The Dark Energy Survey and Beyond

Ofer Lahav (University College London)

UCL THE ROYAL SOCIETY Science & Technology Facilities Council erc

Cosmology @ UCL

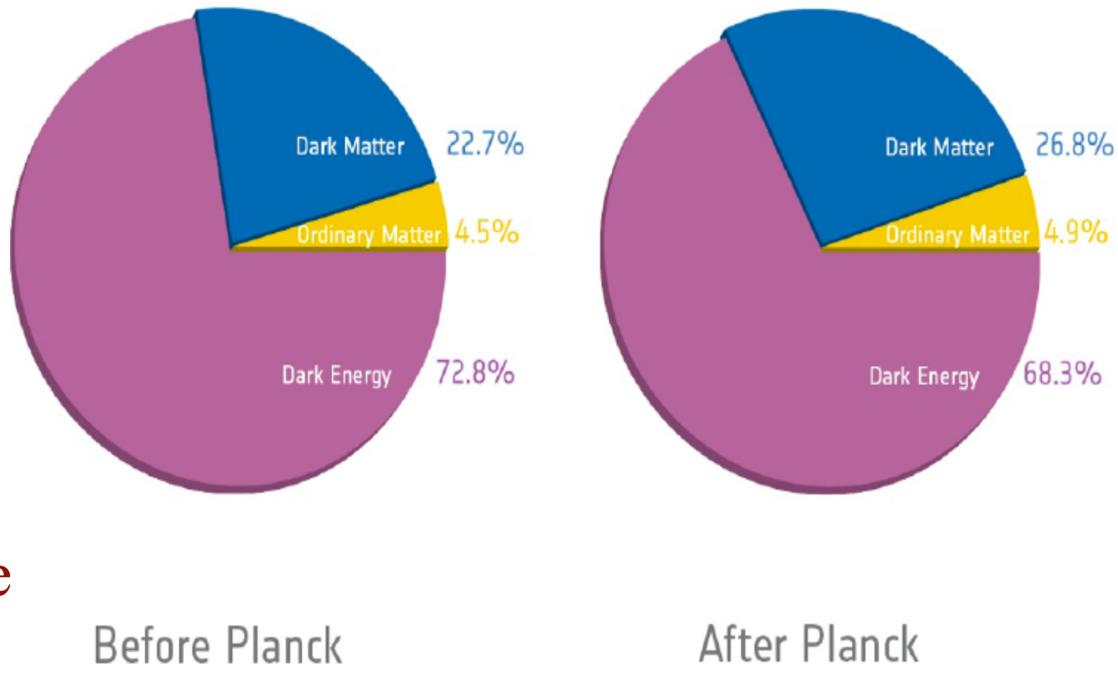
Outline

- Cosmology @ 2014
- Dark Energy on Mpc scales
- The Dark Energy Survey (DES)
- The Dark Energy Spectroscopic Instrument (DESI)
- Combined probes
- The future…

The (known) unknown
95% of the universe

Observational data:

- Gravitational Lensing
- Peculiar Velocities
- Galaxy Clusters
- CMB
- Large Scale Structure
- Type Ia Supernovae
- Integrated Sachs-Wolfe

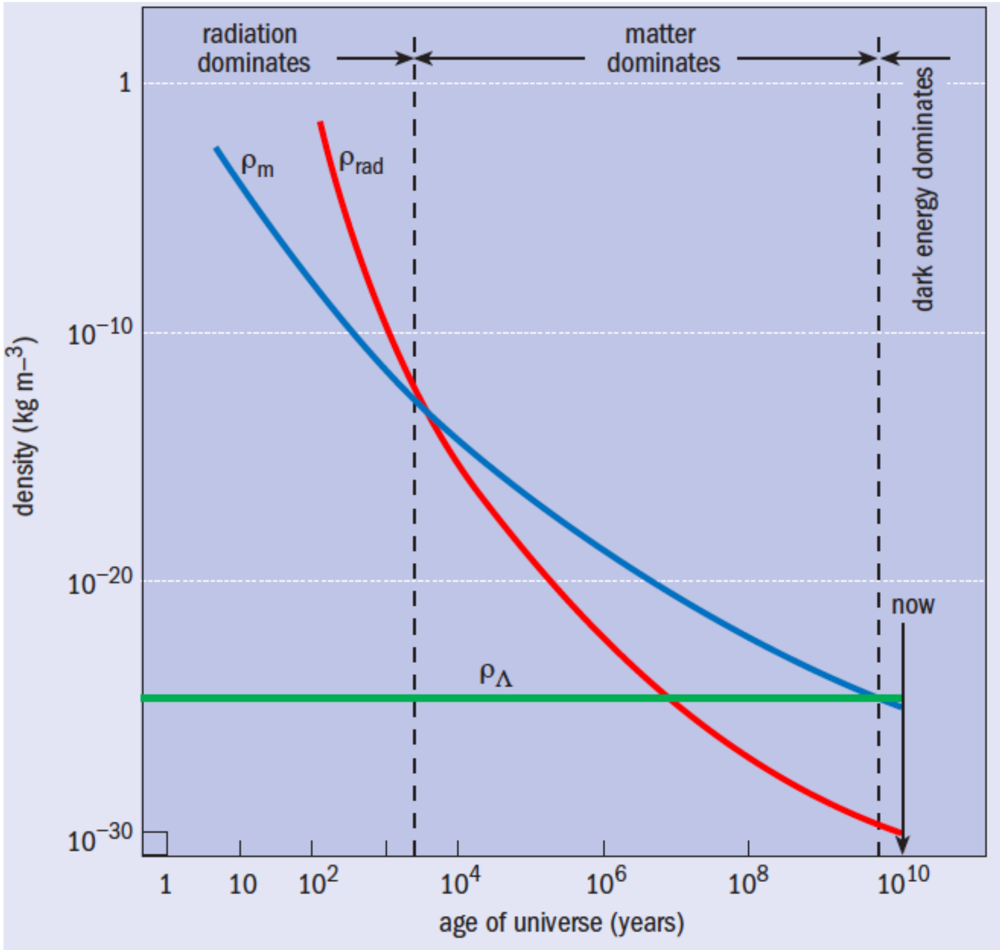


Physical effects:

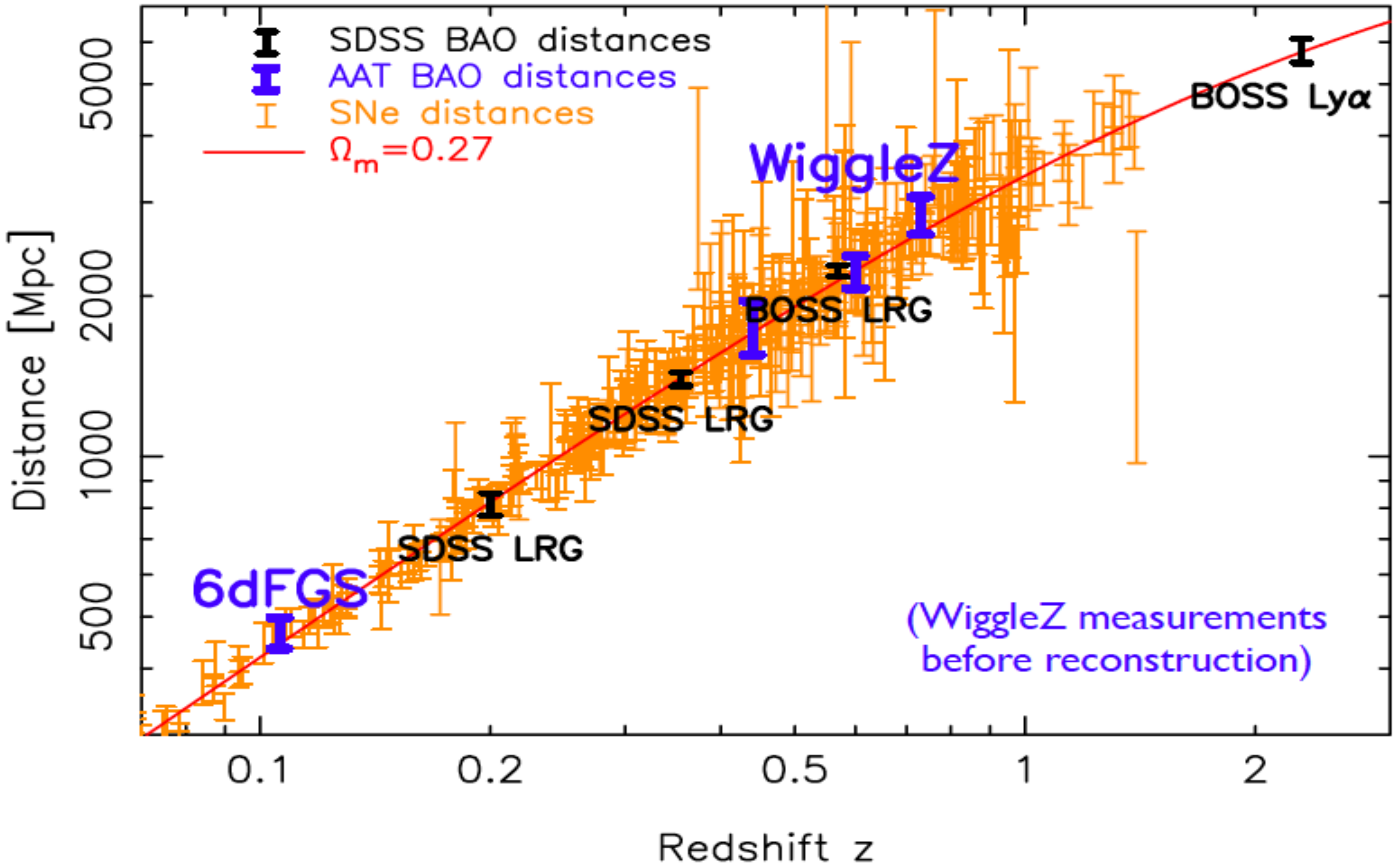
- Geometry
- Growth of Structure

$$C_l^{i,j} = 4\pi \int \Delta^2(k) W_i(k) W_j(k) \frac{dk}{k}$$

The Evolution of Matter, Radiation and Lambda

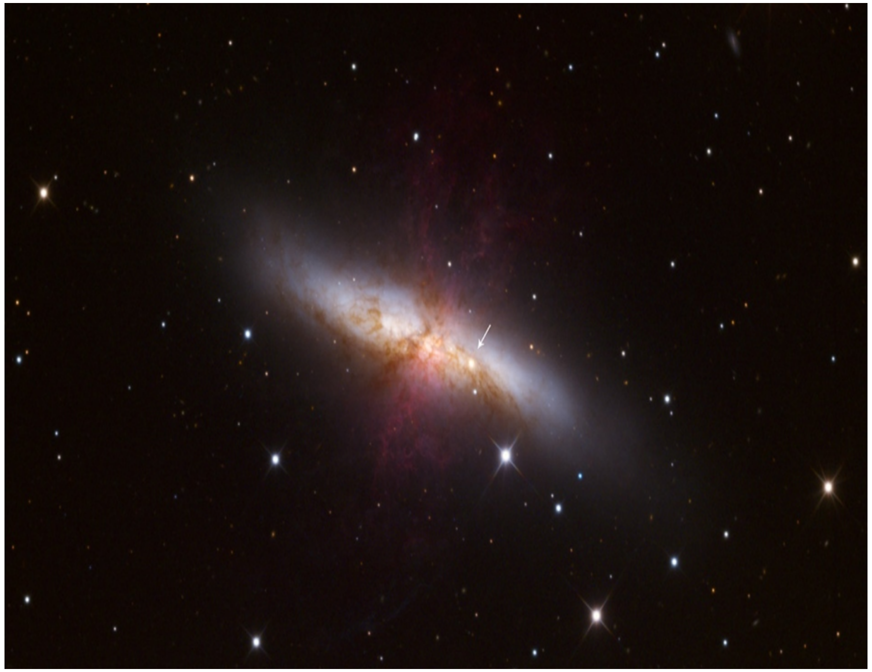


Modern Hubble Diagram



Blake et al. (2013)

SN2014J @ M82 discovered at UCL's teaching observatory in North London!

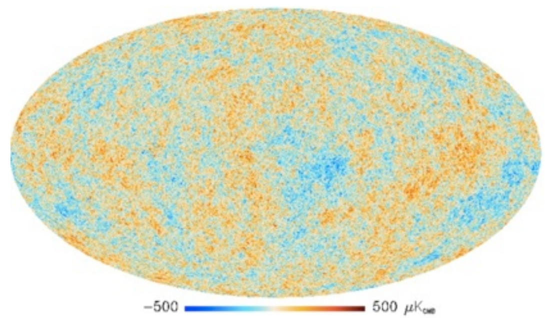


So what is Dark Energy?

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Systematics mimic DE?
- Just Lambda-CDM?
- Dynamical scalar field? $W=P/\rho$
- Signatures of modified gravity?
- Inhomogeneous Universe?
- Anthropic Principle? Multi-verse?
- Something else unpredictable??

Planck CMB results support LCDM:
“an almost perfect universe”
or “a simple but strange universe”?



New Entity or New Theory?

Phenomenon	New Entity	New Theory
Uranus' orbit	Neptune	-
Mercury's orbit	*(Hypothetical planet Vulcan ruled out)*	General Relativity
Beta decay	Neutrino	*(Violation of angular momentum ruled out)*
Galaxy flat rotation curves	Dark Matter?	Modified Newtonian Dynamics?
Accelerating universe (SN Ia and other data)	Dark Energy?	Modified General Relativity?

