# Dark Energy Experiments: Present and Future

Javier Sánchez (FNAL)

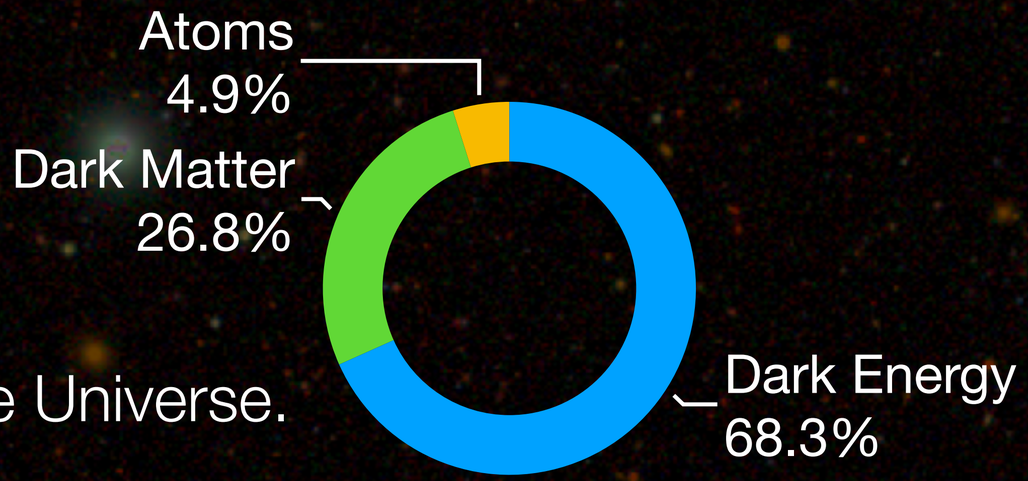
53rd Fermilab's Annual Users meeting

August 11th 2020

# Outline

- Introduction
- Galaxy surveys
  - Present
  - Future
- Beyond Dark Energy
- Joint Quests
- DE at FNAL

# Introduction




- Dark Energy is the dominant energy form in the Universe.
- It is responsible for the accelerated expansion of the Universe.
- Flat-ΛCold Dark Matter (CDM): Currently the most widely accepted cosmological model.
- $\Lambda$: Cosmological constant.
- **But is dark energy constant across time? Does it correspond to the cosmological constant?**

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

# How do we study DE?

- Two main ways:
  - Geometry: Dark energy makes distances and volumes larger with cosmic time.
  - Growth of structure: Dark energy opposes gravity and suppresses the growth of structure.

Ruiz and Huterer 2015

| Cosmological Probe | Geometry | Growth |
|---|---|---|
| SN Ia | $H_0 D_L(z)$ | — |
| BAO | $\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3} / r_s(z_d)$ | — |
| CMB peak loc. | $R \propto \sqrt{\Omega_m H_0^2}\, D_A(z_*)$ | — |
| Cluster counts | $\frac{dV}{dz}$ | $\frac{dn}{dM}$ |
| Weak lens 2pt (and strong) | $\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$ | $P\left(k = \frac{\ell}{r(z)}\right)$ |
| RSD | $F(z) \propto D_A(z) H(z)$ | $f(z)\sigma_8(z)$ |

**Baryon Acoustic Oscillations**

**Redshift Space Distortions**

**+ Gravitational Waves (geometry)**

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**Galaxy surveys**

**CMB experiments**

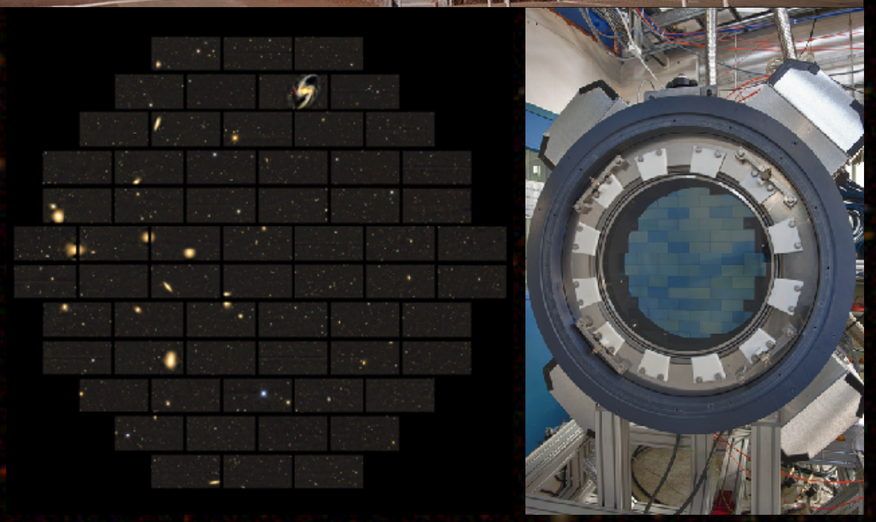
**(and strong)**

**Gravitational wave experiments**

**+ Gravitational Waves (geometry)**

# Galaxy surveys

- We stand on the shoulders of giants:
  - Fermilab has been at the forefront of galaxy surveys since the inception of the Sloan Digital Sky Survey (~ 30 years ago!).
  - Successfully led construction of the Dark Energy Camera (DECam) and operations of the 6-year Dark Energy Survey (DES).



Credit: Dark Energy Survey Collaboration/FNAL

*"If I've seen further it is by standing on the shoulders of Giants."— Isaac Newton*

# Galaxy surveys

- Looking into the future (2020s, decade of precision cosmology!):
  - Key roles in DESI (5-year survey, starting operations this year)
  - And Rubin Observatory LSST (10-year survey, starting 2022 — 2023).

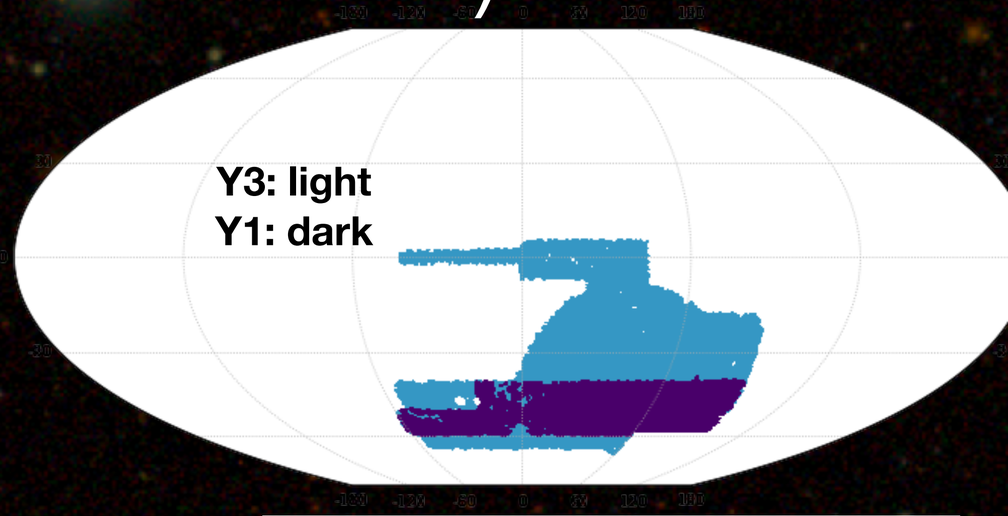
Credit: DESI Collaboration/Berkeley Lab

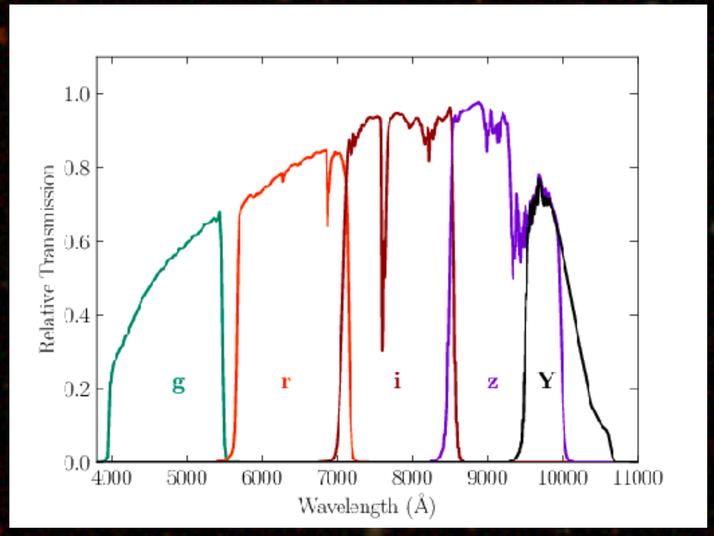
Credit: LSST/NSF/DOE/AURA

*“If I’ve seen further it is by standing on the shoulders of Giants.”— Isaac Newton*

# The present (and immediate future): DES

- DES is a photometric survey, using the 4-m Blanco telescope.
- DES finished its 6 years of observing in January 2019.
- DES analyses for the 3rd year dataset almost ready to be published with lots of updates over the 1st year analyses:
  - Increased footprint (5000 sq-deg vs < 2000 sq-deg) and depth (higher density and higher redshift).
  - Improved photometric redshifts/very comprehensive redshift treatment.
  - Will greatly improve statistical sensitivity to cosmology using our “flagship” analysis, the so-called 3x2pt.




