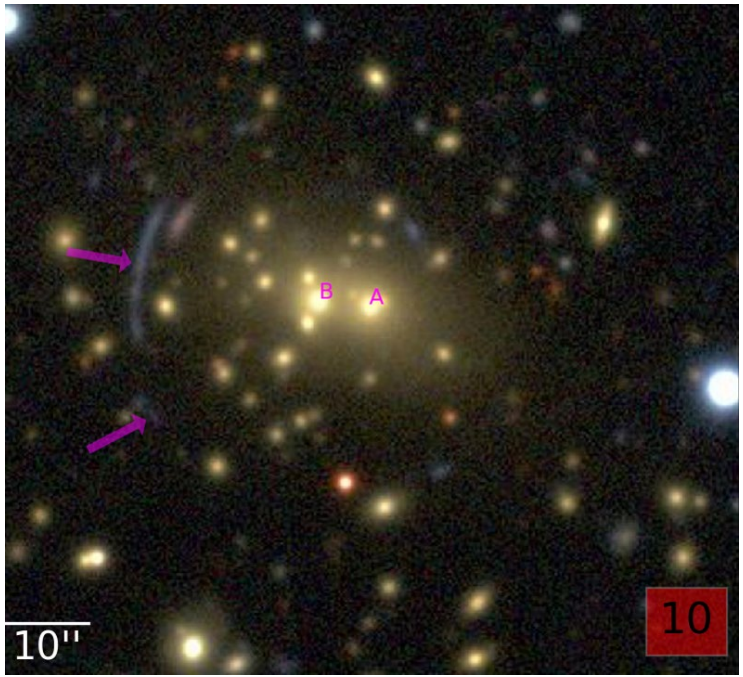
Dark Energy Experiments

Cosmic Surveys

- Dark Energy Survey: New analysis results
- Dark Energy Spectroscopic Instrument: Operations Update
- Legacy Survey of Space and Time (LSST): Construction

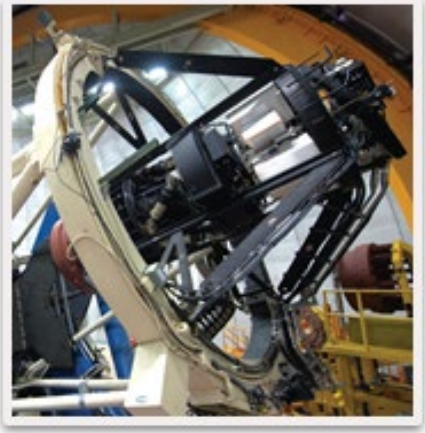


All these are collaborative efforts of Dept. of Energy, NSF, International funding agencies, and US & International University Partners.

Tom Diehl
Fermilab User's Meeting
August 3, 2021

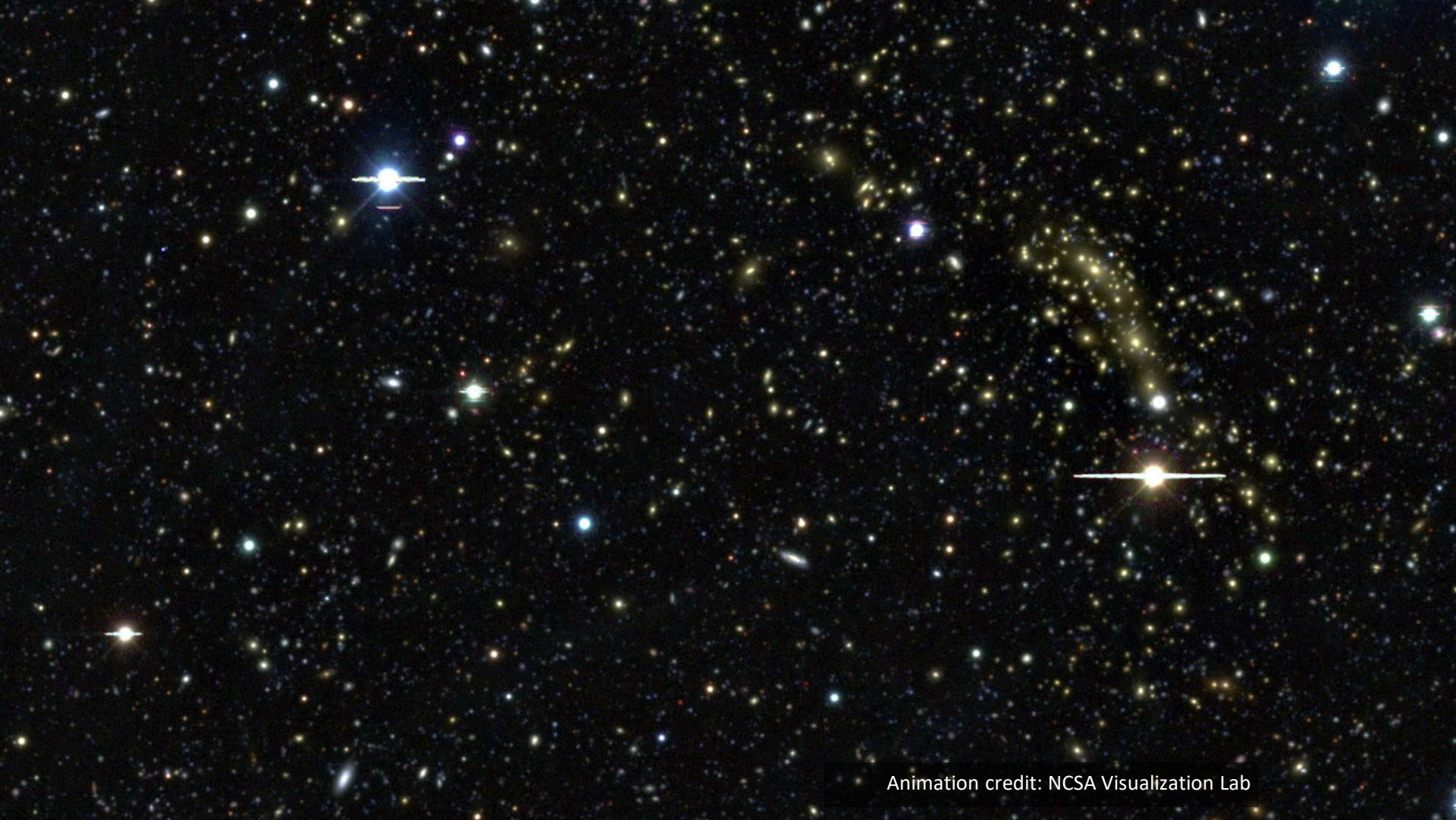
DARK ENERGY SURVEY

- **Led by Fermilab**
- **DECam**: The 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Survey Observations 2013-2019 ("Y3" means 2013-16).
- **Wide field:** 5000 sq. deg. in 5 bands. ~23 magnitude depth.
- 27 sq. deg. 5-yr SNIa survey



N. Jeffrey; Dark Energy Survey Collaboration

Dark Matter map from DES observations


Animation credit: NCSA Visualization Lab

DES Publications Topics

DARK ENERGY SURVEY

Through June 30, 2021, DES has 357 refereed science papers (not counting pre-data technical papers) with 15,700+ citations.

Some of the recent papers (up to May 25th):

Instrumental: "A Machine Learning Approach to the Detection of Ghosting and Scattered Light Artifacts in Dark Energy Survey Images", "Reducing ground-based astrometric errors with Gaia and Gaussian processes" will both be useful to LSST

Solar System: "Testing the isotropy of the Dark Energy Survey's extreme trans-Neptunian objects"

SN1ae: "OzDES multifibre spectroscopy for the Dark Energy Survey: Results and implications for future surveys", "The Effect of Environment on Type Ia Supernovae in the Dark Energy Survey Three-Year Cosmological Sample", "The Dark Energy Survey Supernova Program: Modelling selection efficiency and observed core collapse supernova contamination", "Rates and delay times of type Ia supernovae in the Dark Energy Survey"

Galaxy Clusters: "Is diffuse intracluster light a good tracer of the galaxy cluster matter distribution?", "μ^* Masses: Weak Lensing Calibration of the Dark Energy Survey Year 1 redMaPPer Clusters using Stellar Masses", "The WaZP galaxy cluster sample of the Dark Energy Survey Year 1"

Weak Lensing: "Galaxy Clustering in Harmonic Space from the Dark Energy Survey Year 1 Data: Compatibility with Real Space Results"

Galaxy Clusters + WL: "Combination of cluster number counts and two-point correlations: Validation on Mock Dark Energy Survey", "Dark Energy Survey Year 1 Results: Cosmological Constraints from Cluster Abundances, Weak Lensing, and Galaxy Correlations"

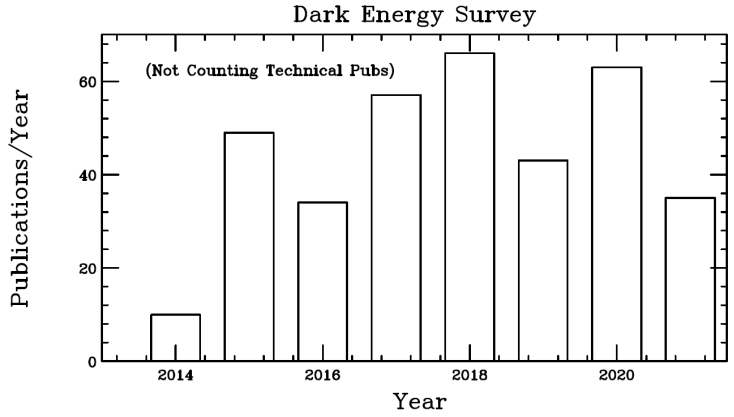
Galaxy Clusters + External Data: "Cosmological Constraints from DES Y1 Cluster Abundances and SPT Multi-wavelength data", "Probing galaxy evolution in massive clusters using ACT and DES: splashback as a cosmic clock", "The Atacama Cosmology Telescope: A Catalog of > 4000 Sunyaev-Zel'dovich Galaxy Clusters"

Modified Gravity: "Probing gravity with the DES-CMASS sample and BOSS spectroscopy", "Galaxy-galaxy lensing with the DES-CMASS catalogue: measurement and constraints on the galaxy-matter cross-correlation"

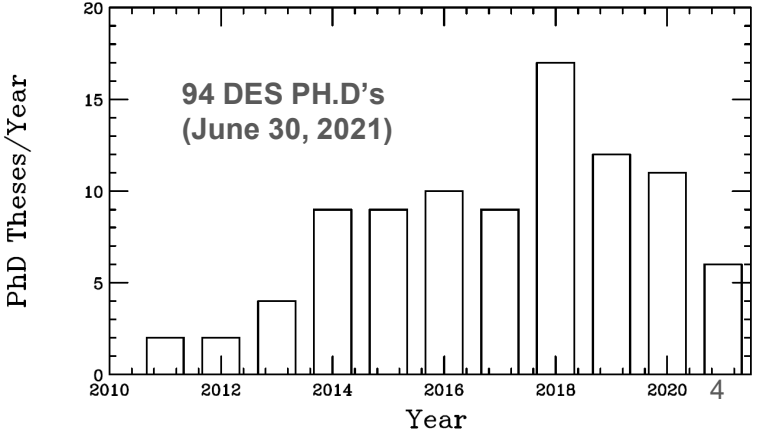
Optical + GW: "Constraints on the Physical Properties of S190814bv through Simulations based on DECam Follow-up Observations by DES"

Dark Matter: "Milky Way Satellite Census. III. Constraints on Dark Matter Properties from Observations of Milky Way Satellite Galaxies", "Constraints on Decaying Dark Matter with DES-Y1 and external data" .

