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THE DARK ENERGY SURVEY

Dark Energy Science with Combined Probes

Maria Elidaiana da Silva Pereira
(Hamburger Sternwarte/Quantum Universe/UHH) | PASCOS 2024

Overview

- **Introduction**
  - Cosmological model, dark energy and its imprints on observations
  - The Dark Energy Survey (DES)
- **DES Year 3 Results**
  - Geometry
    - GW
  - Geometry & Growth of Structures
    - Clusters
    - WL: 3x2pt, Extensions
    - DES is not only DE
- **The “final” results: DES Y6**
- **Summary**

Introduction: The Standard Model of Cosmology - ΛCDM

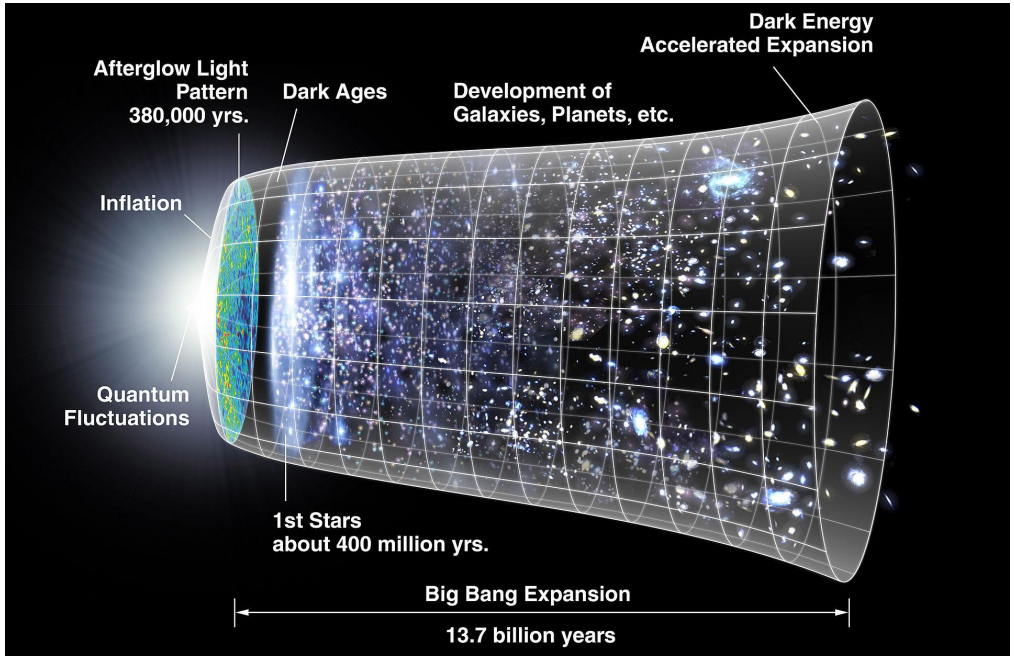


Image Credit: NASA / LAMBDA Archive / WMAP Science Team

- Flat Universe with Dark Energy in the form of a cosmological constant Λ + Cold Dark Matter.
- It assumes General Relativity.
- ΛCDM became the standard model following observations from Type Ia Supernovae and the Cosmic Microwave Background.

Introduction: The Standard Model of Cosmology - ΛCDM

- Parameters of our Universe
  - Densities of matter (Ω_m~0.3), dark energy (Ω_Λ ~0.7), baryons (~0.05), neutrinos
  - Amplitude of structure σ_8~0.8
  - Expansion rate h~0.69

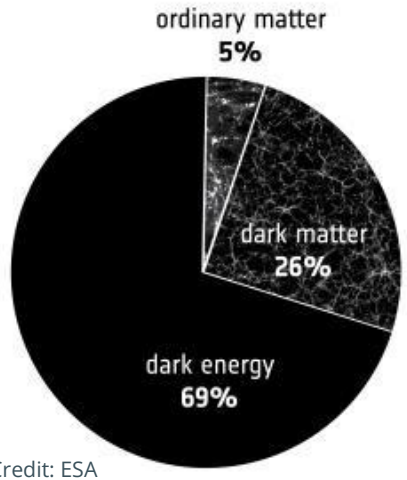


Image Credit: ESA

- Some weaknesses
  - ΛCDM adds **2 new components** to the Standard Model of Physics, neither of which have been observed in a laboratory.
  - The cosmological constant interpreted as the **vacuum energy** is **~120** orders of magnitude **lower** than the naive **prediction** coming from **particle physics**.

Testing the ΛCDM model

- We should test the basic predictions of ΛCDM
  - Are data from early Universe and late Universe fit by the same parameters?
  - Do measurements of cosmic distances and growth of structure agree?
- What if is not a cosmological constant?
  - Does the dark energy density change as space expands?
  - Simple extension: Measure the equation of state ω!
- Is it modified gravity?

How to Survey Dark Energy?

- Early-time Universe vs. late-time Universe
- Do different measurements agree with ΛCDM?
- We need a large sky survey to test that: The Dark Energy Survey!

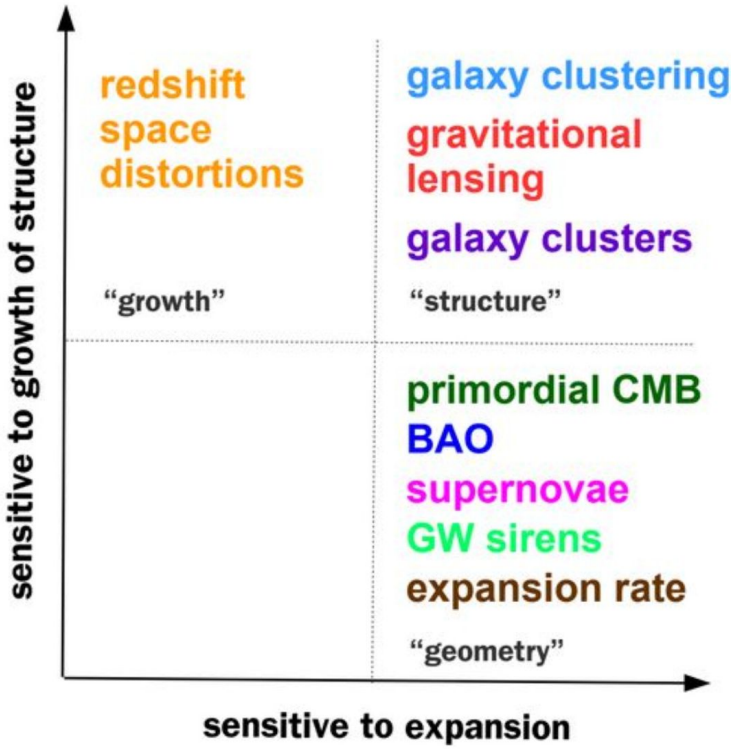


Image: D. Gruen, Blois 2018 & A. Carnero Blois 2019

The Dark Energy Survey

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey 2013-2019 (Y3 2013-16).
- Wide field: 5000 sq. deg. in 5 bands. ~23 magnitude.
- DES Y3: Positions and shapes of > 100M galaxies.

