

Cosmology From The Dark Energy Survey

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The DES Collaboration



Cosmological Standard Model: Λ CDM Model

Flat Universe with (recent)
accelerated expansion

General Relativity

Dark Energy (cosmological
constant Λ)

Cold Dark Matter

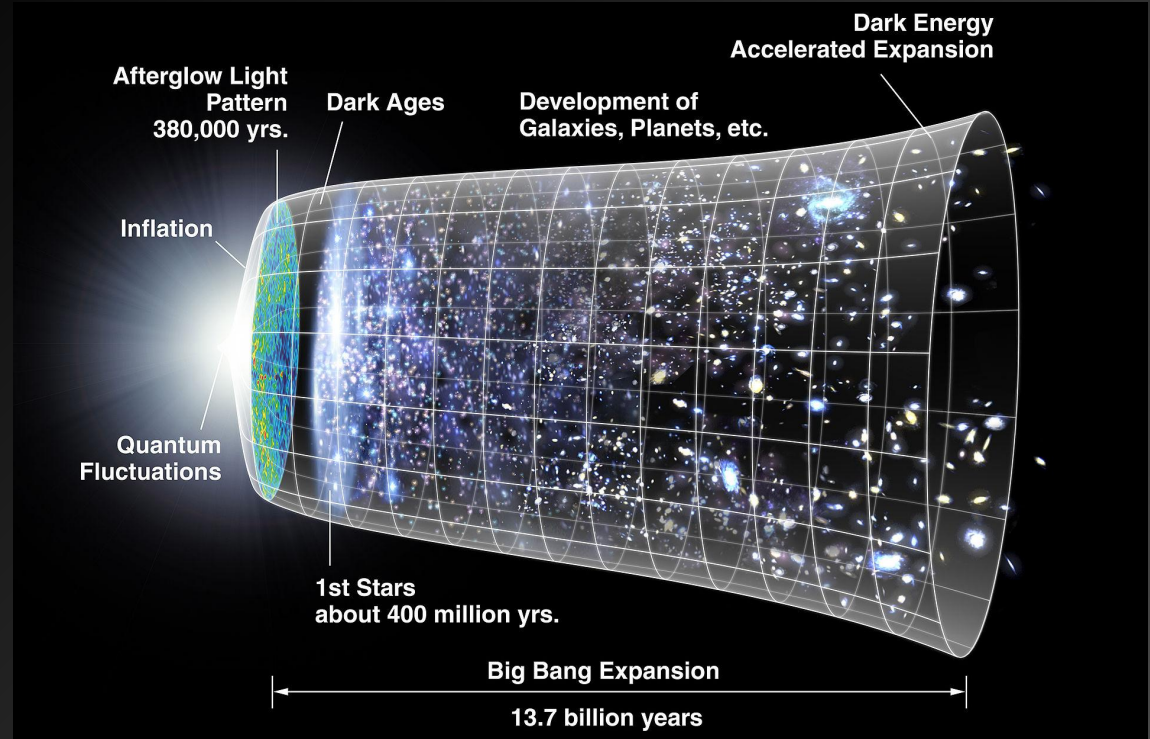


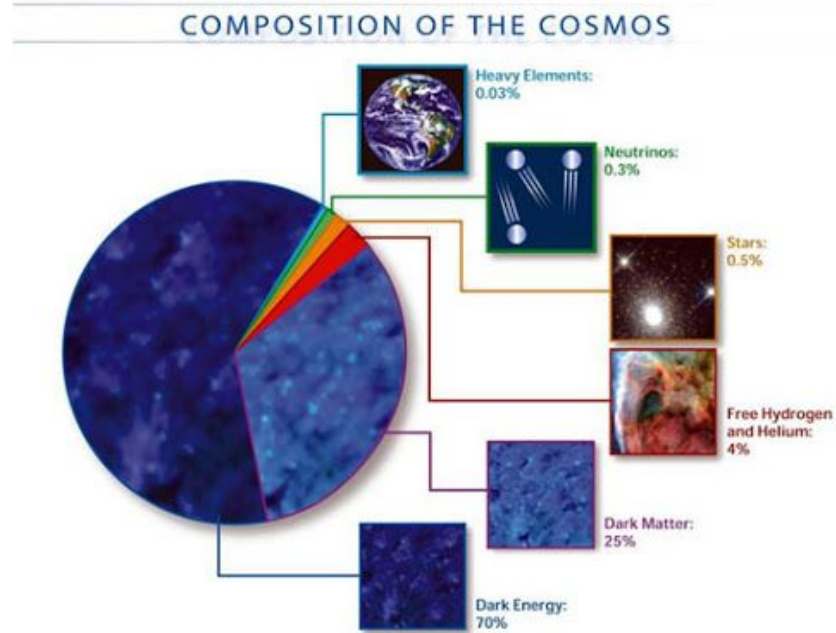
Image Credit: NASA / LAMBDA Archive / WMAP Science Team

Λ CDM Cosmology

Universe composed of:

- Λ /Dark Energy ~68%
- Dark Matter ~ 26%
- Baryonic Matter <5%
- Radiation, neutrinos +

Successfully explains distinct observations!

