Title: Workshop

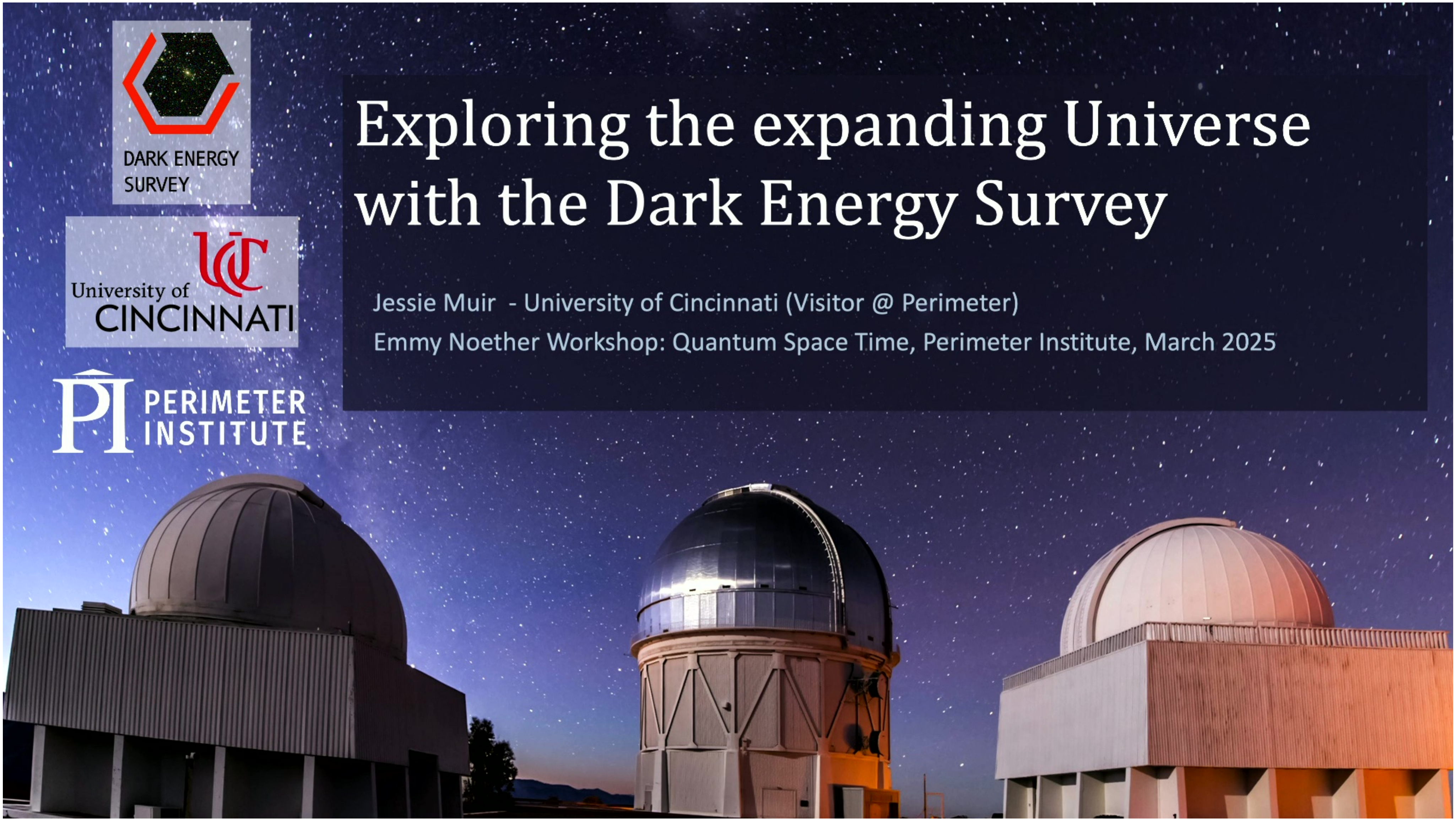
Speakers: Jessica Muir

Collection/Series: Emmy Noether Workshop: Quantum Space Time

Subject: Quantum Gravity

Date: March 11, 2025 - 10:00 AM

URL: https://pirsa.org/25030060



DARK ENERGY SURVEY
University of CINCINNATI
PERIMETER INSTITUTE
Exploring the expanding Universe with the Dark Energy Survey
Jessie Muir - University of Cincinnati (Visitor @ Perimeter)
Emmy Noether Workshop: Quantum Space Time, Perimeter Institute, March 2025

This talk will be:

- Highlighting a new paper out on arXiv today
- A look at how we constrain dark energy properties with cosmological observations
- An overview of some dark energy results that have been the subject of a lot of interest over the past year

J. Mena-Fernandez

S. Avila

A Porredon

M. Vincenzi

DES Collaboration 2025, arXiv:2503.06712

DES-2024-0849
FERMILAB-PUB-25-0127-PPD

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

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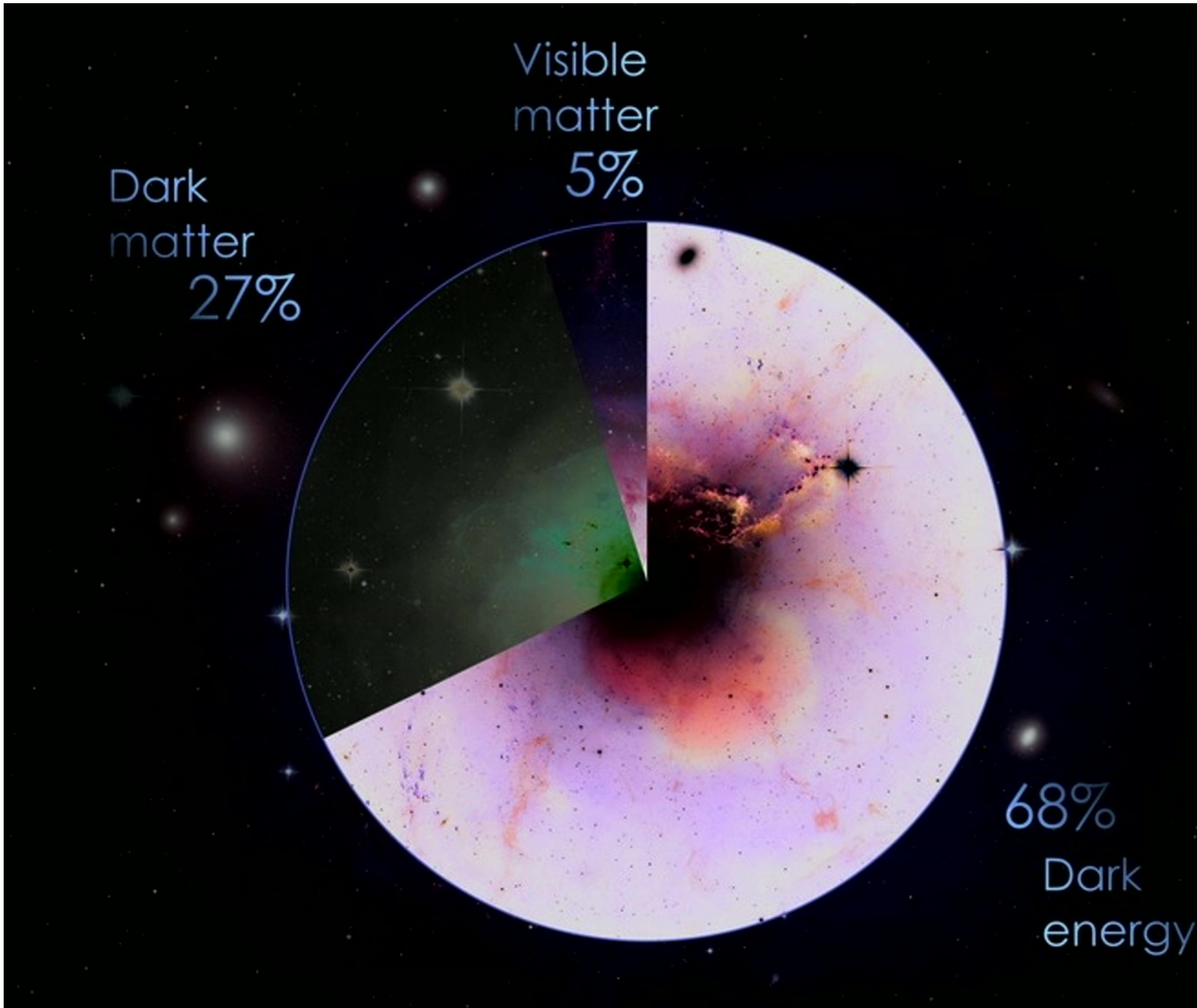
(DES Collaboration)*

The Dark Energy Survey (DES) recently released the final results of its two principal probes of the expansion history: Type Ia Supernovae (SNe) and Baryonic Acoustic Oscillations (BAO). In this paper, we explore the cosmological implications of these data in combination with external Cosmic Microwave Background (CMB), Big Bang Nucleosynthesis (BBN), and age-of-the-Universe information. The BAO measurement, which is $\sim 2\sigma$ away from *Planck*'s ΛCDM predictions, pushes for low values of Ω_m compared to *Planck*, in contrast to SN which prefers a higher value than *Planck*. We identify several tensions among datasets in the ΛCDM model that cannot be resolved by including either curvature (kΛCDM) or a constant dark energy equation of state (wCDM). By combining BAO+SN+CMB despite these mild tensions, we obtain $\Omega_k = -5.5^{+4.6}_{-4.2} \times 10^{-3}$ in kΛCDM, and $w = -0.948^{+0.028}_{-0.027}$ in wCDM. If we open the parameter space to $w_0 w_a$CDM (where the equation of state of dark energy varies as $w(a) = w_0 + (1-a)w_a$), all the datasets are mutually more compatible, and we find concordance in the $[w_0 > -1, w_a < 0]$ quadrant. For DES BAO and SN in combination with *Planck*-CMB, we find a 3.2σ deviation from ΛCDM, with $w_0 = -0.673^{+0.098}_{-0.097}$, $w_a = -1.37^{+0.51}_{-0.50}$, a Hubble constant of $H_0 = 67.81^{+0.96}_{-0.86}$ km s^{-1}Mpc^{-1}, and an abundance of matter of $\Omega_m = 0.3109^{+0.0086}_{-0.0099}$. For the combination of all the background cosmological probes considered (including CMB $\theta_\star$), we still find a deviation of 2.8σ from ΛCDM in the $w_0 - w_a$ plane. Assuming a minimal neutrino mass, this work provides further evidence for non-ΛCDM physics or systematics, which is consistent with recent claims in support of evolving dark energy.



