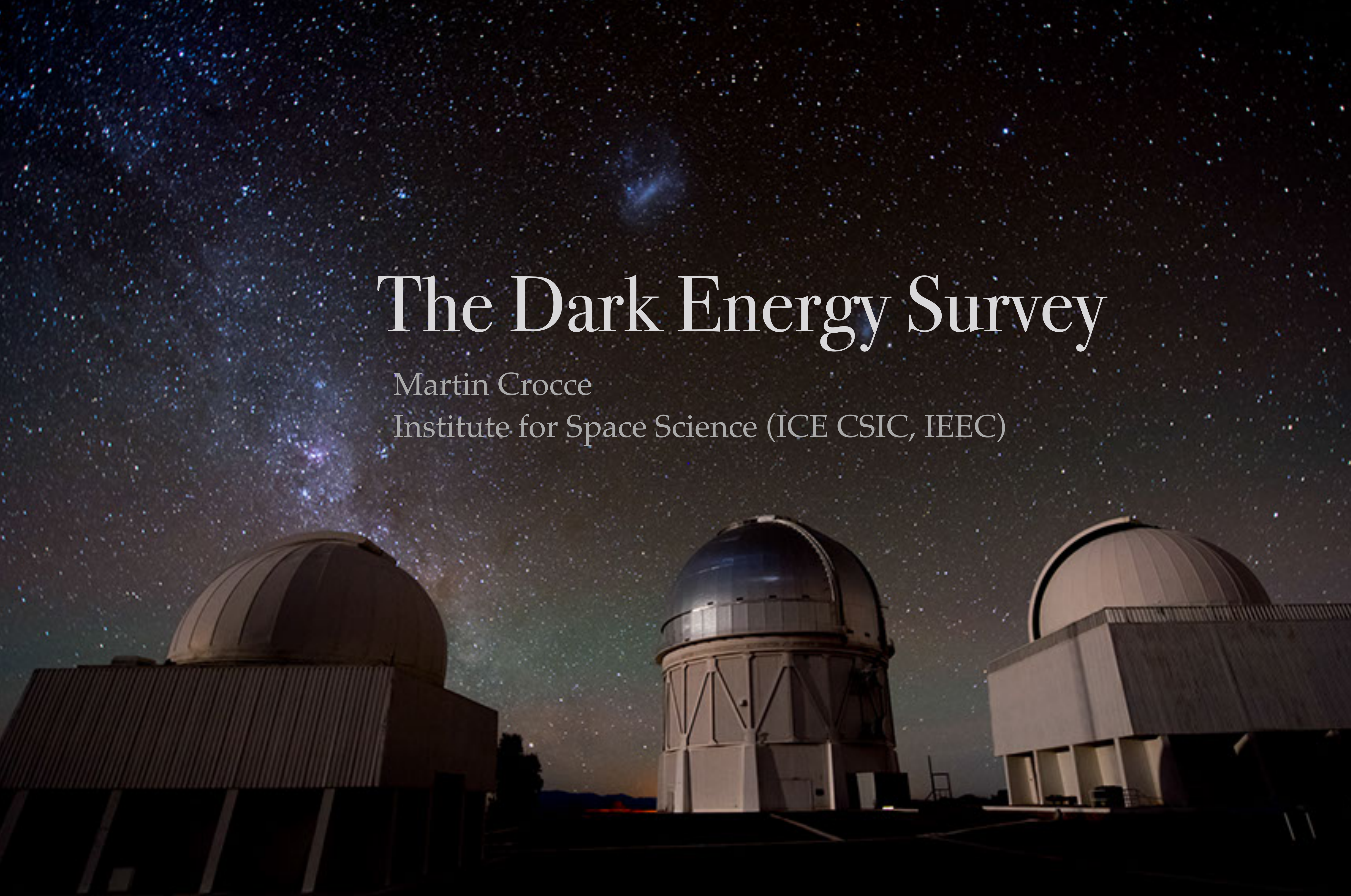


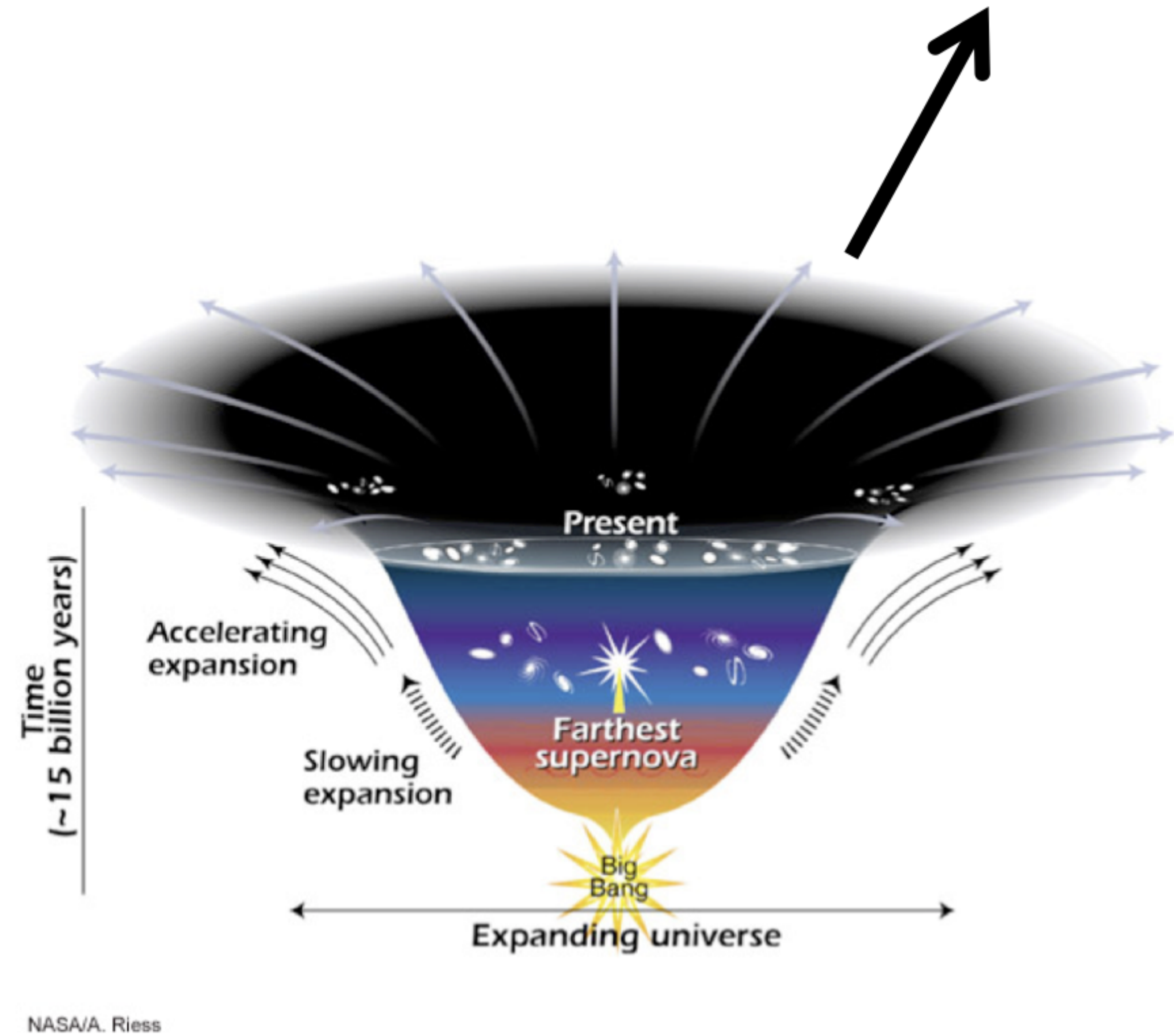
The Dark Energy Survey

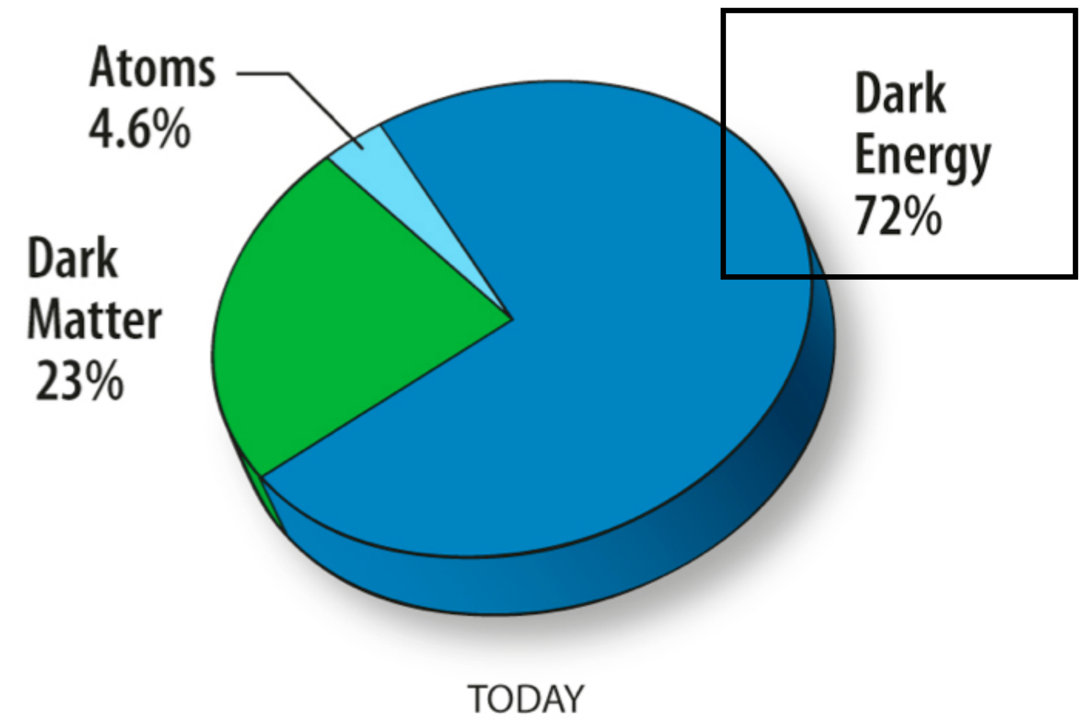
Martin Crocce
Institute for Space Science (ICE CSIC, IEEC)

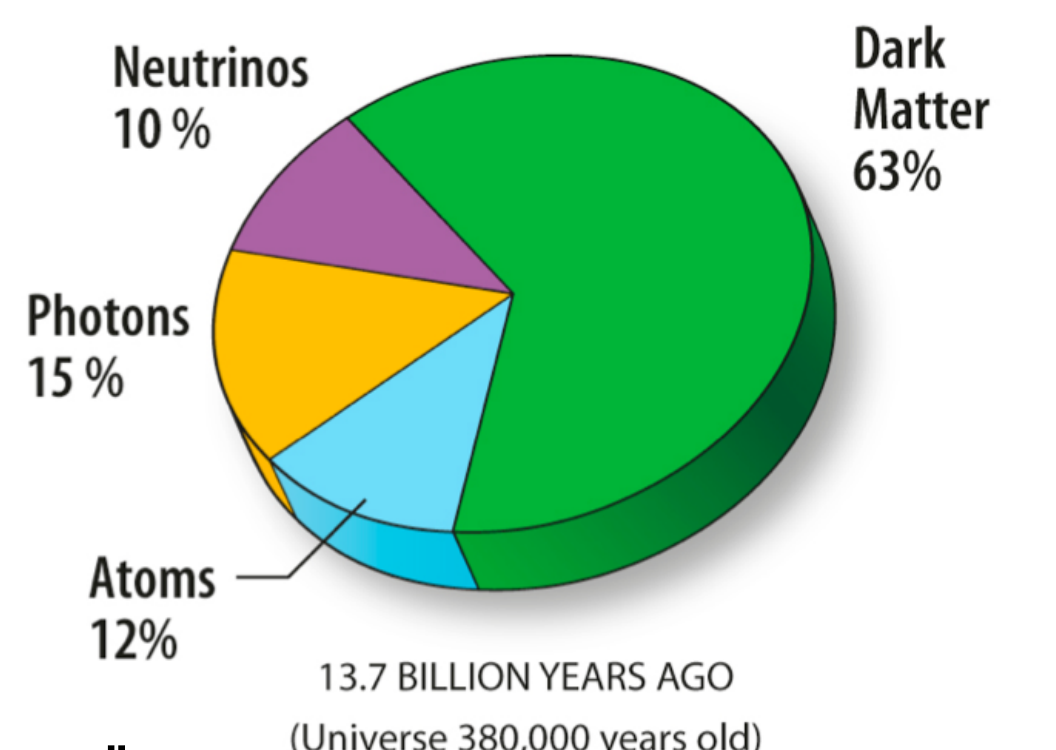
XXIII IFT Christmas Workshop - Madrid - Dec 13th-15th (2017)

Current cosmological model

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$





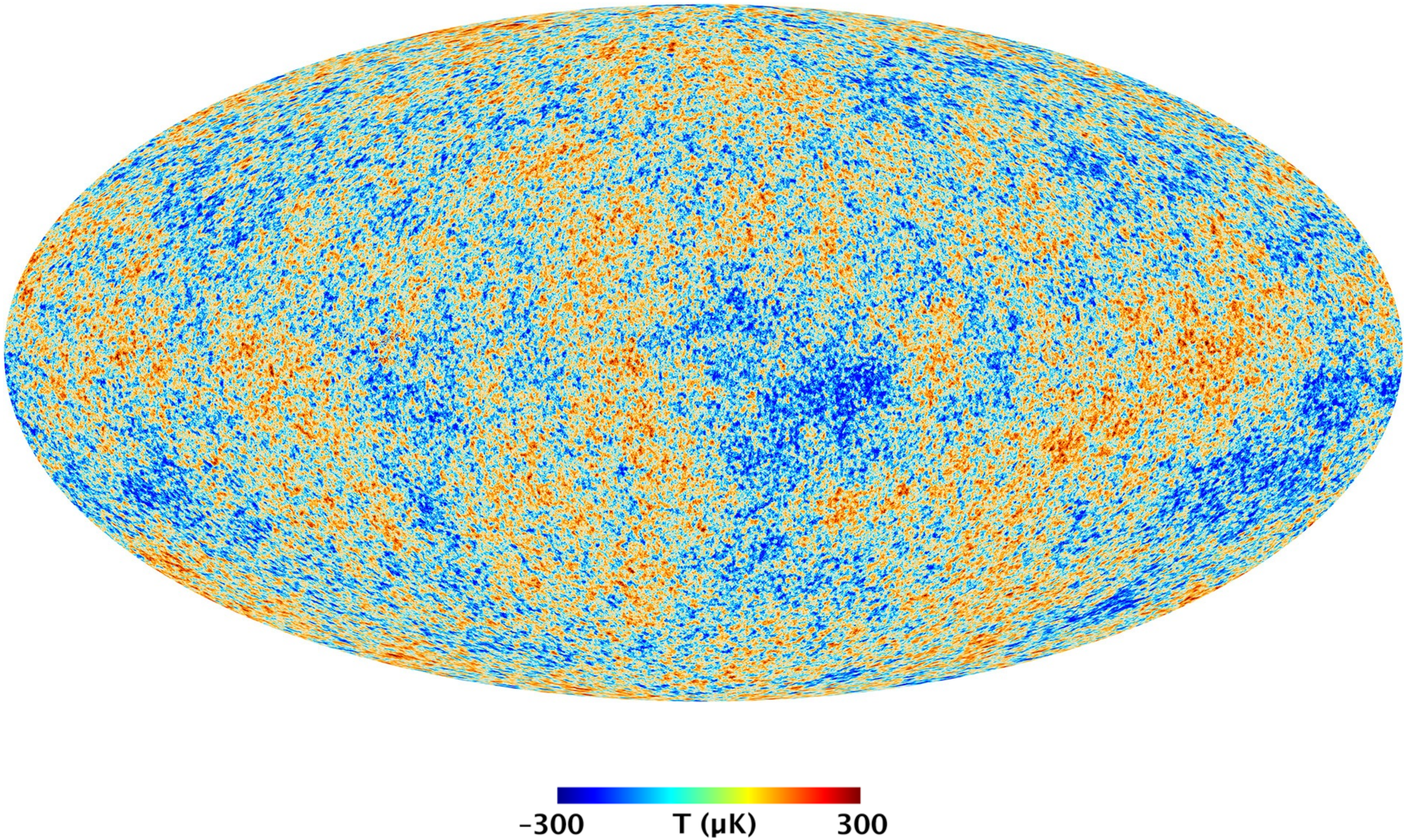


credit : NASA

- It is a “concordance” model although with some “tensions”

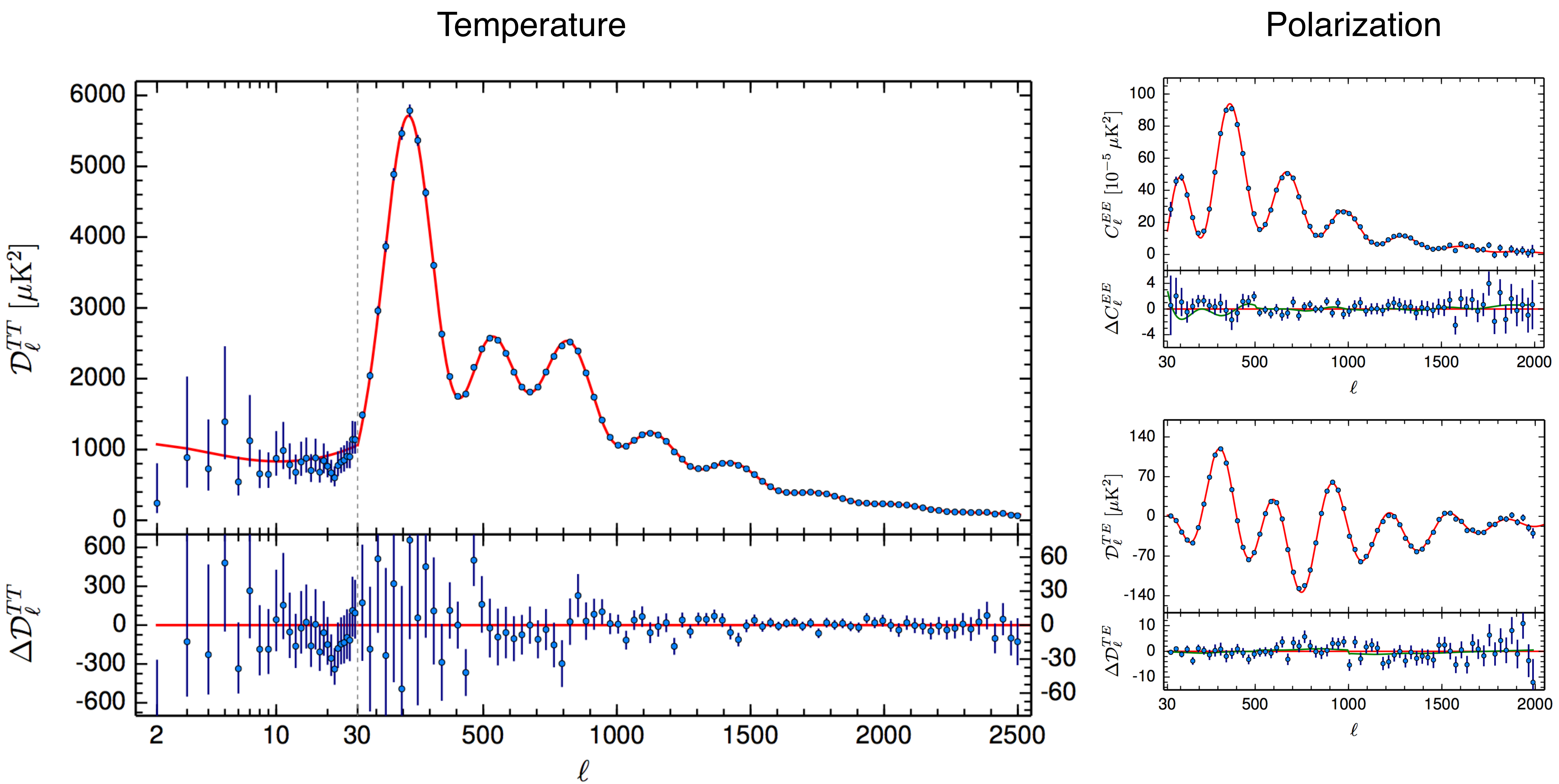
The success of the CMB

COBE, WMAP, Planck ..



The success of the CMB

COBE, WMAP, Planck ..



Planck Collaboration: Cosmological parameters

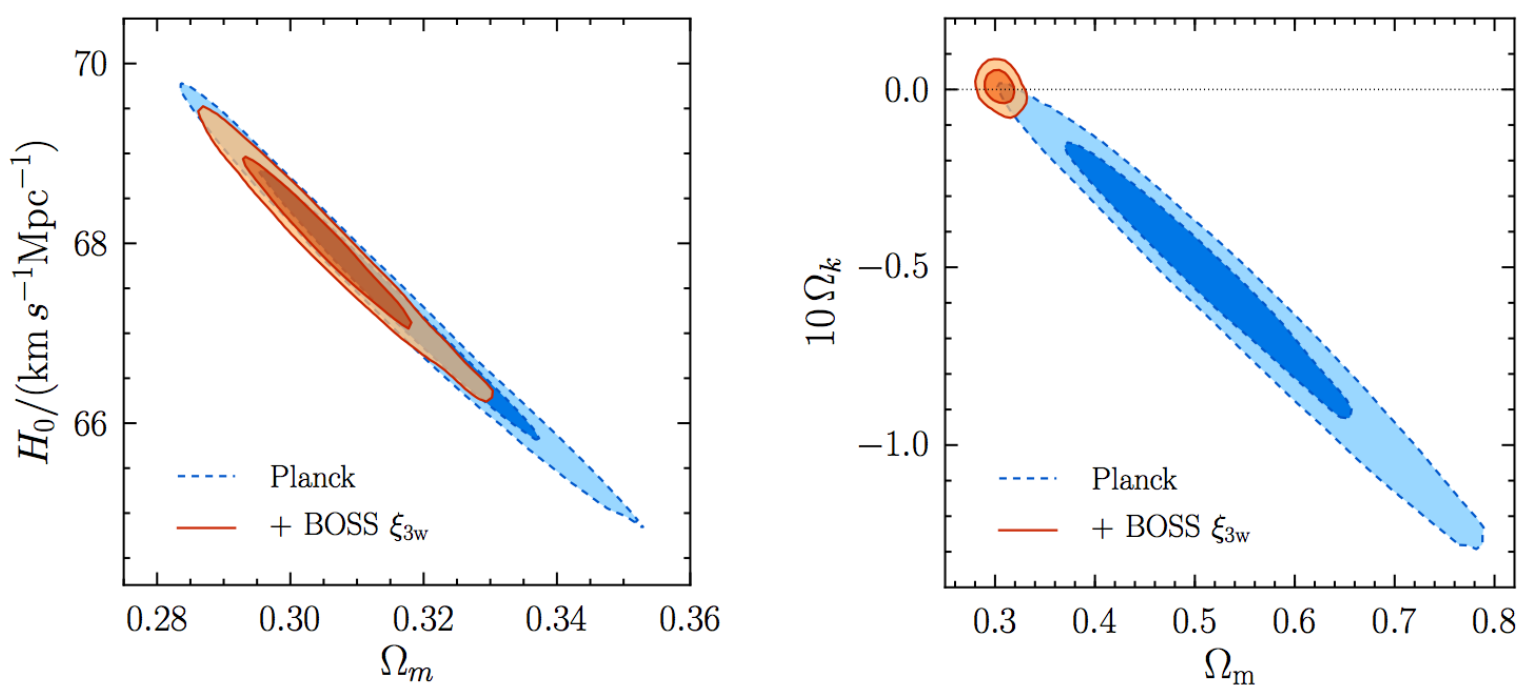
The success and limitations of the CMB

In the context of basic LCDM (+ some assumptions) CMB is extremely constraining:

flat six-parameter LCDM from adiabatic temperature fluctuations.

