Constraining Gravity with Large Scale Structure

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CMB

LSS surveys

Why galaxy surveys?

The main goals

The main probes:

RSD and Growth History

BAO and Expansion History

The present

Galaxy Clustering

BOSS

The ongoing

Weak Lensing surveys

Dark Energy Survey

KiDS

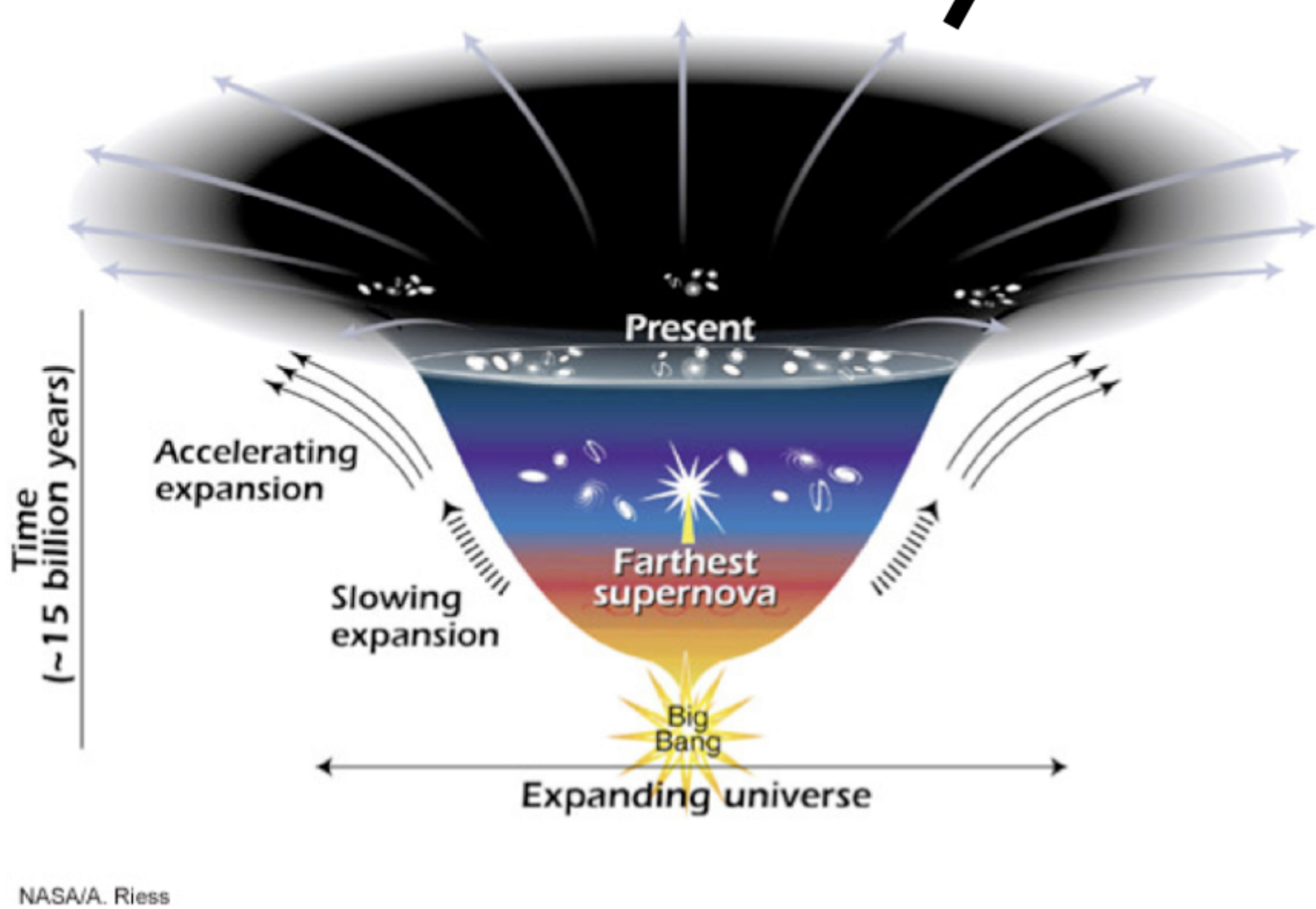
The future

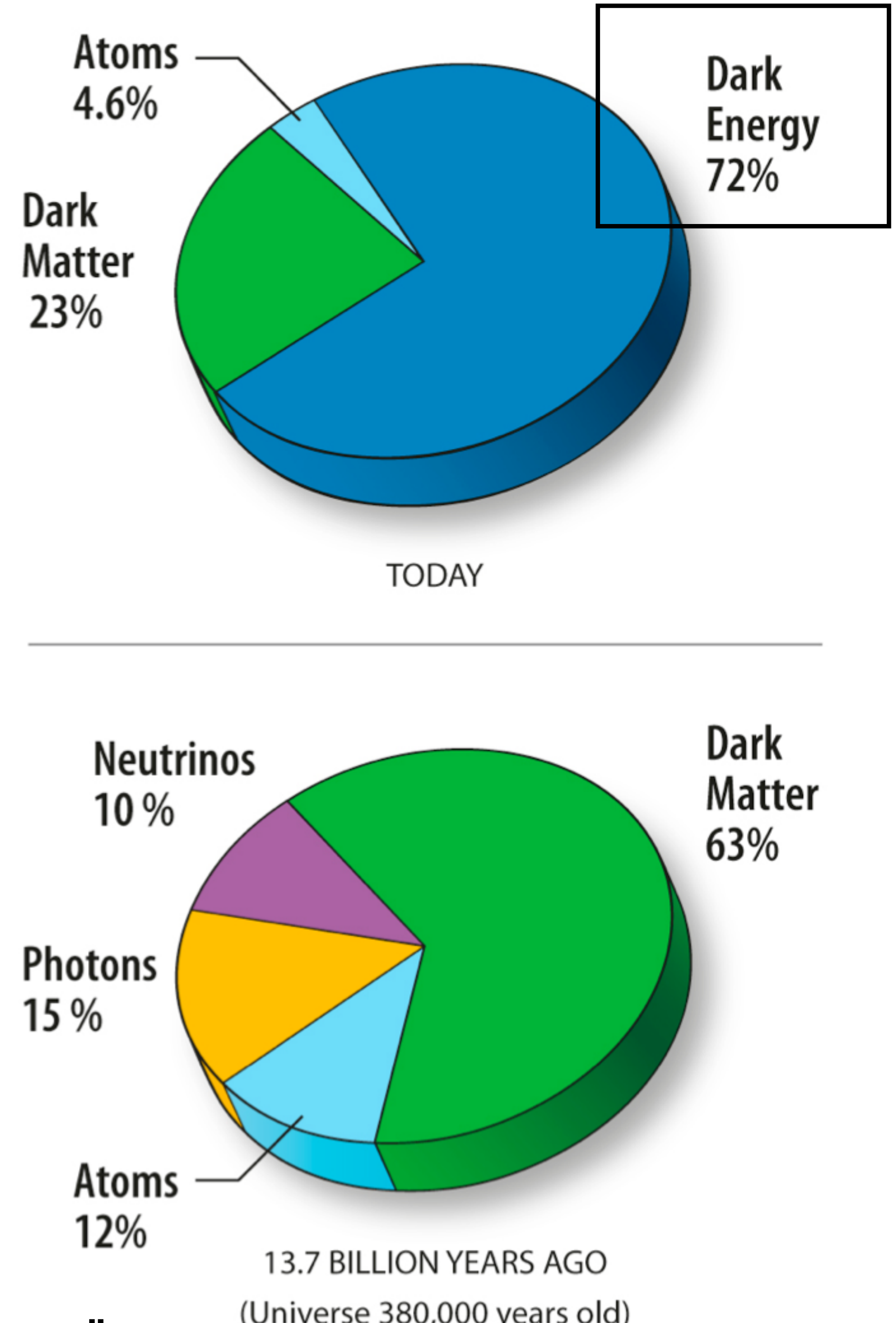
GC + WL + CMB

Euclid Satellite

Current cosmological model

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



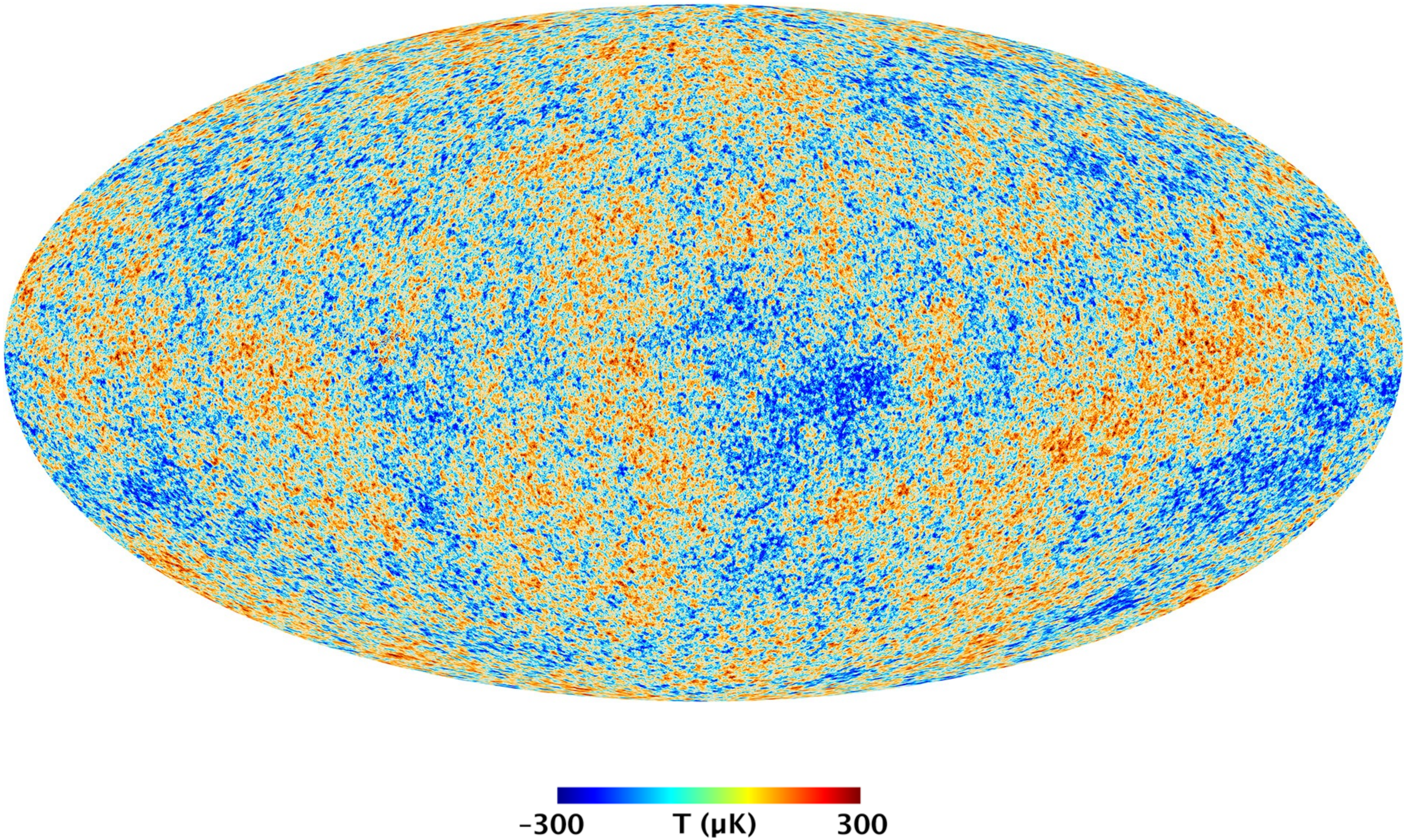


- It is a “concordance” model although with some “tensions”

credit : NASA

The success of the CMB

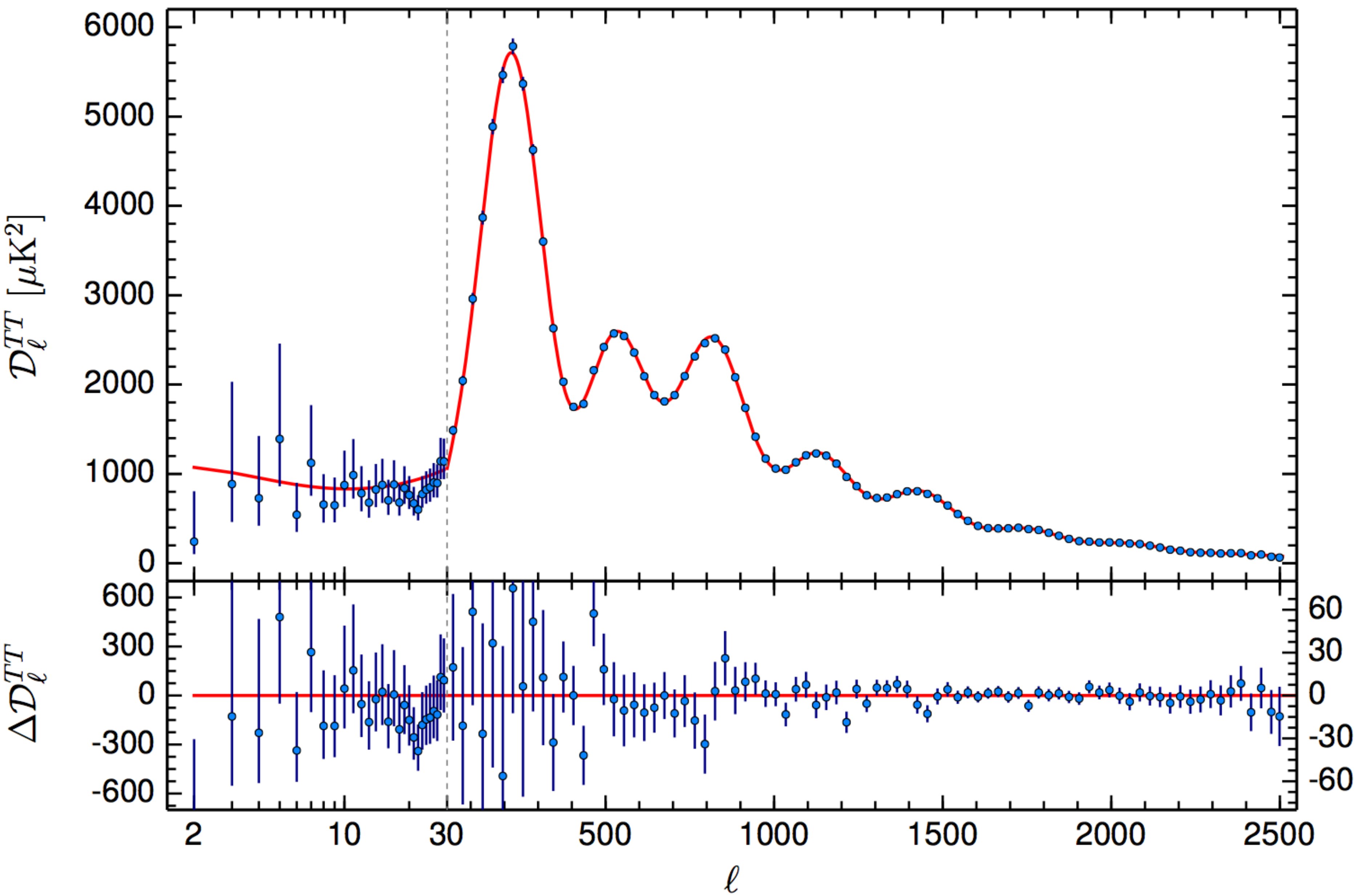
COBE, WMAP, Planck ..



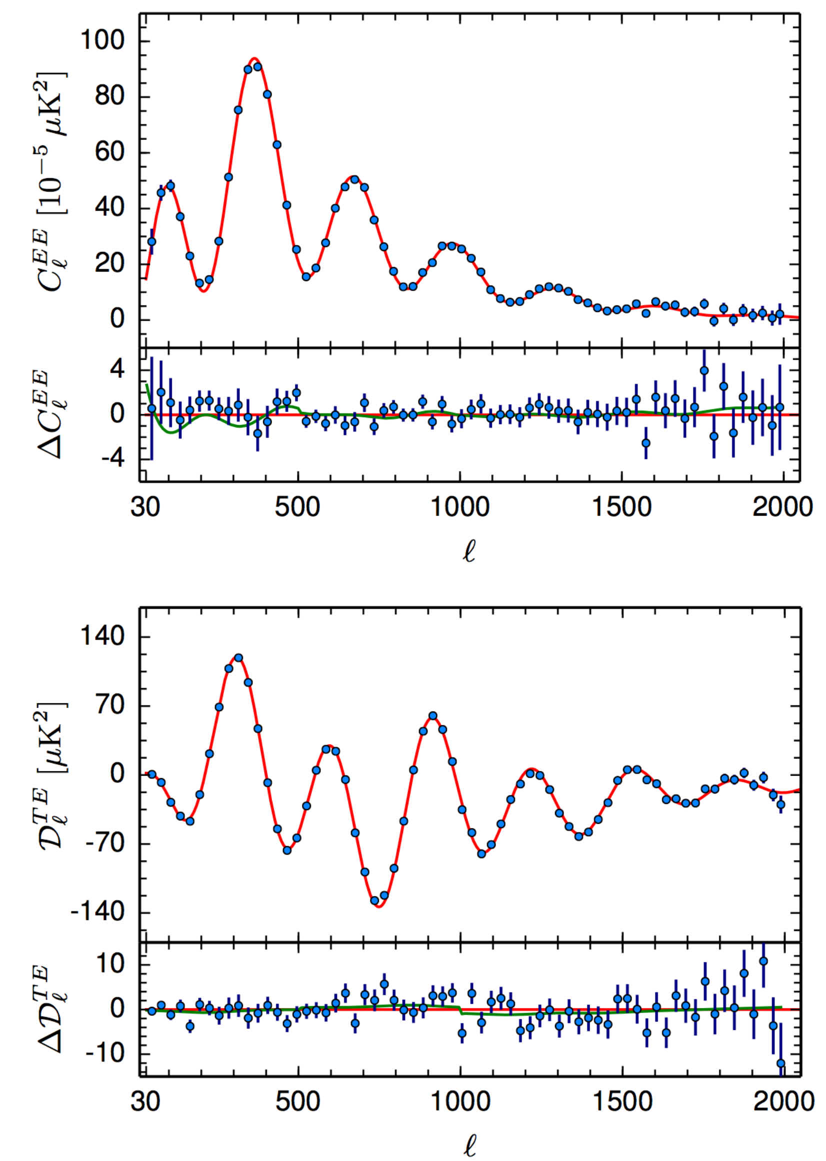
The success of the CMB

COBE, WMAP, Planck ..