Credit: NASA's Goddard Space Flight Center

ΛCDM

Cosmological standard model

- Λ - cosmological constant dark energy
- CDM – cold dark matter
- General relativity
- Gaussian, adiabatic initial density fluctuations

What is dark energy?

Is it a cosmological constant?

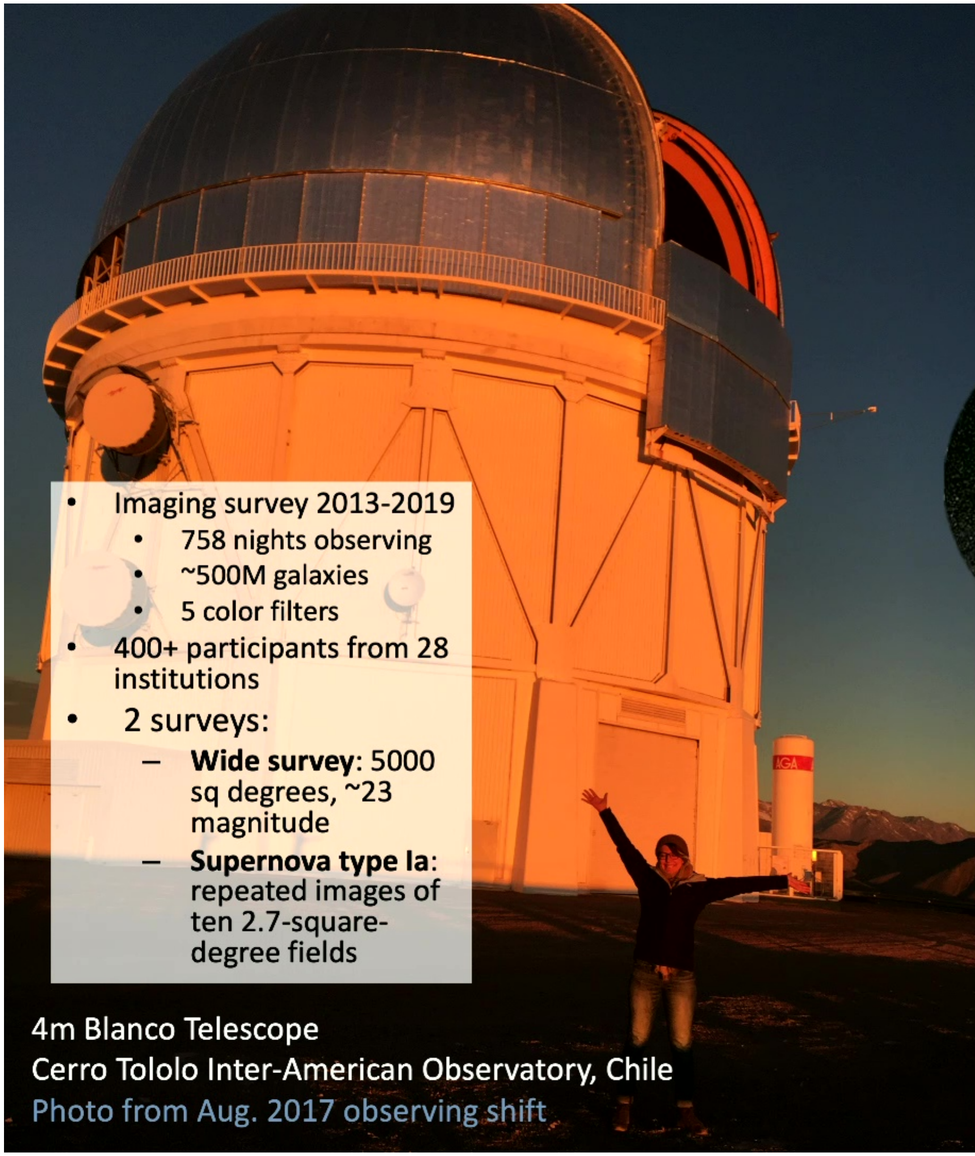
Do we need to extend general relativity?

What is dark matter?

What physics seeded initial density perturbations?

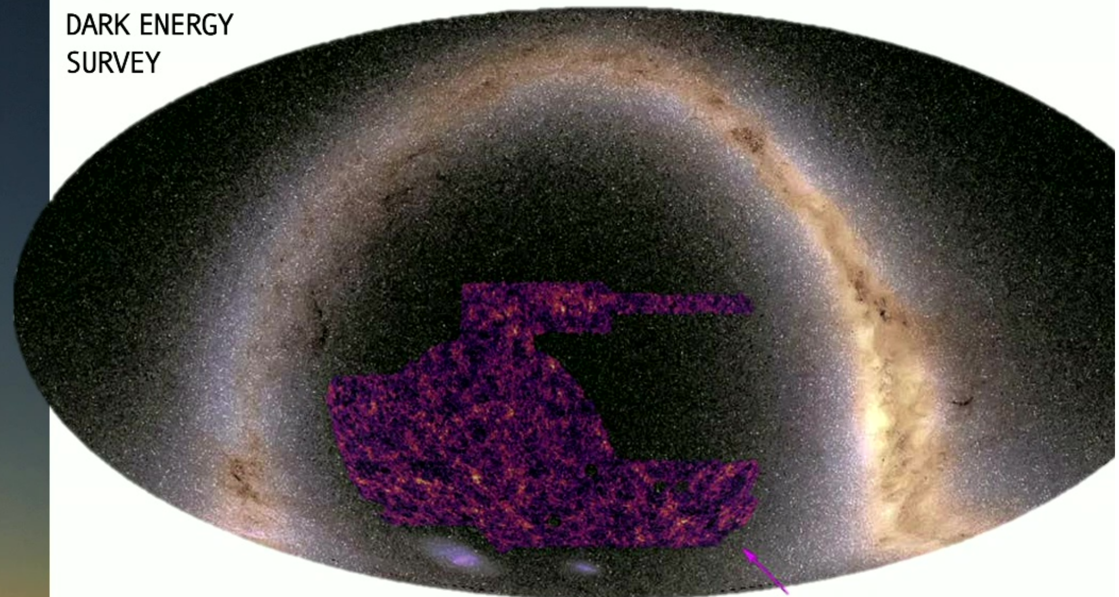
The Dark Energy Survey (DES)

DARK ENERGY SURVEY



- Imaging survey 2013-2019
  - 758 nights observing
  - ~500M galaxies
  - 5 color filters
- 400+ participants from 28 institutions
- 2 surveys:
  - **Wide survey**: 5000 sq degrees, ~23 magnitude
  - **Supernova type Ia**: repeated images of ten 2.7-square-degree fields

4m Blanco Telescope
Cerro Tololo Inter-American Observatory, Chile
Photo from Aug. 2017 observing shift



