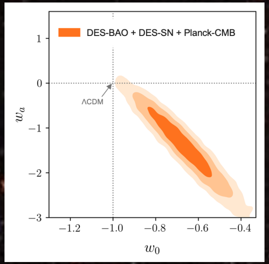
The Dark Energy Survey: expansion history models from the final BAO and SN data



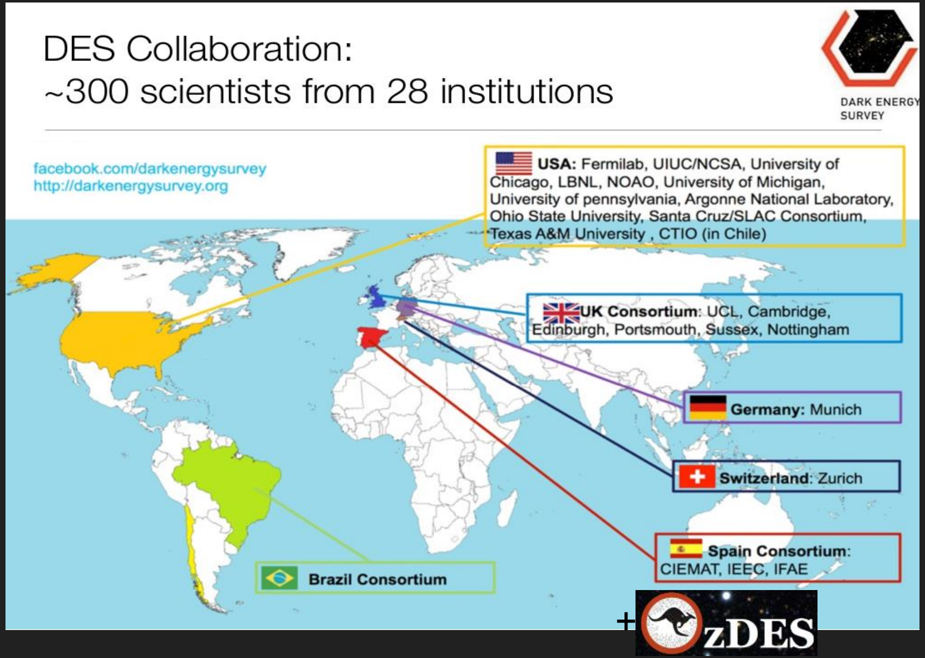
Sesto, Italy
July 8th 2025

Santiago Avila
Ramón y Cajal fellow at CIEMAT, Madrid
Dark Energy Survey Collaboration

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
cfp CIEMAT física de partículas
AGENCIA ESTATAL DE INVESTIGACIÓN
Ayudas Ramón y Cajal
THE DARK ENERGY SURVEY

Dark Energy Survey: Goals

- Constrain the nature of dark energy with four probes:
  - Type Ia Supernovae
  - **Baryonic Acoustic Oscillations**
  - Weak Lensing + Galaxy Clustering
  - Cluster counts



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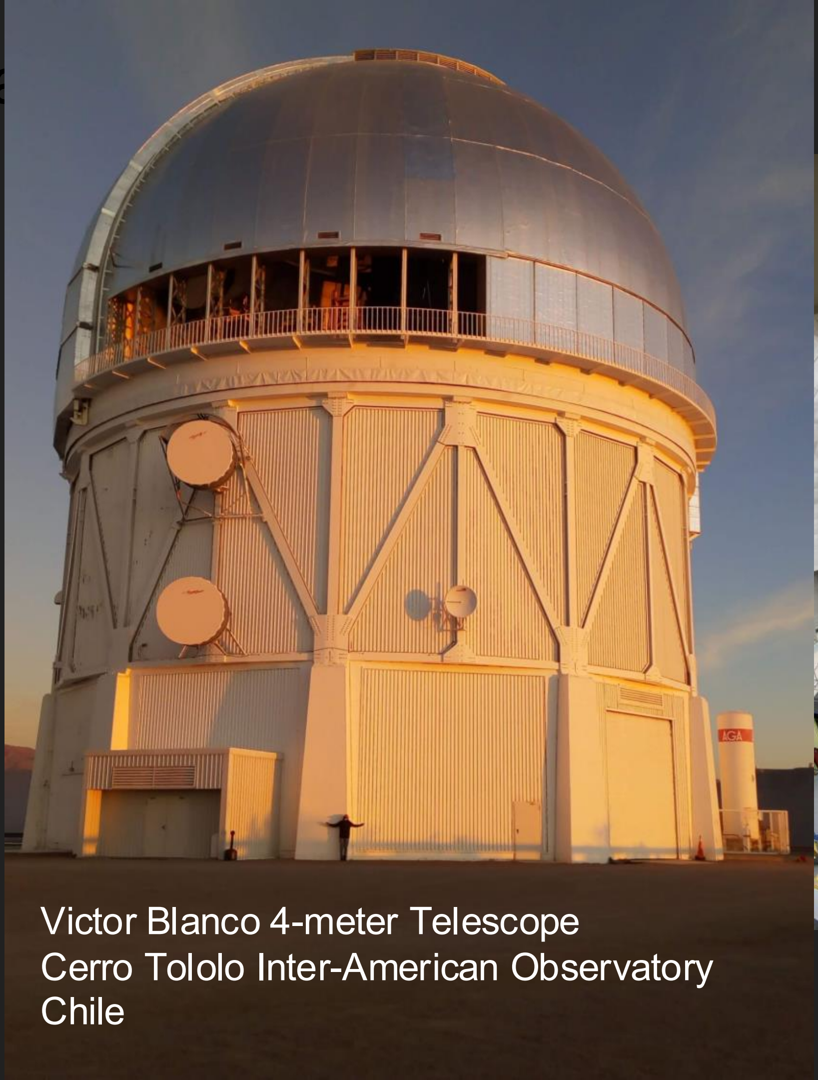
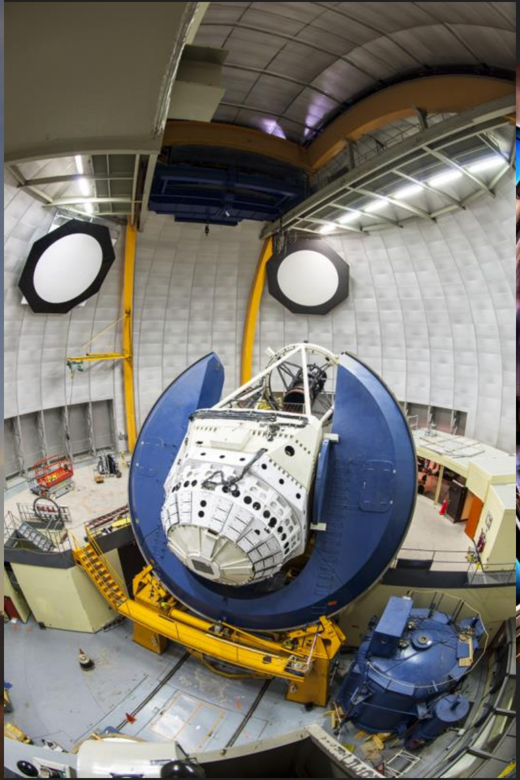
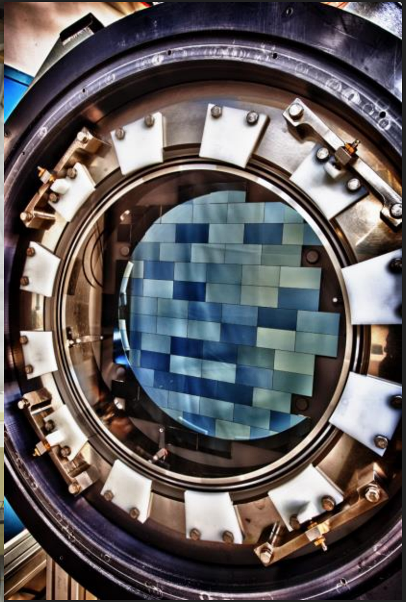


Victor Blanco 4-meter Telescope
Cerro Tololo Inter-American Observatory
Chile





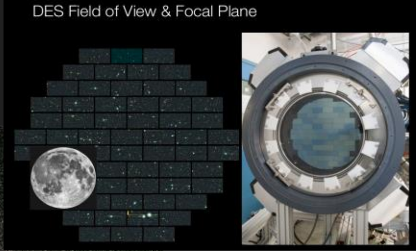
Dark Energy Camera
(DECam)
570Mpix

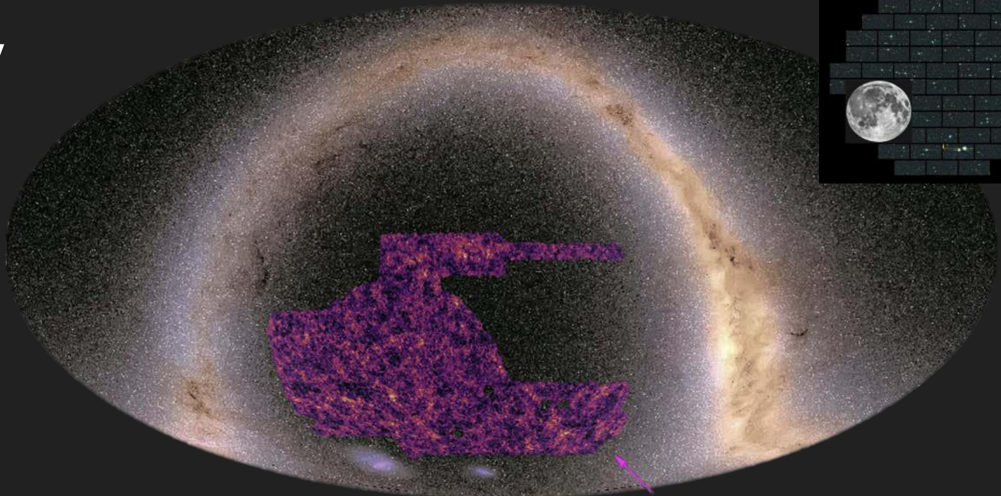
Dark Energy Survey

- 2.2deg field
- 5 bands: g, r, i, z, Y

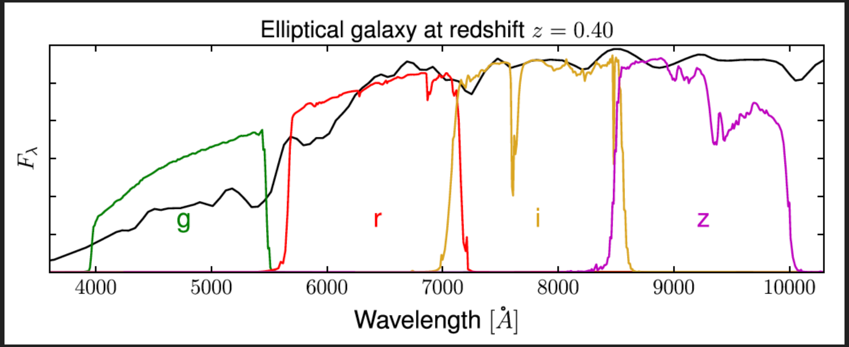
- Wide survey (6 years):
  - 5000 deg^2
  - Depth: i=23.8
  - >100 million galaxies with shapes and photo-z up to z~1.4

- Type Ia Supernova survey:
  - ~3deg^2 x10 fields
  - ~5-day cadence
  - 5 seasons (~6 month each)





N. Jeffrey, Dark Energy Survey Collaboration



BAO as a standard ruler

- Sound waves propagate in the early Universe up to ~recombination (drag epoch)
- Primordial overdensities at the center + overdensities form at the sound horizon radius (r_d)

