Title: Cosmological Constraints from Galaxy Clustering and Weak Lensing in the Dark Energy Survey

Date: Nov 21, 2017 11:00 AM

URL: http://pirsa.org/17110049

Abstract: <p>The Dark Energy Survey (DES) is a five-year, 5000 sq. deg. observing program using the Dark Energy Camera on the 4m Blanco telescope at CTIO. I will describe the cosmological analysis of large-scale structure in the Universe using 1321 sq. deg. of data taken in the first year of DES operations. The analysis combines unprecedented measurements of weak gravitational lensing and the clustering of galaxies over the redshift range 0.2 to 1.3 to derive the most precise such cosmological constraints to date. These DES results from the low-redshift Universe are consistent with those from the cosmic microwave background (CMB) and support the standard cosmological model, LCDM. In the coming years, DES will produce significantly tighter constraints on cosmology through similar and additional analyses using observations over more than three times the sky-area and more than twice the integrated exposure time per object as these results.</p>

# Dark Energy Survey Year 1 Results:
## Cosmological Constraints from Galaxy Clustering and Weak Lensing

**Michael A. Troxel**
CCAPP Fellow at Ohio State University
on behalf of the Dark Energy Survey Collaboration

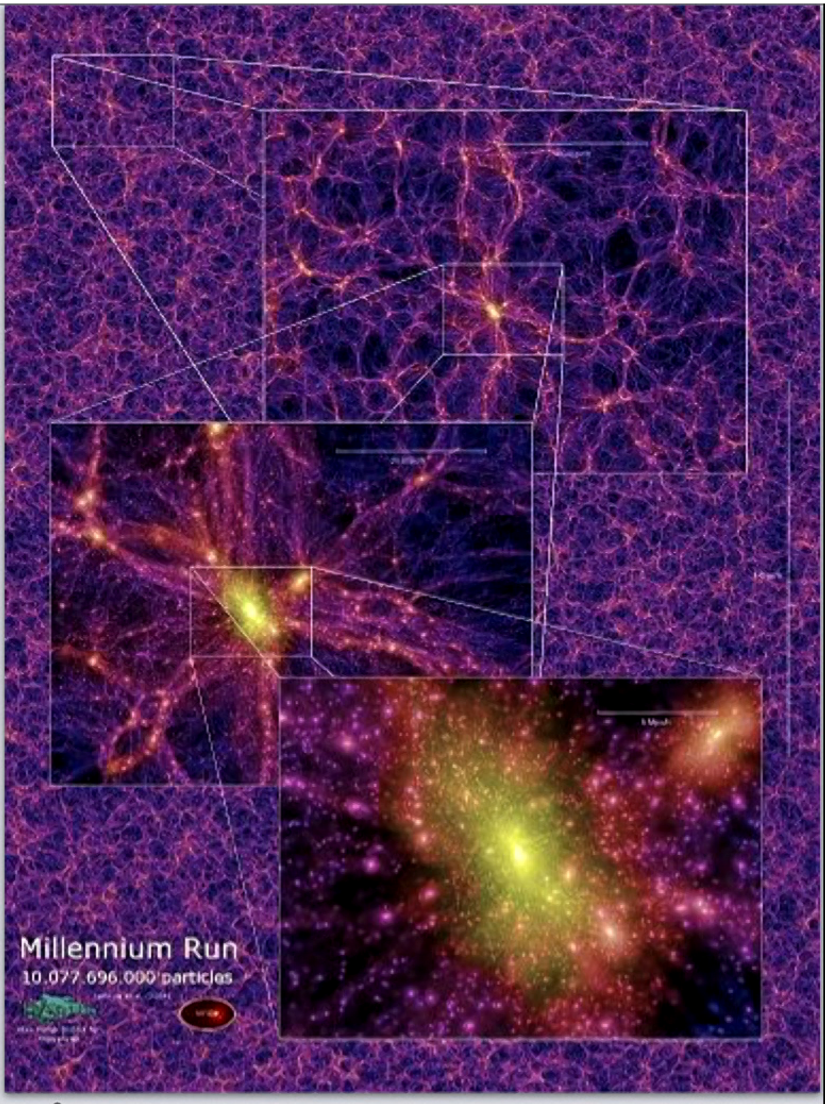
Perimeter Institute, Nov. 21 2017

THE DARK ENERGY SURVEY

1

THE OHIO STATE UNIVERSITY

# Cosmology from Large-Scale Structure



## On large scales, the Universe is described as a homogenous fluid in expanding space

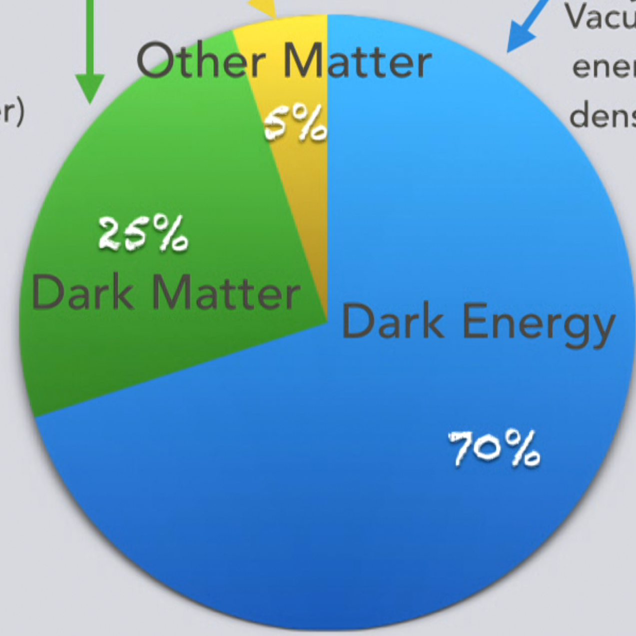
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{H^2}{H_0^2} = \Omega_{0,R}\,a^{-4} + \Omega_{0,M}\,a^{-3} + \Omega_{0,k}\,a^{-2} + \Omega_{0,\Lambda}$$

Scale factor

Hubble constant

Matter density (DM + other matter)

Vacuum energy density

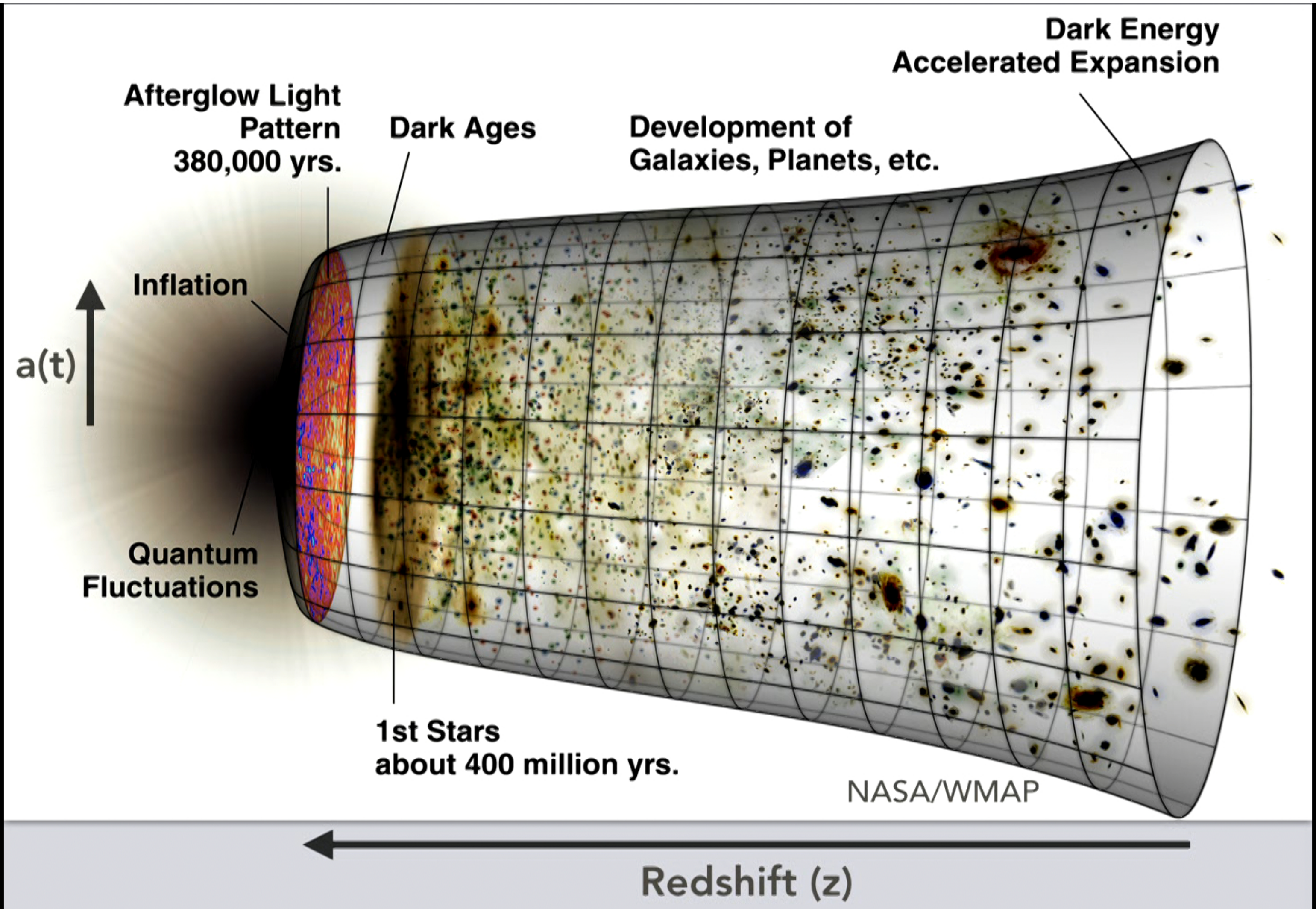



**Standard Model of cosmology:**

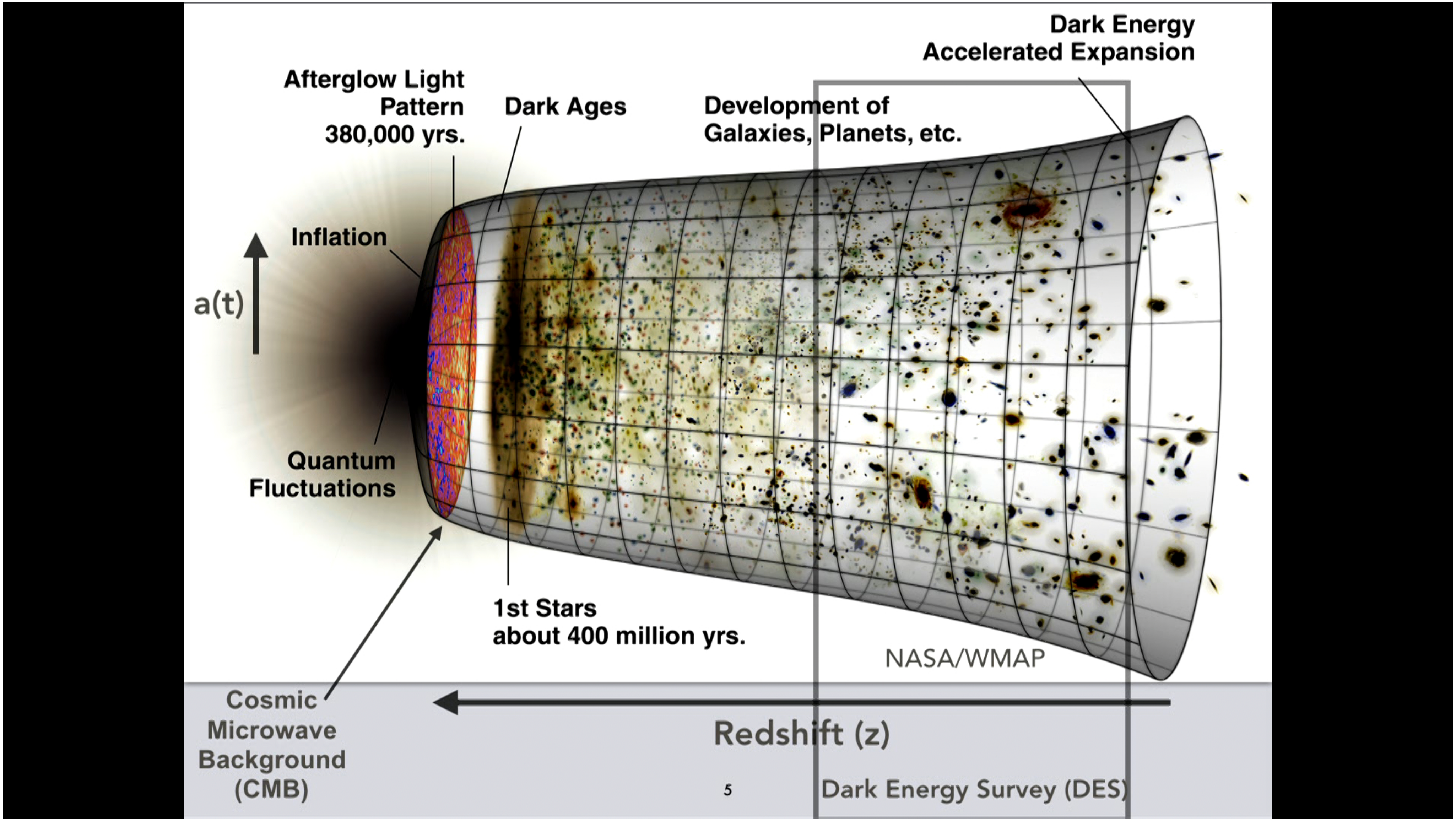
Lambda — Cold Dark Matter (LCDM)

1) Matter density parameter $\Omega_m$
   (Baryon density parameter $\Omega_b$)
   (Physical neutrino density parameter $\Omega_\nu h^2$)
2) Dark energy density parameter $\Omega_\Lambda$
3) Curvature density parameter $\Omega_k$
4) Hubble constant $H_0$
5) Scalar spectral index $n_s$
6) Reionization optical depth $\tau$
7) *Equation of state of dark energy $w = -1$*

3


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
a(t)
Quantum
Fluctuations
1st Stars
about 400 million yrs.
NASA/WMAP
Redshift (z)

4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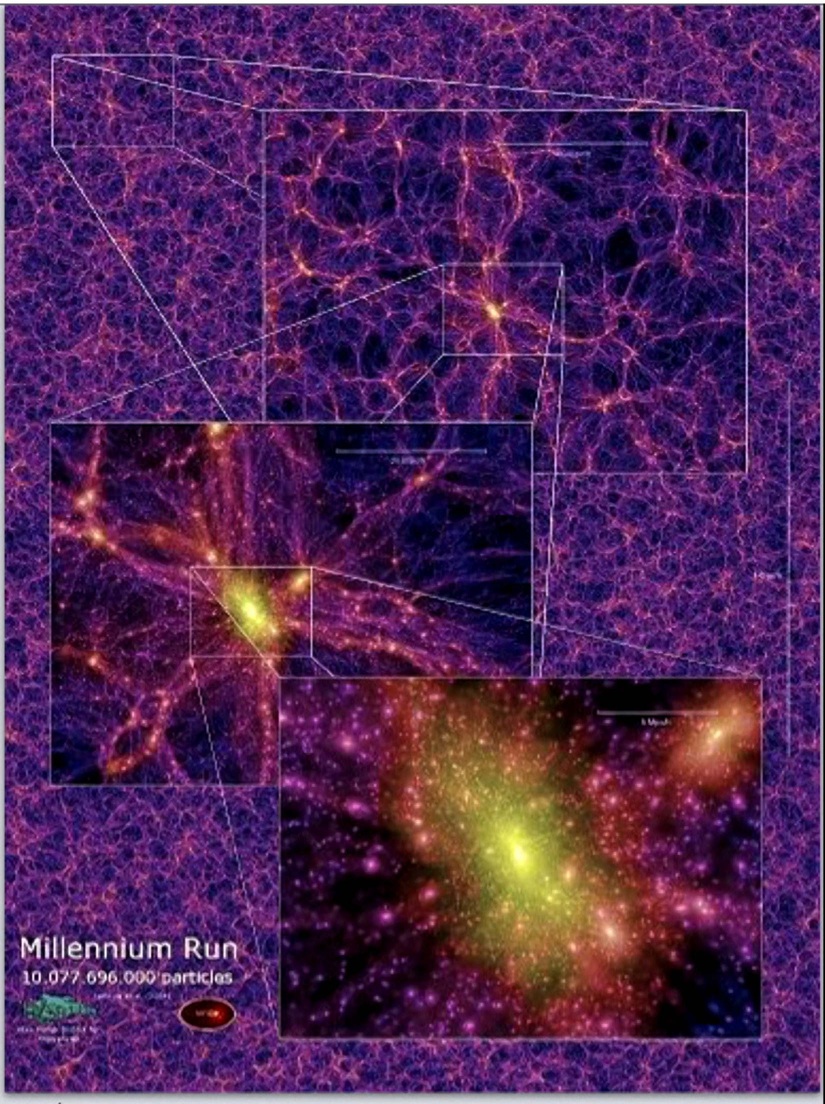
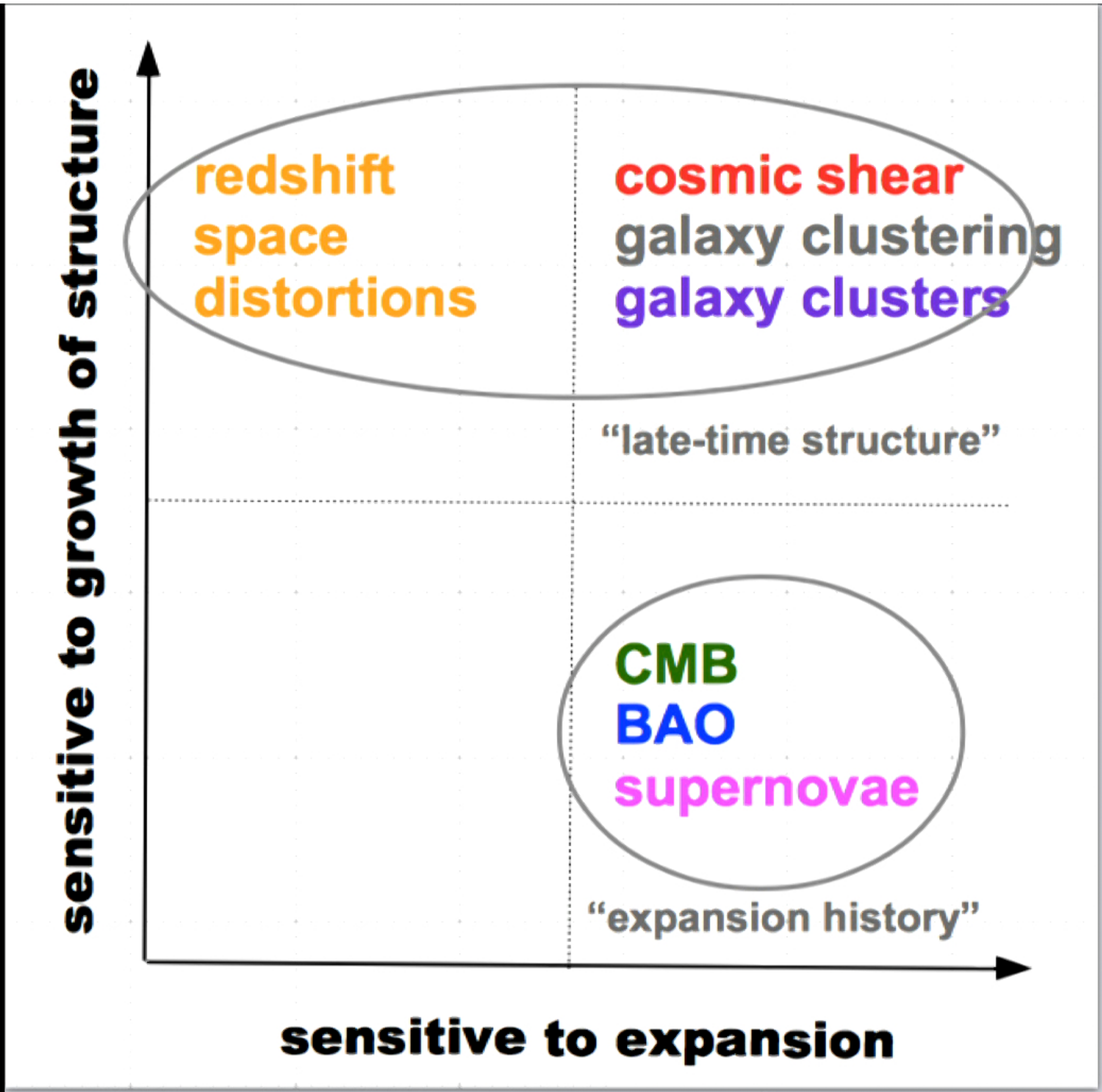
NASA/WMAP
Cosmic
Microwave
Background
(CMB)
Redshift (z)
5
Dark Energy Survey (DES)