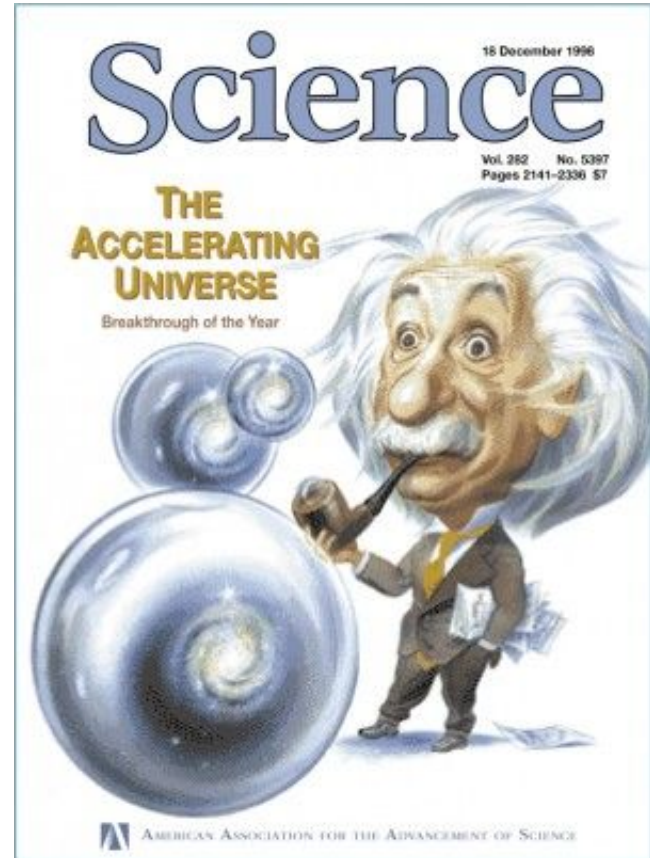


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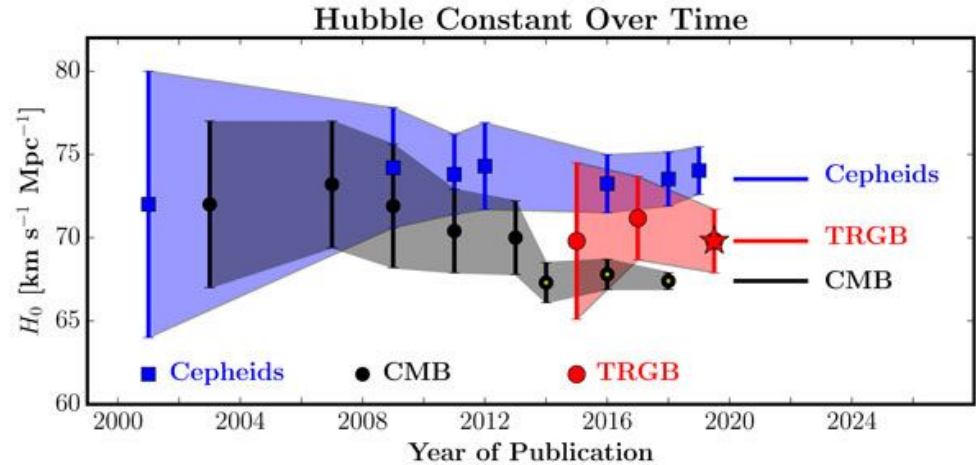
Universe composed of:

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Successfully explains distinct observations!

...but

- No detection of DM particle
- Tension between early and late universe



Λ CDM Cosmology

Universe composed of:

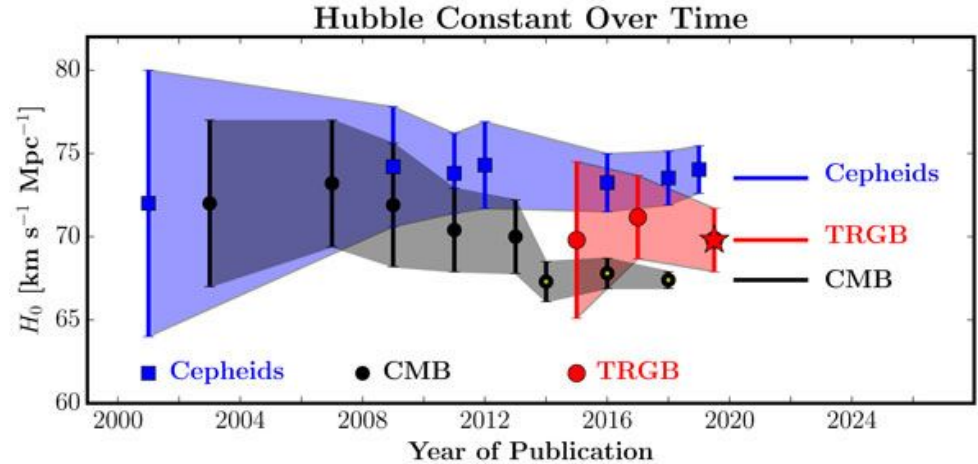
- Λ /Dark Energy
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- Radiation, neutrinos +

Successfully explains distinct observations!

...but

- No detection of DM particle
- Tension between early and late universe
- *BTW, what is Λ ?!*

Why do we have a **huge** mismatch (120mag) between theory and observation?!



We still need to address a lot of exciting questions!

The Dark Energy Survey DES



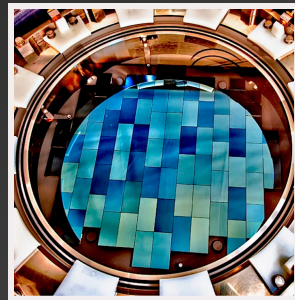
Victor M. Blanco Telescope, CTIO - Chile
Credits: R. Hahn and the DES.

Photometric survey

- Fermilab Led
- DECam: 570 Mpix
- 3 sq. deg FoV
- Vitor M. Blanco Telescope, CTIO (Chile)
- 5 filter bands (grizY)

DES operation:

- 5.5 years (2013-2019)
- 5000 sq.deg
- +400 Members
 - 25 institutions
 - 7 countries
- Year 3: +30 papers!



The largest map of the Universe to date!*

Three Big Questions

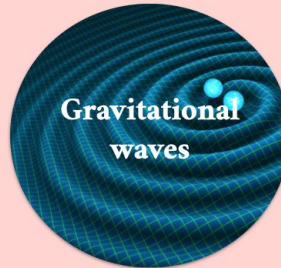
Are the **late Universe** and **early Universe** data explained by the **same** model?

Do the **growth** of structure and **expansion** measurements agree?

