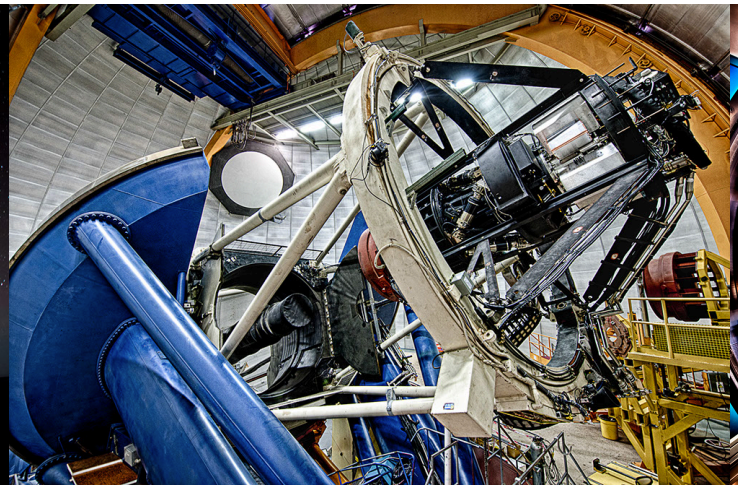
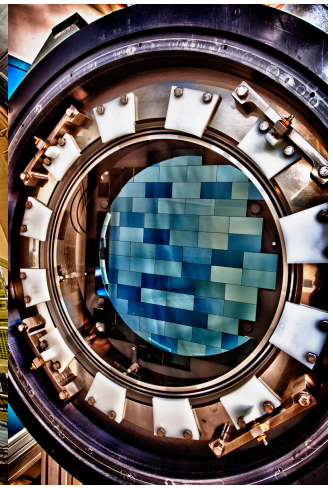
DARK ENERGY SURVEY

UNIVERSITY OF CALIFORNIA SANTA CRUZ

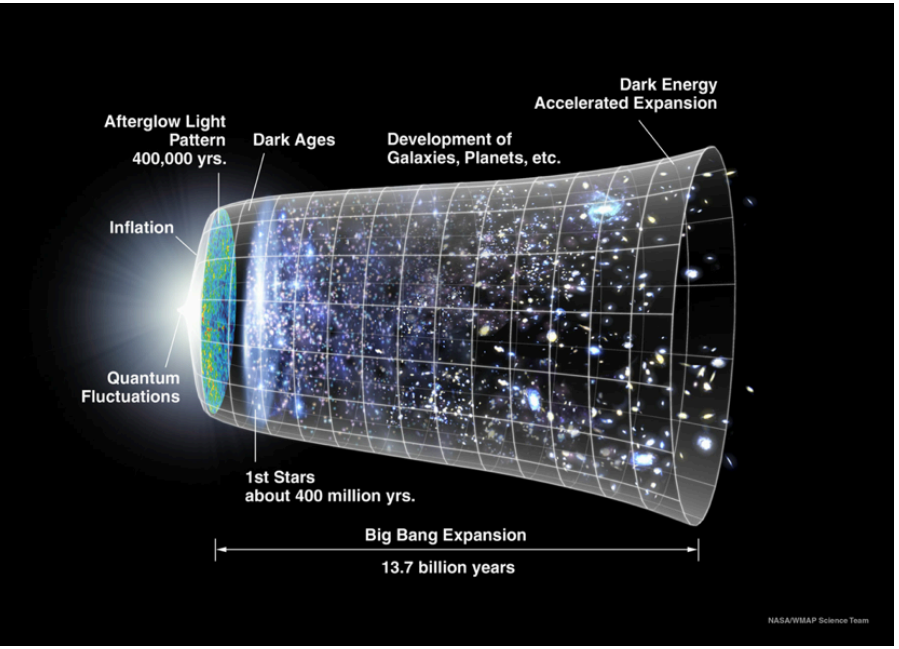
Cosmology in the New Era
(Results from the Dark Energy Survey)

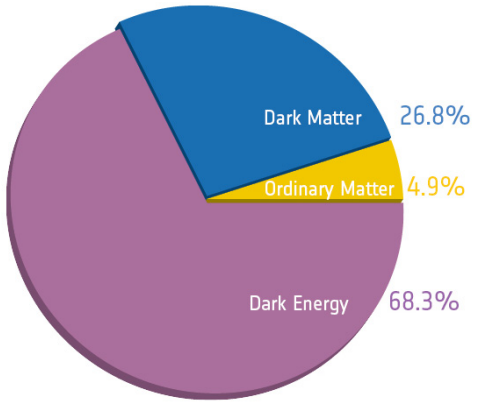
Tesla Jeltema
University of California, Santa Cruz

on behalf of the Dark Energy Survey Collaboration

Dark Energy





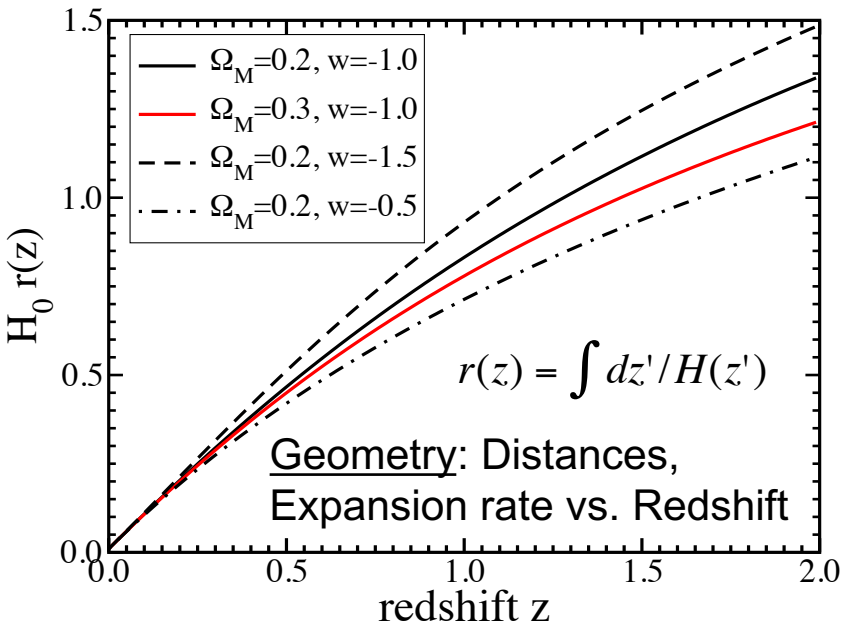
What is the cause of the observed cosmic acceleration?

- Is it dark energy or a modification of general relativity?
  - If it is dark energy, is it constant (Λ) or evolving; what is the DE equation of state?

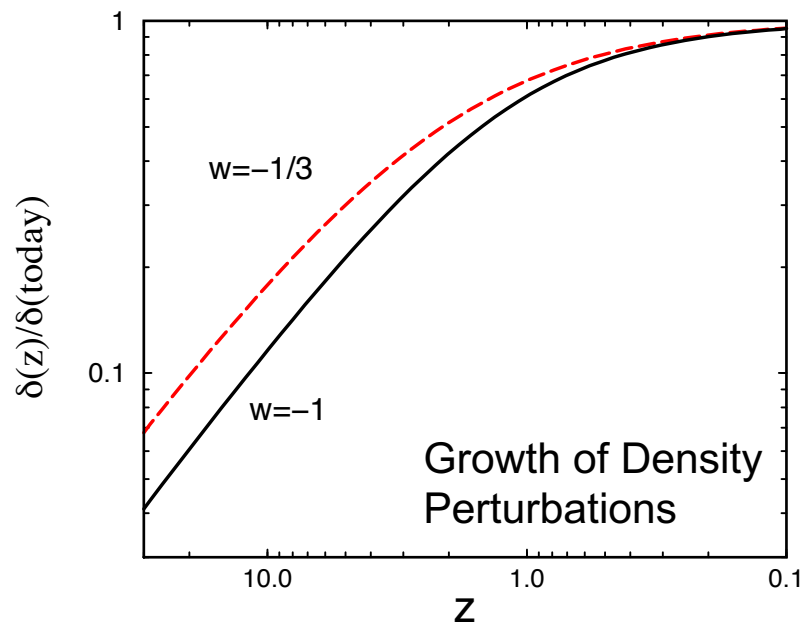
What can we probe?

DARK ENERGY SURVEY

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{H^2}{{H_0}^2} = \Omega_{0,R}a^{-4} + \Omega_{0,M}a^{-3} + \Omega_{0,\Lambda}a^{-3(1+w)}$$



Expansion History

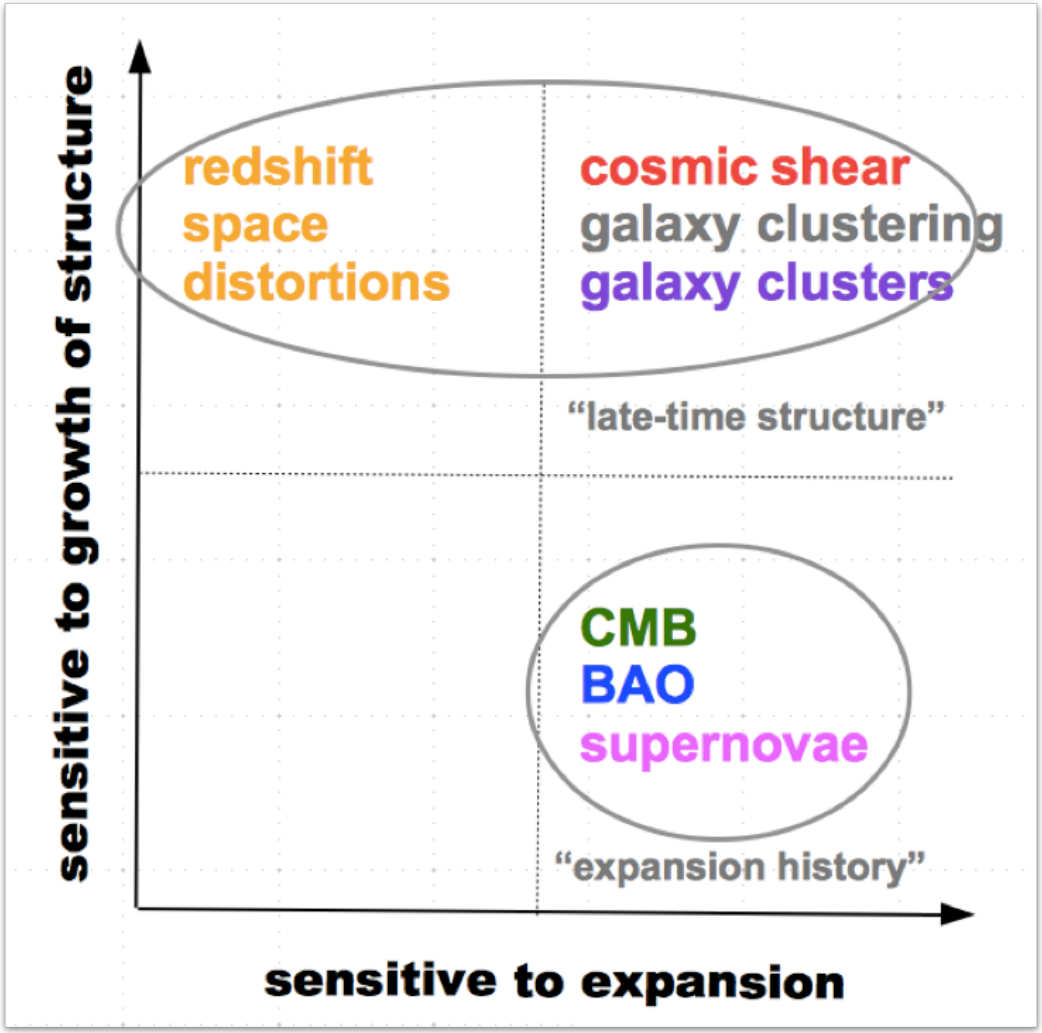


Growth of Structure

Require both to disentangle Dark Energy from Modified Gravity

Frieman, Turner, Huterer 2008

Dark Energy Probes



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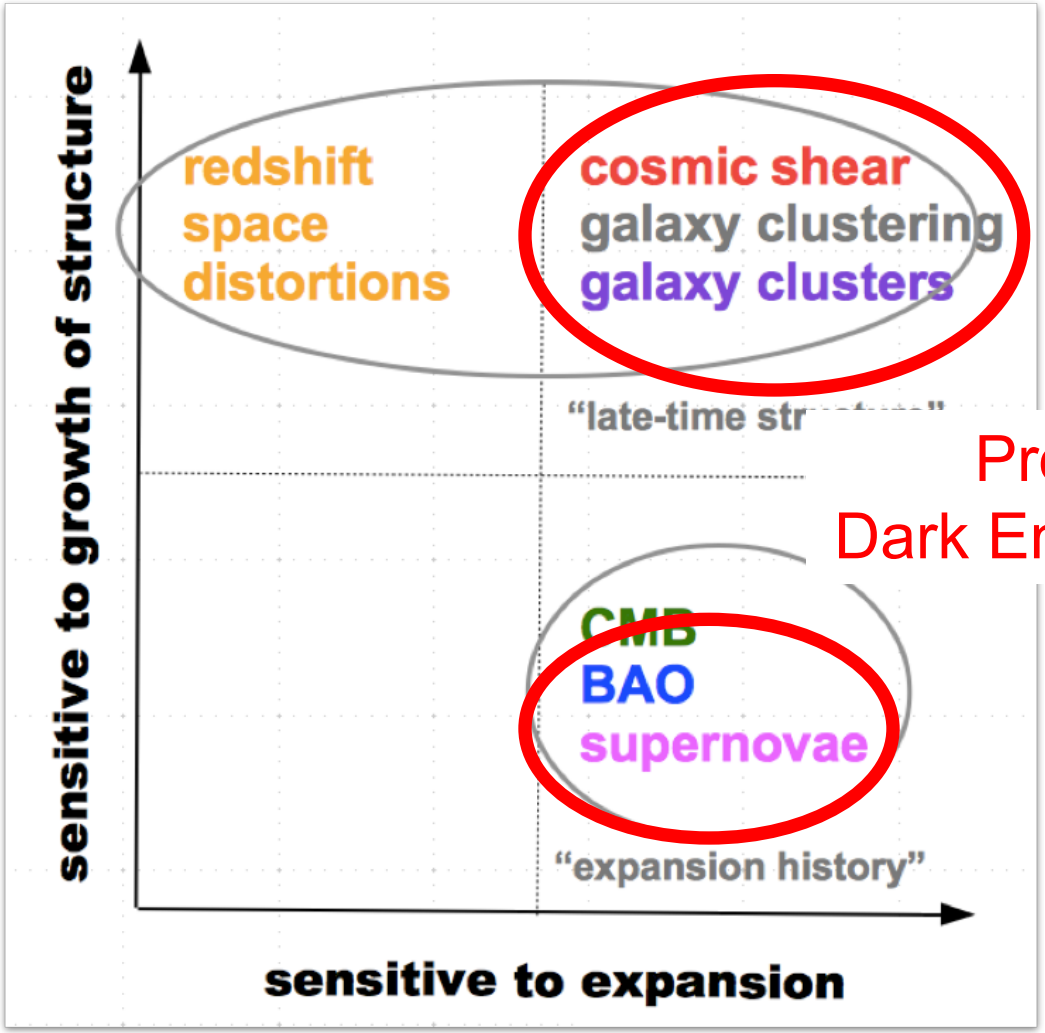
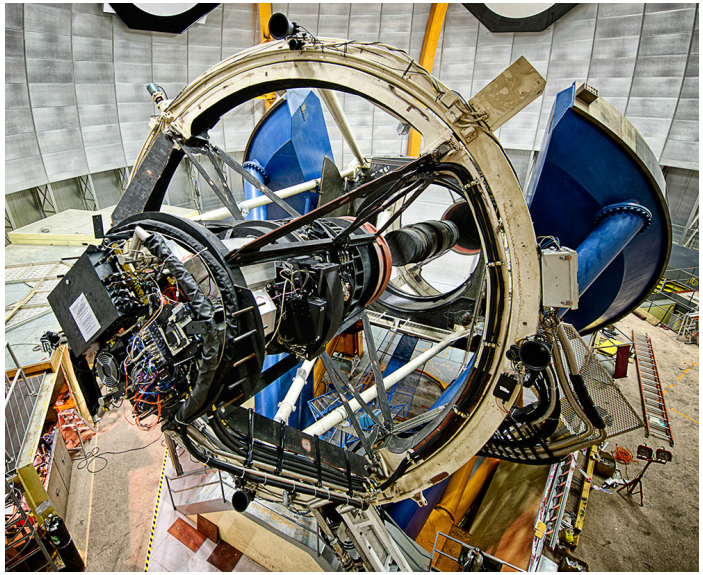