**How do we learn about dark matter and dark energy?**

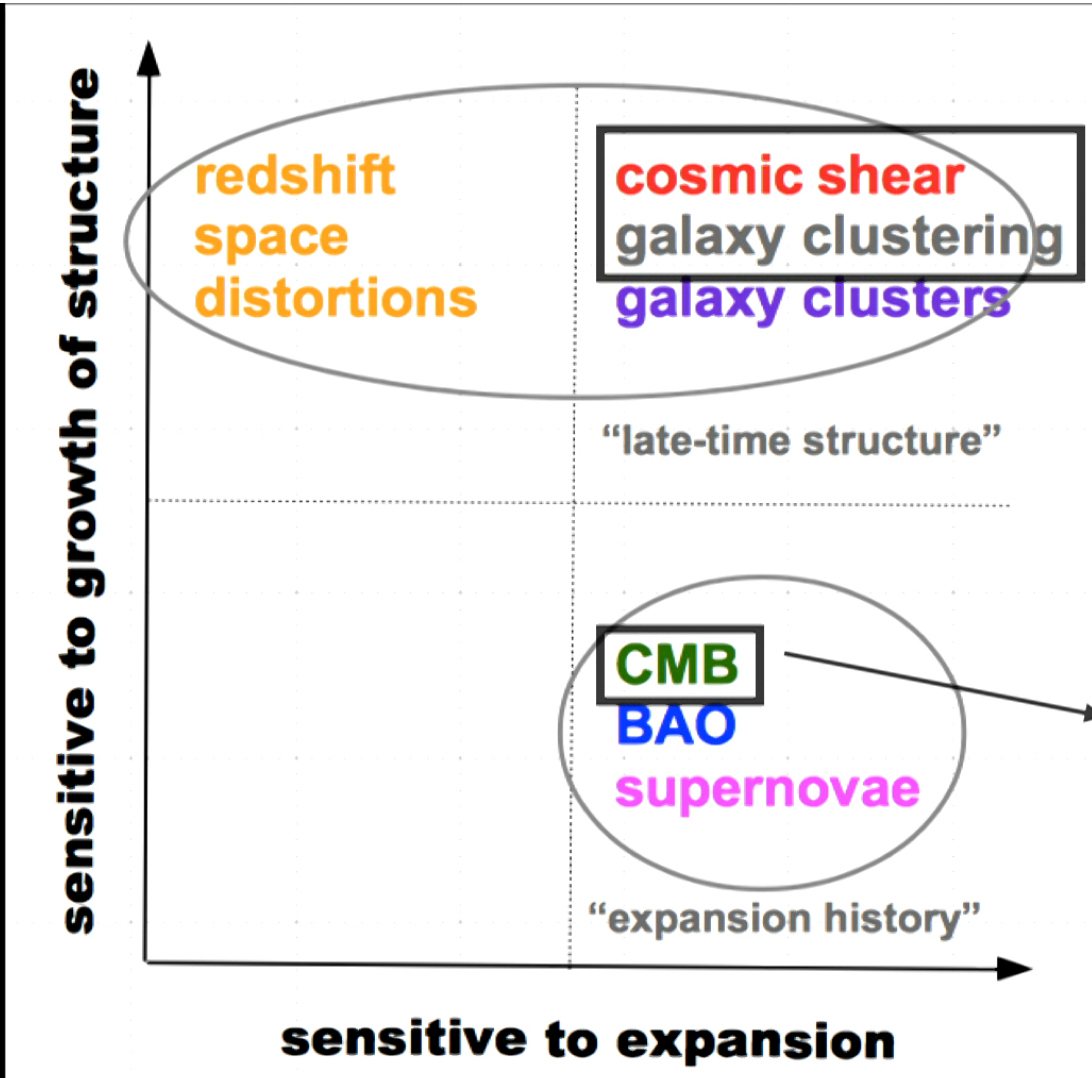
***How do we map something we can't see…?***




6


redshift
space
distortions
cosmic shear
galaxy clustering
galaxy clusters
"late-time structure"
CMB
BAO
supernovae
"expansion history"
sensitive to growth of structure
sensitive to expansion

7

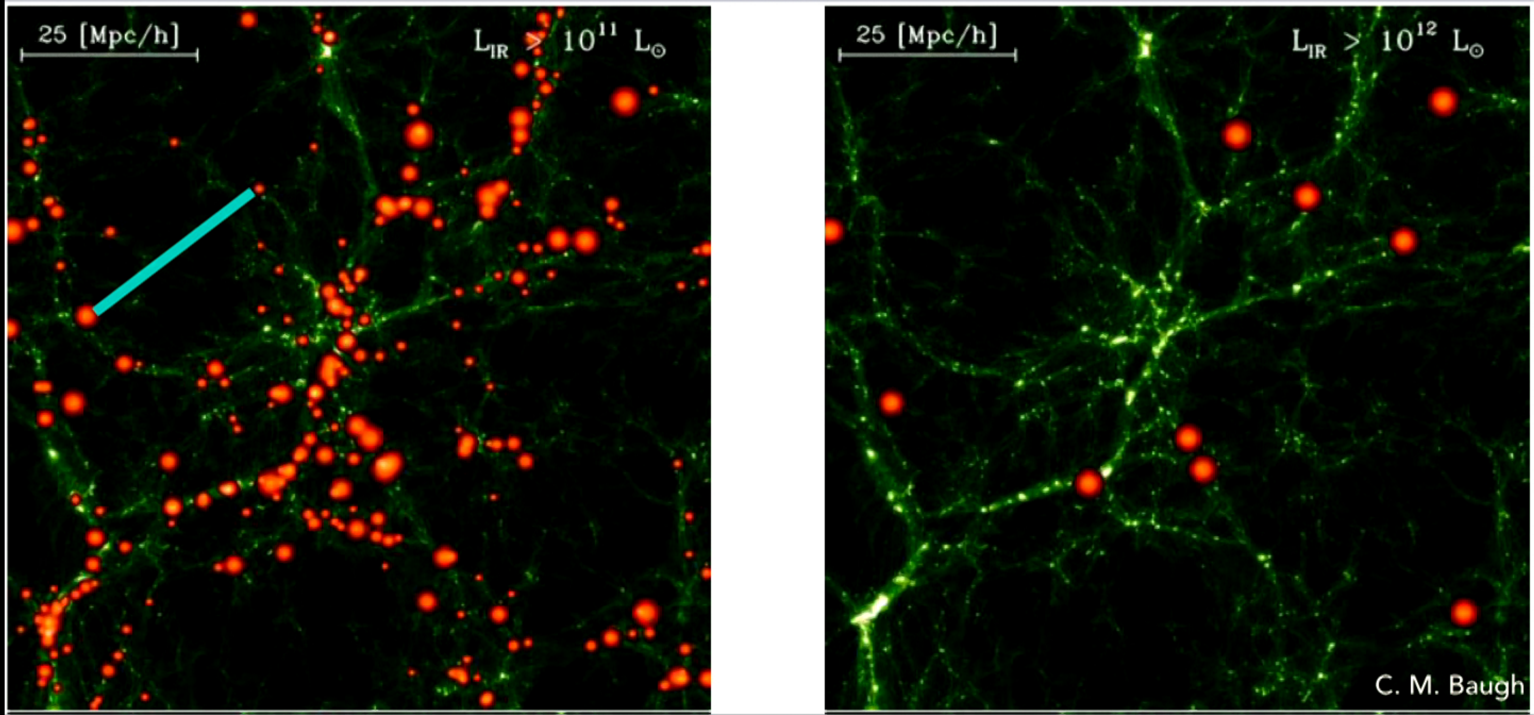



Current DES analysis combines these probes

The CMB has thus far been by far the most powerful cosmological probe

8

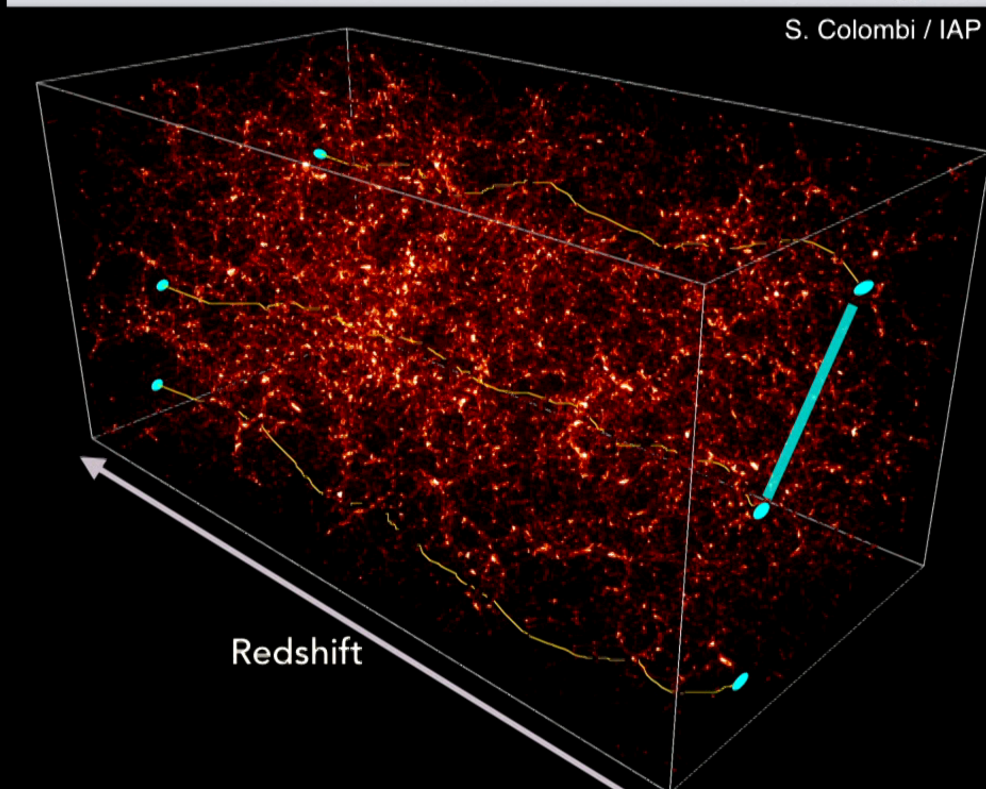
# 1) Galaxy clustering:
# Galaxies tend to form where there is dark matter

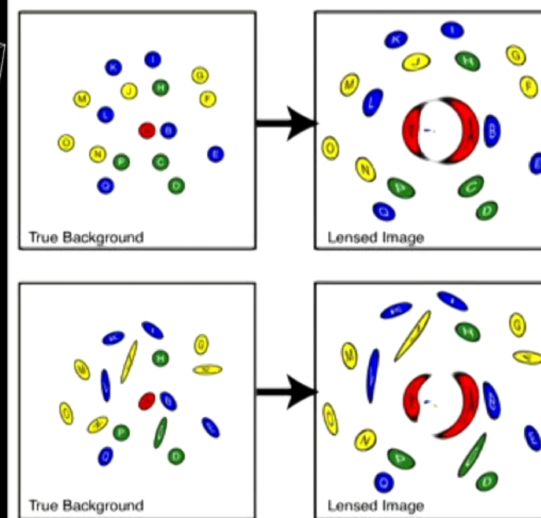



Construct a power spectrum (or real-space correlation function) from positions.
Immensely successful for decades.
Limited by an unknown galaxy bias (how well galaxies really trace dark matter).

9

# 2) Weak Gravitational Lensing (cosmic shear): Galaxies are lensed by dark matter




J. Williamson, Journal of Young Investigators

Construct a power spectrum (or two real-space correlation functions) from spin-2 ellipticity.
Only first measured around 2000, and precision measurements only now.
No galaxy bias…but intrinsic alignment - galaxies aren't spheres.

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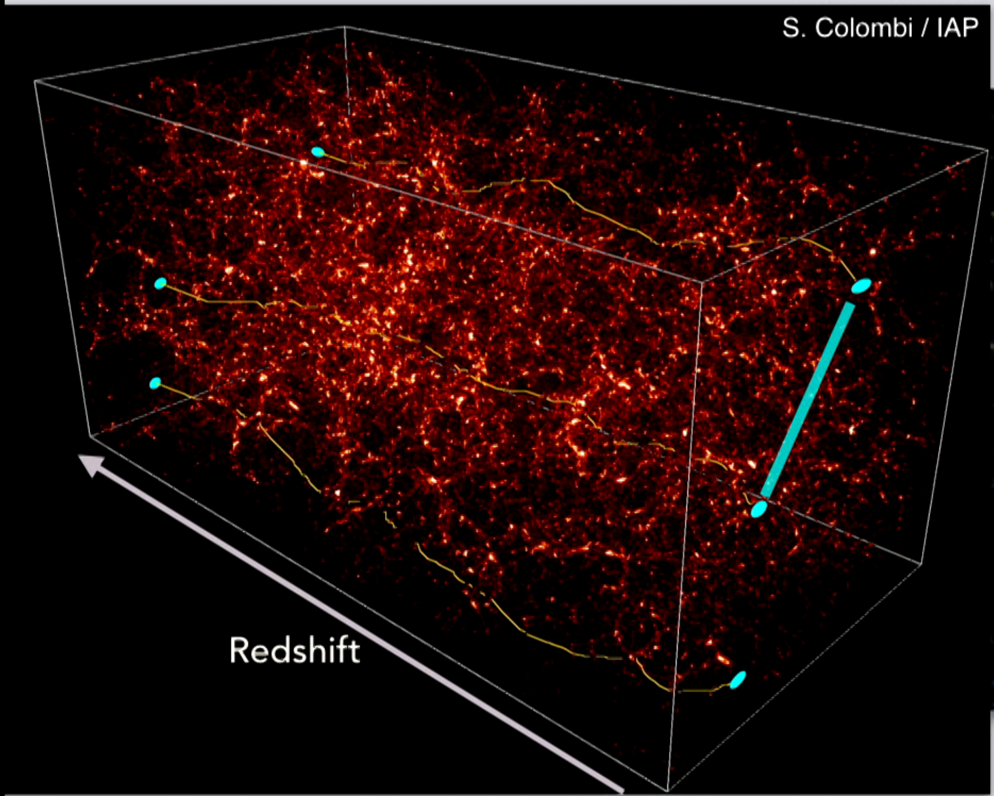


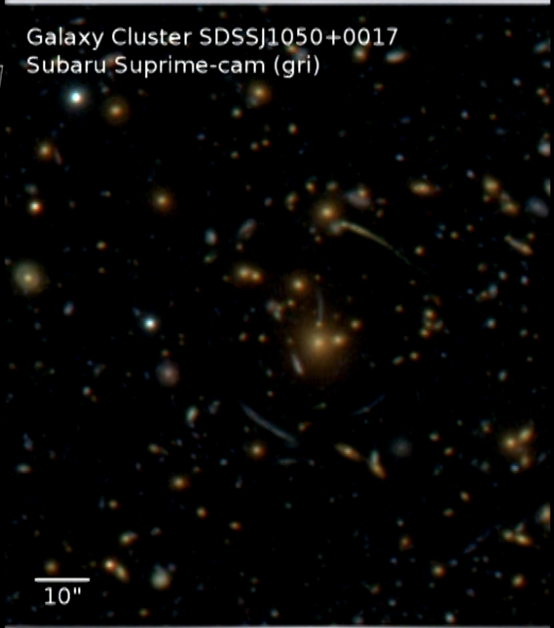


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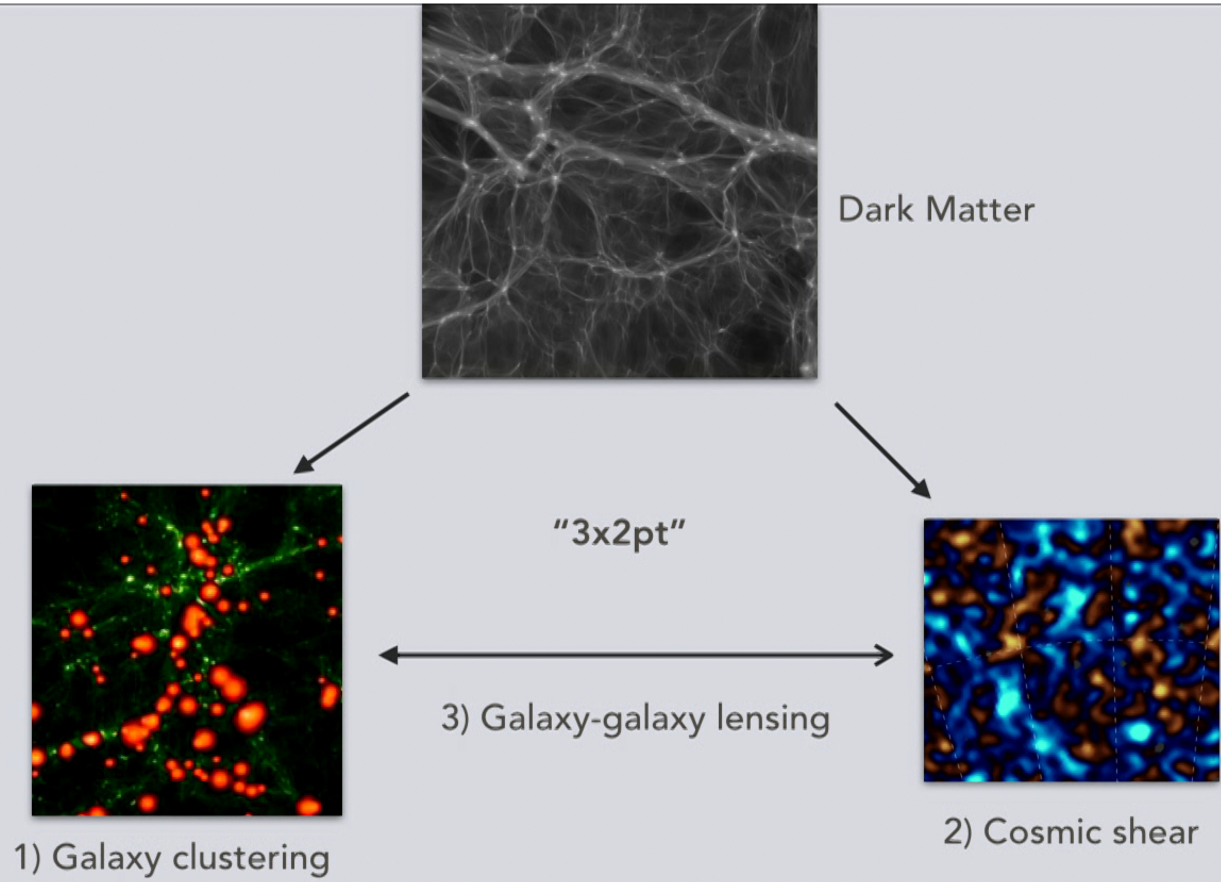
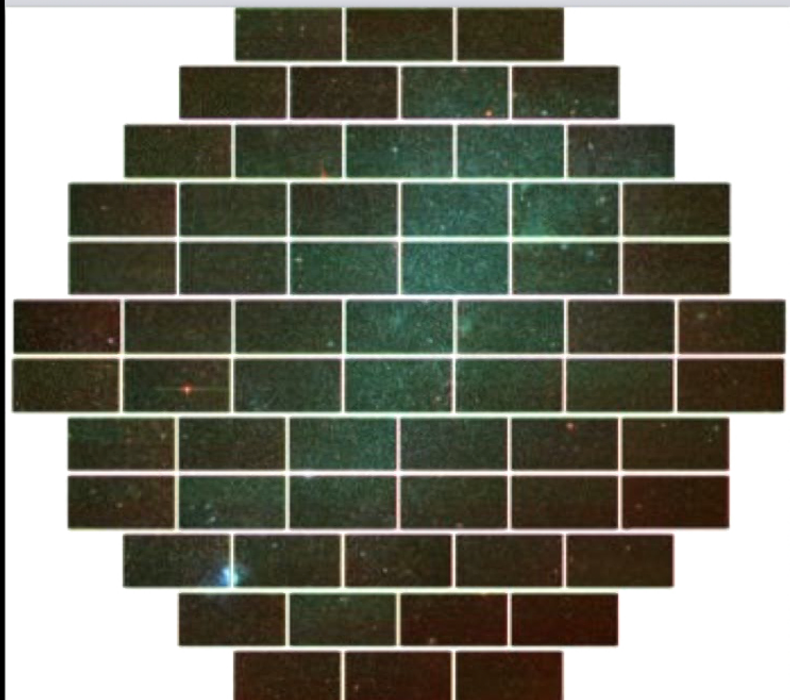



