright galaxies over 4,273 deg^2 in 6 tomographic bins $0.6<z_{ph}<1.2$.
- BAO signal meas. with 3 clustering statistics.
- 3.5σ significance detection of the BAO peak.
- Template-based BAO fit, validated using ~2000 mock catalogs, lots of robustness checks and pre-unblinding tests.
- Consensus likelihood as a function of α.



DES Y6 BAO

DES Collaboration 2024, arXiv:2401.02929



- DES BAO optimized sample of 16M red bright galaxies over 4,273 deg^2 in 6 tomographic bins $0.6<z_{ph}<1.2$.
- BAO signal meas. with 3 clustering statistics.
- 3.5σ significance detection of the BAO peak.
- Template-based BAO fit, validated using ~2000 mock catalogs, lots of robustness checks and pre-unblinding tests.
- Consensus likelihood as a function of α.

Angular distance

$$\alpha = \frac{D_M(z)/r_d}{(D_M(z)/r_d)_{\rm Planck}}$$

BAO scale (sound horizon)

DES Y6 BAO

DES Collaboration 2024, arXiv:2401.02929

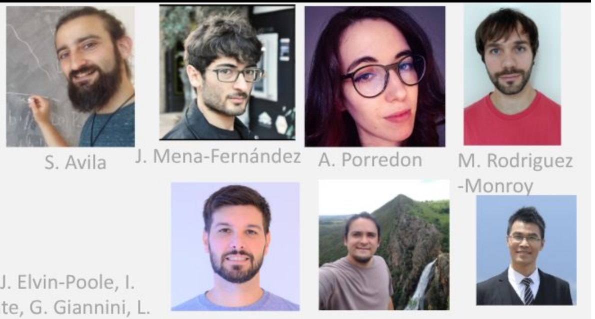
- DES BAO optimized sample of 16M red bright galaxies over 4,273 deg^2 in 6 tomographic bins $0.6<z_{ph}<1.2$.
- BAO signal meas. with 3 clustering statistics.
- 3.5σ significance detection of the BAO peak.
- Template-based BAO fit, validated using ~2000 mock catalogs, lots of robustness checks and pre-unblinding tests.
- Consensus likelihood as a function of α.

Angular distance

$$\alpha = \frac{D_M(z)/r_d}{(D_M(z)/r_d)_{\rm Planck}}$$

BAO scale (sound horizon)

DES BAO team

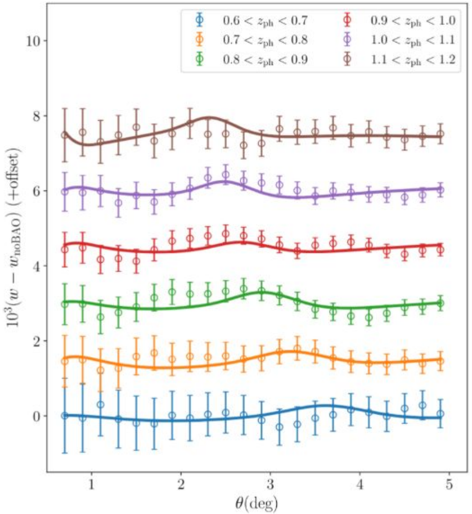


S. Avila, J. Mena-Fernández, A. Porredon, M. Rodriguez -Monroy

I. Ferrero, H. Camacho, K. C. Chan

+ N. Weaverdyck, J. Elvin-Poole, I. Sevilla, J. de Vicente, G. Giannini, L. Toribio, R. Cawthon, others! ++

Angular Correlation Function

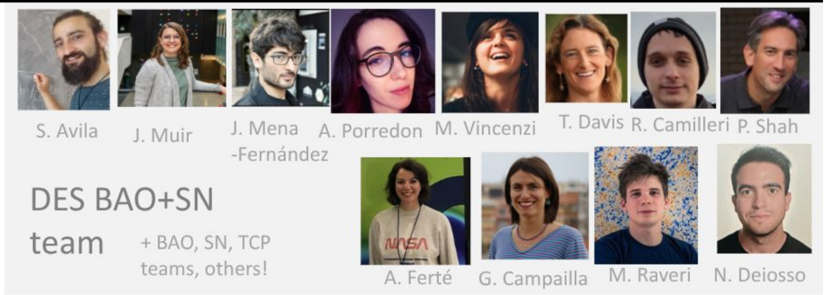


DES BAO + SN combined analysis

DES Collaboration 2025, arXiv:2503.06712

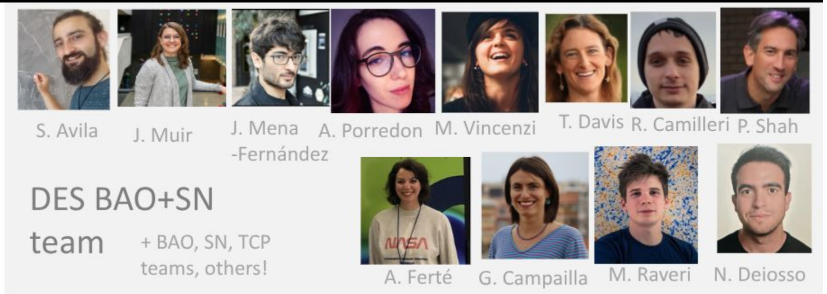
DES BAO + SN combined analysis

DES Collaboration 2025, arXiv:2503.06712



DES BAO + SN combined analysis

DES Collaboration 2025, arXiv:2503.06712

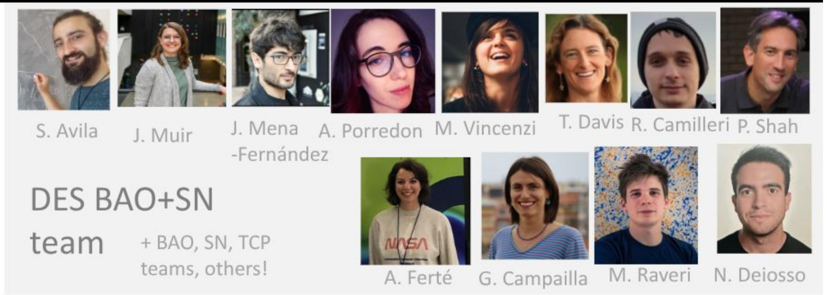


- **BAO** - DES Y6 BAO.
- **SN** - DES Y5 SN.

THE DARK ENERGY SURVEY

DES BAO + SN combined analysis

DES Collaboration 2025, arXiv:2503.06712



- **BAO** - DES Y6 BAO.
- **SN** - DES Y5 SN.

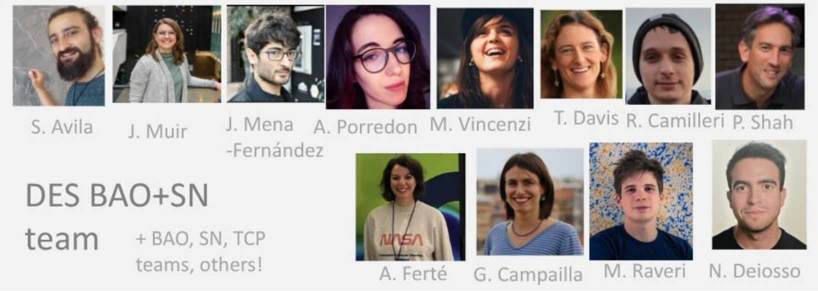
THE DARK ENERGY SURVEY

- **CMB** - Planck 2018 temperature and polarization power spectra.
- **θ_*** - angular scale of the acoustic peak of the CMB spectra.
- **BBN** - Big Bang nucleosynthesis constraints on baryon density (Schoneberg et al. 2024).

