Deep Galaxy Surveys for Dark Energy

From DES to DESI

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Outline

Why Deep Galaxy Surveys

Intro. Dark Energy
Probes of Dark Energy (mainly related to LSS)
Photometric vs Spectroscopic surveys

The Dark Energy Survey (DES)

Science
Spanish Participation
Status

The Dark Energy Spectroscopic Instrument (DESI)

Science
Spanish Participation
Status

Conclusions

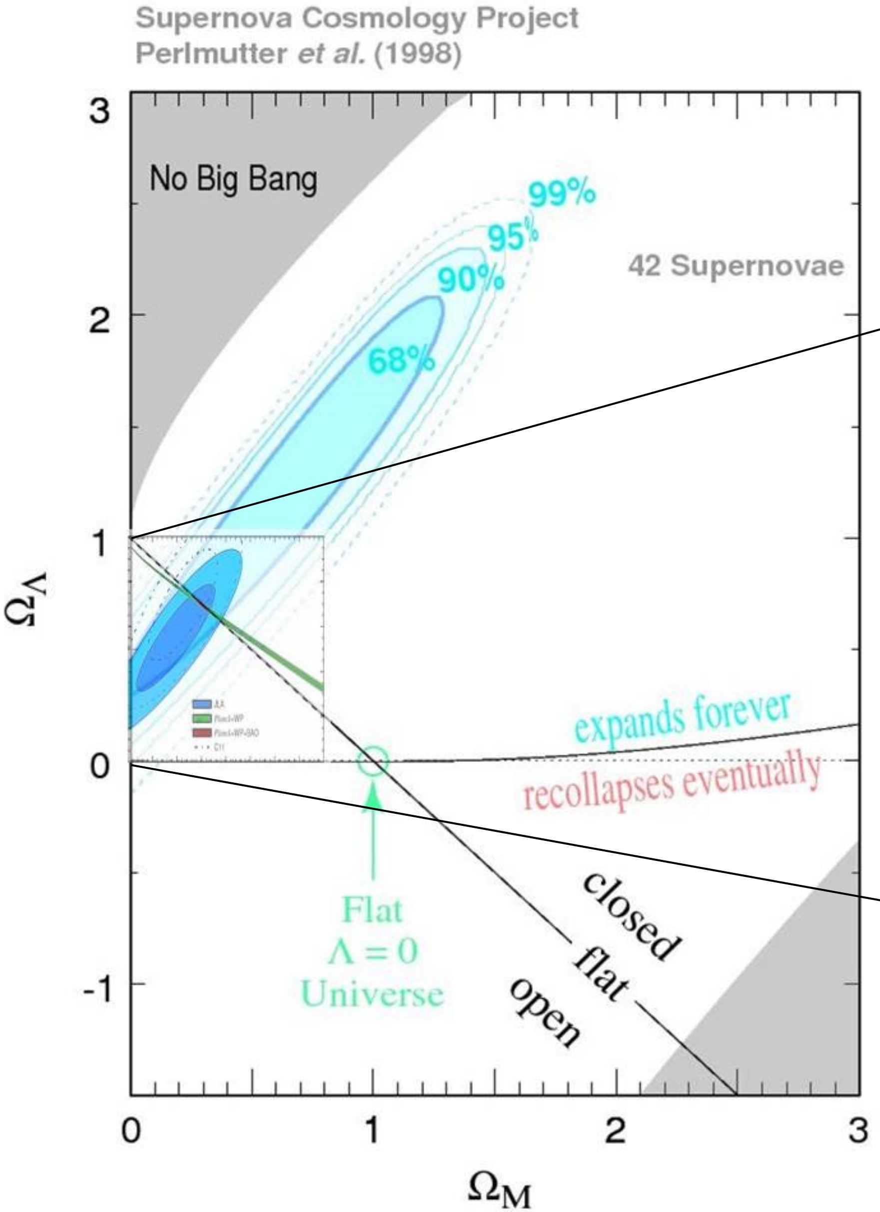
What do we mean by dark energy?

The discovery of the accelerated expansion of the Universe was a huge surprise, since gravity acting on matter slows down the expansion, so we expected a deccelerating expansion, not an accelerating one

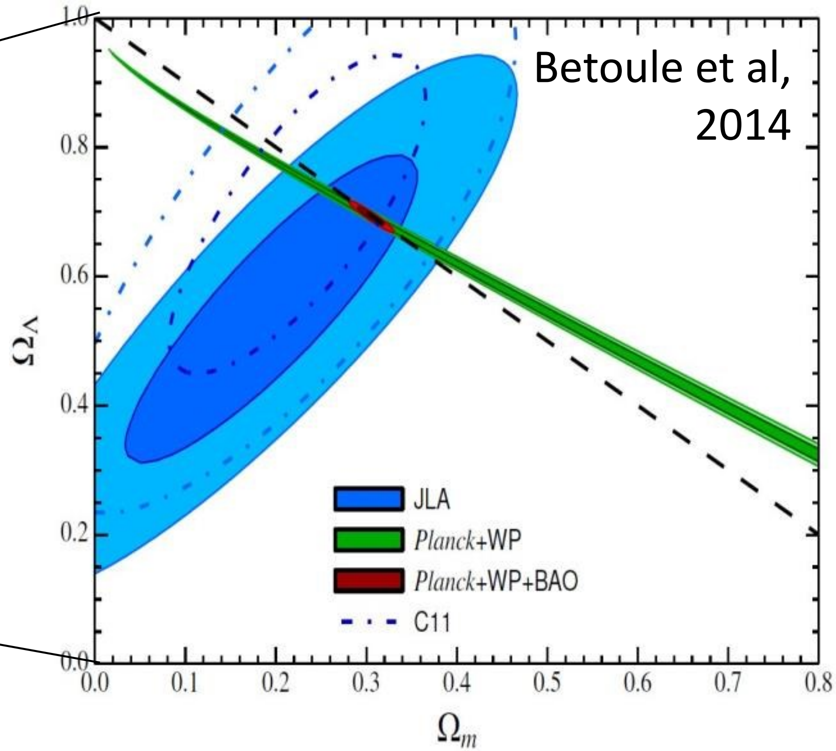
Whatever mechanism causes the acceleration, we call it "dark energy":

- Einstein´s cosmological constant
- Some new field ("quintessence"…)
- Modifications to General Relativity
- …

