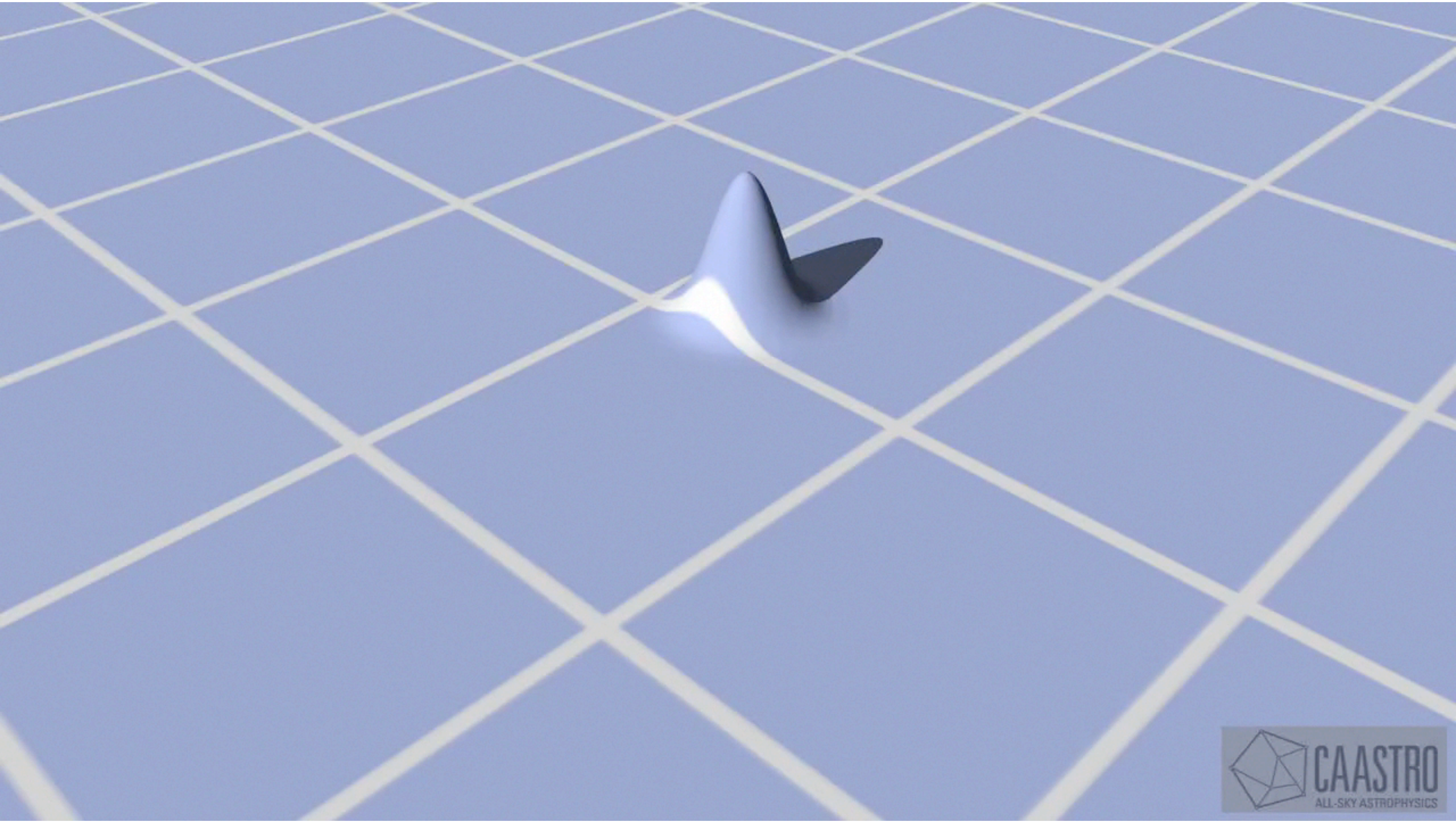
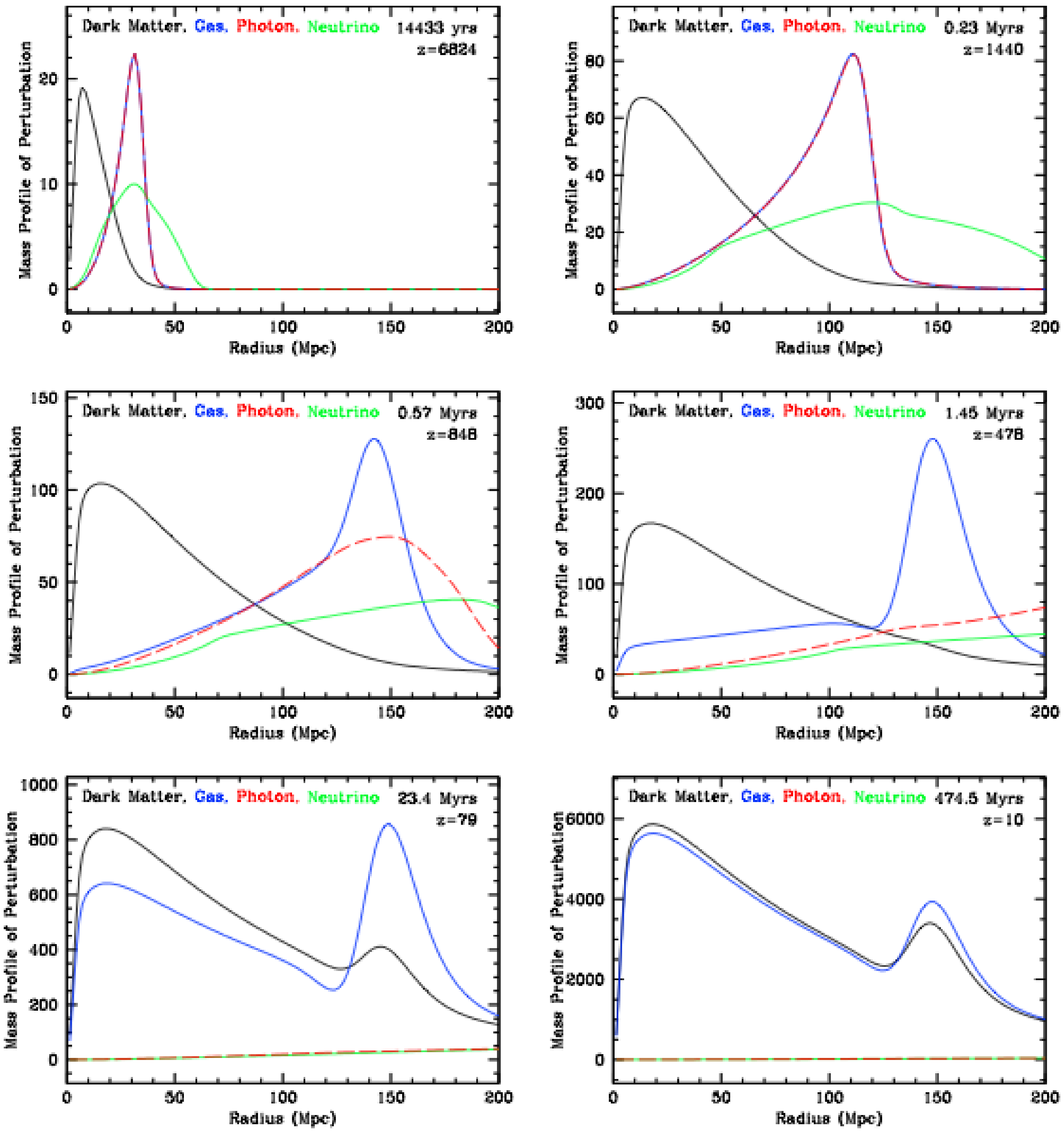
Baryon Acoustic Oscillations



Baryon Acoustic Oscillations



- The acoustic scale is sets by the sound horizon at last scattering

$$s = \int_0^{t_{\rm rec}} c_s\,(1+z)dt = \int_{z_{\rm rec}}^{\infty} \frac{c_s\,dz}{H(z)}$$

$$c_s = [3(1 + 3\rho_b/4\rho_\gamma)]^{-1/2}$$

- The sound horizon is extremely well determined by the structure of the acoustic peaks in the CMB

$$\begin{aligned} s &= 147 \pm 2\ \mathrm{Mpc} \\ &= (4.54 \pm 0.06) \times 10^{24}\mathrm{m} \end{aligned}$$

WMAP 1st year data

Why study baryon oscillations ?

- Measuring the acoustic scale as a function of redshift probes the volume of the universe
- Geometrical probes are clean because the expansion history depends directly on the gravitational theory
- Minimal systematics due to calibration issues suffered by other cosmological probes

Correlations along and across the line of sight give measurements of H and d_A.

Measures $H(z)$

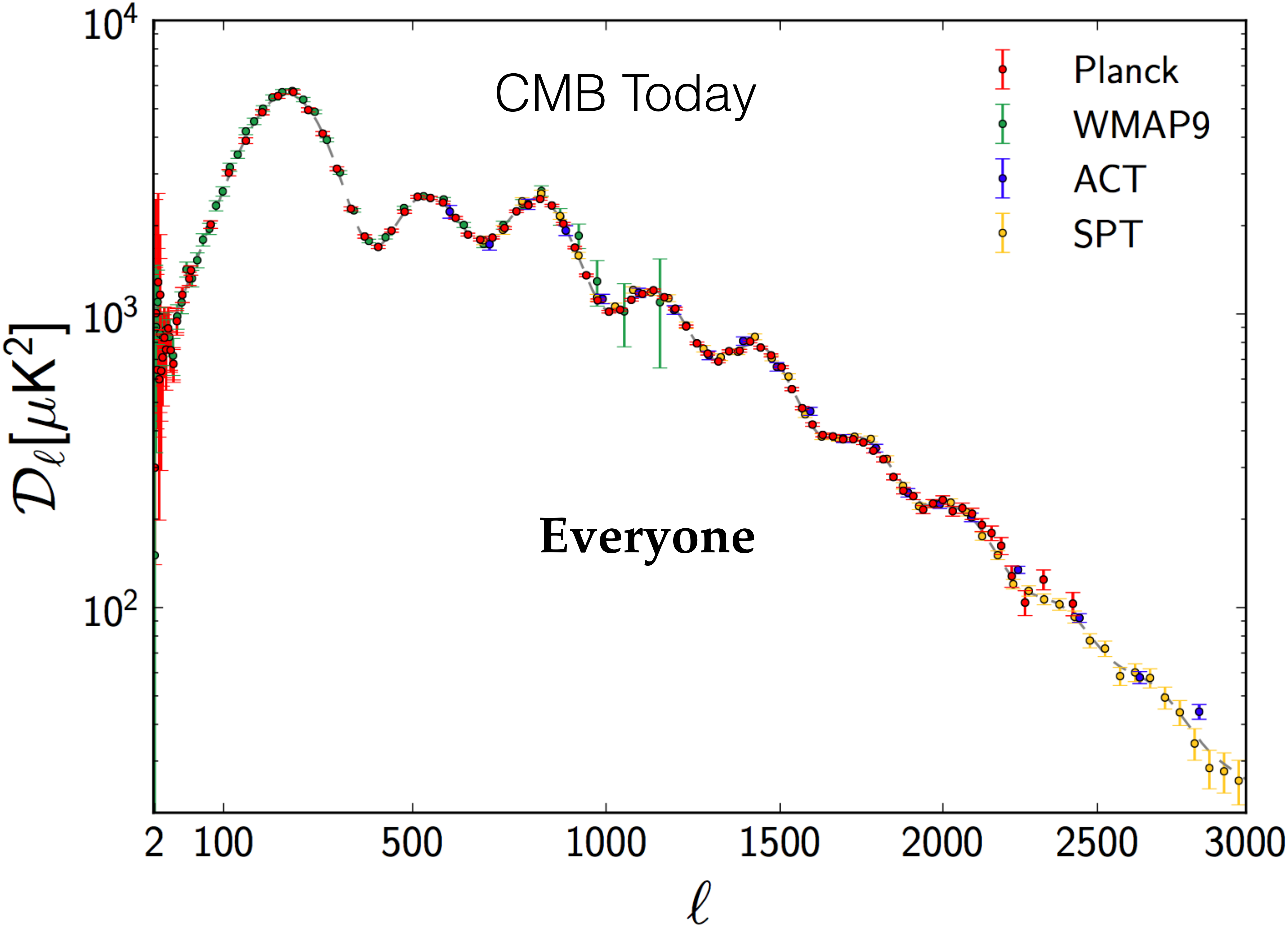
Measures d_A

Provides an internal cross check

$$d_A(z) \propto \int_0^z \frac{dz'}{H(z')}$$

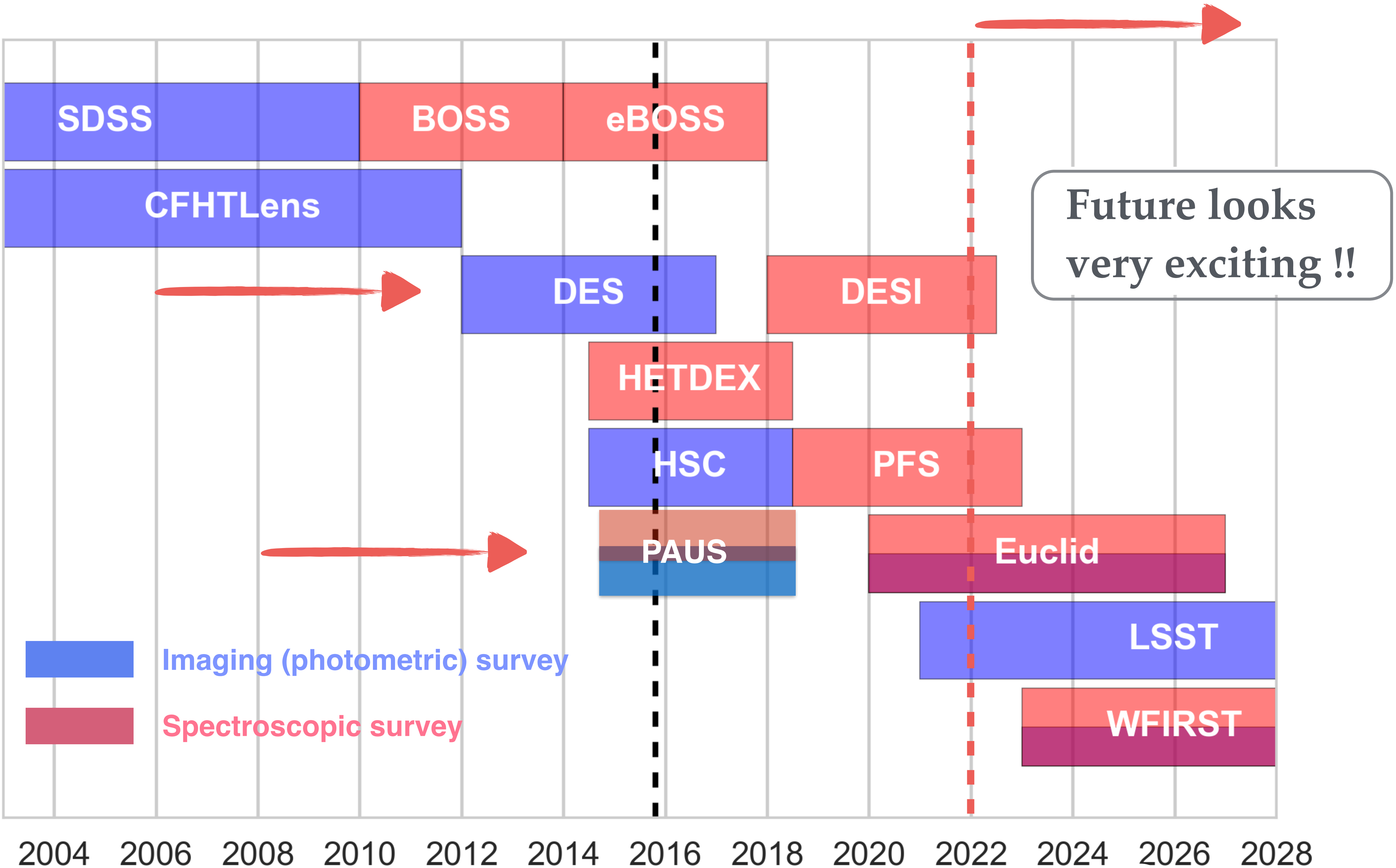
Recap from two weeks

- **General concepts** : metric, horizon, distances, SNIa results pointing towards accelerating Universe !
- **Evolution of dark-matter** fluctuations on large scales (linear theory) from Inflation to Mat / Rad and until today
- **Non-linear evolution,** generation of a log-normal like density field with skewness and kurtosis, agrees with second-order perturbation theory
- **Nonlinear Spherical Collapse**, formation of bound dark matter structure (called dark matter halos!)
- **Halo abundance and mass function** —-> relation to Clusters and problem of mass/observable relation
- **Clustering of tracers**, galaxy bias and halo bias. How galaxies populate dark matter halos (Halo Occupation Distribution).
- **Clustering in redshift space** —-> measuring growth from anisotropic clustering
- **Weak Gravitational Lensing** —> Measuring dark-matter spectrum directly
- **Baryon Acoustic Oscillations** in galaxies —> Another distance measurement



Can fit to nine peaks with only 6 parameters

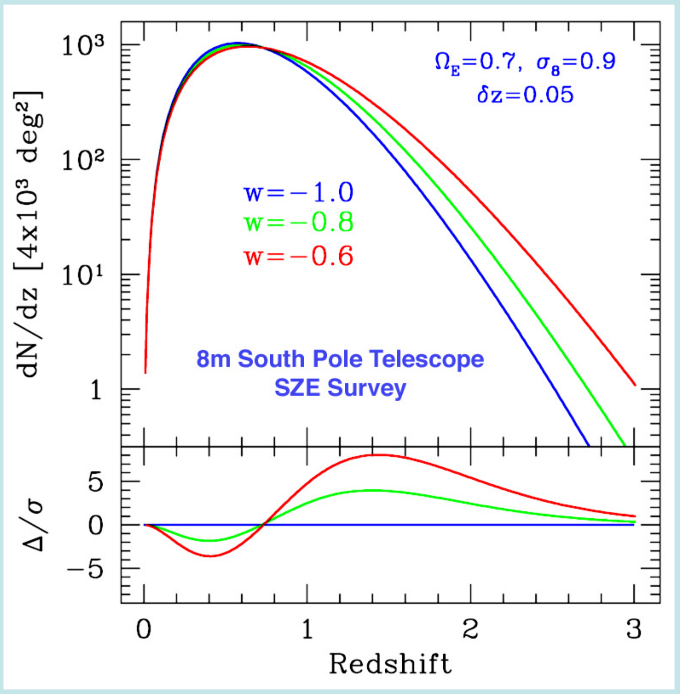
Survey of Cosmological Surveys



+ CMB polarization experiments, radio surveys, SKA (21 cm), ..

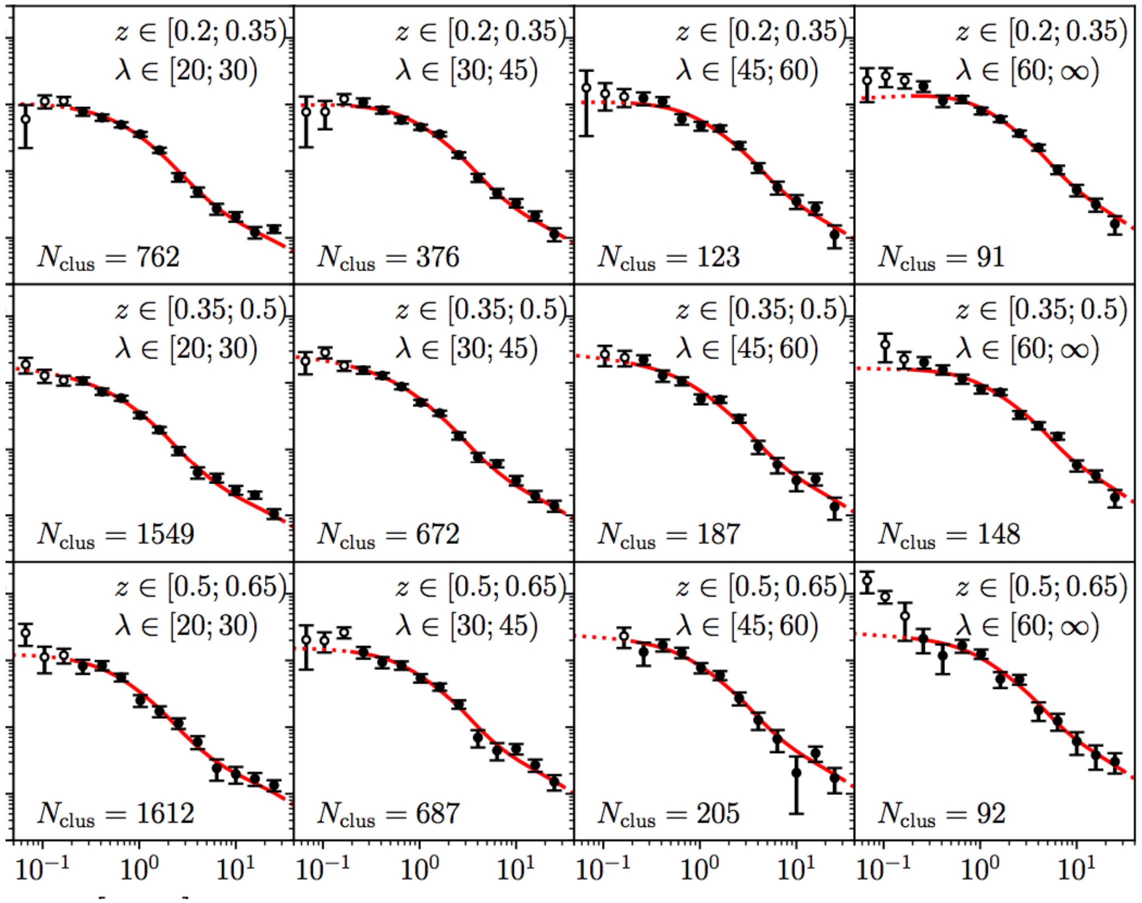
Cluster cosmology in DES-Y1

Cluster abundance sensitive to dark energy.
Challenge is knowing mass-richness relation



Cluster counts probe structure growth & expansion history:

1. masses calibrated with weak lensing
2. systematics include mis-centering, constrained by X-ray data
3. as the statistical errors get smaller, more careful treatment of systematics becomes essential
4. priors on scatter richness at fix mass ?