Planck col. 2020

DES BAO + SN combined analysis

DES Collaboration 2025, arXiv:2503.06712

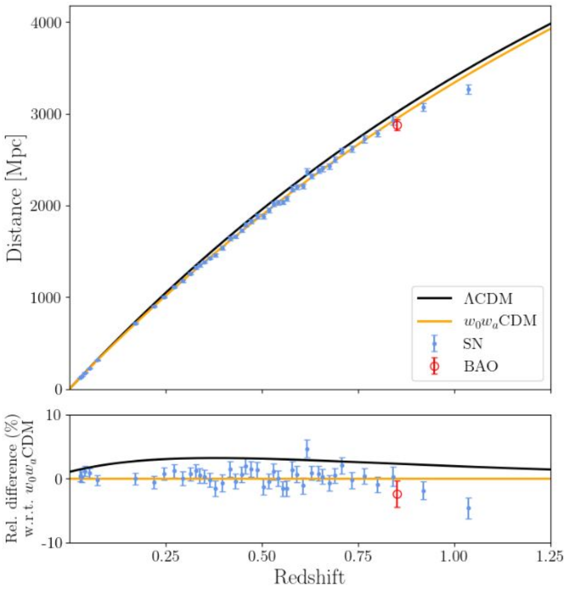


- **BAO** - DES Y6 BAO.
- **SN** - DES Y5 SN.

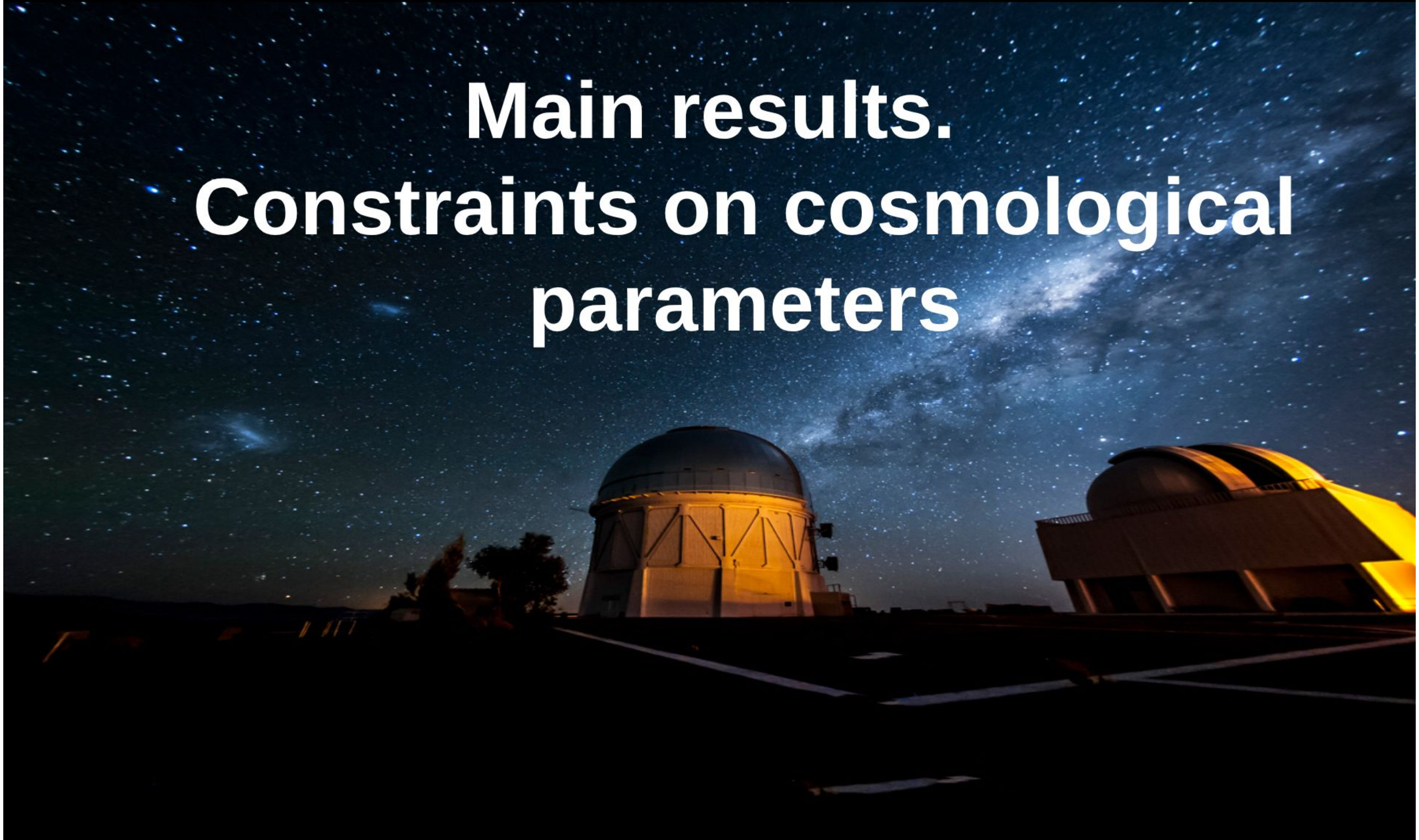
THE DARK ENERGY SURVEY

- **CMB** - Planck 2018 temperature and polarization power spectra.
- **θ_*** - angular scale of the acoustic peak of the CMB spectra.
- **BBN** - Big Bang nucleosynthesis constraints on baryon density (Schoneberg et al. 2024).