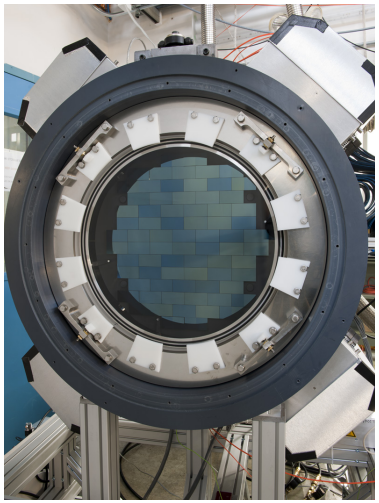
Probed by
Dark Energy Survey

The Dark Energy Survey

DARK ENERGY SURVEY

- Two multicolor surveys:
  - 300 million galaxies over 5000 deg^2, grizY to 24th mag
  - 3000 supernovae (30 deg^2)
- DECam on CTIO Blanco 4-m
  - DECam facility instrument
- Survey started August 2013
  - 5 of 5.5 seasons completed
  - Y1 (1500 sq. deg, 40% depth)
  - Y3 (5000 sq. deg, 50% depth)





DECam:

570 Megapixel Camera

3 deg^2 FOV

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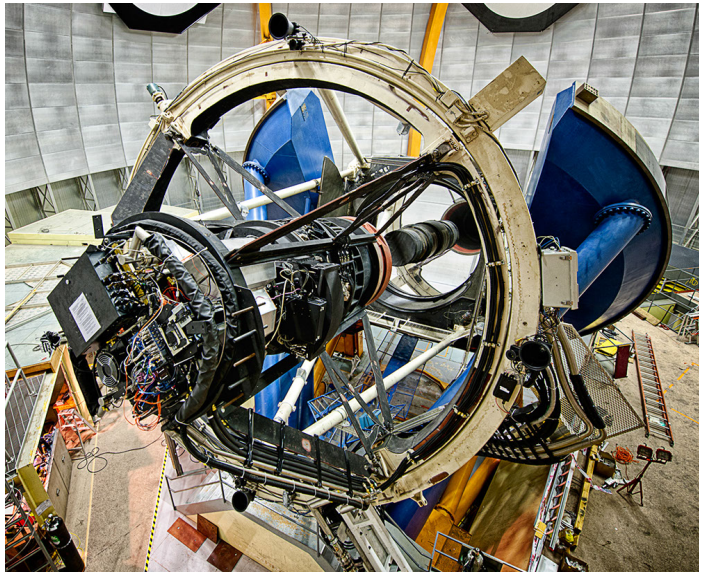
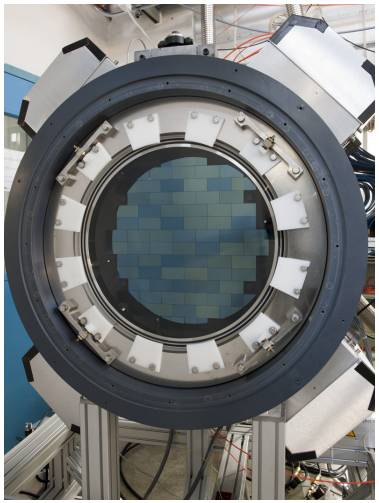
Results today + Y3 SNe





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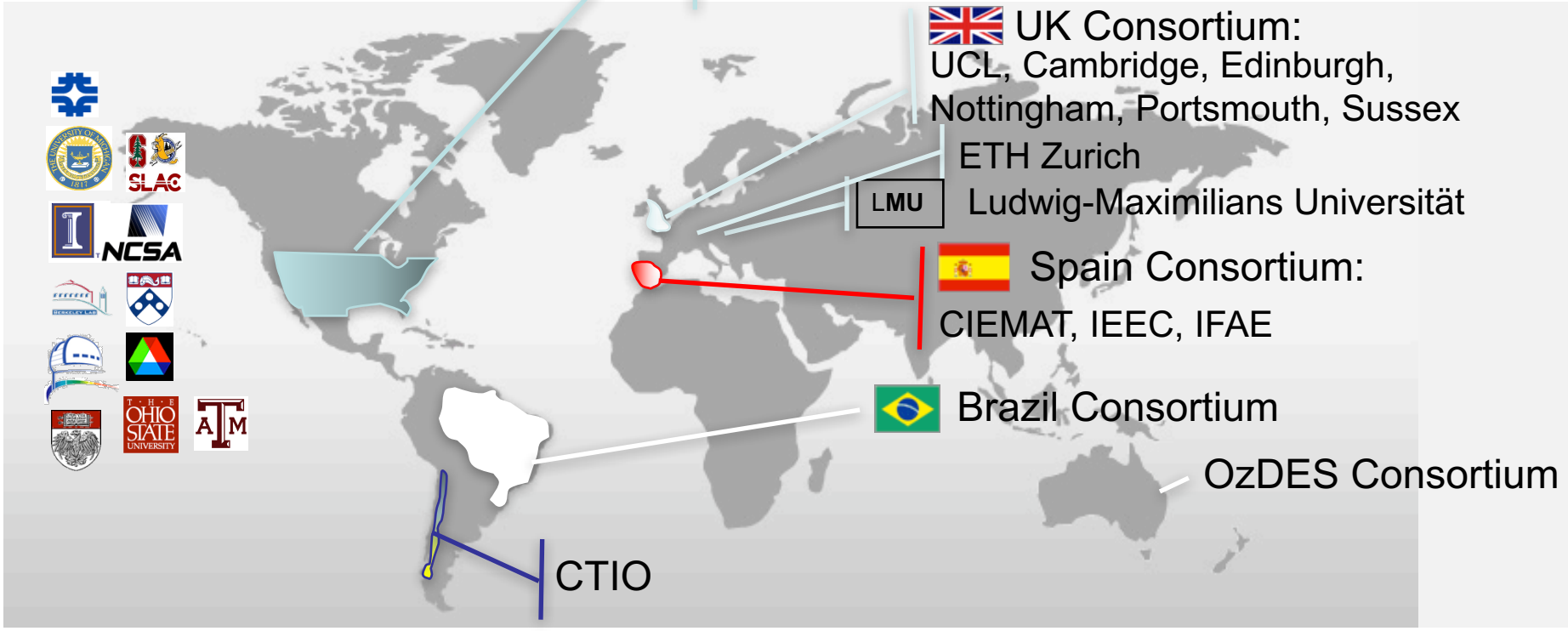
DES Collaboration

DARK ENERGY SURVEY

~ 400 scientists

US support from DOE & NSF

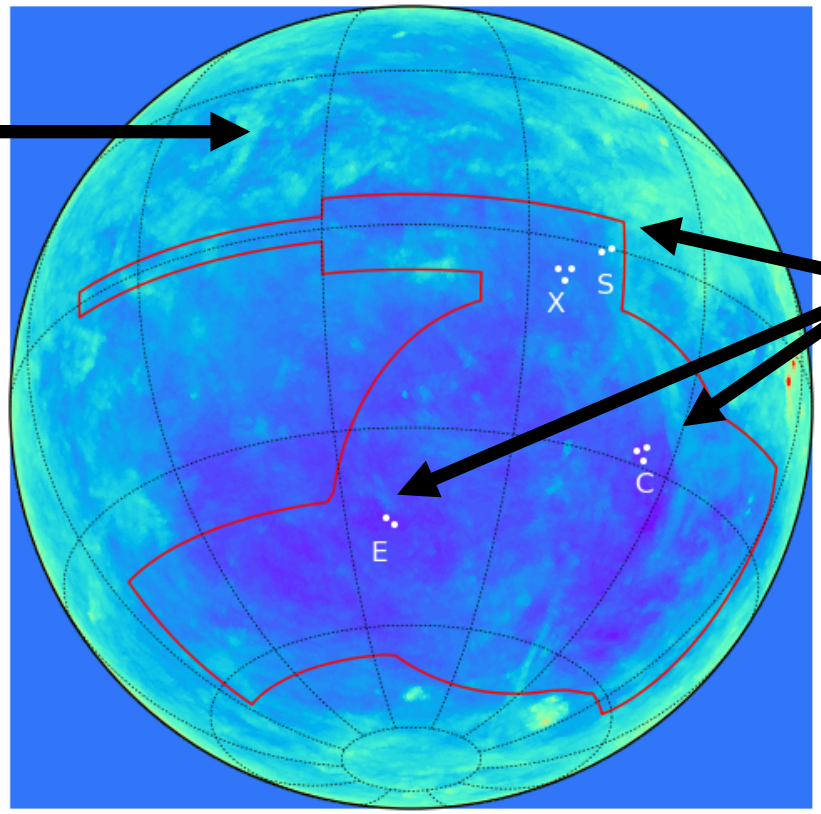
Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M



Survey Footprint

5000 deg^2 footprint to be covered 900 seconds in griz and 450 sec in Y

Milky Way Dust



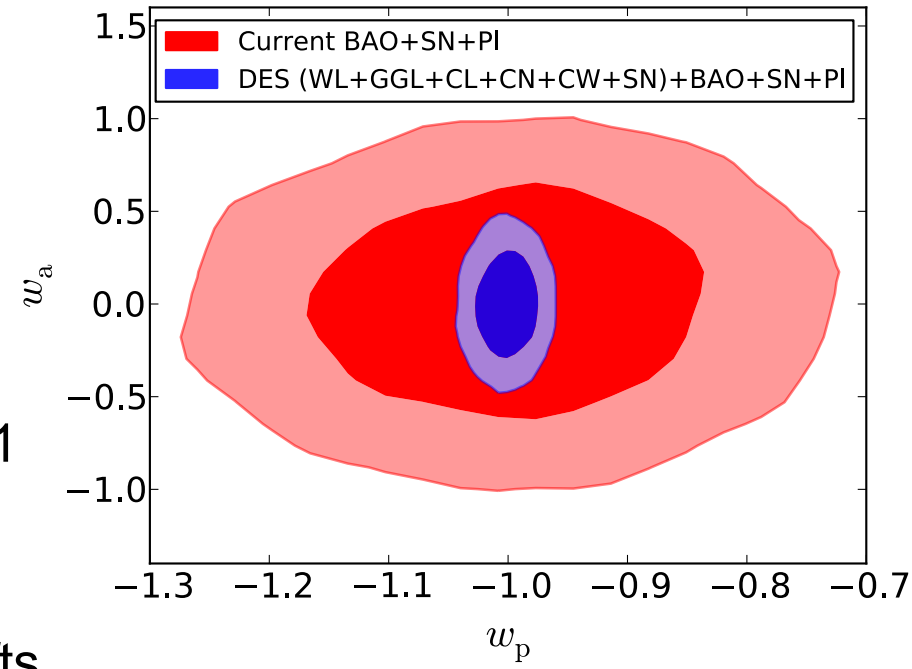
10 SN fields, each observed every ~ 6 nights:
2 deep,
8 shallow

DES Dark Energy Probes

DARK ENERGY SURVEY

- Galaxy Clusters
  - Tens of thousands of clusters to z~1
- Weak Lensing
  - Shapes of 200 million galaxies
- Galaxy Clustering
  - 300 million galaxies to z~1
- Supernovae
  - 3000 well-sampled SNe Ia to z~1
- Strong Lensing
  - ~ 30 QSO lens time delays
  - Arcs with multiple source redshifts
- Cross-correlations
  - Galaxies, shear, CMB

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



DES forecast

(T. Eifler, E. Krause)

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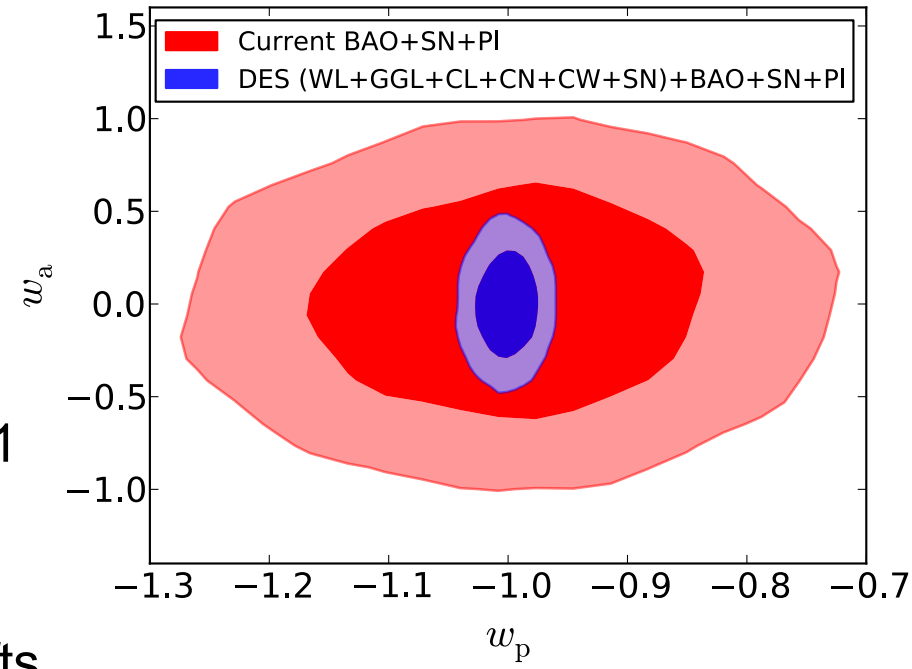

DES forecast

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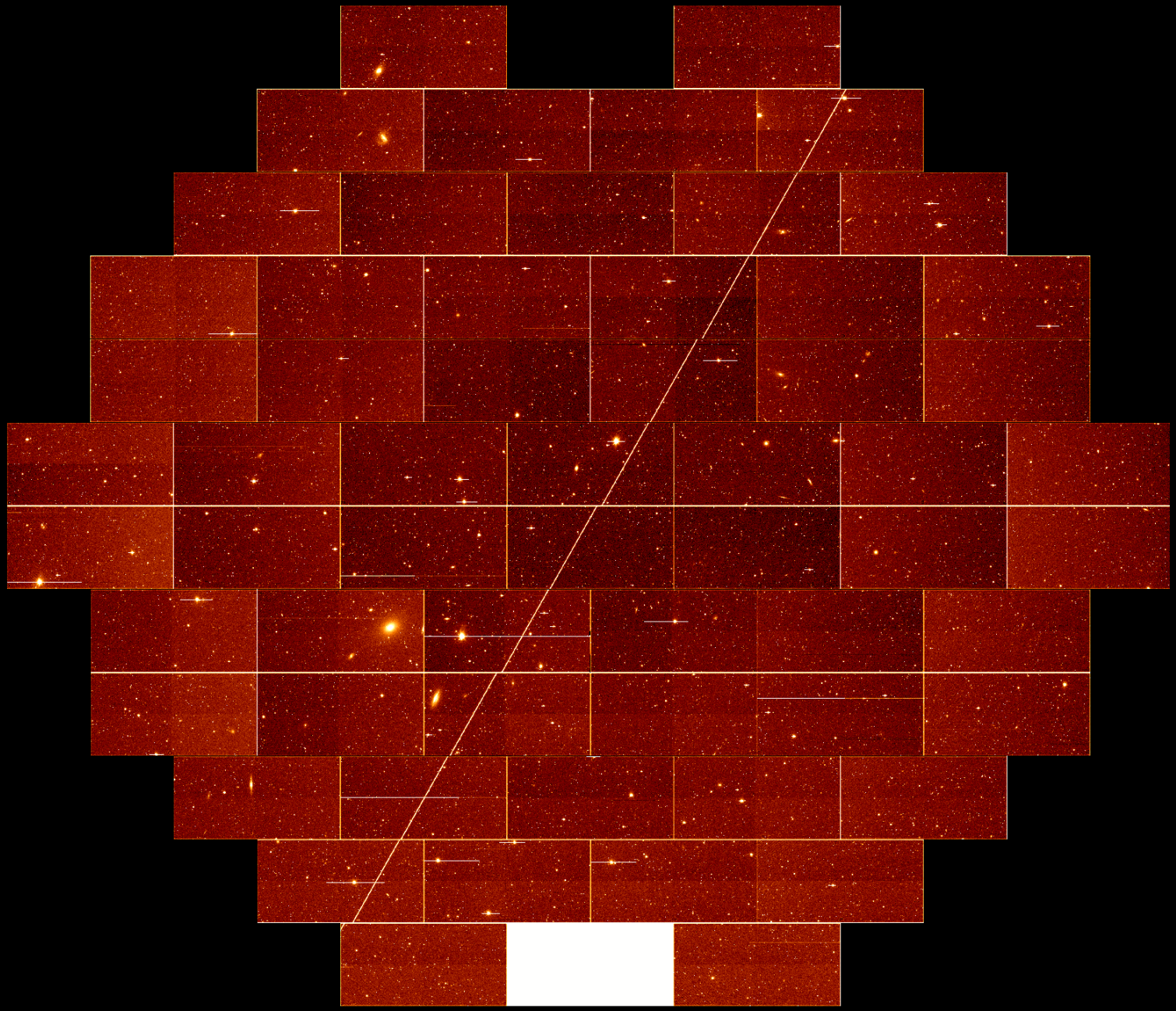
DARK ENERGY SURVEY

