Probing the Large-Scale Structure:
First results from the Dark Energy Survey

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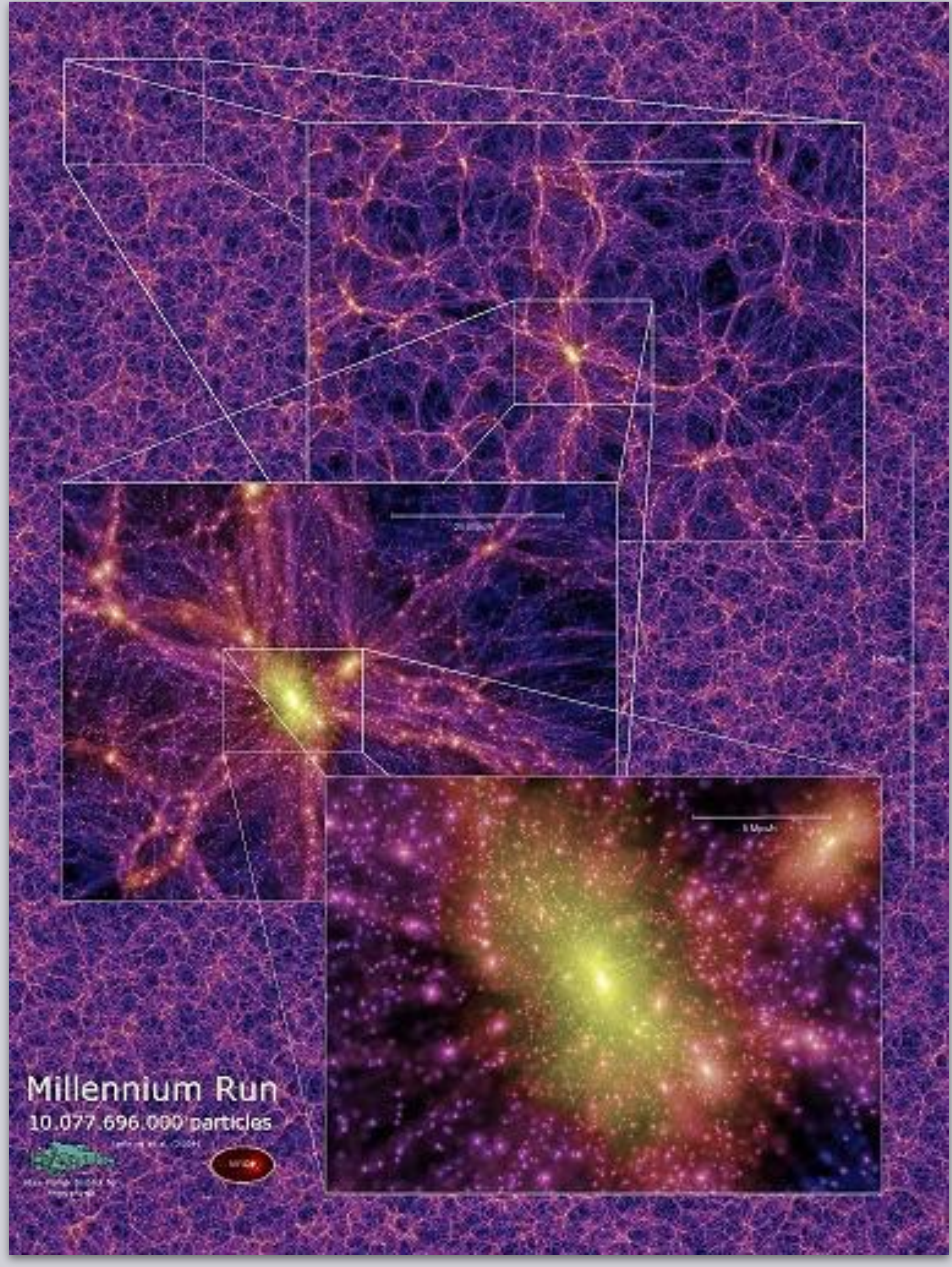
on behalf of the Dark Energy Survey Collaboration

XXVIII International Symposium on Lepton Photon Interactions at High Energies, Guangzhou, Aug 10 2017

THE DARK ENERGY SURVEY

THE OHIO STATE UNIVERSITY

Large-Scale Structure



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

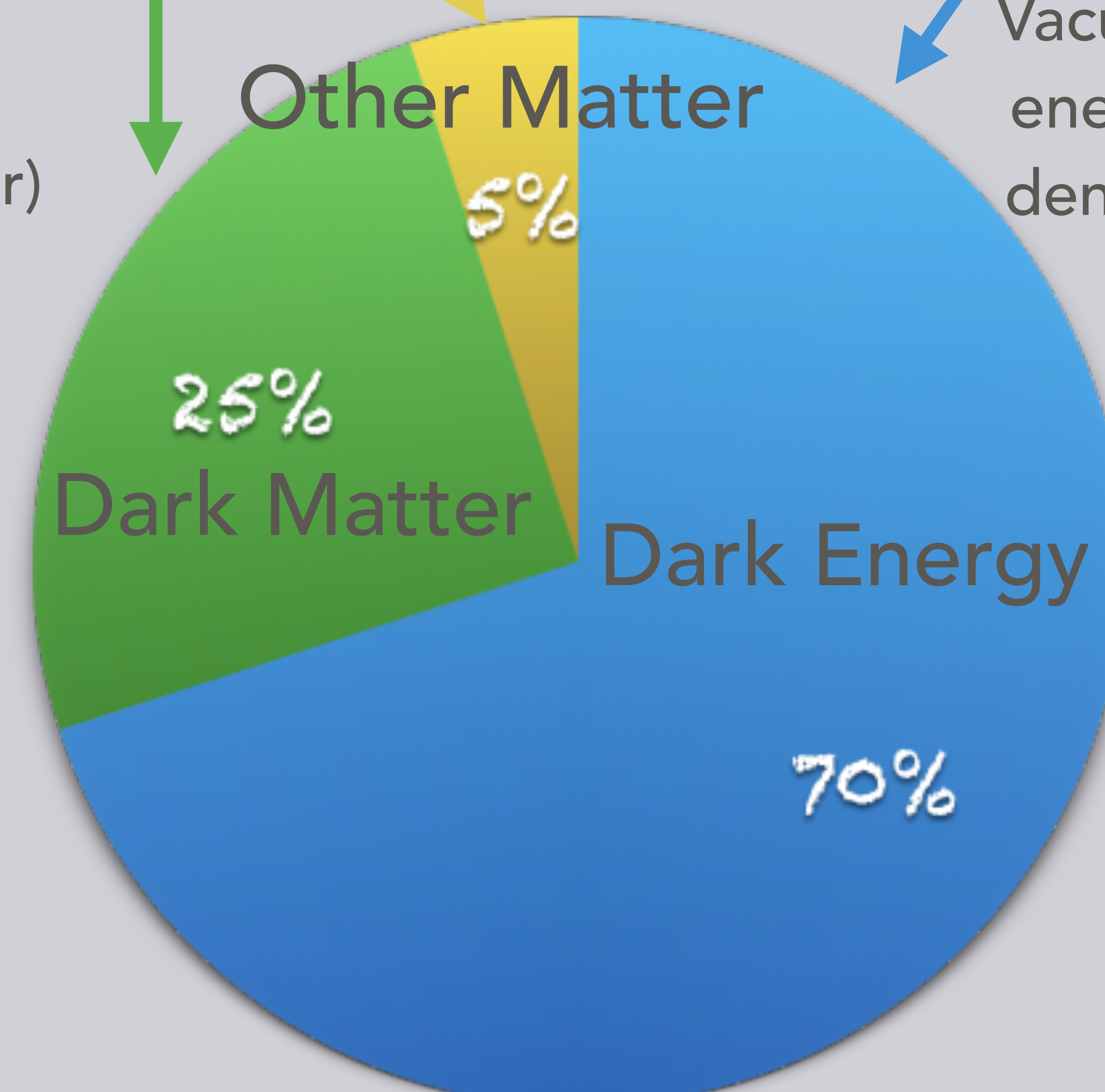
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{H^2}{H_0^2} = \Omega_{0,R}\,a^{-4} + \Omega_{0,M}\,a^{-3} + \Omega_{0,k}\,a^{-2} + \Omega_{0,\Lambda}$$

Scale factor

Hubble constant

Matter density (DM + other matter)

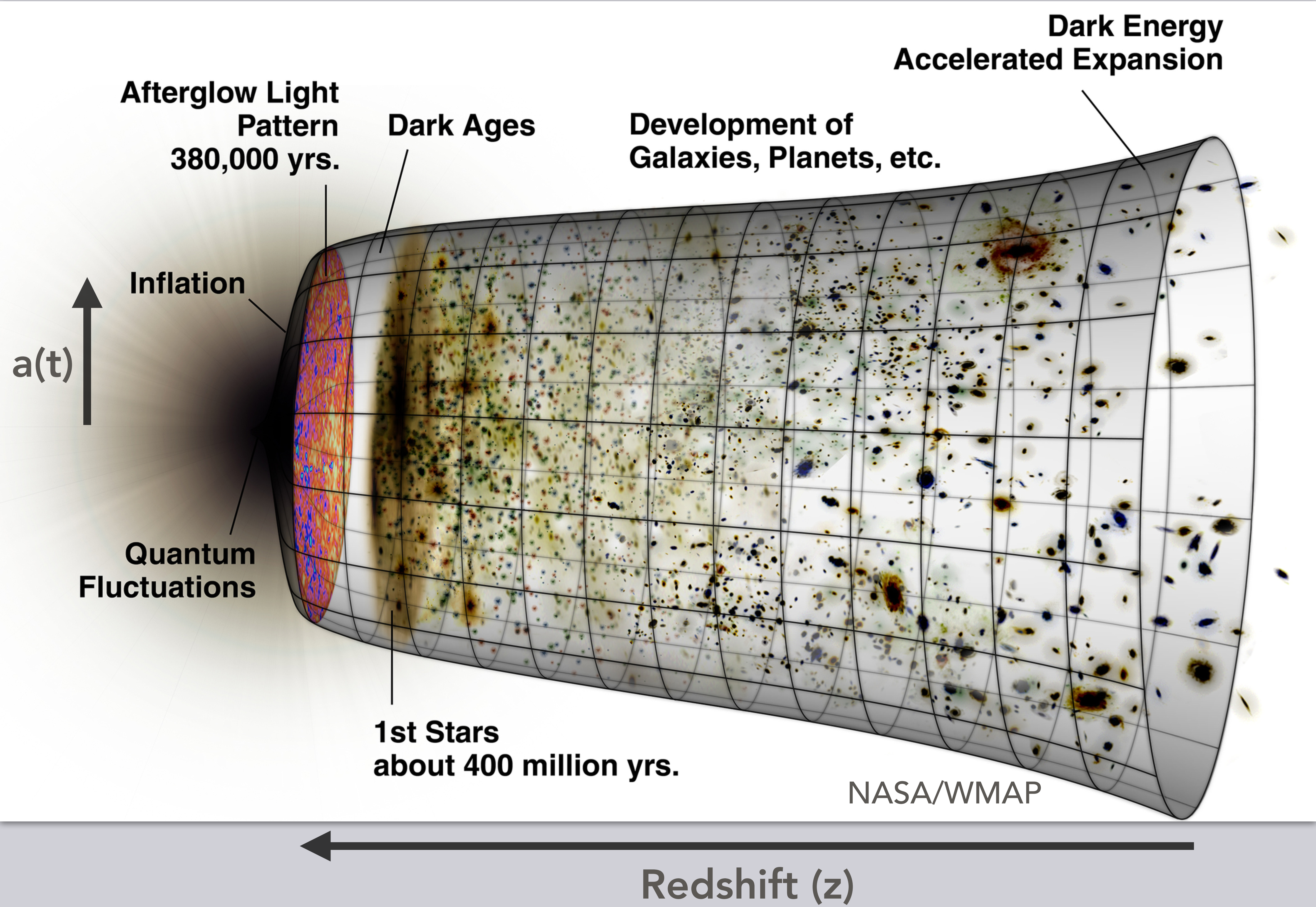
Vacuum energy density

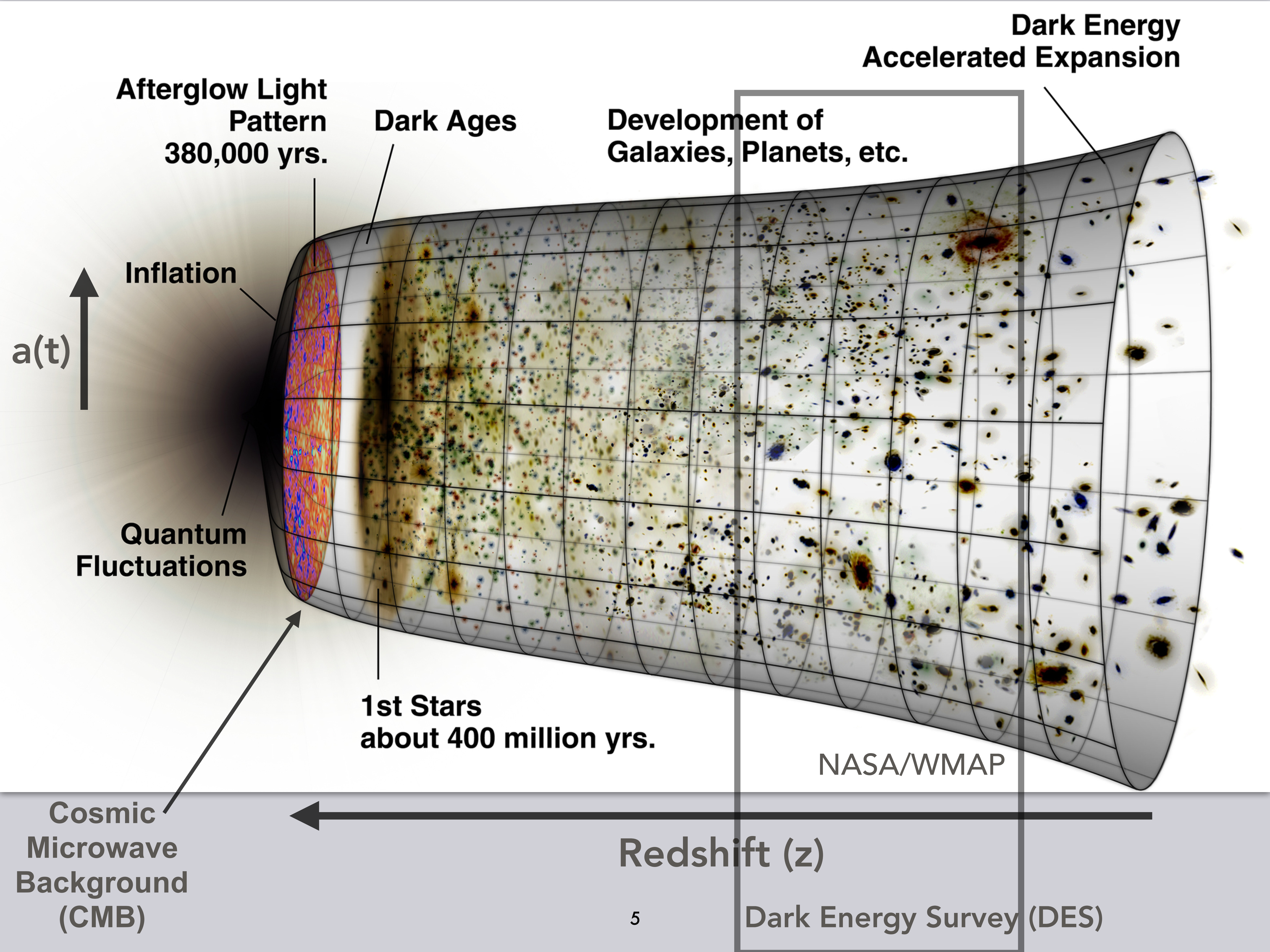


Standard Model of cosmology:

Lambda — Cold Dark Matter (LCDM)

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


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)



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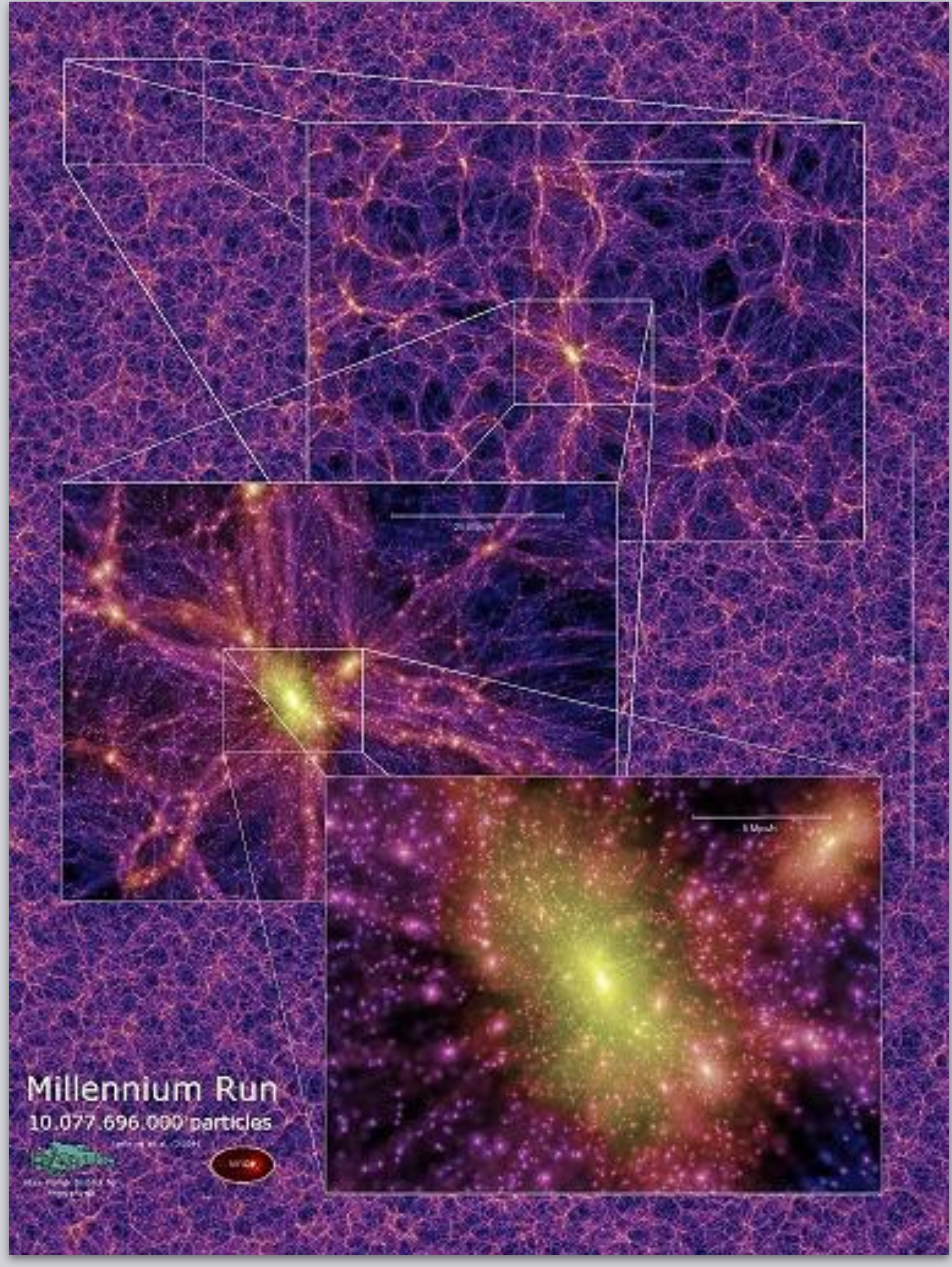
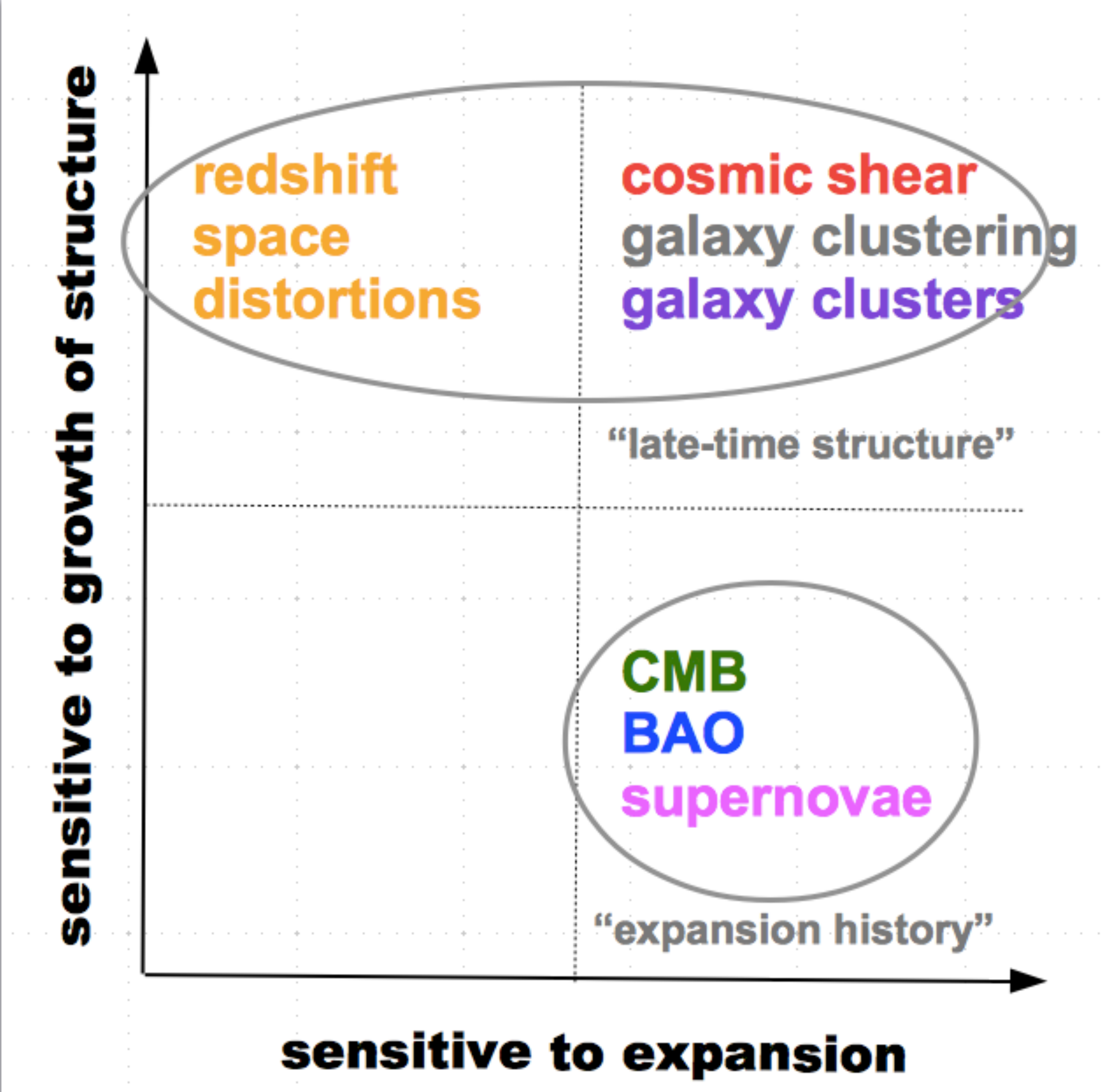
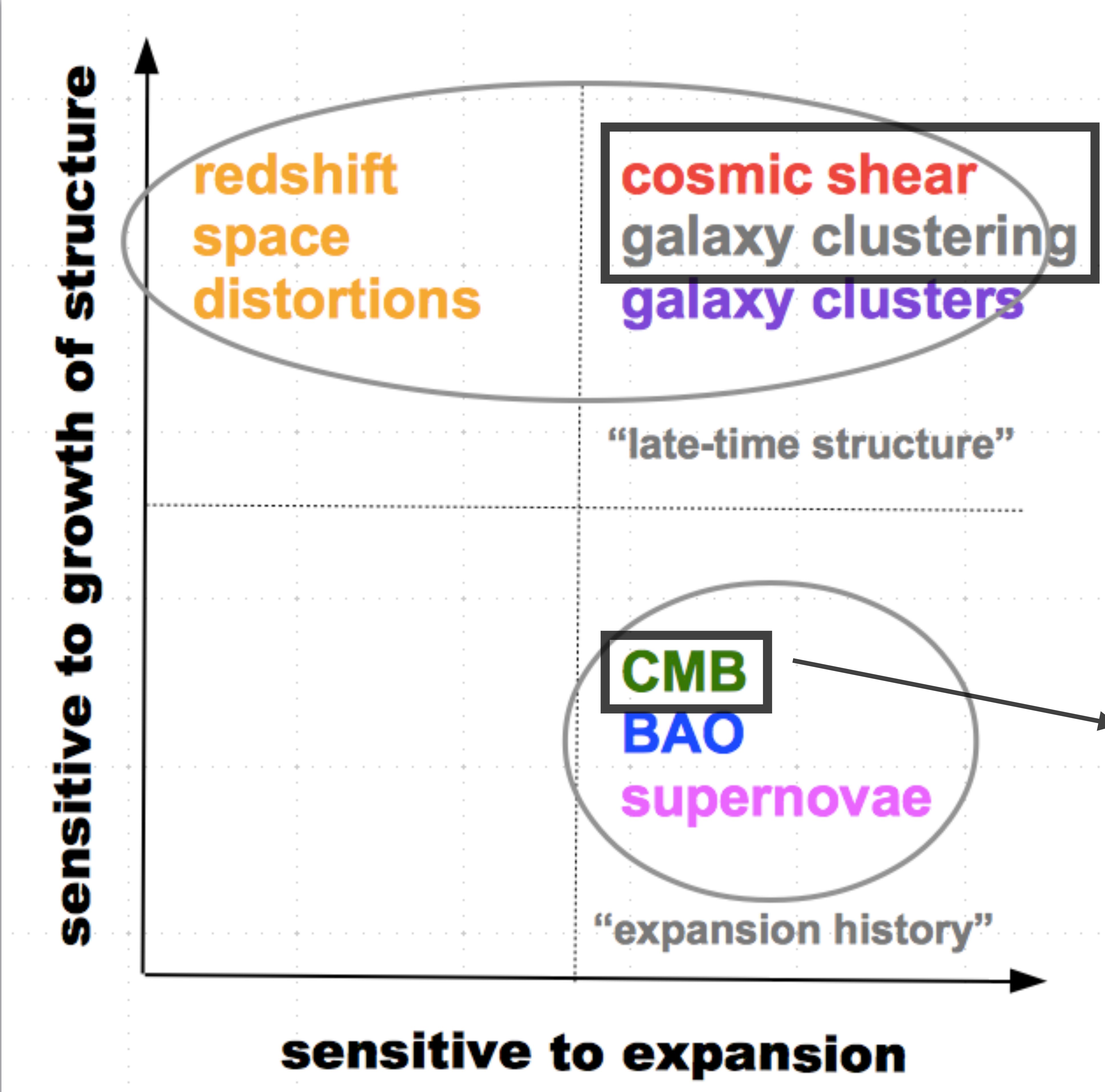
NASA/WMAP
Cosmic
Microwave
Background
(CMB)
Redshift (z)
Dark Energy Survey (DES)

How do we learn about dark matter and dark energy?