Combination of these three probes maximizes use of large-scale structure information and jointly and robustly constrains astrophysical and systematic parameters in the analysis

12

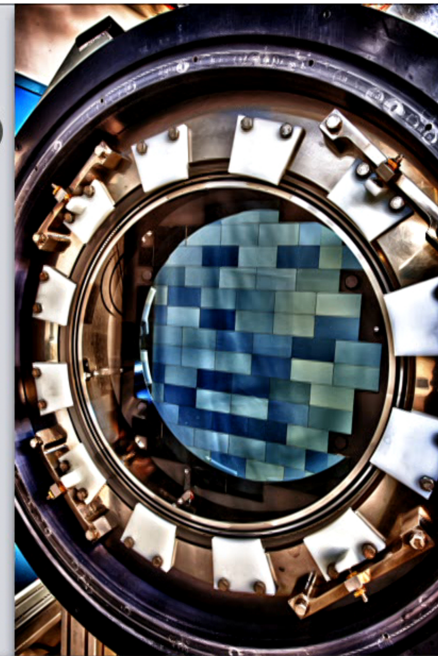
# The Dark Energy Survey

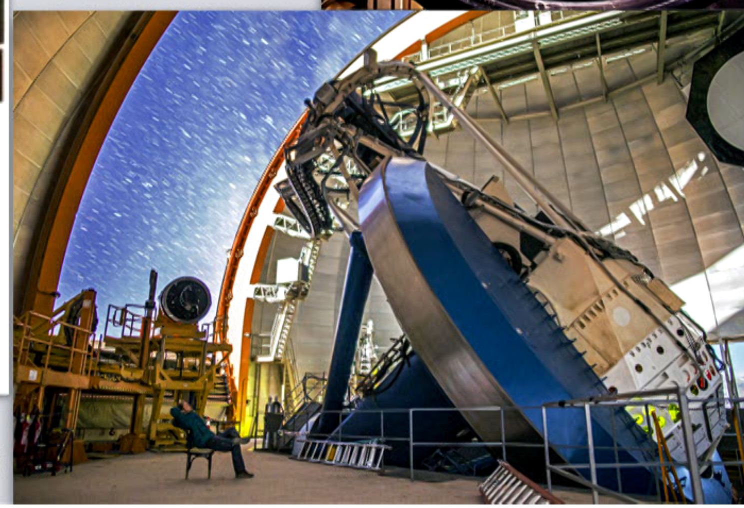
- Nominal 5 year, 5000 deg$^2$ survey to 24th mag (approx. 10 visits)
- DECam: a 570 Mpix camera mounted on 4m Blanco Telescope
- Approx. 3 deg$^2$ field-of-view
- Observing in *grizY* filters
- Beginning analysis of 1st 3 years of data — final observing year



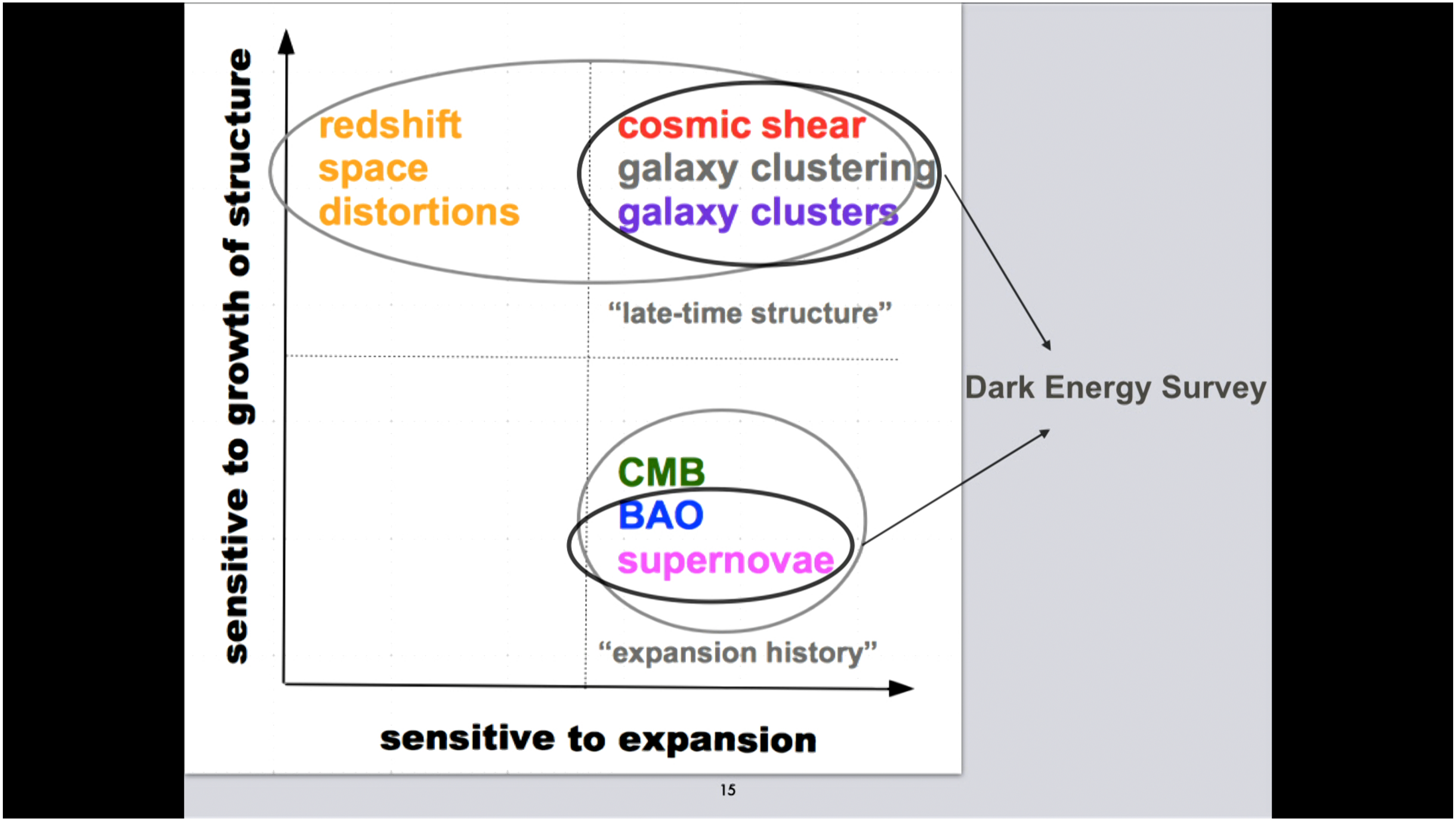
Small Magellanic Cloud

13






Funded by:
U.S. DEPARTMENT OF ENERGY
Office of Science
Finep
~500 participants
~140 publications
Collaborating institutions:
NCSA
THE OHIO STATE UNIVERSITY
LMU
SLAC
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



sensitive to growth of structure
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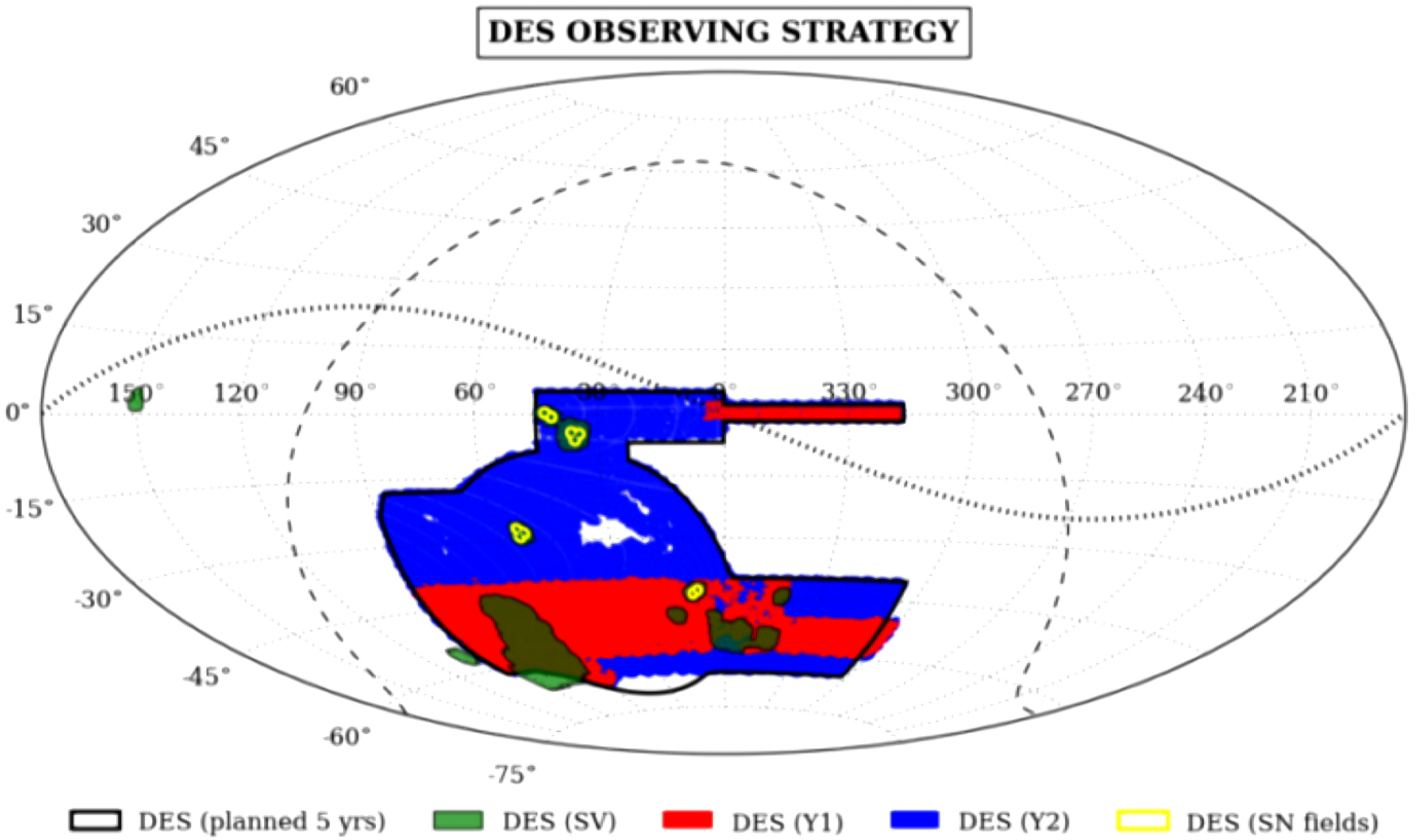
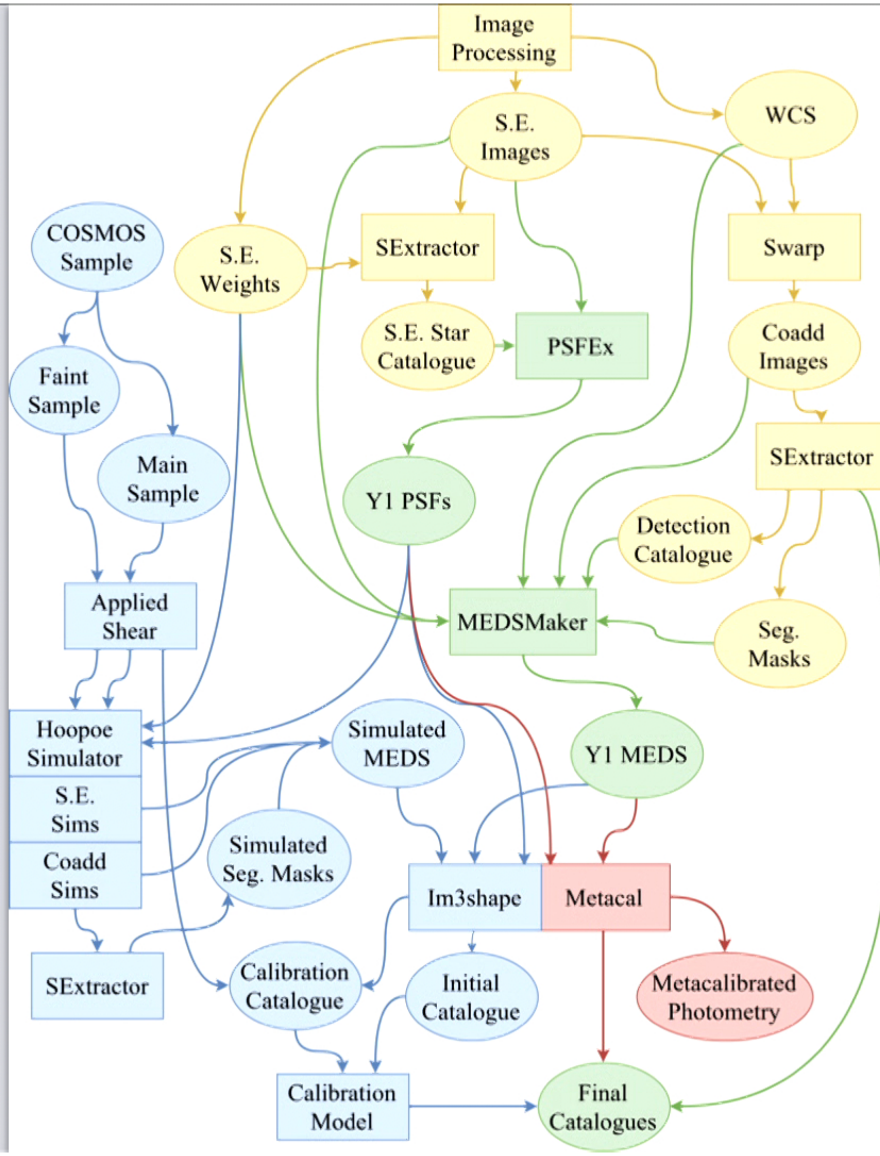
15


DES OBSERVING STRATEGY
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
150°
120°
90°
60°
0°
330°
300°
270°
240°
210°
DES (planned 5 yrs)
DES (SV)
DES (Y1)
DES (Y2)
DES (SN fields)

# Weak Lensing in DES



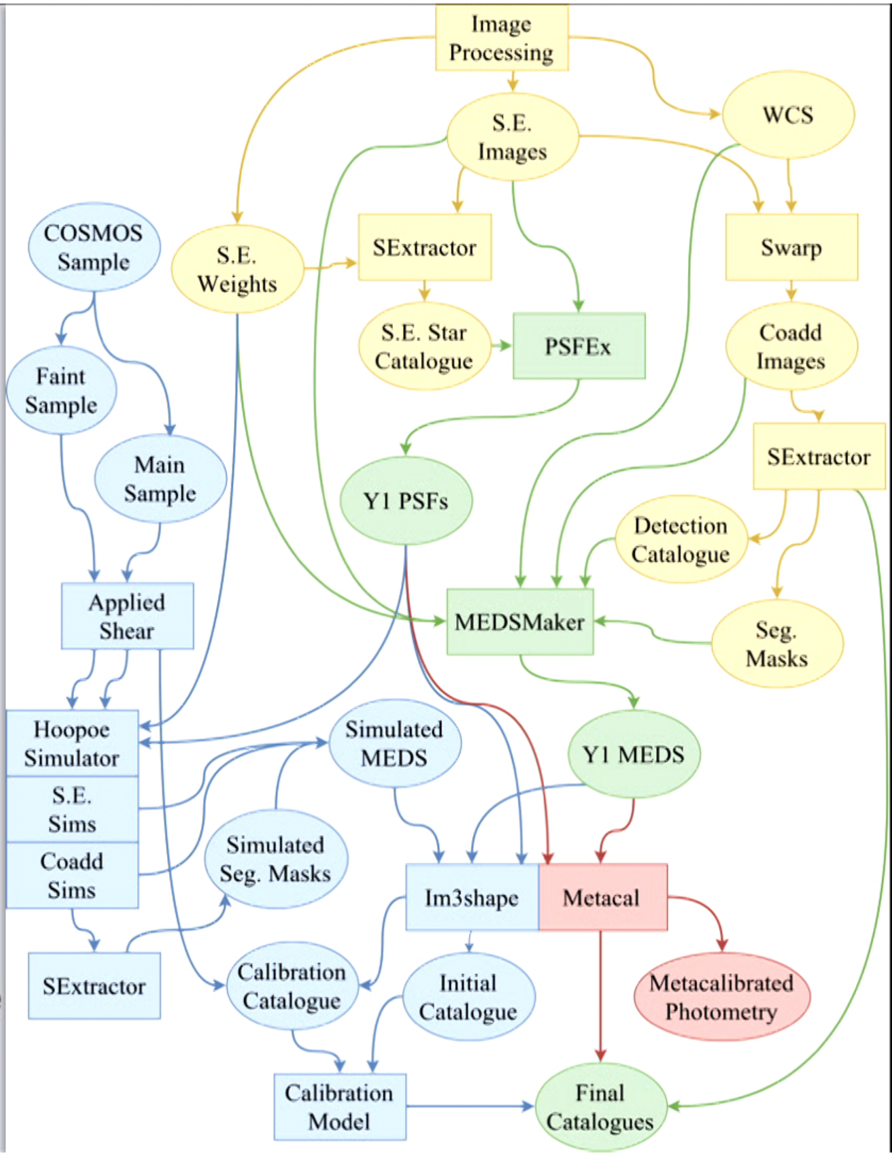
## Shape Measurement

The long road to producing a modern shape catalog

Each bubble often represents months of development and millions of CPU hrs.