Credit: DES Collaboration 2017

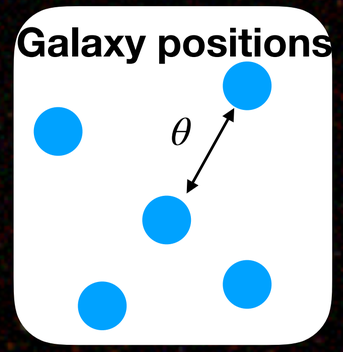
**Y1 clustering: 1 M galaxies**
**Y3 clustering 3 -10 M galaxies**

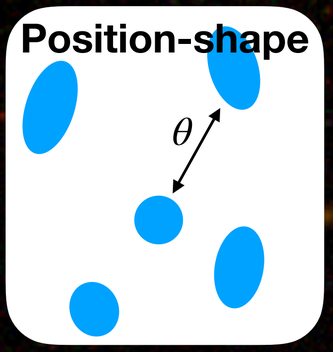
**Y1 WL: 35 M galaxies**
**Y3 WL: 100 M galaxies**

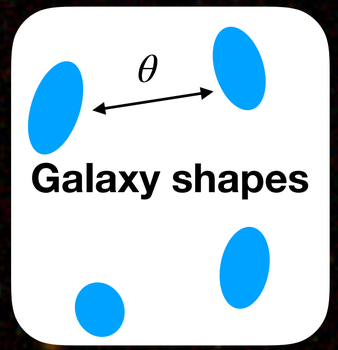
THE DARK ENERGY SURVEY

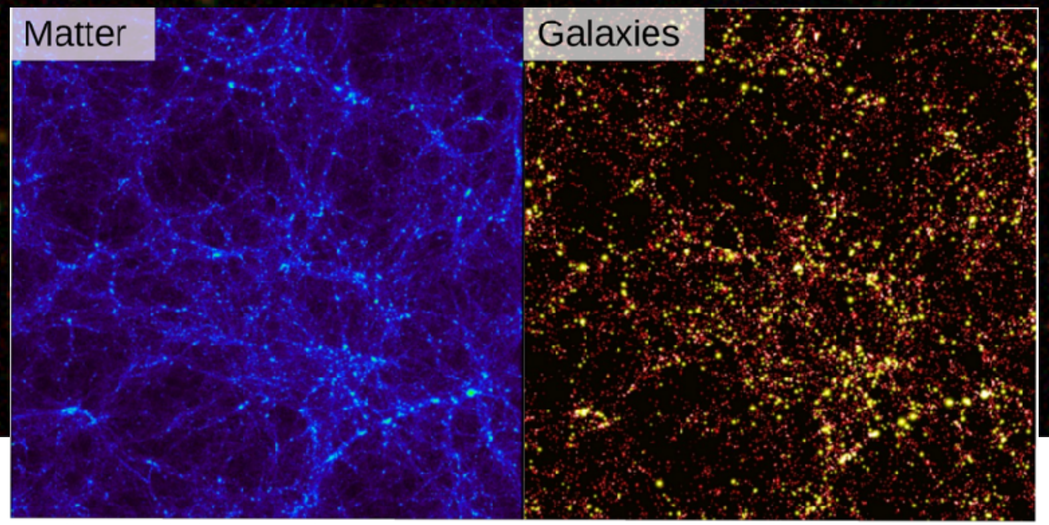
# 3x2pt analysis

- Galaxies trace the dark matter density field.
- Galaxy shapes do that as well!
- Each galaxy contains information and we have (tens of) millions of them.
- Summary statistics! Density-field ~ Gaussian random field; completely described by 2-point statistics (variance).
- Stay tuned for DES-Y3 results!
- This is also thought to be the flagship analysis for LSST but understanding the systematics will be key given the increased statistics (x10-20 larger)



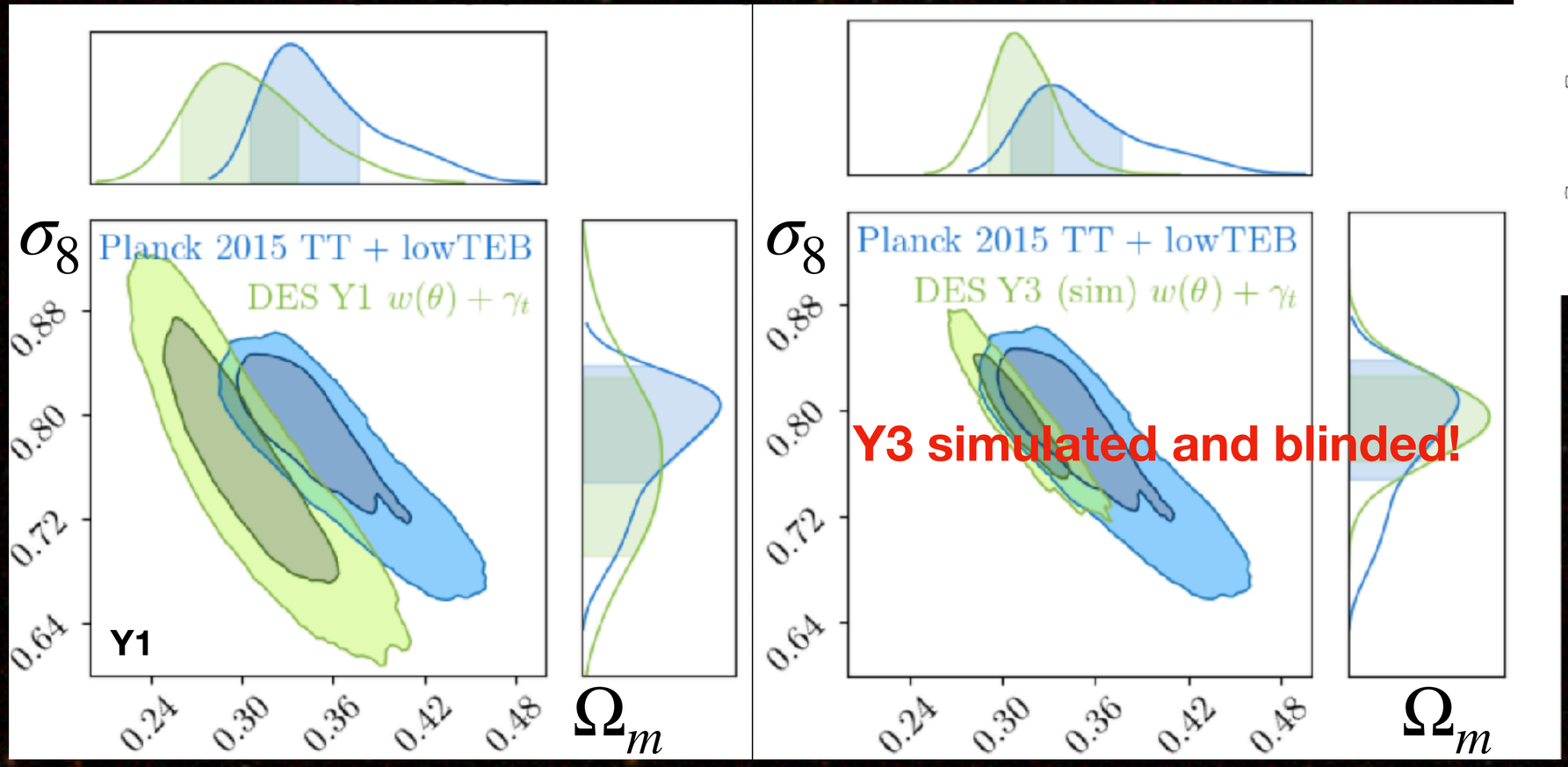




*Credit: Herschel Space Observatory*

# DES Y1 and Y3

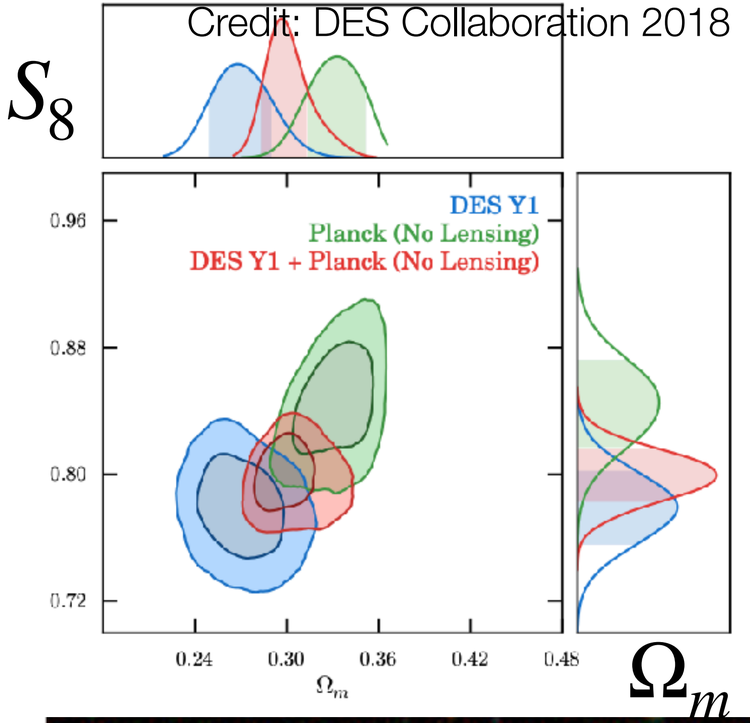
- Sensitivity comparable to Planck!