N. Jeffrey, Dark Energy Survey Collaboration

Funding

U.S. DEPARTMENT OF ENERGY Office of Science

Science and Technology Facilities Council

Member institutions

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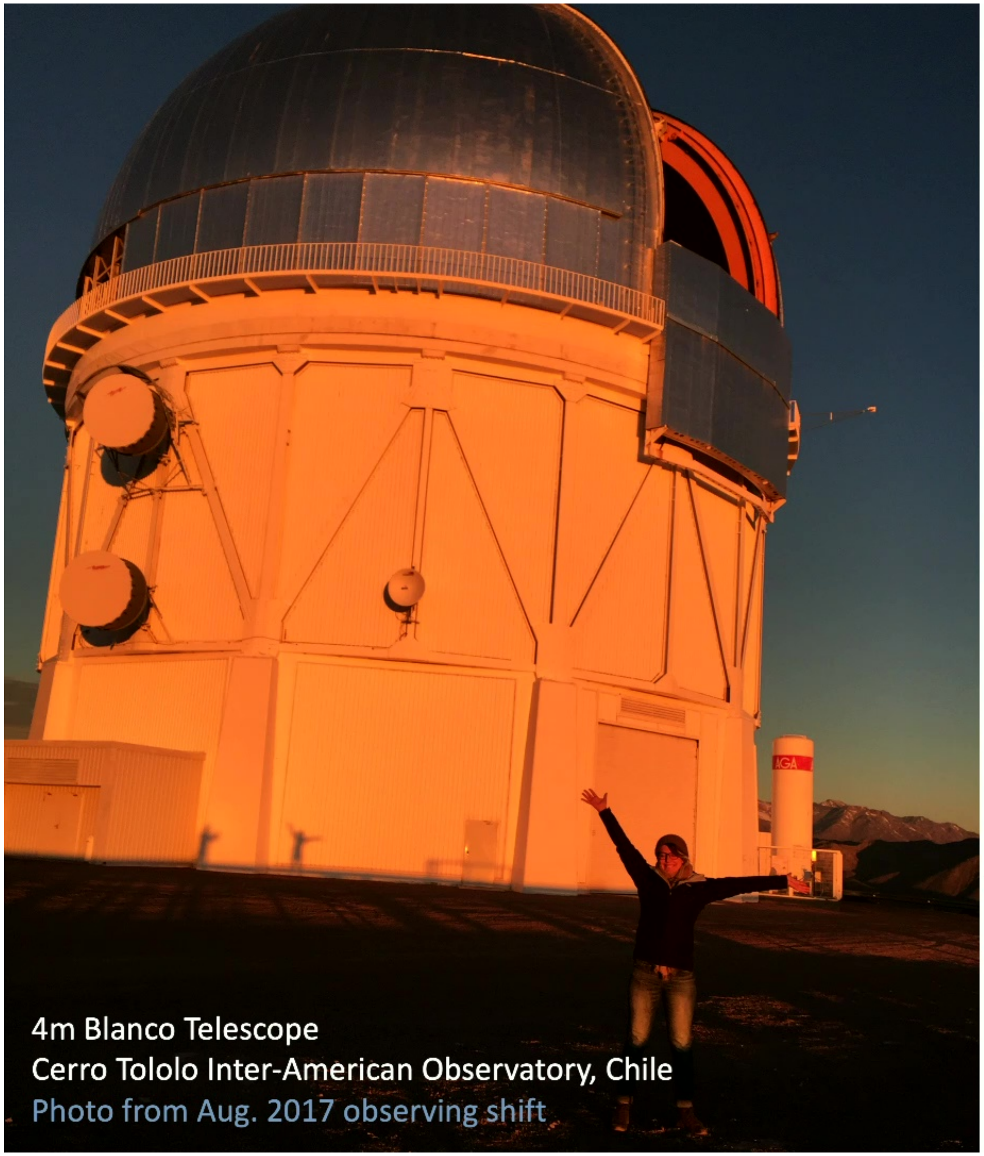
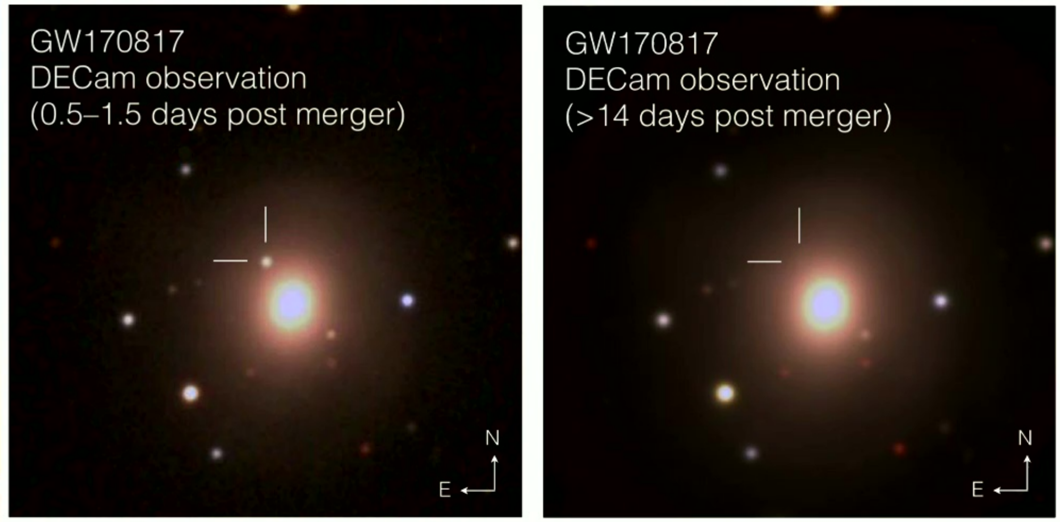
DARK ENERGY SURVEY

Aside: EM counterpart of GW170817



4m Blanco Telescope
Cerro Tololo Inter-American Observatory, Chile
Photo from Aug. 2017 observing shift

M. Soares-Santos et al [DES Collaboration] 2017, arXiv: 1710.05459



See also: Jocelyn Read's talk this afternoon!

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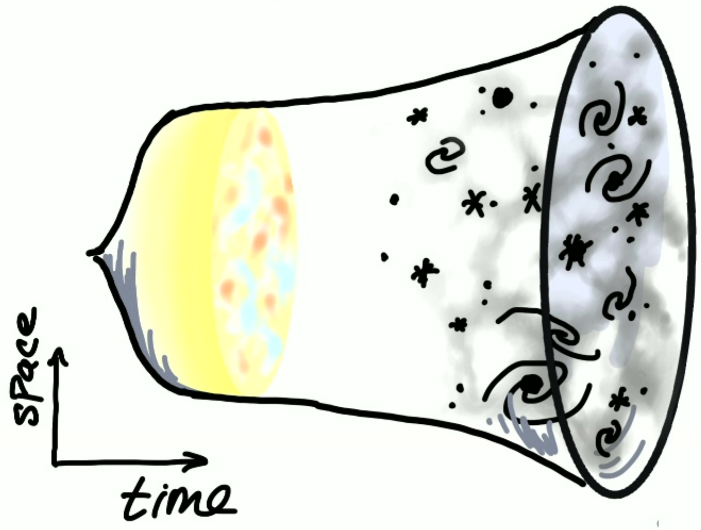
We probe physics with the Dark Energy Survey by observing:

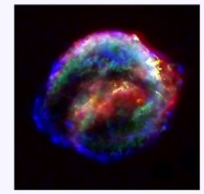
Background expansion



Focus of this talk

Galaxy clustering

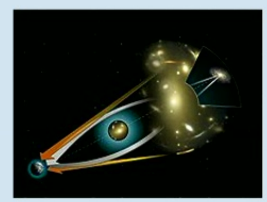
Supernovae



Structure growth

Galaxy clustering

Weak lensing

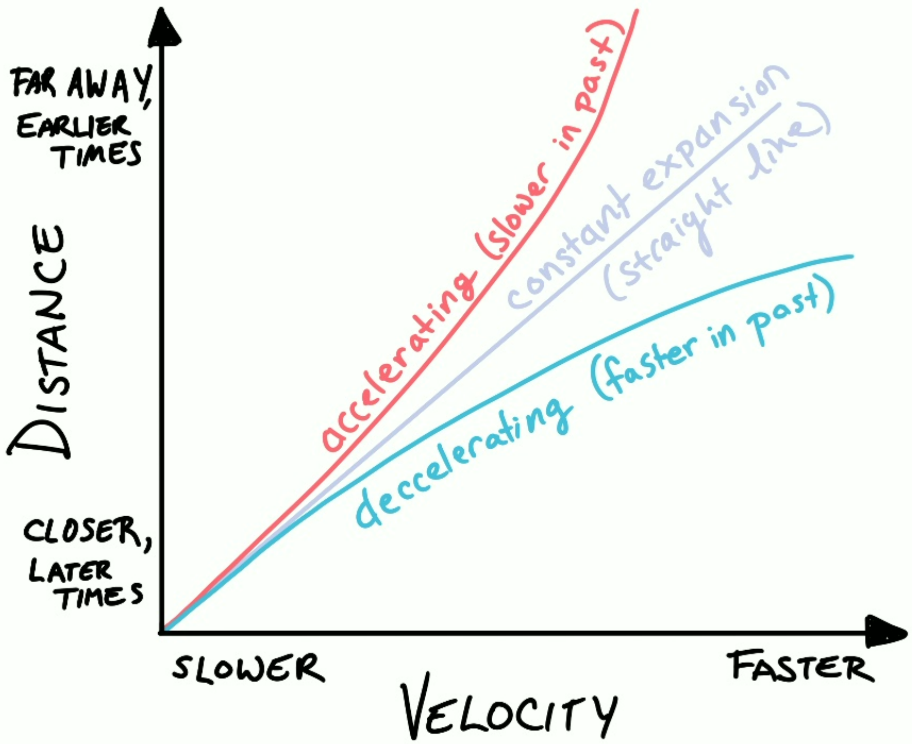


Galaxy clusters

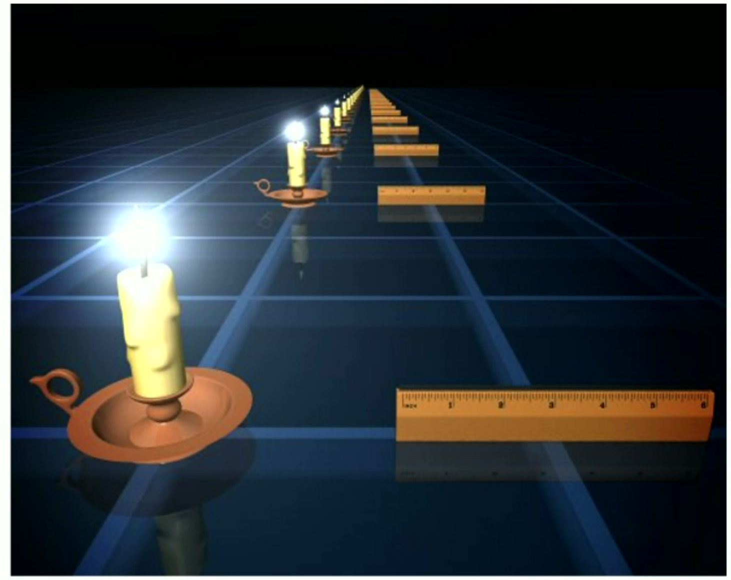
More DES Y6 results expected out later this year!

And more! Milky Way structure, galaxy evolution, QSOs, strong lensing, GW follow-up, solar system objects (TNO, comets)

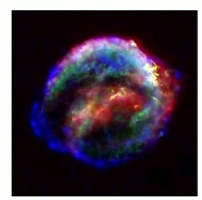
Measuring distances lets us study expansion history.