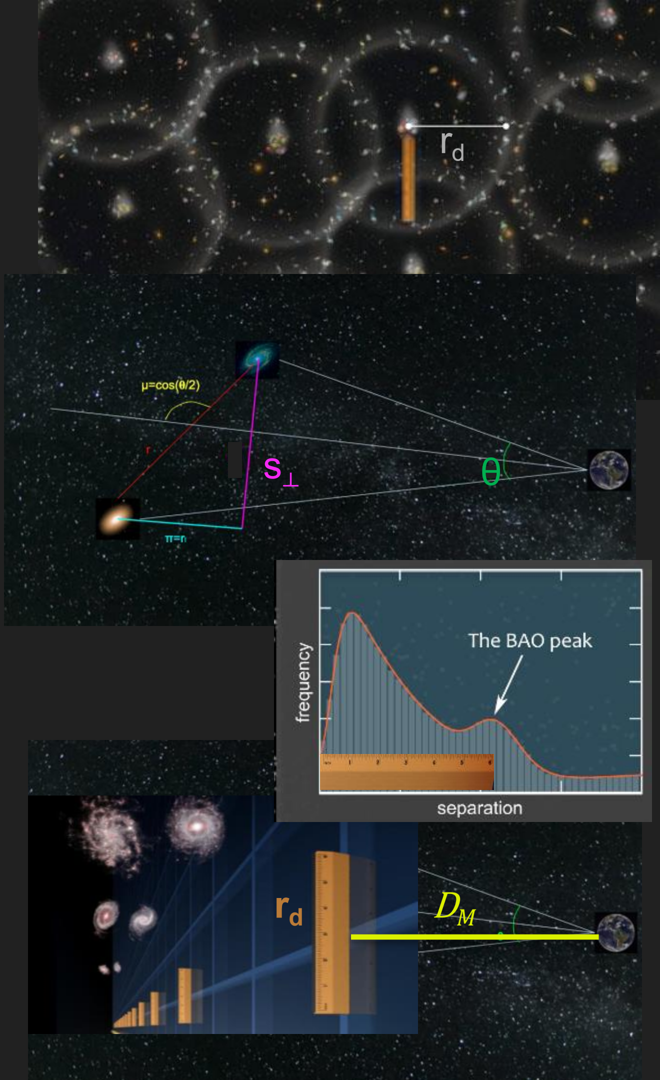
$$r_d = \int_{z_d}^{\infty} \frac{c_s(z; \Omega_b h^2)}{H(z)} dz$$

- Excess of galaxy pair counts separated by this distance $\Rightarrow$ Standard ruler
- The angular distance-redshift relation depends on cosmology

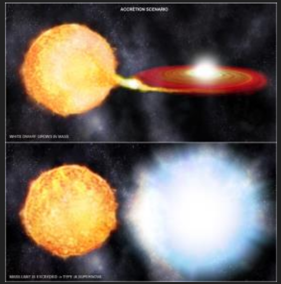
$$D_M(z) = c\, S_k \left[\int \frac{dz}{H(z)} \right],$$

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

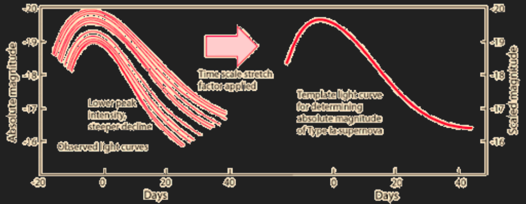
$$\left(\frac{H(a)}{H_0}\right)^2 = \Omega_M \cdot a^{-3} + \Omega_K \cdot a^{-2} + \Omega_{DE} \cdot a^{-3(1+w_a+w_0)}\, e^{-3w_a(1-a)}$$



Type Ia Supernova as standard candle

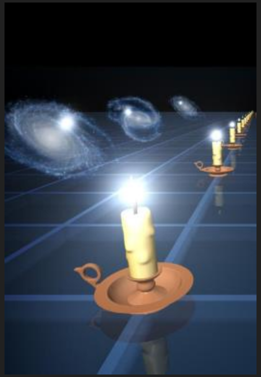


- Binary system of a white-dwarf (WD) and another star
- The WD accretes matter until reaching the Chandrasekhar limit => **SN Ia explosion**



- The peak luminosity of these SNe is standardizable

- Distance-redshift relation tells us about the expansion of the Universe



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

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Main probes:

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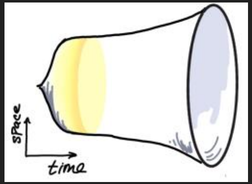
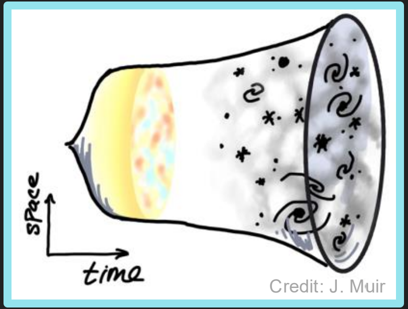
- Cluster counts

Expansion history



Growth of structure



Dark Energy Survey: Goals

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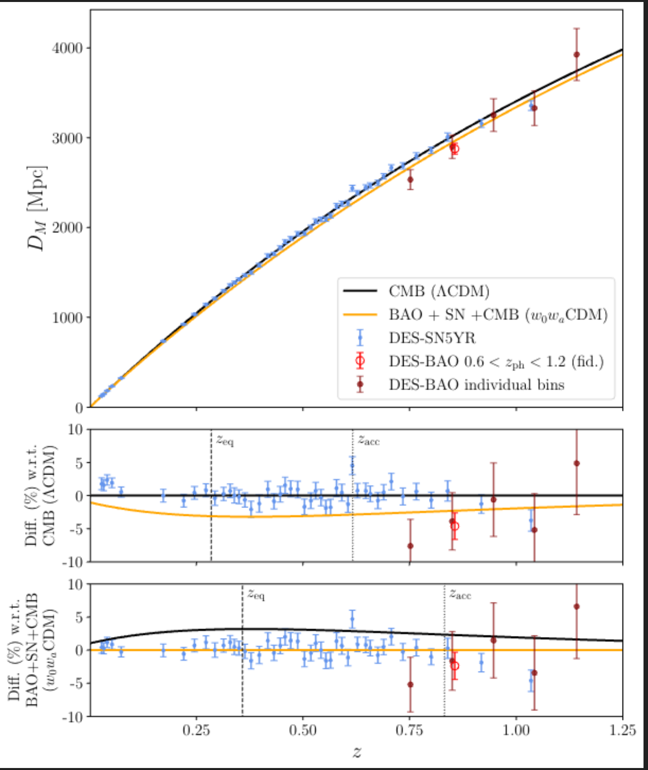
$\}$ Expansion history (this work)



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

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DES Collaboration 2025, arXiv:2503.06712

DES Y6 BAO

- Optimized BAO galaxy sample: 16 million red & bright galaxies (Mena-Fernández+2402.10696)
- 6 tomographic bins in $0.6<z_{ph}<1.2$
- 3 redshift estimators
- 3 clustering statistics
- Tests over 2000 simulations
- Blinding and lots of checks

DES BAO team

2402.10696


J. Mena-Fernandez


S. Avila


M. Rodriguez-Monroy


A. Porredon


I. Ferrero


H. Camacho


K. C. Chan

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

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- 3 redshift estimators
- 3 clustering statistics
- Tests over 2000 simulations
- Blinding and lots of checks

- Isolate the BAO peak position in α, with all the cosmology information

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

Angular distance

BAO scale (sound horizon)

DES BAO team

2402.10696


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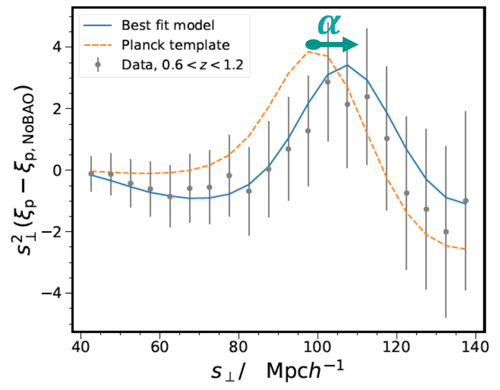
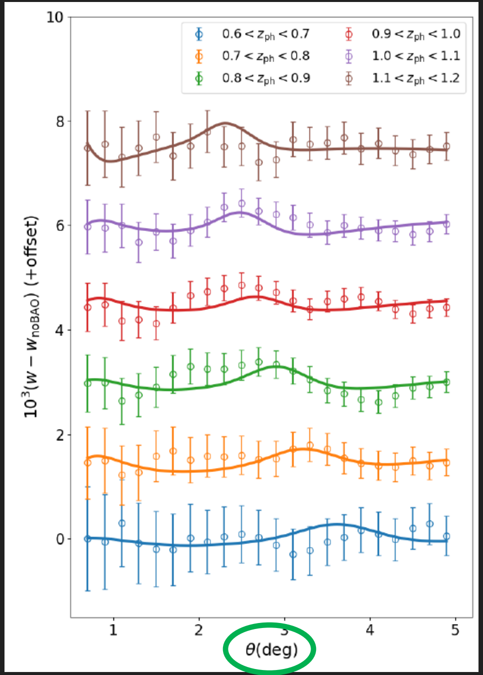
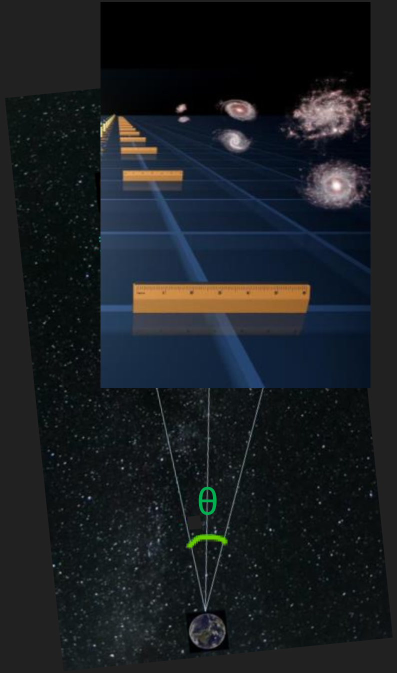
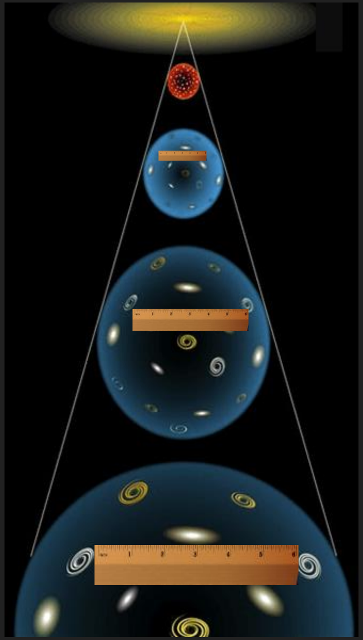