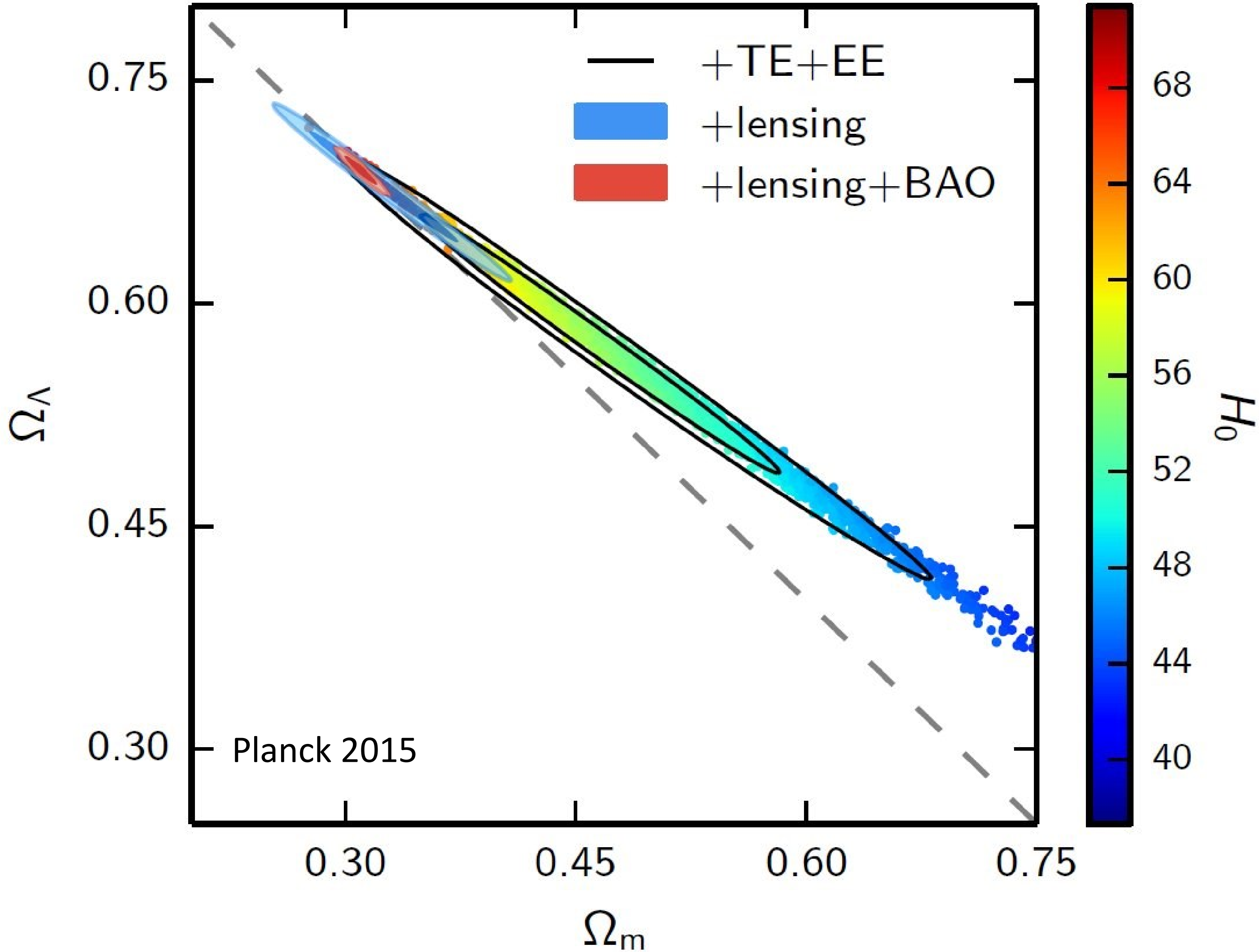
Evidence for dark energy



Huge progress from 1998



Evidence for dark energy



What do we know about dark energy?

1) **It does not emit nor absorbs electromagnetic radiation**
2) **It does not dilute with expansion → Negative pression**
3) **Its distribution is homogeneous. Dark Energy does not cluster significantly with matter on scales at least as large as galaxy clusters**

Dark energy is qualitatively very different from dark matter. Its pressure is comparable in magnitude to its energy density (it is energy-like), while matter is characterized by a negligible pressure

Dark energy is a diffuse, very weakly interacting with matter and very low energy phenomenon. Therefore, it will be very hard to produce it in accelerators. As it is not found in galaxies or clusters of galaxies, the whole Universe is the natural (and perhaps the only one) laboratory to study it.

Distances

Scale factor is **related to observations through distances.**

Comoving distance:

$$r(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_\Lambda + \Omega_k(1+z')^2 + \Omega_M(1+z')^3 + \Omega_r(1+z')^4}}$$

Several distances can be measured observationally

Luminosity distance: "Standard Candle" with luminosity L

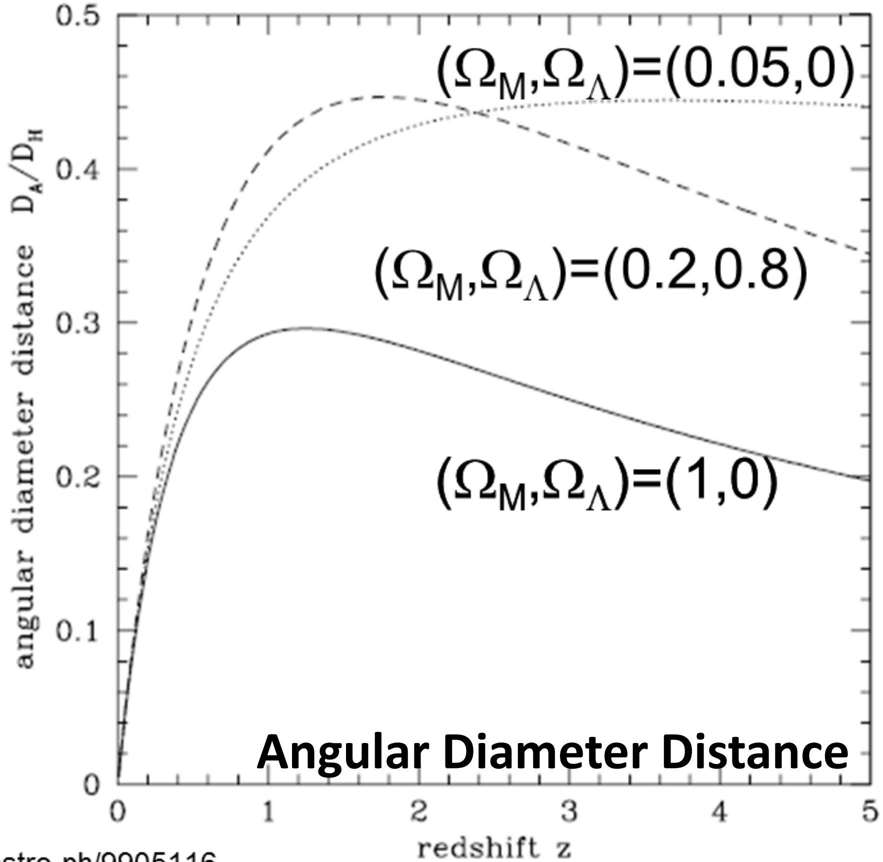
$\phi = L/4\pi d_L^2$; $\mathbf{d_L = r(z)(1+z)}$ (flat Universe)

Angular diameter distance: "Standard Ruler" with length l

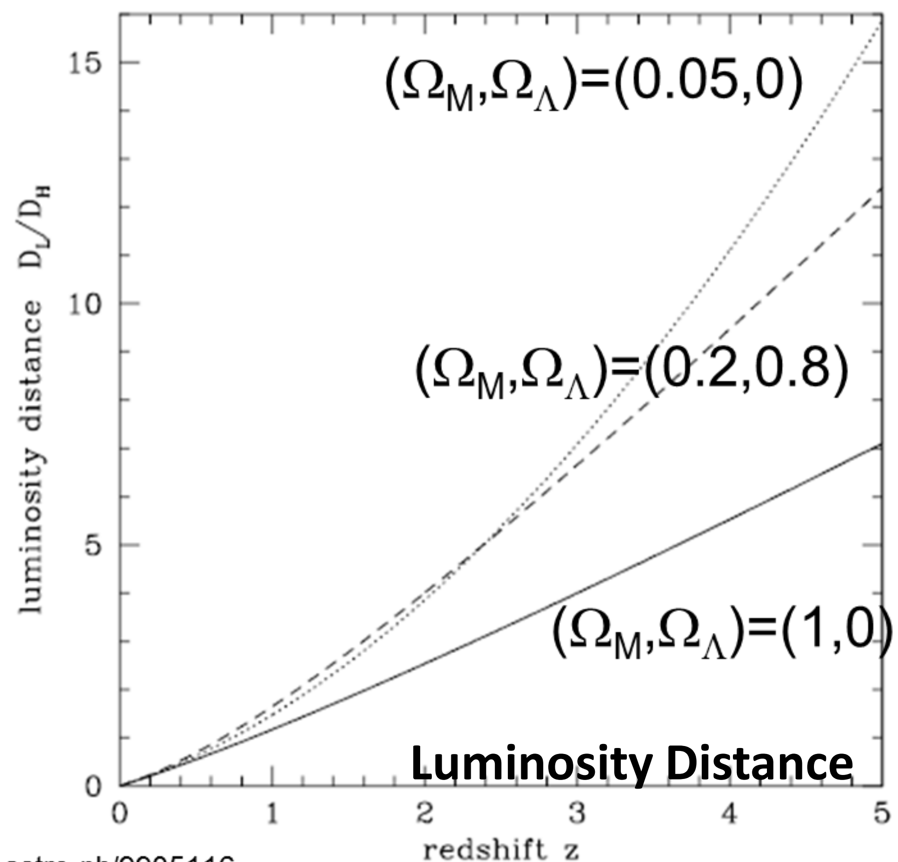
$\Delta\theta = l/d_A$; $\mathbf{d_A = r(z)/(1+z)}$ (flat Universe)