Credit: DES Collaboration 2018

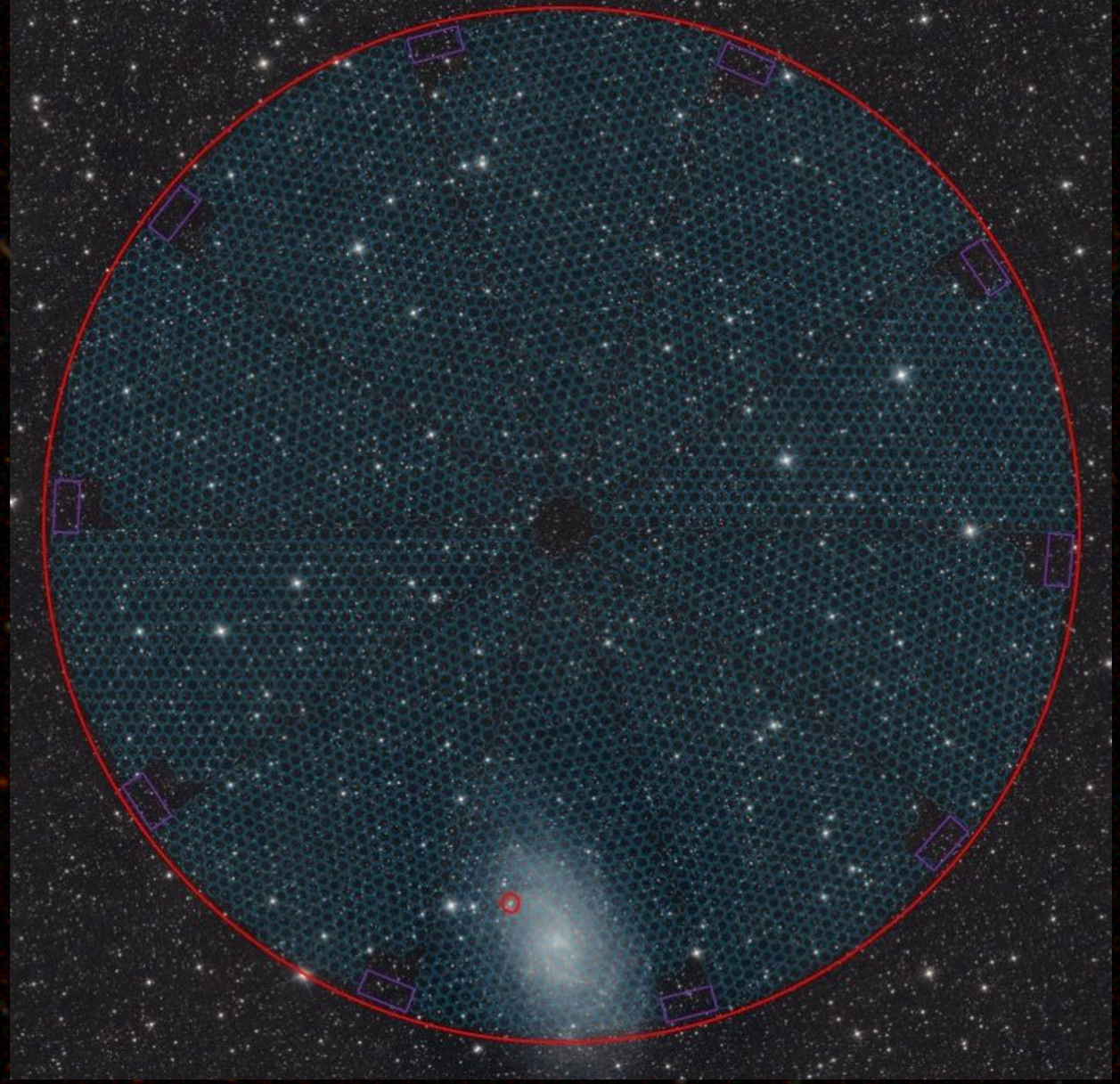



**Credit: J. Elvin-Poole (at APS-DPF). Using DES Collaboration 2018 products**

THE DARK ENERGY SURVEY

# DESI

- DESI: Dark Energy Spectroscopic Instrument.
  - Collects spectra from 5000 galaxies simultaneously.
  - Focused on Baryon-Acoustic Oscillations (geometry) and Redshift Space Distortions (geometry+growth), using ~30 million galaxies.
  - First light in October 2019.
  - Commissioning complete. Soon-to-start operations.
  - FNAL plays key role in operations and analysis.



Credit: DESI Collaboration/Legacy Surveys/NASA/JPL-Caltech/UCLA

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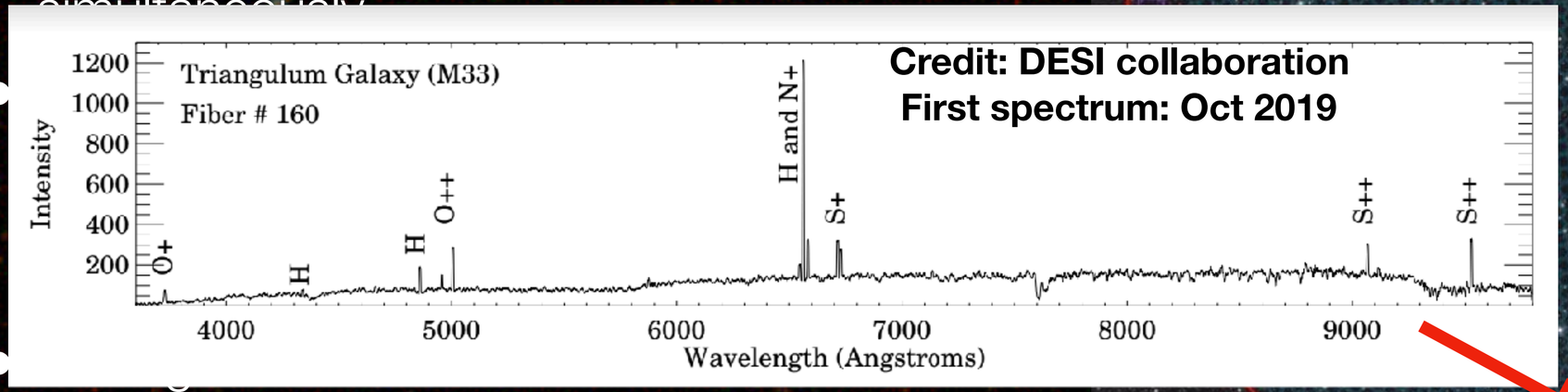
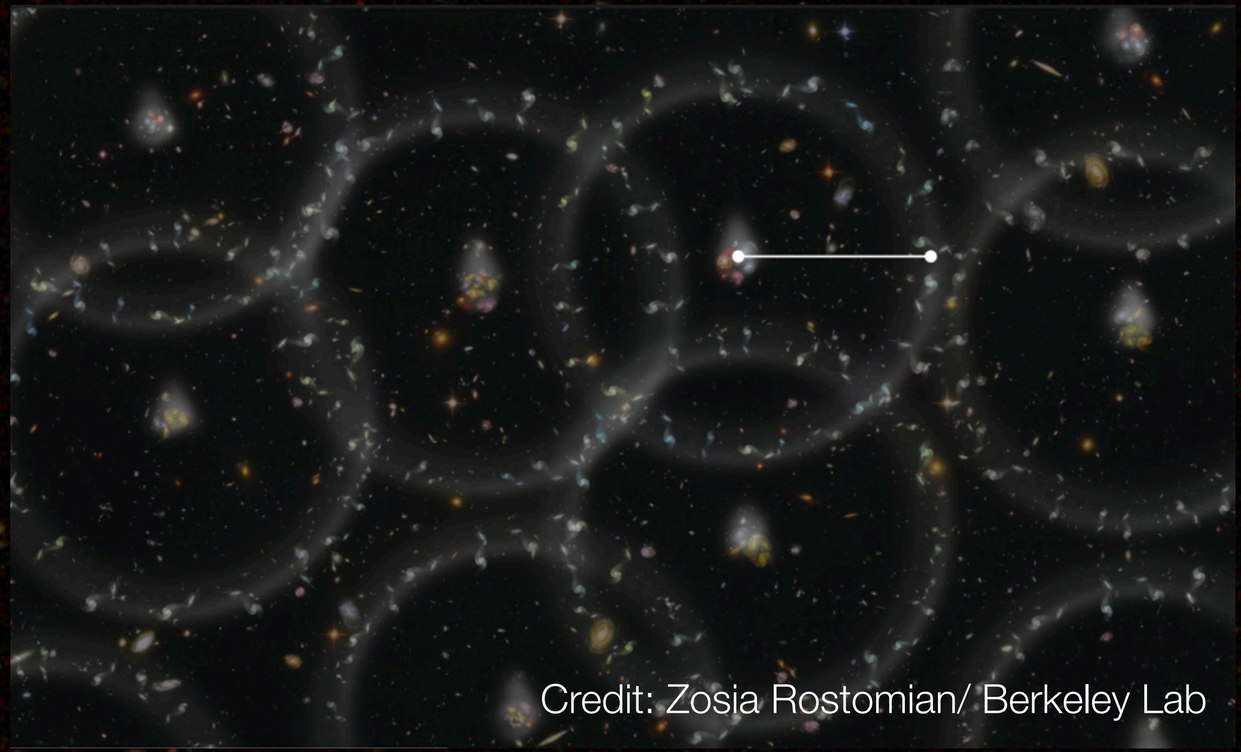