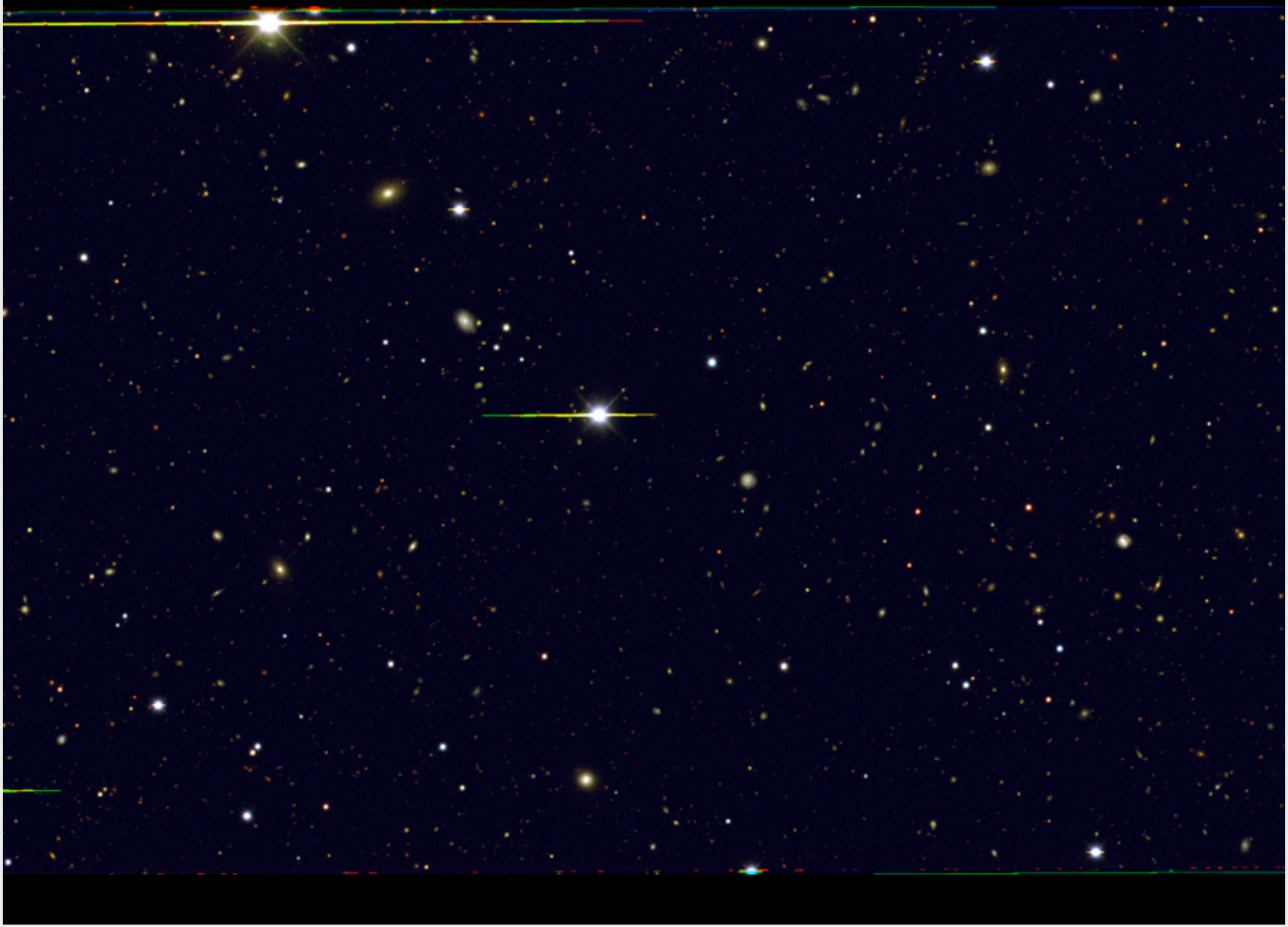
Raw DECam image

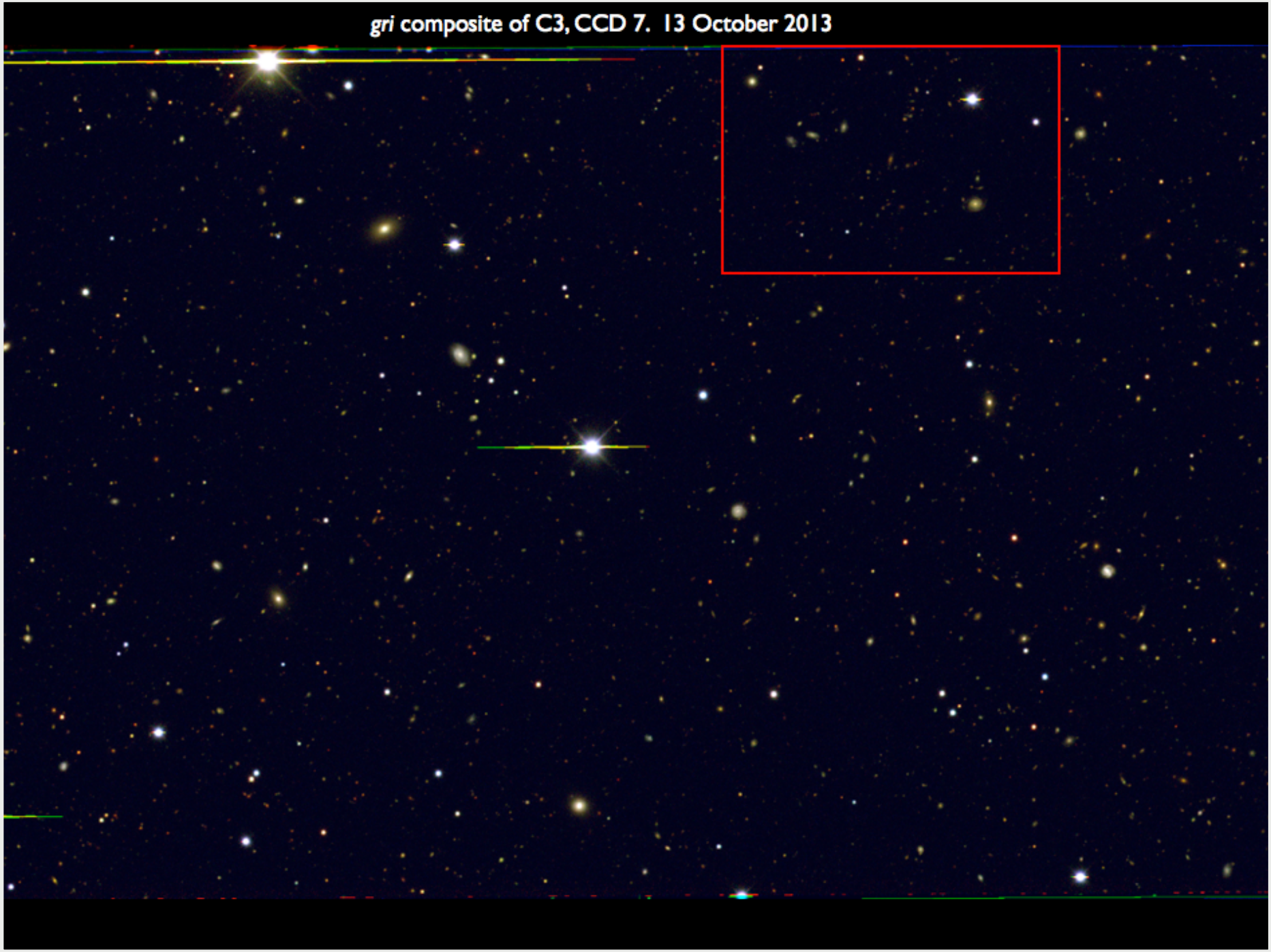


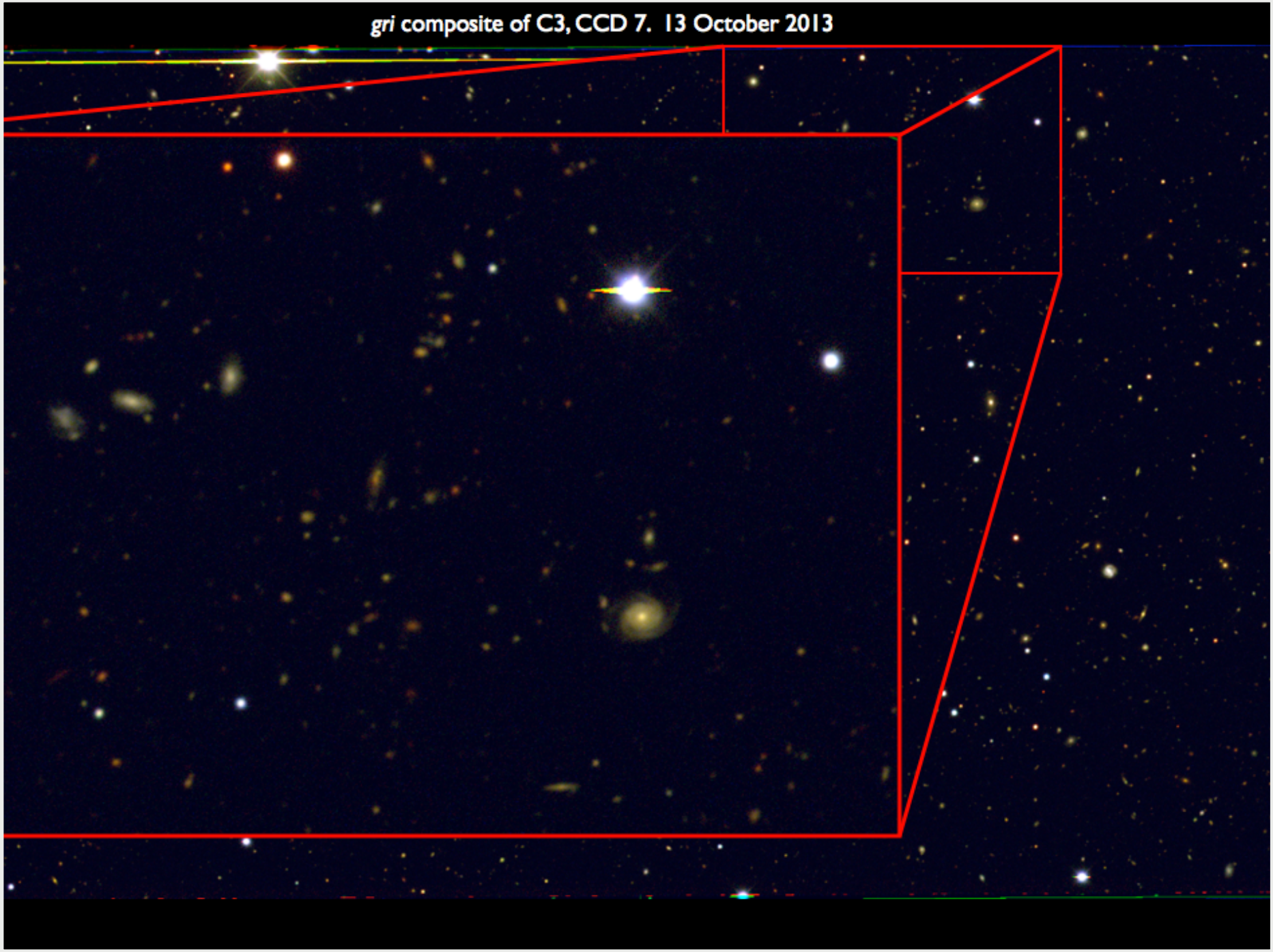
DARK ENERGY SURVEY

NGC 1672

gri composite of C3, CCD 7. 13 October 2013




gri composite of C3, CCD 7. 13 October 2013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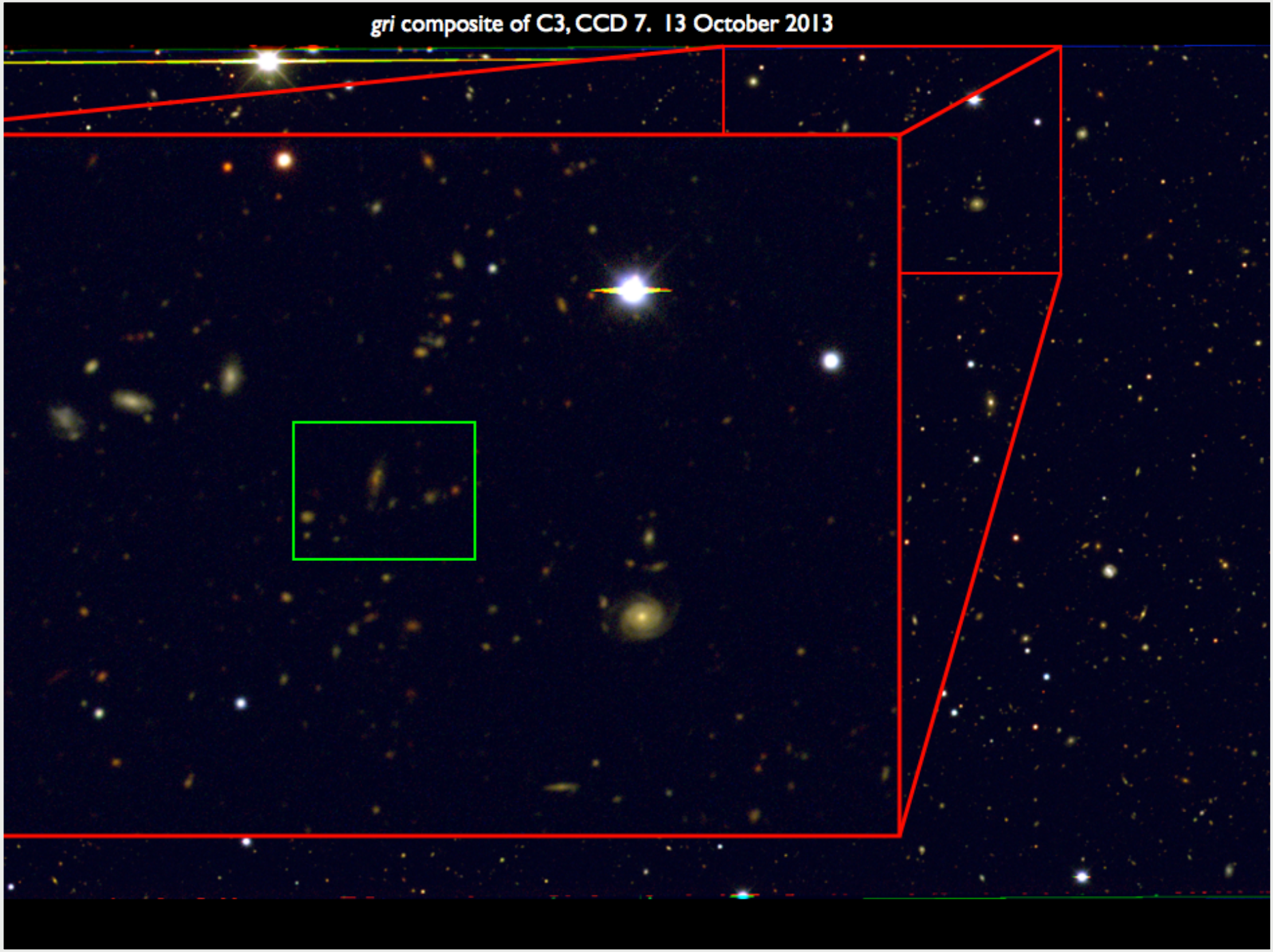
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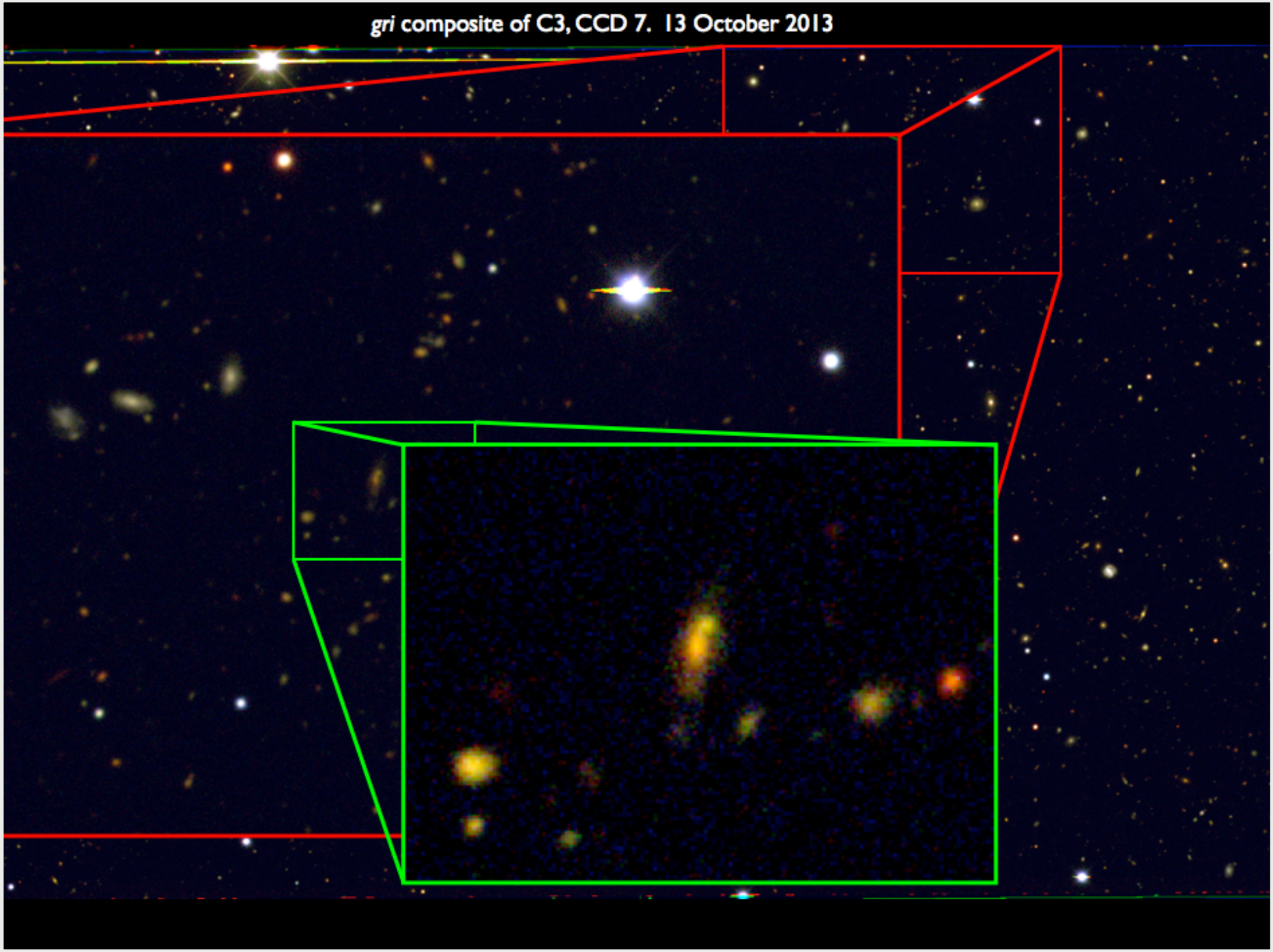
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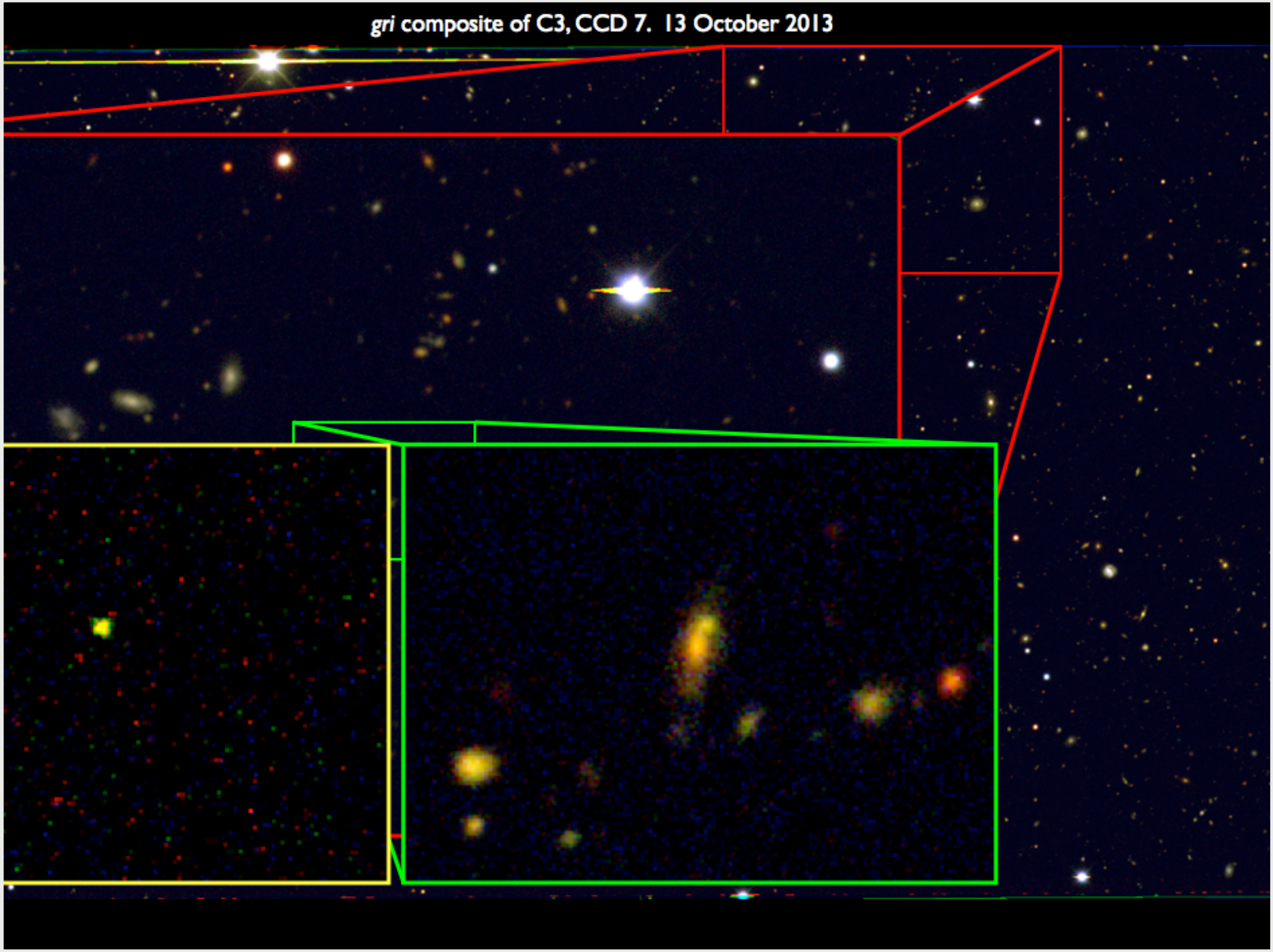