Having a collection of standard candles or rulers at different known redshifts, we can reconstruct the densities and properties of the fluids in the Universe

Distances



astro-ph/9905116



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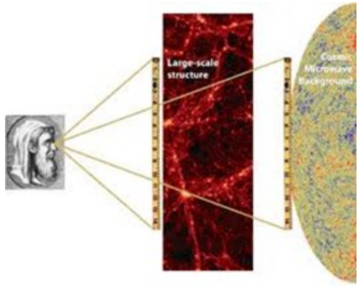
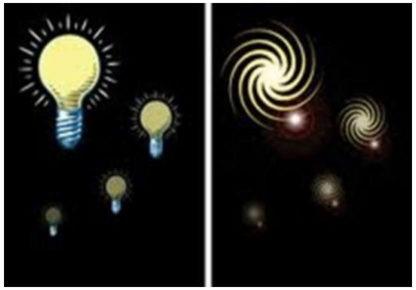


STANDARD RULERS



STANDARD CANDLES

Growth of Structure

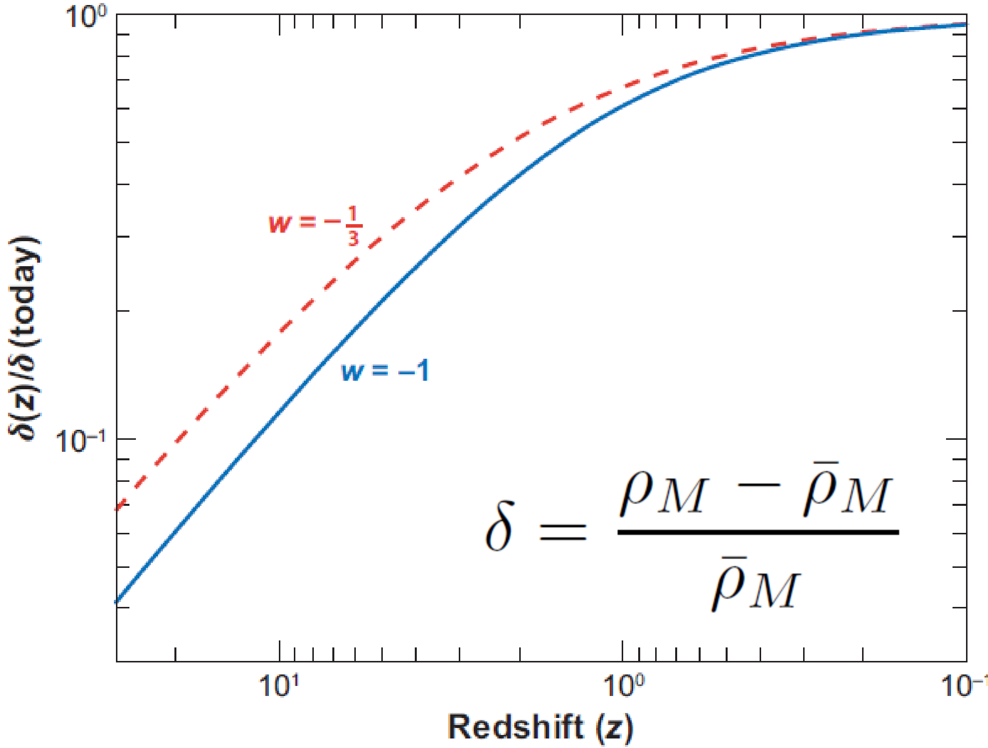
ΛCDM is able to account for the observed structure in the Universe

- Structure grows due only to gravity (and dark energy) from initally small perturbations
- Cold Dark Matter
- Initial power spectrum of density perturbations nearly scale invariant (inflation)

$$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho_M\delta_k = 0$$

The distribution of fluctuations depends on primordial perturbations and also on the composition of the universe

CDM: Small Structures form first



$$\delta = \frac{\rho_M - \bar{\rho}_M}{\bar{\rho}_M}$$

Dark matter and energy are new physics

The dark side of the Universe opens the door for new physics, with potential discoveries that are relevant both for cosmology and particle physics

ΛCDM requires new physics 3 times:

Dark Matter

Dark Energy

Early universe (inflation, baryogenesis…)

Many different properties of the dark side of the universe can be studied using huge galaxy surveys

The Cosmological Constant Case

All current observations are compatible with dark energy being the cosmological constant. This is the most simple and the most puzzling dark energy candidate

$w=-1.006 \pm 0.045$ from Planck 2015

If it is the vacuum energy

$$\Omega_\Lambda \sim 0.7 \rightarrow \rho_\Lambda \sim (10\ \mathrm{meV})^4$$

while the (naive!!!) estimate from QFT is

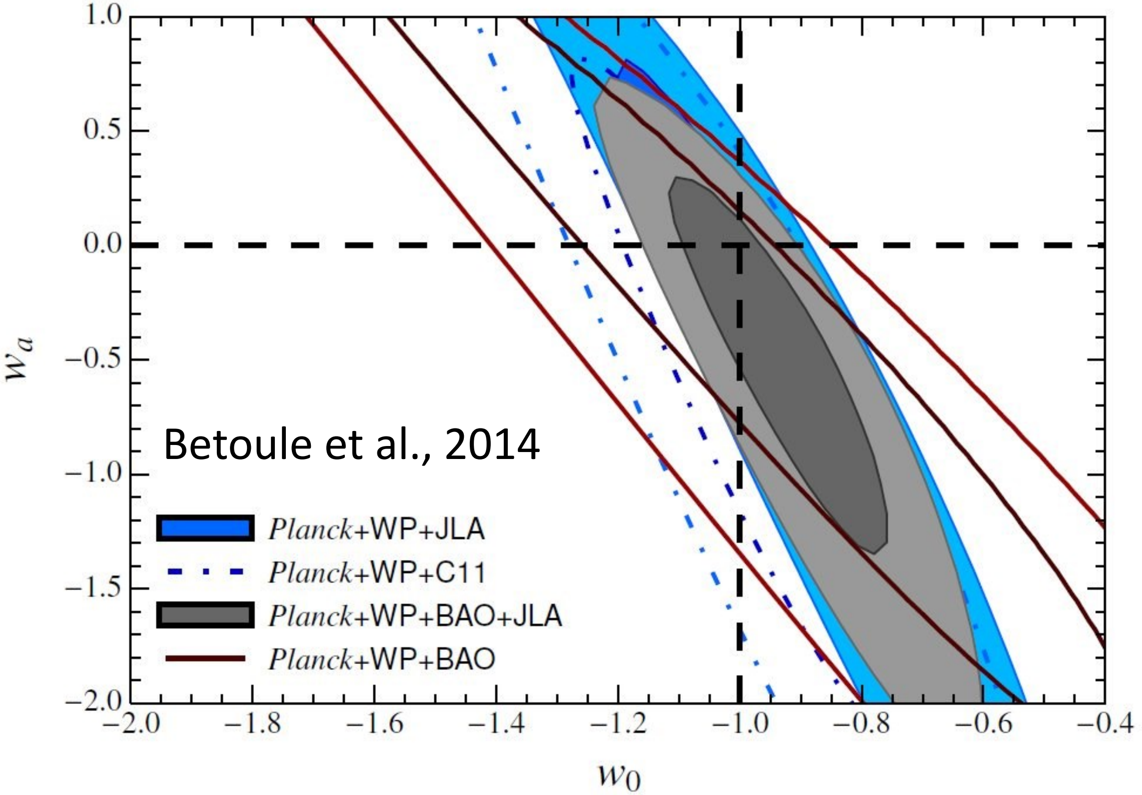
$$\rho_\Lambda \sim m_{Planck}{}^4 \sim 10^{120} x \sim (10\ \mathrm{meV})^4$$