Everything but yellow region done via coordination of scientists within the DES weak lensing working group

- **Yellow**: Reduced and calibrated images (DES DM)
- **Green**: PSF measurement and data formatting
- **Red**: Metacalibration pipeline
- **Blue**: Im3shape pipeline Including image simulations

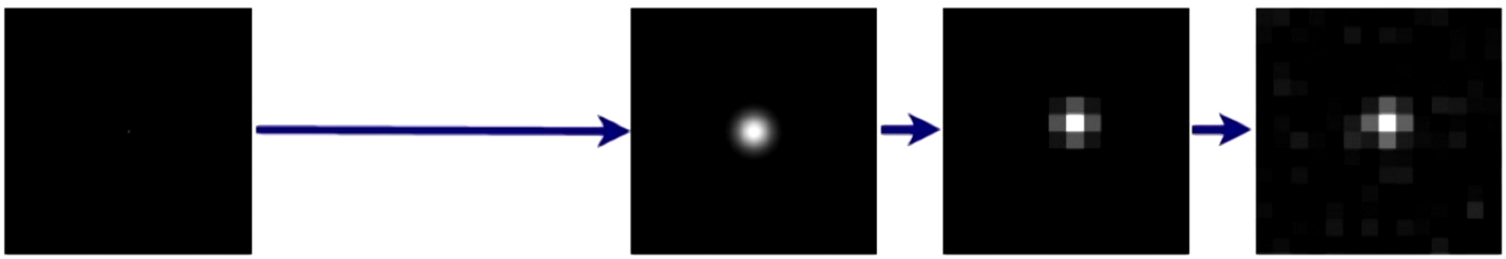


# Shape Measurement

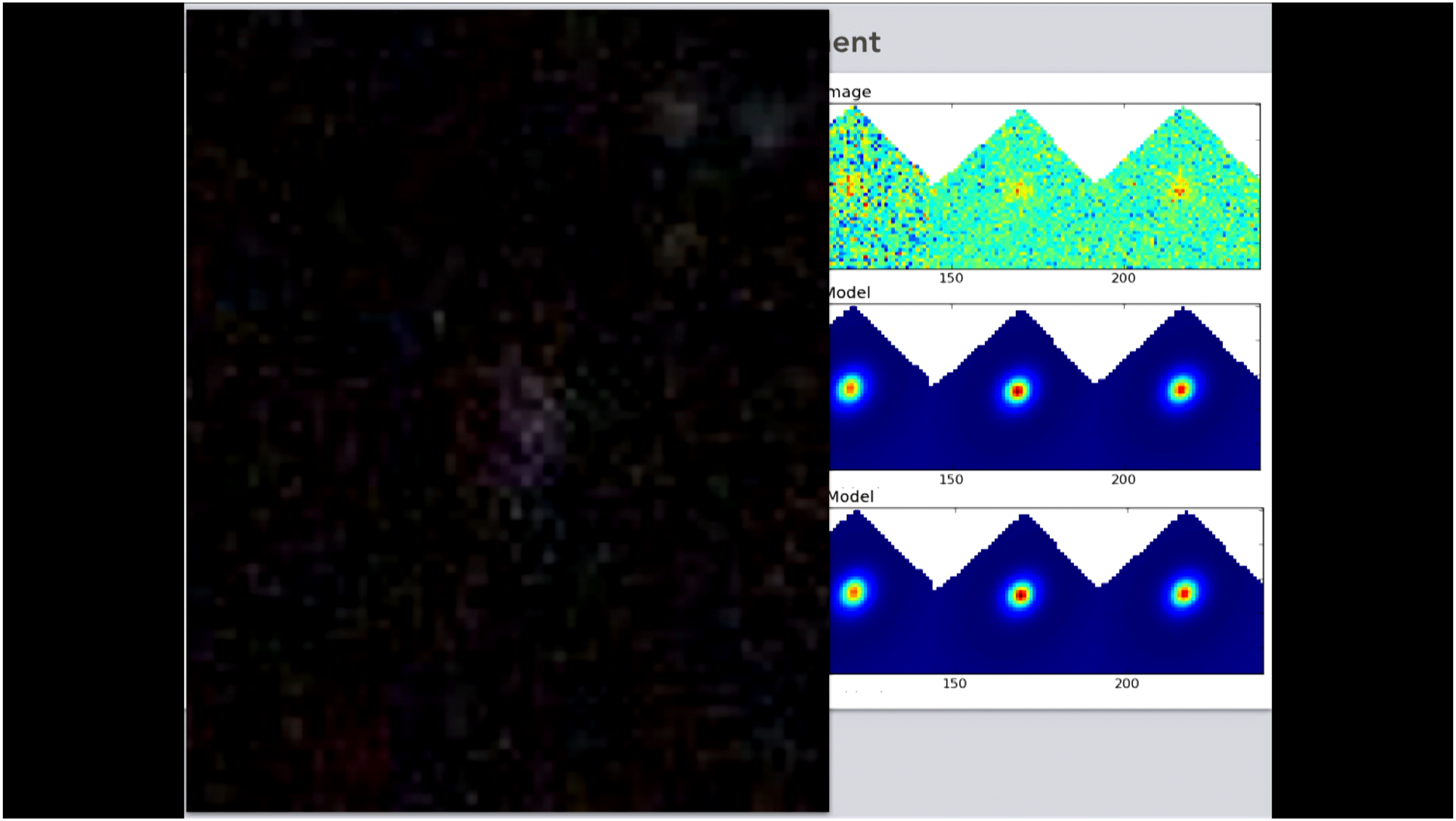
**Galaxies:** Intrinsic galaxy shapes to measured image:

Bridle et al. 2008


**Stars:** Point sources to star images:



# Shape Measurement



ent
mage
150
200
Model
150
200
Model
150
200

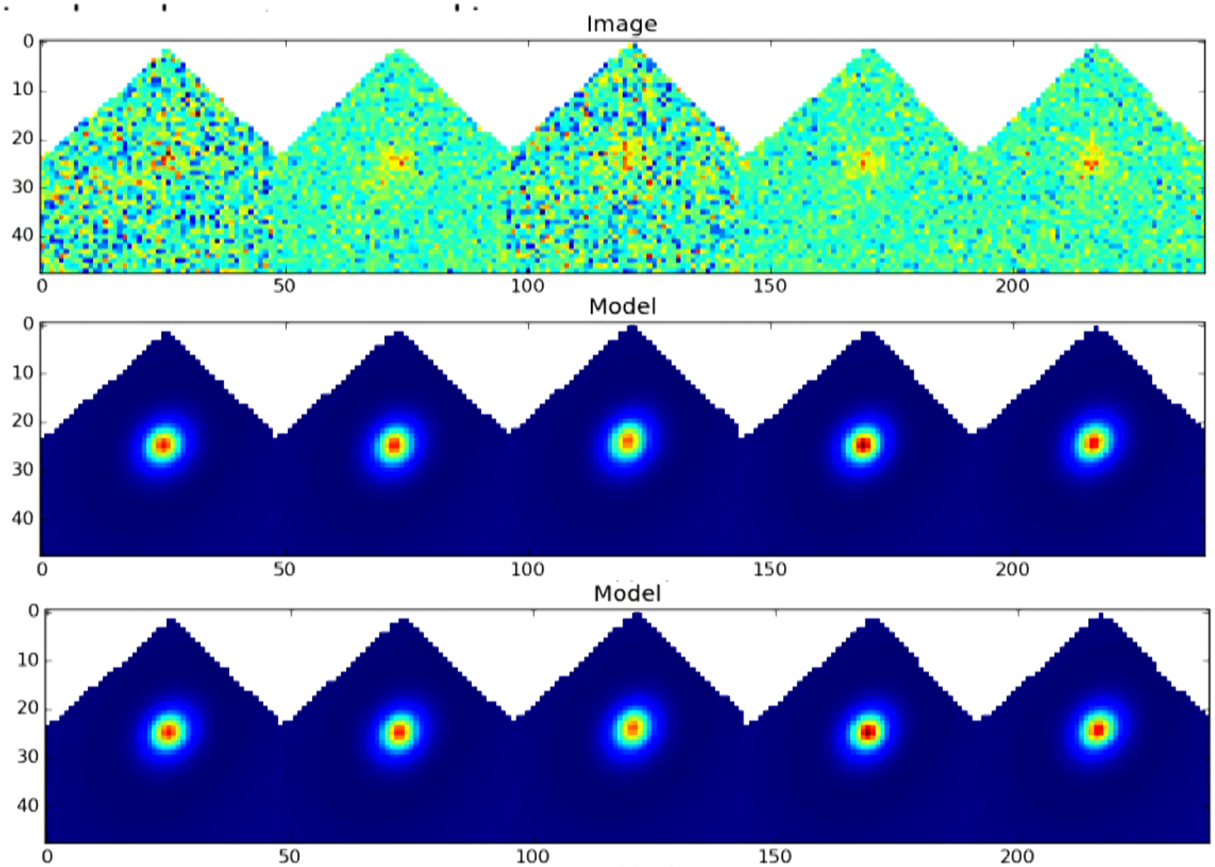
# Shape Measurement

**Galaxies:** Intrins

Intrinsic galaxy
(shape unknown)

**Stars:** Point sou

Intrinsic star
(point source)



## Shape Measurement

Caption:

The struggle to create a shape catalog worthy of cosmic shear measurements…

Featuring key contributors to the DES Y1 Key cosmology effort at a recent shape measurement workshop.

*"Everything you might think to do (or not do) will impart a shear selection bias. You will never discover it until months later."* — A wise weak lenser

23

# Dark Energy Survey Year 1 Shape catalogs

Two fully independently calibrated and very different shape measurement methods produce complementary catalogs over 1500 sq. deg. (Zuntz et al. 2017)

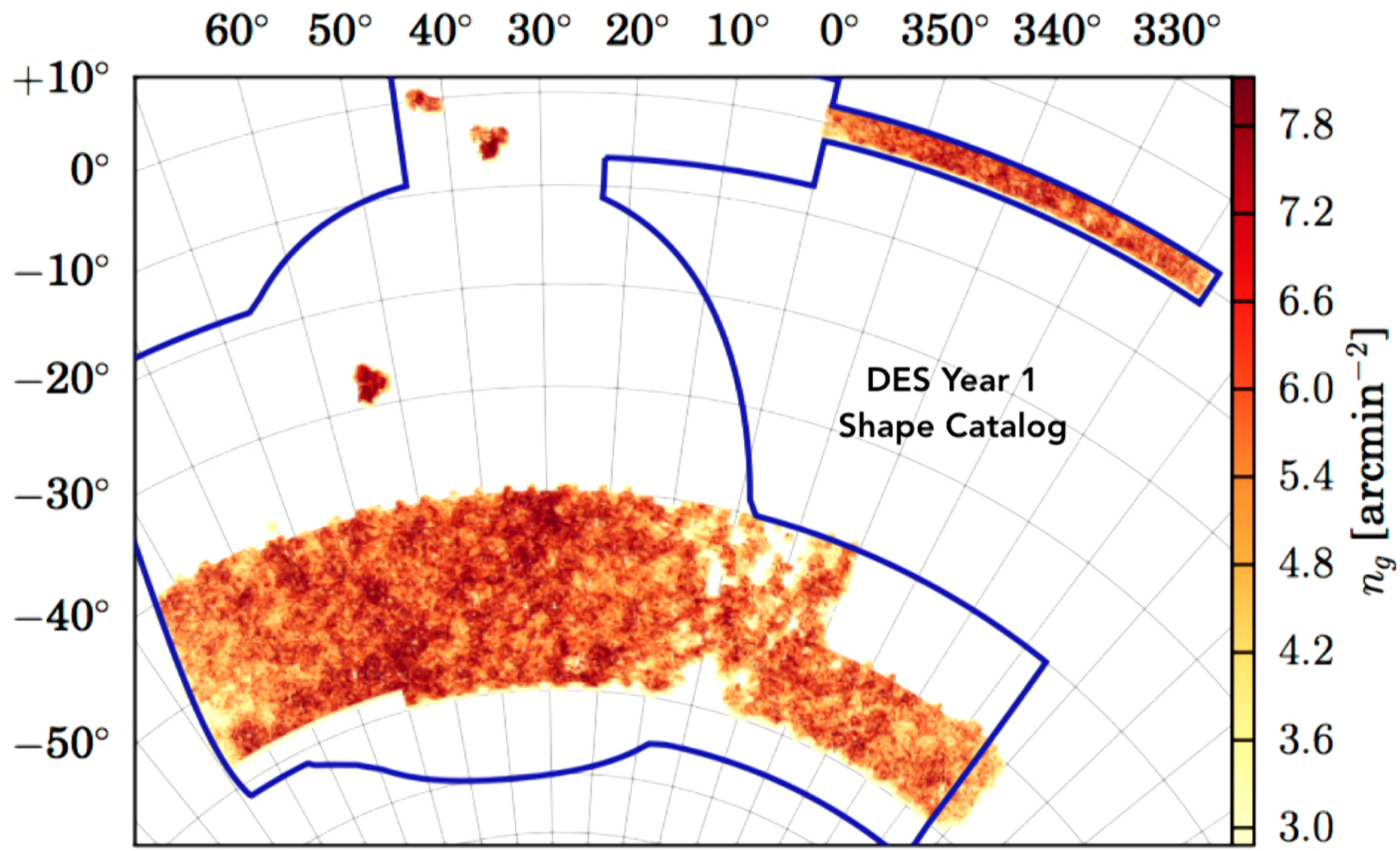
**Metacalibration - Sheldon et al 2017**

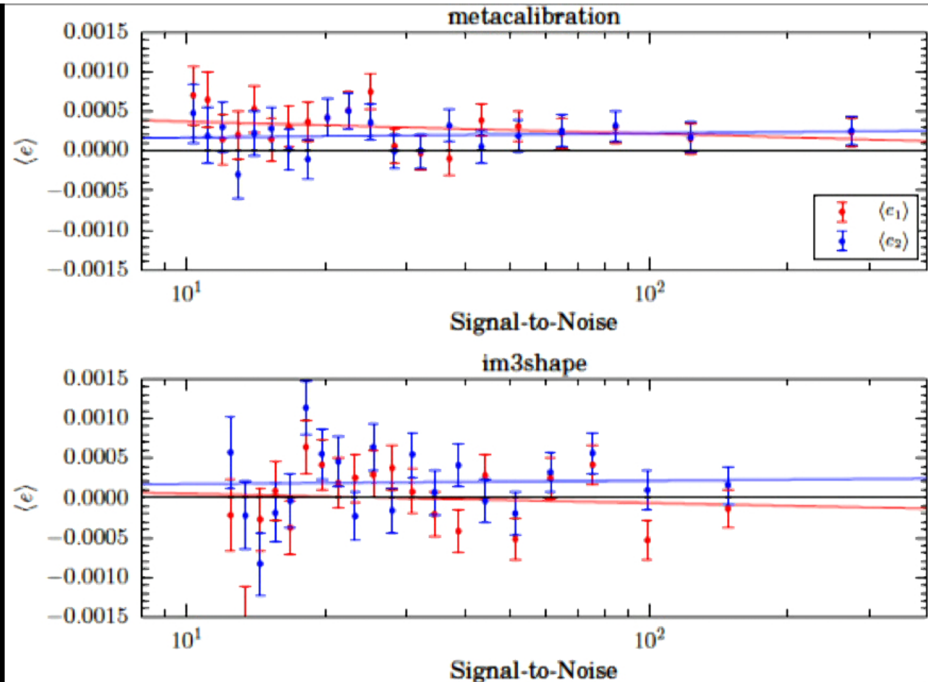
- 34.8M galaxies
- Factors of 2 (4) in number (area) of objects from next-best cosmic shear catalog
- riz-band shape measurement
- Calibration performed by directly measuring the shear response and selection bias galaxy-by-galaxy (create 5 versions of all catalogs and measurements)

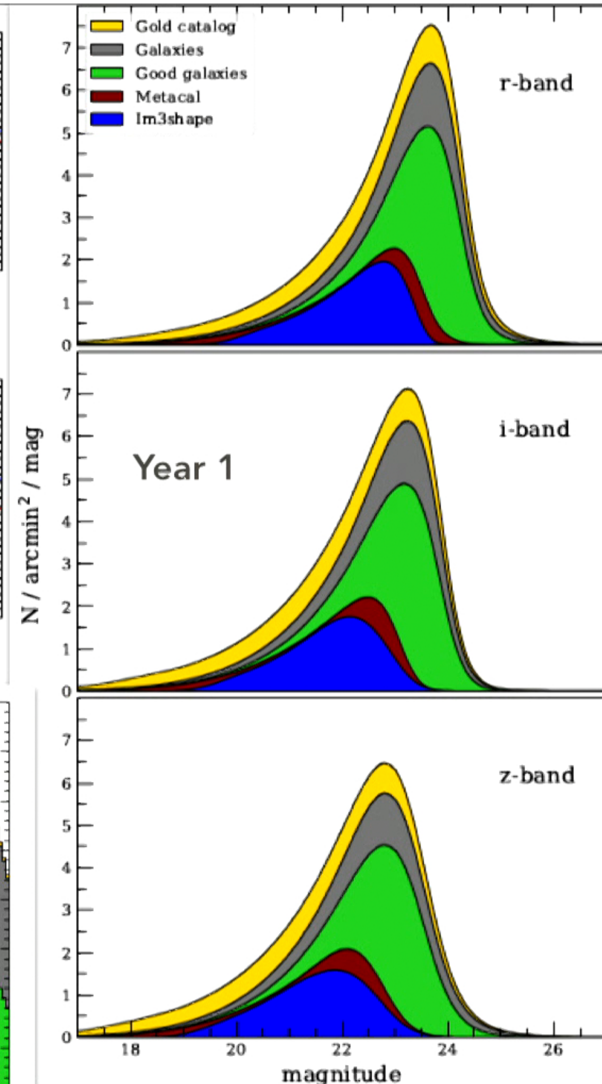
**Im3shape - Zuntz et al 2013** (unchanged from DES SV)

- 21.9M galaxies
- r-band shape measurement
- Calibrated by redesigned, state-of-the-art image simulations

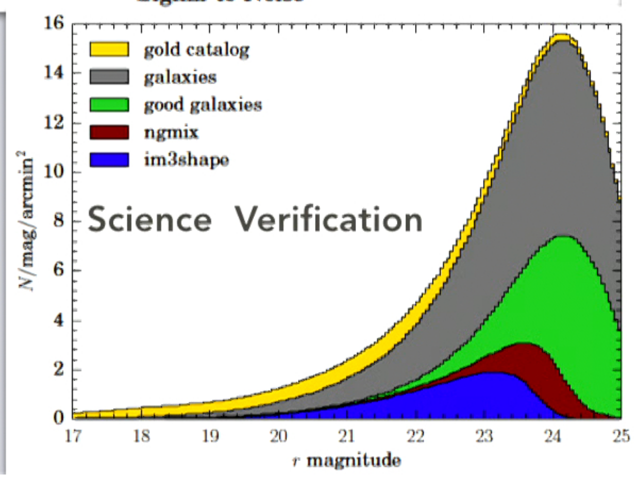
These catalogs are ground-breaking… Not just in size, but in quality - precision of bias corrections in metacalibration shears is unprecedented, and tests indicate it can perform at levels required for Stage IV surveys in the coming decade.


60° 50° 40° 30° 20° 10° 0° 350° 340° 330°
+10°
0°
−10°
−20°
−30°
−40°
−50°
DES Year 1
Shape Catalog
7.8
7.2
6.6
6.0
5.4
4.8
4.2
3.6
3.0
$n_g$ [arcmin$^{-2}$]



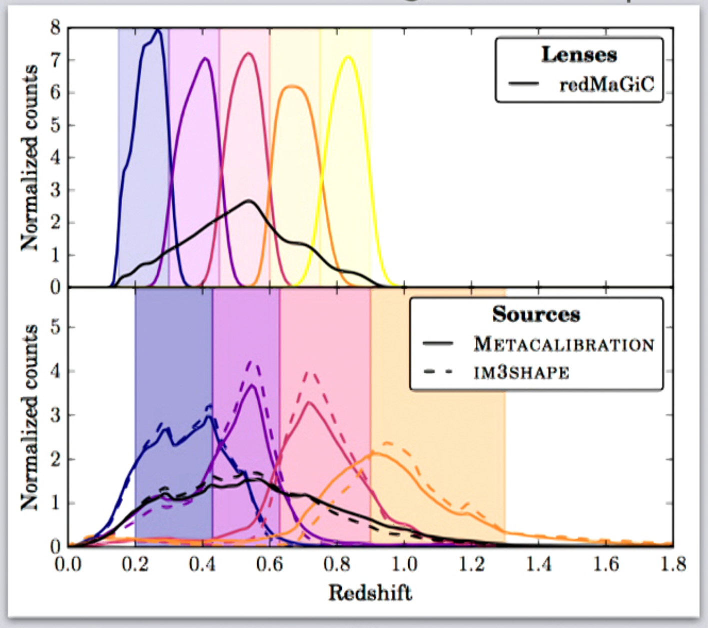

Understood, but outstanding, PSF measurement issues remain in Y1 and has been fixed for Y3.