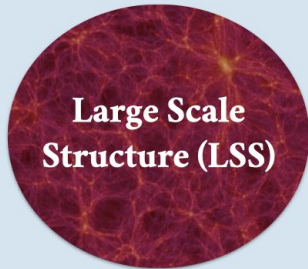
Does the **Dark Energy density change** with cosmic expansion

Probing Dark Energy within DES

History of Expansion



History of Growth + History of Expansion

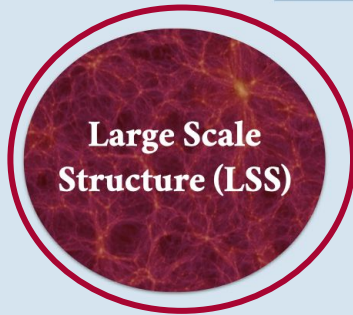


Probing Dark Energy within DES

History of Expansion



History of Growth + History of Expansion



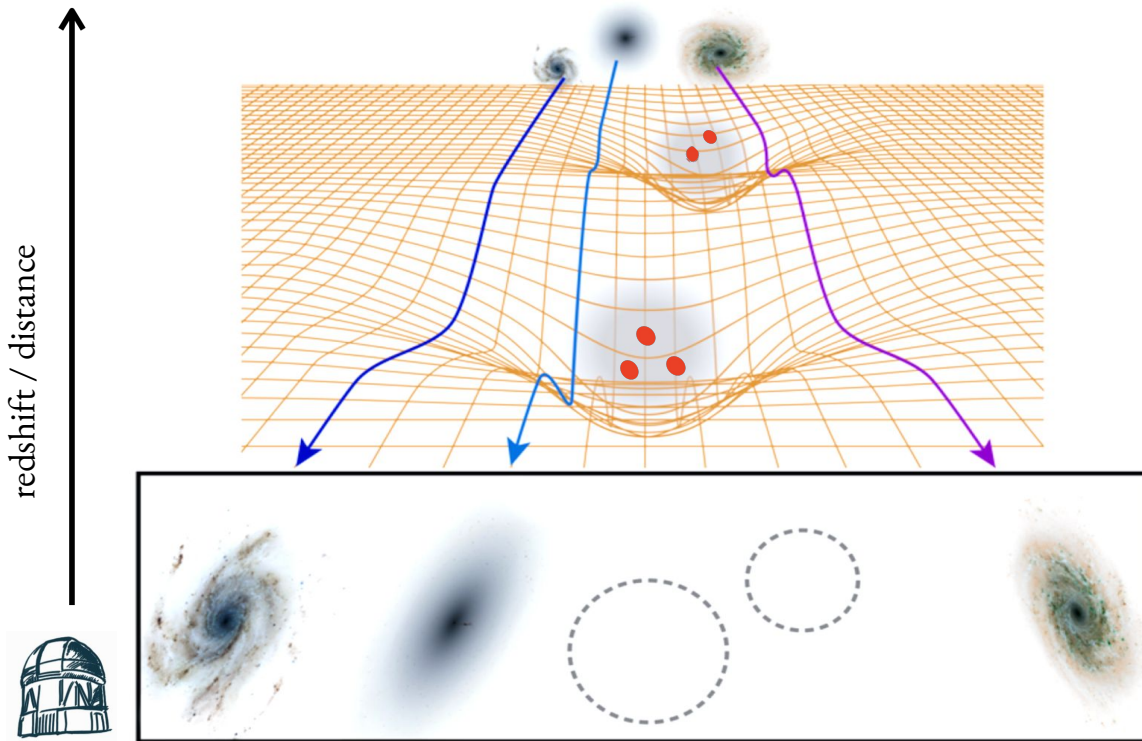
Weak Gravitational Lensing and Clustering

The light from distant **source galaxies** crosses the invisible dark matter field in their way to us.

Weak gravitational lens causes a subtle distortion in the shapes of these galaxies, the **cosmic shear**.

Dark matter field is not visible, but we can trace it using **lens galaxies**.

The distortion of **source galaxies** field has an angular correlation with the **lens field**.



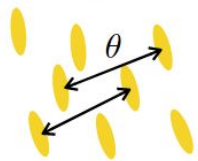
Blanco
Telescope

credit: adapted from DES-Y3 webinar

2pt Correlation

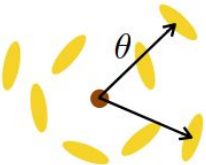
We summarize the cosmological information from galaxy samples through 2-point Angular Correlation Functions

1) Cosmic shear



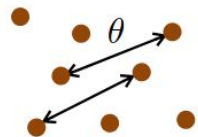
Cosmic shear: 2-pt correlation of shapes