Planck col. 2020

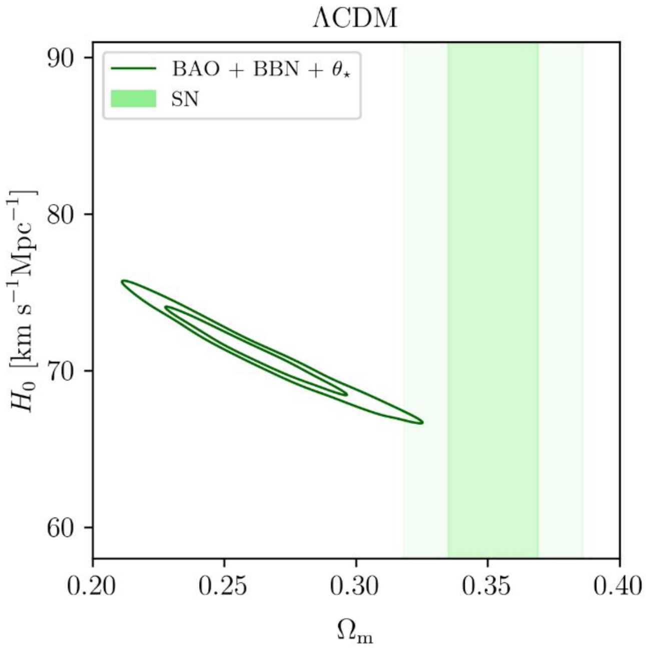


Main results. Constraints on cosmological parameters



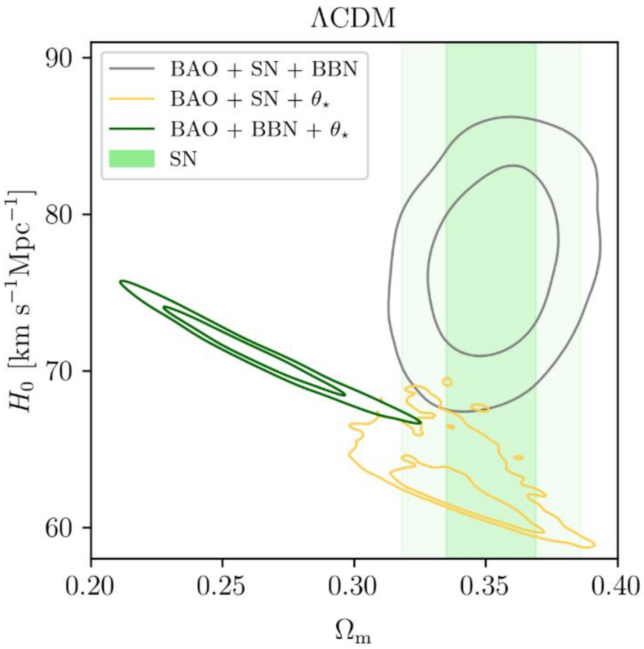
Results in ΛCDM

- Tension in Ω_m:
  - BAO → lower Ω_m.
  - SN → higher Ω_m.



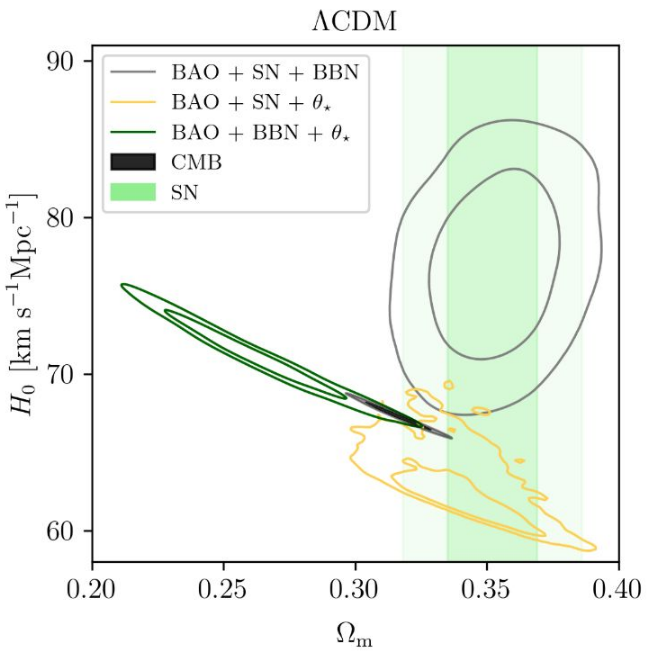
Results in ΛCDM

- Tension in Ω_m:
  - BAO → lower Ω_m.
  - SN → higher Ω_m.
- Tension in H_0:
  - BAO+SN+BBN → higher H_0.
  - BAO+SN+θ_* → lower H_0.



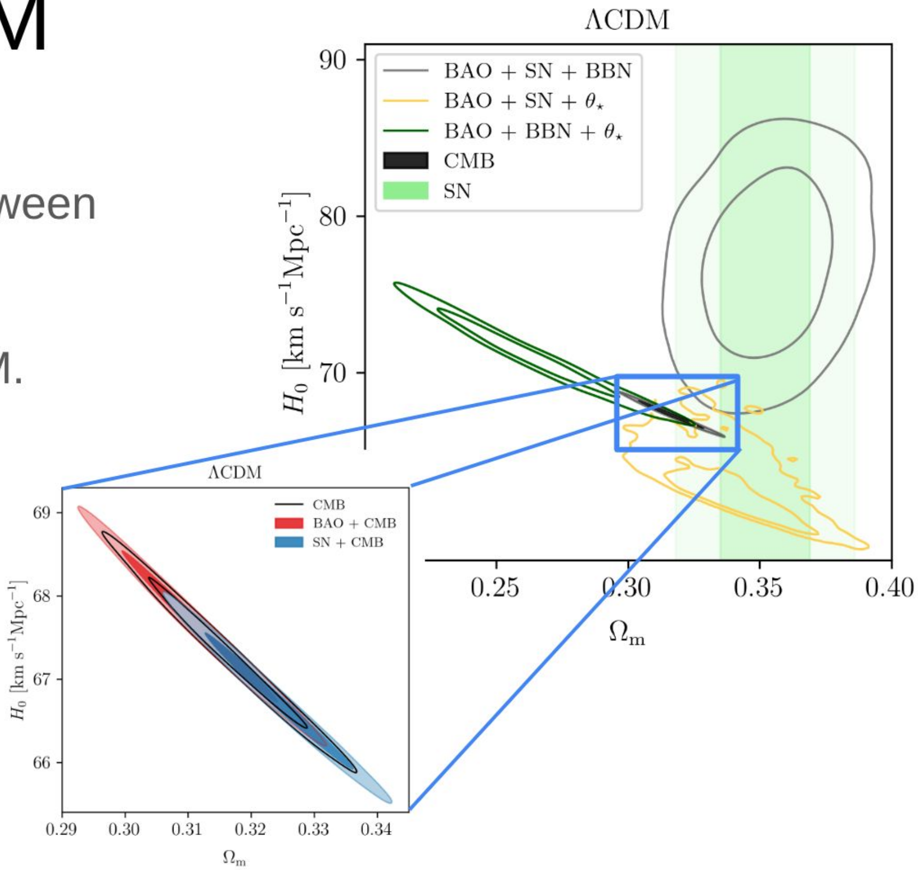
Results in ΛCDM

- Several 2-3σ tensions between data sets.
- Difficulties to interpret our different datasets in ΛCDM.