Temperature



Polarization



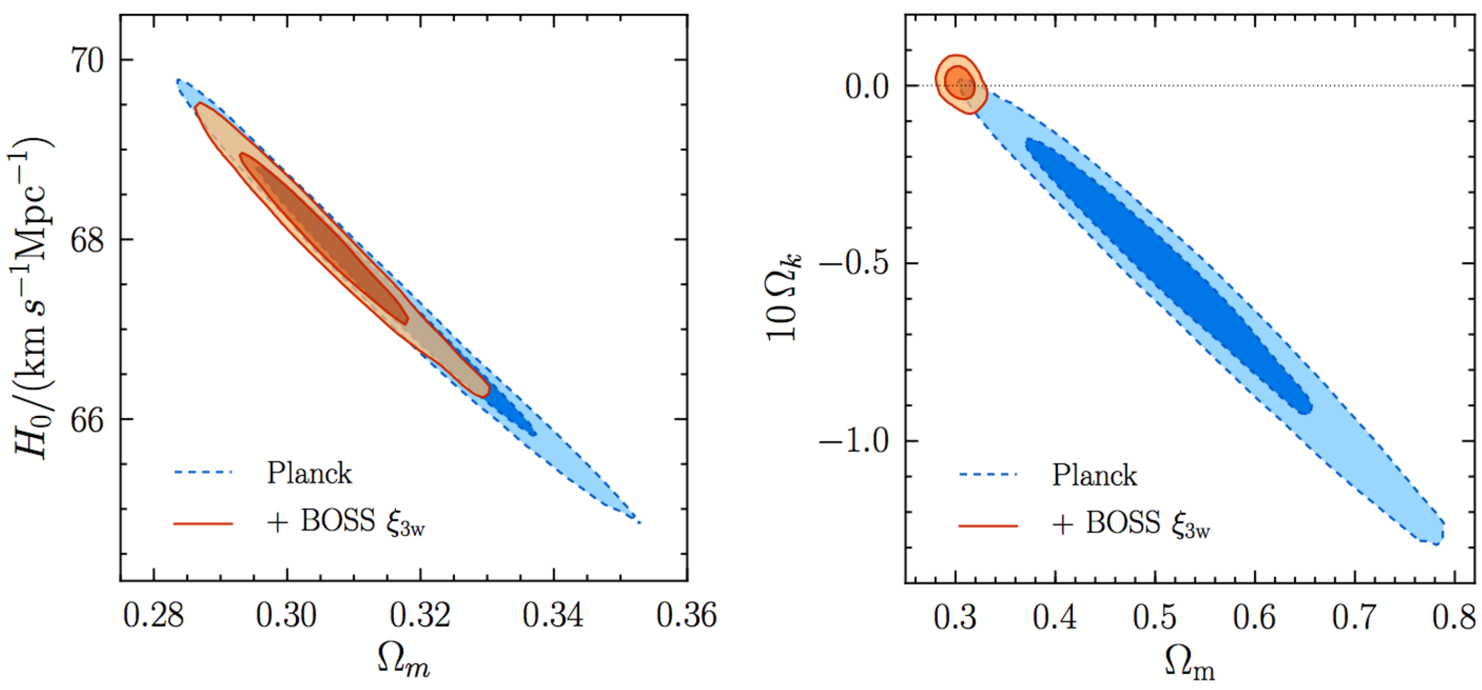
Planck Collaboration: Cosmological parameters

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



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.

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

Bottom line

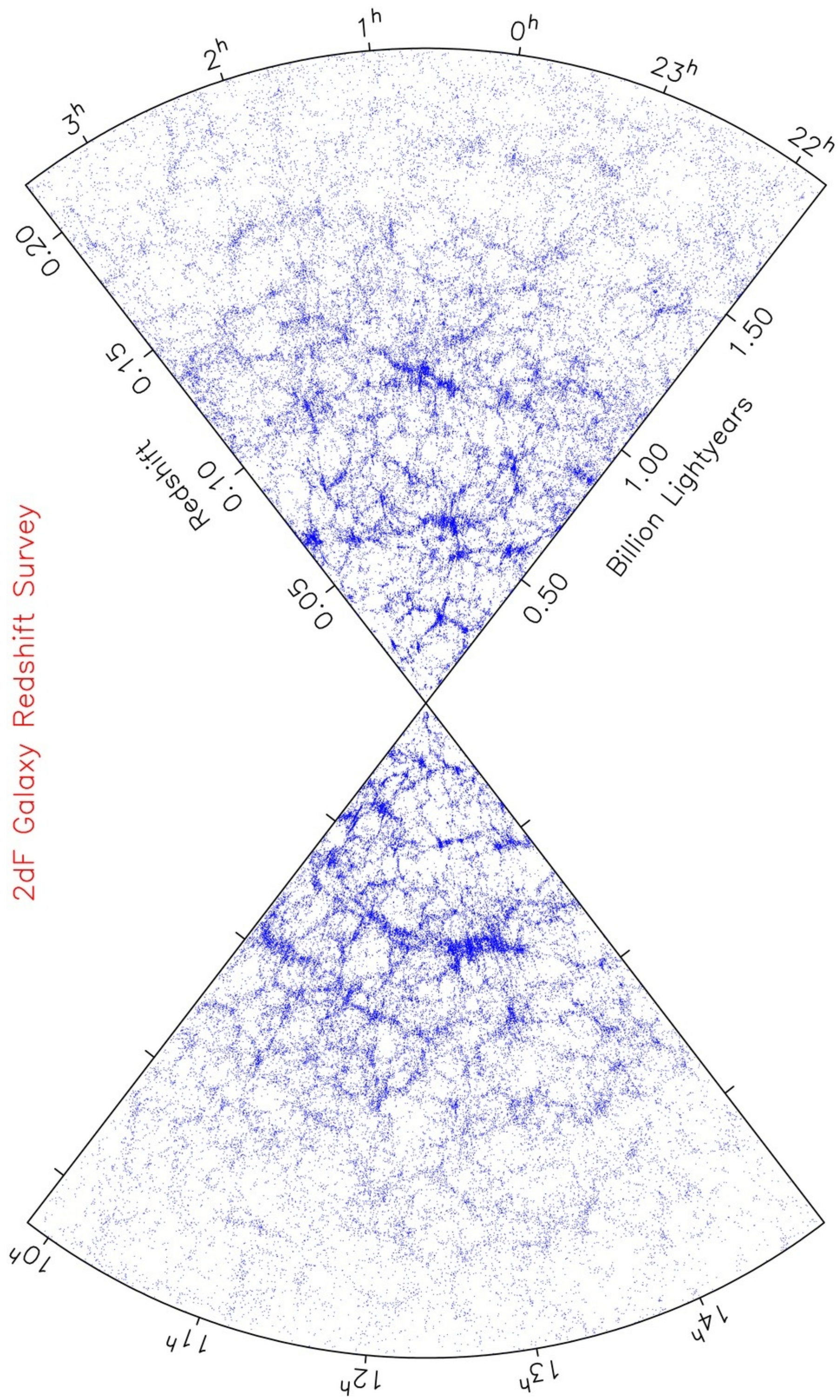
CMB power spectrum provides strong evidence that dark energy exists, but its sensitivity to the actual nature of this component is limited.

Extension to the “simplest” LCDM can’t be constrained e.g.

- nature of dark matter (although we have ruled about baryonic origin)
- nature of dark energy (other than Lambda, e.g. quintessence fluid)
- modifications of gravity and growth of structure
- 3D mapping (test isotropy and homogeneity)

.. room for galaxy surveys

.. 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?

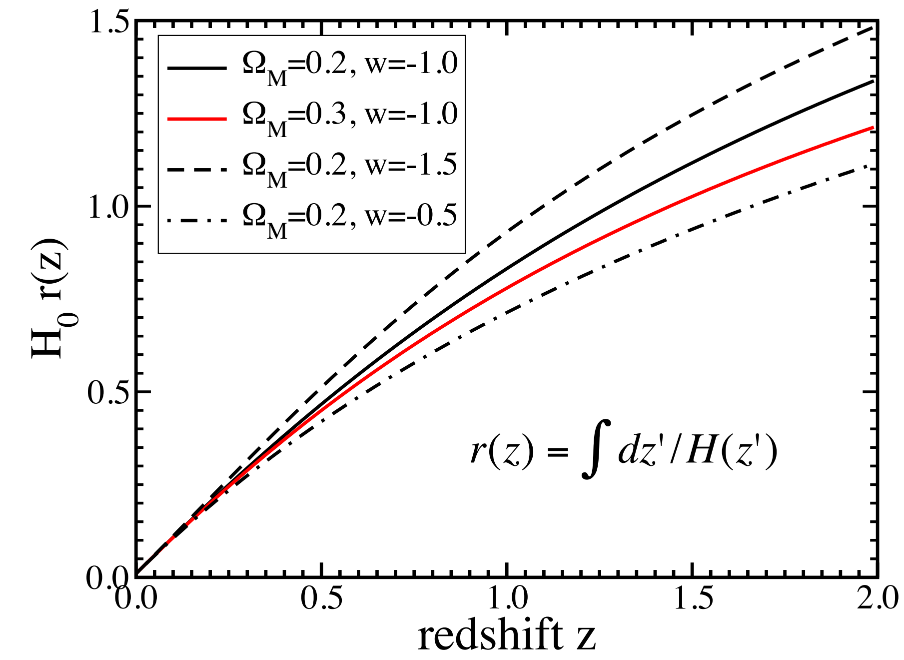
Dark Matter: What is dark matter? What is the absolute neutrino mass scale and what is the number of relativistic species in the Universe?

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)

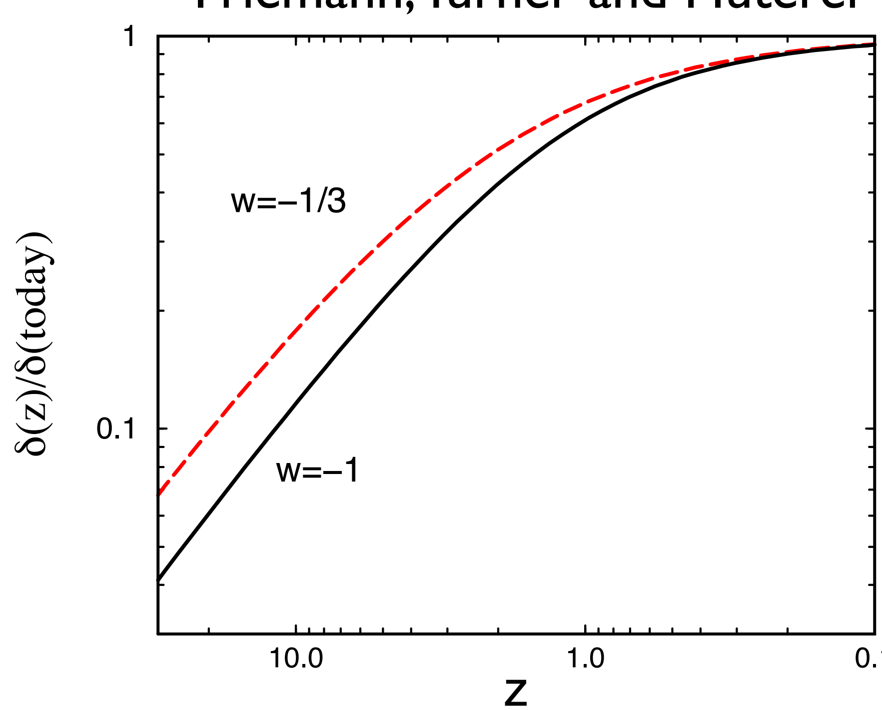
✦ redshift tells degree of expansion
✦ light-travel distance = time



➡ Dynamics: structure growth
(growth history)

✦ growth rate depends on matter density
✦ evolution in matter density ⟷ evolution in dark energy density

Friemann, Turner and Huterer



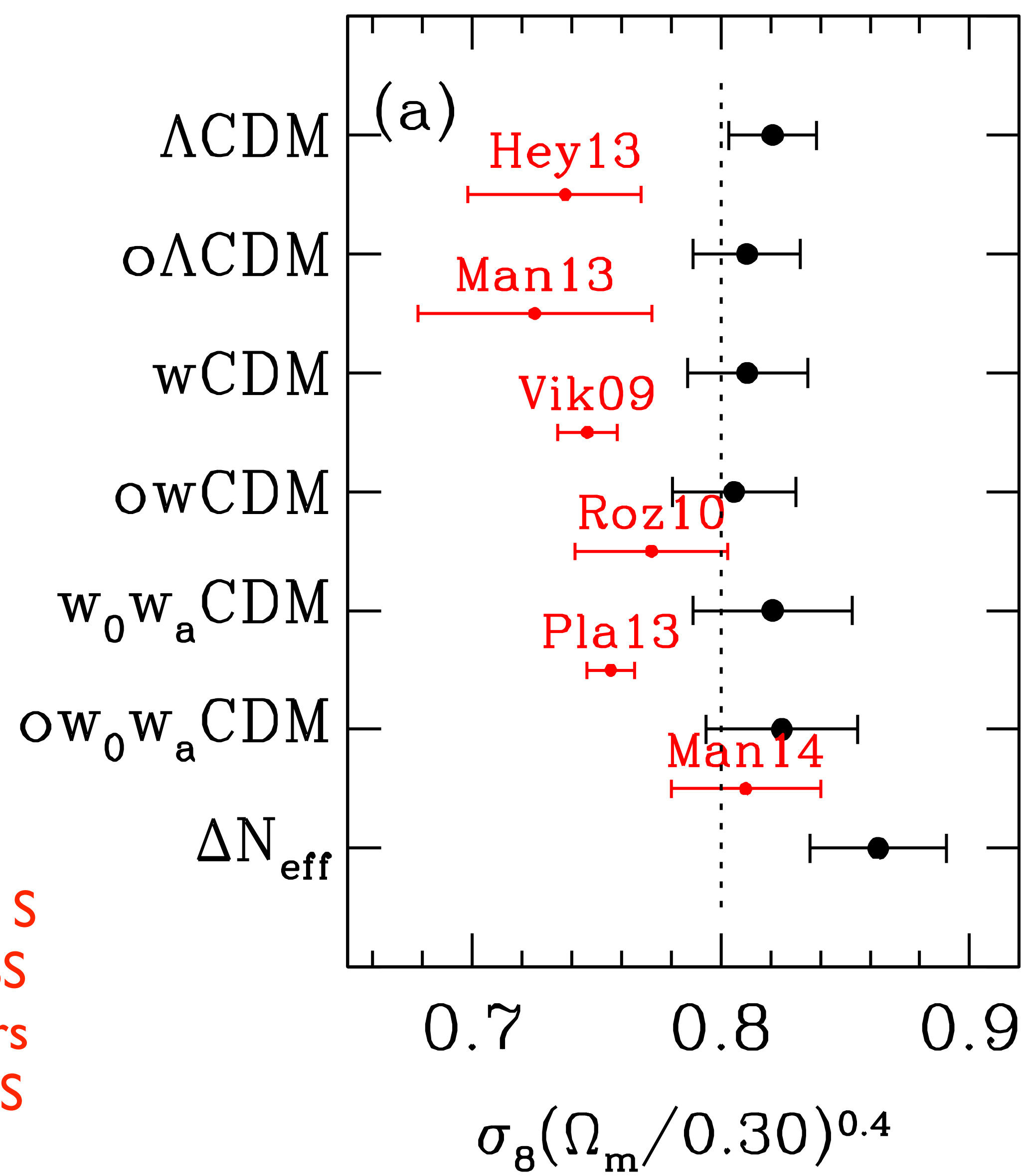
we need both to disentangle GR vs DE !

Measuring Dark Energy

Currently there is some tension between geometrical and structure growth measurements

Red points: structure growth measurements at low-z

- 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



level of matter clustering

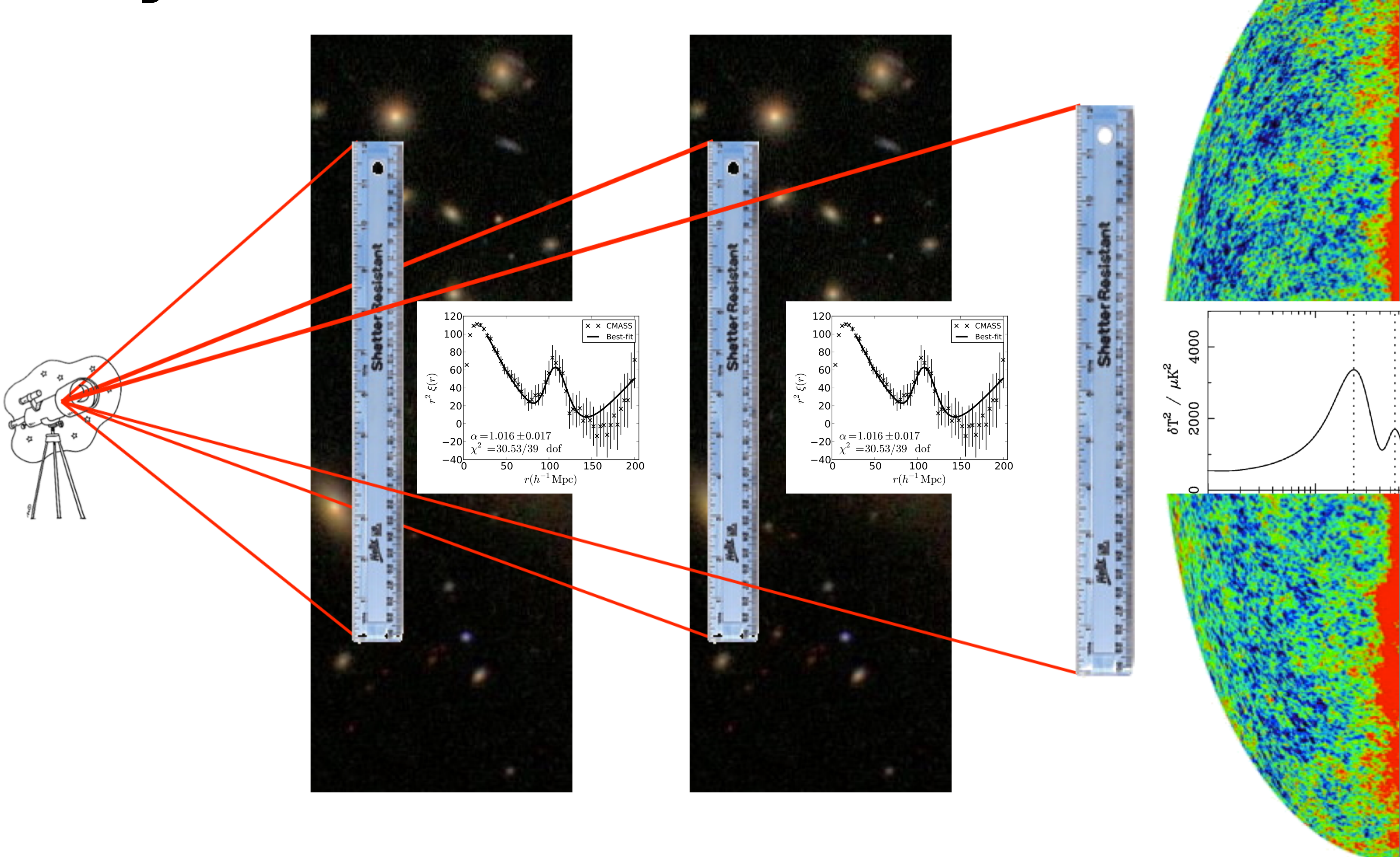
Black points: Derived from geometrical measurements for DE model

BAO + SNIa + CMB

Aubourg et al. (2014)