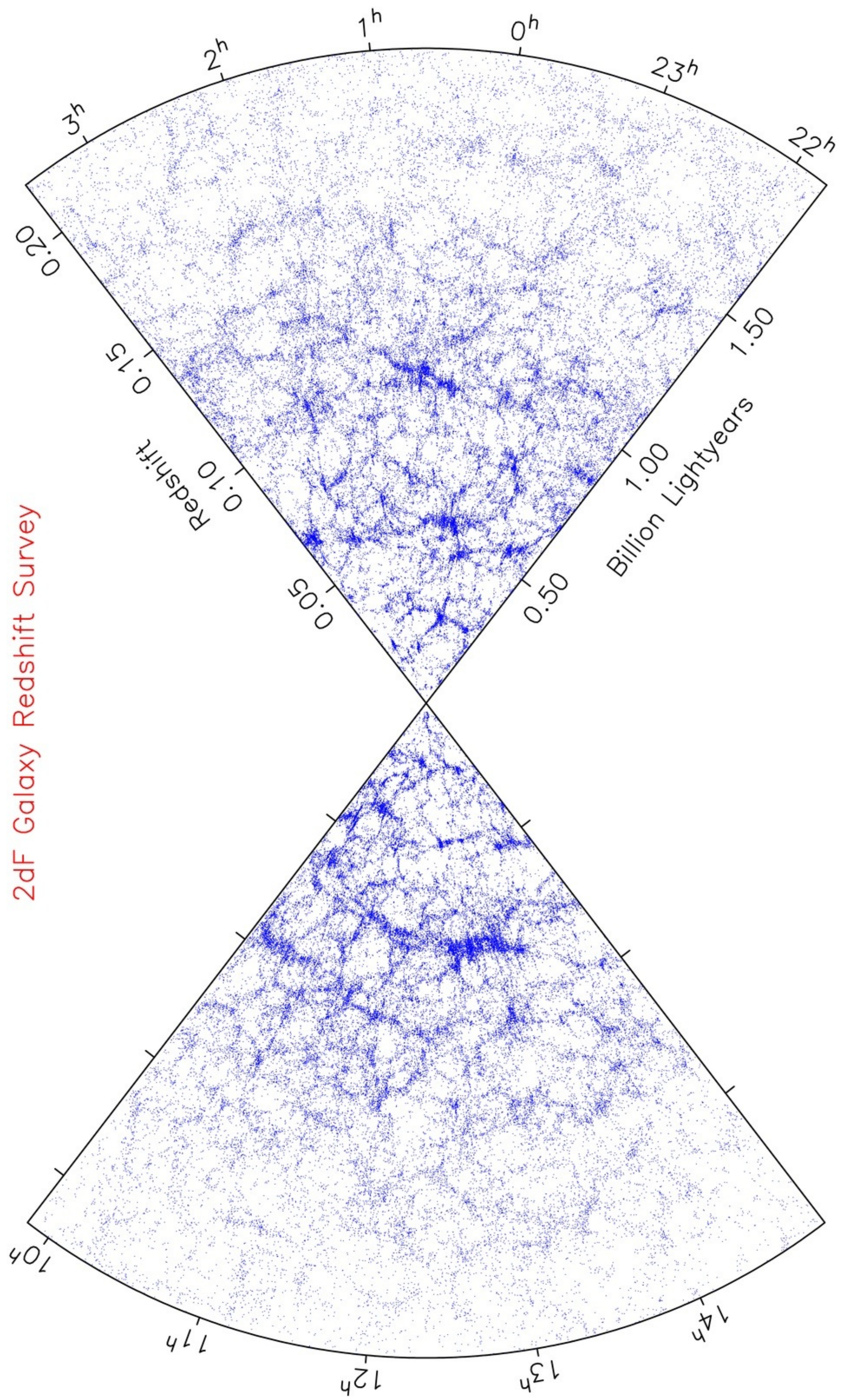
but some **Tension** —> Planck prefers lower values of H_0 compared to local measurements (at $3.4-\sigma$) and higher Ω_m and σ_8 compared to WL and cluster abundance.

and **CMB is only projected** —> strong geometrical degeneracies which are almost perfect (anything leaving angular diameter distance to sound horizon fix) :



Need to add additional datasets with information sensitive to low redshift (to "anchor" the distance to the last-scattering surface)

.. galaxy surveys



Dynamical Dark Energy: Is the dark energy simply a cosmological constant, or is it a field that evolves dynamically with the expansion of the Universe?

Modification of Gravity: Alternatively, is the apparent acceleration instead a manifestation of a breakdown of General Relativity on the largest scales, or a failure of the cosmological assumptions of homogeneity and isotropy?

Dark Matter / Nuetrinos : What is dark matter? What is the absolute neutrino mass scale and what is the number of relativistic species in the Universe?

Initial Conditions: What is the power spectrum of primordial density fluctuations, which seeded large-scale structure, and are they described by a Gaussian probability distribution?

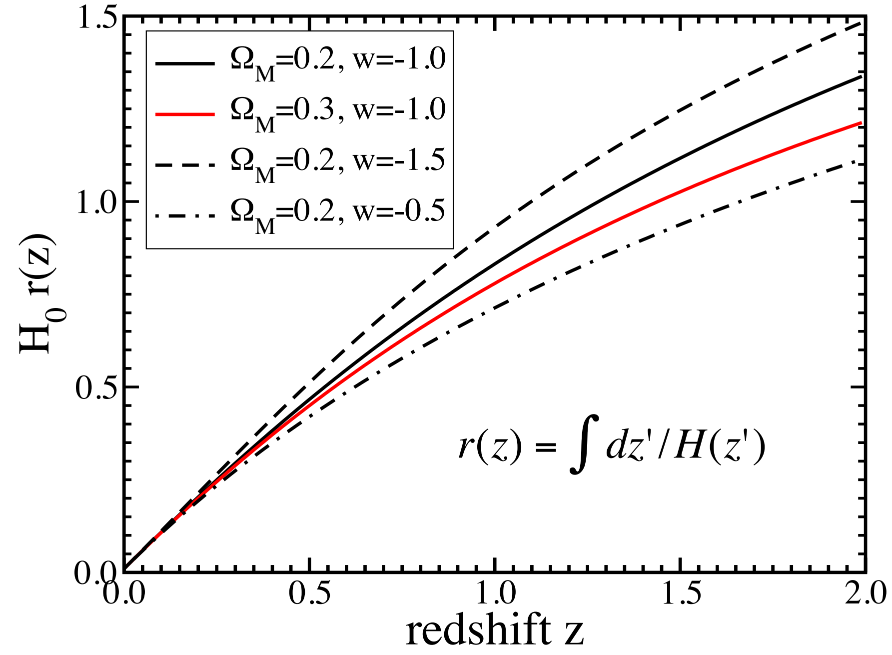
Measuring Dark Energy

➡ Geometry: distance vs. redshift

(expansion history = SNIa, BAO)

✦ redshift tells degree of expansion

✦ light-travel distance = time



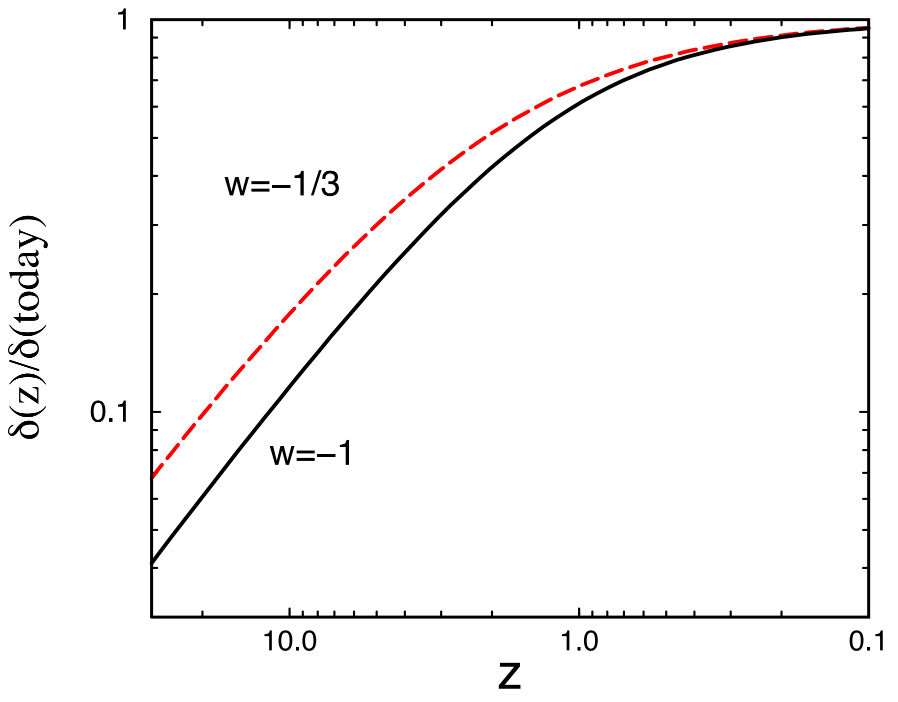
➡ Dynamics: structure growth

(growth history = Lensing, Clusters, RSD)

✦ growth rate depends on matter density

✦ evolution in matter density ⟷ evolution in dark energy density

Friemann, Turner and Huterer

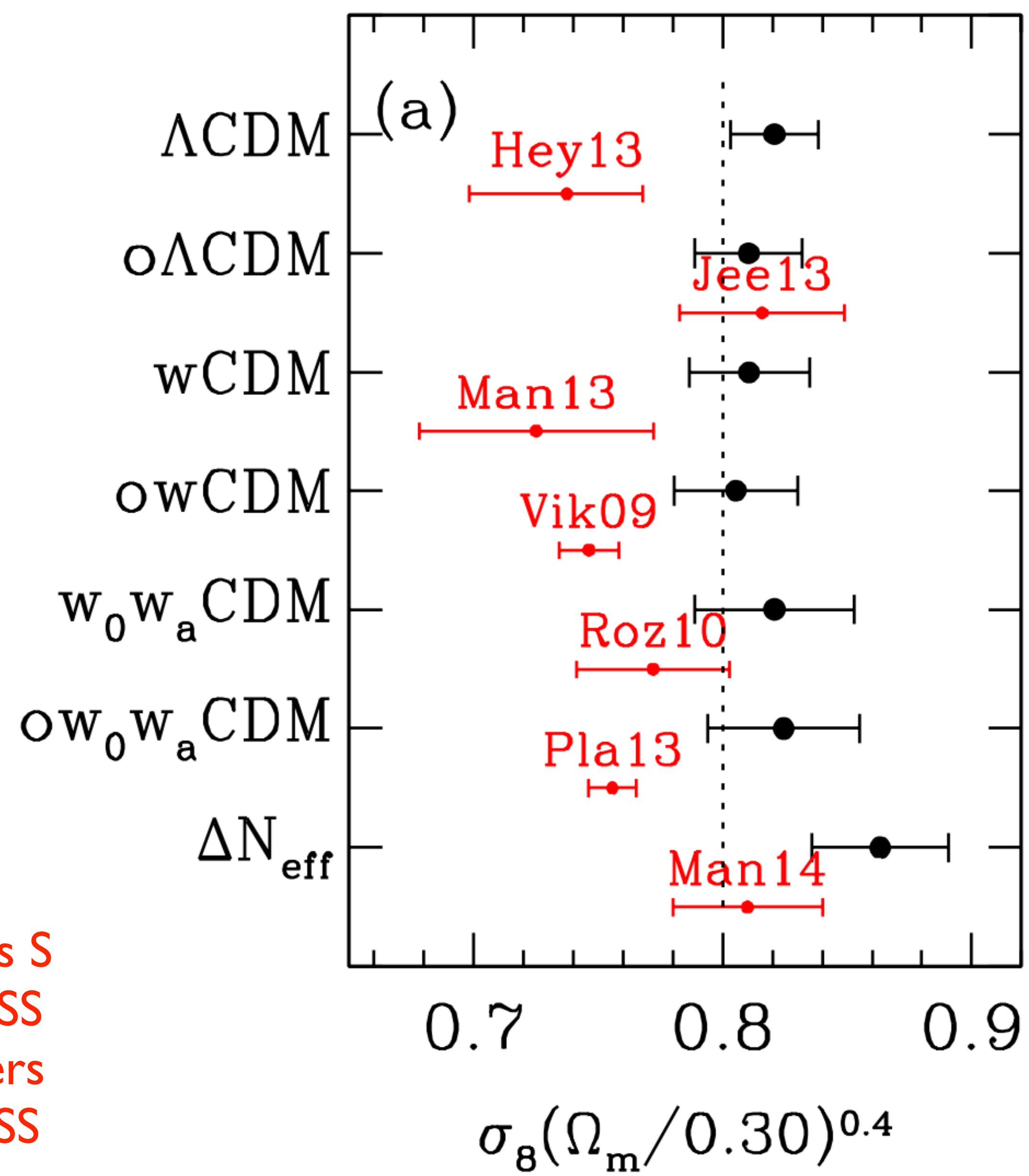


we need both to disentangle GR vs DE !

The growth tension

Currently there is some tension between geometrical and structure growth measurements

Red points: structure growth measurements at low-z



level of matter clustering

Black points: Derived from geometrical measurements for DE model

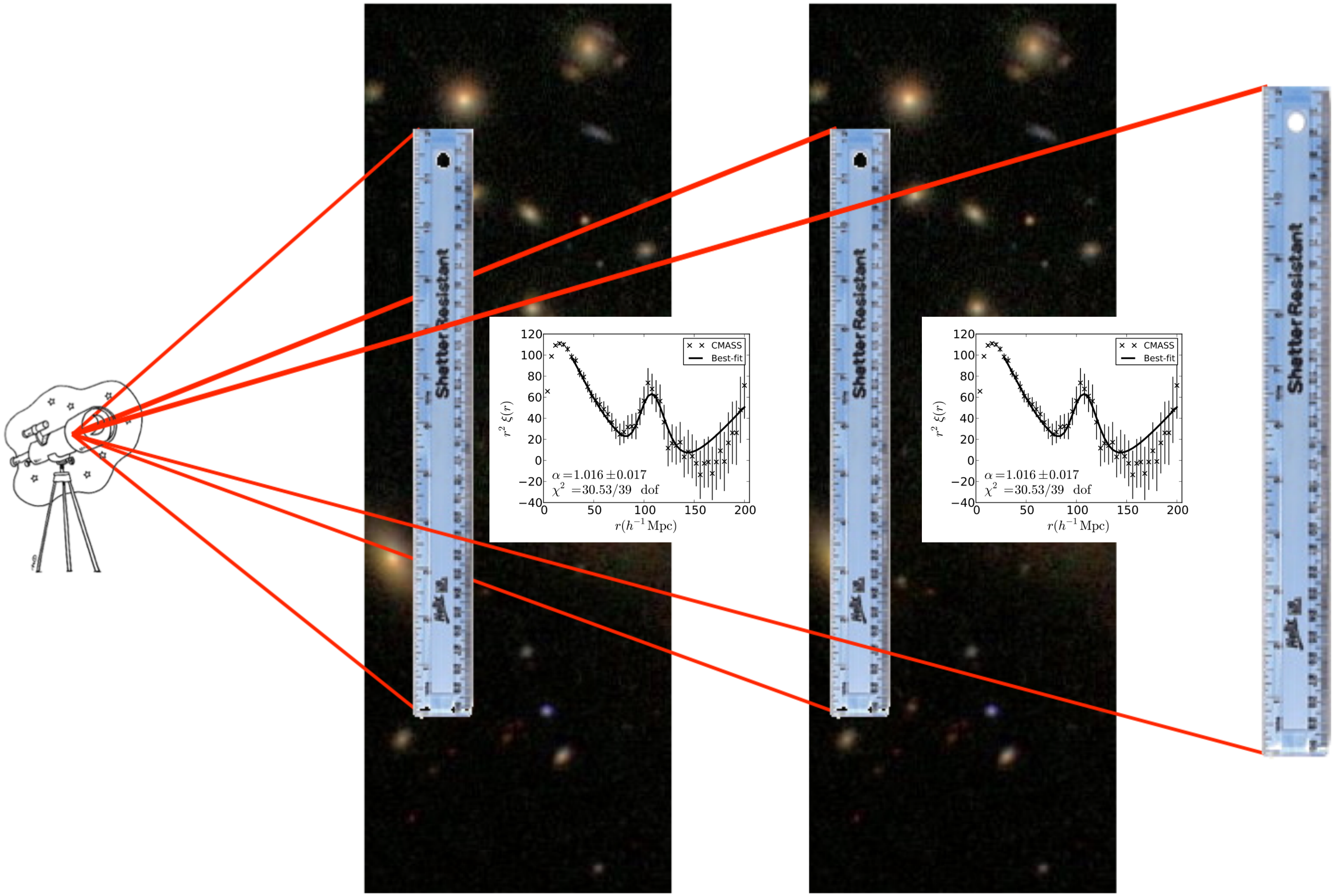
BAO + SNIa + CMB

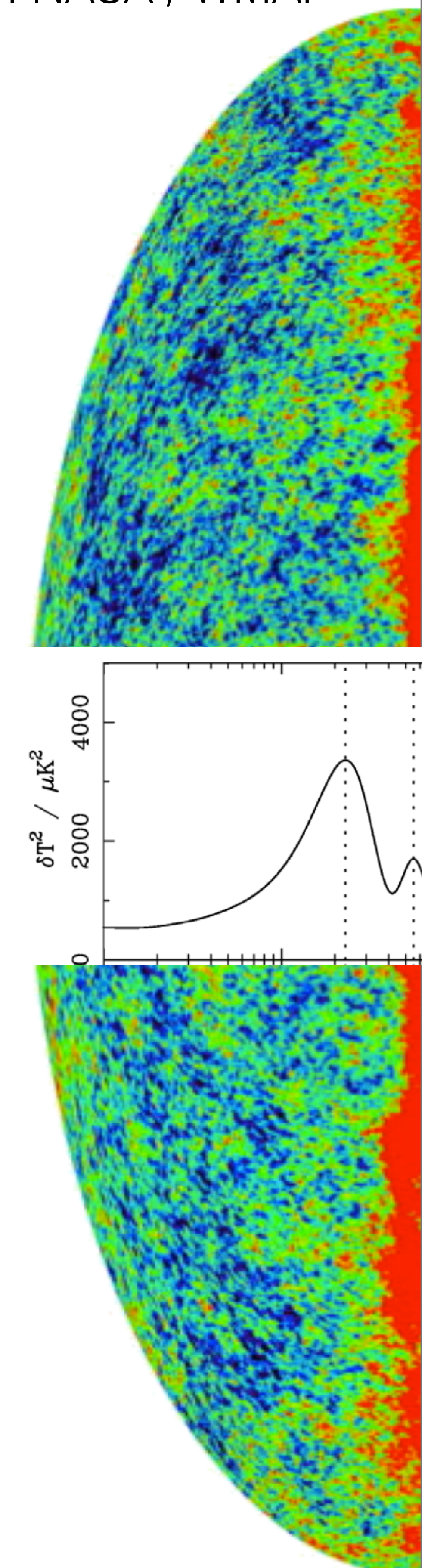
Aubourg et al. (2014)

- Cosmic Shear in CFHTLS
- Cosmic Shear in Deep Lens S
- GalGal-lensing + LSS in SDSS
- Abundance of X-ray Clusters
- Stack WL of clusters in SDSS
- SZ clusters in Planck

credit : NASA / WMAP

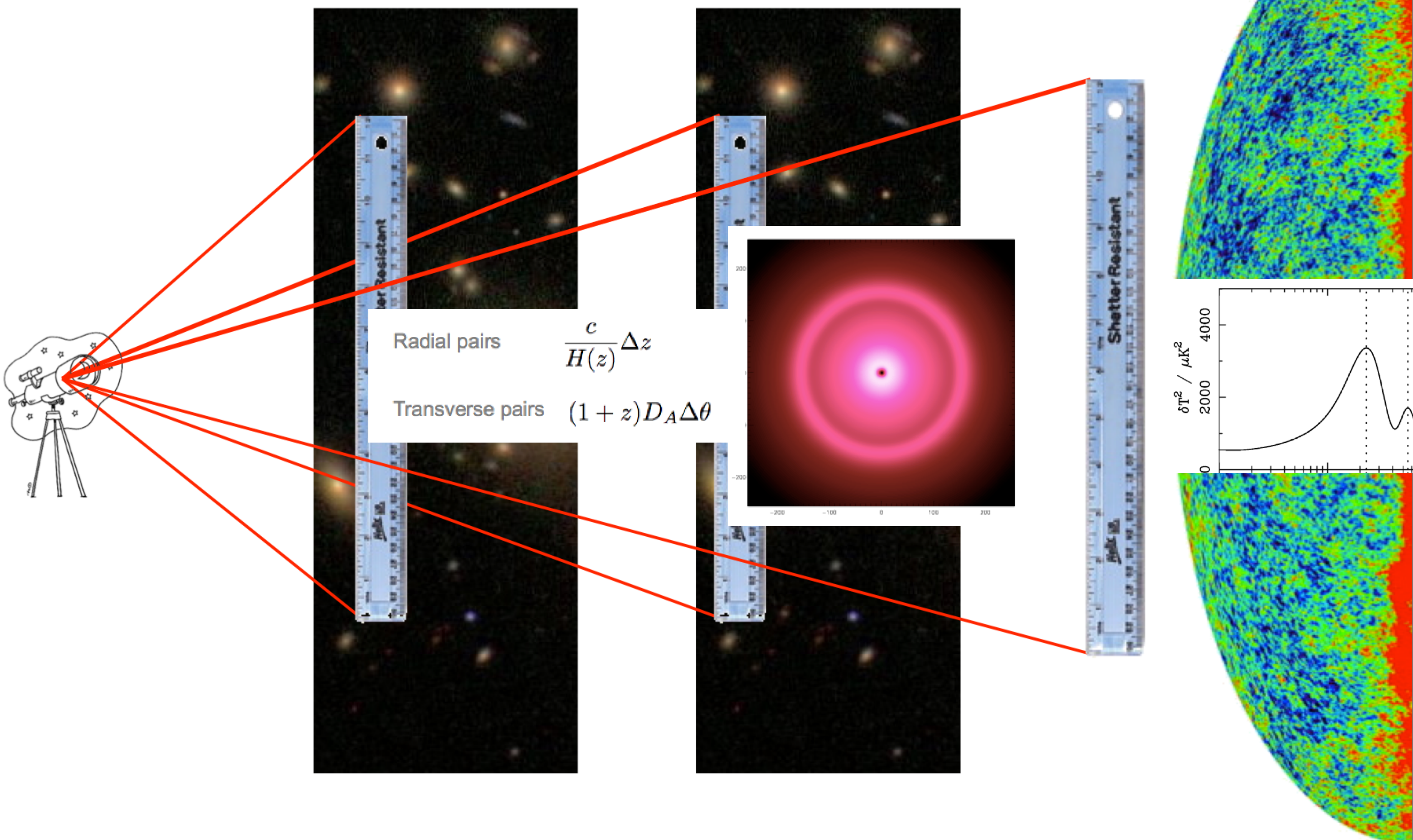
Baryon Acoustic Oscillations





Use the acoustic peak in galaxies as a standard ruler, calibrated by CMB credit : NASA / WMAP

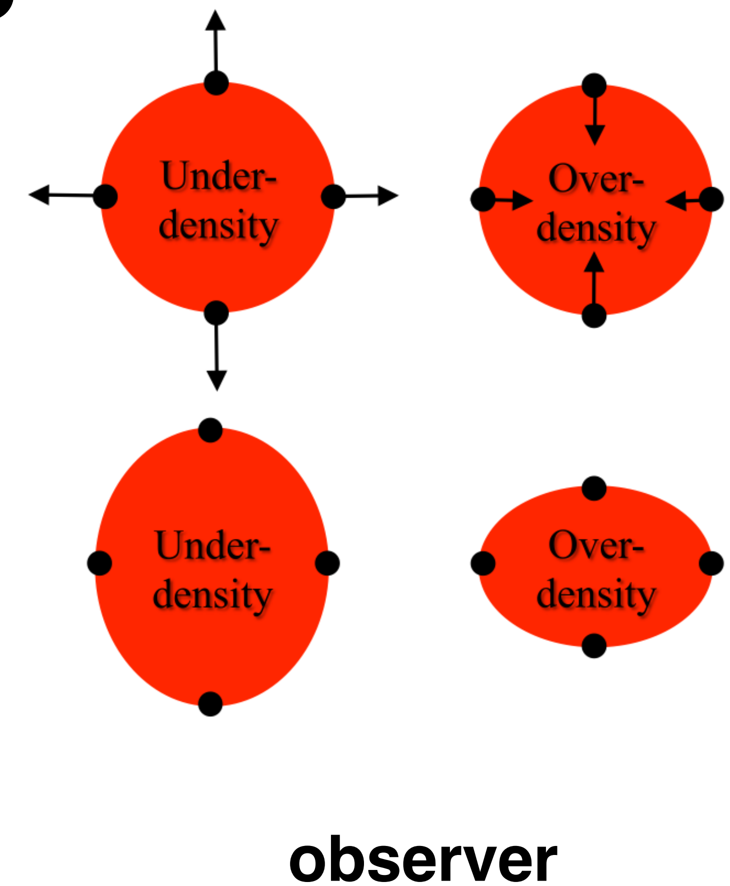
Baryon Acoustic Oscillations



Use the acoustic peak in galaxies as a standard ruler, calibrated by CMB

Redshift Space Distortions

On large-scales galaxies move coherently towards over densities and away from under densities



This generates an additional "observed" fluctuation that is proportional to the amplitud of the velocity field (the infall / outfall)

$$\delta(\mu) \sim -\mu \nabla \vec{v}$$

On large-scales the velocity divergence is proportionality to the growth rate of density perturbations