(redshift z)

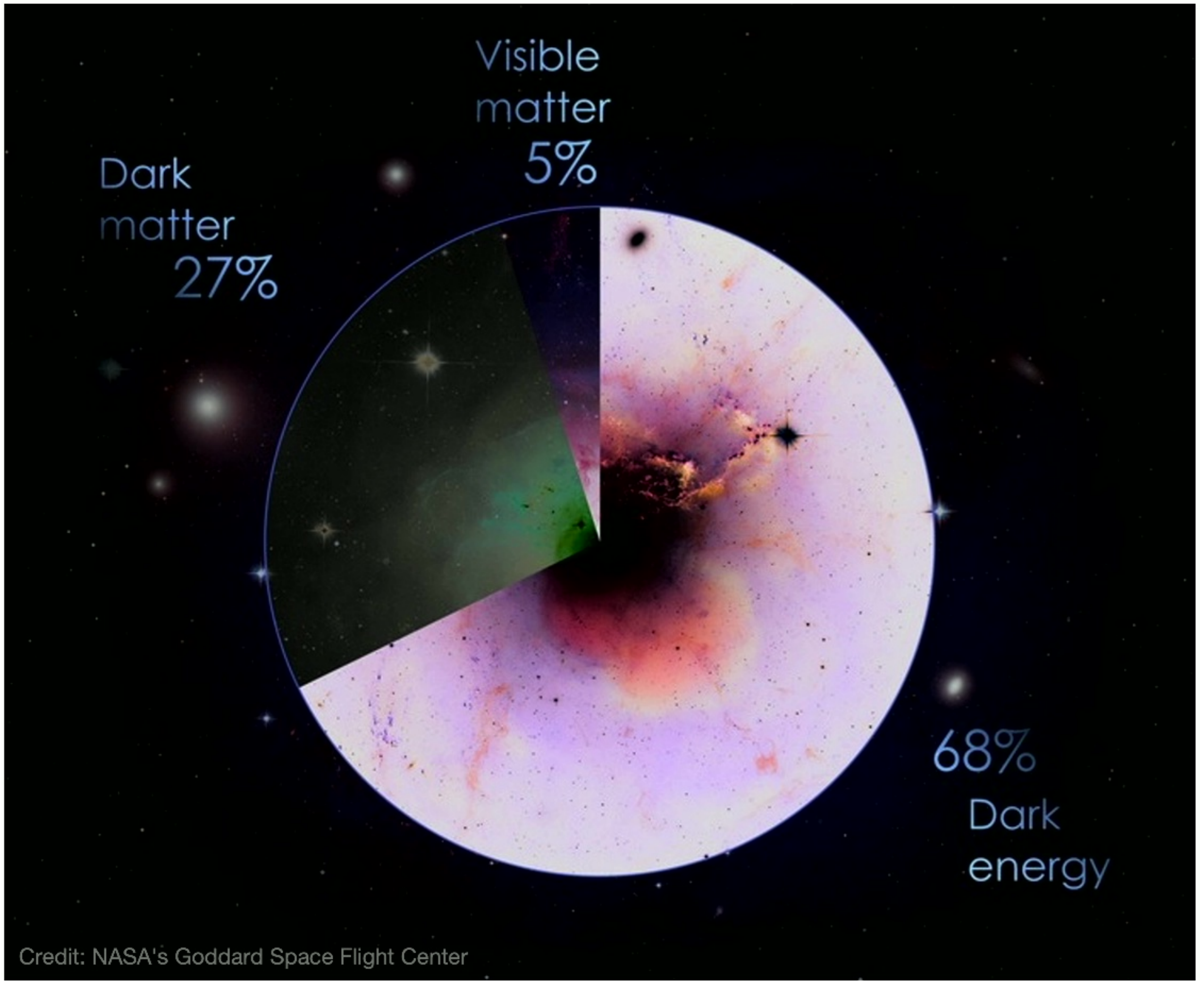


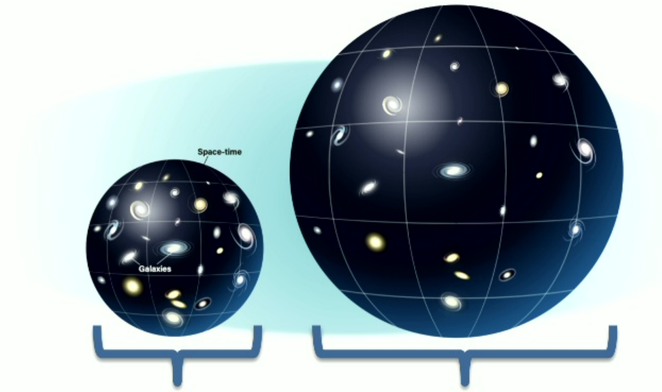
Supernovae



Galaxy clustering

Expansion history tells us about the mass-energy contents of the Universe.





$a(t_1)$ $a(t_2)$ Scale factor

Expansion rate $H(t) = \frac{\dot{a}}{a}$

$$H^2(a) = \frac{8\pi G}{3} \sum_i \rho_i(a)$$

density contributions

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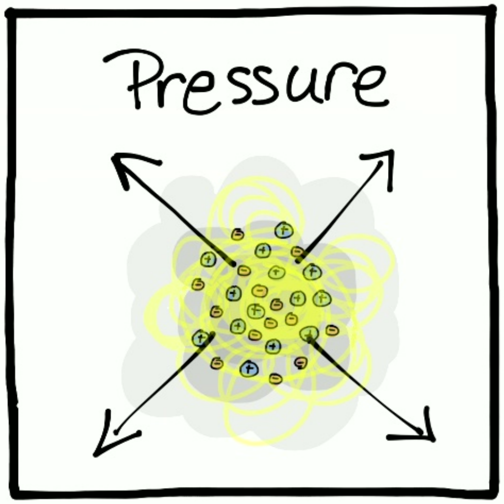
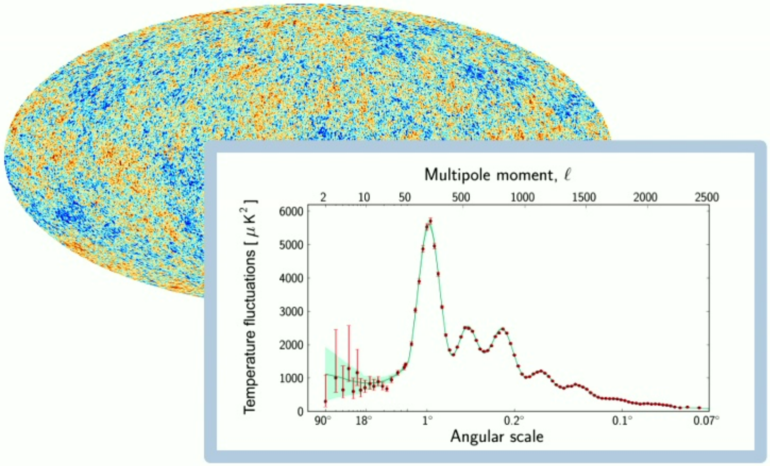
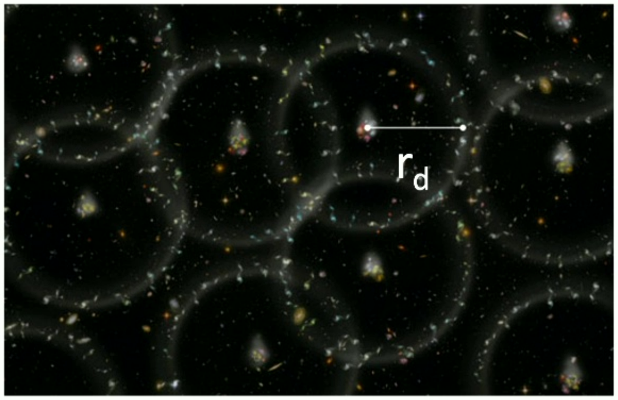
The Baryon Acoustic Oscillation (BAO) signal is an imprint of sound waves in the early Universe on the distribution of galaxies.





Credit: ESA and the Planck Collaboration



Pre-recombination

Oscillations in coupled baryon-photon fluid.

Recombination

z=1100, t_U=~380 Kyr

Photons & baryons decouple.

1st peak in CMB temperature power spectra corresponds to sound horizon at time of decoupling.

Post-recombination

Baryons trace dark matter overdensities but retain imprint of enhanced clustering at ~150Mpc from BAO.

Using DES Y6 galaxy clustering, we measure the BAO scale to 2.1% accuracy.

DES Collaboration 2024, arXiv:2402.10696

- DES BAO optimized sample of 16M red bright galaxies 6 line-of-sight bins.
- 3.5σ significance detection of the BAO peak
- Clustering signal in all 6 bins fit simultaneously with a template, validated using ~2000 mock catalogs, lots of robustness checks.
- Consensus likelihood reported as constraints on

Angular diameter distance → D_M ; Drag scale → r_d

$$\alpha = \frac{D_M/r_d}{[D_M/r_d]_{\mathrm{fid}}}$$

DES BAO team


J. Mena-Fernandez


M. Rodriguez-Monroy


S. Avila


A. Porredon

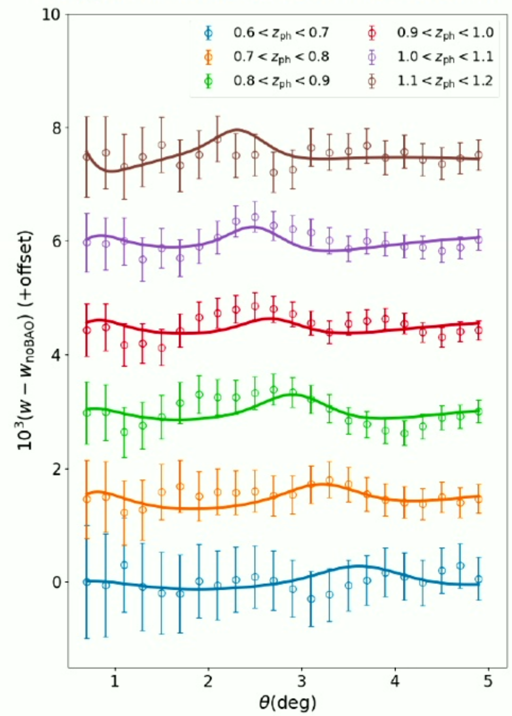
+ N. Weaverdyck, J. Elvin-Poole, I. Sevilla, J. de Vincente, G. Giannini, L. Toribio, R. Cawthon, others! ++