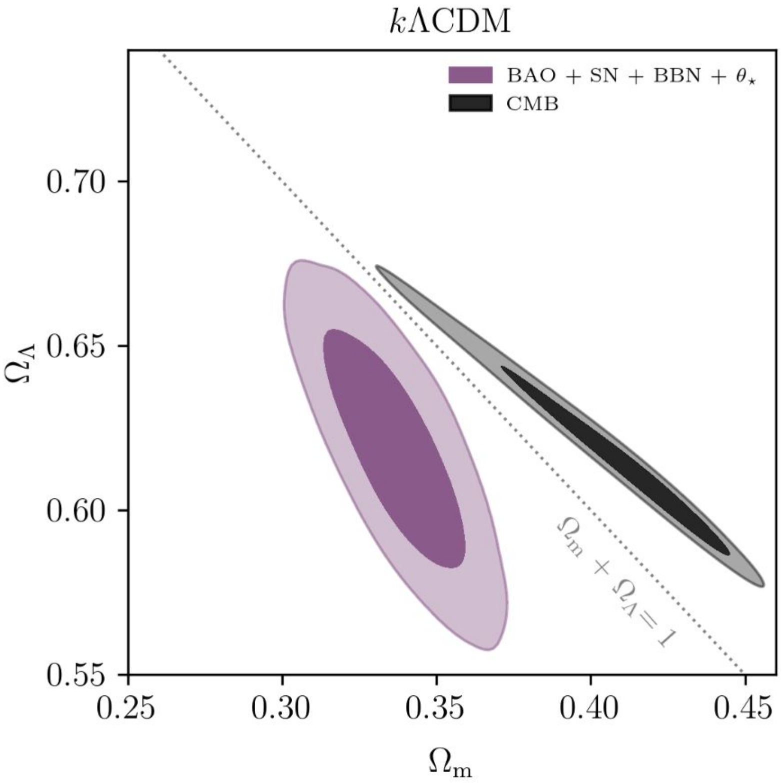
Results in ΛCDM

- Several 2-3σ tensions between data sets.
- Difficulties to interpret our different datasets in ΛCDM.



Results in kΛCDM

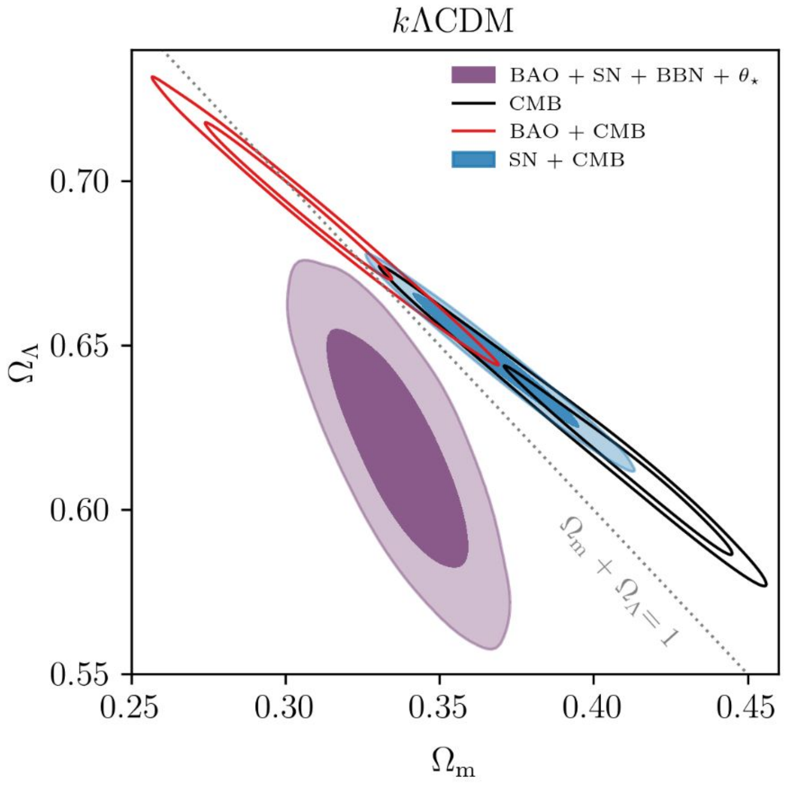
- Tensions between **geometric probes** and **CMB**.



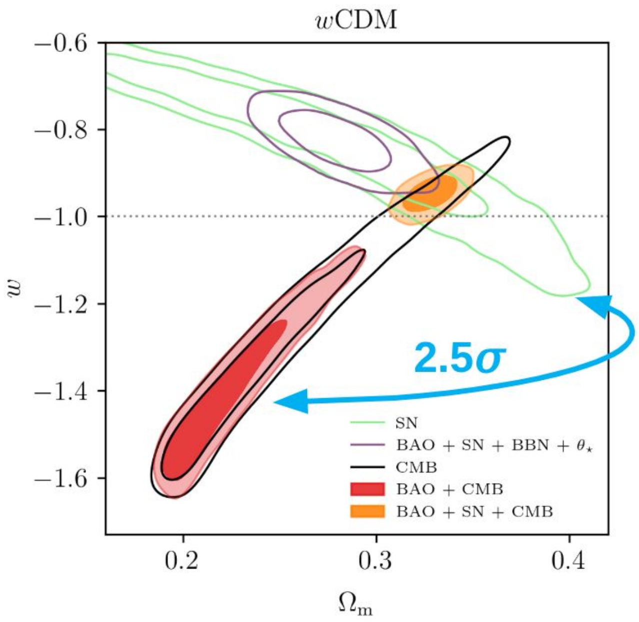
Results in kΛCDM

- Tensions between **geometric probes** and **CMB**.
- Curvature strongly dependent on data combination: tensions.

  - CMB: $10^3\Omega_k = -23.6^{+4.2}_{-7.9}$
  - BAO+CMB: $10^3\Omega_k = -1.4^{+5.8}_{-4.0}$
  - SN+CMB: $10^3\Omega_k = -14.2^{+5.3}_{-4.9}$
  - BAO+SN+BBN+$\theta_\star$: $10^3\Omega_k = +45^{+15}_{-14}$



Results in wCDM

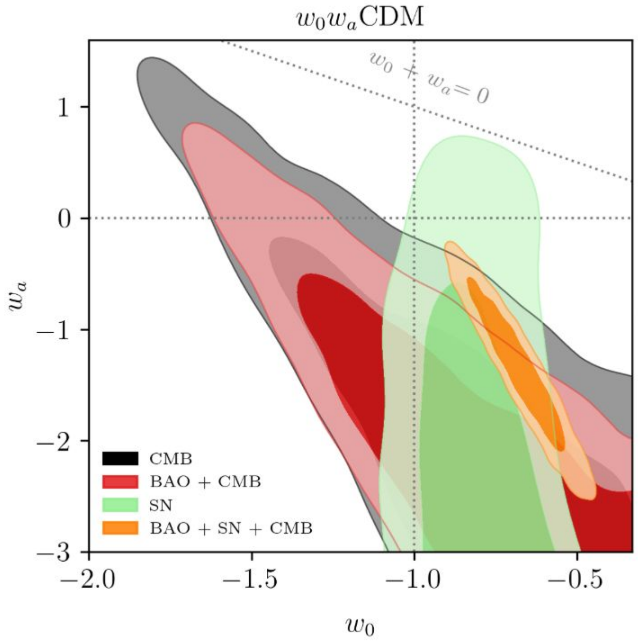


- Tensions among probes persist at ~2-3σ: SN vs. CMB+BAO.
- Most constraining case BAO+SN+CMB: w=-0.948±0.028.
- **BAO** and **SN** still push in different directions:
  - Different effective redshift.
  - Evolving dark energy?