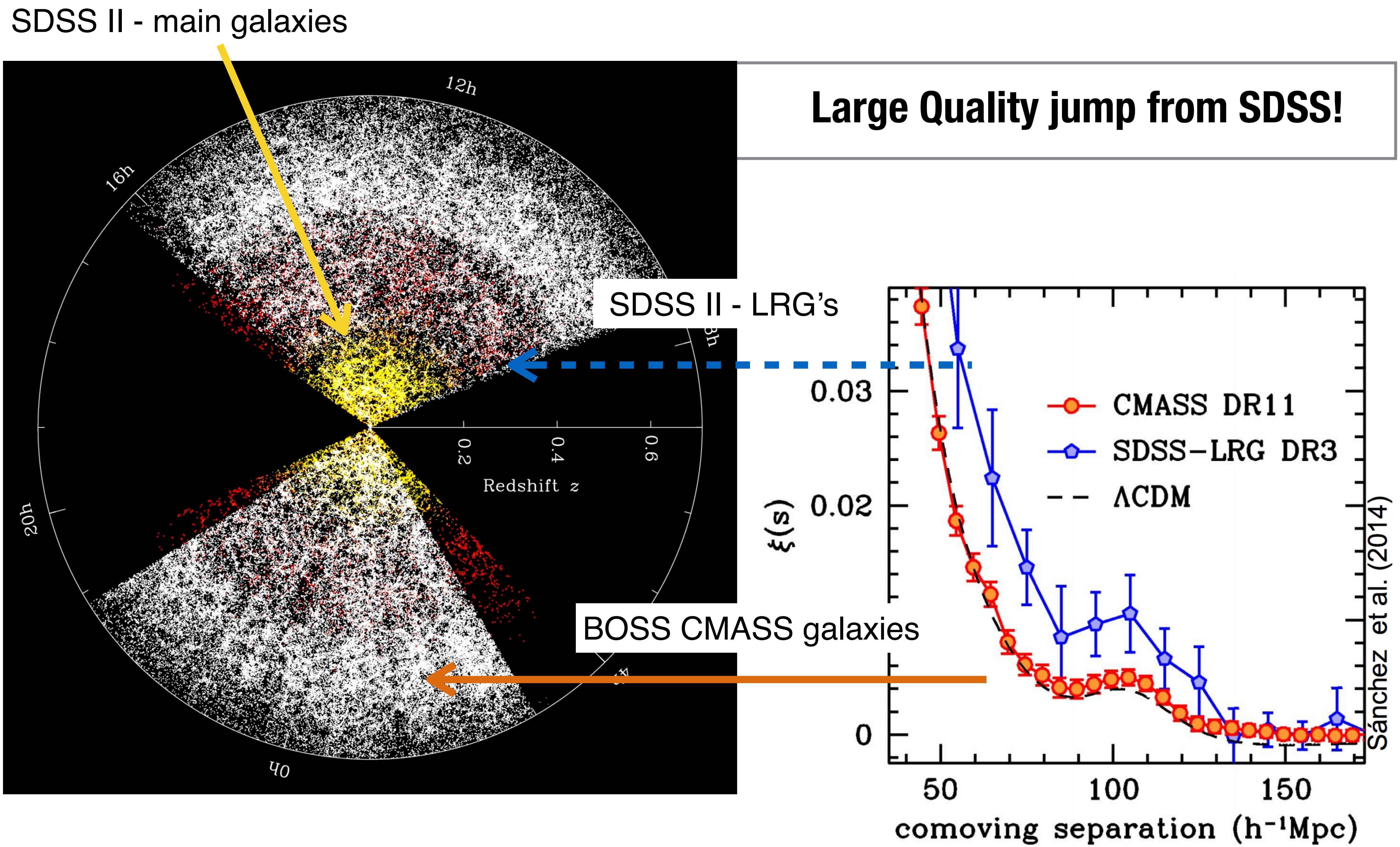
$$\nabla \vec{v} = \dot{\delta} = -f\delta \qquad f \equiv \frac{d \log D}{d \log a} \qquad f\sigma_8 \propto \frac{dD}{d \log a}$$

$$\delta_{\rm gal}(k,\mu) \quad = \quad b\delta_{\rm mass} + \mu^2 f \delta_{\rm mass}$$

measure anisotropic 2-pt correlations

intrinsic z-space

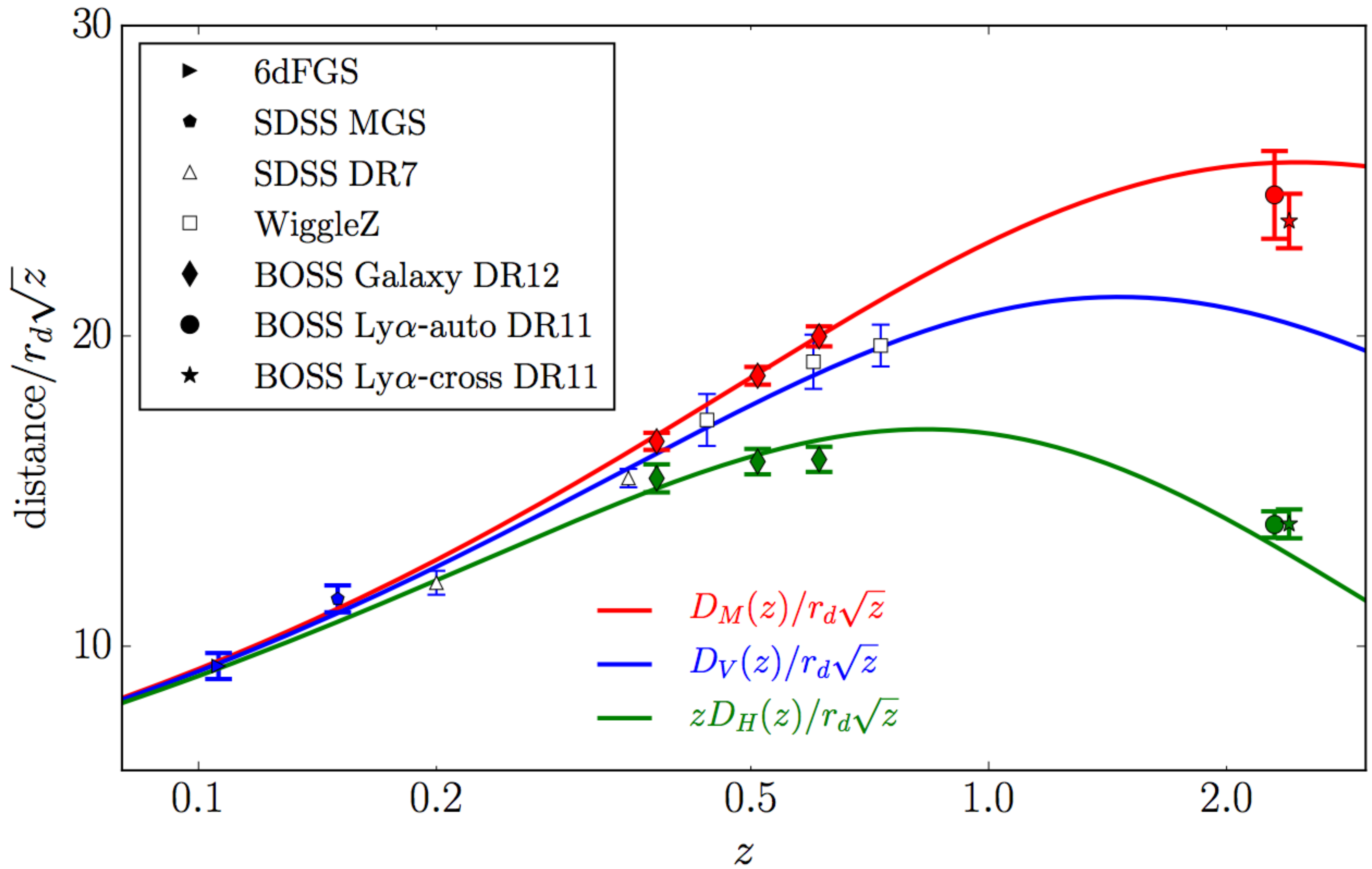
BOSS (baryon acoustic oscillation survey)



Distance Measurements

Hubble diagram from Baryon Acoustic Oscillations

- Angular diameter distance better than 1.5% in all bins
- Hubble parameter better than 2.4% in all bins

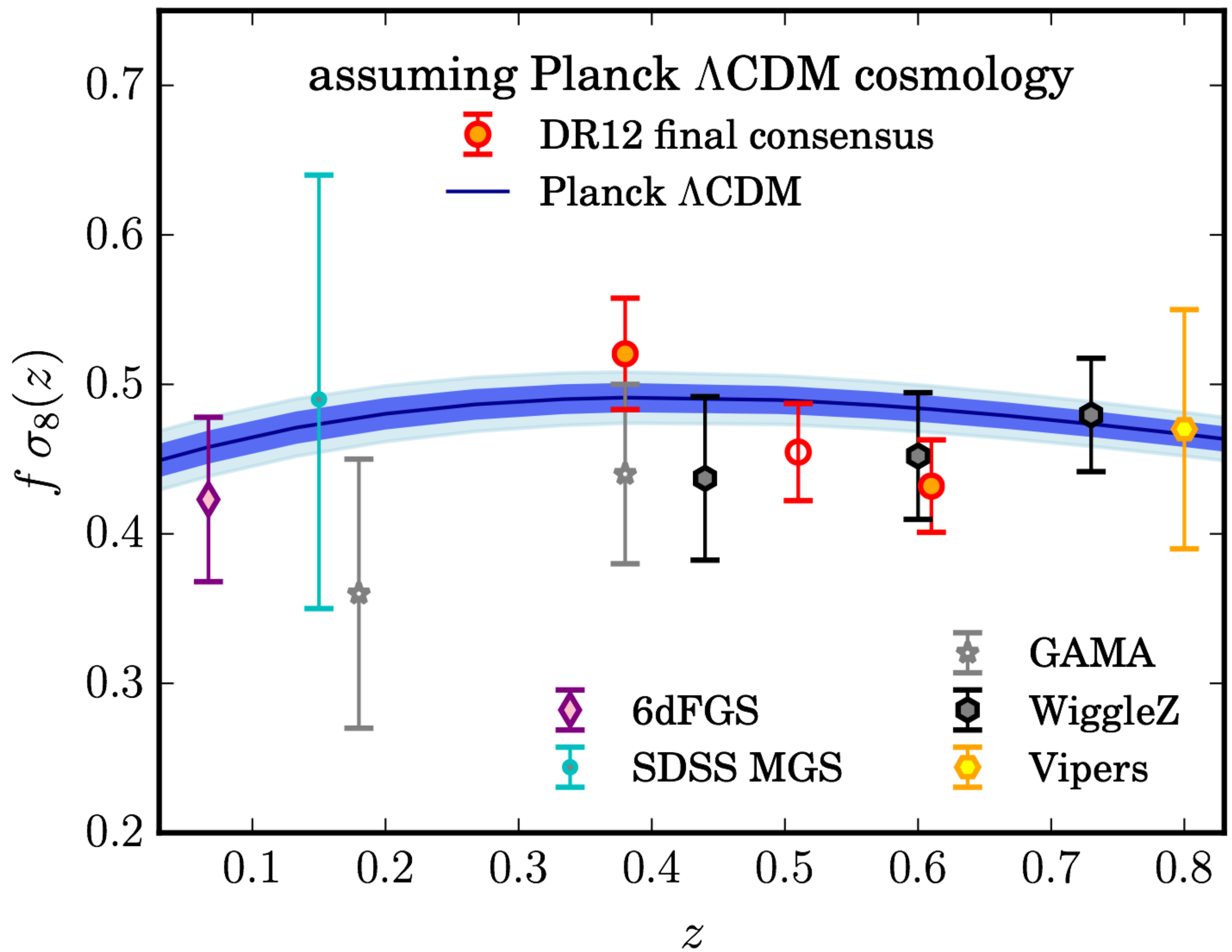


Alam et al (BOSS Collaboration) 2016

Growth Measurements

from Redshift Space Distortions

- about 9.2% or better precision in each bin

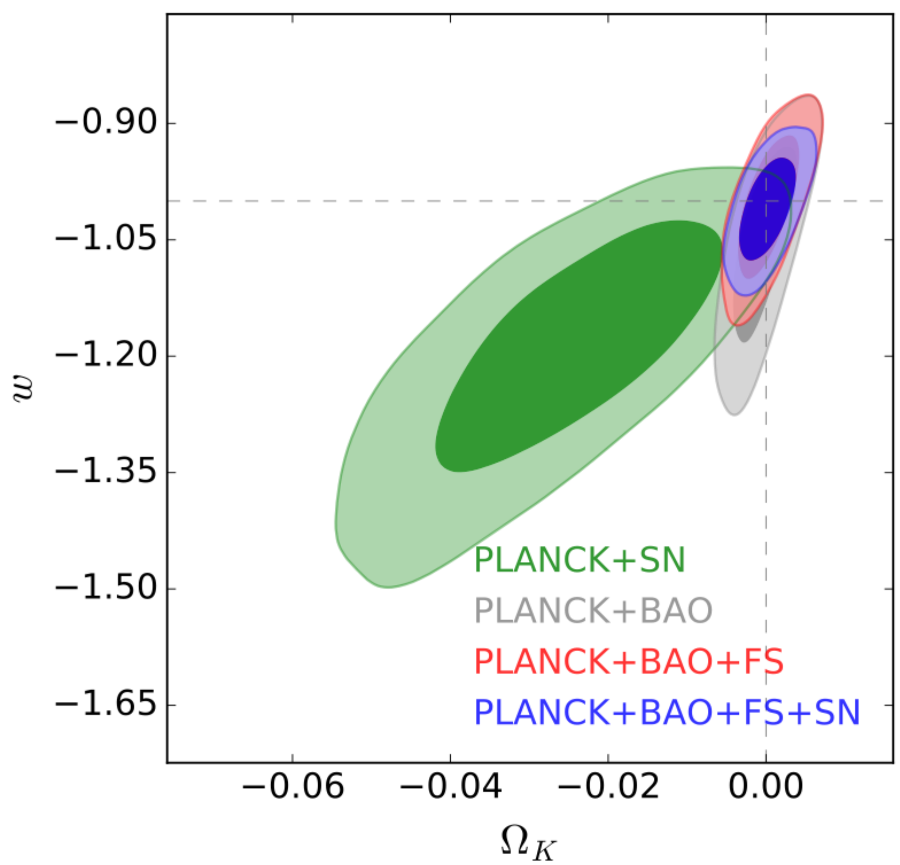


Alam et al (BOSS Collaboration) 2016

Dark Energy

equation of state

Final BOSS analysis: arXiv 1607.03155

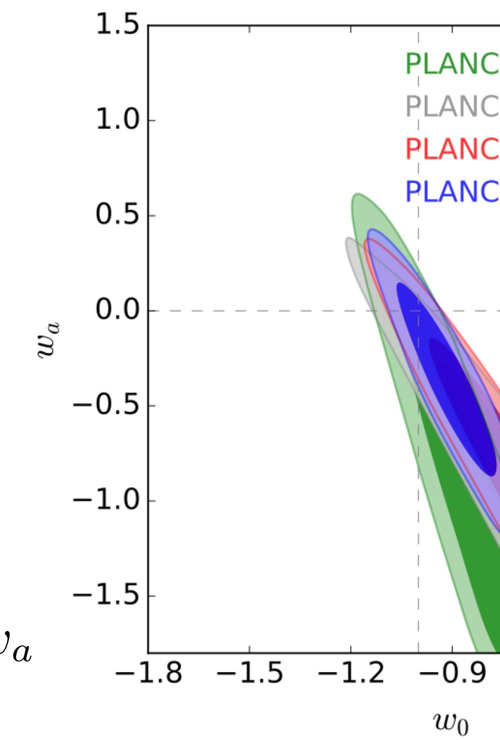


CMB alone can't constrain models that open up the low-z distance scale

Opening two degrees of freedom (jointly or separately)

$\Omega_K = -0.0003 \pm 0.0027$	consistent with flat
$w = -1.01 \pm 0.06$	consistent with Λ

"Strong affirmation of spatially flat cold dark matter model with a cosmological constant"



$w_a = -0.3 \pm 0.5$

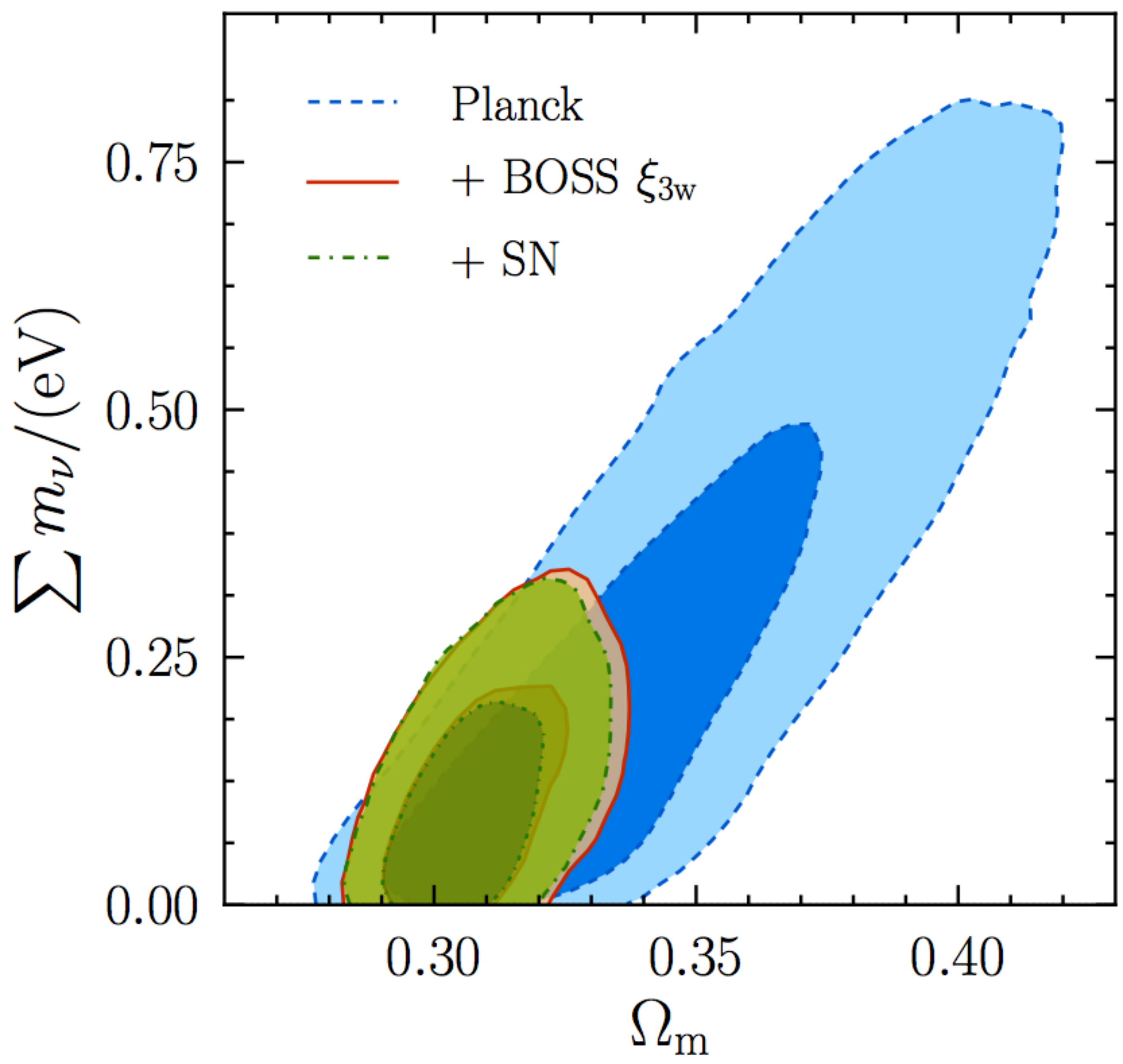
No evidence for evolving dark energy :

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

FS = full-shape = ~ RSD

SN = SNIa (JLA, Betoule et al 2014)

Massive Neutrinos



$$\sum m_\nu < 0.25\,\mathrm{eV}\ \mathrm{at}\ 95\%\ \mathrm{CL}$$

dominated by the BOSS distance measurement (not the growth).

Combining with CMB lensing reduces it

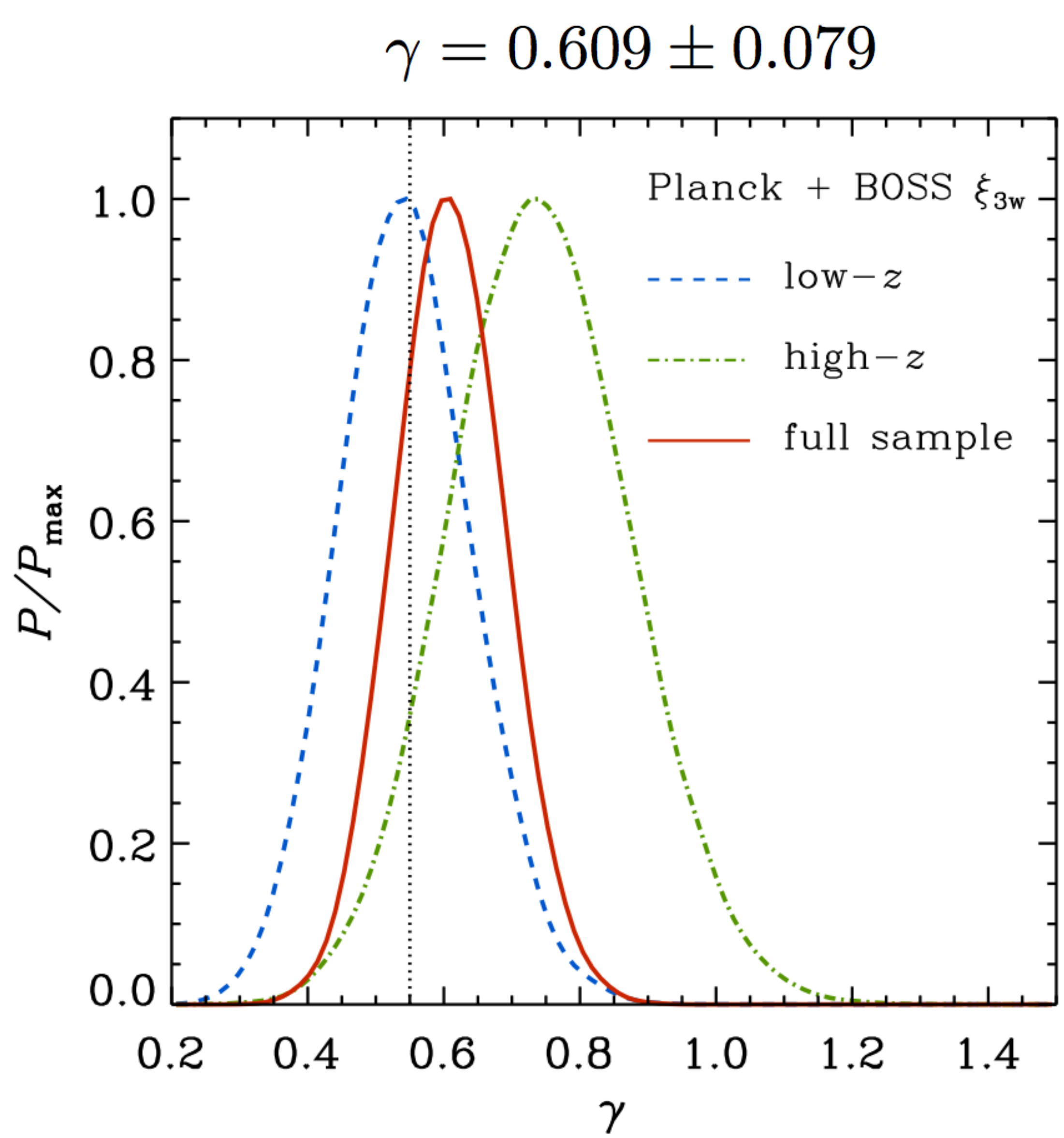
$$\sum m_\nu < 0.16\,\mathrm{eV}\ \mathrm{at}\ 95\%\ \mathrm{CL}$$

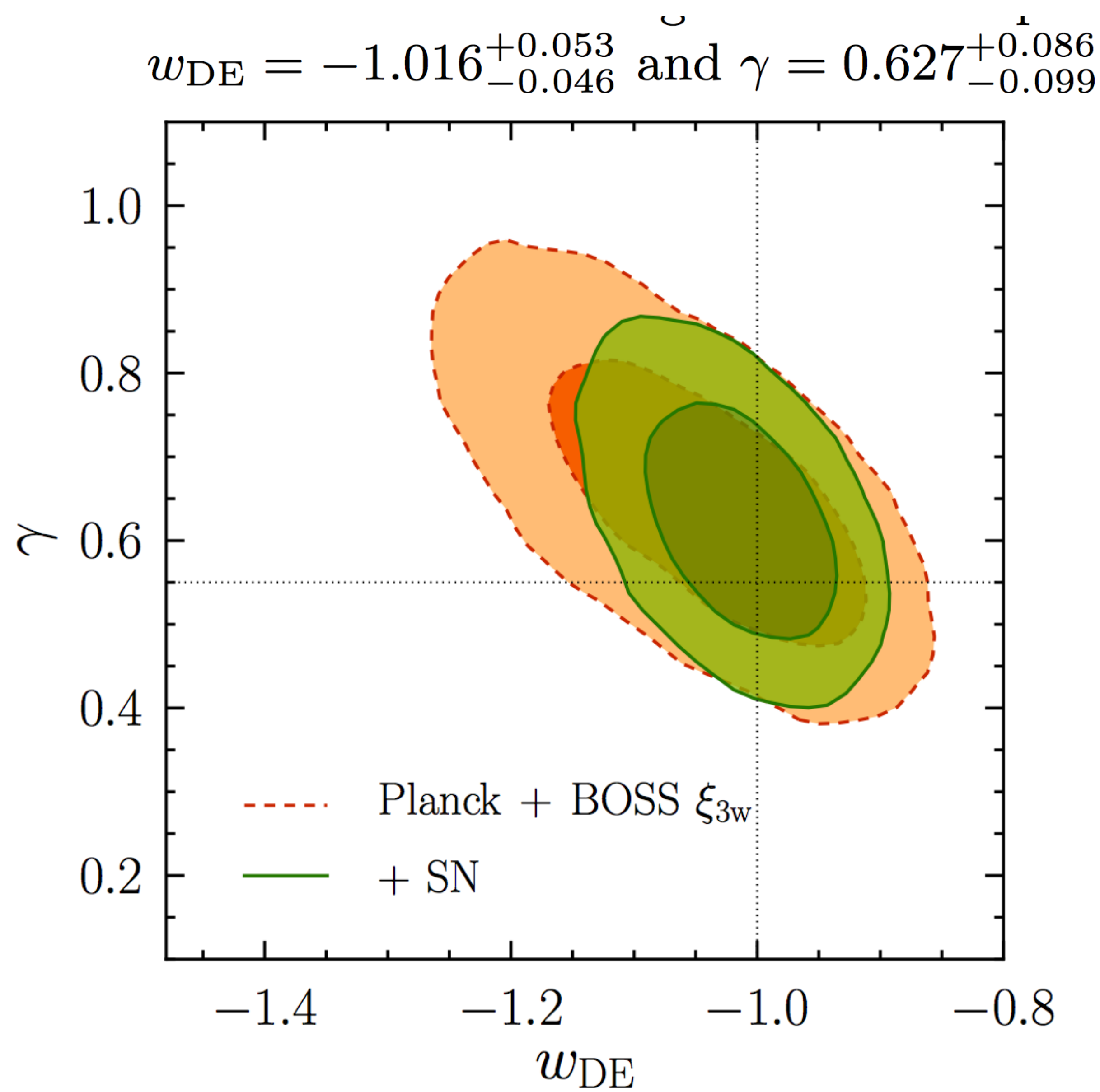
although with some potential concerns due to tensions in the CMB(lensing) data.