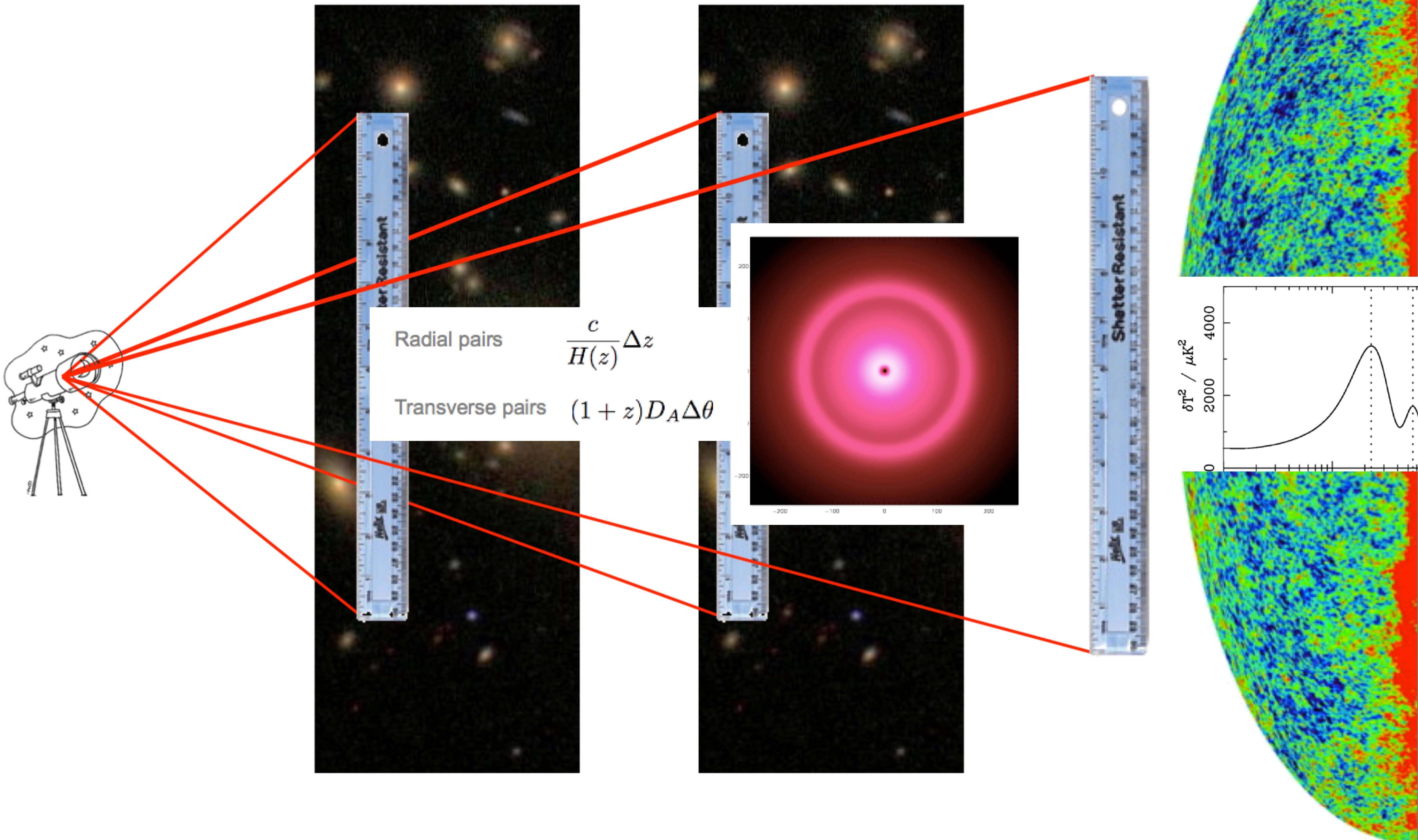
credit : NASA / WMAP

Baryon Acoustic Oscillations



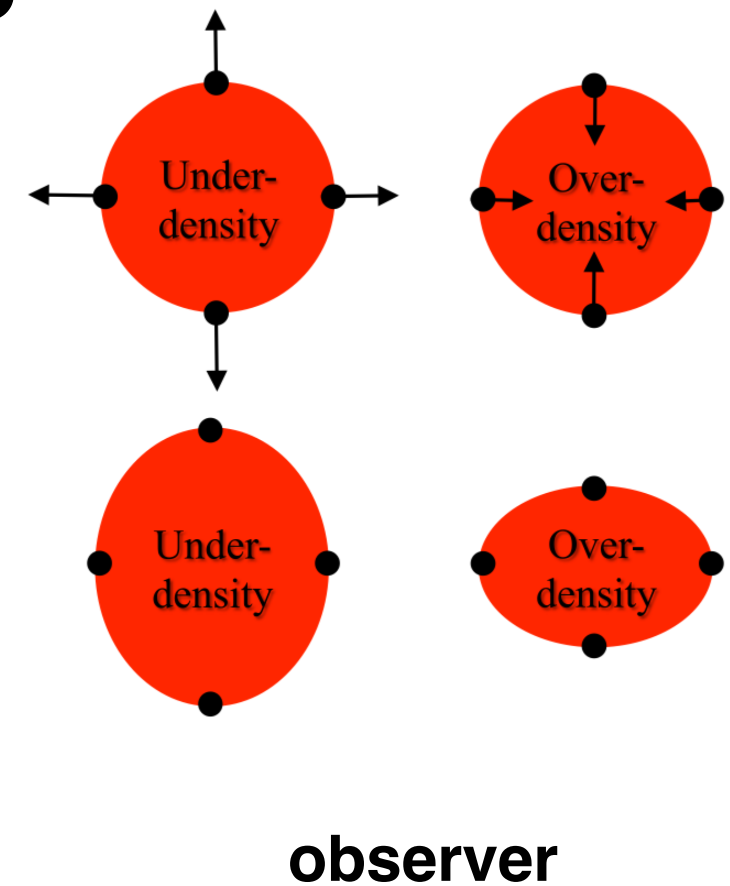
Use the acoustic peak in galaxies as a standard ruler, calibrated by CMB credit : NASA / WMAP

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

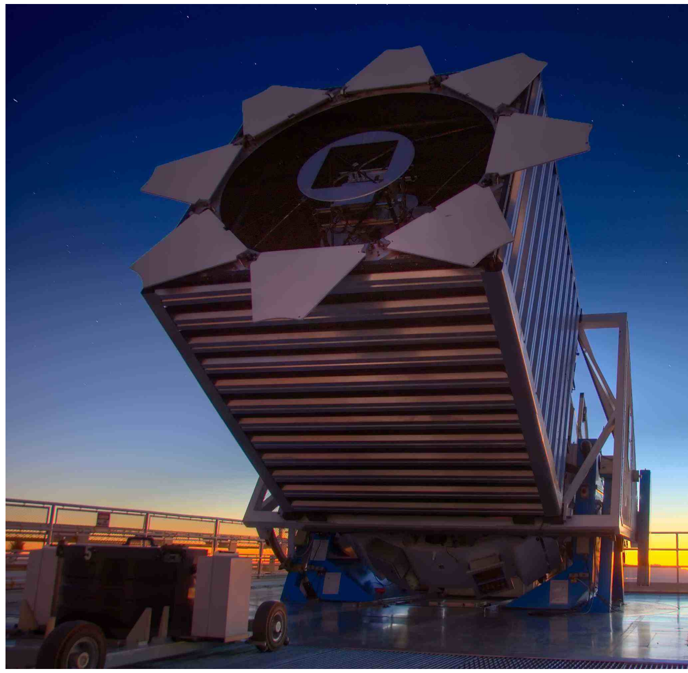
$$\nabla \vec{v} = \dot{\delta} = -f\delta \qquad f \equiv \frac{d \log D}{d \log a} \qquad f\sigma_8 \propto \frac{dD}{d \log a}$$

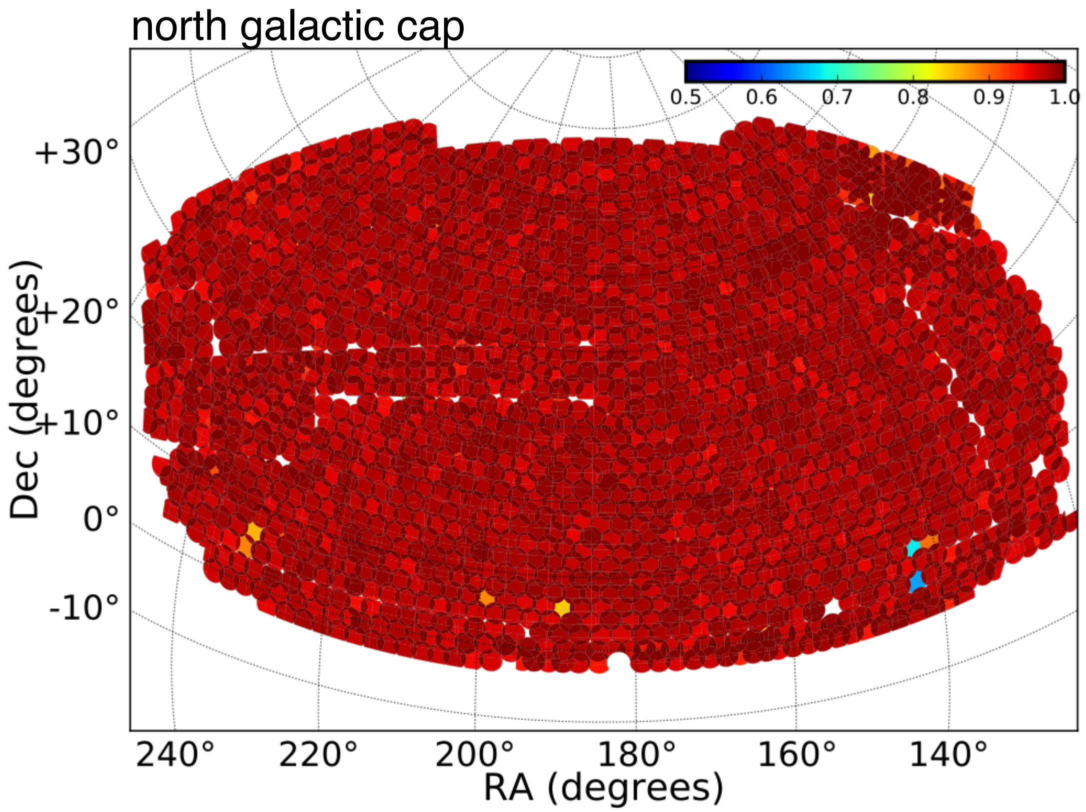
$$\delta_{\mathrm{gal}}(k,\mu) \quad = \quad \underbrace{b\delta_{\mathrm{mass}}}_{\text{intrinsic}} + \underbrace{\mu^2 f \delta_{\mathrm{mass}}}_{\text{z-space}}$$

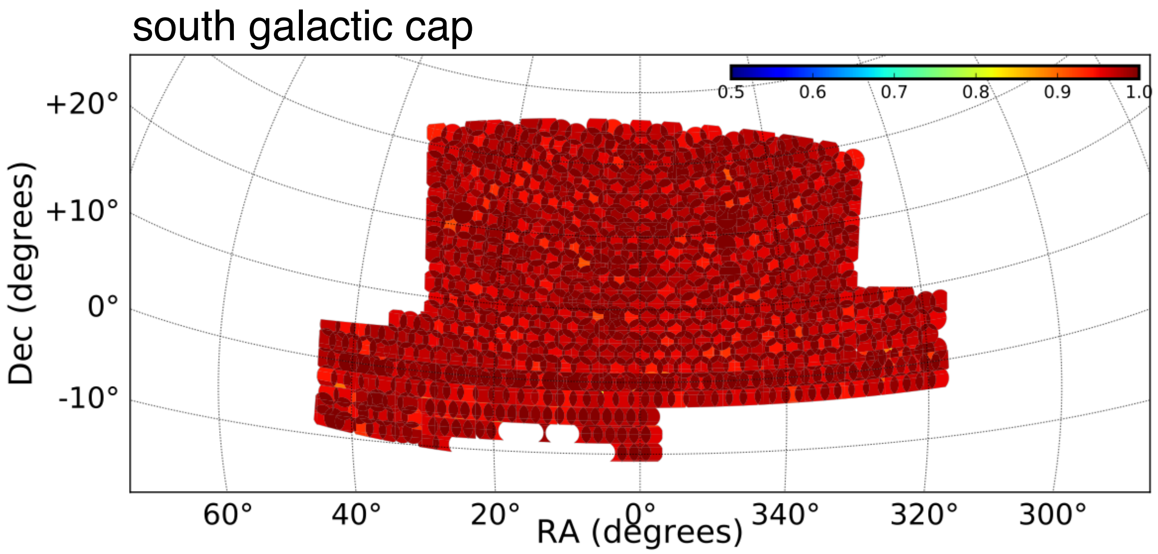
measure anisotropic 2-pt correlations

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

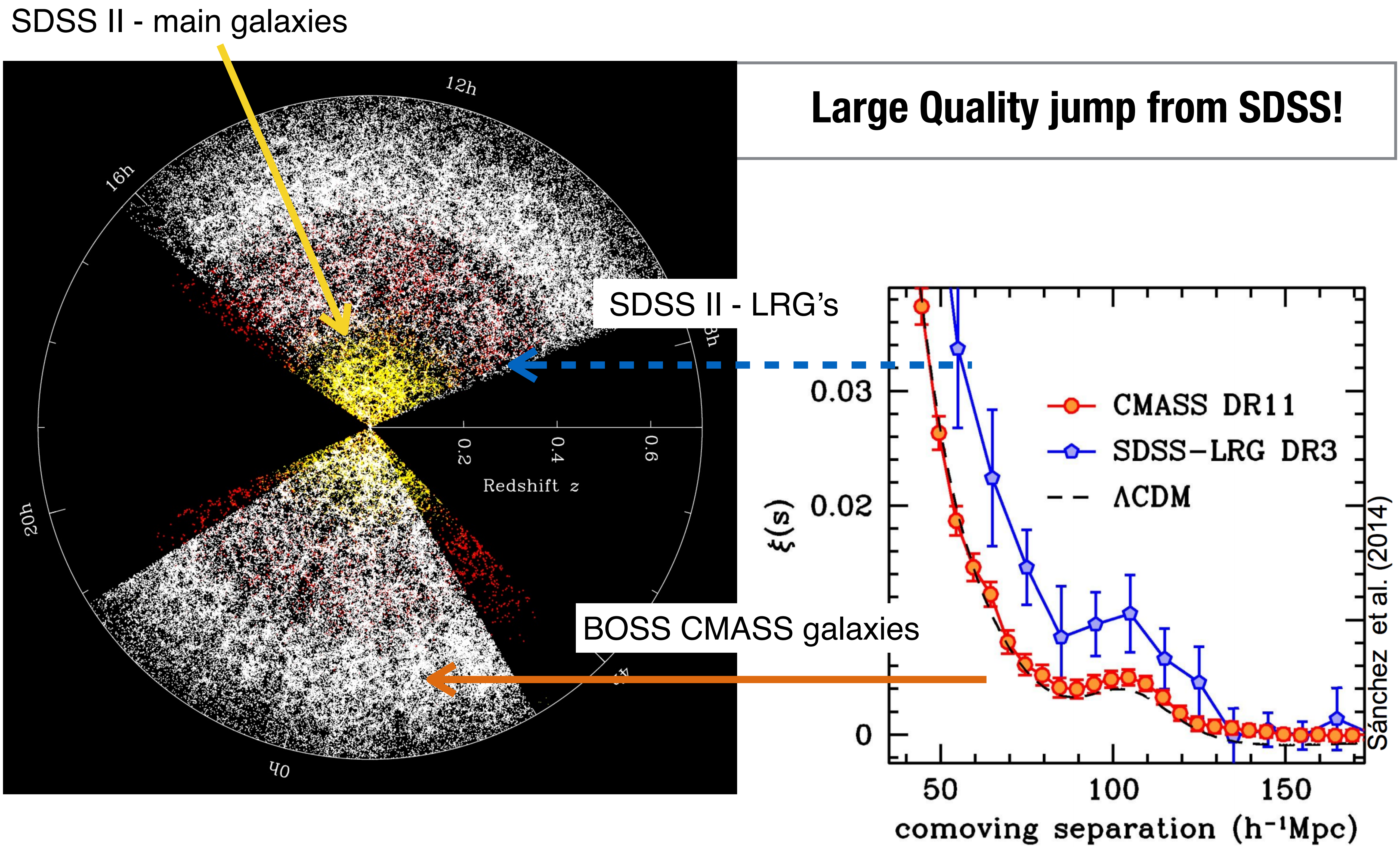






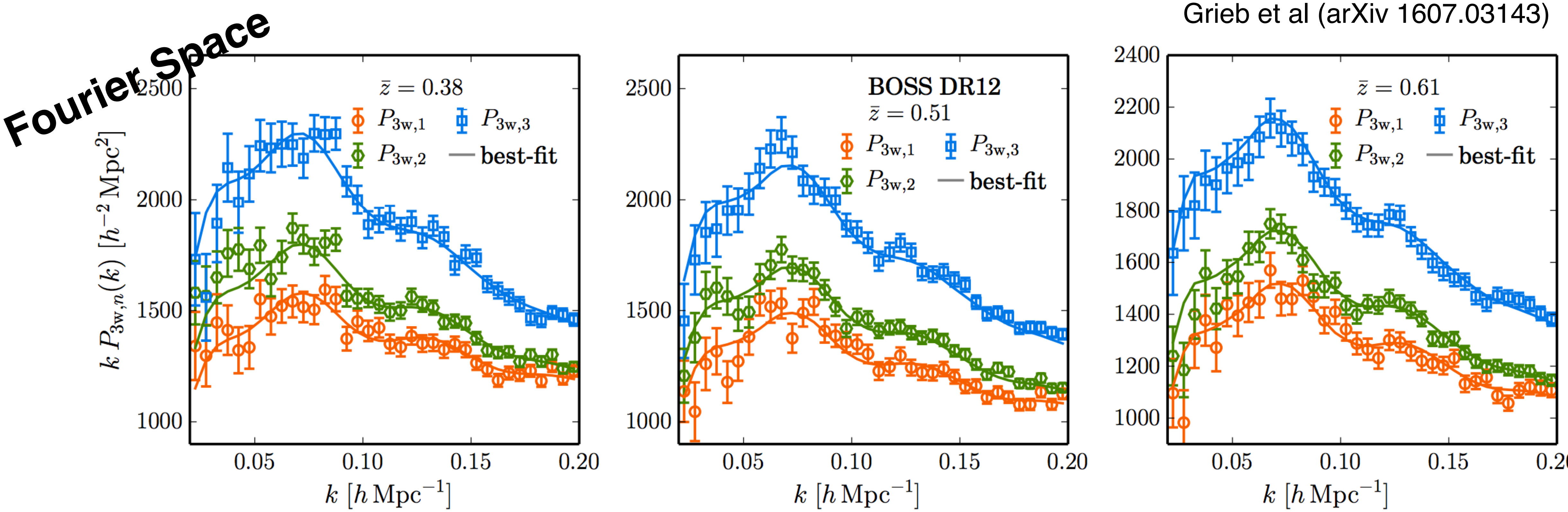
BOSS (baryon acoustic oscillation survey)

Large Quality jump from SDSS!