Galaxy Clustering: BAO signal

- Angular Correlation Function







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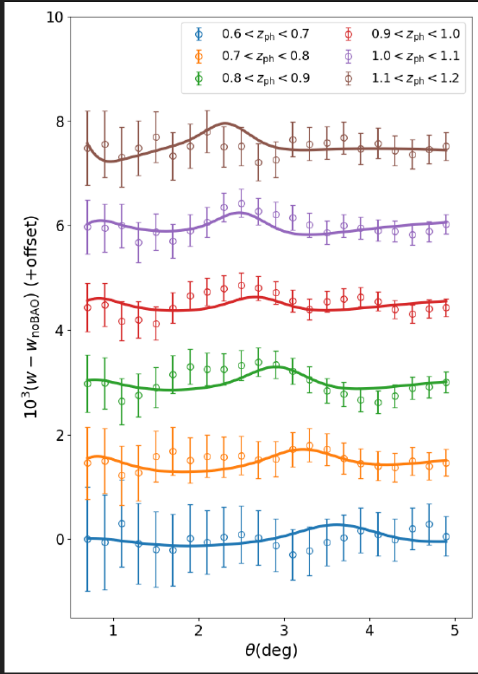
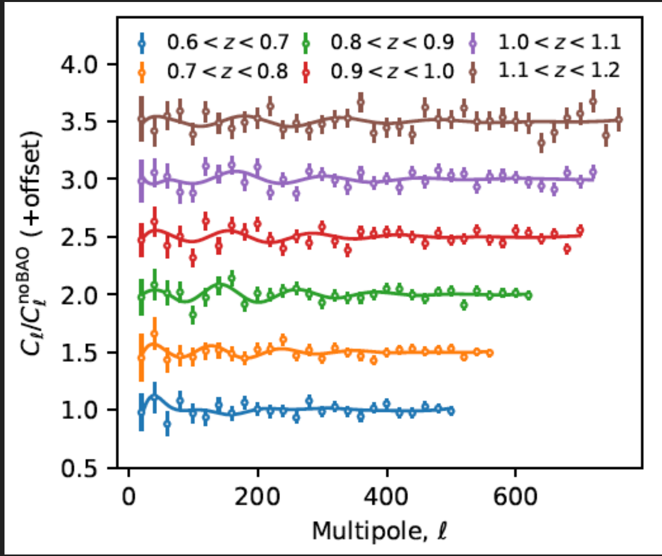


- Angular Power Spectrum



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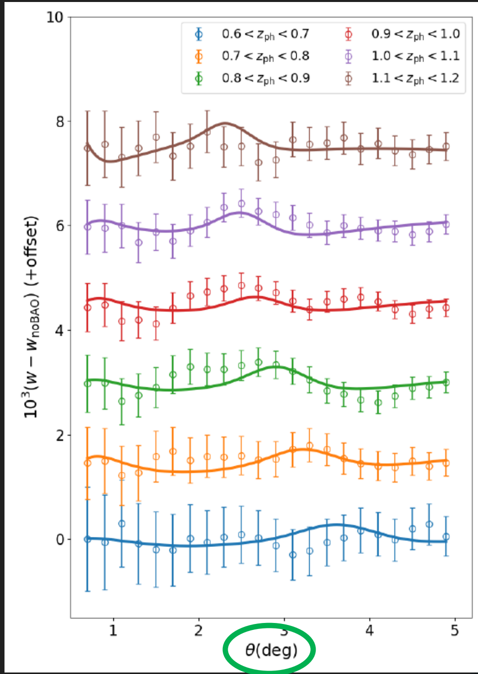
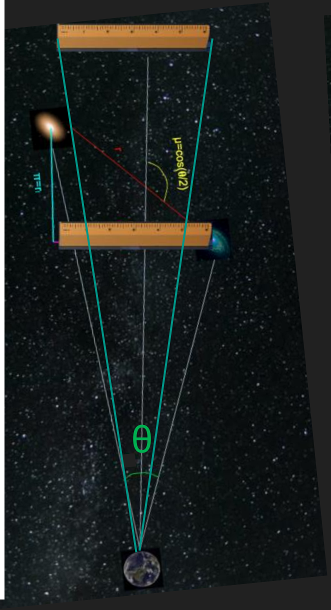
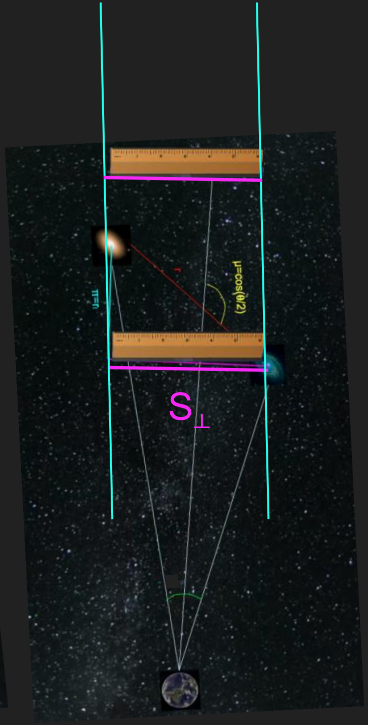
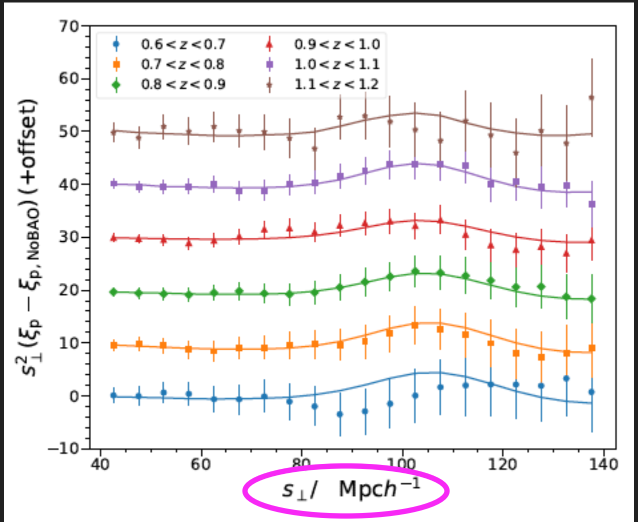






- Projected Correlation Function

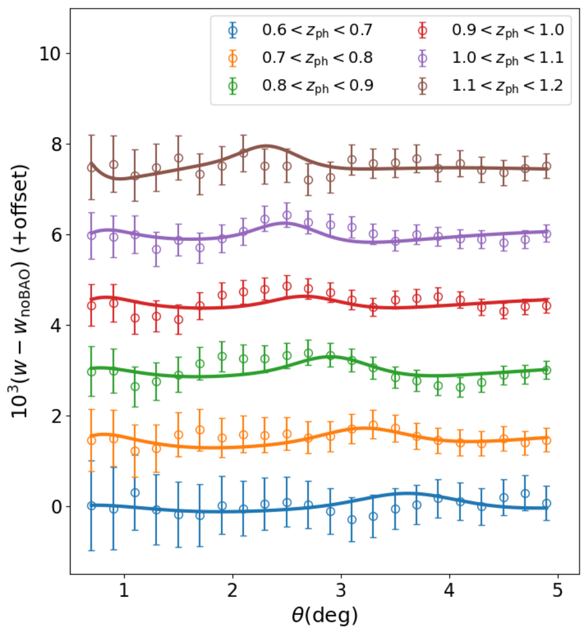


Comoving transverse distance

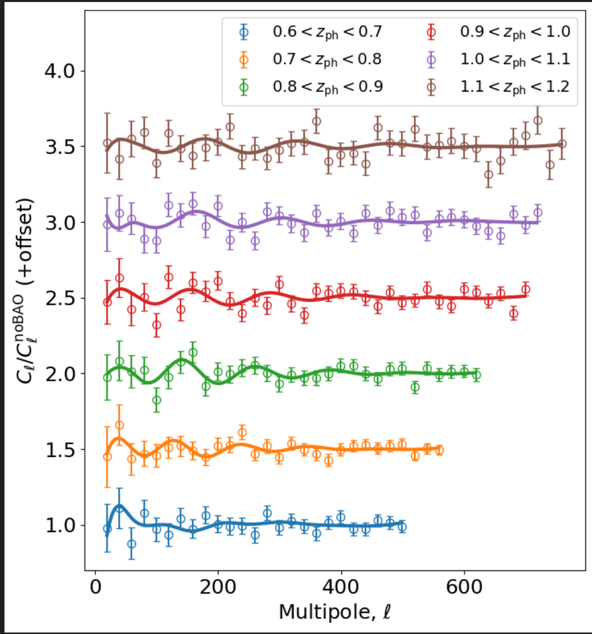
S. Avila for the Dark Energy Survey Collaboration – Y6 BAO 2402.10696

Galaxy Clustering: BAO signal

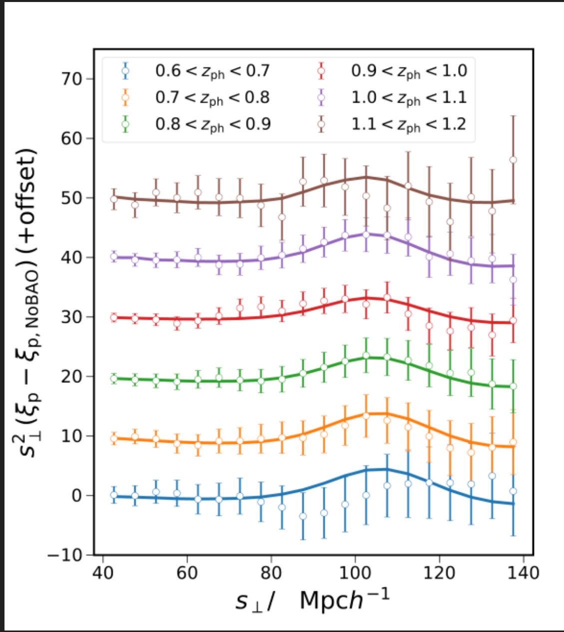
Angular Correlation Function (ACF)



Angular Power Spectrum (APS)

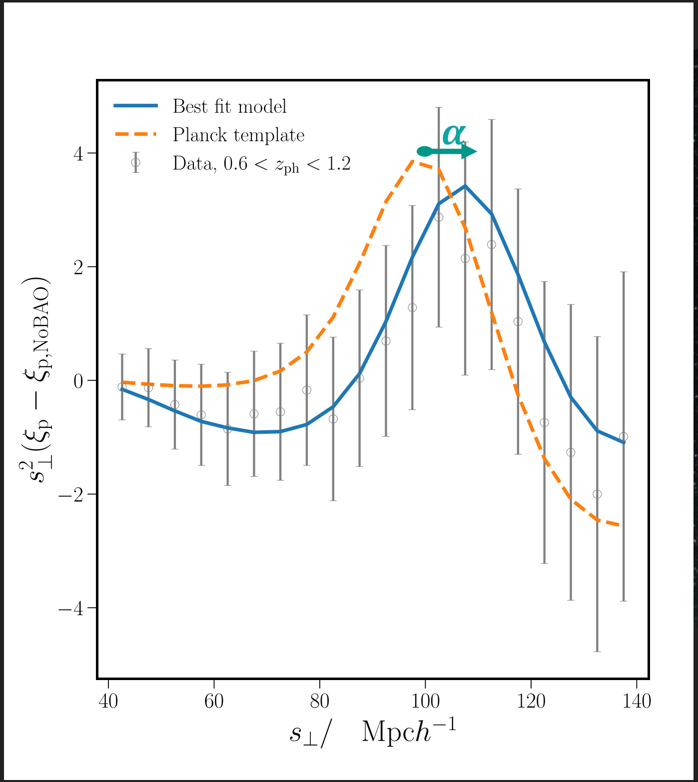


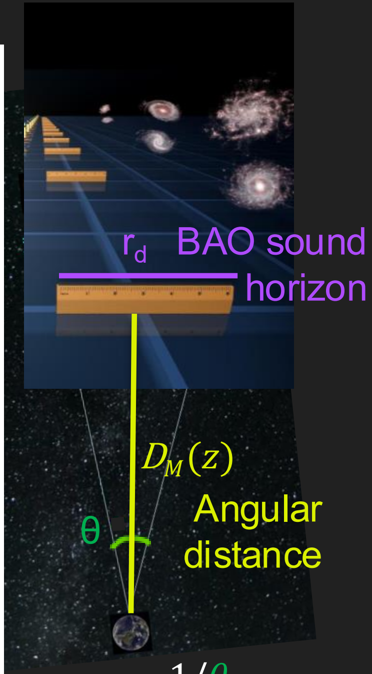
Projected Correlation Function (PCF)