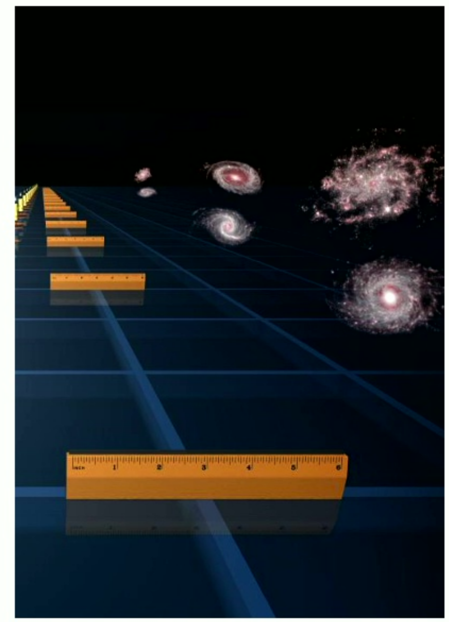

I. Ferrero


H. Camacho


K. C. Chan

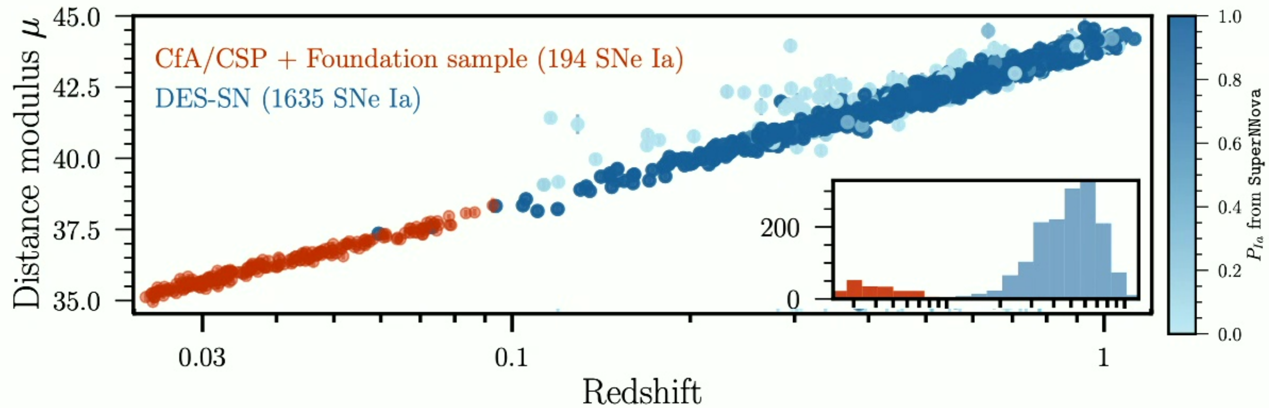
Angular Correlation Function

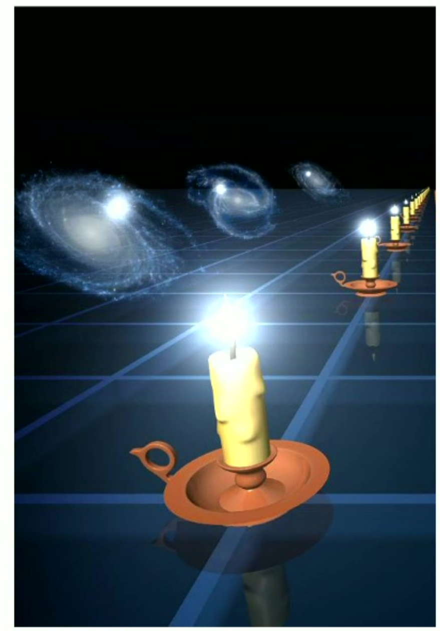




10

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





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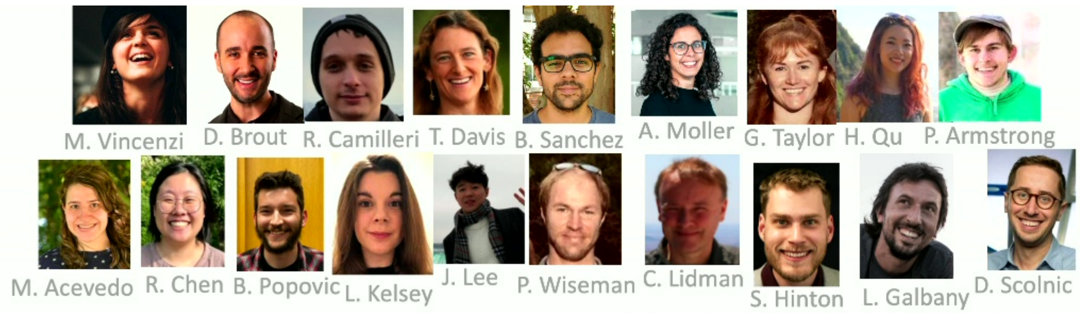
DES Y5 SN is the largest and deepest supernova sample ever compiled from a single telescope.

DES Collaboration 2024, arXiv:2401.02929



DES SN team

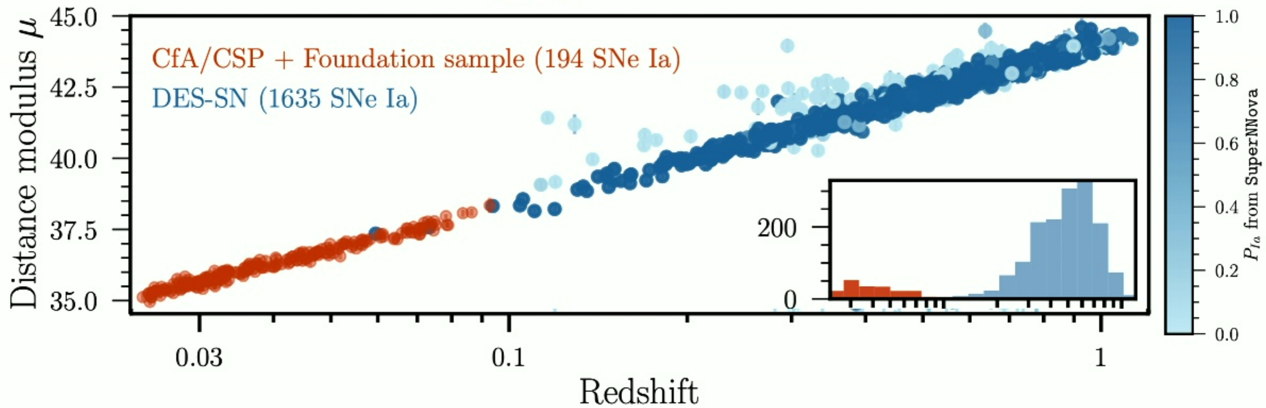
+ A. Carr, M. Sullivan, M. Sako, R. Kessler, J. Lee, E. Kovacs, M. Smith, and others! ++

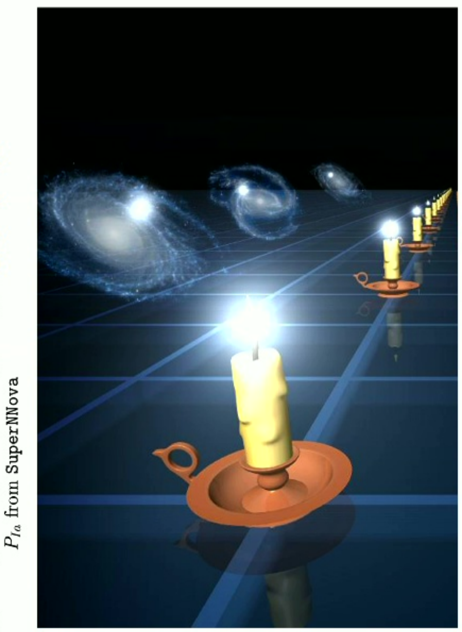
- 1635 photometrically classified SNe Ia with spectra for host galaxy redshifts
- For cosmology, combined with data from 194 low-z SN from other samples

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

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

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





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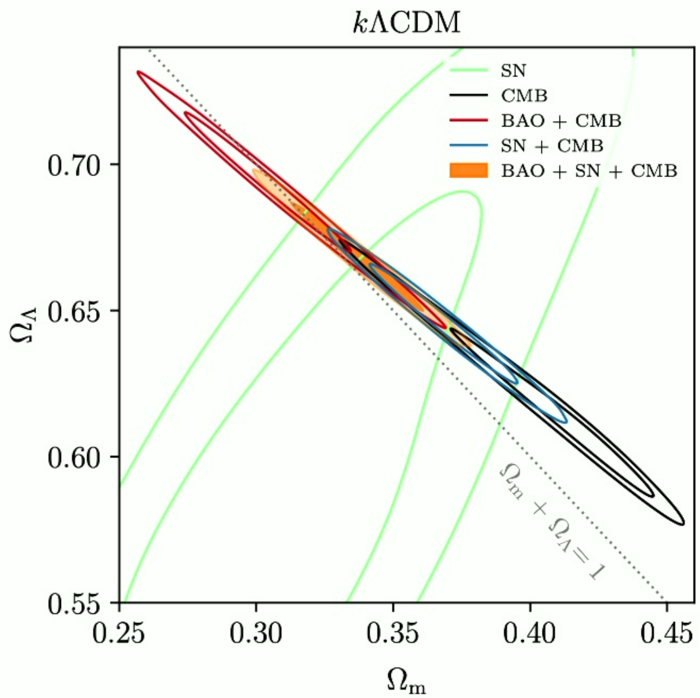
We've performed a cosmology analysis using expansion history probes (BAO & SN) from the completed DES survey.

