# Dark Energy


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UCLA Dark Matter Conference

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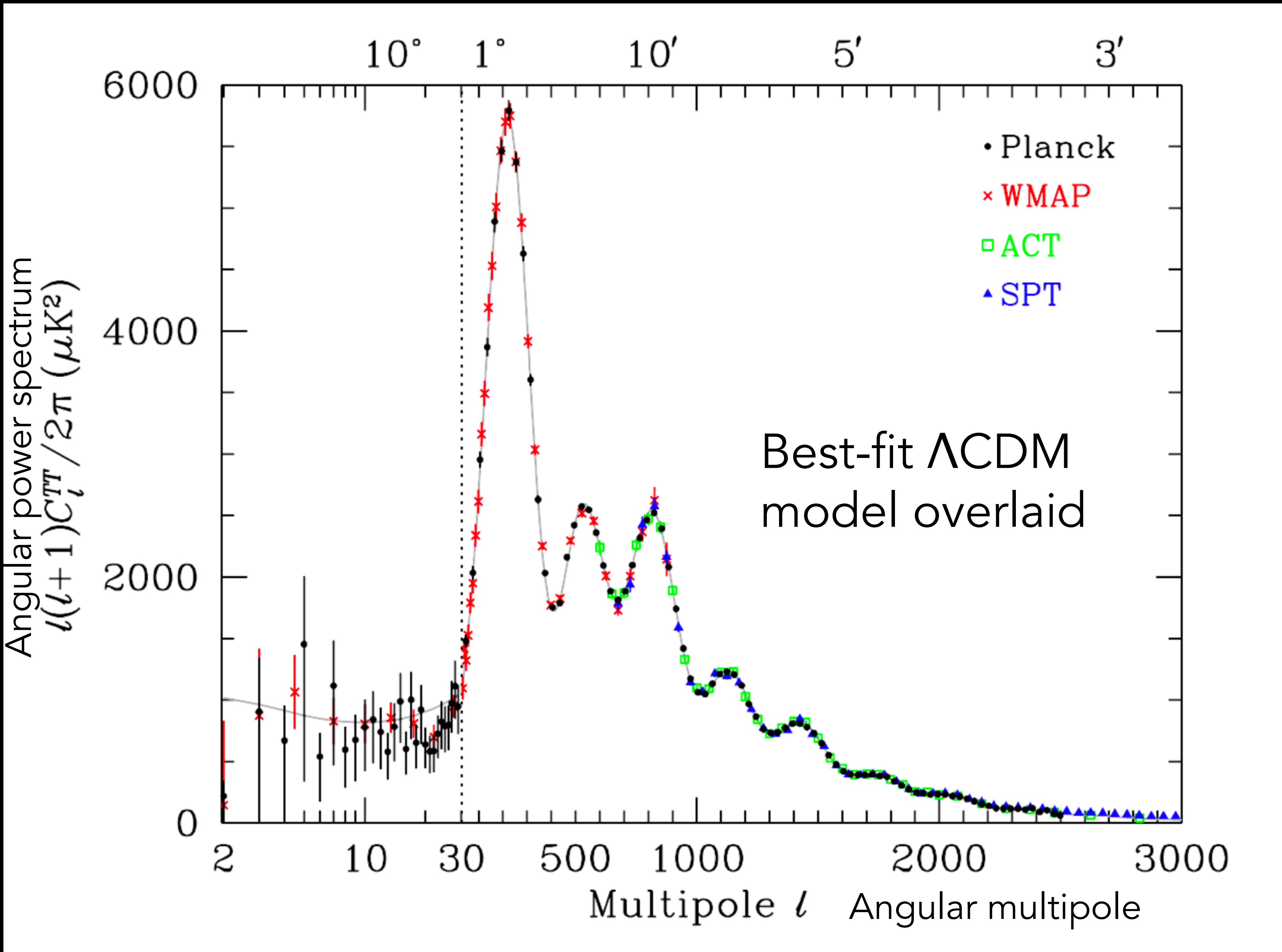
# Cosmology 2023: ΛCDM

- Well-tested (6-parameter) cosmological model:
  - Universe expanding from hot, dense, early phase 13.8 billion years ago.
  - Early epoch of accelerated expansion (inflation) produced nearly flat & smooth spatial geometry and generated large-scale density perturbations from quantum fluctuations.
  - From these, structure formed via gravitational instability of cold dark matter (CDM, 25%) in currently cosmological constant-dominated (Λ,70%) universe, which is again accelerating.
- Consistent with all data from the Cosmic Microwave Background, large-scale structure, gravitational lensing, supernovae, clusters, light element abundances, …

# CMB Temperature Anisotropy



# Cosmological Physics

- Despite remarkable success of $\Lambda$CDM, we don't understand the *physics* of dark matter, dark energy, or inflation.
- What is the Dark Matter?
- Who is the Inflaton?
- What is the origin of Cosmic Acceleration?
  - Dark Energy or Modification of General Relativity?
  - Nature of Dark Energy: $\Lambda$ or dynamical component (e.g., an ultra-light field)?
- How do they fit into extensions of the Standard Model of Particle Physics?

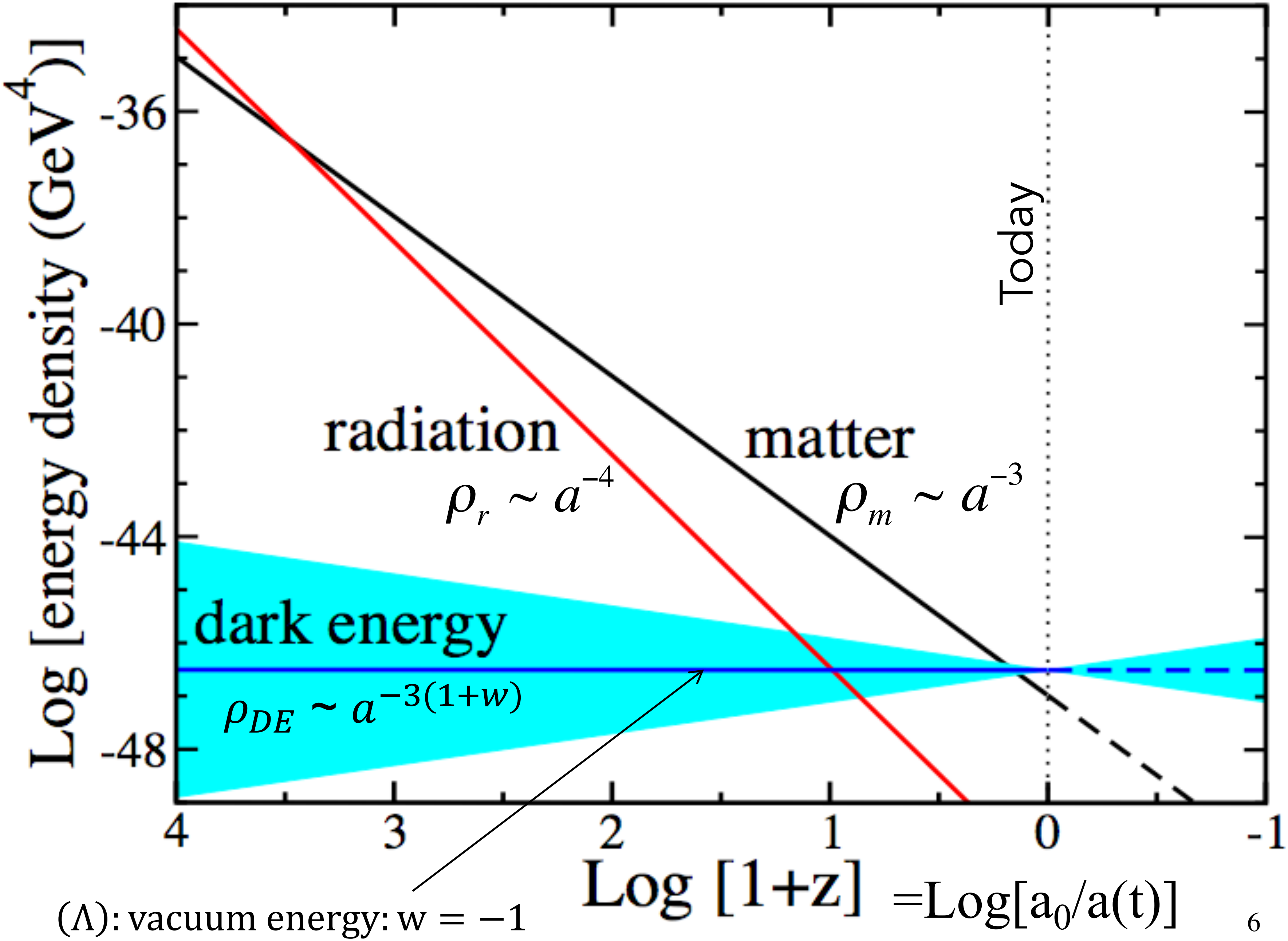
# Cosmological Dynamics

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i \rho_i \left(1+3w_i\right)$$

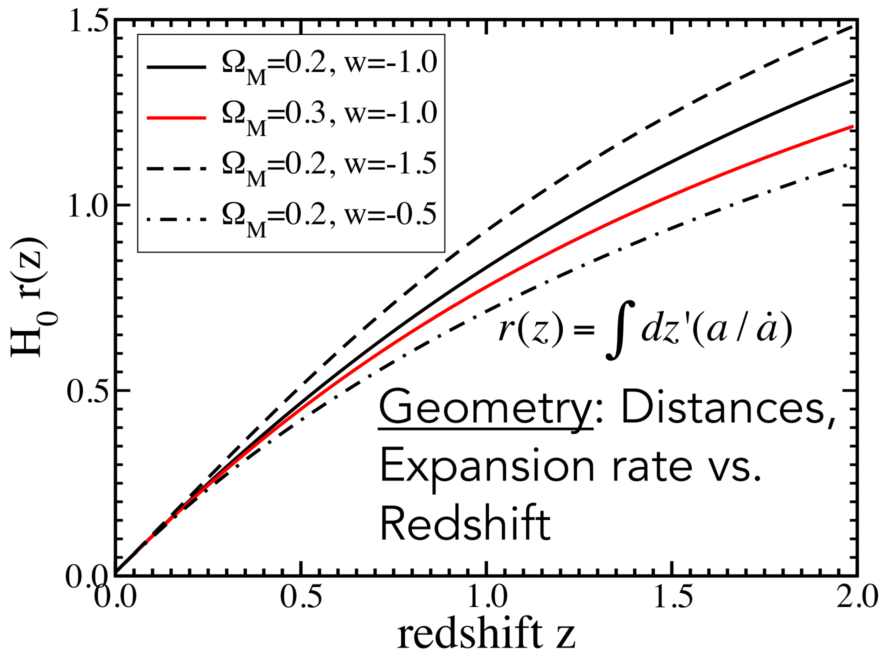
Friedmann Equation from General Relativity

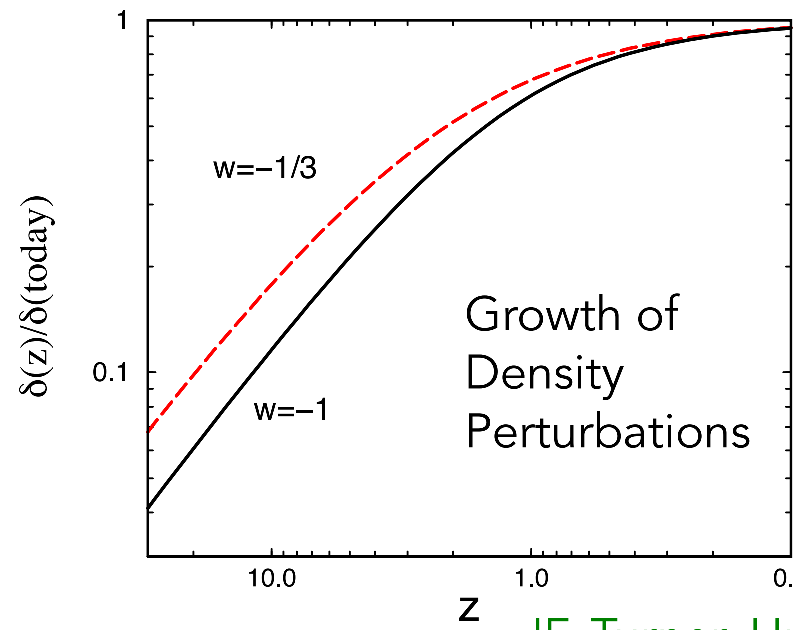
- Dark Energy: dominant, "repulsive gravity" component of the energy density that drives cosmic acceleration ($\ddot{a} > 0$) via an equation of state parameter, $w = \frac{p}{\rho} < -1/3$.
- Special case: vacuum energy, $w = -1$, equivalent to Einstein's cosmological constant $\Lambda$.
- Alternative: replace GR with a new theory of gravity.

# DE Equation of State parameter *w* determines Cosmic Evolution



# Signatures of Dark Energy




JF, Turner, Huterer

## Expansion History

## Growth of Structure

Probes: SNe, BAO

WL, CL, RSD

To constrain DE and test ΛCDM, we're aiming toward 1%-level measurements. In GR, there's a fixed relation between expansion history and structure growth: consistency test.

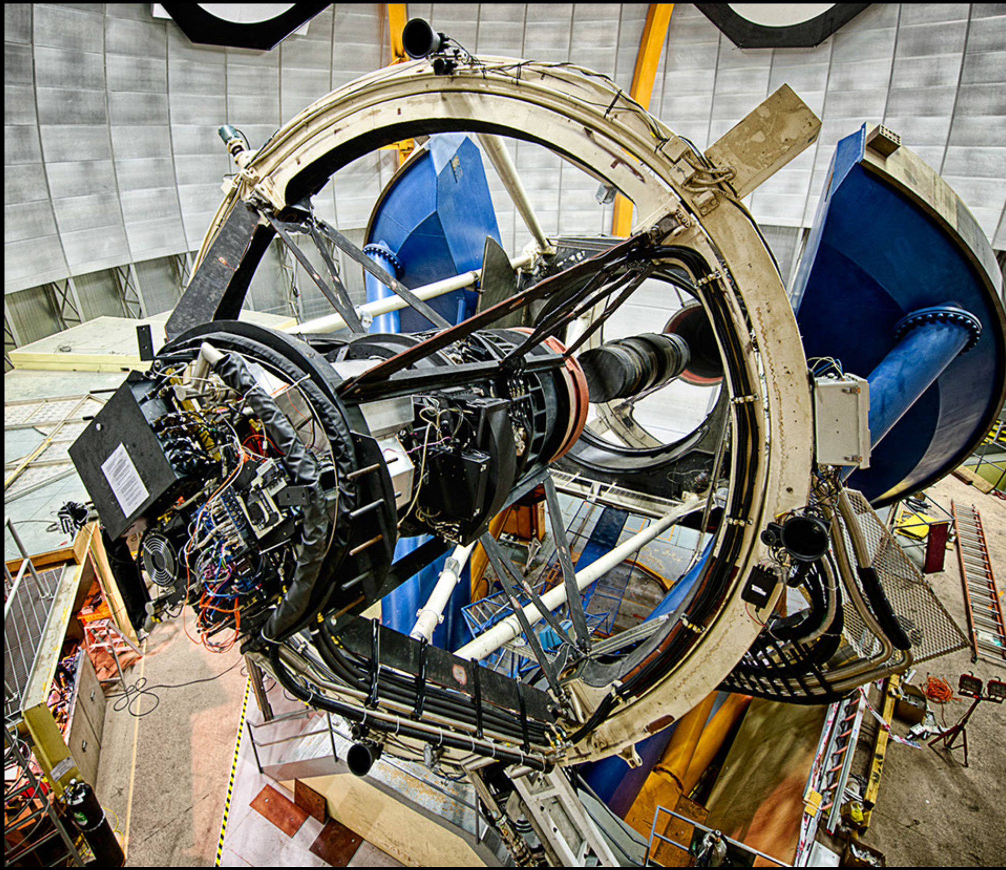
# Cosmic Surveys: Stage III to Stage IV

| | Project | Dates | Area/deg$^2$ | Data | Spec-$z$ Range | Methods |
|---|---|---|---|---|---|---|
| Stage III | BOSS | 2008–2014 | 10,000 | Opt-S | 0.3–0.7 (gals) | BAO/RSD |
| | | | | | 2–3.5 (Ly$\alpha$F) | |
| | KiDS | 2011–2019 | 1350 | Opt-I | —— | WL/CL |
| | DES | 2013–2019 | 5000 | Opt-I | —— | WL/CL |
| | | | | | | SN/BAO |
| | eBOSS | 2014–2018 | 7500 | Opt-S | 0.6–2.0 (gal/QSO) | BAO/RSD |
| | | | | | 2–3.5 (Ly$\alpha$F) | |
| | SuMIRE | 2014–2024 | 1500 | Opt-I | | WL/CL |
| | | | | Opt/NIR-S | 0.8–2.4 (gals) | BAO/RSD |
| | HETDEX | 2017–2023 | 450 | Opt-S | $1.9 < z < 3.5$ (gals) | BAO/RSD |
| Stage IV | DESI | 2021–2026 | 14,000 | Opt-S | 0–1.7 (gals) | BAO/RSD |
| | | | | | 2–3.5 (Ly$\alpha$F) | |
| | VRO/LSST | 2025-2035 | 20,000 | Opt-I | —— | WL/CL |
| | | | | | | SN/BAO |
| | *Euclid* | 2023-2029 | 15,000 | Opt-I | | WL/CL |
| | | | | NIR-S | 0.7–2.2 (gals) | BAO/RSD |
| | *Roman* | 2026–2031 | 2200 | NIR-I | | WL/CL/SN |
| | | | | NIR-S | 1.0–3.0 (gals) | BAO/RSD |