2) Galaxy-galaxy lensing

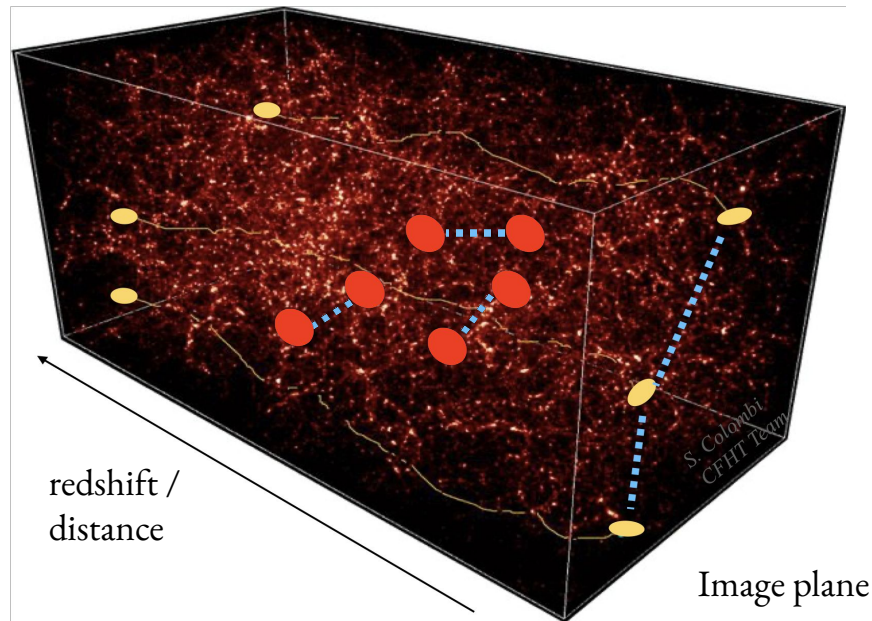


Galaxy-Galaxy lensing: 2-pt correlation between position and shape

3) Galaxy clustering

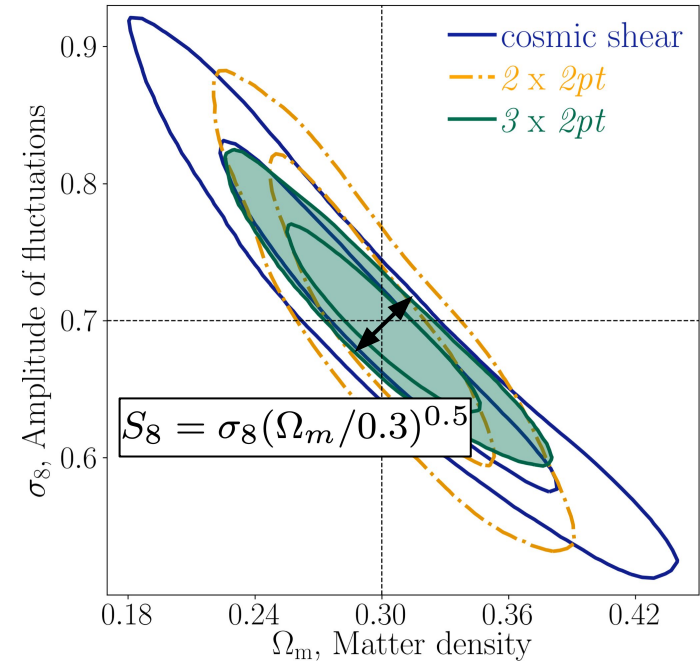
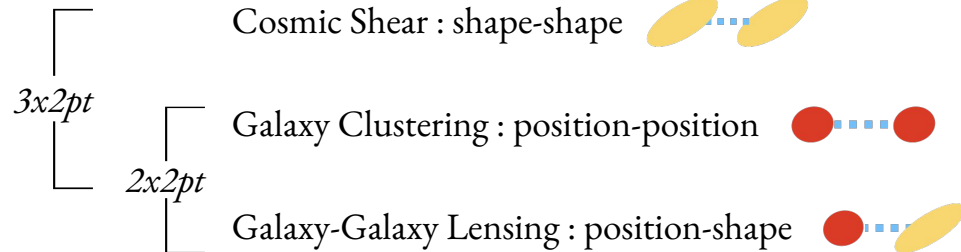


Galaxy clustering: 2-pt correlation of positions



3x2pt Cosmology

The main DES analysis:
Combination of the three 2pt angular
correlation functions

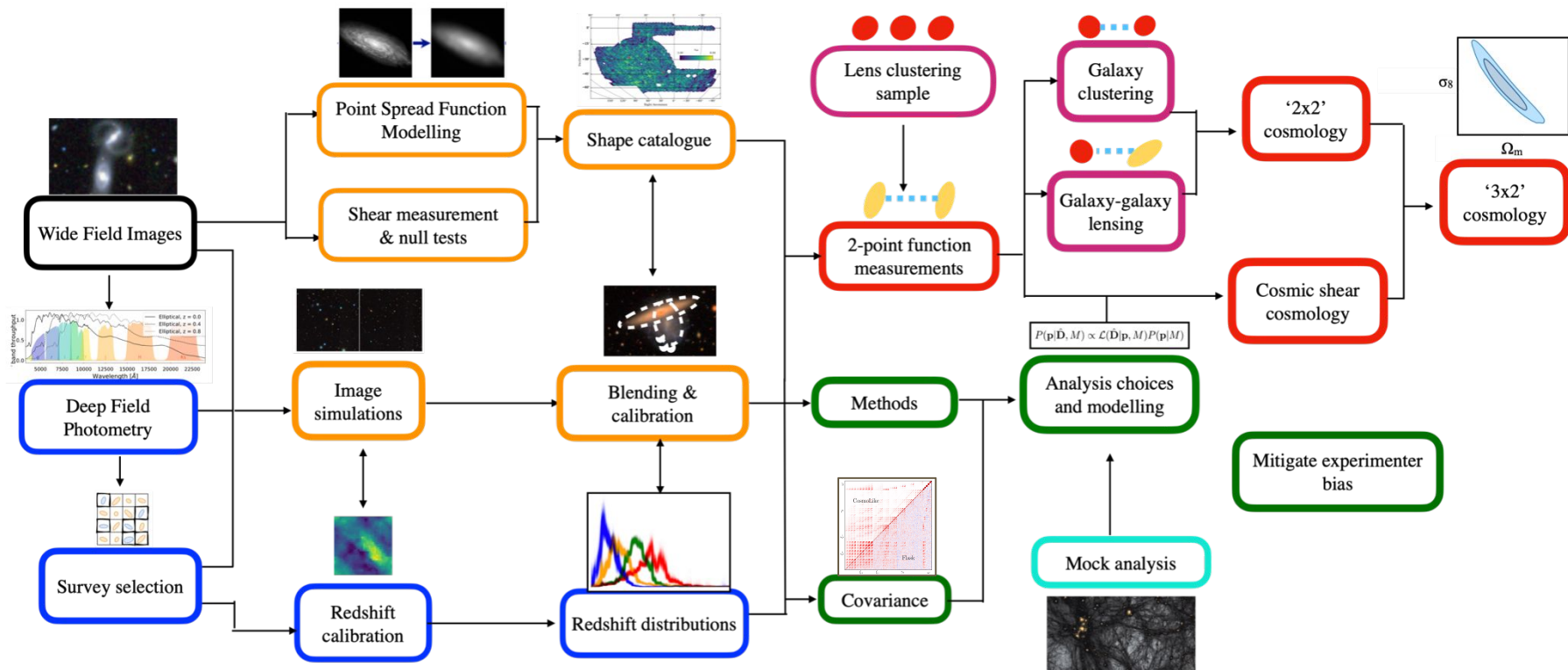


A joint analysis maximises the cosmological information and robustly constrains astrophysical & observational systematic priors in the analysis!