DES Collaboration 2025, arXiv:2503.06712

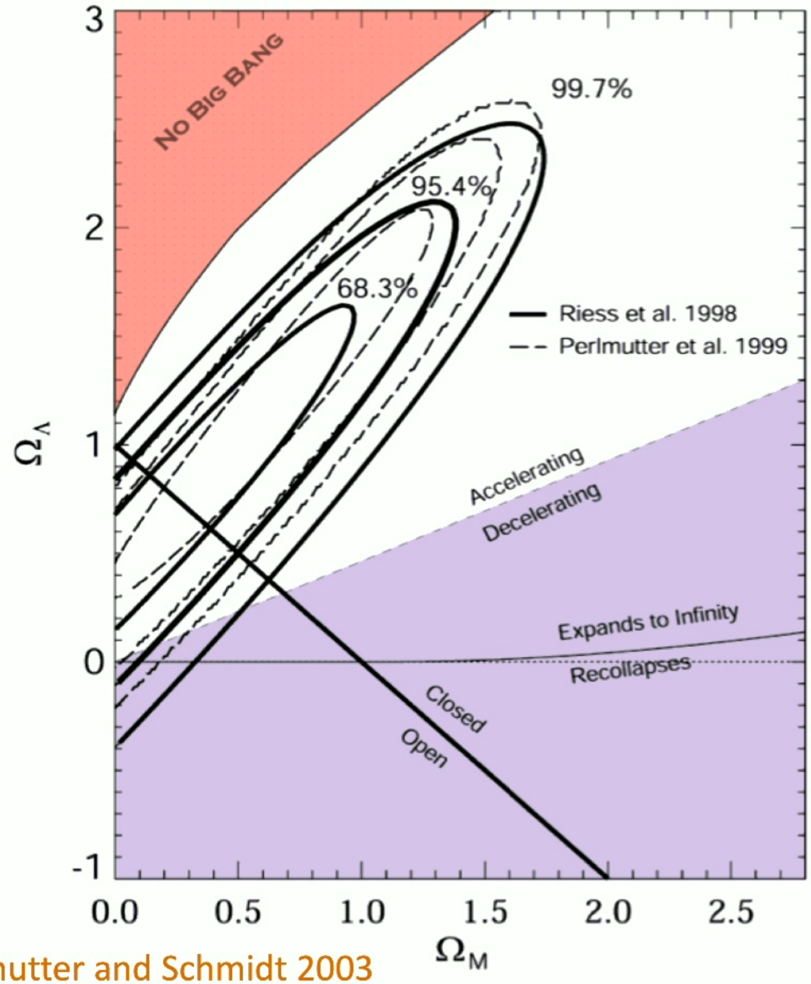
- **BAO** - DES Y6 BAO
- **SN** - DES Y5 SN
- **CMB** = Planck 2018 temperature and polarization power spectra



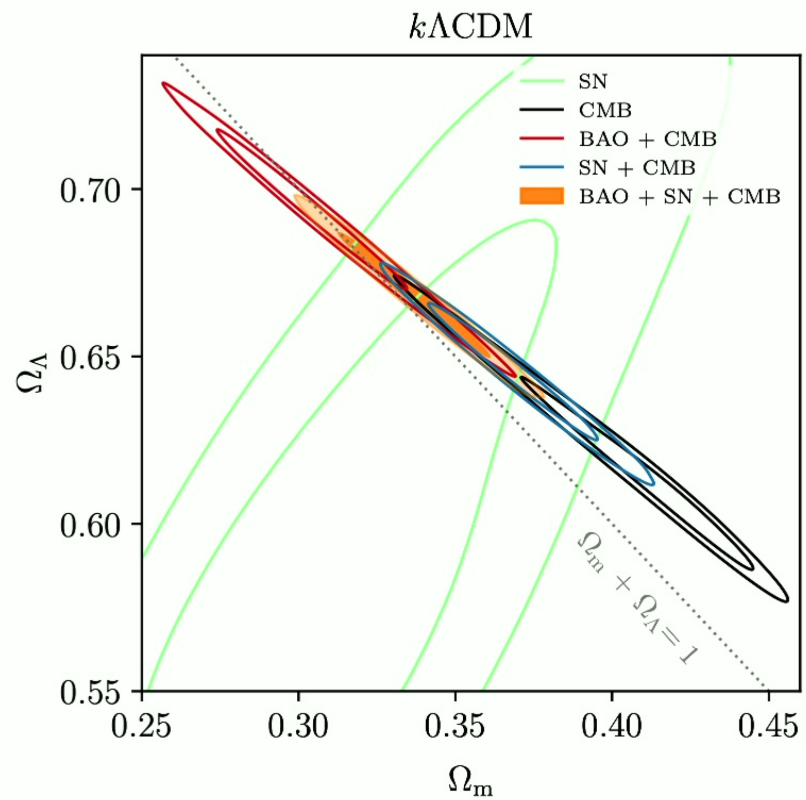
BAO tends to pull constraints towards lower Ω_m, SN towards higher Ω_m.

N.b. Previous study reporting cosmology with DES Y6 BAO and DES Y5 SN in Notari, Redi, & Tesi 2024, arXiv:2411.11685

Some historical perspective:



Perlmutter and Schmidt 2003



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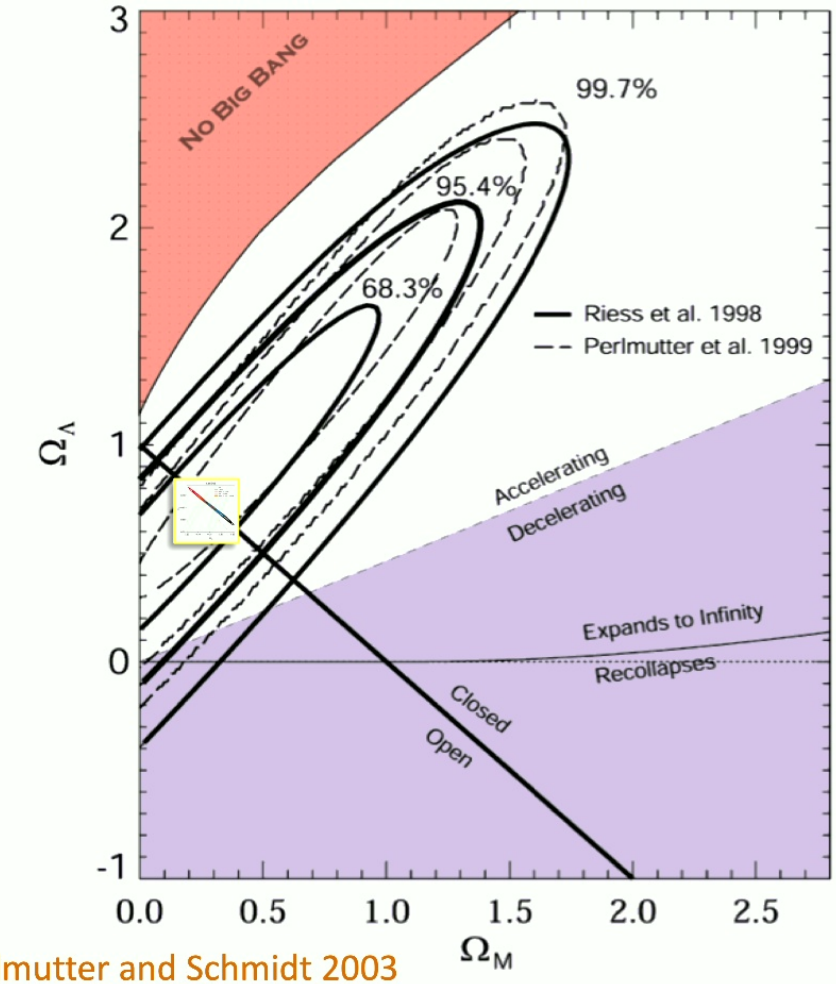
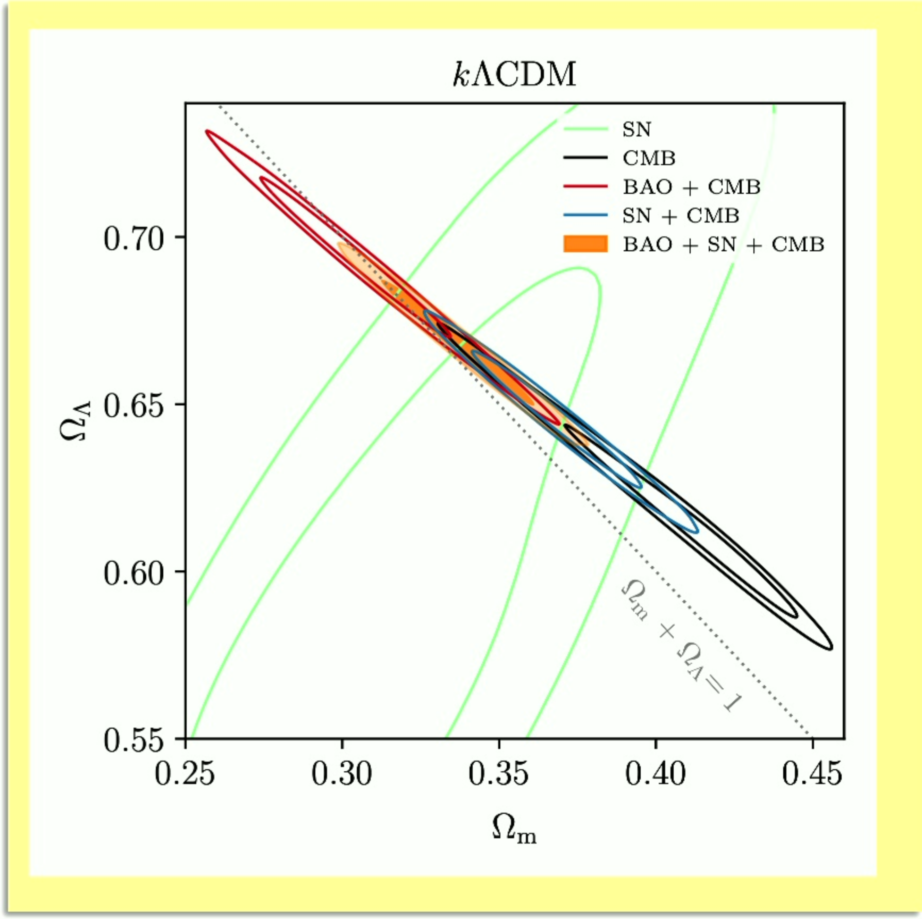