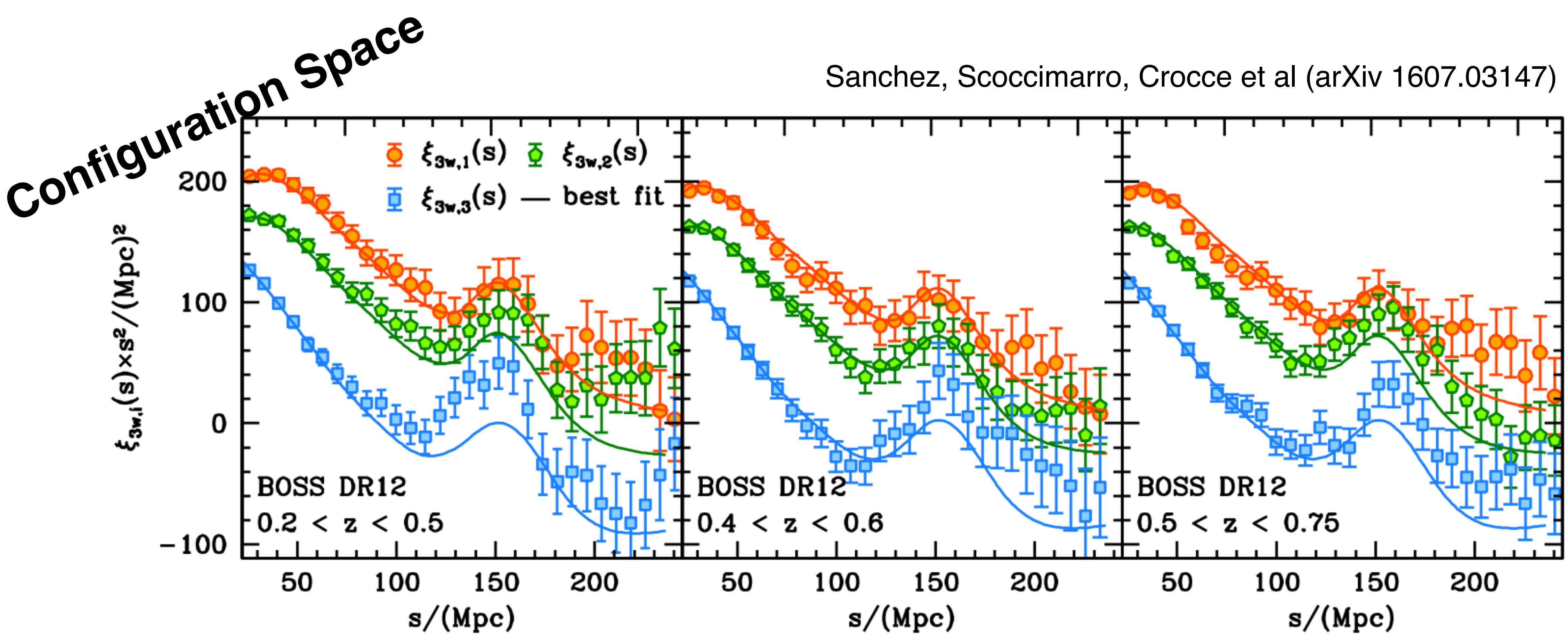


Clustering measurements

Grieb et al (arXiv 1607.03143)



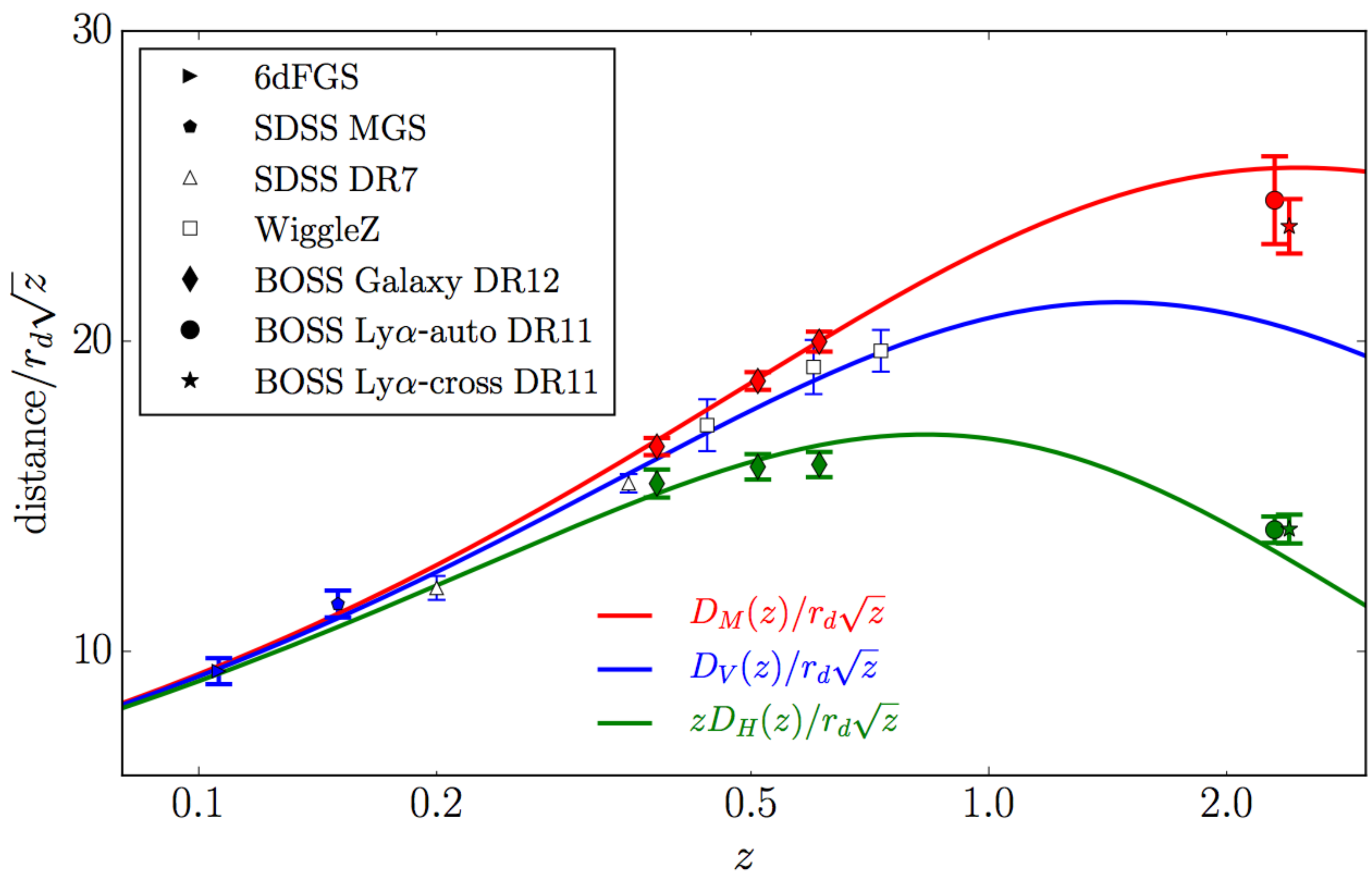
Sanchez, Scoccimarro, Crocce et al (arXiv 1607.03147)



Distance Measurements

Hubble diagram from Baryon Acoustic Oscillations

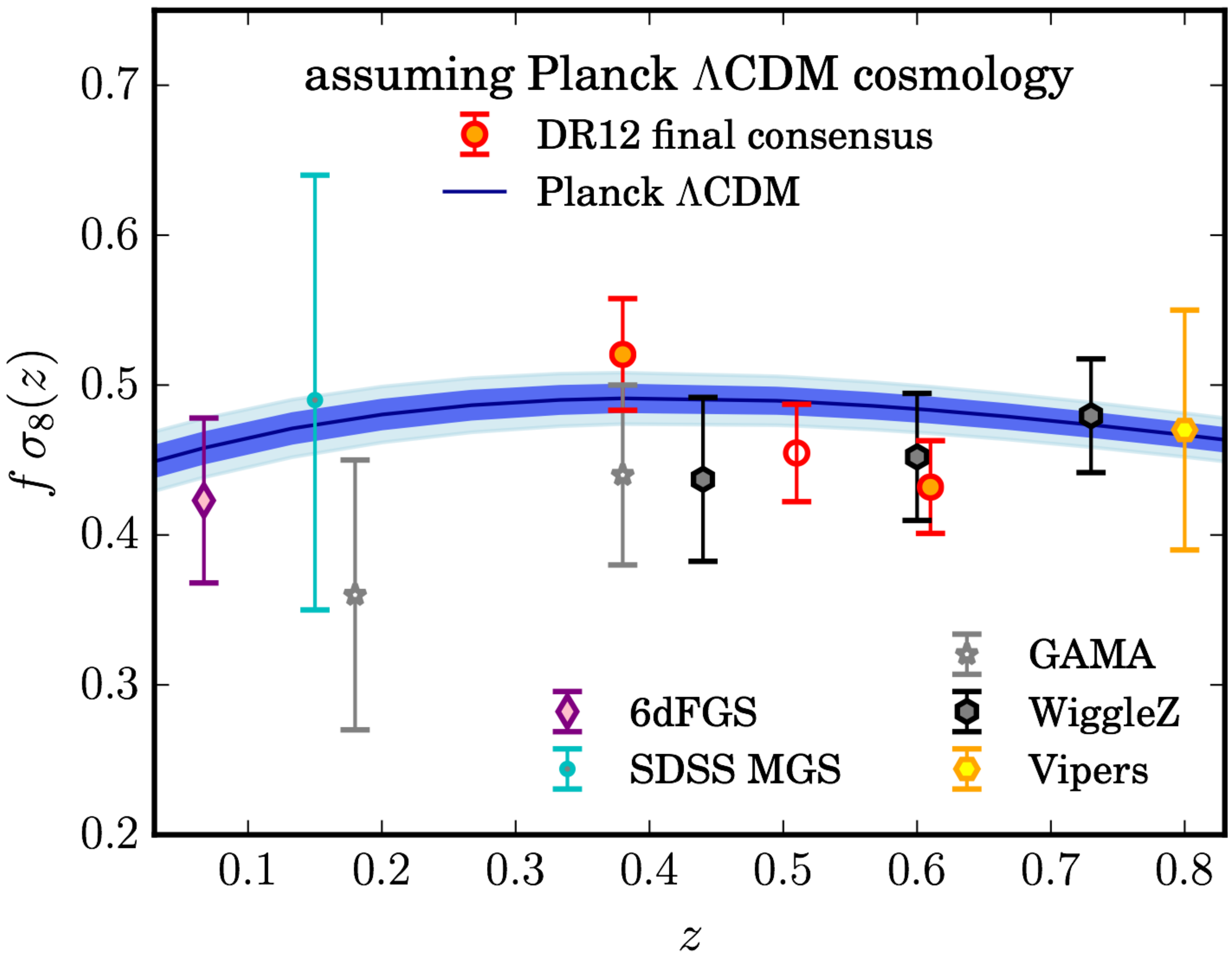
- Angular diameter distance better than 1.5% in all bins
- Hubble parameter better than 2.4% in all bins



Growth Measurements

from Redshift Space Distortions

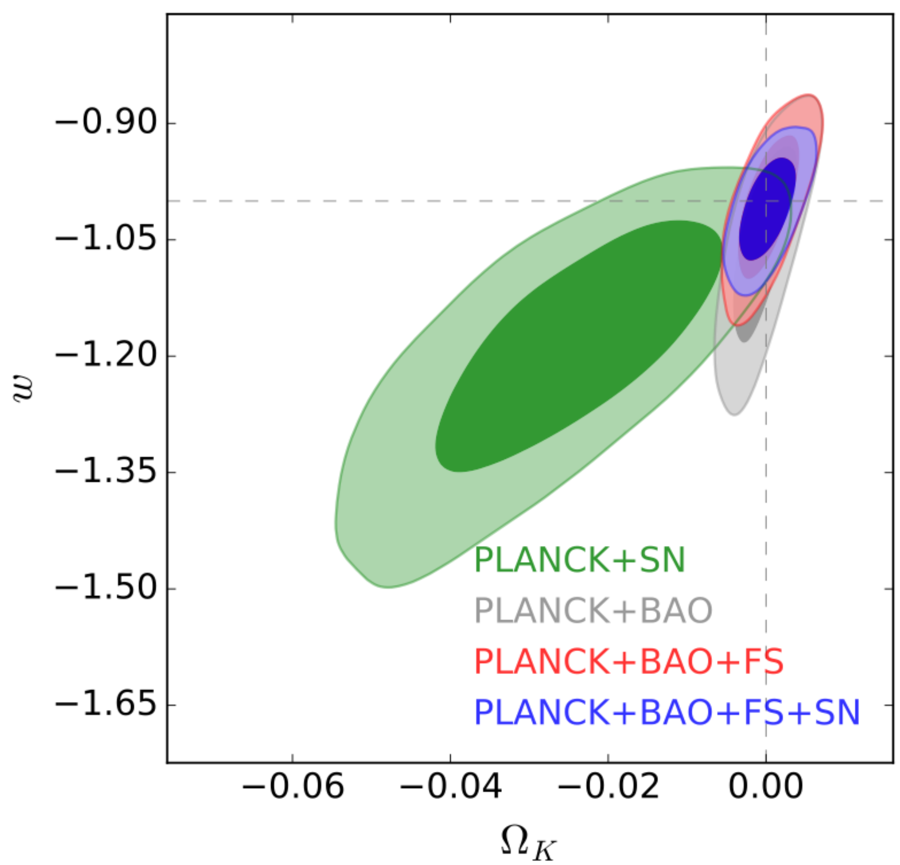
- about 9.2% or better precision in each bin



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

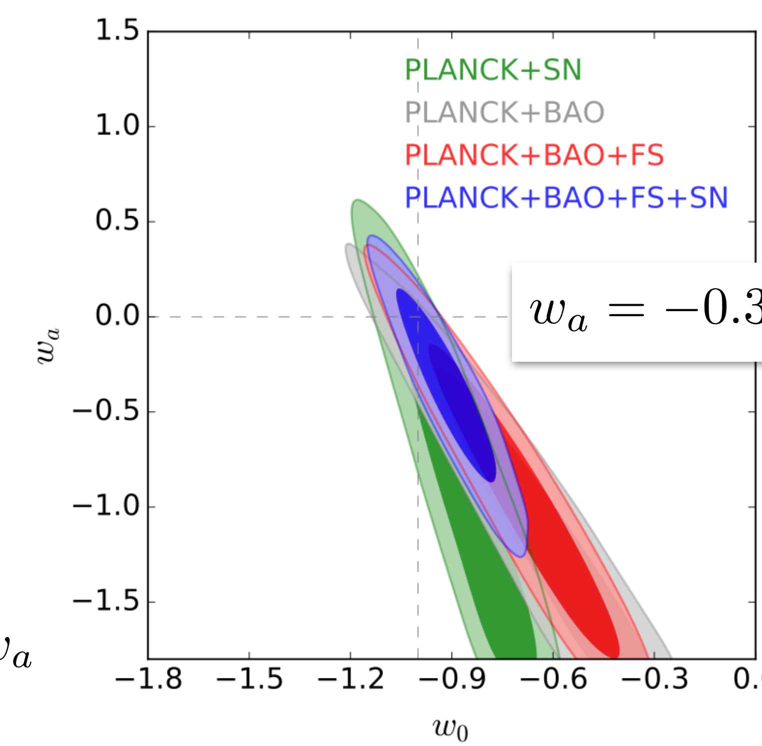
Opening two degrees of freedom (jointly or separately)

$\Omega_K = -0.0003 \pm 0.0027$	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)

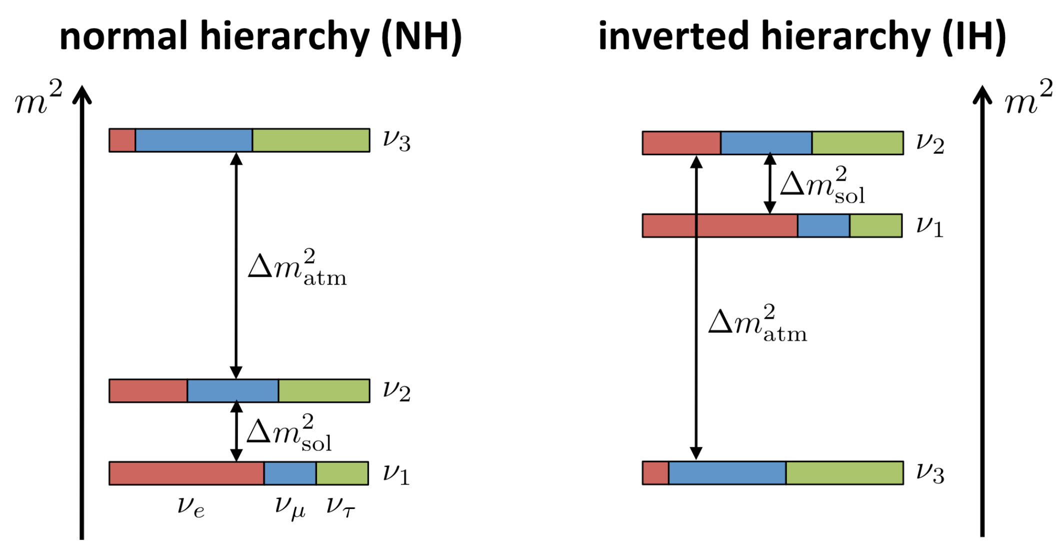
Massive Neutrinos

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

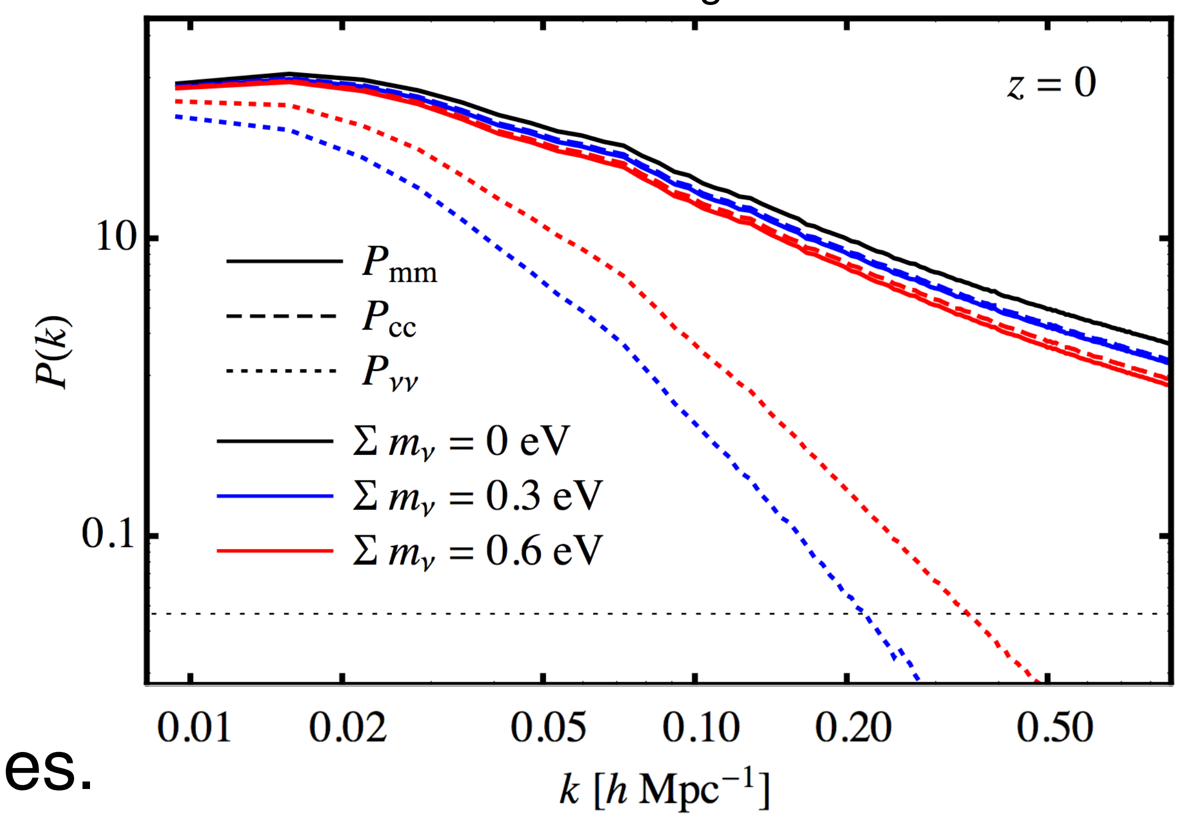
- Measure a non-zero detection of total mass
- Reach an upper limit that excludes the inverted hierarchy

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.