Galaxy Evolution: "Galaxy Morphological Classification Catalogue of the Dark Energy Survey Year 3 data with Convolutional Neural Networks"



DES Publications
Span all optical astrophysics

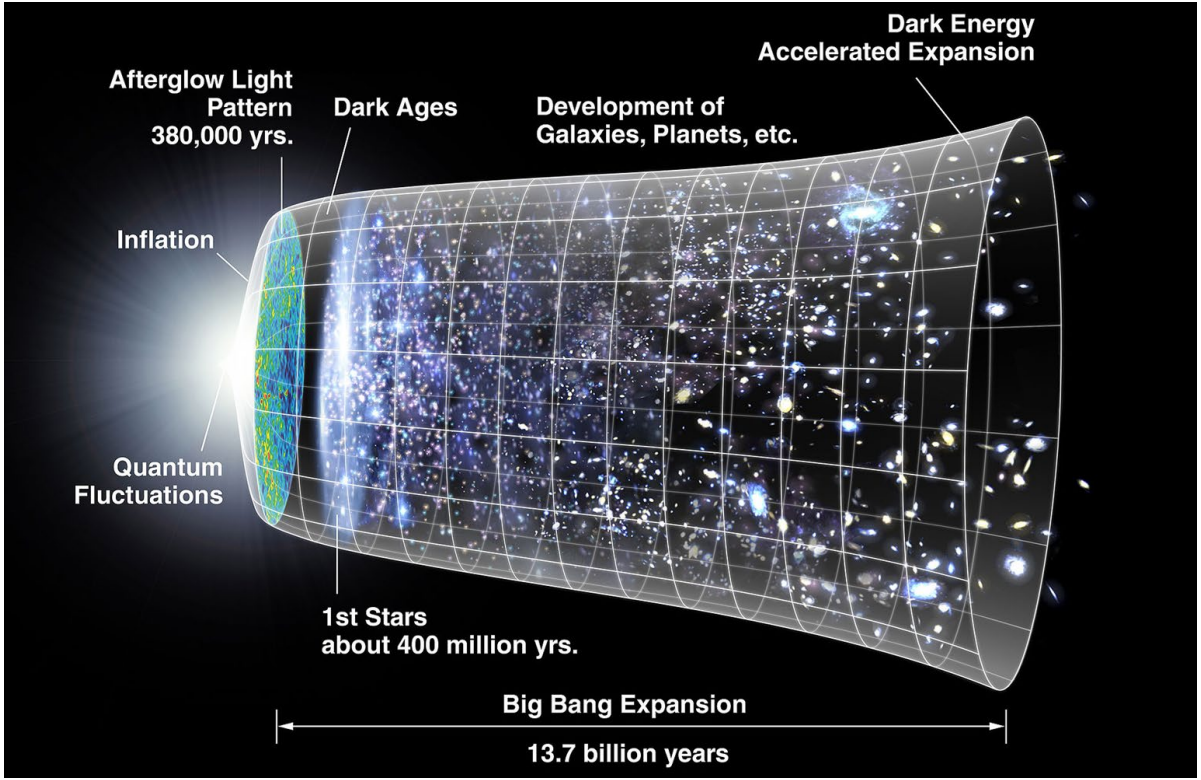


Current Standard Cosmological model: ΛCDM

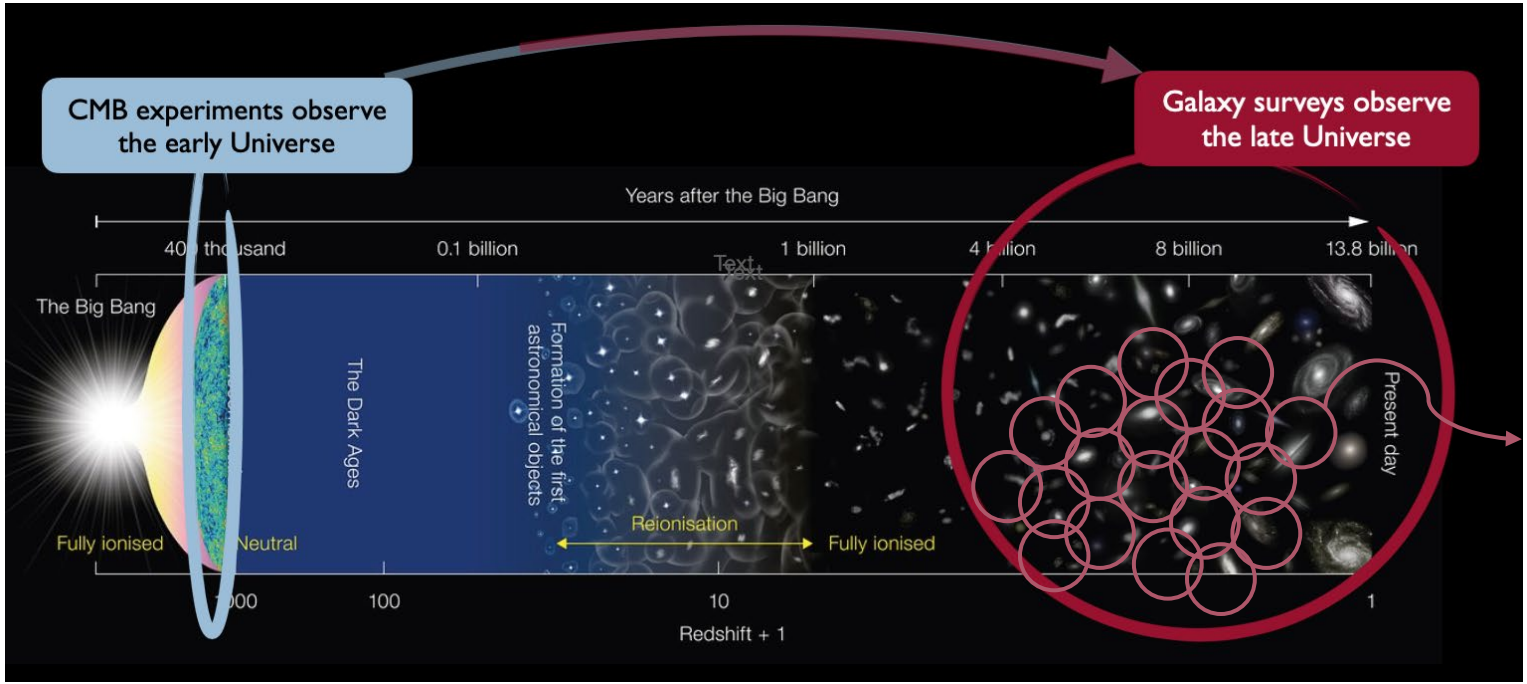
Flat Universe with Dark Energy in the form of a cosmological constant Λ + Cold Dark Matter.

It assumes General Relativity.

ΛCDM became the standard model following observations from Type Ia Supernovae and the Cosmic Microwave Background.



Testing ΛCDM: Is the late time clustering compatible with the ΛCDM prediction assuming initial conditions from the CMB?



Spheres with radius 8 Mpc/h

A_s: Amplitude of primordial scalar density fluctuations.

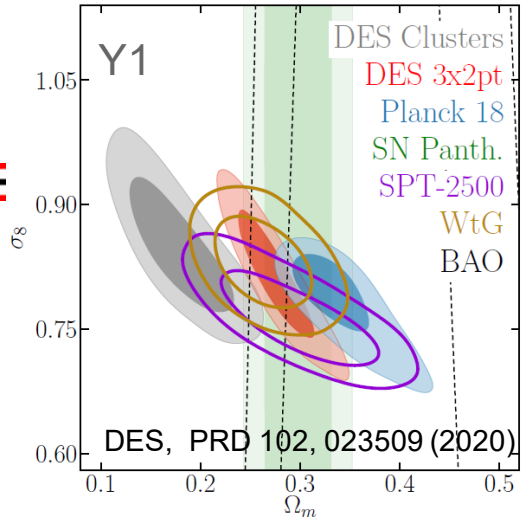
σ_8: Amplitude of mass fluctuations today, at distance 8 Mpc/h

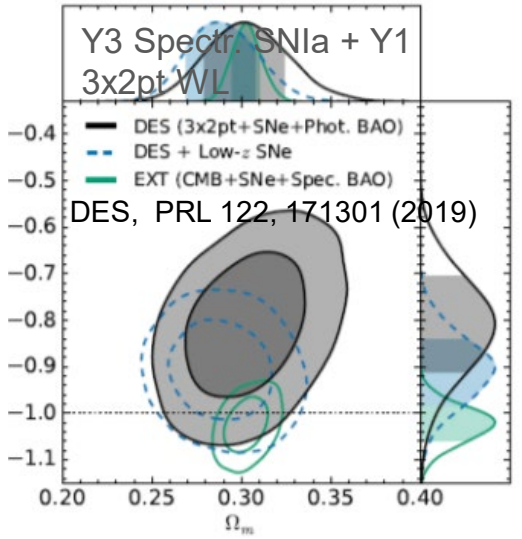
DES: Cosmology 7 Ways

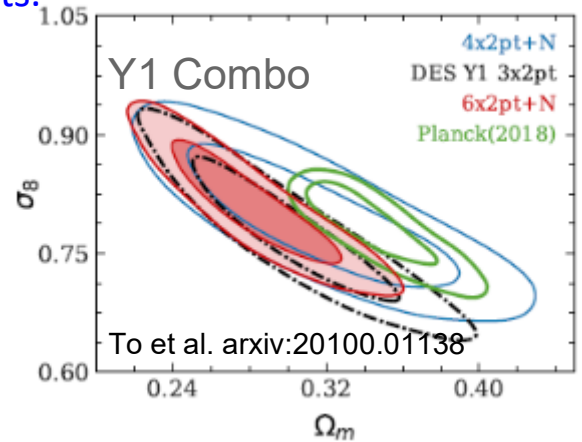
DARK ENERGY SURVEY

Growth rate of structure and Expansion History: Weak Gravitational Lensing, Galaxy Clustering, & Galaxy Cluster Abundance

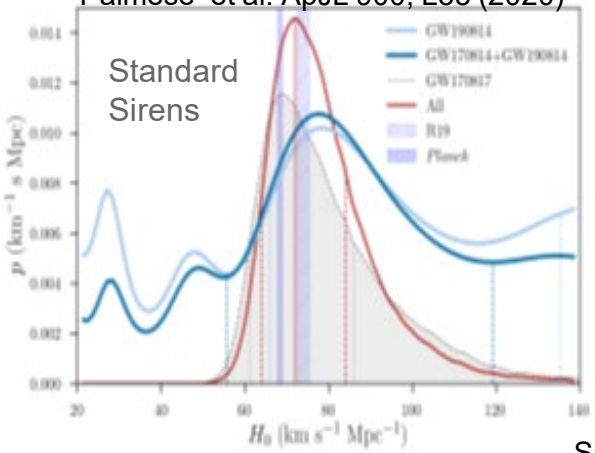
Expansion History: BAO (standard rulers), SNIa (standard candles), Gravitational Wave Follow up (standard sirens), Strongly-Lensed Transients.