I=Imaging, S=Spectroscopic

# The Dark Energy Survey

DECam on the CTIO Blanco 4m

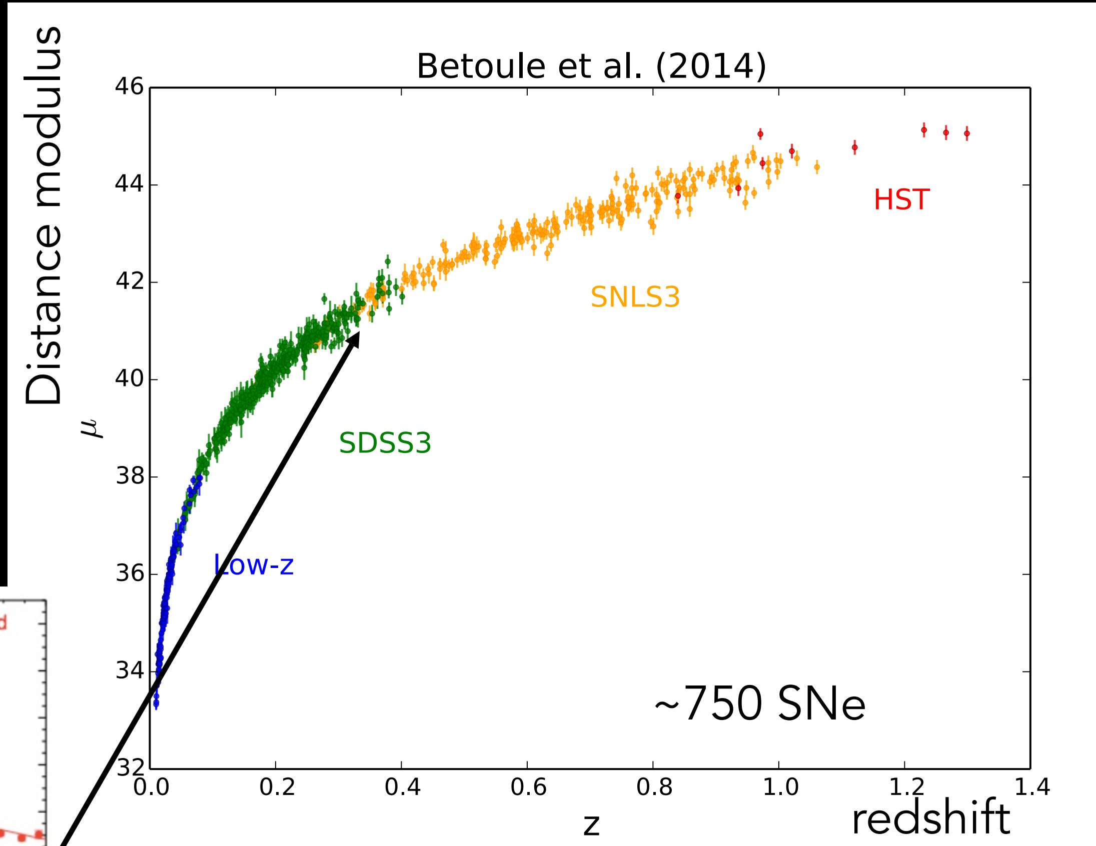


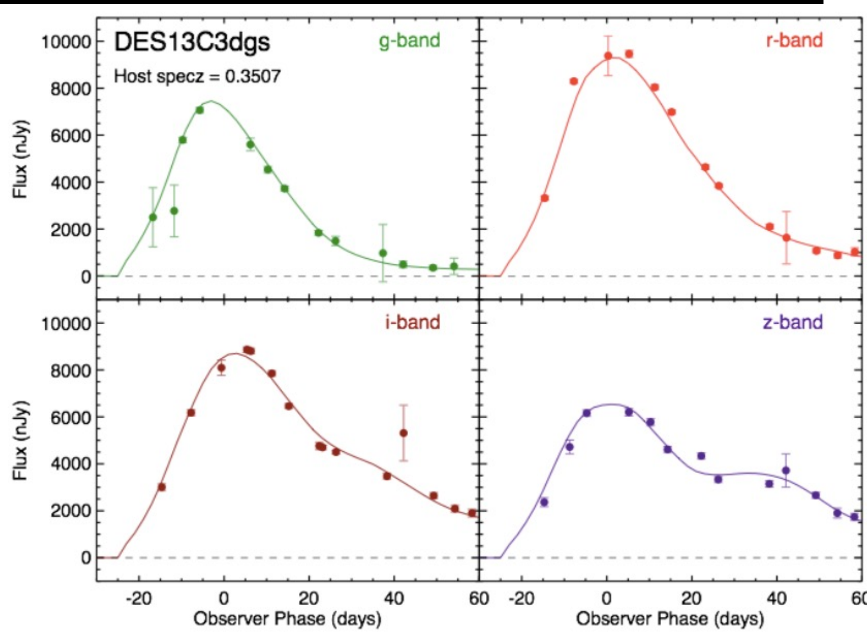
- Probe origin of Cosmic Acceleration:
  - Clusters, Weak Lensing, Galaxy clustering, Supernovae
- Two multicolor surveys:
  - 200 M galaxies over 1/8 sky
  - 2000 supernovae (27 sq deg)
- 570 Megapixel Camera built at Fermilab
  - DECam Facility instrument
- Survey Aug. 2013-Jan. 2019
  - 575 nights
  - Final analyses on-going

International collaboration; US support from DOE+NSF

# Type Ia Supernovae

Standardizable candles probe relative distance vs. redshift (expansion history).



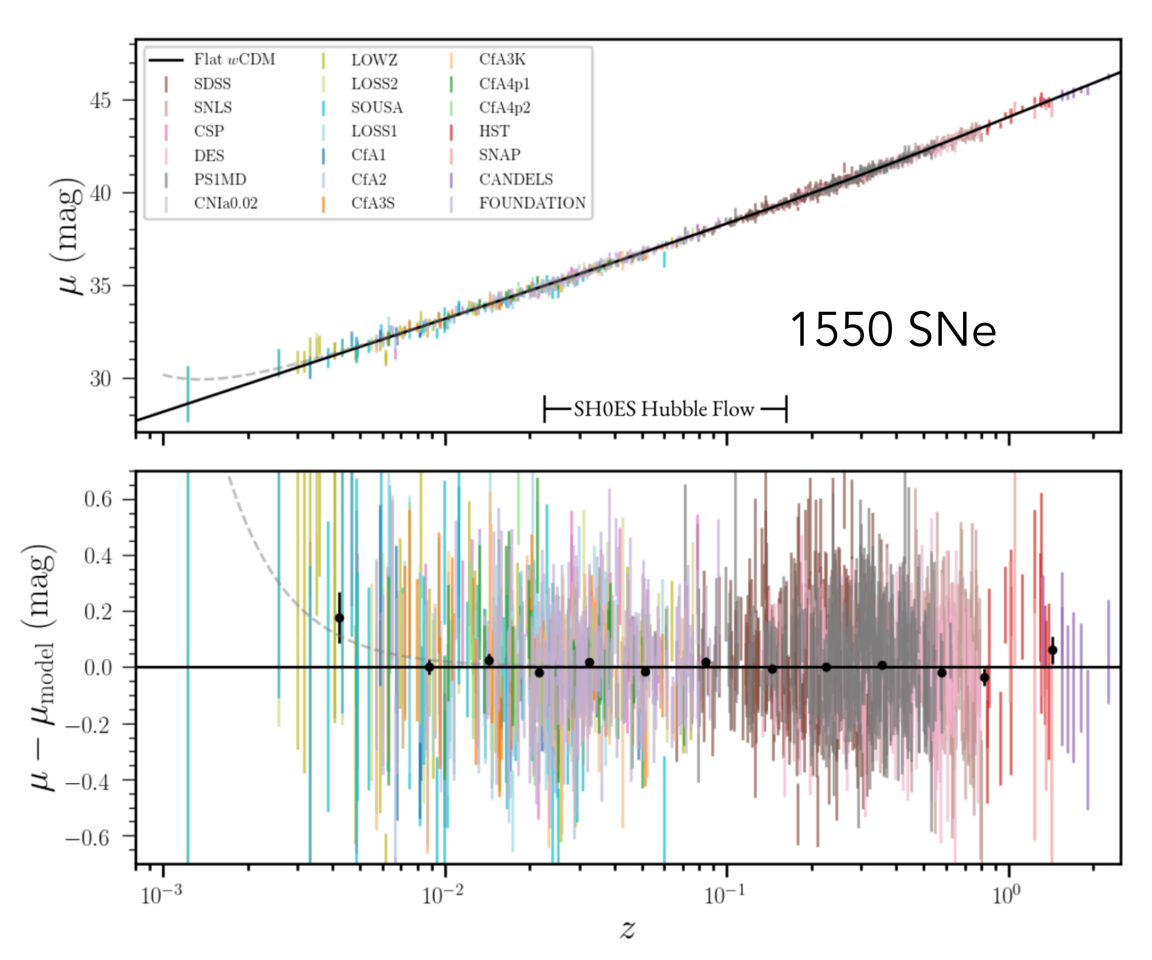

SN Ia brightness (light-curve) & color provide low-dispersion estimate of its distance.

# Type Ia Supernovae

Current state of the art: Pantheon+

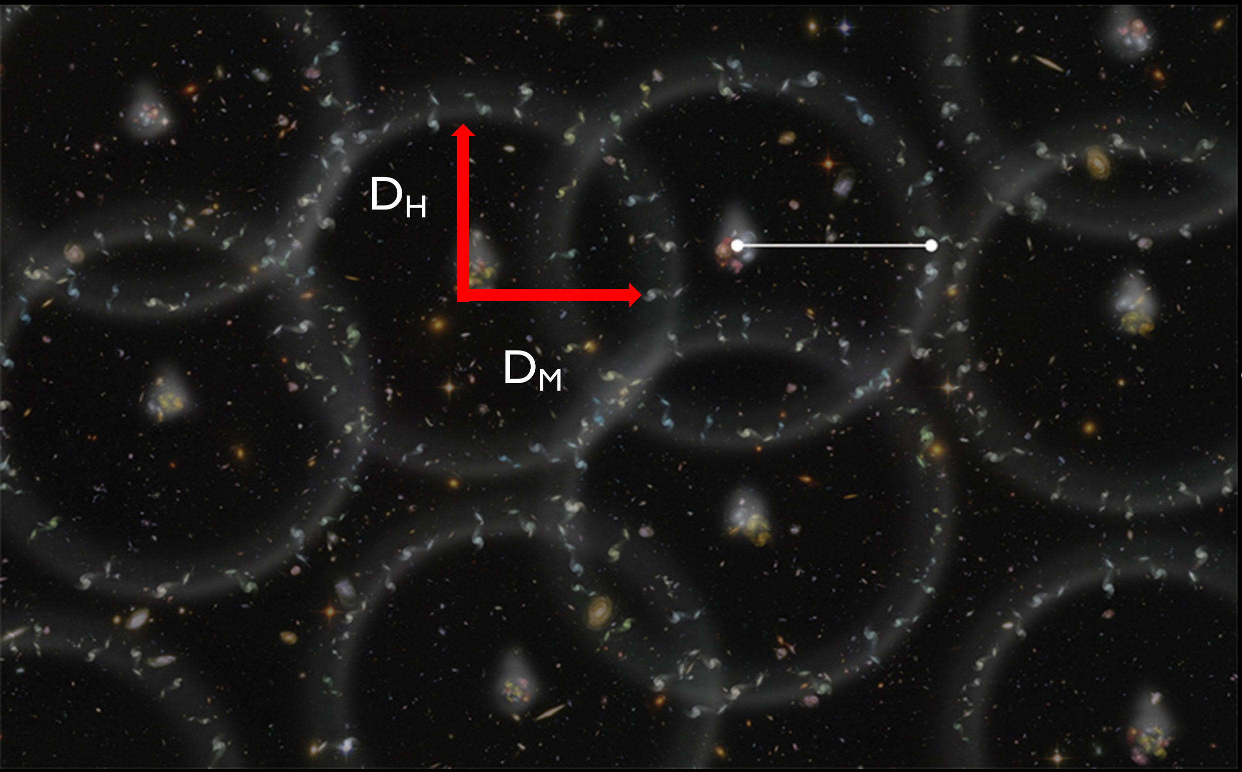
Coming soon: DES Y5 SN results.

Recent progress in modeling SN Ia color and luminosity variation.




Brout+22

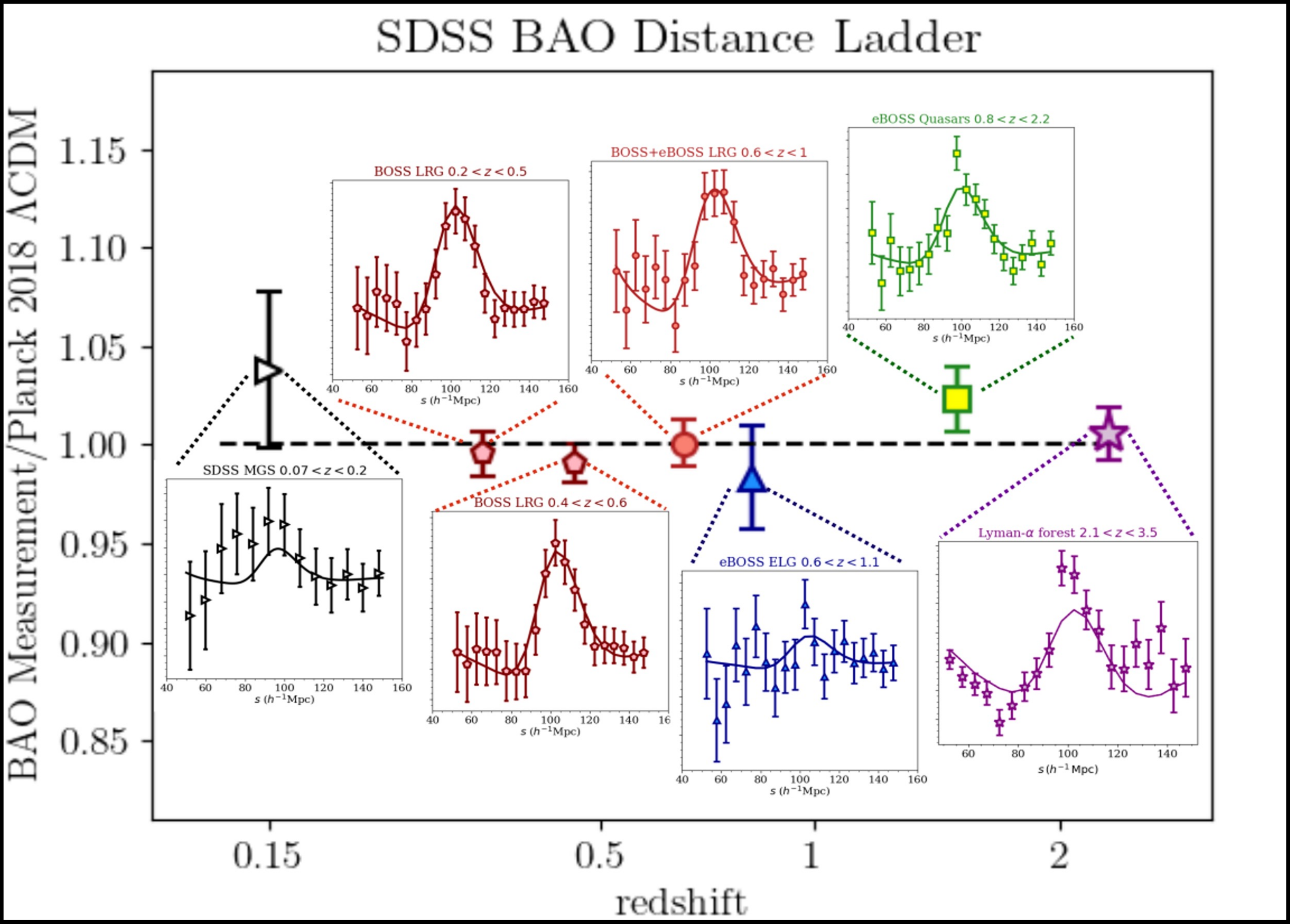
# Baryon Acoustic Oscillations (BAO)




$$D_H(z) = \frac{c}{H(z)} = \frac{r_d}{\Delta z}$$

- Distance $r_d = 150$ Mpc travelled by sound waves up to photon decoupling imprints peak(s) in CMB angular power spectrum.
- Same feature appears as a ~10% bump in galaxy 2-point correlation function along and transverse to line of sight and provides a standard ruler.

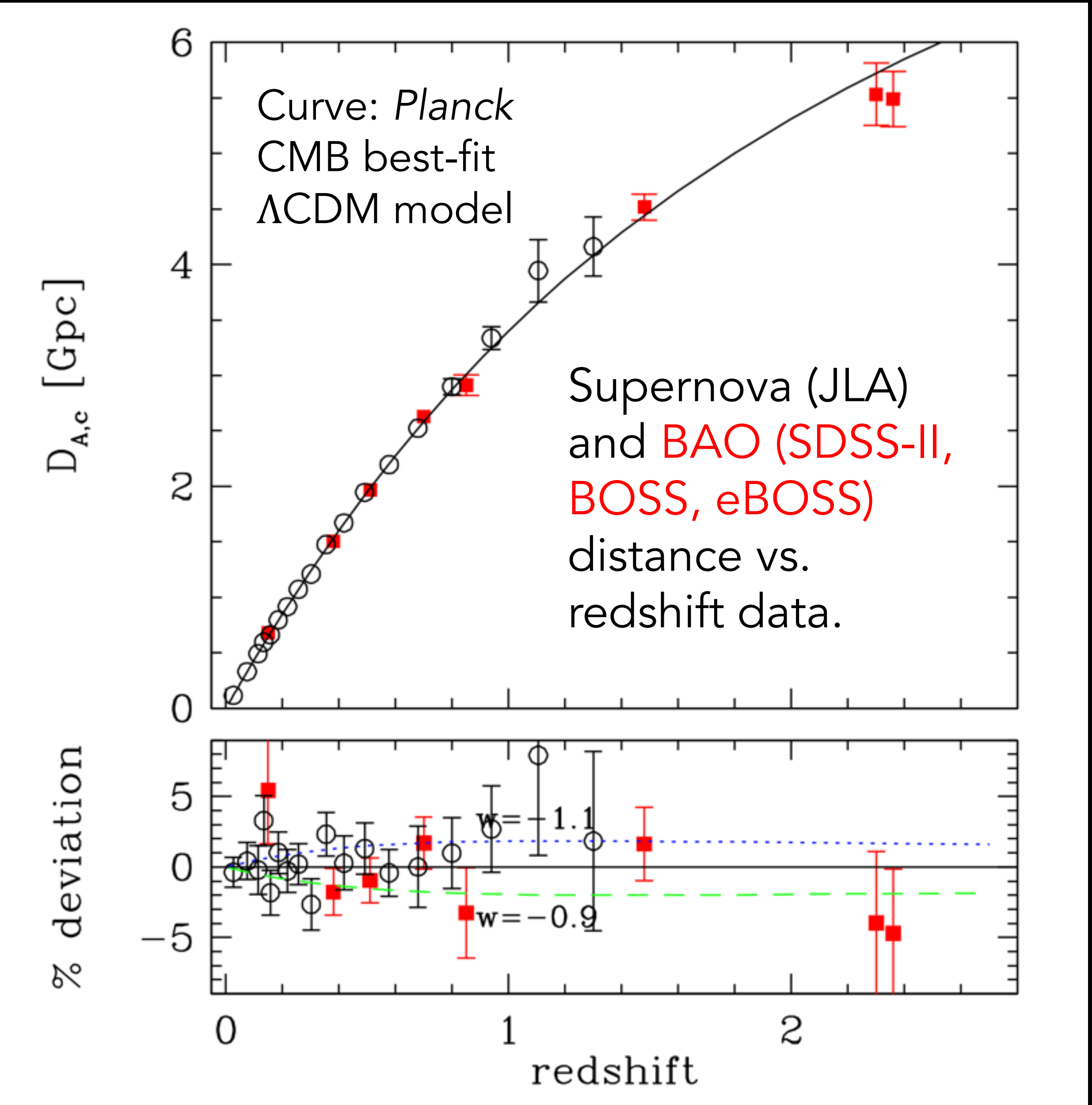
# Baryon Acoustic Oscillations (BAO)