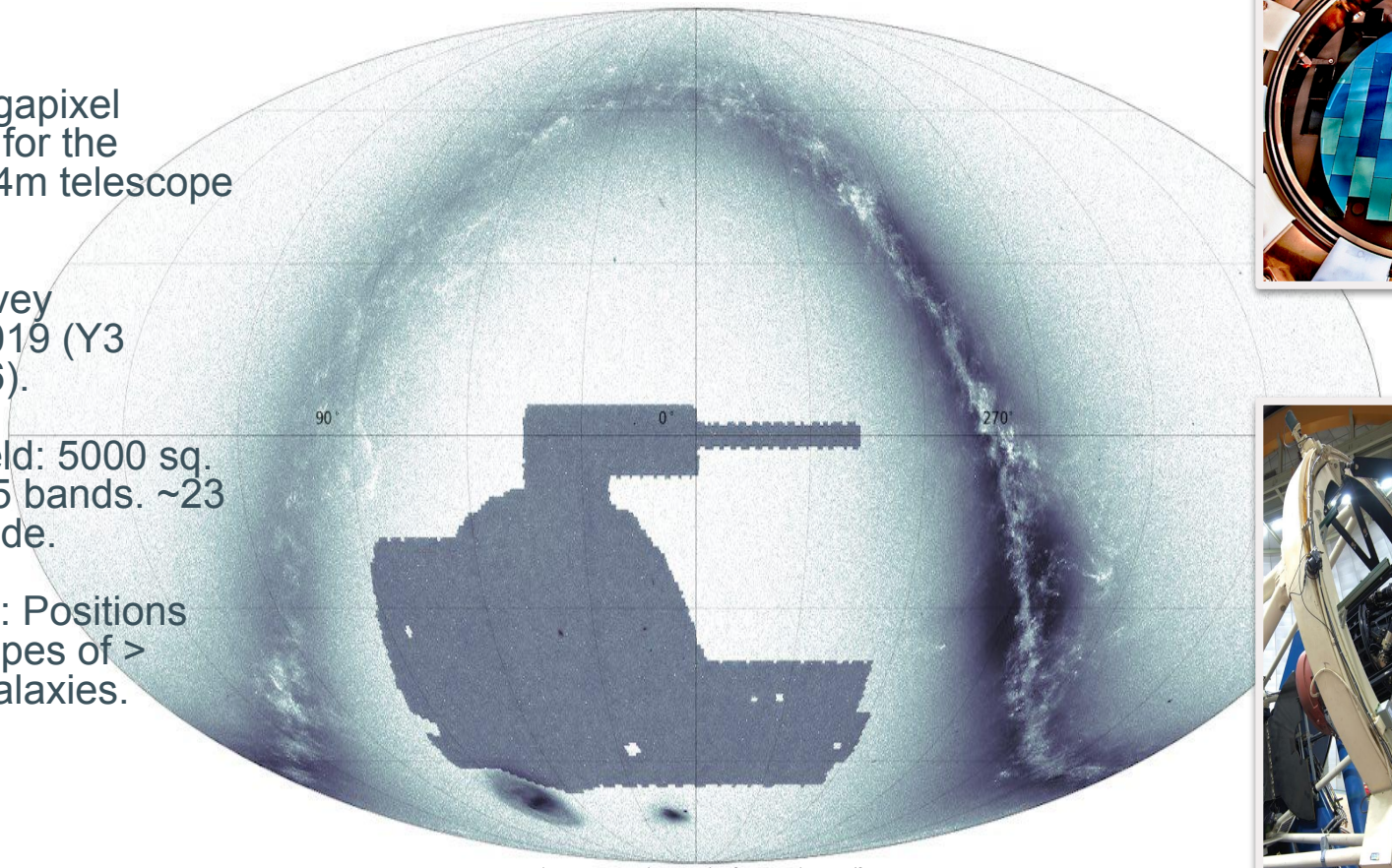
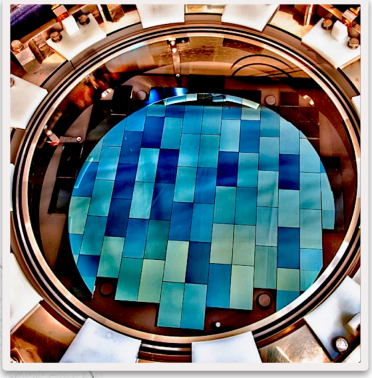
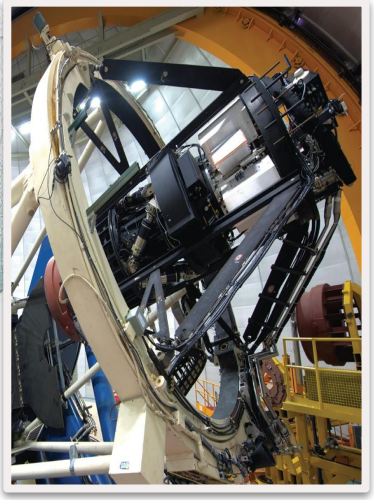


Image Credit: CosmoHub,Port d'Informació Científica (PIC)