Consistency of GR

$f(z) = \Omega_m(z)^\gamma$ Assuming GR (LCDM) one gets γ ~ 0.55

Translate measurements of $f(z)$ into constrains in γ to see consistency of GR





Summary of galaxy clustering

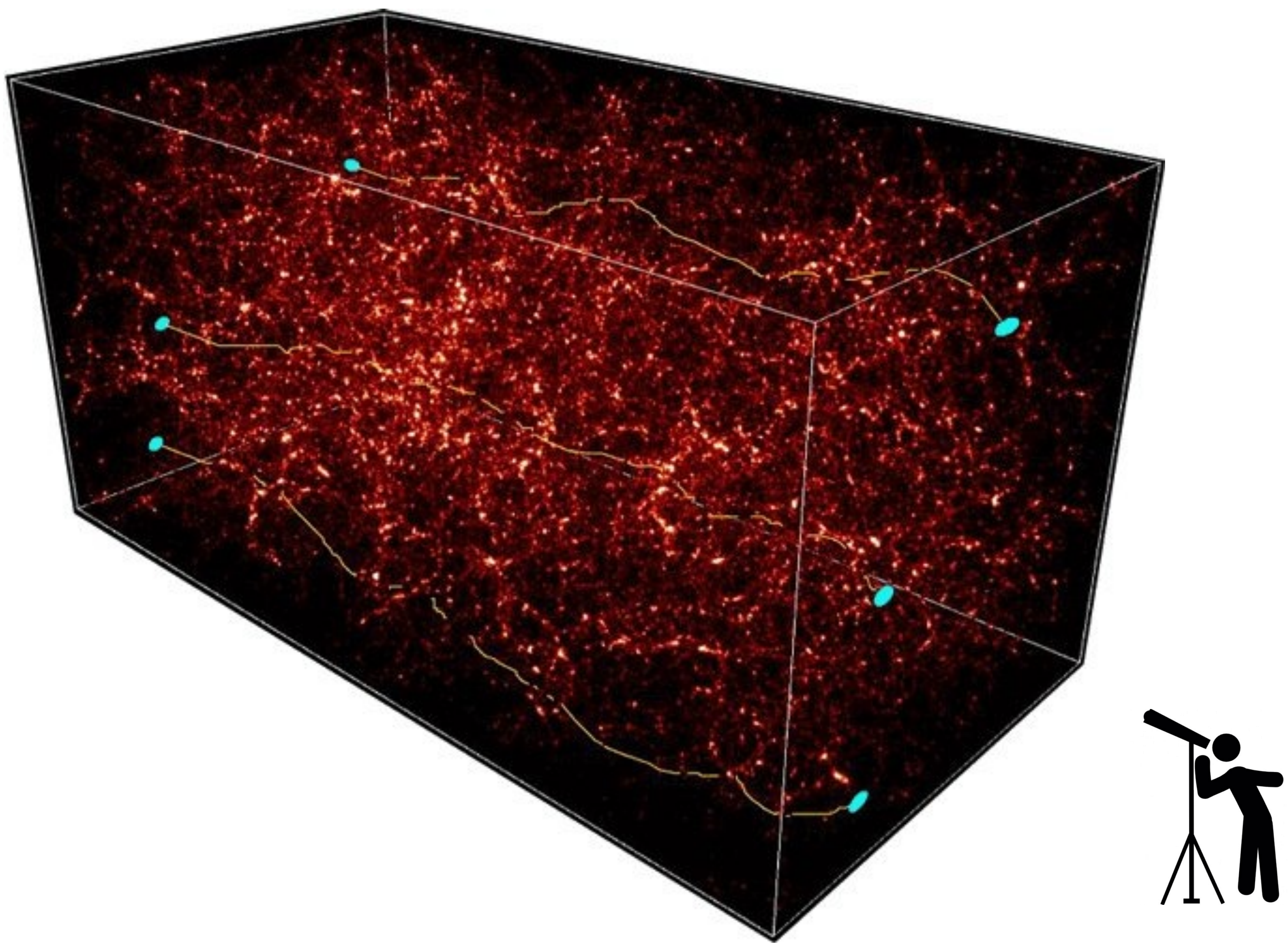
- Good agreement with Planck. No preference for extensions of the 6-parameter LCDM model (even with SNIa are included).
- Opening of flatness and DE returns flat and lambda (!).
- Time varying dark-energy is not well constrained
- Stable values of $H_0 = 67 \pm 1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, the tension with local measurements of $H_0 = 73 \pm 1.8\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Riess et al. 2016) still present

led to the era of Weak Lensing surveys (DES, KiDS)

Weak Lensing

technology has enabled shape measurements

source galaxies at
z ~ 1



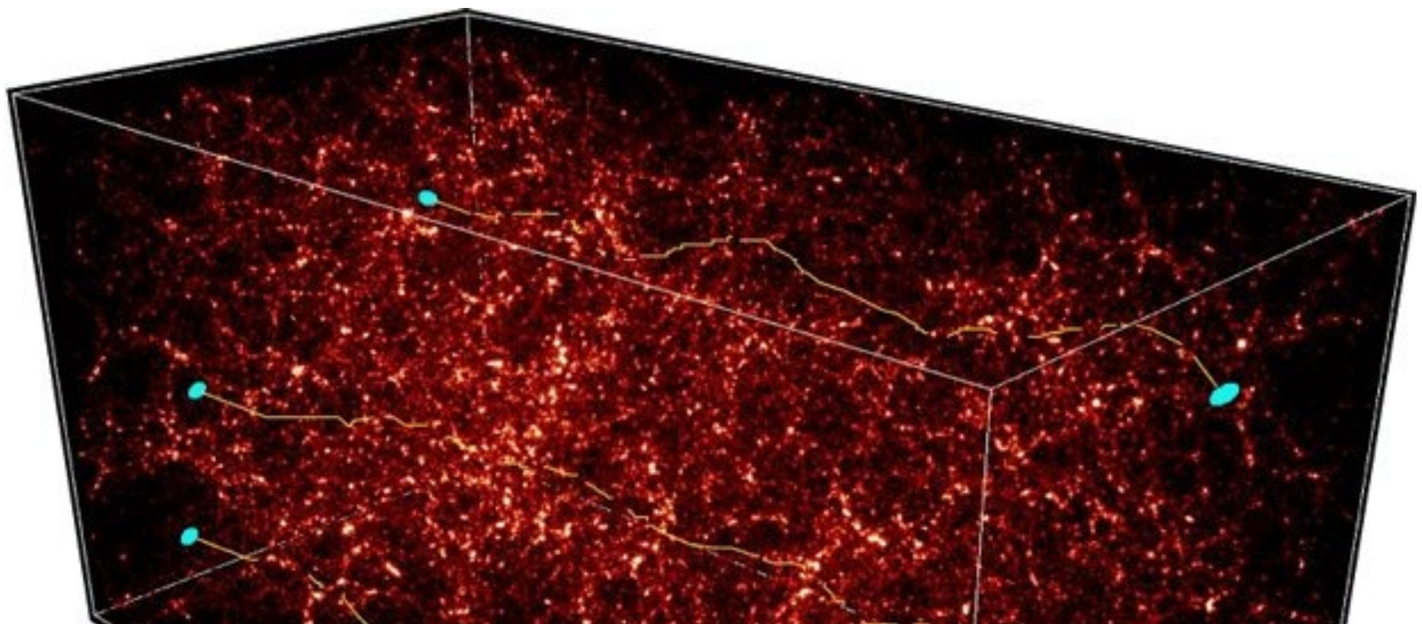
- Matter distorts back-ground galaxy shapes
- Measure shapes to obtain "shear" catalog
- Shear–shear correlations is an unbiased tracer of matter distribution

Observer : shapes have been "sheared" coherently by the large-scale structure

- **Problems** – Intrinsic Alignments, Baryon Physics, Shapes biases

Weak Lensing

technology has enabled shape measurements



- Matter distorts back-ground galaxy shapes
- Measure shapes to obtain “shear” catalog
- Shear-shear correlations is an unbiased tracer of matter distribution

The “cosmic-shear” era

2003-2008: Canada-France-Hawaii Legacy Survey: 154 deg^2

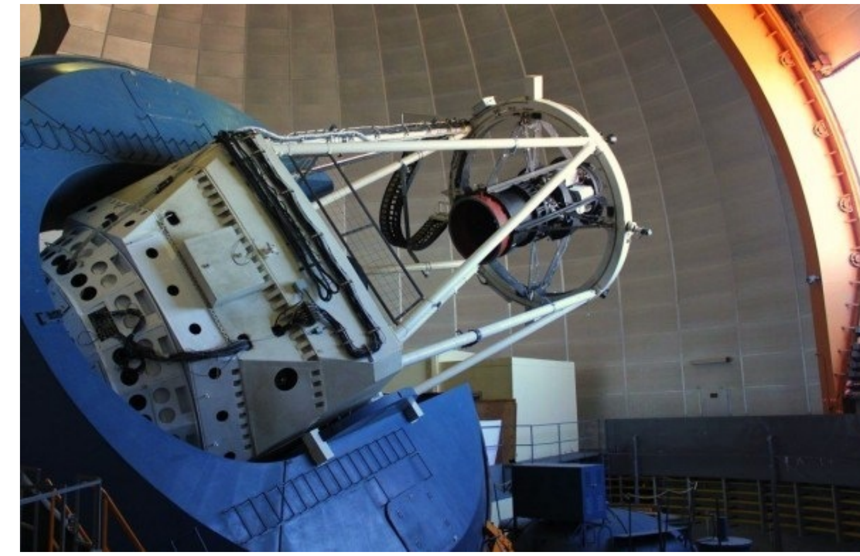
2014-2019: **Hyper-Suprime Cam Survey**, 1400 deg^2

2013-2018: **Dark Energy Survey**, 5000 deg^2

2011-2018: **Kilo-Degree Survey**, 1350 deg^2

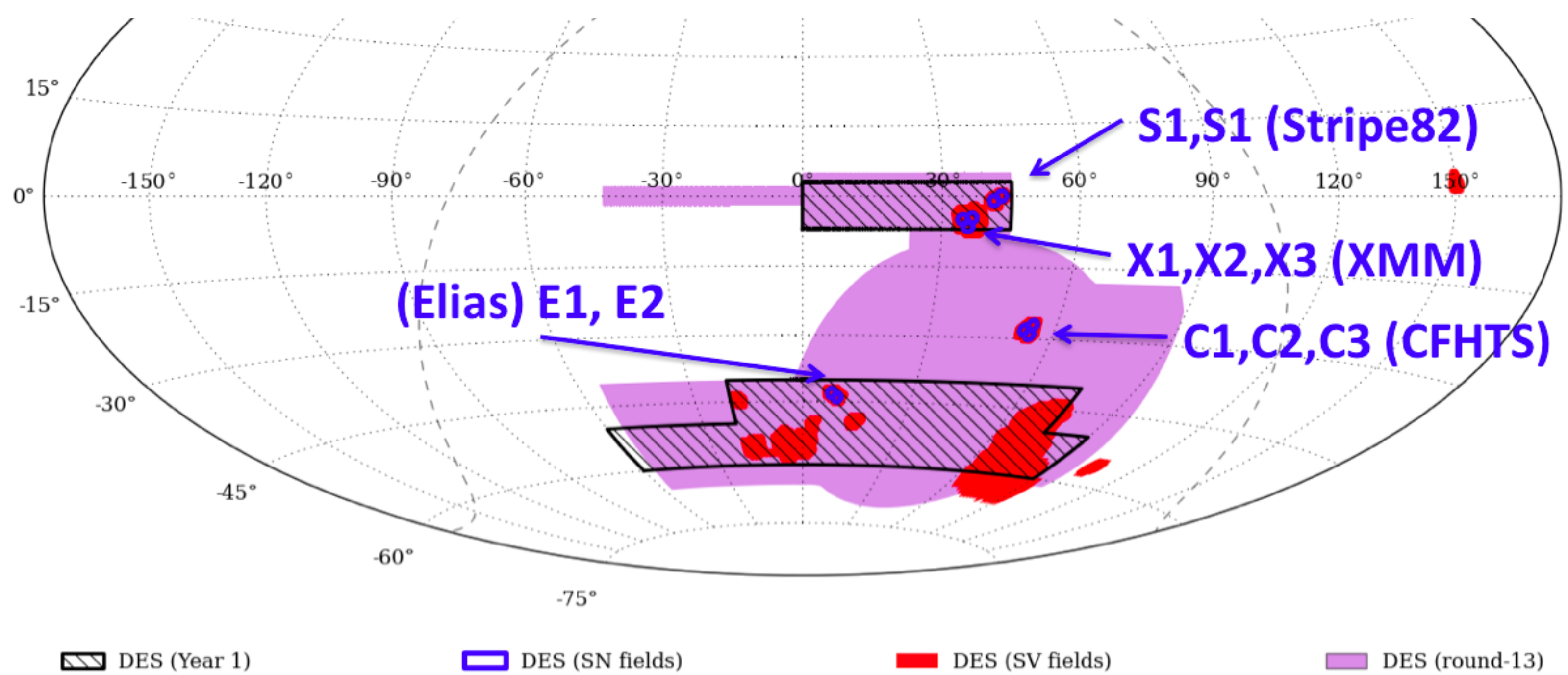
Dark Energy Survey

overview



- Wide Optical and near IR survey (grizY bands)
- 525 nights over 5 seasons in 5 imaging bands
- 5000 deg^2 of which 2500 overlap with South Pole Telescope
- i-band magnitud limit ~24 at S/N=10, largest survey at this sensitivity
- 30 deg^2 in time domain, SN fields visited at least once per week

Finished
4th 1/2 years of
observations.



Dark Energy Survey

Weak lensing (distance, structure growth)
shapes of 200 millions galaxies

Baryonic acoustic oscillations (distance)
300 millions galaxies to z=1 and beyond

Galaxy clusters (distance, structure growth)
hundred of thousands of clusters up to z~1
synergies with SPT, VHS

robust combination of probes

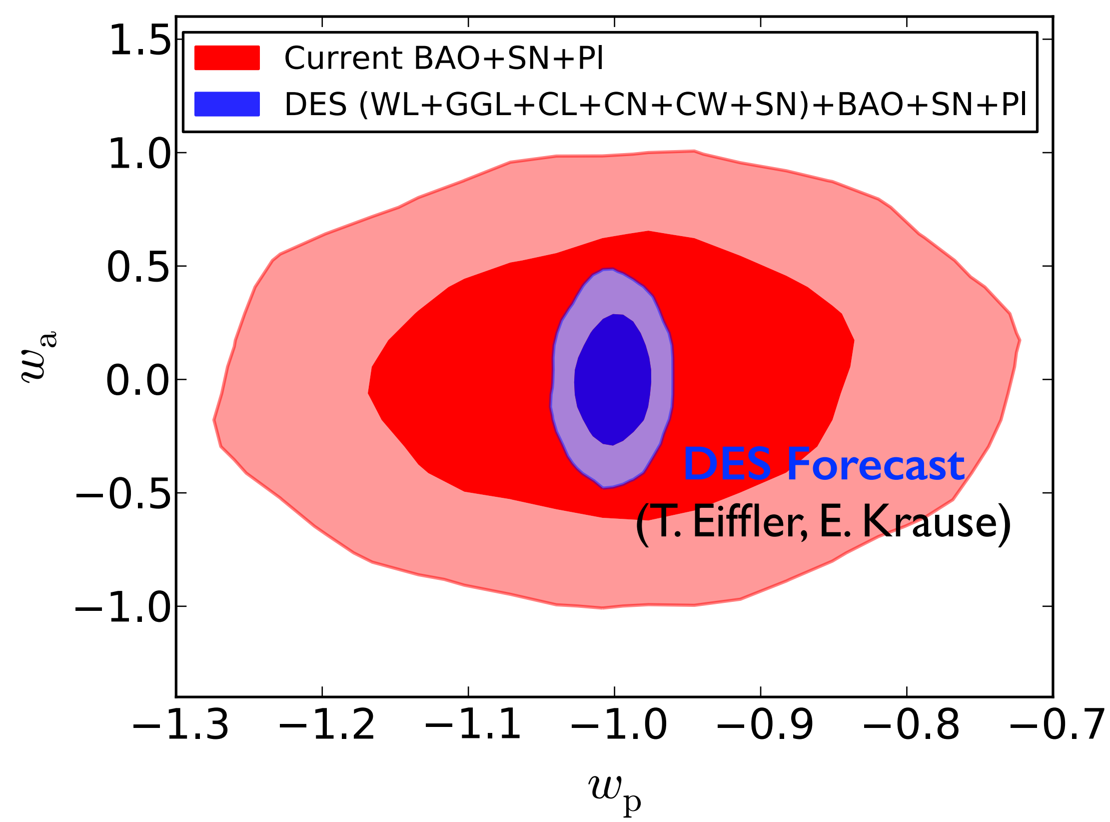
→ shared photometry/footprint

→ shared analysis of systematics

→ shared galaxy redshift estimates

Type Ia supernovae (distance)
30 sq. deg. SN fields
3000 SNIa to z~1

DE equation of state $w \equiv p/\rho$
$w(a) = w_0 + (1-a)w_a$



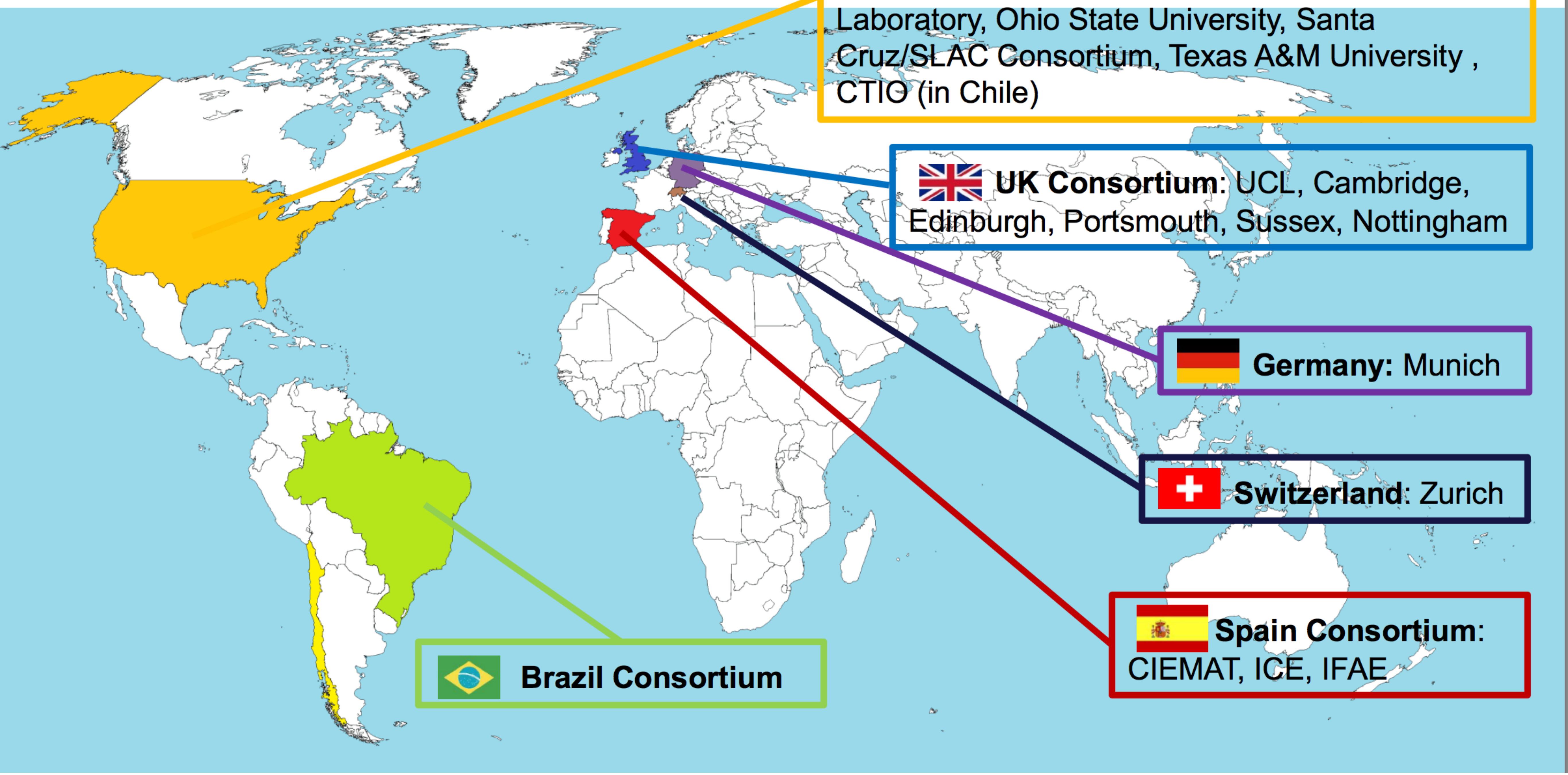
+ **Strong Lensing** (distance)
30 QSO lens time delays
Arcs with multiple source redshifts

+ **Cross-correlations**
Galaxies and WL x CMB lensing

The DES collaboration

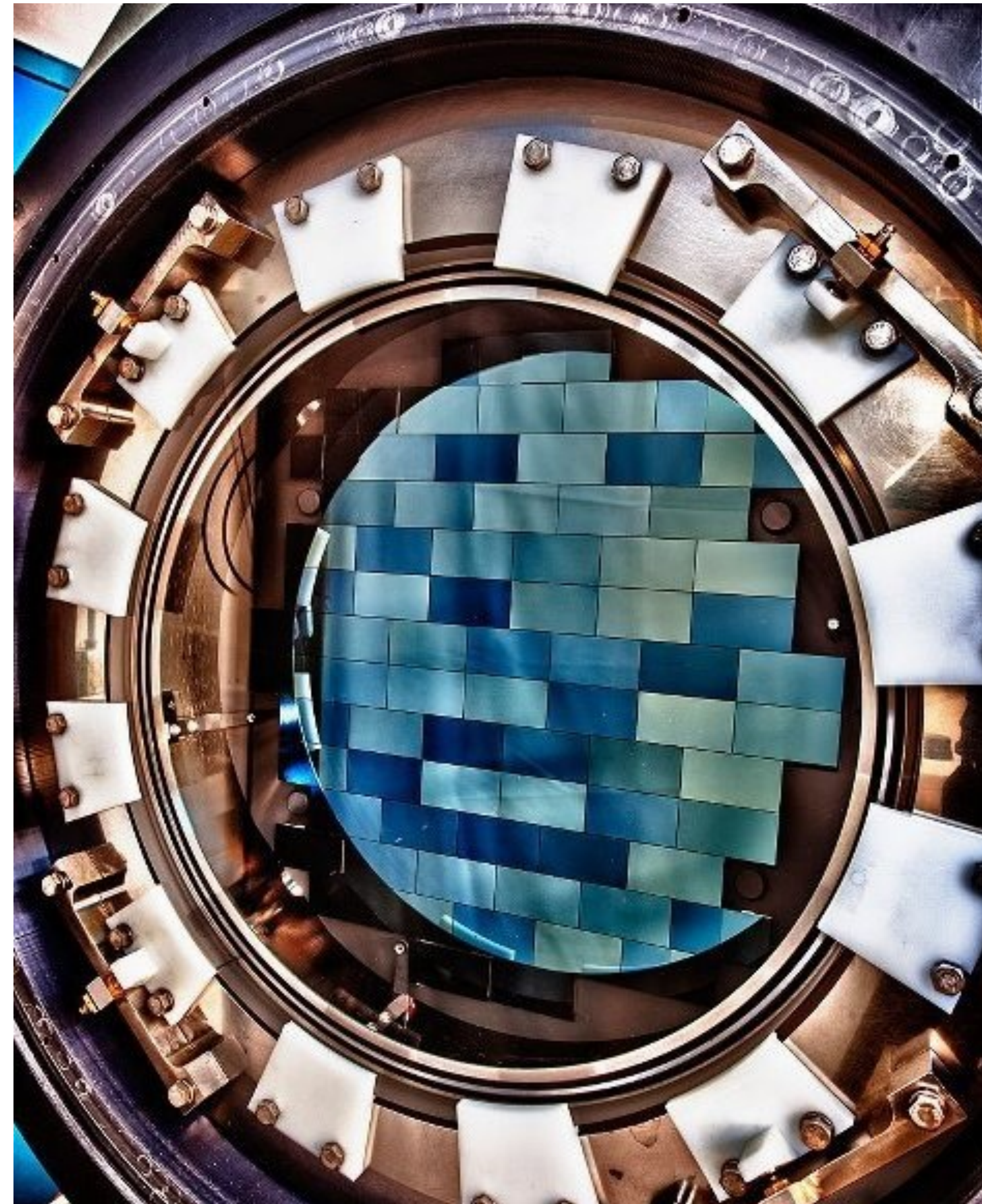
400 scientist from 28 institutions

facebook.com/darkenergysurvey
http://darkenergysurvey.org



DECam

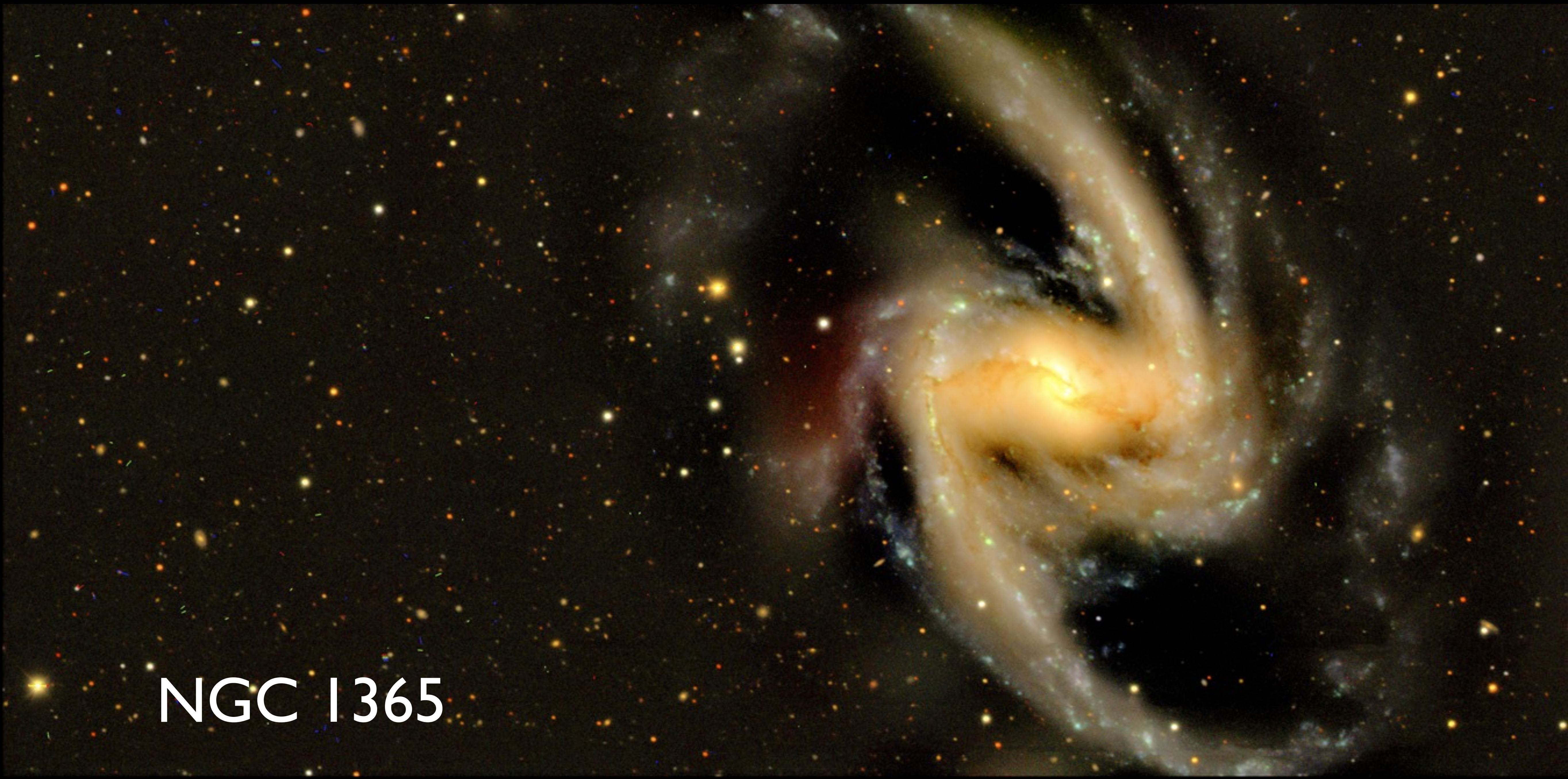
a 570 Mpx per image with very good image quality
designed and built by the Collaboration
3 deg^2 Field of View