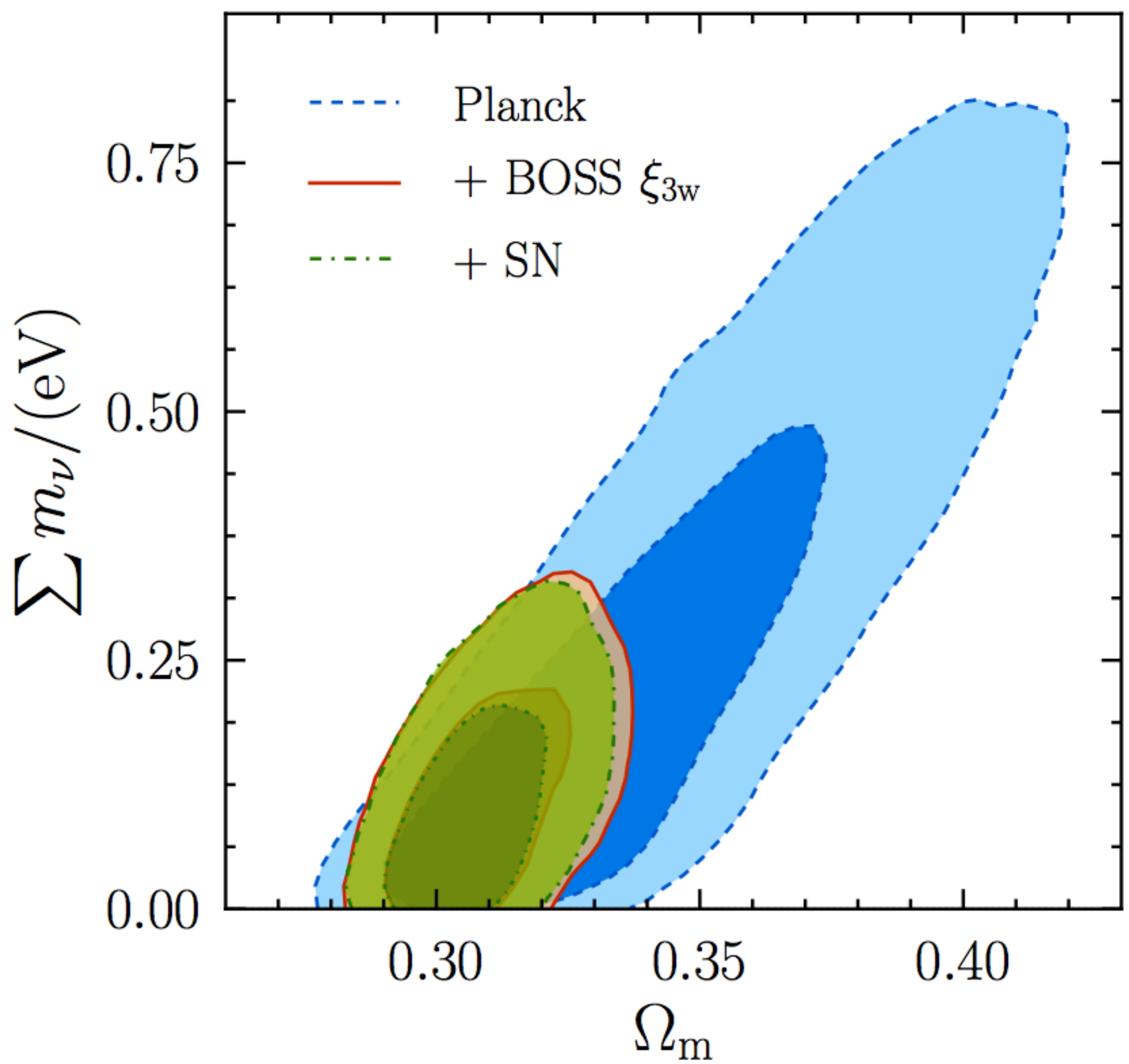
$$k_{nr} = k_{fs}(z_{nr}) \simeq 0.018\Omega_m^{1/2} \left(\frac{m_\nu}{1\,eV}\right) h\,\mathrm{Mpc}^{-1}$$

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



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

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

Combining with CMB lensing reduces it

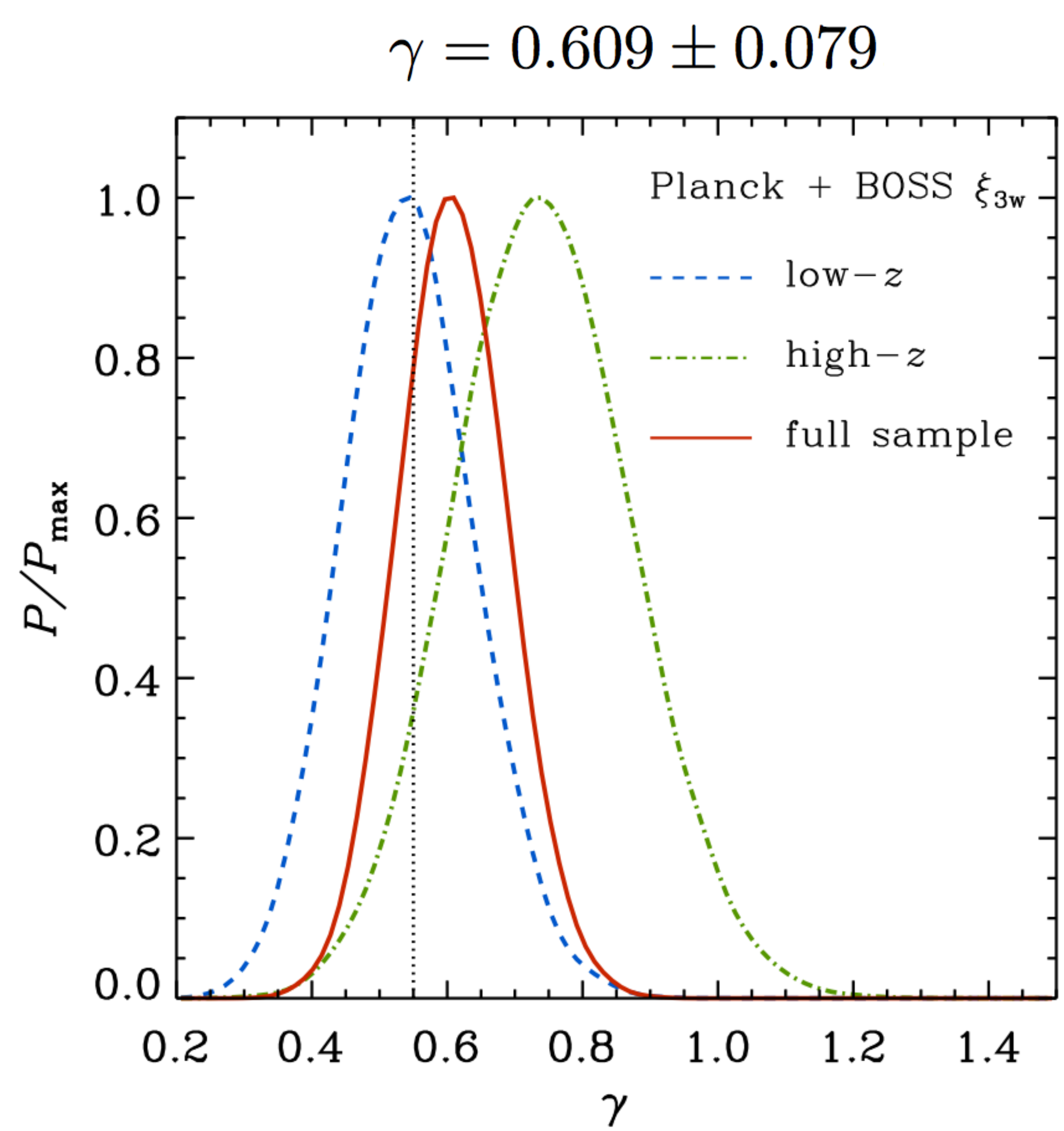
$$\sum m_\nu < 0.16\,\mathrm{eV\ at\ 95\%\ CL}$$

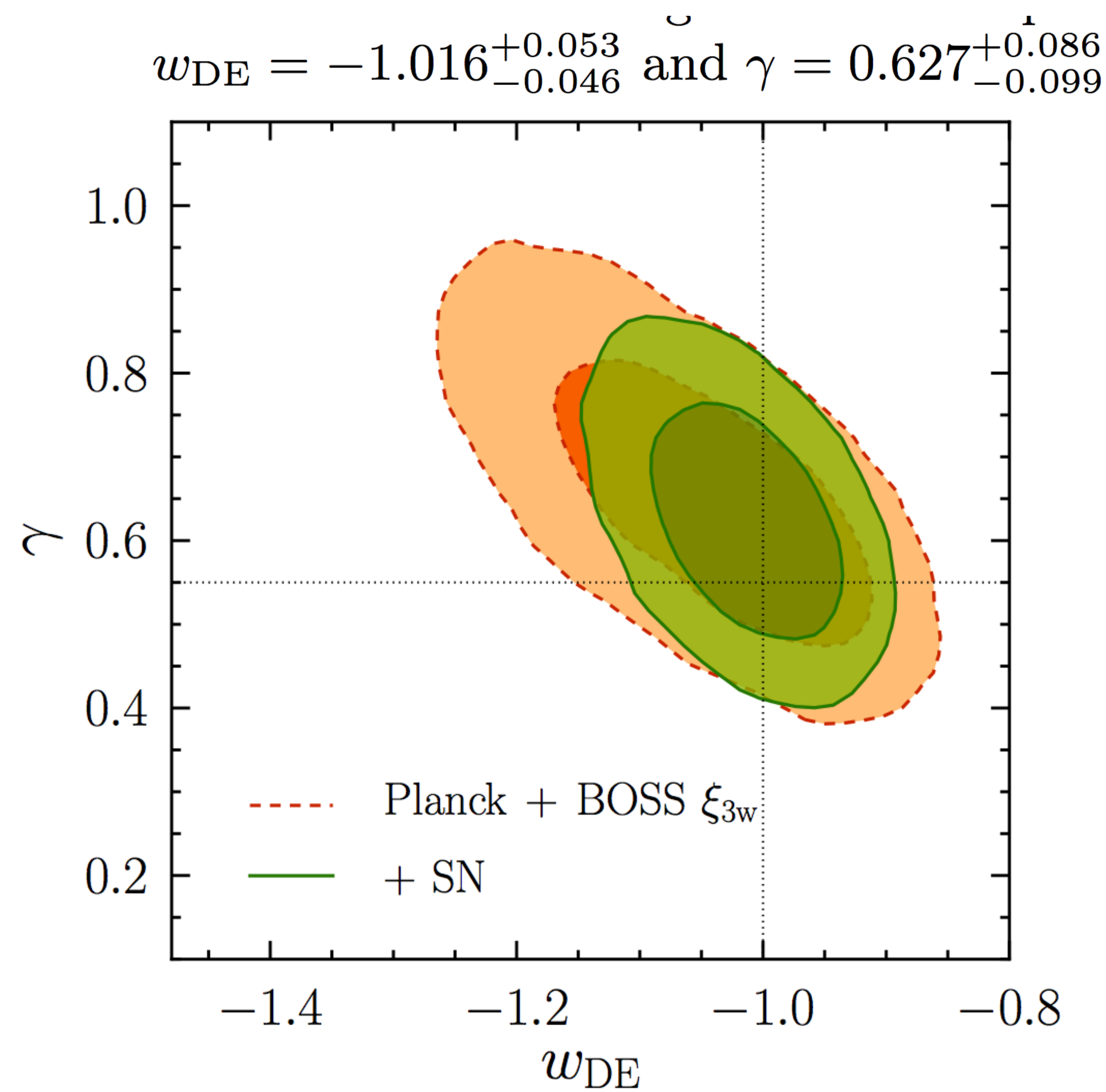
although with some potential concerns due to tensions in the CMB(lensing) data.

Consistency of GR

$f(z) = \Omega_{\rm m}(z)^{\gamma}$ Assuming GR (LCDM) one gets γ ~ 0.55

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





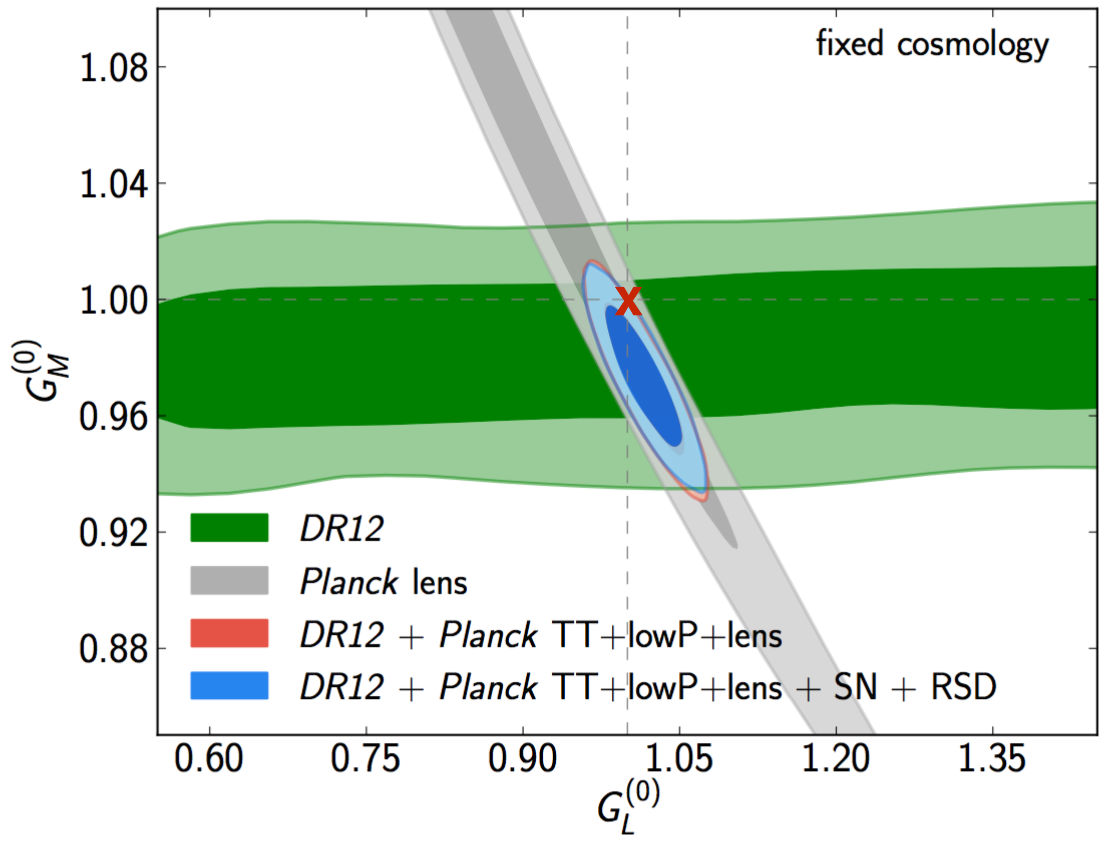
Modified Gravity

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

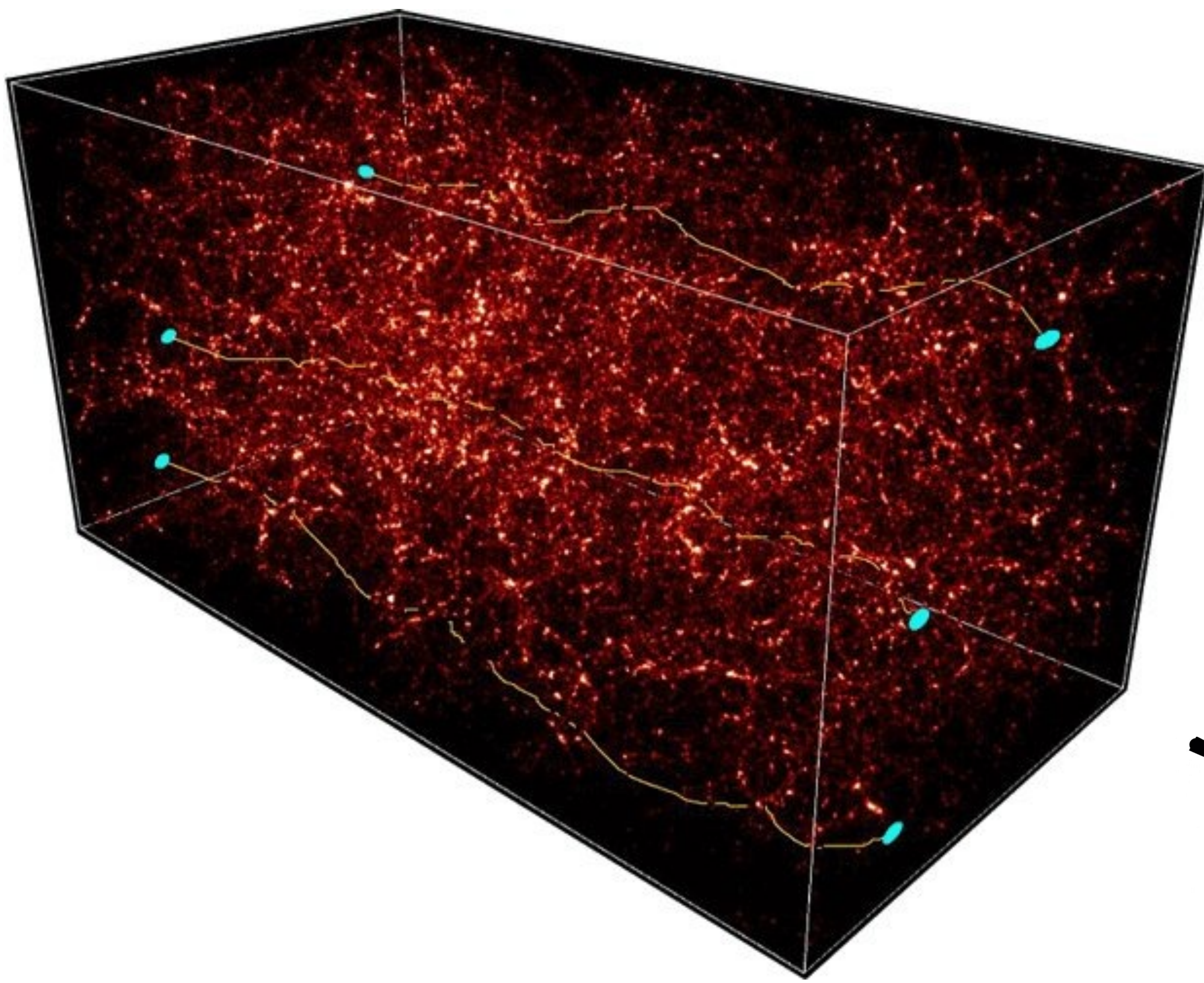
Summary of BOSS - galaxy clustering

- 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

The ongoing

Opened door to Weak Lensing surveys (DES, KiDS)