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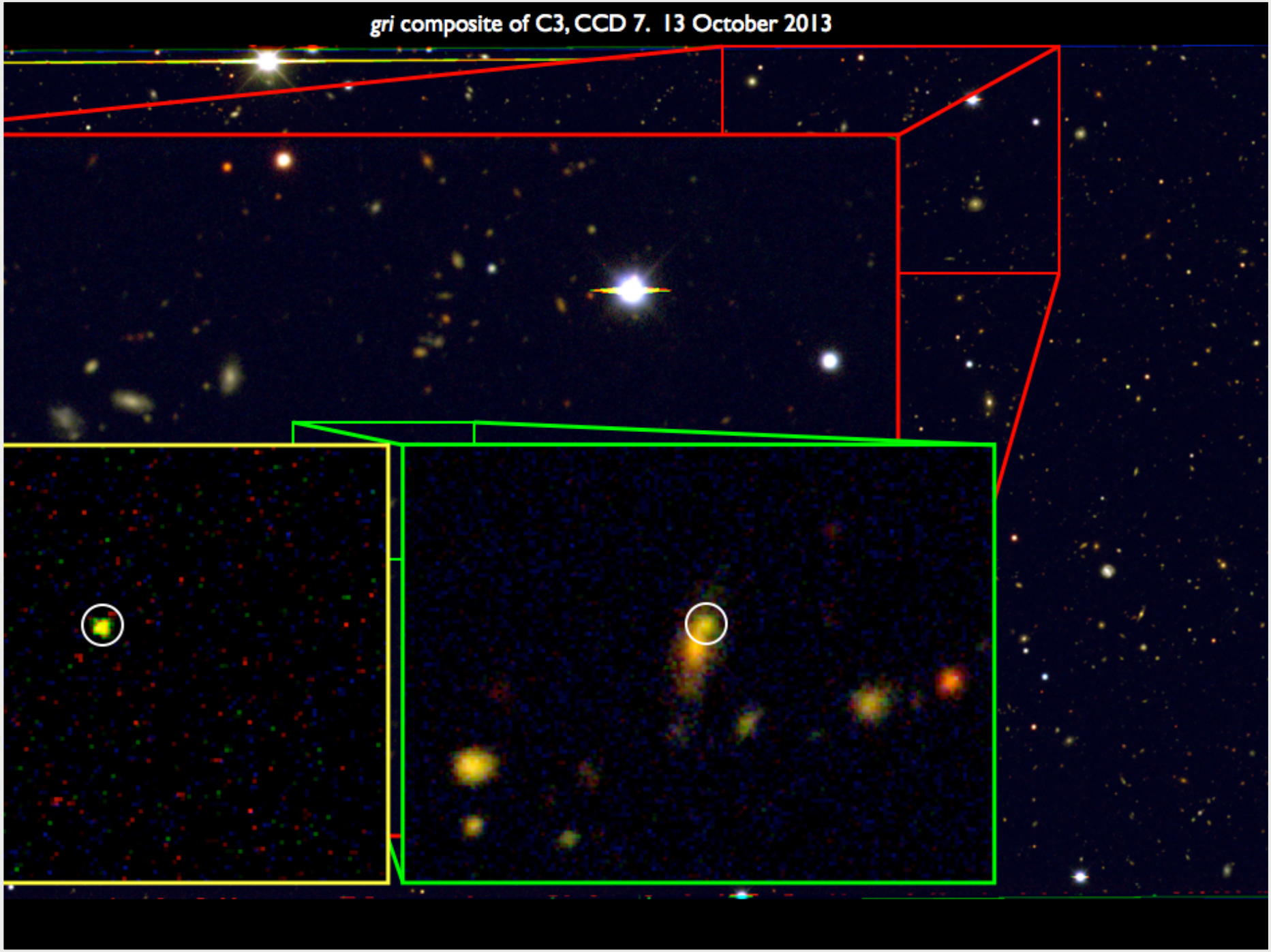

gri composite of C3, CCD 7. 13 October 2013

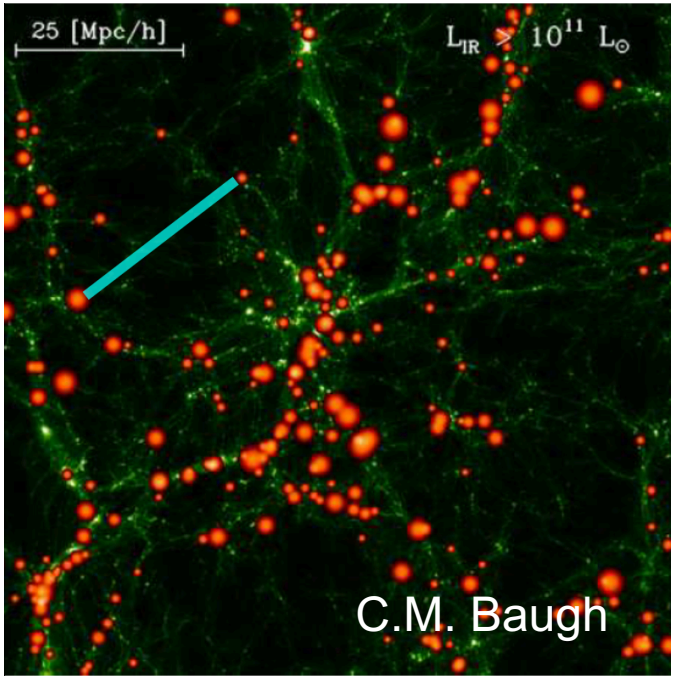
Galaxy Clustering

Galaxies form in dark matter overdensities.

Galaxy positions trace matter distribution

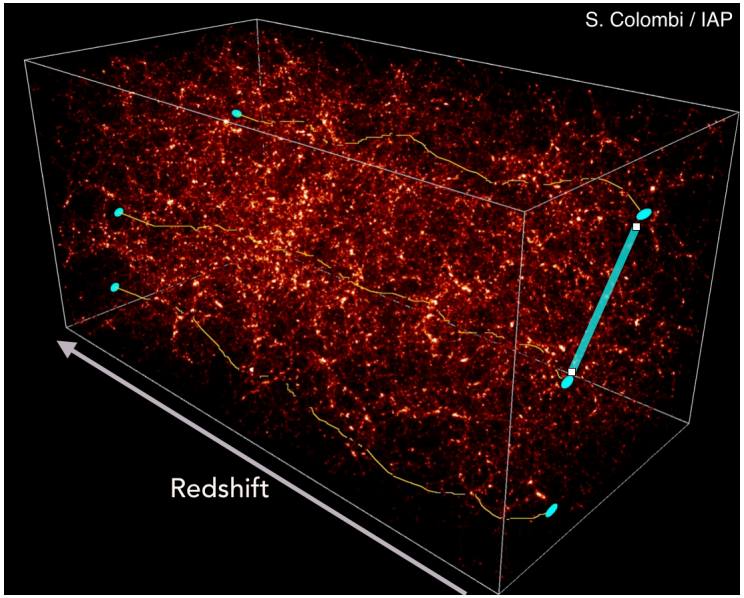
→ Construct power spectrum (or real-space correlation function) from positions

(Limited by an unknown galaxy bias relative to dark matter).