Cluster cosmology in DES-Y1

Recall that initially overdense regions overcome expansion to collapse to form structures

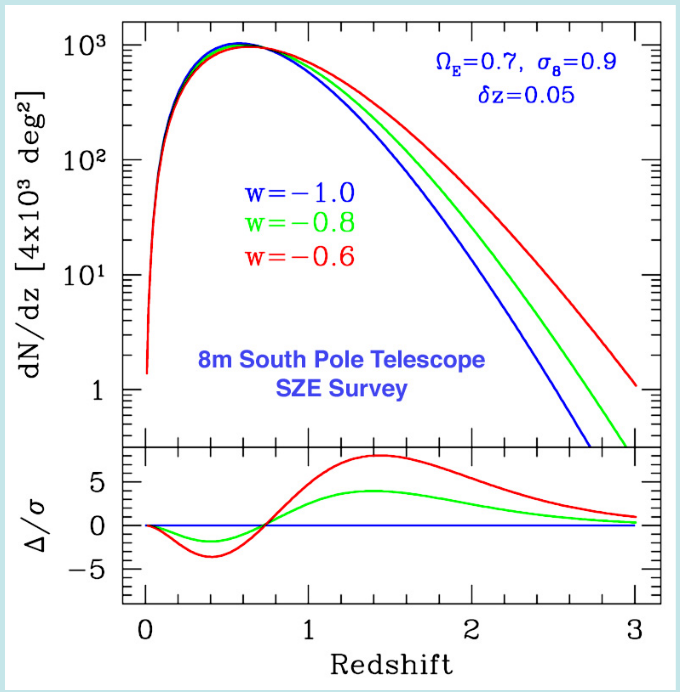
Structure in Universe depends on

- ★ expansion history: E(z)
- ★ initial density distribution: σ_8

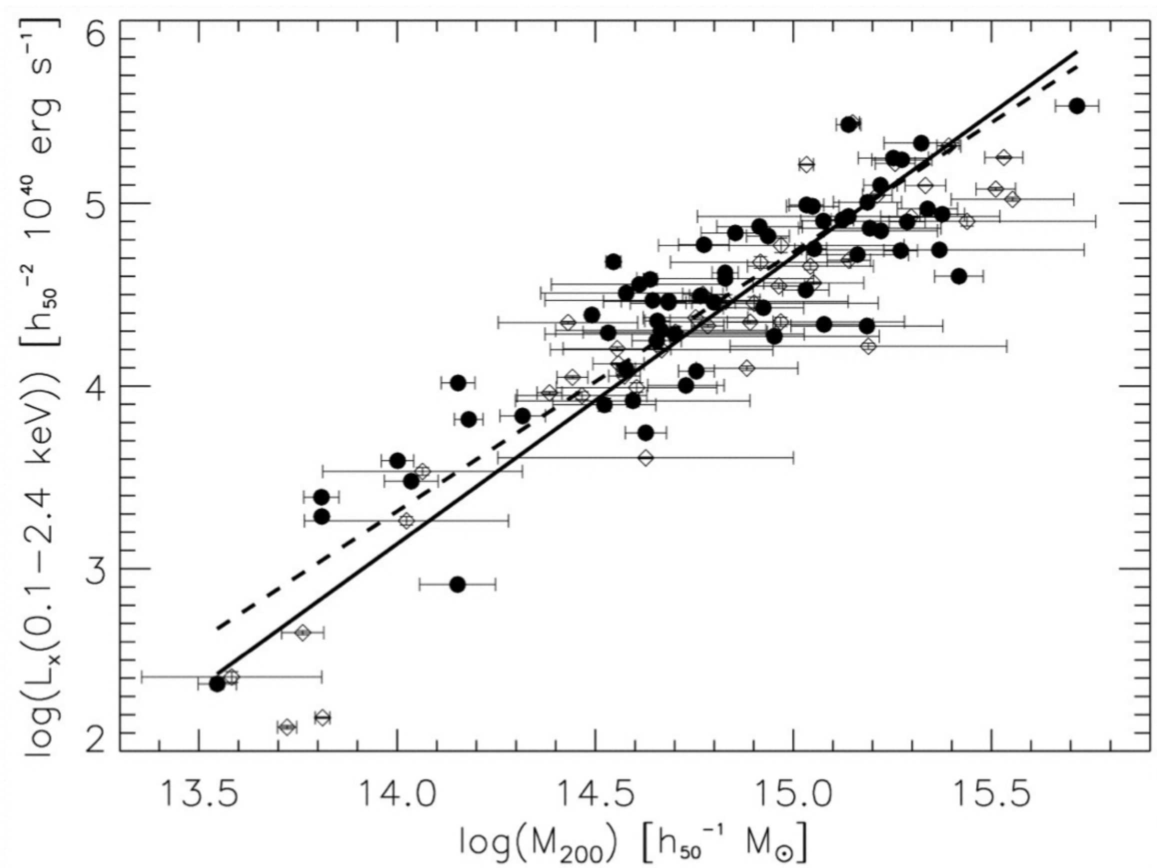
Number density of clusters sensitive to growth of structure

- ★ also sensitive to volume sampled
- ★ additional E(z) constraints

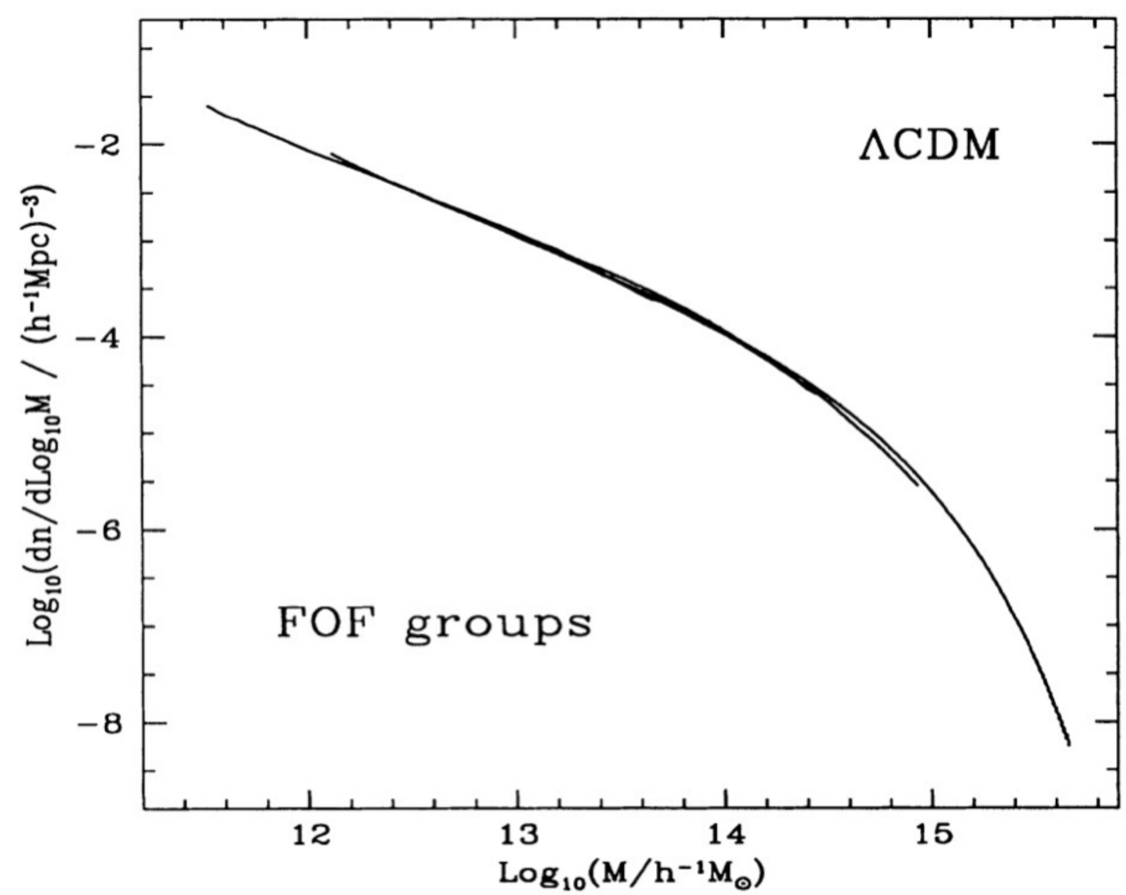
$$dV_\chi(z) = \frac{c}{a_0 H_0} \frac{(1+z)^2 d_A^2}{E(z)} d\Omega dz$$



Cluster cosmology in DES-Y1

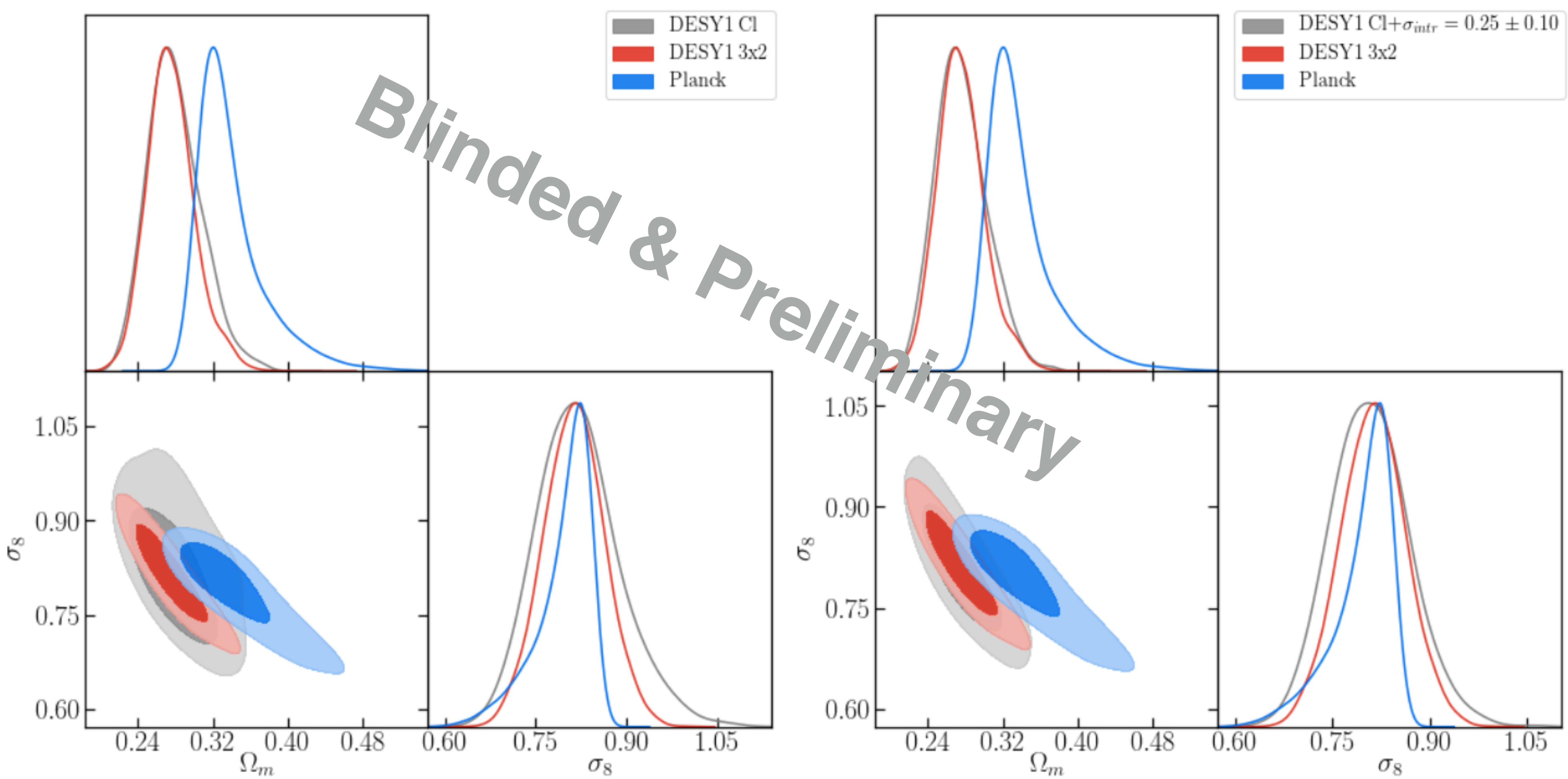


Mass observable relation



Cluster cosmology in DES-Y1

DES redmapper clusters

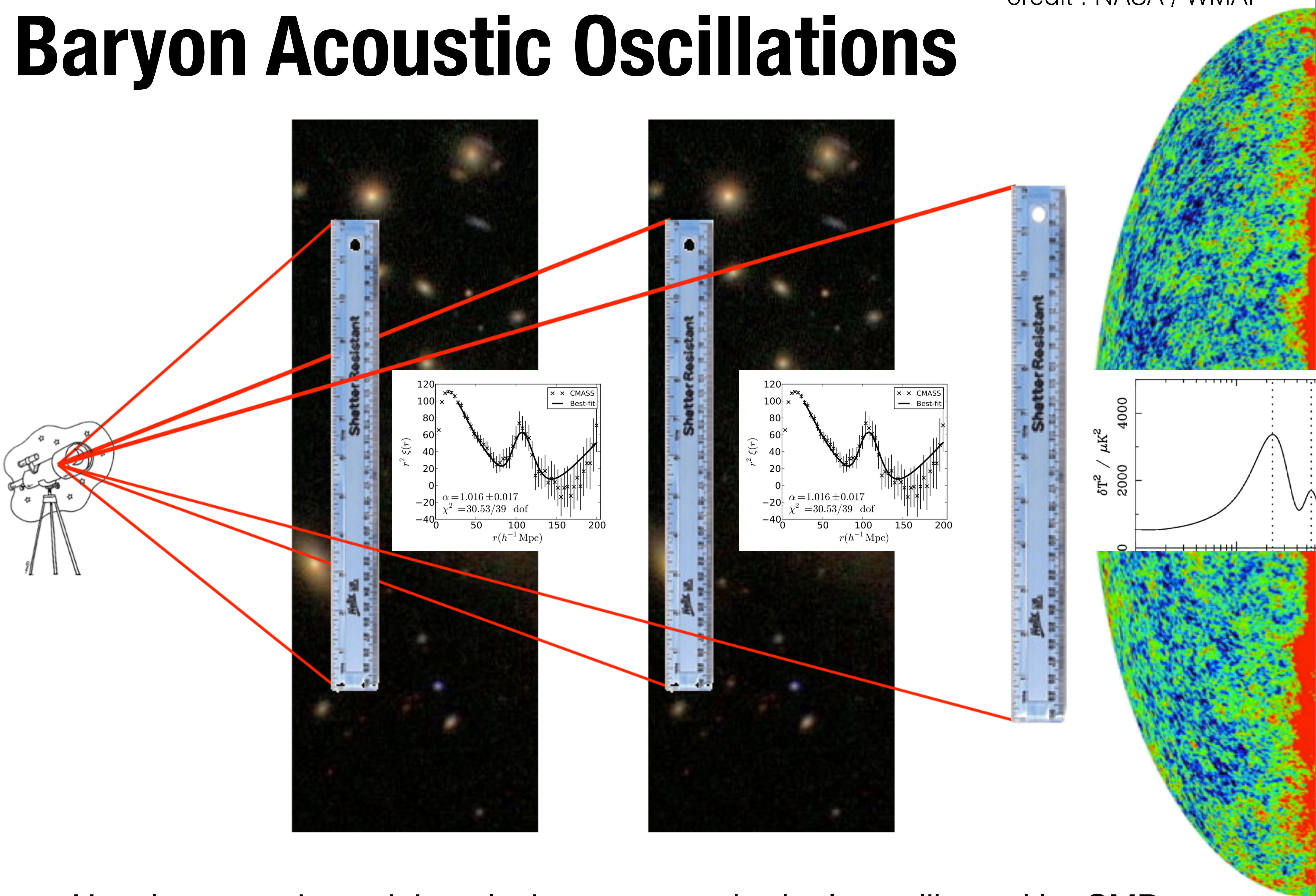


- DES analysis of RedMapper clusters
- Mass-observable relation from weak-lensing
- Scatter priors : None (Left) Yes, from Xray observations (Right)
- Error bars will look similar to 3x2pt ! (time-scale > 6 month?)

BAO

credit : NASA / WMAP

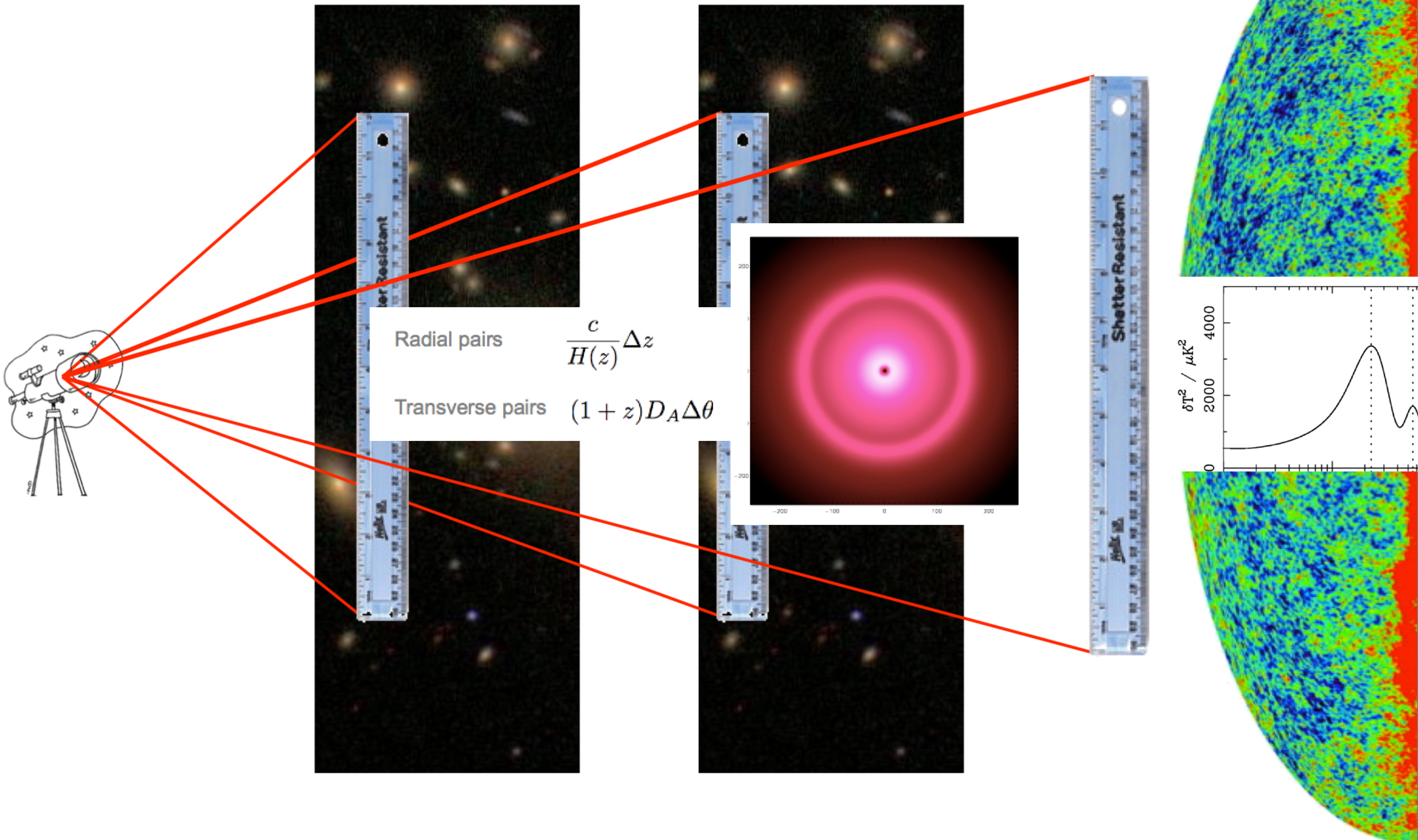
Baryon Acoustic Oscillations



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

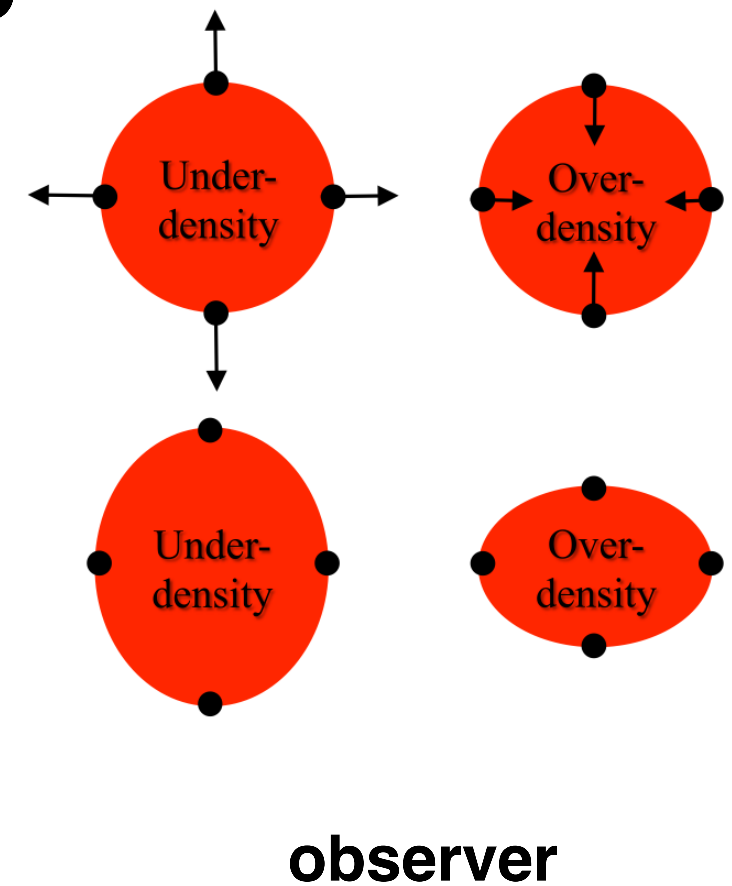
Baryon Acoustic Oscillations

credit : NASA / WMAP



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

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

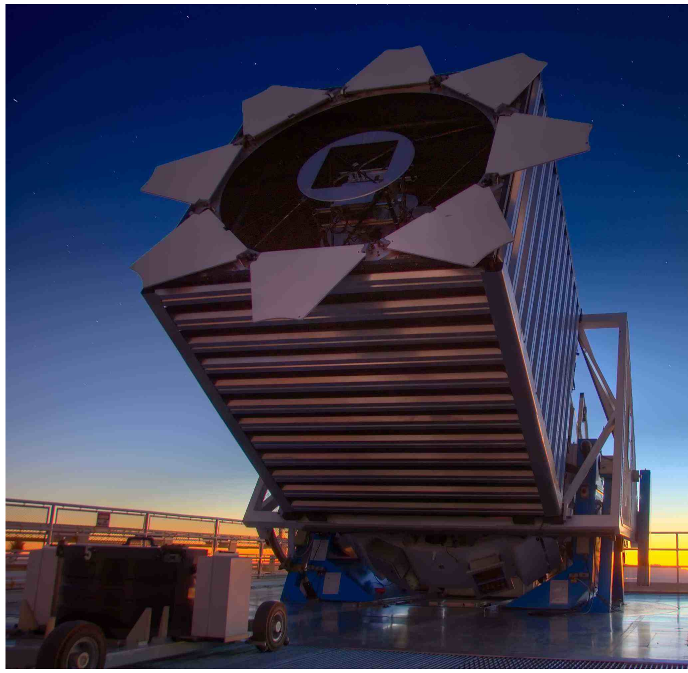
$$\delta_{\rm gal}(k,\mu) \quad = \quad b\delta_{\rm mass} + \mu^2 f \delta_{\rm mass}$$