The Dark Energy Survey: telescope

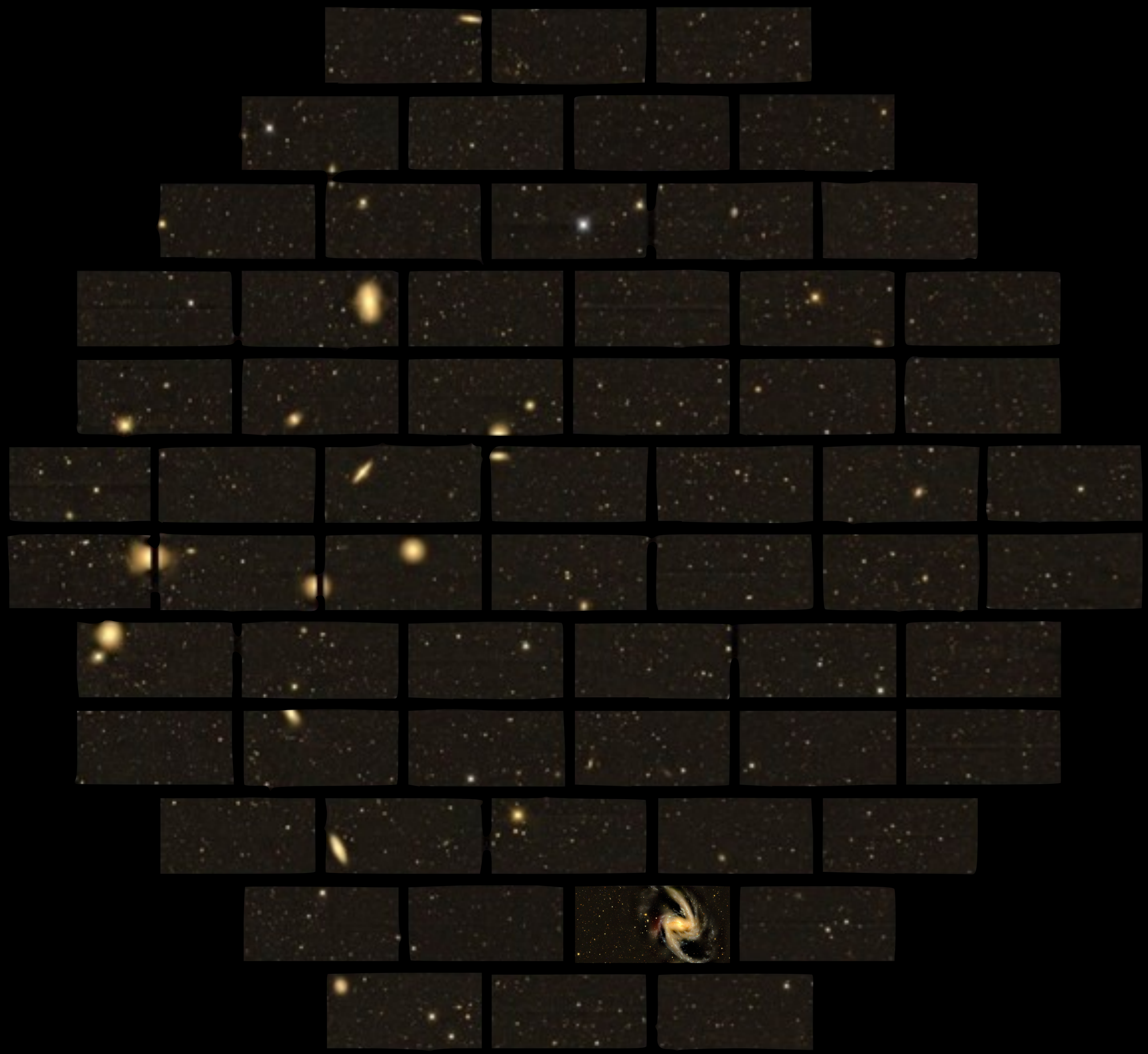
The Blanco 4-meter at CTIO Chile

1st light: 12 Sept. 2012



1 chip

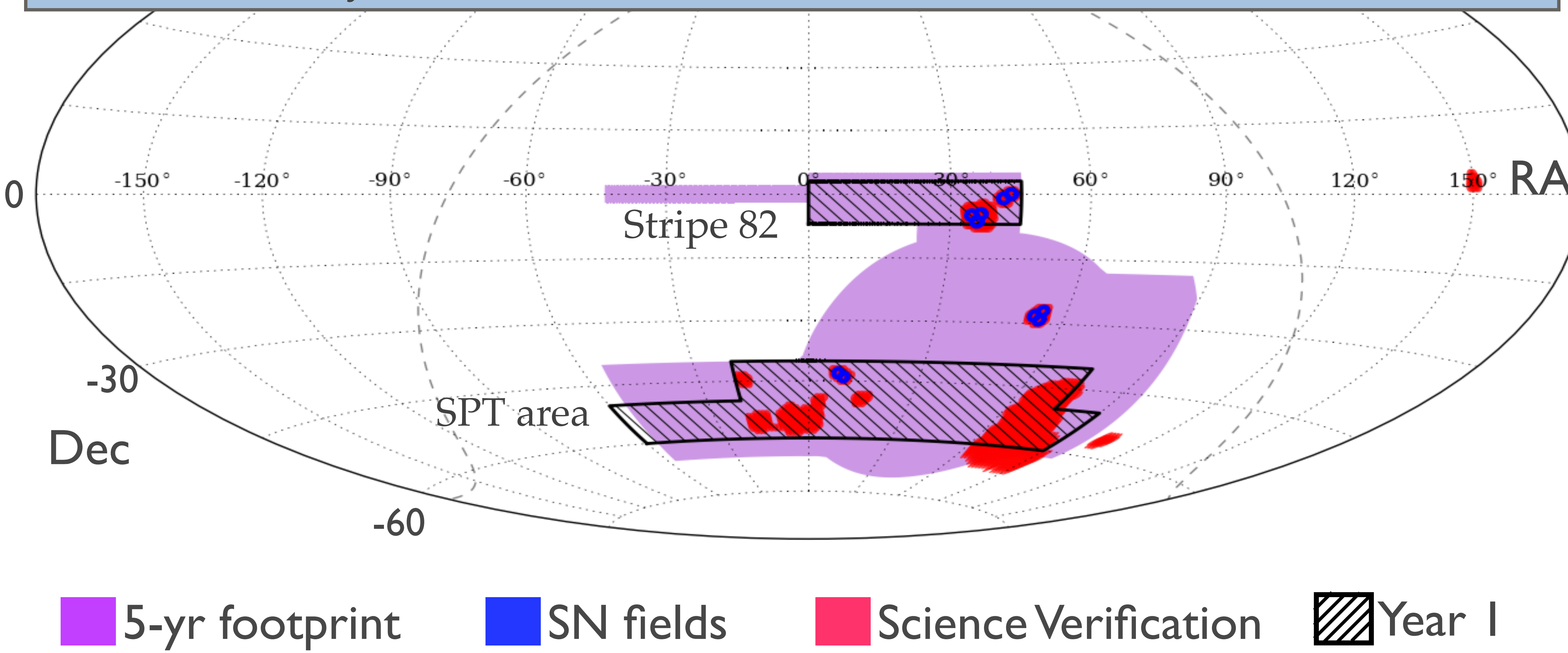
1st light: 12 Sept. 2012



Fornax cluster

DES footprints and science status

- Nov 2012-Feb 2013: Science verification, 150 deg^2, papers **published**
- Aug 2013-Feb 2014: Y1, ~1500 deg^2: key papers **finishing**
- through Feb 2016: Y3, 5000 deg^2: internal release, cosmology **starting,** DR1 late this year

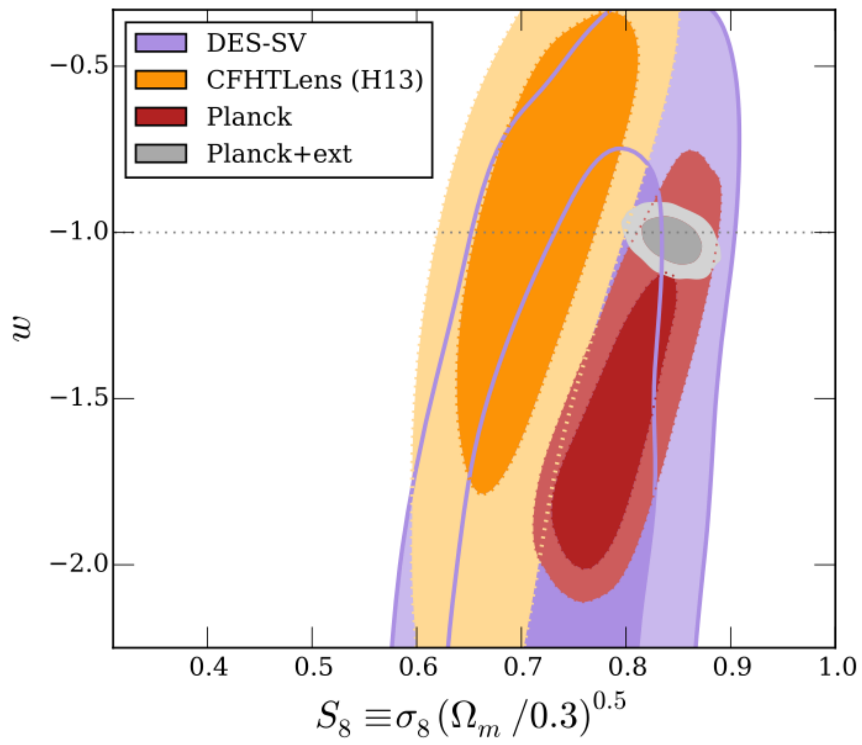


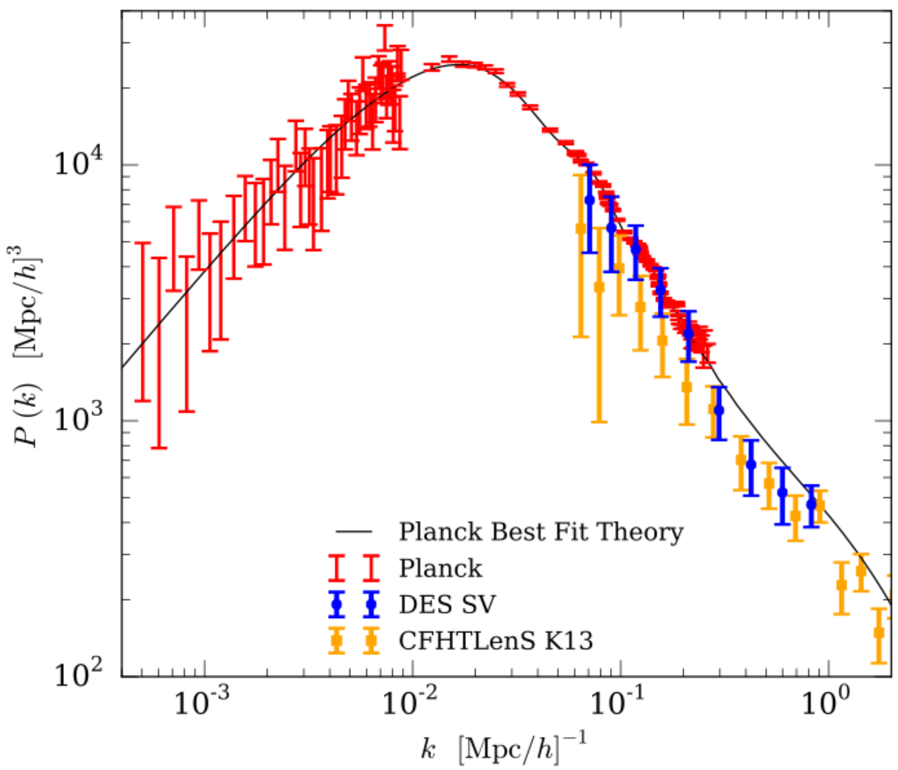
Weak Lensing: Shear Catalog

"The DES SV weak lensing shear catalogs" Jarvis, Sheldon, Zuntz, Kacprazk, Briddle et al., arXiv 1507.05603

- Two independent shape measurement pipelines in place, NGmix and IM3Shape
- 6.9 and 4.2 "shapes" per arc-min^2 respectively (~ 3 million galaxies)
- Several null tests (eg. B-mode signal consistent with 0, ..)

- Marginalizing over 3 cosmological parameters and 7 systematic ones. In 3 tomographic bins.



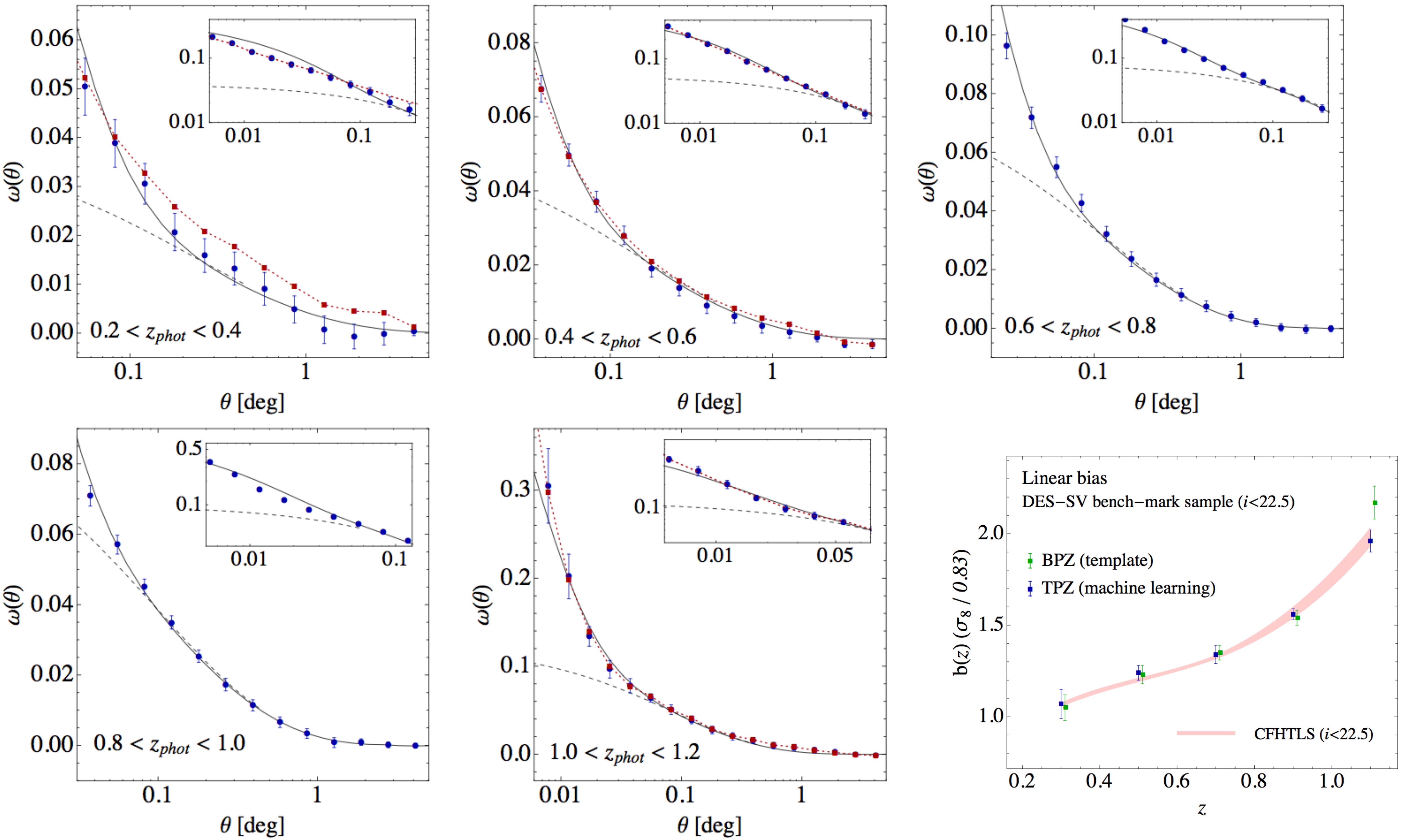


First alphabetical paper

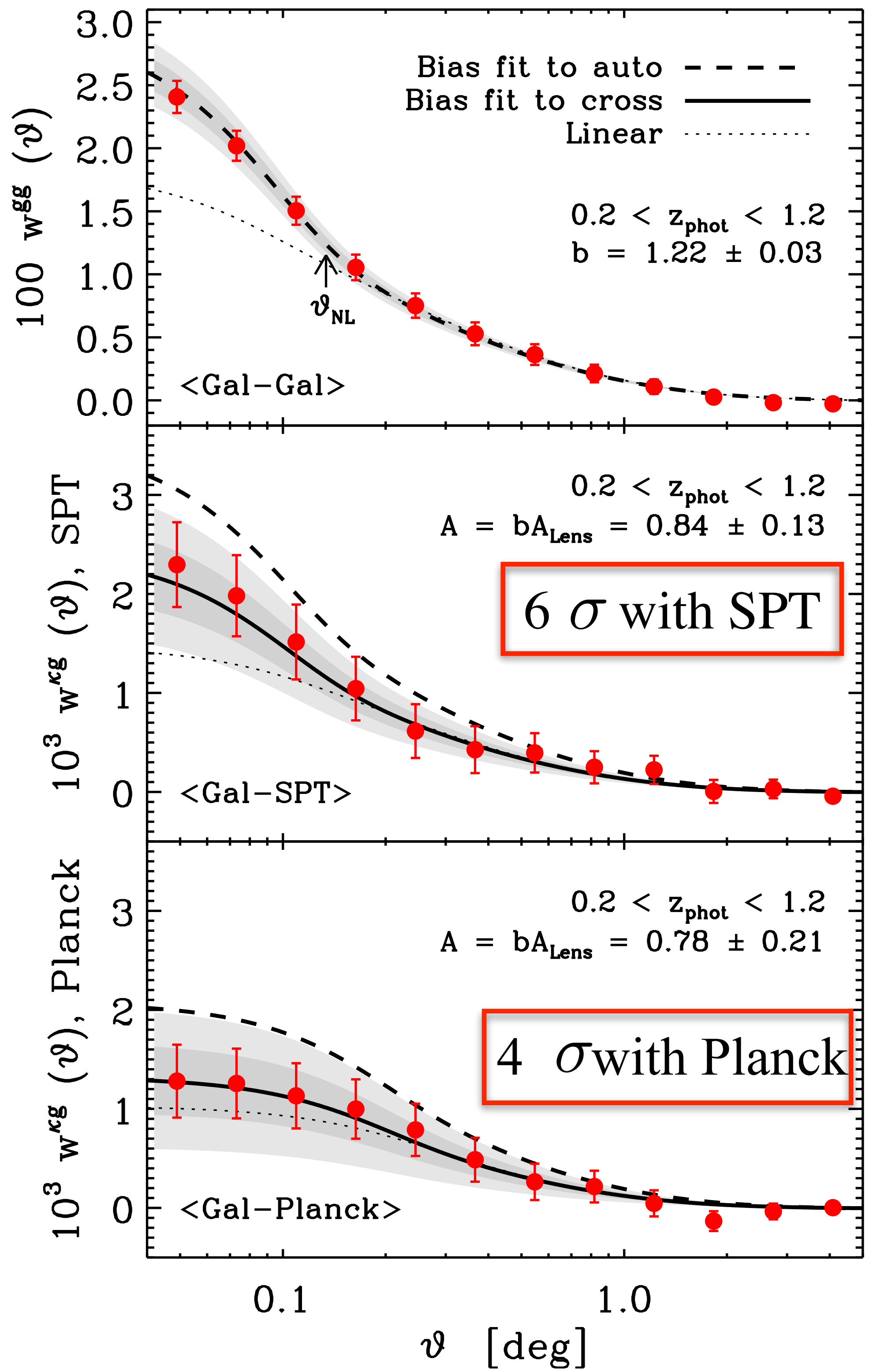
arXiv 1507.05552

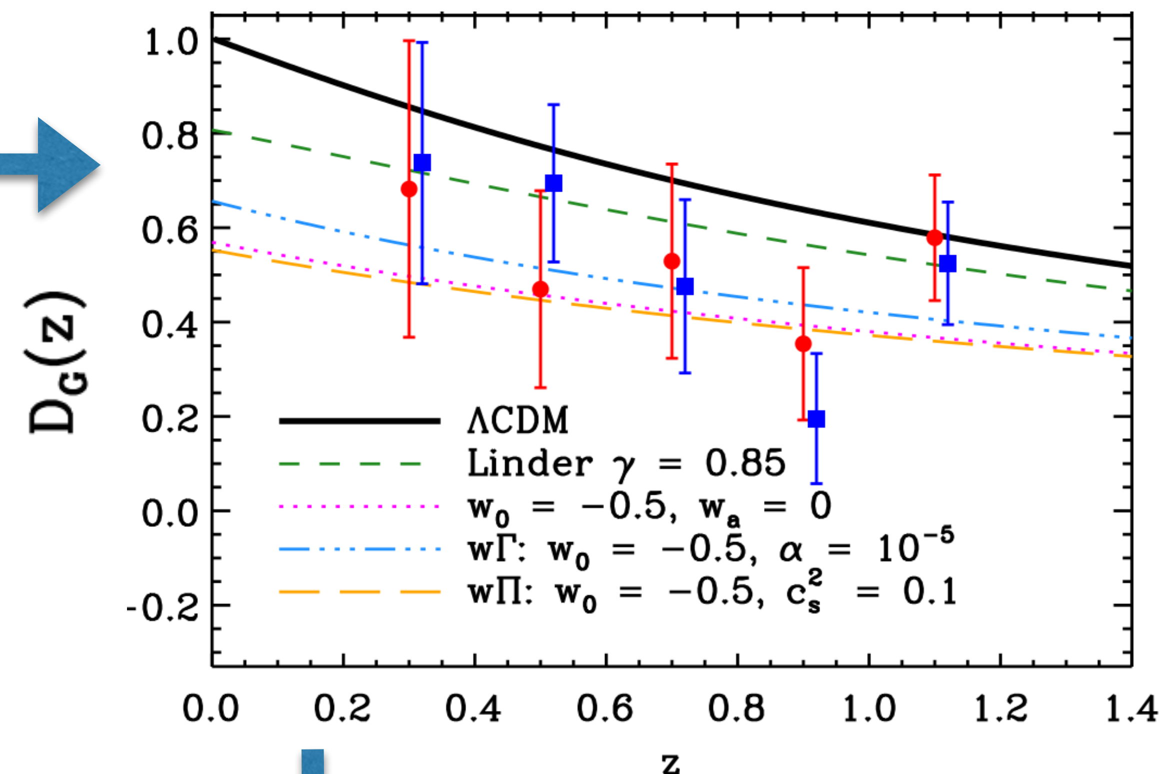
Galaxy Clustering as a function of redshift