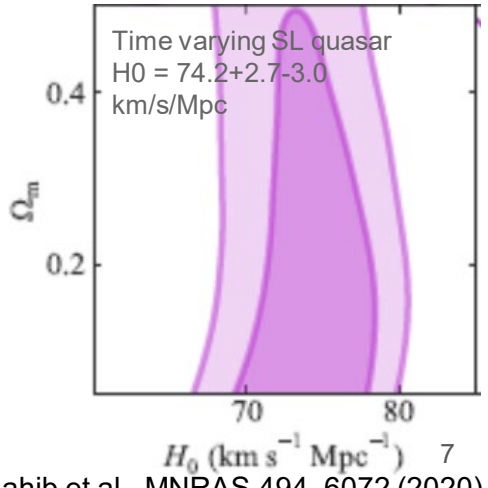






Palmese et al. ApJL 900, L33 (2020)





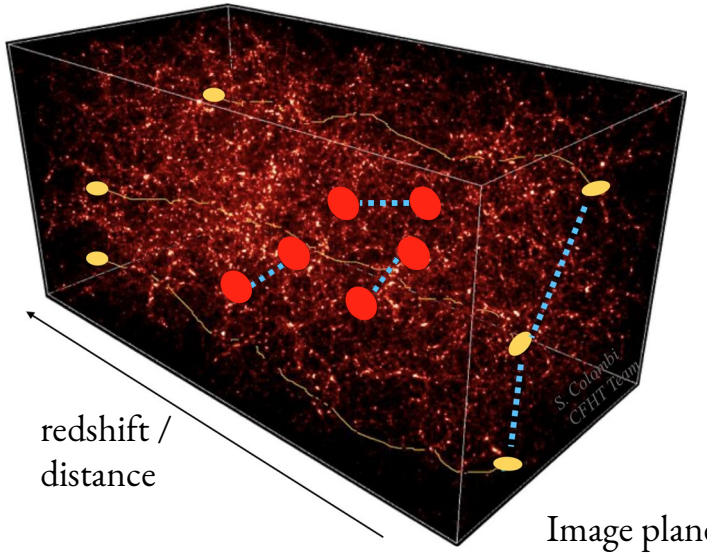
Shahib et al., MNRAS 494, 6072 (2020)

New Results from DES: “Y3 Weak Gravitational Lensing & Galaxy Clustering”: Sources and Lenses

Galaxies trace the underlying dark matter structure : they are observed to be spatially ***clustered***.

Light from distant galaxies passes the foreground structures and acquires coherent distortions : they are observe to be ***lensed (sheared).***

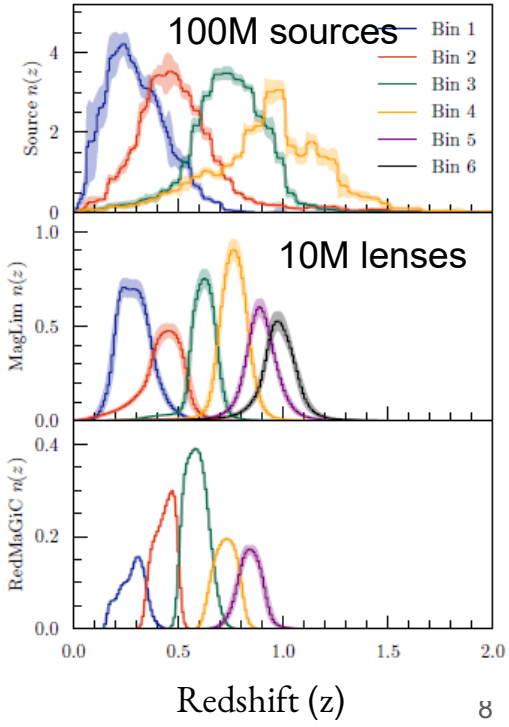
We also measure the correlation of the shapes of source galaxy pairs as a function of angular radius and redshift ***(shear-shear)***.



Summary:

2x2pt
- Galaxy Clustering : position-position
- Galaxy-Galaxy Lensing : position-shear
- Cosmic Shear : shape-shape (shear-shear)

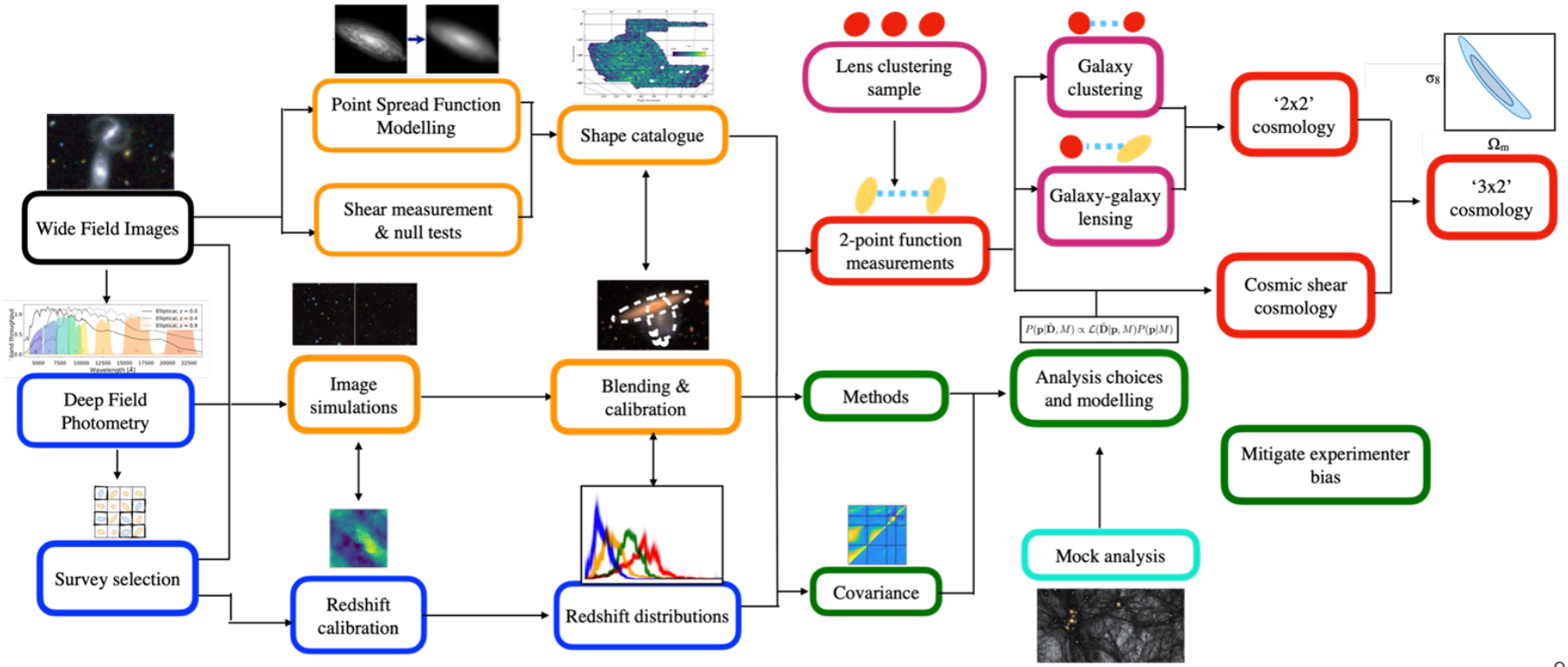
3x2pt



Y3 "3x2pt" Methodology: Pixels to Cosmology

Webinar from May 27, 2021 https://www.youtube.com/watch?v=8aHbLMUOwLc

30 Paper Compilation @ https://www.darkenergysurvey.org/des-year-3-cosmology-results-papers/



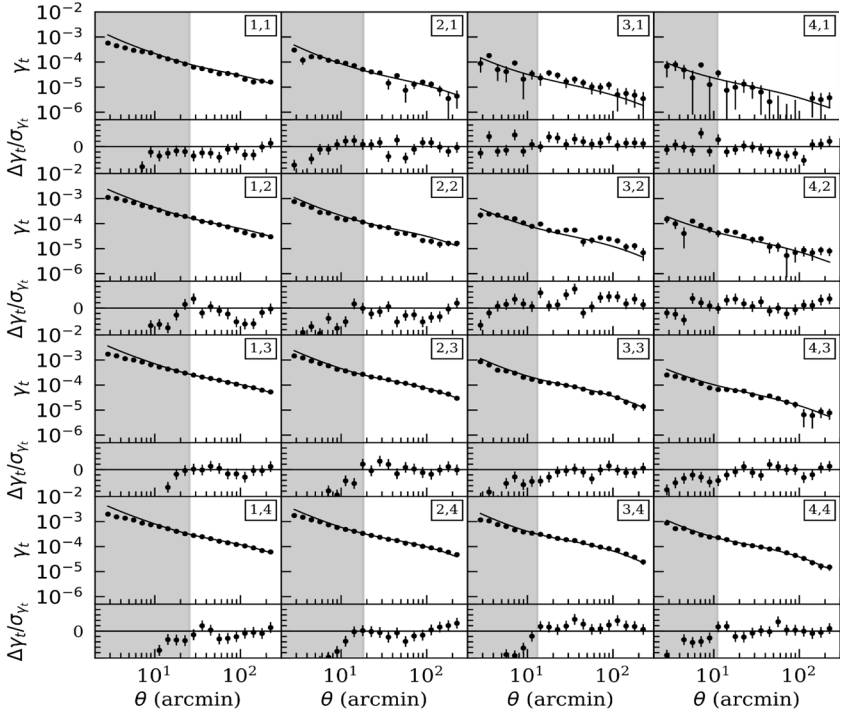
LCDM —— WL+LSS —— Redshifts —— Shapes —— Clustering — Simulations —— Theory —— Results