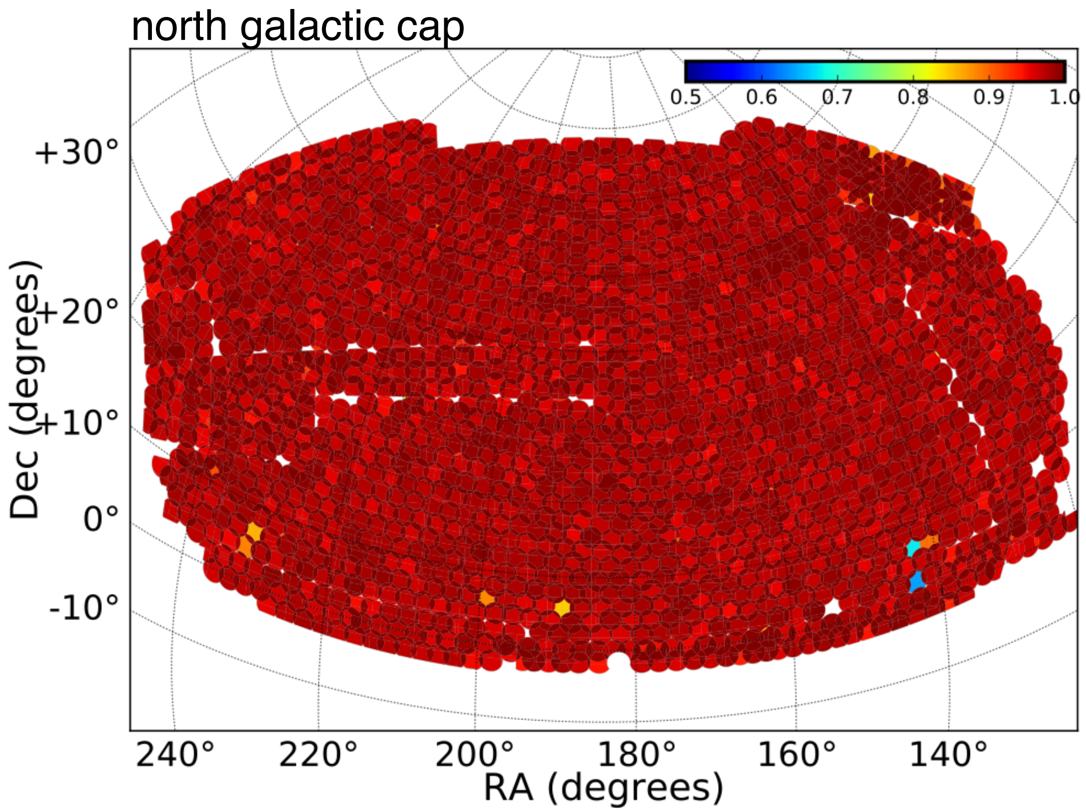
measure anisotropic 2-pt correlations

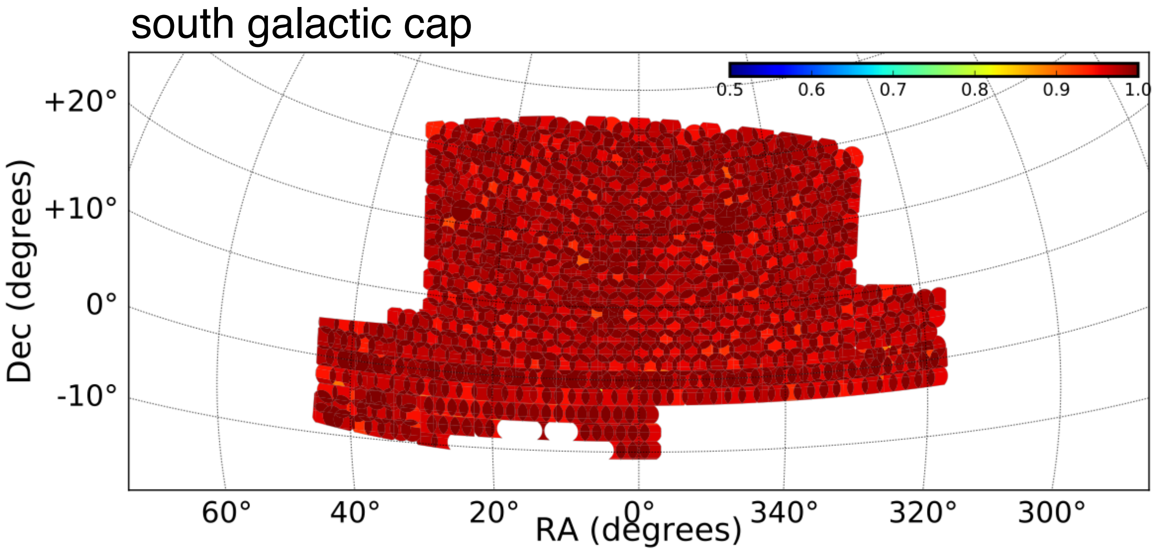
intrinsic z-space

BOSS (baryon acoustic oscillation survey)

- Part of SDSS III (and continuation of SDSS).
- 1000 fiber spectrograph, observations in 2009 - 2014.
- **9,329 square degrees** (almost 20 Gpc^3 in volume)
- Redshifts of **1.2 million luminous galaxies to $0.2 < z < 0.75$**
- Lyman-α forest spectra of **160,000 quasars** at $2.2 < z < 3$
- Latest science papers release in 2016.
- Largest and most precise map of the large-scale structure today



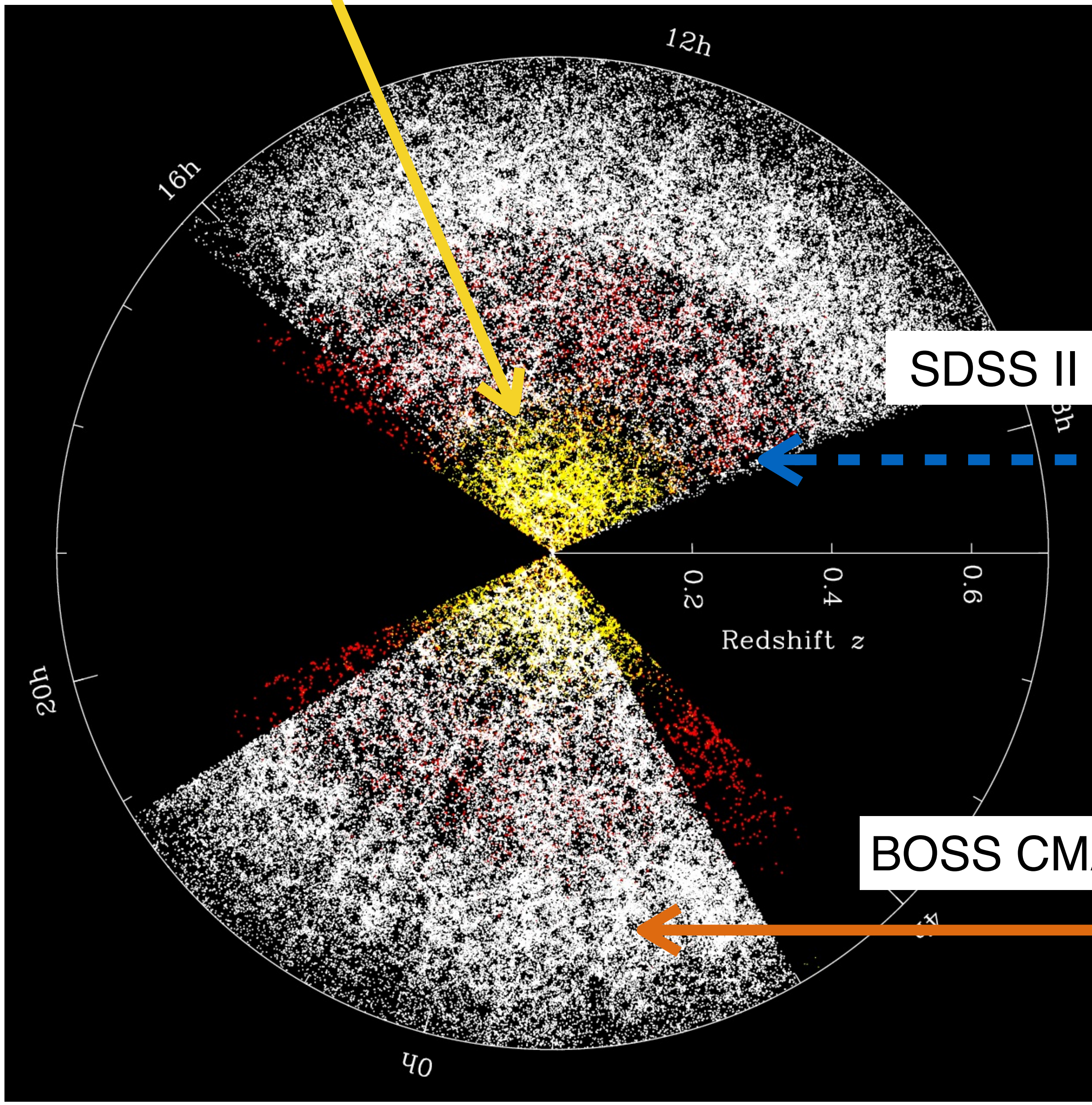




BOSS (baryon acoustic oscillation survey)

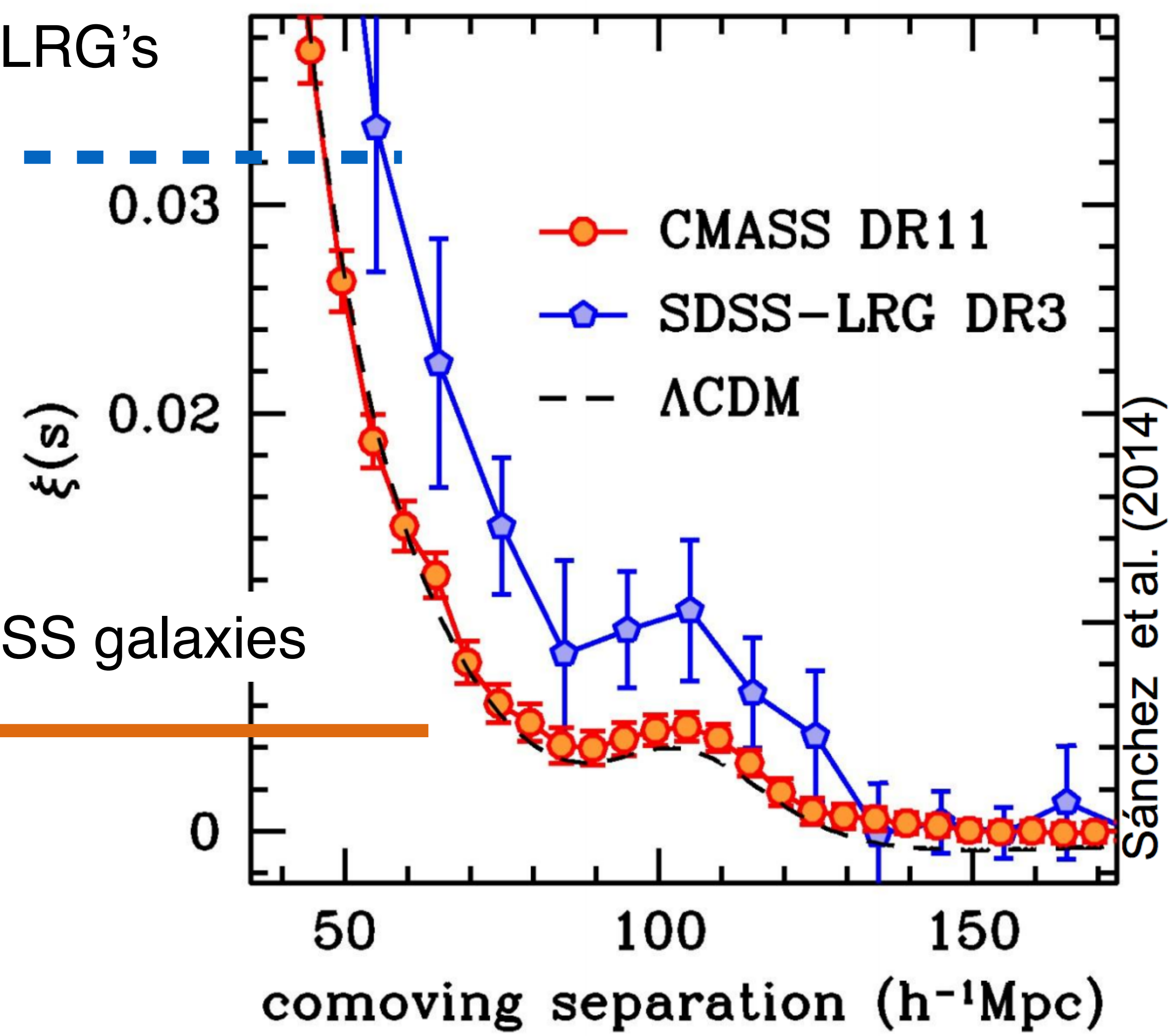
SDSS II - main galaxies

Large Quality jump from SDSS!



SDSS II - LRG's

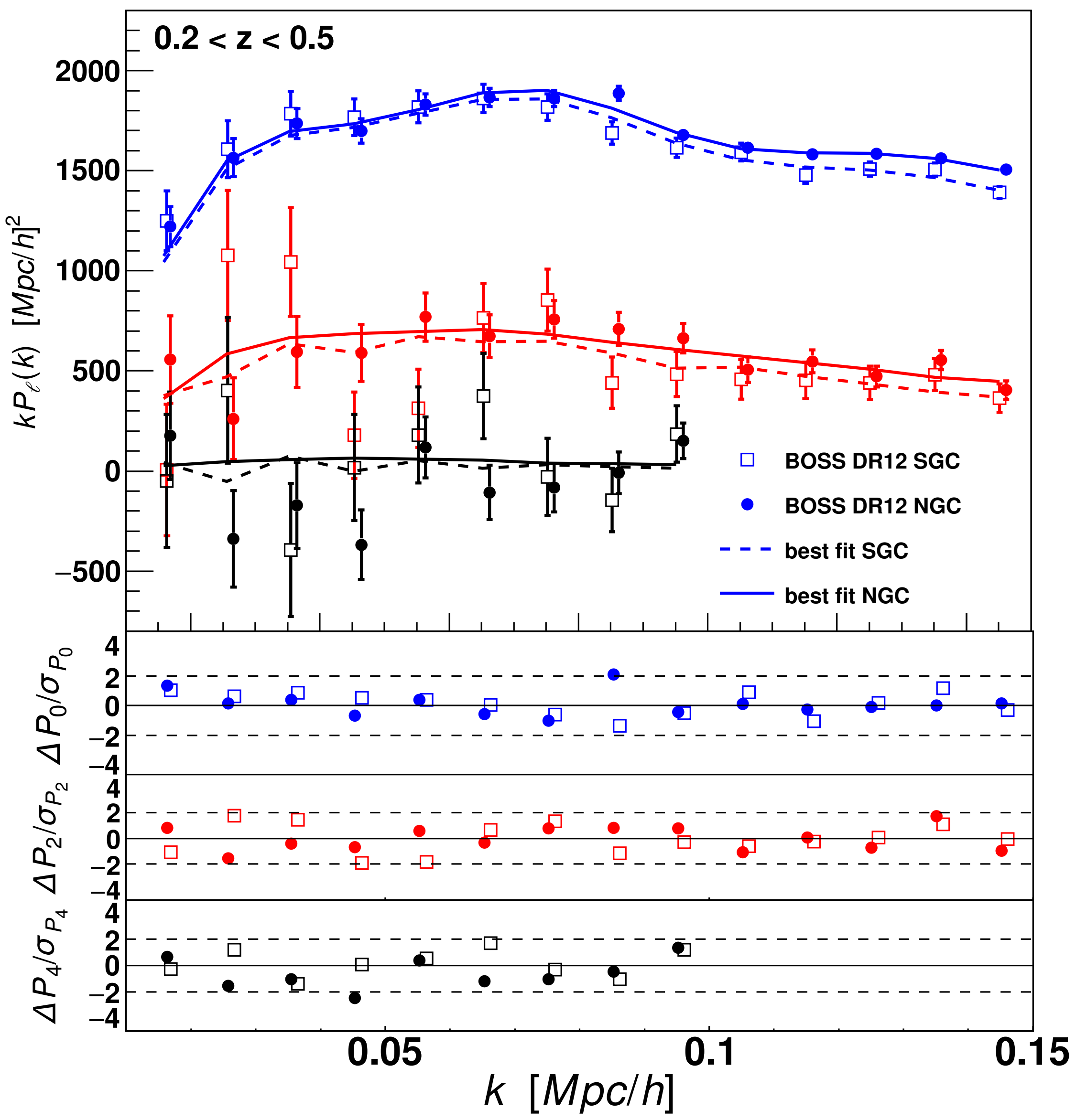
BOSS CMASS galaxies

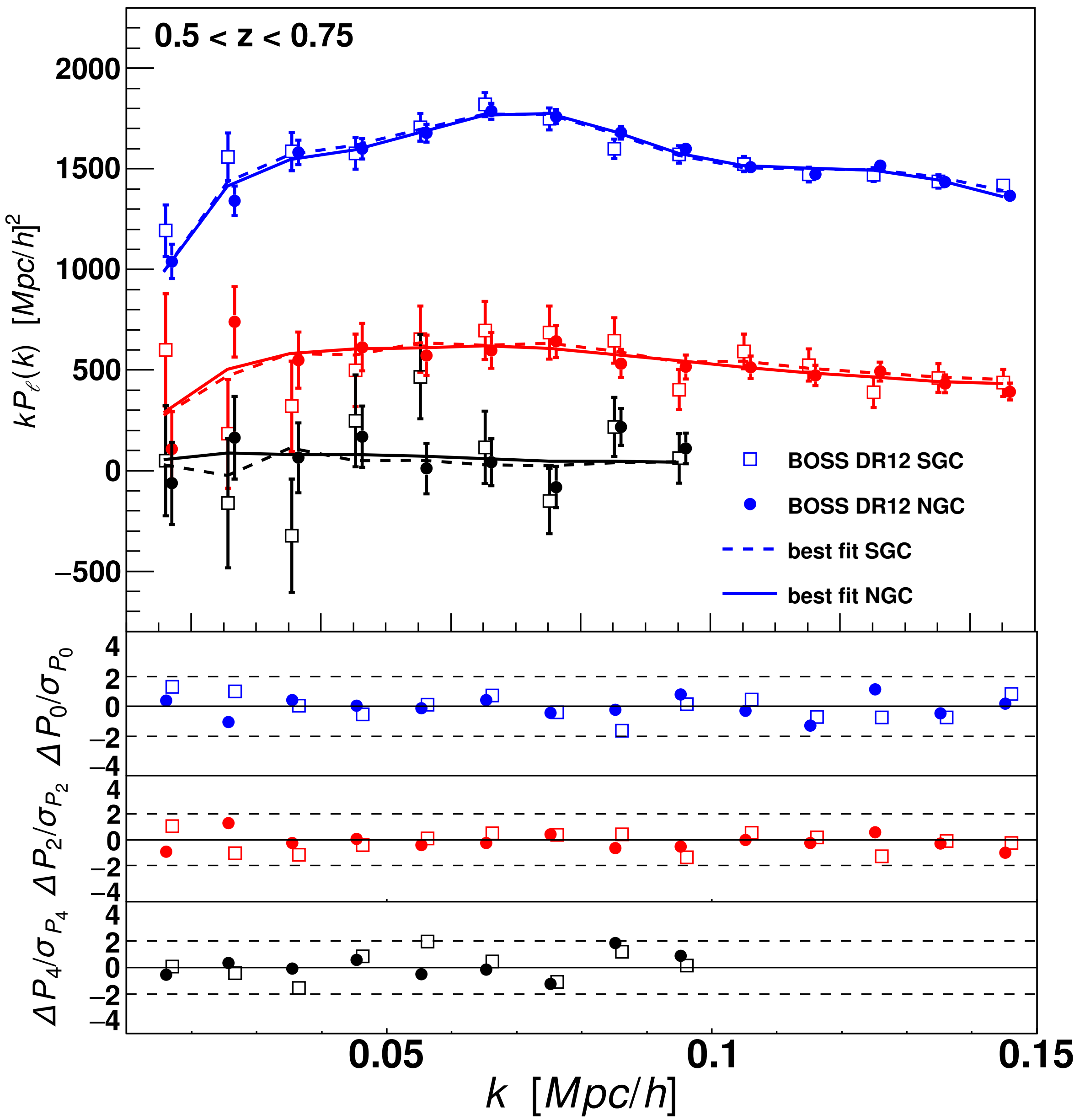


Redshift space (anisotropic) measurements

Power spectrum multipoles

Beutler et al (arXiv 1607.03143)