or from the Higgs potential, $\rho_\Lambda \sim 10^{55} x \sim (10\ \mathrm{meV})^4$

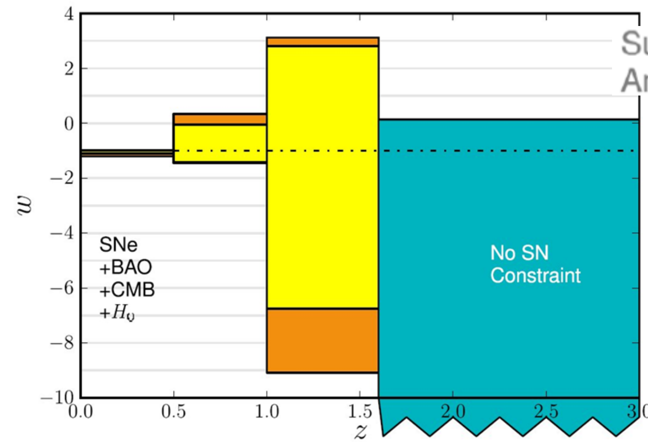
Why such a huge difference?

The Cosmological Constant Case

However, the precision of the current measuremet of the EoS parameter for dark energy is still limited



One of the main goals of current and future projects is to improve this measurement (as much as possible)



Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)

Observational Probes of dark energy

Test if $w_0 = -1$ and $w_a \neq 0$

DETF Figure of merit: Inverse of the area of the error ellipse enclosing 95% confidence limit in the w0-wa plane. Standard way to compare sensitivities for dark energy projects

Standard Candles: Measure $d_L = (1+z)\, r(z)$

Standard Rulers: Measure $d_A = r(z)/(1+z)$

Number Counts: Measure $\frac{dV}{dz d\Omega} = r^2(z)/\sqrt{(1 - kr^2(z))}$

Growth of structure: A more complicated function of H(z)

Observational Probes of dark energy

Many practical implementations:

Distance probes: SN1a, BAO, CMB, weak lensing, galaxy clusters,…

Growth of Structure probes: CMB, redshift space distortions, weak lensing, galaxy clusters…

No single technique is sufficiently powerful to improve the knowledge of dark energy at the level of one order of magnitude

Combination of techniques: More statistical power, ability to discriminate among dark energy models, robustness against systematic errors

Observational Probes: Galaxy Surveys

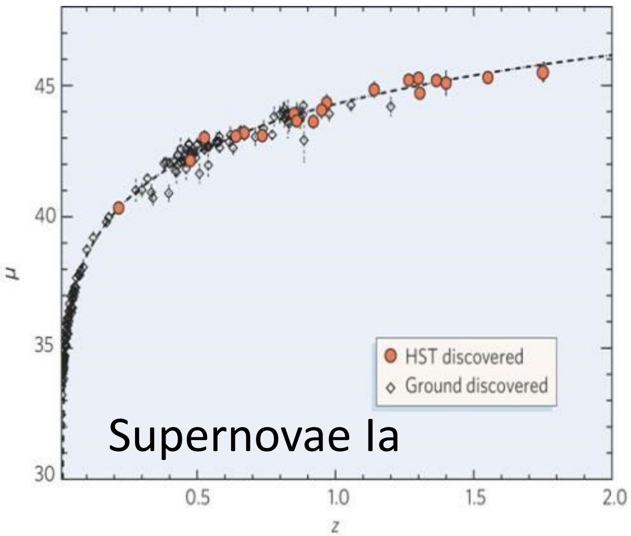
Apart from CMB, many of these probes are implemented by means of Galaxy Surveys

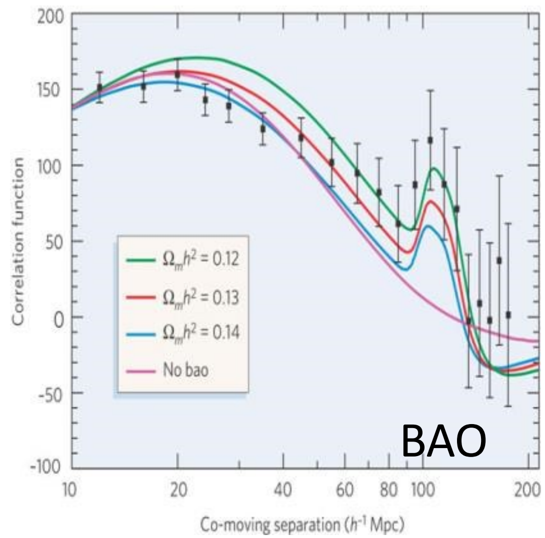
Galaxy surveys trace the LSS of the Universe at late times → Where the relative contribution of dark energy is larger, complementary to CMB

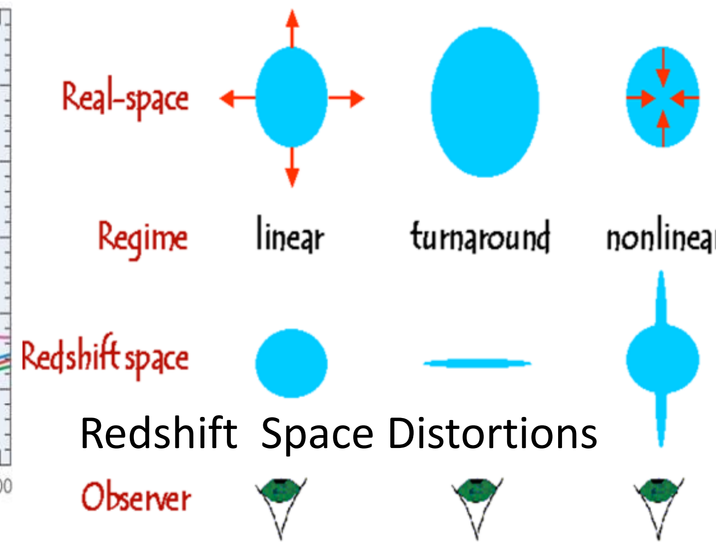
The optimal survey for each probe is different → Different surveys for different probes