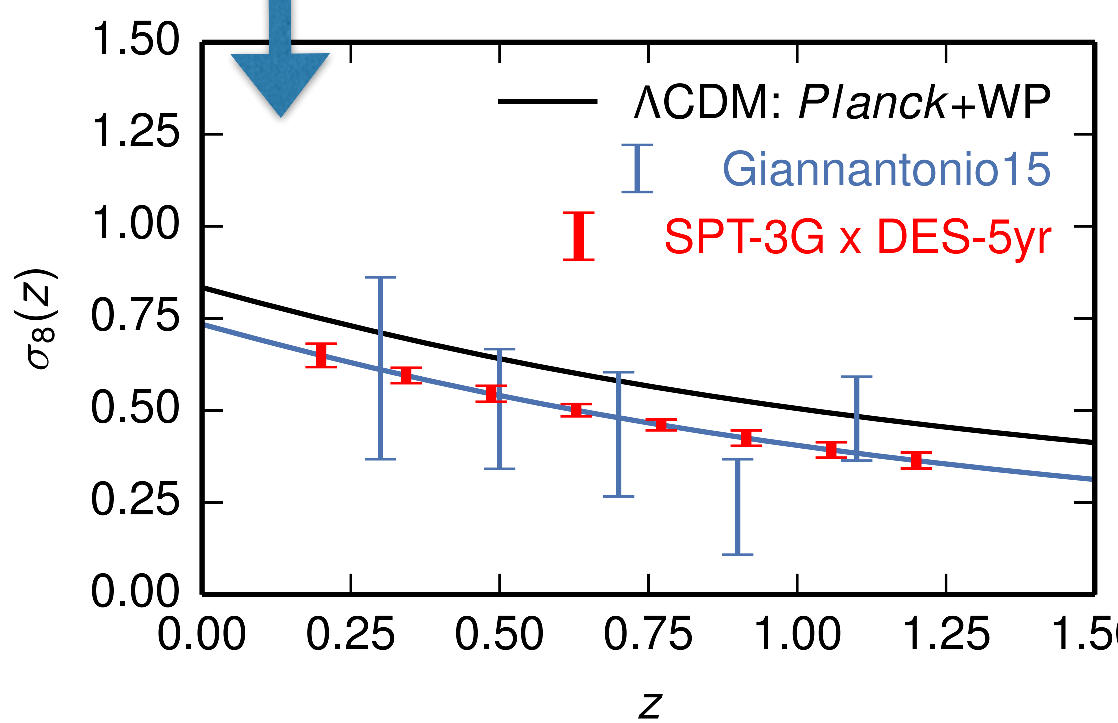
Crocce et al., MNRAS, 455, 4301 (2016)



DES Galaxies x CMB Lensing







DES Y1 - Cosmological Analysis

DES-2017-0226
FERMILAB-PUB-17-294-PPD

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

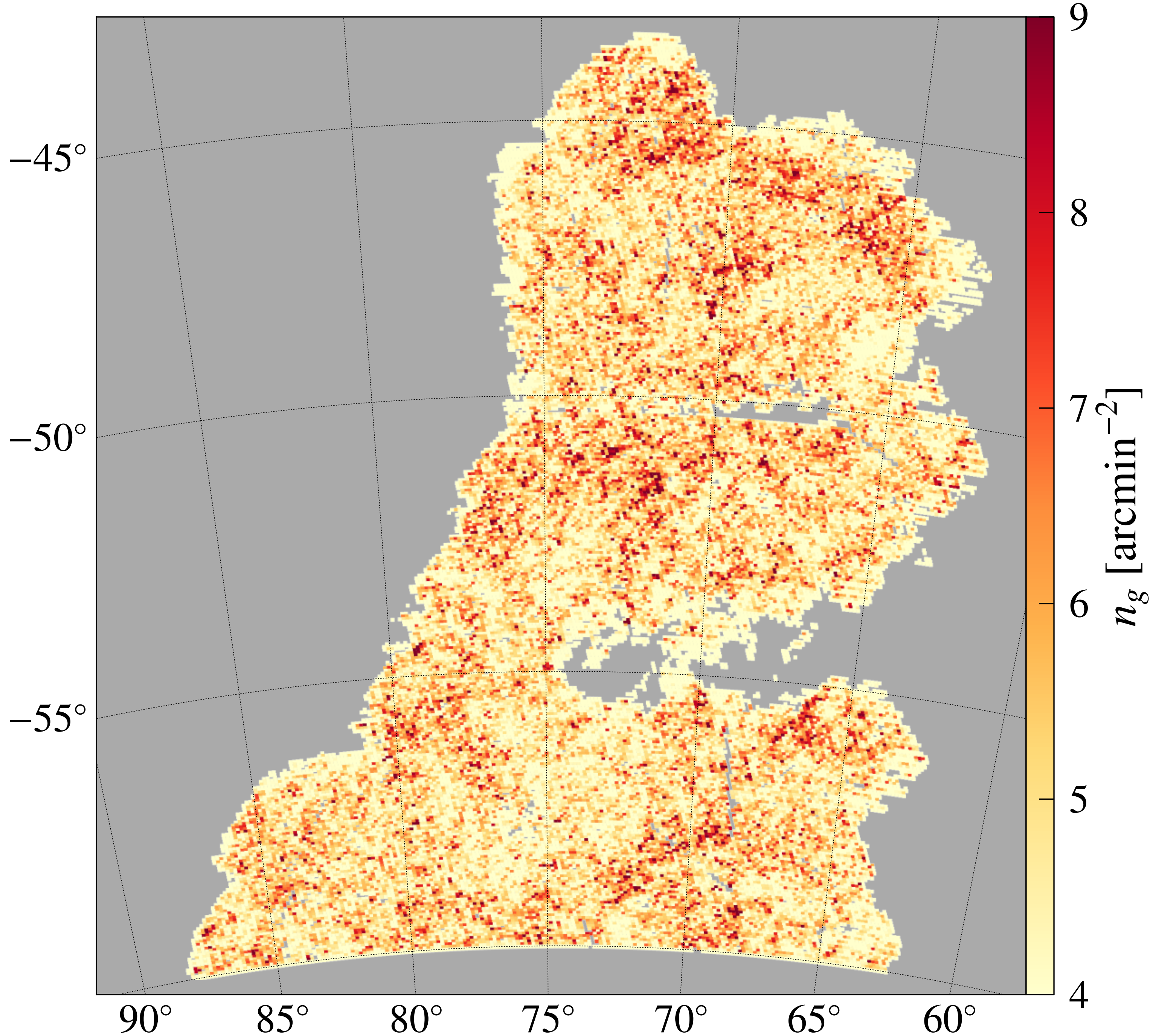
T. M. C. Abbott,[1] F. B. Abdalla,[2,3] A. Alarcon,[4] J. Aleksić,[5] S. Allam,[6] S. Allen,[7] A. Amara,[8] J. Annis,[6] J. Asorey,[9,10]
S. Avila,[11,12] D. Bacon,[11] E. Balbinot,[13] M. Banerji,[14,15] …

+ 10 supporting papers

DES Y1 cosmology

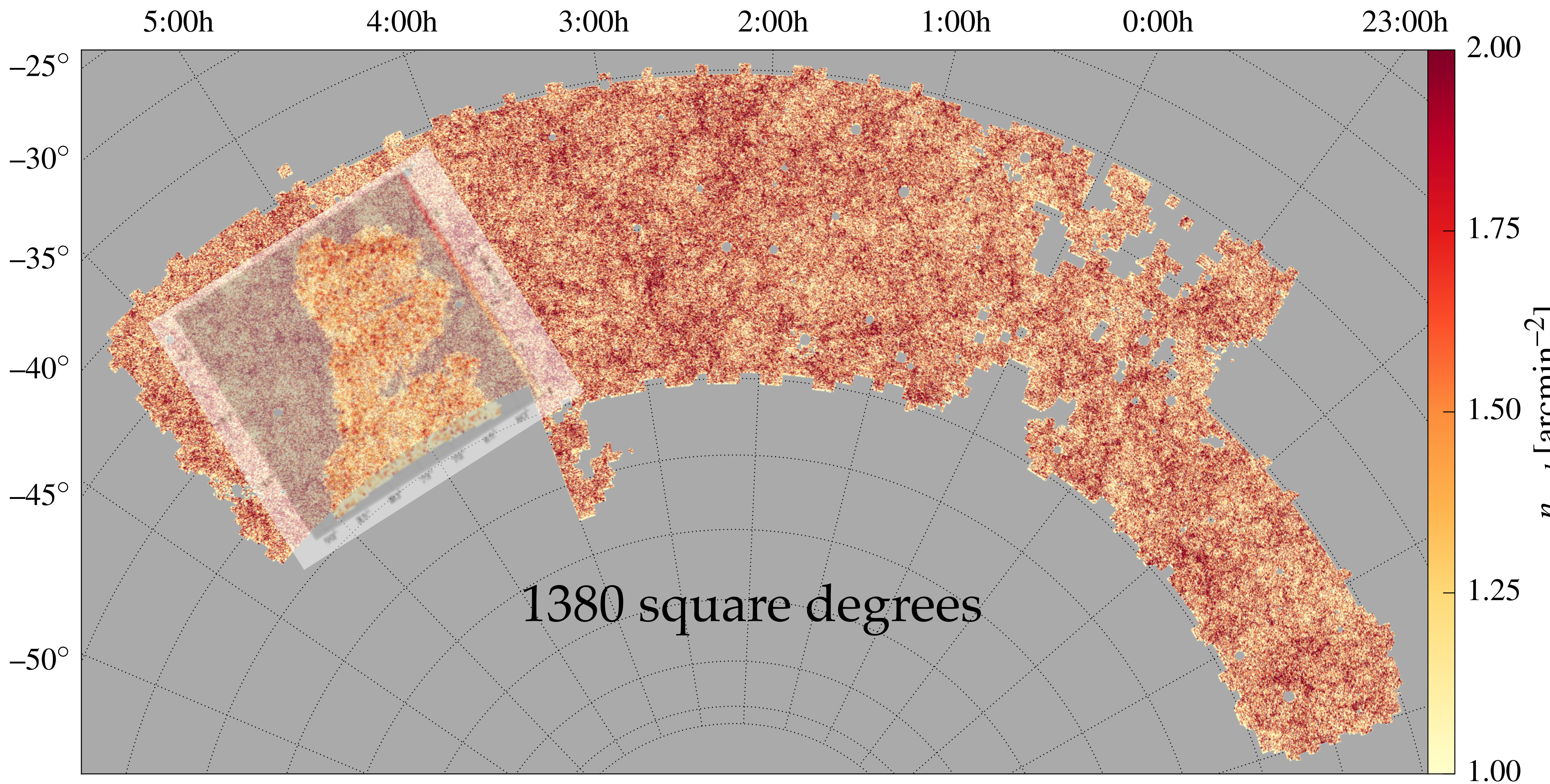
- SV was 3% of final survey area, ~100% of final depth.
- DES Y1 uses ~30% of final area, ~40% of final integration time.
- Primary goal: "multi-probe" cosmology, combining
  - "Cosmic shear" correlations using source galaxy sample
  - X-correlation of "source shapes" with "lens" galaxy positions
  - Auto-correlation of lens sample (galaxy clustering)
- Two shape catalogues: Metacal (main); im3shape (cross-check)
- Redshift distributions: calibrate with COSMOS 30-band z's, cross-correlation method

DES Science Verification Galaxy Distribution



2.3 million galaxies used in LSS (i < 22.5) in 0.2 < z < 1.2

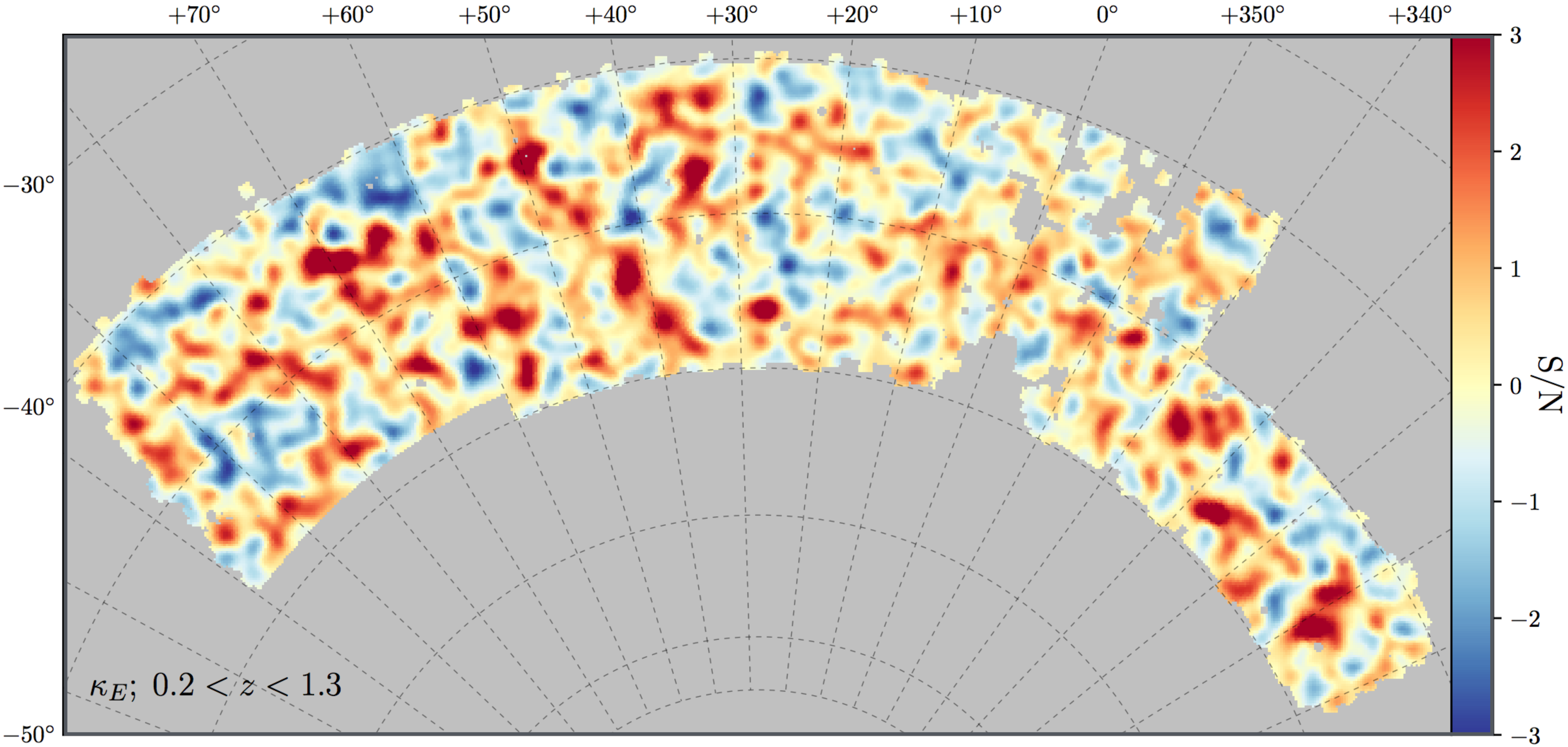
DES Year 1 Foreground Galaxies



650,000 red galaxies with optimal photo-z errors

Chang et al (arxiv 1708.01535)

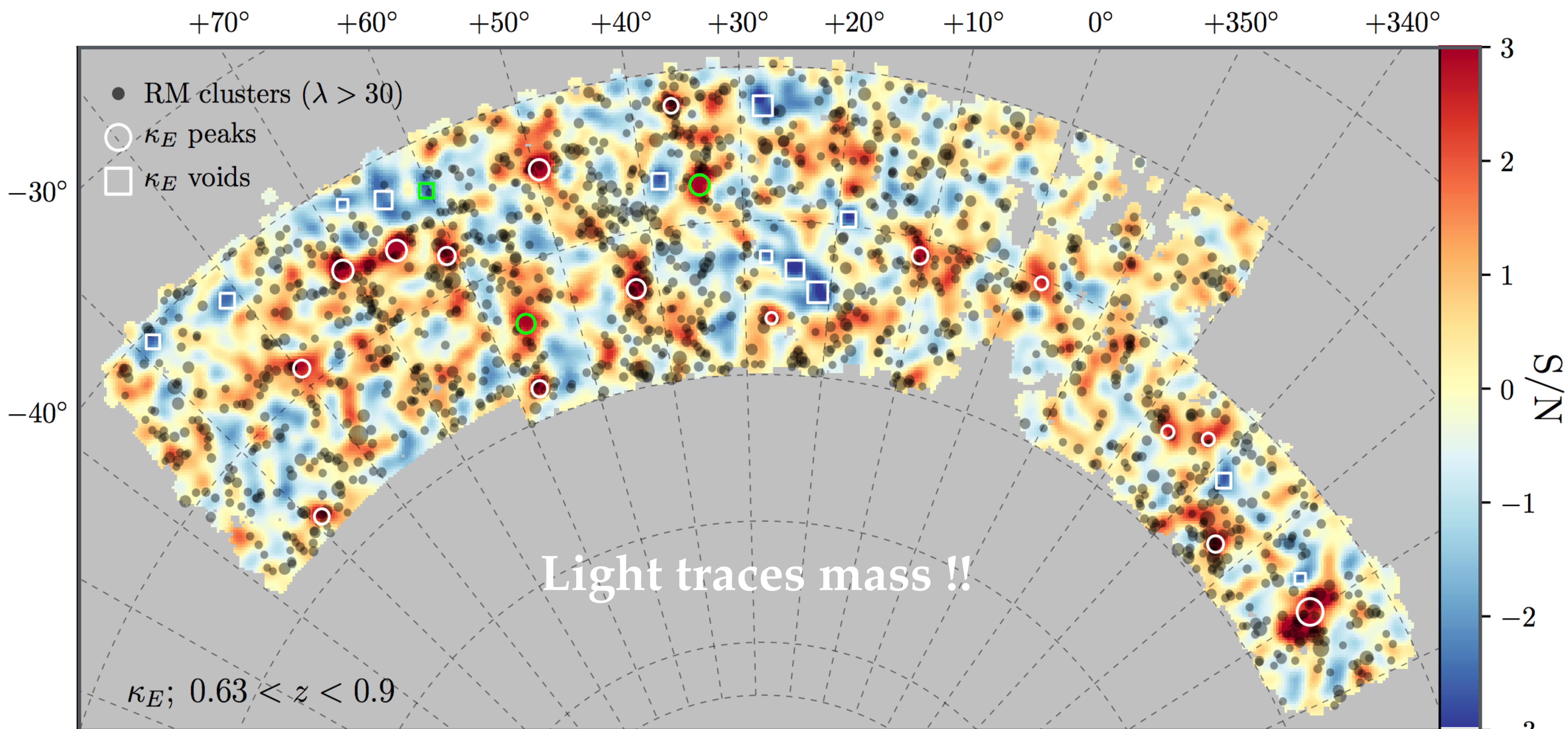
DES Year 1 Projected Dark-Matter



from 23 million galaxy shapes measured over 1300 deg²

Chang et al (arxiv 1708.01535)