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

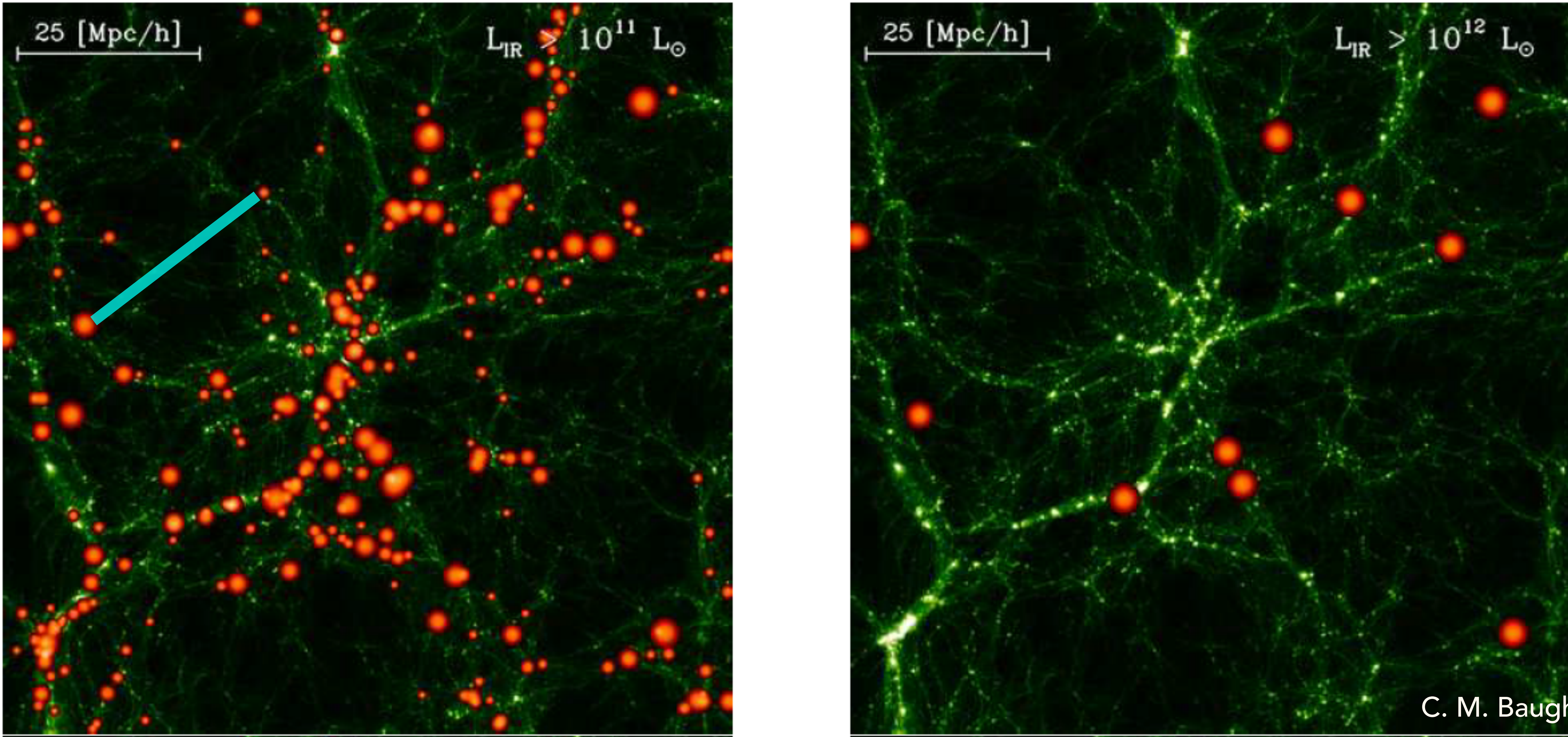



redshift space distortions
cosmic shear
galaxy clustering
galaxy clusters
"late-time structure"
CMB
BAO
supernovae
"expansion history"
sensitive to growth of structure
sensitive to expansion



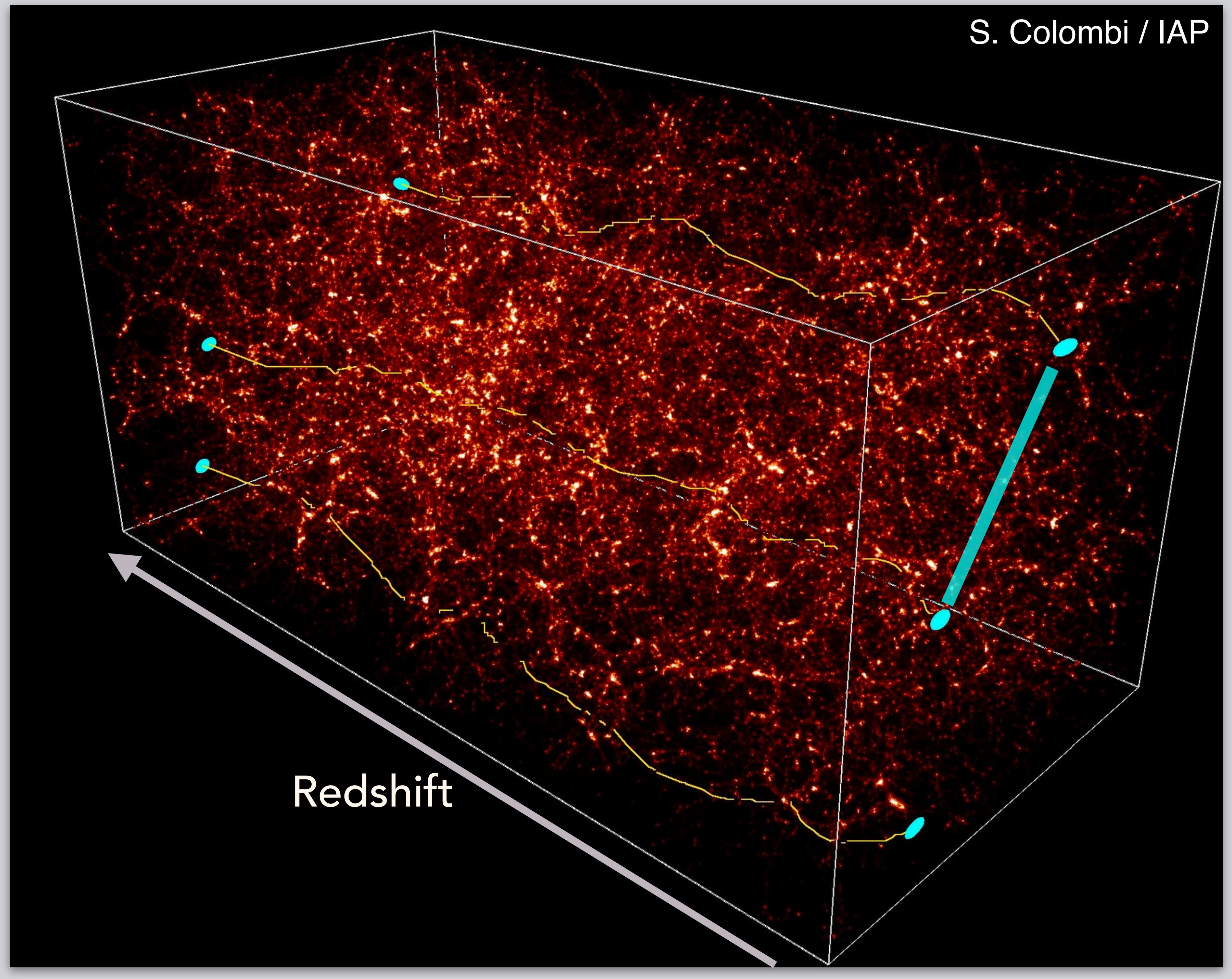
Up to now, the CMB has been by far the most powerful cosmological probe

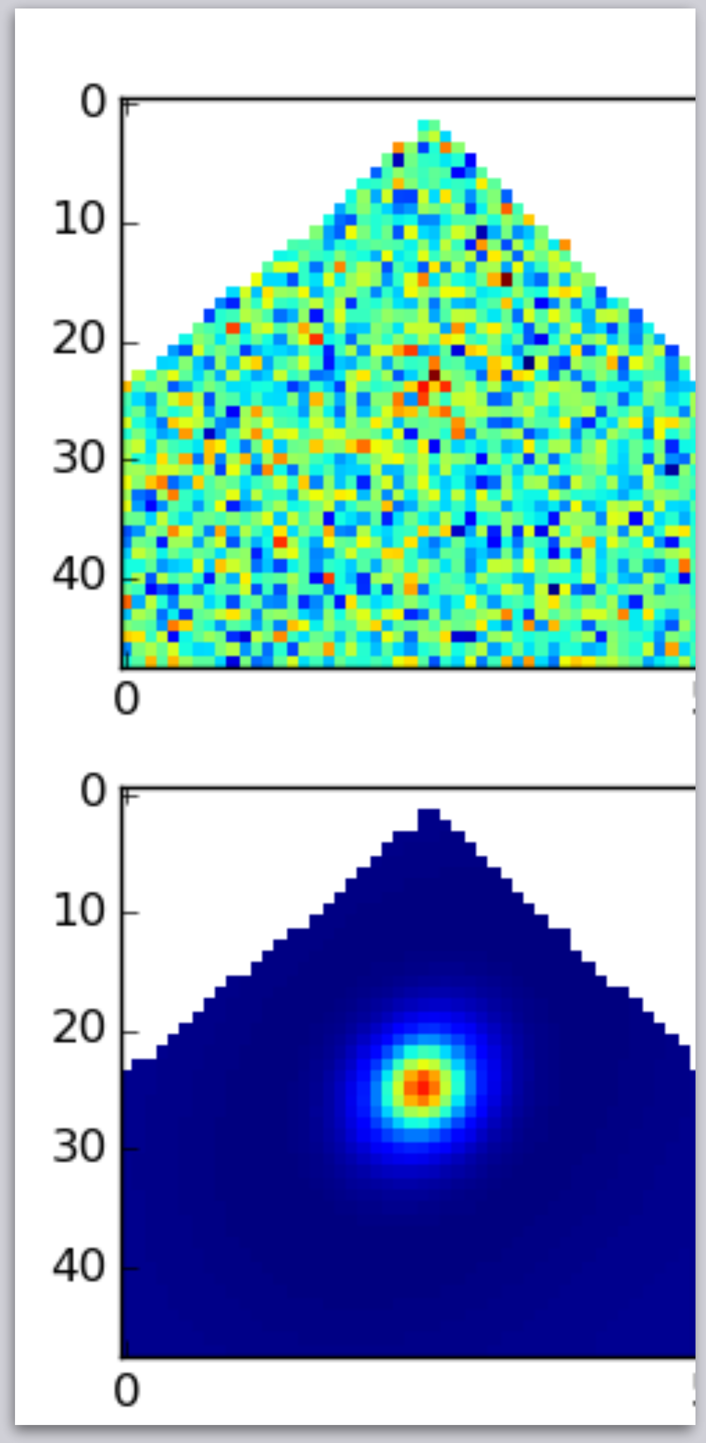
1) Galaxy clustering:
Galaxies tend to form where there is dark matter



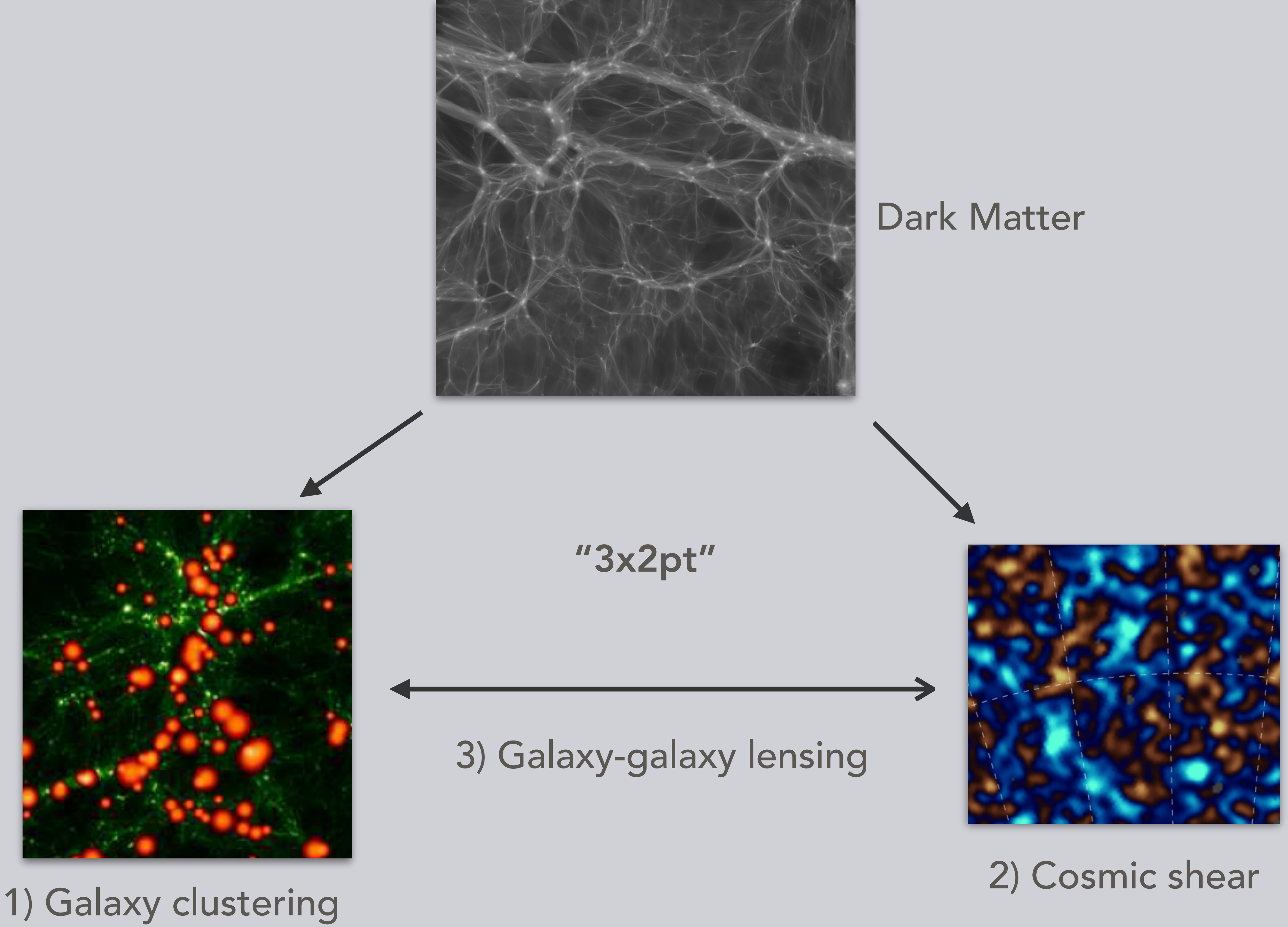
Construct a power spectrum (or real-space correlation function) from positions.
Immensely successful for decades.
Limited by an unknown galaxy bias (how well galaxies really trace dark matter).