Example of Modified Gravity Formalism

$$ds^2 = -a(\tau)^2\left[1 + 2\Psi(\mathrm{x}, t)\right]d\tau^2 + a(\tau)^2\left[1 - 2\phi(\mathrm{x}, t)\right]d\mathrm{x}^2$$

Two-parameter model:

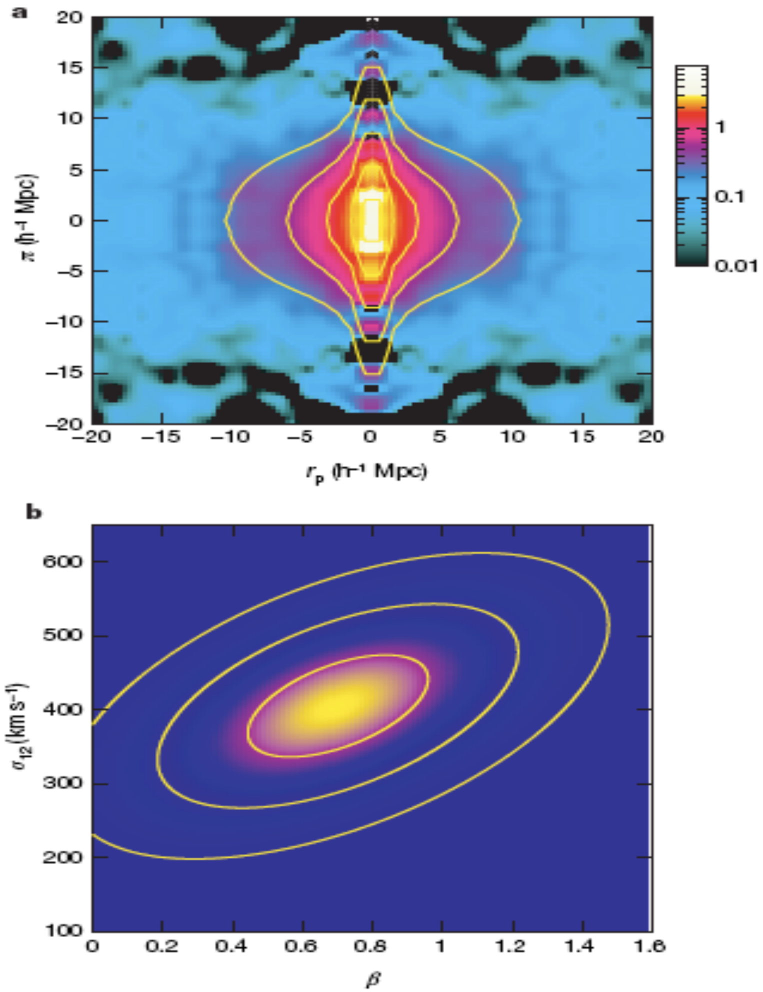
1. A Modification of Poisson's equation: $k^2\psi(x,t) = -4\pi G Q \rho a^2 \delta$
2. An inequality in Newton's potentials: $\psi(x,t) = R\phi(x,t)$

In Standard GR: Q=R=1
Q,R may be z-dependent.

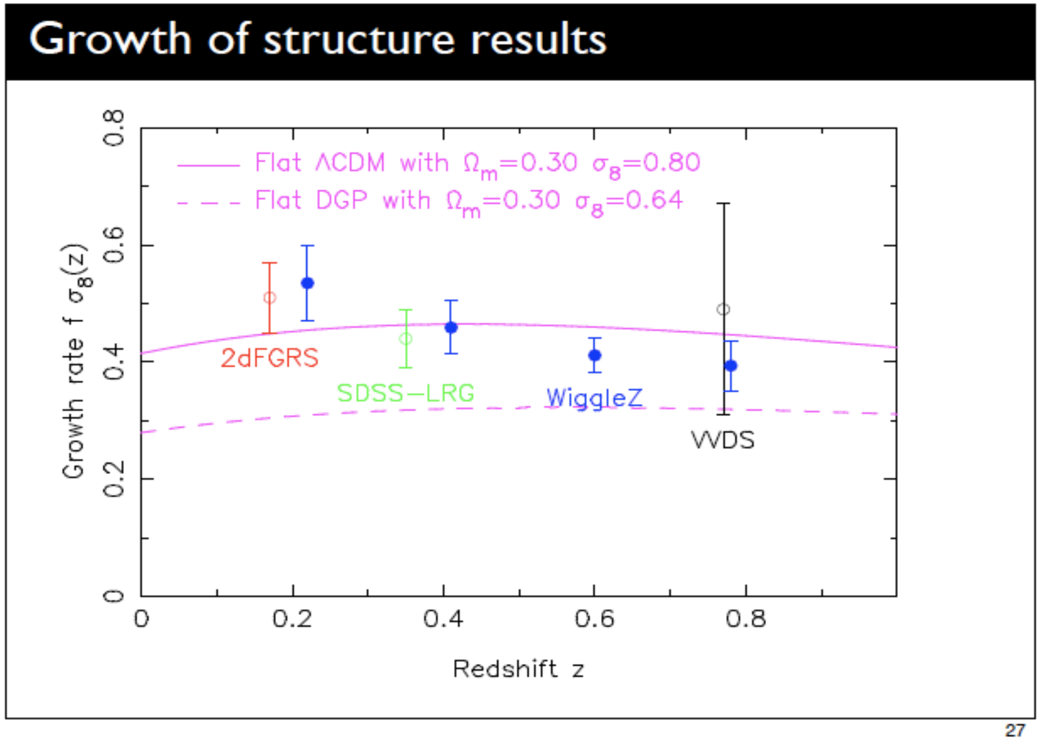
Cosmic shear is sensitive to sum of potentials

Peculiar velocities are sensitive to the temporal potential

Redshift Distortion as a test of Dark Energy vs. Modified Gravity



Guzzo et al. 2008



Blake et al. 2011

Bound Systems (L-T-B)

Physical coordinates

Equation of motion:

$$\frac{d^2 r}{dt^2} = -\frac{GM}{r^2} + \frac{\Lambda}{3} r$$

Energy equation:

$$\epsilon = \frac{v^2}{2} - \frac{GM(r)}{r} - \frac{4\pi}{3} G \rho_\Lambda r^2$$

Given observed r, v, t & Λ
Can solve for M

Cf. spherical collapse: Lahav et al. 1991; Wang & Steinhardt 1998; Nandra, Lasenby & Hobson 2013

Weighing the Local Group in the presence of Dark Energy

Partridge, Lahav & Hoffman

(MNRAS Letters, arXiv:1308.0970)

- At present the Milky Way and Andromeda are:
  - * separated by r = 770 ±40 kpc
  - * infall at v = -109 ±4 km/sec

  (Van der Marel 2012)
- Given the age of the universe t=13.81 ± 0.06 Gyr and Dark Energy fraction of 69% (Planck 2013) we find that the mass is (4.73 ± 1.03) x 10^{12} M_{sun}
- Mass 13% higher than in the absence of Lambda

  cf. Kahn & Woltjer 1959; Lynden-Bell 1981

  Chernin et al. 2009, Binney & Tremaine 2008

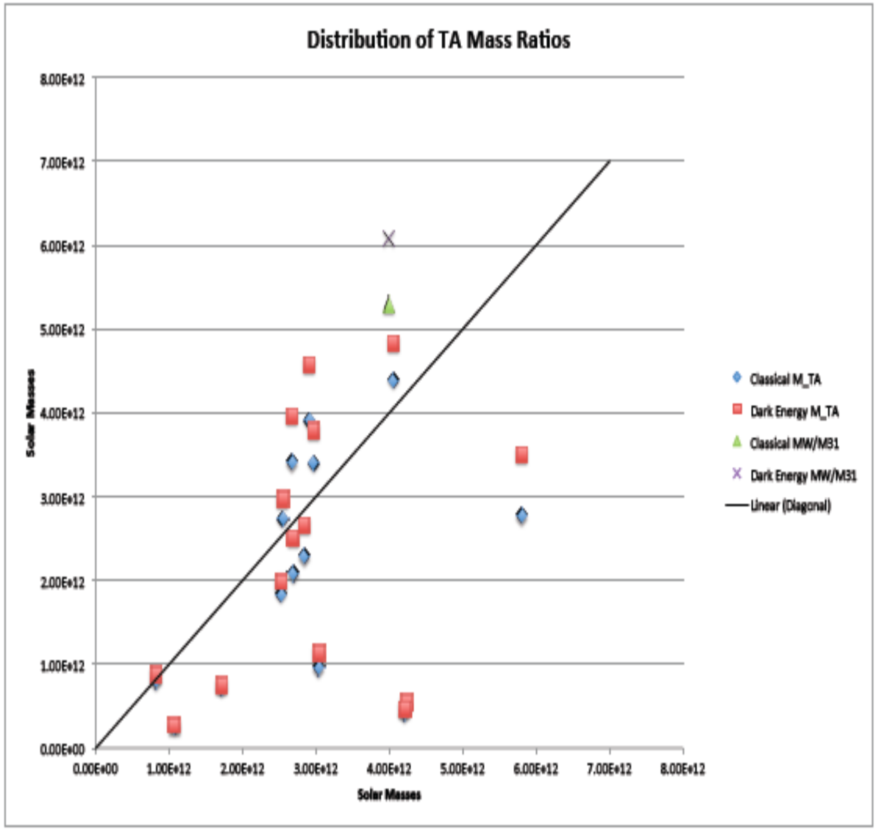
Mass calibration with 16 simulated galaxy pairs

- $M_{vir}/M_{ta} = 1.34 \pm 0.26$
- $M_{vir}/M_{ta\Lambda} = 1.04 \pm 0.16$

- Estimate for LG:

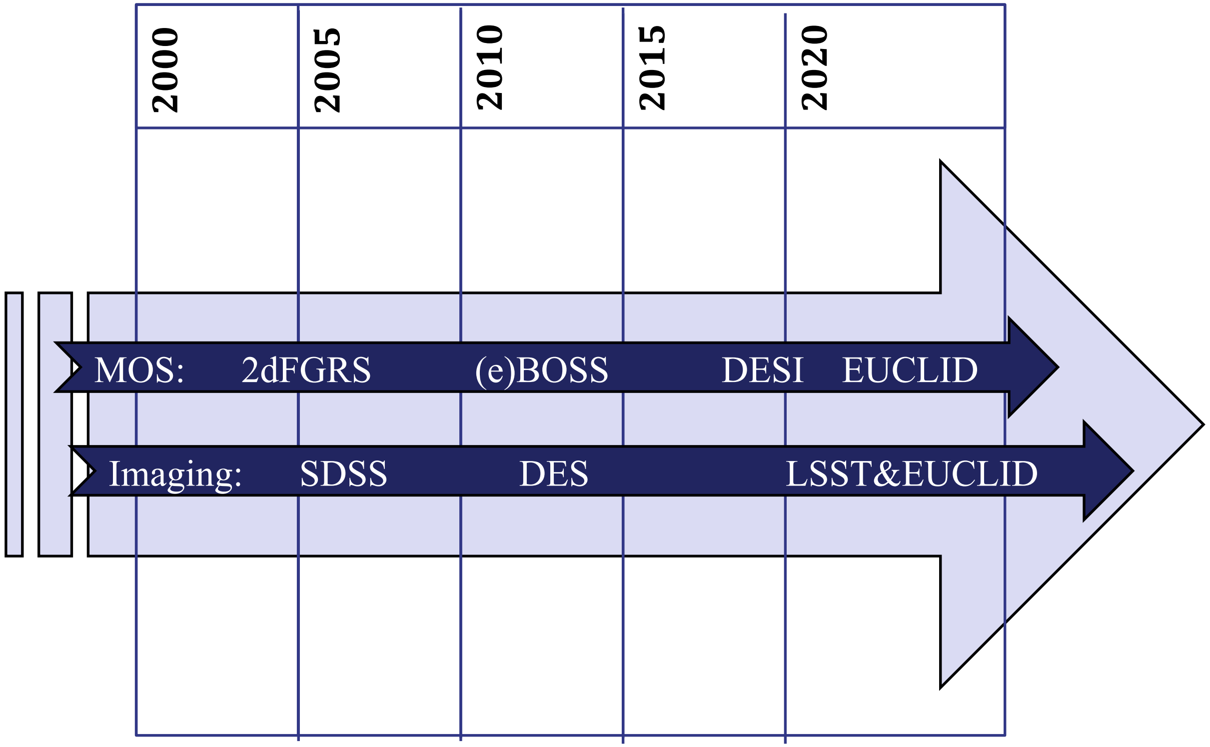
  $M_{vir} / 10^{12} M_{sun} = 4.92$

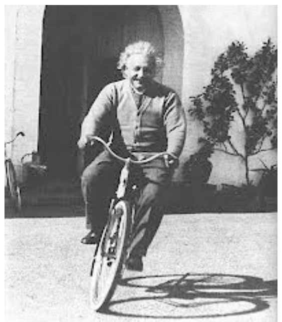
  $\pm 1.08 (obs) \ \pm 0.79 (sys)$



Partridge, Lahav & Hoffman (2013) ***CLUES simulations*** (Cf. Li and White 2008)

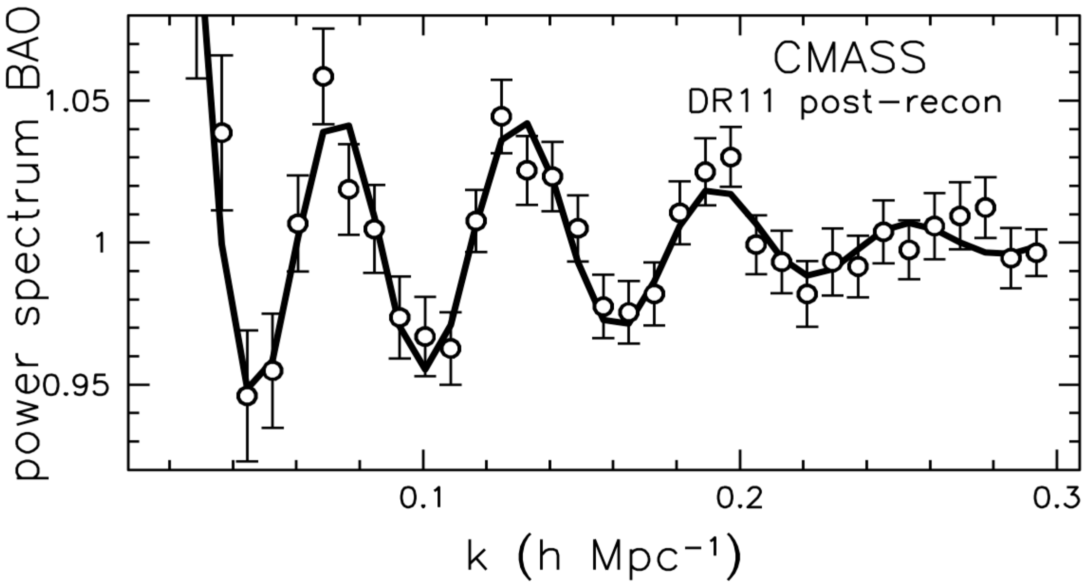
Timeline of cosmology projects

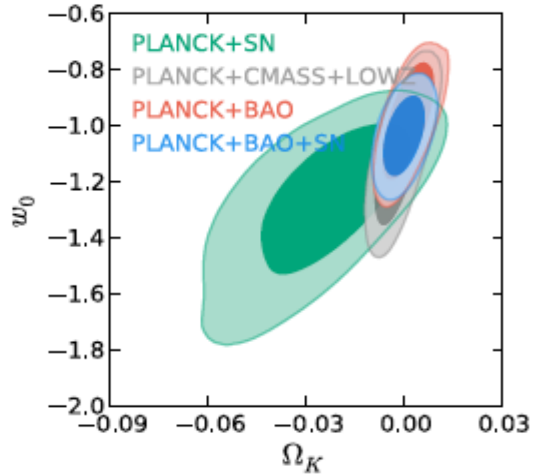




Just Λ?
Dark Energy? Modified Gravity?