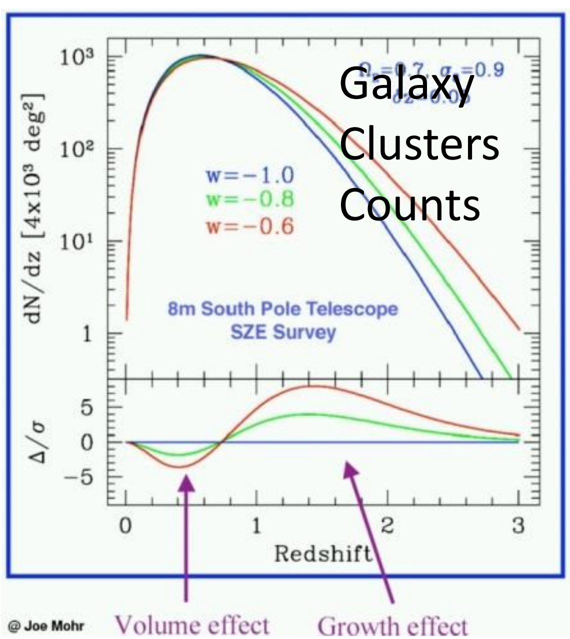
I will concentrate in 2 main surveys, where several dark energy probes can be measured, but there are many more