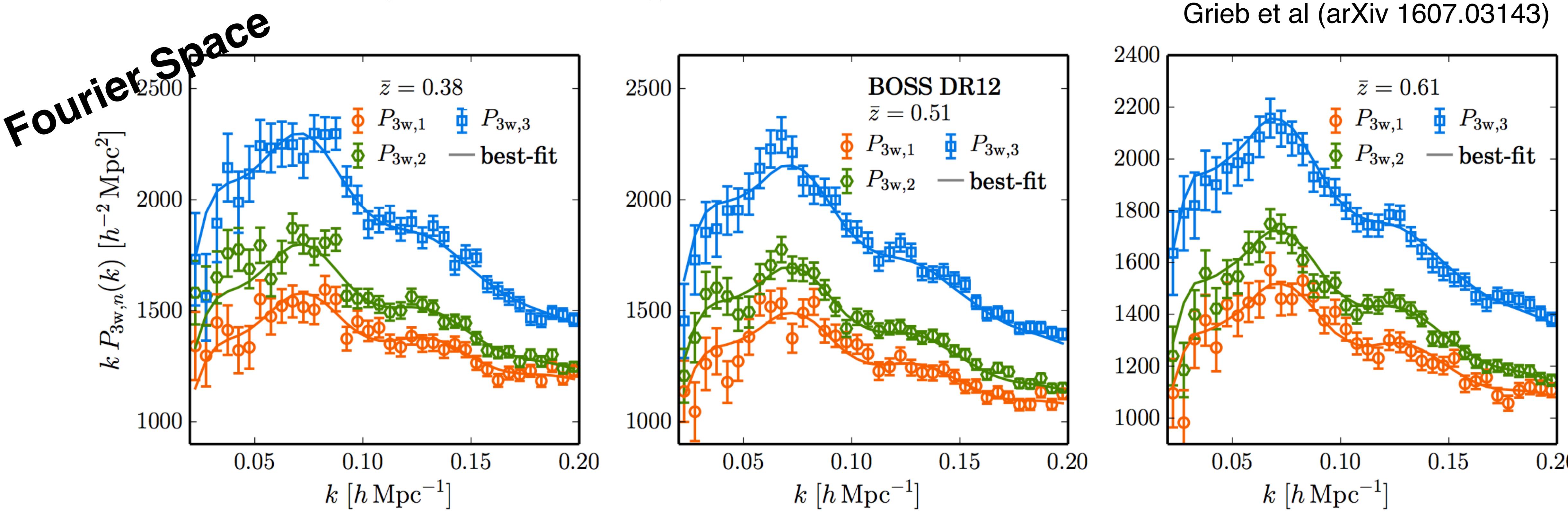




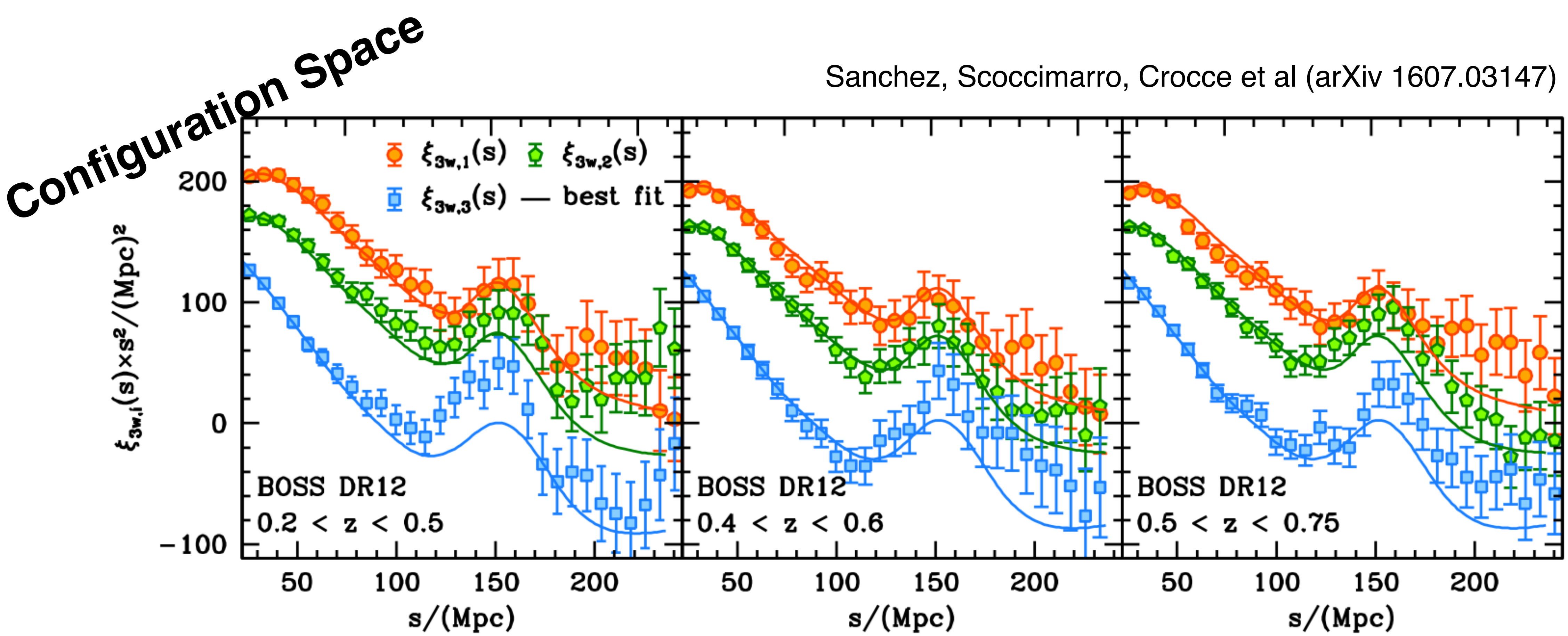
Redshift space (anisotropic) measurements

note these are wedges, not multipoles

Grieb et al (arXiv 1607.03143)



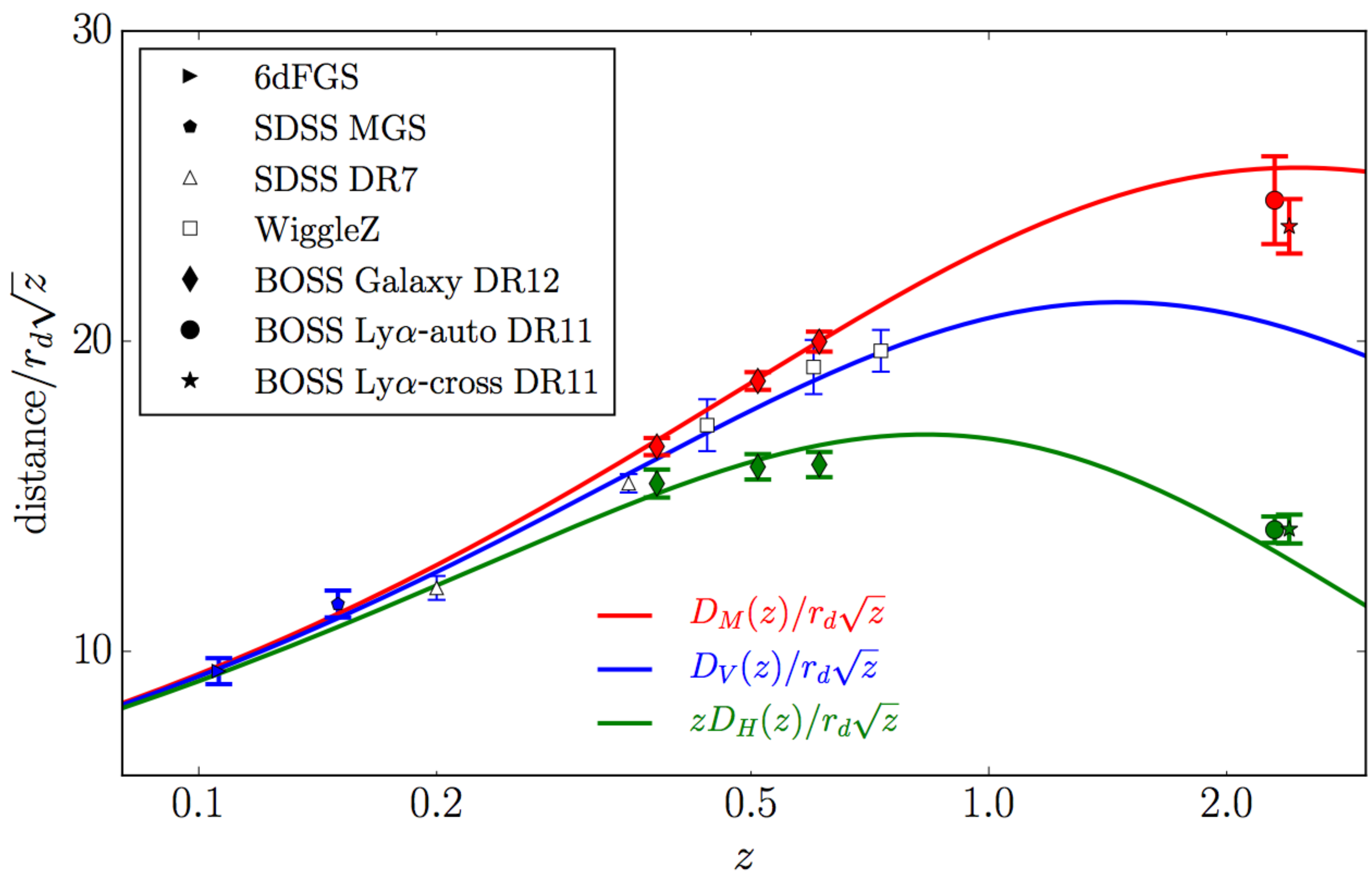
Sanchez, Scoccimarro, Crocce et al (arXiv 1607.03147)



Distance Measurements

Hubble diagram from Baryon Acoustic Oscillations

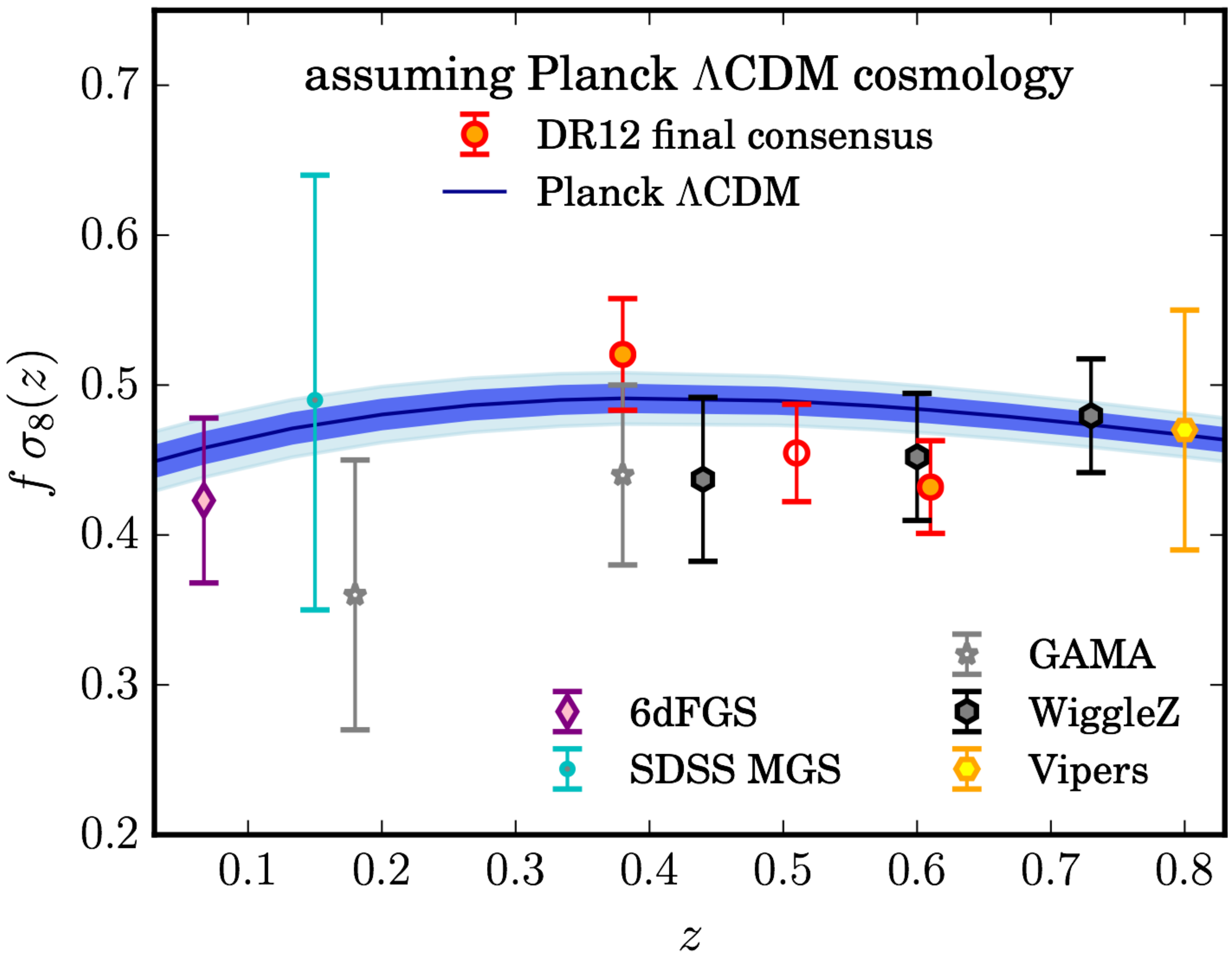
- Angular diameter distance better than 1.5% in all bins
- Hubble parameter better than 2.4% in all bins



Growth Measurements

from Redshift Space Distortions

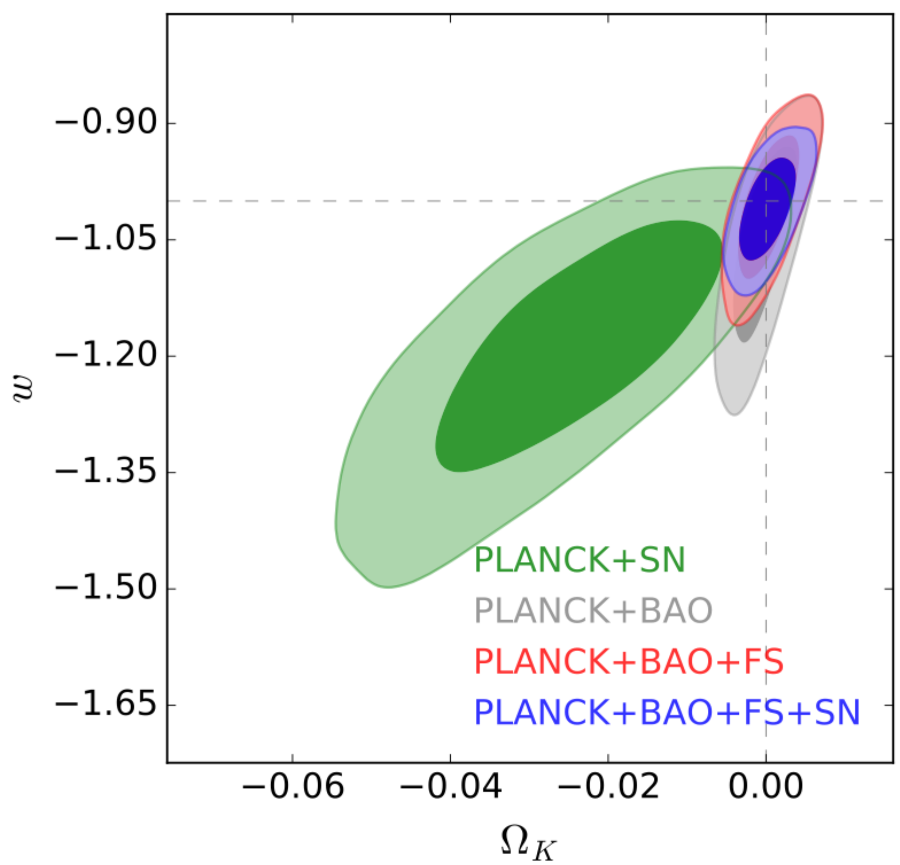
- about 9.2% or better precision in each bin



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

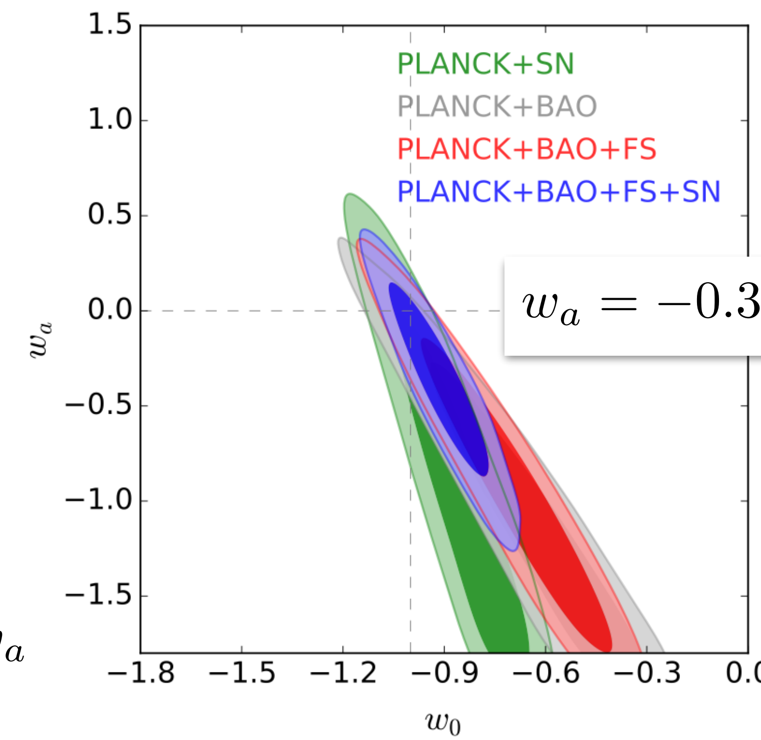
Opening two degrees of freedom (jointly or separately)

$\Omega_K = -0.0003 \pm 0.0027$	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"

No evidence for evolving dark energy :

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



$w_a = -0.3 \pm 0.5$

FS = full-shape = ~ RSD

SN = SNIa (JLA, Betoule et al 2014)

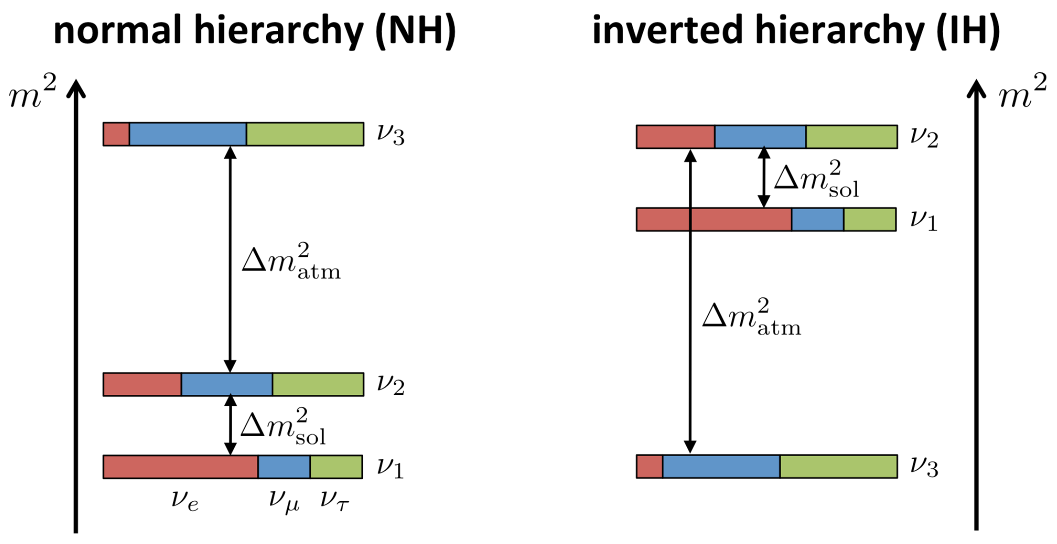
Massive Neutrinos

Neutrino oscillations experiments sensitive to mass differences.

two hierarchies

$$|\Delta m^2_{31}| \cong 2.4 \times 10^{-3} \mathrm{eV}^2$$

$$\Delta m^2_{21} \cong 7.6 \times 10^{-5} \mathrm{eV}^2$$



These imply a lower limit to the sum of masses ~ 0.06 eV

For the inverted hierarchy the lower limit ~ 0.0982 eV (not far from future constrains)

Cosmology is sensitive mostly to the sum of the neutrino masses

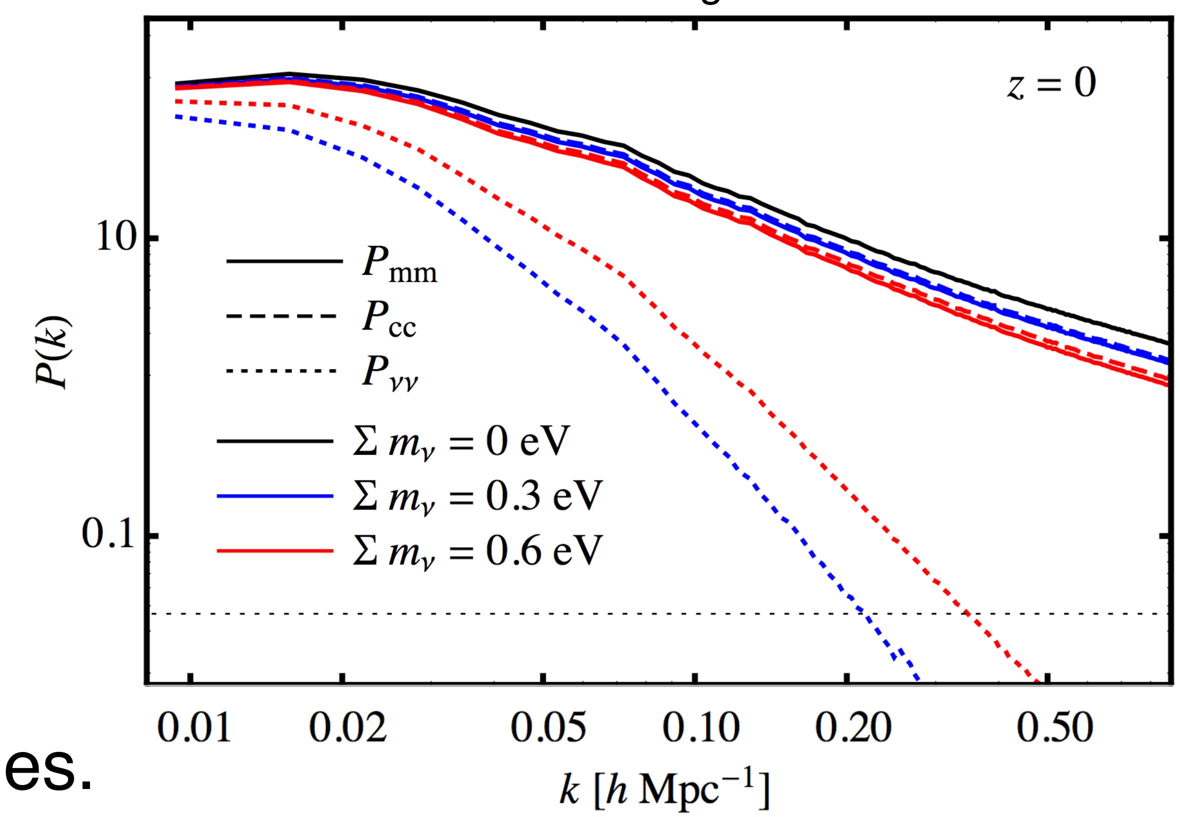
- Measure a non-zero detection of total mass
- Reach an upper limit that excludes the inverted hierarchy

Massive Neutrinos

Neutrinos affect

Cosmic history : At fixed matter-radiation equality, an increased neutrino mass changes Ω_m today (which can be absorbed in H_0). This degeneracy can be broken with low redshift distance measurements.