BOSS – 1% BAO distances

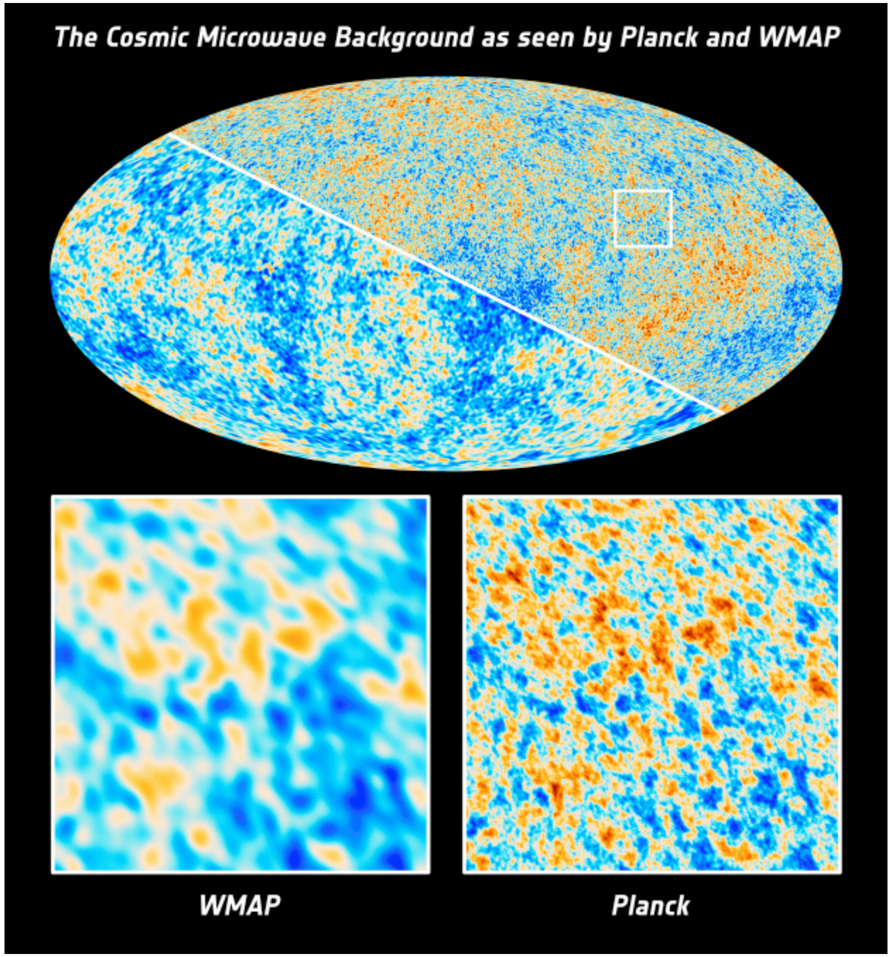




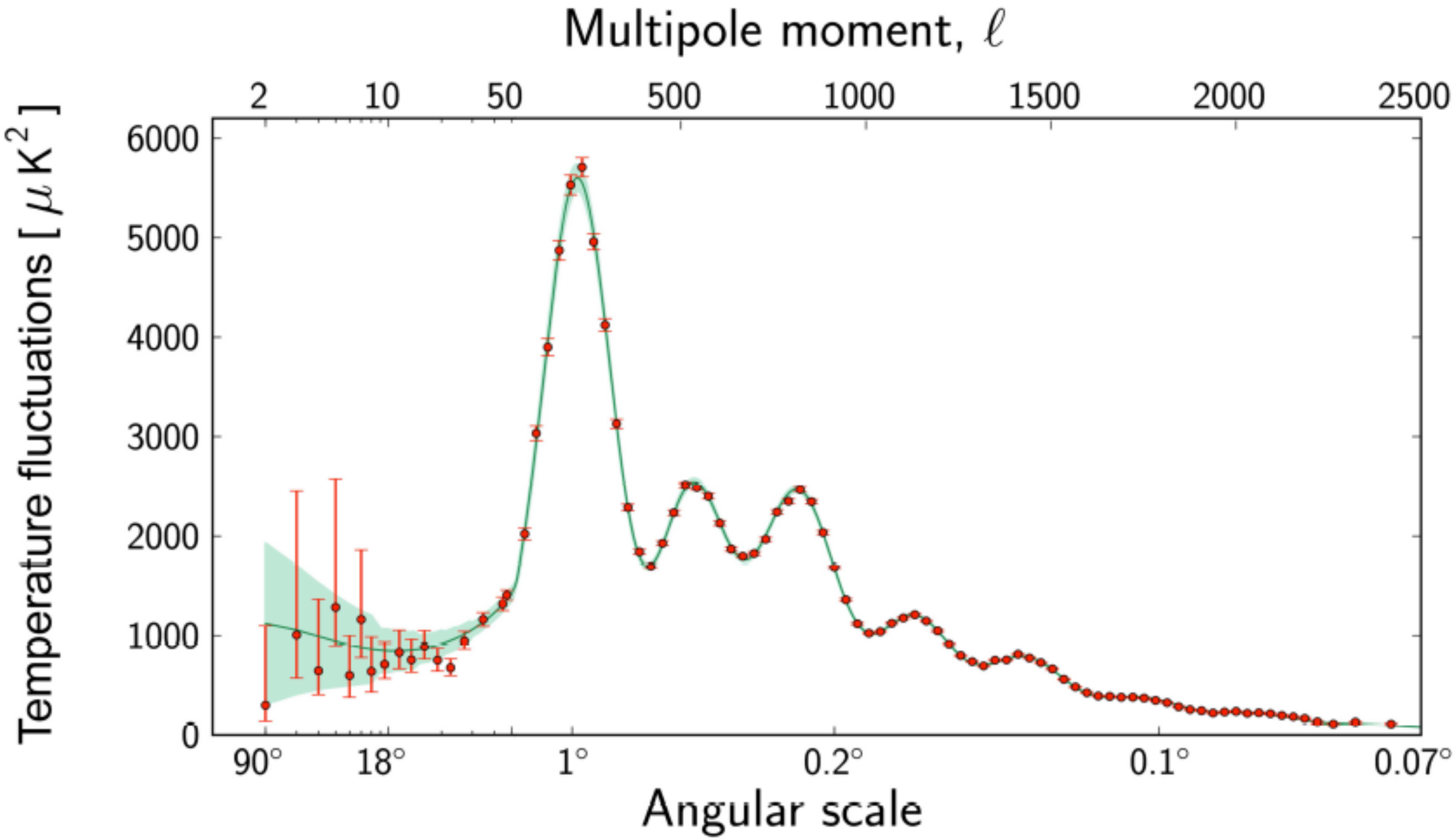
Cosmological Model	Data Sets	$\Omega_m h^2$	Ω_m	H_0 km s^{-1} Mpc^{-1}
ΛCDM	Planck + CMASS-iso + LOWZ	0.1403 (14)	0.300 (8)	68.4 (6)
ΛCDM	Planck + CMASS + LOWZ	0.1416 (13)	0.309 (8)	67.7 (6)
ΛCDM	Planck + BAO	0.1418 (13)	0.310 (8)	67.6 (6)
ΛCDM	Planck + CMASS + LOWZ + SN	0.1415 (13)	0.308 (8)	67.8 (6)
ΛCDM	Planck + BAO + SN	0.1417 (13)	0.309 (8)	67.7 (6)

Anderson et al (2013)