**Credit: DESI collaboration**
**First spectrum: Oct 2019**

Credit: DESI Collaboration/Legacy Surveys/NASA/JPL-Caltech/UCLA

# DESI: BAO

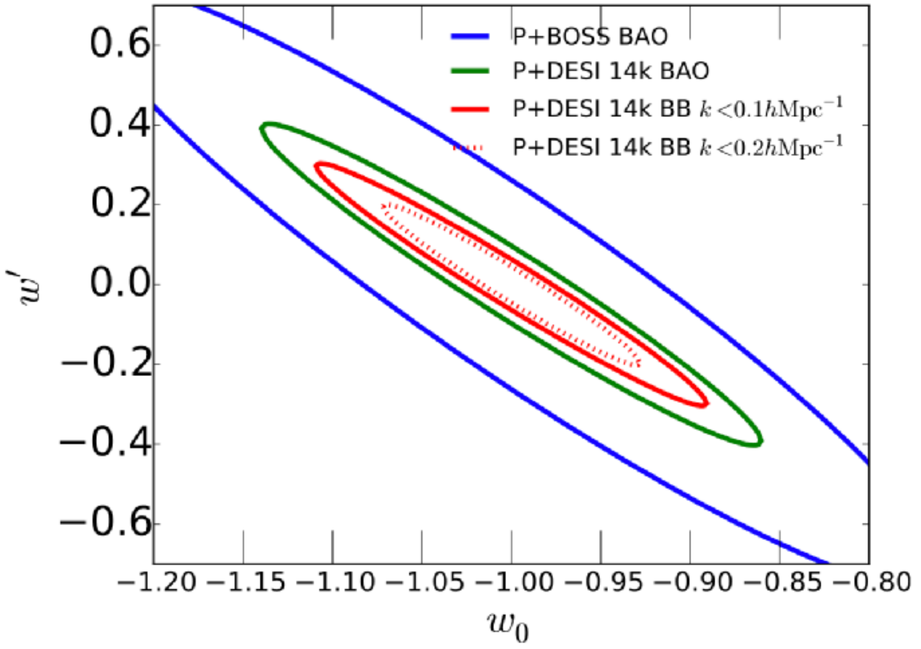
- Spectra allows for very accurate determination of 3D distance.
- BAO: Frozen scale from early Universe that only changes because of the influence of Dark Energy.
- If we factor out DE influence, it is constant: standard ruler.
- Can also use the “shadows” cast by hydrogen illuminated by distant very energetic objects (QSO - Lyman-alpha forest)

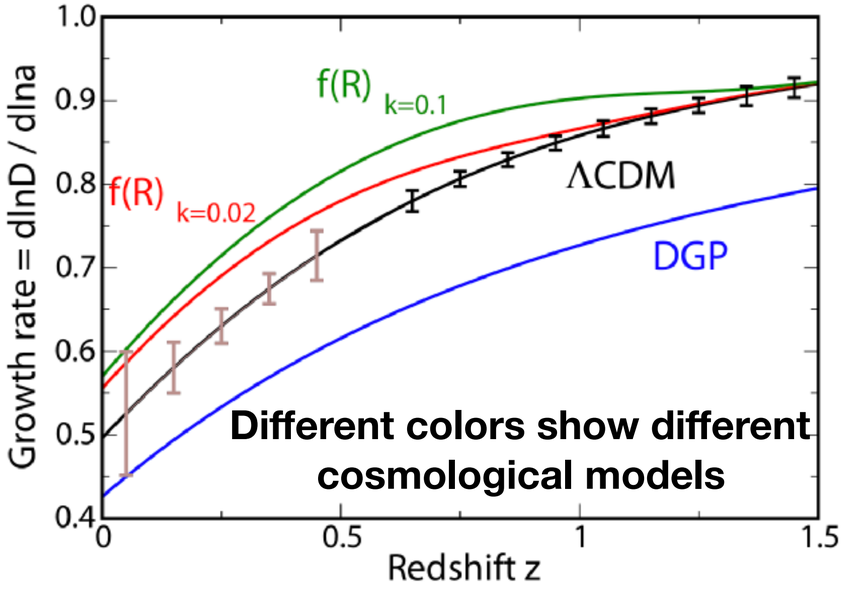


Credit: Zosia Rostomian/ Berkeley Lab

# DESI: RSD

- Redshift is not a perfect measurement of distance.
- Peculiar velocities of objects change the redshift.
- But peculiar velocities are correlated with large-scale density fluctuations (velocities will on average tend to point towards potential wells generated by large overdensities).



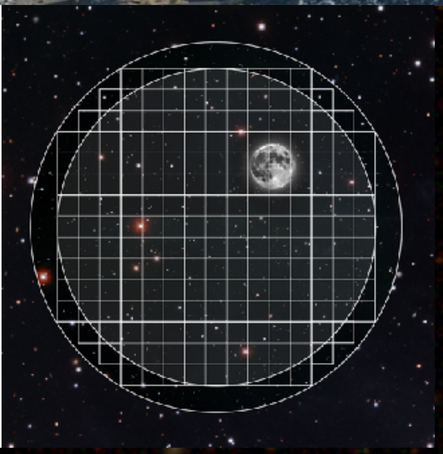

Credit: DESI Collaboration. arXiv:1611.00036

# Rubin Observatory. LSST

- Brand-new 8.4-m telescope in Cerro Pachón (Chile).
- 3.2 Gpix camera (189 4k sensors).
- FOV 9.6 sq-deg (40 times full Moon).
- 10 year survey in 6 filters.
- 37 billion stars and galaxies.
- 10 million transient alerts.
- 20 TB/night. Expected ~15 PB database at the end of the project.
- Hosts the Dark Energy Science Collaboration (DESC).

Credit: lsst.org

Credit: NSF/LSST/AURA

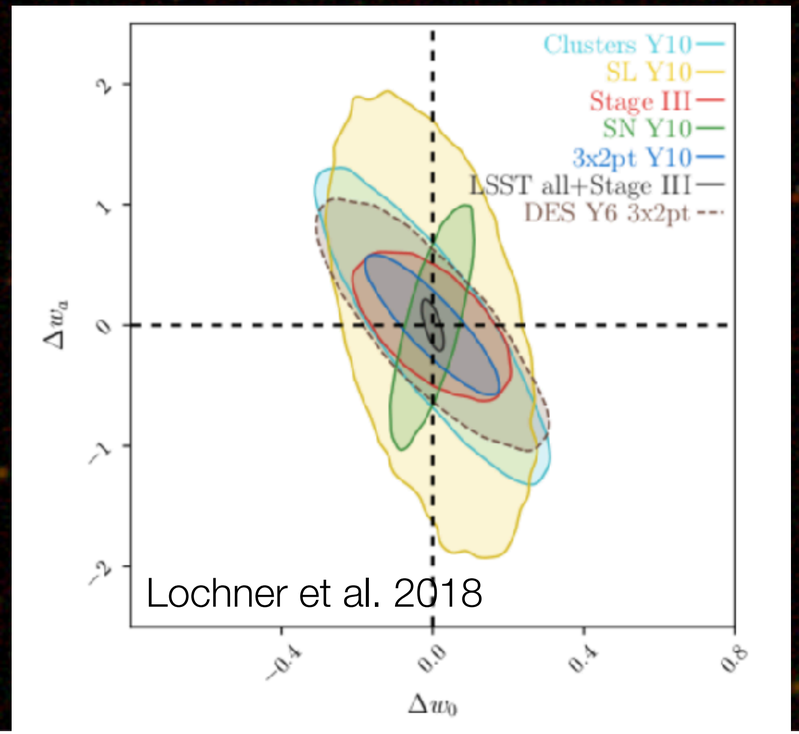


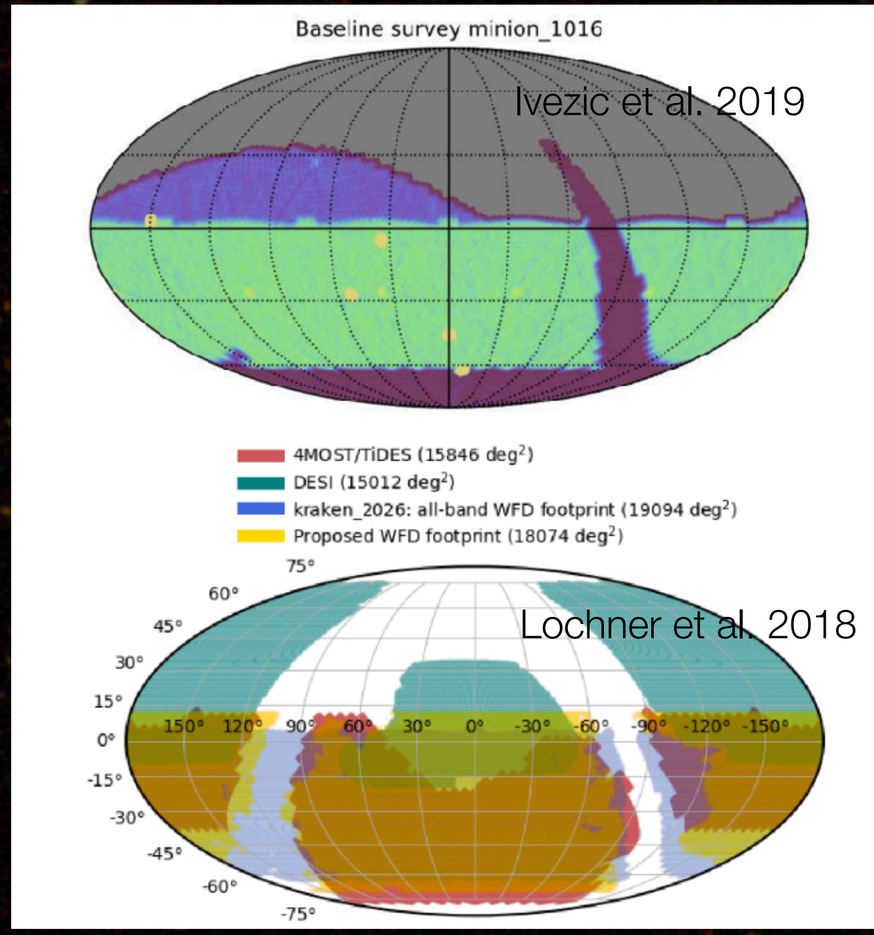
Rubin Observatory

LSST Legacy Survey of Space and Time

# Rubin Observatory. LSST

- FNAL playing key roles in operations and preparations for analysis.
- 18,000 sq-deg. wide-fast-deep (WFD) cadence: main field for 3x2pt analyses. ~30,000 sq-deg total surveyed area.