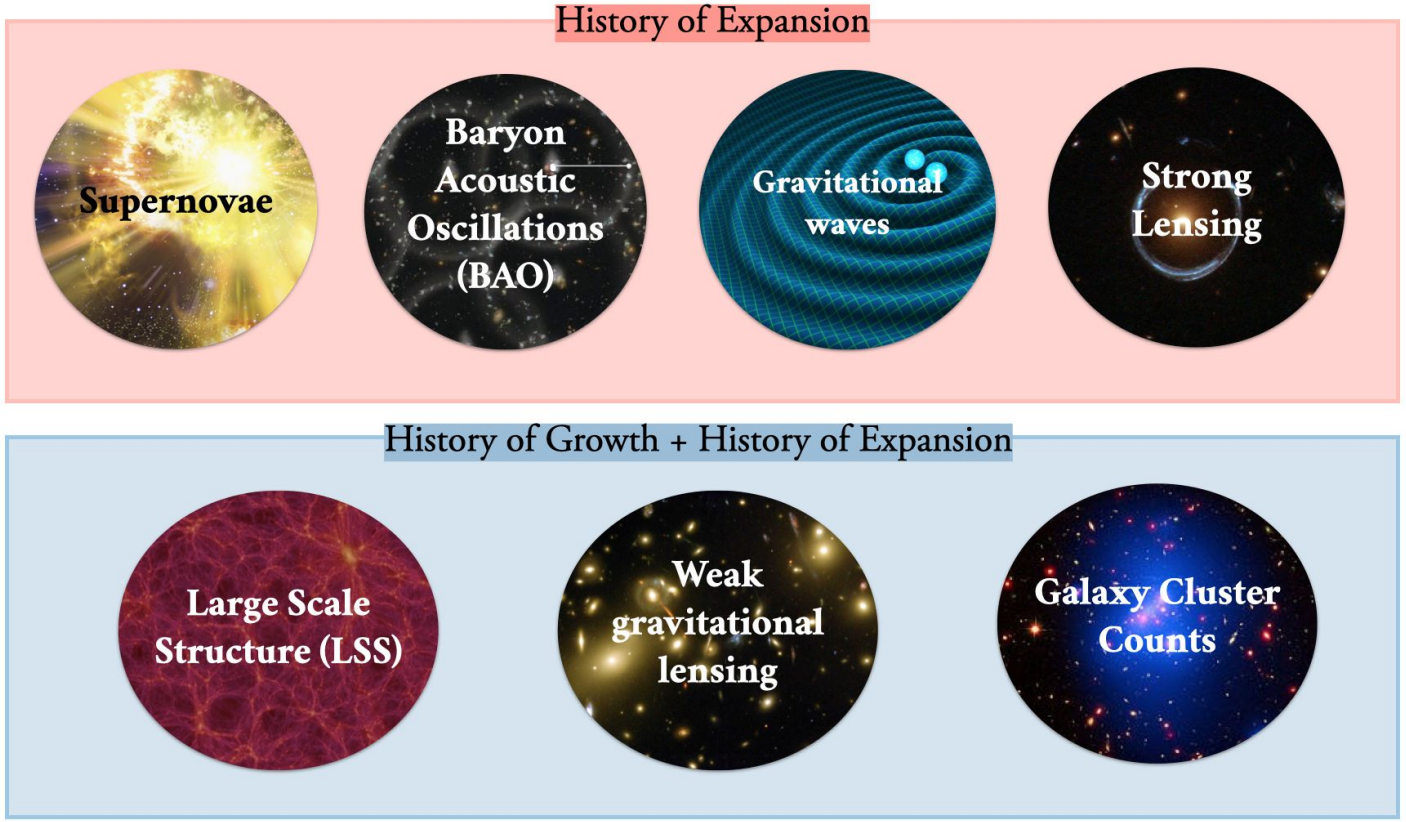


The Dark Energy Survey Collaboration

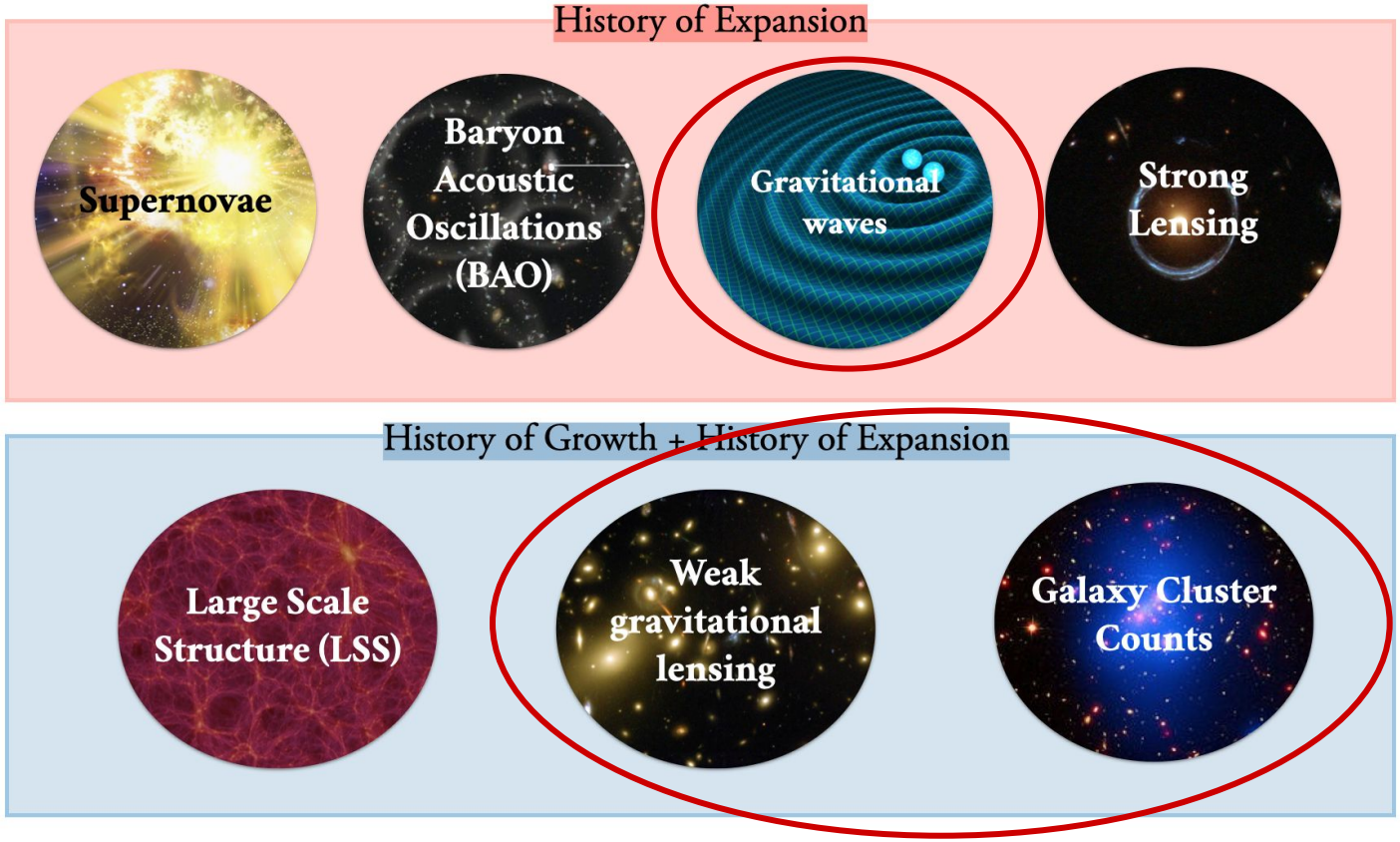
~500 scientists

Image Credit: DES collaboration

Probes to Test a Cosmological Model within DES



Probes to Test a Cosmological Model within DES



Gravitational Wave Standard Sirens

- **Gravitational wave** (GW) signals are absolute **distance indicators**
  - Phase and amplitude are well defined
  - Can be used as **"standard sirens"**
- Binary neutron stars merger: If **electromagnetic counterpart** is found
  - From LIGO: localization, distance
  - From a galaxy survey: host galaxy, redshift
- Then, we can compute **distance-redshift relation!**
- We can also use "**dark sirens**"!

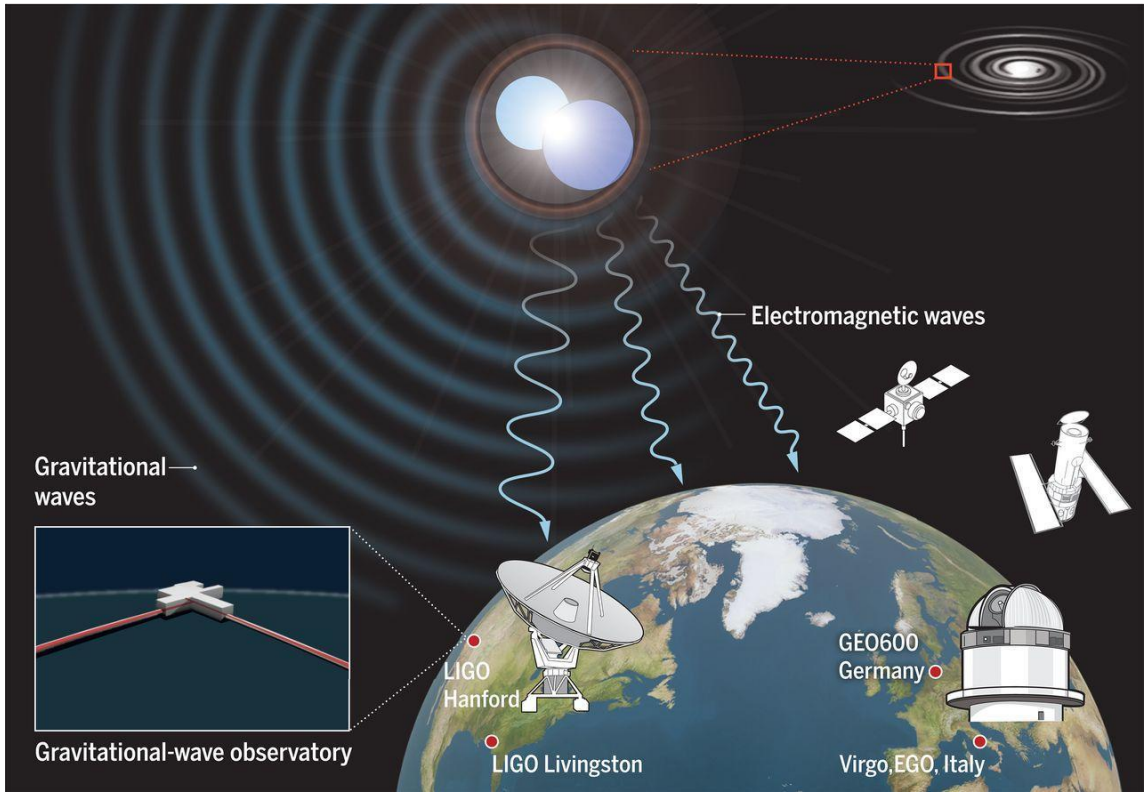
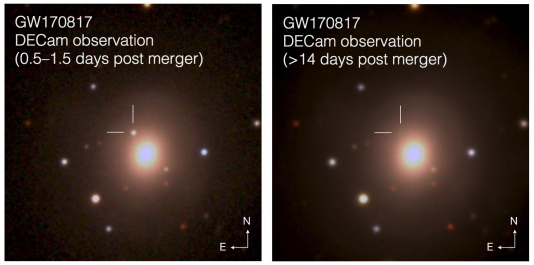