Results in $w_0 w_a$CDM

$$w_{DE}(a) = w_0 + (1 - a)w_a$$

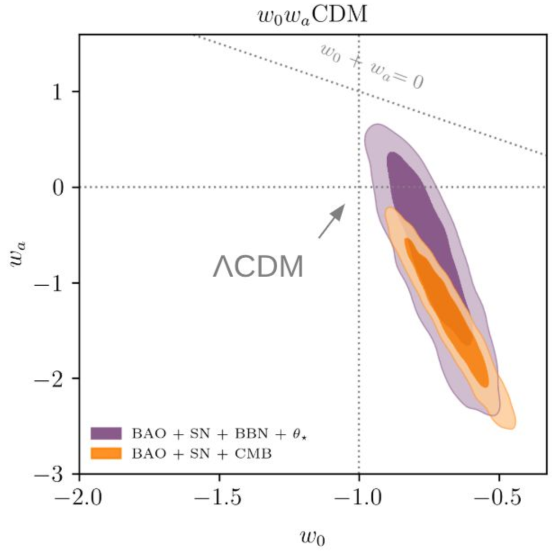
- **All probes compatible.**



Results in w_0w_aCDM

$w_{DE}(a) = w_0 + (1-a)w_a$

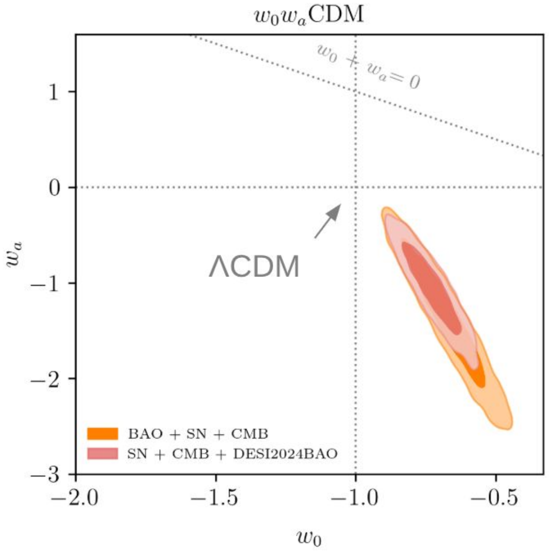
- **All probes compatible.**
- **BAO+SN+CMB:** 3.2σ deviation from ΛCDM.
- Only background (BAO+SN+BBN+$\theta_\star$): 2.8σ.



Results in w_0w_aCDM

$$w_{DE}(a) = w_0 + (1 - a)w_a$$

- **All probes compatible.**
- **BAO+SN+CMB:** 3.2σ deviation from ΛCDM.
- Only background (BAO+SN+BBN+$\theta_\star$): 2.8σ.
- Similar deviation from ΛCDM as DESI-DR1 (+ DES-SN + CMB): 3.6σ.

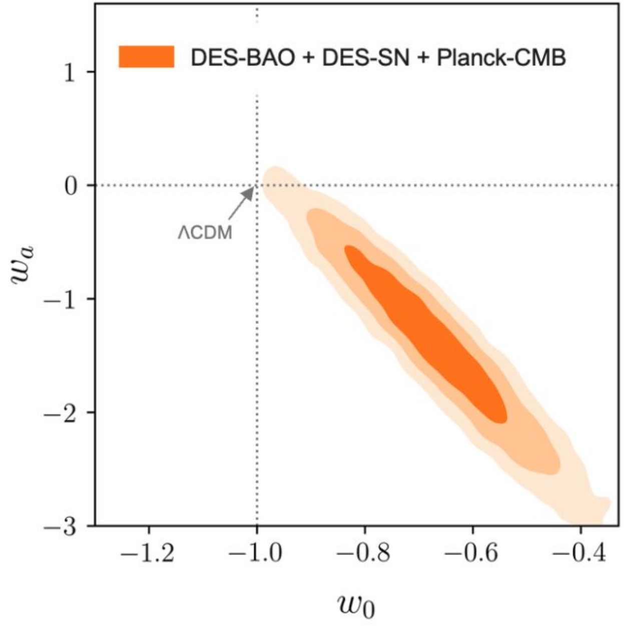


Baseline result: $w_0 w_a$CDM

- **Combination of BAO and SN from the final DES dataset with CMB from Planck.**

- **BAO+SN+CMB:** 3.2σ deviation from ΛCDM

  (g.o.f. $\Delta\chi^2 = 11.6$, 2.7σ)



Conclusions

Conclusions

- These cosmology results from DES Y6 BAO and DES Y5 SN represent a culmination of what the completed Dark Energy Survey can tell us about the expansion of the Universe via geometric probes (arXiv:2503.06712).

Conclusions

- These cosmology results from DES Y6 BAO and DES Y5 SN represent a culmination of what the completed Dark Energy Survey can tell us about the expansion of the Universe via geometric probes (arXiv:2503.06712).

- In ΛCDM and the one-parameter extensions we considered, BAO tends to pull combined constraints towards lower Ω_m, SN towards higher Ω_m, with some ~2-3σ tensions between data combinations.

Conclusions

- These cosmology results from DES Y6 BAO and DES Y5 SN represent a culmination of what the completed Dark Energy Survey can tell us about the expansion of the Universe via geometric probes (arXiv:2503.06712).

- In ΛCDM and the one-parameter extensions we considered, BAO tends to pull combined constraints towards lower Ω_m, SN towards higher Ω_m, with some ~2-3σ tensions between data combinations.

- All data sets are compatible in $w_0 w_a$CDM.

Conclusions

- These cosmology results from DES Y6 BAO and DES Y5 SN represent a culmination of what the completed Dark Energy Survey can tell us about the expansion of the Universe via geometric probes (arXiv:2503.06712).

- In ΛCDM and the one-parameter extensions we considered, BAO tends to pull combined constraints towards lower Ω_m, SN towards higher Ω_m, with some ~2-3σ tensions between data combinations.

- All data sets are compatible in w_0w_aCDM.

- We found a **~3σ preference for w_0w_aCDM**.

Thanks for your attention!

Back up slides

Data sets: CMB

1. Temperature and polarization anisotropy (CMB)

We incorporate measurements of the CMB temperature and polarization anisotropies using the *Planck* 2018 likelihood [51], which we will subsequently refer to using the label "CMB". Specifically, for temperature and polarization spectra for $\ell \geq 30$, we employ the `Plik-lite` likelihood, which incorporates the effects of marginalizing over *Planck* foreground and nuisance parameters and includes measurements of spectra up to $\ell_{\rm max} = 2508$ for TT, and $\ell_{\rm max} = 1996$ for TE and EE. Following the standard *Planck* analysis, at low multipoles ($2 \leq \ell < 30$) we use the `Commander` likelihood for the TT spectrum and the `SimAll` likelihood for the EE polarization spectrum. We do not include CMB lensing constraints.

2. Angular scale of the acoustic peak ($\theta_\star$)

In order to isolate geometric/background information from the CMB, in some cases we instead consider a constraint on

$$\theta_\star = r_s(z_\star)/D_M(z_\star) \ , \tag{4}$$

the ratio between the baryon-photon sound horizon and the comoving distance at the redshift of recombination, $z_\star$. We incorporate this via a Gaussian likelihood taken from the same *Planck* 2018 temperature and polarization data described above, [53], having

$$100\,\theta_\star = 1.04109 \pm 0.00030\,. \tag{5}$$

For ease of comparison, we note that the $\theta_\star$ likelihood used in DESI analyses [20] has a nearly identical mean based on *Planck* 2018 constraints which include lensing, but DESI additionally increased this width by 75% to account for possible modeling uncertainties.