From Light to Knowledge



credit: Jessie Muir



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

credit: DES Y3

DES Y3 Catalogs

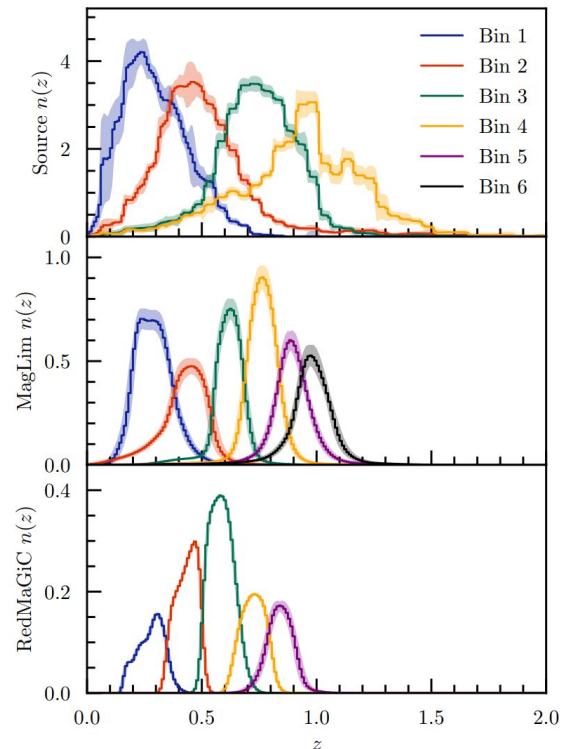
Footprint: 4143 sq. deg.

Sources catalog:

- 326,049,983 galaxies
- Final cut: 100,204,026 galaxy shapes
- $n_{\text{eff}}=5.59 \text{ gal/arcmin}^2$

Lenses catalog:

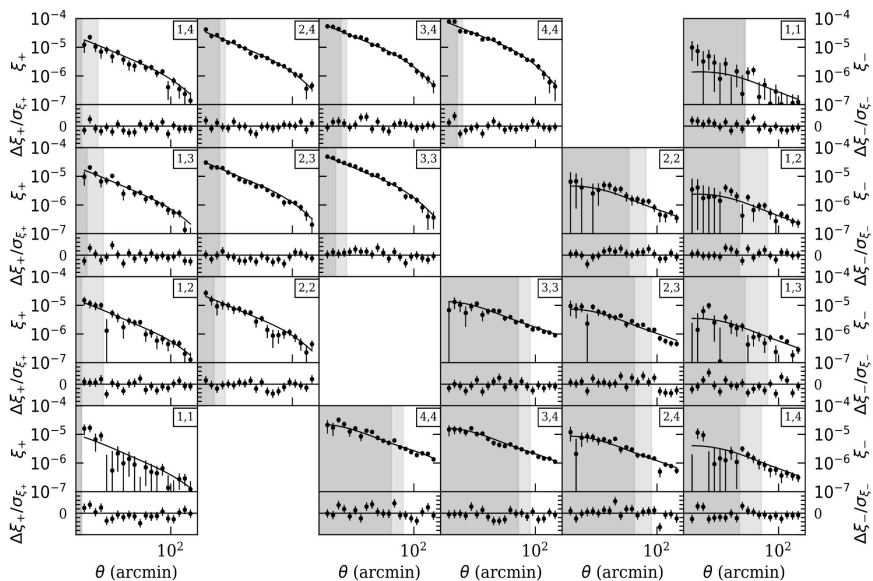
- 2 independent catalogs + BAO optimized
- 10.7M galaxies (MagLim sample)



DES Collaboration 2105.13549

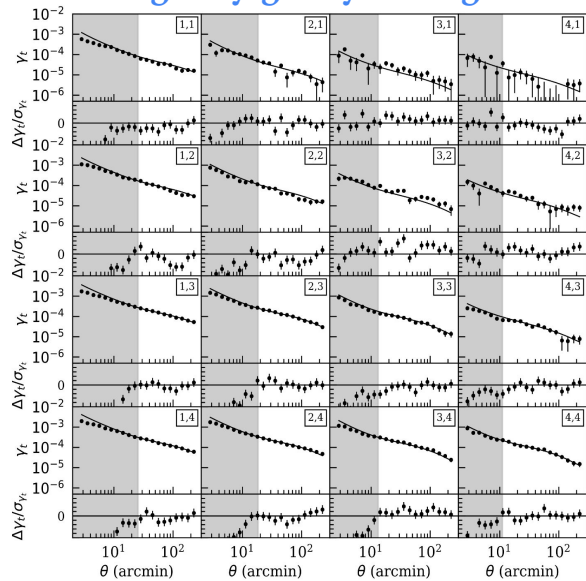
3x2pt Data Measurement

... cosmic shear Amon+, Secco, Samuroff+

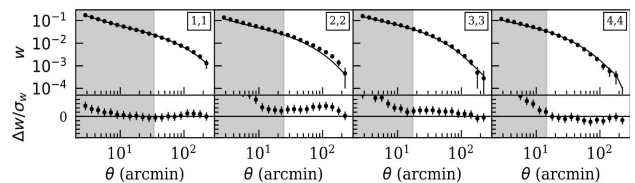


slide credit: DESY3

... galaxy-galaxy lensing Prat+



... galaxy clustering Rodriguez-Monroy+



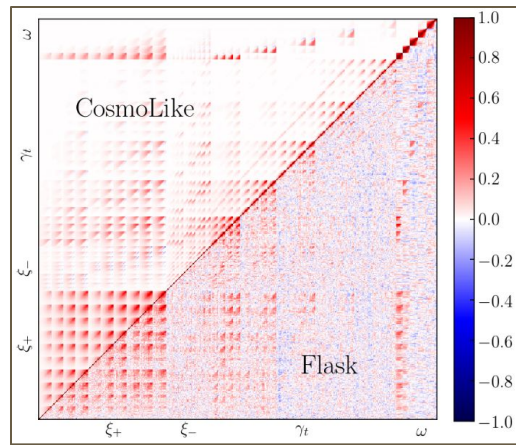
Covariances

3x2pt probes are highly correlated

- Tests in covariance validation
 - Gaussian Likelihood
 - Trispectrum
 - Wrong Model
 - Masking and Survey Geometry
 - Non-poissonian Shot Noise
 - Finite angular bin width
 - Galaxy Weighting schemes
 - RSD, Curved-Sky, random point SN + others...
- Strategies:
 - Linearized likelihood for min χ^2 tests
 - “Simple χ^2 ” approach
 - Parameter estimation