S. Avila for the Dark Energy Survey Collaboration – Y6 BAO 2402.10696

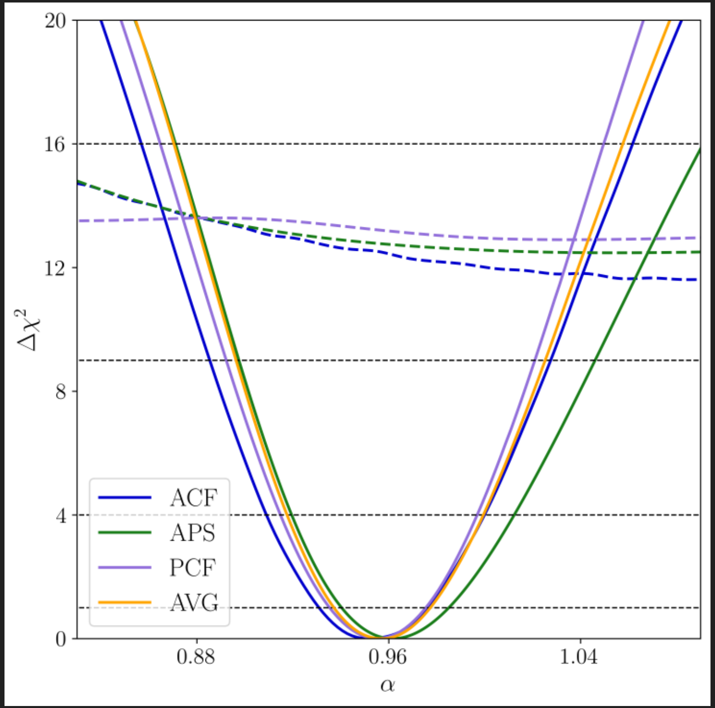
All SNR in one 2PCF:
(not used as default)





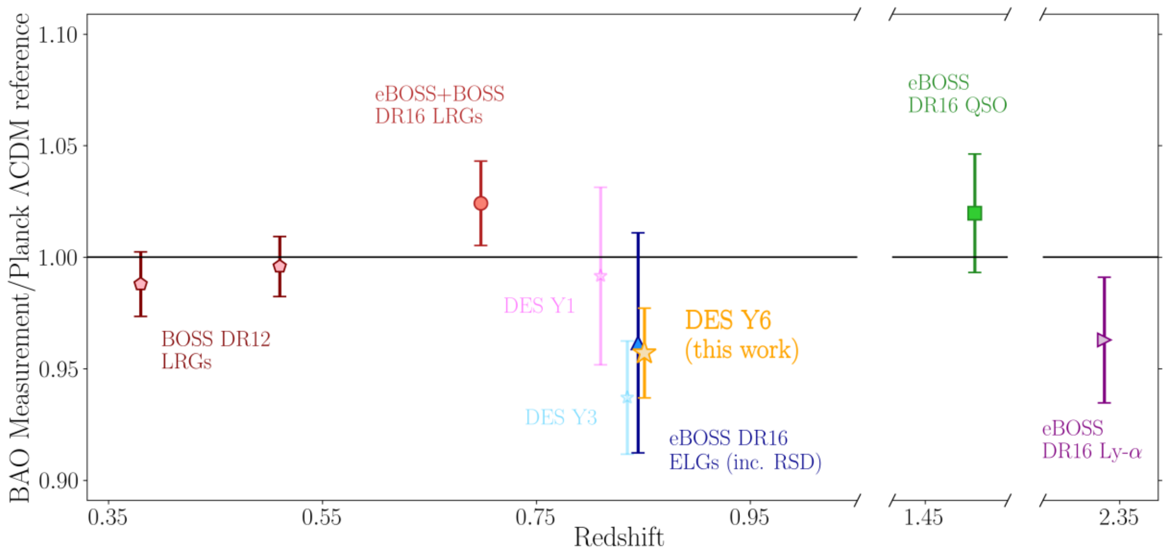
$$\alpha = \frac{1/\theta_{measured}}{1/\theta_{expected}} = \frac{D_M(z)/r_d}{(D_M/r_d)_{Planck}}$$

Likelihood



S. Avila for the Dark Energy Survey Collaboration – Y6 BAO 2402.10696

BAO angular distance-ladder at the end of Stage-III



DES Collaboration 2402.10696 $\alpha = \mathbf{0.9571 \pm 0.0201}$

+ eBOSS collaboration 2007.08991

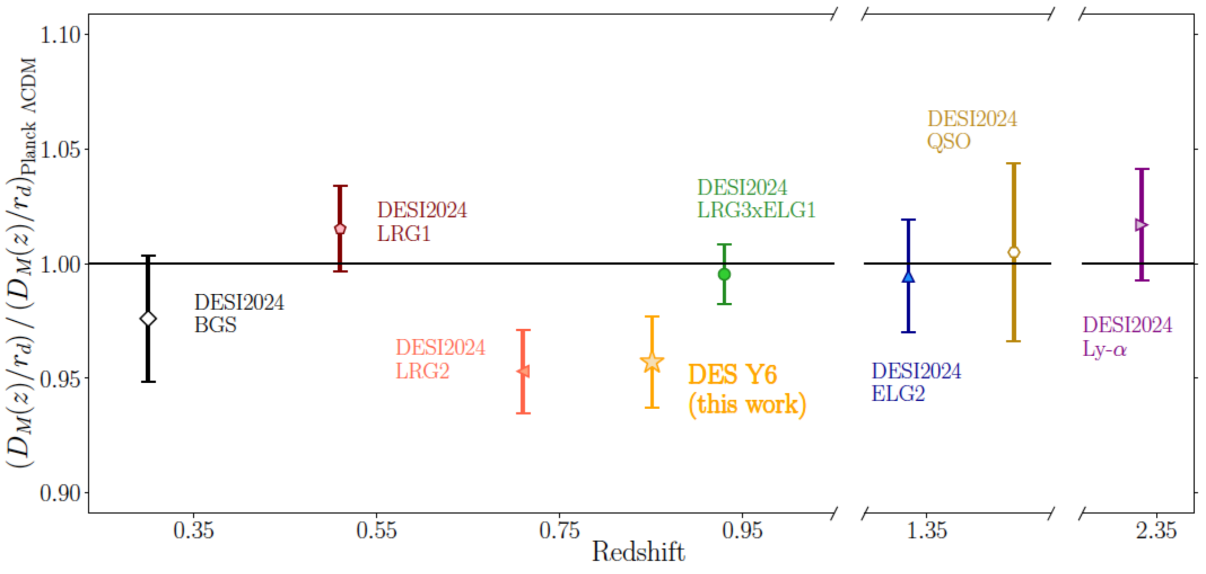
DES Y6 BAO:

- 2.1% precision angular BAO measurement

$$\frac{D_A(z_{eff} = 0.85)}{r_d} \cdot (1+z) = 19.51 \pm 0.41$$

- 4.3% and 2.1σ below Planck
- 3.5σ significance of the BAO peak
- Most precise BAO measurement from a photometric survey
- Competitive with spectroscopic surveys, designed for BAO
- Most precise stage-III angular BAO at z>0.75.
- In agreement with central value of eBOSS ELGs, but ½ error.
- This is the screenshot of angular BAO at the closure of stage-III

BAO angular distance-ladder released in 2024



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+ DESI collaboration 2404.03000

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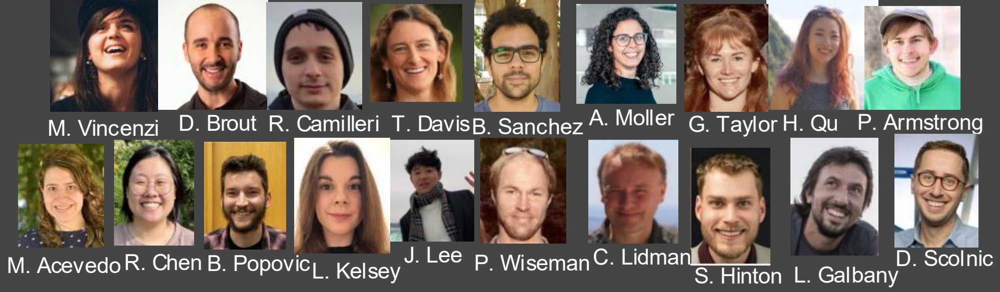
- Most precise BAO measurement from a photometric survey
- 1 angular BAO, which is. competitive with spectroscopic surveys, designed for BAO
- This is the snapshot of the angular BAO released in 2024

DES Y5 SN is the largest and deepest supernova sample ever compiled from a single telescope.

DES Collaboration 2024, arXiv:2401.02929



DES SN team

+ A. Carr, M. Sullivan, M. Sako, R. Kessler, J. Lee, E. Kovacs, M. Smith, and others! ++

- 1635 photometrically classified SNe Ia
  - calibrated to 5 mmag accuracy
  - Spectra for host galaxy redshifts (OZDES)
- For cosmology, combined with data from 194 low-z SN from other samples

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

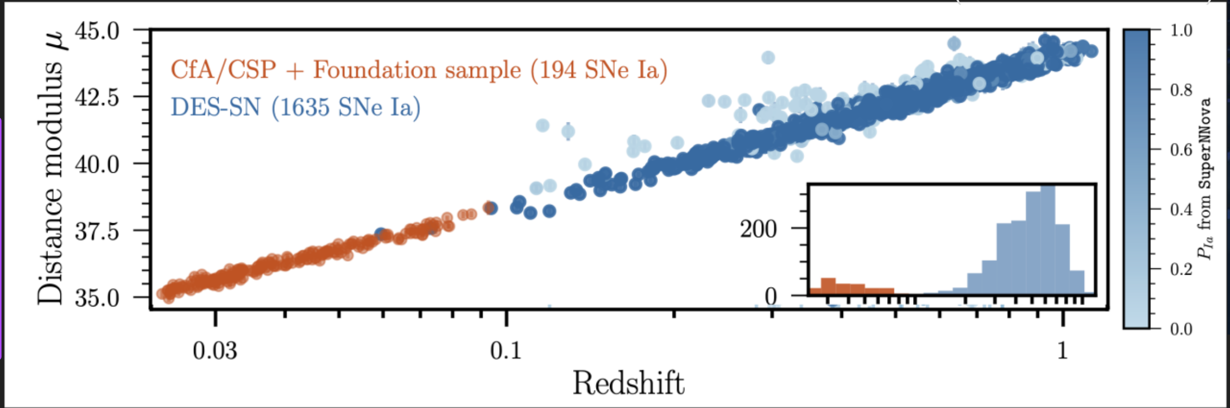
Calibrated distance modulus

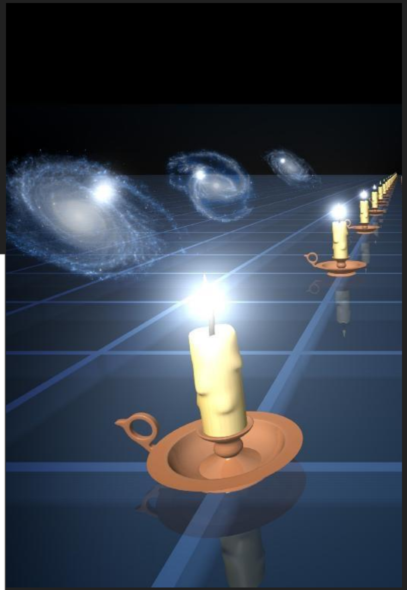
Measured magnitude

SN intrinsic mag. (degenerate with H_0)