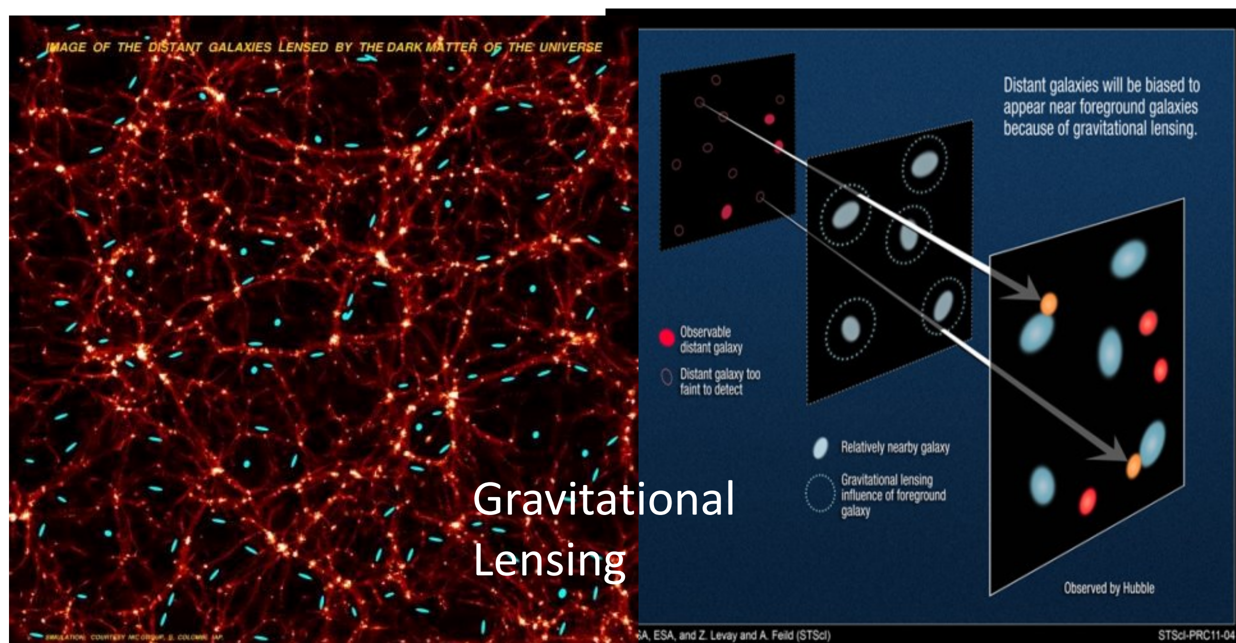
Observational Probes of dark energy



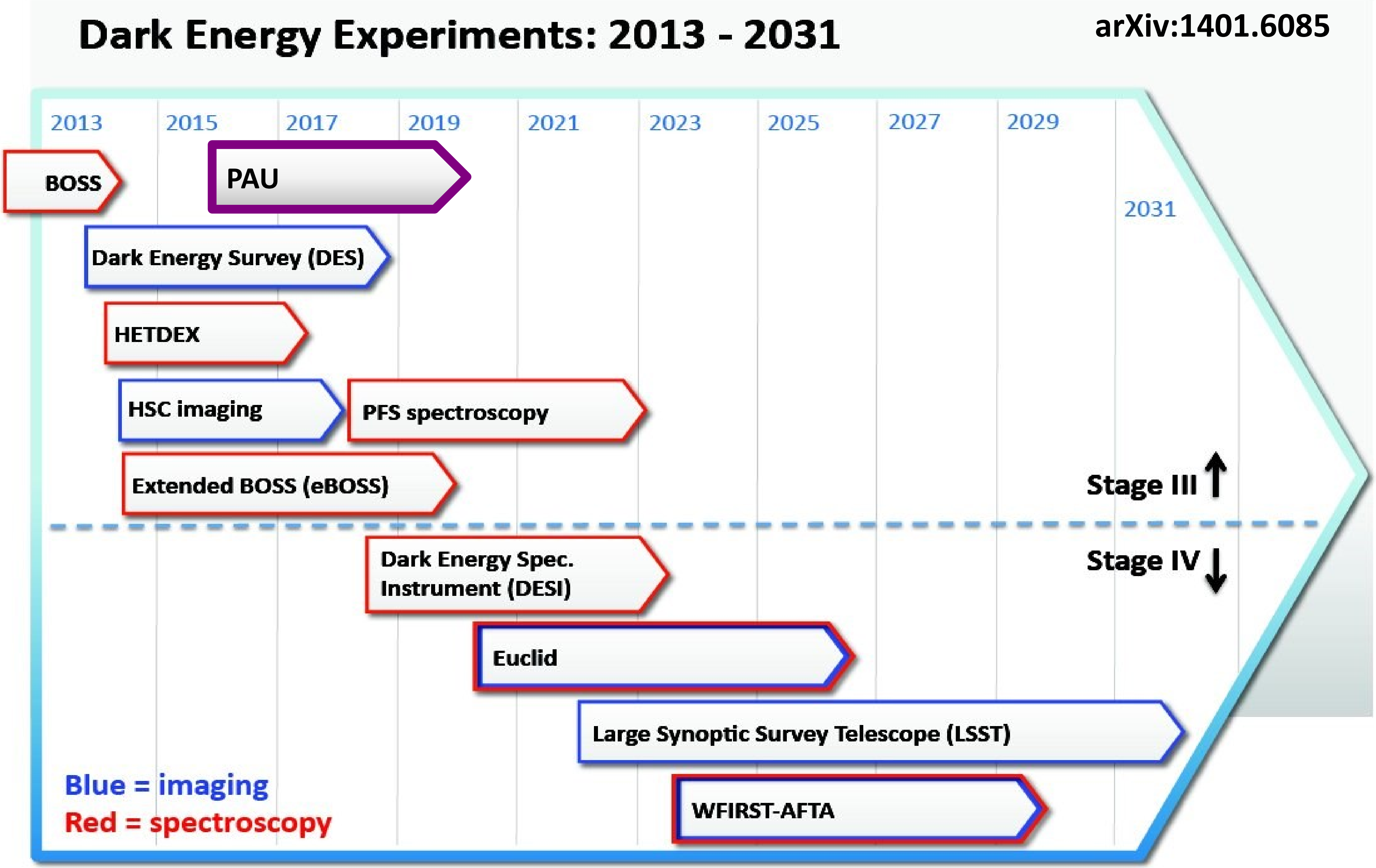








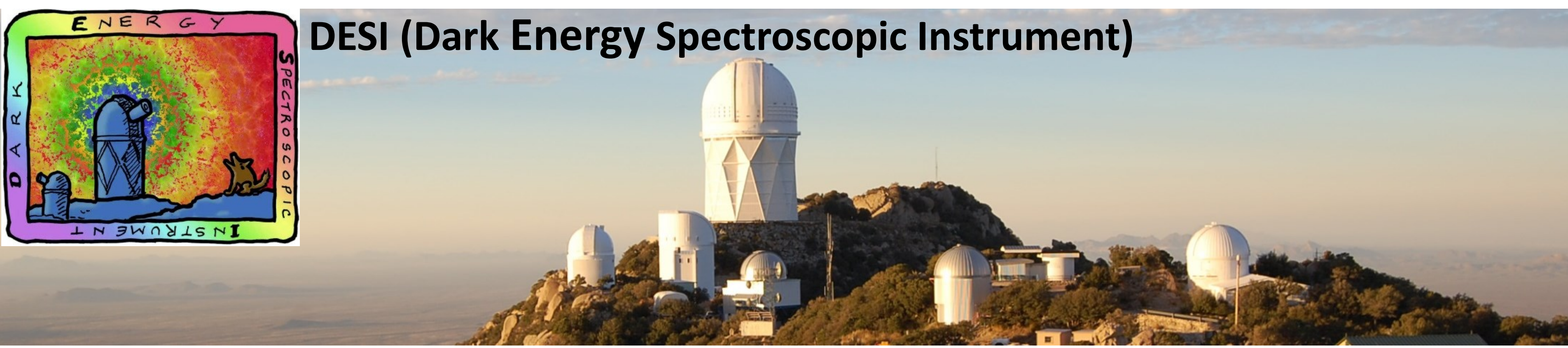
CURRENT AND FUTURE PROJECTS



DES & DESI

DES (Dark Energy Survey)

DESI (Dark Energy Spectroscopic Instrument)



The Dark Energy Survey

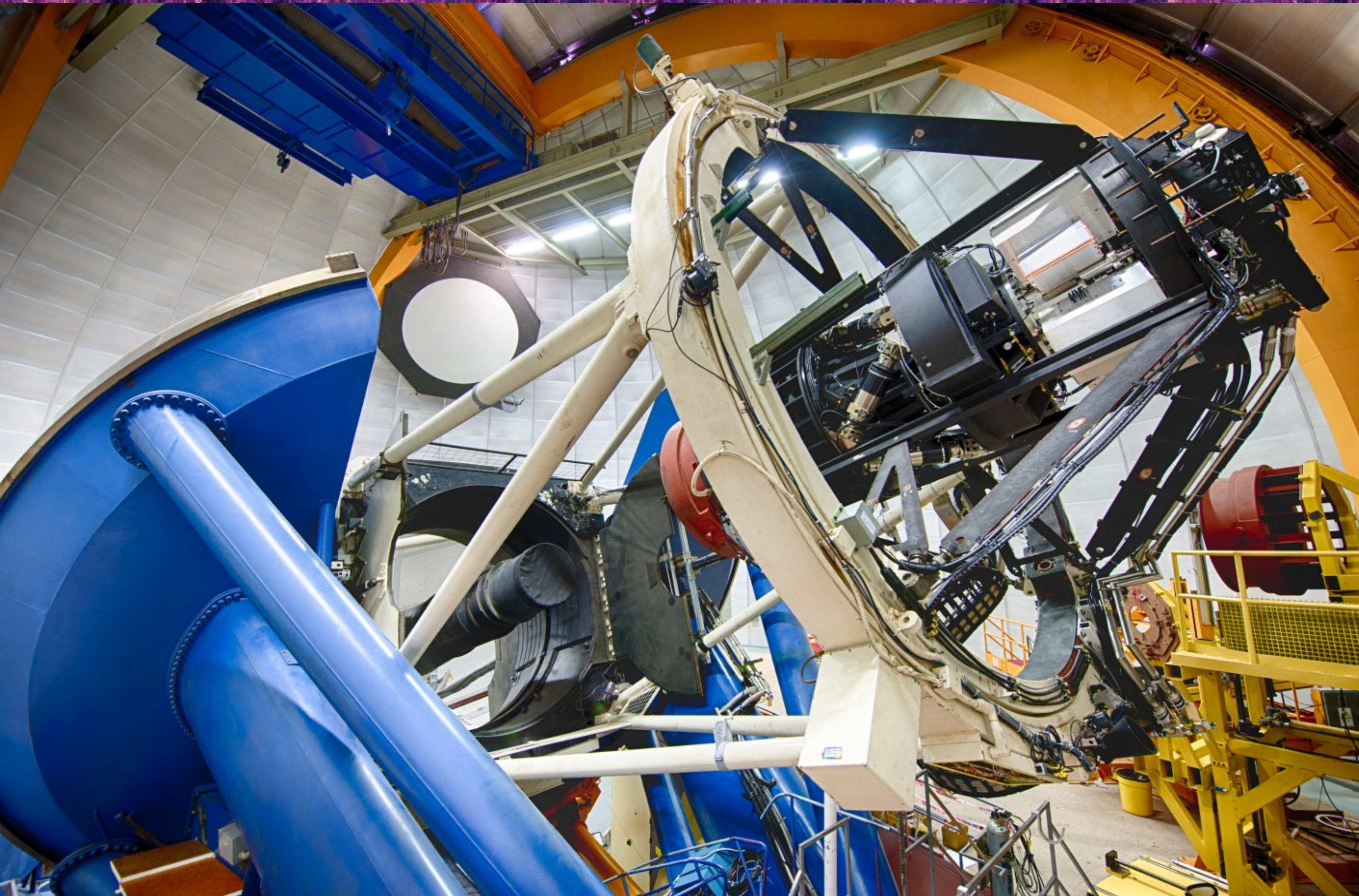
Optical/IR imaging survey with the Blanco 4m telescope at Cerro Tololo Inter-American Observatory(CTIO) in Chile

5000 sq-deg (1/8 of the sky) in grizY bands (2500 sq-deg overlapping with SPT survey) + 30 sq-deg time-domain griz (SNe)

Up to i_{AB} ~ 24th magnitude at 10 σ (z~1.5)

New 570 Mpx camera with 3 sq-deg FoV, DECam

Installed on Blanco since august 2012



NGC 1365

NGC 1365 (the Great Barred Spiral Galaxy) is a barred spiral galaxy about 56 million light-years away in the constellation Fornax. (DECam, DES Collaboration)

NGC 1566

NGC 1566 (the Spanish Dancer) is a spiral galaxy in the constellation Dorado. (DECam, DES Collaboration)