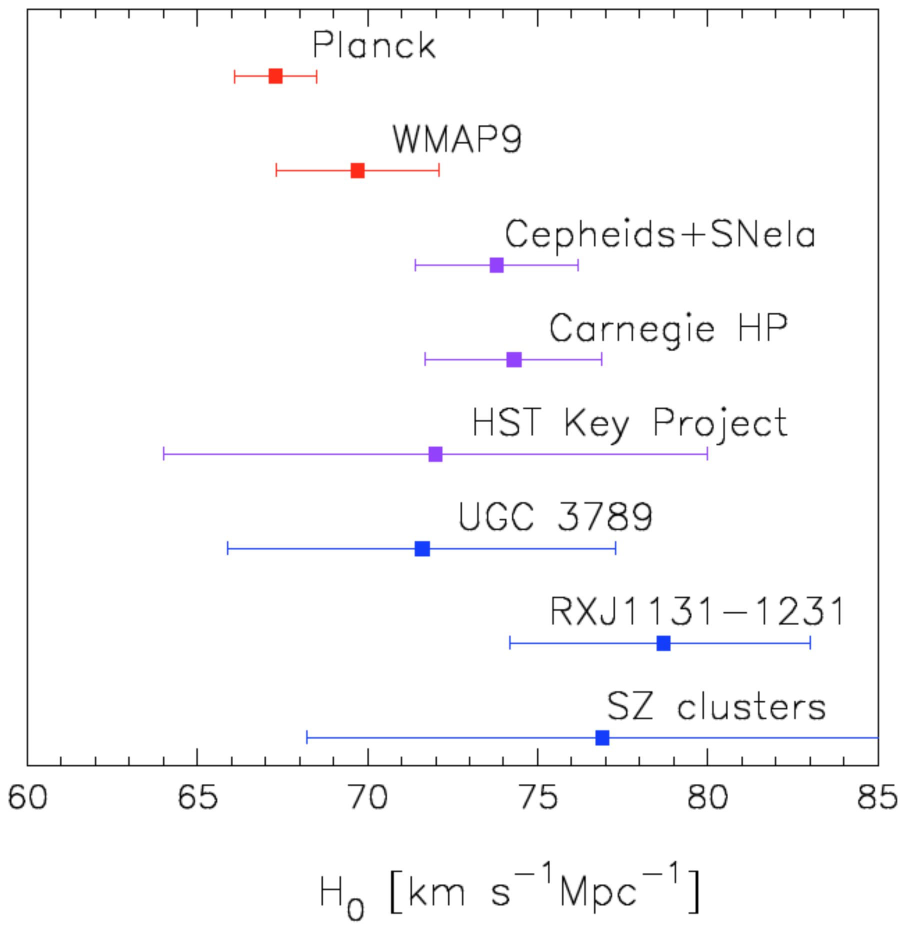
Planck


The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

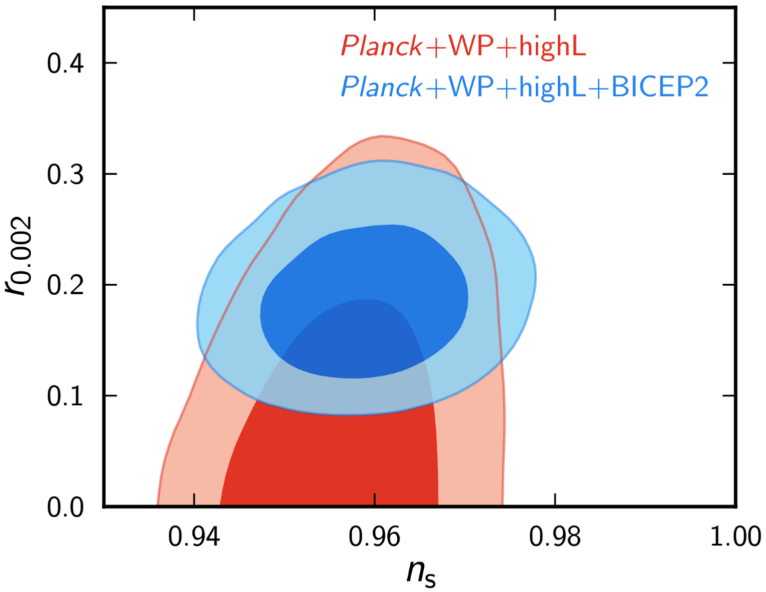
Planck Temperature fluctuations

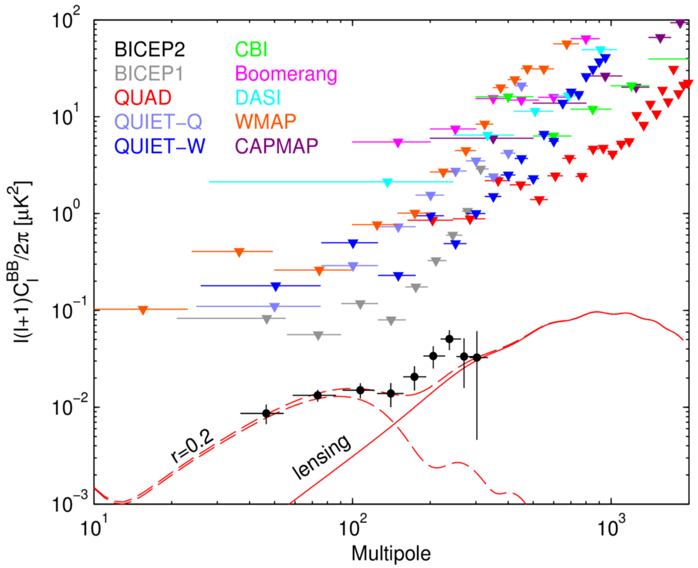


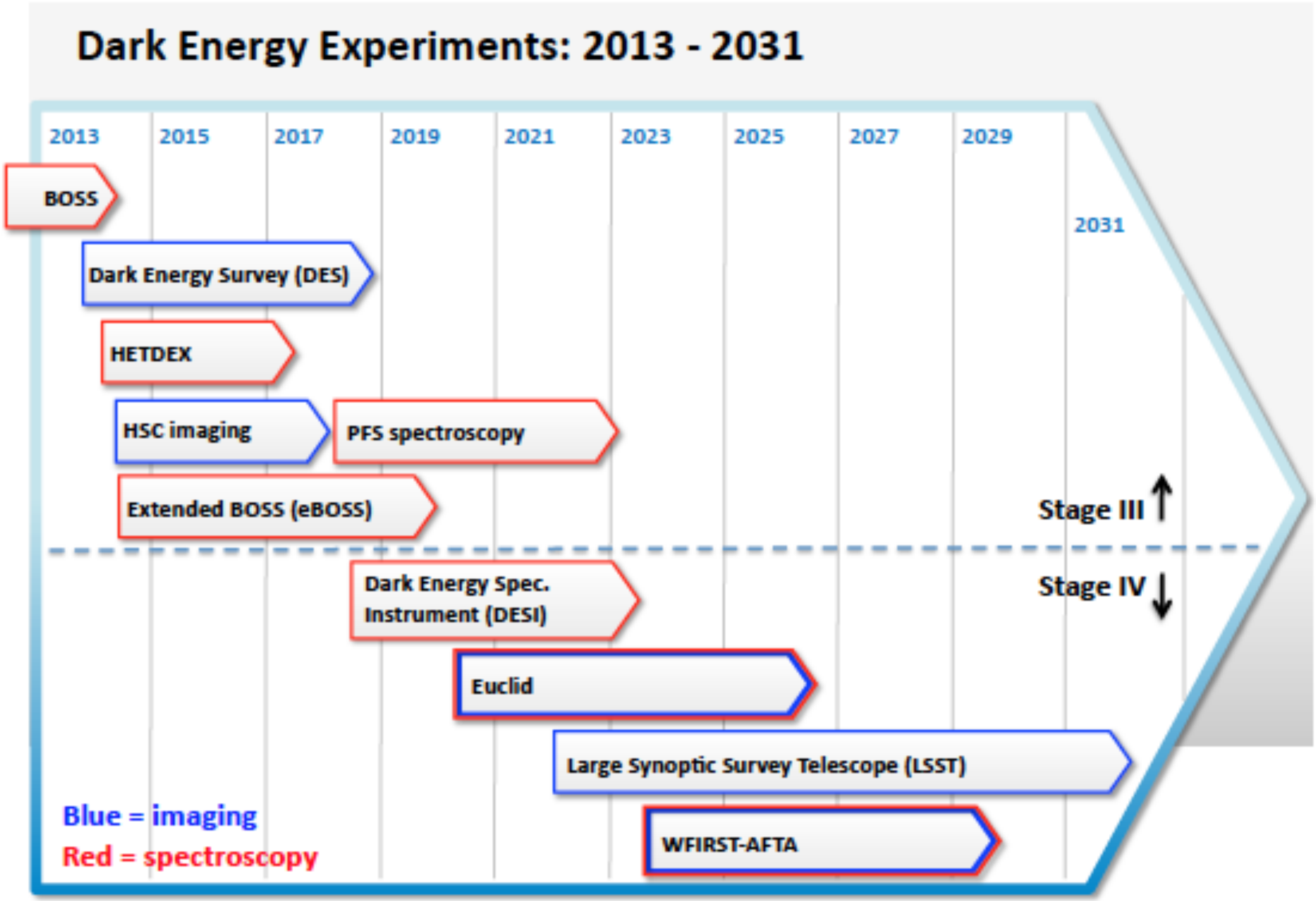
The Hubble Constant tesnion



BICEP2 detection of primordial gravitational waves (cf. Planck)







About $1 per galaxy!

Space vs Ground & their Synergy

Probe	Space	Ground
SN Ia	- Sharp and stable PSF, flux calibration - lower sky NIR background	- High-cadence light-curve sampling and colours in optical rest frame
LSS (BAO & RSD)	- Slitless spectroscopy (low sky NIR background) - 10^8 galaxies over $1<z<2$	- Multi-fibre spectroscopy for 10^7 galaxies for $z<1$ - Ly-alpha forest at $z> 2$ - 21cm
WL	- Sharp and stable PSF - Lower sky NIR background - but galaxy colour gradients, cosmic rays	- Smaller pixel size, high S/N - Photo-z from optical bands - Currently wins on sky area

The Dark Energy Survey

First Light in 9/12, First season 9/13 – 2/14

DARK ENERGY SURVEY

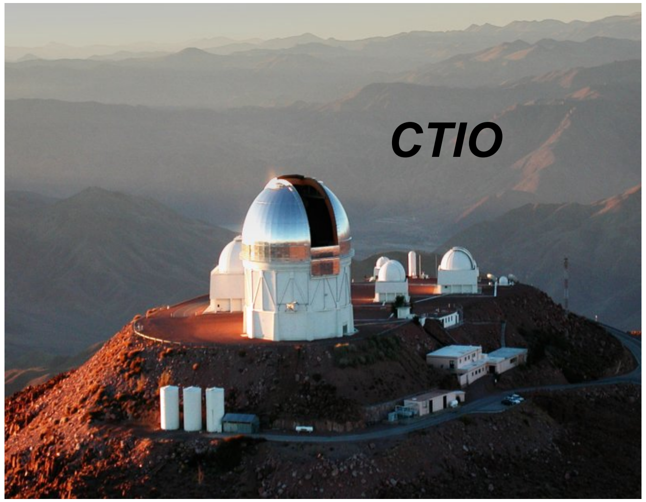
- Multi-probe approach

  Cluster Counts

  Weak Lensing

  Large Scale Structure

  Supernovae Ia



- survey

  300 million photometric redshifts (grizY) over 5000 deg^2

  + 4000 SN Ia (30 deg^2 fields)

  + *JHK* from VHS

  +SPT SZ clusters + OzDES spectra + …

THE DES COLLABORATION (~300 scientists from 6 countries)

Fermilab — The Fermi National Accelerator Laboratory

Chicago — The University of Chicago

NOAO — The National Optical Astronomy Observatory

United Kingdom DES Collaboration

- UCL - University College London
- Cambridge - University of Cambridge
- Edinburgh - University of Edinburgh
- Portsmouth - University of Portsmouth
- Sussex - University of Sussex
- Nottingham - University of Nottingham

DES-Brazil Consortium

- ON - Observatorio Nacional
- CBPF - Centro Brasileiro de Pesquisas Fisicas
- UFRGS - Universidade Federal do Rio Grande do Sul

UIUC/NCSA — The University of Illinois at Urbana-Champaign

LBNL — The Lawrence Berkeley National Laboratory

Spain DES Collaboration

- IEEC/CSIC - Instituto de Ciencias del Espacio,
- IFAE - Institut de Fisica d'Altes Energies
- CIEMAT - Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas

Michigan — The University of Michigan

Pennsylvania — The University of Pennsylvania

ETH-Zuerich — Eidgenoessische Technische Hochschule Zuerich

OSU — The Ohio State University

TAMU — Texas A&M University

Munich—Universitäts-Sternwarte München

- Ludwig-Maximilians Universität
- Excellence Cluster Universe

ANL — Argonne National Laboratory

Santa Cruz-SLAC-Stanford DES Consortium

- Santa Cruz - University of California Santa Cruz
- SLAC - SLAC National Accelerator Laboratory
- Stanford - Stanford University

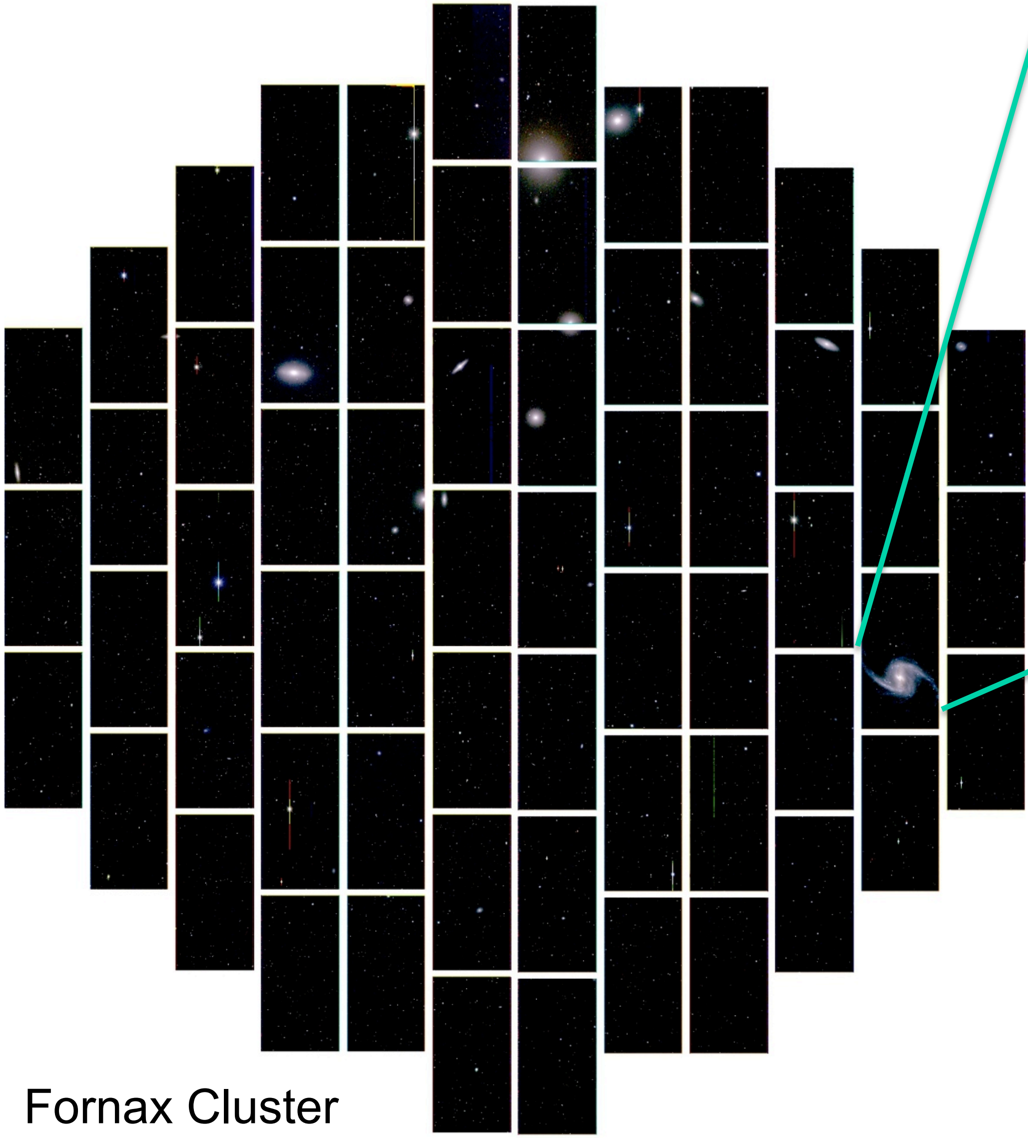
DES Science Committee

- SC Chair: O. Lahav
- Large Scale Structure: E. Gaztanaga & W. Percival
- Weak Lensing: S. Bridle & B. Jain
- Clusters: J. Mohr & C. Miller
- SN Ia: M. Sako & B. Nichol
- Photo-z: F. Castander & H. Lin
- Simulations: G. Evrard & A. Kravtsov
- Galaxy Evolution: D. Thomas & R. Wechsler
- QSO: P. Martini & R. McMahon
- Strong Lensing: L. Buckley-Geer & M. Makler
- Milky Way: B. Santiago & B. Yanny
- Theory & Combined Probes: S. Dodelson & J. Weller
- + Spectroscopic task force: F. Abdalla & A. Kim
- + Ad-hoc Committees

Regular WG telecons; Monthly SC telecons; sessions at collaboration meetings; reports to the DES Director, ExeC & MC