Depends on SN color, stretch, host galaxy mass, sample selection, (calib. w simulations)

$$\propto \log_{10}\left[\frac{D_L(z)}{10\text{pc}}\right]$$



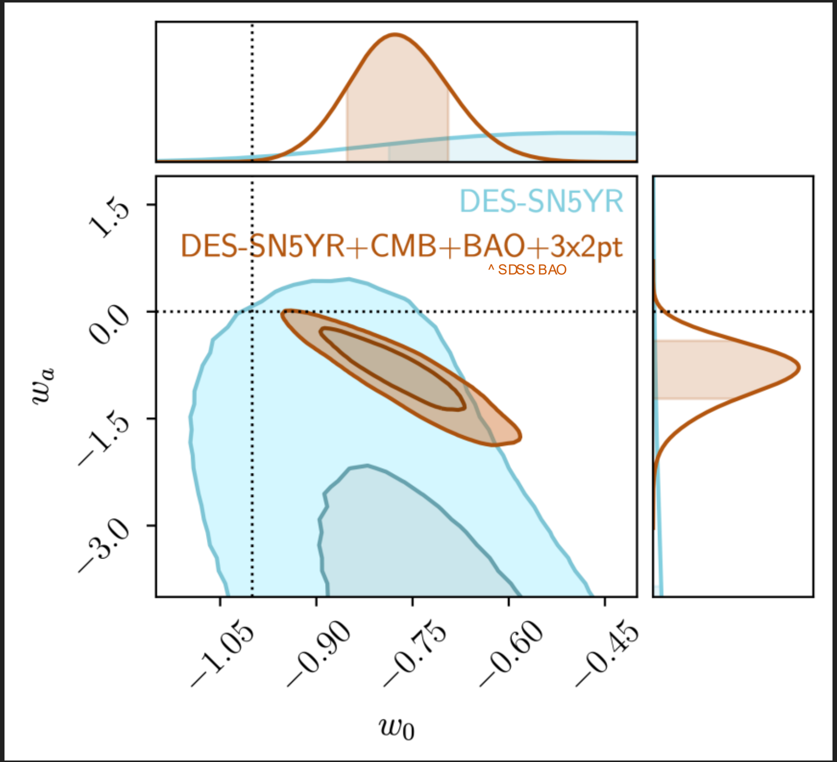


DES Y5 SN: main results

- If we allow the equation of state ($w=P/\rho$) of dark energy to vary

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

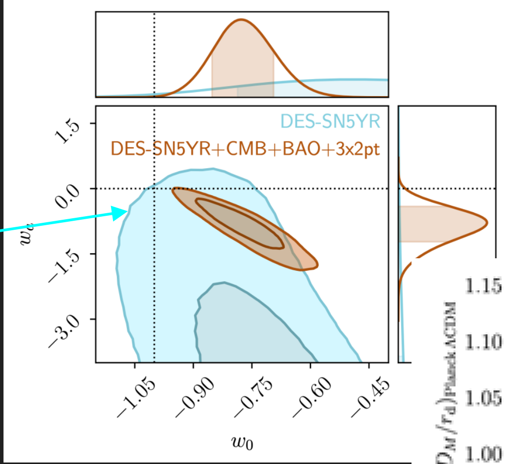
- SN shows a ~2σ deviation from ΛCDM ($w_0=-1$, $w_a=0$)
- Larger significance, if combined with other probes

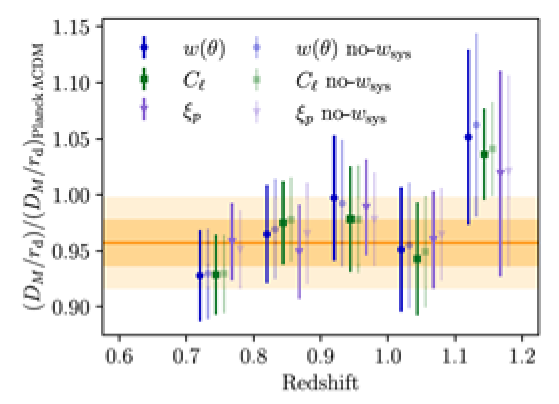


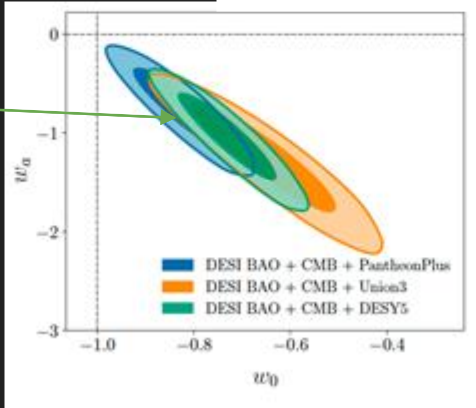
DES Collaboration 2024, arXiv:2401.02929

2024: Λ's Annus Horribilis

- January 2024, **DES-SN:** ~2σ preference for w_0w_aCDM
- February 2024, **DES-BAO:** ~2.1σ $D_M(z=0.85)/r_d$ deviation from Planck-ΛCDM
- April 2024, **DESI-BAO + CMB + DES-SN**: ~3.9σ preference for w_0w_aCDM







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} Expansion history (this work)


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J. Muir


S. Avila


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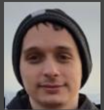
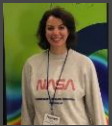
M. Vincenzi


R. Camilleri


T. Davis

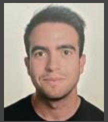
DES BAO+SN comb. team


P. Shah

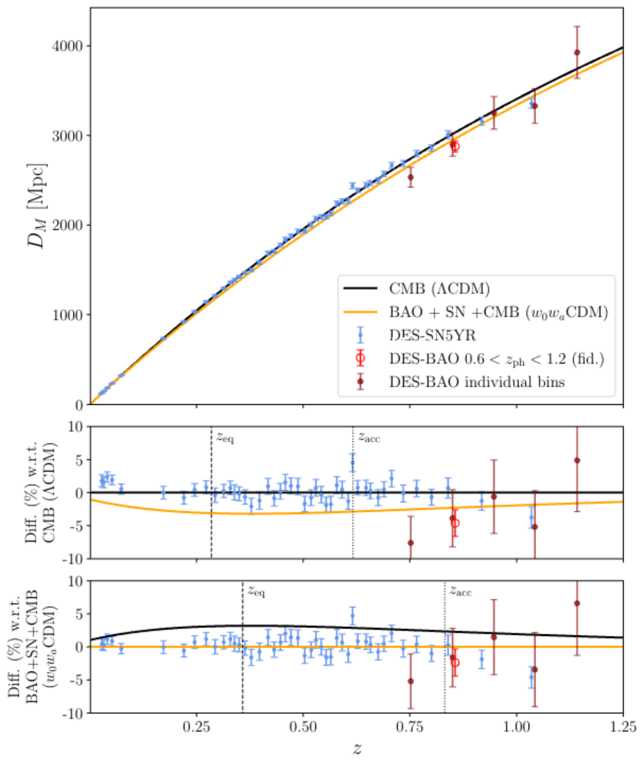

A. Ferté


G. Campailla


M. Raveri


N. Deiosso

+ P. Wiseman, D. Huterer, S. Lee, C. Chang, M. Toxel, + BAO team, + SN team, + exts. team



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DES Collaboration 2025, arXiv:2503.06712

DES BAO+SN

DES Collaboration 2025, arXiv:2503.06712

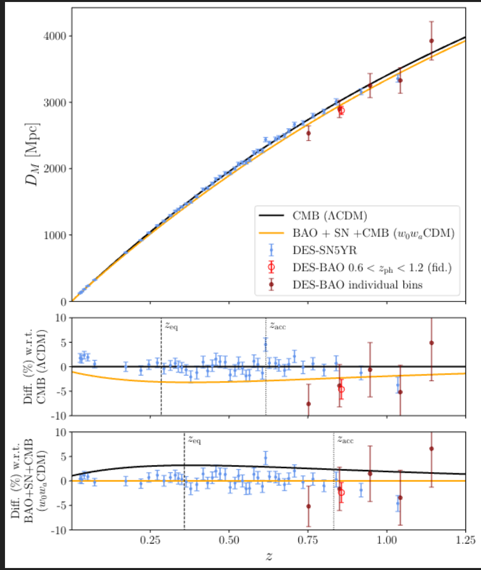
- BAO - DES Y6 BAO
- SN - DES Y5 SN
- CMB = Planck 2018 temperature and polarization power spectra
- θ* - angular scale of the acoustic peak of the CMB spectra
- BBN - Big Bang nucleosynthesis constraints on baryon density

THE DARK ENERGY SURVEY

2402.10696
2401.02929

$D_M(z)/r_d$

$D_L(z)/L_{SN}$



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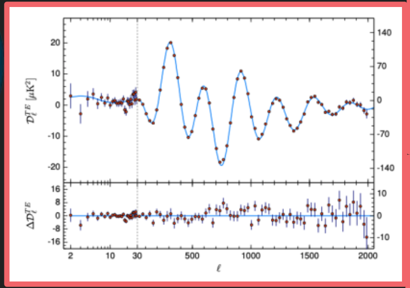
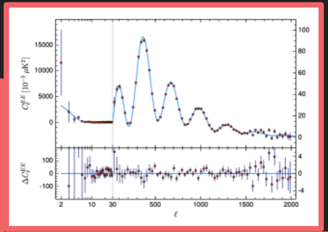
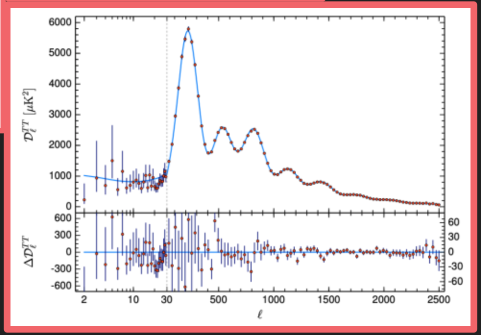
THE DARK ENERGY SURVEY







(Planck Collaboration 2020)

DES BAO+SN

DES Collaboration 2025, arXiv:2503.06712

- BAO - DES Y6 BAO
- SN - DES Y5 SN
- 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)

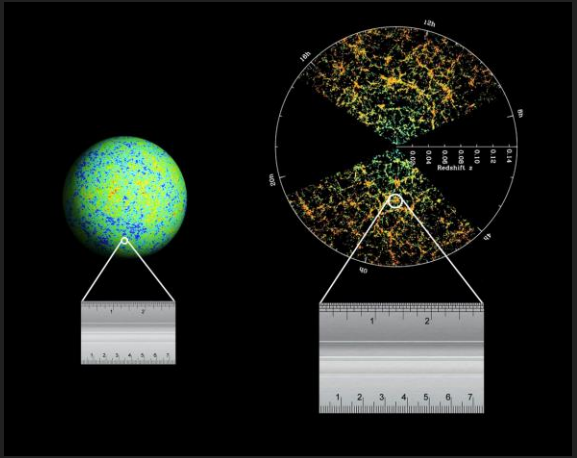
THE DARK ENERGY SURVEY

2401.02929
2402.10696.