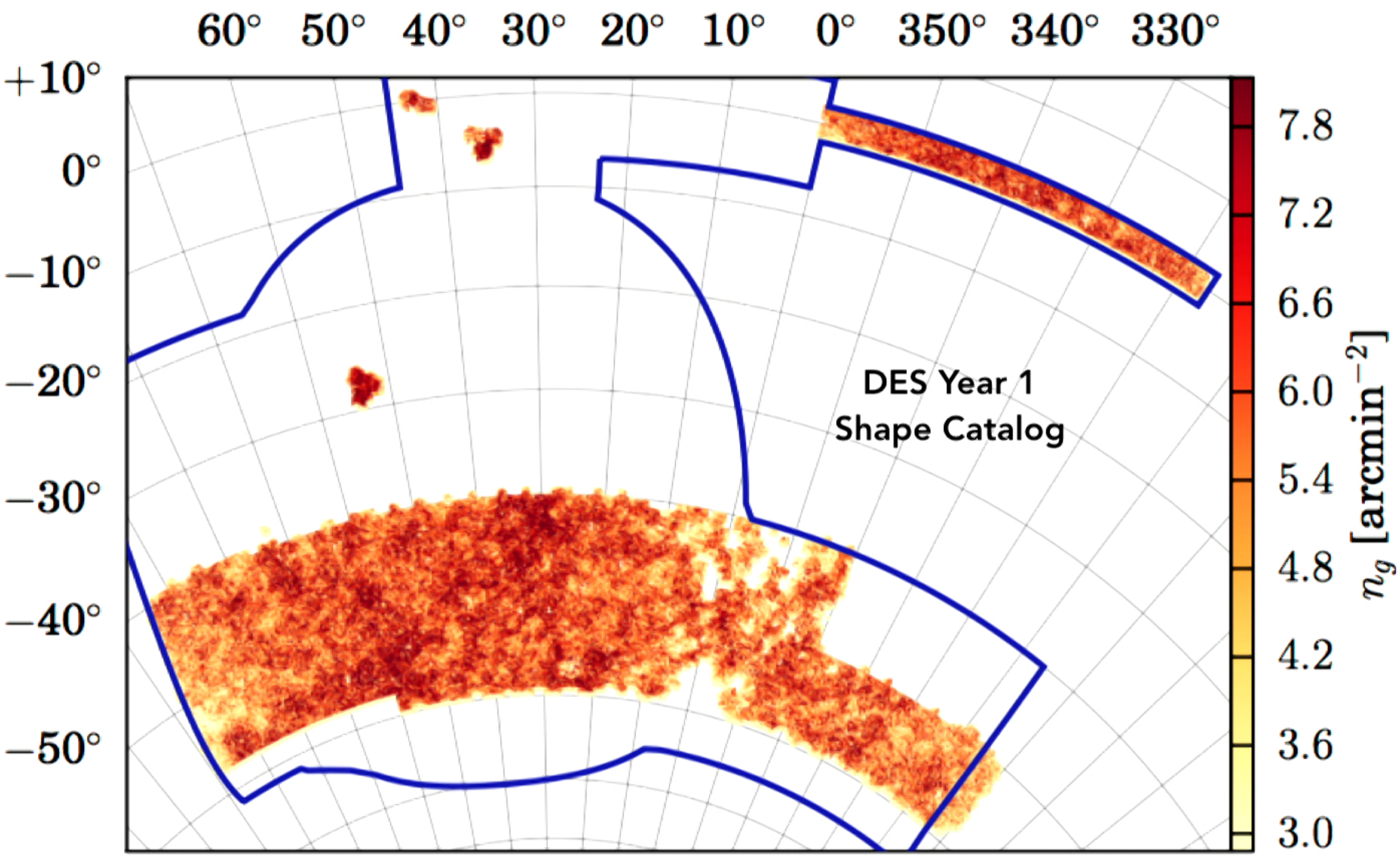


# Dark Energy Survey Year 1 Results

First cosmology constraints from main survey: large-scale structure combination of galaxy clustering and weak lensing

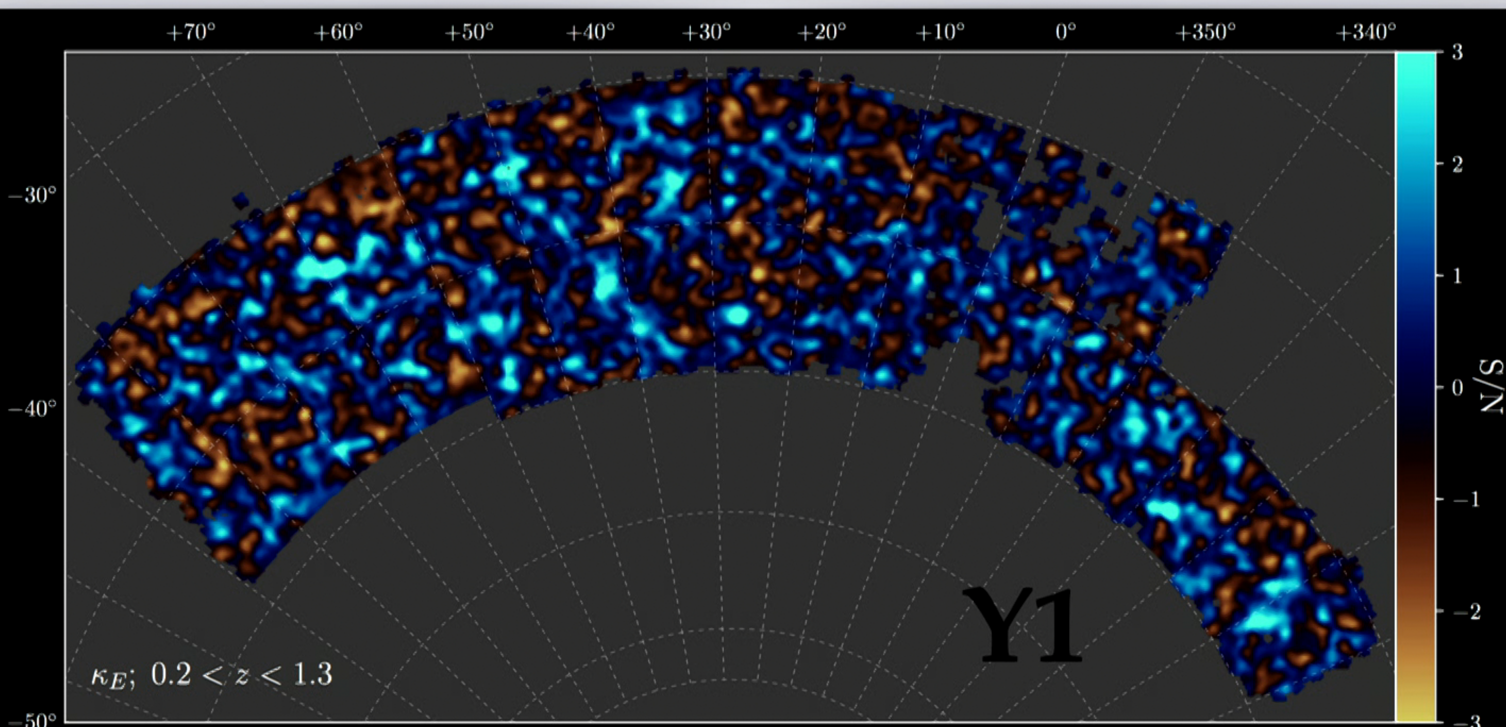
- Shapes of 26M galaxies were used for cosmology over 1321 deg$^2$
  - Factor of two larger shape catalog than current best competing cosmic shear meas.
  - Two independent shape measurement pipelines and calibration strategies
- 600k red-sequence galaxies used for clustering, chosen for precise redshift constraints




60° 50° 40° 30° 20° 10° 0° 350° 340° 330°
+10°
0°
−10°
−20°
−30°
−40°
−50°
DES Year 1
Shape Catalog
7.8
7.2
6.6
6.0
5.4
4.8
4.2
3.6
3.0
$n_g$ [arcmin$^{-2}$]

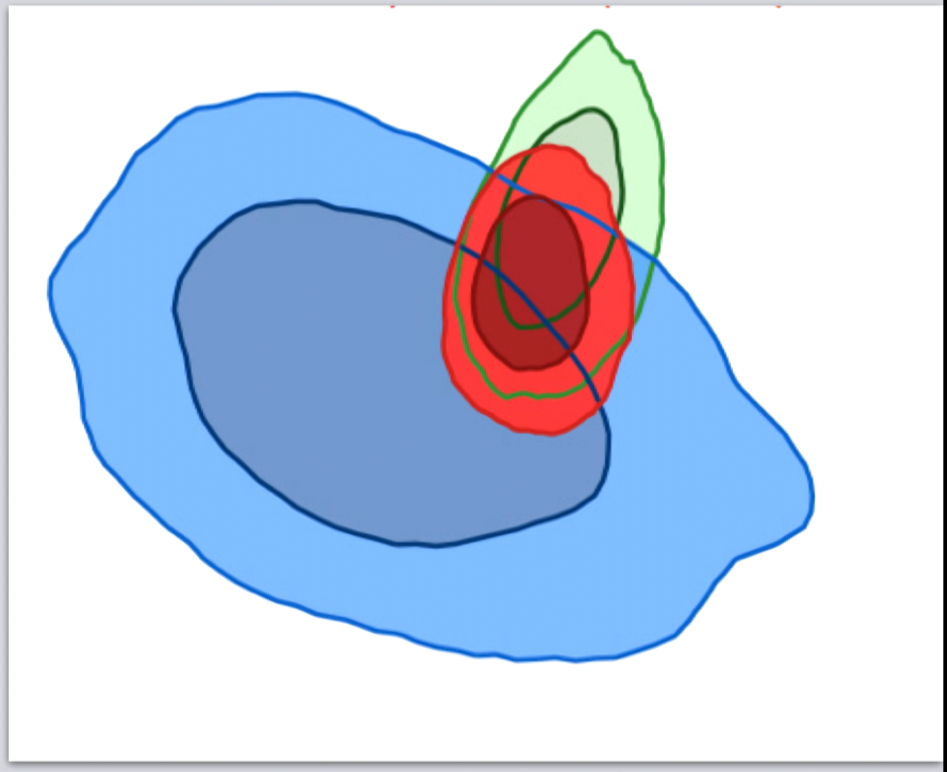
28

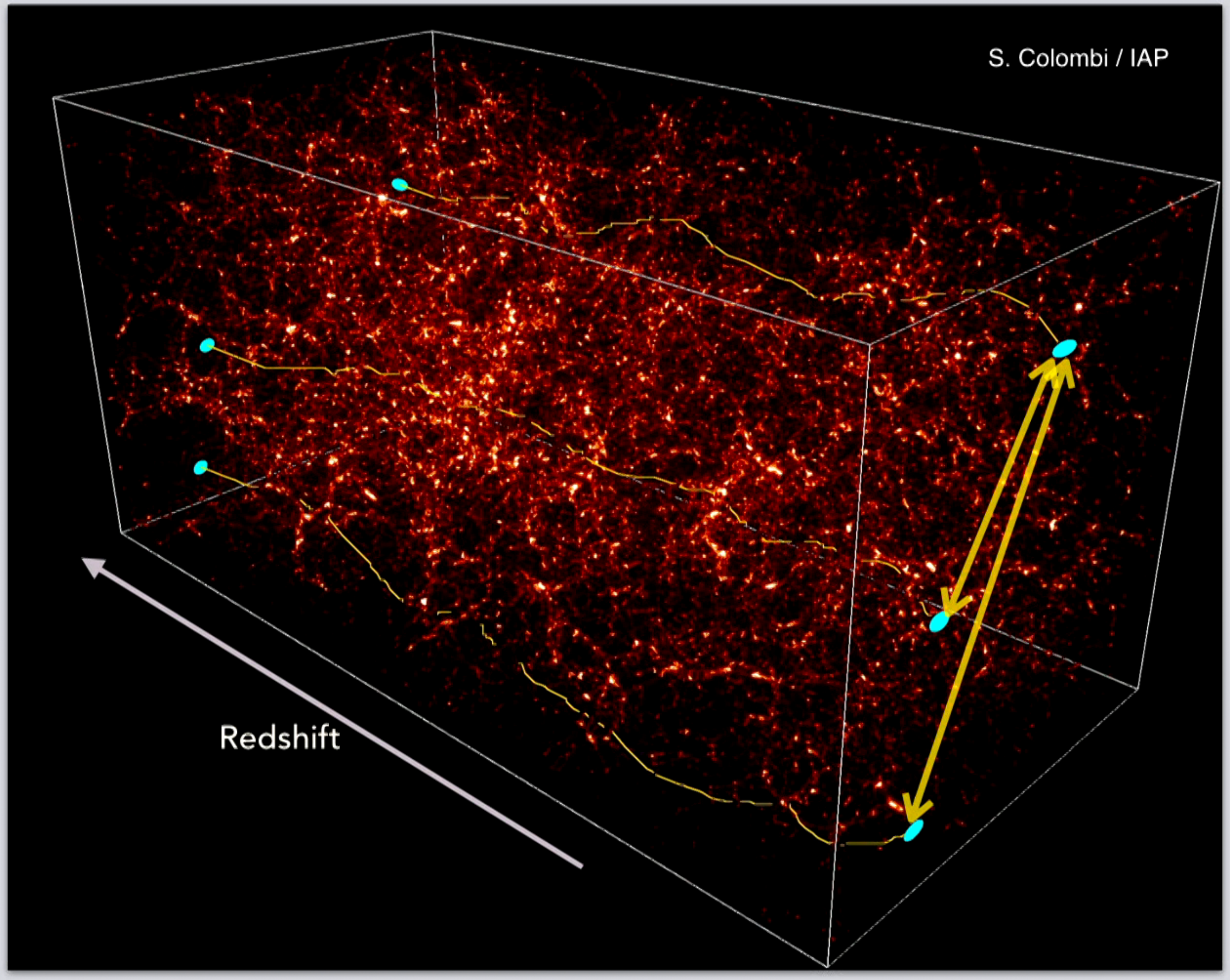
## Map of dark matter (convergence) — Chang et al. arXiv:1708.01535