DES FIRST LIGHT

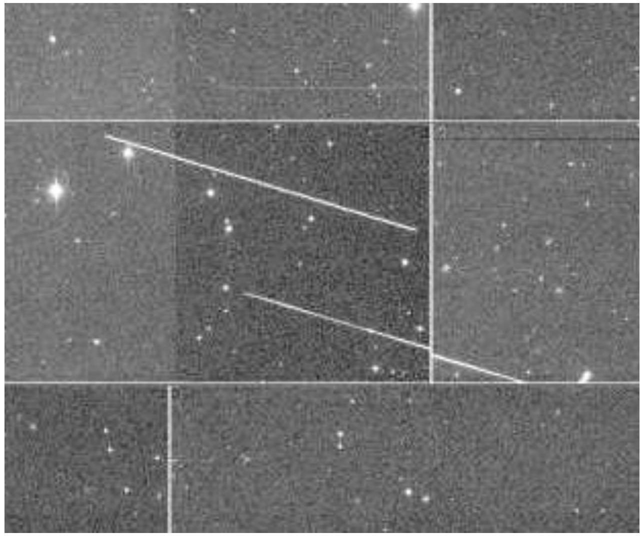
NGC 1365

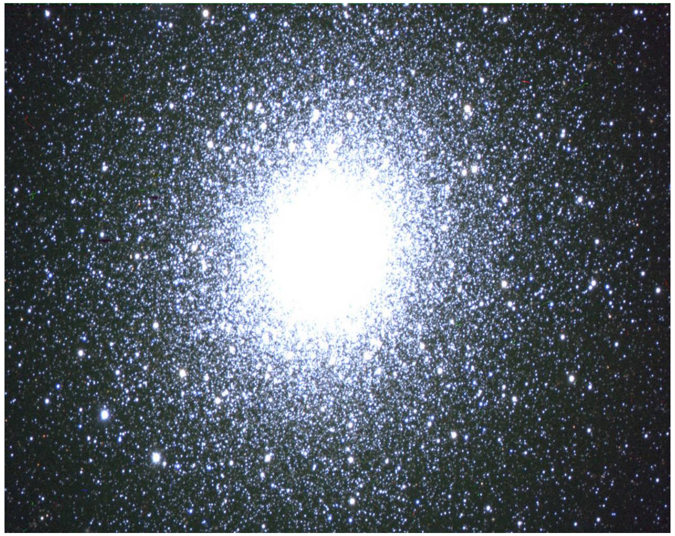


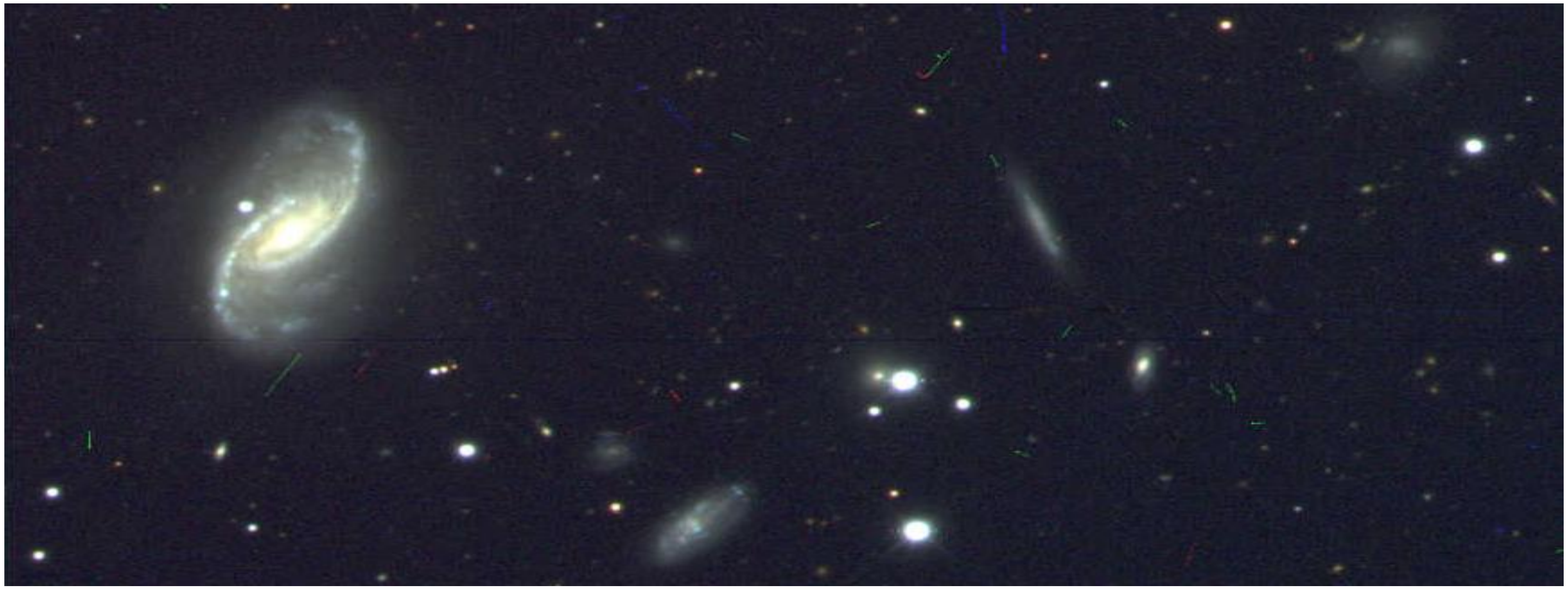
0.8” images recorded within first few nights of first light!

Fornax Cluster

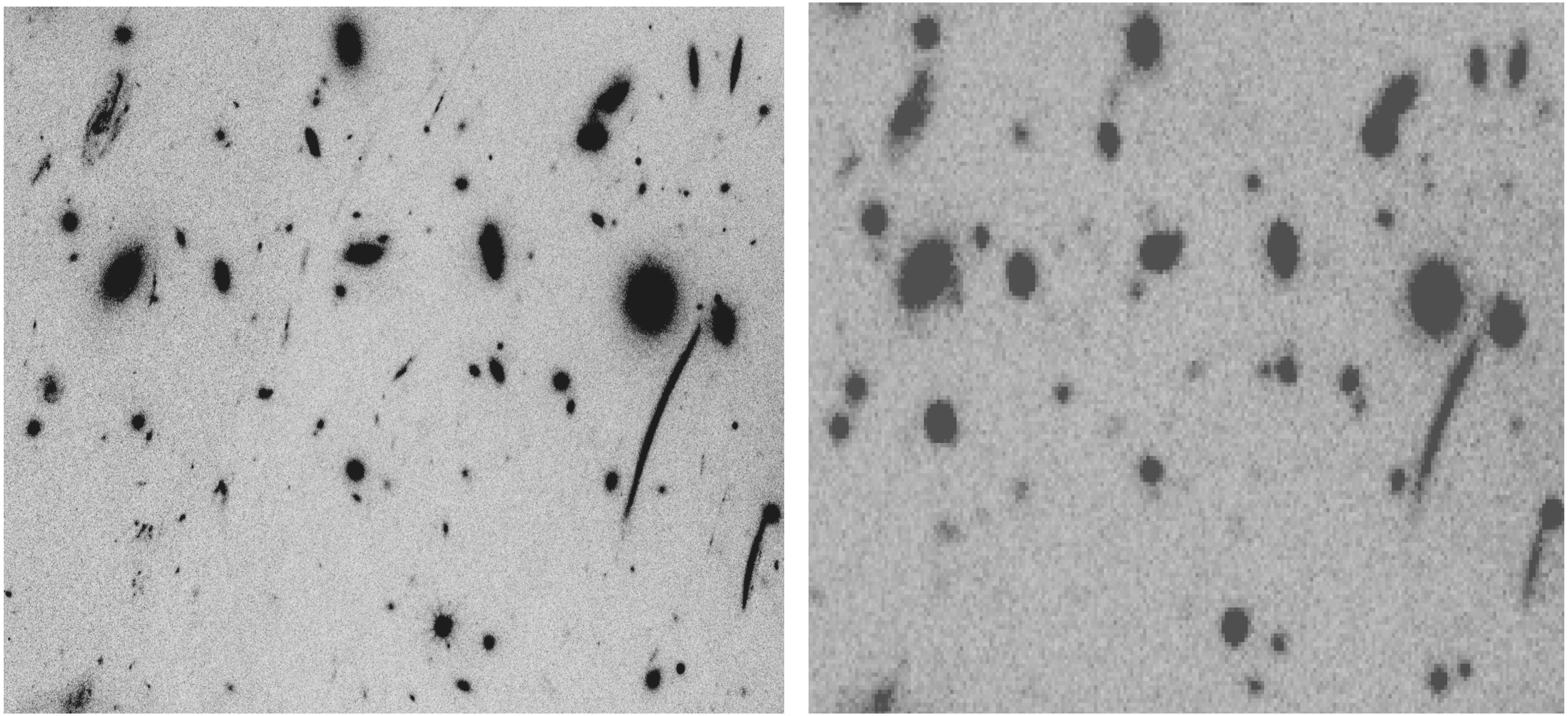
DES first images







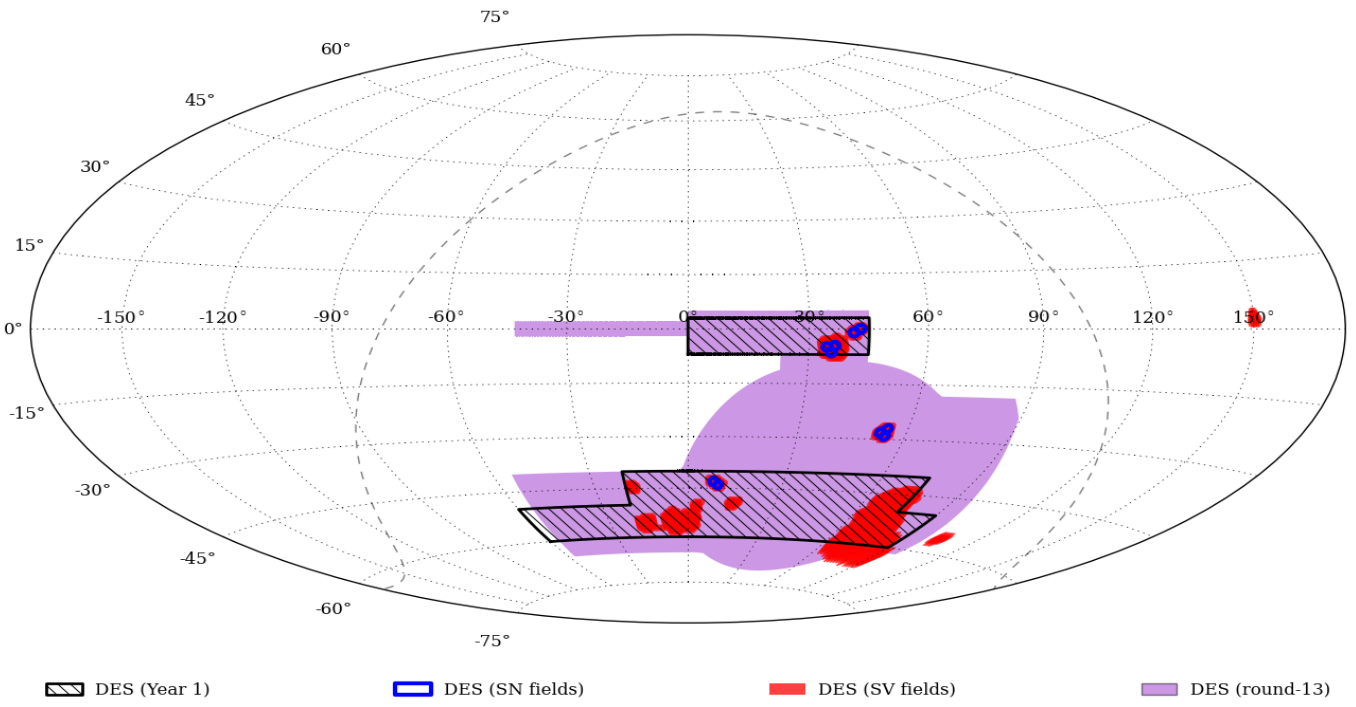
CLASH as a ‘truth table’ for DES



RXJ 2248, 61” x 43” , F435W VS. riz (Palmase, Banerji, Jouvel, OL et al., in prep)

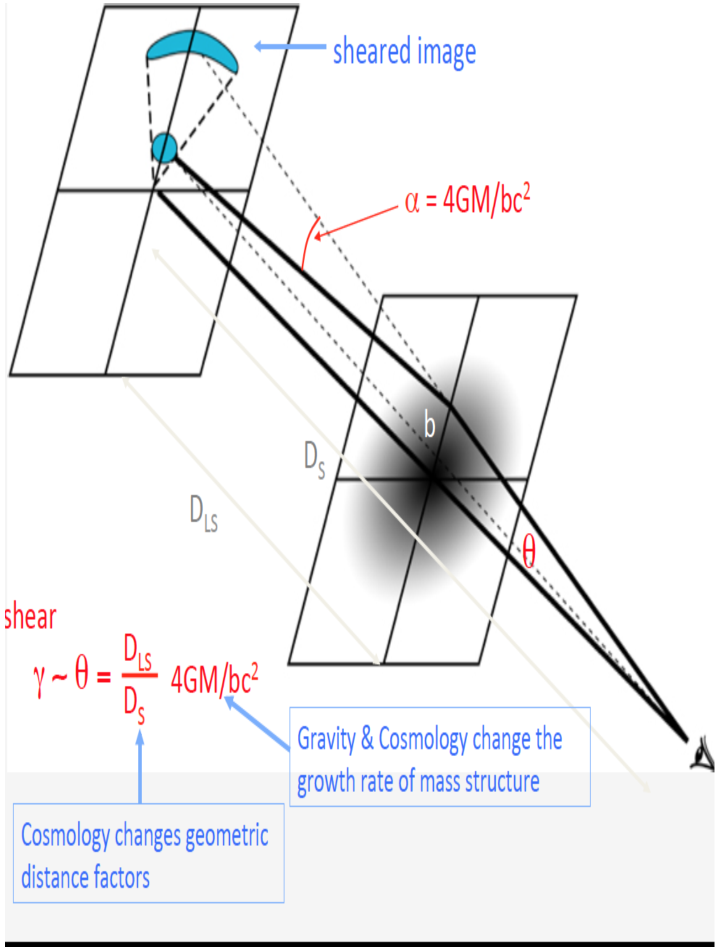
DES survey footprint

year:	1	2*	3	4	5
g	24.1	24.6	24.9	25.1	25.2
r	23.8	24.2	24.5	24.6	24.7
i	23.1	23.5	23.8	23.9	24.0
z	22.5	23.0	23.3	23.3	23.4
y	20.0	21.2	21.4	21.6	21.7



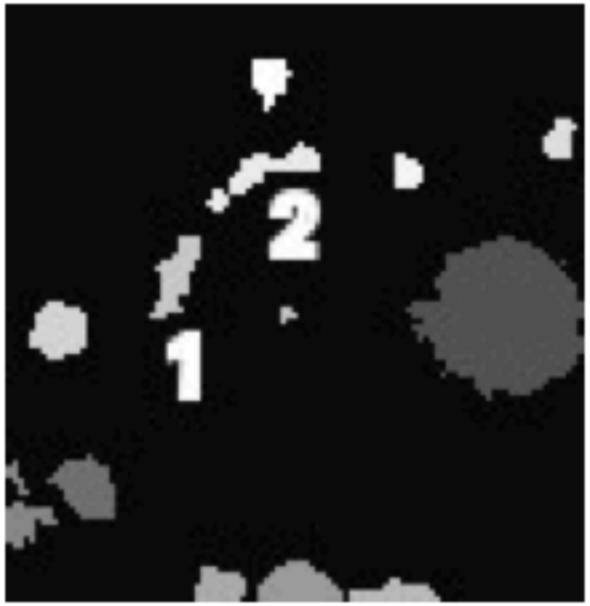
- 5000 sq deg survey to be covered: 1st year strategy is to cover ~2500 sq deg in 4 tilings overlapping SPT, VHS, BOSS

Gravitational Lensing: Weak and Strong



HST CLASH cluster MACS1206

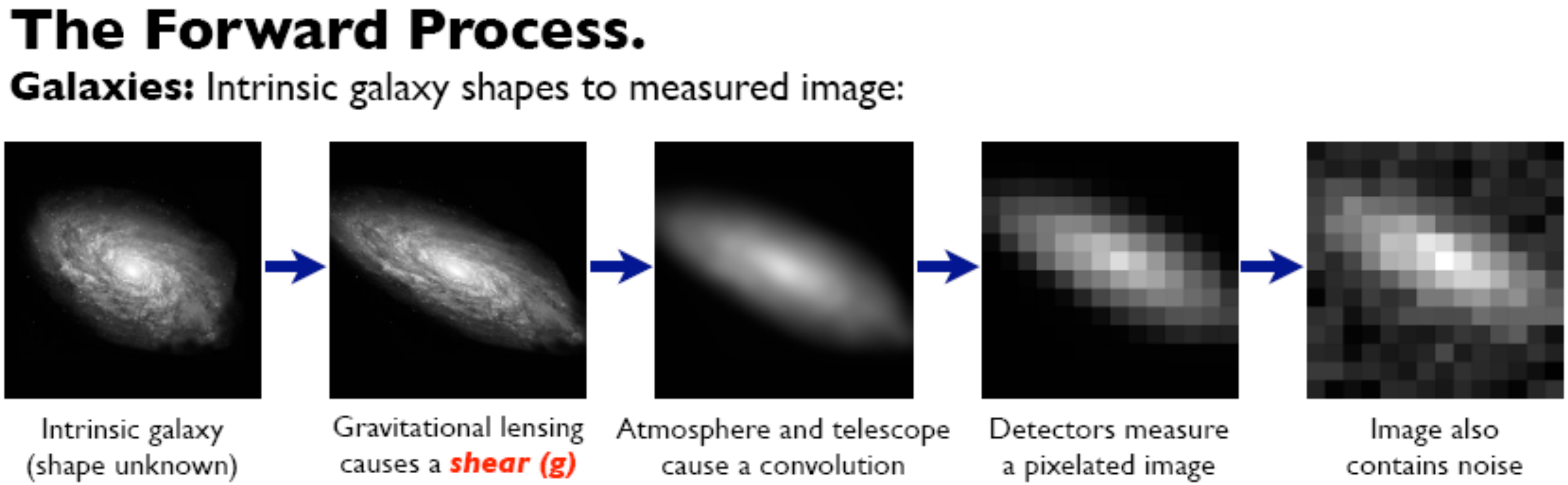
DES Strong Lensing Candidates



ID	Mag Auto g	Mag Auto r	Mag Auto i
1	22.6744	21.7603	21.5612
2	22.6586	21.5880	21.1973