Final sample size: 4M galaxies with redshifts Alam+ 21

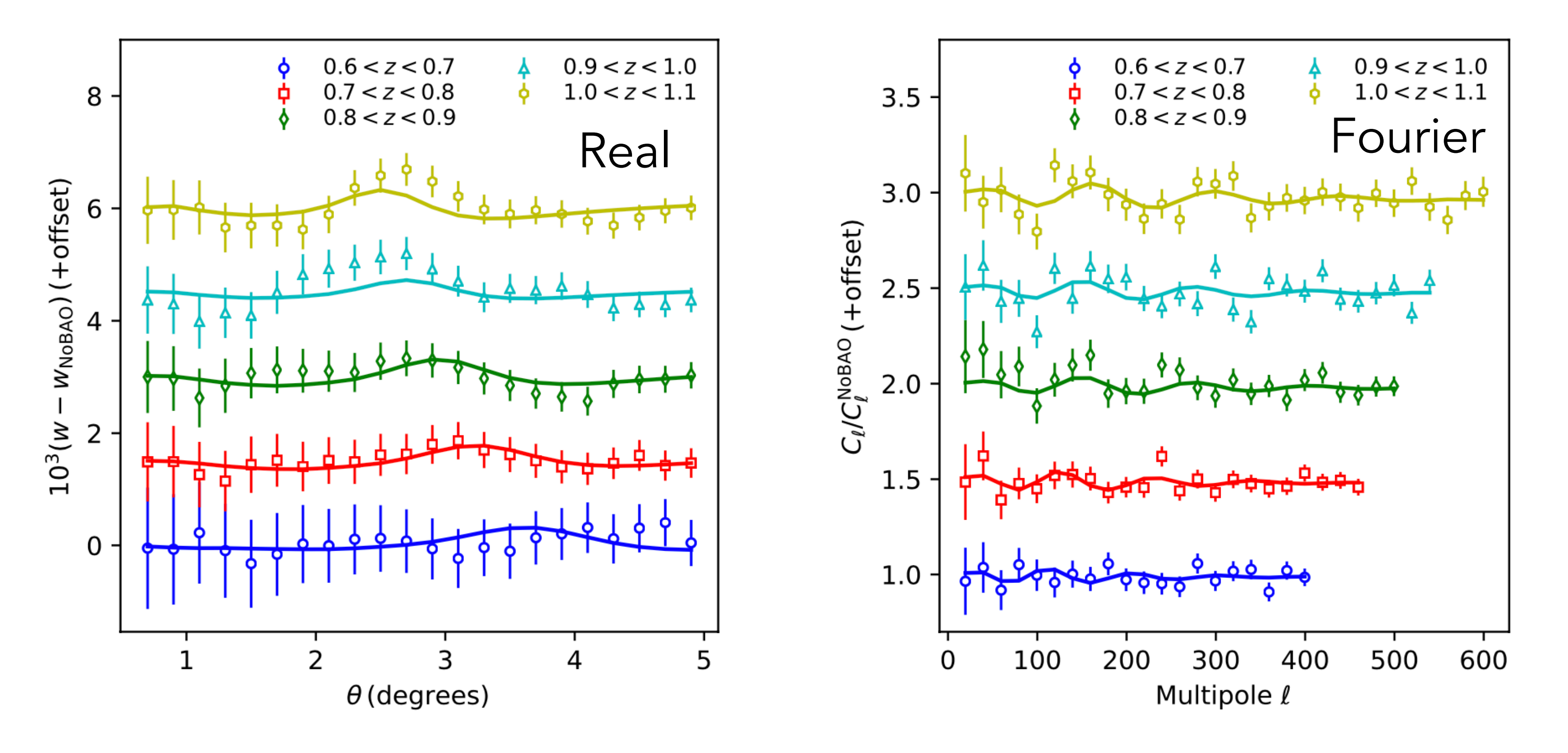
# Distance Measurements

Consistency of CMB, BAO, and SN distances in ΛCDM allows us to combine them to get tighter constraints (see below).




Alam+ 21; Weinberg & White 22

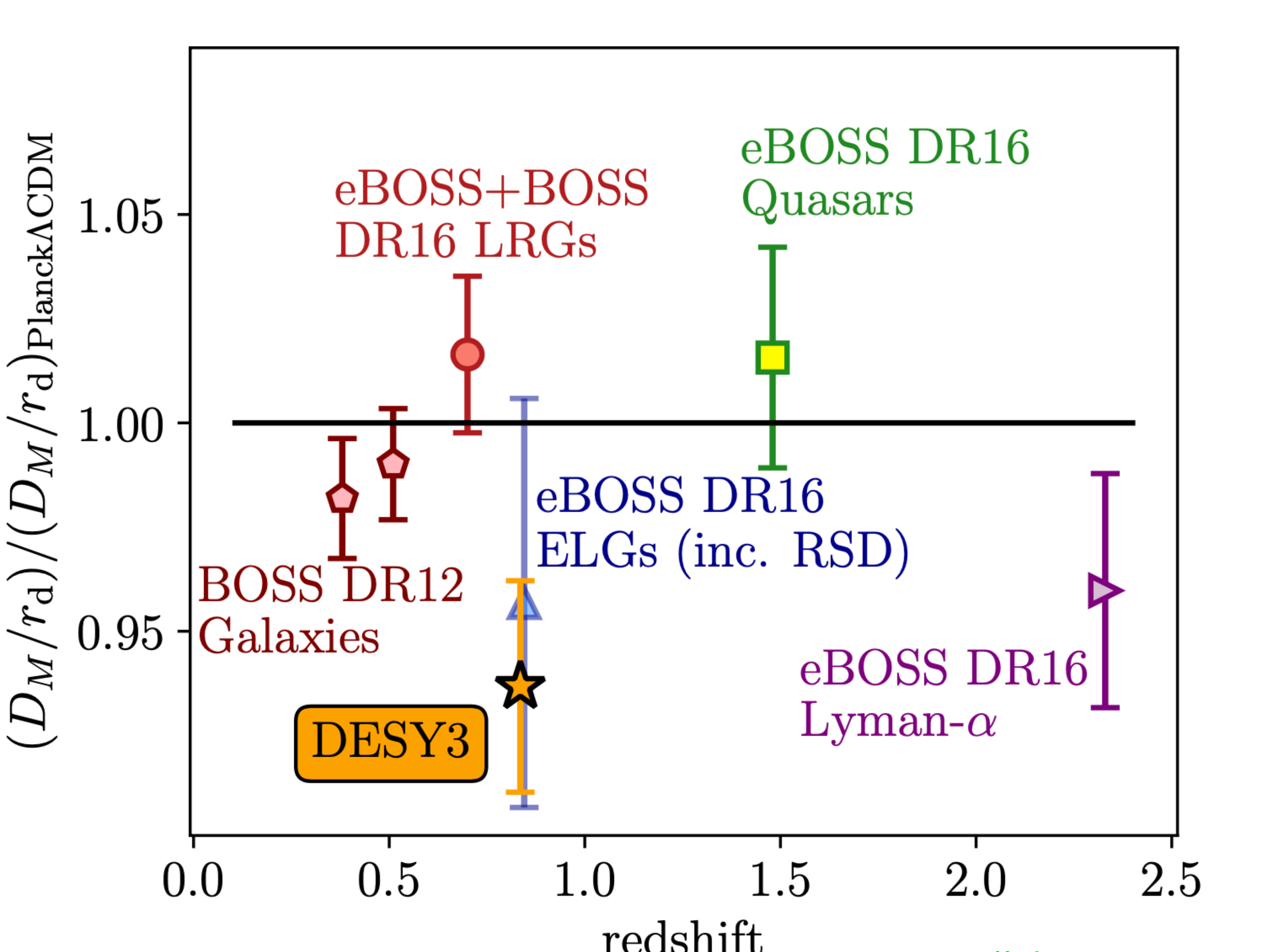
# Dark Energy Survey Y3 BAO Results




- Transverse BAO measurement from 7 million galaxies; 2.7% distance measurement to z=0.835.

DES Collaboration 21

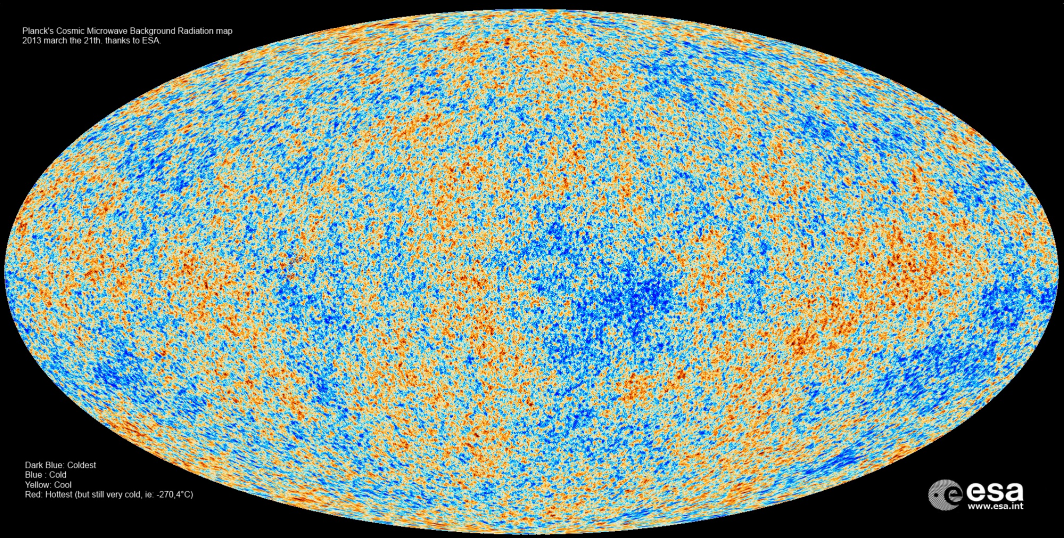
# BAO Angular Diameter Measurements




DES consistent with Planck at $2.3\sigma$

DES Collaboration 21

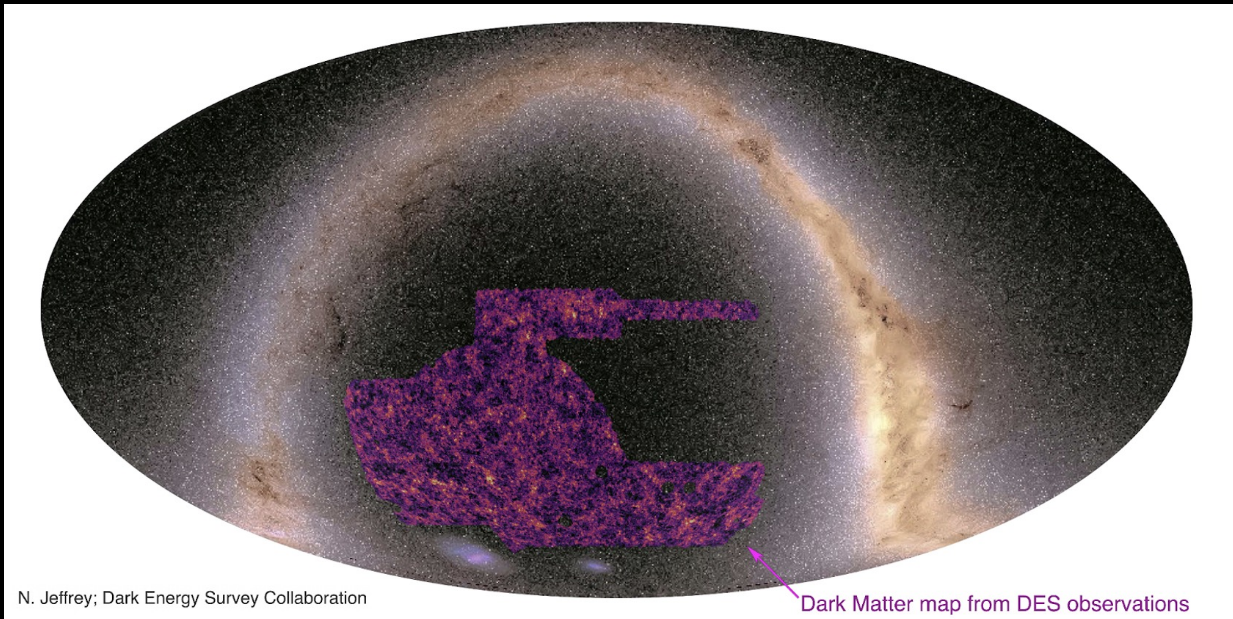
# Growth of Structure



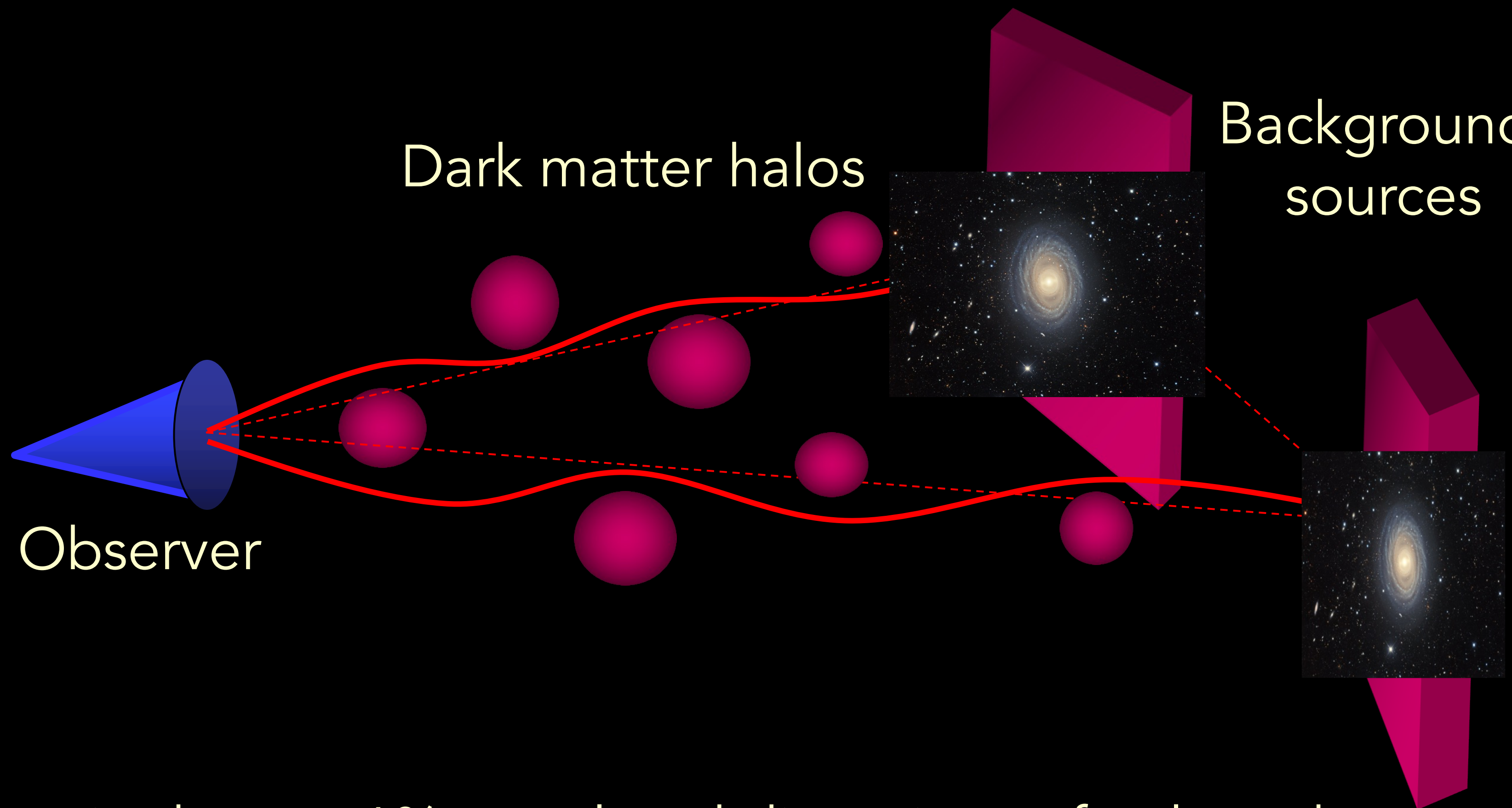

Best-fit ΛCDM model to CMB data (*Planck*, z=1000) *predicts* amplitude, shape, and growth rate of structure in cosmic surveys at low redshift (z<1). Do they agree?

Planck Temperature map (z~1000)

DES Weak Lensing mass map (z~0-1). 5000 sq. deg.



# Weak Lensing




- Cosmic shear: ~1% correlated distortions of galaxy shapes
- Radial distances depend on *expansion history* of Universe
- Foreground mass distribution depends on *growth* of structure

# DES Year 3 Cosmology Analysis: 3x2

DARK ENERGY SURVEY

- Compare & consistently combine three 2-point correlation function measurements:
  - Galaxy clustering: 10.7M foreground galaxy positions
  - Cosmic shear weak lensing:100M source galaxy shapes
  - Galaxy-galaxy lensing: source galaxy tangential shear around foreground galaxy positions
  - Fully blind analysis; ~30 papers released to May 2021

- New analysis algorithms developed for DES:
  - Metacalibration weak lensing shape measurement
  - Photo-z estimation using self-organizing maps & cross-correlation, calibrated from deep 8-band imaging.
  - Balrog: measure selection function by inserting artificial galaxies into DES images, derived from deep fields.