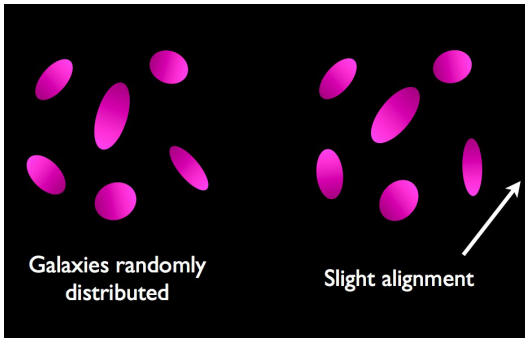


Weak Lensing Shear

Light from distant galaxies passes through the same structure



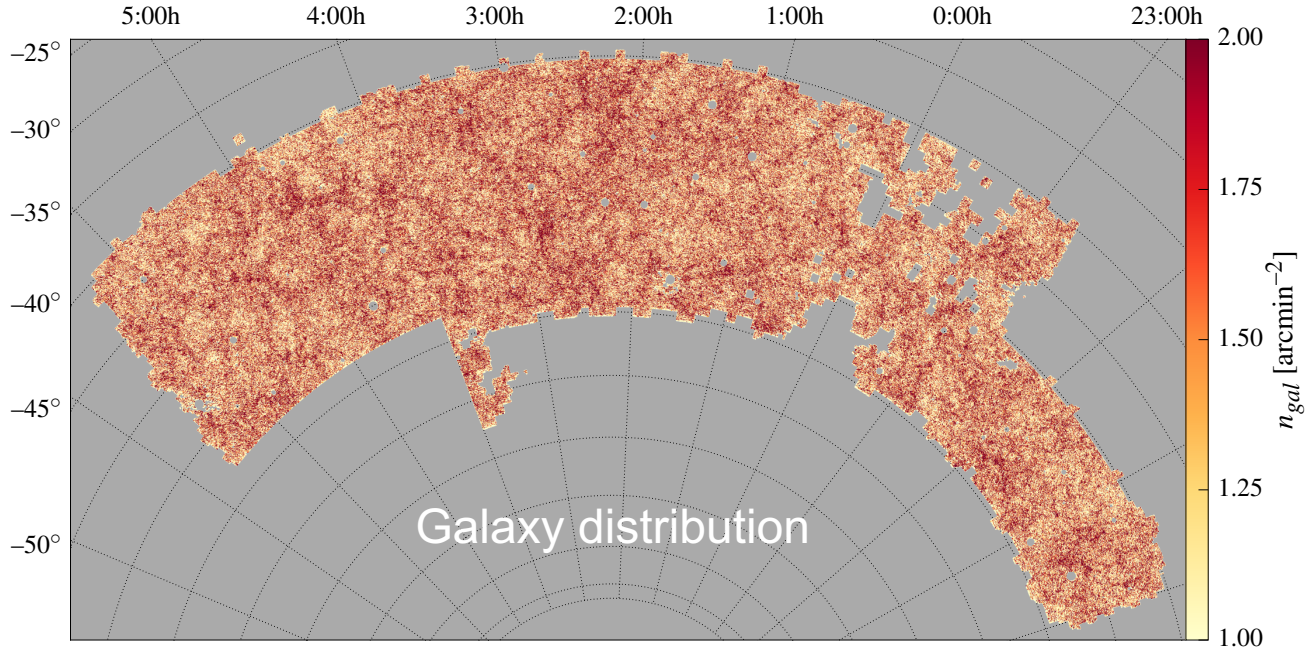
→ Change in ellipticities correlated

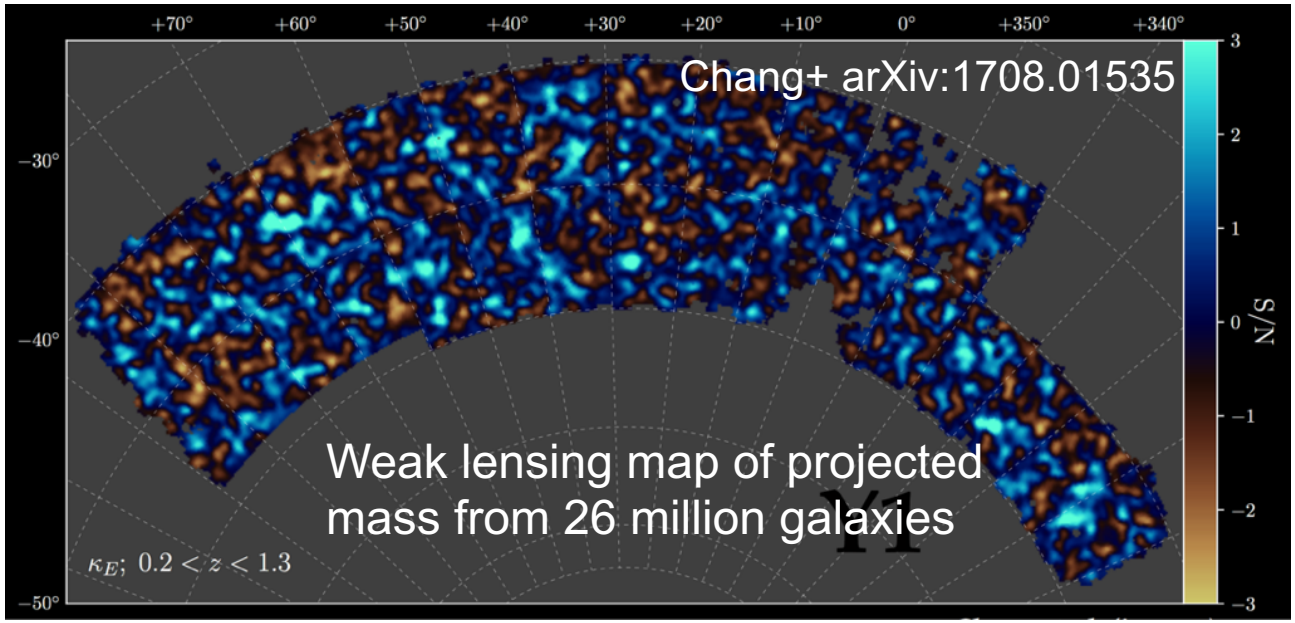


- Measure galaxy shapes
- Measure correlation of shapes of pairs on galaxies.

DARK ENERGY SURVEY

DES Year 1
~1500 deg^2



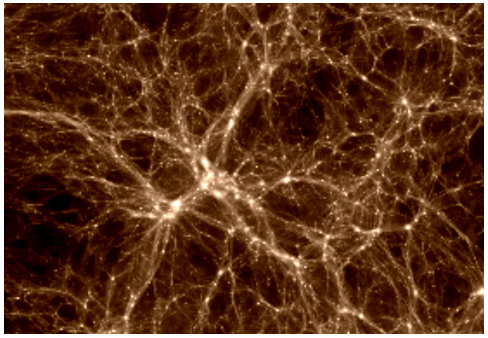


Cross Correlations

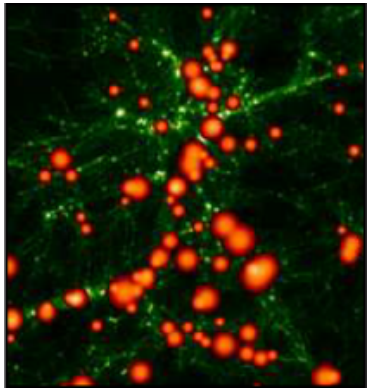
DARK ENERGY SURVEY

Combination jointly constrains astrophysical and systematic parameters

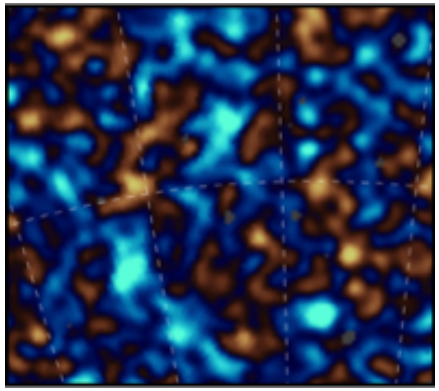
Dark matter



Galaxy clustering



Cosmic shear



3x2pt

Elvin-Poole+ 1708.01536

Troxel+ 1708.01538

Galaxy-galaxy lensing

Prat, Sanchez+ 1708.01537

Cosmology: 3x2pt DES Year 1

DARK ENERGY SURVEY

Double everything:

- Two shape measurement codes
- Two photo-z codes
- Two analysis pipelines

Similar constraining power to Planck on matter density and amplitude (1-2σ tension)

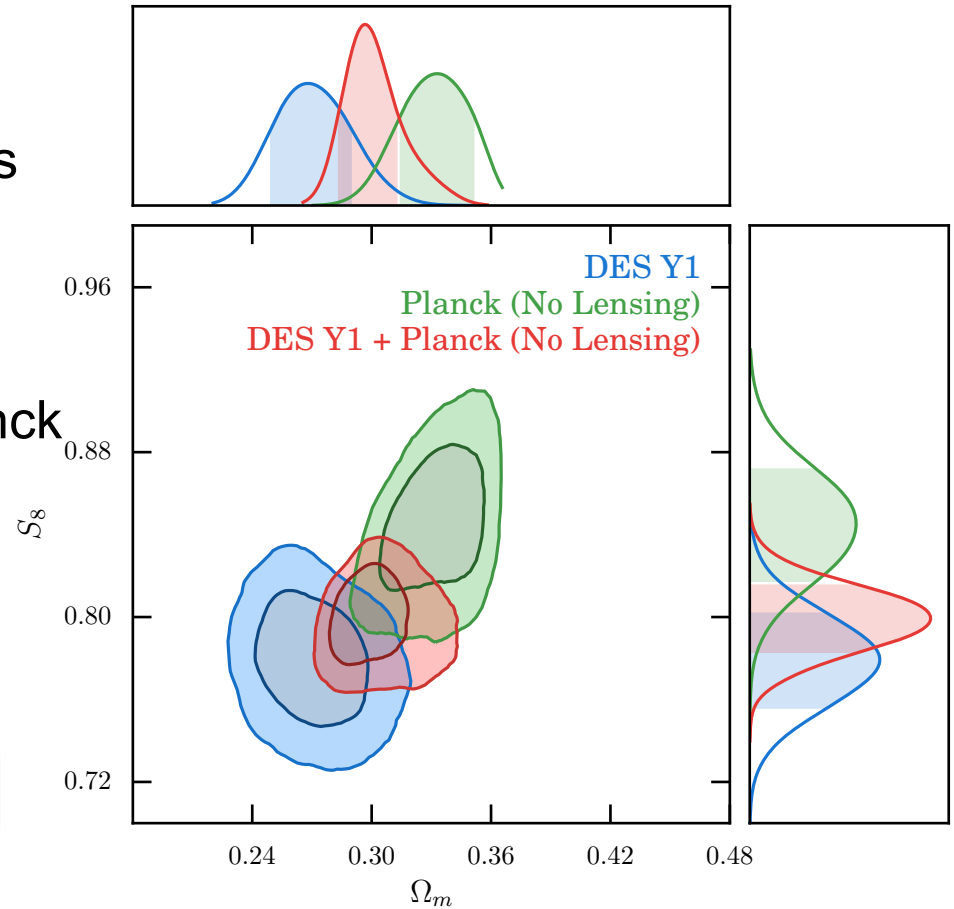
$$\Omega_m = 0.301^{+0.006}_{-0.008}$$

$$\sum m_\nu < 0.29\,\mathrm{eV}$$

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

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

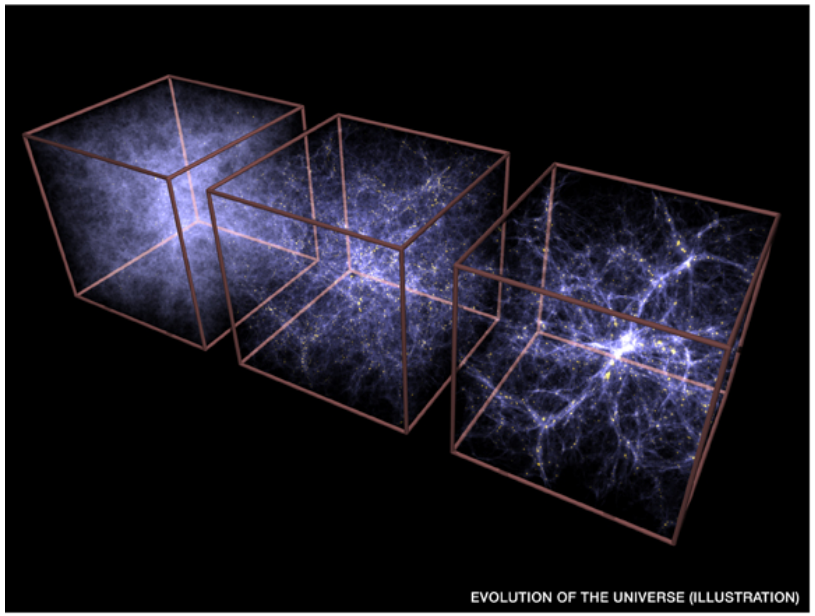
wCDM, DES+Planck+BAO+SNe



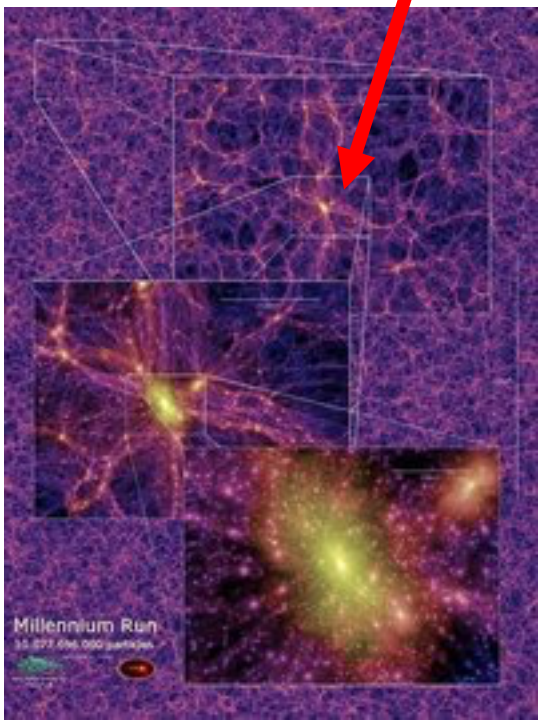
DES collaboration 2017, arXiv:1708.01530