Magnitudes from GALFIT

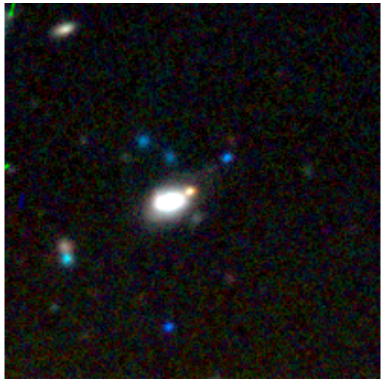
Cosmic shear measurement



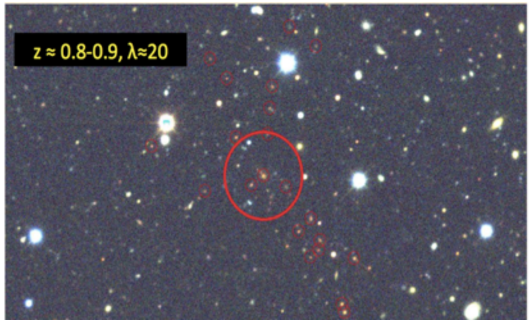
1% effect, to be measured to 1% to get w to 1%

GREAT08 (Bridle et al.); GREAT10 (Kitching et al.);
GREAT3 (Mandelbaum & Rowe et al)

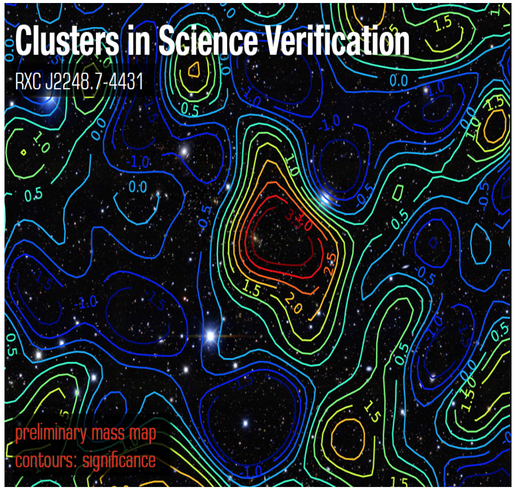
Highlights from DES early data



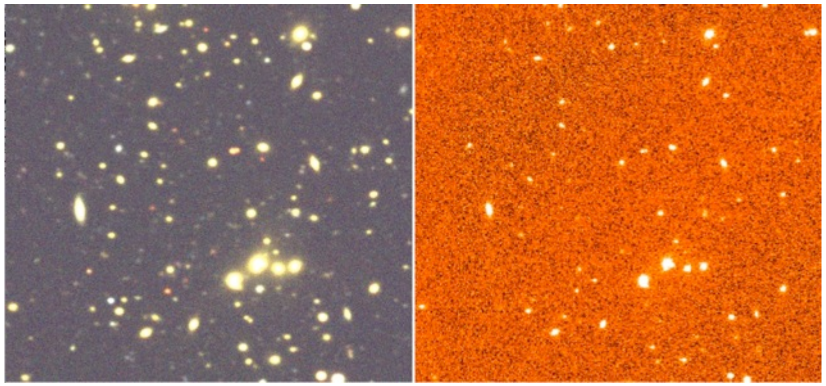
New SN Ia



A new cluster
@ z= 0.87



Mass reconstruction of cluster RXJ2248 @z=0.35



DES gri VHS K

A142 @ z=0.25

Systematics & Nuisance Parameters

- Theoretical (the cosmological model & parameters, e.g. w/out neutrino mass)
- Astrophysical (e.g. galaxy biasing in LSS, dust in SN, intrinsic alignments in WL)
- Instrumental (e.g. image quality, photo-z)

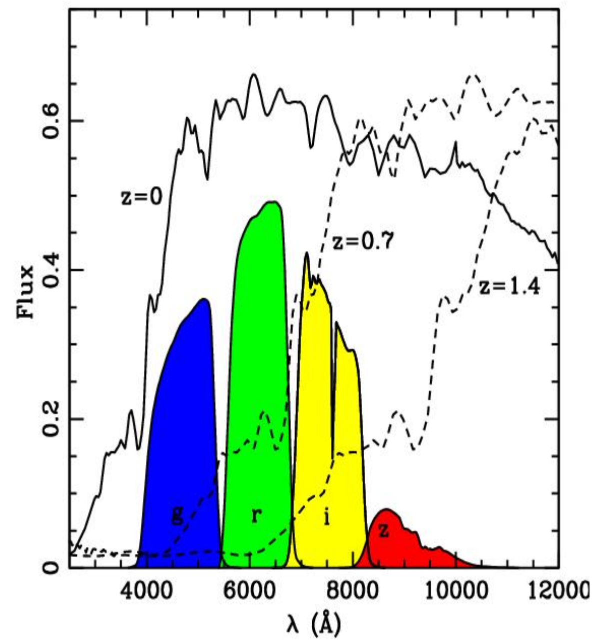
Potentially hundreds of nuisance parameters (while the whole universe is fitted by 6 parameters!)

Photo-z –Spectra cross talk

- Approximately, for a photo-z slice:

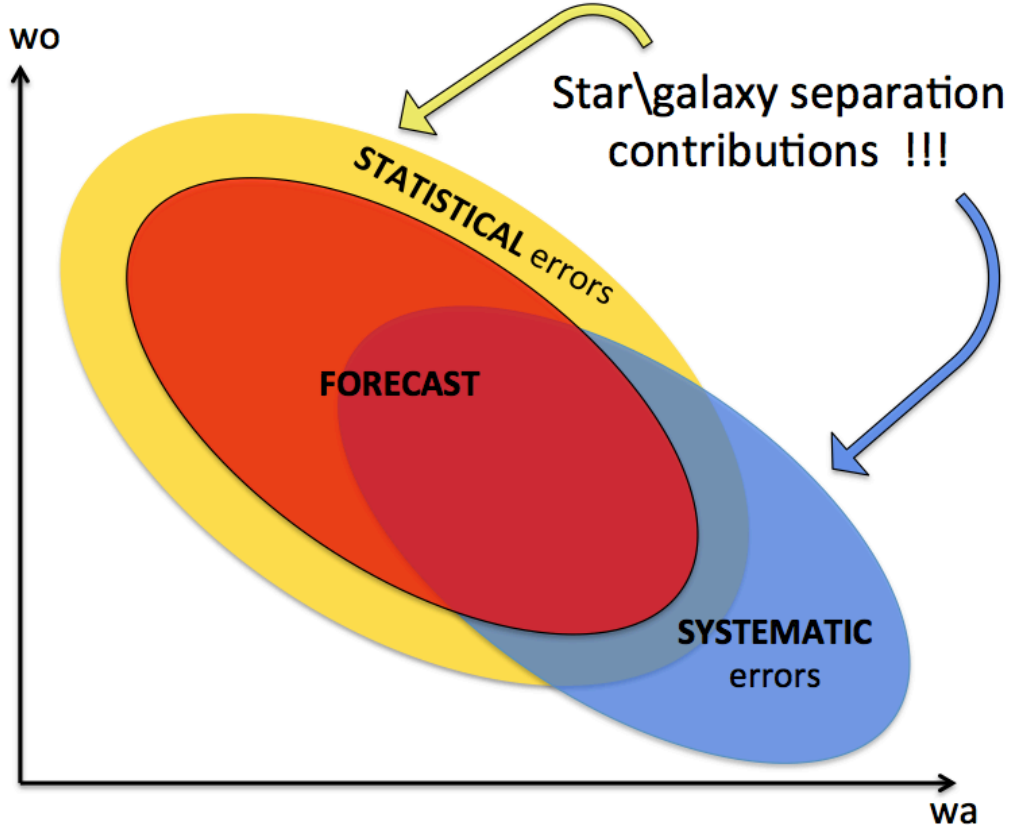
$$(\delta w/ w) = 5 (\delta z/ z) = 5 (\sigma_z/z) N_s^{-1/2}$$

=> the target accuracy in w and photo-z scatter σ_z dictate the number of required spectroscopic redshifts $N_s = 10^5 - 10^6$



Methods: Template (e.g. Hyper-Z, BPZ), Training (e.g. ANNZ)

Star-galaxy separation



Soumagnac, Abdalla, OL et al. (2013)

Photometry,
Shape,
Photo-Z …

PCA + ANNz

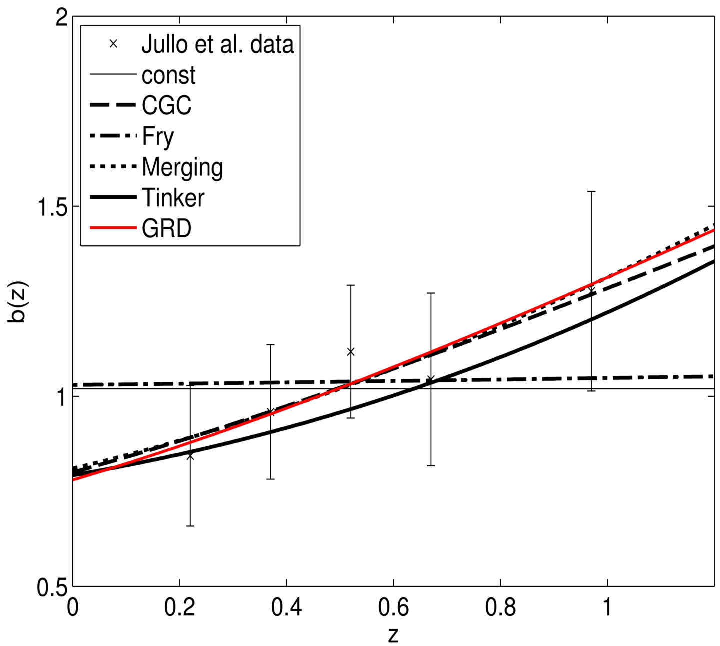
Requirements achieved at Fainter magnitudes

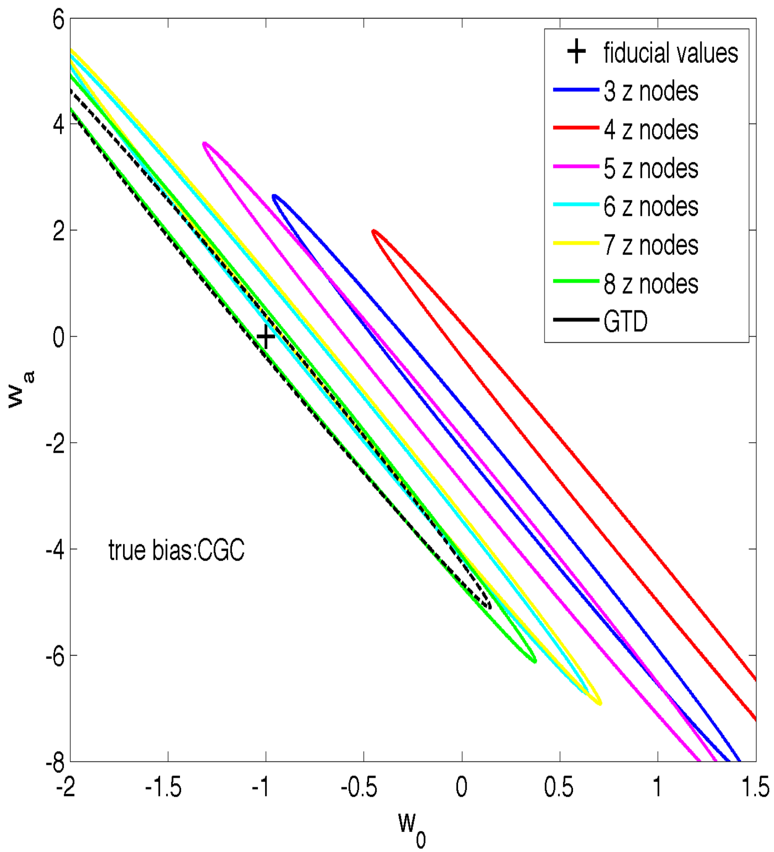
Purity improves by up to 12% for galaxies and by up to 20% for stars.