DECam

74 CCD chips (570 Mpx/image) (62 2kx4k image, 8 2kx2k alignment/focus, 4 2kx2k guiding)

Red Sensitive CCDs
QE>50% @ 1000 nm
250 microns thick

3 sq-deg FoV
Excellent image quality
0.27´´/pixel

Low noise electronics (<15 e @ 250 kpx/s) **<u>done by DES-Spain group</u>**

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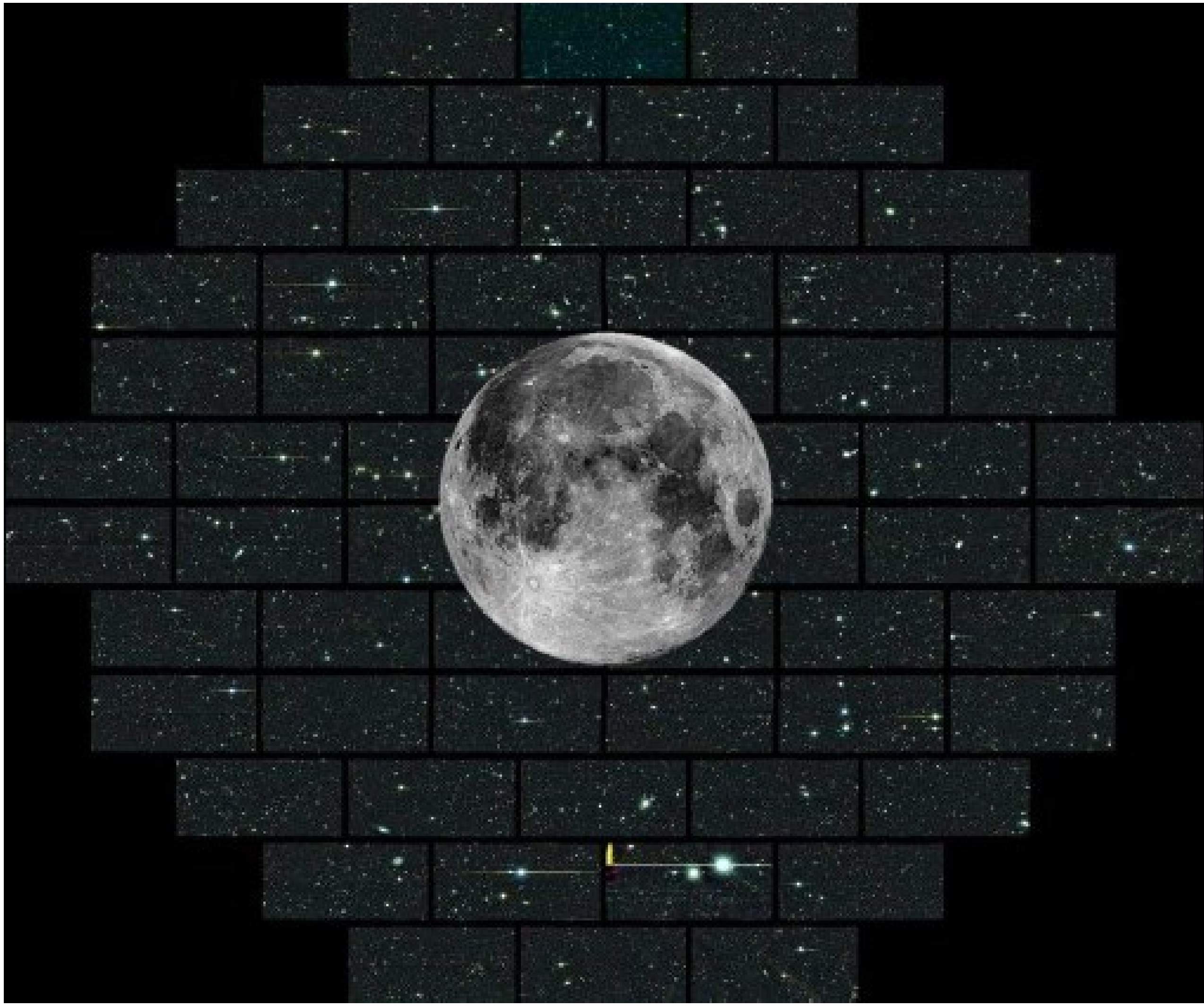


DES Science Summary

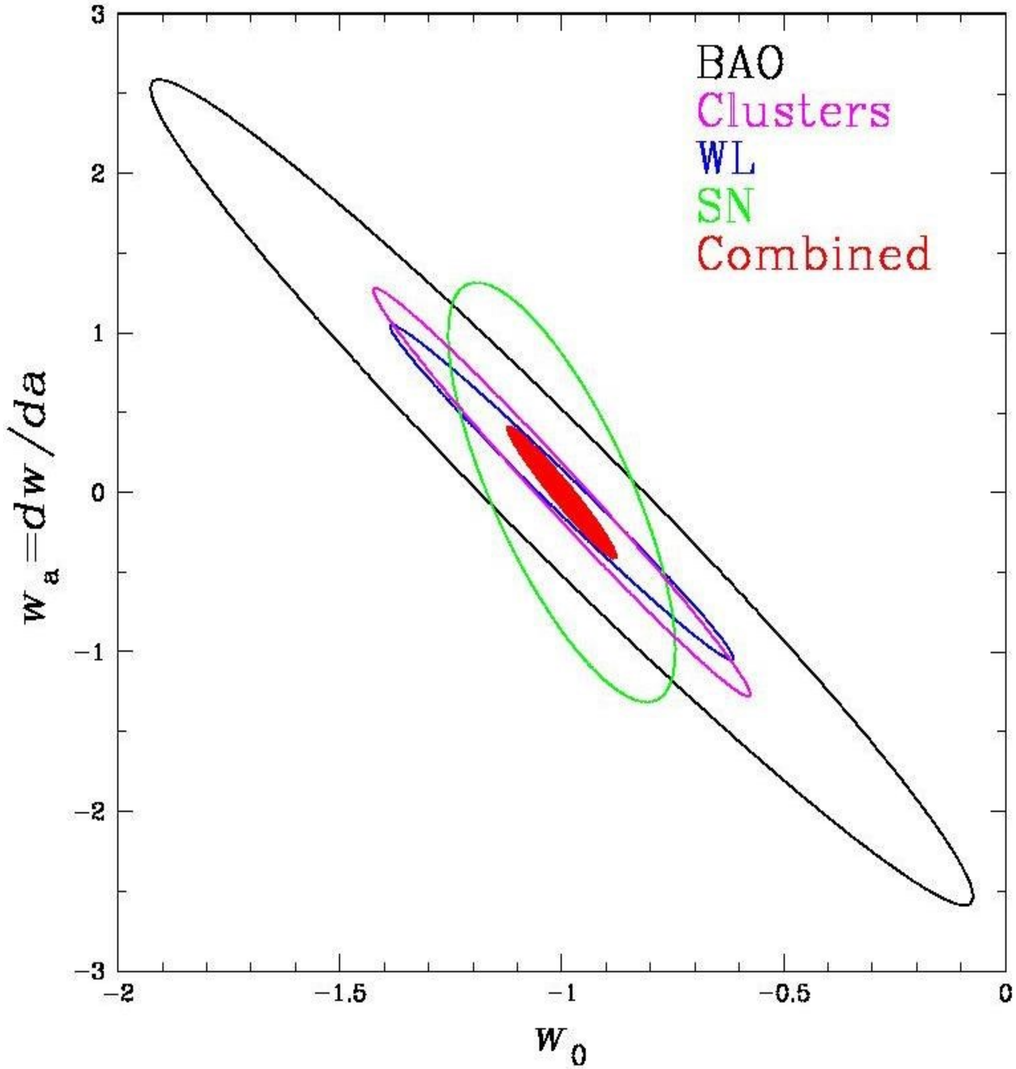
4 Probes of Dark Energy

Galaxy Clusters (dist & struct)
Tens of thousands of clusters to z~1
Synergy with SPT, VHS

Weak Lensing (dist & struct)
Shape and magnification measurements of 200 million galaxies