(Planck Collaboration 2020)

$$100\,\theta_\star = 1.04109 \pm 0.00030$$

$$\theta_\star = \frac{r_\star}{D(z_\star)}$$



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THE DARK ENERGY SURVEY

2401.02929
2402.10696

$D_M(z)/r_d$

esa
planck

(Planck Collaboration 2020)

$$\Omega_b h^2 = 0.02218 \pm 0.00055$$

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z; \Omega_b h^2)}{H(z)} dz$$

DES BAO+SN ΛCDM: tensions

DES Collaboration 2025, arXiv:2503.06712

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- θ* - angular scale of the acoustic peak of the CMB spectra
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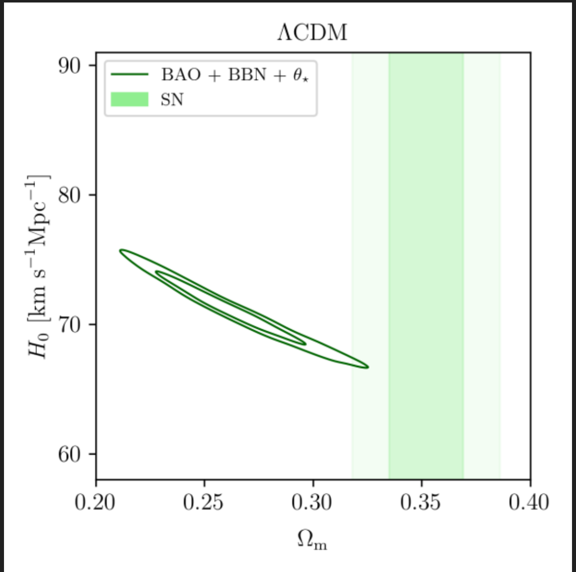
Hubble parameter



Matter density

DES BAO+SN ΛCDM: tensions

DES Collaboration 2025, arXiv:2503.06712

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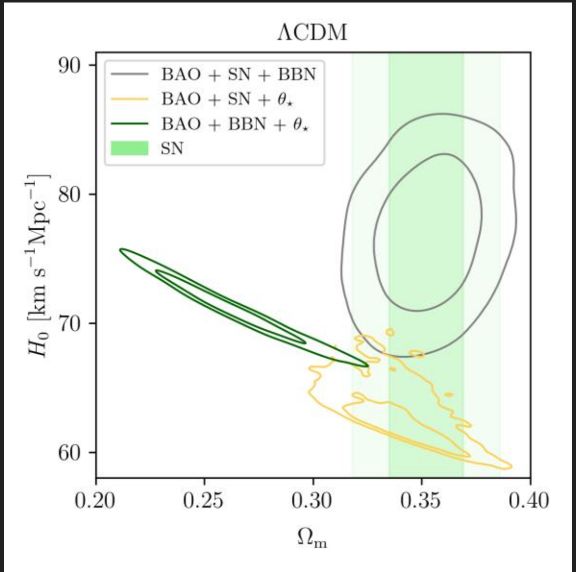

Matter density

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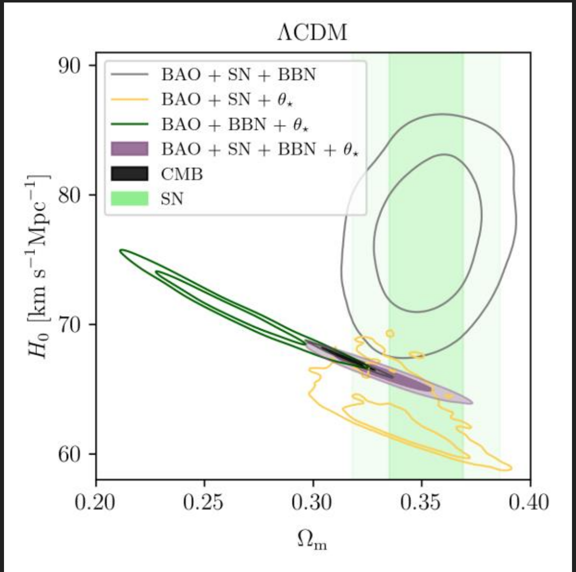

Matter density

DES BAO+SN ΛCDM: tensions

DES Collaboration 2025, arXiv:2503.06712

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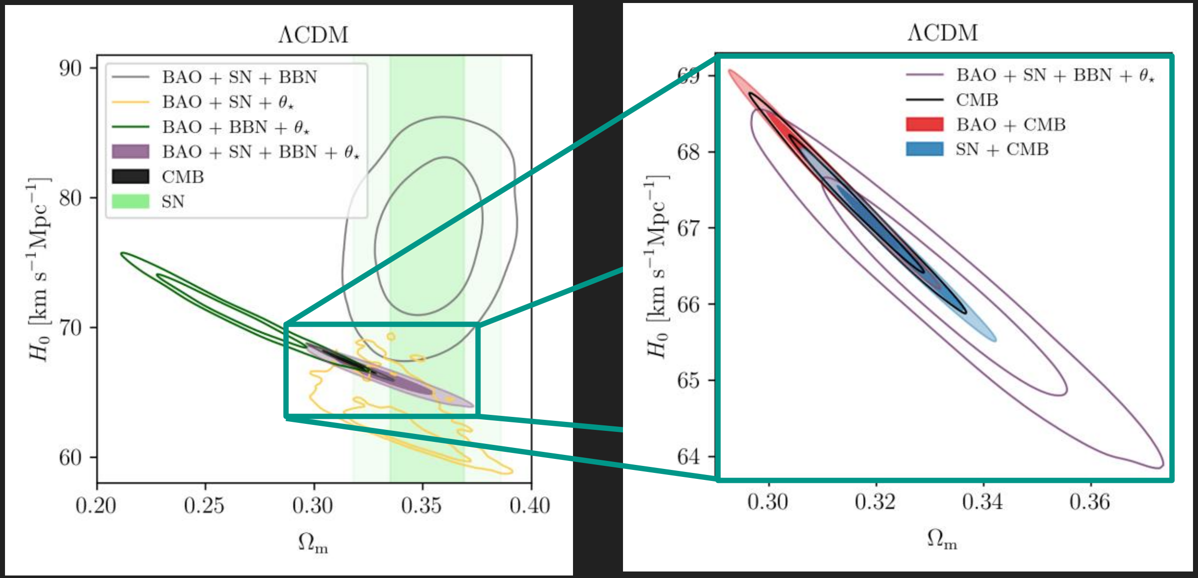


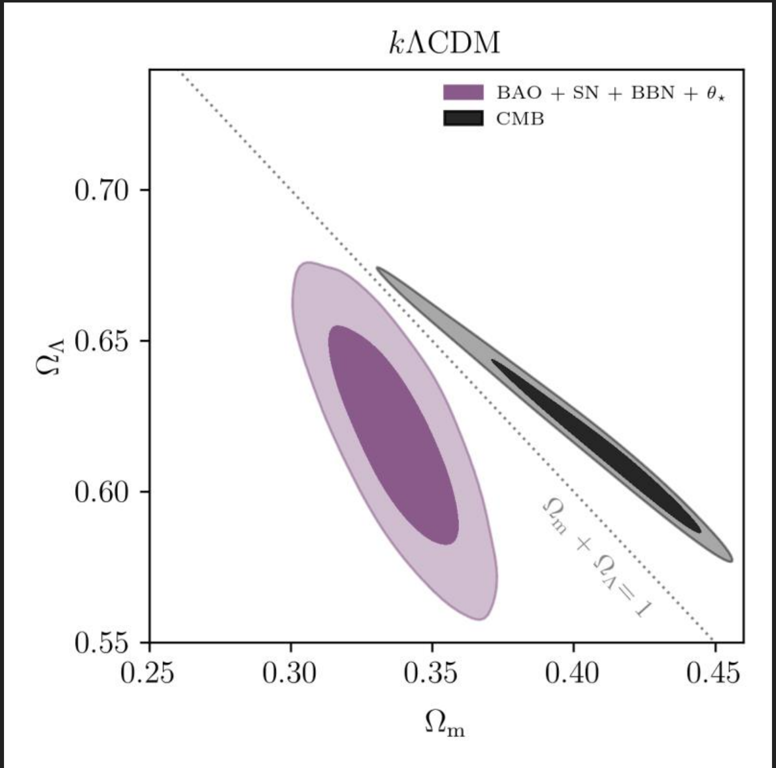
Matter density

BAO tends to pull constraints towards lower Ω_m, SN towards higher Ω_m, producing several 2-3σ tensions between datasets.

DES expansion history models: kΛCDM

$$\Omega_k = 1 - \Omega_M + \Omega_\Lambda \neq 0$$
$$\propto a^{-2}$$

- Tensions among probes persist or increase



DES Collaboration 2025, arXiv:2503.06712

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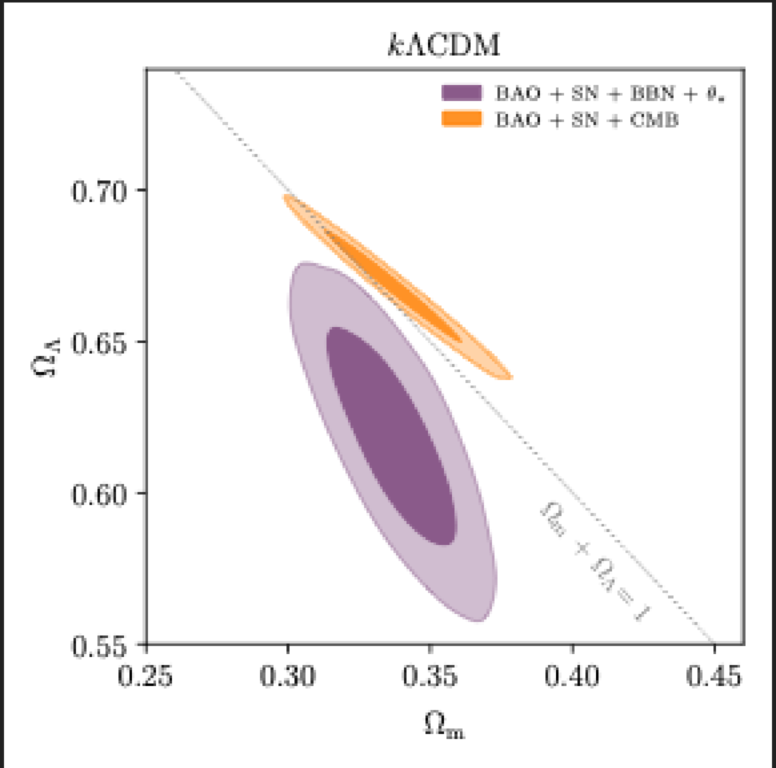
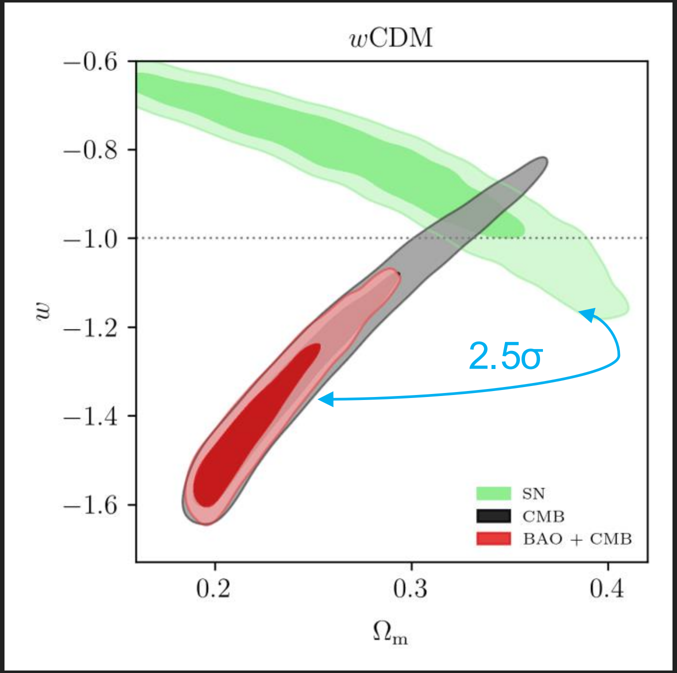


DES Collaboration 2025, arXiv:2503.06712

DES expansion history models: wCDM

$\Omega_{DE}(a) = (1 - \Omega_M)\, a^{-3(1+w)}$

- Tensions among probes persist
  ~2-3σ: e.g. SN vs. CMB+BAO



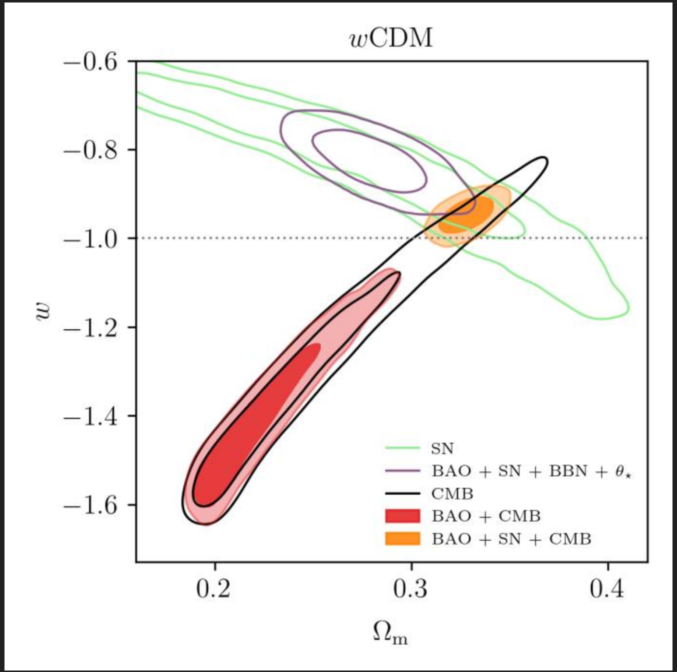
DES Collaboration 2025, arXiv:

DES expansion history models: wCDM

$$\Omega_{DE}(a) = (1\text{-}\ \Omega_M)\ a^{-3(1+w)}$$

- Tensions among probes persist ~2-3σ
- Most constraining case BAO+SN+CMB:

  $w=-0.948\pm0.028$
- BAO and SN still push in different directions
  - Different effective redshift
  - Evolving dark energy?