Y3 3x2pt Data + Model Fit

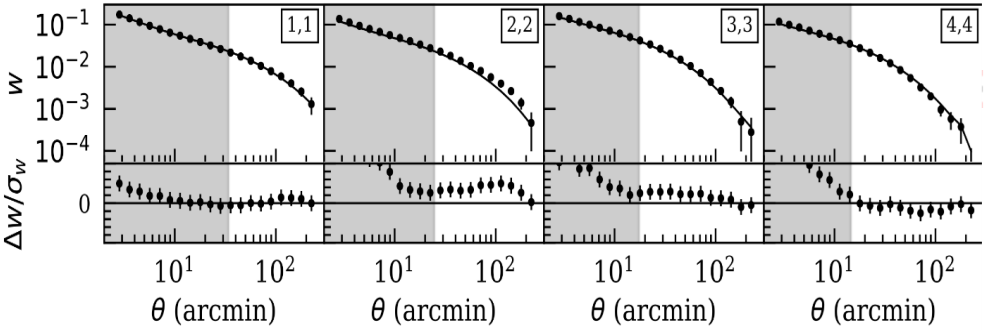
Largest area and Biggest samples so far for any WL analysis

DARK ENERGY SURVEY

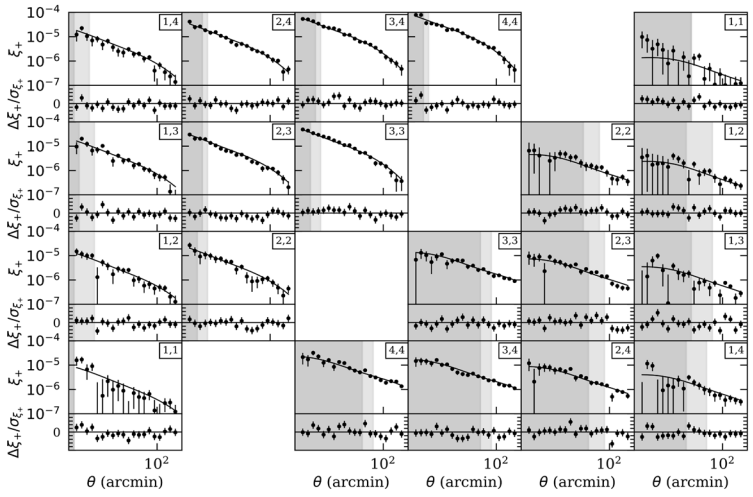
galaxy-galaxy lensing Prat+



Lens galaxy clustering Rodriguez-Monroy+



cosmic shear Amon+, Secco, Samuroff+



DES Y3 Weak Lensing Cosmology Results

DARK ENERGY SURVEY

ΛCDM

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

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

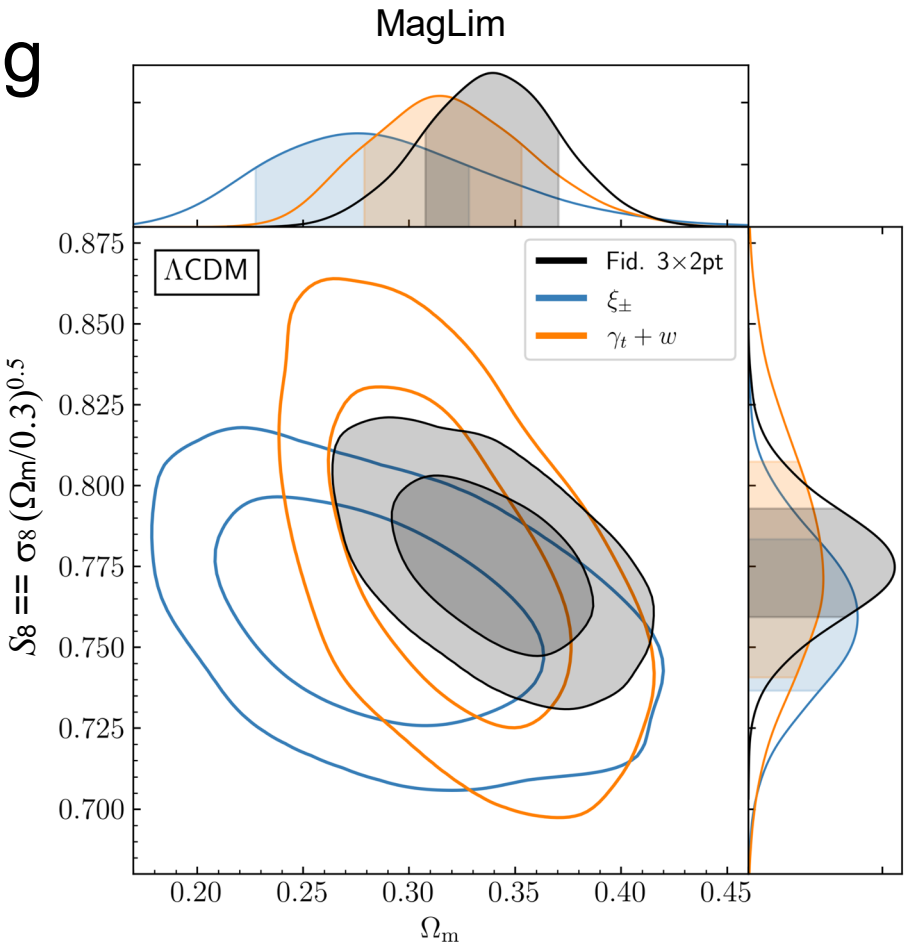
$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)$$

***w*CDM**

$$\Omega_{\rm m} = 0.352^{+0.035}_{-0.041} \quad (0.339)$$

$$w = -0.98^{+0.32}_{-0.20} \quad (-1.03)$$

- Lens samples MagLim and redMaGiC 3x2 in perfect agreement
- Evidence for potential systematics in the redMaGiC clustering data vector at all redshifts and above the fiducial lens redshift range for MagLim. arXiv:2105.13549 DES Collaboration (2021)



Press Release: https://news.fnal.gov/2021/05/dark-energy-survey-releases-most-precise-look-at-the-universes-evolution/

Combinations

We find **no significant evidence for inconsistency in ΛCDM** between DES 3x2pt and *Planck*, and good agreement between DES + other complementary low-redshift probes and *Planck*.

DARK ENERGY SURVEY

arXiv:2105.13549 DES Collaboration (2021)

ΛCDM

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

$$\Omega_m = 0.306^{+0.004}_{-0.005} \quad (0.306)$$

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

$$h = 0.680^{+0.004}_{-0.003} \quad (0.681)$$

$$\sum m_\nu < 0.13 \text{ eV} \ (95\% \text{ CL})$$

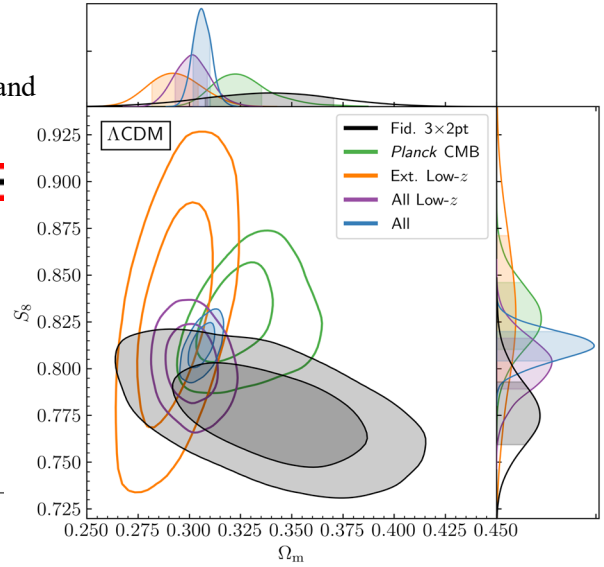
wCDM

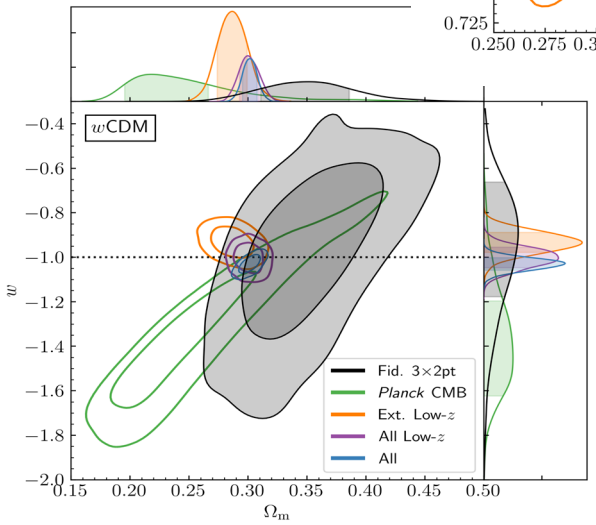
$$\sigma_8 = 0.810^{+0.010}_{-0.009} \quad (0.804)$$

$$\Omega_m = 0.302^{+0.006}_{-0.006} \quad (0.298)$$

$$w = -1.03^{+0.03}_{-0.03} \quad (-1.00)$$

"Low-redshift non-lensing data" is SNe Ia (but not DES), BAO, RSD



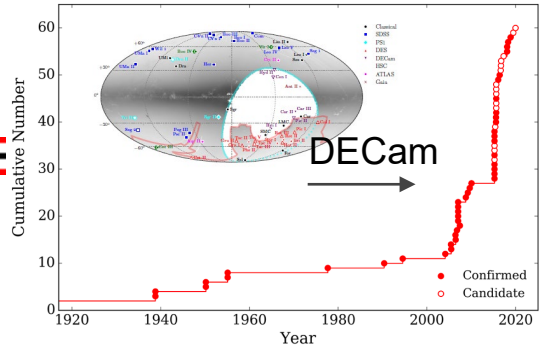


Fid. 3×2pt
Planck CMB
Ext. Low-z
All Low-z + DES
All

Missing Satellites Problem & Dark Matter Physics

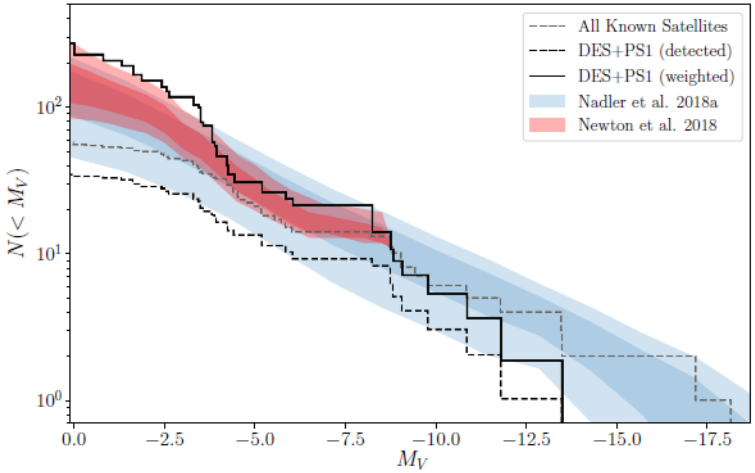
DARK ENERGY SURVEY

Known MW satellites vs year



A long-time controversy: DM halo models predict hundreds of captured “satellite” galaxies for the Milky Way. DES data and selection function vs. magnitude (mass proxy) shows that there are!