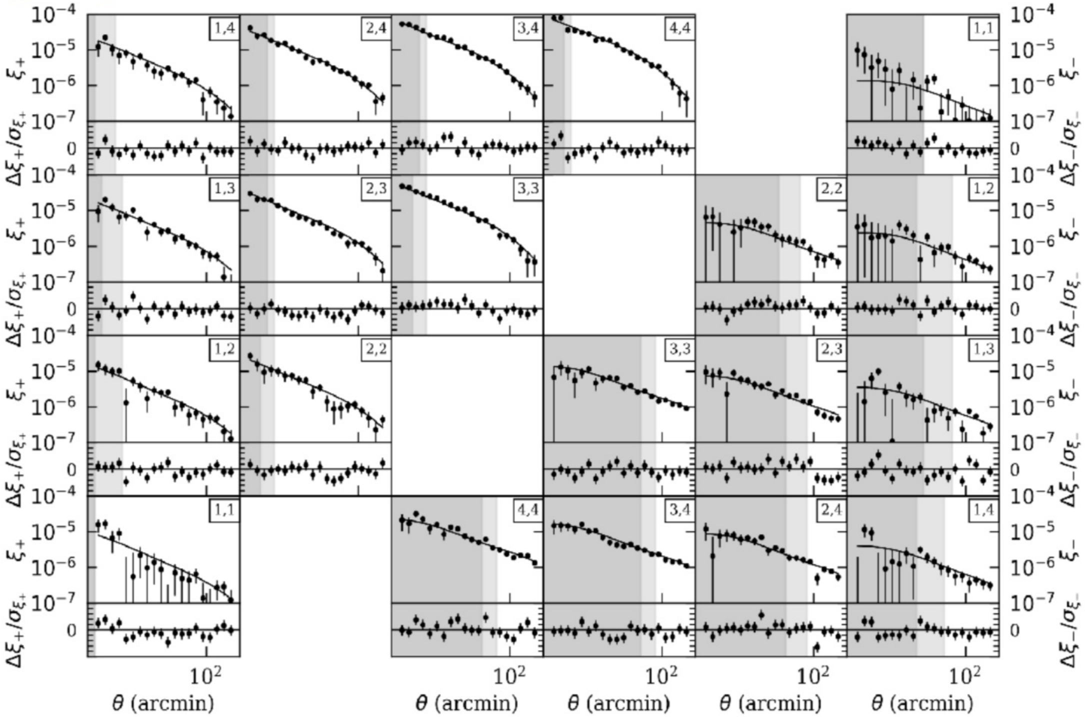
# DES Year 3 Measurements

DES Collaboration 2021

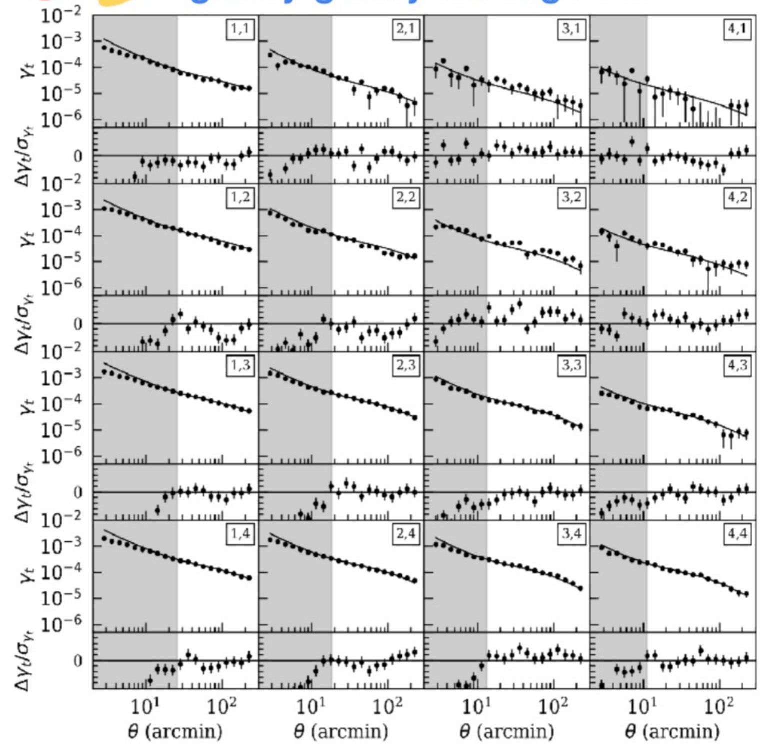
## Measurements + joint model fit

+26 nuisance parameters $\Lambda$CDM

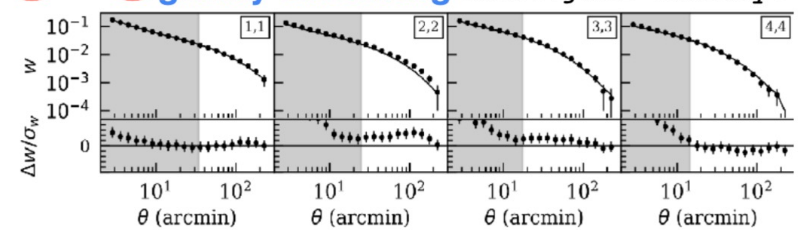
**cosmic shear** Amon+, Secco, Samuroff+




**galaxy-galaxy lensing** Prat+




**galaxy clustering** Rodriguez-Monroy+




Each panel shows (cross-)correlation between photometric redshift bins.

# 3x2 DES Constraints: ΛCDM

DARK ENERGY SURVEY

## 3x2pt results

$$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$$

**Cosmic shear** (blue)

**Galaxy clustering** and **tangential shear** (orange)

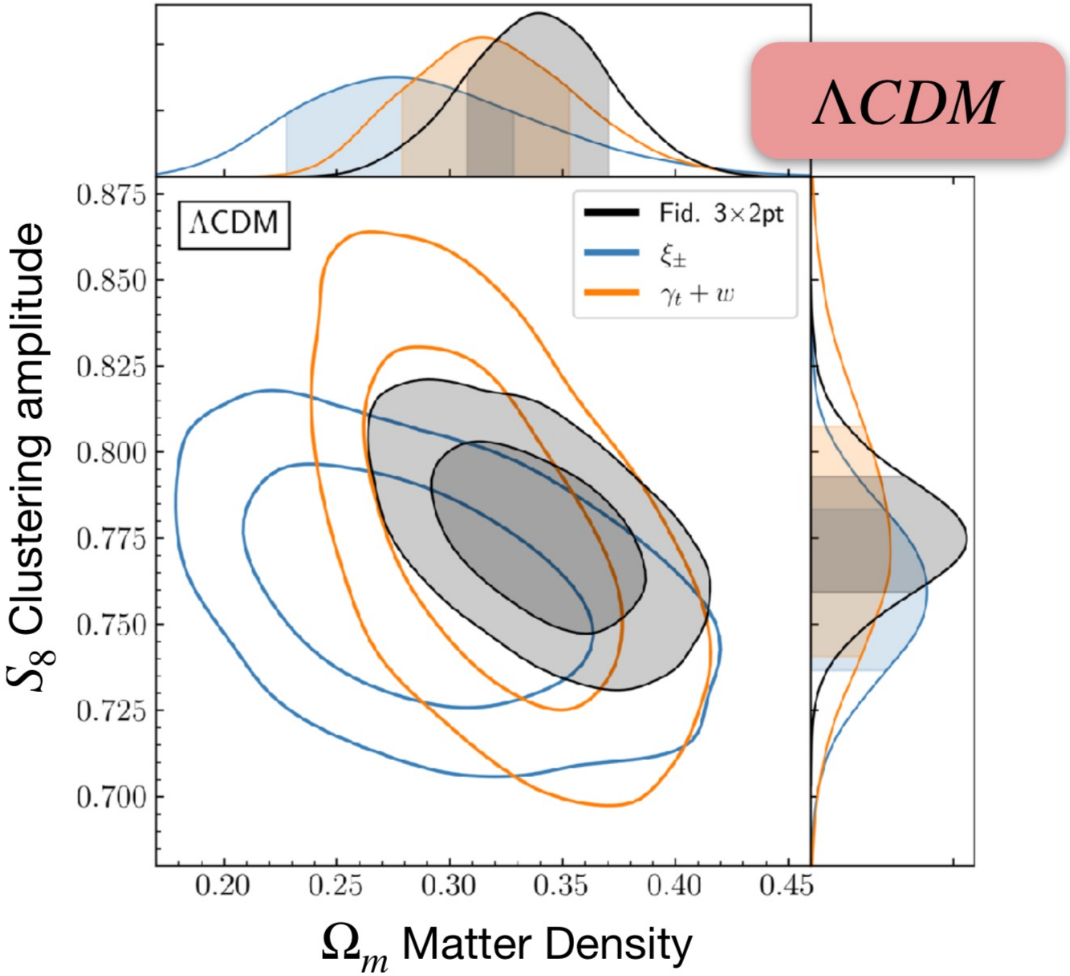
DES-only results:

$$S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776)$$

$$\Omega_m = 0.339^{+0.032}_{-0.031} \quad (0.372)$$

$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)$$

DES Collaboration 2021



# DES vs Planck: ΛCDM

DARK ENERGY SURVEY

## Consistency with the CMB in ΛCDM

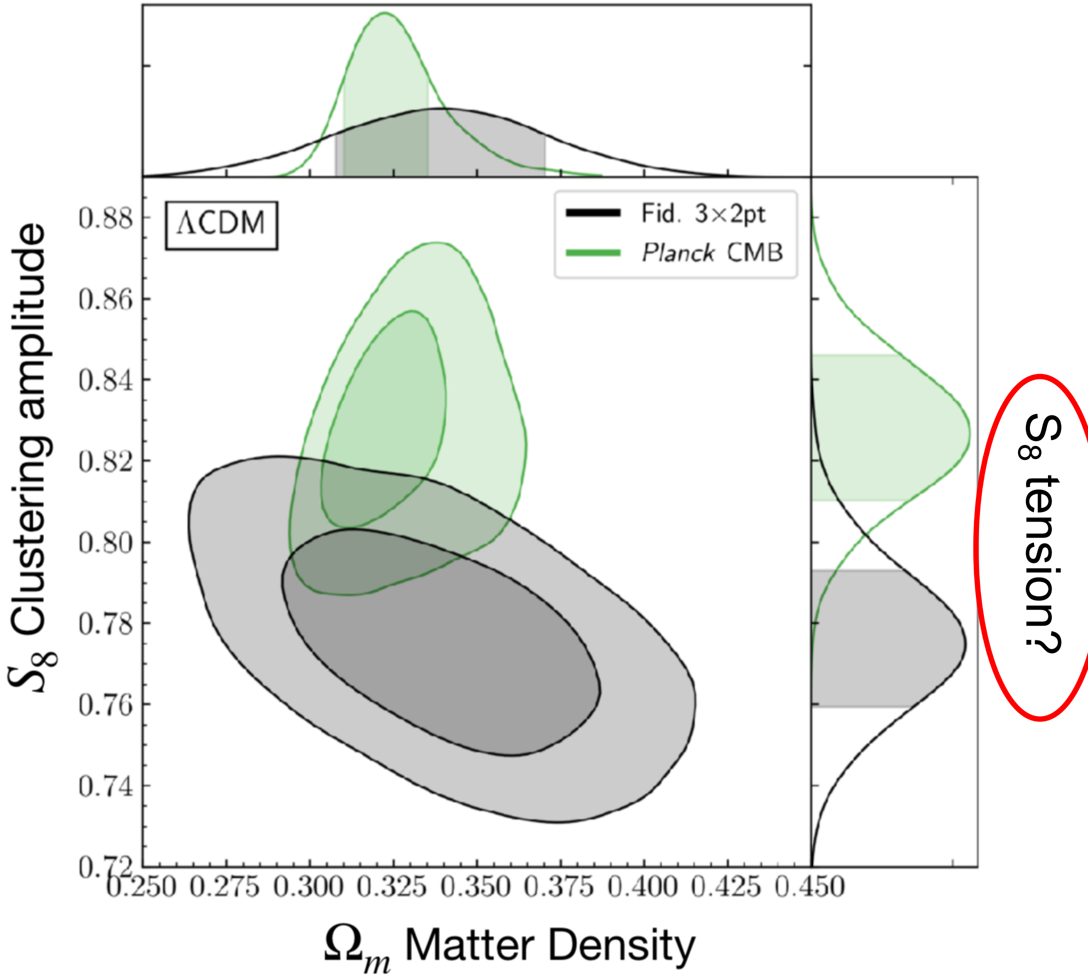
DES Collaboration 2021

Planck+ΛCDM predicts factor $10^3$ growth in fluctuations from z=1000 to 2% with no free parameters.

No significant evidence of inconsistency between **DES Y3 3x2pt** and *Planck* CMB at 0.7-1.5$\sigma$ or p=0.13-0.48

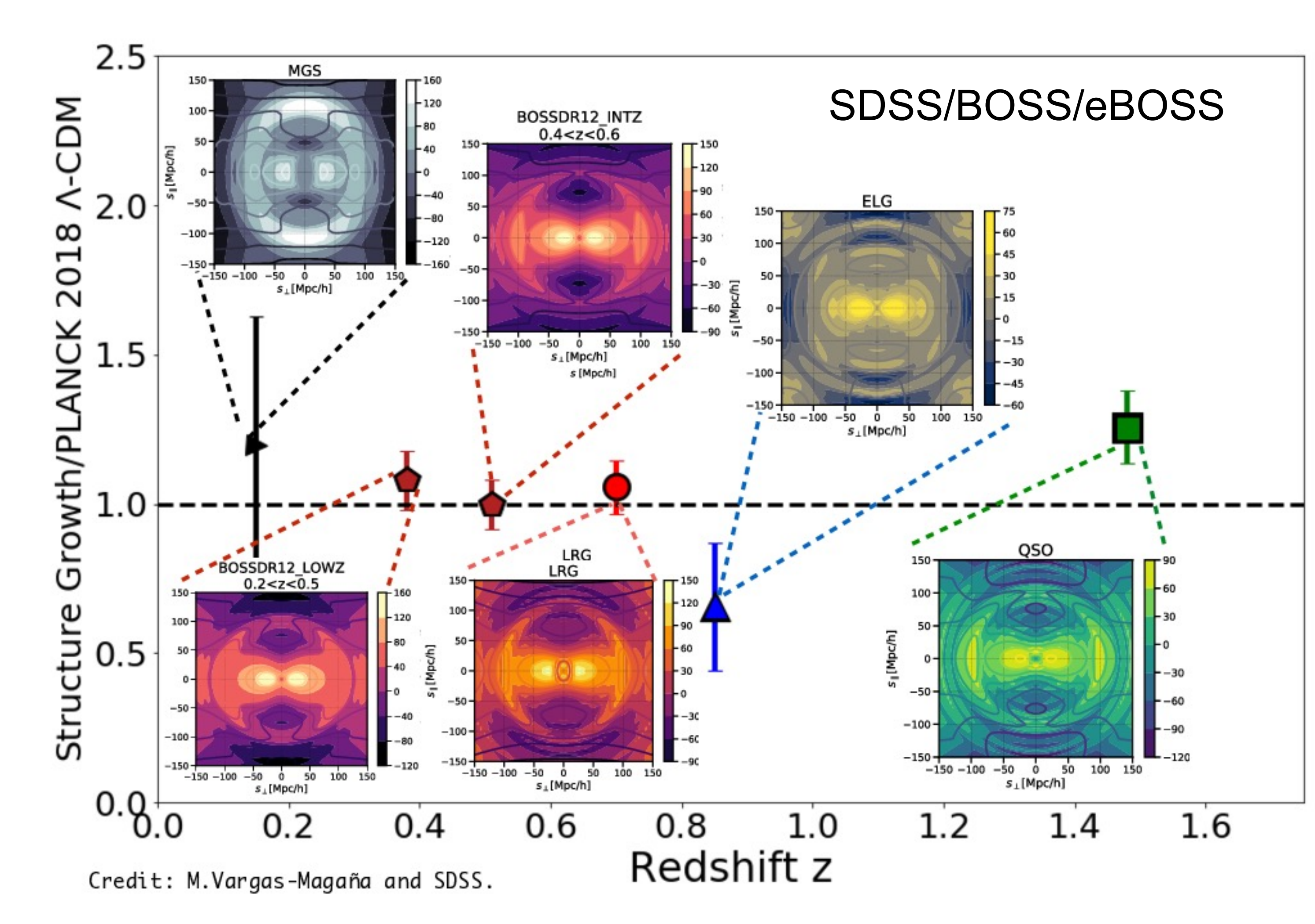
Important consistency test for ΛCDM.

DES contours will shrink with Y3→Y6 and inclusion of clusters, BAO, supernovae,…



# Redshift Space Distortions (RSD)

Anisotropy of clustering in redshift space encodes growth rate of structure




Alam+ 21

# Combined Constraints: ΛCDM

## Consistency with the CMB in ΛCDM

DES Collaboration 2021

$$S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)$$

$$\Omega_{\rm m} = 0.306^{+0.004}_{-0.005} \quad (0.306)$$

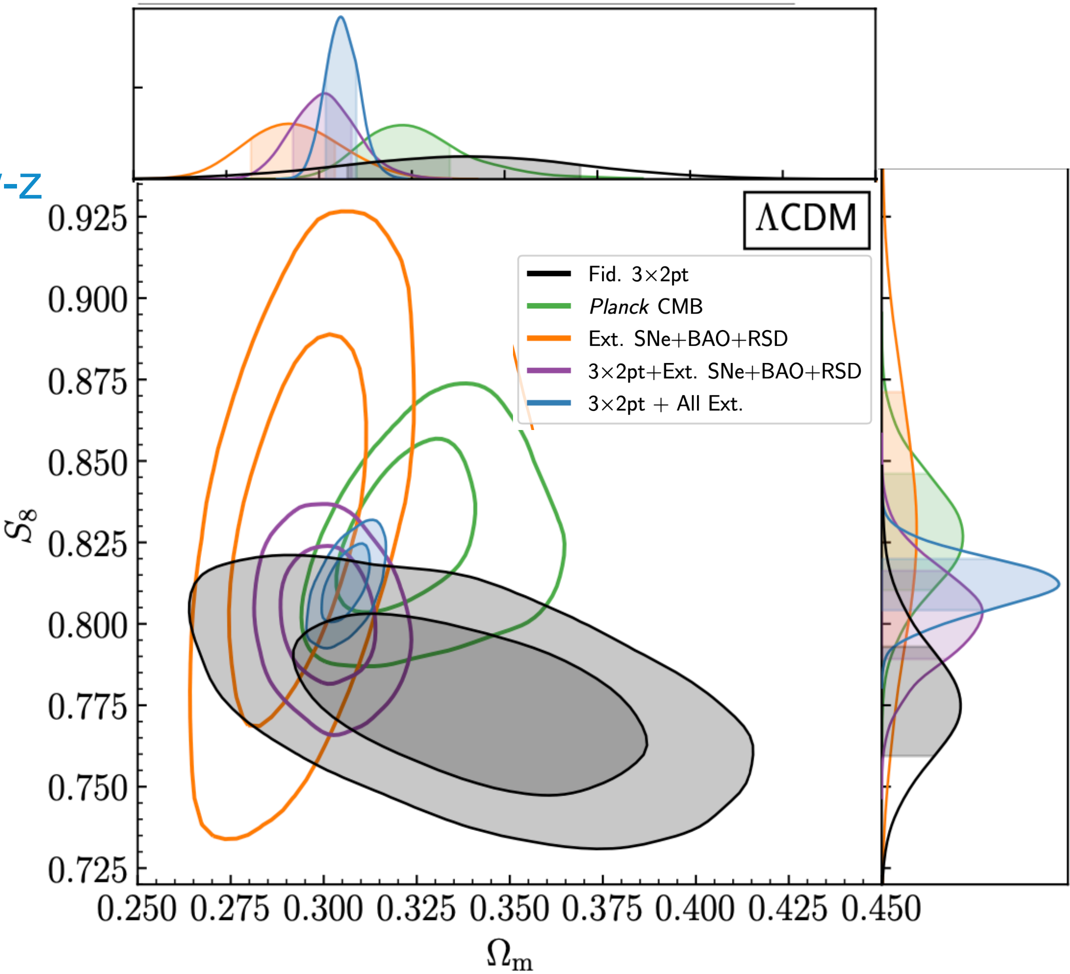
$$\sigma_8 = 0.804^{+0.008}_{-0.008} \quad (0.807).$$

All data sets combined: DES + Ext. Low-z + Planck

add other low redshift probes (Ext. Low-z) :