Perlmutter and Schmidt 2003



Jan 2024: DES Y5 SN constraints prefer time-dependent dark energy properties ~2σ from ΛCDM

Time-varying dark energy equation of state (-1 in ΛCDM)

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

DES SN alone

$$w_a = -8.8^{+3.7}_{-4.5}$$

(>2σ less than 0)

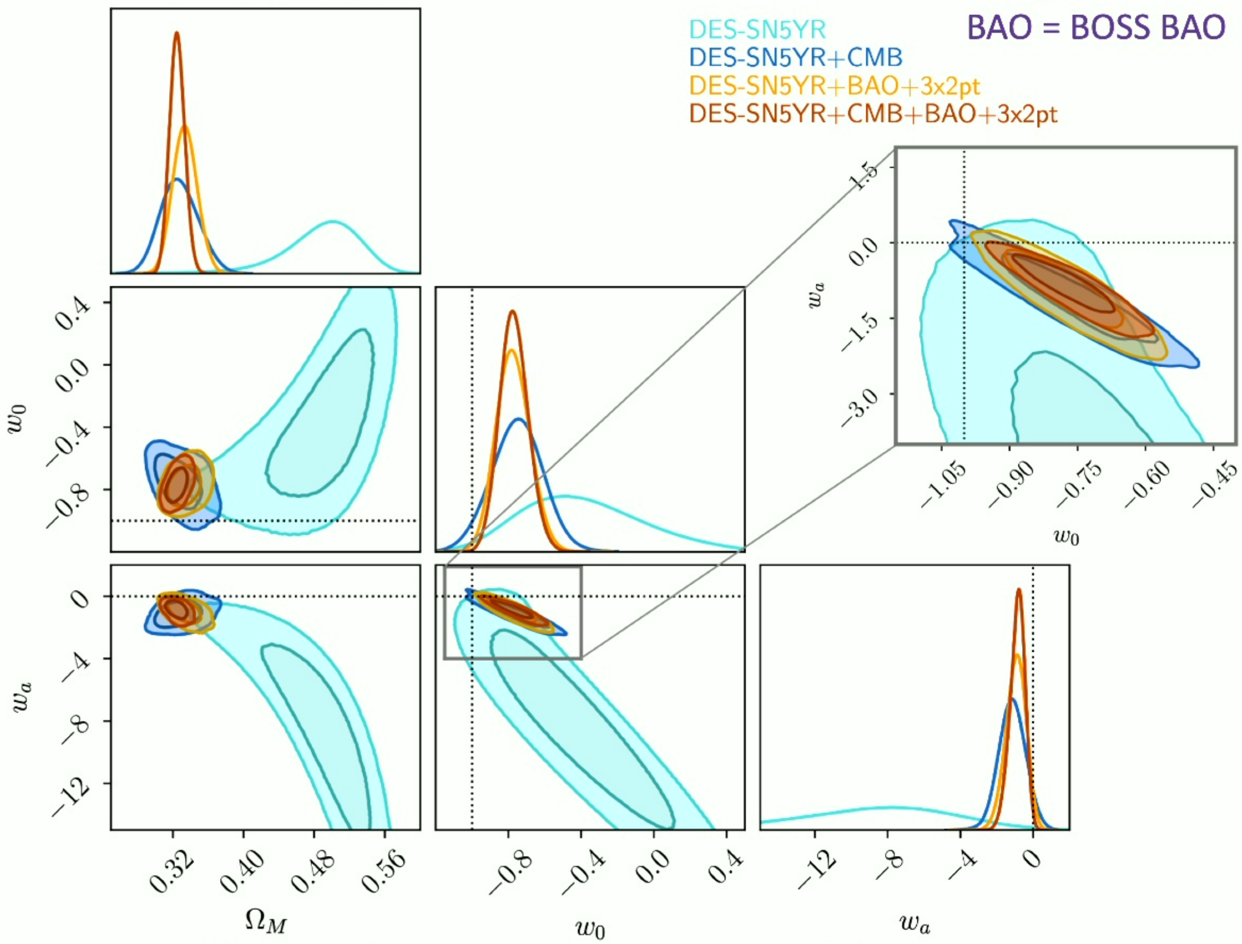
DES SN + CMB + BOSS BAO

$$w_a = -0.83^{+0.33}_{-0.42}$$

(>2σ less than 0)

DES Collaboration 2024
arXiv:2401.02929

Here,
BAO = BOSS BAO



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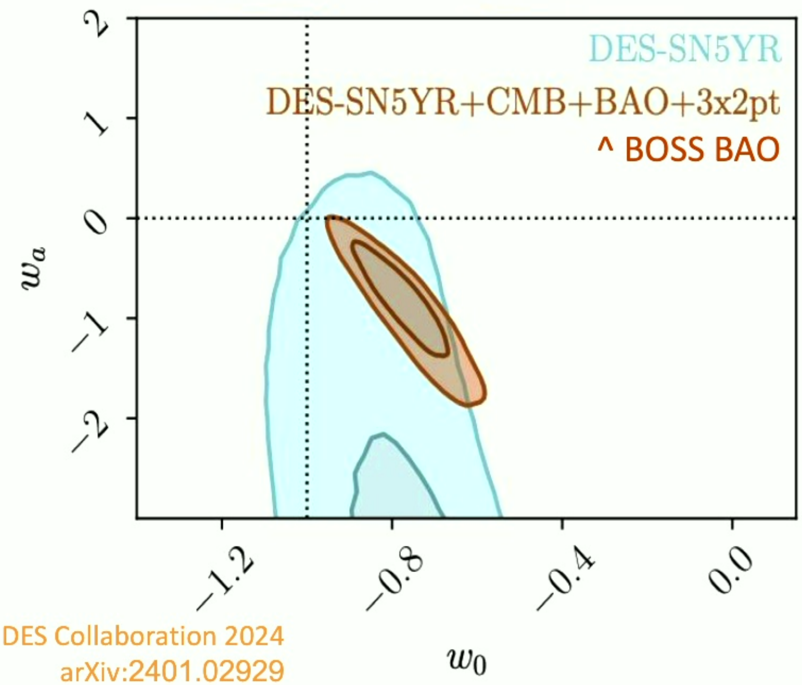
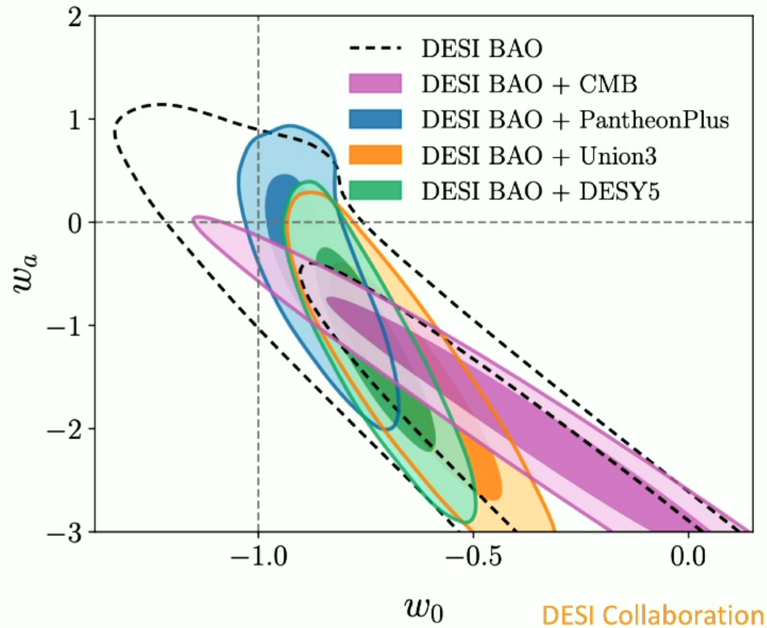
April 2024: When DES Y5 SN are combined with DESI BAO this discrepancy with ΛCDM increases to ~3.5σ.



DES Collaboration 2024
arXiv:2401.02929



DESI Collaboration 2024,
arXiv:2404.03002

Watch this space: Updated results from DESI DR2 (3 years of data) are being released next week!

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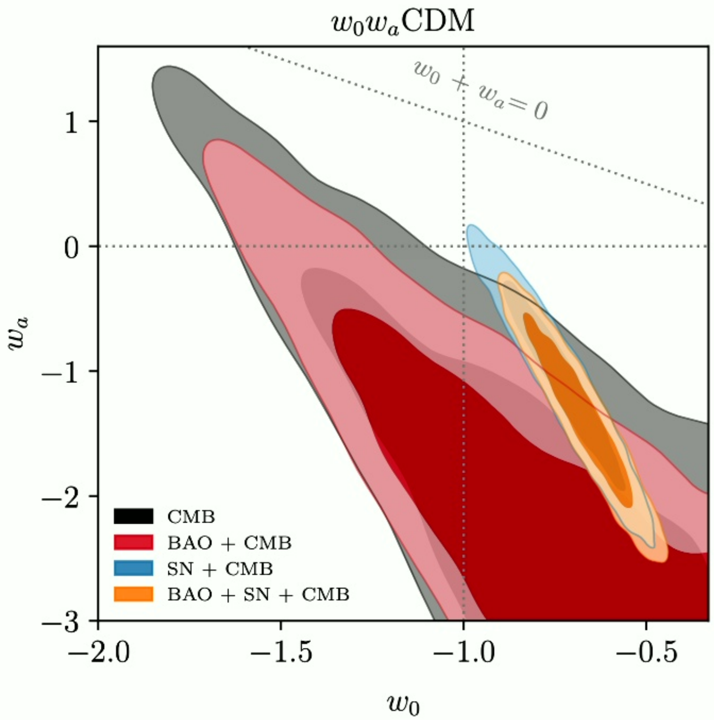
Today: When combining DES Y6 BAO with DES Y5 SN and the CMB, we find a parameter shift of 3.2σ away from ΛCDM (g.o.f. $\Delta\chi^2 = 11.6$, 2.7σ)