60 Tb of simulations for 3x2pt
and 5x2pt !

1Tb of simulations for B-mode and ggl
systematics



Friedrich, F A-O, Camacho+ 2020

Cosmological Constraints from 3x2pt

Infer parameter posterior distribution $P(\mathbf{p}|\hat{\mathbf{D}}, M)$ within model M using Bayes' theorem:

$$P(\mathbf{p}|\hat{\mathbf{D}}, M) \propto \mathcal{L}(\hat{\mathbf{D}}|\mathbf{p}, M)P(\mathbf{p}|M)$$

Ingredients

- Data likelihood with data covariance \mathbf{C}
 - Gaussian data likelihood
 - halo model covariance
- Criteria which measurements to combine
- Blinding scheme to minimize observer bias
- Model M with parameters \mathbf{p} , and prior
- Free parameters: 7 cosmological, 23 nuisance (for syst. control)

Cosmology

Parameter	Prior	
Cosmology		
Ω_m	Flat	(0.1, 0.9)
$10^9 A_s$	Flat	(0.5, 5.0)
n_s	Flat	(0.87, 1.07)
Ω_b	Flat	(0.03, 0.07)
h	Flat	(0.55, 0.91)
$10^3 \Omega_\nu h^2$	Flat	(0.60, 6.44)
w	Flat	(-2.0, -0.33)

Nuisance

Lens Galaxy Bias		
$b_i (i \in [1, 4])$	Flat	(0.8, 3.0)
Lens magnification		
C_1^1	Fixed	1.21
C_1^2	Fixed	1.15
C_1^3	Fixed	1.88
C_1^4	Fixed	1.97
Lens photo-z		
$\Delta_{z_1^1} \times 10^2$	Gaussian	(-0.9, 0.7)
$\Delta_{z_1^2} \times 10^2$	Gaussian	(-3.5, 1.1)
$\Delta_{z_1^3} \times 10^2$	Gaussian	(-0.5, 0.6)
$\Delta_{z_1^4} \times 10^2$	Gaussian	(-0.7, 0.6)
$\sigma_{z,1}^1$	Gaussian	(0.98, 0.06)
$\sigma_{z,1}^2$	Gaussian	(1.31, 0.09)
$\sigma_{z,1}^3$	Gaussian	(0.87, 0.05)
$\sigma_{z,1}^4$	Gaussian	(0.92, 0.05)
Intrinsic Alignment		
$a_i (i \in [1, 2])$	Flat	(-5, 5)
$\eta_i (i \in [1, 2])$	Flat	(-5, 5)
b_{TA}	Flat	(0, 2)
z_0	Fixed	0.62
Source photo-z		
$\Delta_{z_s^1} \times 10^2$	Gaussian	(0.0, 1.8)
$\Delta_{z_s^2} \times 10^2$	Gaussian	(0.0, 1.5)
$\Delta_{z_s^3} \times 10^2$	Gaussian	(0.0, 1.1)
$\Delta_{z_s^4} \times 10^2$	Gaussian	(0.0, 1.7)
Shear calibration		
$m^1 \times 10^2$	Gaussian	(-0.6, 0.9)
$m^2 \times 10^2$	Gaussian	(-2.0, 0.8)
$m^3 \times 10^2$	Gaussian	(-2.4, 0.8)
$m^4 \times 10^2$	Gaussian	(-3.7, 0.8)



Current Results From DES

<https://www.darkenergysurvey.org/des-year-3-cosmology-results-papers/>

The DES Y3 Results Λ CDM

Year 3 Analysis:

Planck CMB

DES 3x2pt

Combination

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

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

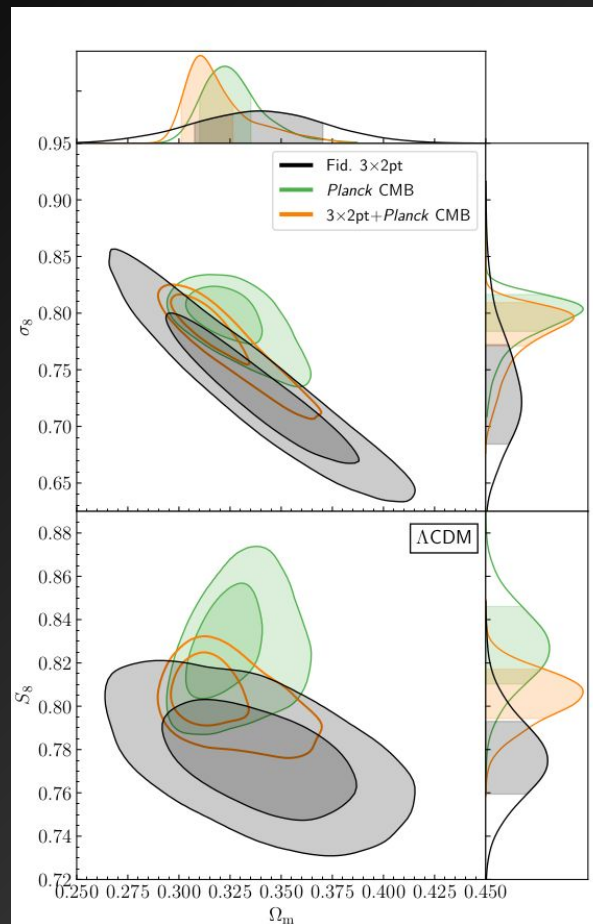
$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)$$