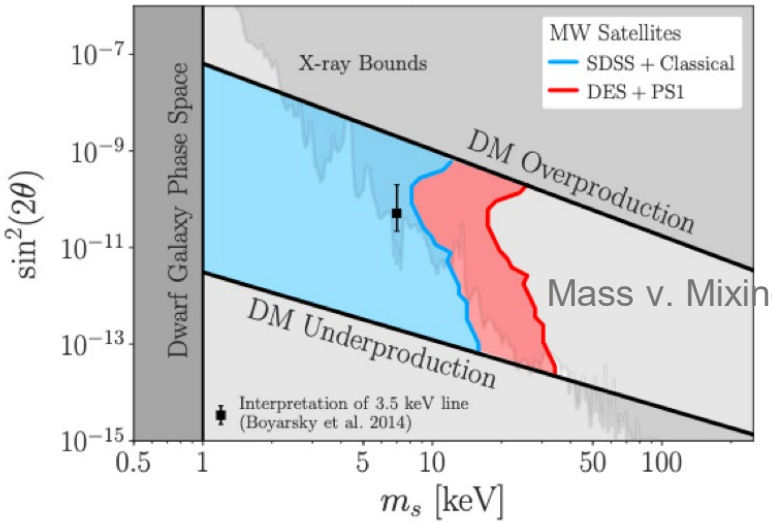
Distribution of MW satellite masses enables model-dependent constraints on Dark Matter properties. i.e. DM must be massive.



Absolute Magnitude

Drlica-Wagner et al. ApJ 893, 1 (2020)

Sterile Neutrino WDM

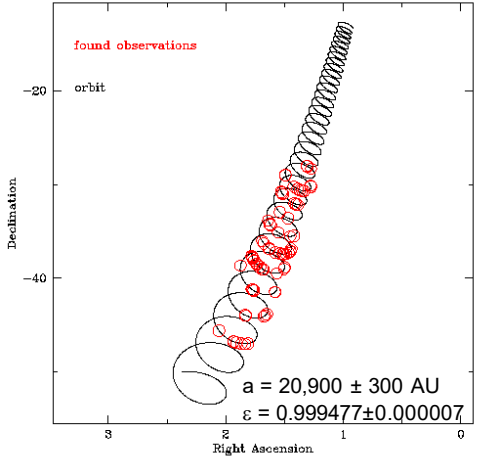


Mass v. Mixing angle

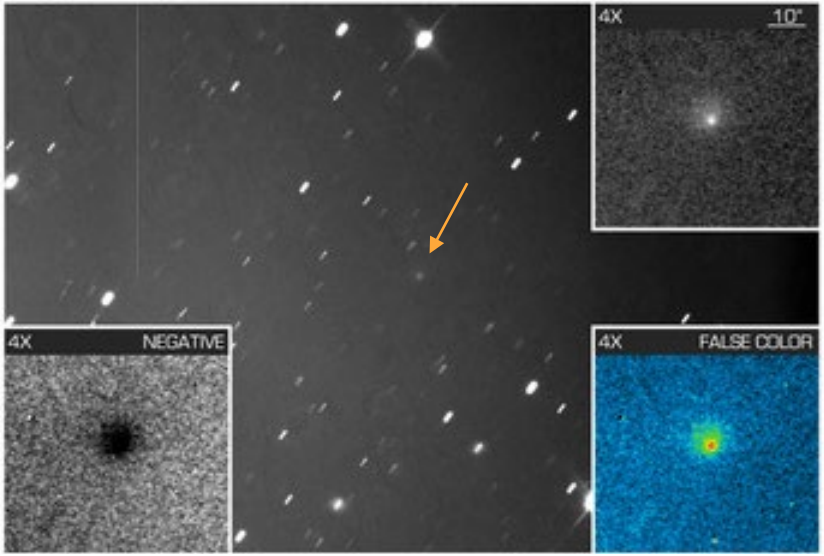
Nadler et al. PRL 126, 091101 (2021)

Most Massive & Most Distant Comet C/2014 UN271 “Bernardinelli-Bernstein”

DARK ENERGY SURVEY



- DES data is great for finding “Transient and Moving Objects”
- 245+ New Trans-Neptunian Objects @ 30 to 100 AU



- C/2014 UN271 was detected as it came in from the Oort cloud at 29 to 23 AU
- Massive (~200 km wide) comet discovered.
- Early studies of the coma show sub-mm sized grains at 7 m/s as well as sublimation of CO
- Perihelion at 11 AU in 2031, so we’ll watch this one “turn on” for a long time

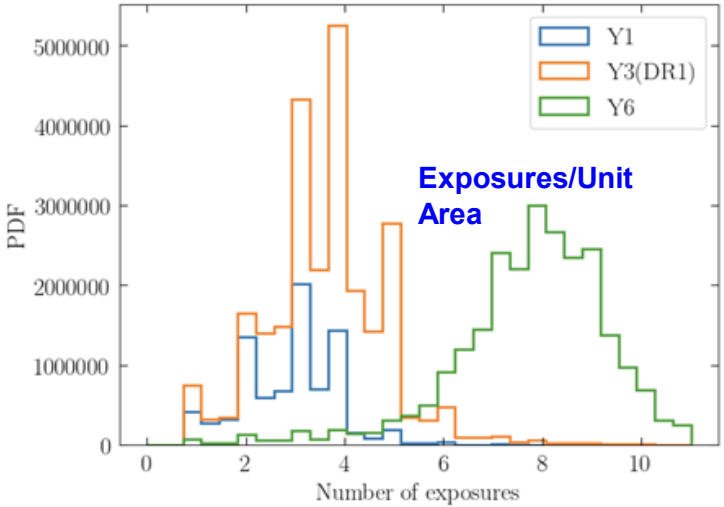
https://www.syfy.com/syfywire/gigantic-comet-is-currently-inbound-toward-the-sun

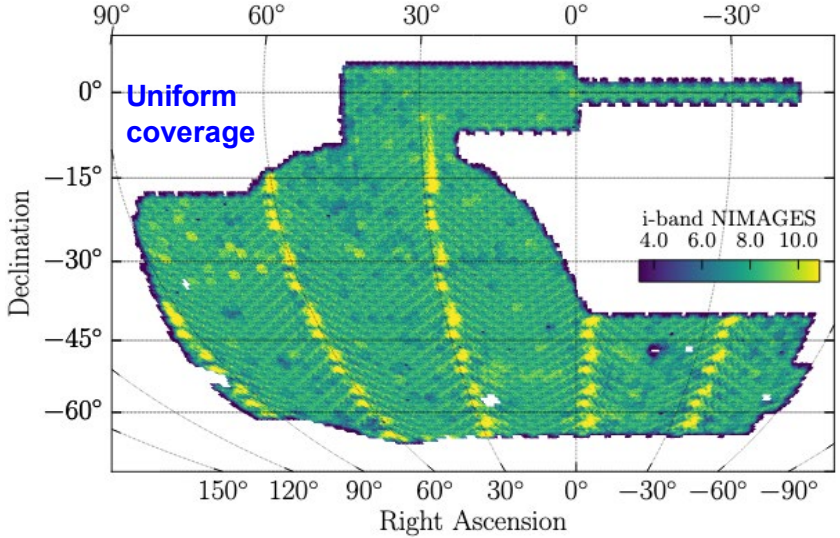
DES Y6 Data is Amazing!

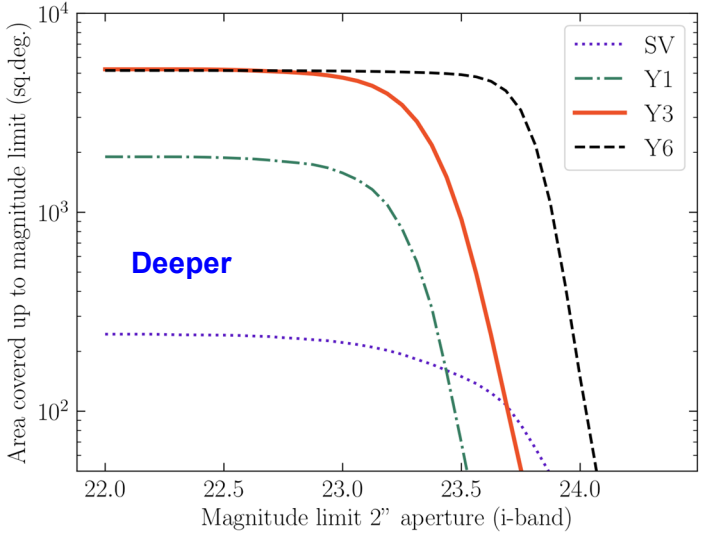
https://des.ncsa.illinois.edu/releases/dr2

DARK ENERGY SURVEY

- Y6 more homogenous than Y3 (typically 8 vs. 4)
- Y3 -> Y6 depth increase by completeness ~ 0.7 mag (partly attributed to detection threshold adjustments)
- 400M objects -> 700M objects

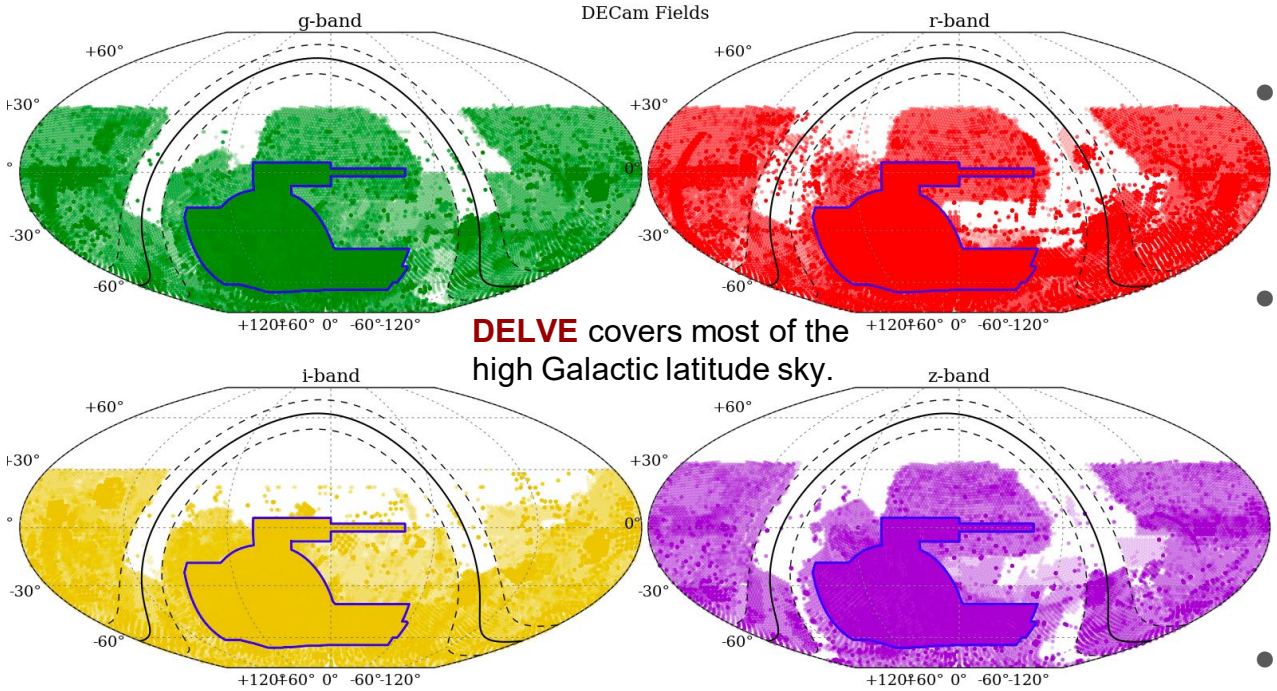






DECam Local Volume Exploration Survey

DES area outlined in blue



DELVE covers most of the high Galactic latitude sky.