Priors

Parameter	Prior
ΛCDM	
H_0 [km s^{-1}Mpc^{-1}]	[55, 91]
Ω_m	[0.1, 0.9]
Ω_b	[0.03, 0.07]
kΛCDM	
Ω_k	[-0.25, 0.25]
wCDM	
w	[-3, -0.33]
$w_0 w_a$CDM	
w_0	[-3, -0.33]
w_a	[-3, 3]
νΛCDM	
$\sum m_\nu [eV]$	[0, 1]
Chains that include CMB	
τ	[0.04, 0.15]
$A_s \times 10^9$	[0.5, 5.0]
n_s	[0.87, 1.07]
a_{Planck}	(1.0, 0.0025)

Quoting tensions with ΛCDM

To quantify preferences for an extended model relative to ΛCDM we compare constraints on cosmological parameters. To do so, we compute the probability of a shift in the alternative model's added cosmological parameters relative to their corresponding ΛCDM values. This probability is defined as:

$$\Delta(D, M) \equiv \int_{P(\mathbf{p} \mid D,M) > P(\mathbf{p}^* \mid D,M)} P(\mathbf{p} \mid D, M) \mathrm{d}\mathbf{p} \,, \qquad (19)$$

where $\mathbf{p}$ represents the additional parameters of the model M with respect to ΛCDM (e.g., w_0 and w_a in $w_0 w_a$CDM), and $\mathbf{p}^*$ denotes the ΛCDM values of these parameters (e.g. $w_0 = -1$, $w_a = 0$). This integral quantifies the posterior mass exceeding the iso-density contour defined by the ΛCDM posterior value, $P(\mathbf{p}^* \mid D, M)$. Note that if the extra parameters have flat priors, as it is in the cases considered here, this result is parameter invariant.

We always report results as the effective number of standard deviations. Given an event of probability Δ, it is given by [74]:

$$n_\sigma \equiv \sqrt{2}\, \mathrm{Erf}^{-1}(\Delta) \,. \qquad (21)$$

This corresponds to the number of standard deviations that an event with the same probability would have had if it had been drawn from a Gaussian distribution.

Comparison with other approaches

- Our approach:
  - for weakly constrained posteriors, its reported significance may be impacted by how prior bounds (including in other parameter directions) shape the marginalized posteriors of the beyond-ΛCDM parameters.

- Evidence ratios:
  - more directly sensitive to the choice of parameters' prior ranges.

- Frequentist $\Delta\chi^2$ improvements:
  - less sensitive to the prior and projection effects.
  - subject to the uncertainty due to noise in the χ^2 minimization procedure.
  - translating $\Delta\chi^2$ estimates to model comparison significances relies on assumptions of Gaussianity – both of the likelihood in data space and of the posterior in parameter space – which may not hold for all data combinations we consider.
  - equivalent to our approach in the limit of Gaussian posteriors.

Deviations from ΛCDM

	Deviations from **ΛCDM** (σ)		
Dataset	$\boldsymbol{k\Lambda}$**CDM**	$\boldsymbol{w}$**CDM**	$\boldsymbol{w_0 w_a}$**CDM**
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**

TABLE II. Statistical significance, in σs, of deviations from ΛCDM based on shifts in the additional parameter(s) in the extended model: Ω_k in $k\Lambda$CDM, w in wCDM and $\{w_0, w_a\}$ in $w_0 w_a$CDM. See the methodology described in Section III C 1. For the case of t_U priors, we consider the fiducial Gaussian prior case and, in parenthesis, the case where only a lower bound on t_U is set. We highlight in bold the case for BAO+SN+CMB, our most constraining combination, which in the $w_0 w_a$CDM model shows a 3.2σ deviation from ΛCDM.

Deviations from ΛCDM (from $\Delta\chi^2$)

	$\Delta\chi^2$ improvement compared to **ΛCDM**		
Dataset	k**ΛCDM**	w**CDM**	$w_0 w_a$**CDM**
BAO + SN + BBN	1.0 (0.5)	1.6 (0.8)	5.7 (1.6)
BAO + SN + $\theta_\star$	2.9 (1.3)	3.8 (1.6)	5.0 (1.4)
BAO + SN + $\theta_\star$ + BBN	9.3 (2.3)	10.4 (3.0)	10.9 (2.6)
SN	1.0 (0.5)	1.6 (0.8)	5.9 (1.6)
CMB	5.0 (2.0)	0.4 (0.0)	0.9 (0.0)
SN + CMB	8.3 (2.7)	3.8 (1.6)	7.4 (2.0)
BAO + CMB	0.8 (0.3)	7.3 (2.5)	7.8 (2.1)
BAO + SN + CMB	1.1 (0.5)	3.5 (1.5)	**11.6 (2.7)**

TABLE III. Improvement in goodness-of-fit from freeing additional model parameters computed via the difference between the minimum χ^2 estimated for ΛCDM and that for each extended model. Positive values indicate an improved fit in the extended model. Numbers in parentheses indicate the statistical significance in σs assuming a Gaussian approximation for the posterior, which may not be accurate for less constraining data combinations.

$$\mathrm{CDF}_{\chi^2}\left(\Delta\chi^2_{\mathrm{MAP}}\,|\,2\,\mathrm{dof}\right) = \frac{1}{\sqrt{2\pi}}\int_{-N}^{N} e^{-t^2/2}\,dt$$

Quoting tensions between datasets

We start by building the posterior distribution of parameter differences. We consider each dataset, and in particular the two data sets denoted 1 and 2, to be independent. Under the assumption that the two-parameter sets that describe the datasets, $\mathbf{p}_1, \mathbf{p}_2$, differ, the joint distribution of their parameter determinations is given by the product of their posteriors:

$$P(\mathbf{p}_1, \mathbf{p}_2 | d_1, d_2) = P_1(\mathbf{p}_1 | d_1) P_2(\mathbf{p}_2 | d_2). \tag{1}$$

To compute the distribution of parameter differences, we change variables by defining $\Delta\mathbf{p} \equiv \mathbf{p}_1 - \mathbf{p}_2$, including all parameters shared by the two datasets. The distribution of $\Delta\mathbf{p}$ is obtained by marginalizing over one of the parameters:

$$P(\Delta\mathbf{p}) = \int P_1(\mathbf{p}) P_2(\mathbf{p} - \Delta\mathbf{p}) \mathrm{d}\mathbf{p}. \tag{2}$$

The distribution of parameter differences, $P(\Delta\mathbf{p})$, provides insight into whether the parameter determinations from two datasets are consistent. Intuitively, if $P(\Delta\mathbf{p})$ has most of its support when $\Delta\mathbf{p}$ has large deviations from zero, the two parameter sets are incompatible, indicating a tension between the datasets. To quantify the probability of a parameter shift, we calculate it as