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





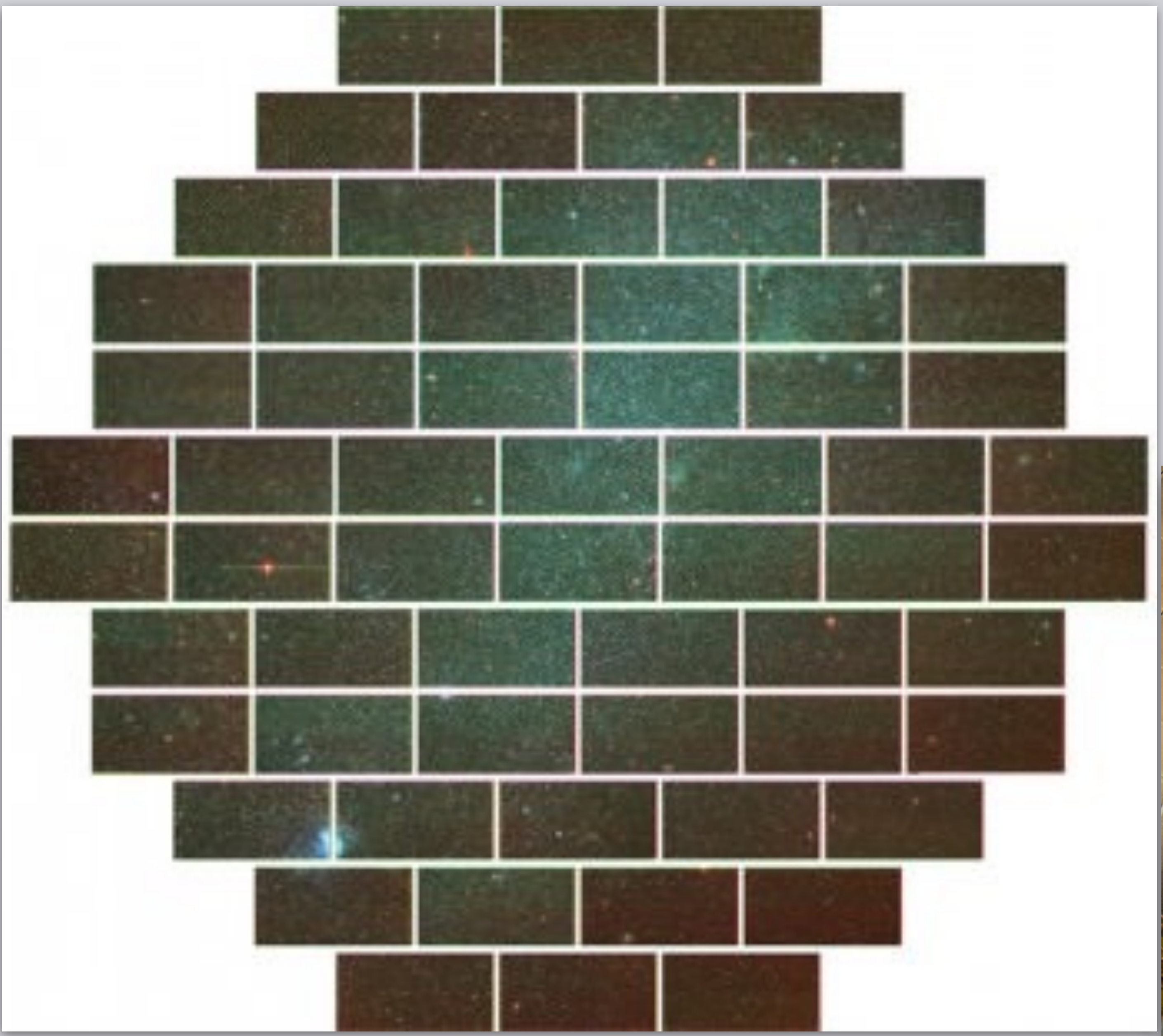
Construct a power spectrum (or two real-space correlation functions) from spin-2 ellipticity.
Only first measured around 2000, and precision measurements only now.
No galaxy bias…but intrinsic alignment - galaxies aren't spheres.



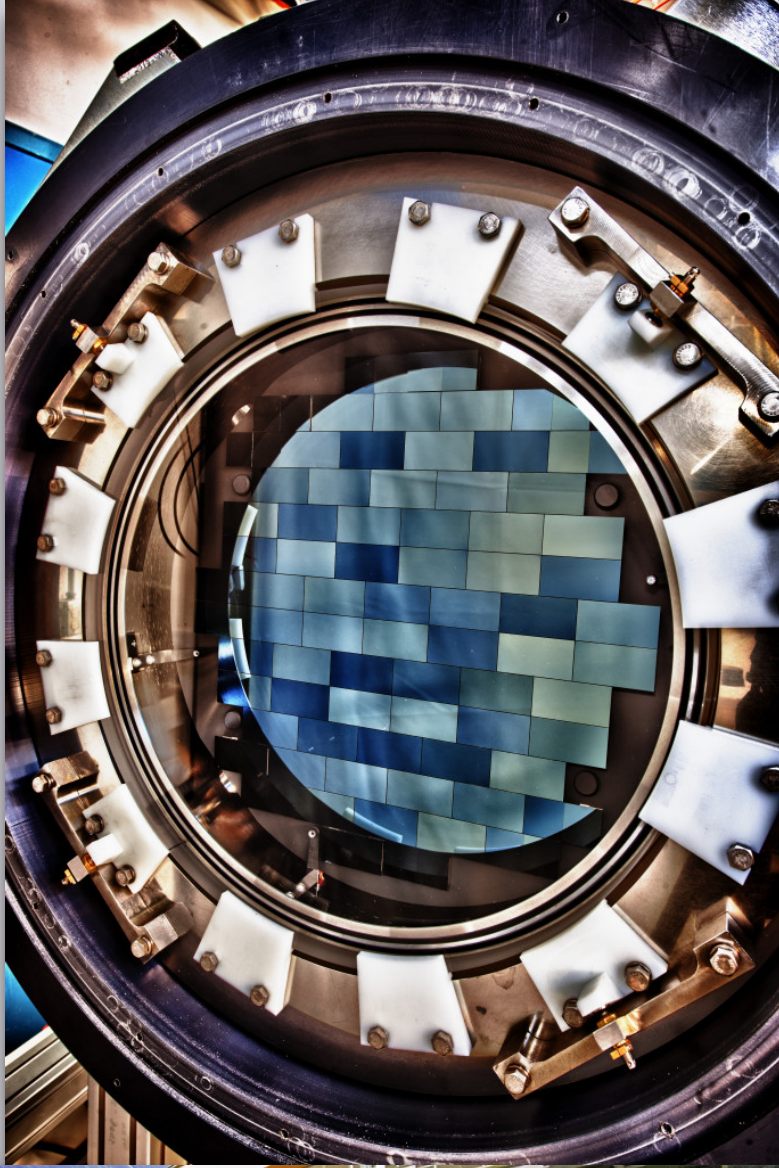
Combination of these three probes maximizes use of large-scale structure information and jointly and robustly constrains astrophysical and systematic parameters in the analysis

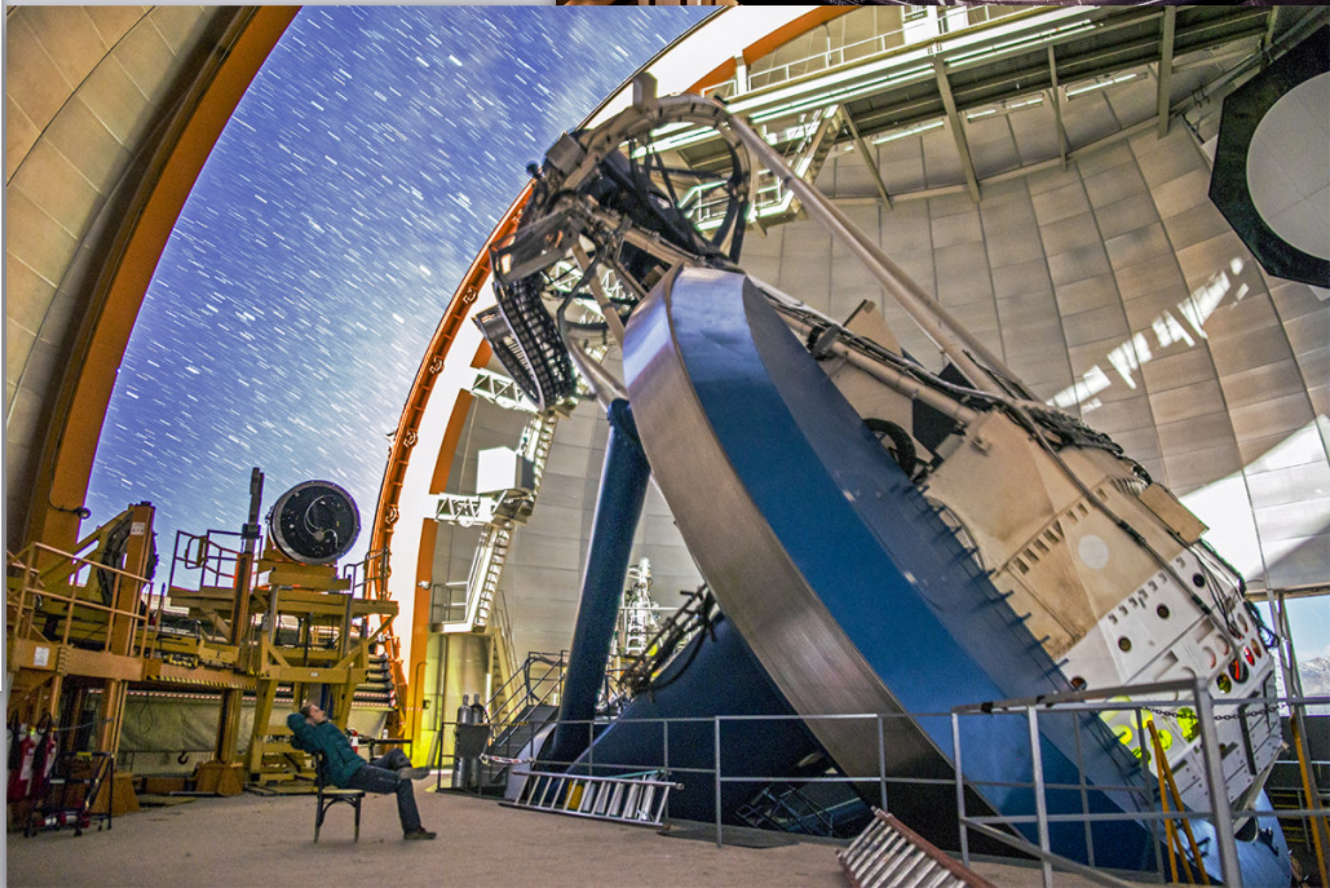
The Dark Energy Survey

- 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* bands
- Just finished analysis of first year of data — observed four years