Image credit: N. Cary/Revista Science (VITALE, 2021)

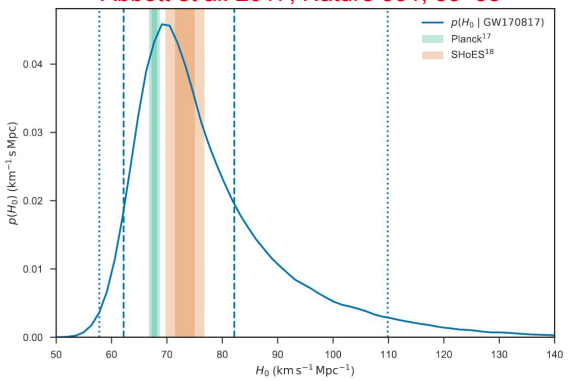
Gravitational Wave Standard Sirens

- Current results:
  - Only 1 bright siren event observed GW170817
  - Many more dark sirens, but just a few with small localization areas
- We are not in a precision era with GW standard sirens
- But, there is great potential with the future GW detectors!

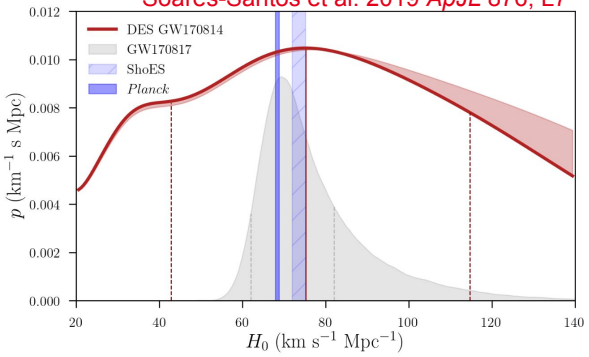
Soares-Santos et al. 2017 ApJL 848 L16



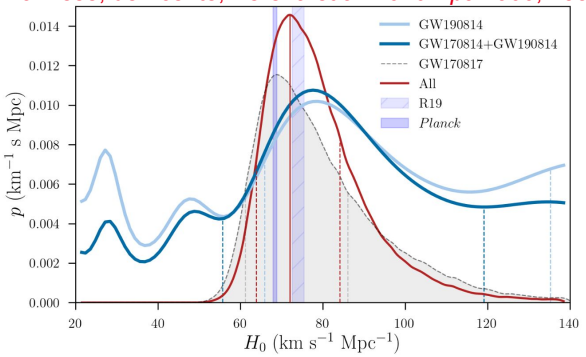
Abbott et al. 2017, Nature 551, 85–88



Soares-Santos et al. 2019 *ApJL* 876, L7



Palmese, deVicente, Pereira et al. 2020 *ApJL* 900, L33



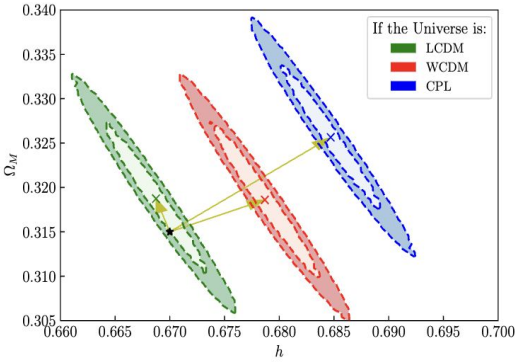
DES-GW on LVK O4

- LIGO started the **Observing Run 4** (O4) in the first semester of 2023; it was joined this year by Virgo; KAGRA will also join before O4 ends
- LVK is expected **to run until June 2025**
- More sensitive than previous runs → more detections and higher distances (0 to 62 detections of NS, distances up to 190 Mpc)
- **DES-GW** is performing the **search for the electromagnetic counterpart** of the mergers
  - Search of candidates: Optimized **optical search strategy** with DECam (Bom et al. 2024 ApJ 960 122)
  - Detection confirmation: We've applied for **spectroscopic follow-up** time
- Goals: measurements of H_0(bright and dark sirens), combination with DES cosmological results, astrophysics, etc

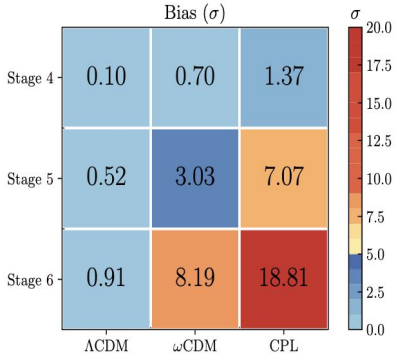
GW beyond O4

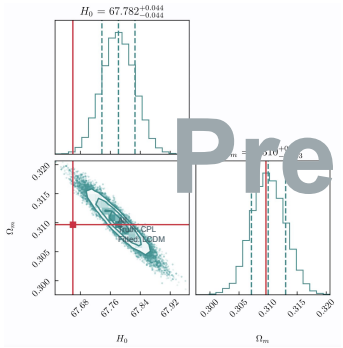
- O5, A+...but at Snowmass 2021: synergy between current and **next-generation GW** experiments (e.g. Cosmic Explorer, ET) and astrophysical surveys is explored in a White Paper on transient science
  - Can we go beyond H_0? Other cosmological parameters?
  - How can we combine GW bright sirens with other probes?
  - Will GW give us hints on tensions in the cosmological model?
- Simple estimates, but now we are performing a forecast of more realistic events, and adding more DE models
  - How can we make optical searches of bright sirens work for the next generation of GW?