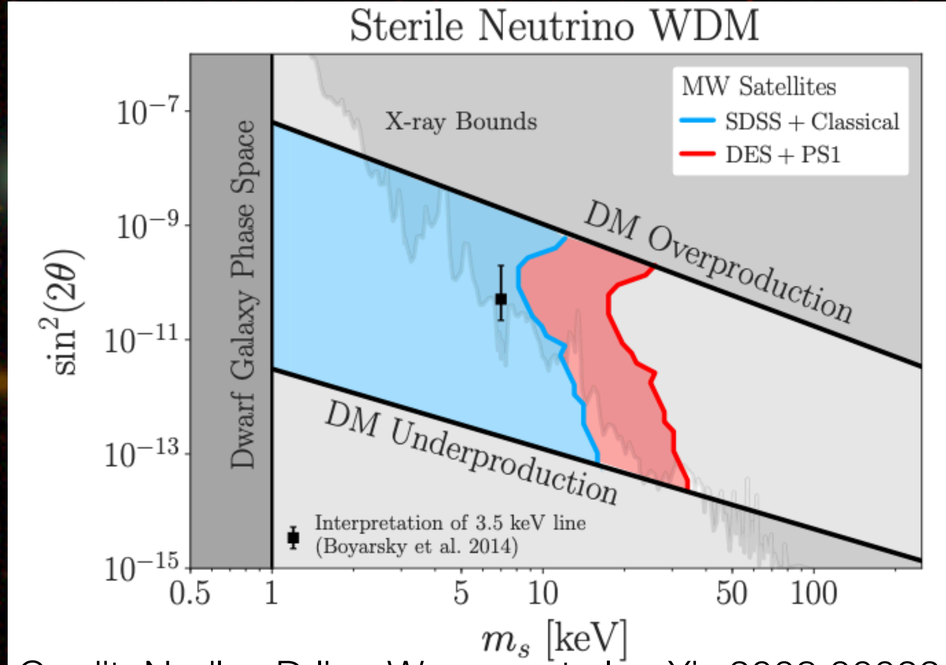


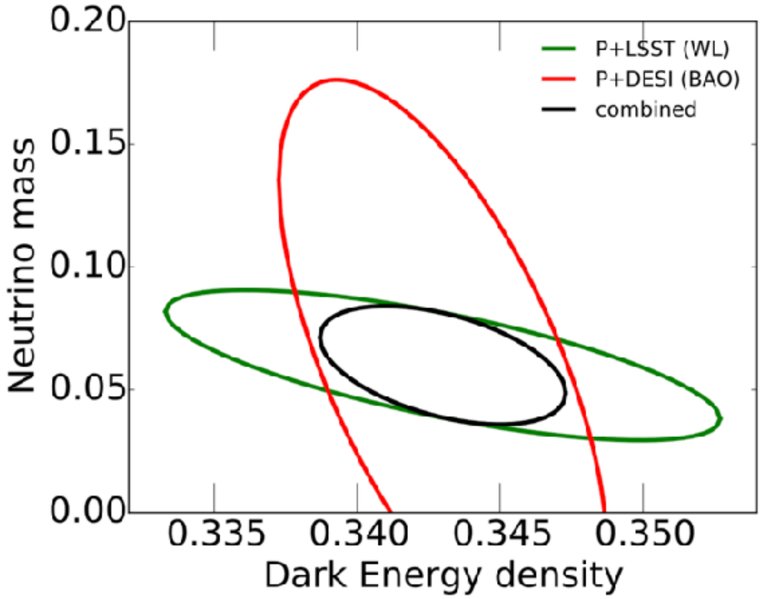

Rubin Observatory

# Galaxy surveys: Beyond dark energy

- Discovery of ultra-faint galaxies: particularly interesting for the study of dark matter.
- Milky Way and stellar streams.
- Number of neutrino species/sum of neutrino masses (they prevent growth of structure).
- Primordial non-Gaussianities.