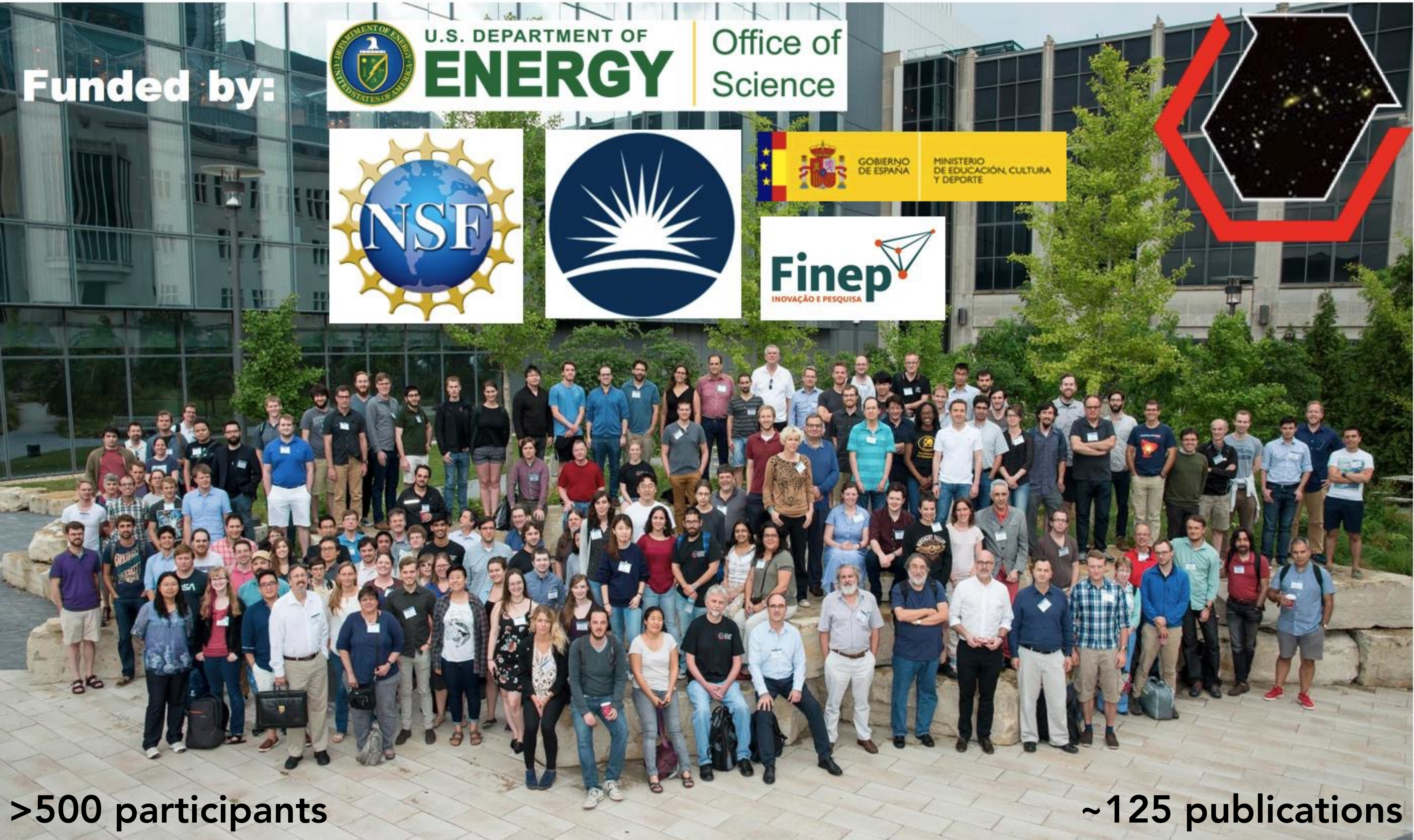


Small Magellanic Cloud





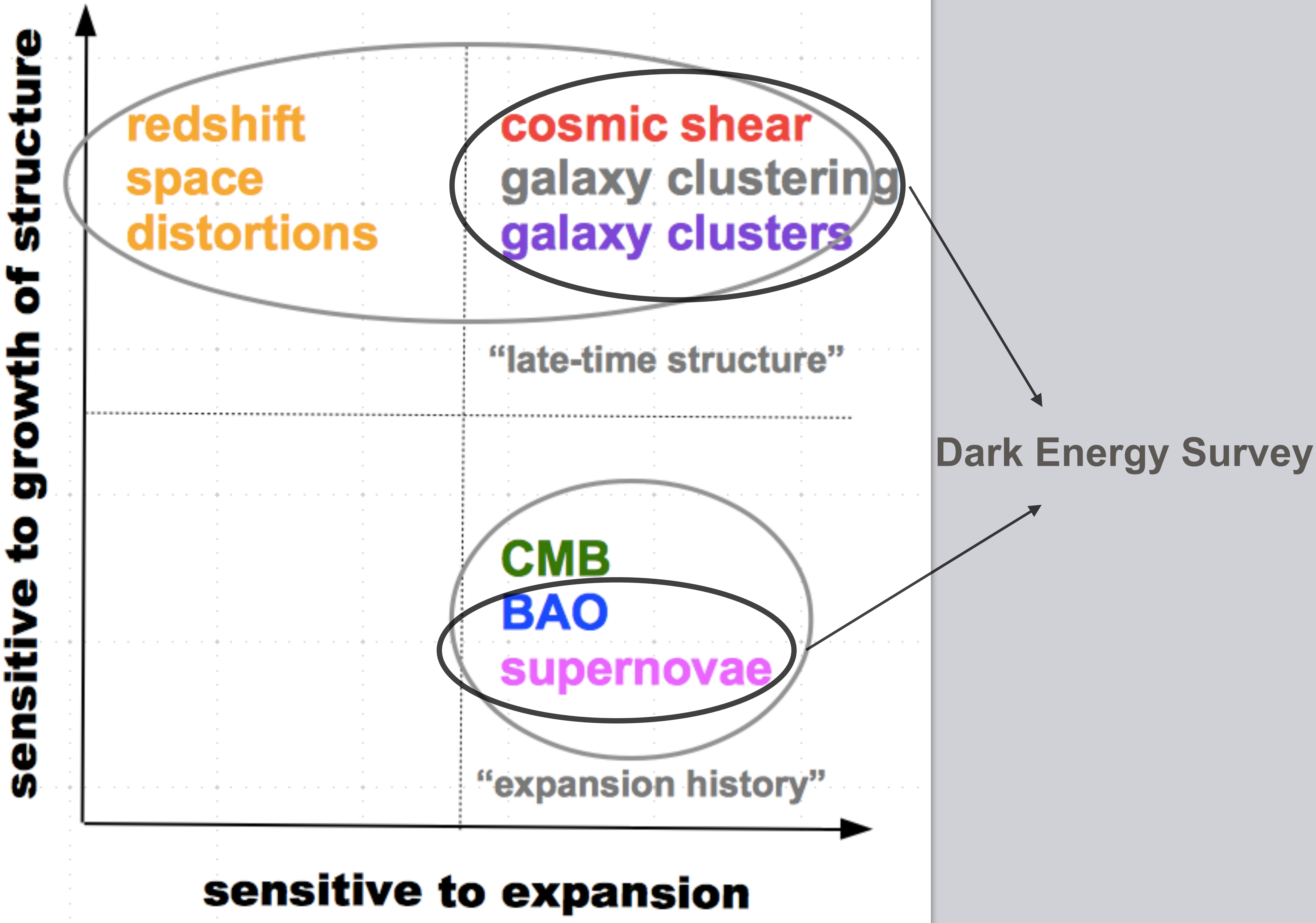
Funded by:



>500 participants

~125 publications

Collaborating institutions: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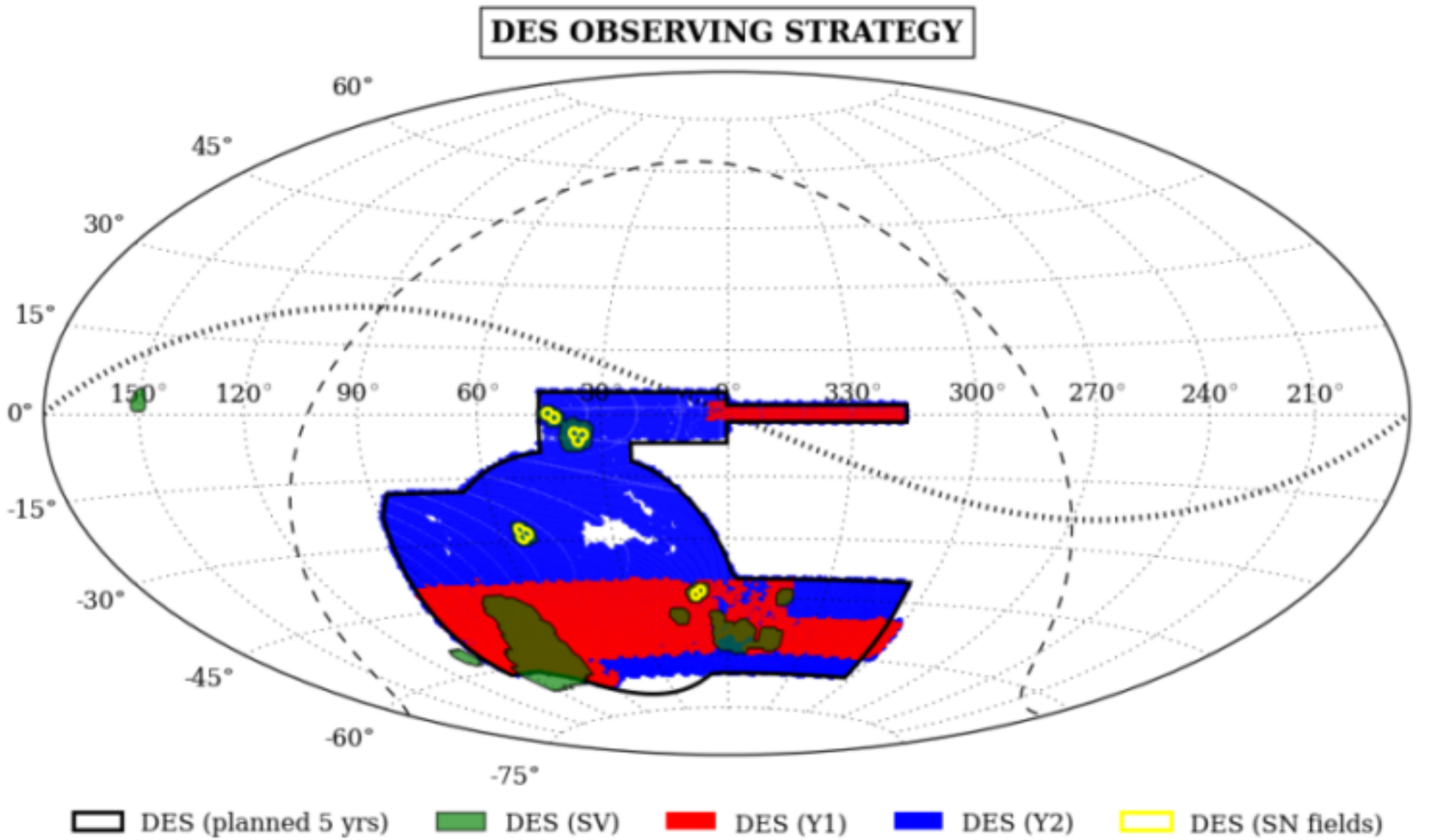

DES OBSERVING STRATEGY
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
DES (planned 5 yrs)
DES (SV)
DES (Y1)
DES (Y2)
DES (SN fields)

Dark Energy Survey Year 1 Results

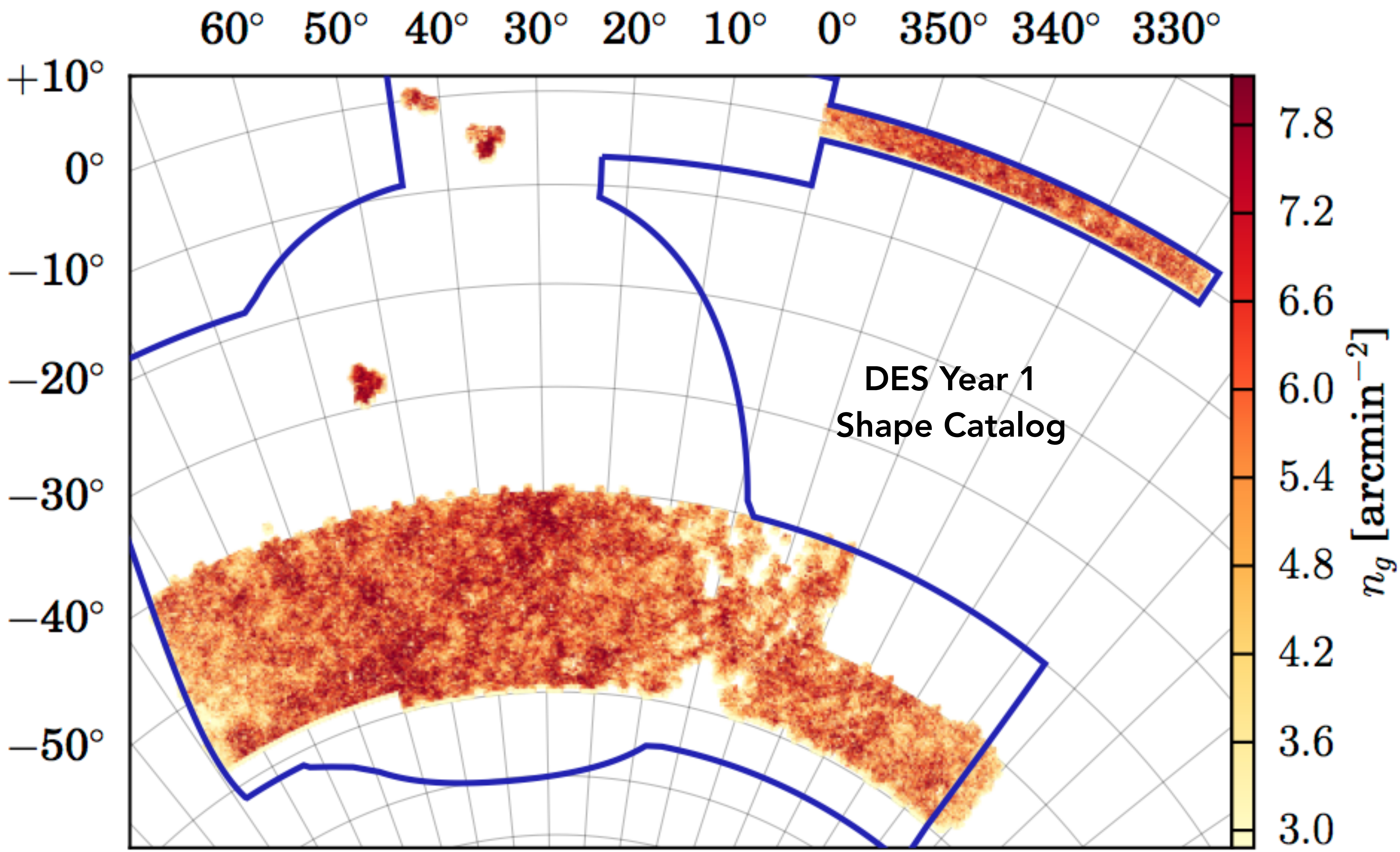
First cosmology constraints from main survey: large-scale structure combination of galaxy clustering and weak lensing

- Detected 130M objects, measured shapes for 35M in ~1500 deg^2 of imaging
- Measured robust shapes for 35M, 26M used for cosmology in 1321 deg^2
  - Factor of two larger shape catalog than best competing survey
- 600k red-sequence galaxies used for clustering, chosen for precise redshift constraints

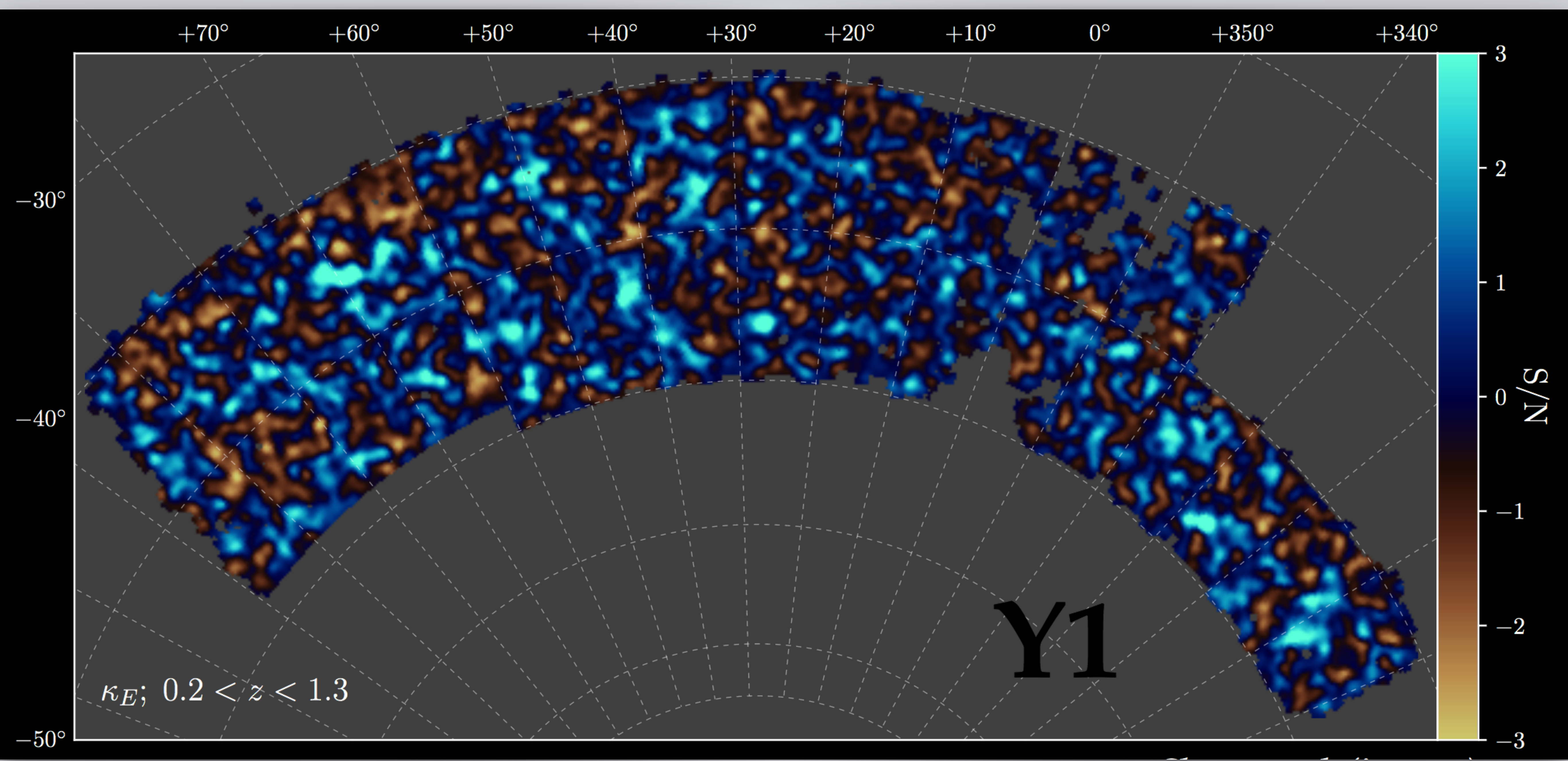
Primary cosmological analysis combining 1) galaxy clustering, 2) cosmic shear, and 3) galaxy-galaxy lensing to probe large-scale structure of the Universe