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

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

- ~2.1 improvement from Y1
- No large tensions

Clumpiness of the Universe



Matter Density

The DES Y3 Combined Results

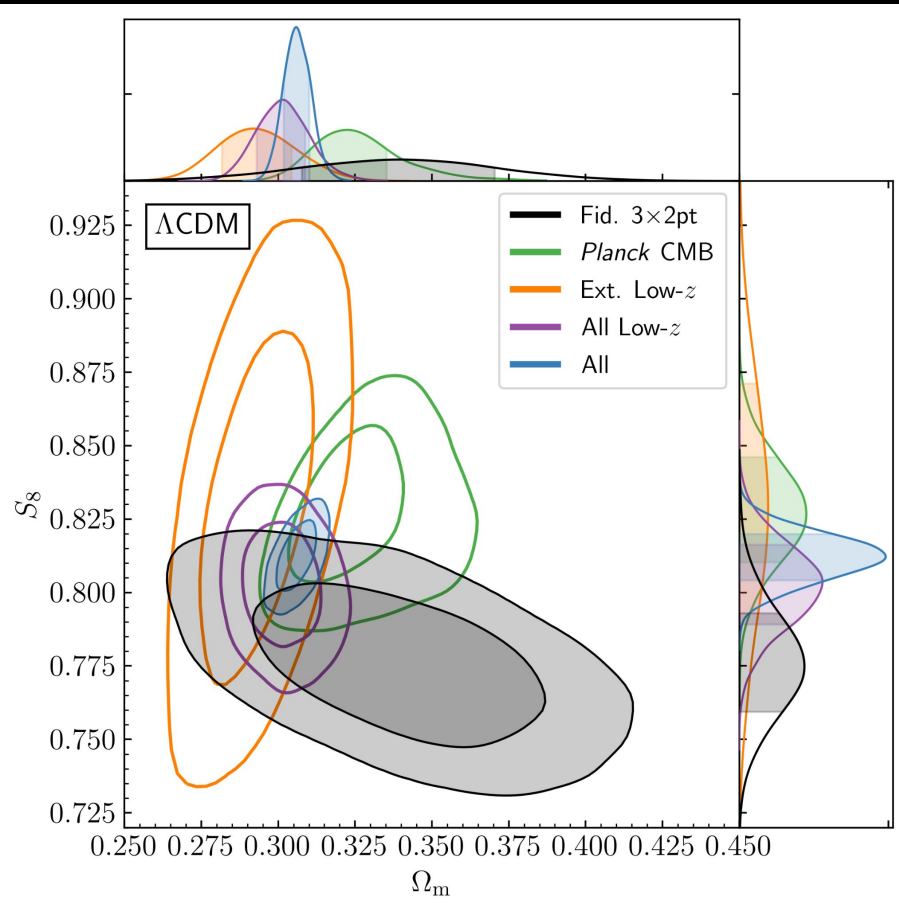
$$S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)$$

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

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

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

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



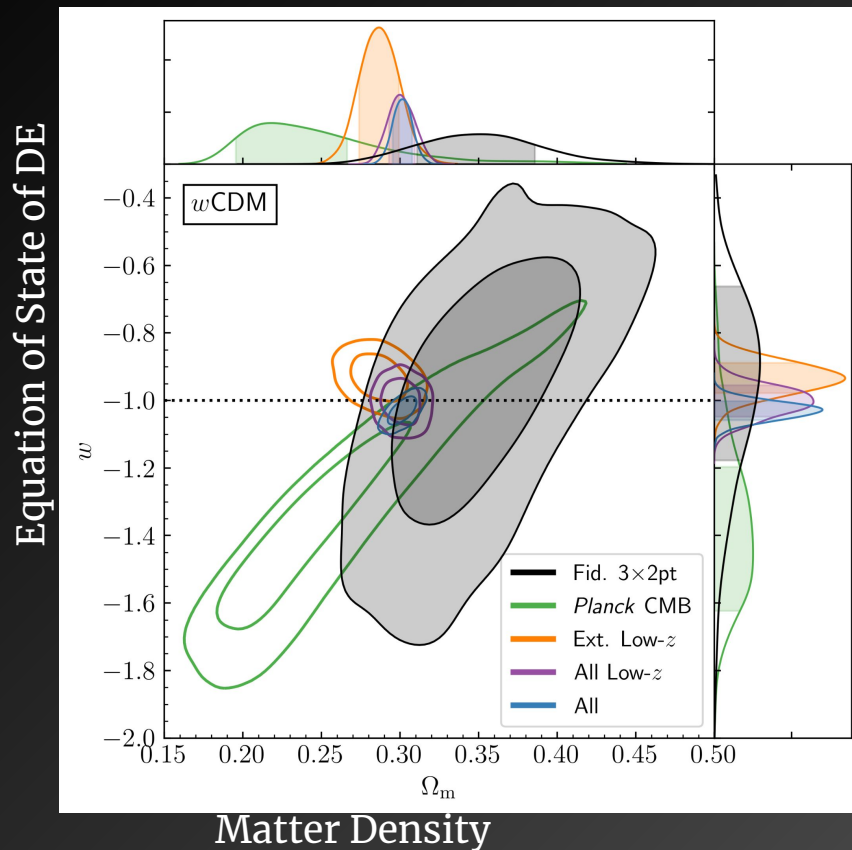
The DES Y3 w CDM Combined Results

Cosmological
constant: $w = -1$

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

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

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



The DES Y3 Results + Baryon Acoustic Oscillations

Year 3 Analysis:

DES Y3 + SN + BAO + Planck

DES (3x2pt + SN)

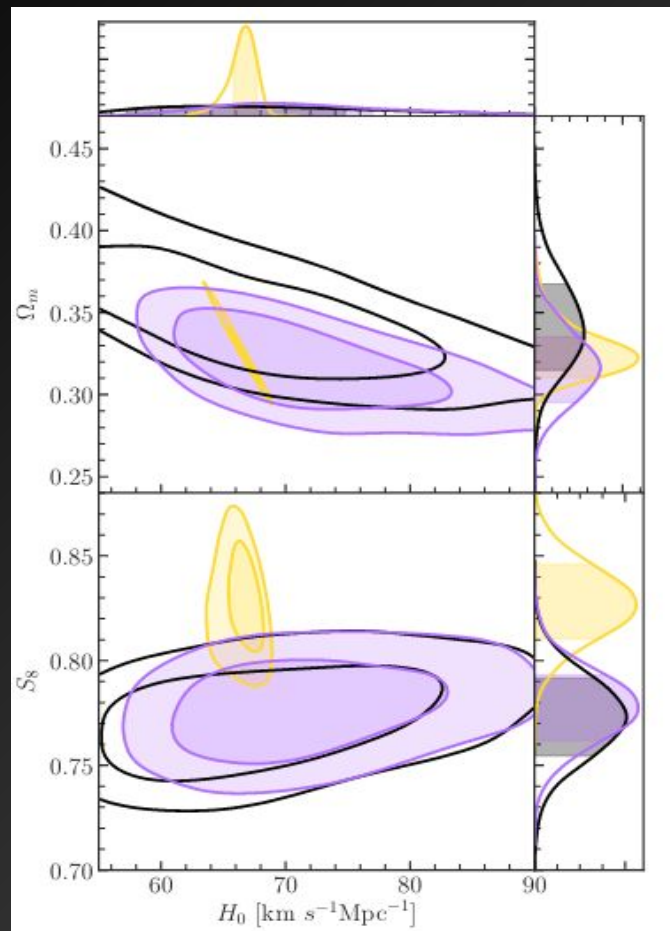
Planck

$$\begin{aligned} h &= 0.691^{+0.138}_{-0.043}, \\ \Omega_m &= 0.344^{+0.029}_{-0.025}, \\ S_8 &= 0.773^{+0.018}_{-0.019}, \end{aligned}$$