Cosmology with Clusters

Growth rate depends on balance between gravity and expansion rate



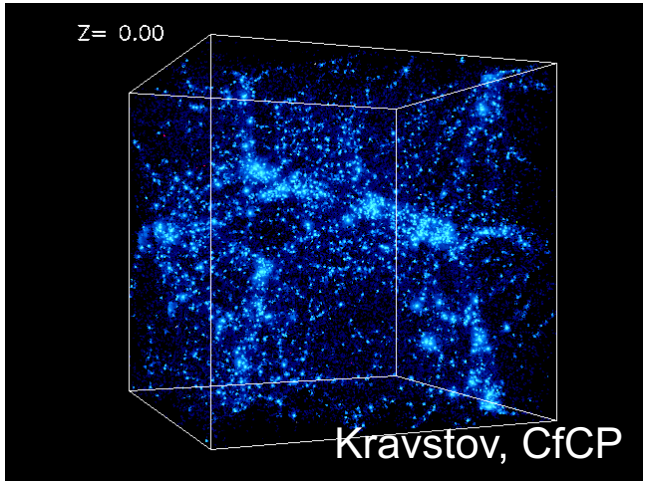
Clusters are rare overdensities



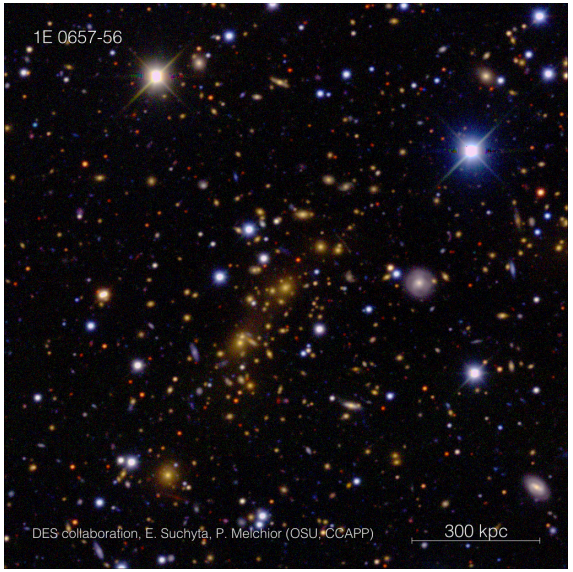
Cosmology with Clusters

DARK ENERGY SURVEY

What we can predict:
(# of massive halos)/volume at z

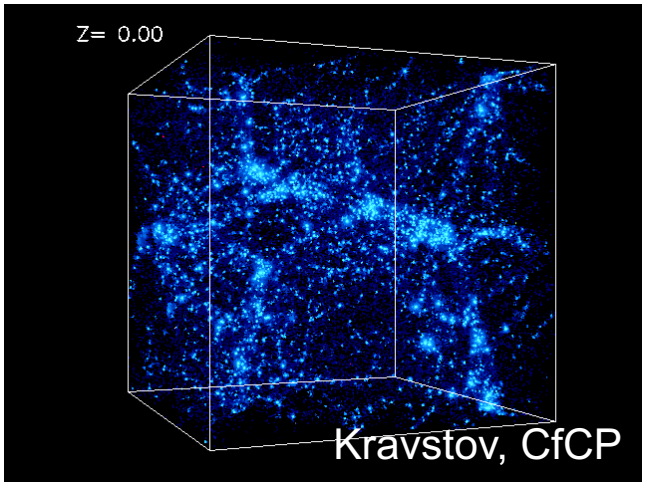


What we see:
Galaxies in survey solid angle at photometric z



Cosmology with Clusters

DARK ENERGY SURVEY



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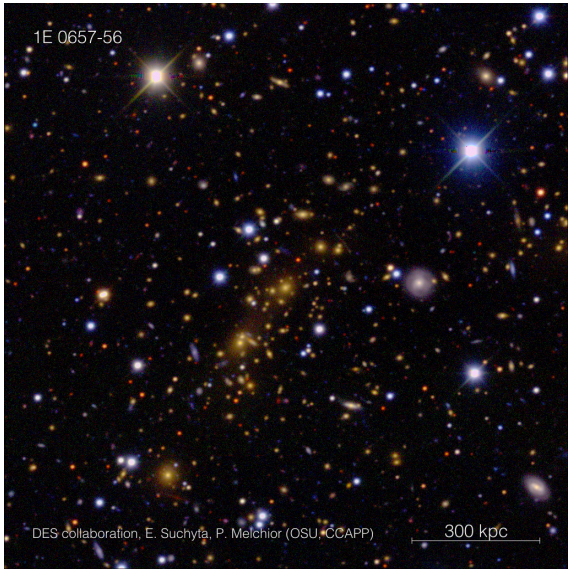


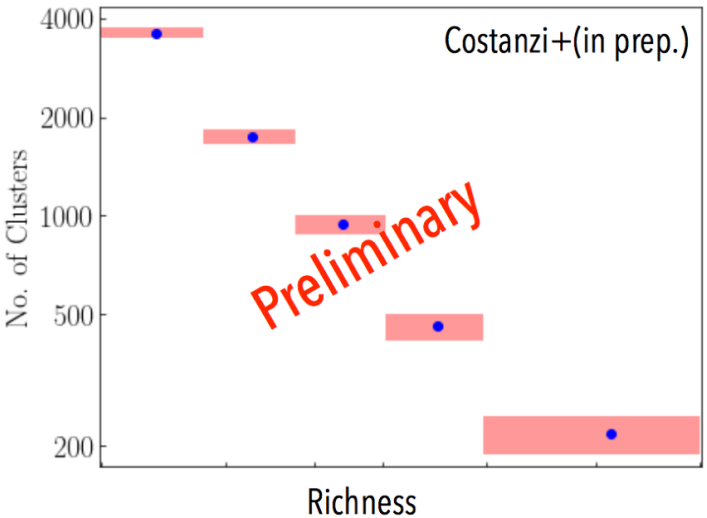
Richness (# of galaxies) → cluster mass

Solid angle → volume (cosmology dependent)

Counting Clusters

DARK ENERGY SURVEY

Measure number of clusters
(bins of richness and redshift)



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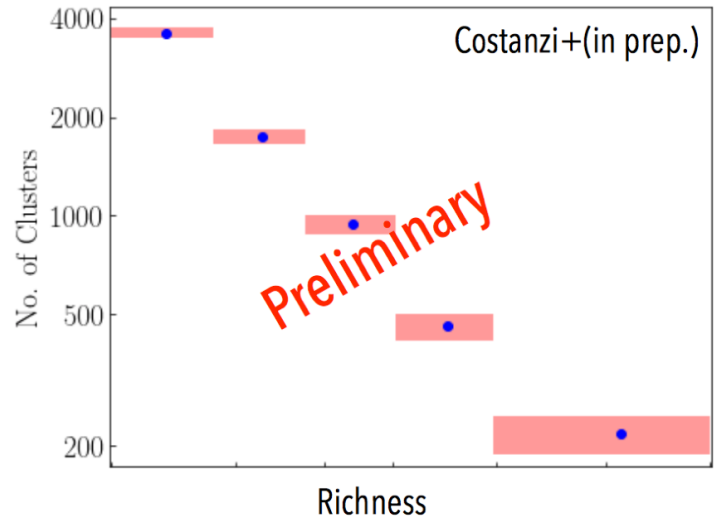
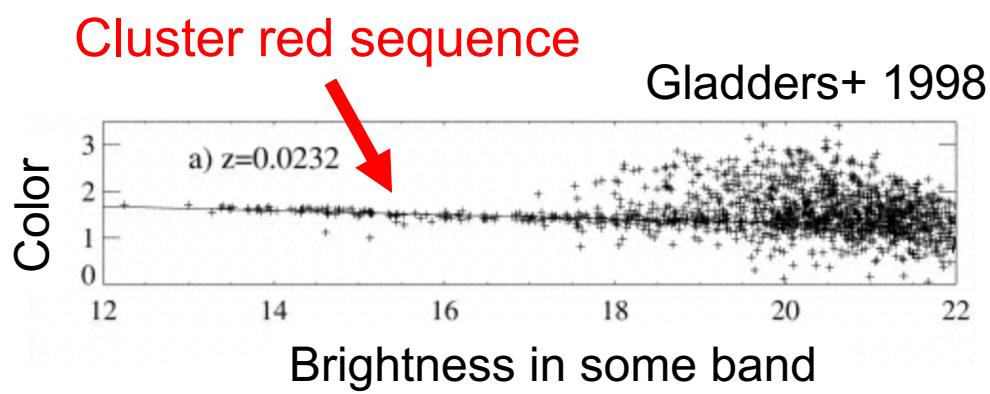


Step 1: Find clusters

Overdensity of galaxies with the same color
redMaPPer (Rykoff+ 2014)



Counting Clusters

Step 2: Determine position, redshift, and richness

Counting Clusters

DARK ENERGY SURVEY

Step 2: Determine position, redshift, and richness

Color of red sequence → redshift (accurate to ~1%, McClintock+ 2018)

Counting Clusters

DARK ENERGY SURVEY

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Candidate central galaxy → position

Counting Clusters

DARK ENERGY SURVEY

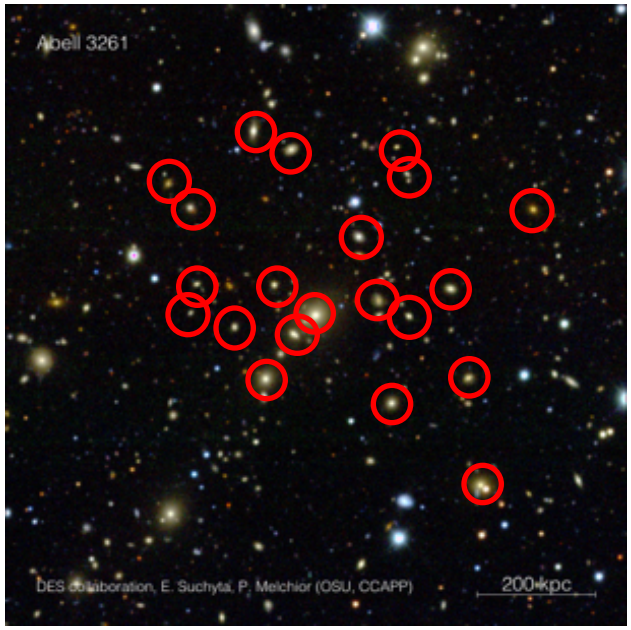
Step 2: Determine position, redshift, and richness

Color of red sequence → redshift (accurate to ~1%, McClintock+ 2018)

Candidate central galaxy → position

Assign galaxies a membership probability

$\lambda_{RM} = \Sigma p_{mem}$ → richness



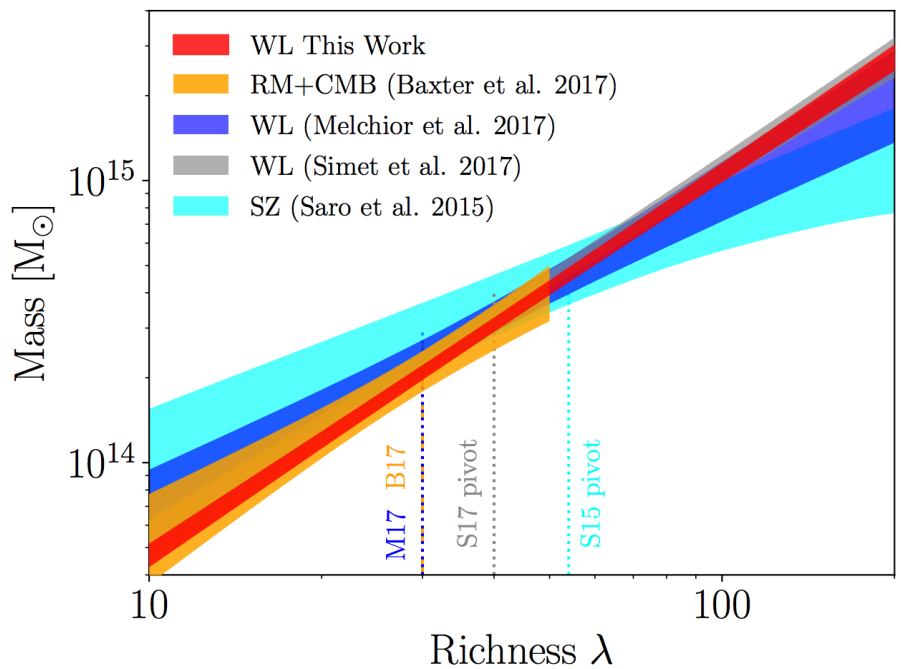
Mass Calibration – DES Year 1

DARK ENERGY SURVEY

Mean mass-richness relation – stacked weak lensing

McClintock et al. 2018, arXiv:1805.00039

Source of systematic	SV Amplitude uncertainty	Y1 Amplitude Uncert
Shear measurement	4%	1.7%
Photometric redshifts	3%	2.6%
Modeling systematics	2%	0.73%
Cluster triaxiality	2%	2.0%
Line-of-sight projections	2%	2.0%
Membership dilution + miscentering	$\leqslant$ 1%	0.78%
Total Systematics	6.1%	4.3%
Total Statistical	9.4%	2.4%
Total	11.2%	5.0%



Total uncertainty of ~5%

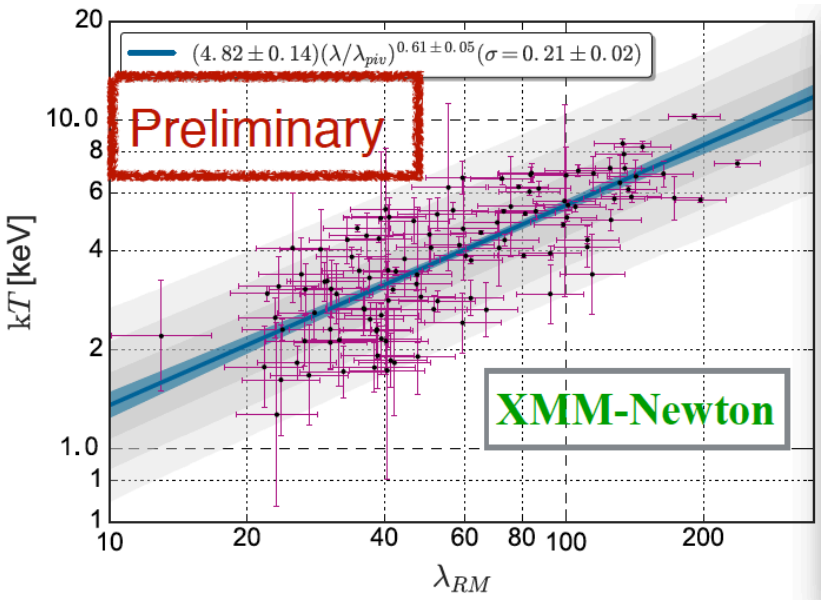
Systematics dominated with largest contributions from photo-z's and projection effects

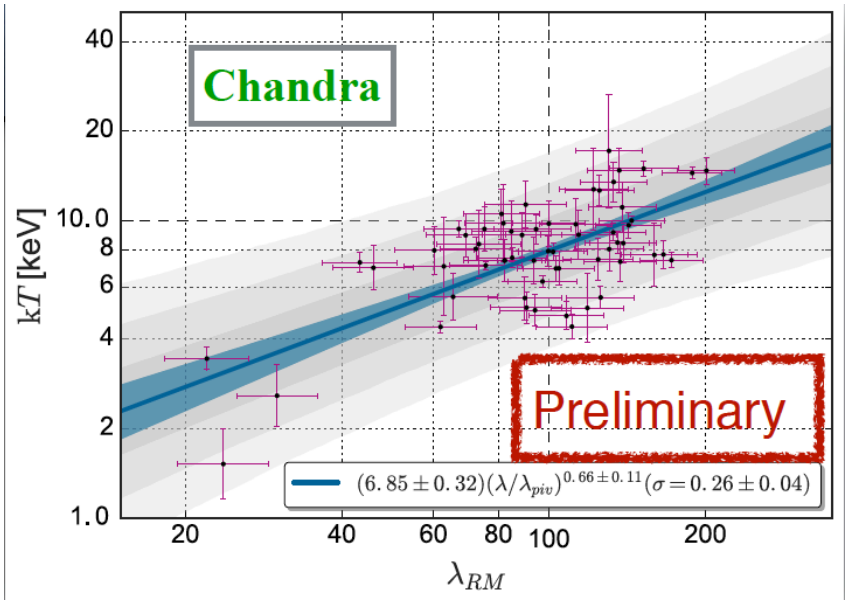
Mass Calibration – Scatter

DARK ENERGY SURVEY

Mass-richness scatter – X-ray and SZ observations

Hollowood+ in prep, Farahi+ in prep.





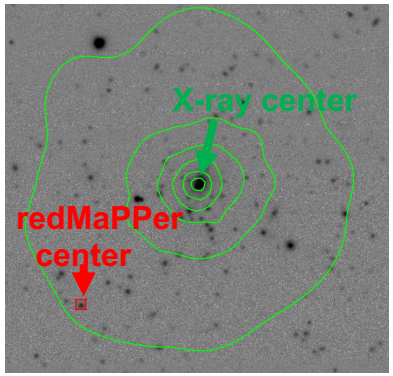
Scatter of 0.25 ± 0.13

Systematics

Miscentering: Zhang+ in prep.