Spectroscopic surveys (BAO + RSD)
- BOSS + eBOSS

Supernovae
- Pantheon

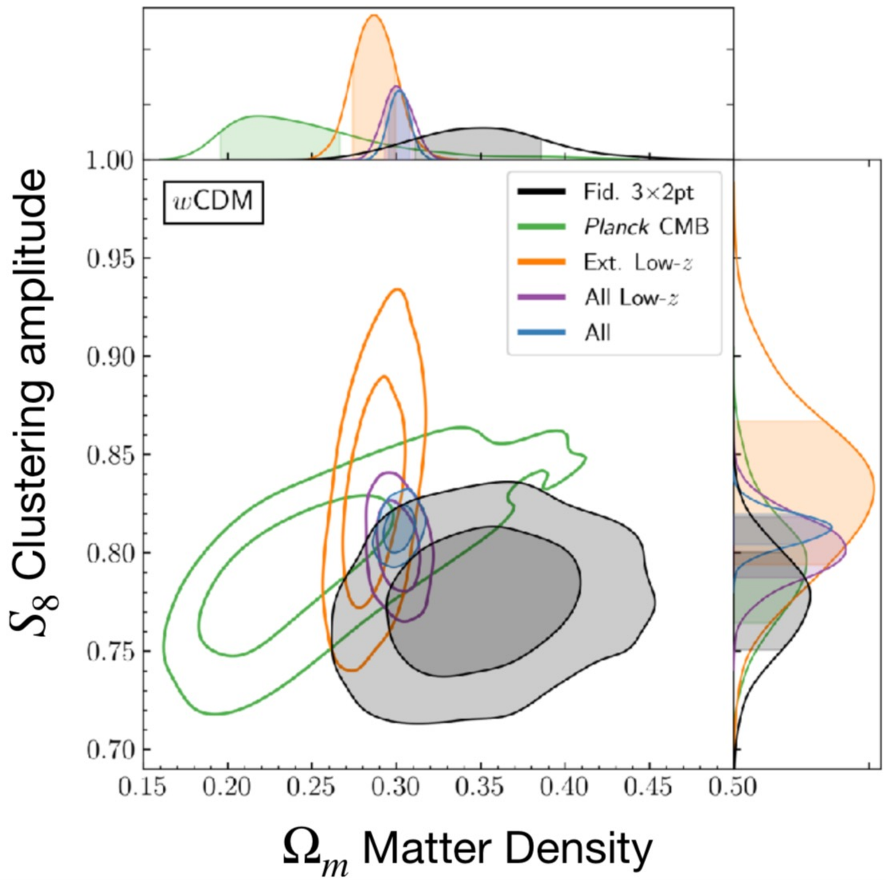


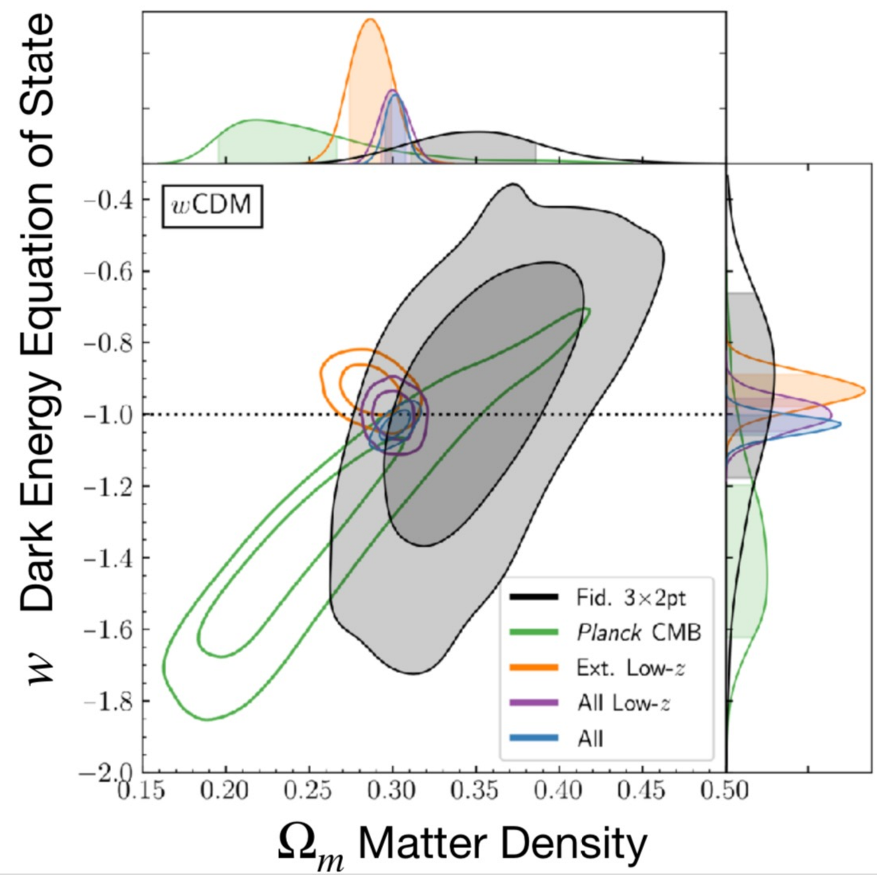

Coming soon: joint analysis of DES and KIDS-1000, to be followed by DES Y6.

# Combined Constraints: wCDM

Allow Dark Energy equation of state to differ from $w$ = -1. Results consistent with $\Lambda$CDM.

| | |
|---|---|
| DES 3x2pt only | $w = -0.98^{+0.32}_{-0.20} \quad (-1.03)$ |
| DES + CMB + Low-z | $w = -1.03^{+0.03}_{-0.03} \quad (-1.00)$ |



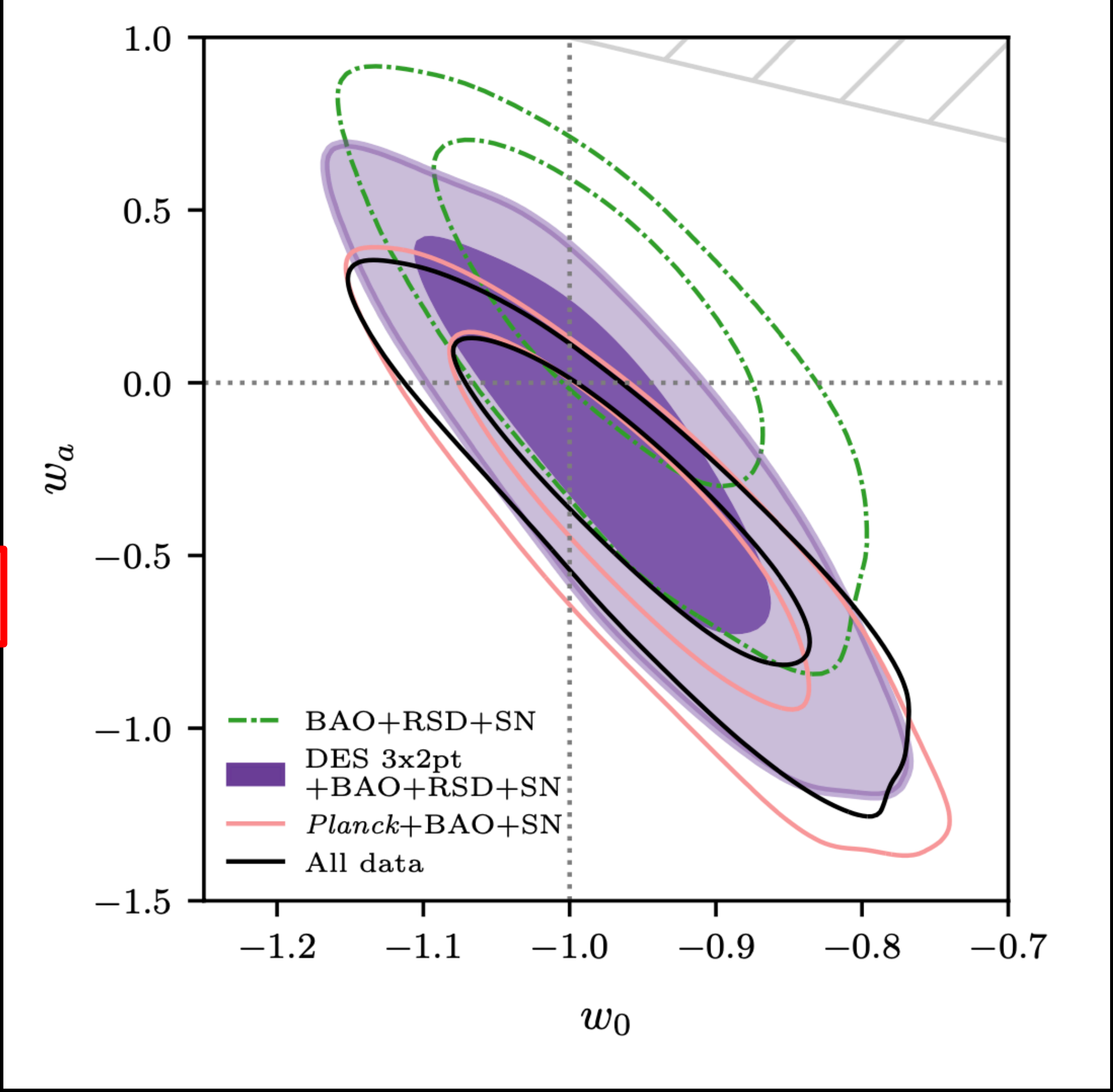
# Combined Constraints: $w_0w_aCDM$

Evolving DE EOS model:

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

$$w_0 = -0.95 \pm 0.08, \quad w_a = -0.4^{+0.4}_{-0.3}$$

consistent with ΛCDM




DES Collaboration 2022

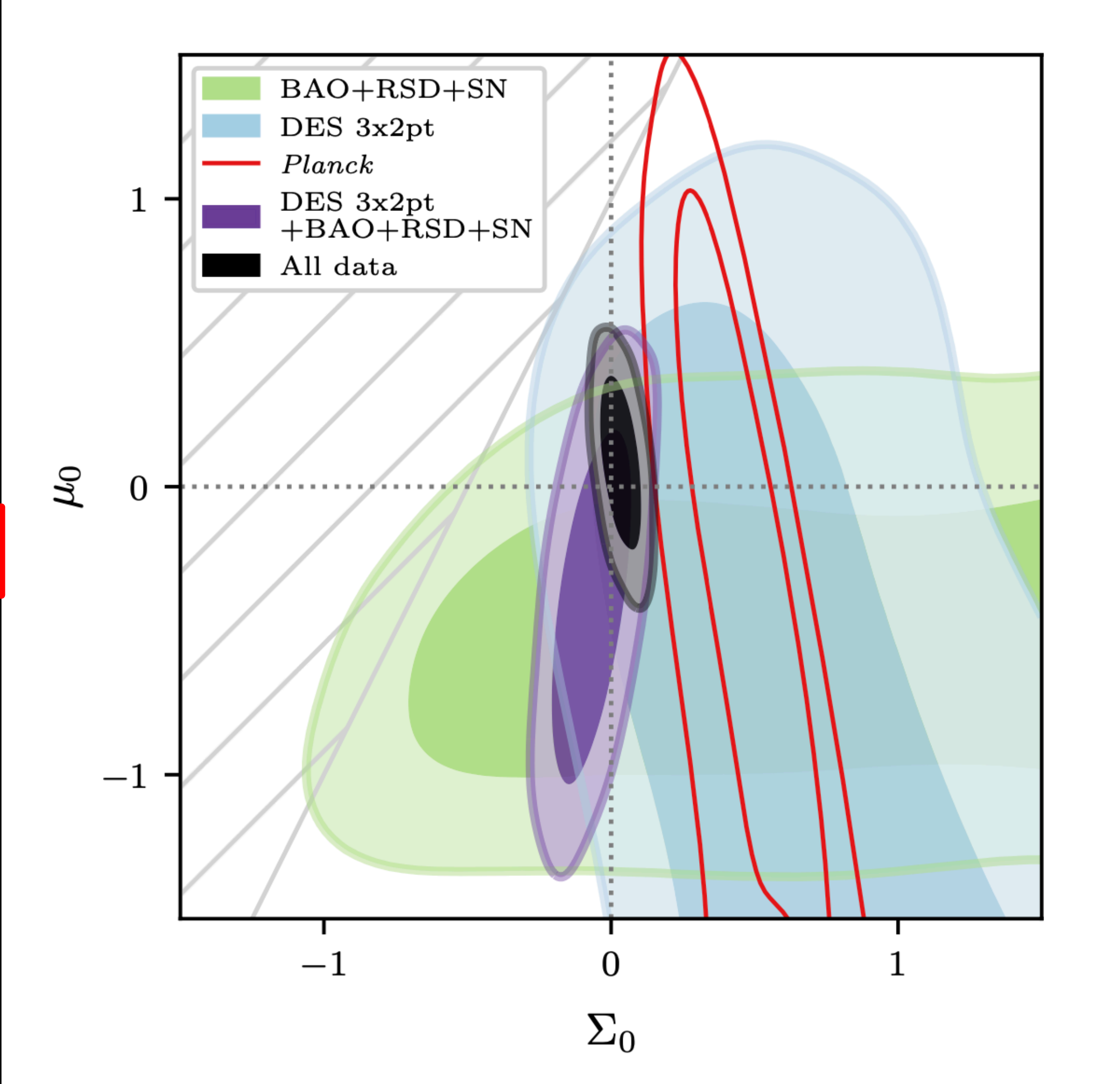
# Combined Constraints: Modified Gravity

Modified Gravity model:

$$k^2\Psi = -4\pi G a^2\left[1+\mu(a,k)\right](\rho\delta + 3(\rho+P)\sigma),$$
$$k^2\Phi = -4\pi G a^2\left[1+\Sigma(a,k)\right](2\rho\delta + 3(\rho+P)\sigma).$$

$$\Sigma_0 = 0.04 \pm 0.05, \quad \mu_0 = 0.08^{+0.21}_{-0.19}$$

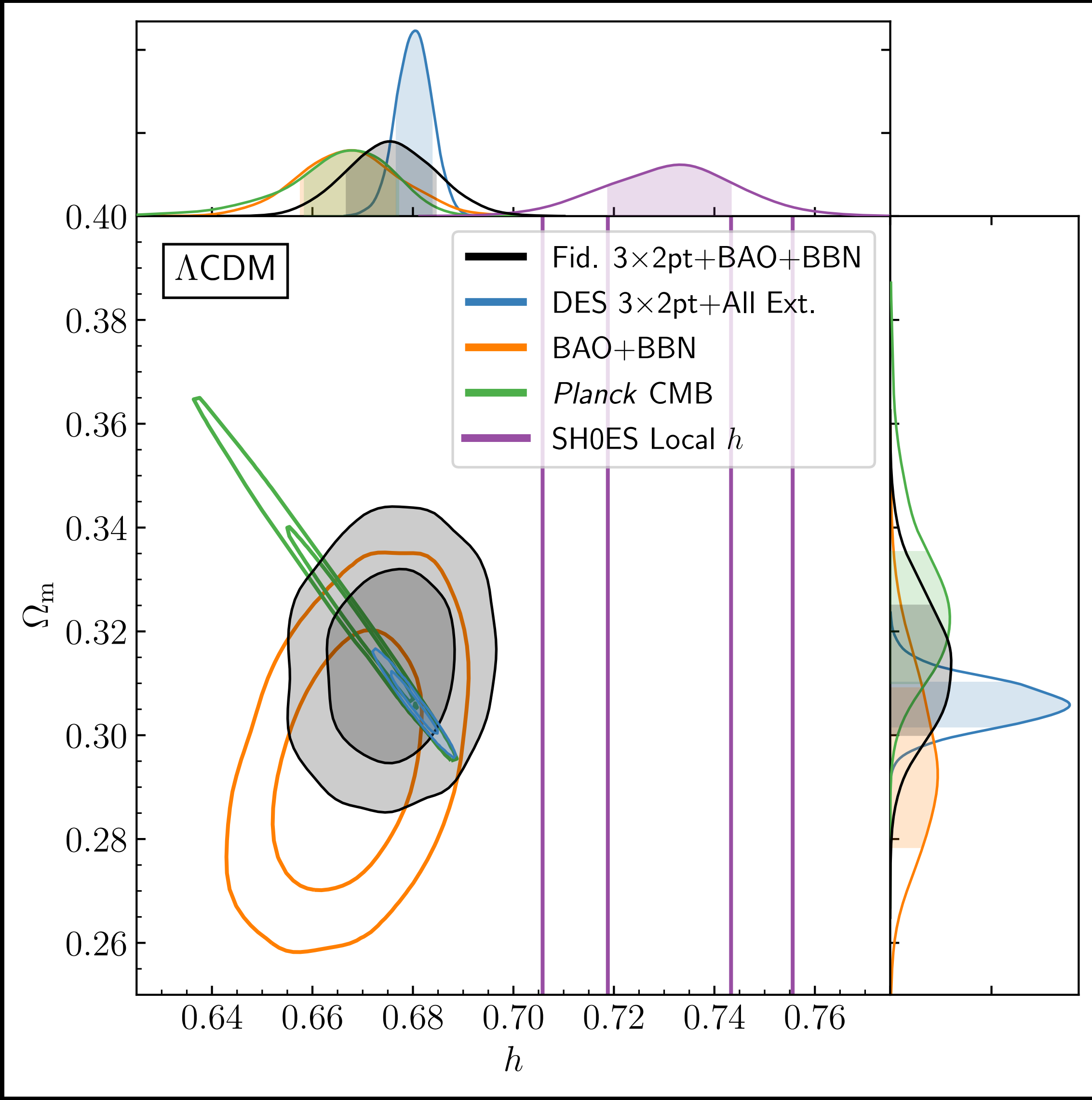
consistent with GR




DES Collaboration 2022

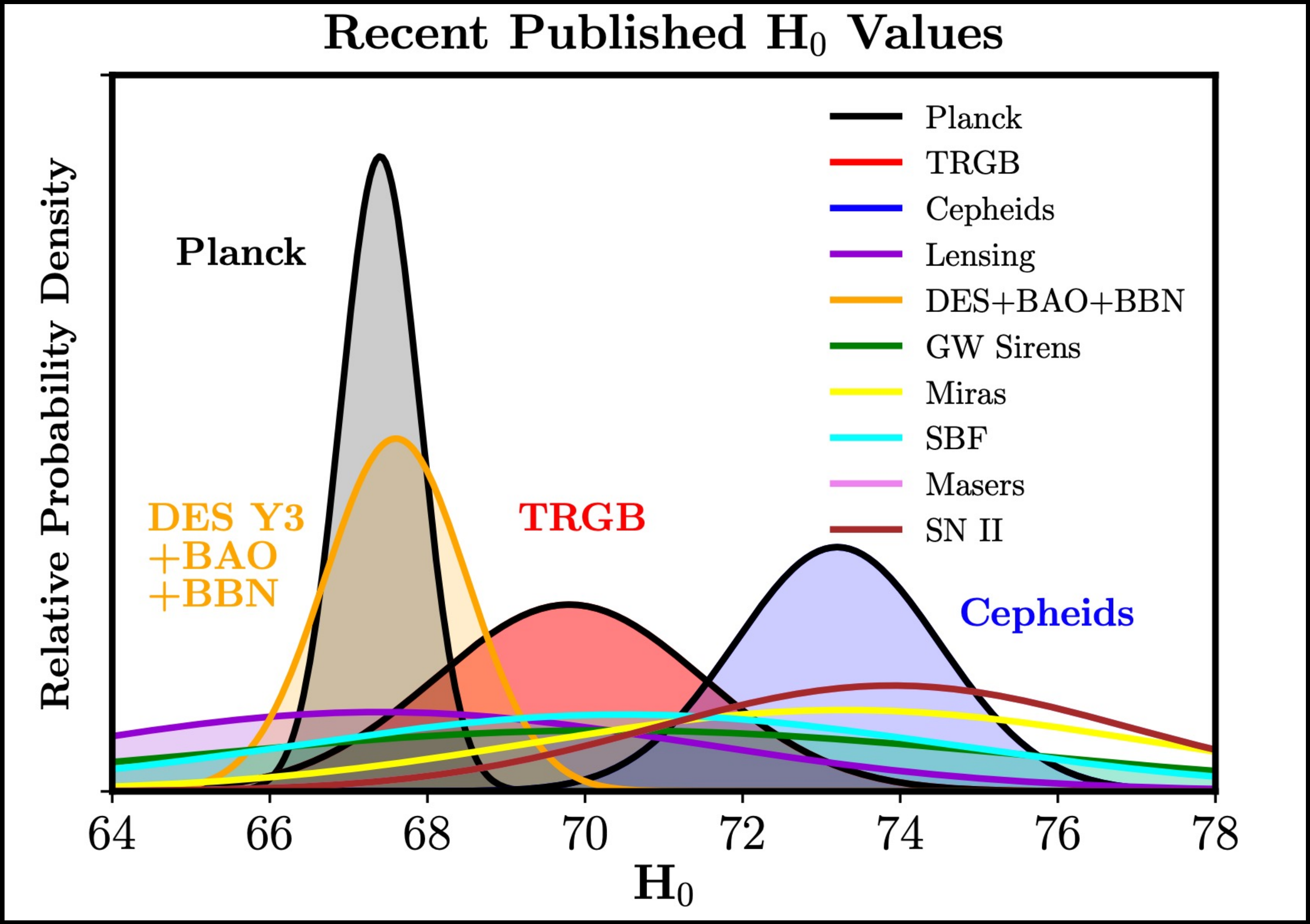
# Hubble Tension

- Tension between LSS and Cepheids (SHOES) even without Planck.
- Simple extensions to ΛCDM don't resolve the tension.
- Systematics or new early Universe (z~1000) physics.