$$\begin{aligned} h &= 0.72^{+0.090}_{-0.053}, \\ \Omega_m &= 0.317^{+0.021}_{-0.020}, \\ S_8 &= 0.778^{+0.016}_{-0.017}. \end{aligned}$$

Matter density

Clumpiness



Cosmic Expansion Rate

Final Remarks

DES team produced best cosmological constraints from imaging survey to date

Combination of probes:

- We have been developing multiple techniques to model systematics
- Signals of unknown systematics from the clustering and lensing amplitudes, though they do not significantly impact Λ CDM cosmology

Λ CDM model is still alive:

- No evidence of exotic dark energy model so far
- No significant tension between CMB (early) and LSS (late) data in S_8

Final Remarks

For the DES Year 6

- Better statistics: more data , more depth
- From ~300M to 700M galaxies!
- Improved modelling
- Systematics modelling

DES Beyond Cosmology:

- Milky way
- Solar System
- MW Satellites

Much more DES cosmology beyond this talk:

- The best BAO detection in $0.6 < z < 1.1$
- Supernovae Ia Cosmology
- GW Cosmology
- Extensions of DE
 - EoS, Modified Gravity, Alternative Dark Energy Models, and Dark Matter Models
- Harmonic Space Analysis
- Cluster Cosmology & 3x2pt +1pt
- CMB + LSS & 5x2pt
- Higher order statistics, PNG
- Strong Lensing, +...



Thanks For Listening!

List of participants

(Early Career Scientists in bold)

Beatrice Moser	Adam Amara	Ramon Miquel	Alyssa Garcia	Felipe Andrade-Oliveira	Ken Herner	Alex Drlica-Wagner
Dan Scolnic	Santiago Avila	Jenna Freudenberg	Dhayaa Anbajagane	Jack Elvin-Poole	Danielle Leonard	Simon Birrer
Robert Morgan	Sunayana Bhargava	David Bacon	Andresa Campos	Juan P. Cordero	Gaston Gutierrez	Brian Yanny
Nacho Sevilla	Antonella Palmese	Tomasz Kacprzak	Cyrille Doux	Mike Jarvis	Federica Tarsitano	Sahar Allam
Paul Rogozenski	Zhiyuan Zhou	Giulia Giannini	Jessie Muir	Eric Huff	Juan Mena Fernández	Scott Dodelson
Elisabeth Krause	Aaron Roodman	Chihway Chang	Georgios Zacharegkas	Chris Conselice	David Sánchez Cid	Jim Annis
Joe DeRose	Matthew Becker	Anderson Souza	William Hartley	Eric Neilsen	Seshadri Nadathur	Andras Kovacs
Richard Kron	Risa Wechsler	Jacobo Asorey	Nick Kokron	Javier Sanchez	Gary Bernstein	Hugo Camacho
H. Thomas Diehl	Andrés Plazas	David Burke	Michael Troxel	Andres Navarro	Sujeong Lee	Kai Hoffmann
Ofer Lahav	Rafael Gomes	Isaac Tutusaus	Judit Prat	Tae-hyeon Shin	Prudhvi Varma	Mandeep Gill
Reese Wilkinson	Ian Harrison	Jamie McCullough	Pablo Fosalba	Chun-Hao To	Oliver Friedrich	Jonathan Blazek
Peter Melchior	Romain Buchs	Paul Ricker	Douglas Tucker	Tesla Jeltema	Simon Samuroff	Lucas James Faga
David Weinberg	Ami Choi	Eduardo Rozo	Eli Rykoff	Kevin Wang	Richard Kessler	Joe Zuntz
Anqi Chen	Maria Pereira	Noah Weaverdyck	Michael Johnson	Niall MacCrann	Huan Lin	Steve Kent
Dominik Zuercher	Alex Alarcon	Pauline Vielzeuf	Masaya Yamamoto	Erin Sheldon	Rutuparna Das	Martin Crocce
Niall Jeffrey	Bhuvnesh Jain	Eusebio Sanchez	Dillon Brout	Agnes Ferte	Lorne Whiteway	Spencer Everett
Mitch McNanna	Raphael Sgier	Boyan Yin	Matias Carrasco	Ross Cawthon	Anushka Shrivastava	Juan Estrada
Alexandre Refregier	Albert Stebbins	Robert Gruendl	Daniel Gomes	Manda Banerji	Tamara Davis	Donald Petravick
Dylan Britt	Dragan Huterer	Vivian Miranda	Nico Hamaus	Yuuki Omori	Jimena Gonzalez	Hung-Jin Huang
Pablo Lemos	Justin Myles	Xiao Fang	Ismael Ferrero	Brenna Flaughner	Tim Eifler	Yuanyuan Zhang
Alexandra Amon	Youngsoo Park	Marco Gatti	Mike Wang	Alfredo Zenteno	Giorgia Pollina	Georgios Zacharegkas
Shantanu Desai	Marco Raveri	Heidi Wu	Andrew Liddle	Mathew Smith	Ashley Ross	Shivam Pandey
			Daniel Gruen	Otavio Alves	Eleonora di Valentino	Helen Qu
			Keith Bechtol	Eve Kovacs	Lucas Secco	Eric Baxter
			Juan De Vicente	Martin Rodriguez Monroy	Ji Won Park	Jack Odonnell
			Anna Porredon	Megan Tabbutt	Andrew Pace	Sebastian Bocquet