Figure : Emiliano Sefusatti



Growth history : Neutrino mass (if sub-eV) suppresses growth of structure between the epoch of decoupling and today below a free streaming scale.

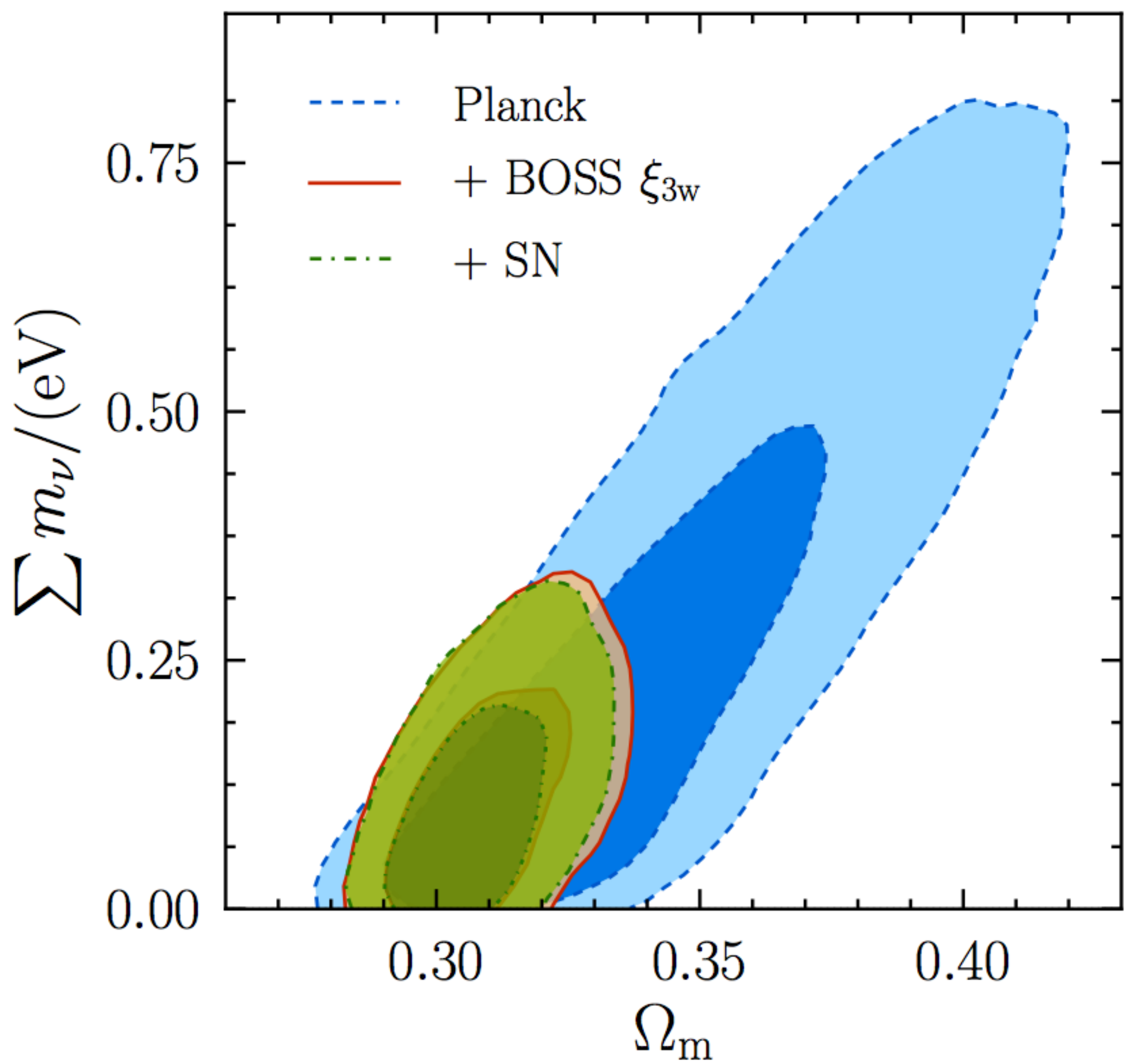
$$k_{nr} = k_{fs}(z_{nr}) \simeq 0.018\Omega_m^{1/2}\left(\frac{m_\nu}{1\,eV}\right)\,h\,\mathrm{Mpc}^{-1}$$

Their velocities prevents falling into small-scales.

This will modify the expected value of σ_8 at z=0 (given the CMB amplitude)

Measurements of low-redshift amplitude of structure also constrain neutrino mass.

Massive Neutrinos



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

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

Combining with CMB lensing reduces it

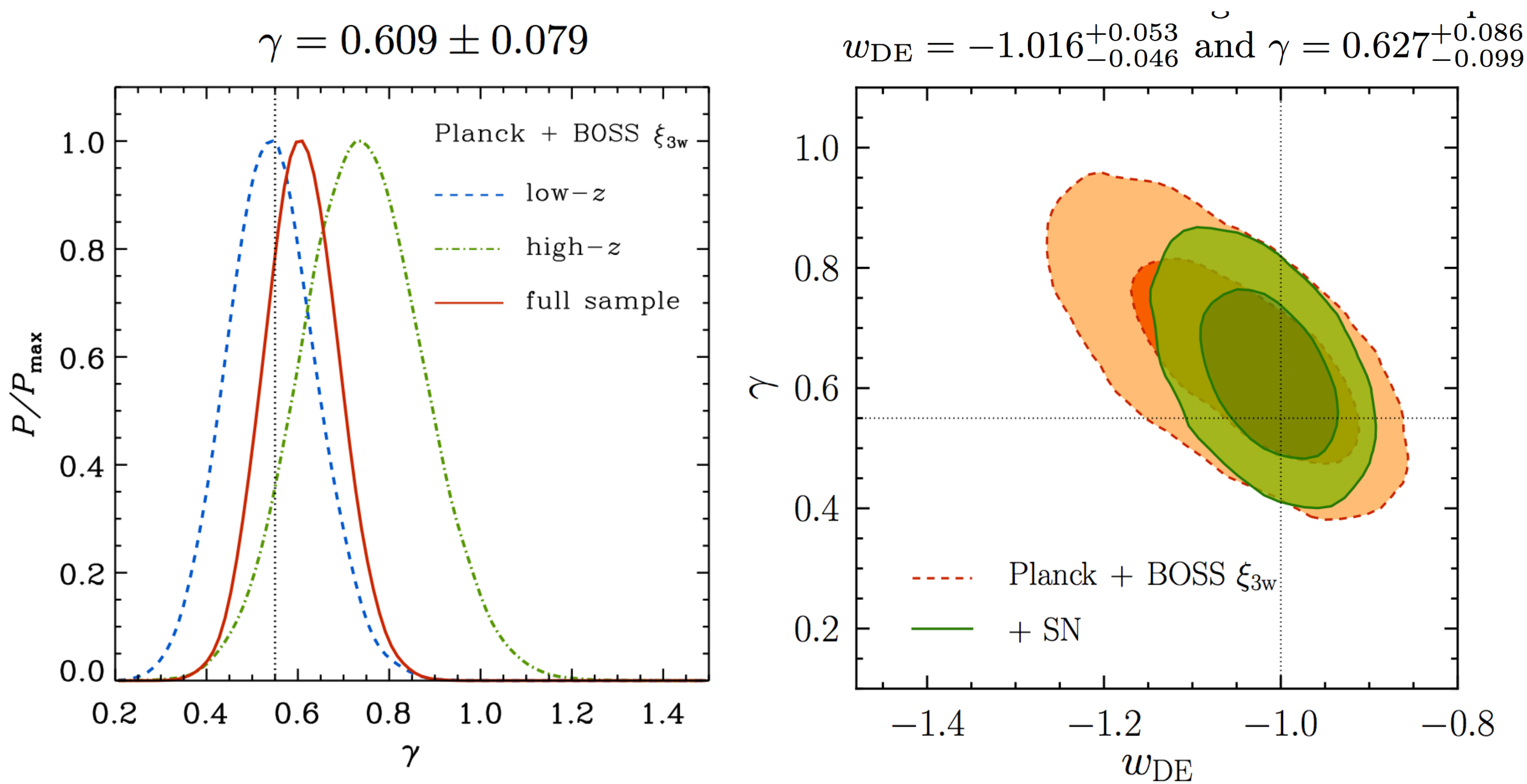
$$\sum m_\nu < 0.16\,\mathrm{eV\ at\ 95\%\ CL}$$

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



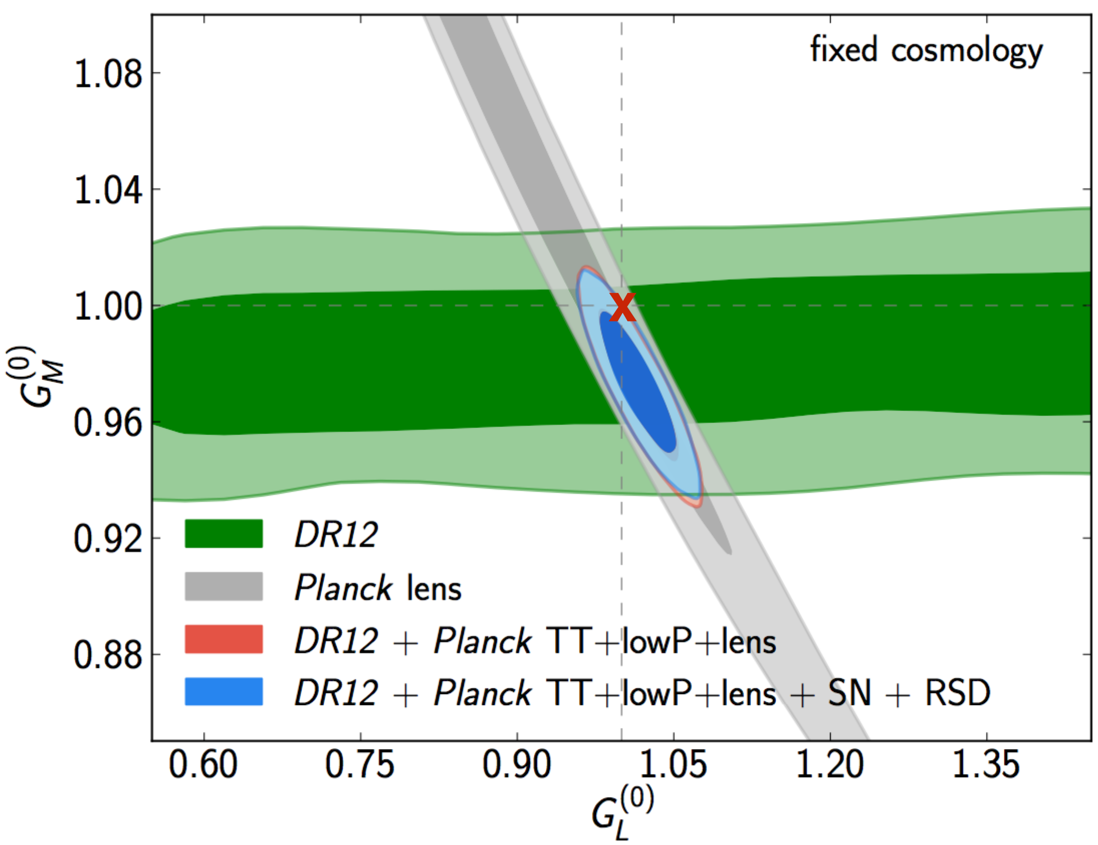
Modified Gravity

Changing metric potentials

$$ds^2 = a^2[-(1+2\psi)d\tau^2 + (1-2\phi)d\mathbf{x}^2]$$

$$\nabla^2\psi = 4\pi G a^2 \rho\Delta \times G_{\rm M}$$ slowly moving particles, "growth of structure"

$$\nabla^2(\psi+\phi) = 8\pi G a^2 \rho\Delta \times G_{\rm L}$$ lensing of light



parametrised evolution with time $G_{\rm X} = 1 + (G_{\rm X}^{(s)} - 1)a^s$

model	$G_M^{(s)}$	$G_L^{(s)}$
$s = 0$: constant	0.991 ± 0.022	1.030 ± 0.030
$s = 1$: linear	0.980 ± 0.096	1.082 ± 0.060
$s = 3$: cubic	1.01 ± 0.36	1.31 ± 0.19

Consistent with GR within less than two sigma

Summary of BOSS - 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 (!).

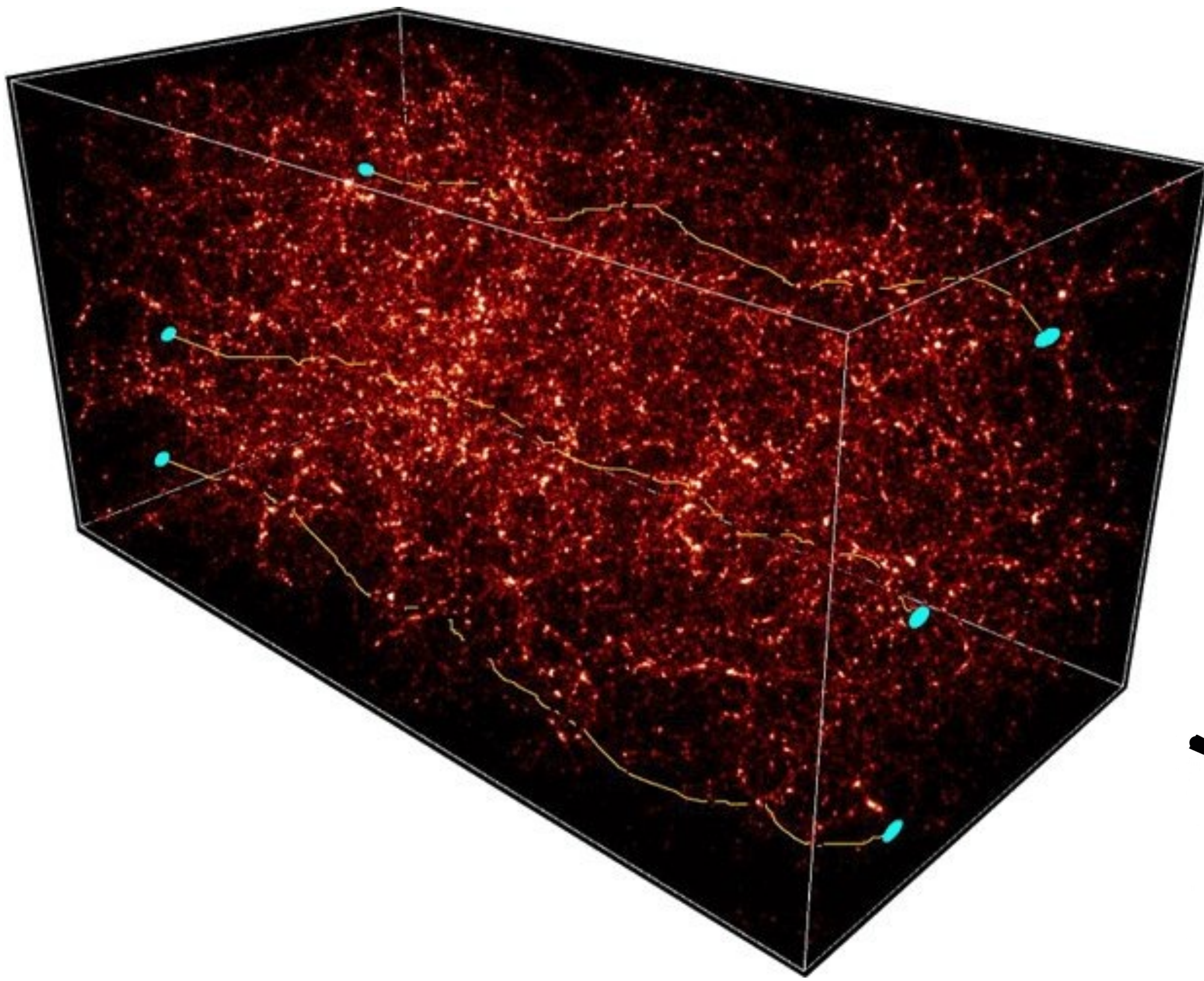
- Time varying dark-energy is not well constrained

- 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

Opened door to Weak Lensing surveys (DES, KiDS)

Weak Lensing

source galaxies at
z ~ 1



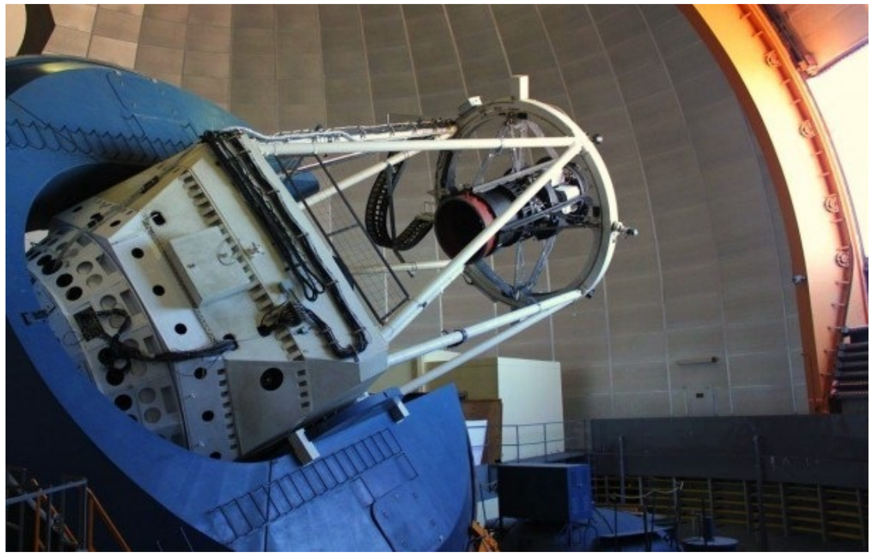
- Matter distorts back-ground galaxy shapes
- Measure shapes to obtain "shear" catalog
- Shear-shear correlations is an unbiased tracer of matter distribution

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

- **Problems** - Intrinsic Alignments, Baryon Physics, Getting shapes

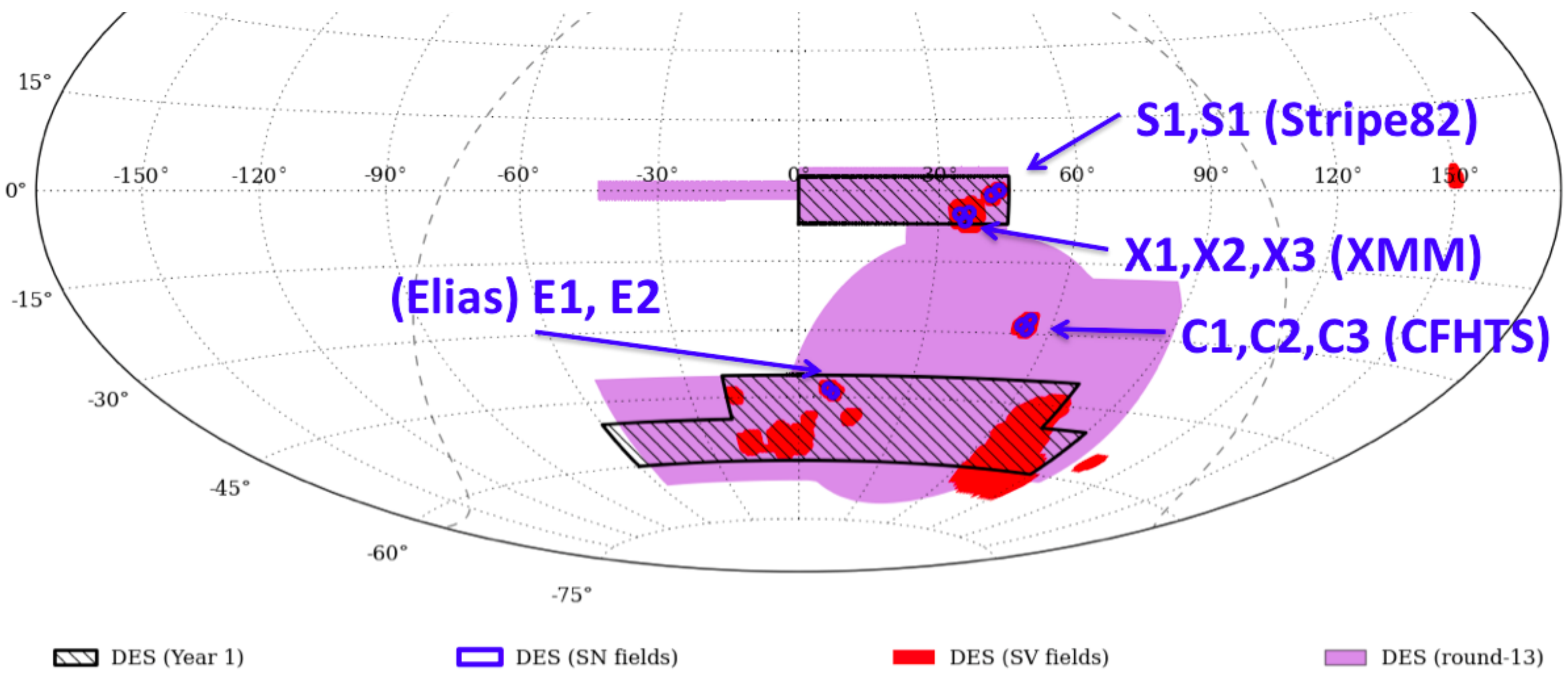
Dark Energy Survey

overview



- Wide Optical and near IR survey (grizY bands)
- 525 nights over 5 seasons in 5 imaging bands
- 5000 deg2 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