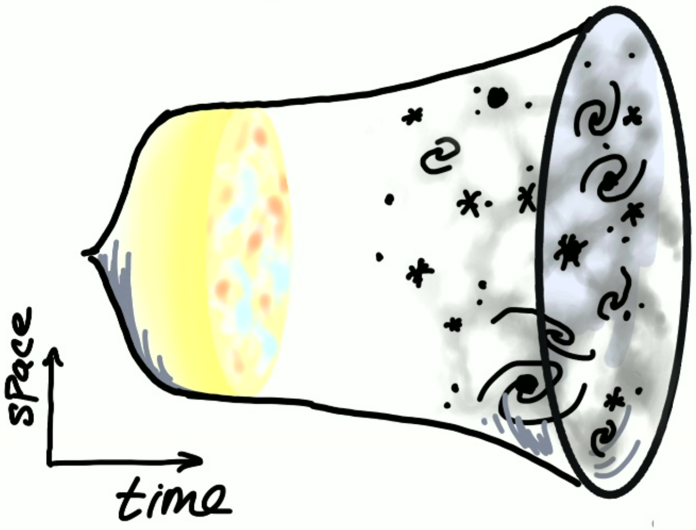


Comparing to SN + CMB + DESI BAO

Using same likelihood set-up, priors

- 3.6σ parameter shift
- $\Delta\chi^2 = 16.5$ (3.5σ)

There's more exciting DES science to come!

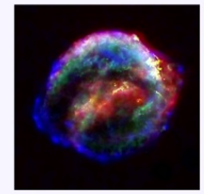


Background expansion

Focus of this talk

Galaxy clustering

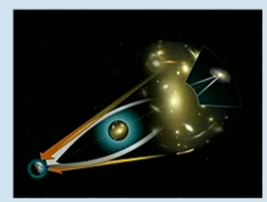
Supernovae



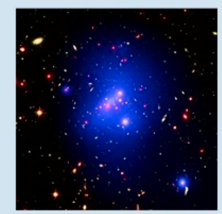
Structure growth

Galaxy clustering

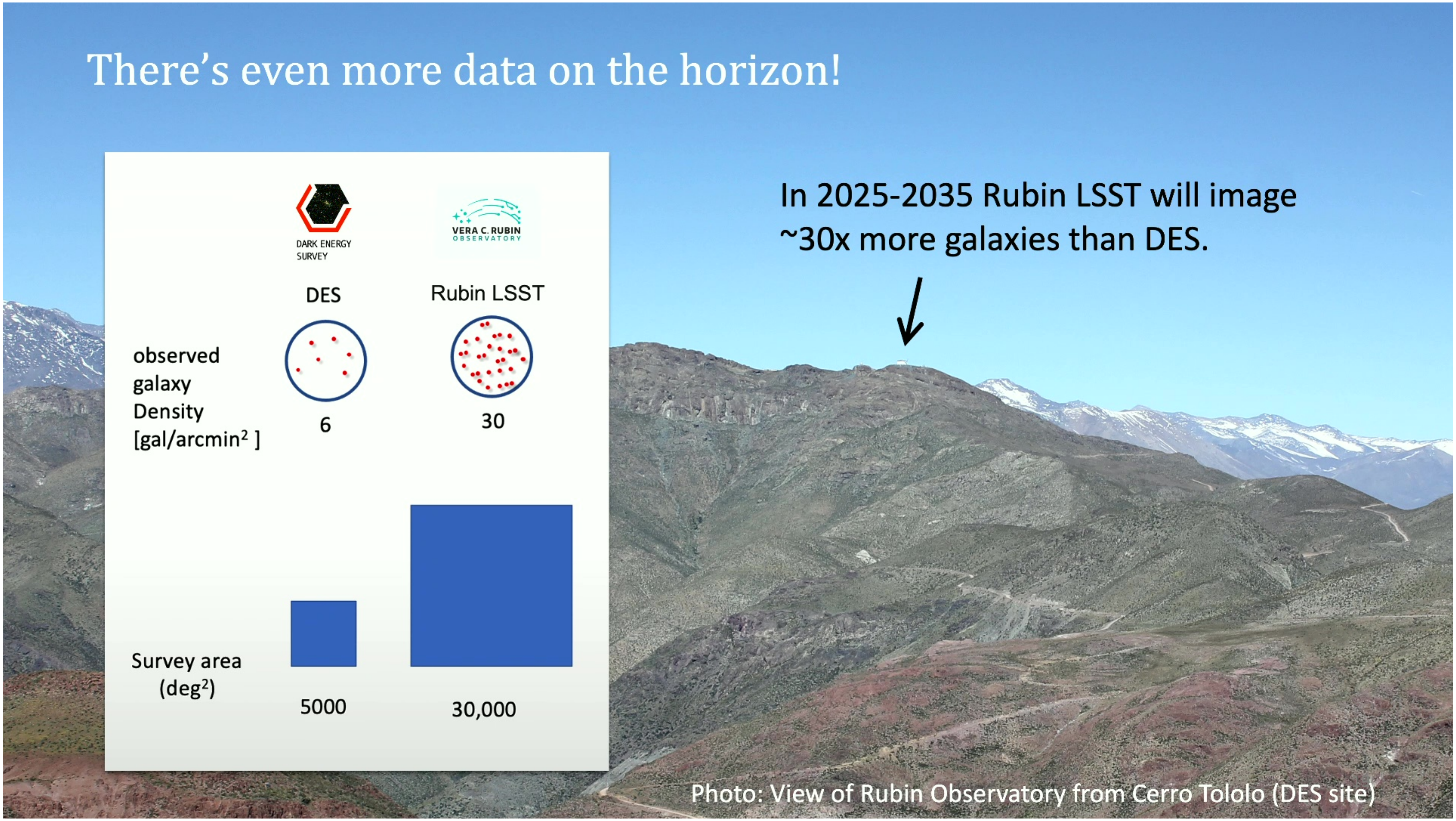
Weak lensing



Galaxy clusters



More DES Y6 results expected out later this year!

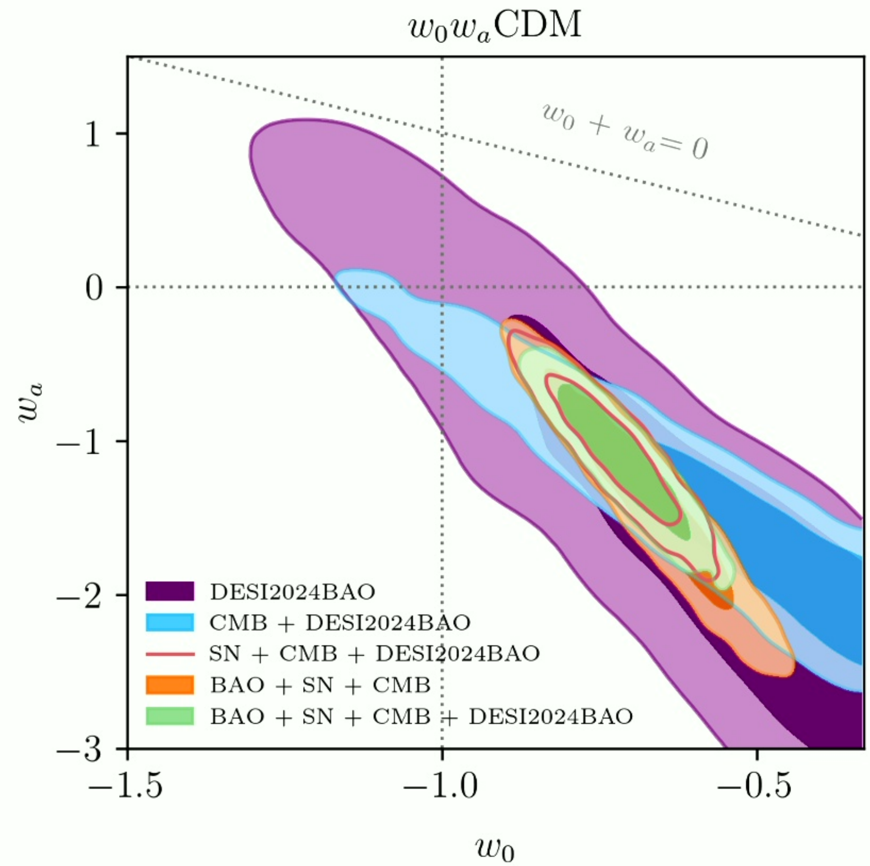

There's even more data on the horizon!
DARK ENERGY SURVEY
VERA C. RUBIN OBSERVATORY
DES
Rubin LSST
observed galaxy Density [gal/arcmin²]
6
30
Survey area (deg²)
5000
30,000
In 2025-2035 Rubin LSST will image ~30x more galaxies than DES.
Photo: View of Rubin Observatory from Cerro Tololo (DES site)

DARK ENERGY SURVEY

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.
  - DES Collaboration 2025, arXiv:2504:XXXXX
  - Reflects years of collaborative work!
- In ΛCDM and one-parameter extensions we considered, BAO tends to pull combined constraints towards lower Ω_m, SN towards higher Ω_m, with implications for other cosmological parameters.
- Dynamic dark energy w_0w_aCDM shows ~3σ discrepancy with ΛCDM, similar but slightly lower significance that when using DESI Y1 BAO.
- There's lots more to learn!
  - DES Y6 analyses in progress: these constraints will be combined with weak lensing, galaxy clustering, and galaxy clusters, with results out later this year.
  - Looking beyond the w_0w_aCDM parameterization, building a deeper understanding of how projection effects & degeneracies might impact constraints.
  - Studies with future and ongoing surveys (DESI, Rubin LSST, ++)

DES vs DESI Y1 results



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