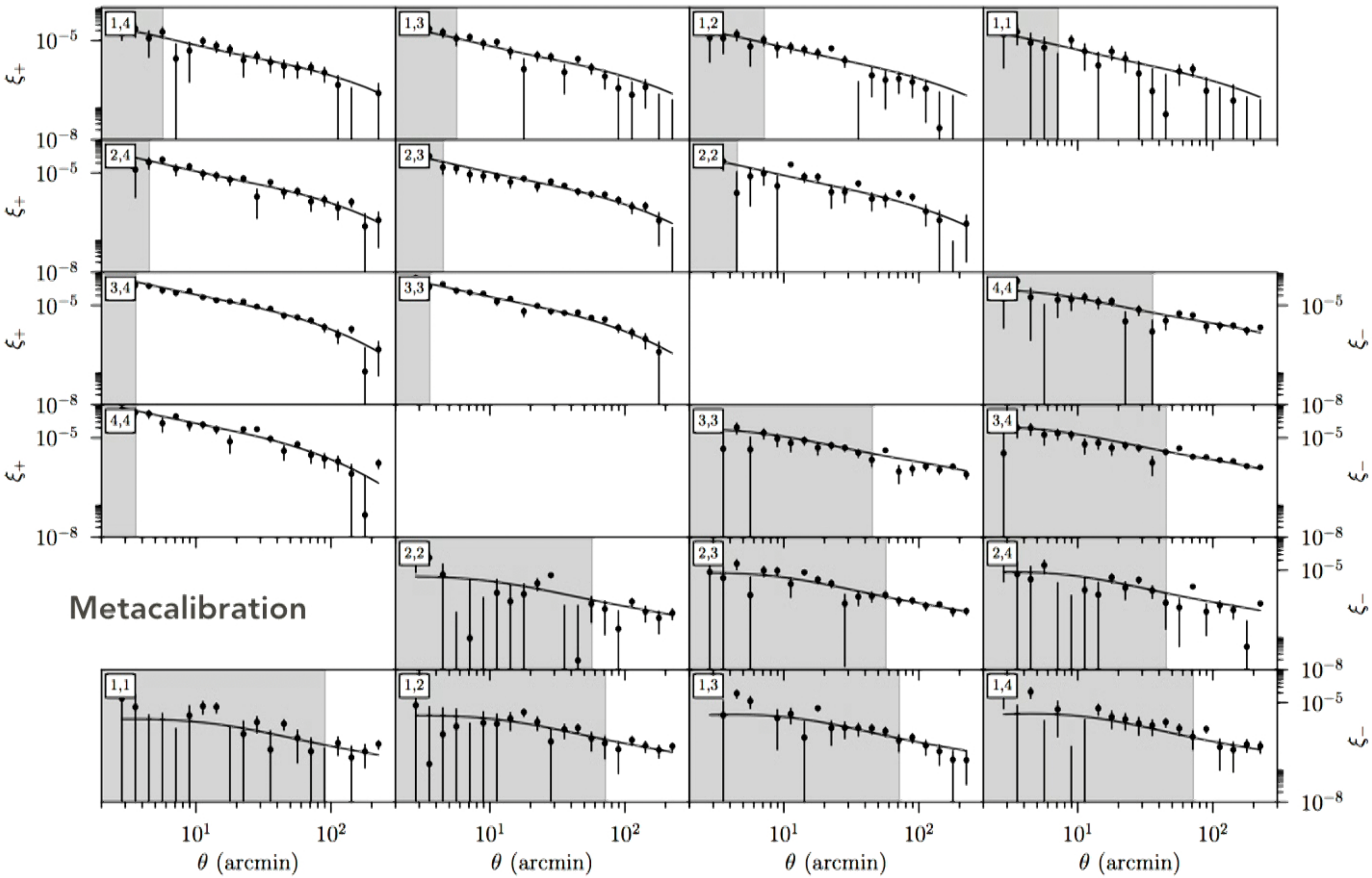

29

# Dark Energy Survey Year 1 Cosmology



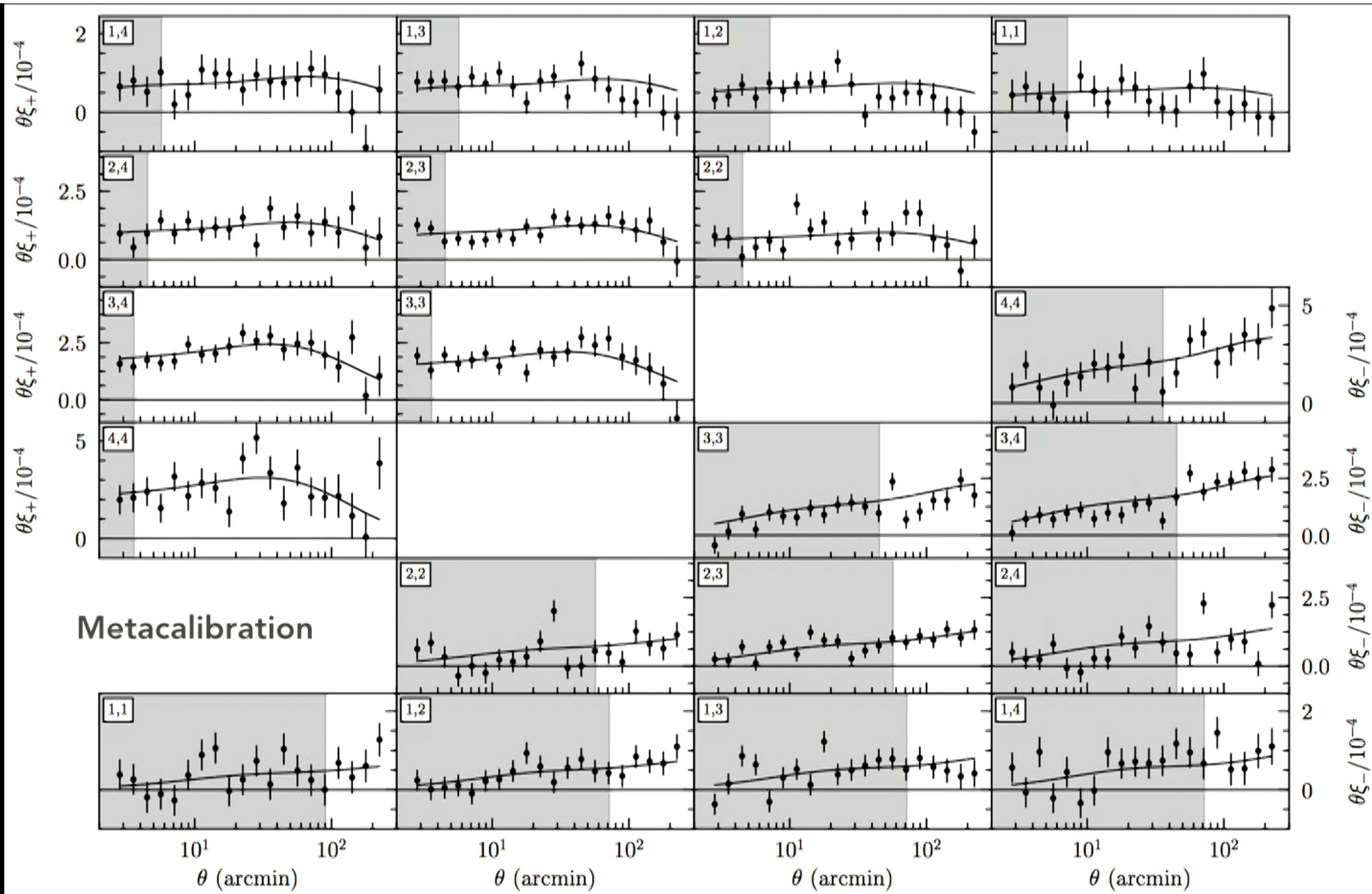



31




Troxel et al. arXiv:1708.01538

## Cosmic Shear

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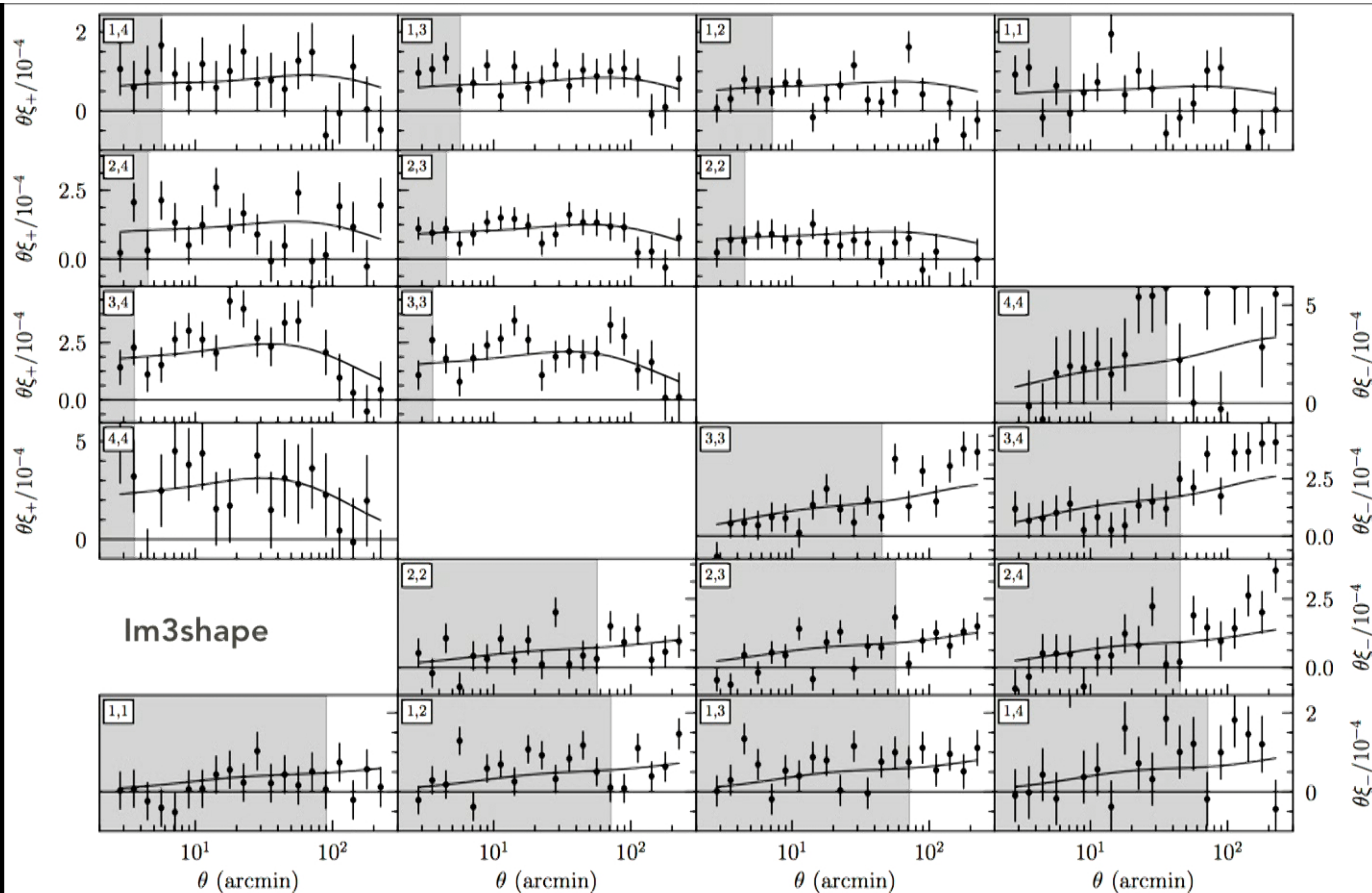
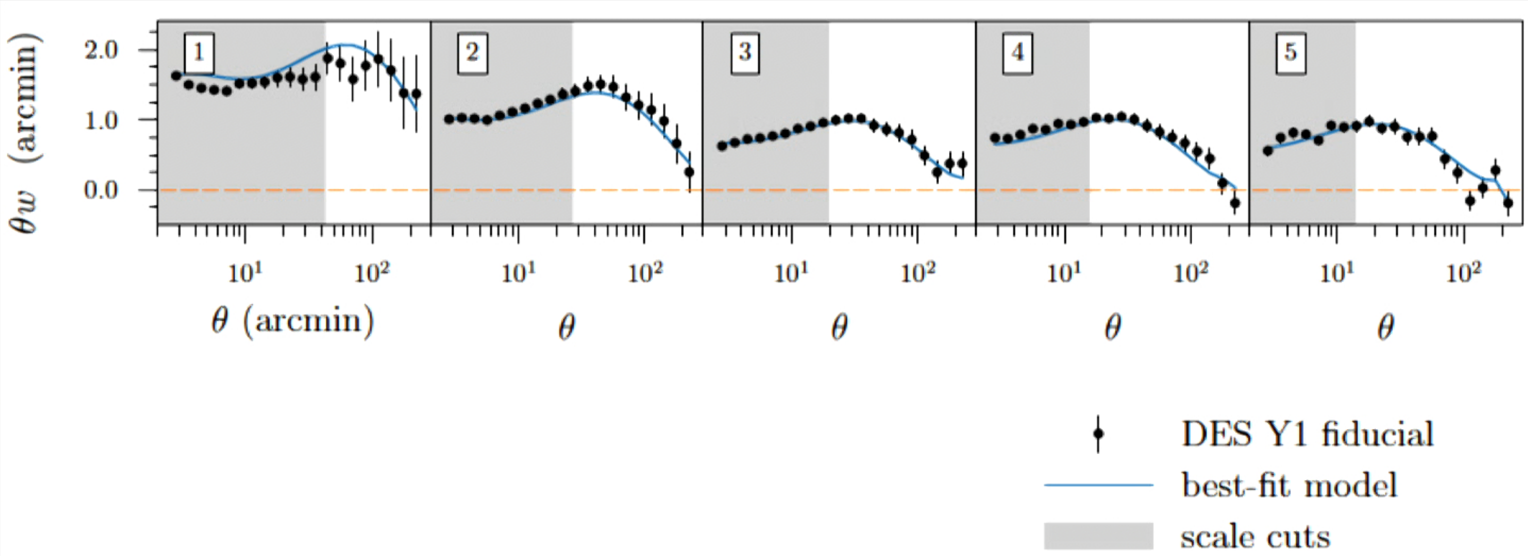



Troxel et al. arXiv:1708.01538

## Cosmic Shear

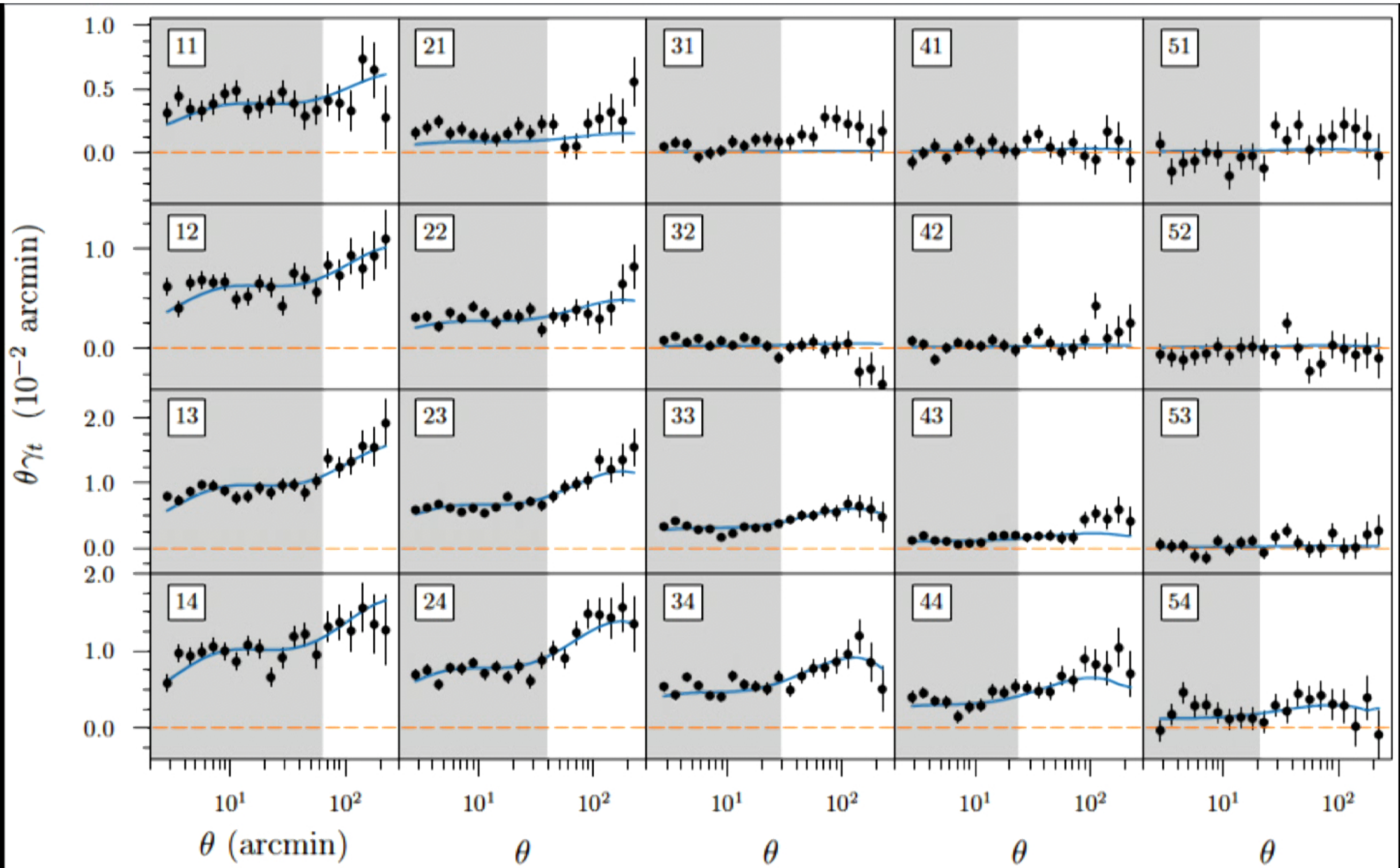
34




Elvin-Poole et al. arXiv:1708.01536

35

## Galaxy Clustering




Prat et al. arXiv:1708.01537

# Tangential Shear

36

# Dark Energy Survey Year 1 Results

Primary cosmological analysis combining 1) galaxy clustering, 2) cosmic shear, and 3) galaxy-galaxy lensing to probe large-scale structure of the Universe

- Most significant detection of cosmic shear in a galaxy survey to date — 27 sigma (compare to 10 in Science Verification measurement)
- Two-stage blinding
  - Catalog-level blinding unknown to anyone
  - Blinding of all individual results (e.g., cosmological parameter values)
- Redundant and independent components of core analysis:
  - Two shape measurement pipelines and calibration strategies
  - Two redshift calibration methods
  - Two analysis pipelines (theory & parameter sampling)
  - Two parameter sampling methods

A set of ~~9~~ 13 papers (~~~250~~ 300+ pages of results) released in Aug. + more to come.

## Combined "3x2pt" cosmological analysis

Combination of:

1) Galaxy clustering
2) Cosmic shear
3) Galaxy-galaxy lensing

Marginalizing over:

- 6 (+w) cosmological parameters
  - including the neutrino mass density with prior from oscillation exps.
- 7 astrophysical parameters
- 13 systematic parameters

Data and analysis testing and validation extended over more than two years

Unblinded & saw results for the first time July 7 — public release 27 days later.

| Parameter | Prior |
|---|---|
| **Cosmology** | |
| $\Omega_m$ | flat (0.1, 0.9) |
| $A_s$ | flat $(5 \times 10^{-10}, 5 \times 10^{-9})$ |
| $n_s$ | flat (0.87, 1.07) |
| $\Omega_b$ | flat (0.03, 0.07) |
| $h$ | flat (0.55, 0.91) |
| $\Omega_\nu h^2$ | flat$(5 \times 10^{-4}, 10^{-2})$ |
| $w$ | flat $(-2, -0.33)$ |
| **Lens Galaxy Bias** | |
| $b_i(i = 1, 5)$ | flat (0.8, 3.0) |
| **Intrinsic Alignment** | |
| $A_{\rm IA}(z) = A_{\rm IA}[(1+z)/1.62]^{\eta_{\rm IA}}$ | |
| $A_{\rm IA}$ | flat $(-5, 5)$ |
| $\eta_{\rm IA}$ | flat $(-5, 5)$ |
| **Lens photo-$z$ shift (red sequence)** | |
| $\Delta z_l^1$ | Gauss $(0.001, 0.008)$ |
| $\Delta z_l^2$ | Gauss $(0.002, 0.007)$ |
| $\Delta z_l^3$ | Gauss $(0.001, 0.007)$ |
| $\Delta z_l^4$ | Gauss $(0.003, 0.01)$ |
| $\Delta z_l^5$ | Gauss $(0.0, 0.01)$ |
| **Source photo-$z$ shift** | |
| $\Delta z_s^1$ | Gauss $(-0.001, 0.016)$ |
| $\Delta z_s^2$ | Gauss $(-0.019, 0.013)$ |
| $\Delta z_s^3$ | Gauss $(+0.009, 0.011)$ |
| $\Delta z_s^4$ | Gauss $(-0.018, 0.022)$ |
| **Shear calibration** | |
| $m^i_{\rm METACALIBRATION}(i = 1, 4)$ | Gauss $(0.012, 0.023)$ |
| $m^i_{\rm IM3SHAPE}(i = 1, 4)$ | Gauss $(0.0, 0.035)$ |