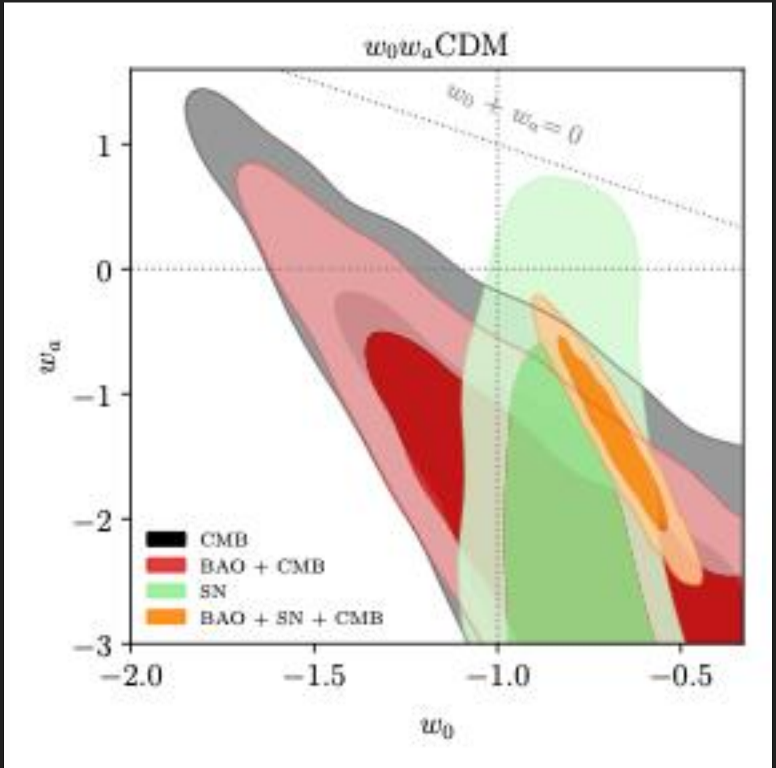


DES Collaboration 2025, arXiv:2503.06712

DES expansion history models: $w_0 w_a$CDM

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

- **All probes compatible**

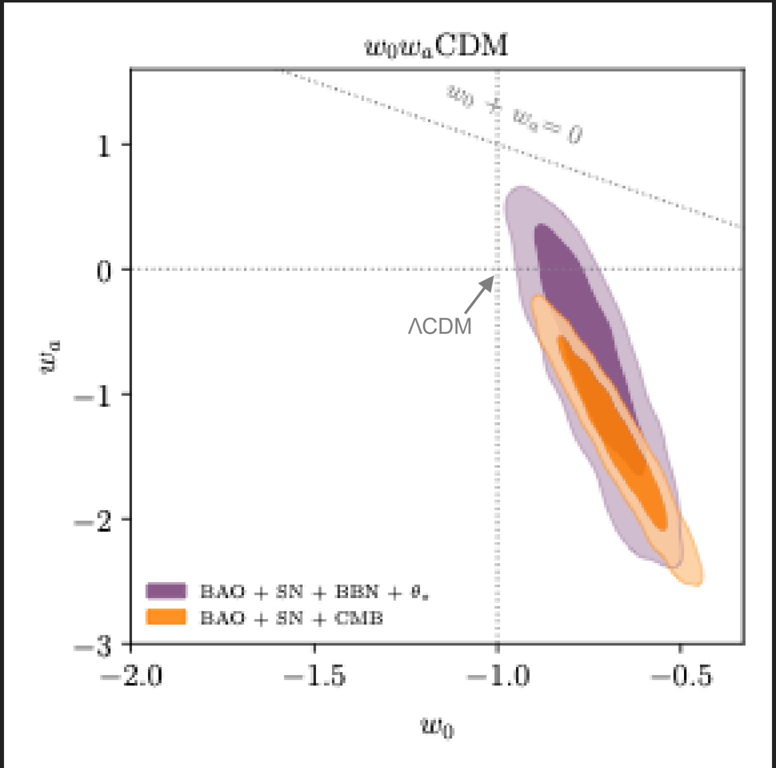


DES Collaboration 2025, arXiv:2503.06712

DES expansion history models: 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



DES Collaboration 2025, arXiv:2503.06712

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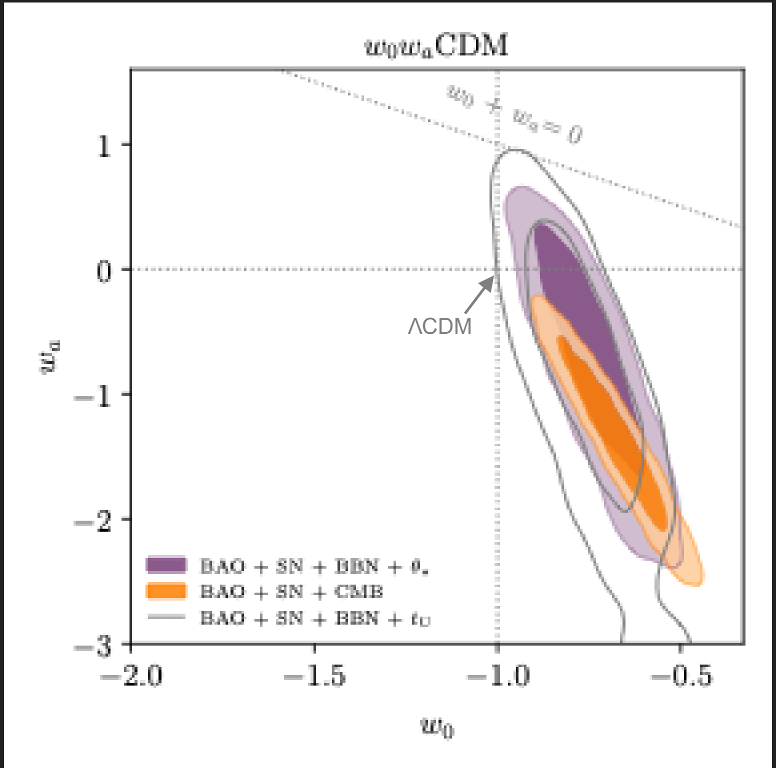
- Only background (BAO+SN+BBN+$\theta_\star$): 2.8σ
- Non-CMB, with age-of-the-Universe priors ~2σ (BAO+SN+BBN+t_U)
  t_U: Globular Clusters
  Valcin et al. 2020



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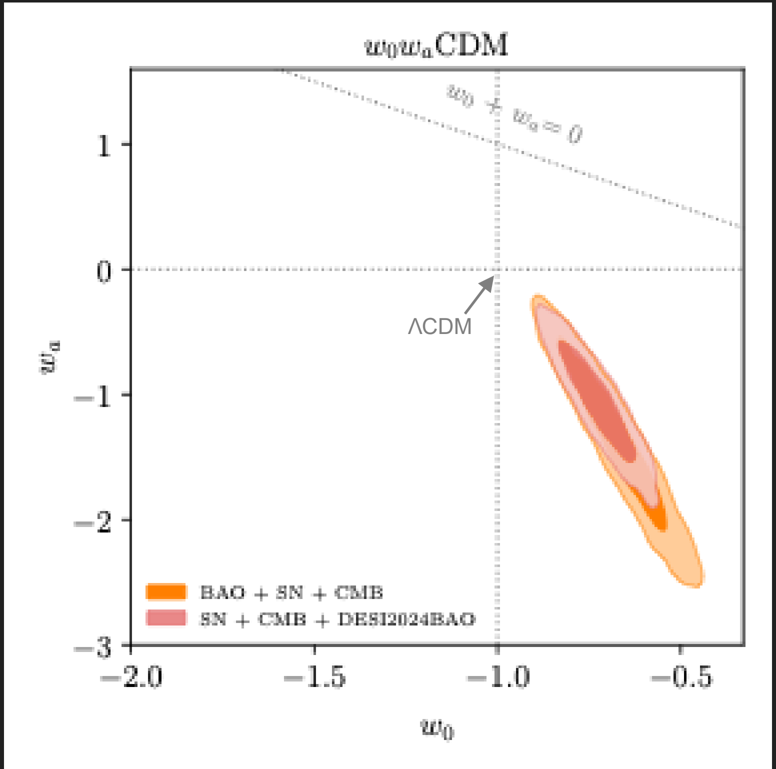
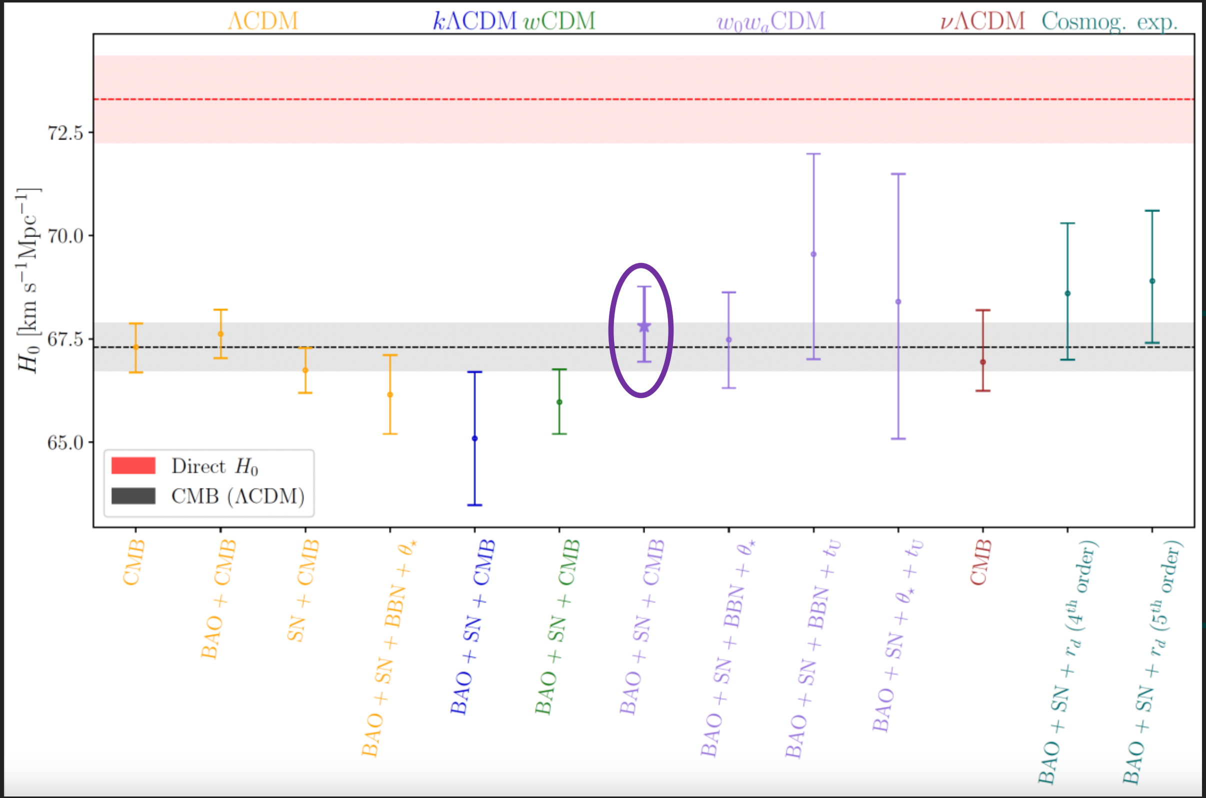
- Only background (BAO+SN+BBN+$\theta_\star$): 2.8σ
- Non-CMB, with age-of-the-Universe priors ~2σ (BAO+SN+BBN+t_U)
- Similar deviation from ΛCDM as DESI-DR1 (+DES-SN + CMB): 3.6σ