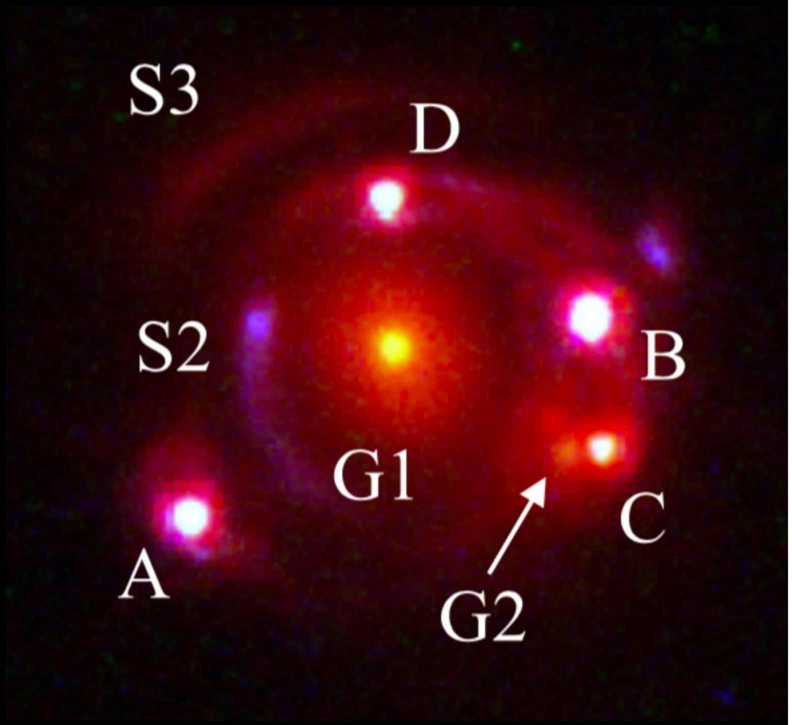

DES Collaboration 2021

# Compilation of $H_0$ Estimates



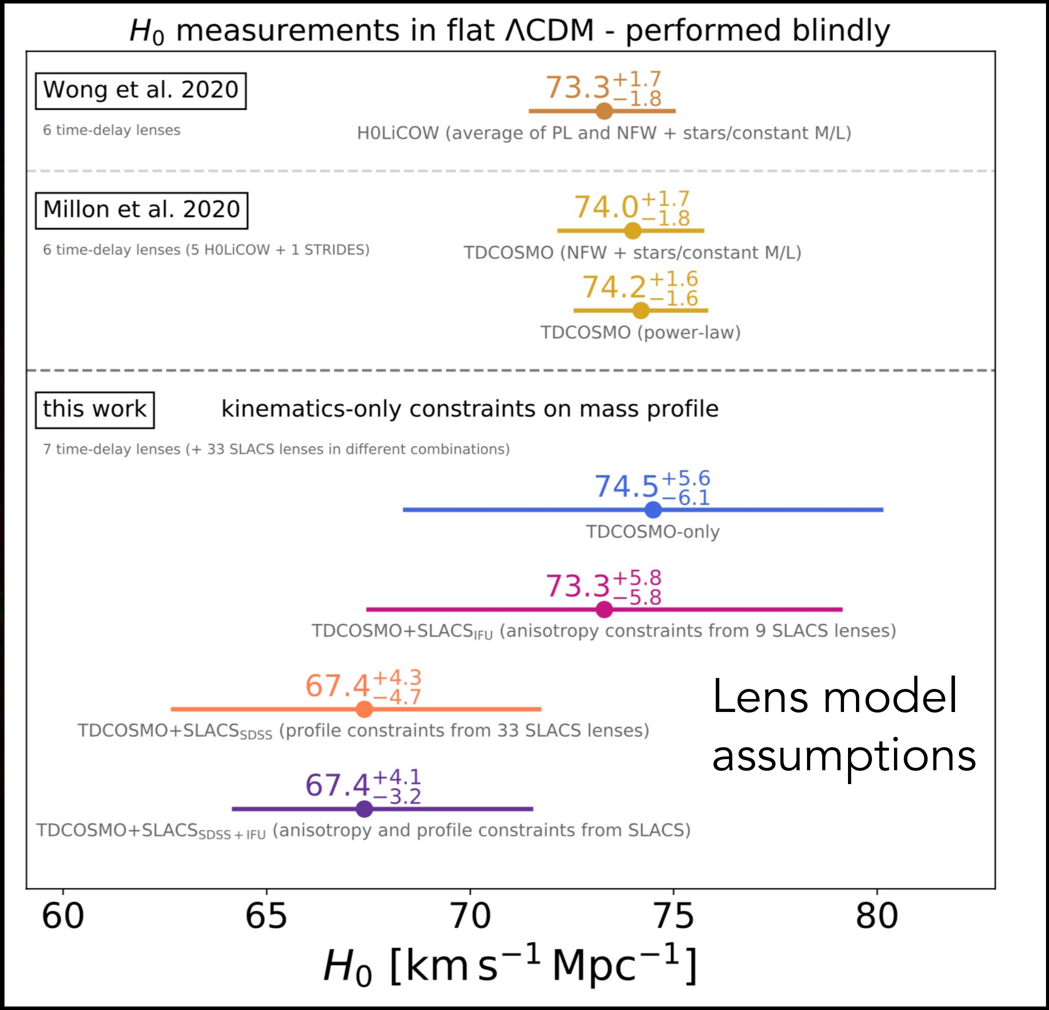

Freedman, 2021

# Strong Lensing Time Delays and $H_0$




DESJ0408-5354
Quadruply imaged QSO

Shajib+ 2020




Birrer+ 2020

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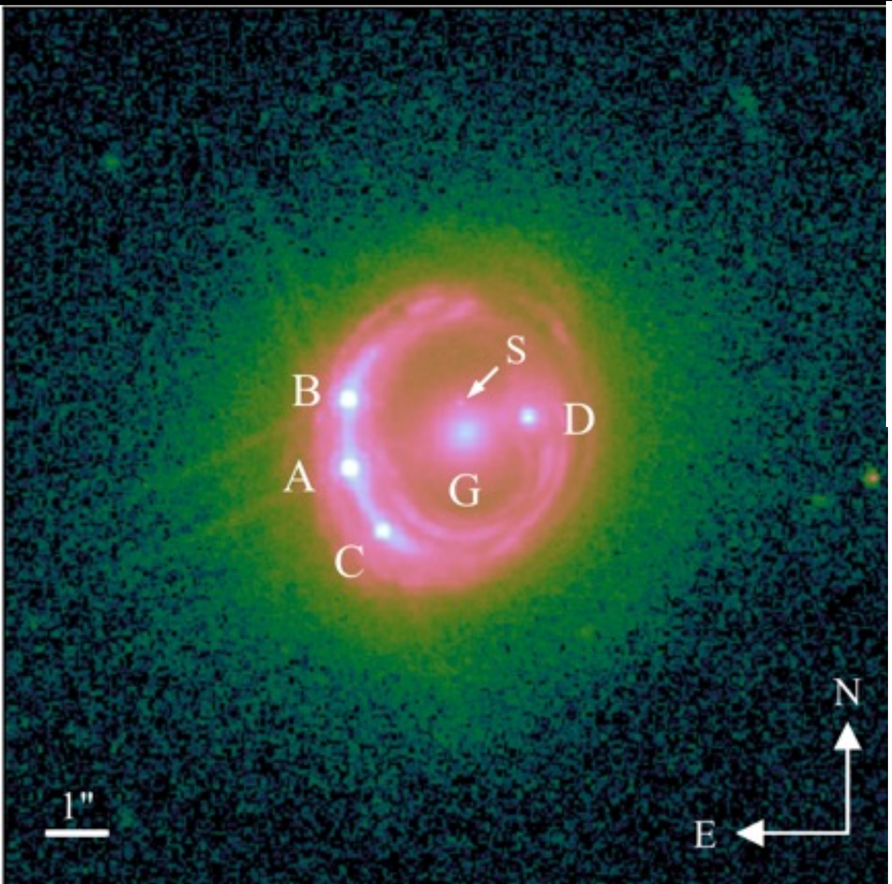
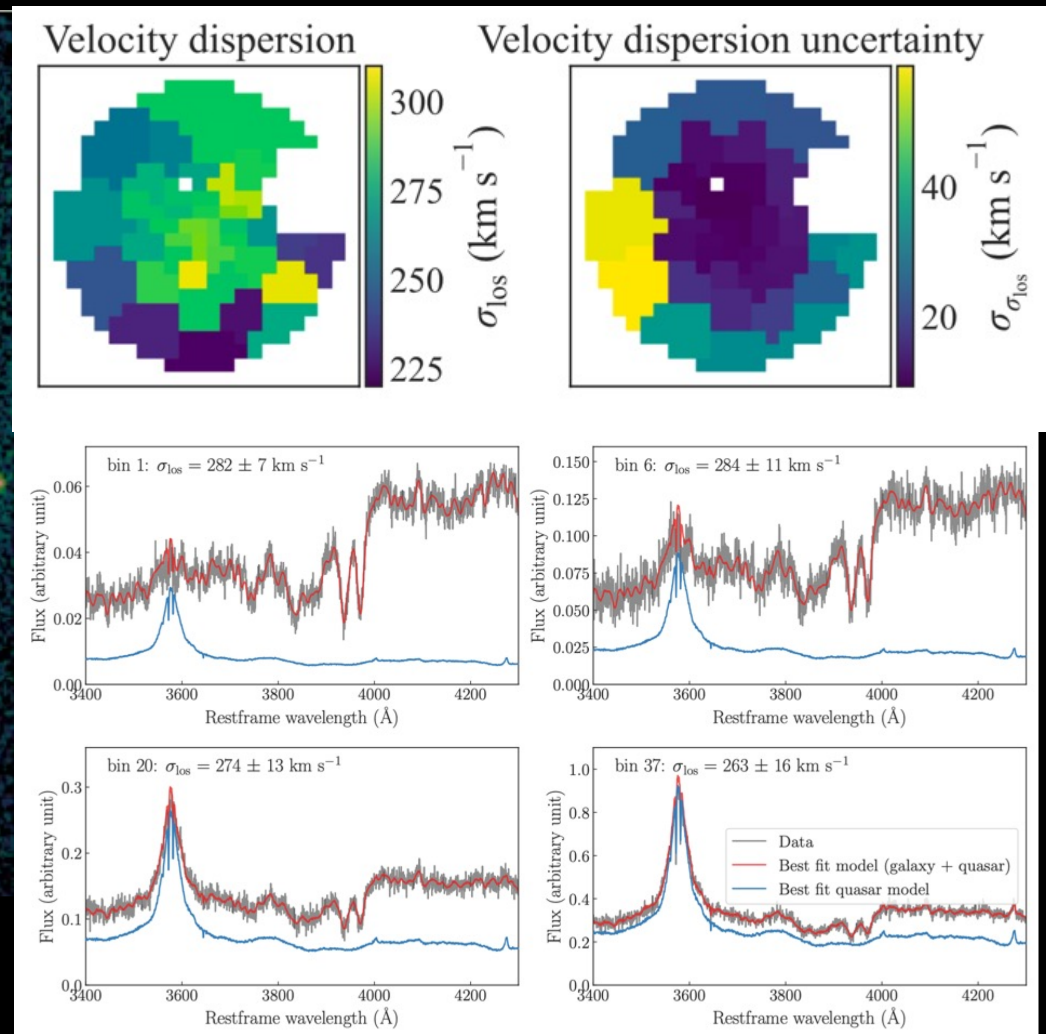


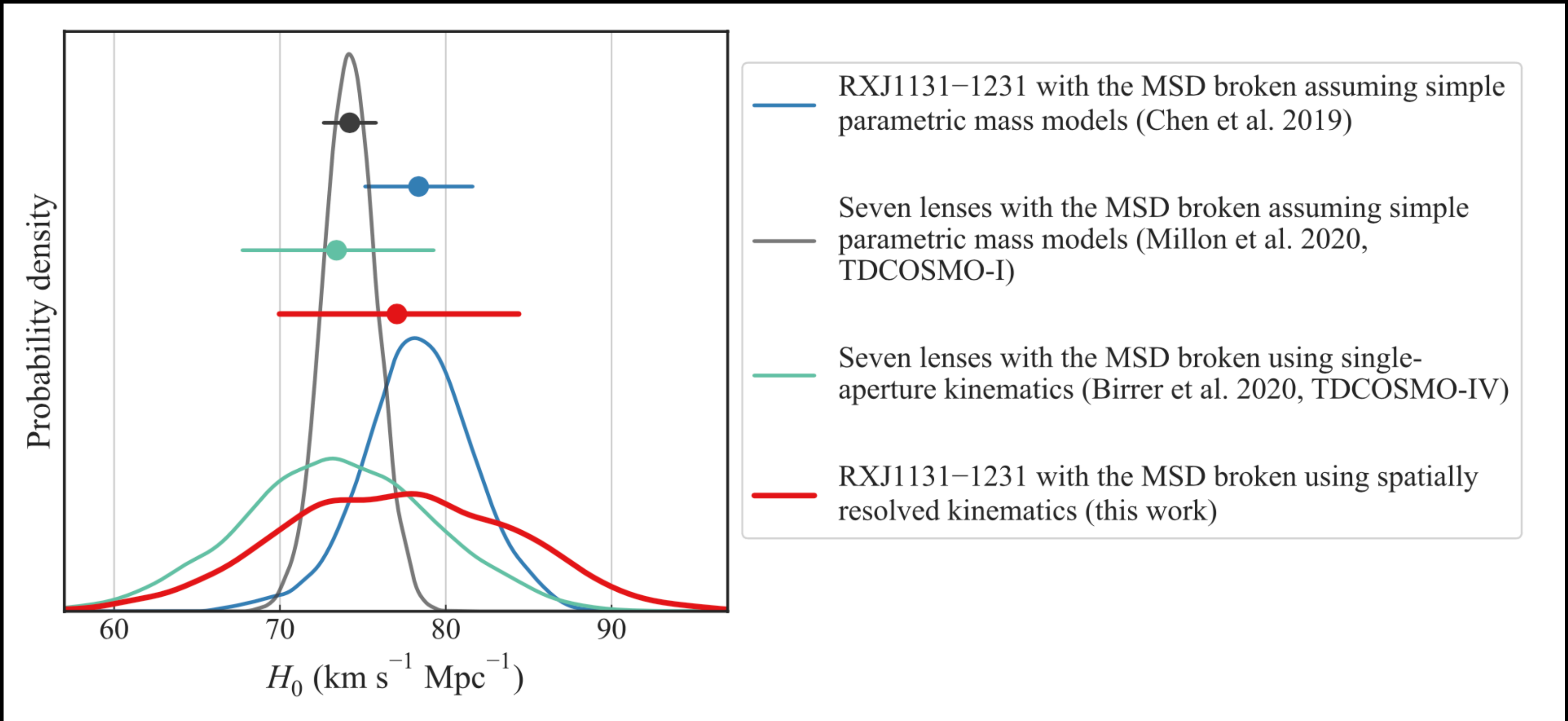

RXJ1131-1231
Quadruply imaged QSO

Shajib+2023

Spatially resolved lens galaxy velocity dispersion measurement better constrains lens model

# Strong Lensing Time Delays and $H_0$

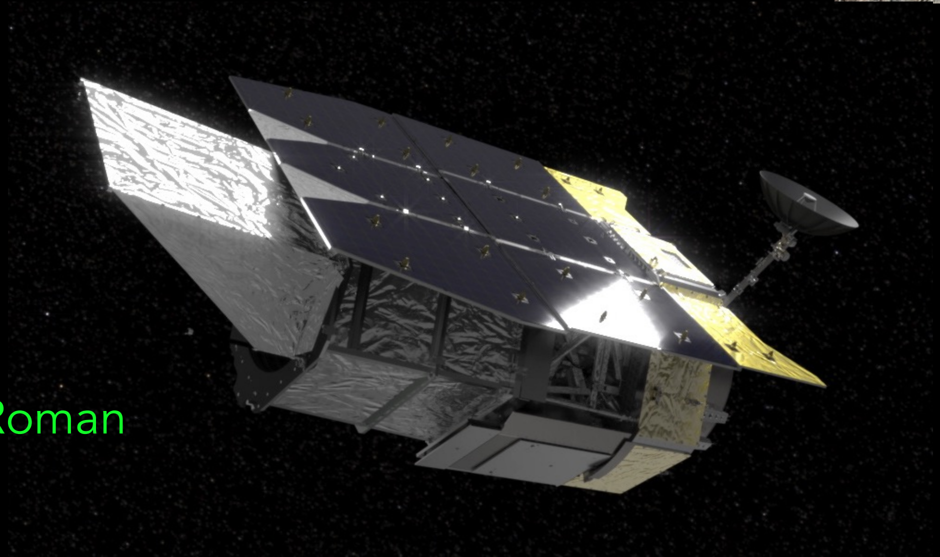
Spatially resolved lens galaxy velocity dispersion measurements enable more flexible models & more robust constraints, without sacrificing precision.