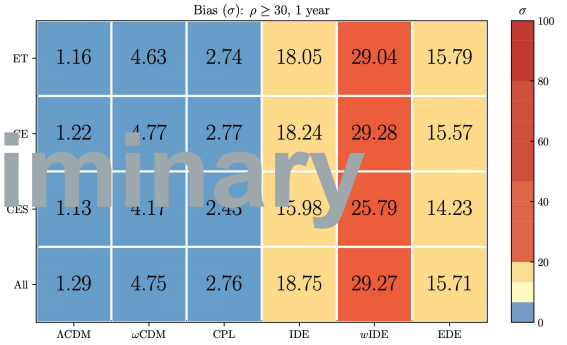
Kim, Palmese, Pereira et al 2022,
Arxiv: 2203.11226



Stage	GW network type	z range	No. of events
IV	HLVKI	0.5	110
V	Voyager	1.0	1300
VI	Cosmic Explorer	4.0	6000





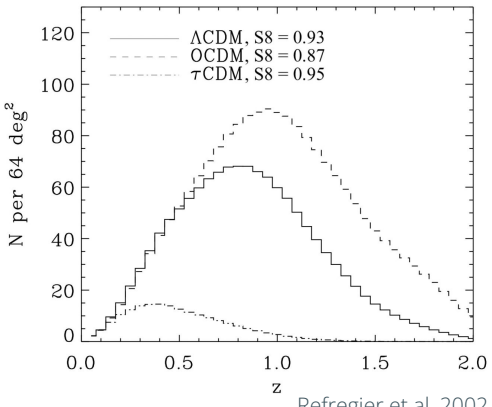


Preliminary

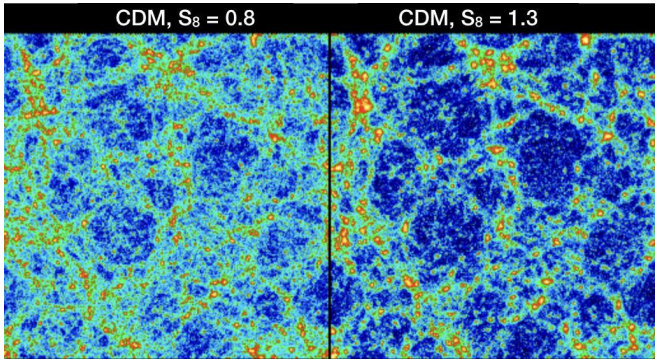
Perfect scenario: finding counterpart of all BNS event up to z<0.5 (+10K events/year), mock data-vectors from 6 DE models, fit ΛCDM

Galaxy Clusters

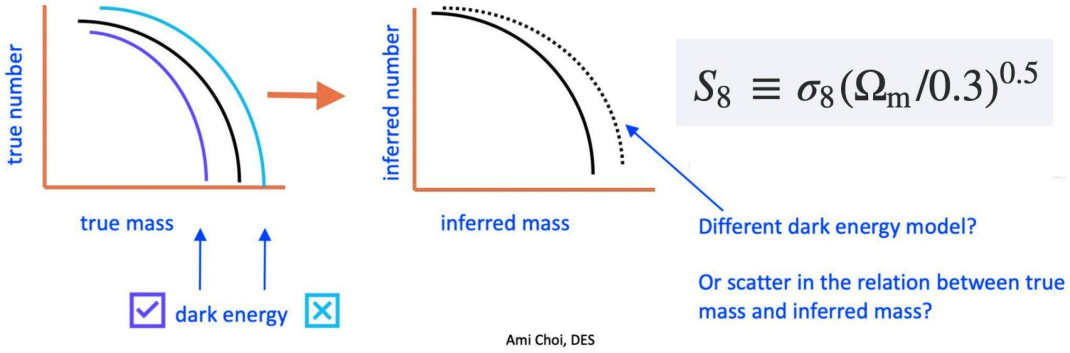
- Galaxy clusters are powerful **cosmological probes**
- Largest astronomical objects bound by gravity
- Measurements of its **mass** and **abundance** tell us about the **amount of dark matter** in the Universe and **structure formation**
- Can provide unique constraints on the **quantity** and **properties** of dark matter and **dark energy** in the Universe



Refregier et al, 2002



Credit: Warren et al. (Los Alamos), adapted.



Galaxy Clusters

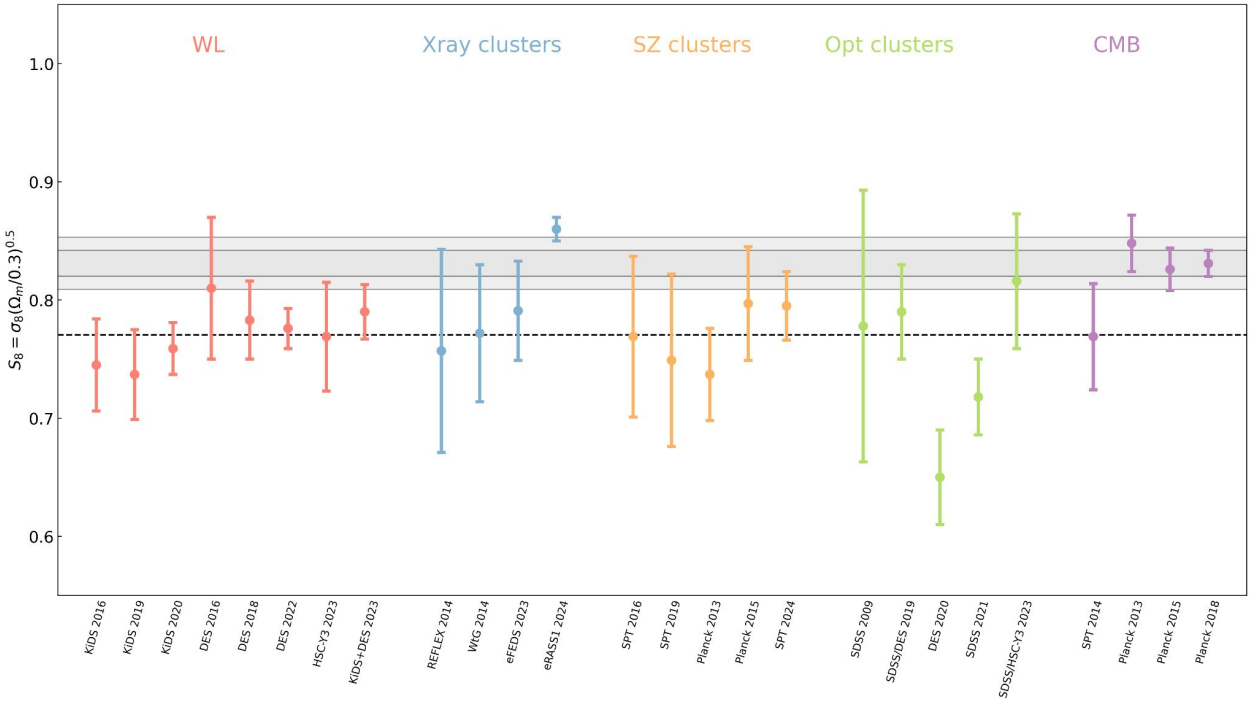


Image: Pereira

- Several surveys in different wavelengths
- Systematic lower value in comparison to CMB
- Systematics? New physics?