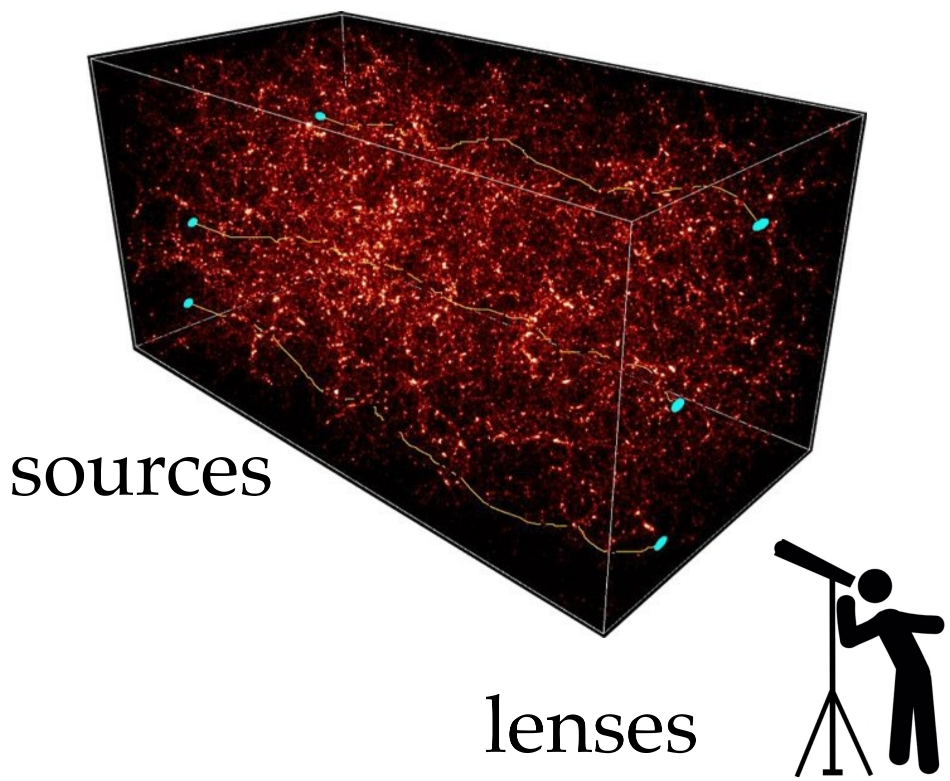
DES Year 1 Projected Dark-Matter

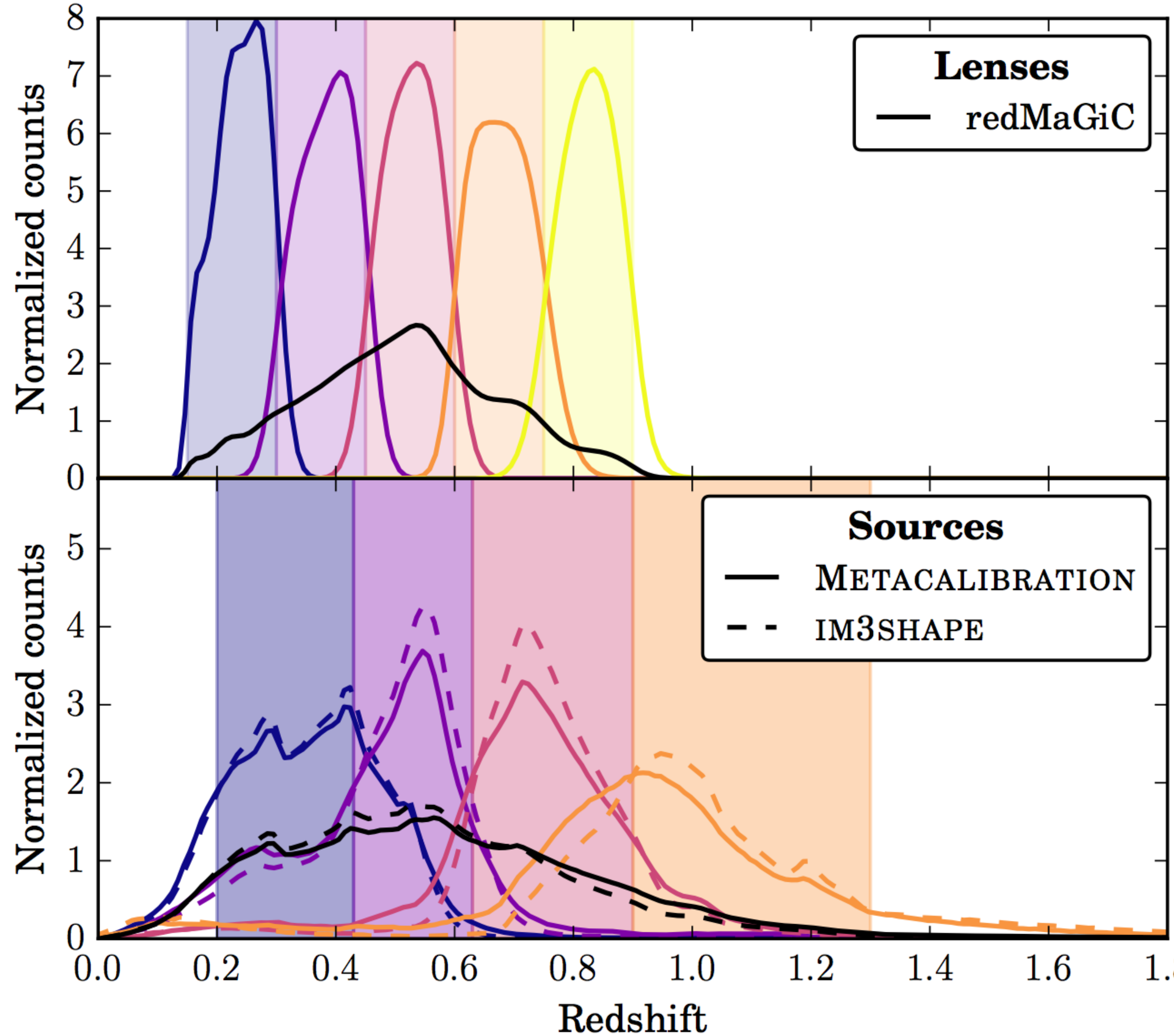


+ Clusters over-imposed

from 23 million galaxy shapes measured over 1300 deg^2

DES Y1 cosmology





Lens sample

- RedMagic 0.6 M. galaxies

Source Sample

- Metacalibration 26 M. shapes
- Im3shape 18 M. shapes

DES Y1 cosmology

LSS $\delta_{gal} \sim b \times \delta_m$

WL $\delta_{gal\,shapes} \sim \delta_m$

$$w_{gal-gal} \sim b^2 \times D^2(z)$$

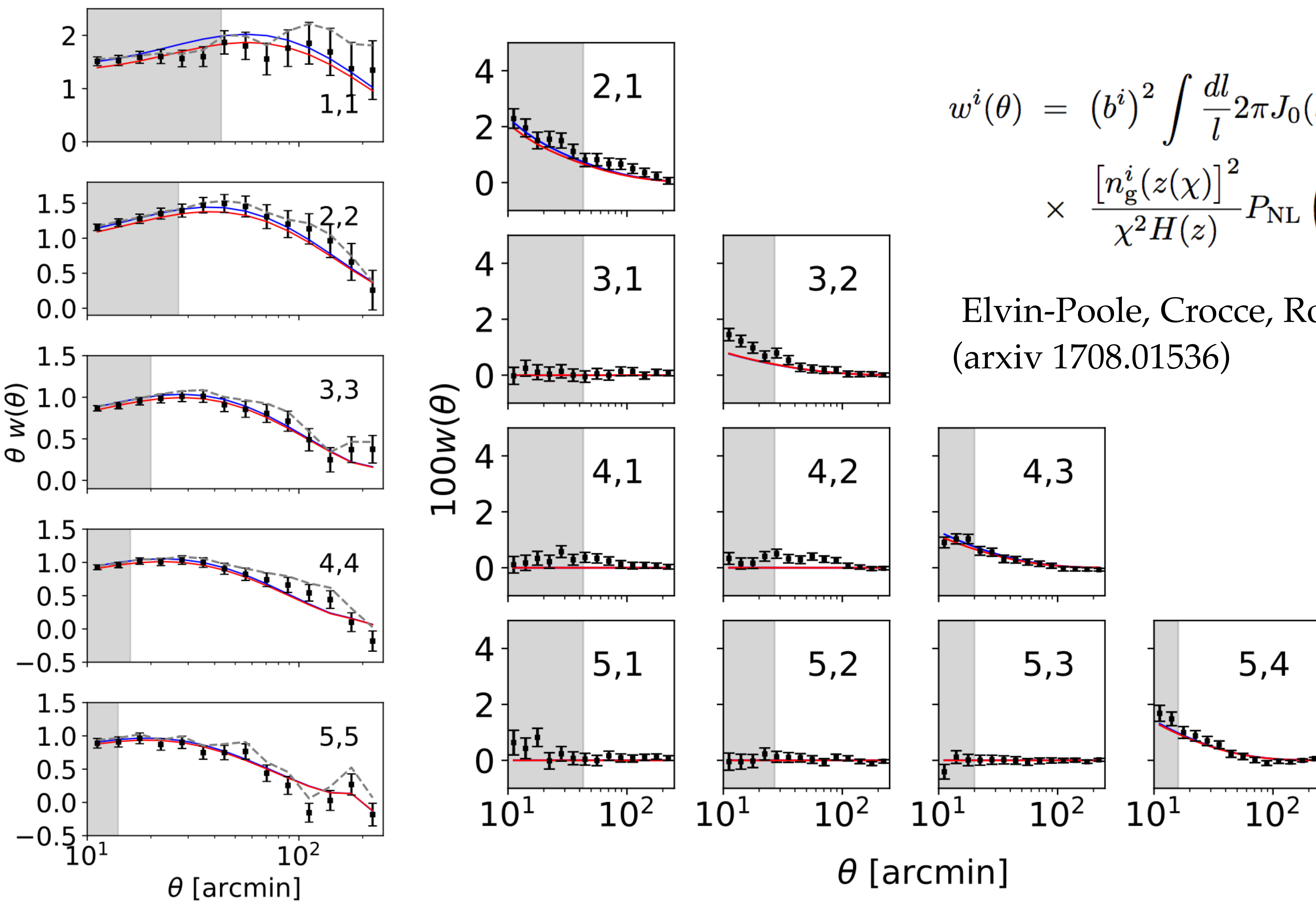
$$w_{gal-shear} \sim b \times D^2(z)$$

$$w_{shear-shear} \sim D^2(z)$$

Measures growth of structure as function of redshift

DES Y1 gal-gal clustering

- **5 lens bins** (0.6 million objects with ~ 1% redshift error),



$$w^i(\theta) = (b^i)^2 \int \frac{dl}{l} 2\pi J_0(l\theta) \int d\chi \times \frac{\left[n_g^i(z(\chi)\right]^2}{\chi^2 H(z)} P_{\rm NL}\left(\frac{l+1/2}{\chi}, z(\chi)\right)$$

Elvin-Poole, Crocce, Ross et al 2017 (arxiv 1708.01536)

DES Y1 shear-shear correlations

$$\xi_+(\theta) = \langle\gamma\gamma^*\rangle(\theta) = \langle\gamma_t\gamma_t\rangle(\theta) + \langle\gamma_\times\gamma_\times\rangle(\theta);$$
$$\xi_-(\theta) = \Re\left[\langle\gamma\gamma\rangle(\theta)e^{-4i\phi}\right] = \langle\gamma_t\gamma_t\rangle(\theta) - \langle\gamma_\times\gamma_\times\rangle(\theta).$$

one measures these correlations by accumulating the relative shear of pairs of galaxies

$$\hat{\xi}^{ij}_{\pm}(\theta) = \frac{1}{2\pi}\int d\ell\ell J_{0/4}(\theta\ell)P^{ij}_{\kappa}(\ell)$$

amplitude and growth rate of structure

$$P^{ij}_{\kappa}(\ell) = \int_0^{\chi_H} d\chi \frac{q^i(\chi)q^j(\chi)}{\chi^2} P_{\rm NL}\left(\frac{\ell+1/2}{\chi}, \chi\right)$$

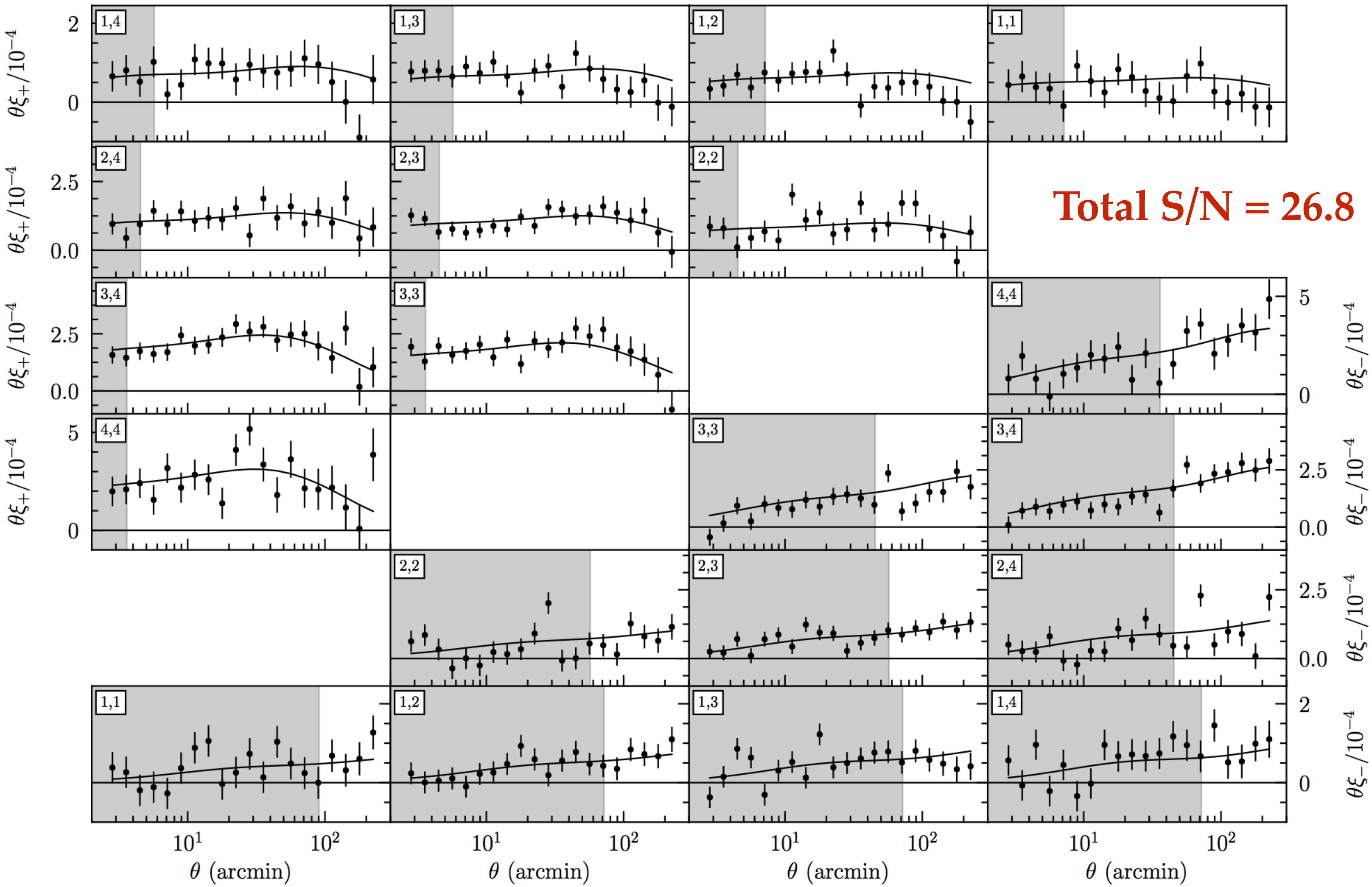
$$q^i(\chi) = \frac{3}{2}\Omega_m\left(\frac{H_0}{c}\right)^2 \frac{\chi}{a(\chi)}\int_{\chi}^{\chi_H} d\chi' n^i(\chi')\frac{dz}{d\chi'}\frac{\chi'-\chi}{\chi'}.$$

Geometry (distances or expansion)

DES Y1 shear-shear correlations

- 10 two-point correlations

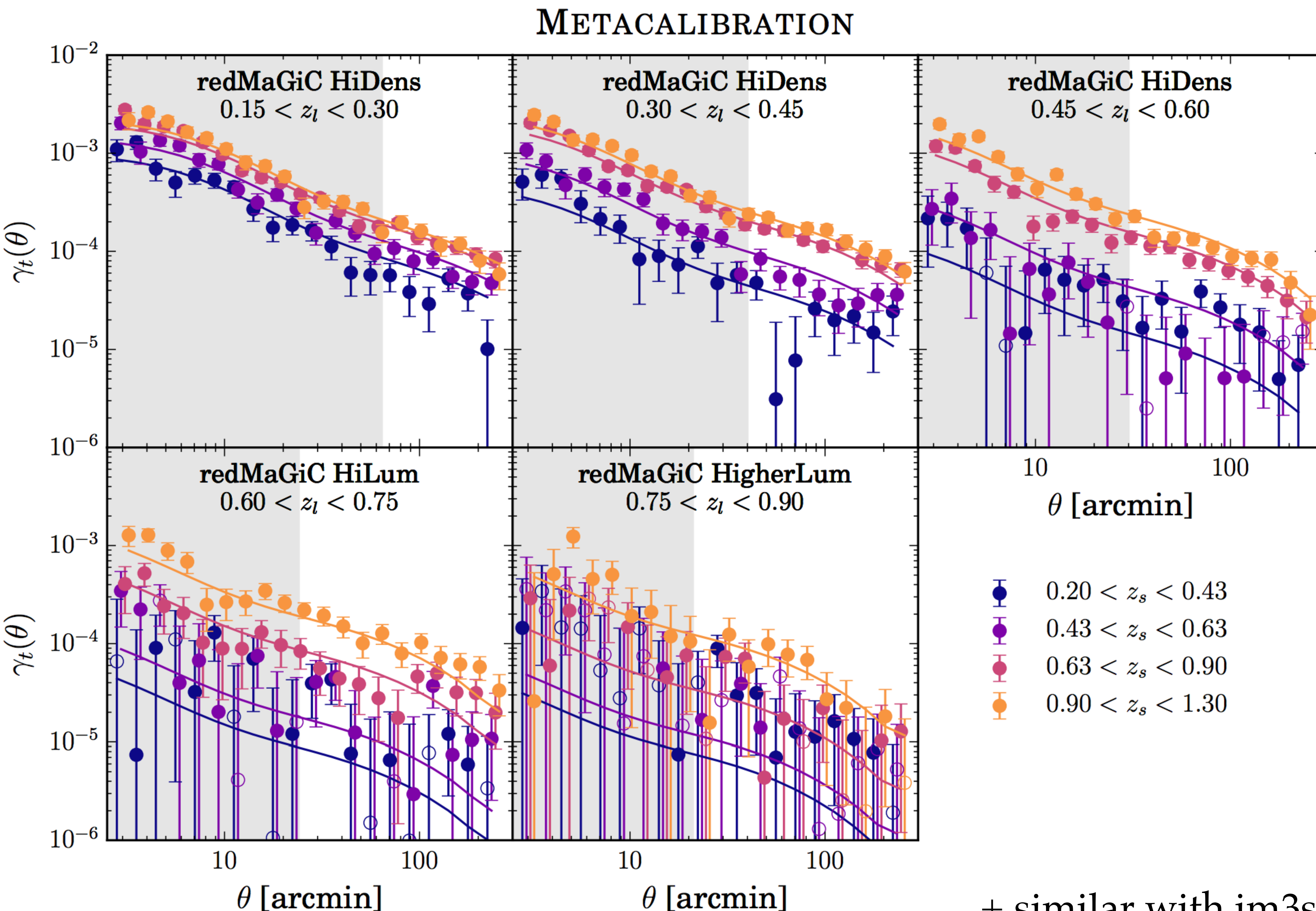
Troxel et al 2017 (arxiv 1708.01538)



DES Y1 gal-gal lensing

- **20 correlations**

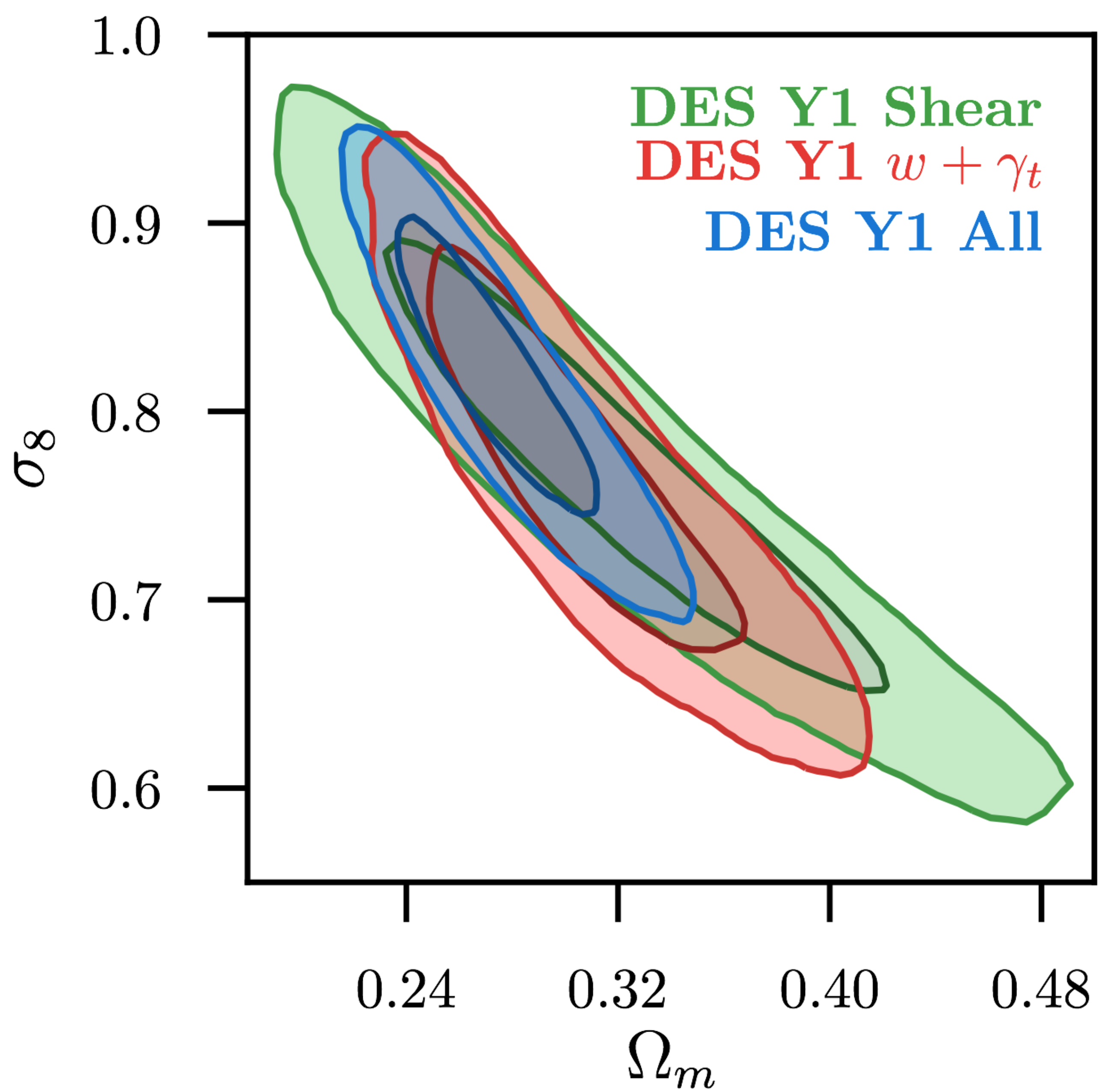
Prat, Shanchez et al 2017 (arxiv 1708.01537)



+ similar with im3shape

DES Collaboration (arxiv 1708.01530)

We gain by combing : 3x2pt



Marginalised

- 4 cosmological parameters
- 10 clustering parameters (nuisance + systematics)
- 10 lensing parameters (nuisance + systematics)

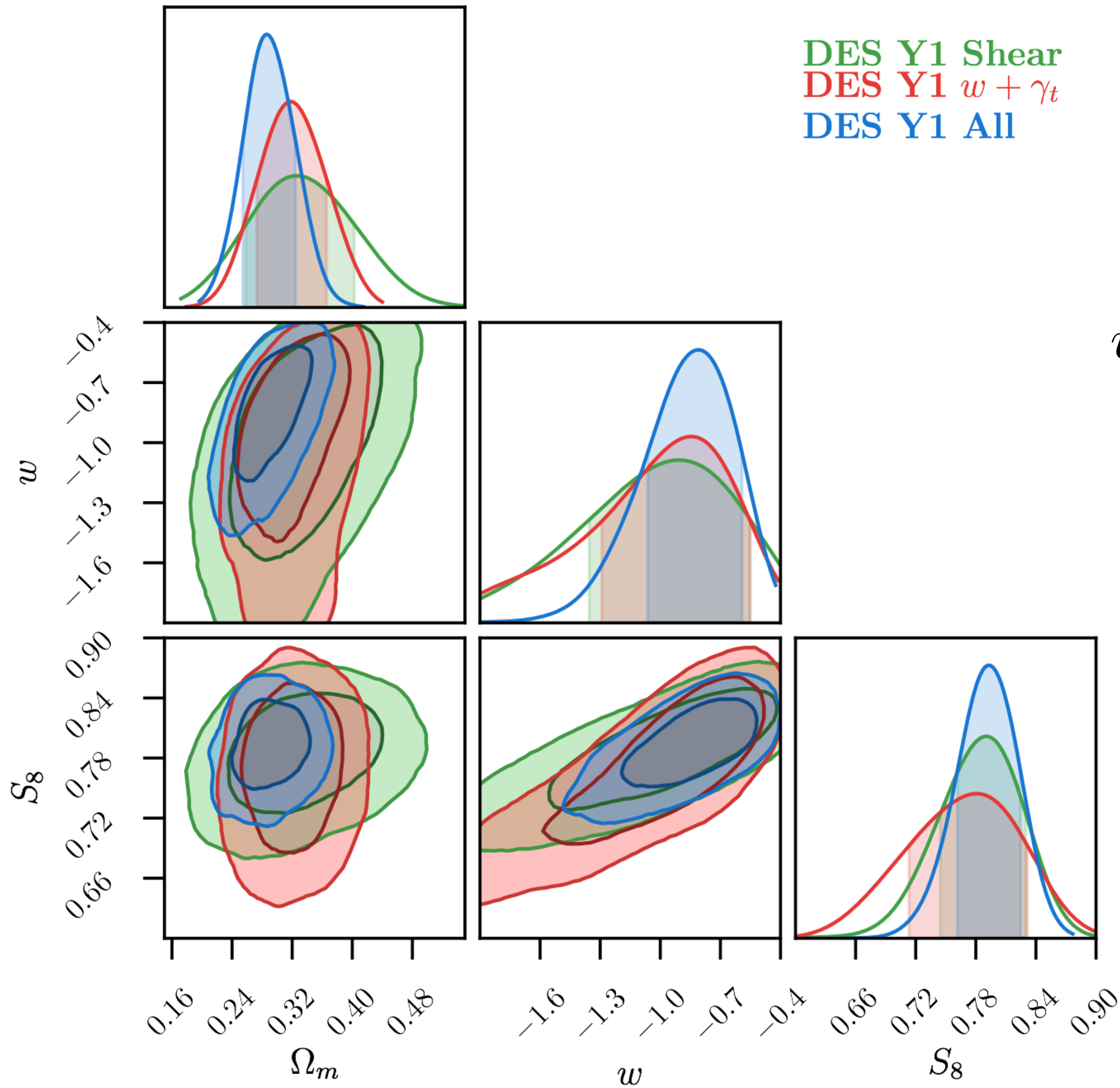
Consistency

- Consistent cosmology constrains from WL and LSS with factors of ~ 2 in gain when combined

DES Collaboration (arxiv 1708.01530)

wCDM

- **DES alone**



$$w = -0.80^{+0.20}_{-0.22} \quad (68\%\ \mathrm{CL})$$

$$R_w = \frac{P(\mathbf{D}|w\mathrm{CDM})}{P(\mathbf{D}|\Lambda\mathrm{CDM})} = 0.36$$

DES Collaboration (arxiv 1708.01530)

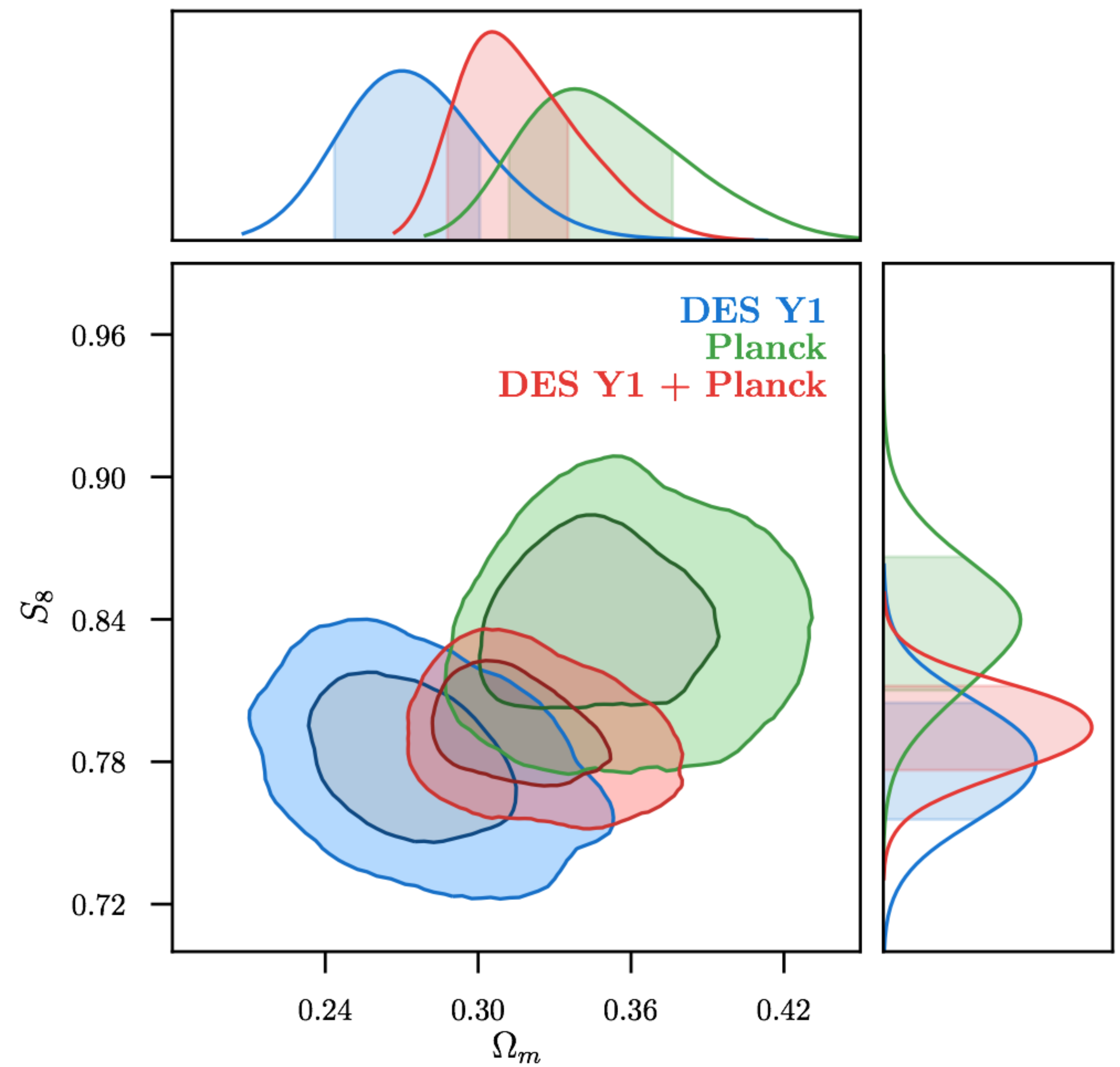
DES and Planck

- **Consistency tests**

- DES and Planck (here **without CMB lensing**) constrain S8 and Ωm with comparable strength
- Bayes factor (evidence ratio):