Nuisance parameters e.g. galaxy biasing

Generalized biasing

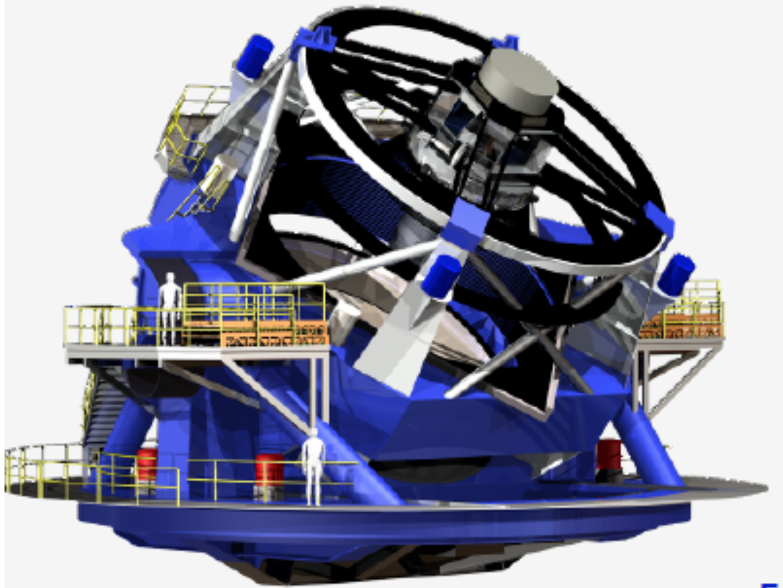
$$b(z) = C + (b_0 - C)/D(z)^{\alpha},$$

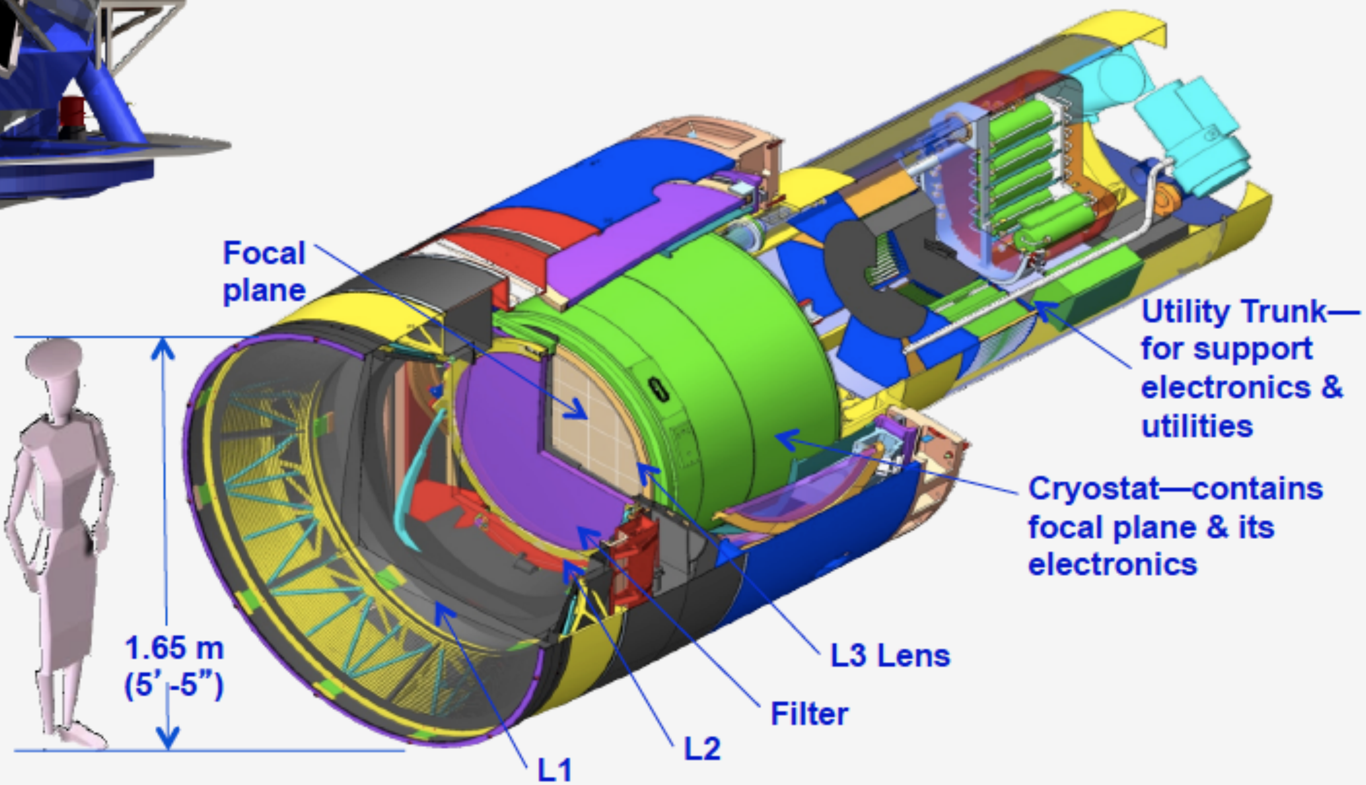




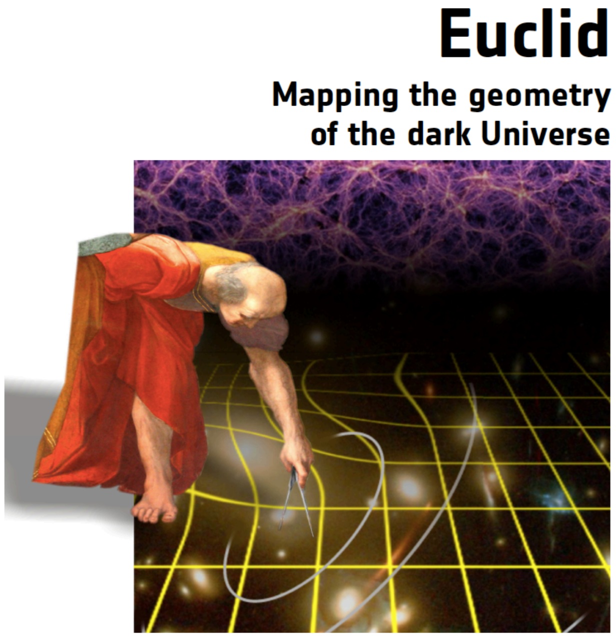
Clerkin, Kirk, OL, Abdalla et al (in prep)

8m telescope + 3 Billion Pixel Camera





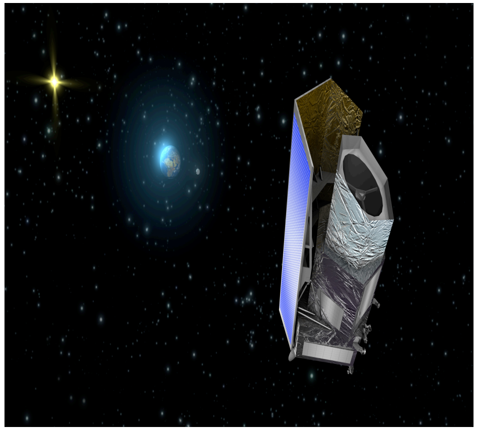
EUCLID



ESA Cosmic Vision planned launch 2020

The key original ideas:
weak lensing from space
and photo-z from the ground
(DUNE) + spectroscopy (SPACE)

The new Euclid: 15000 sq deg
1B galaxy images + 50M spectra
(+ground based projects,
e.g. PS, DES, LSST,…)



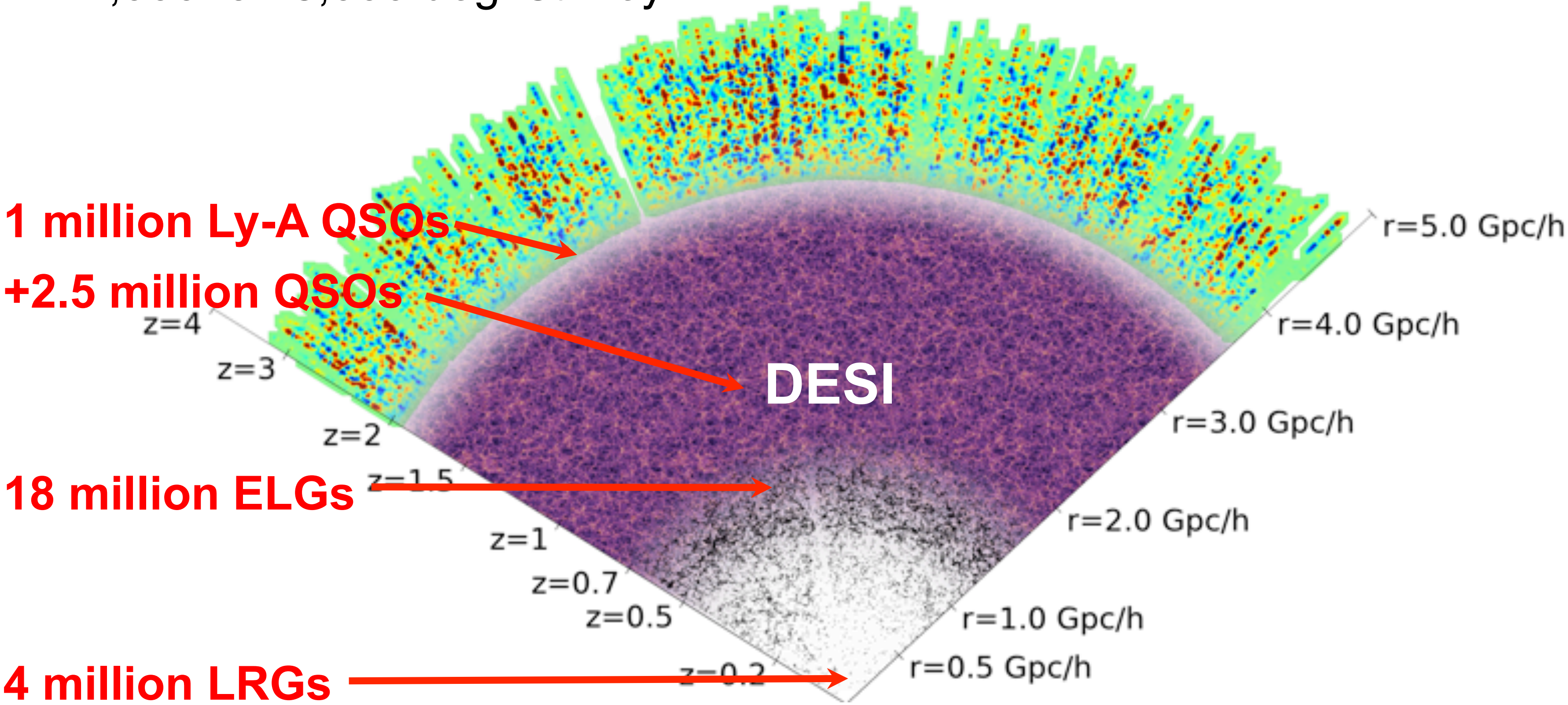
Dark Energy Spectroscopic Instrument (DESI) – 10 times BOSS