Weak Lensing



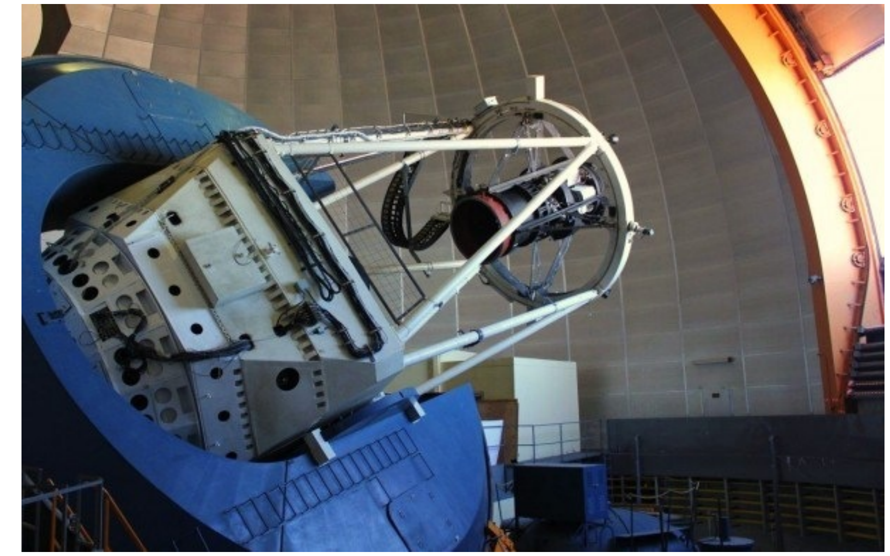
- Matter distorts back-ground galaxy shapes
- Measure shapes to obtain "shear" catalog
- Shear-shear correlations is an unbiased tracer of matter distribution

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

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

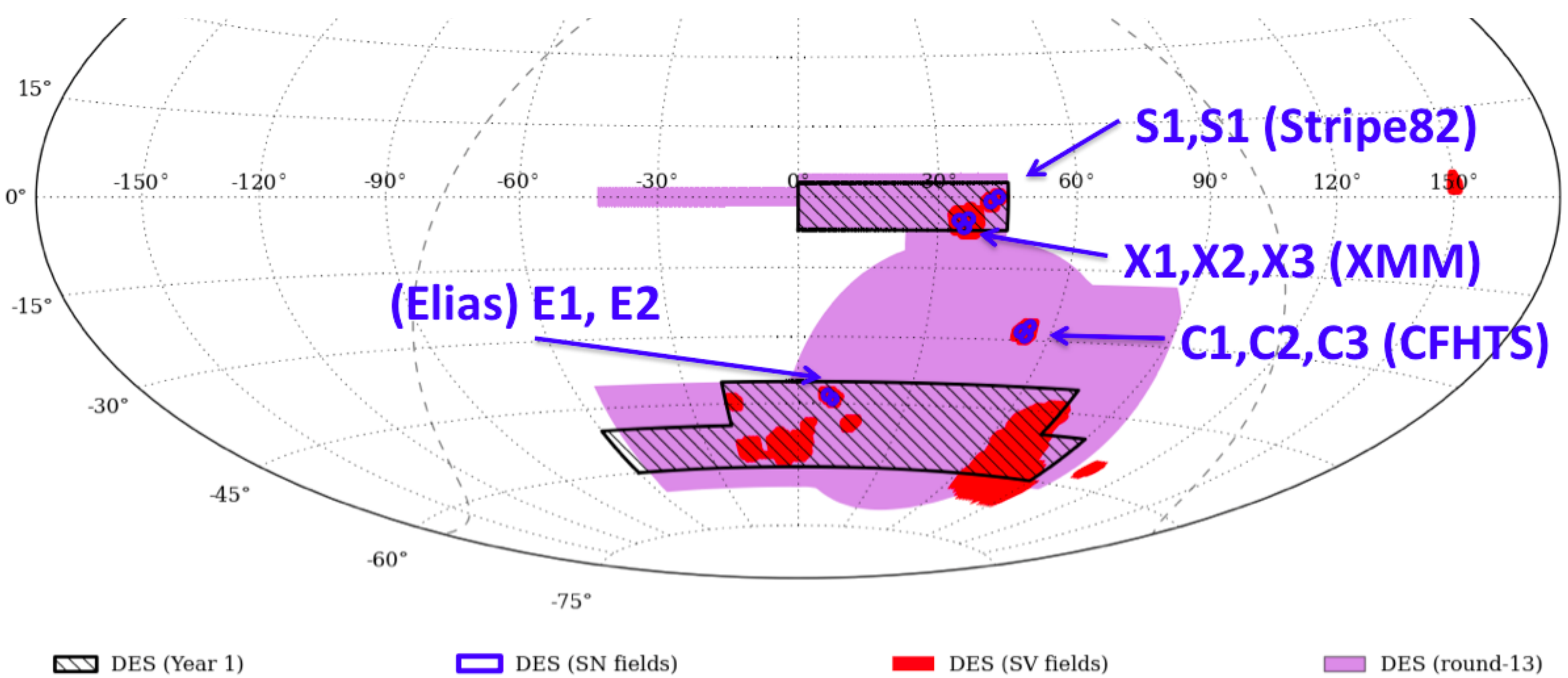
Dark Energy Survey

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

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

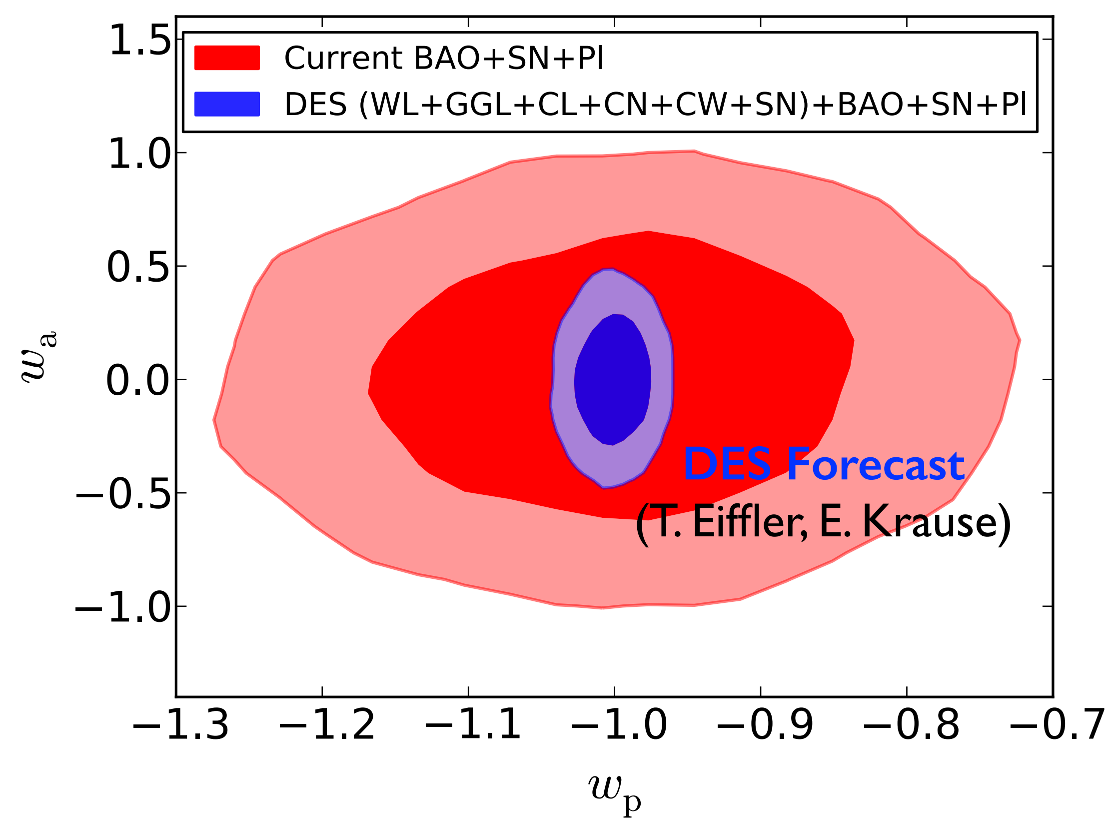
Strong Lensing (distance)
30 QSO lens time delays
Arcs with multiple source redshifts

Cross-correlations
Galaxies and WL x CMB lensing

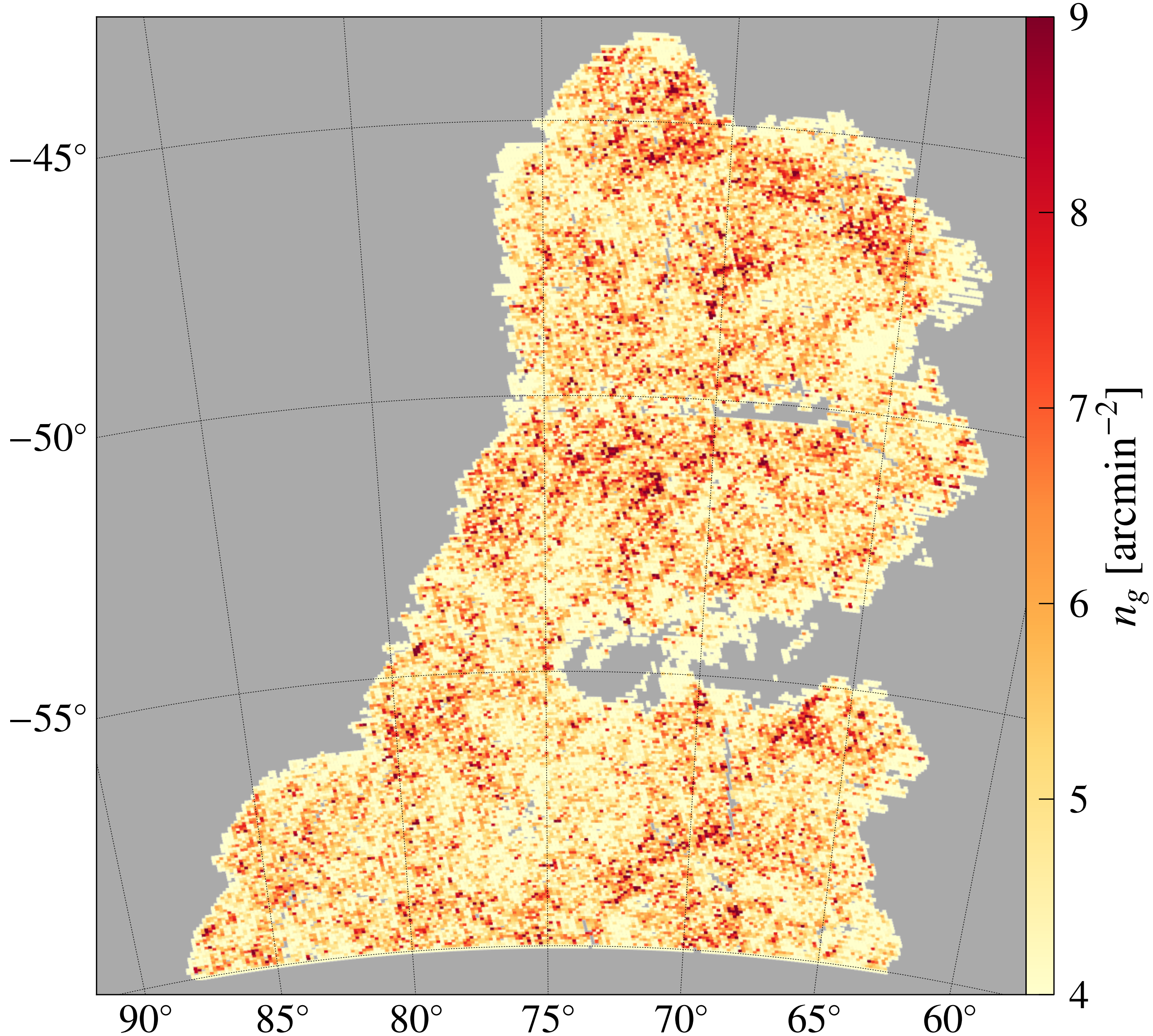
robust combination of probes

→ shared photometry/footprint
→ shared analysis of systematics
→ shared galaxy redshift estimates

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

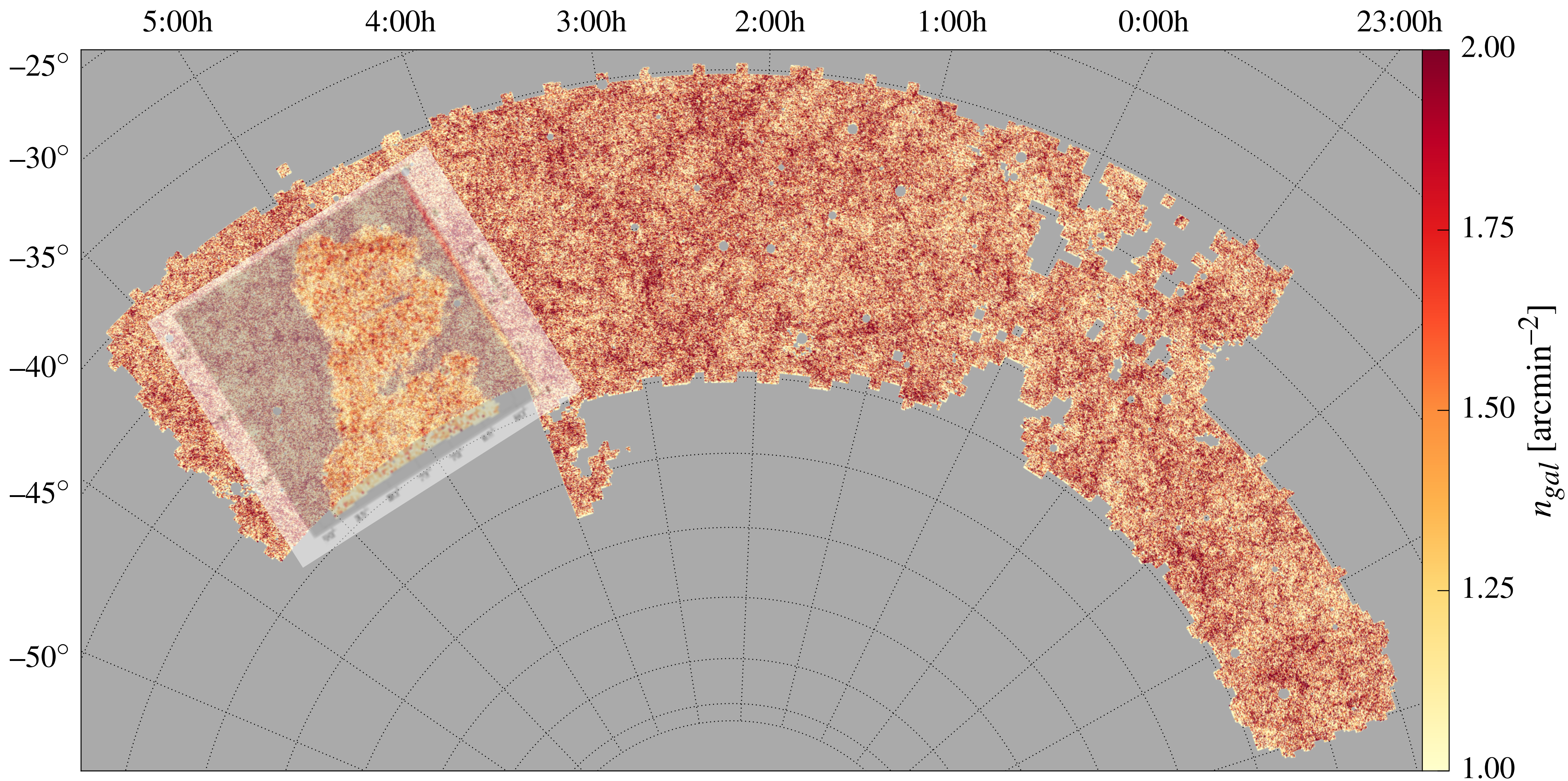


DES Science Verification Galaxy Distribution



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

DES Year 1 Galaxy Distribution



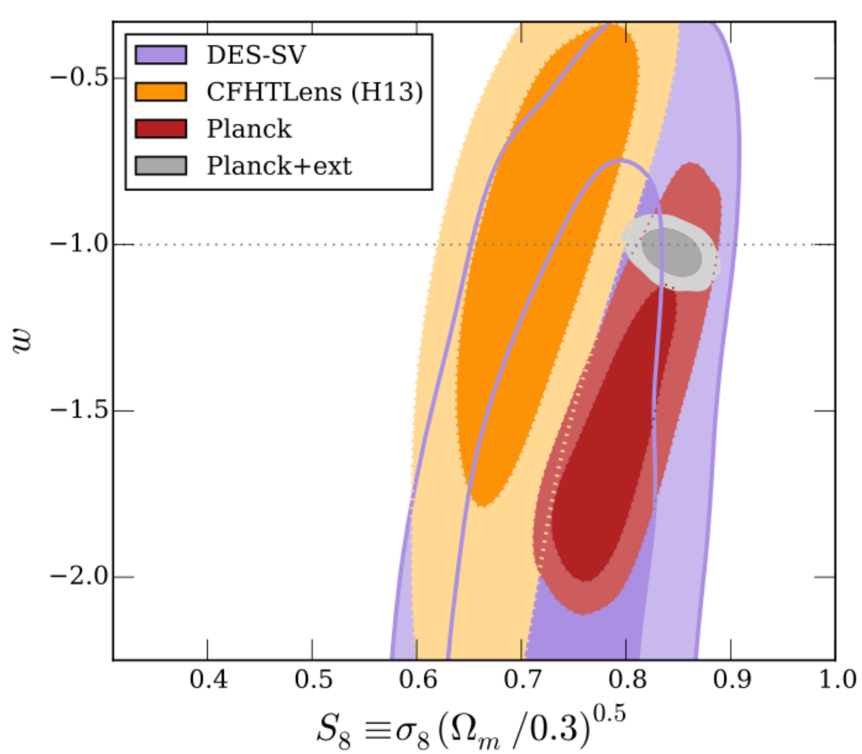
9 million galaxies in LSS (i < 21) over 1500 deg^2