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

DES Collaboration 2025, arXiv:2503.06712

Hubble tension is not resolved



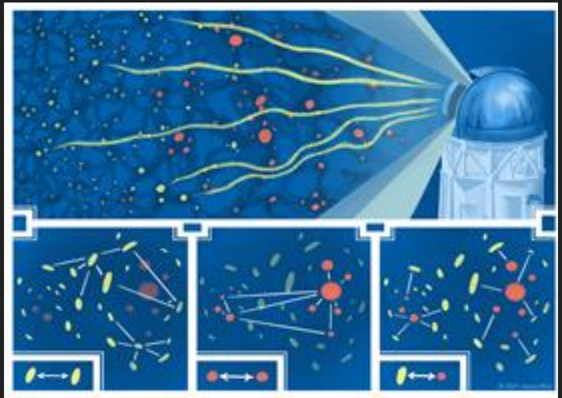
Even when allowing our most flexible model (w_0w_aCDM), we recover a value compatible with Planck-ΛCDM:

$$H_0 = 67.8 \pm 0.9 \text{ km s}^{-1}\text{ Mpc}^{-1}$$

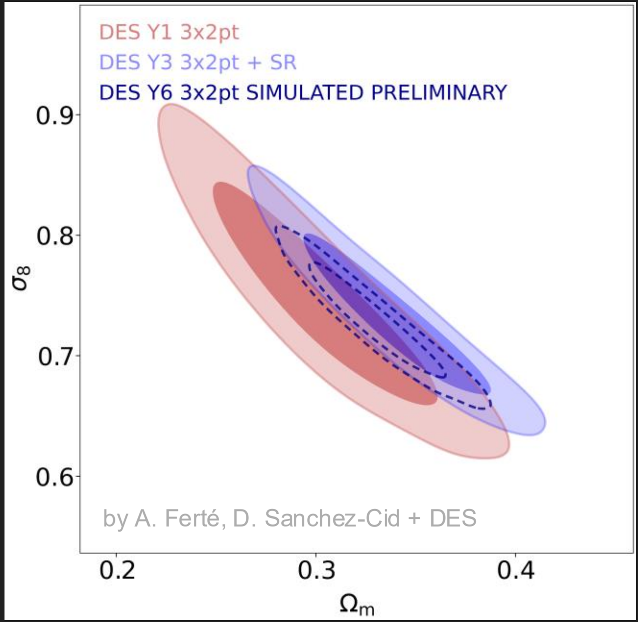
(BAO+SN+CMB)

Dark Energy Survey: Goals

- Constrain nature of dark energy with four probes:
  - Type Ia Supernovae
  - Baryonic Acoustic Oscillations
  - **Weak Lensing (+ Galaxy Clustering)**
  - Cluster counts



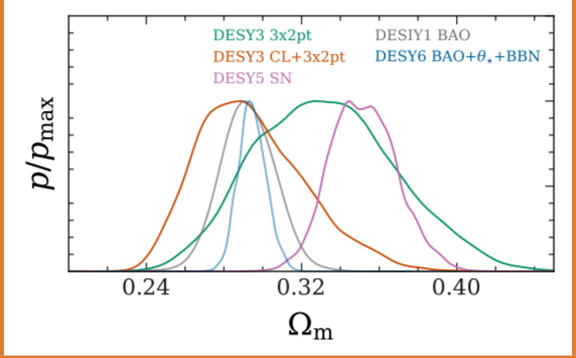
Y6 Coming soon… (forecast)



Dark Energy Survey: Goals

- Constrain nature of dark energy with four probes:
    - Type Ia Supernovae
    - Baryonic Acoustic Oscillations
    - Weak Lensing + Galaxy Clustering
    - Cluster counts

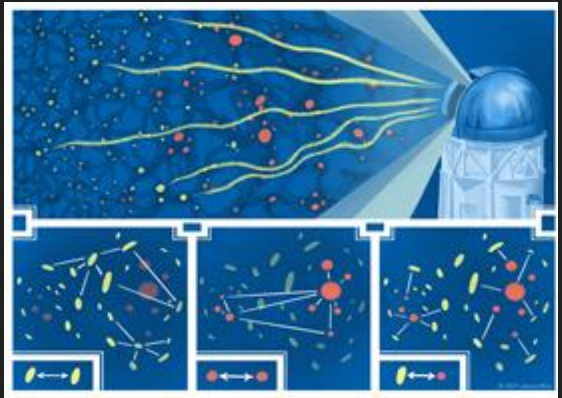
Y3 results: 2503.13632

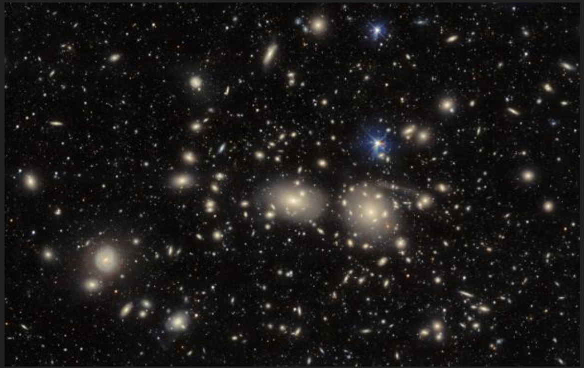


Dark Energy Survey: Goals

- Constrain nature of dark energy with four probes:
    - Type Ia Supernovae
    - Baryonic Acoustic Oscillations
    - Weak Lensing + Galaxy Clustering
    - Cluster counts

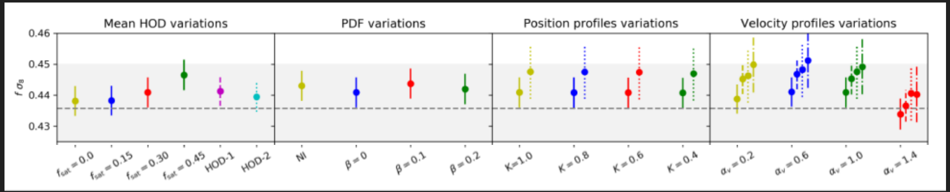
All probe combinations later this year
Methods: To+2503.13631





ELG-halo connection

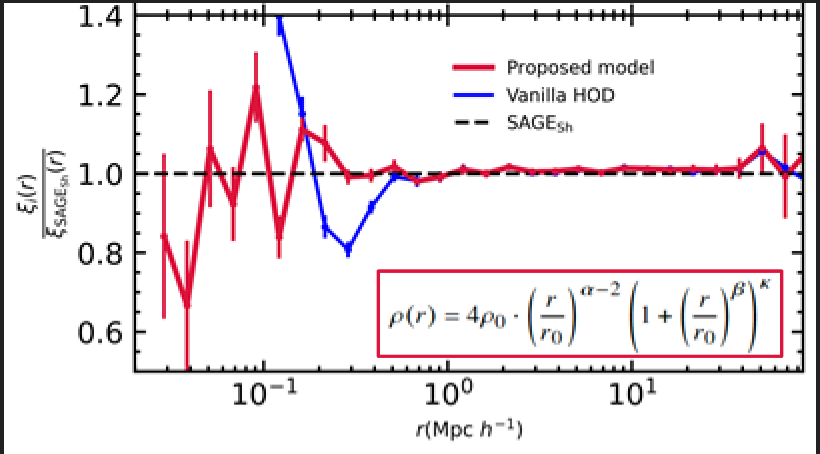
- ELG small scale clustering sensitive to
  - Central-Satellite split
  - Conformity (galaxy-central correlation)
  - Probability distribution Function of satellites
  - Radial Profile of satellites
  - Velocity profile of satellites



Avila, V. Gonzalez-Perez+ eBOSS 2007.09012
+ PDF: in B Vos-Gines, SA,VGP, 2310.18189

- Hα ELGs:
  - Conformity
  - Non-classical profile

G. Reyes-Peraza, ***SA,*** V. Gonzalez-Perez,+ 2312.13199

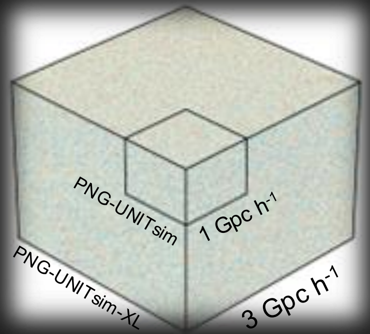


PNG-UNITsim suite

- PNG-UNITsim
  (A. Gutierrez Adame, ***SA***, Gonzalez-Perez +2312.12405)
  - **f_{NL} = 100**
  - L=1Gpc/h   N=4096^3
  - $m_p=1.2 \cdot 10^9\ h^{-1}\ M_{sun}$
  - Fixed, and phases Matched to (f_{NL}=0) PNG-UNITsim.
    => V_{eff} x70
- Goals:
  - Measure $\mathbf{b_\Phi}$ for different tracers
    - SAMs on the plan
  - Develop new methods: high-resolution

- PNG-UNITsim-XL
  (A.G. Adame, + SA + in prep.)
  - **f_{NL} = 20**
  - L=3Gpc/h   N=6144^3
  - $m_p=1 \cdot 10^{10}\ h^{-1}\ M_{sun}$
  - Fixed, and phases Matched to (f_{NL}=0) PNG-UNITsim-XL.
    => V_{eff} x70
  - DESI-like tracers + geom.
- Goals:
  - Test largest scales
  - Test observational effects
  - Test low $\mathbf{f_{NL}}$

Test your higher-order / FLI model to search for PNG
http://www.unitsims.org/



Conclusions

- DES Y5 SN is the largest compilation of SN from a single telescope
  - 2σ deviation from ΛCDM
- DES Y6 BAO
  - Tightest constrain from a photometric survey
  - Competitive with spec surveys
  - 2σ (4%) deviation from Planck-ΛCDM
- Combining final BAO + SN from DES
  - Show several 2-3σ tensions in ΛCDM, kΛCDM, and wCDM.
- Hints for evolving dark energy (w_0w_aCDM)
  - All data considered is consistent in this space
  - DES-BAO + DES-SN + Planck-CMB: 3.2σ away from ΛCDM
  - Consistent for expansion-only (BAO+SN+BBN+t_U: 2.8σ)
- Coming soon from DES:
  - Galaxy Clustering and Weak Lensing (3x2pt)
  - Combination of BAO+SN+3x2pt+Clusters
- PNG-UNITsim suite: state-of-the-art
- ELG-halo connection:
  - Affects small scale clustering
  - Many ingredients to consider.
  - Confirmity and non-NFW fundamenal