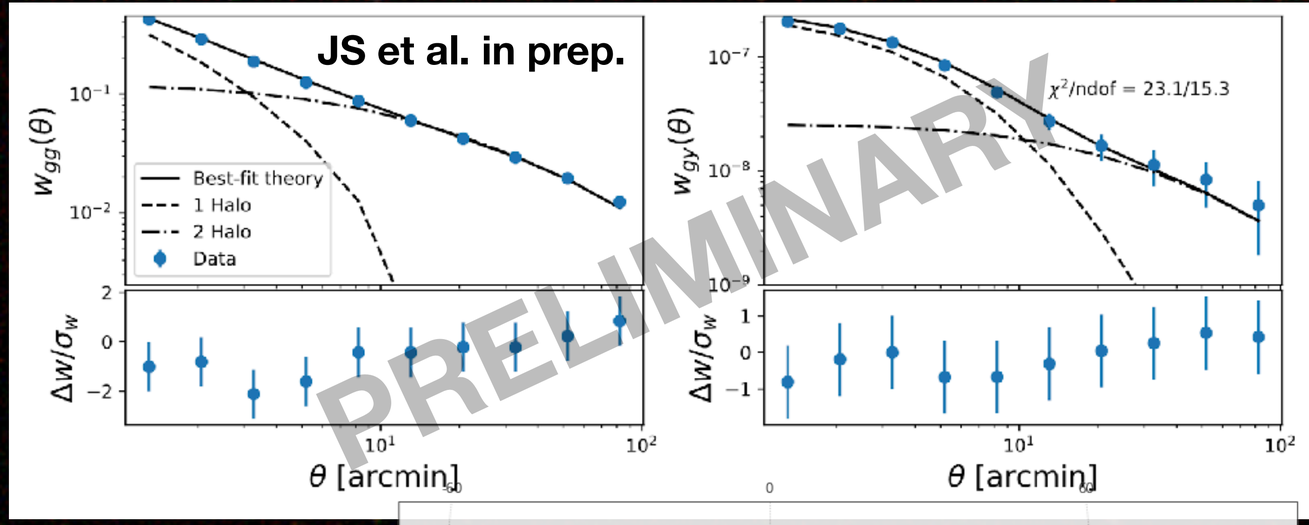

Credit: Nadler, Drlica-Wagner, et al. arXiv:2008.00022

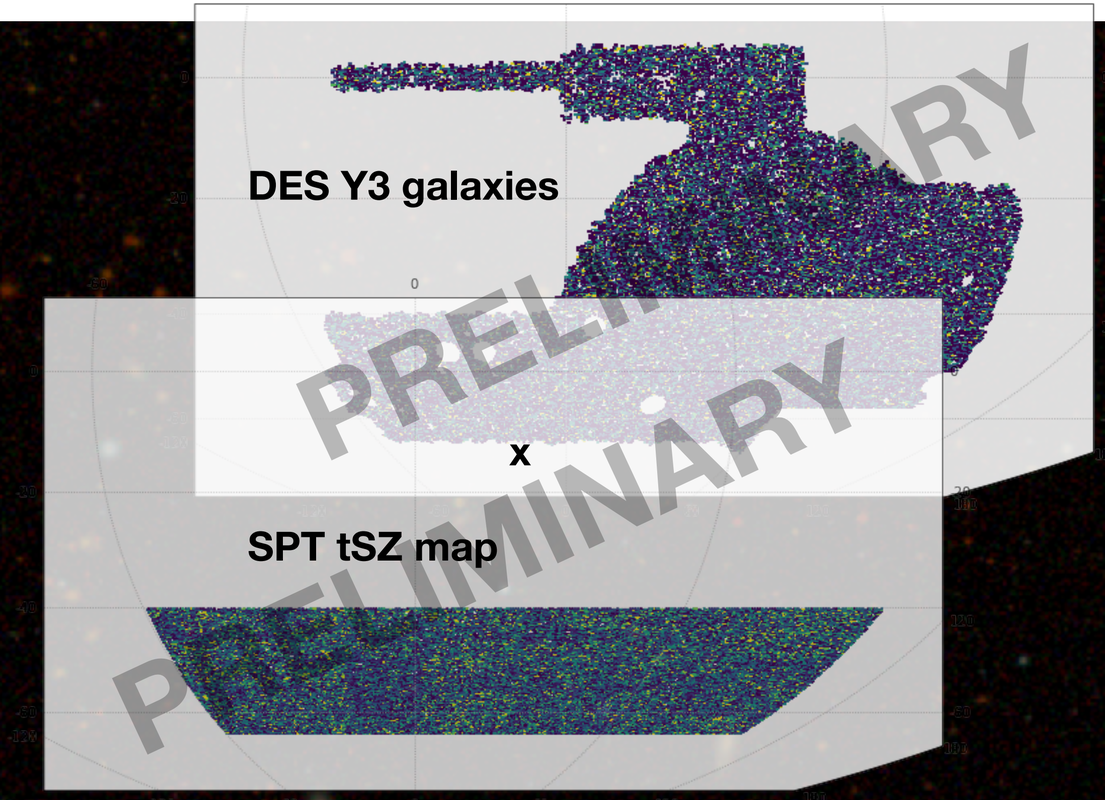



Credit: DESI Collaboration. arXiv:1611.00036

# Joint quests

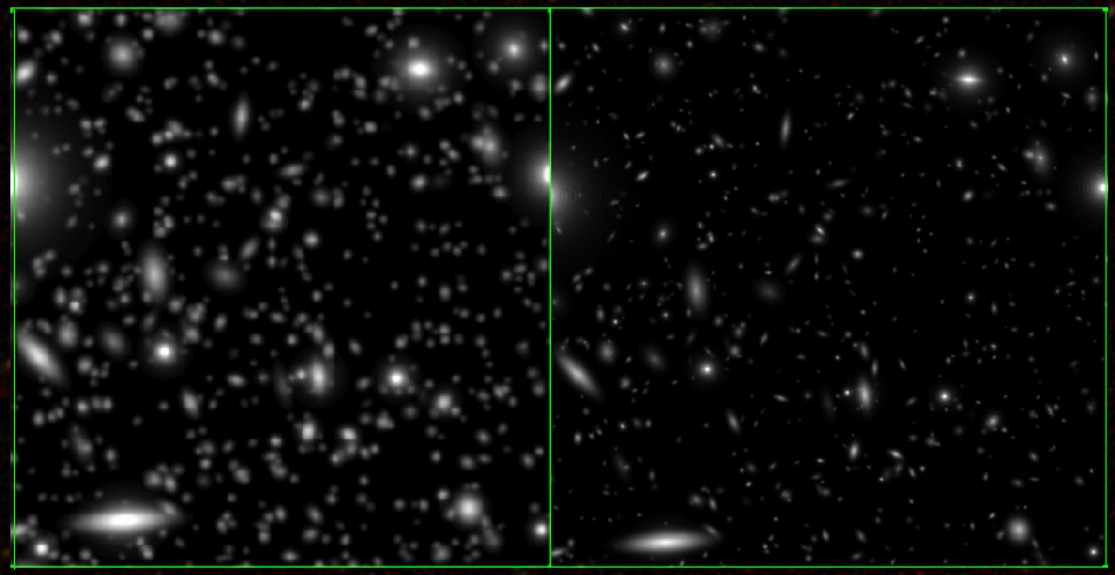
- CMB also traces the same density field.
- Can cross-correlate galaxies positions and shapes with CMB temperature and polarization (6x2pt) to improve sensitivity (and mitigate impact of systematics which will be the limiting factor in LSST).
- Can also use secondary anisotropies (tSZ, kSZ) to cross-correlate with galaxies and learn about galaxy-halo connection/gas profiles.



# Joint quests II: At the pixel level?

- Combination of data from different experiments will be crucial in order to obtain the maximum performance of the experiments.
- Joint pixel-level processing may become necessary: Euclid+Roman+Rubin.
- Gravitational waves also trace the same matter density! (and a potential Gravitational Wave Background)



LSST full-depth

Euclid full-depth

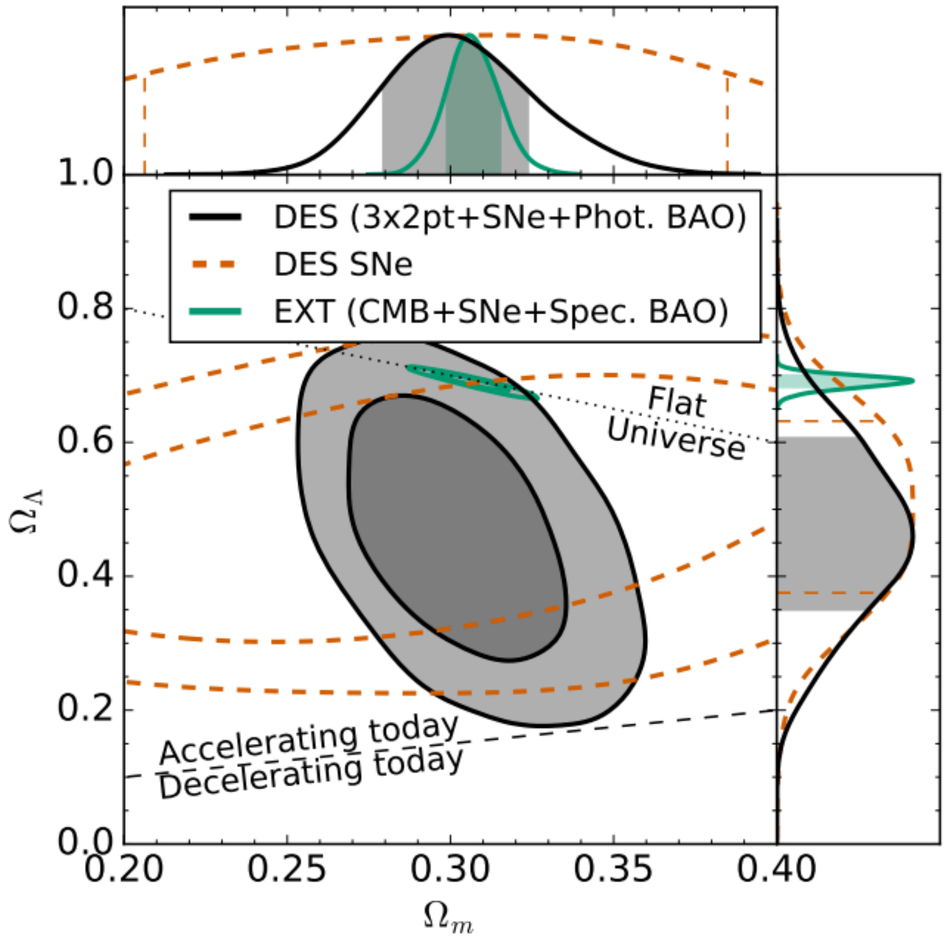
# Dark Energy (and more!) at FNAL

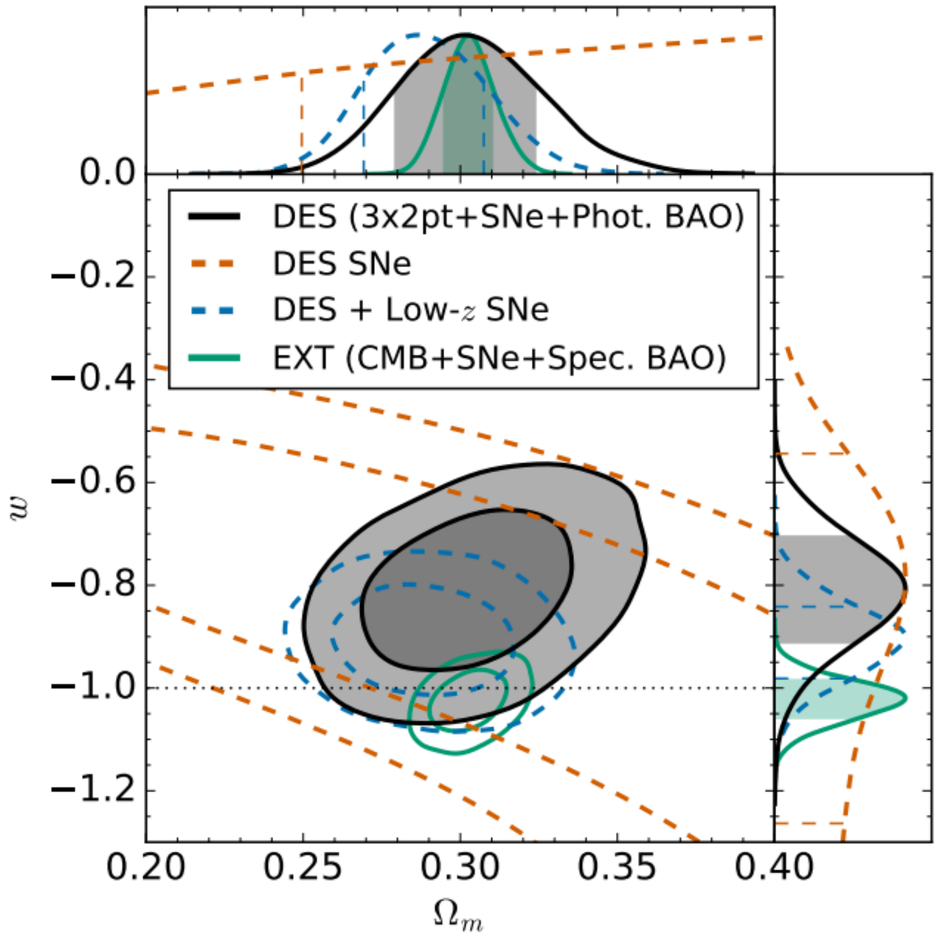
- Led DES operations.
- Heavily involved in analyses (for DES and preparations for LSST):
  - Galaxy clusters (Y. Zhang, J. Annis, A. Palmese).
  - Photometric redshifts (H. Lin).
  - Strong lensing (B. Nord, T. Diehl, L. Buckley-Geer, H. Lin).
  - Milky Way/Dark Matter studies (A. Drlica-Wagner, B. Yanny).
  - Object injection (N. Kuropatkin, B. Yanny).
  - Photometric calibrations (S. Allam, D. L. Tucker)
  - GW + standard sirens (A. Palmese, K. Herner).
  - 3x2pt analyses. (G. Gutiérrez, M. Paterno, JS).
  - Cross-correlations galaxy x CMB (JS).
  - Telescope scheduling (E. Neilsen).
  - Image simulations (N. Kuropatkin, B. Yanny, A. Drlica-Wagner, JS).
  - And much more!!
- Key roles in DESI and Rubin operations.