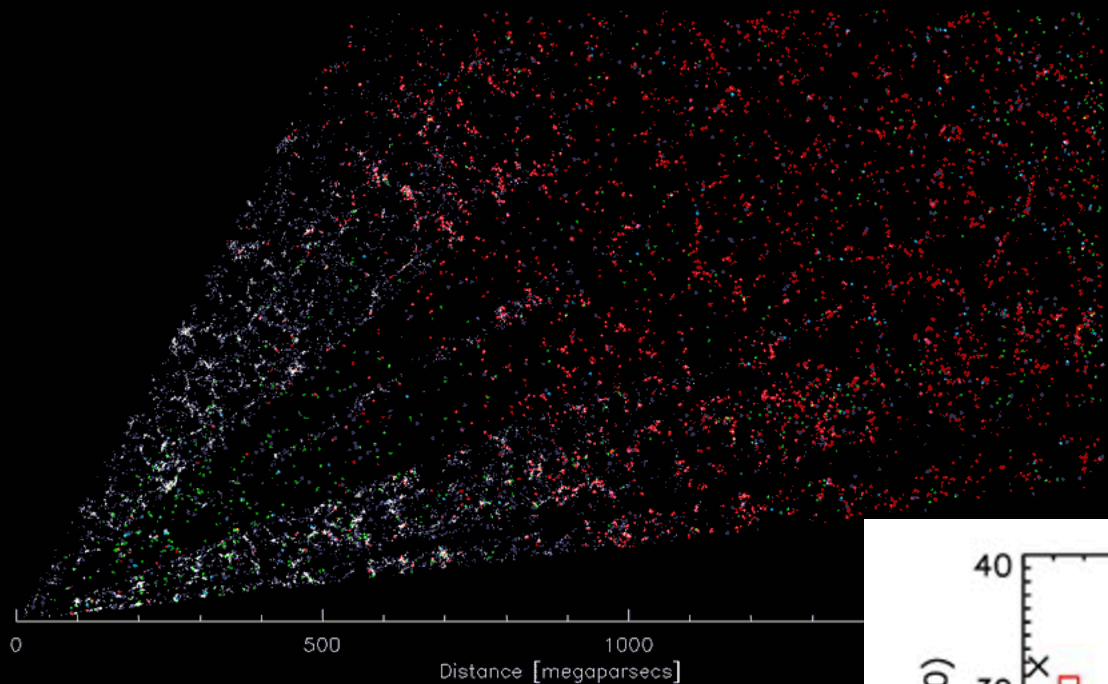

Shajib+2023

# What's next: Stage IV Surveys

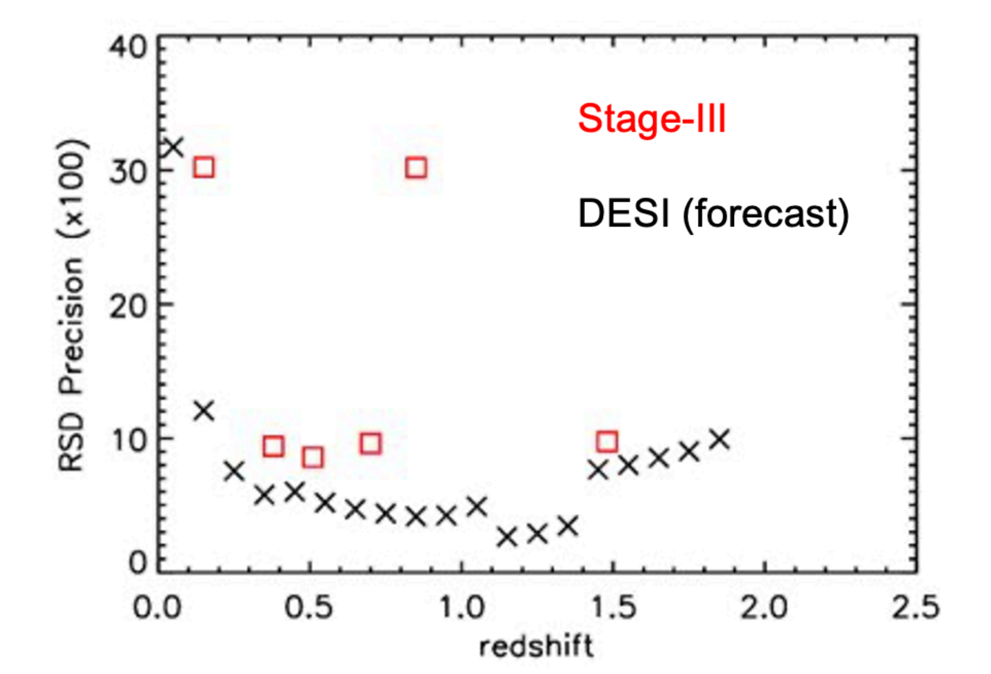





# DESI

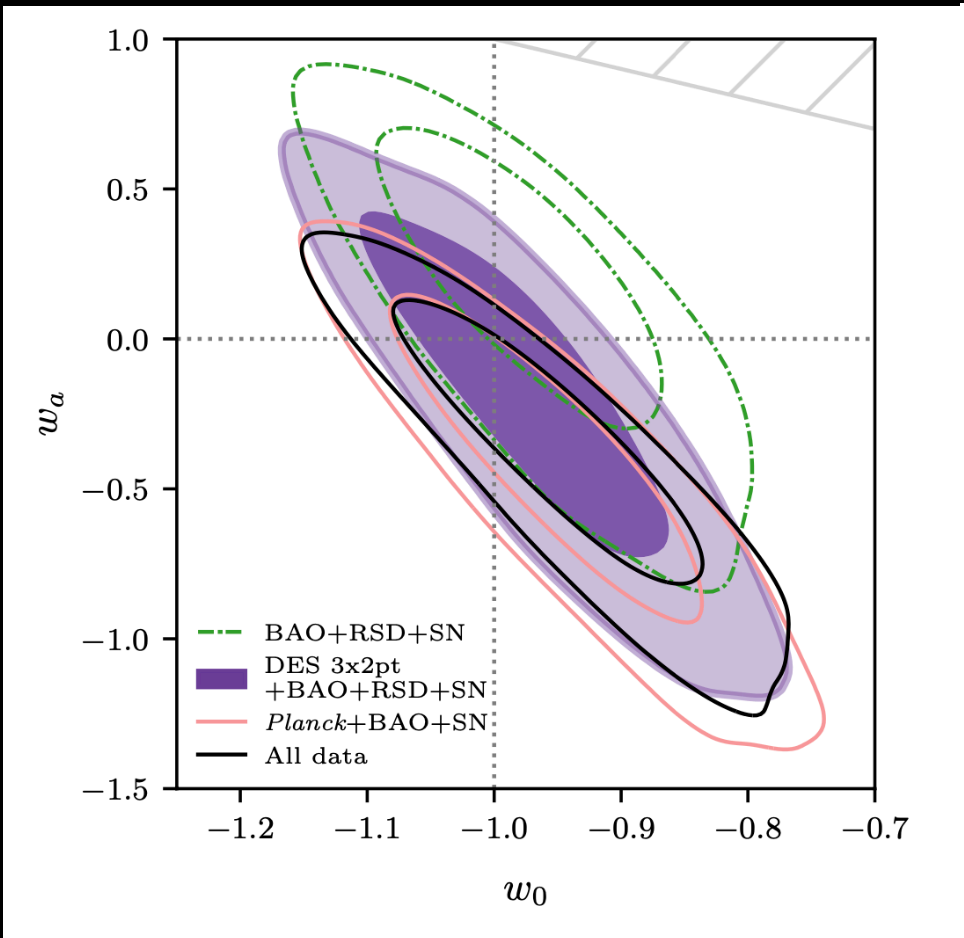


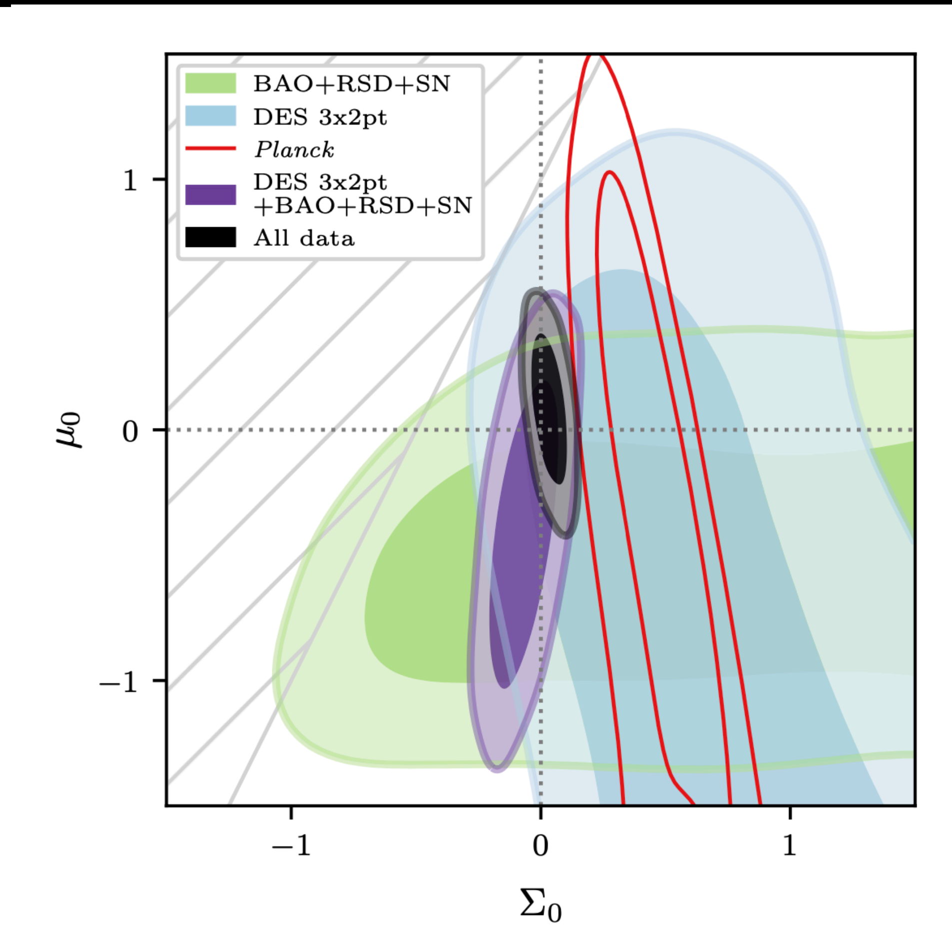

- 5000-fiber spectrograph on the Mayall 4m at Kitt Peak
- 40M extragalactic redshifts over 5 years




- 10X sample size of SDSS+
- 3X BAO precision
- Improved RSD precision across redshifts

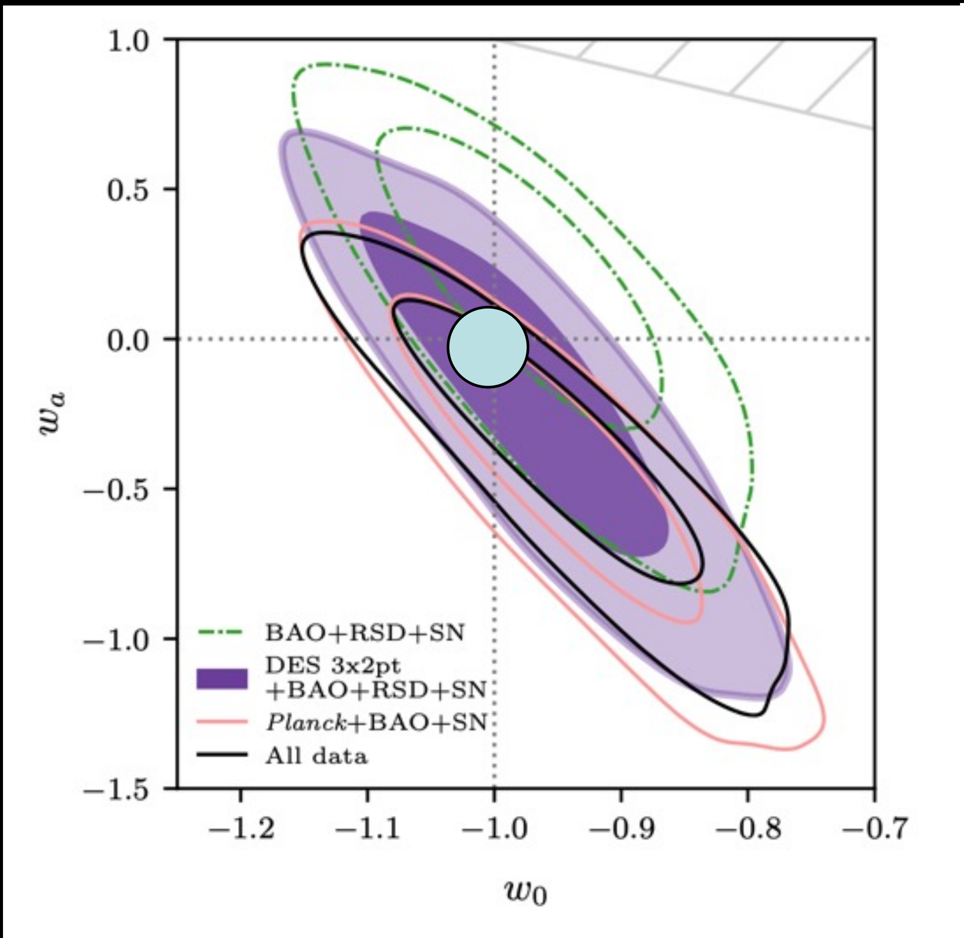
# Dark Energy & Modified Gravity

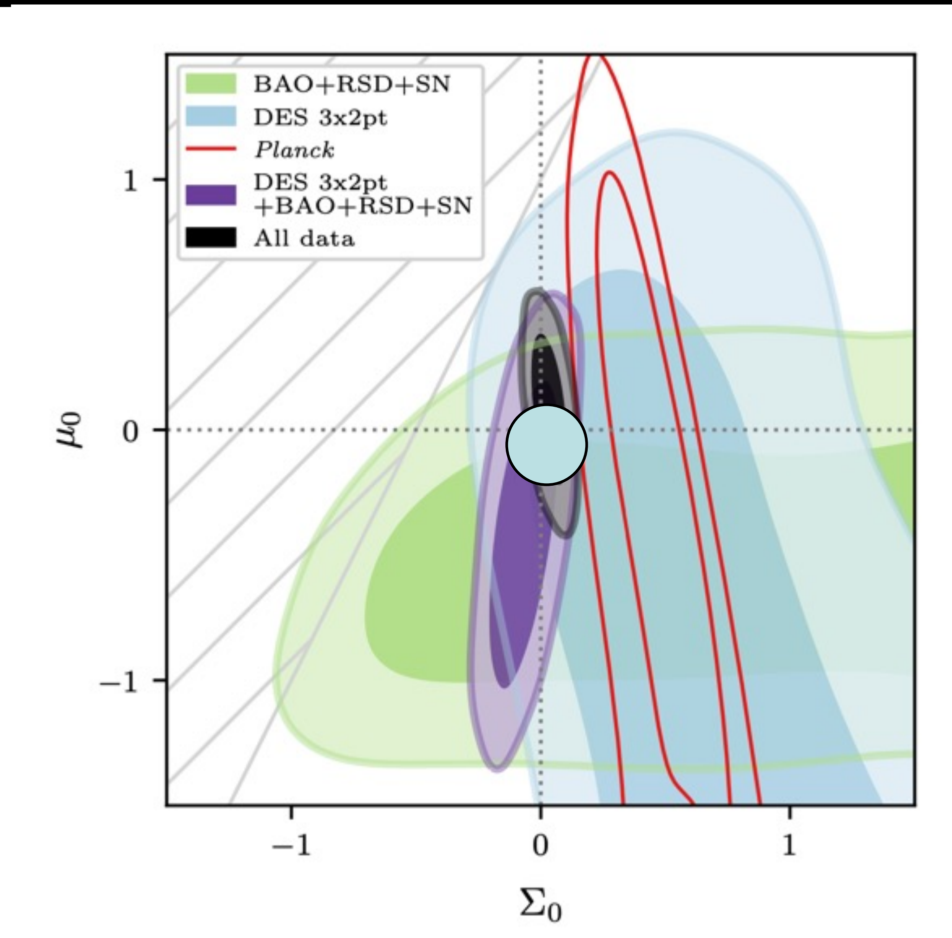



Data are consistent with cosmological constant and GR. But still room for surprises/discoveries (new physics).

# Dark Energy & Modified Gravity

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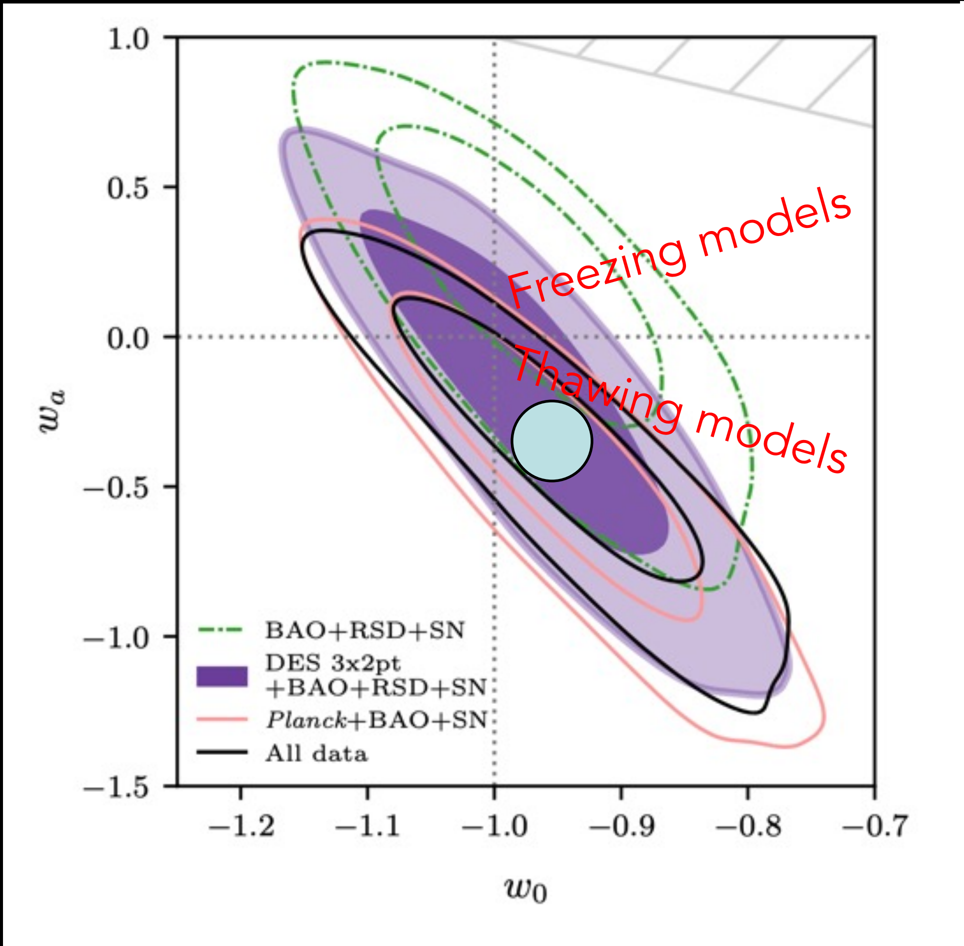