Galaxy Clusters

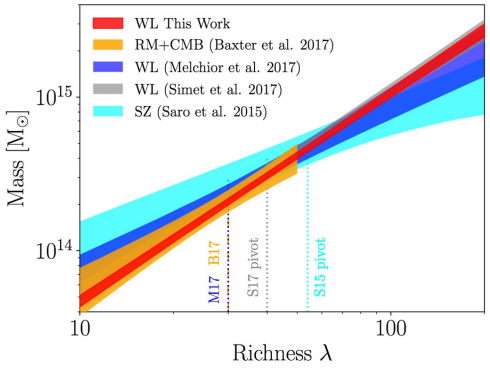
- redMaPPer Cluster Catalog (~6K)
- Metacal Shears (~30M)
- BPZ photo-z's (~0.7)

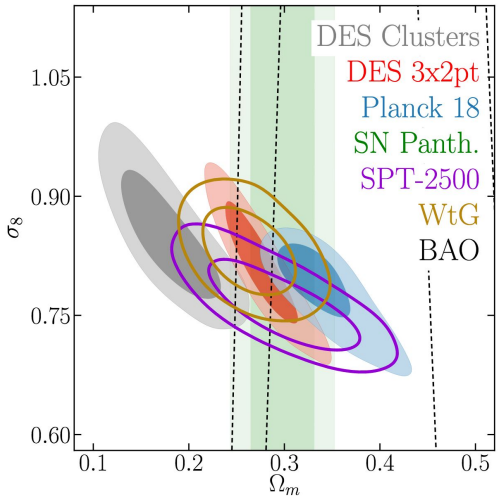
Mass-Calibration (MOR) 1

Number Counts (NC) 2

Cosmology
$S_8(\sigma_8, \Omega_m)$

McClintock et al. 2019 (DES Collaboration), MNRAS, Vol. 482, Issue 1





- DES Y1 (small-scales) result was very surprising
- Some issue with the **mass** of **low richness** clusters
- Offset in cosmological parameters is most like driven by **systematics**: projection and selection effects
- DES Y3 small-scales analysis is under development

T. M. C. Abbott et al. 2020 (DES Collaboration)
Phys. Rev. D 102, 023509, Published 7 July 2020

Galaxy Clusters

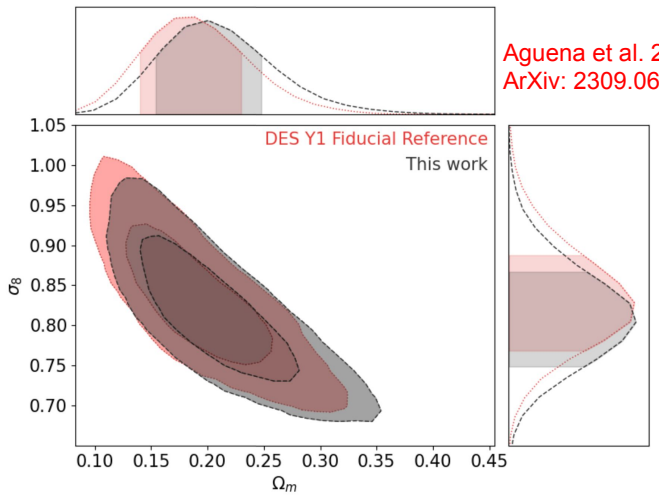
- redMaPPer Cluster Catalog (20K)
- Metacal Shears (~100M)
- BPZ photo-z's (~0.7)

Shear Signal (γ_t) + Number Counts (NC)

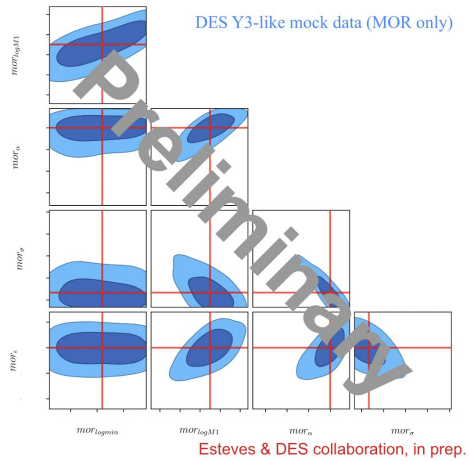
1

Cosmology $S_8(\sigma_8, \Omega_m)$

- DES Y3: new approach → forward modelling
- Y3 pipeline in C++ and performs the full integrations, no approximations (slower computation)
  - We run a simplified version of Y3 pipeline on Y1 data
  - Currently, working on GPU version of the Y3 pipeline



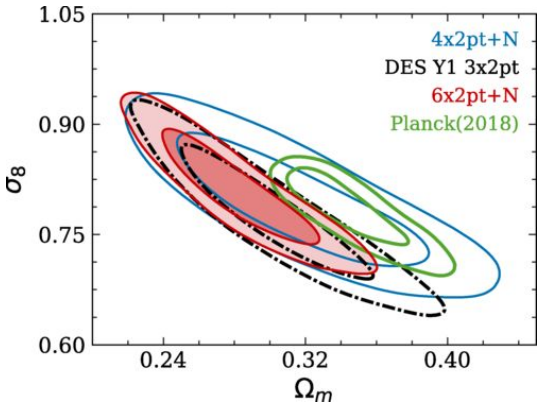
Aguena et al. 2023, ArXiv: 2309.06593



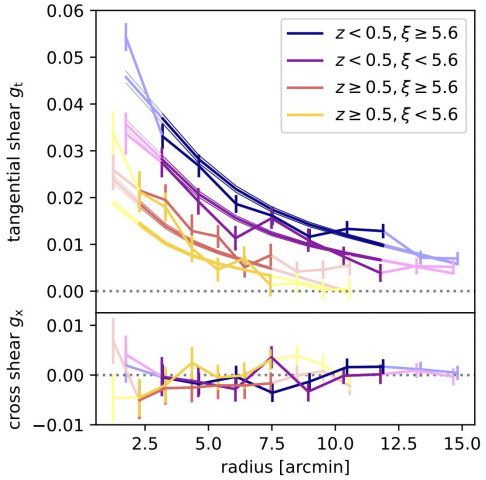
Galaxy Clusters

- Several cluster cosmology analyses in DES
- **Large-scale analysis** under development: cluster abundance + galaxy clustering, lensing (N+4x2pt)
- **SZ analysis**: 1000 SZ clusters + Y3 weak lensing. **See results at S. Bocquet's talk on Wed, W1P5 Cosmology session**
- Different mass indicators being tested: e.g. stellar masses

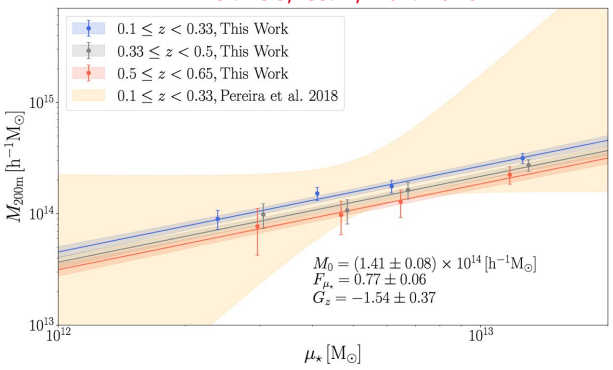
C. To *et al.* (DES Collaboration);
Phys. Rev. Lett. 126, 141301, 2021



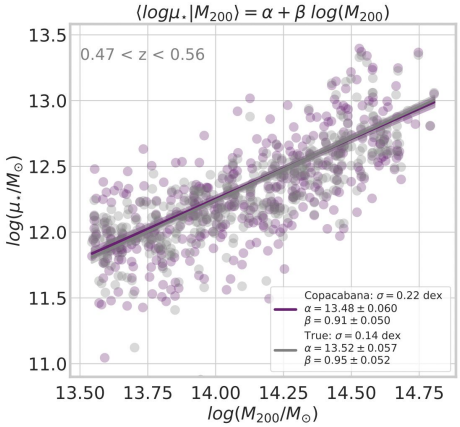
Bocquet et al, 2024
Arxiv: 2401.02075, PRD accepted.