38

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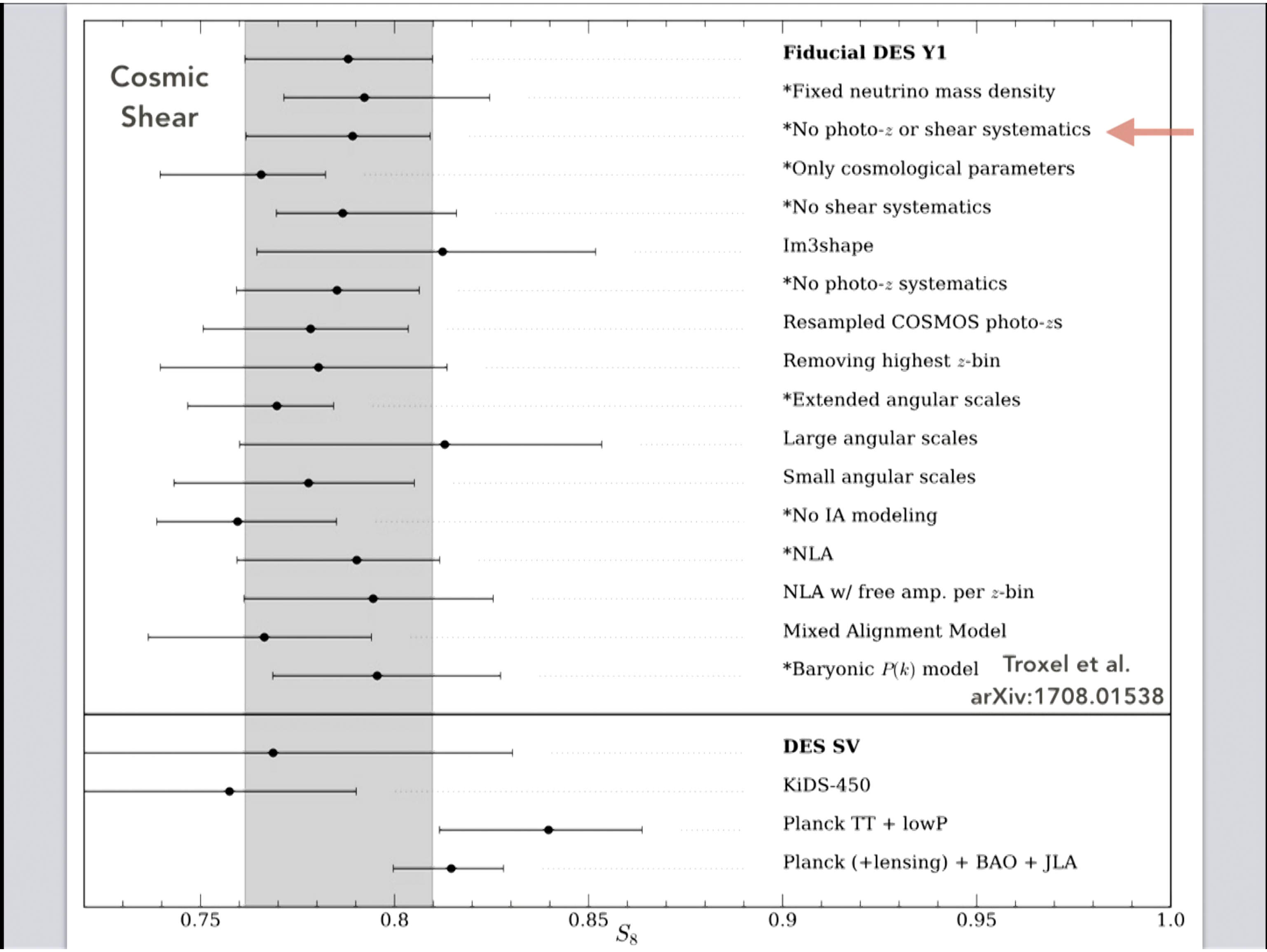
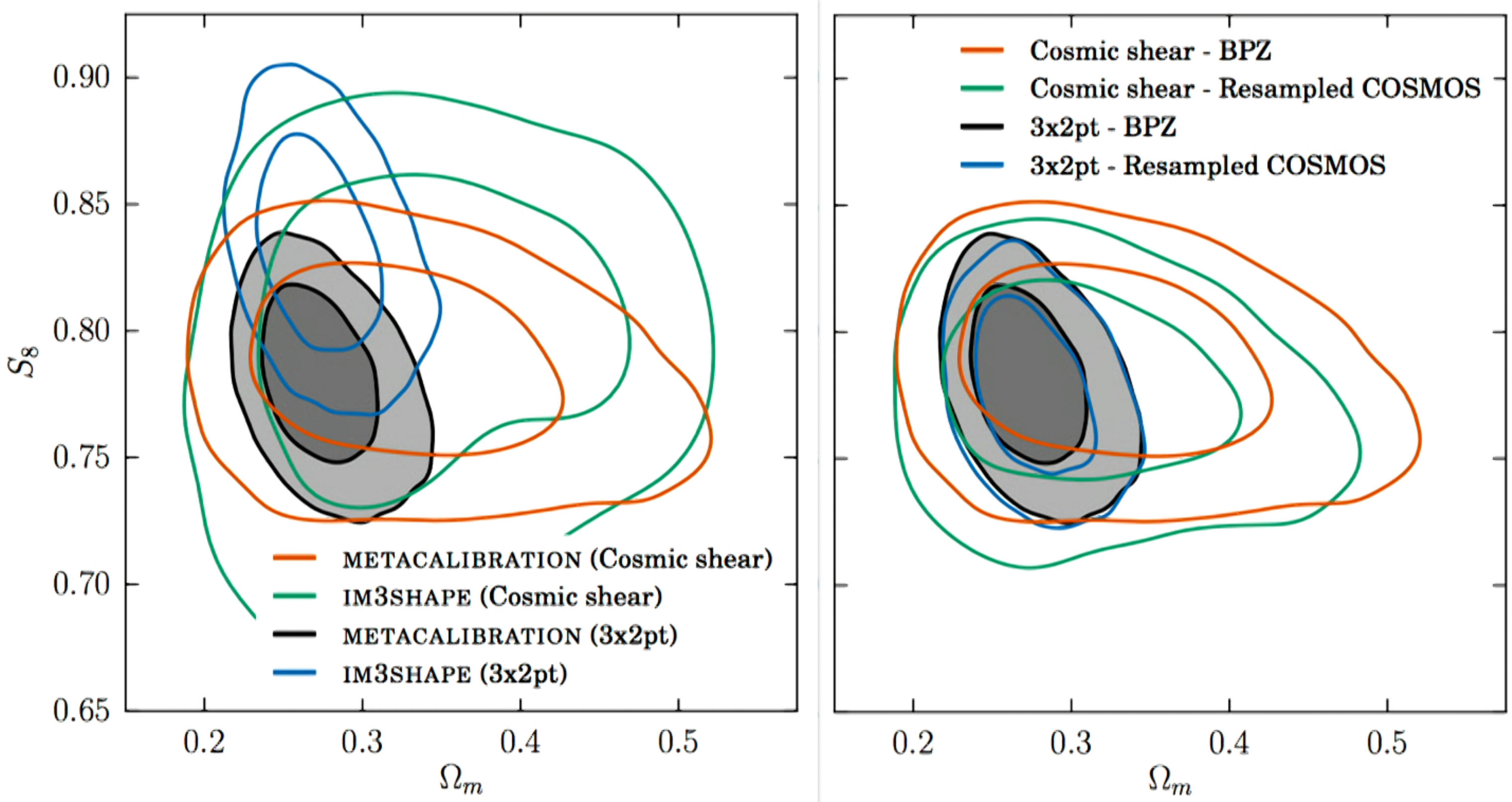
| $m^i_{\rm METACALIBRATION} (i = 1, 4)$ | Gauss $(0.012, 0.023)$ |
| $m^i_{\rm IM3SHAPE} (i = 1, 4)$ | Gauss $(0.0, 0.035)$ |


Cosmic
Shear
Fiducial DES Y1
*Fixed neutrino mass density
*No photo-z or shear systematics
*Only cosmological parameters
*No shear systematics
Im3shape
*No photo-z systematics
Resampled COSMOS photo-zs
Removing highest z-bin
*Extended angular scales
Large angular scales
Small angular scales
*No IA modeling
*NLA
NLA w/ free amp. per z-bin
Mixed Alignment Model
*Baryonic P(k) model
Troxel et al.
arXiv:1708.01538
DES SV
KiDS-450
Planck TT + lowP
Planck (+lensing) + BAO + JLA
0.75
0.8
0.85
0.9
0.95
1.0
S8

## Internal consistency




Shear measurement consistency

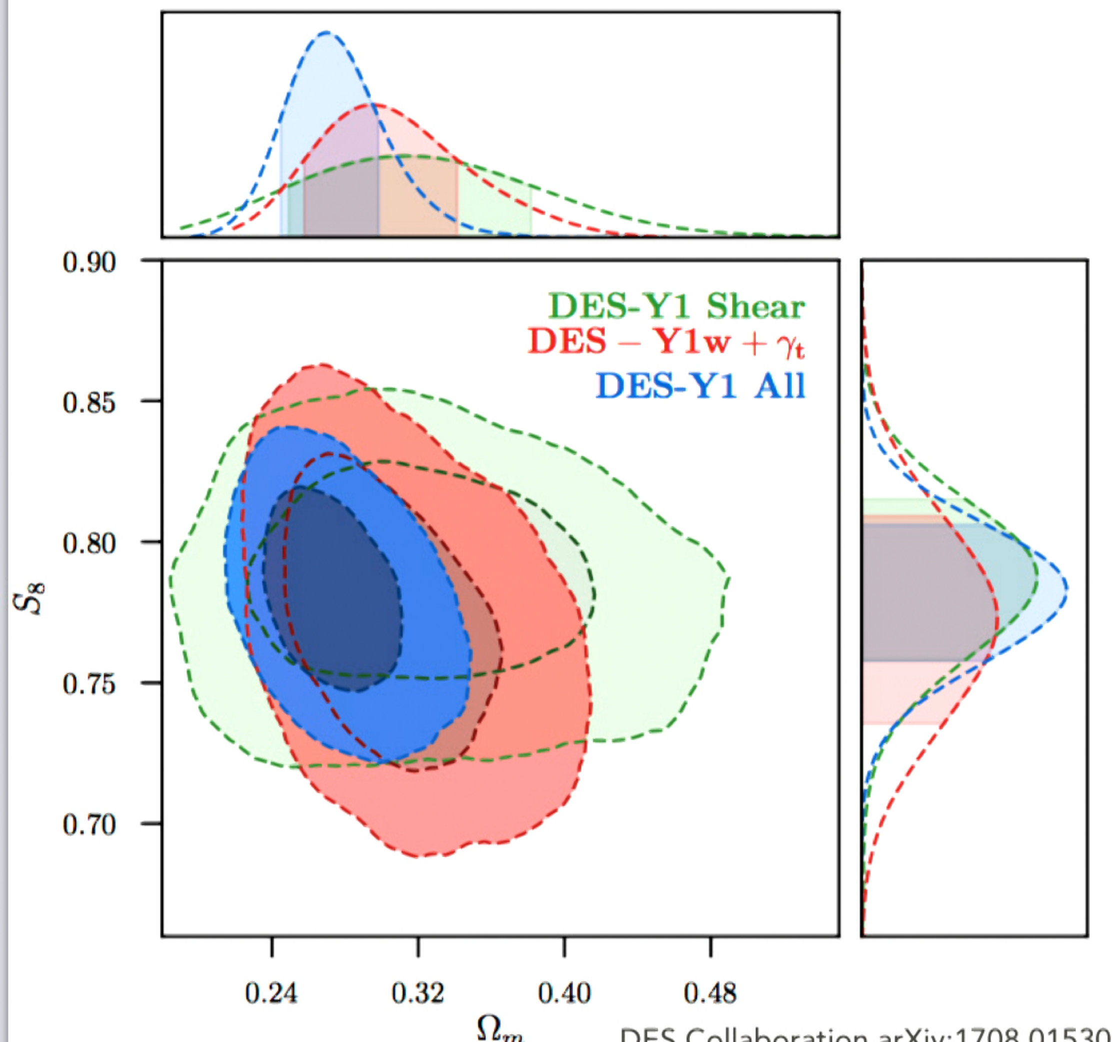
Photo-z consistency

## Internal consistency

Agreement of lensing and galaxy clustering probes of large-scale structure has never been demonstrated at this level of statistical precision.

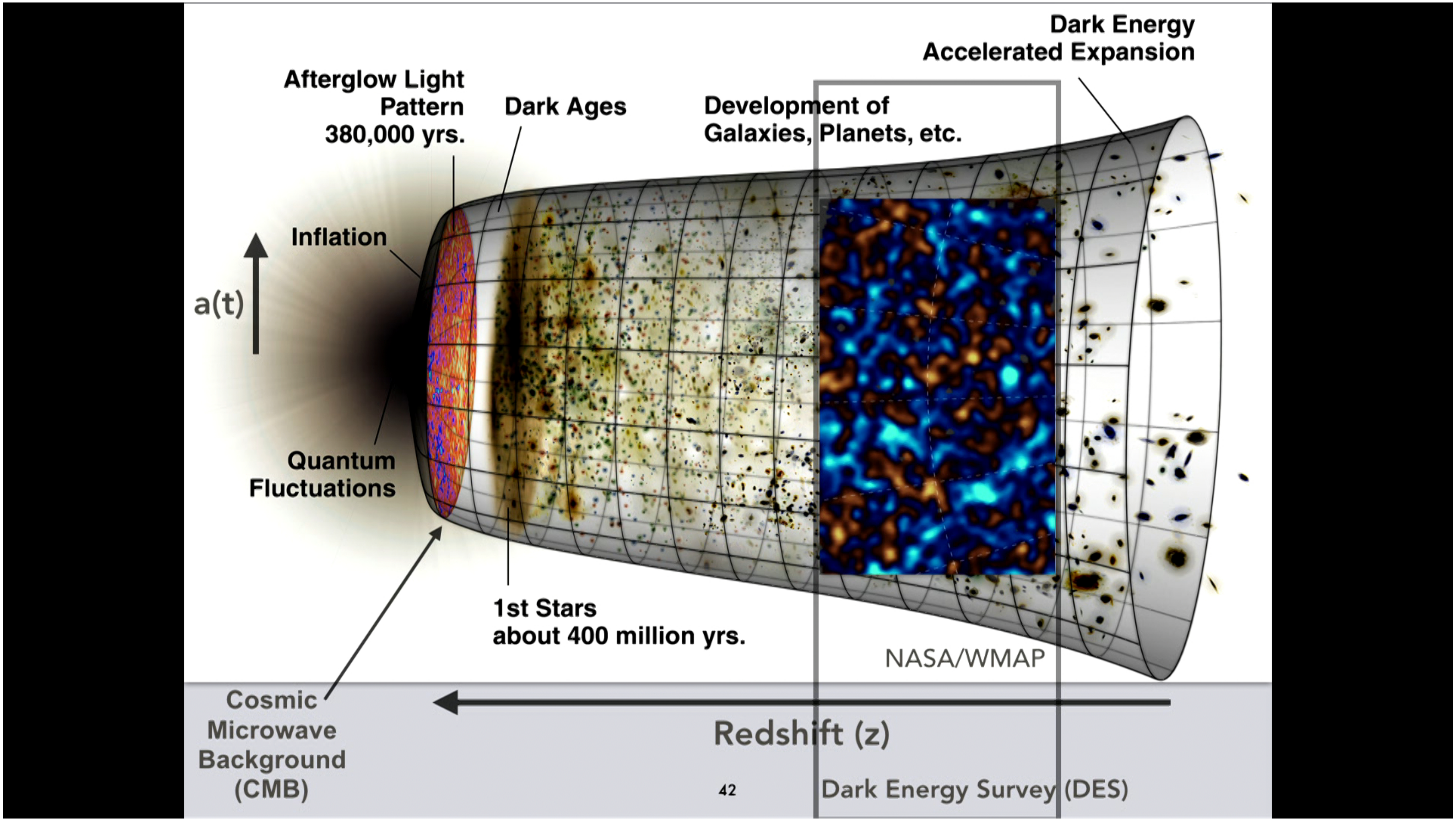
Most precise constraint on cosmology from large-scale structure to date.

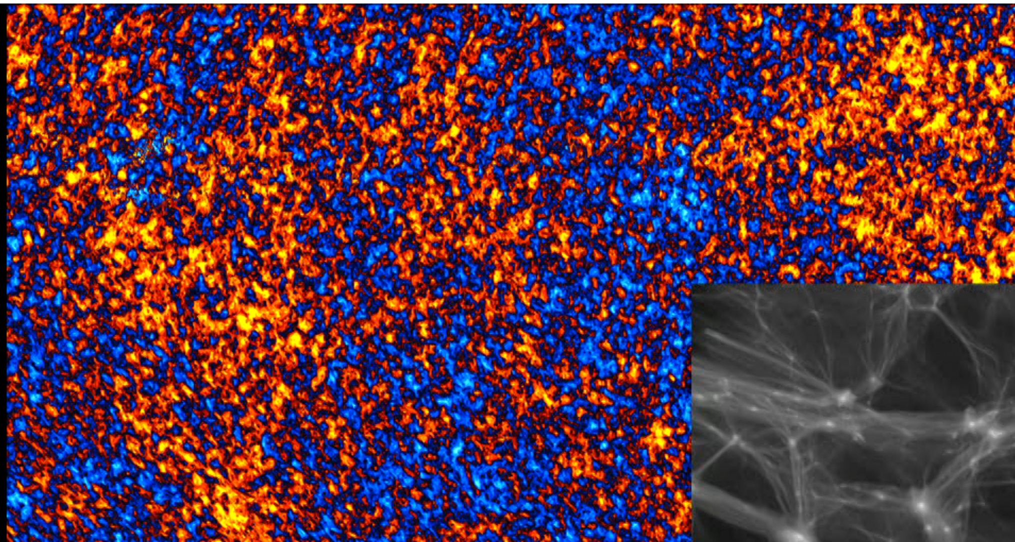
Before showing context…




DES Collaboration arXiv:1708.01530

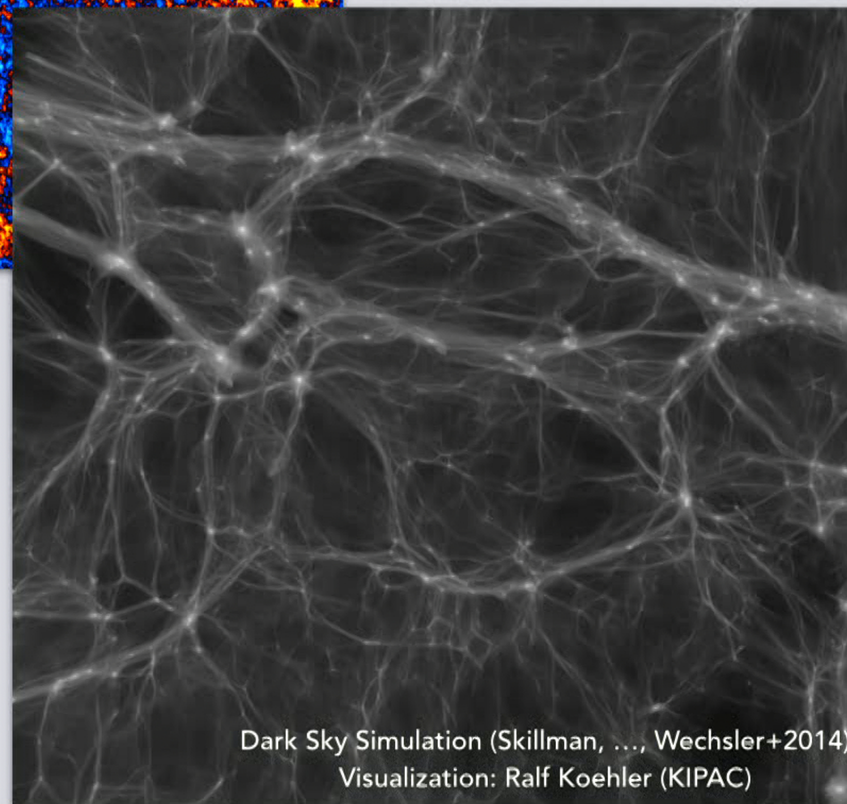
41


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
a(t)
Quantum
Fluctuations
1st Stars
about 400 million yrs.
NASA/WMAP
Cosmic
Microwave
Background
(CMB)
Redshift (z)
42
Dark Energy Survey (DES)



Planck CMB temperature
z=1100; $\delta$ of O($10^{-5}$)

Dark matter simulation
z=0; $\delta$ >> 1



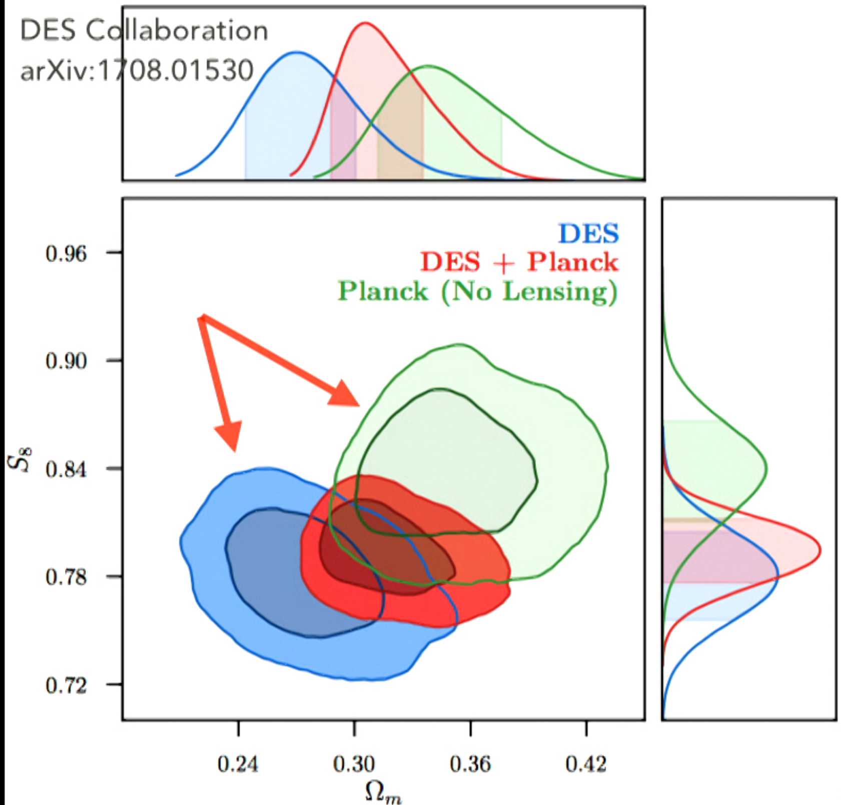
Dark Sky Simulation (Skillman, …, Wechsler+2014)
Visualization: Ralf Koehler (KIPAC)

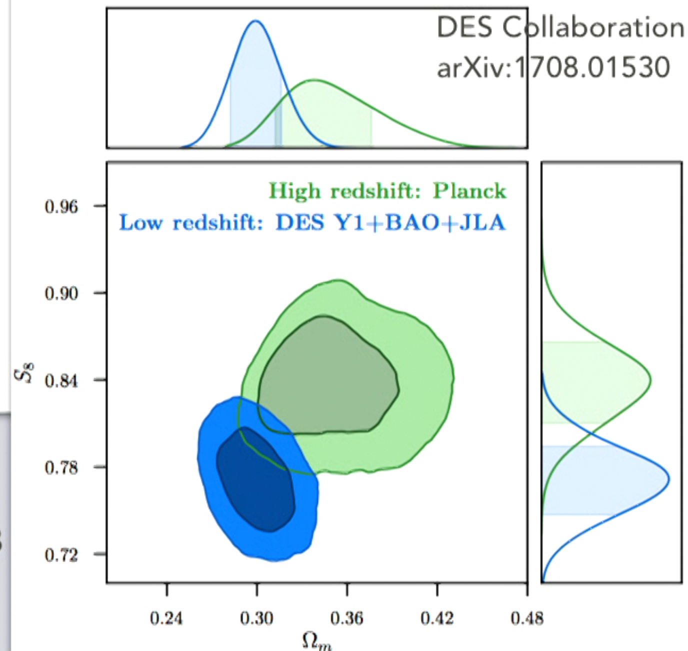
Comparing CMB with LSS: Incredible test of LCDM at two extremely different stages of the Universe 6 billion years apart.