- reduces lensing shear
- reduces observed richness

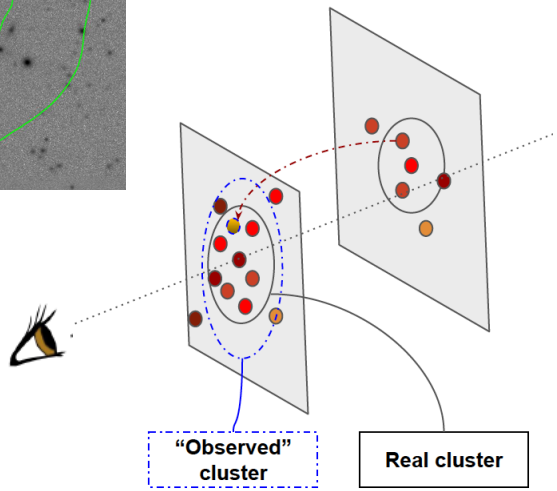
Calibrate with X-ray data



Projection: Costanzi+ 2018

- changes observed richness

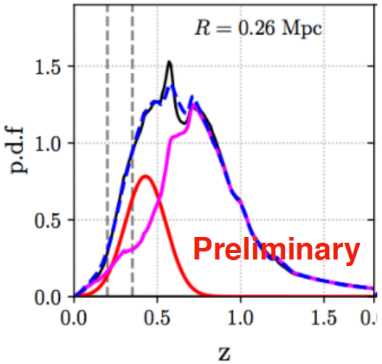
Calibrate $p(\lambda_{obs}|\lambda_{true})$ with simulations



Cluster member contamination: Varga+ in prep.

- Reduces shear by adding unsheared galaxies

Calibrate boost using p(z) distribution

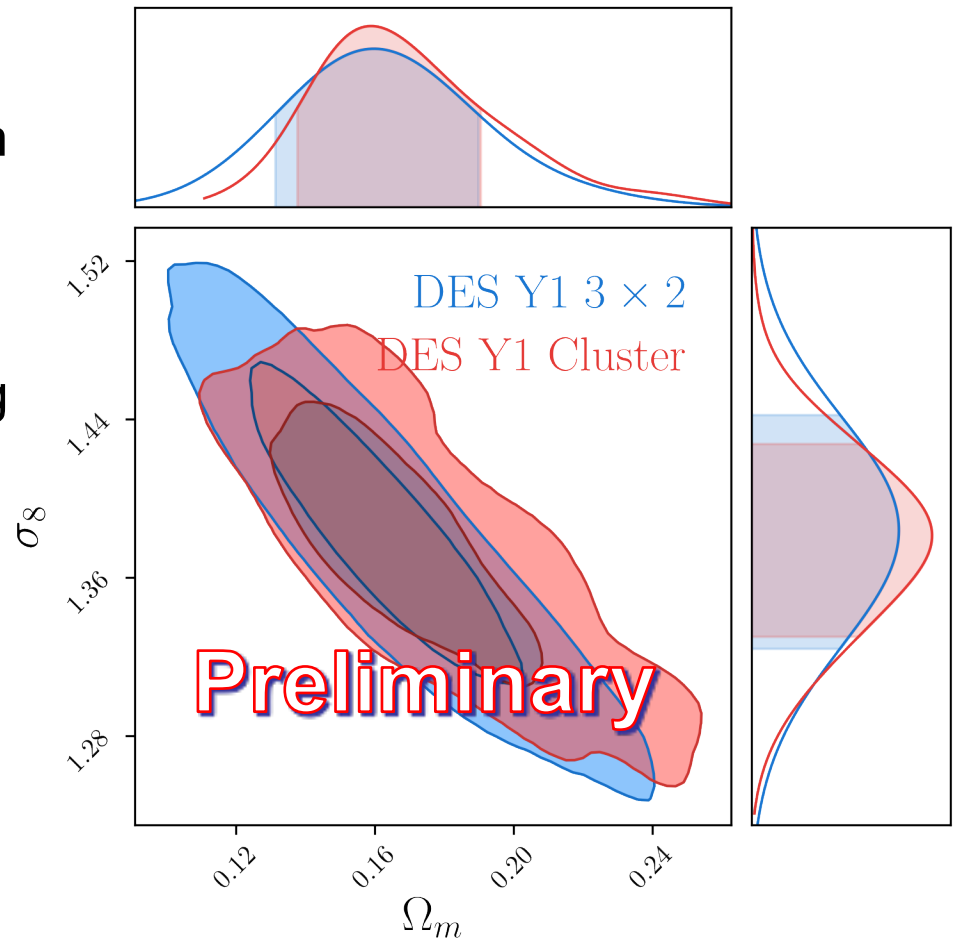


Y1 Cluster Cosmology - Blinded

Coming soon: DES Key Paper on Year 1 cluster cosmology

Blinded results show constraining power equals combined 3x2pt

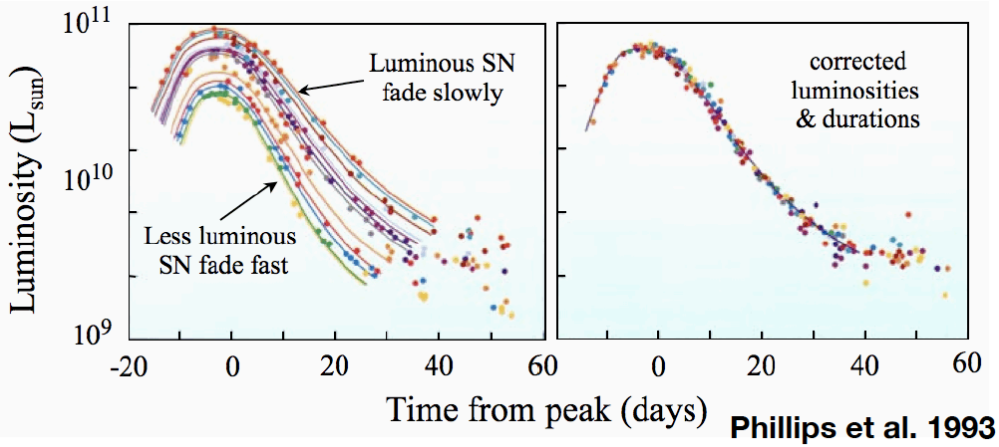
* blinded means position of contours unknown. Here they are artificially shifted to overlay 3x2pt.



Supernovae

DARK ENERGY SURVEY

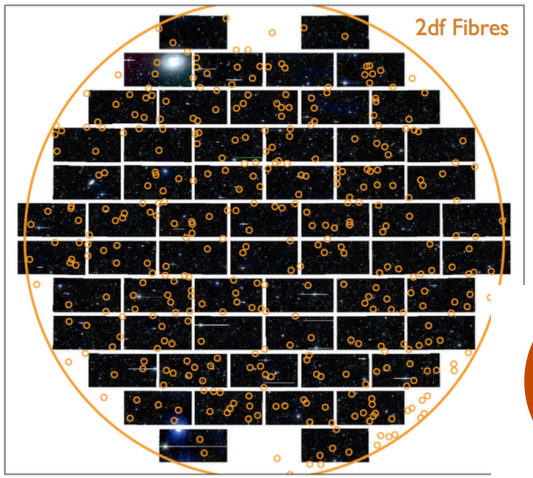
Type Ia Supernovae:
Standardizable candles



Phillips et al. 1993

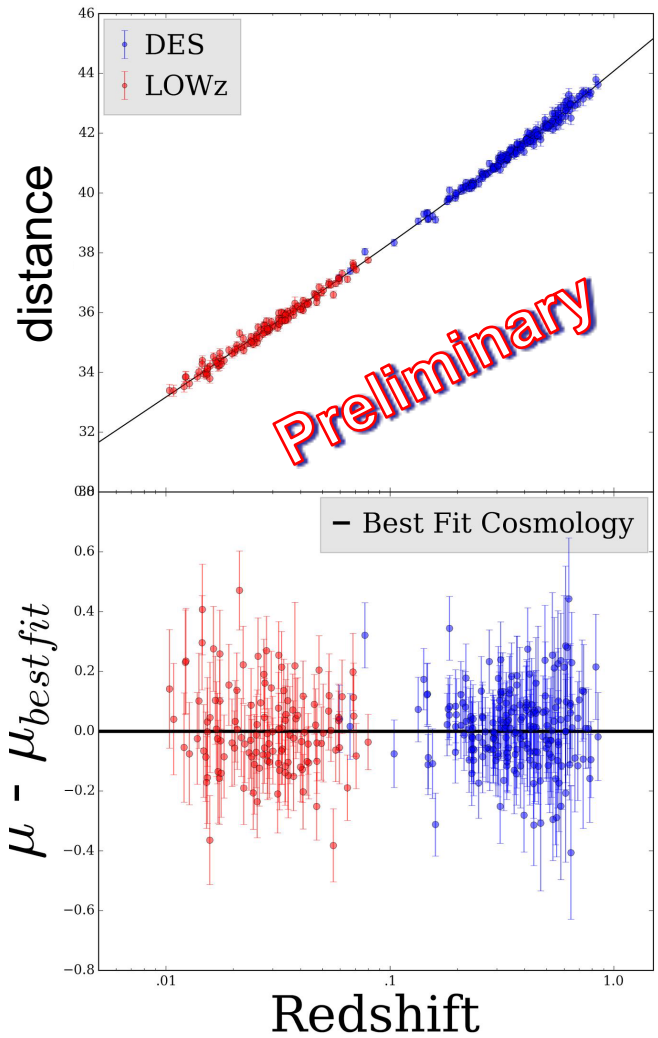
DES supernova survey:

- 10 SNe fields visited every few days
- Spectroscopic follow-up by OzDES using AAT



OzDES

Supernovae – DES Year 3



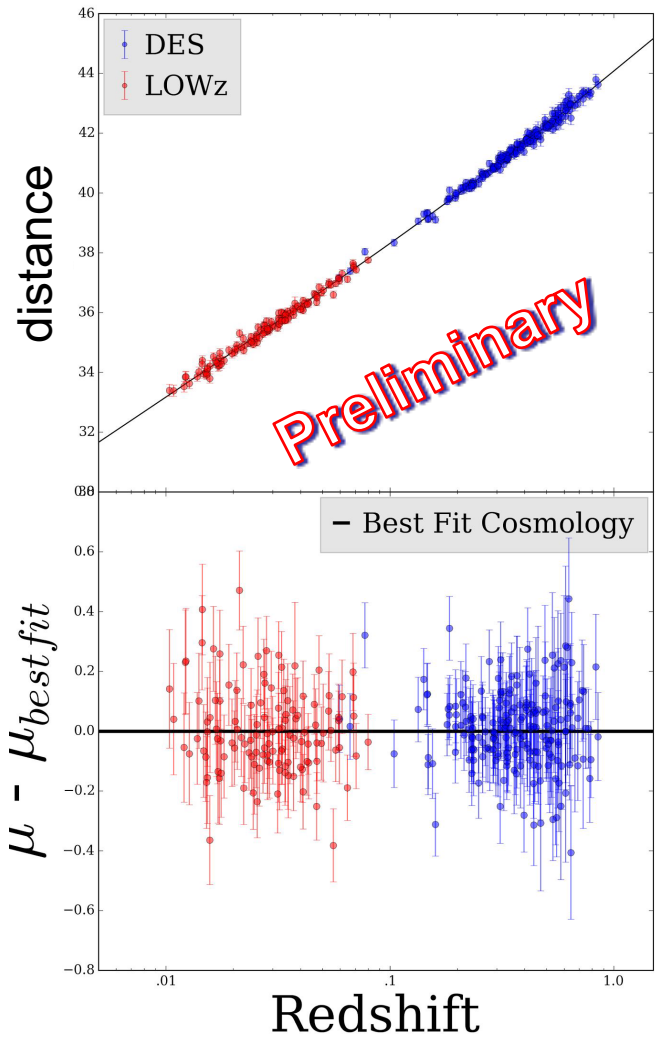
206 spectroscopically confirmed SNe Ia, 0.08 < z < 0.85

+ 128 low-z external

DES collaboration, in prep.

Supernovae – DES Year 3

DARK ENERGY SURVEY



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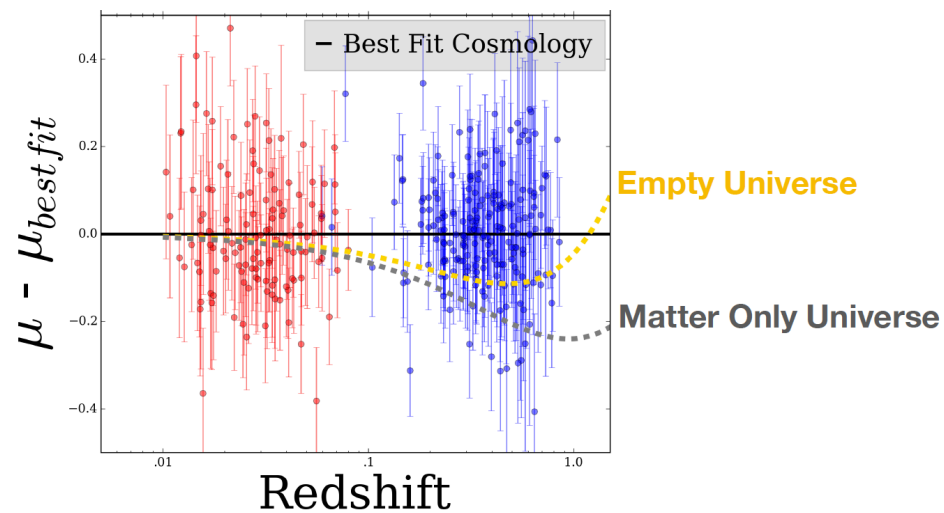
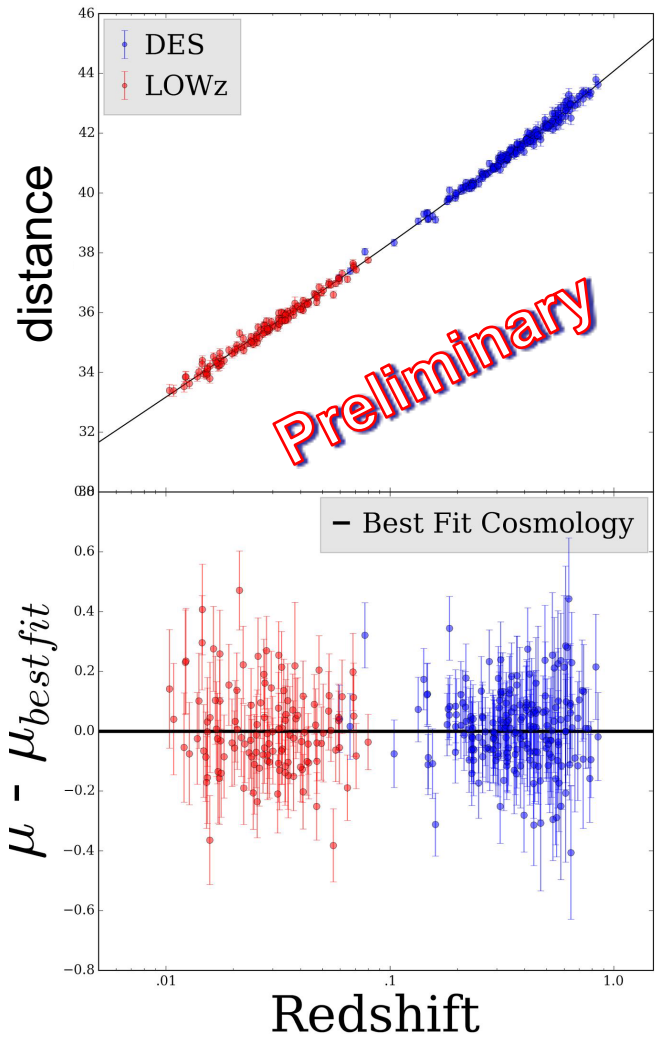


DES collaboration, in prep.