Pereira et al. 2020 MNRAS,
Vol. 498, Iss. 4, Nov. 2020

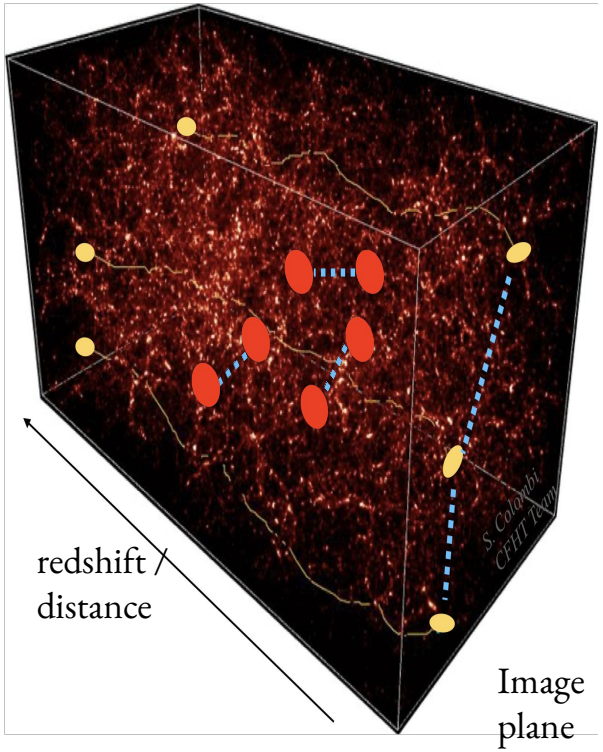


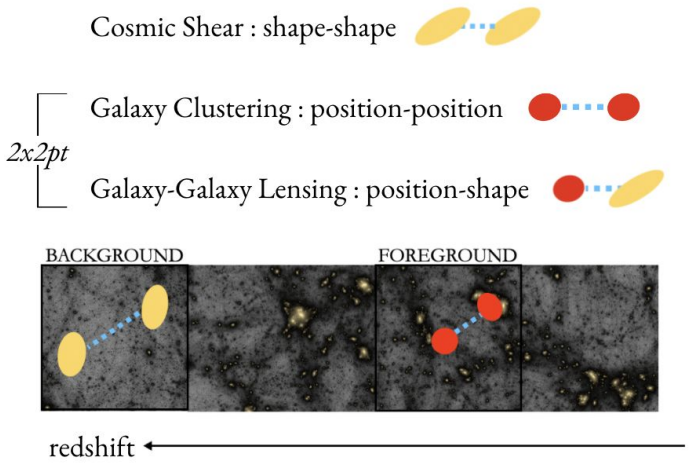
Esteves, Pereira et al. 2024,
Arxiv: 2401.12049



Weak Lensing and Clustering (3x2pt)

- Weak lensing
  - Light from distant galaxies passes the same foreground structure and acquires coherent distortions: they are observe to be **lensed**.
- Galaxy distribution
  - Galaxies trace the underlying dark matter structure: they are observed to be spatially **clustered**.
- A **joint analysis** maximises the cosmological information and robustly constrains astrophysical & observational systematic priors in the analysis!

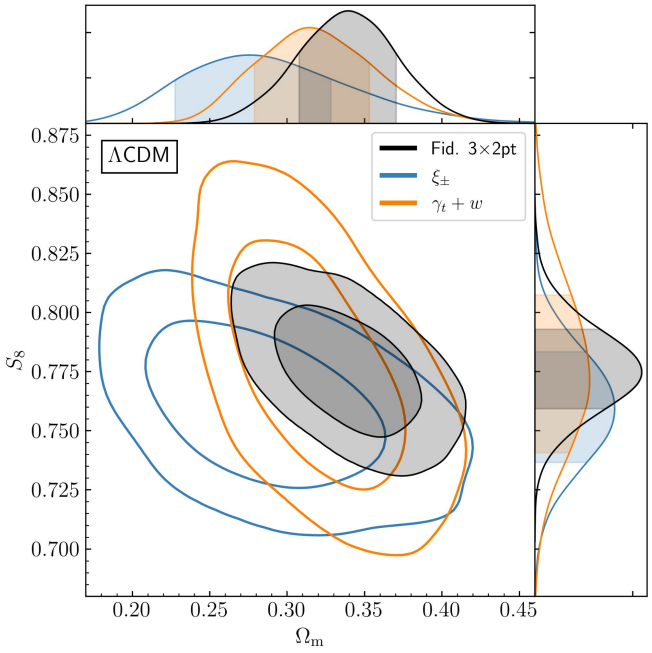


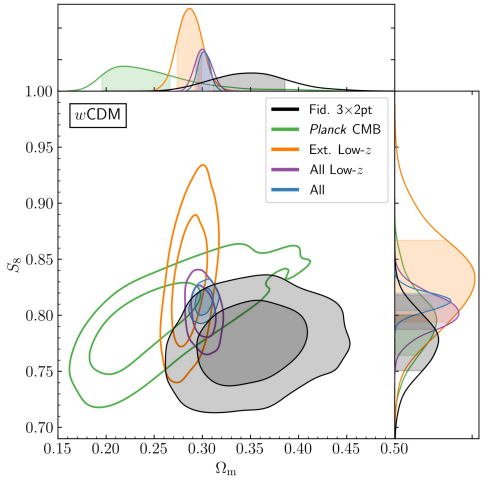


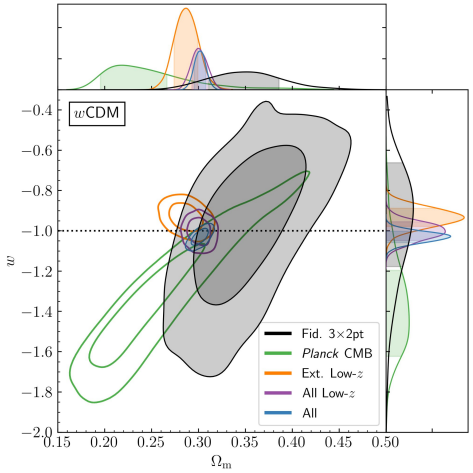
Slide credit: DES collaboration, May 2021, DES Y3 results release

Weak Lensing and Clustering (3x2pt)