Extensive discussion of tension between weak lensing and CMB in recent years.

## High- vs low-redshift probes

Though there is mild visual 'tension' in this set of parameters, we find the Bayesian evidence for the full parameter space to be consistent between low- and high-redshift probes — LCDM works.

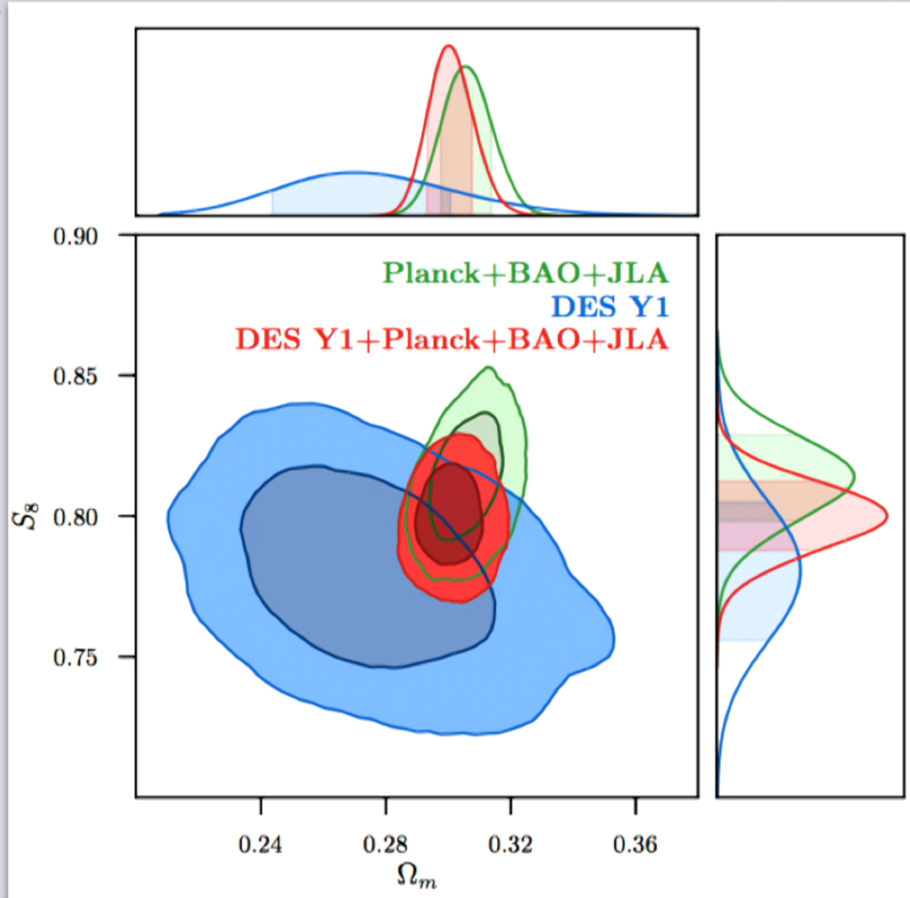



DES Y1 data is able to constrain the clustering amplitude and matter density as well as the CMB for the first time using a large-scale structure probe.

Combining DES large-scale structure constraints + BAO + JLA + Planck gives us the tightest constraint ever placed on the LCDM parameters most closely related to structure in the Universe.

DES Collaboration
arXiv:1708.01530

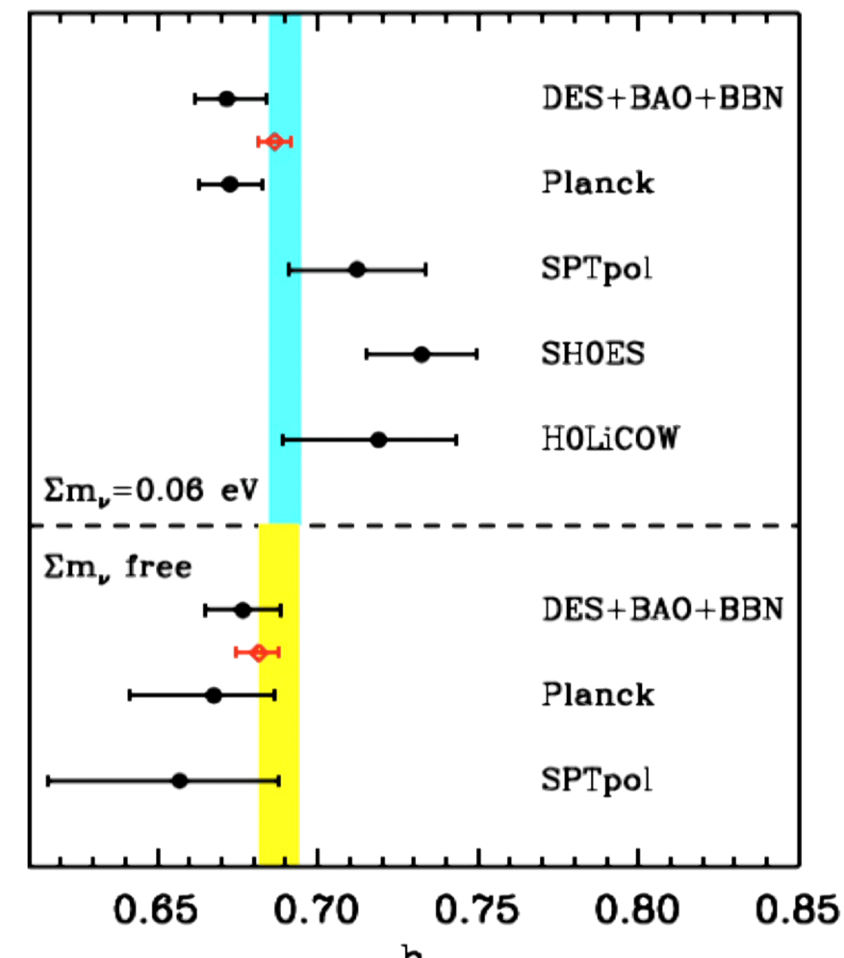



45

# Is the expansion rate in tension between high- and low-z probes?

- Followup paper including BBN
- Five independent H0 measurements: distribution is consistent at 2.1 sigma

$$H_0 = 69.1^{+0.4}_{-0.6}\ \mathrm{km/s/Mpc}$$




DES et al 2017b

46

## Other highlights from the analysis:

We do not find evidence for a wCDM model, either with DES alone or combined with external data.

Combining DES with Planck shifts the preferred Hubble constant by >1sigma toward local H0 measurements.

DES relaxes the previous upper limit on the neutrino mass density by 20% when combined with external probes.

Specific values of interest:

$$\Omega_m = 0.301^{+0.006}_{-0.008}$$

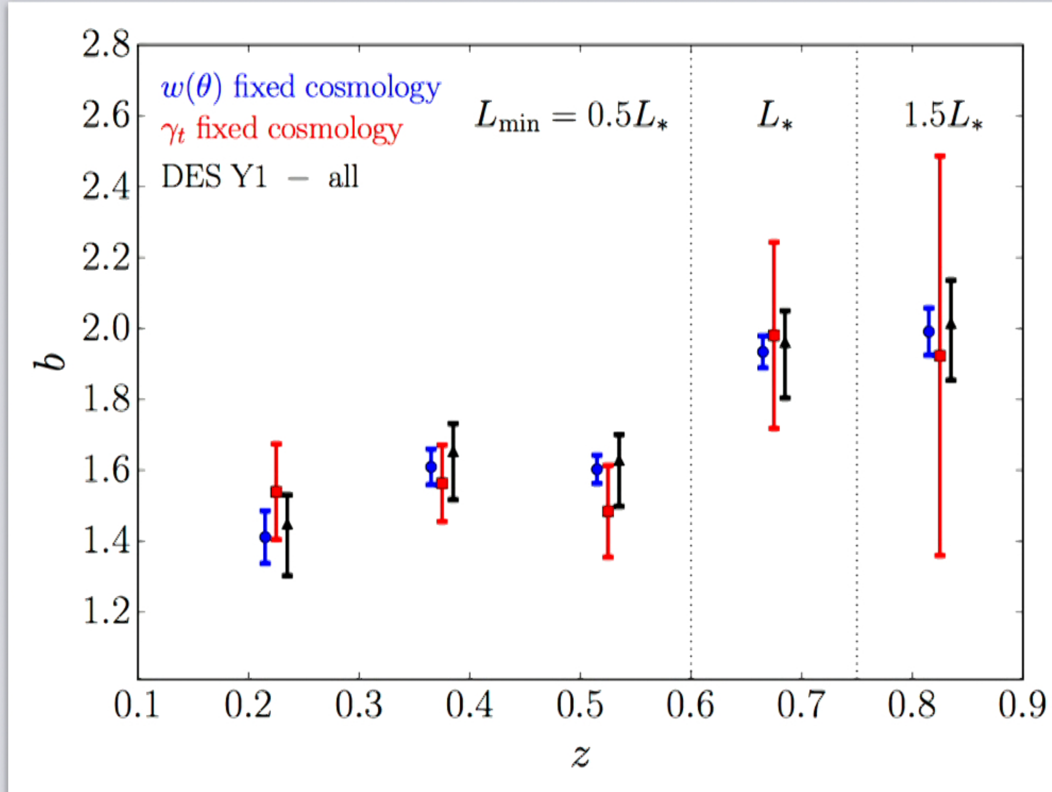
$$\sum m_\nu < 0.29\,\mathrm{eV}$$ (95% CL)

$$S_8 = 0.799^{+0.014}_{-0.009}$$

$$w = -1.00^{+0.04}_{-0.05}$$ (wCDM)

# Astrophysical highlights from the analysis: Galaxy bias

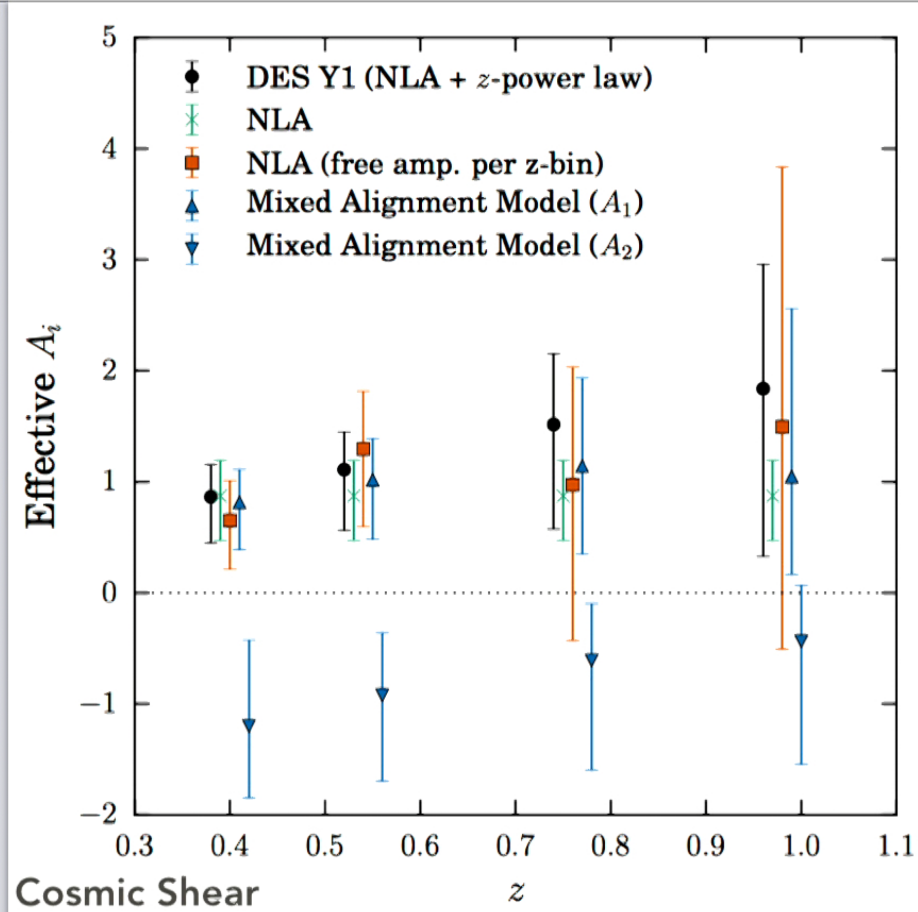
- Consistent with no redshift evolution
- Consistent between probes
- Full 3x2pt (varying 26 param.) only a factor of two weaker than using w(theta) and fixing cosmology (5 param.)




48

## Astrophysical highlights from the analysis: Intrinsic alignment

- Detection of intrinsic alignment at 99.98% CL (nearly 4 sigma)
- Consistent amplitudes across multiple intrinsic alignment models
- First indication of non-zero $A_2$ ("blue" alignment) in general weak lensing sample from cosmic shear alone




49

## This is just the beginning…

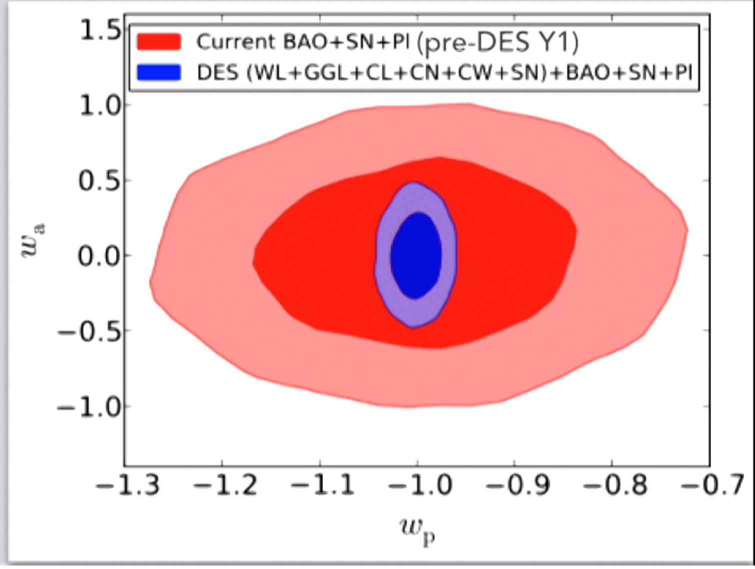
*35M -> 90M WL galaxies!*

Area of DES footprint will more than triple with Year 3 analysis (beginning now) and exp. time will more than double by Year 5.

DES is only using 3% of the sky (1/8 in Year 5). Future experiments are already being built to utilize up to half of the sky and/or observe to significantly deeper redshifts than DES: LSST (ground), WFIRST & Euclid (space).

Extended models to study:

- Non-zero curvature
- Evolving DE ($w_a$)
- Modified gravity




50

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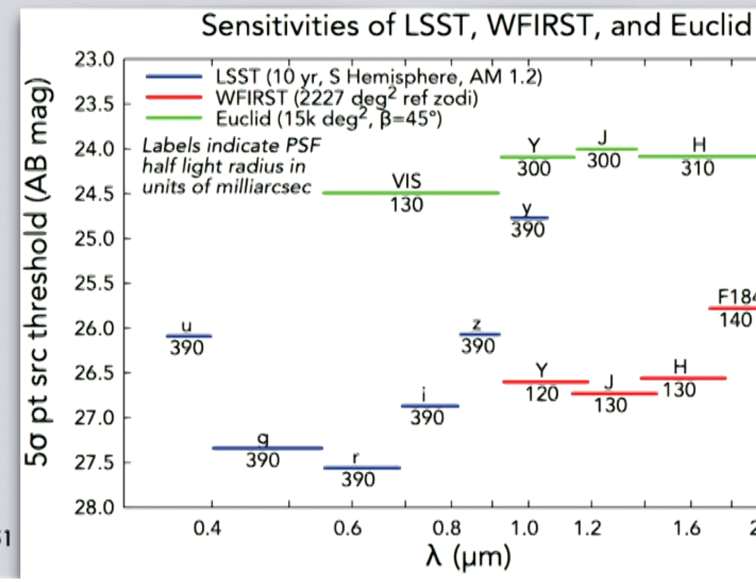


51

## Summary

Large-scale structure probes from DES Y1 have begun to rival the cosmological constraining power of the CMB.

We find consistency within LCDM at current statistical precision between DES Y1 large-scale structure probes (with other low-redshift probes) and the CMB.

We find no evidence for a wCDM model.

Constraining power and the range of models and parameters constraint will increase rapidly over the next few years as DES ramps up analysis of later years of data, and much further still when analysis of a new generation of experiments begins in the 2020s.

## Combined "3x2pt" cosmological analysis

List of related papers:

1. DES Collaboration et al., Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing, submitted to PRD, arXiv:1708.01530
2. DES Collaboration et al., Dark Energy Survey Year 1 Results: A Precise H0 Measurement from DES Y1, BAO, and D/H Data, submitted to PRD, arXiv:1711.00403
3. Troxel et al., Dark Energy Survey Year 1 Results: Cosmological Constraints from Cosmic Shear, submitted to PRD, arXiv:1708.01538
4. Prat et al., Dark Energy Survey Year 1 Results: Galaxy-Galaxy Lensing, submitted to PRD, arXiv: 1708.01537
5. Elvin-Poole et al., Dark Energy Survey Year 1 Results: Galaxy clustering for combined probes, submitted to PRD, arXiv:1708.01536
6. Chang et al., Dark Energy Survey Year 1 Results: Curved-Sky Weak Lensing Mass Map, submitted to MNRAS, arXiv:1708.01535
7. Samuroff et al., Dark Energy Survey Year 1 Results: The Impact of Galaxy Neighbours on Weak Lensing Cosmology with im3shape, submitted to MNRAS, arXiv:1708.01534
8. Zuntz et al., Dark Energy Survey Year 1 Results: Weak Lensing Shape Catalogues, submitted to MNRAS, arXiv:1708.01533
9. Hoyle et al., Dark Energy Survey Year 1 Results: Redshift distributions of the weak lensing source galaxies, submitted to MNRAS, arXiv:1708.01532
10. Gatti et al., Dark Energy Survey Year 1 Results: Cross-Correlation Redshifts - Methods and Systematics Characterization, submitted to PRD, arXiv:1709.00992
11. Davis et al., Dark Energy Survey Year 1 Results: Cross-Correlation Redshifts in the DES -- Calibration of the Weak Lensing Source Redshift Distributions, submitted to PRD, arXiv:1710.02517
12. Drlica-Wagner et al., Dark Energy Survey Year 1 Results: Photometric Data Set for Cosmology, submitted to ApJS, arXiv:1708.01531
13. Krause et al., Dark Energy Survey Year 1 Results: Multi-Probe Methodology and Simulated Likelihood Analyses, submitted to PRD, arXiv:1706.09359
14. Blazek, MacCrann, Troxel, Fang, Beyond Linear Galaxy Alignments, submitted to PRD, arXiv: 1708.09247