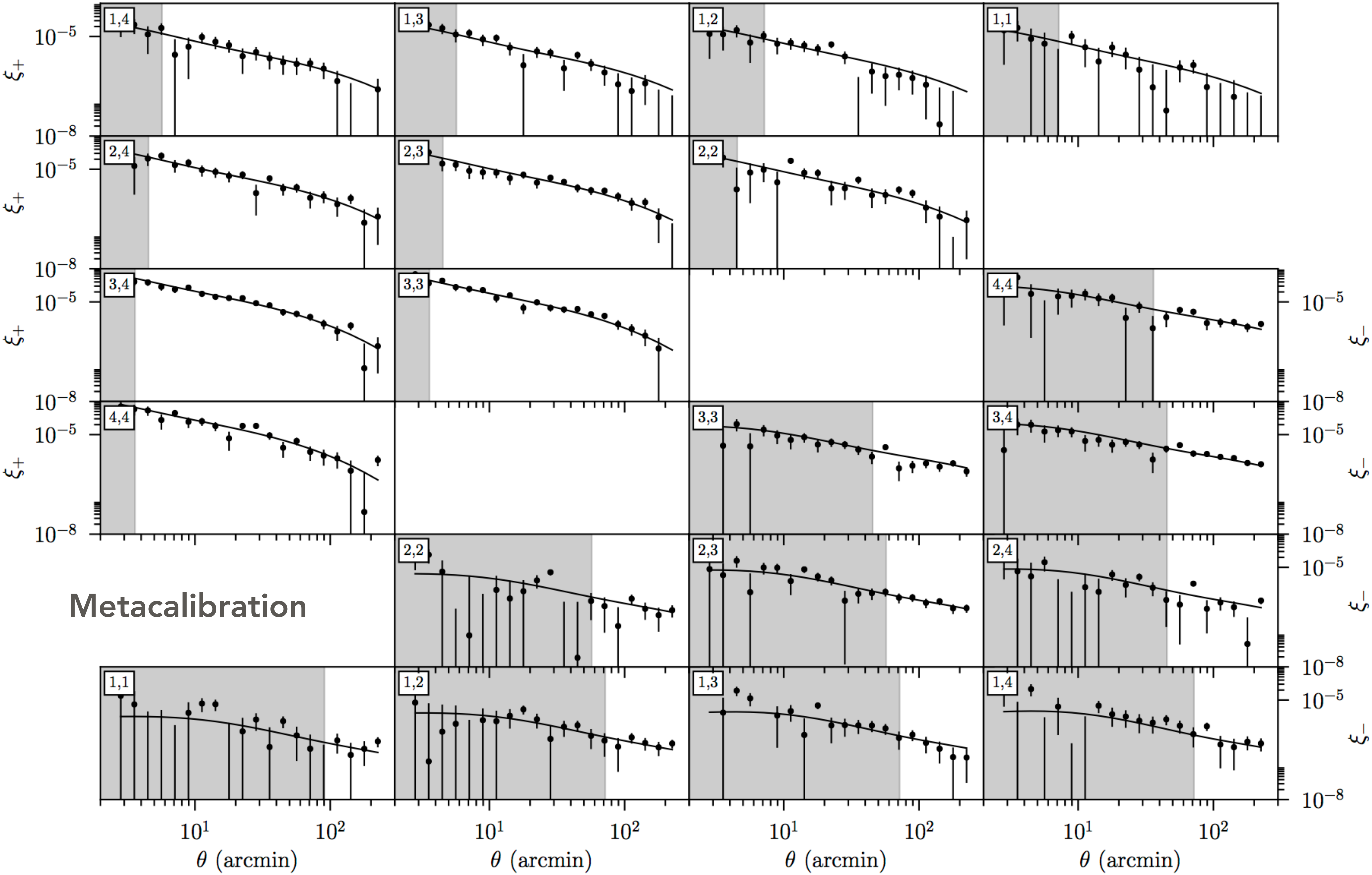
- Most significant detection of cosmic shear in a galaxy survey to date — 27 sigma
- Two-stage blinding
  - Catalog-level blinding unknown to anyone + blinding of all individual results
- Redundant and independent components of core analysis:
  - Two shape measurement pipelines and calibration strategies
  - Two redshift calibration methods
  - Two analysis pipelines

A set of 9 papers (~250 pages of results) released one week ago, on arXiv Monday.

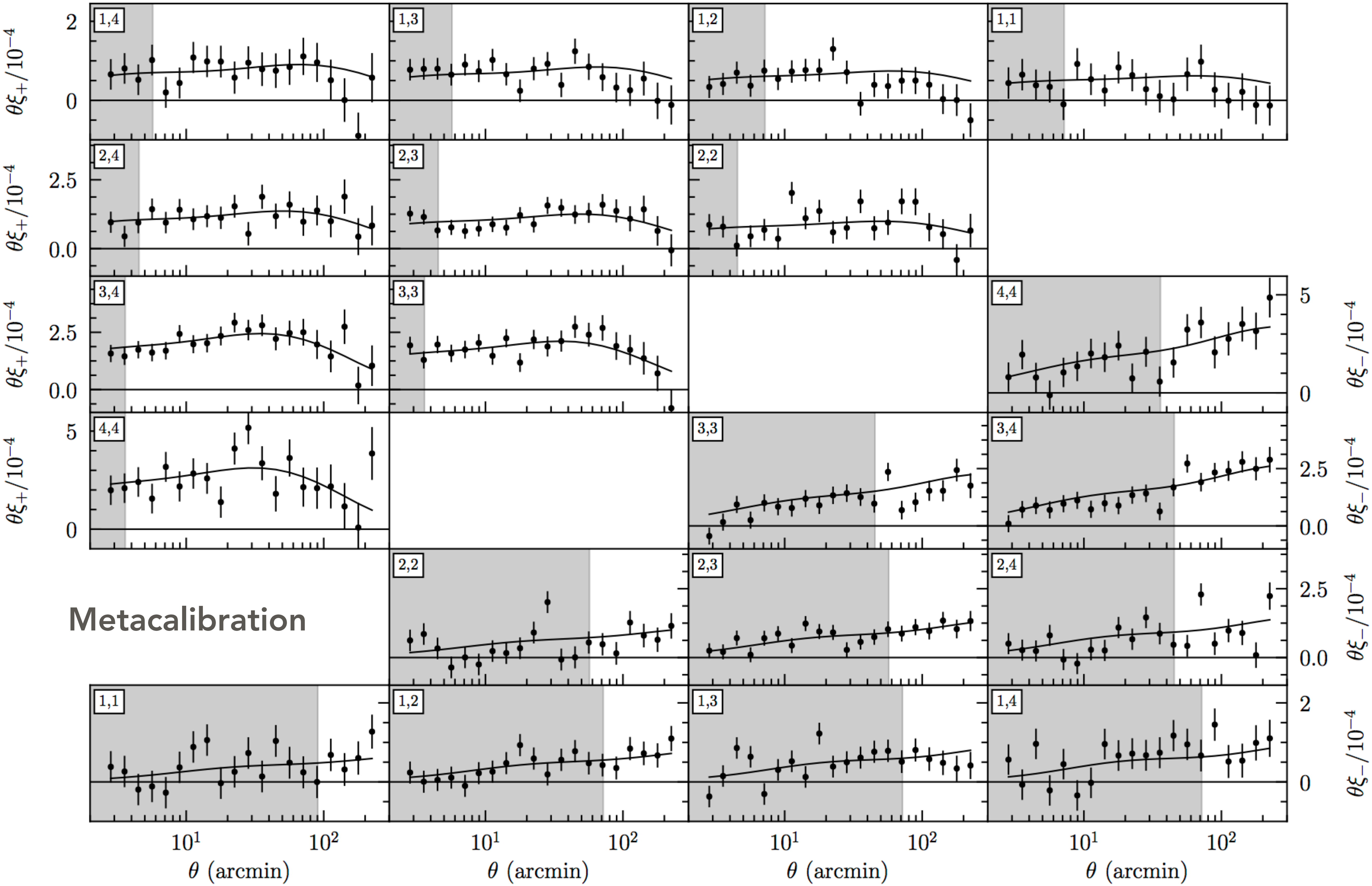

60° 50° 40° 30° 20° 10° 0° 350° 340° 330°
+10°
0°
−10°
−20°
−30°
−40°
−50°
DES Year 1
Shape Catalog
7.8
7.2
6.6
6.0
5.4
4.8
4.2
3.6
3.0
n_g [arcmin^{-2}]

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





Troxel et al. arXiv:1708.01538



Troxel et al. arXiv:1708.01538

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.

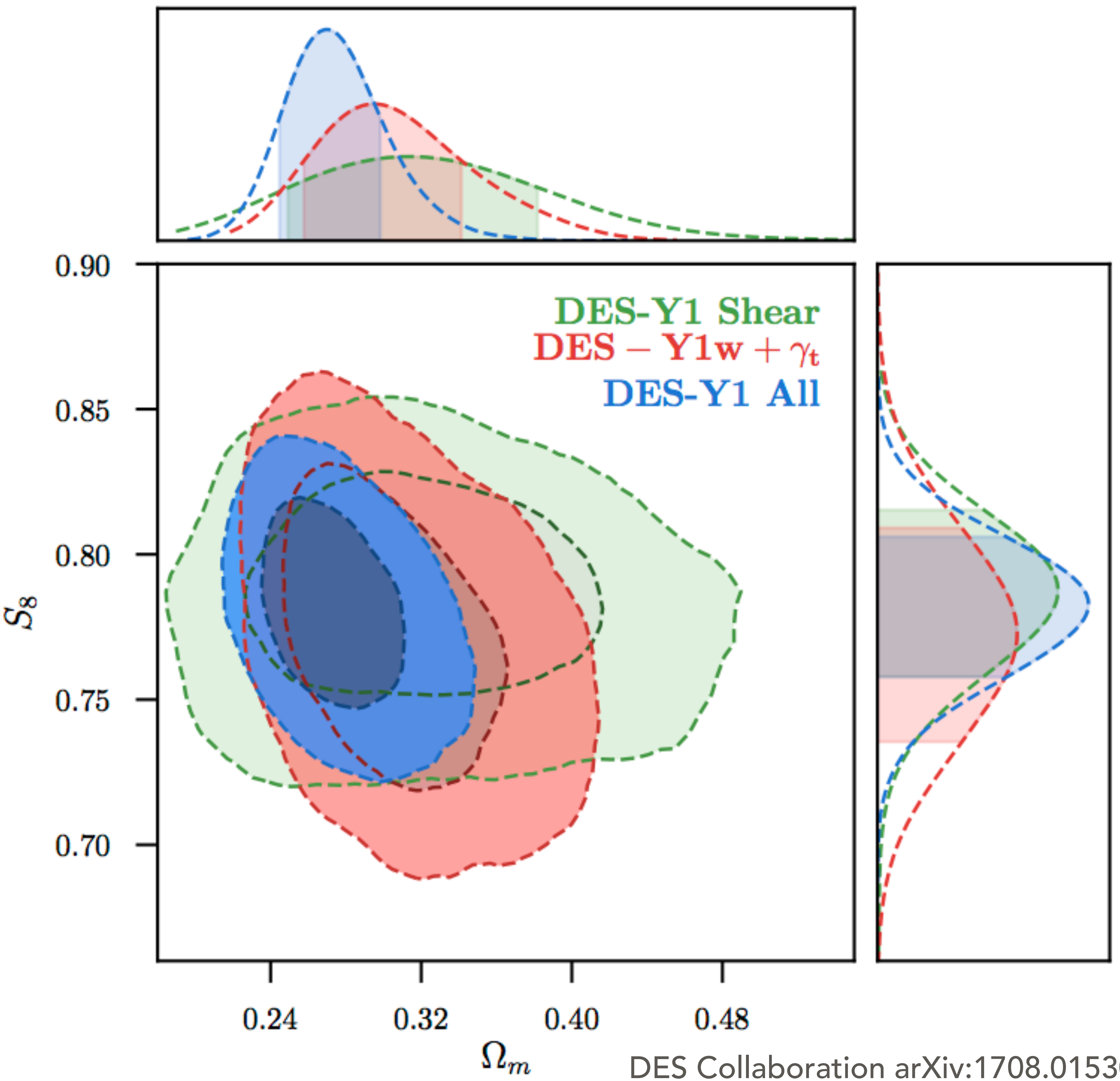
Parameter	Prior
Cosmology	
Ω_m	flat (0.1, 0.9)
A_s	flat $(5 \times 10^{-10}, 5 \times 10^{-9})$
n_s	flat (0.87, 1.07)
Ω_b	flat (0.03, 0.07)
h	flat (0.55, 0.91)
$\Omega_\nu h^2$	flat$(5 \times 10^{-4}, 10^{-2})$
w	flat (−2,−0.33)
Lens Galaxy Bias	
$b_i (i = 1, 5)$	flat (0.8, 3.0)
Intrinsic Alignment	
$A_{\rm IA}(z) = A_{\rm IA}[(1+z)/1.62]^{\eta_{\rm IA}}$	
$A_{\rm IA}$	flat $(-5, 5)$
$\eta_{\rm IA}$	flat $(-5, 5)$
Lens photo-z shift (red sequence)	
Δz_l^1	Gauss (0.001, 0.008)
Δz_l^2	Gauss (0.002, 0.007)
Δz_l^3	Gauss (0.001, 0.007)
Δz_l^4	Gauss (0.003, 0.01)
Δz_l^5	Gauss (0.0, 0.01)
Source photo-z shift	
Δz_s^1	Gauss (−0.001, 0.016)
Δz_s^2	Gauss (−0.019, 0.013)
Δz_s^3	Gauss (+0.009, 0.011)
Δz_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)