Mayall telescope available up to 100% of dark time,

5000 fibres, 20min base integration time

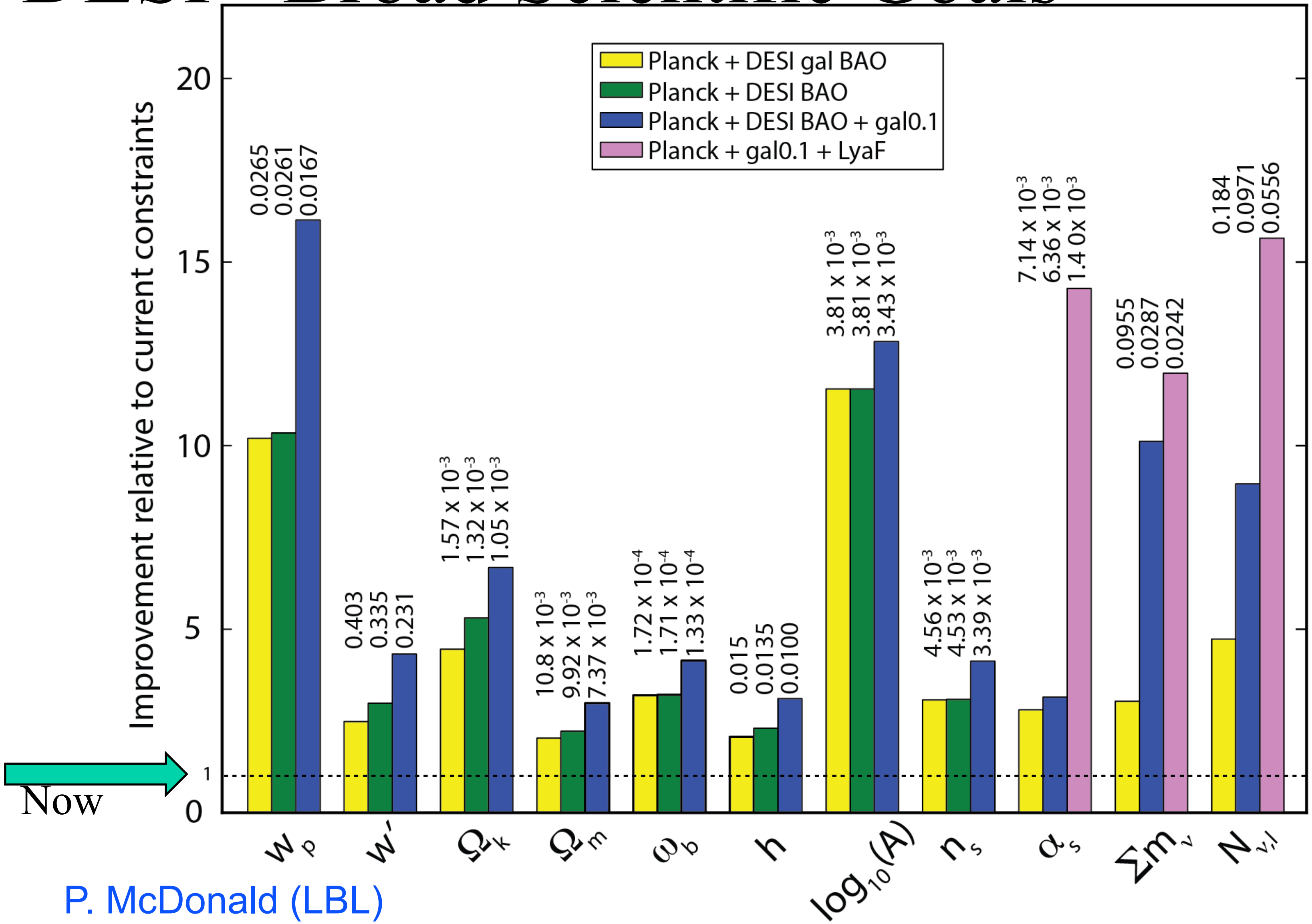
> 20 million targets

14,000 to 18,000 deg^2 survey



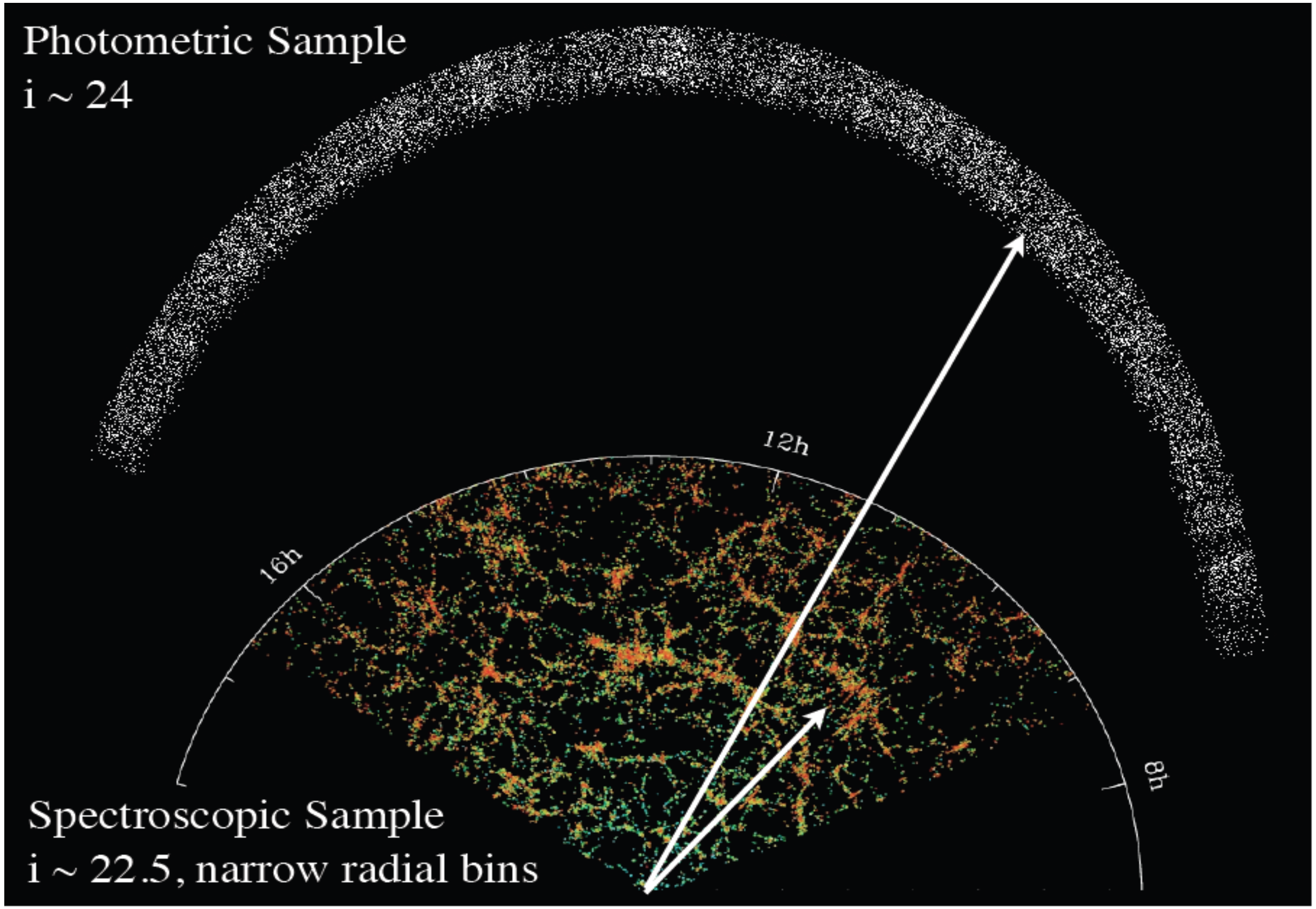
Improvement in current constraints (normalized to 1.0):

DESI - Broad Scientific Goals



P. McDonald (LBL)

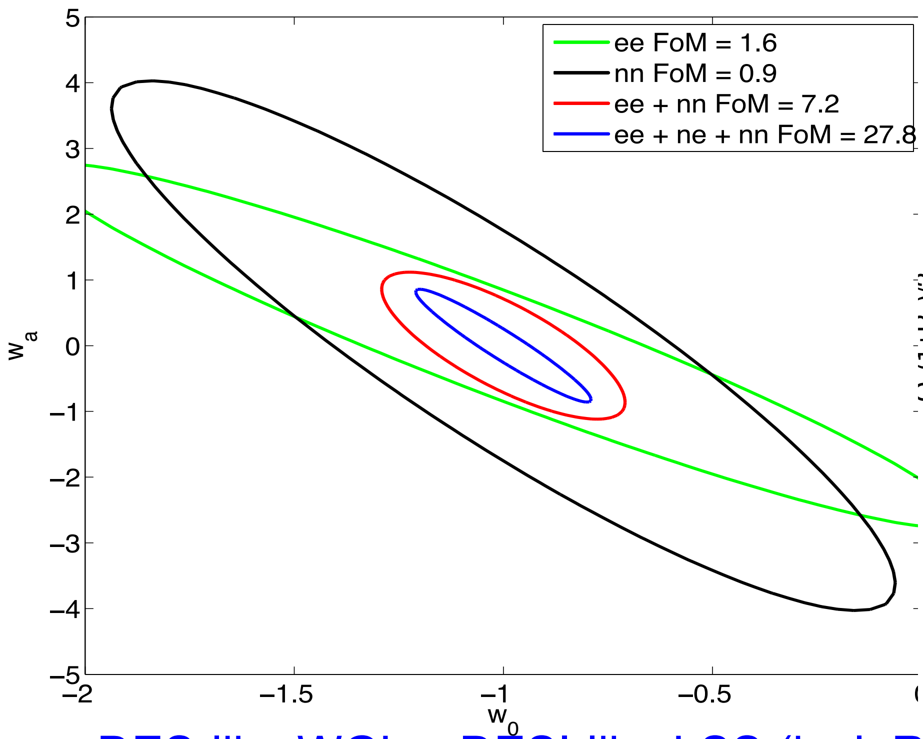
Same Sky: How Important?



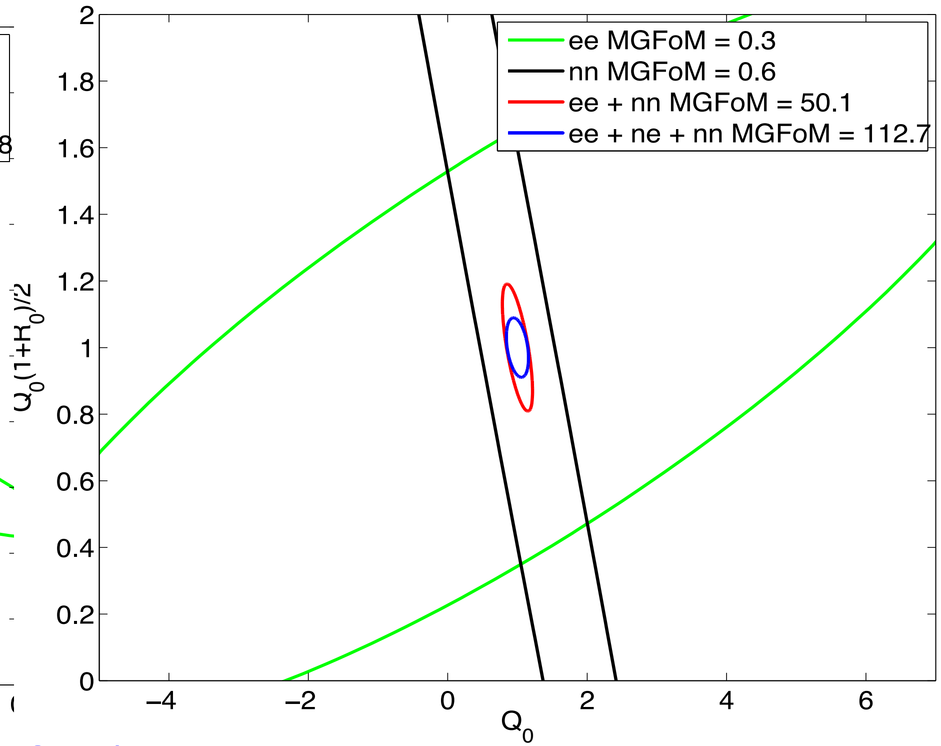
Gaztanaga et al.

Combining imaging and spectroscopy

Dark Energy (W_0, W_a)



Mod Grav (Q, R)



- DES-like WGL + DESI-like LSS (incl. RSDs)
- Assumes 5000 sq deg for each survey,
- 300 million DES galaxies
- 10 million DESI galaxies

$$C_l^{i,j} = 4\pi \int \Delta^2(k) W_i(k) W_j(k) \frac{dk}{k}$$

Kirk, Lahav, Bridle, Jouvel, Abdalla, Frieman, arXiv:1307.8062

Summary

- w=const=-1 is not ruled out by the data
- But w(z), ModGrav are also still possible
- Ground-Space synergy
- How to deal with systematics and nuisance parameters?
- When to stop?
- What will be the next paradigm shift?
- Other physics from same DE surveys, e.g detection of neutrino mass, MW, QSO, galaxy evolution

Extra slides

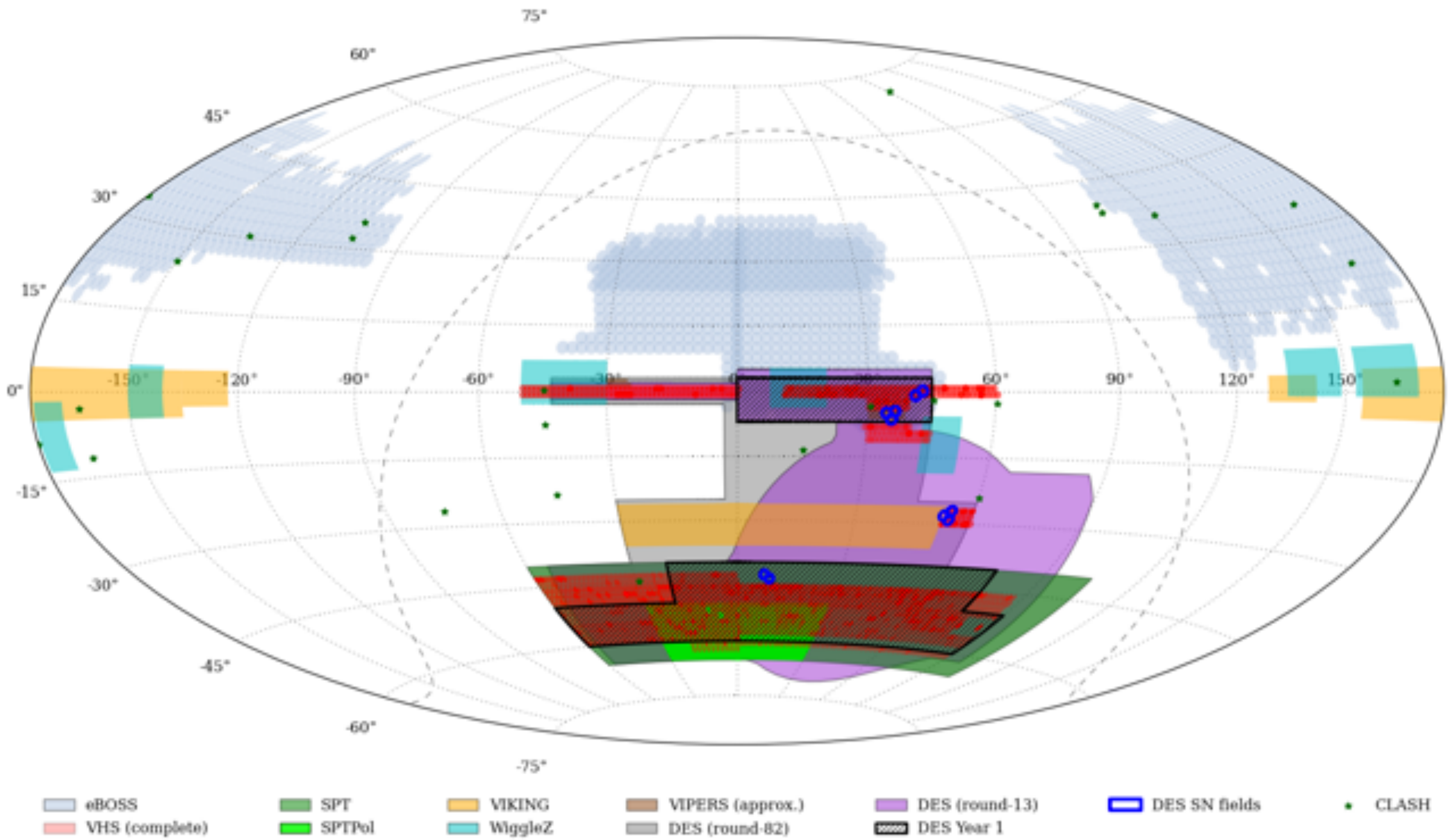
The Landscape of Surveys
(some under construction, some proposed)

Photometric surveys: DES, KIDS, VISTA, Pan-STARRS, HSC, Skymapper, PAU, JPASS, LSST, Euclid, WFIRST…

Spetroscopic surveys: WiggleZ, BOSS, e-BOSS, (MS)DESI, HETDEX, SuMIRe PFS, 4MOST, SKA, Euclid,WFIRST

About $1 per galaxy!

The DES footprint
& overlapping surveys



Planck vs WMAP

	Planck+WP +highL	*Planck*+WP +highL+BAO	*WMAP*9+eCMB +BAO
$\Omega_b h^2$	0.02207 ± 0.00027	0.02214 ± 0.00024	0.02211 ± 0.00034
$\Omega_c h^2$	0.1198 ± 0.0026	0.1187 ± 0.0017	0.1162 ± 0.0020
$100\,\theta_{MC}$	1.0413 ± 0.0006	1.0415 ± 0.0006	–
n_s	0.958 ± 0.007	0.961 ± 0.005	0.958 ± 0.008
τ	$0.091^{+0.013}_{-0.014}$	0.092 ± 0.013	$0.079^{+0.011}_{-0.012}$
$\ln(10^{10} \Delta^2_{\mathcal{R}})$	3.090 ± 0.025	3.091 ± 0.025	3.212 ± 0.029
h	0.673 ± 0.012	0.678 ± 0.008	0.688 ± 0.008
σ_8	0.828 ± 0.012	0.826 ± 0.012	$0.822^{+0.013}_{-0.014}$
Ω_m	$0.315^{+0.016}_{-0.017}$	0.308 ± 0.010	0.293 ± 0.010
Ω_Λ	$0.685^{+0.017}_{-0.016}$	0.692 ± 0.010	0.707 ± 0.010

Planck's two clouds…

Planck cluster counts: The σ_8 problem