Thank you!

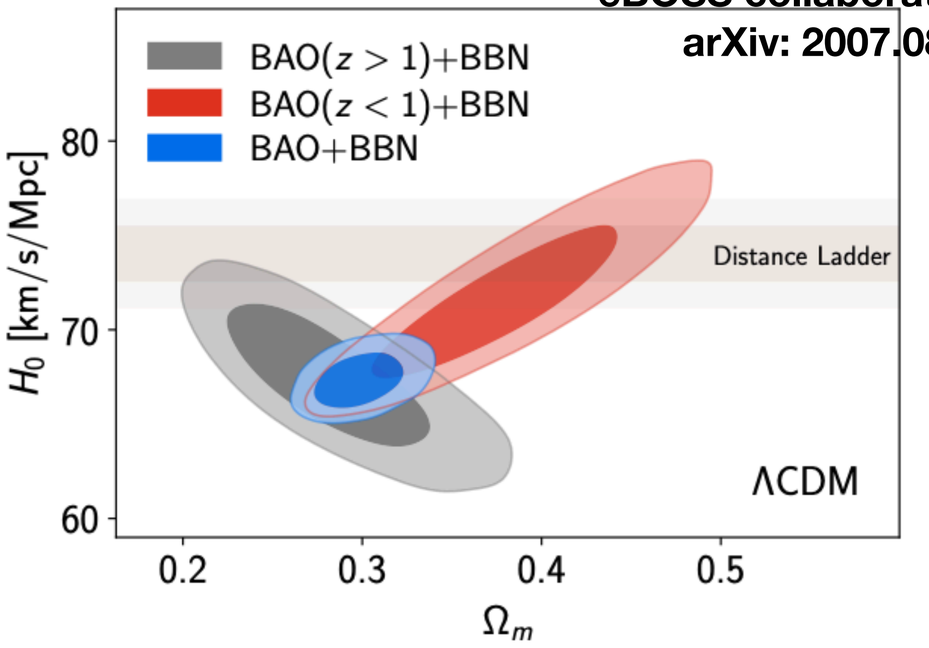
# Backup

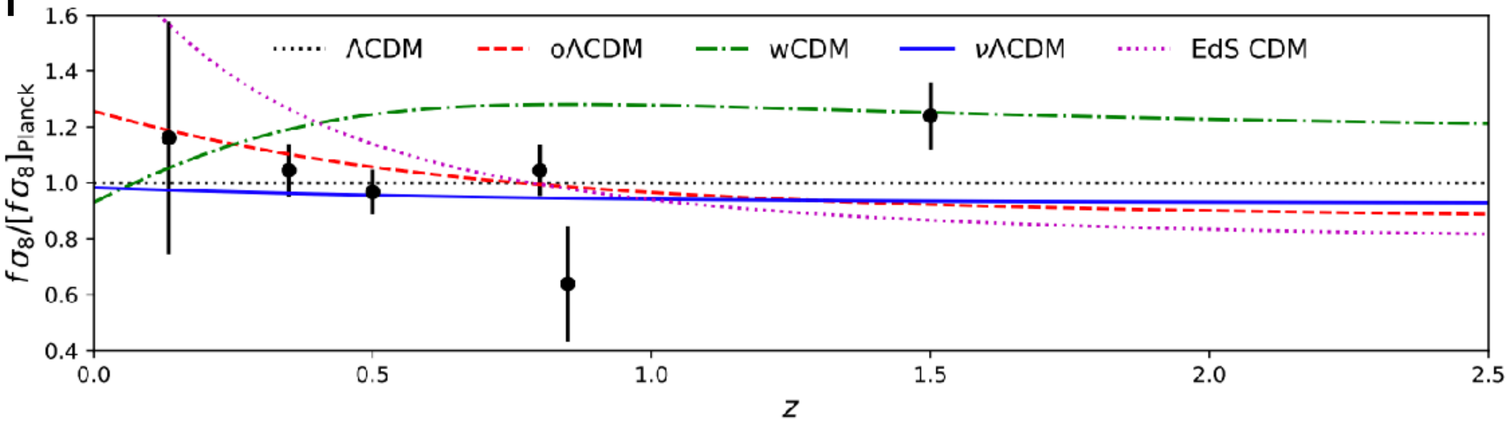
**DES Collaboration 2018**
**arXiv: 1811.02375**

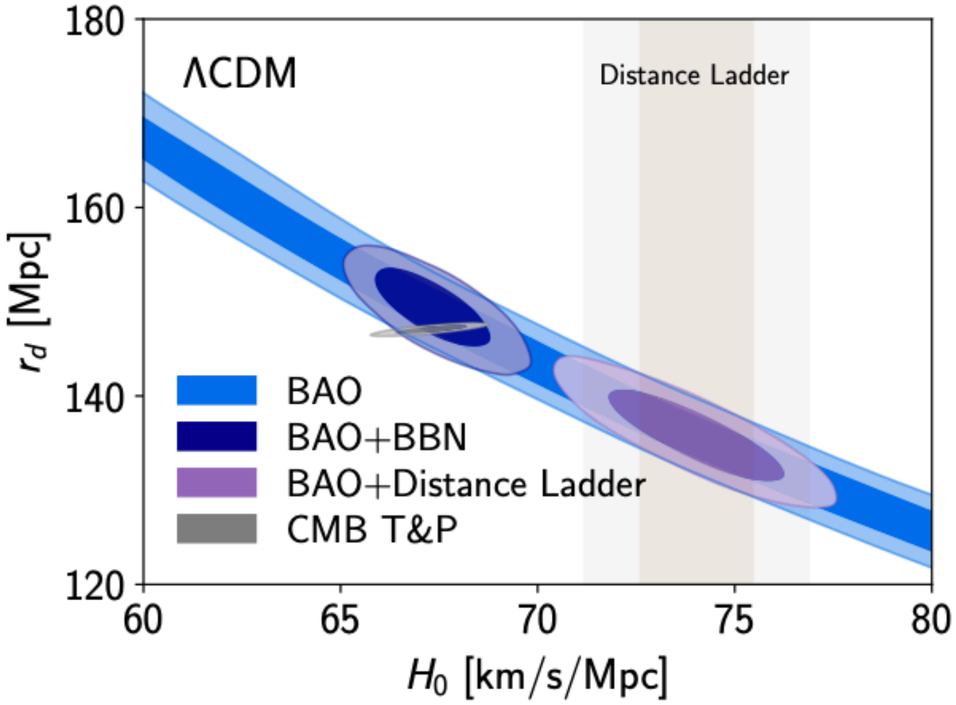


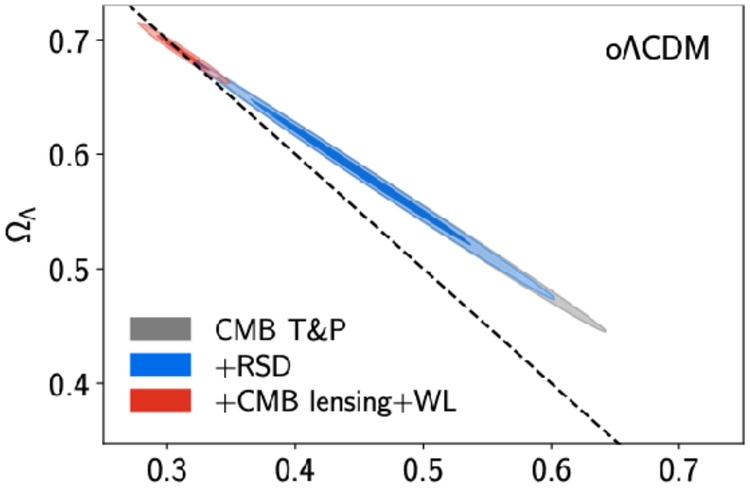



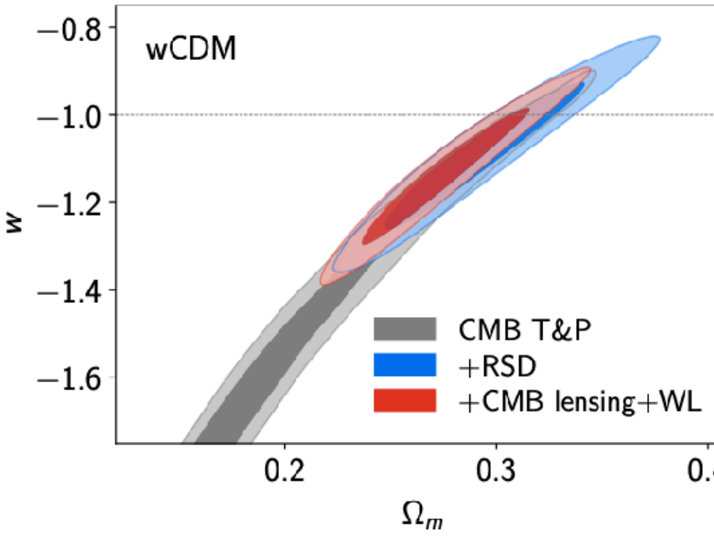
**eBOSS collaboration 2020**
**arXiv: 2007.08991**