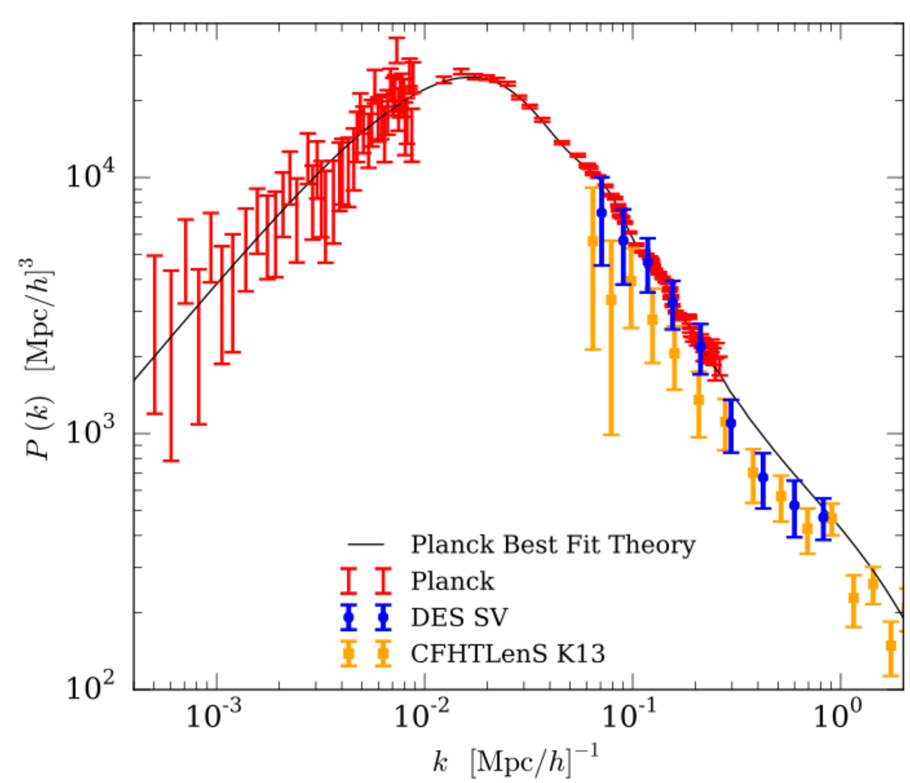
Weak Lensing: Shear Catalog

"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)
- B-mode signal consistent with 0

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



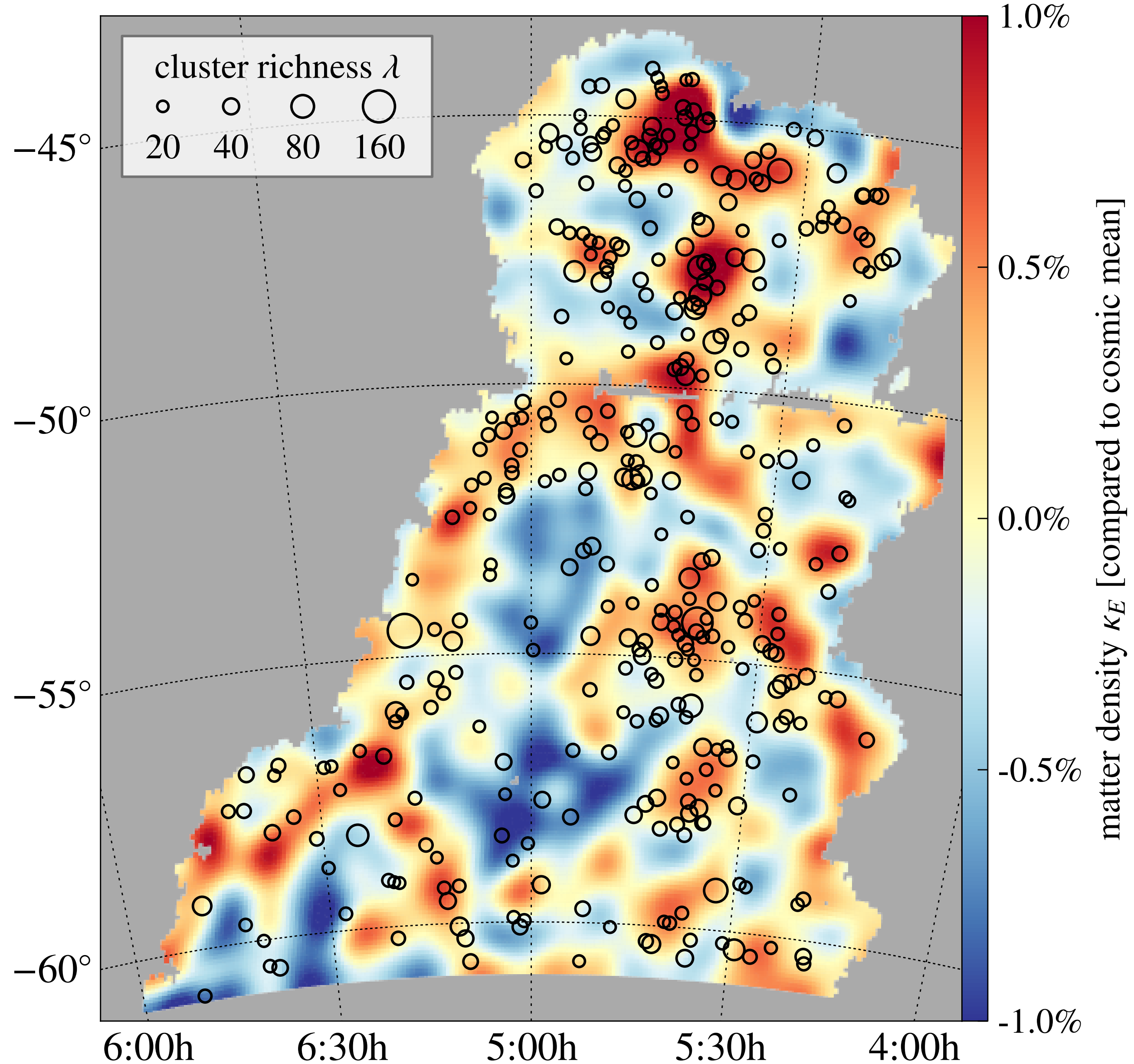


First alphabetical paper

arXiv 1507.05552

Weak Lensing: Mass mapping

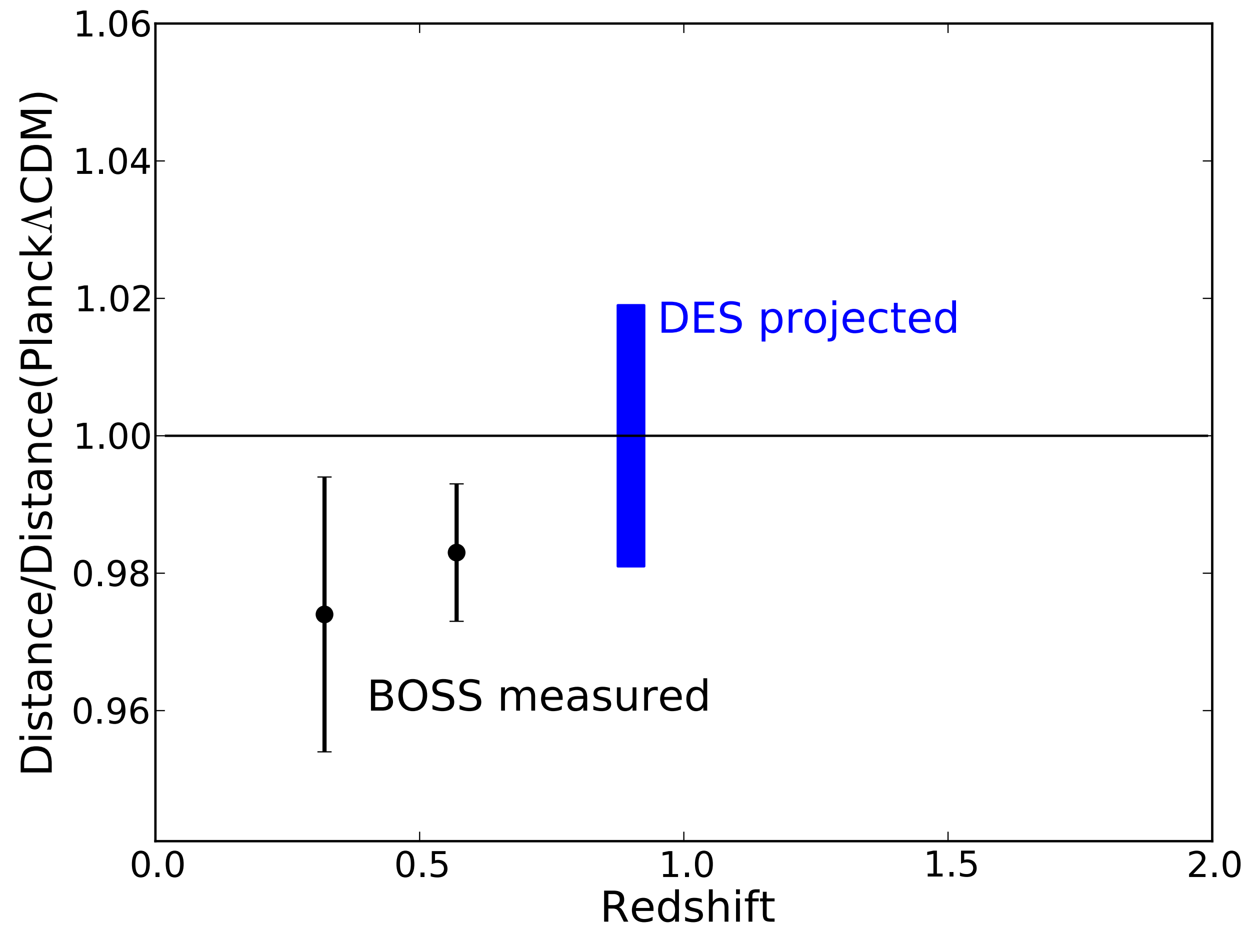
Shear -> map of projected mass distribution for z < 0.5



Light traces matter !

"Wide Field lensing mass maps from DES SV" Chang, Vikram, Jain, Bacon et al., Phys Rev. Let 115, 051301 (2015)
arXiv 1505.01871 and arXiv 1504.03002

BAO in DES



Y1-analysis

Main probe is to combine shear-shear, galaxy-shear (aka gg lensing) and galaxy-galaxy correlations

- **5 lens bins (0.6 million objects with ~ 1% redshift error),**
- **4 source bins (31 million galaxies with shapes, two "shape" catalogues)**
- **20 two-point correlations and a data vector of size ~ 600-800.**

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

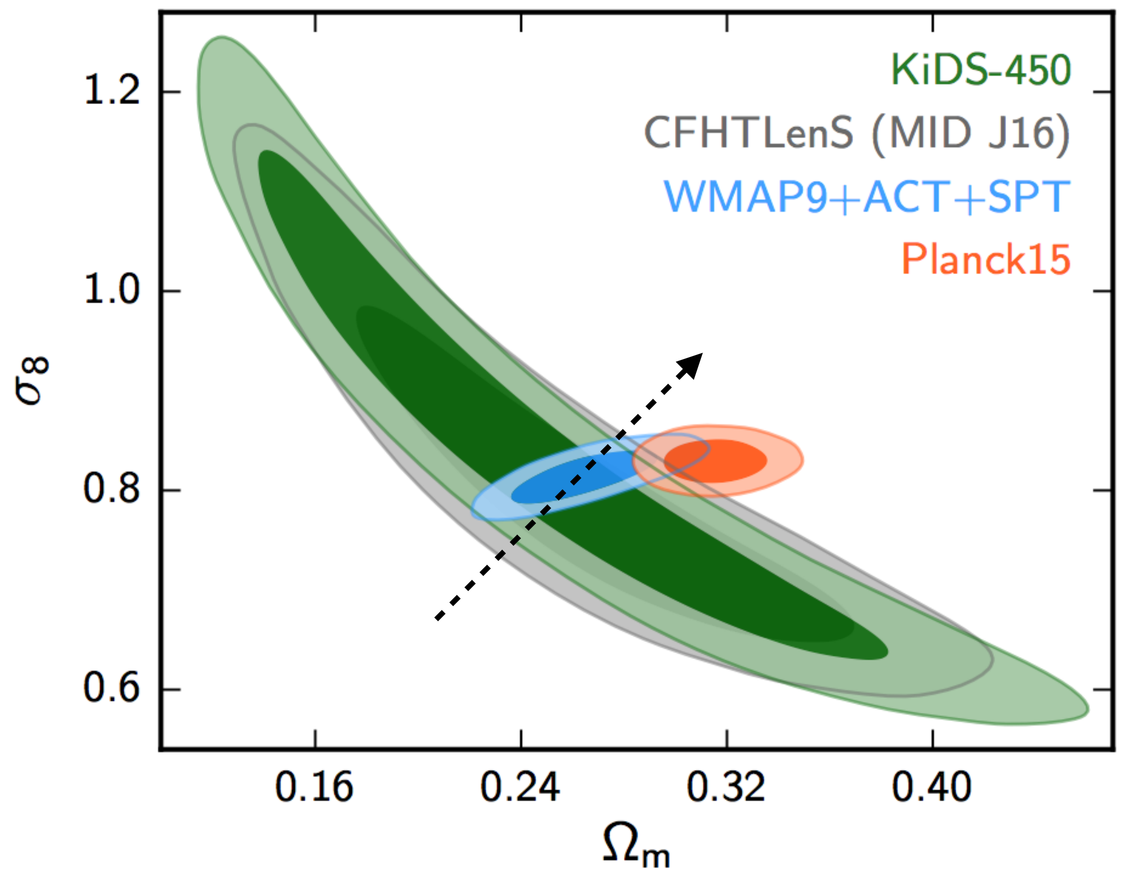
H. Hildebrandt[1*],

KiDS-450

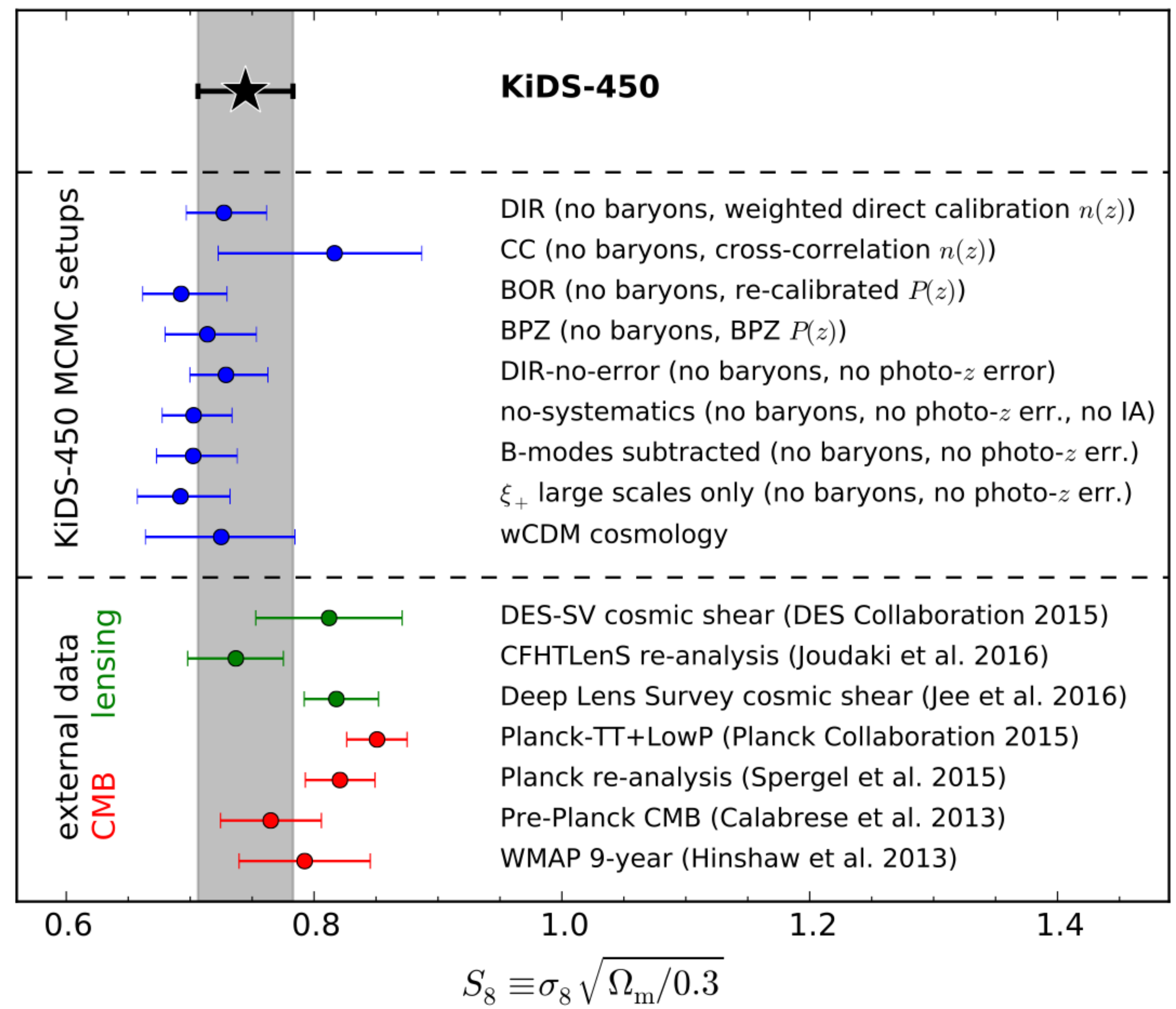
- 15 million galaxies in 450 deg^2
- one shape measurement pipeline
- 3 photo-z error estimations