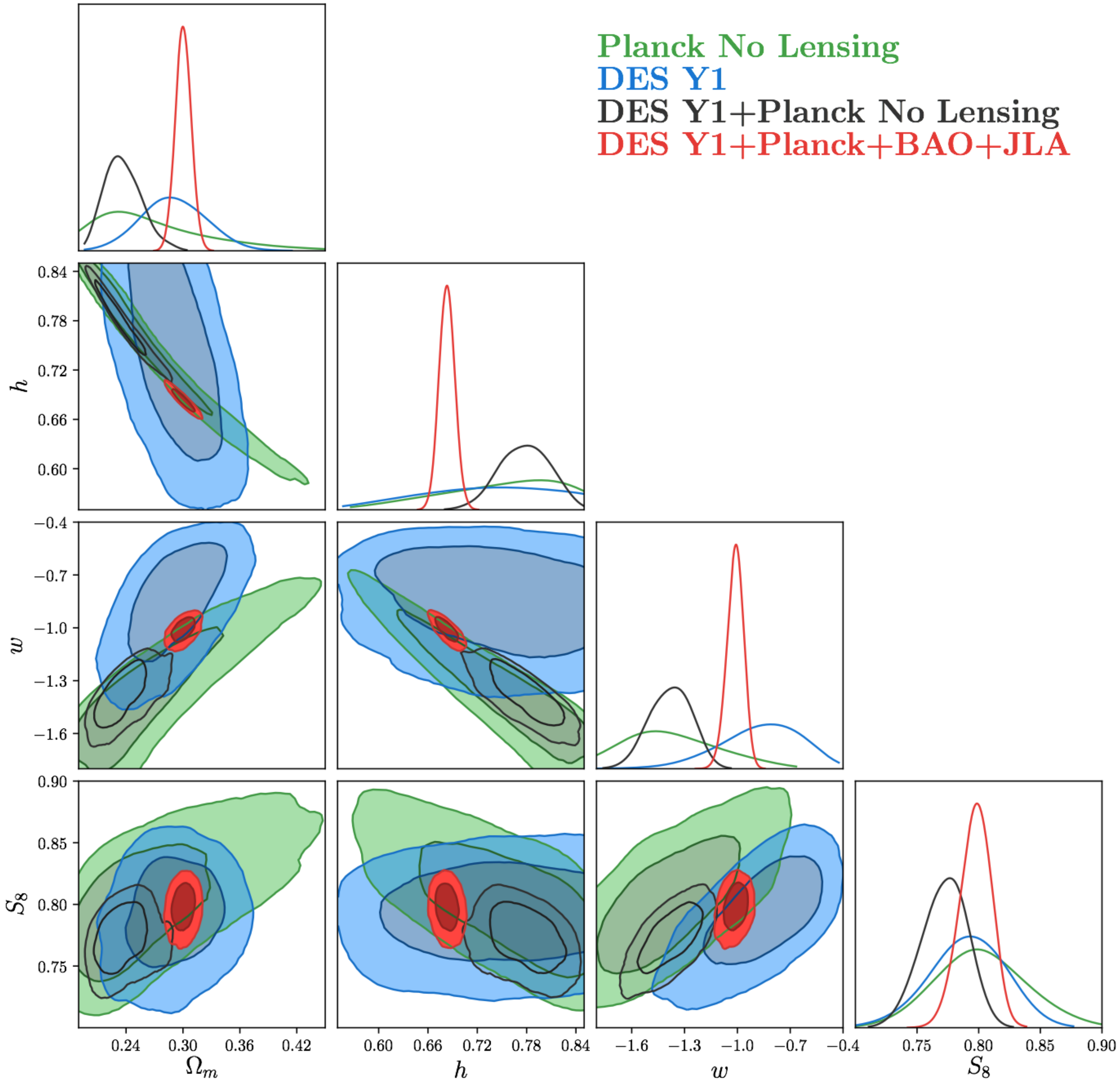
  R = P(DES,Planck | ΛCDM) / [P(DES | ΛCDM)•P(Planck | ΛCDM)]

  =4.2
- "Substantial" evidence for consistency in ΛCDM
- Consistency even stronger comparing Planck to multiple low-z probes: DES+BAO+JLA (SN)



DES Collaboration (arxiv 1708.01530)

DES + external data-sets



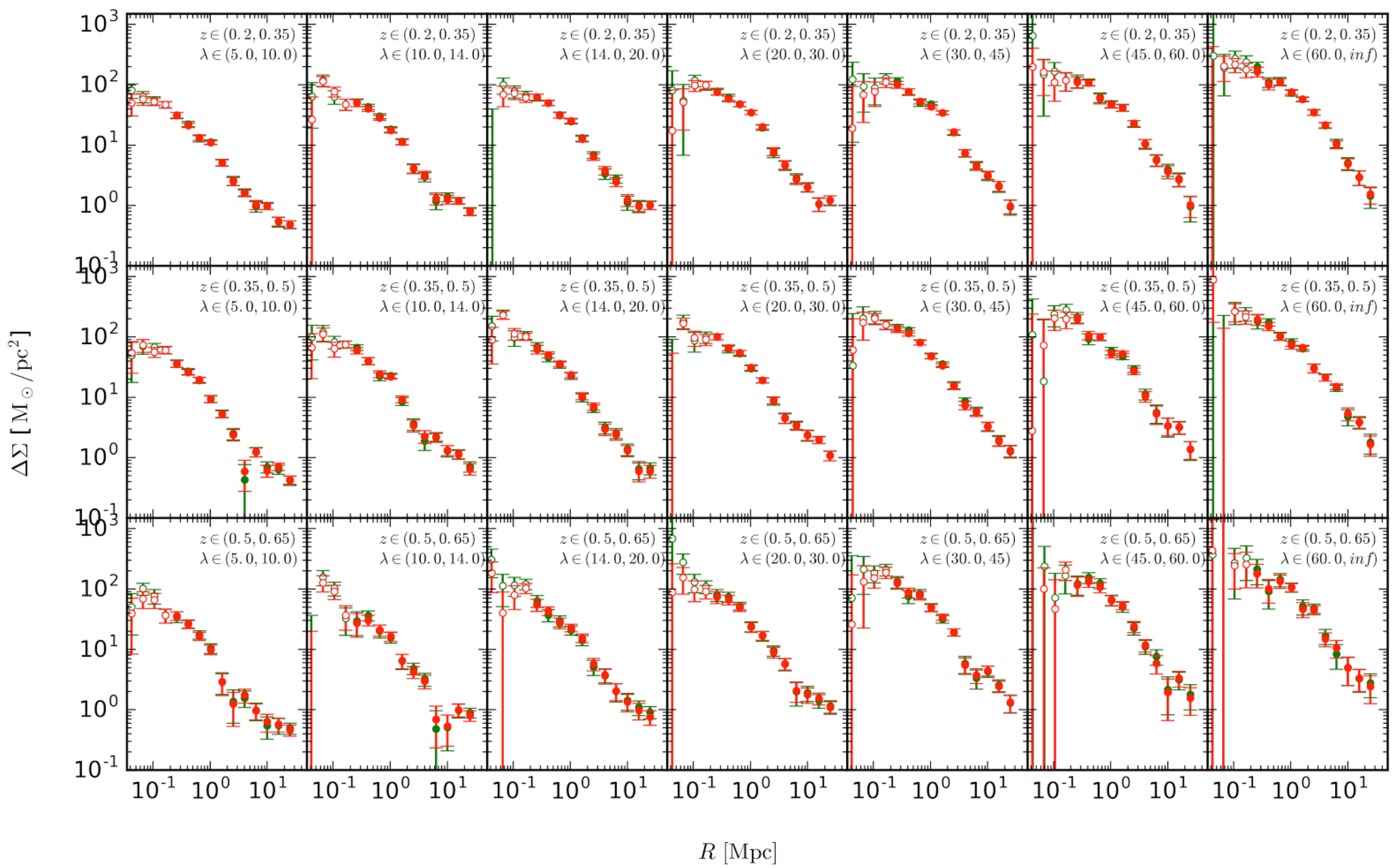
$$w = -1.00^{+0.04}_{-0.05}$$

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

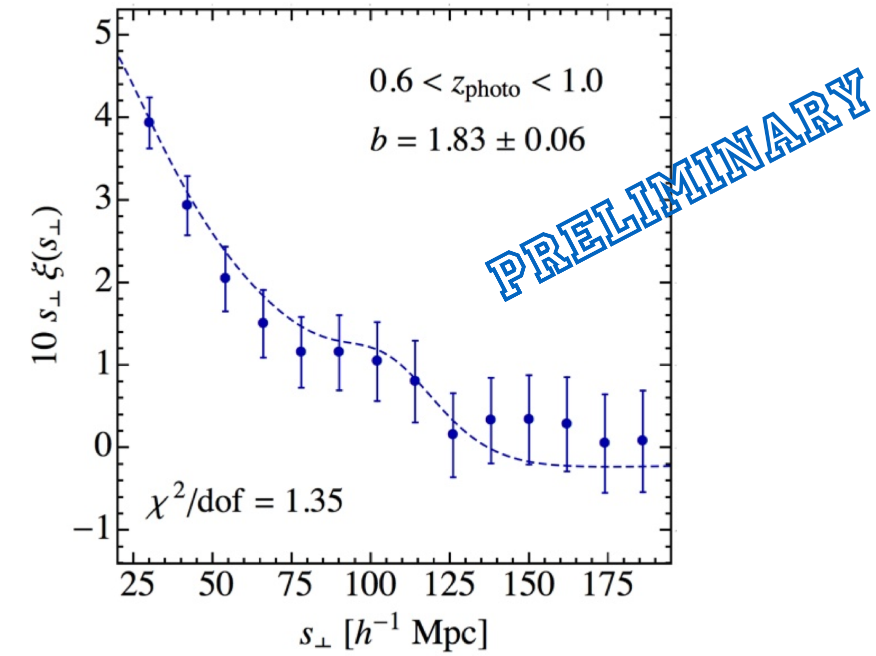
$$\Omega_m = 0.301^{+0.006}_{-0.008}$$

DES other science

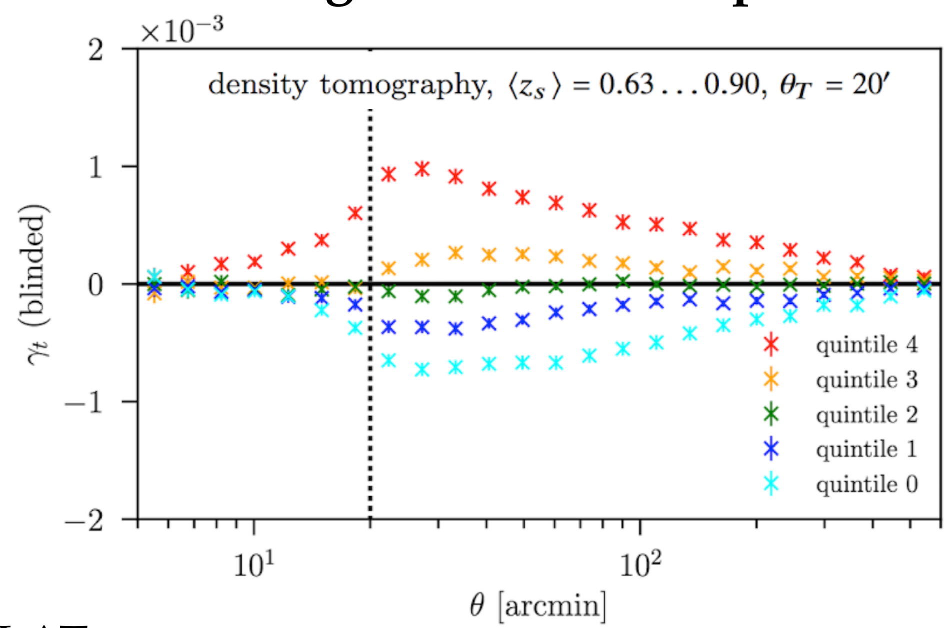
Cluster mass from lensing



Large Scale Galaxy Clustering



Lensing around voids / peaks



(a very incomplete list of discoveries):

- constrained dark matter annihilation from Milky Way dwarfs with Fermi-LAT;
- detected the kinematic Sunyaev-Zel'dovich effect in concert with SPT;
- discovered and confirmed new lensed galaxies and QSOs plus a number of very high-redshift QSOs; discovered the 2nd most distant dwarf planet in the solar system;
- discovered the highest-redshift, spectroscopically confirmed supernova and has now accrued over 1000 photometrically classified type Ia supernovae with host-galaxy redshifts;

DES Science: new dwarf MW satellites

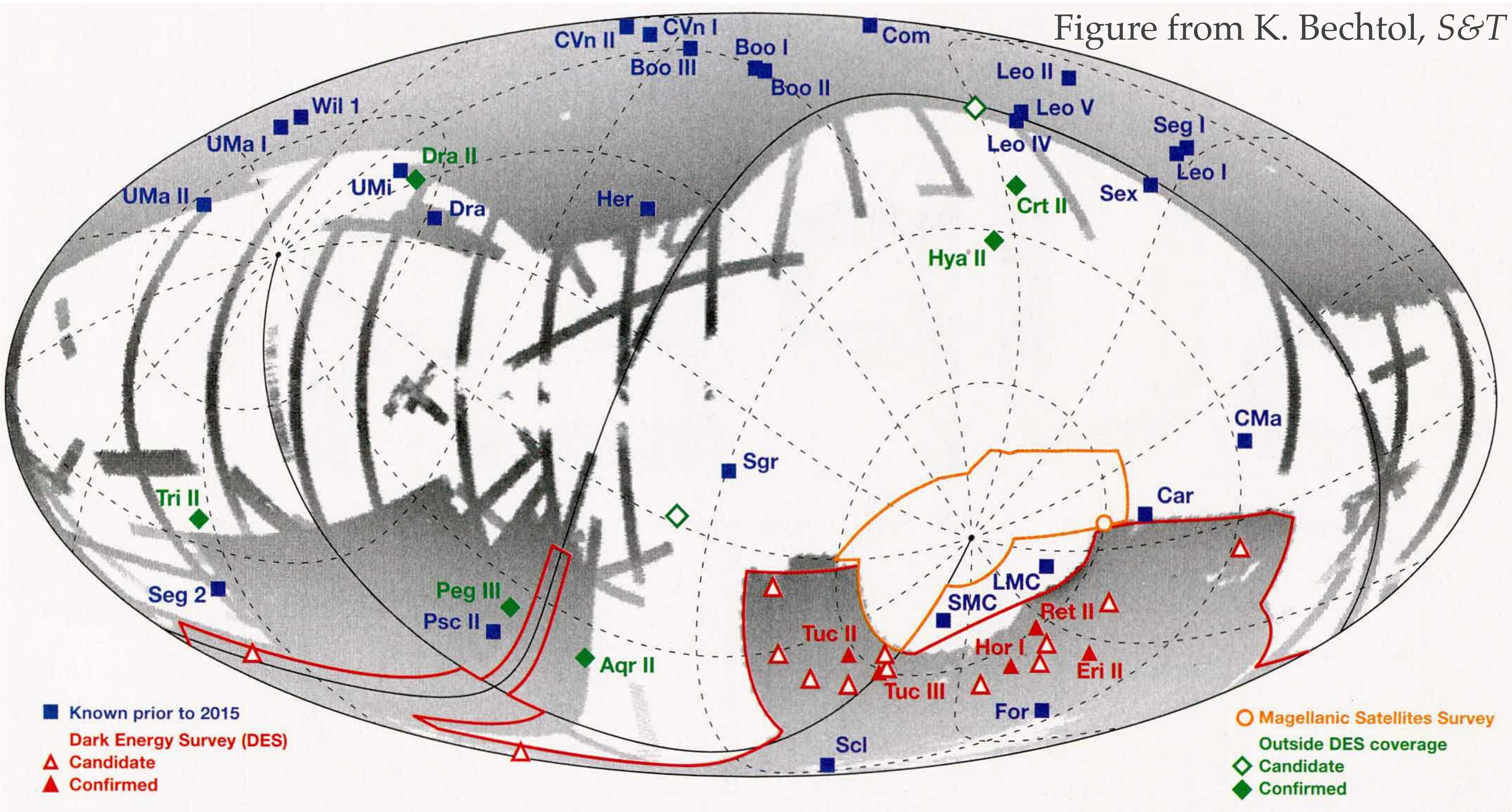
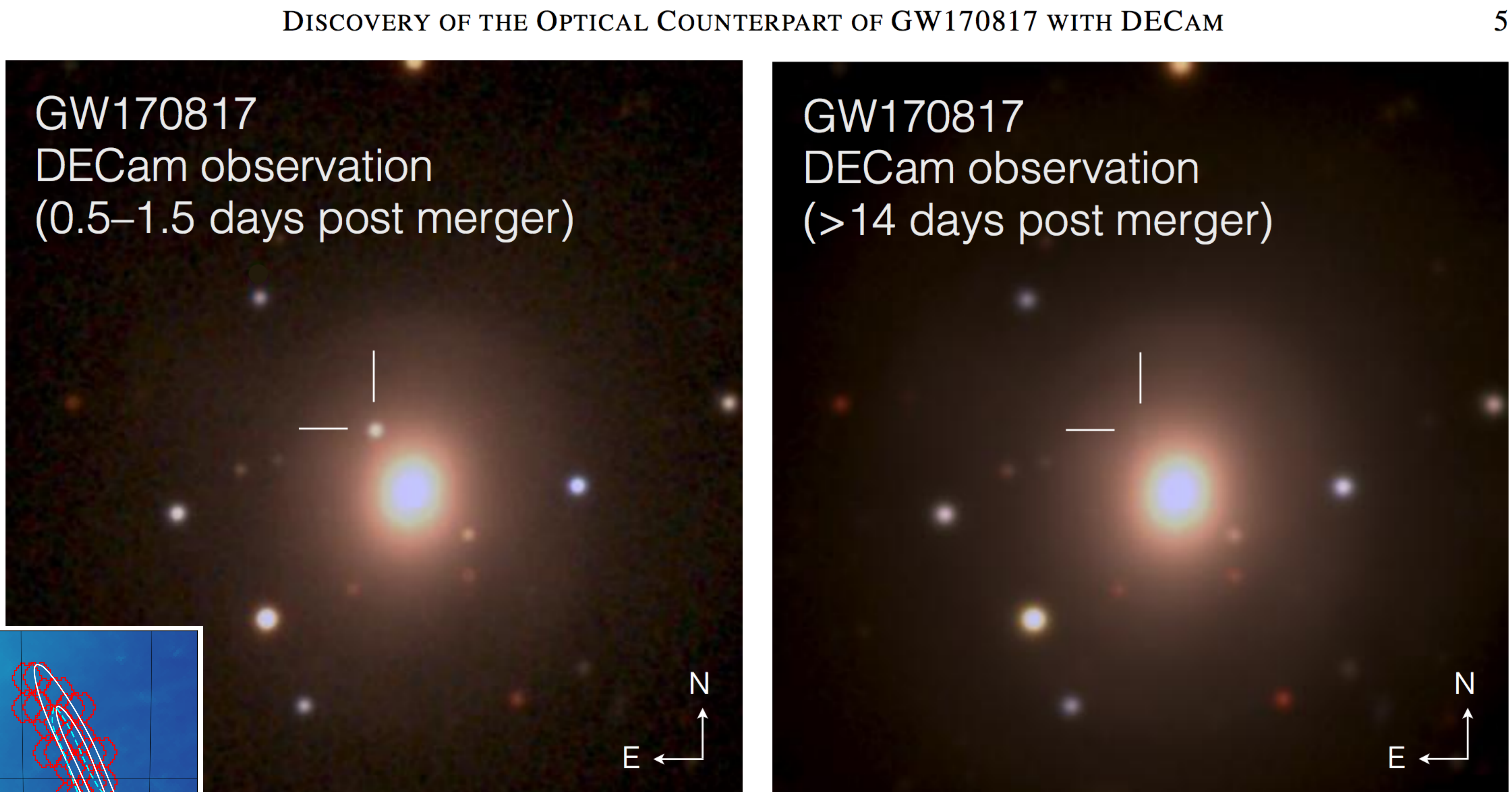
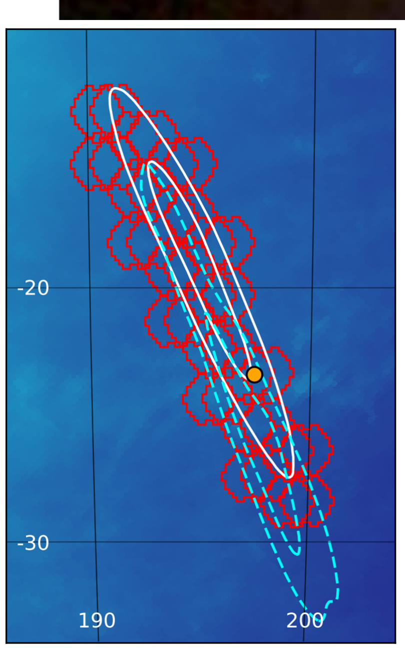


Figure from K. Bechtol, *S&T*

Discoveries by Bechtol *et al*, ApJ 807, 50, (2015),
and external group Koposov *et al.* (arXiv:1503.02079)

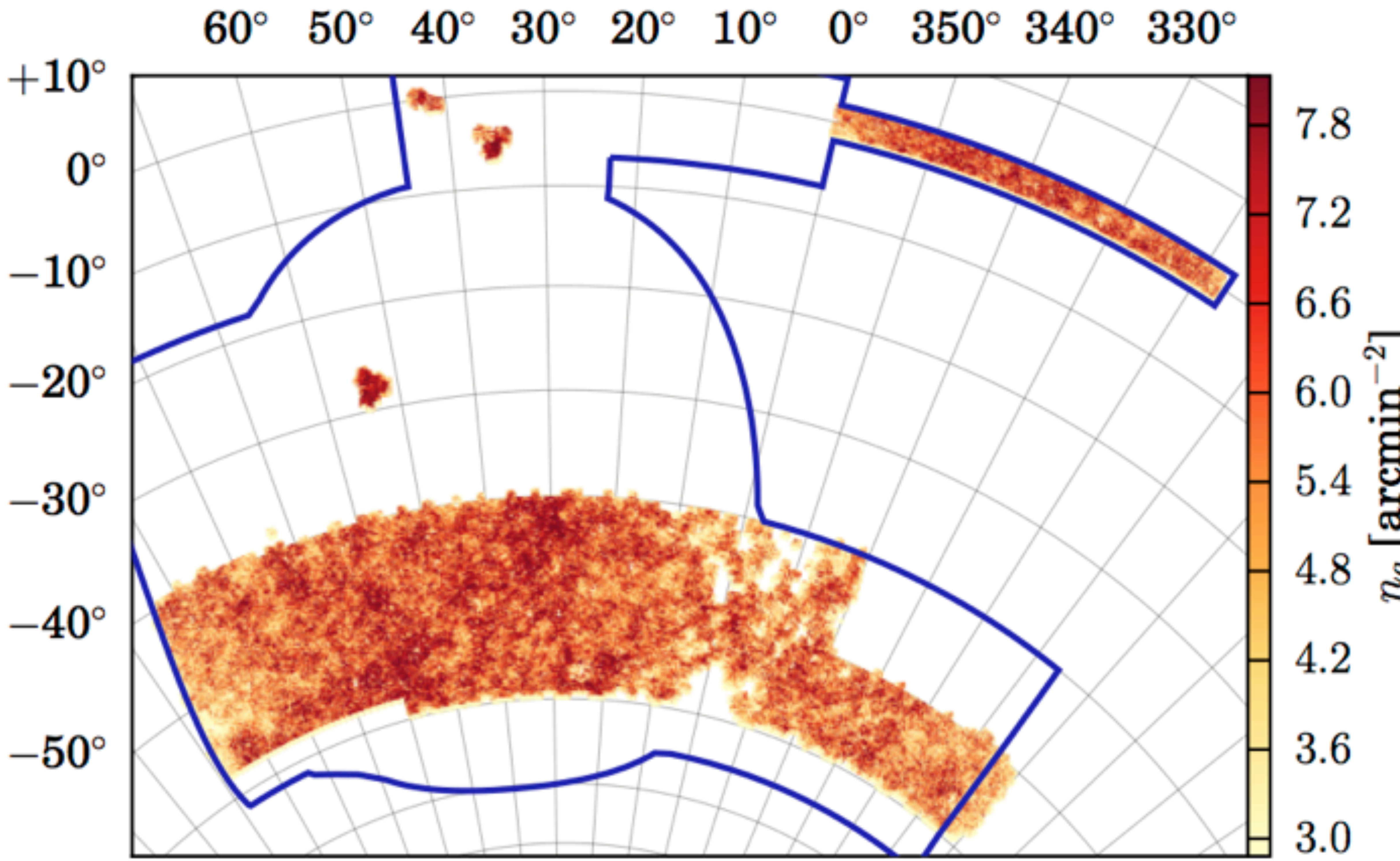
Optical Counter Parts of Neutron Star merger





M. Soares-Santos et al arxiv 1710.05459

DES Year 3 footprint - ~ 5000 deg^2



Conclusions

- DES : Huge potential from combining probes and correlating with external data
- DES Y1 uses 30% of final area, ~ 40% integration time
- DES Y1 Cosmology results from galaxy clustering, galaxy-galaxy lensing, and cosmic shear (3x2) unblind and submitted
- In ΛCDM, galaxy surveys now rival precision of Planck CMB results for certain parameters: low- vs. high-z Universe.

Movie by Elizabeth Krause

Conclusions

- DES Y1 results consistent with Planck CMB in context of ΛCDM.
- DES Y1 results in combination with Planck, BAO, JLA SN provide stringent constraints on ΛCDM parameters
- Precision will increase with larger data sets (Y1/Y3/Y5) and by bringing in more probes (clusters, SN, cross-correlations…), enabling tests of more complex models (w0waCDM, mod GR…)

Movie by Elizabeth Krause

Thanks.