- DES covers only 1/6th of the sky accessible to DECam.
- DELVE leverages Fermilab infrastructure and expertise to cover 5x the sky area of DES.
- DELVE studies the nature of dark matter and dark energy through a combination of near-field cosmology, strong lensing, and weak lensing.
- First DELVE data release in January 2021

Dark Energy Spectroscopic Instrument

DESI is a spectroscopic survey

- Led by LBNL
- Goal: Measure precise redshifts of targets that come from Imaging Surveys
- Survey from 2021 - 2025: ~30M galaxies and Quasars to measure Baryon Acoustic Oscillations and Redshift Space Distortions to redshift ~ 3.5.

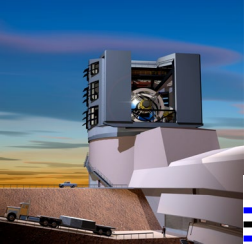
Large instrument mounted at Prime Focus of the Mayall 4m telescope at Kitt Peak in Arizona

- 5,000 independently controllable optical fiber positioners

DESI focal plane, July 2019
R. Besuner, LBNL

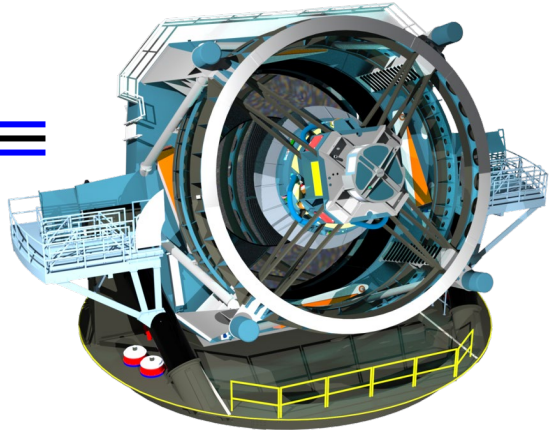
Dark Energy Spectroscopic Instrument

- Kitt Peak reopened for work in mid-Sept 2020 after a 6-month shutdown because of COVID
- Recommissioning was completed in December 2020
  - Many improvements/fixes to all systems (e.g., Instrument Control System, focal plane, spectrographs, fiber view camera)
  - The goal was to improve reliability and efficiency, reduce need for “experts”.
  - There was also work on the telescope and facilities
- Survey Validation (SV) December 2020 - March 2021
- 1% survey April-May 2021
  - Conduct 1 month of observations in survey mode
- **5-year survey started in mid-May 2021**
- Currently in summer shutdown: mid-July to mid-September
  - Remove all **10** petals and install new versions of some electronics boards then reinstall those petals
  - Remove two dozen of the failed positioners for in-lab forensics



Legacy Survey of Space and Time

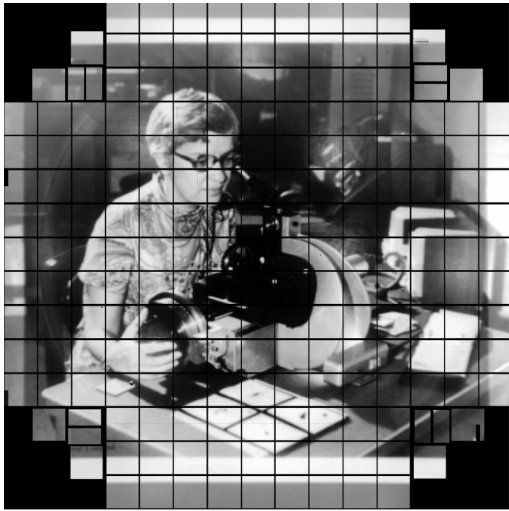
Vera C. Rubin Observatory on Cerro Pachon in Chile

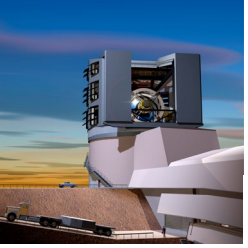


- Novel 3-mirror optical design @ F/1.2
- 8.4 m primary mirror (6.67 m “filled aperture”) and
- A 3.2B pixel Imaging Camera mounted at the top of the telescope will be the world’s largest digital camera
- 9.5 sq.deg. FOV will allow fast mapping of ½ the sky
- Science Stage IV DE

Led By SLAC

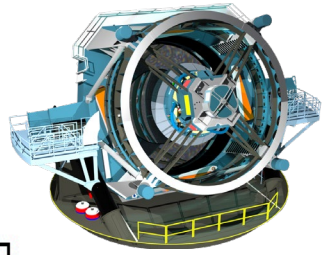
LSST DESC
Dark Energy Science Collaboration



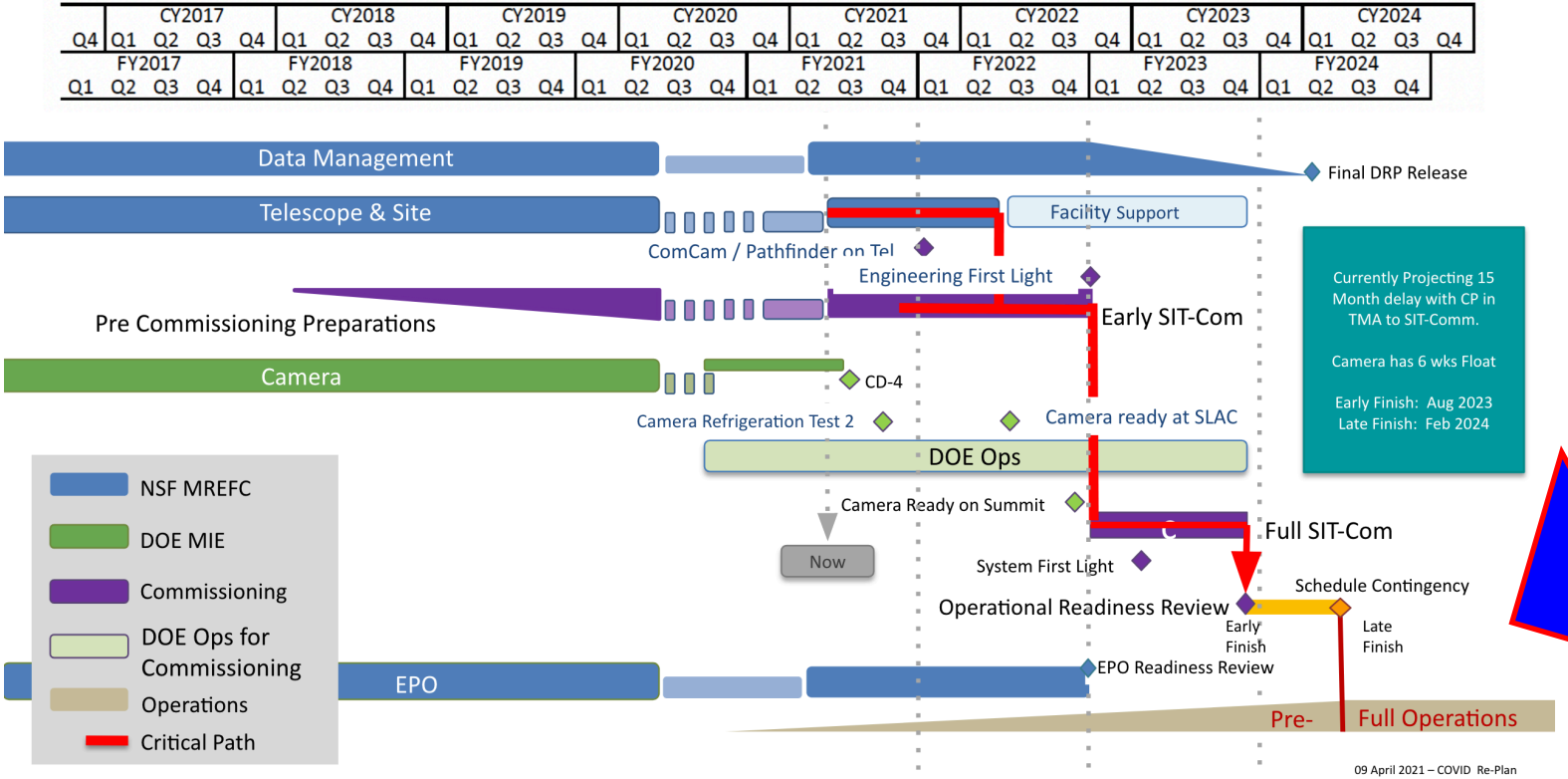


Legacy Survey of Space and Time

Vera C. Rubin Observatory



Schedule as of April 2021



Summary: Dark Energy Experiments
Cosmic Surveys

The Dark Energy Survey finished observations in 2019. It produced images and catalogs that is a gold mine for astrophysics and cosmology.

- For Weak Lensing & Galaxy Clustering "3x2pt" analysis, the unprecedented Y3 data sample required the development of novel methods at every stage
- We find **no significant evidence for inconsistency in ΛCDM** between DES 3x2pt and *Planck*, and good agreement between DES + other complementary low-redshift probes and *Planck*. There are hints of a previously unknown systematic that doesn't impact the Y3 results.
- DES Y6 data is fantastic, and we are initiating the Y6 cosmology analyses

The Dark Energy Spectroscopic Instrument

- Start of observations was impacted by COVID
- Now in summer maintenance shutdown. Will continue 5-year observation program next month.

LSST

- System 1st light in Oct. 2023, start of regular observations about a year later.