DES Collaboration, 2022, PRD, 105, 2







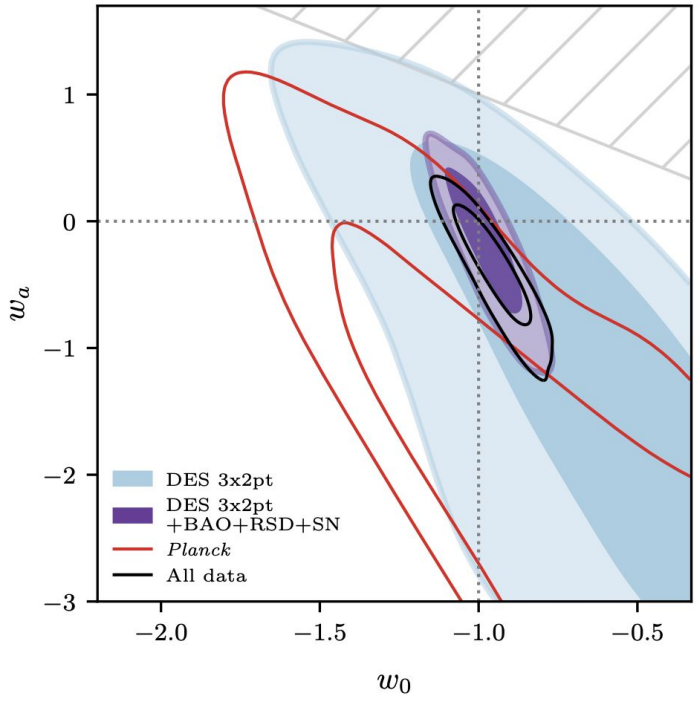
- This combination of DES data is consistent ΛCDM
- For wCDM: $\Omega m = 0.352^{+0.035}_{-0.041}$, and dark energy equation of state parameter $w = -0.98^{+0.32}_{-0.20}$.
- A puzzling systematic appeared: anomalously high clustering signal

Beyond ΛCDM: 3x2pt Extensions

- DES Y3 data analysis of a few extensions of the standard flat ΛCDM and wCDM models considered in Y3, namely the possibilities of:
  - Time-variation of the dark energy equation-of-state;
  - Nonzero spatial curvature;
  - Sterile neutrinos;
  - Modifications of the laws of gravity on cosmological scales;
  - Binned σ8(z) model as a probe of structure growth: i.e. deviations of the rate of cosmological structure growth from that expected in standard cosmology
- Results: consistent with ΛCDM!

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

DES Collaboration 2023, PRD, 107, 8



Other highlights

- Solar system:
  - TNO and Centaurs, Planet 9 search
- Galactic searches:
  - Brown dwarfs, RR lyrae
- Milky Way formation:
  - Large Scale Structure, Stellar streams discoveries
- Local Universe:
  - MW faint companions
- Galaxy evolution, galaxy cluster astrophysics

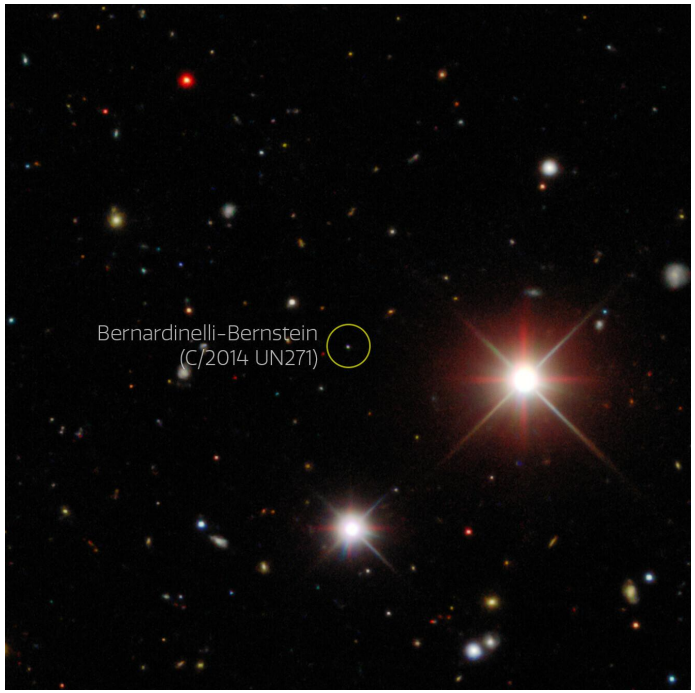
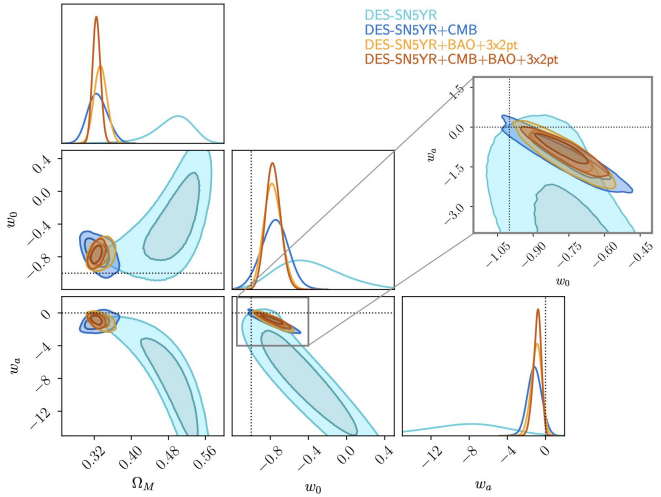


Image: Dark Energy Survey/DOE/FNAL/DECam/CTIO/NOIRLab/NSF/AURA/P. Bernardinelli & G. Bernstein (UPenn)/DESI Legacy Imaging Surveys

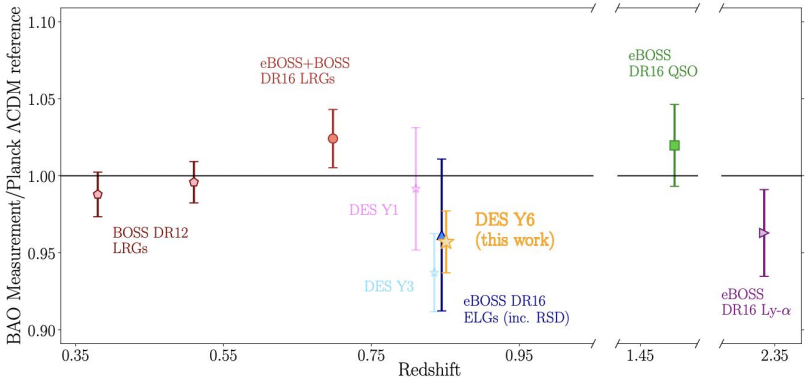
The DES “final results”: DES Y6

- **Supernova (DESY5)** done
- **BAO** done
- Weak lensing and Clusters ongoing:
  - Full depth, >500M galaxies, ~35K clusters at redshift ~1
- DES-GW searches on LVK O4 (until June 2025)
  - Hopefully, find more BNS events
  - And BBH events with improved localization areas
  - Cosmology measurements and combination with DES final dataset

Abbott et al, 2024
Arxiv: 2401.02929, ApJL accepted



Abbott et al, 2024, Arxiv: 2402.10696



Summary

DES Overview

- The Dark Energy Survey combines geometric and large-scale structure probes to test the ΛCDM model
- To date, no significant inconsistencies have been found between DES and Planck, or between DES + other complementary low-redshift probes and Planck

Current Highlights

- Some puzzling systematics have been identified and are under investigation
- DES Year 3 cluster cosmology small-scale results are coming soon
- DES-GW is actively conducting transient searches in LVK O4 (until June 2025)

Upcoming Results

- DES Year 6 Final Results:
  - Supernova and BAO analyses are complete
  - Weak lensing and cluster analyses are currently under development. Stay tuned!

- DES continues to provide state-of-the-art large-scale structure results from optical surveys
- DES has significantly contributed to understanding and improving systematic uncertainties, paving the way for future surveys like Rubin and Euclid