KiDS

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



$$S_8 \equiv \sigma_8 \sqrt{\Omega_{\rm m}/0.3} = 0.745 \pm 0.039.$$



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

DES and KiDs 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

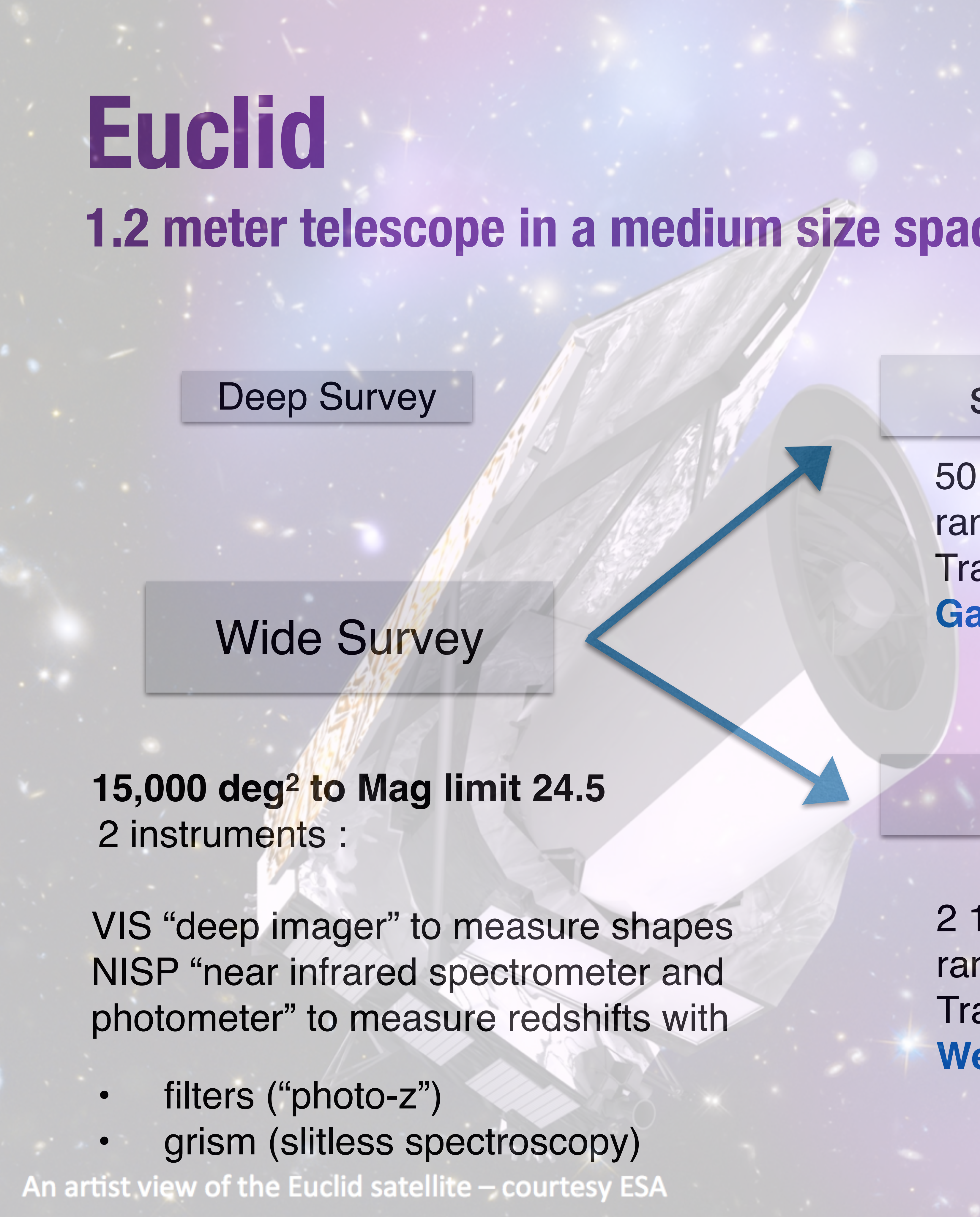
& open the door to some of the largest surveys doing both (from space!)

The future

Euclid / ESA mission

Euclid

1.2 meter telescope in a medium size space mission



An artist view of the Euclid satellite – courtesy ESA

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)

spectroscopic survey

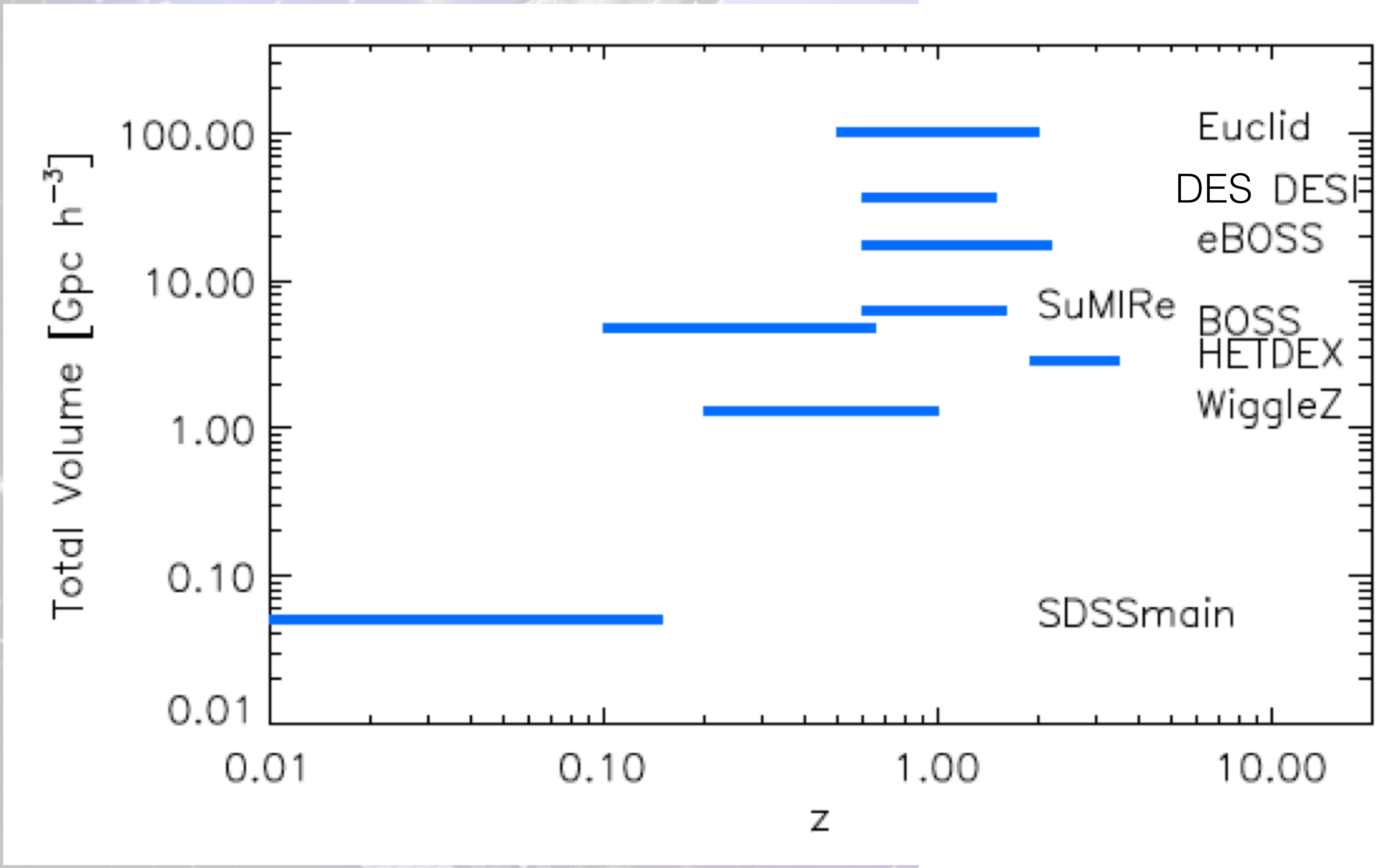
50 million galaxies in the range $1 < z < 2$
Trace 3D distribution of galaxies
Galaxy Clustering

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

Euclid Imaging

Courtesy J. Brinchmann, Steve Warren

M51

SDSS @ z=0.1 | Euclid @ z=0.1 | Euclid @ z=0.7

measuring dark energy with Euclid
proof or disproof a cosmological constant scenario

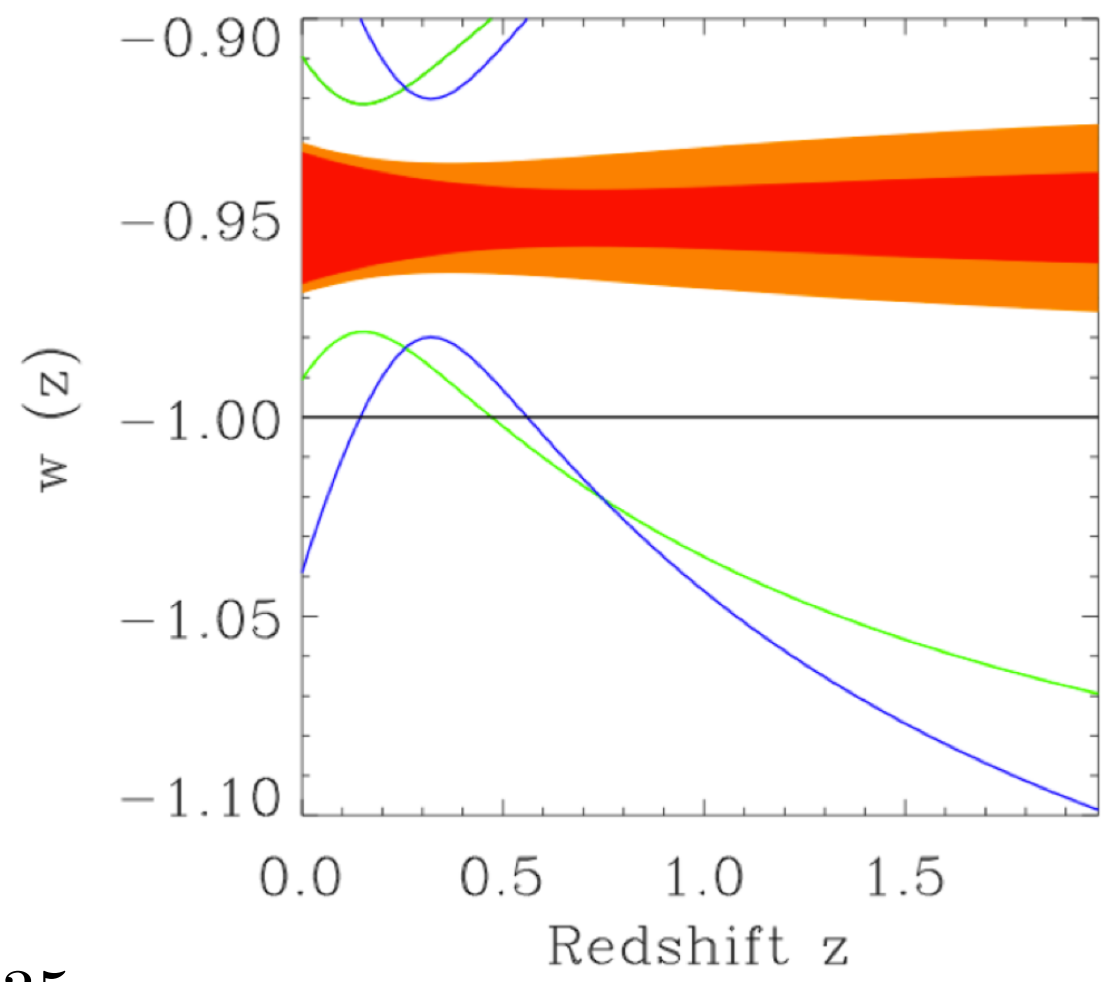
- Equation of state of DE is the ratio of pressure to density $$w(a) = p(a)/\rho(a)$$
- Expand w.r.t scale-factor

$$w(a) = w_p + (a - a_p) w_a$$

- Measuring $w_a \neq 0$ at any redshift would demonstrate that DE is not a cosmological constant

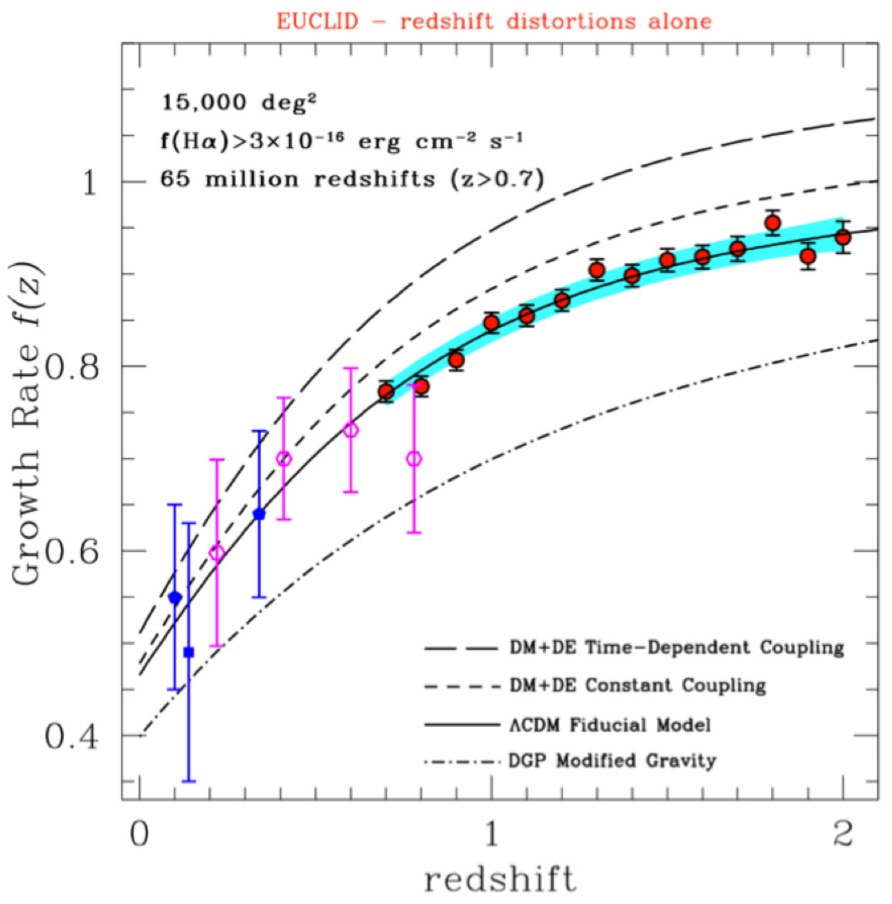
- Forecasted constrains

$$\Delta(w_p) = 0.007 \qquad \Delta(w_a) = 0.035$$



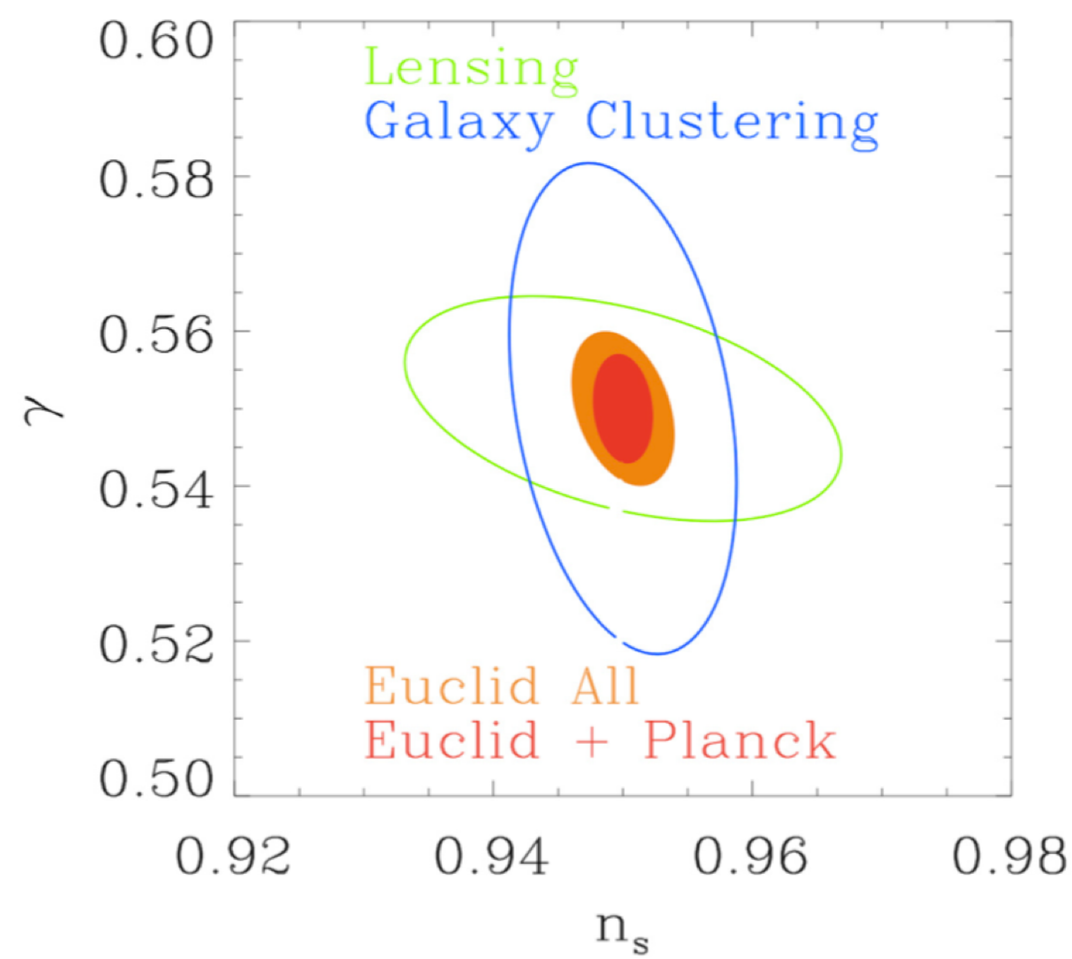
modified gravity

- Growth factor and its derivative, growth rate f(z), quantifies efficiency at which structure is built
- Growth rate $f(z) = \Omega_m(z)^\gamma$
- A detection of $\gamma \neq 0.55$ implies a deviation of GR (cosmic acceleration originated by other than DE).
- Euclid constrains $\Delta(\gamma) = 0.007$
- In more general terms, constrains on growth rate as a function of redshift



initial conditions

- Current model = Gaussian initial perturbations with power law index n_s
- Euclid+Planck $\Delta(n_s) \sim 1\%$ (2 x Planck alone)
- If initial conditions are not Gaussian f_{nl} is used to parametrize deviations (e.g.)
- Euclid $\Delta(f_{nl}) \sim 2$ Planck $\Delta(f_{nl}) \sim 5$ (still competitive and certainly complementary)



massive neutrinos

- Massive neutrinos damp structure growth on small scales. The larger the mass the more damping occurs, leaving a clear signature in the matter power spectrum
- Euclid + Planck $\Delta(\sum m_\nu) = 0.02 - 0.03$

Summary slide (for the future ..)

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	FoM
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.08	0.16	~ 5	0.05	0.53	
Improvement Factor	**~ 10**	**~ 10**	**~ 2 ~ 3**	**~ 10**	**~ 10**	

source = Euclid Definition Study Report (arXiv 1110.3193)
current = BOSS analysis (RSD+BAO) combined with Planck: Alam et al. (1607.03155) and Sanchez, Scoccimarro, Crocce, et al (arXiv:1607.03147)

Euclid Primary = Weak Lensing Tomography (WL) and Galaxy Clustering (GC)
Euclid All = WL + GC + Cluster abundance + ISW

Thanks.

BOSS alone prefers prefiere valores de Omegam un poco mas bajos y de h mas altos que Planck, pero igual consistente. Hecho con Gaussian priors en torno a los valores de BOSS.