Internal consistency

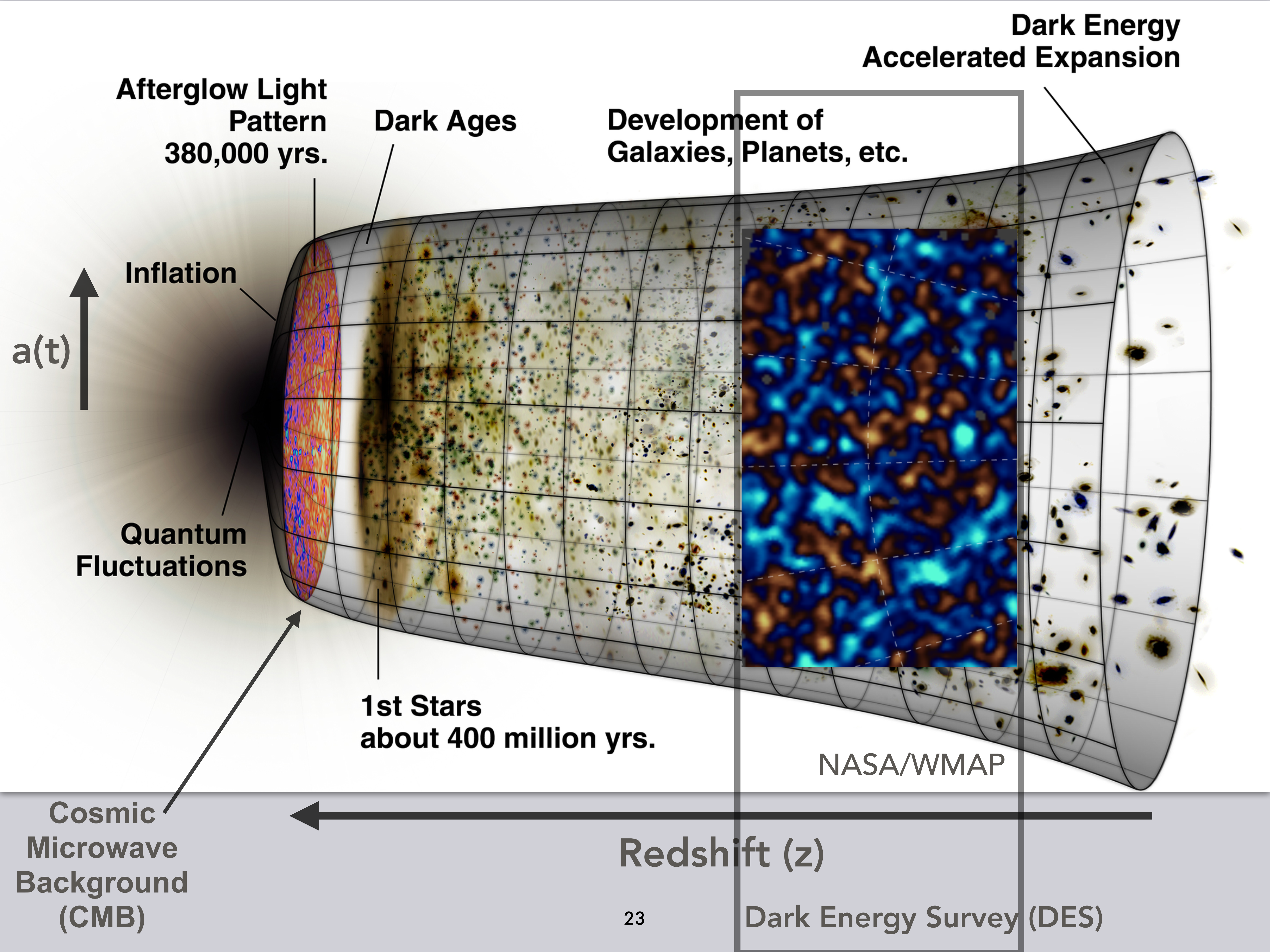
Agreement of lensing and galaxy clustering probes of large-scale structure has never been demonstrated at this level of statistical precision.

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

Before showing context…



DES Collaboration arXiv:1708.01530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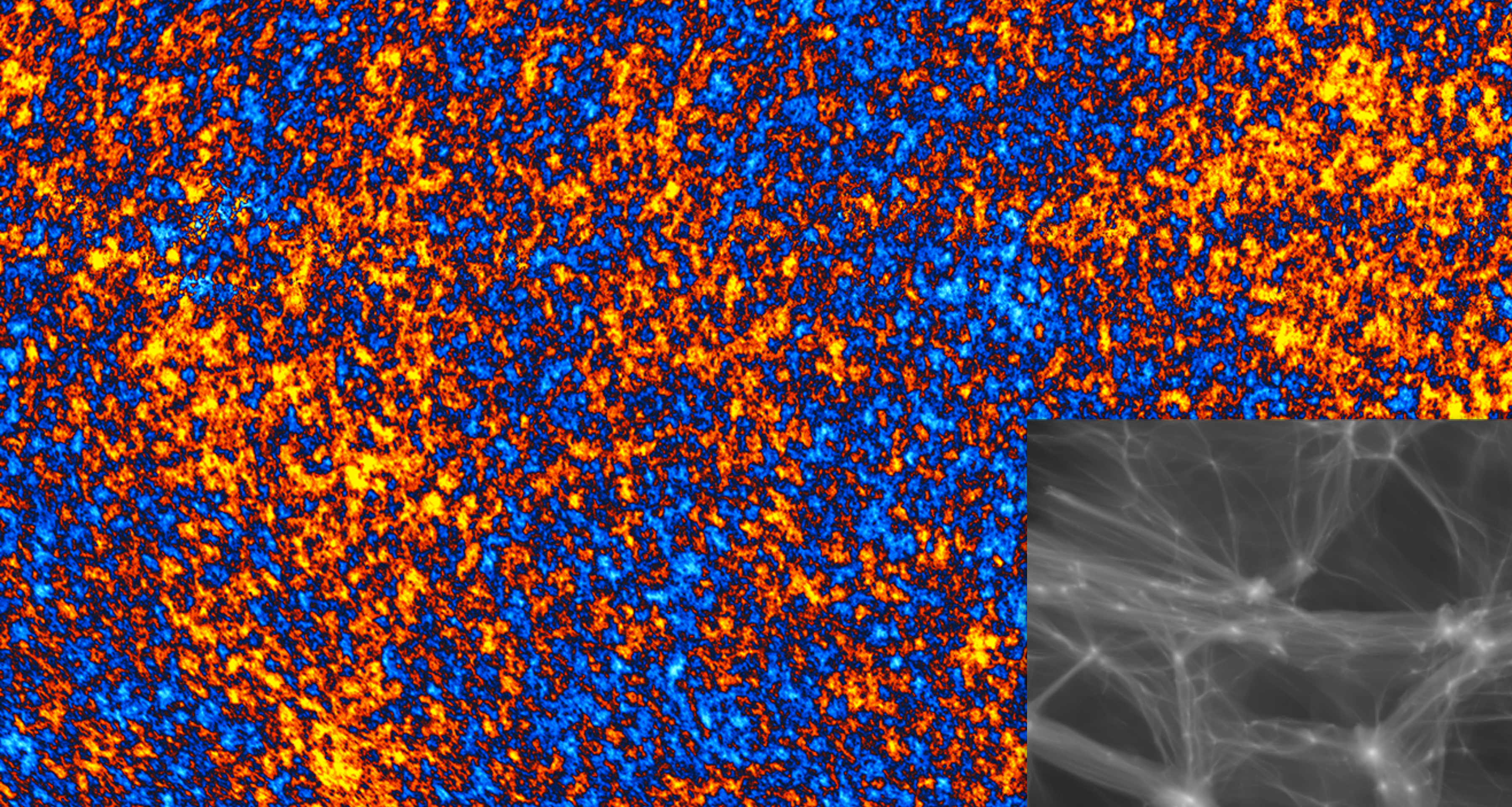
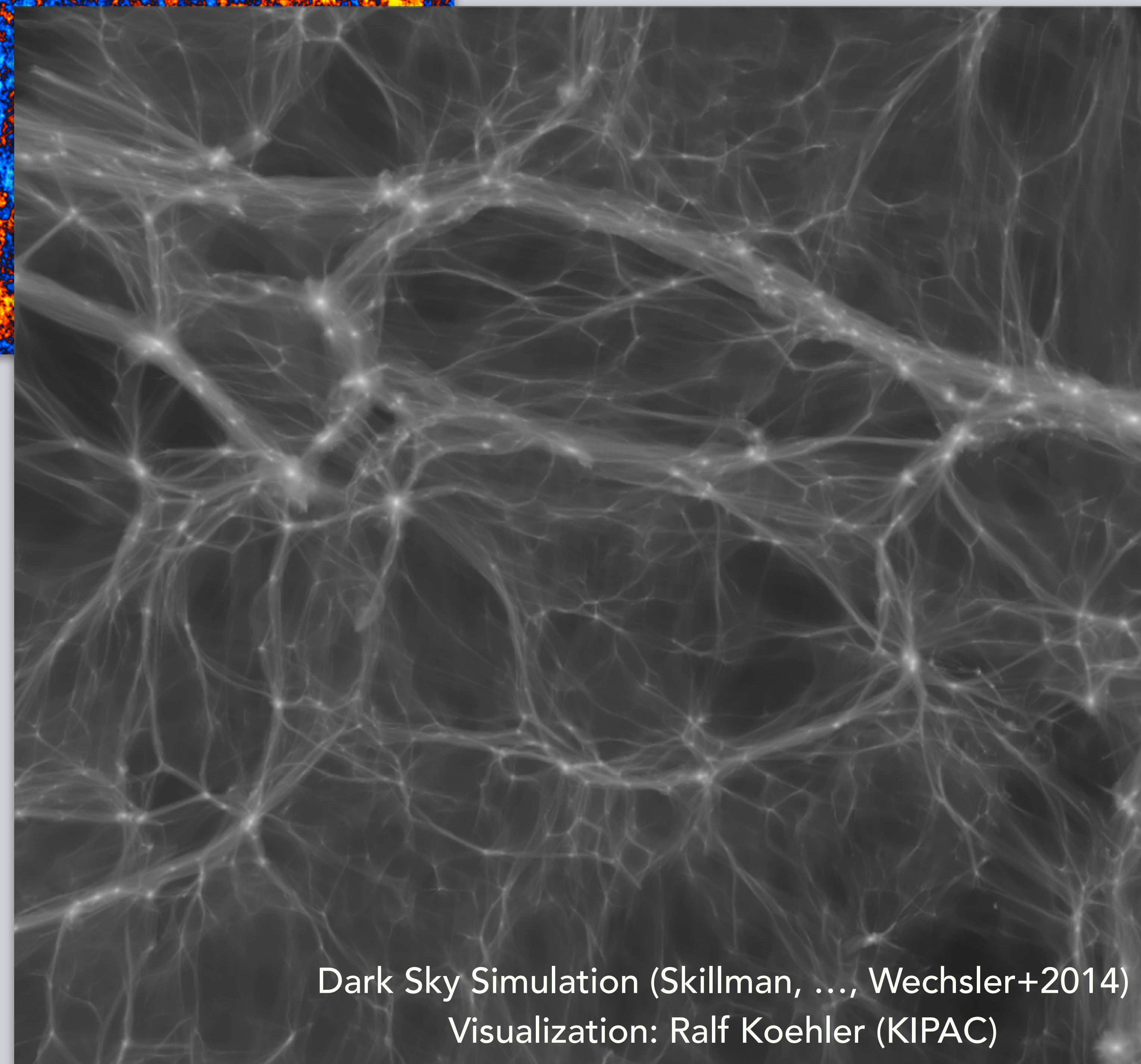


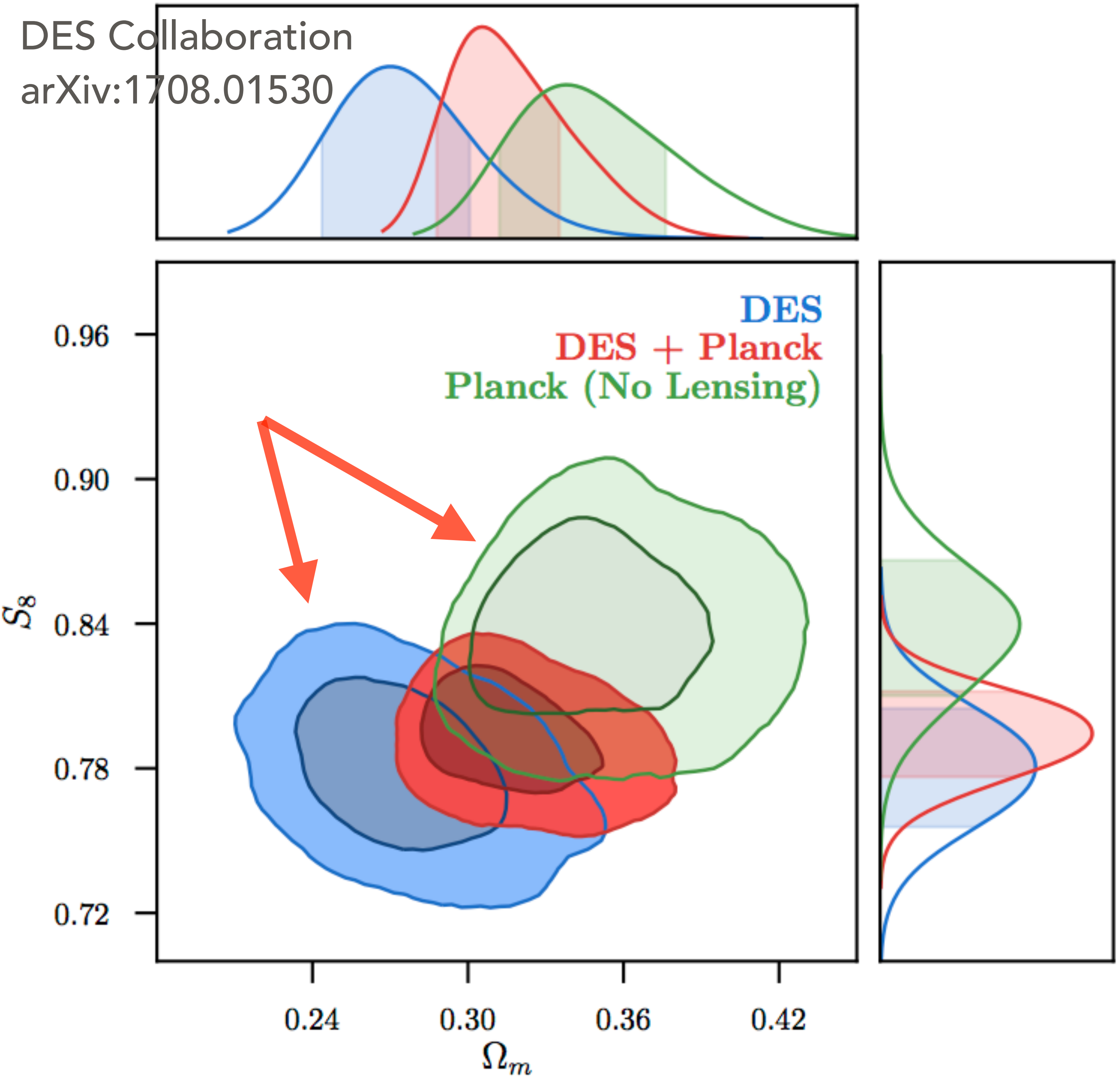
Planck CMB temperature
z=1100; δ of $O(10^{-5})$