Just finished 4th year 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

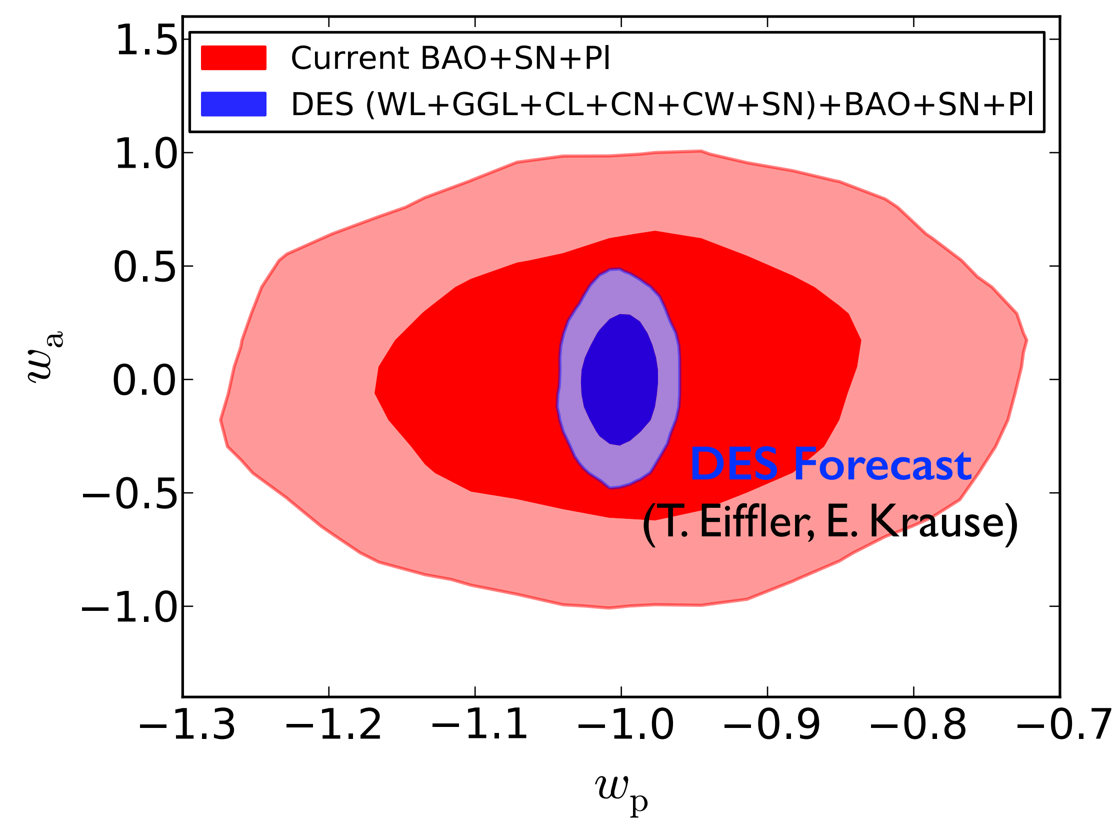
→ shared photometry/footprint

→ shared analysis of systematics

→ shared galaxy redshift estimates

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

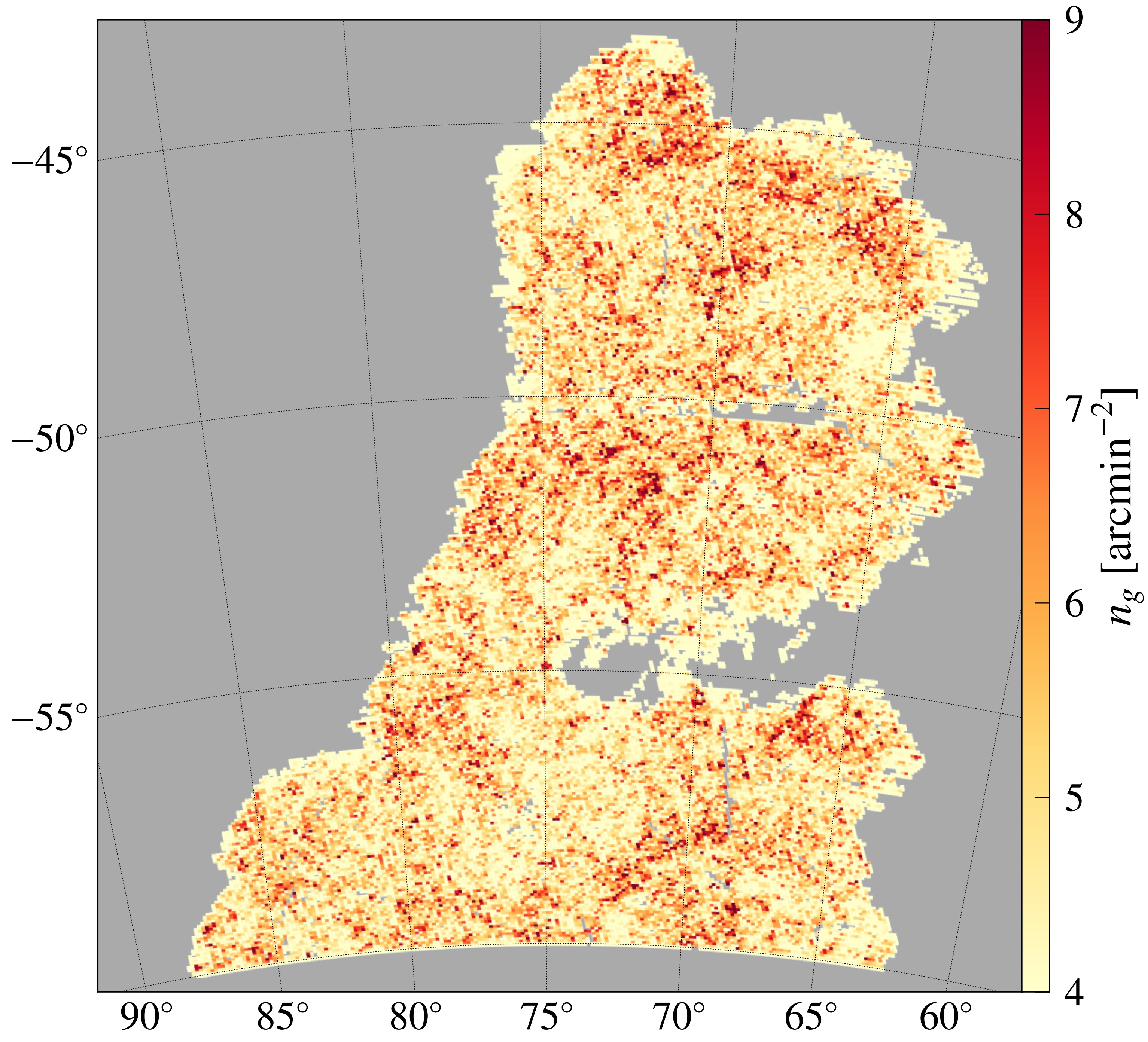
Type Ia supernovae (distance)
30 sq. deg. SN fields
3000 SNIa to z~1



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

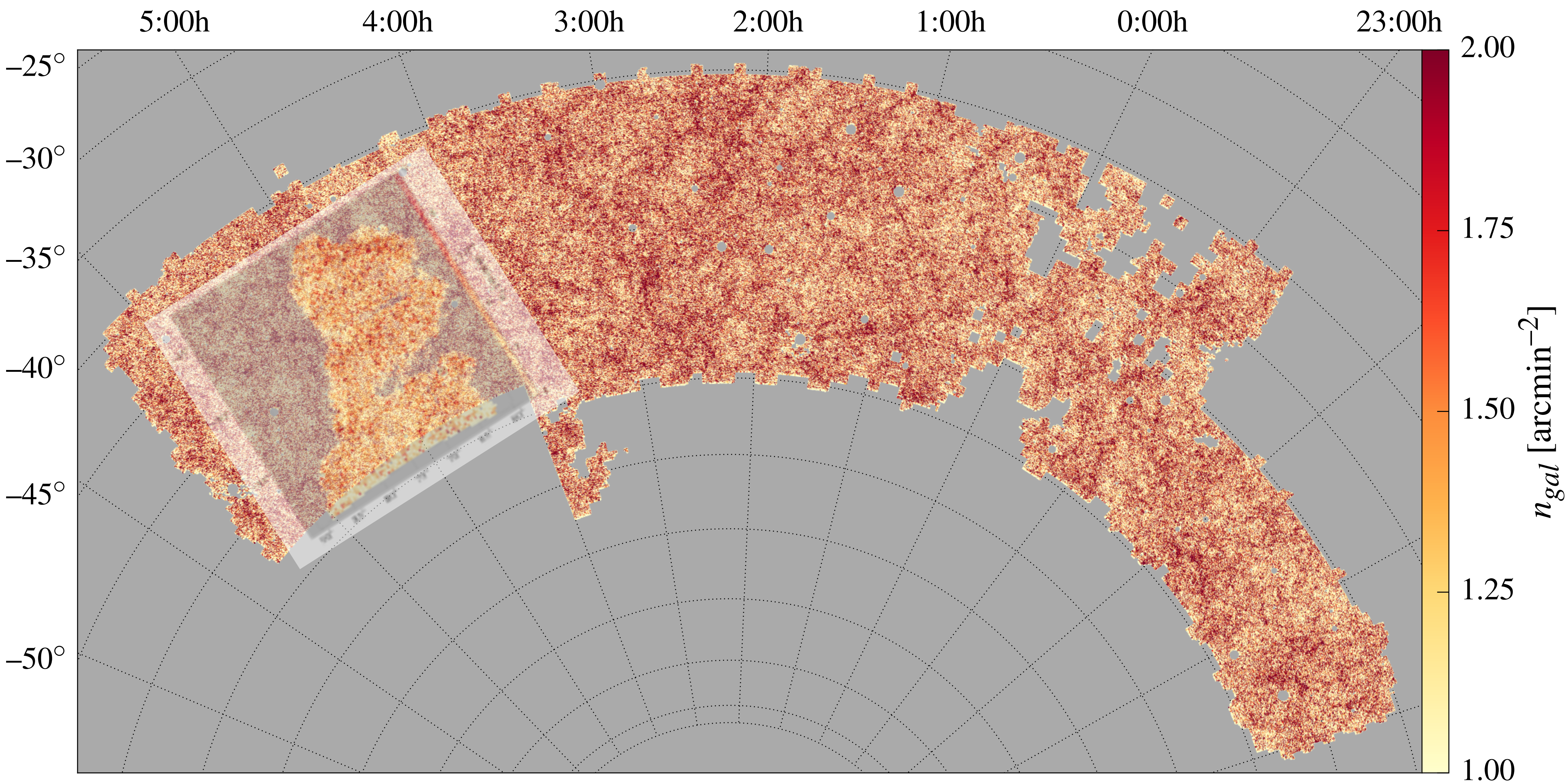
Cross-correlations
Galaxies and WL x CMB lensing

DES Science Verification Galaxy Distribution



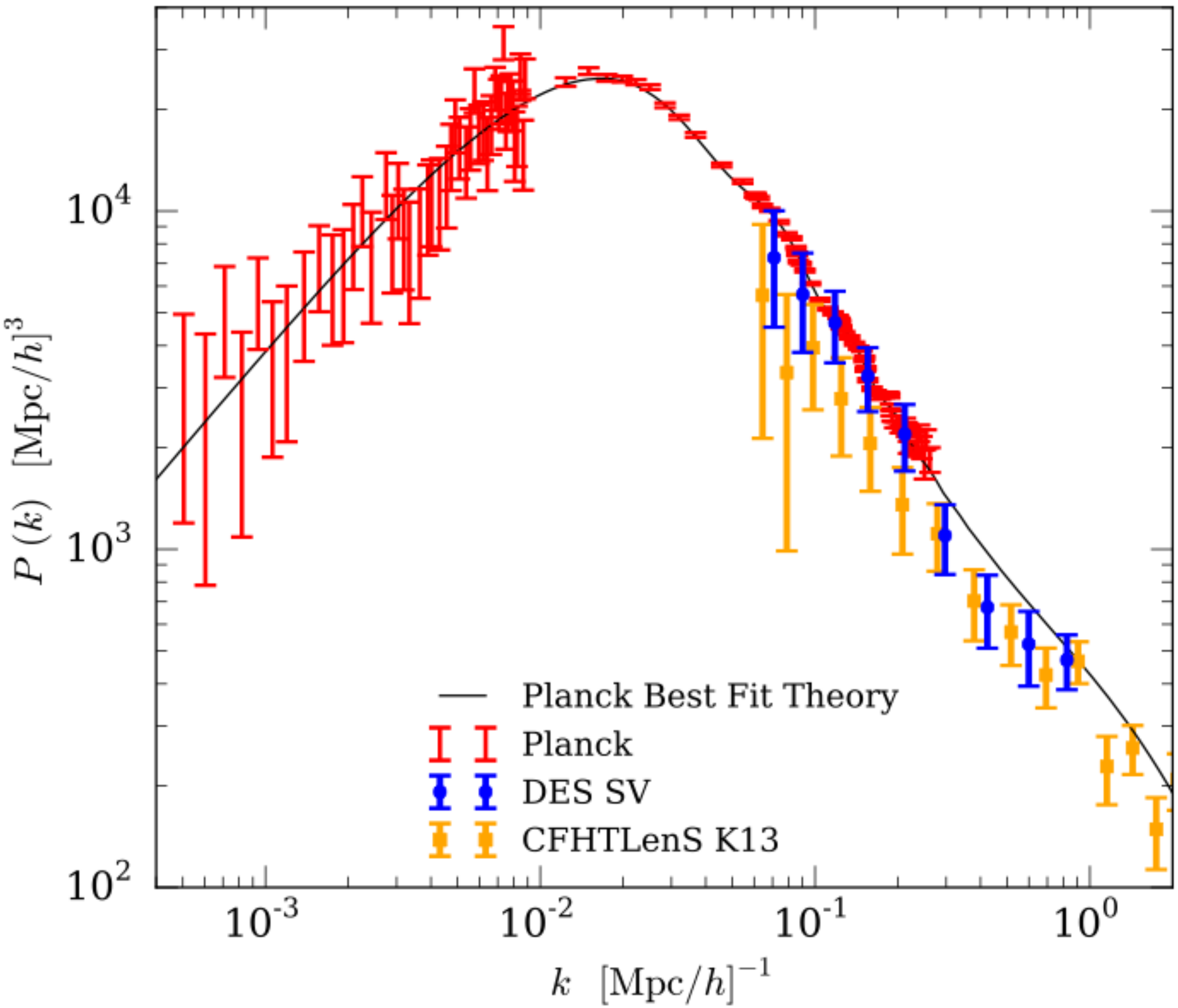
2.3 million galaxies used in LSS (i < 22.5) in 0.2 < z < 1.2

DES Year 1 Galaxy Distribution



9 million galaxies in LSS (i < 21) over 1500 deg^2

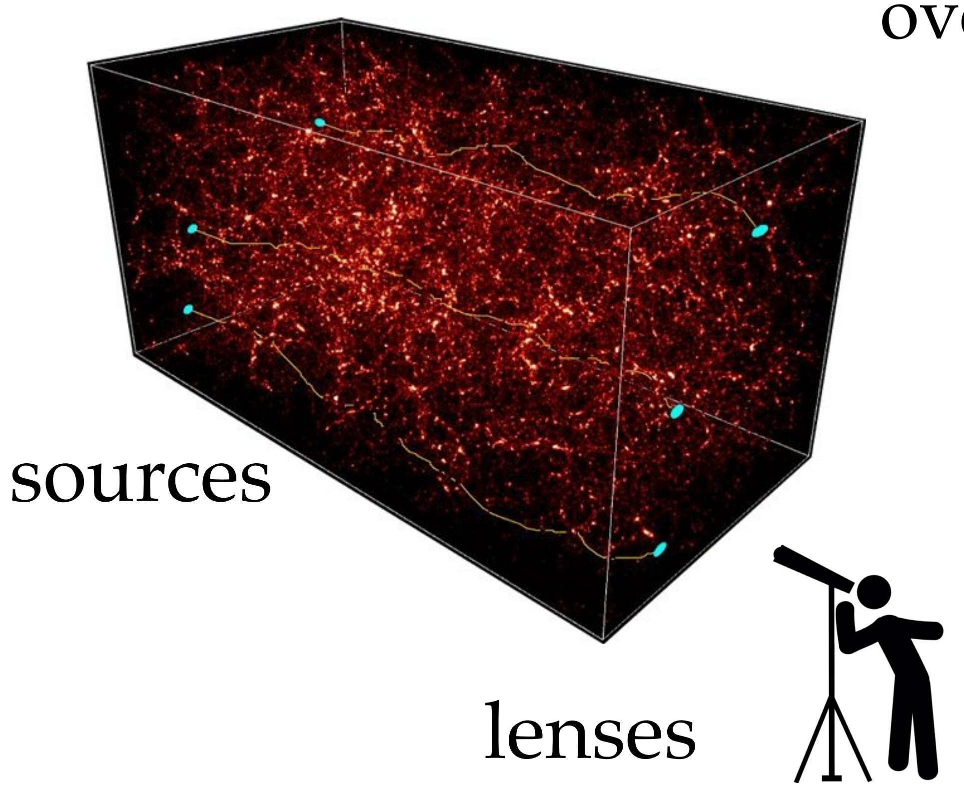
CMB and Cosmic Shear

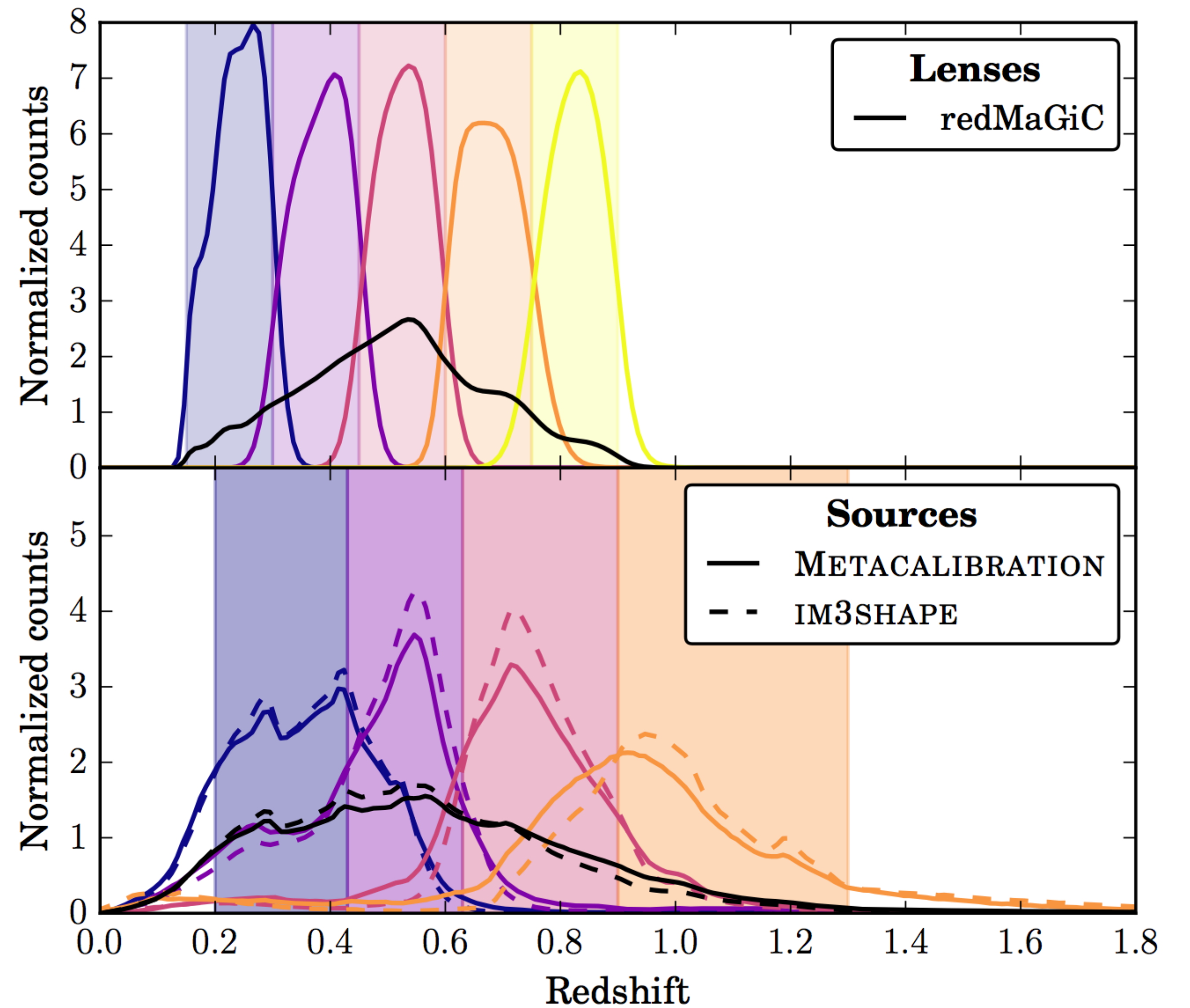


DES SV
arXiv 1507.05552
Just look at scales, lensing results are old by now

DES Y1 cosmology

over 1321 deg^2





Lens sample

- 600,000 red sequence galaxies

Accurate photo-z, optimal for clustering

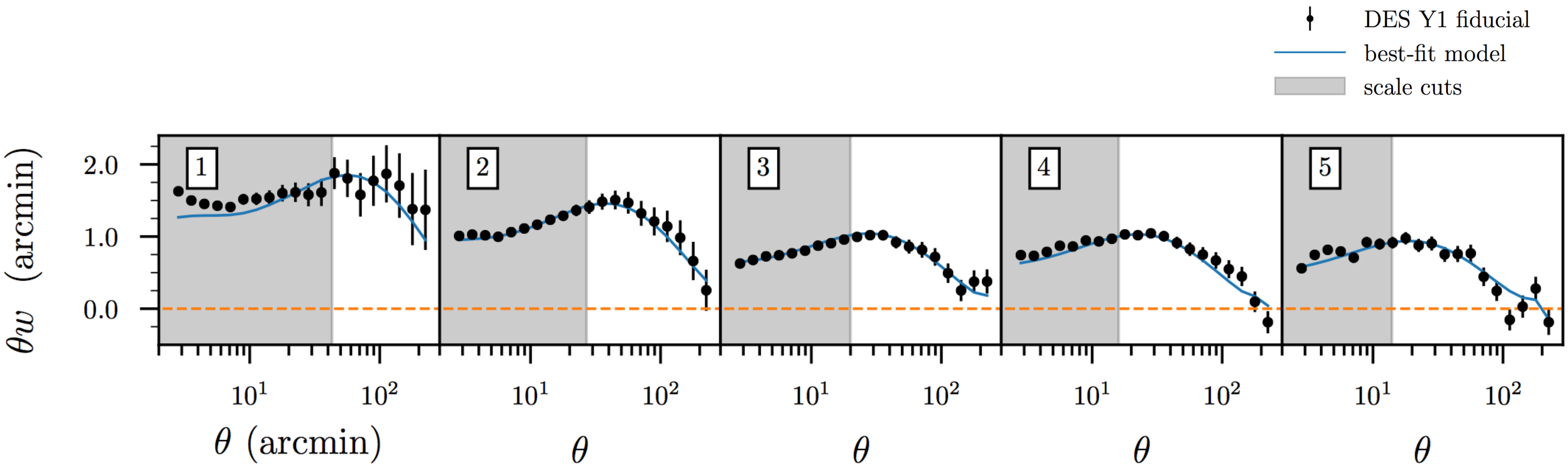
Source Sample

- Metacalibration 26 Millon shapes
- Im3shape 18 M. shapes

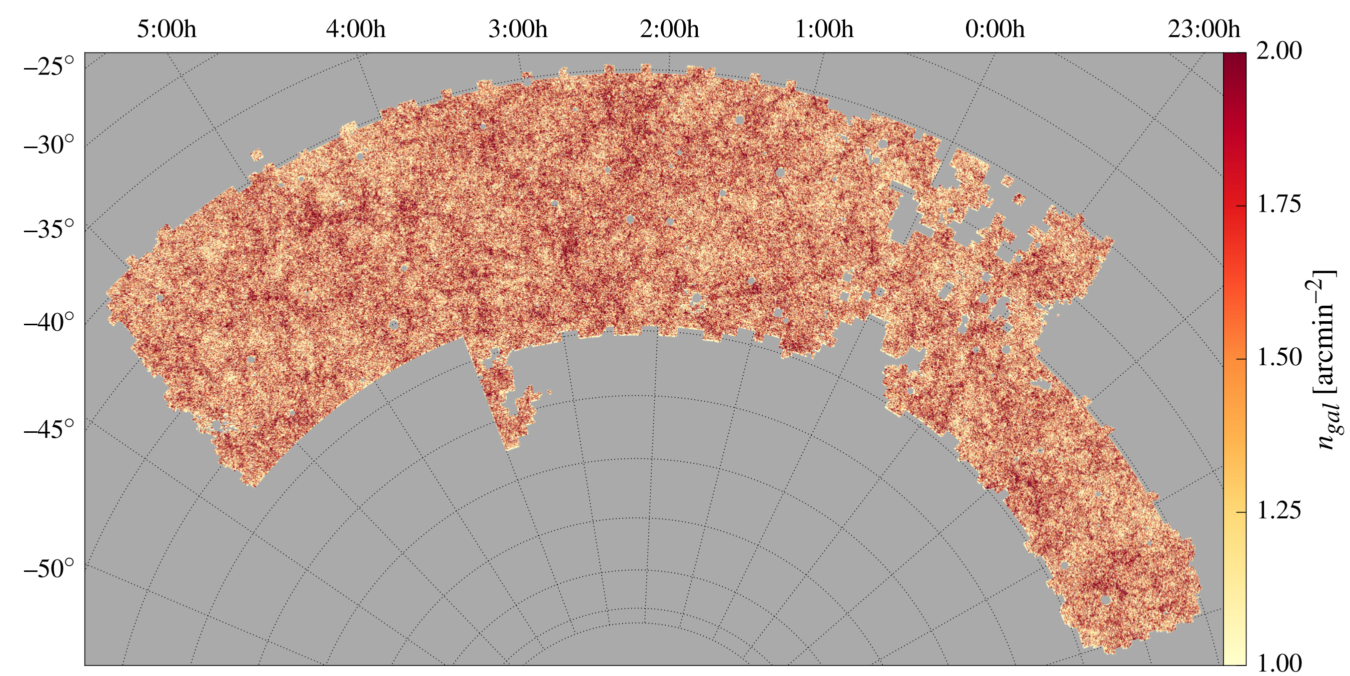
Two independent shape measurements pipelines (different systematics & assumptions)