Supernovae – DES Year 3

DARK ENERGY SURVEY



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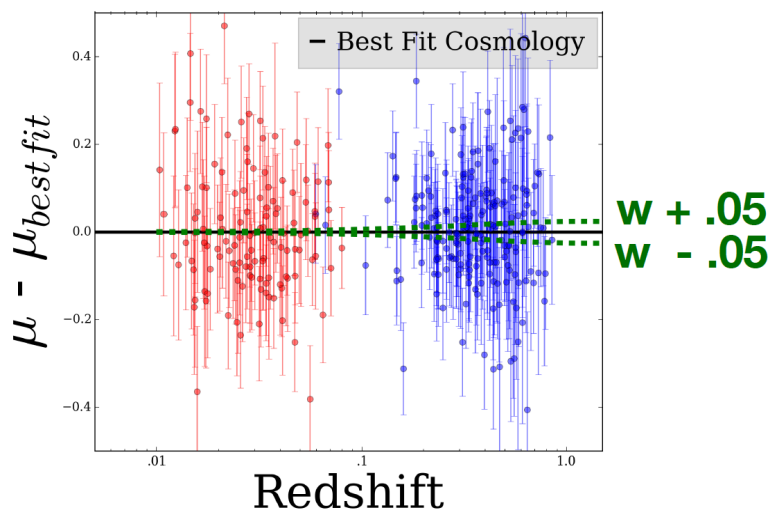


DES collaboration, in prep.

Supernovae – DES Y3 Cosmology

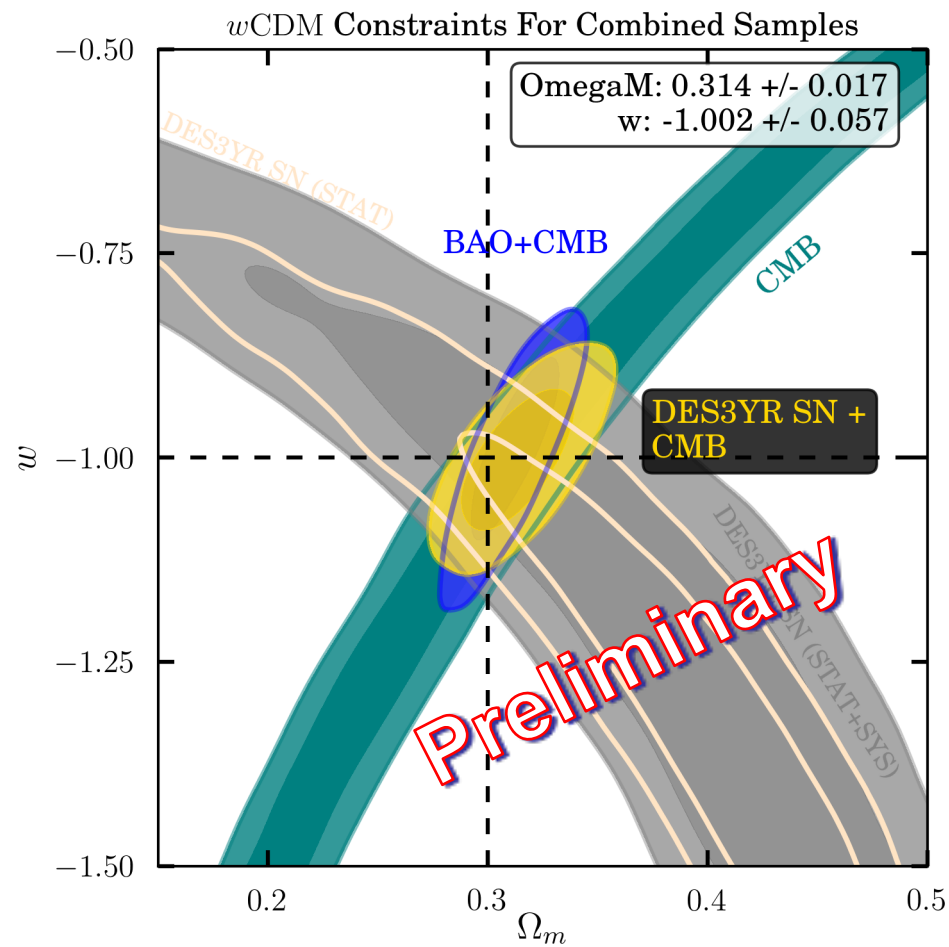
DARK ENERGY SURVEY

$$w = -1.002 \pm 0.057$$

$$\sigma_w = 0.041(STAT), 0.040(SYS)$$

$$\Omega_M = 0.314 \pm 0.017$$

(wCDM, DES Y3 SNe+CMB)

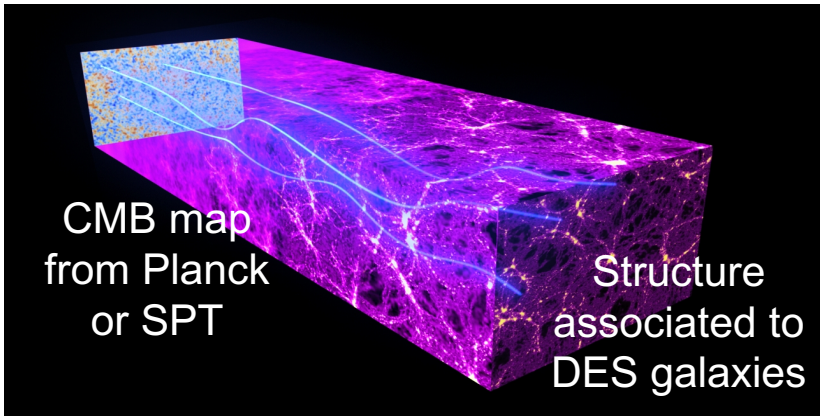


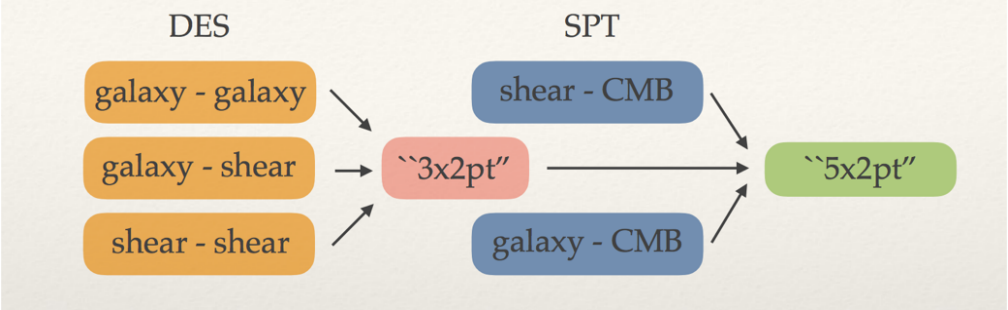
DES collaboration, in prep.

D. Brout, AAS talk

Coming Soon

DARK ENERGY SURVEY

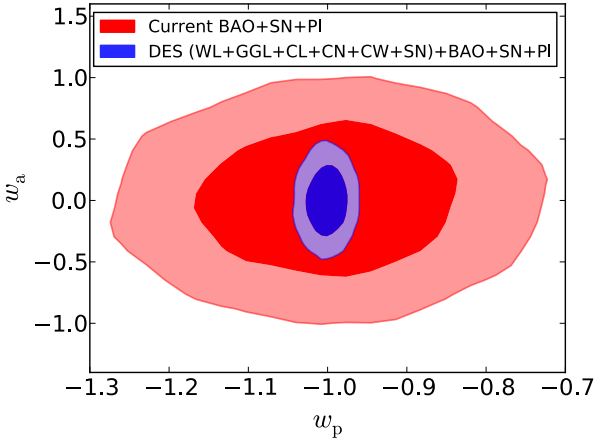




5x2pt (+ DES clusters + DES SNe)

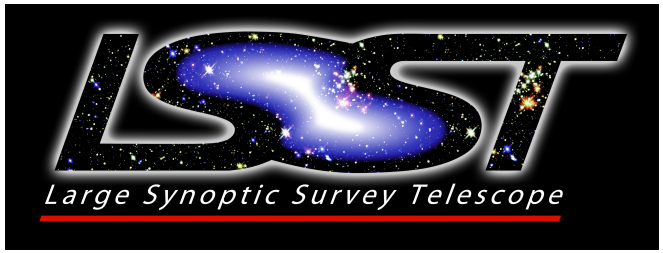
→ DES Year 3 triples area → more than double exposure by DES Year 5

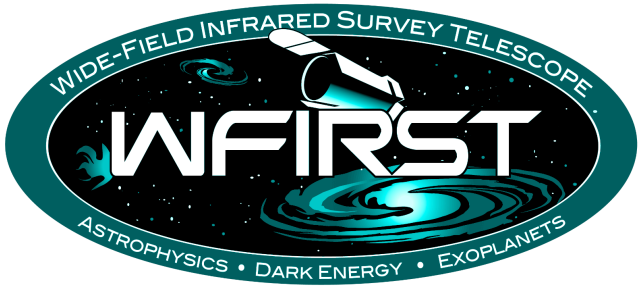
DES forecast
(T. Eifler, E. Krause)



Summary

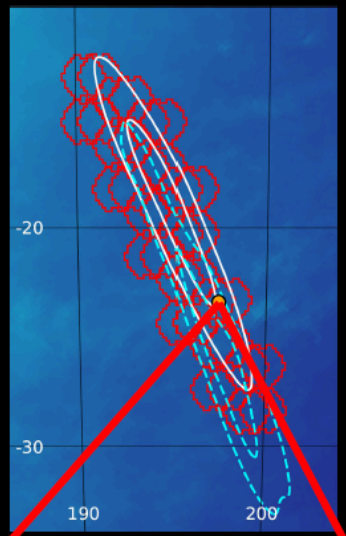
- DES gives precise constraints on late-time structure, starting to rival CMB
- Wide range of probes (early and late time, geometric and structure growth) agree on ΛCDM.
- The future is bright!






Thank you!

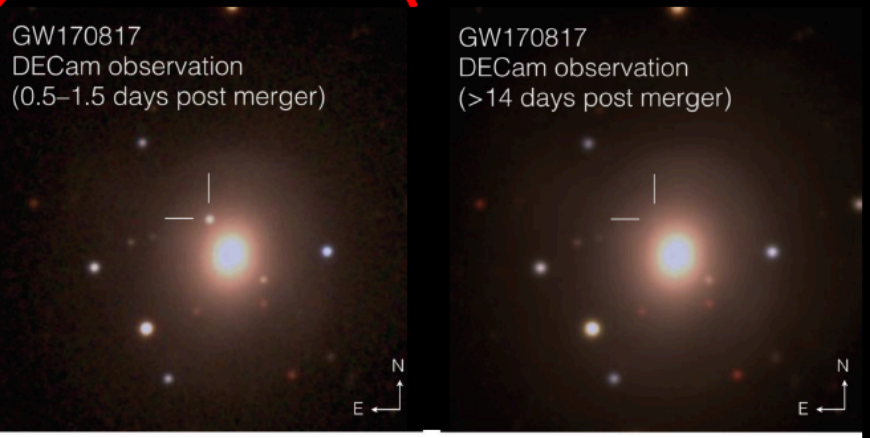
Looking for more than dark energy: Discovery* of GW170817 counterpart



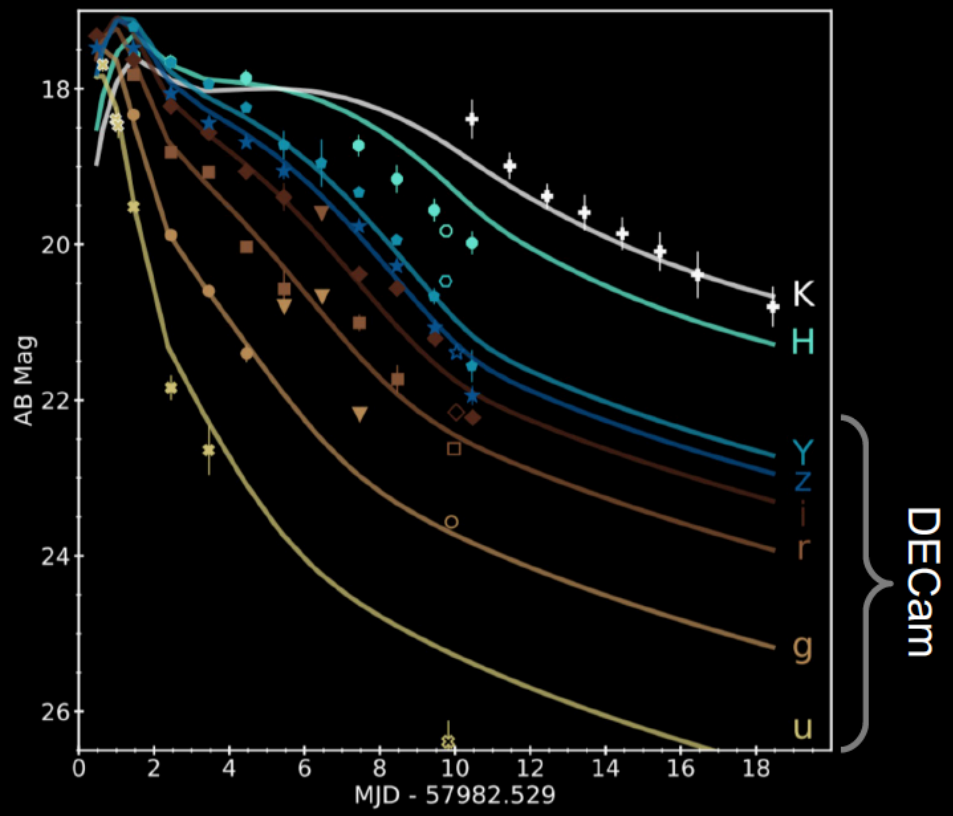
10.5 hours post-merger among 1500 candidates

25 deg^2 LIGO/VIRGO positional constraint (90 % C.L.) >90% covered by DECam

Soares-Santos, … DG+ ArXiv:1710.05459

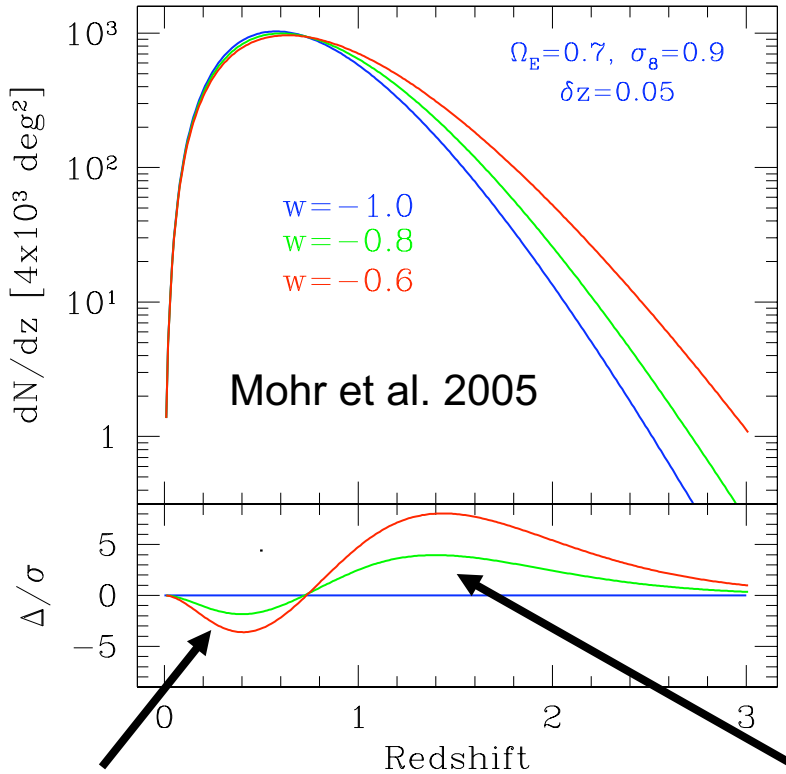


Above left: DECam discovery image *grz* color co-add for the optical counterpart of GW170817. Above right: template image. From Soares-Santos et al (2017).



UV, optical, and NIR light curves of the GW170817 source. Cowperthwaite et al (2017).

Cosmology with Clusters



survey area covers less volume

Constant Ω_{DE} with increasing w

structure must form earlier to be in place before DE domination