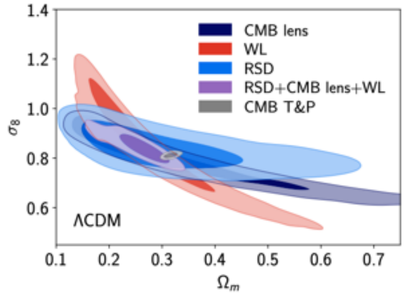


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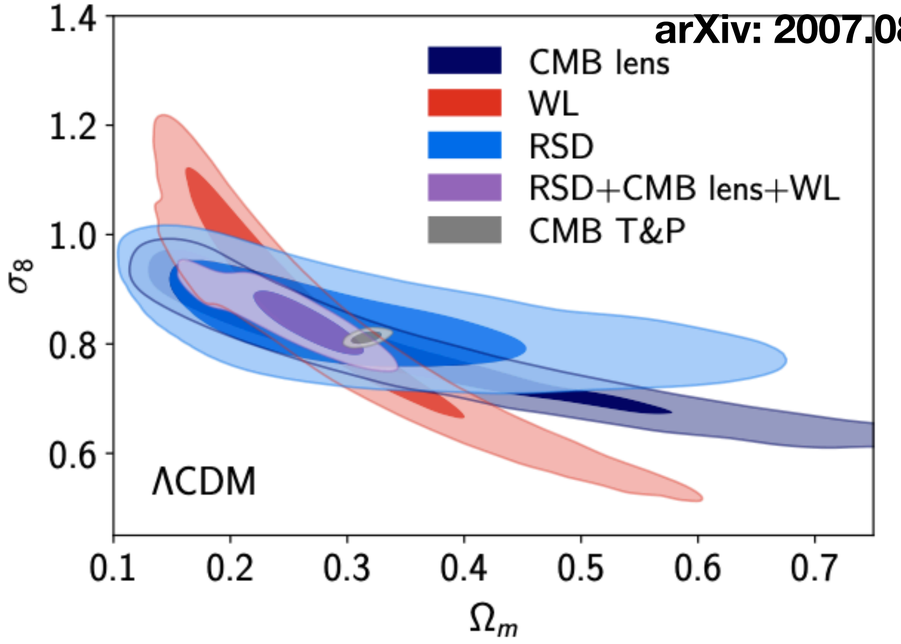


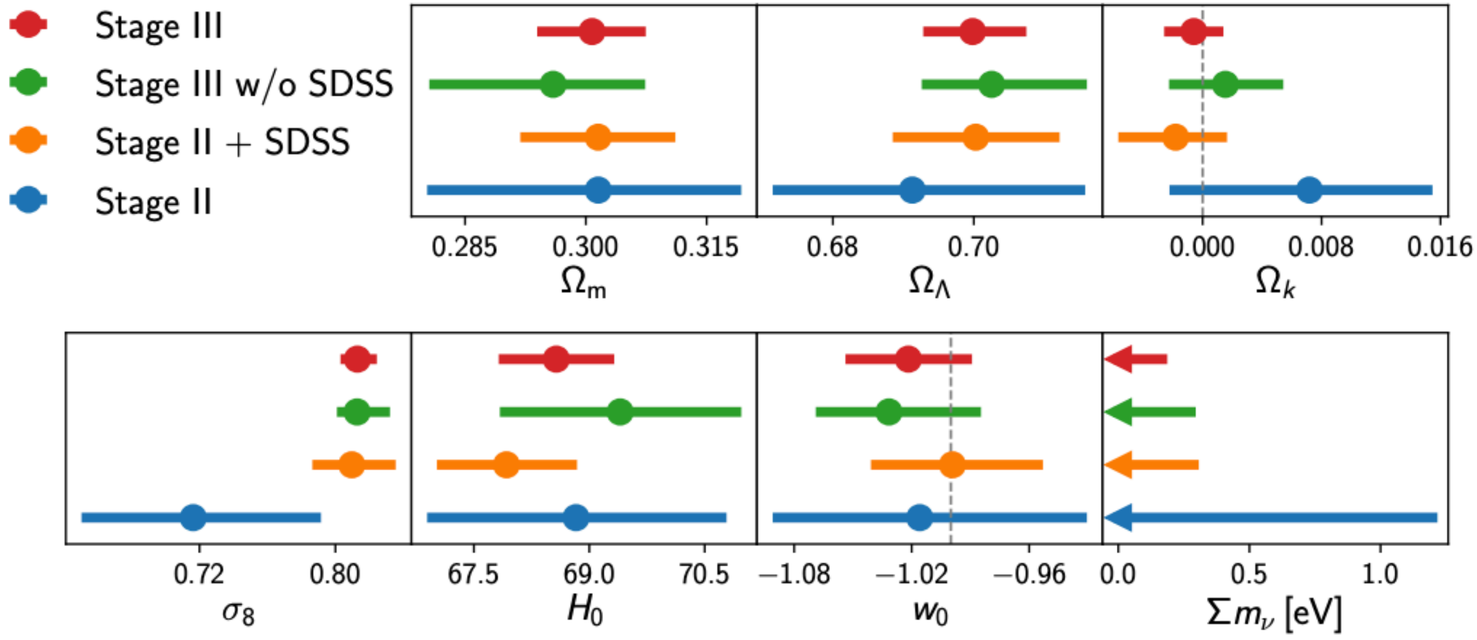


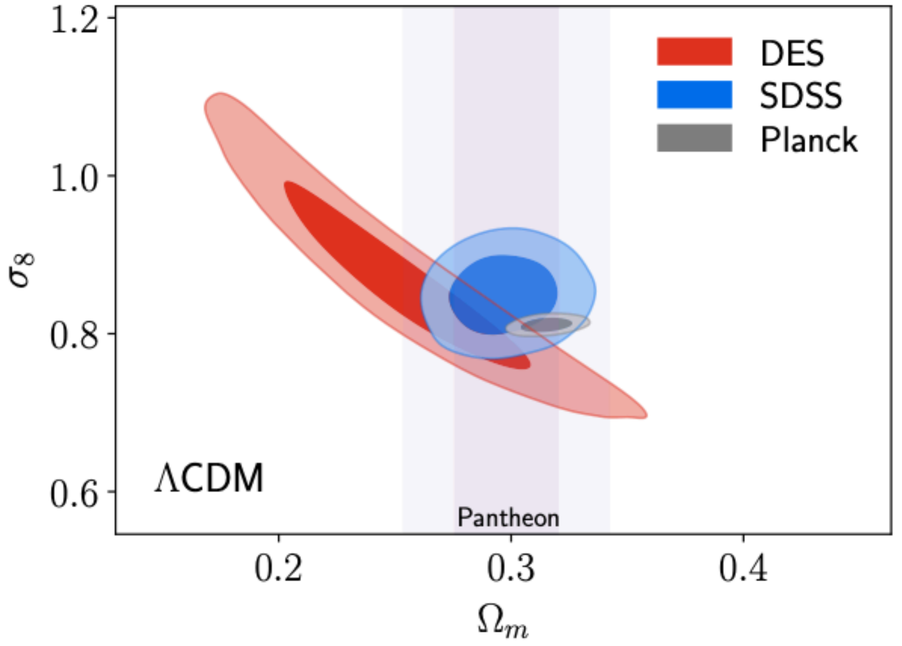


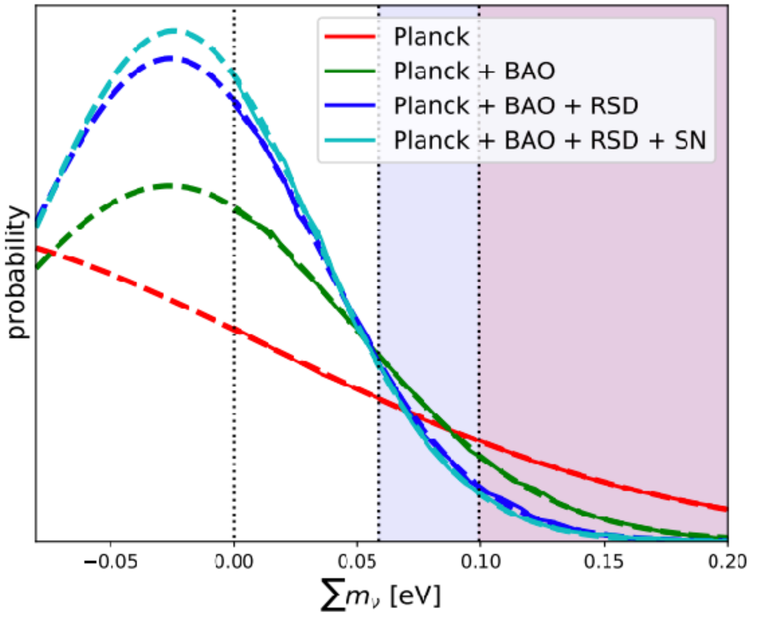

**Heymans et al. 2020: arXiv:2007.15632**