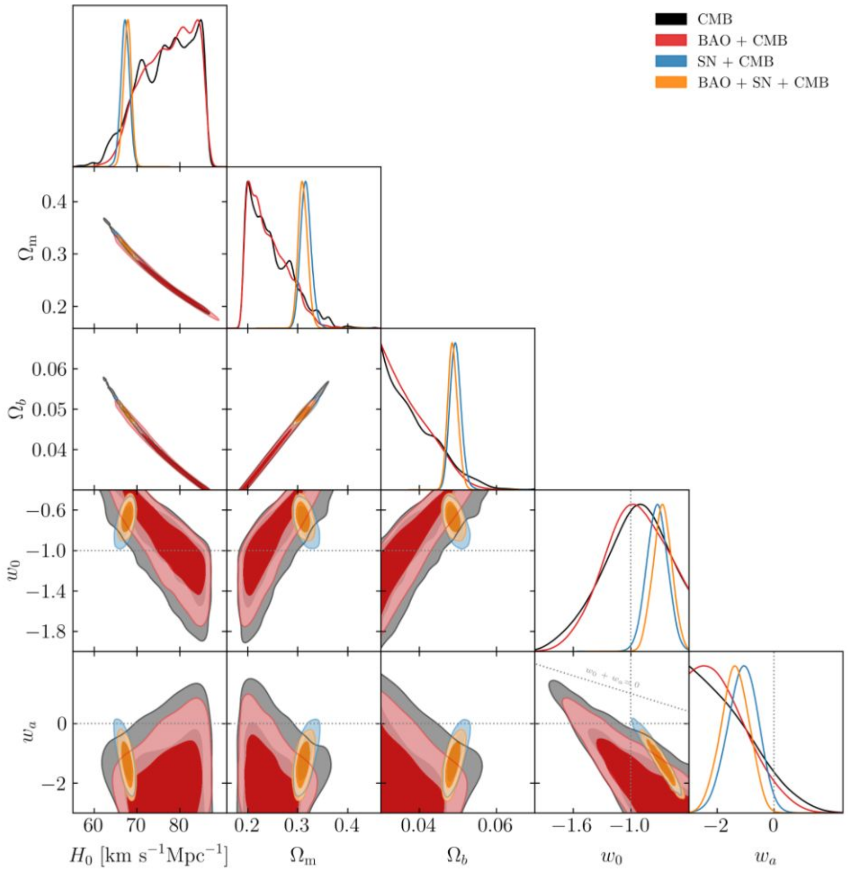
$$\Delta \equiv \int_{P(\Delta\mathbf{p}) > P(0)} P(\Delta\mathbf{p})\, \mathrm{d}\Delta\mathbf{p}, \tag{1}$$

Tensions between datasets

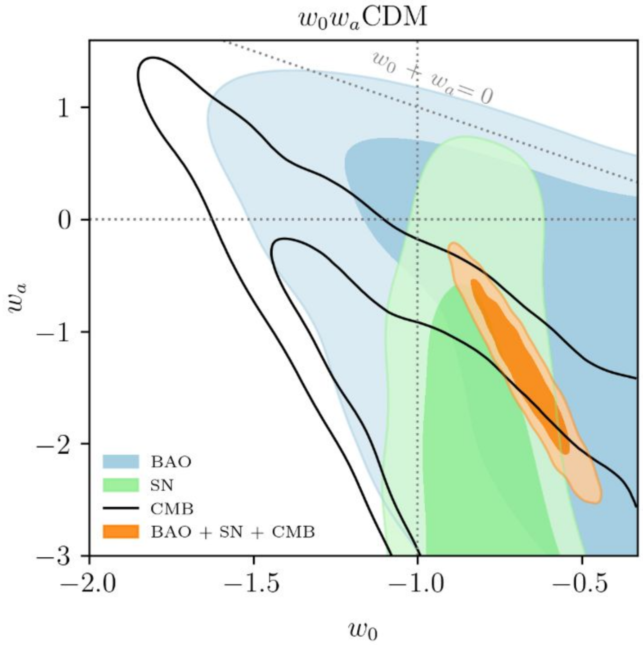
	Tension (σ)				
Datasets	ΛCDM	$k\Lambda$CDM	wCDM	$w_0 w_a$CDM	$\nu\Lambda$CDM
BAO vs SN	0.5	0.0	0.0	0.3	0.2
CMB vs SN	1.7	1.5	1.3	1.1	1.2
CMB vs BAO	2.0	3.2	0.6	0.1	2.0
SN vs BAO + $\theta_\star$	2.4	-	-	-	-
CMB vs BAO + SN + BBN	2.2	3.3	2.2	1.2	-
SN vs BAO + BBN	0.4	-	-	-	-
SN vs BAO + BBN + $\theta_\star$	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)	-

TABLE IV. Tensions, in σs, among independent (combinations of) probes for a given model. See the methodology described in Section III C 2. For the case of t_U priors, we consider the fiducial Gaussian prior case and, in parenthesis, the case where only a lower bound on t_U is set. We note that these tensions are reported in the whole parameter space unlike deviations in Table II, which refer to the parameter additional to ΛCDM.