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



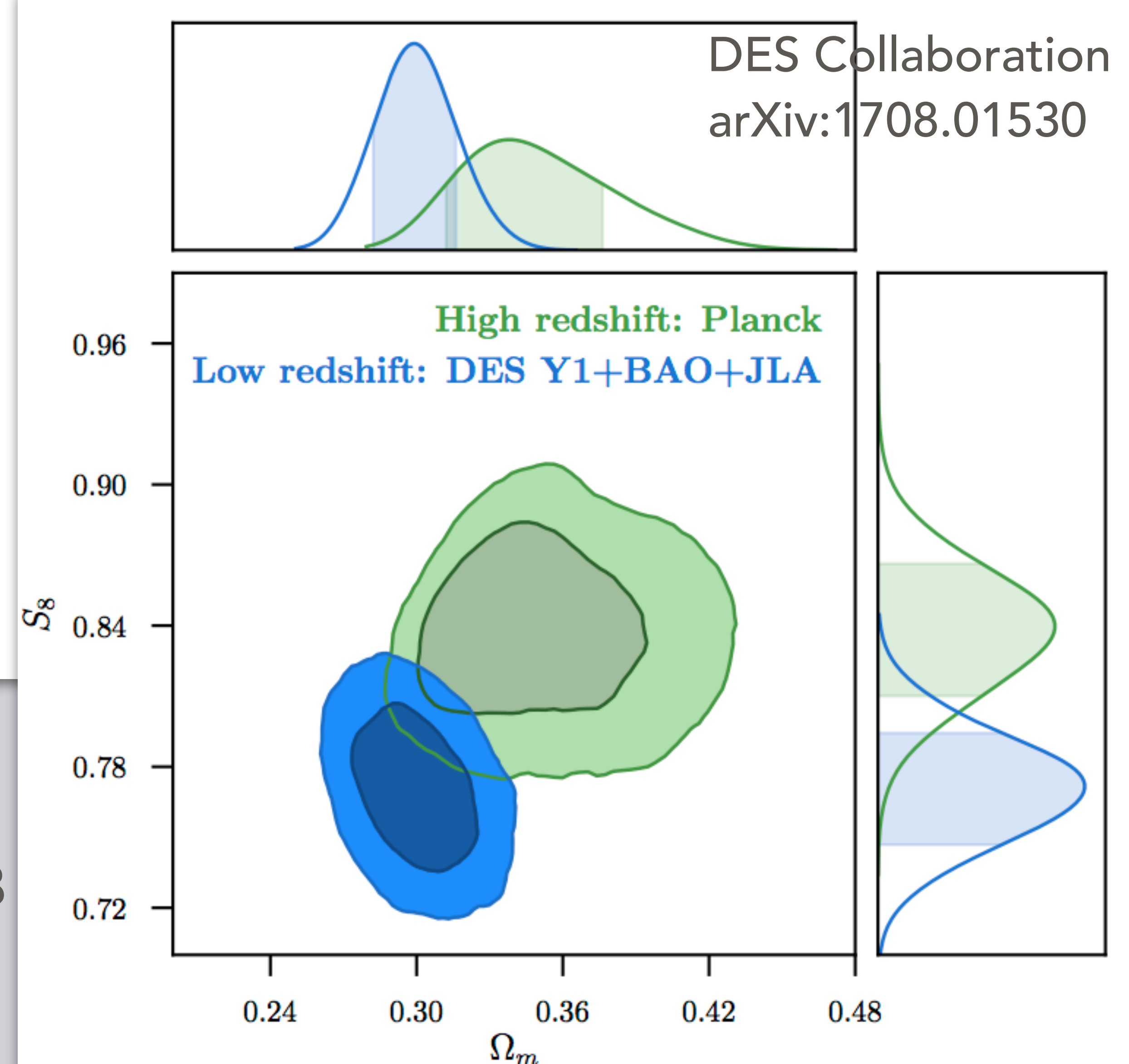
Comparing CMB with LSS:
Incredible test of LCDM at two extremely different stages of the Universe 6 billion years apart.

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



High- vs low-redshift probes

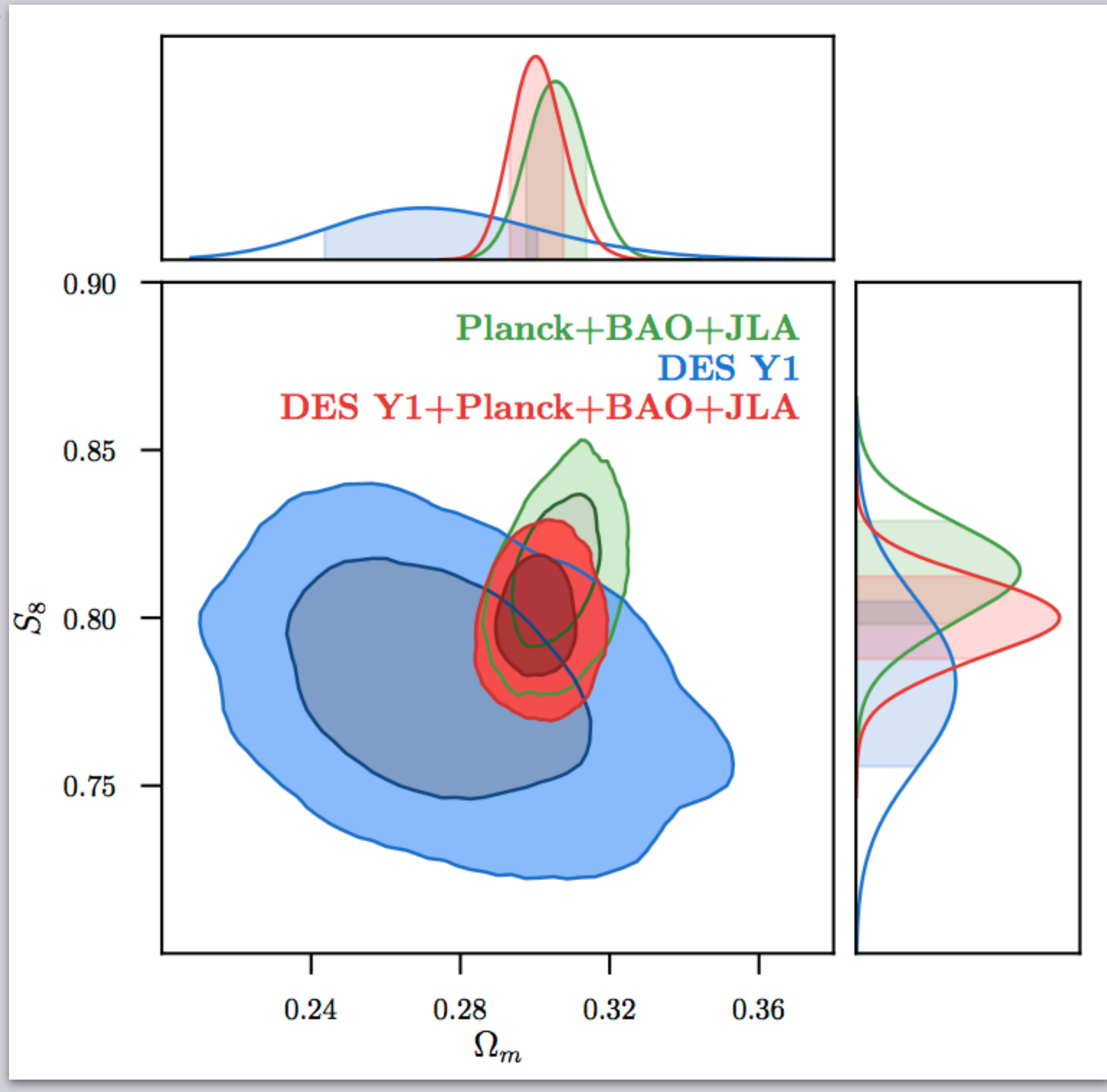
Though there is mild visual 'tension' in this set of parameters, we find the Bayesian evidence for the full parameter space to be consistent between low- and high-redshift probes — LCDM works.



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



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.

We find a non-zero galaxy intrinsic alignment signal at the 99.98% CL.

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)

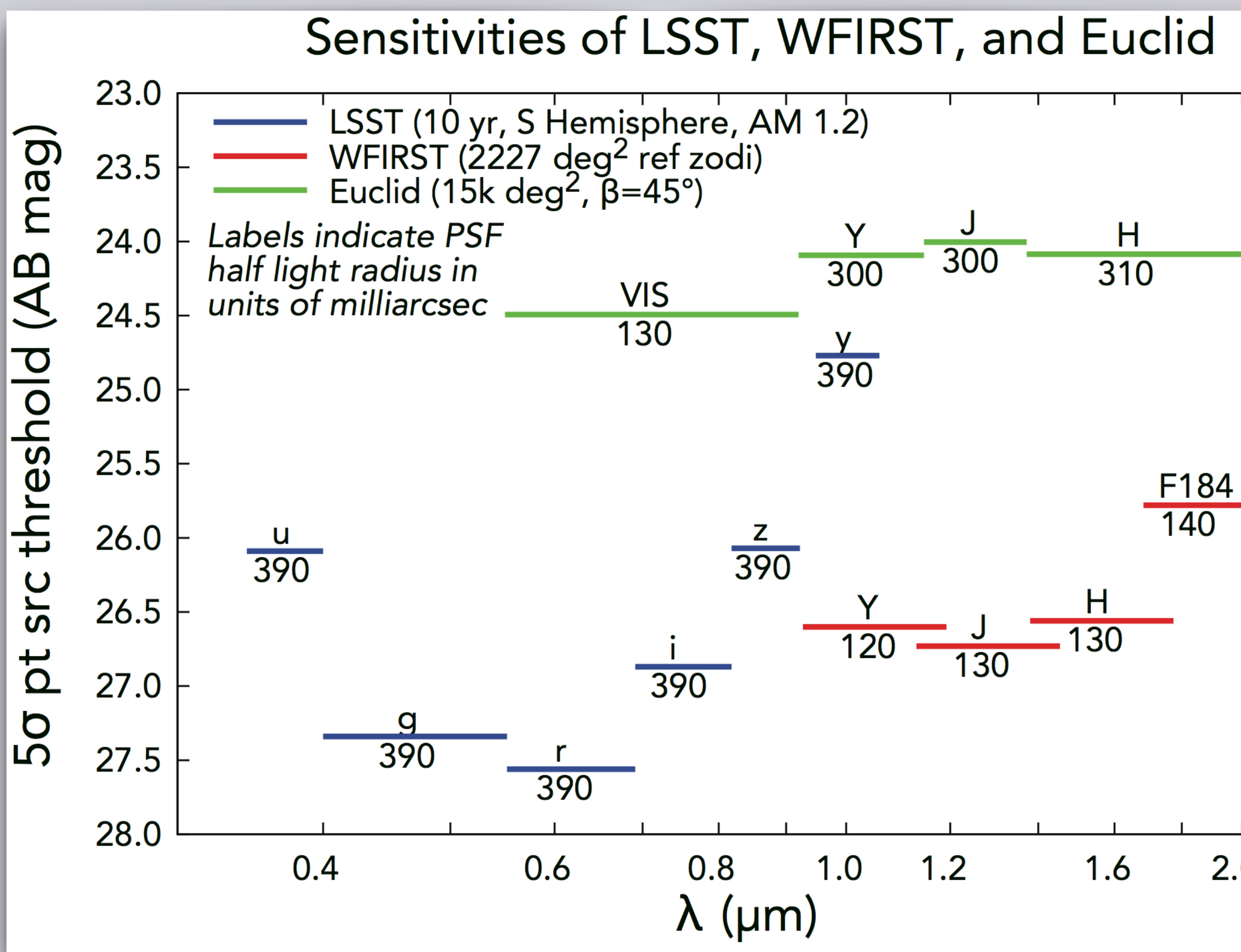
This is just the beginning…

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 to significantly deeper redshifts than DES: LSST (ground), WFIRST & Euclid (space).

Extended models to study:

- Non-zero curvature
- Evolving DE
- Modified gravity



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 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. Troxel et al., Dark Energy Survey Year 1 Results: Cosmological Constraints from Cosmic Shear, submitted to PRD, arXiv:1708.01538
3. Prat et al., Dark Energy Survey Year 1 Results: Galaxy-Galaxy Lensing, submitted to PRD, arXiv:1708.01537
4. Elvin-Poole et al., Dark Energy Survey Year 1 Results: Galaxy clustering for combined probes, submitted to PRD, arXiv:1708.01536
5. Chang et al., Dark Energy Survey Year 1 Results: Curved-Sky Weak Lensing Mass Map, submitted to MNRAS, arXiv:1708.01535
6. 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
7. Zuntz et al., Dark Energy Survey Year 1 Results: Weak Lensing Shape Catalogues, submitted to MNRAS, arXiv:1708.01533
8. Hoyle et al., Dark Energy Survey Year 1 Results: Redshift distributions of the weak lensing source galaxies, submitted to MNRAS, arXiv:1708.01532
9. Drlica-Wagner et al., Dark Energy Survey Year 1 Results: Photometric Data Set for Cosmology, submitted to ApJS, arXiv:1708.01531
10. Krause et al., Dark Energy Survey Year 1 Results: Multi-Probe Methodology and Simulated Likelihood Analyses, submitted to PRD, arXiv:1706.09359

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