After that? See Snowmass Process

Credits

DARK ENERGY SURVEY

DES Y3 3x2pt analysis

List of participants

(Early Career Scientists in bold)

Beatrice Moser
Dan Scolnic
Robert Morgan
Nacho Sevilla
Paul Rogozenski
Elisabeth Krause
Joe DeRose
Richard Kron
H. Thomas Diehl
Ofer Lahav
Reese Wilkinson
Peter Melchior
David Weinberg
Anqi Chen
Dominik Zuercher
Niall Jeffrey
Mitch McNanna
Alexandre Refregier
Dylan Britt
Pablo Lemos
Alexandra Amon
Shantanu Desai

Adam Amara
Santiago Avila
Sunayana Bhargava
Antonella Palmese
Zhiyuan Zhou
Aaron Roodman
Matthew Becker
Risa Wechsler
Andrés Plazas
Rafael Gomes
Ian Harrison
Romain Buchs
Ami Choi
Maria Pereira
Alex Alarcon
Bhuvnesh Jain
Raphael Sgier
Albert Stebbins
Dragan Huterer
Justin Myles
Youngsoo Park
Marco Raveri

Ramon Miquel
Jenna Freudenberg
David Bacon
Tomasz Kacprzak
Giulia Giannini
Chihway Chang
Anderson Souza
Jacobo Asorey
David Burke
Isaac Tutusaus
Jamie McCullough
Paul Ricker
Eduardo Rozo
Noah Weaverdyck
Pauline Vielzeuf
Eusebio Sanchez
Boyan Yin
Robert Gruendl
Vivian Miranda
Xiao Fang
Marco Gatti
Heidi Wu

Alyssa Garcia
Dhayaa Anbajagane
Andresa Campos
Cyrille Doux
Jessie Muir
Georgios Zacharegkas
William Hartley
Nick Kokron
Michael Troxel
Judit Prat
Pablo Fosalba
Douglas Tucker
Eli Rykoff
Michael Johnson
Masaya Yamamoto
Dillon Brout
Matias Carrasco
Daniel Gomes
Nico Hamaus
Ismael Ferrero
Mike Wang
Andrew Liddle
Daniel Gruen
Keith Bechtol
Juan De Vicente
Anna Porredon

Felipe Andrade-Oliveira
Jack Elvin-Poole
Juan P. Cordero
Mike Jarvis
Eric Huff
Chris Conselice
Eric Neilsen
Javier Sanchez
Andres Navarro
Tae-hyeon Shin
Chun-Hao To
Tesla Jeltema
Kevin Wang
Niall MacCrann
Erin Sheldon
Agnes Ferte
Ross Cawthon
Manda Banerji
Yuuki Omori
Brenna Flaugher
Alfredo Zenteno
Mathew Smith
Otavio Alves
Eve Kovacs
Martin Rodriguez Monroy
Megan Tabbutt

Ken Herner
Danielle Leonard
Gaston Gutierrez
Federica Tarsitano
Juan Mena Fernández
David Sánchez Cid
Seshadri Nadathur
Gary Bernstein
Sujeong Lee
Prudhvi Varma
Oliver Friedrich
Simon Samuroff
Richard Kessler
Huan Lin
Rutuparna Das
Lorne Whiteway
Anushka Shrivastava
Tamara Davis
Jimena Gonzalez
Tim Eifler
Giorgia Pollina
Ashley Ross
Eleonora di Valentino
Lucas Secco
Ji Won Park
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Alex Drlica-Wagner
Simon Birrer
Brian Yanny
Sahar Allam
Scott Dodelson
Jim Annis
Andras Kovacs
Hugo Camacho
Kai Hoffmann
Mandeep Gill
Jonathan Blazek
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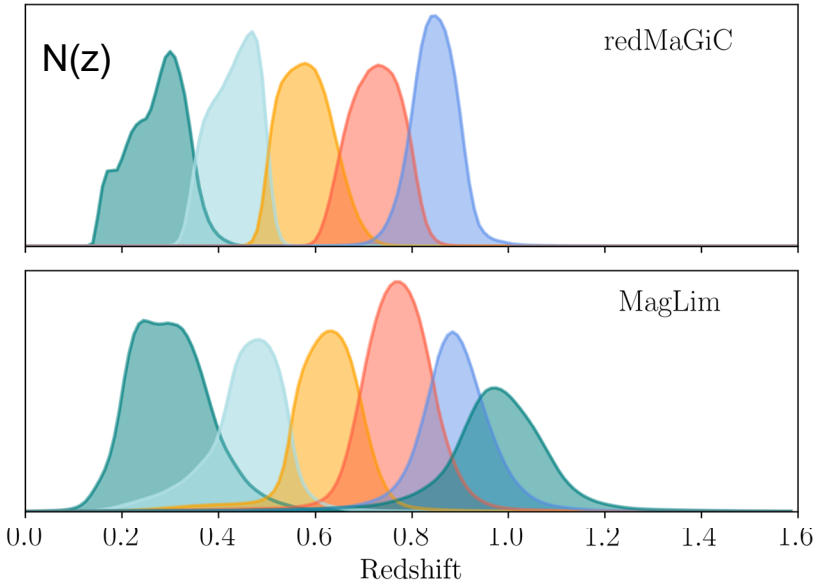
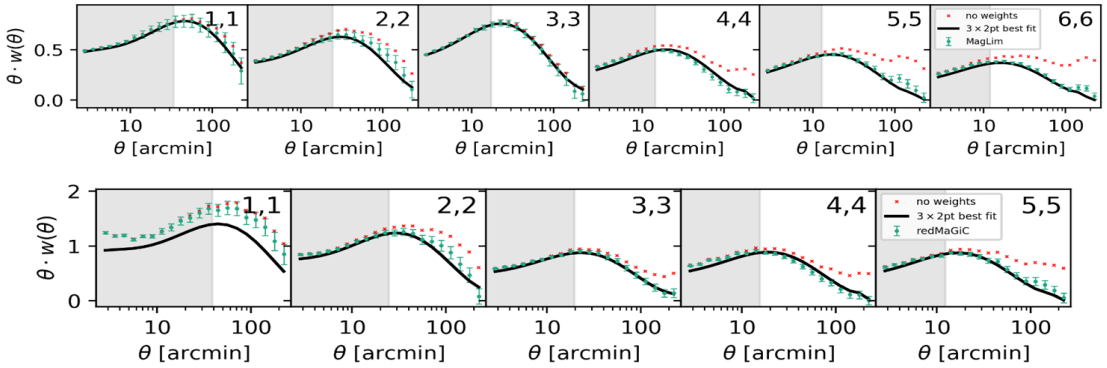
Joe Zuntz
Steve Kent
Martin Crocce
Spencer Everett
Juan Estrada
Donald Petravick
Hung-Jin Huang
Yuanyuan Zhang
Georgios Zacharegkas
Shivam Pandey
Helen Qu
Eric Baxter
Jack Odonnell
Sebastian Bocquet

Plus Slides from:
Elizabeth Buckley-Geer
Alex Drlica-Wagner
James Tiberius Annis
Pedro Bernardinelli
Gary Bernstein
Kevin Reil & the
Rubin Observatory Webpages

Two Lens Samples

- redMagic: LRG selection 2.9M galaxies in 5 redshift bins
- MagLim: Brightness selection 10.1M in 6 redshift bins
- Below: galaxy clustering (position-position)



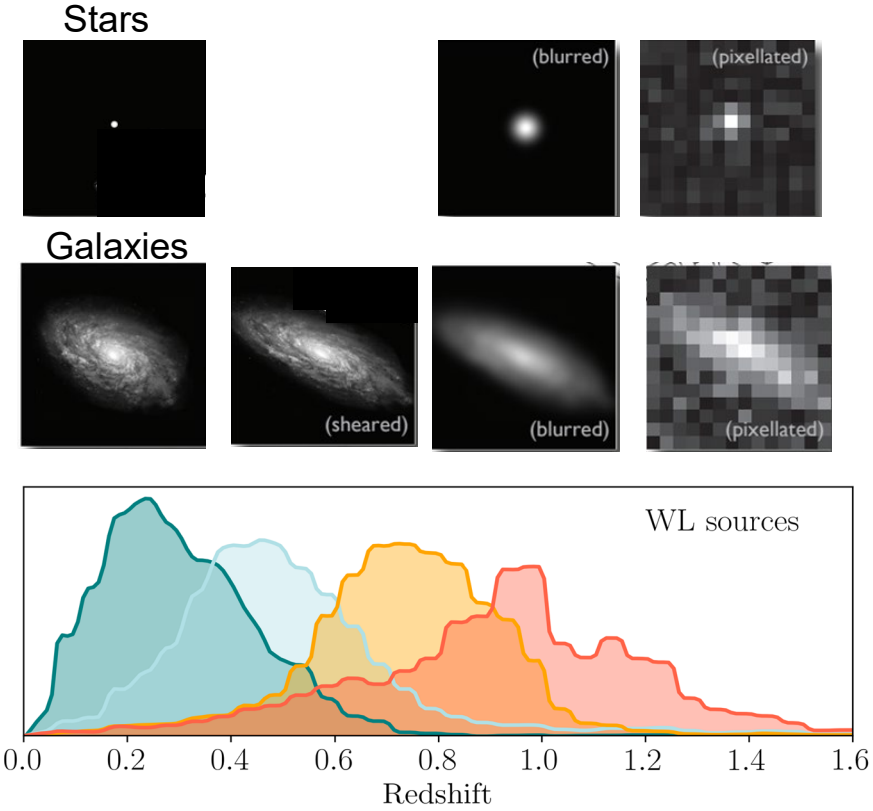


Weights correct for effects of airmass, seeing, exposure time, depth, stellar density, dust, sky brightness, calibration residuals

Myles, Alarcon et al. (2021),
Porredon et al. (2021),
Gatti, Giannini et al. (2021),
Sanchez, Prat et al. (2021),
Cordero, Harrision et al. (2021),
Cawthon et al. (2021),
de Vicente et al (2015)
Rodriguez-Monroy et al. (2021)
Everett et al. (2020), ++

100.2 M source galaxy shapes for DES Y3

DES Science Verification: 2-3 million shapes, DES Y1: 34.8 million



Many more source galaxy shapes than any previous analysis

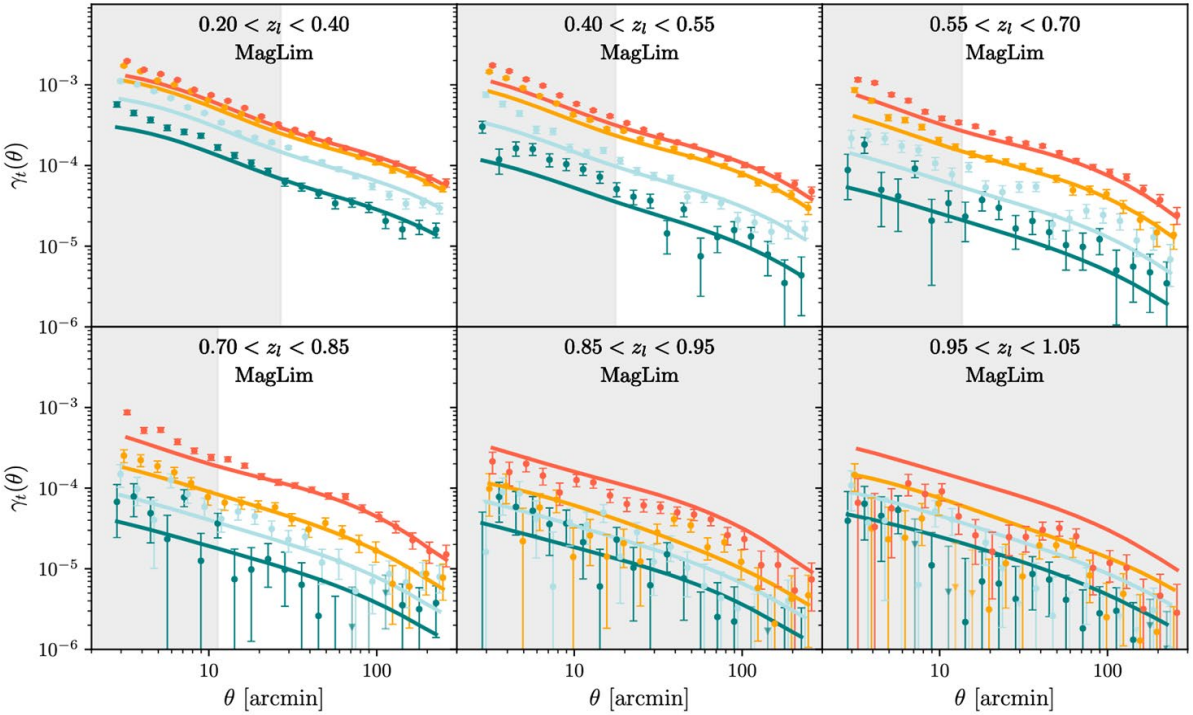
Key improvements over DES Y1:

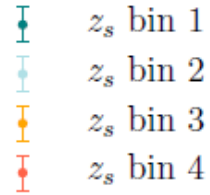
- More sky
- More accurate PSF models (Piff, Jarvis+2020) => better shear measurements
- Improved astrometry
- Expanded suite of null tests (**Gatti**, Sheldon+2021)
- Effects of deblending systematic (**MacCrann**+ 2021)

Position-Shear Measurements

Galaxy-Galaxy lensing around foreground galaxies

The two-point function between lens galaxy positions and source galaxy tangential shear.





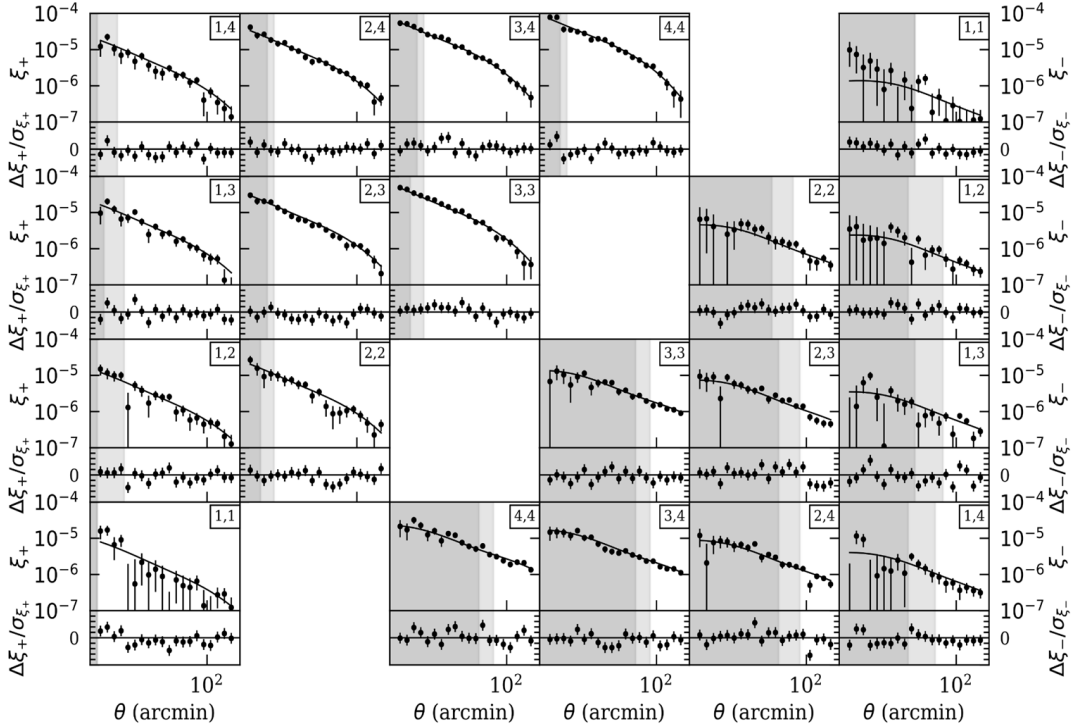
Shown for MagLim

Prat et al. (2021)

The Correlation of Pairs of Galaxy Shapes

DARK ENERGY SURVEY

ξ_+ estimator of cosmic shear



ξ_- estimator of cosmic shear

Amon et al. 2021
Secco, Samuroff et al. 2021

$\xi_\pm$: EE ± BB

Detection significance ~27 (Y1) → 40 (Y3)

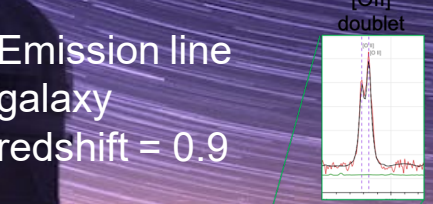
Final results from a Blinded Fit:
Cosmology (7 params)
Astrophysical Model (9 params)
Calibration (16 params)

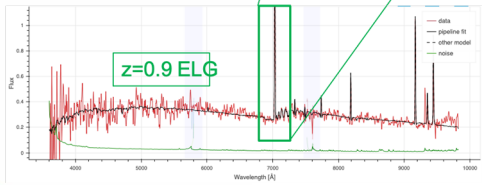
Equity, Diversity, and Inclusion Initiatives

- Currently engaged with the NOVA Collective (HOME - The Nova Collective),
  - We recently completed a climate survey. We'll get the results soon.
- Mentorship Program
  - Volunteer Mentors. 25 Mentor/Mentee pairs. A dedicated Mentorship Coordinator.
- Adjustments to DES Collaboration written policies so that engagement with underrepresented people in STEM is encouraged
- Focus at recent Collaboration Meeting
  - Plenary Speaker from outside DES
  - EDI Parallel Sessions: Connecting with minority-serving institutions, Focusing EPO efforts on inclusion, Giving Credit in DES
  - EDI One-slides at the beginning of every Plenary session

Dark Energy Spectroscopic Instrument

Emission line galaxy redshift = 0.9





0.7M Ly-α QSOs
1.7M QSOs
1.0 < *z* < 3.5

z = 4
z = 3
z = 2
z = 1.5
z = 1
z = 0.7
z = 0.5
z = 0.2

r = 5.0 Gpc/*h*
r = 4.0 Gpc/*h*
r = 3.0 Gpc/*h*
r = 2.0 Gpc/*h*
r = 1.0 Gpc/*h*
r = 0.5 Gpc/*h*

18M Emission Line Galaxies (ELGs)
0.6 < *z* < 1.6

4M Luminous Red Galaxies (LRGs)
0.4 < *z* < 1.0

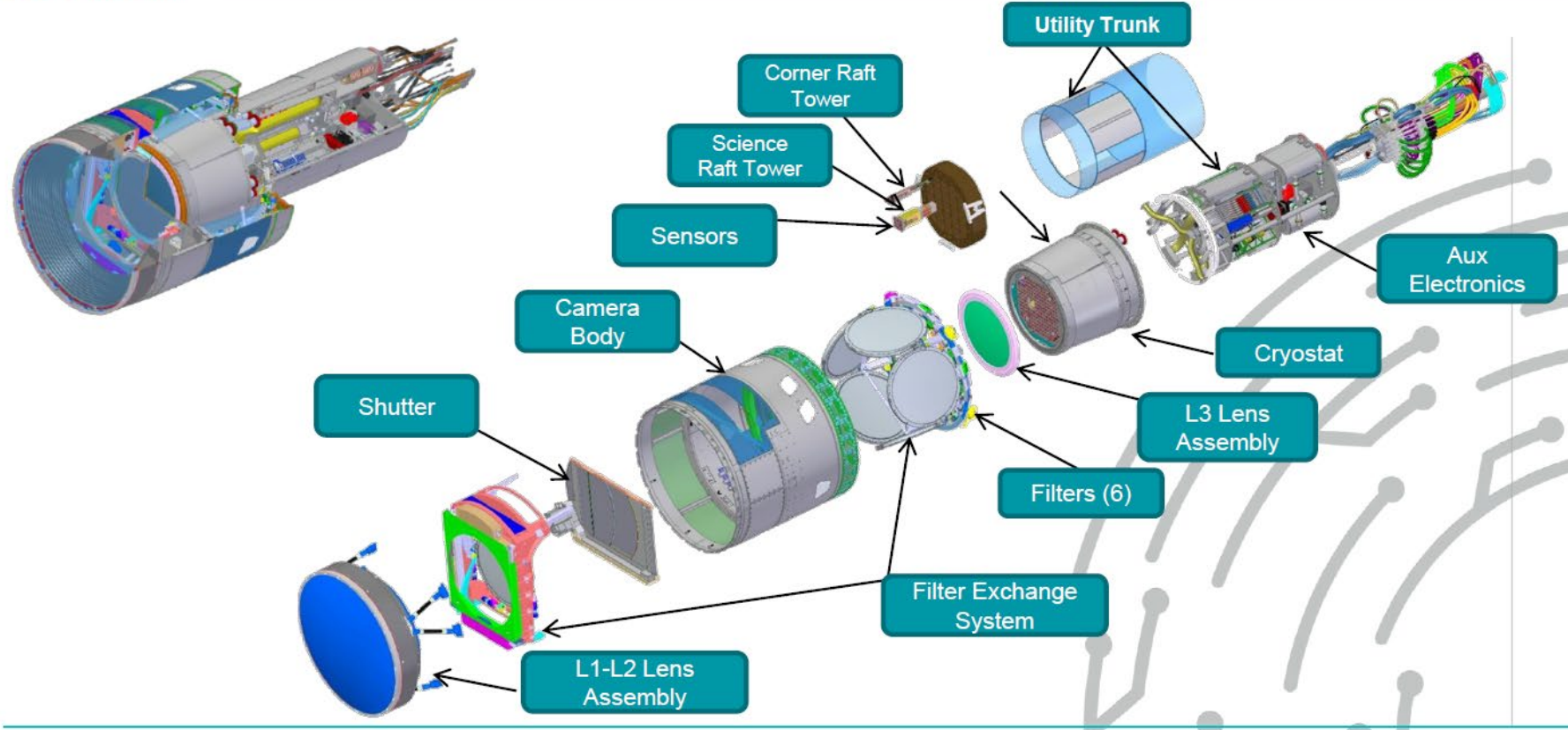
Dark Time

10M Bright Galaxies (**BGS**)
r < 19.5, *z* < 0.4

Milky Way Survey: 10M stars

Bright Time

Major Camera Elements



All Camera hardware has been fabricated at the sub-system level except for some of the filters