DES Y1 gal-gal clustering

- **5 lens bins** (660,000 red galaxies with ~ 1%~2% redshift error),



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



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

DES Y1 shear-shear correlations

Two fully independently calibrated and very different shape measurement methods produce complementary catalogs over 1600 sq deg

Metacal - Sheldon et al 2017

- 34.8M galaxies in an effective footprint selection of ~1300 deg^2 used for cosmological analyses
- riz-band shape measurement
- Calibration performed by directly measuring the shear response and selection bias galaxy-by-galaxy

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

- 24.6M galaxies in same footprint
- r-band shape measurement
- Calibrated by redesigned, state-of-the-art image simulations

DES Y1 shear-shear correlations

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

Shapes of galaxies are Spin-2 quantities. Sum and difference of the product of the tangential and cross components of the shear (ellipticity) w.r.t line connecting pairs of galaxies.

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

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

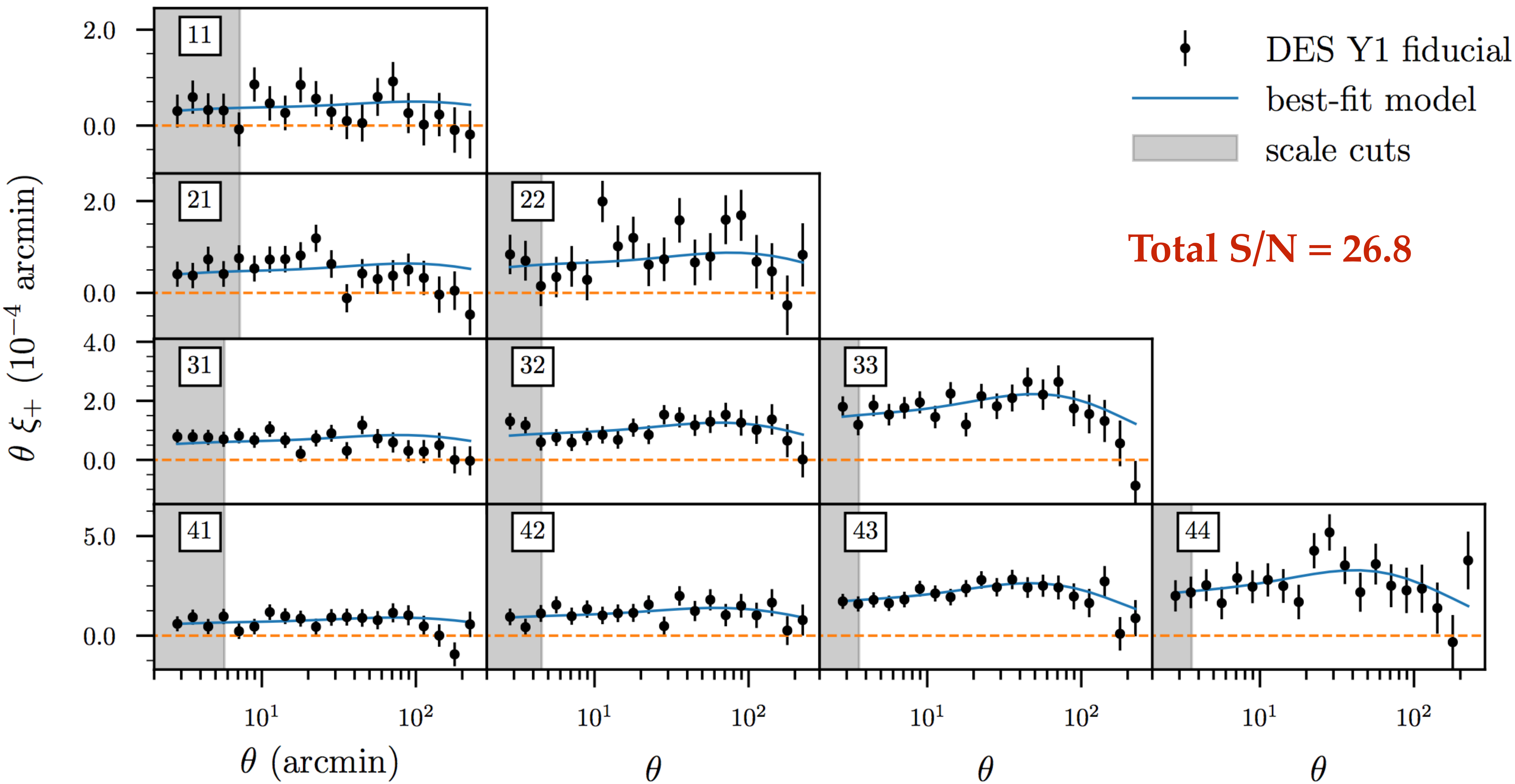
amplitude and growth rate of structure

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

Geometry (distances or expansion)

DES Y1 shear-shear correlations

- **10 two-point correlations (26 million sources)**



Total S/N = 26.8

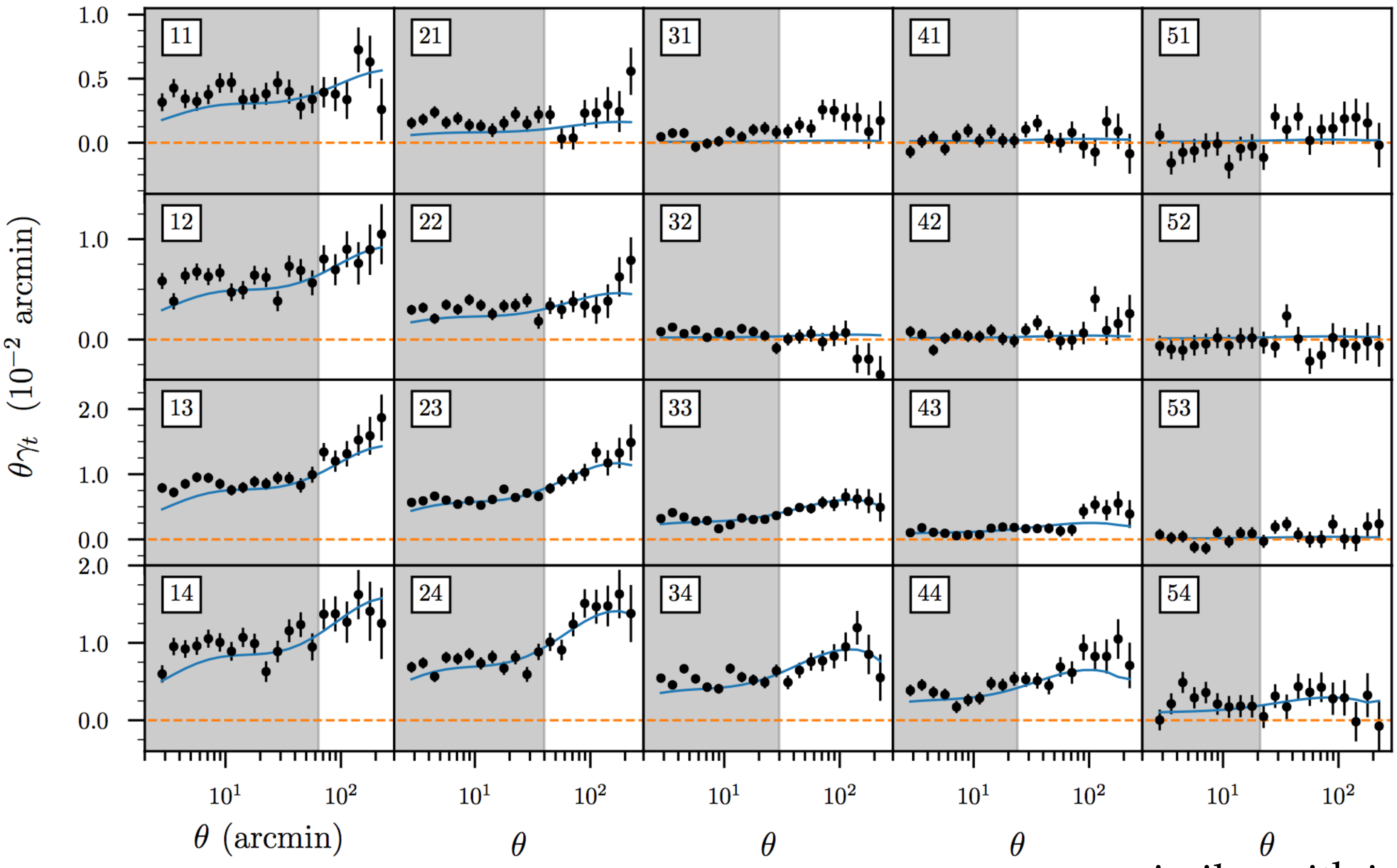
Troxel et al 2017 (arxiv 1708.01538)

- **Another 10 for xi_minus**

DES Y1 gal-gal lensing

- **20 correlations**

Prat, Shanchez et al 2017 (arxiv 1708.01537)

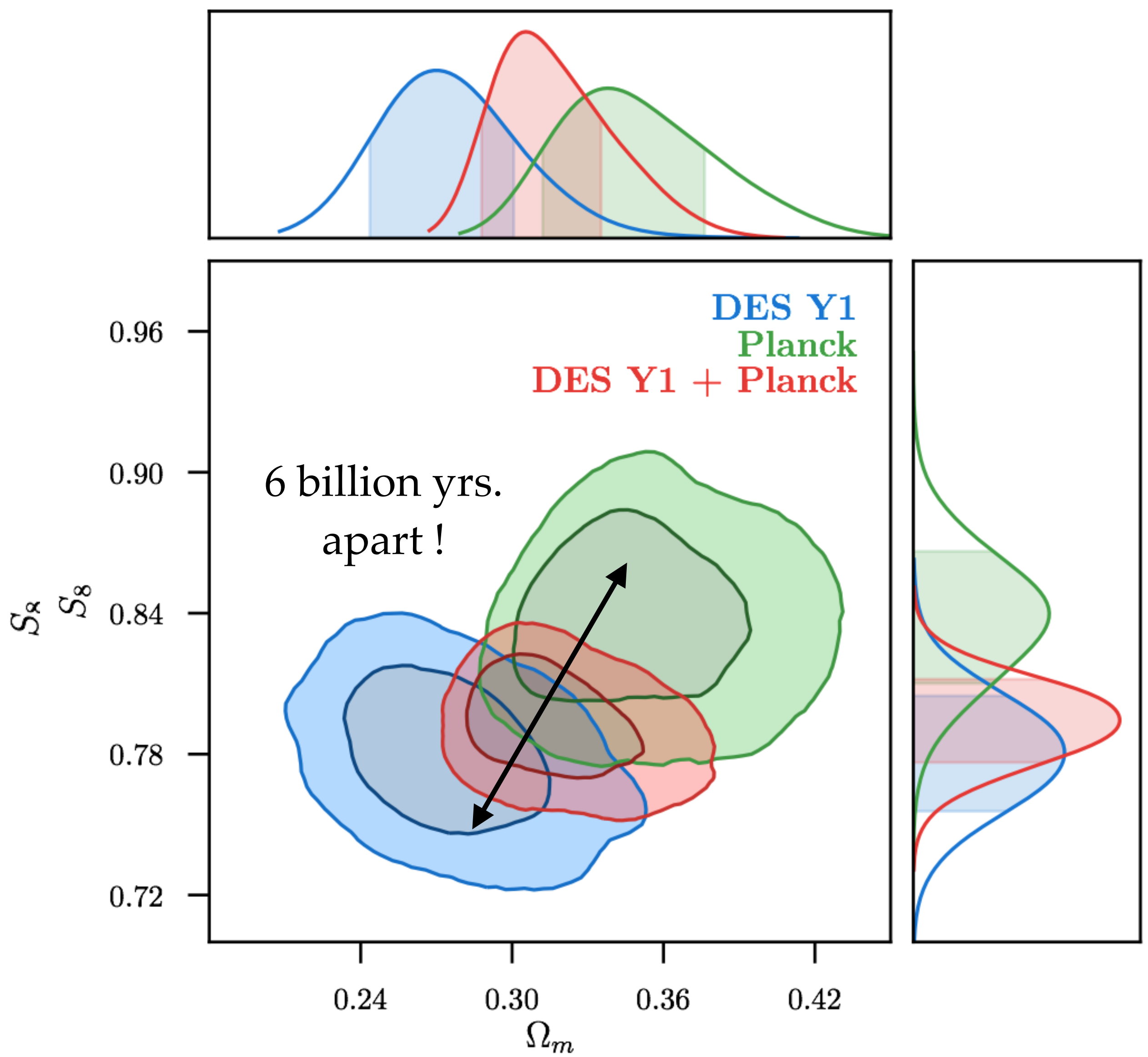


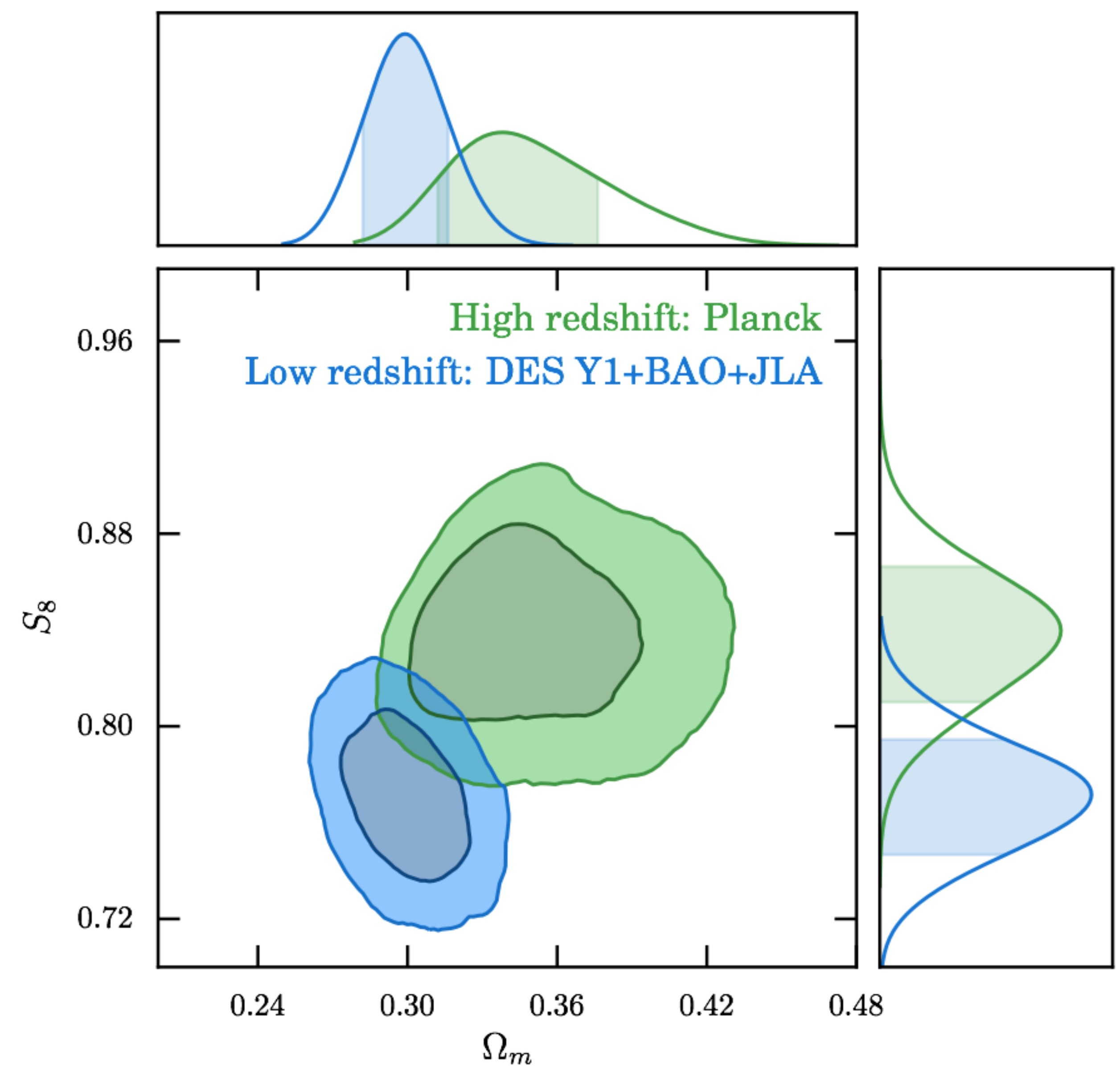
+ similar with im3shape

Cosmology from high-z to low-z

the money plot

Consistent and comparable constrains between LSS and CMB





Cosmology from high-z to low-z

the Universe at its two extremes

Combining DESY1 + Planck (w/lensing) + BAO + JLA —> most stringent constrains so far of large-scale structure related parameters

$$\Omega_m = 0.298 \pm 0.007.$$

$$\sigma_8 = 0.808^{+0.009}_{-0.017}$$

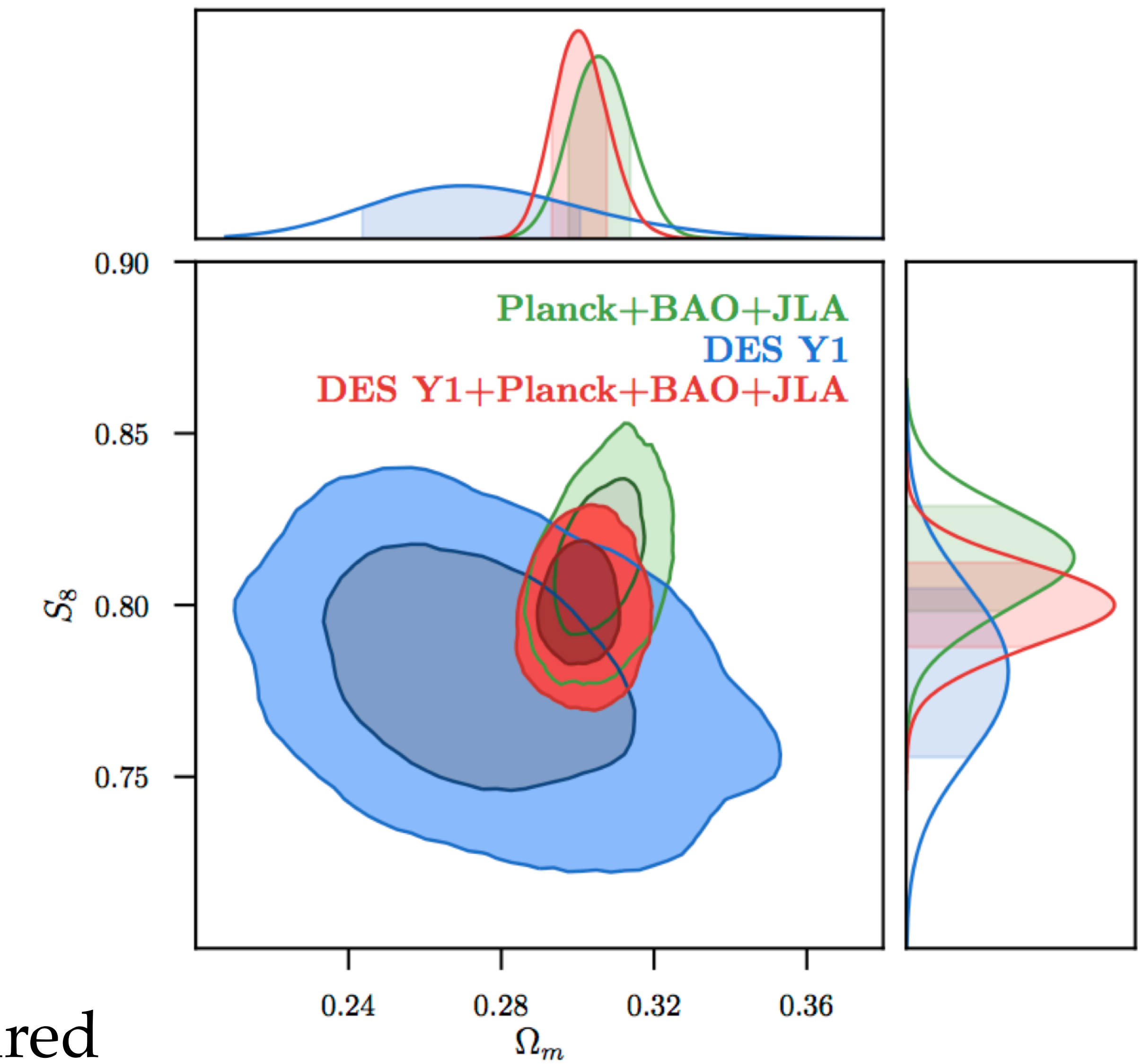
$$S_8 = 0.802 \pm 0.012.$$

$$h = 0.685^{+0.005}_{-0.007}$$

wCDM :

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

Introducing w is not formally favoured



another lensing survey KiDS

kilo degree survey

- Will map 1500 deg^2 in four broad-band filters (u, g, r, i)
- OmegaCAM has 32-ccd, 300-million pixel camera on the VST.
- Field of view is a full square degree,
- Smaller but a bit better resolution and site (seeing) than DECam.