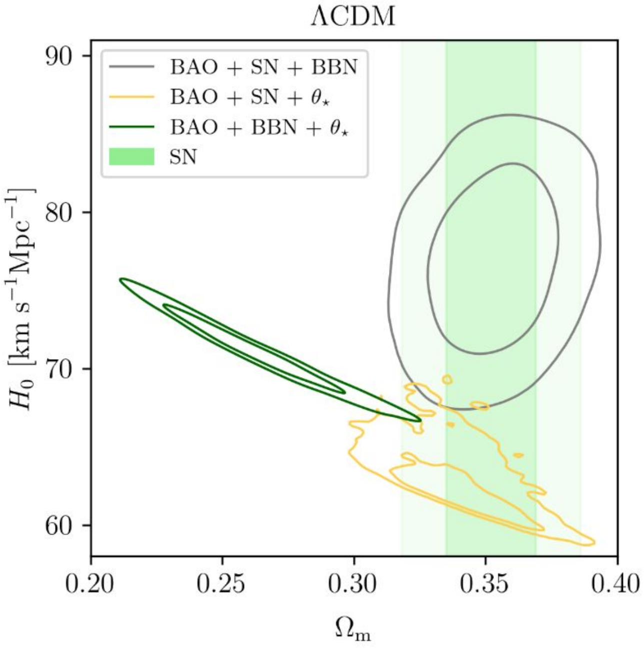
w_0w_aCDM all params

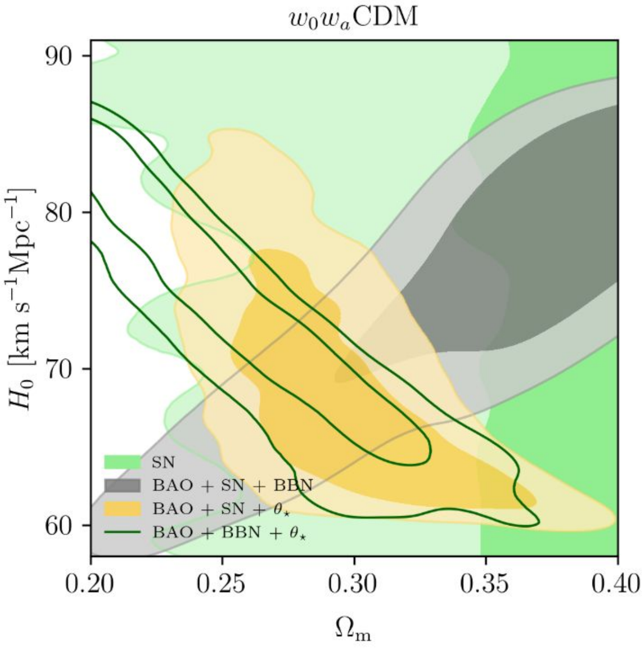


w_0w_aCDM

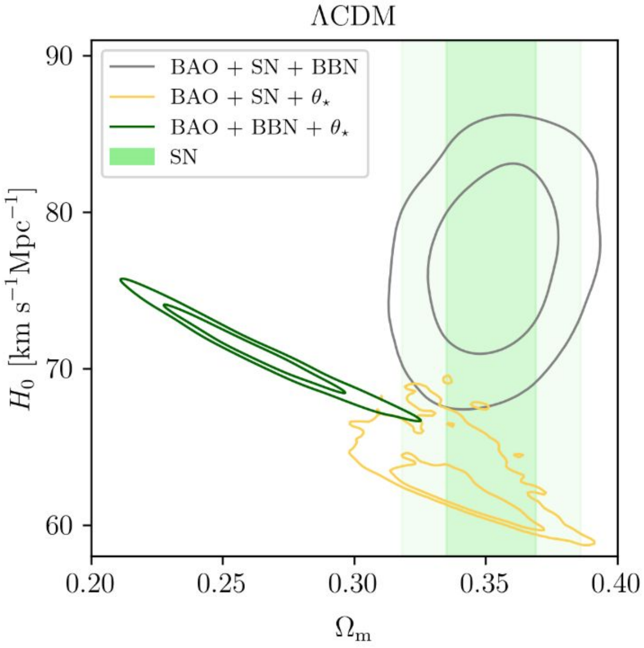


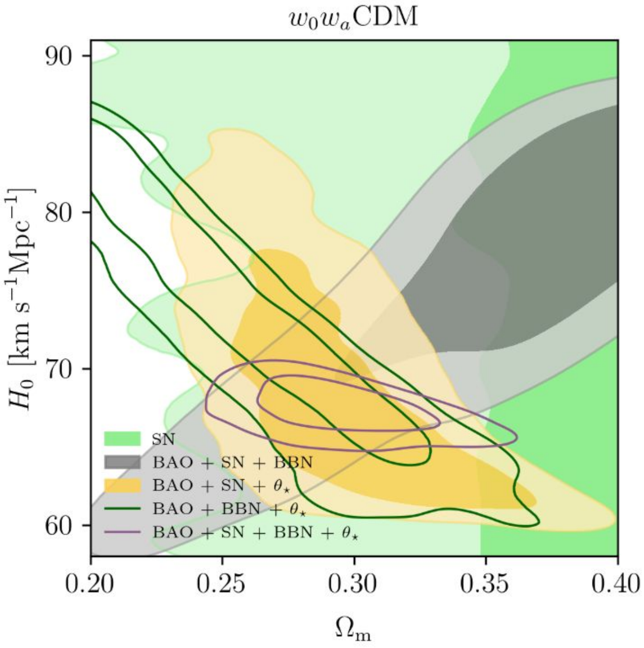
ΛCDM vs. w_0w_aCDM



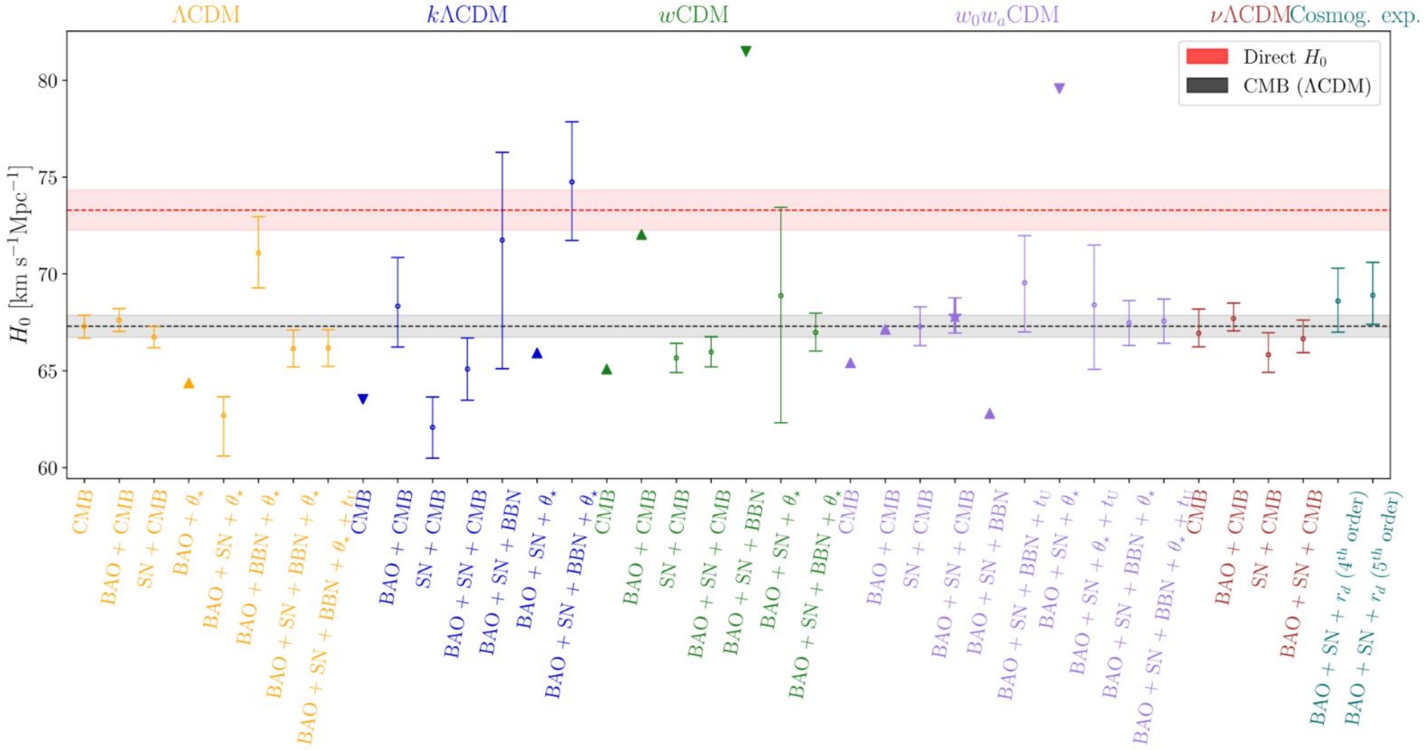


ΛCDM vs. w_0w_aCDM





Hubble constant



DES vs. DESI BAO