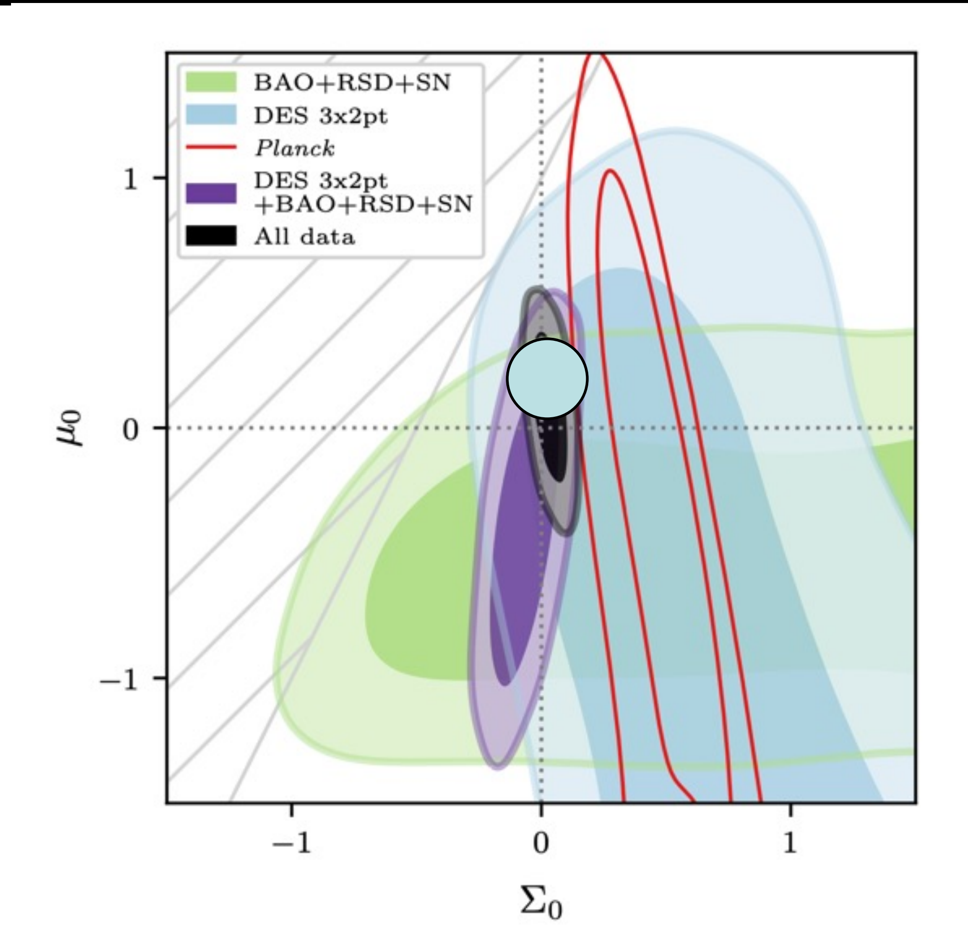


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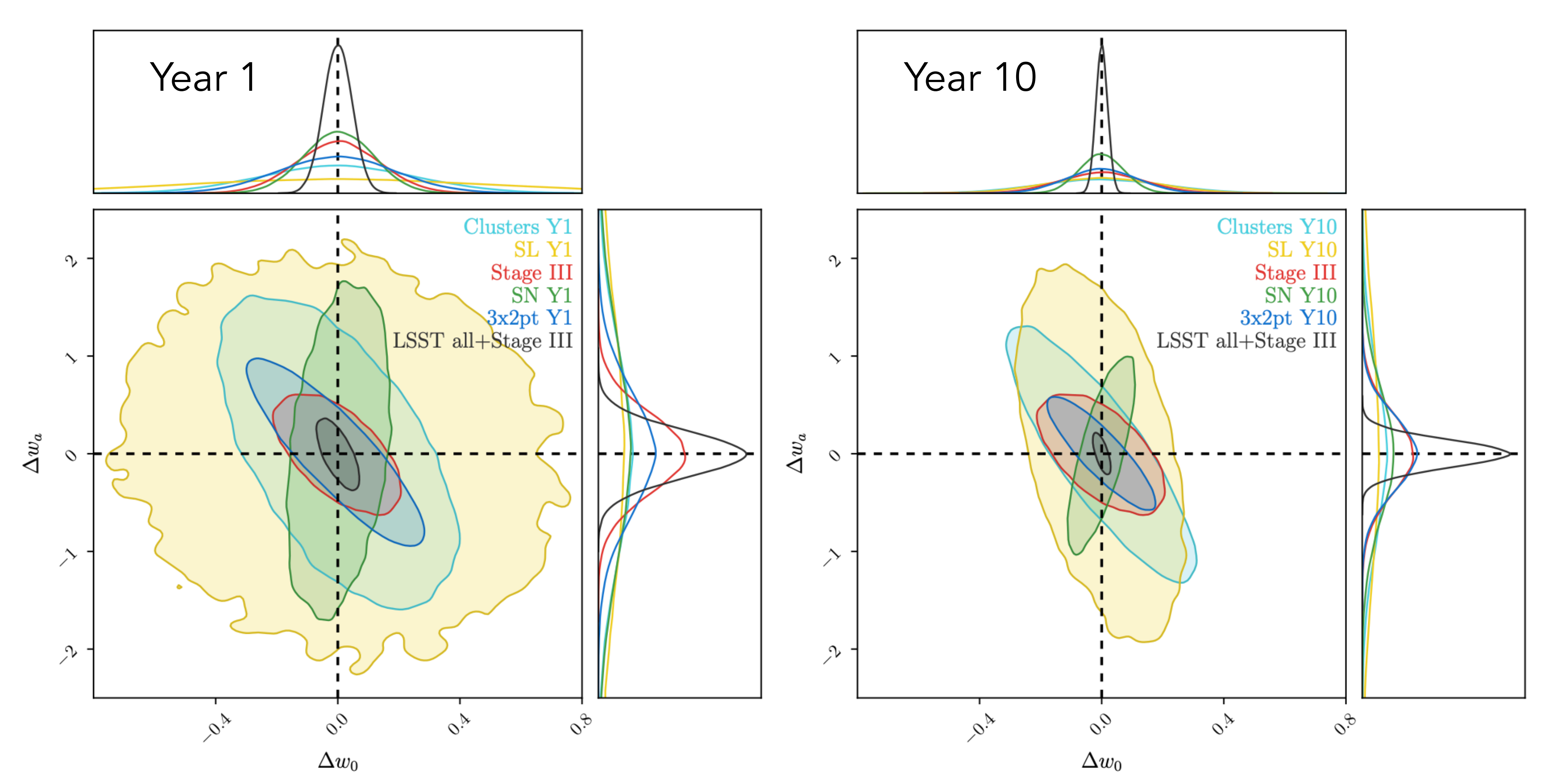
# Vera Rubin Observatory

Legacy Survey of Space and Time (LSST): 10-year multi-band imaging survey with 3 Gigapixel camera on new 6.5m telescope in Chile (Cerro Pachon)

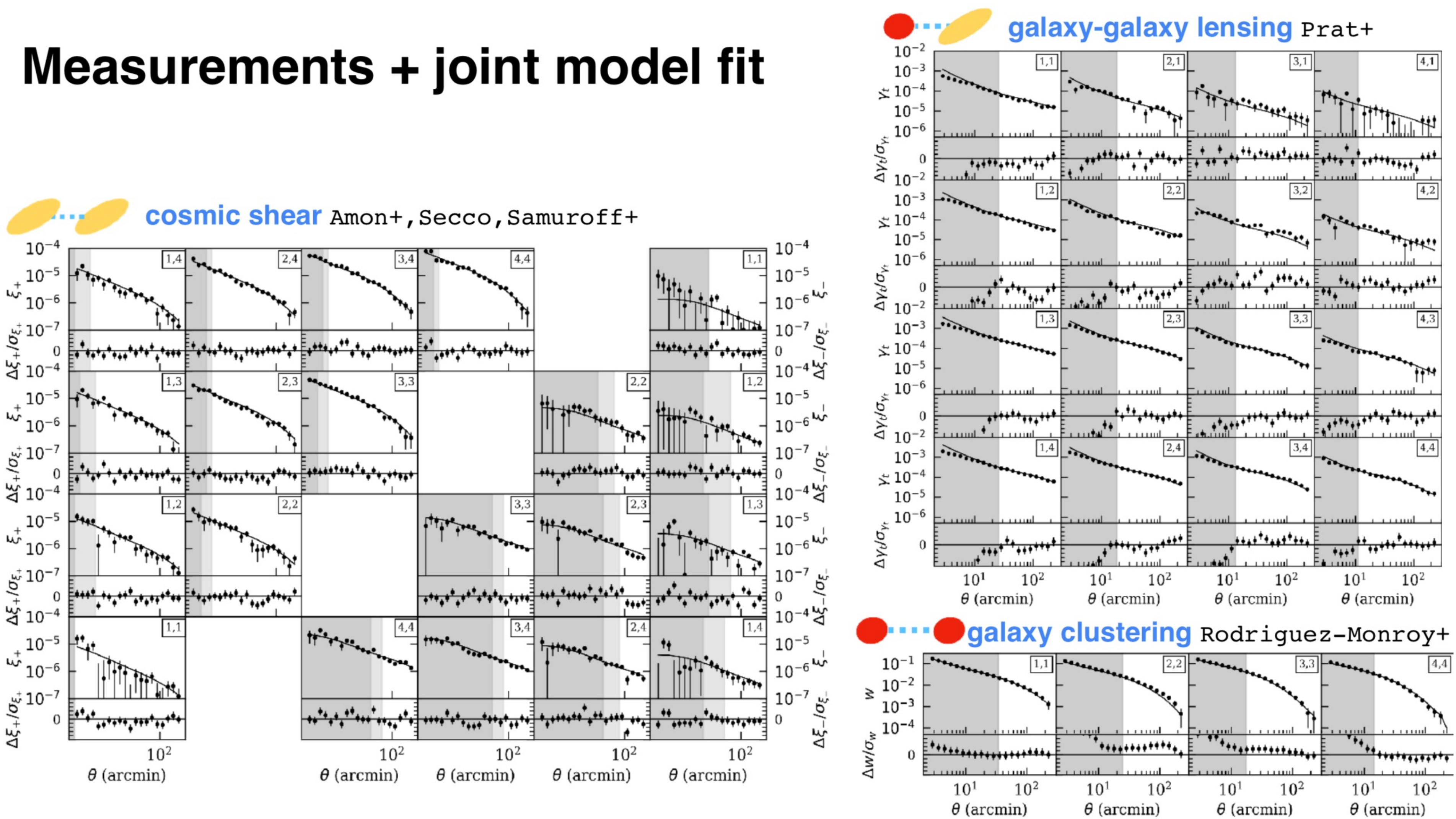



LSST Forecasts (LSST DESC 2018-21)

# The Information Scandal

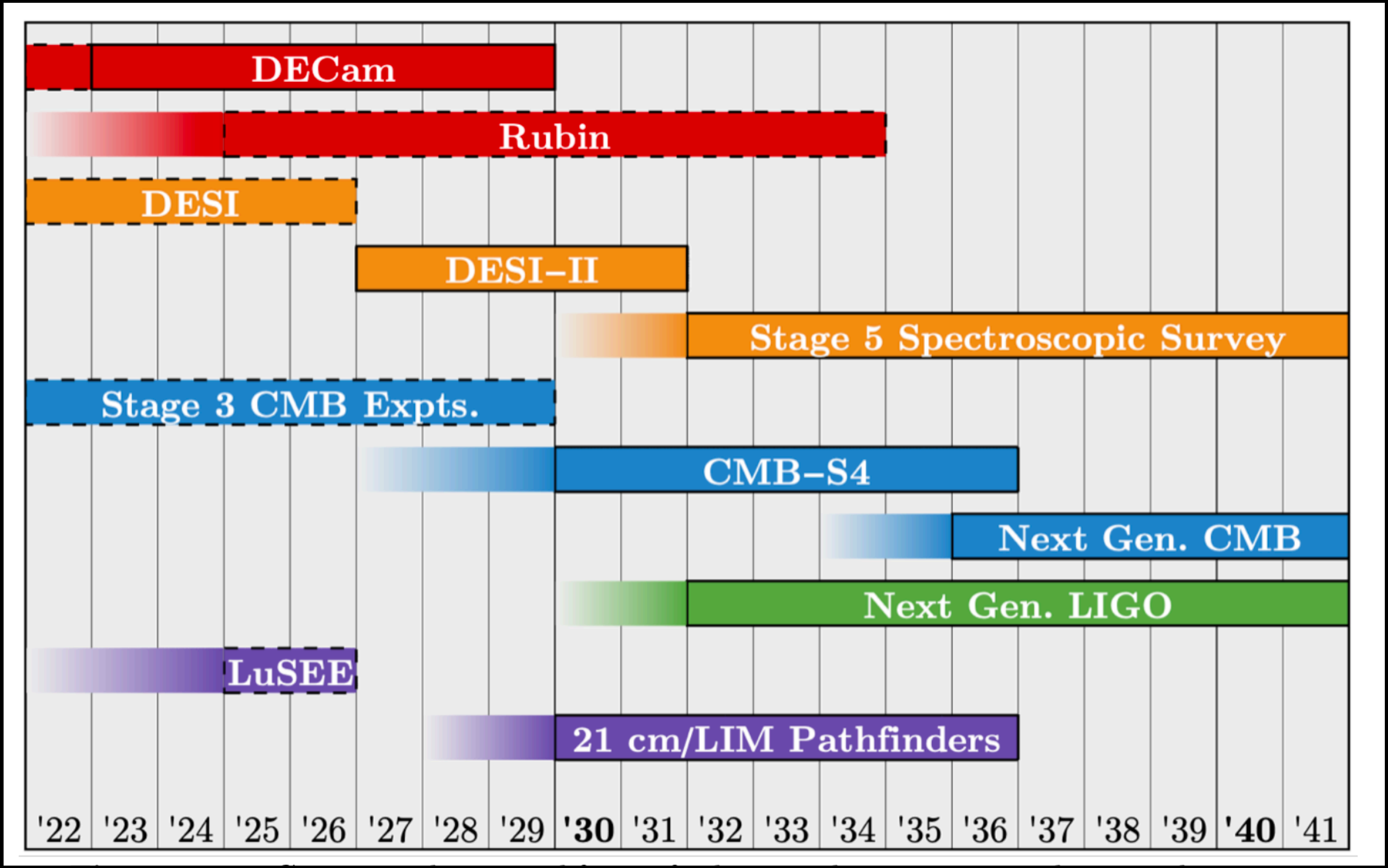
- We’re not extracting all the cosmic information from current surveys:
  - We discard small-scale information, since we can’t yet reliably model it (baryonic effects).
  - The large-scale mass distribution is non-Gaussian, so there is cosmic information in N>2 point correlations. But they are computationally challenging to measure and model.
  - On the other hand, theorists and analysts are cheap compared to the ~$5B price tag of Stage IV experiments. Theory & modeling advances could perhaps net ~20-40% cosmological gains.

# Unused Information



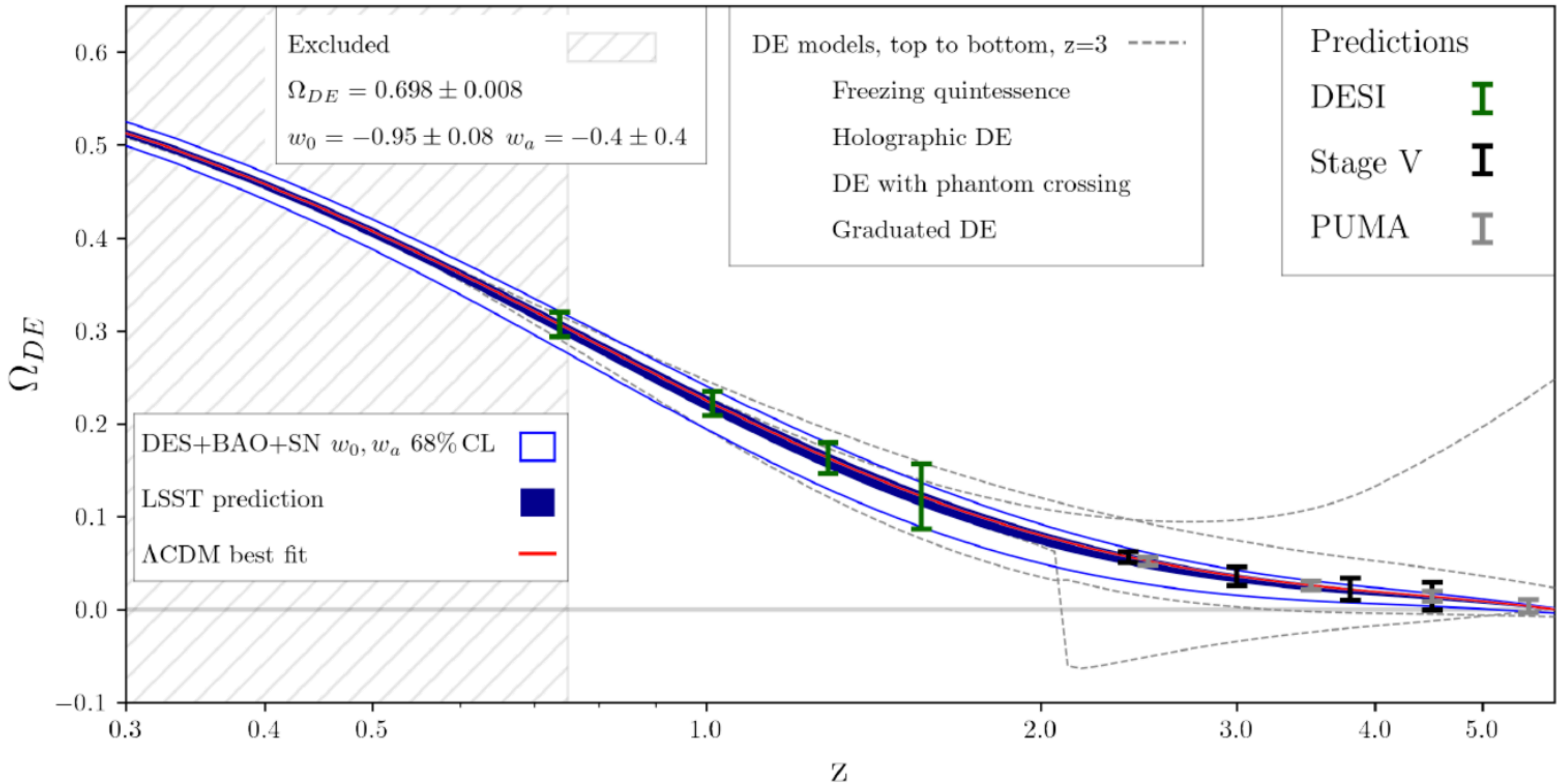

Points in grey regions not used in the cosmological analysis.

# Beyond Stage IV




Snowmass: Flaugher+ 2022

# Beyond Stage IV




Exploit information at redshifts z>2

Snowmass: Chou+ 2022

# The Precision Frontier

- Cosmic surveys will stress-test ΛCDM and may break it.
- Precision as a potential route to new physics.
  - HEP analogy: muon g-2 experiments.
- We know *w* was very close to -1 during inflation but not equal to it. Theoretical prejudice for Λ not historically well-motivated.
- But estimating (almost) anything to percent-level precision *and* accuracy is hard:
  - Sources of systematic errors proliferate.
  - DES 3x2pt analysis: 26 nuisance parameters. It's likely that systematic error models will need to become *more* complex as statistical uncertainties shrink.
- Prediction: cosmologists' lives will be better but harder.