KiDS-450: Cosmological parameter constraints from tomographic weak gravitational lensing

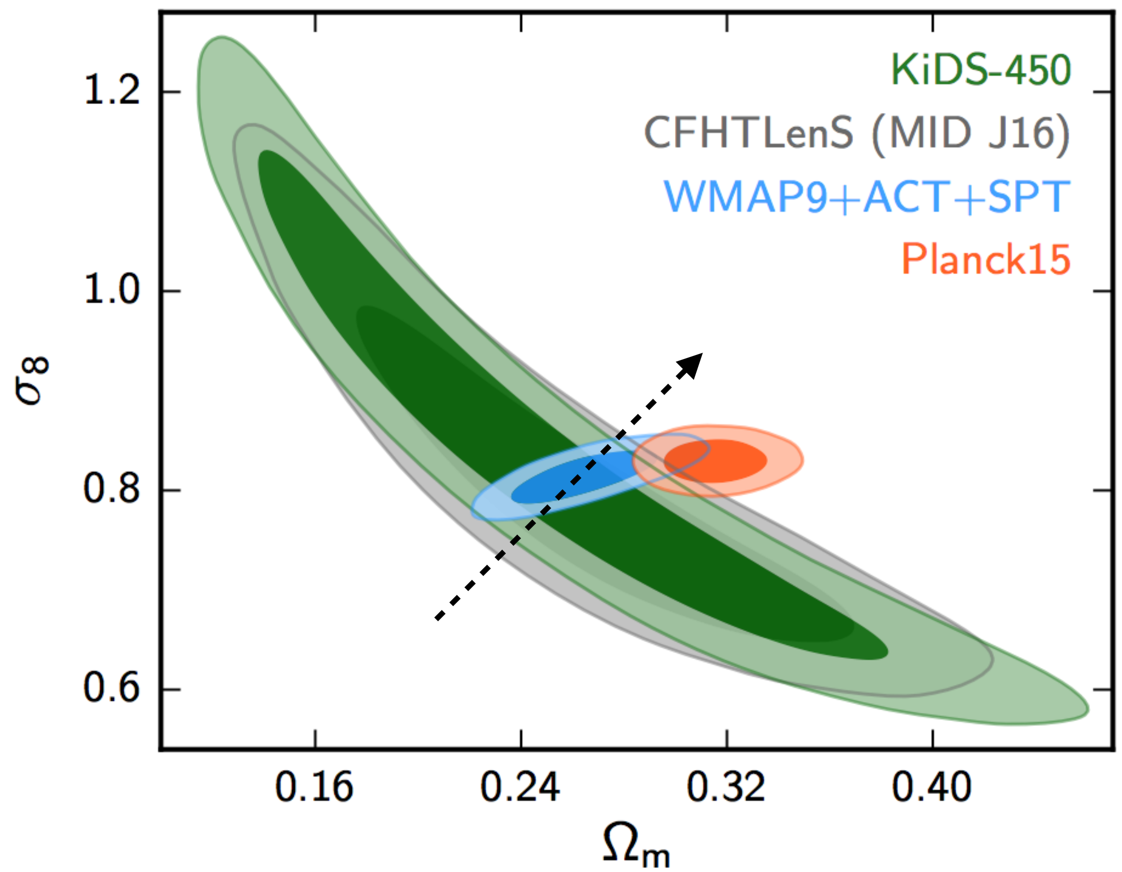
H. Hildebrandt[1*],

KiDS-450

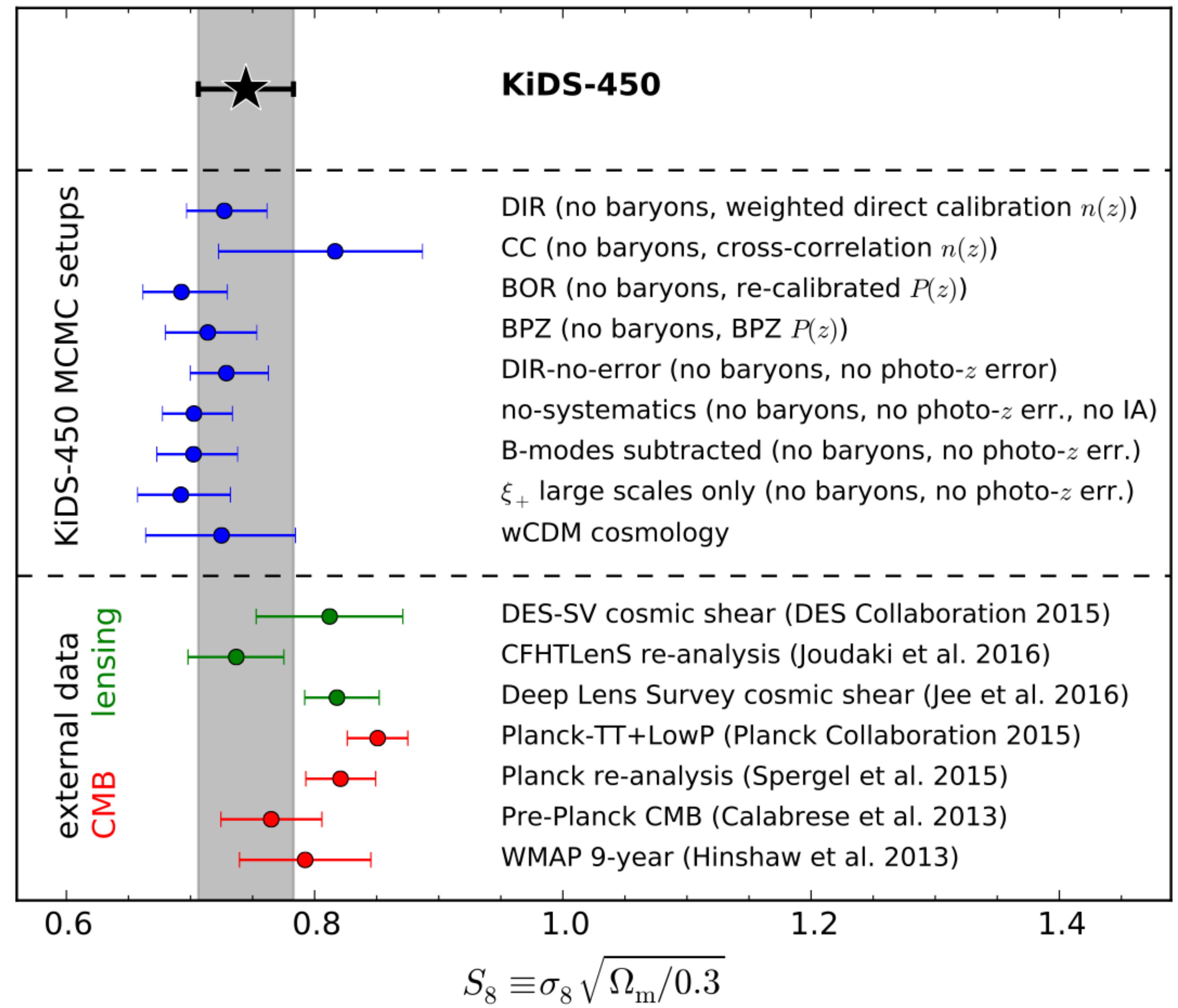
- 15 million galaxies in 450 deg^2
- one shape measurement pipeline
- 3 photo-z error estimations

another lensing survey: KiDS

- (blind) Analysis of 4 tomographic bins 0.1 < z < 0.9



$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3} = 0.745 \pm 0.039.$$



There is a $2.3-\sigma$ tension with Planck 2015

Lensing surveys recap

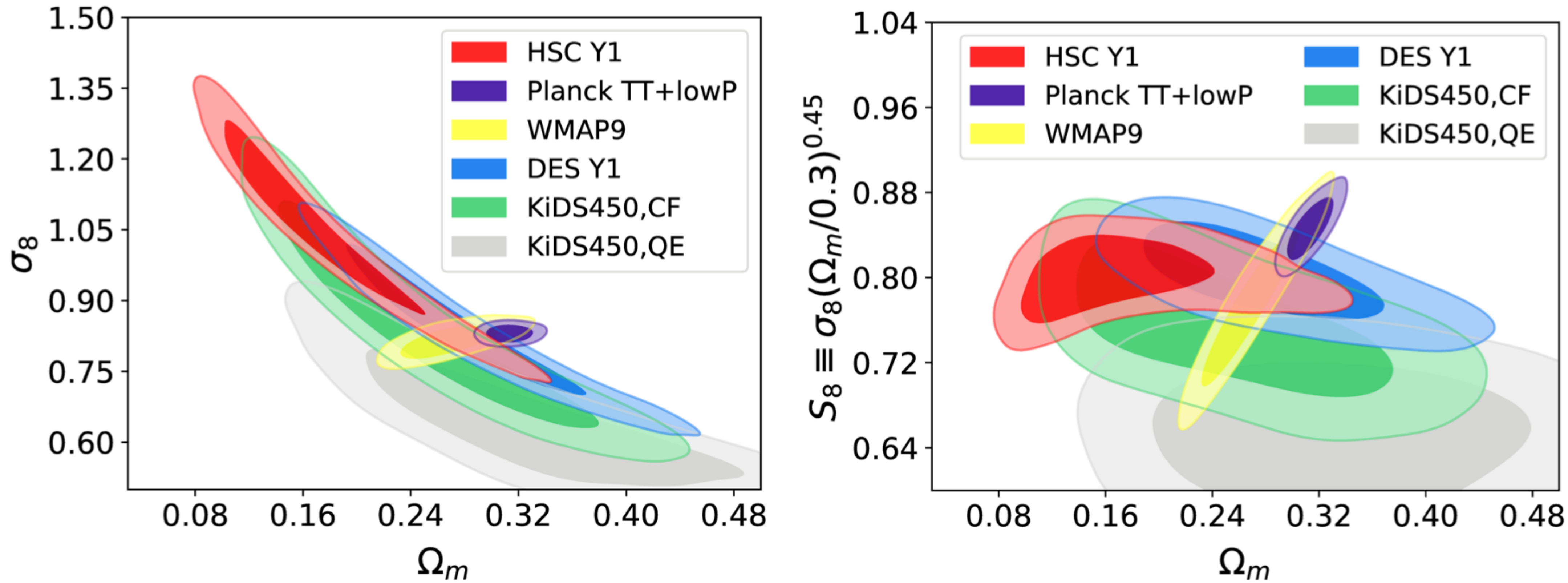
Results from other experiments also point towards low amplitude in weak lensing measurements [days ago]

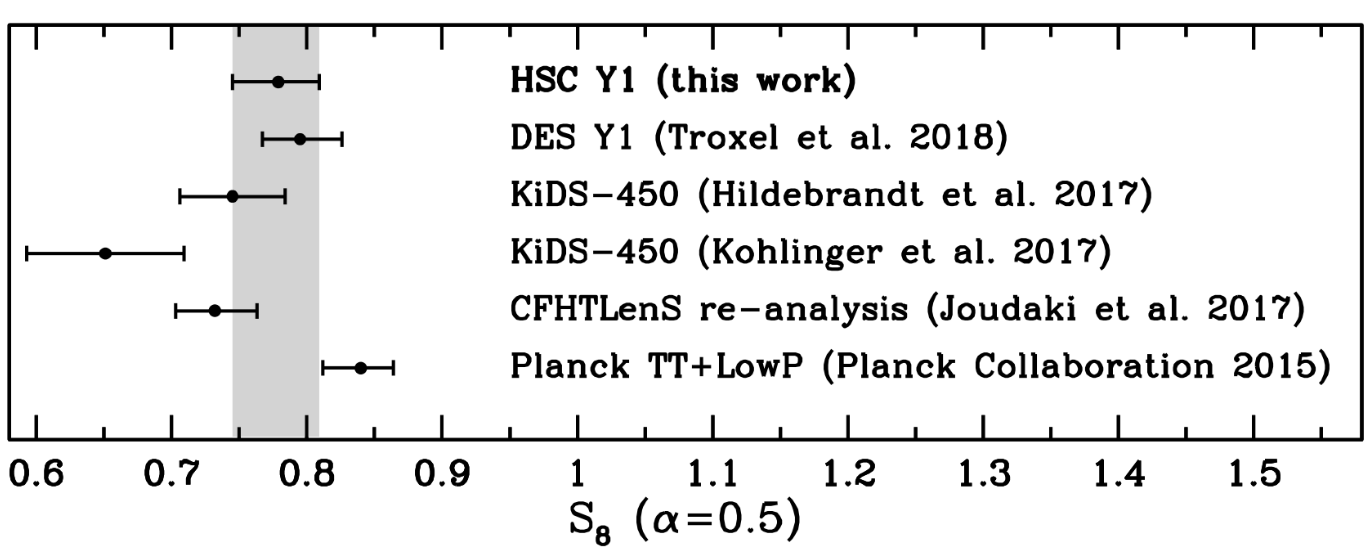
survey catalog	area [deg^2]	No. of galaxies	$n_{\mathrm{g,eff}}$ [arcmin^{-2}]	z range	tomography
KiDS-450	450	14.6M	6.85	0.1 – 0.9	4 bins
DES Y1	1321	26M	5.14	0.2 – 1.3	4 bins
HSC Y1	137	9.0M	16.5	0.3 – 1.5	4 bins

Hildebrandt et. al 2017
Troxel et al. 2017
Hikage et al. 2018

Lensing surveys recap ; they agree!

Results from other experiments also point towards low amplitude in weak lensing measurements [HSC results two days ago]





Hikage et al. 2018

DES KiDs HSC should take weak lensing science to another level

- Improve the photo-z methodology for redshift estimation
- Shape measurement pipelines
- Understand / calibrate the impact of baryon physics
- Limit the impact of intrinsic alignments
- Set up for multi-probe combination

& open the door to some of the largest surveys doing both (from space!)

The future

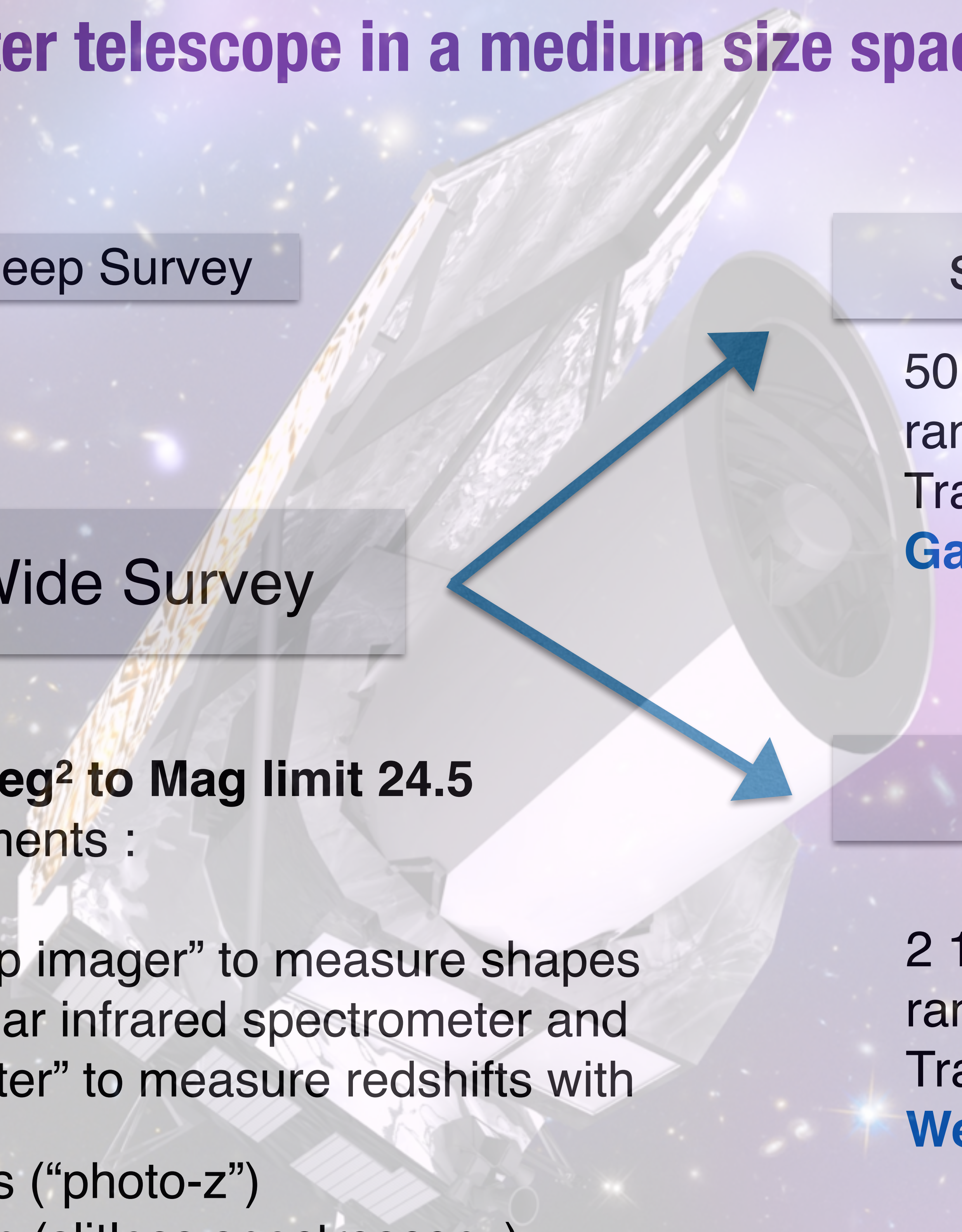
Euclid / ESA mission

Euclid

1.2 meter telescope in a medium size space mission

Deep Survey

Wide Survey



15,000 deg^2 to Mag limit 24.5

2 instruments :

VIS “deep imager” to measure shapes
NISP “near infrared spectrometer and photometer” to measure redshifts with

- filters (“photo-z”)
- grism (slitless spectroscopy)

An artist view of the Euclid satellite – courtesy ESA

spectroscopic survey

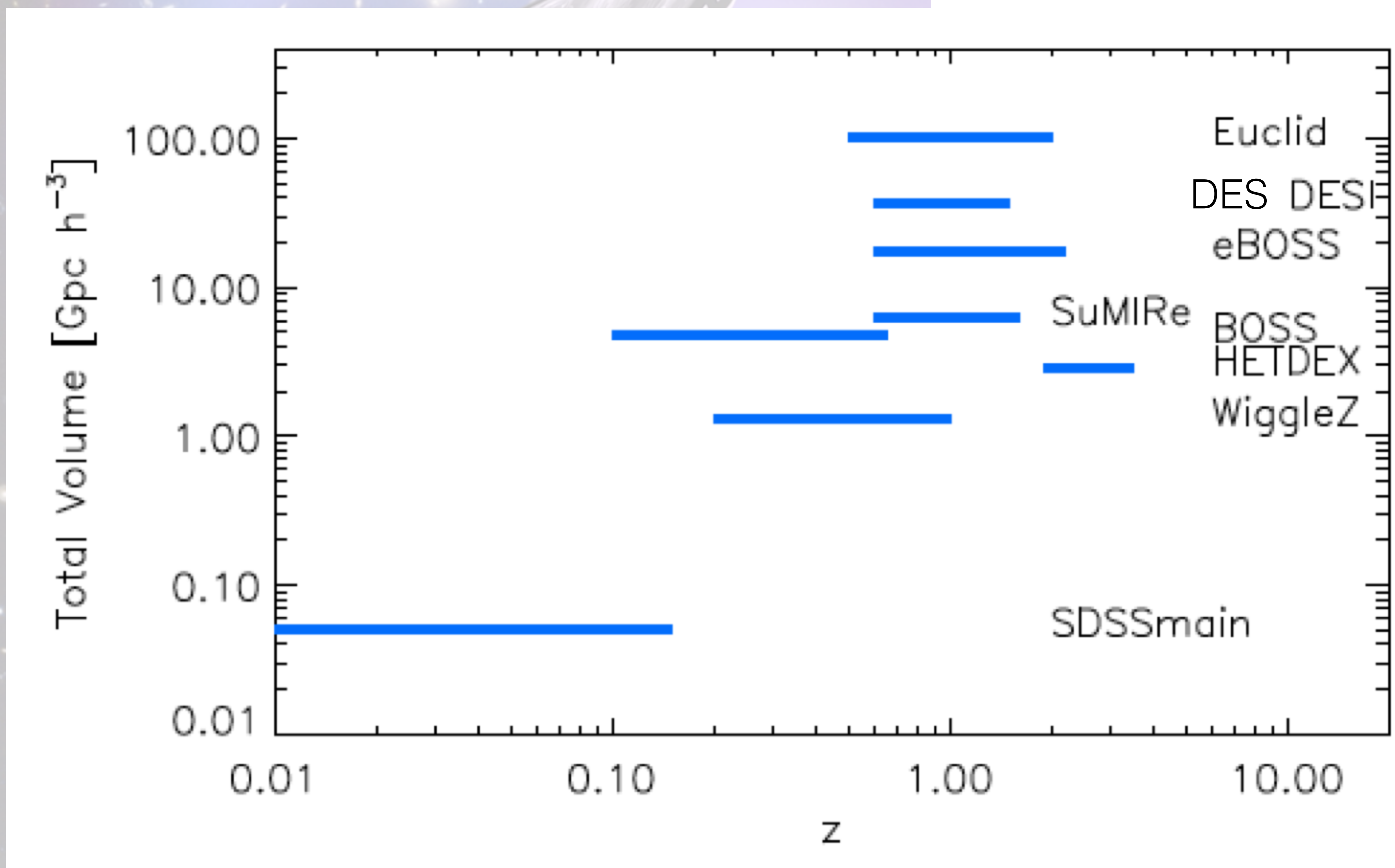
50 million galaxies in the range $1 < z < 2$
Trace 3D distribution of galaxies
Galaxy Clustering

imaging survey

$2\ 10^9$ million galaxies in the range $0 < z < 2$
Trace the dark matter in tomography
Weak Gravitational Lensing

Euclid

1.2 meter telescope in a medium size space mission



An artist view of the Euclid satellite – courtesy ESA