Baryon Acoustic Oscillations (dist)
300 million galaxies to z~1.4

Supernovae (dist)
3500 well-sampled Sne Ia to z~1



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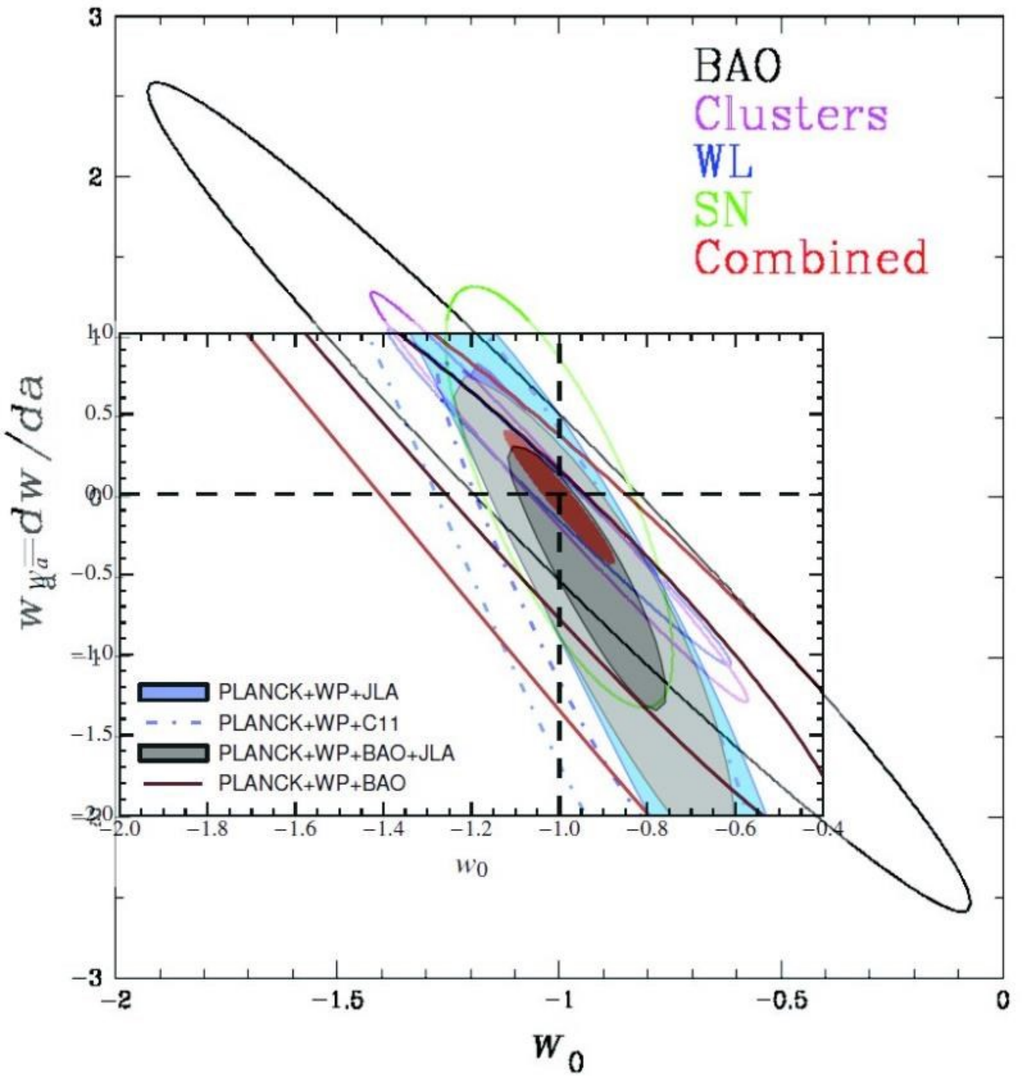
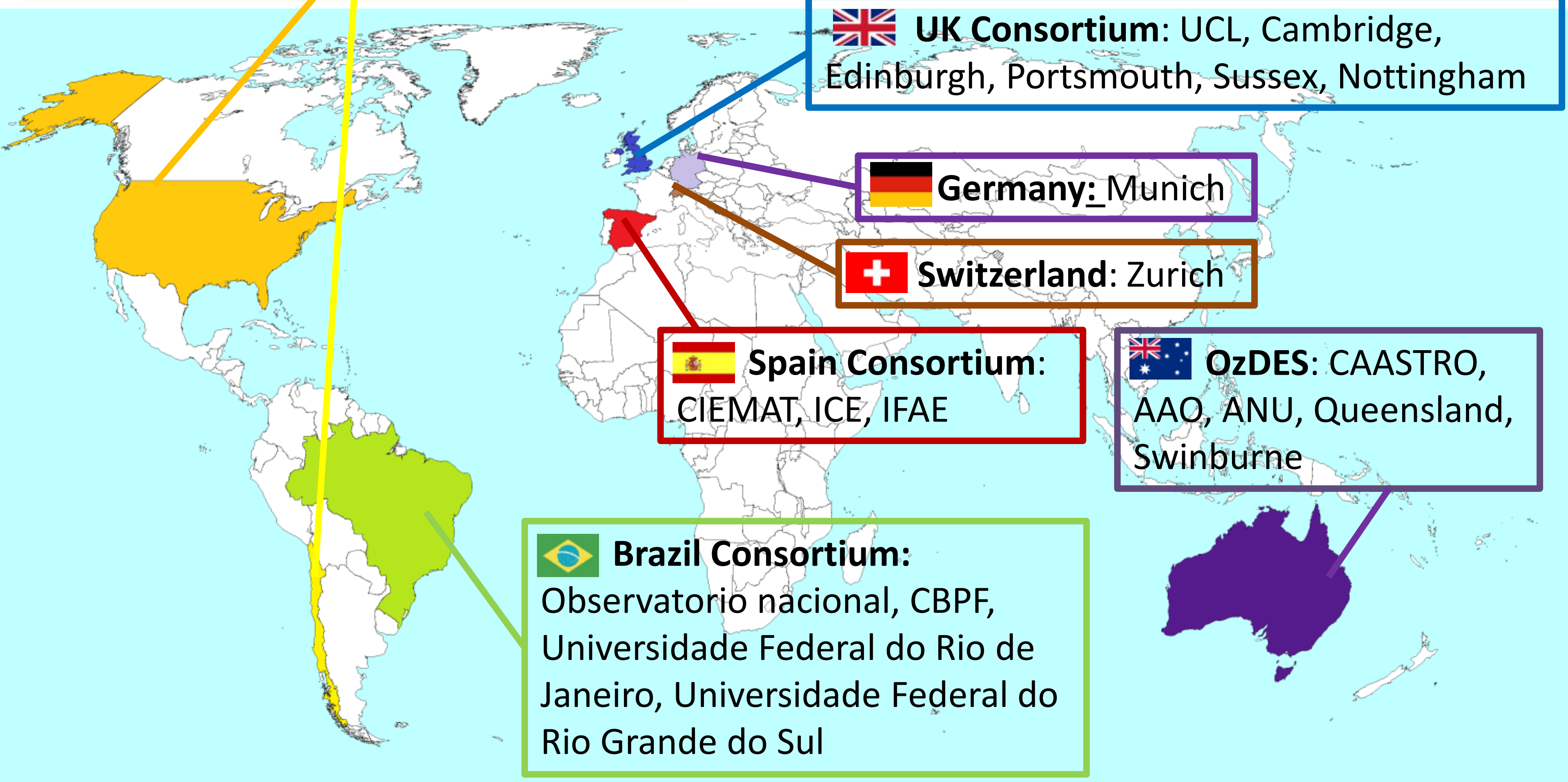


DES Collaboration

~300 scientists from
25 institutions in 7 countries
darkenergysurvey.org
Facebook.com/darkenergysurvey

DARK ENERGY SURVEY

USA: Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of pennsylvania, Argonne National Laboratory, Ohio State University, Santa Cruz/SLAC Consortium, Texas A&M University , CTIO (in Chile)



UK Consortium: UCL, Cambridge, Edinburgh, Portsmouth, Sussex, Nottingham

Germany: Munich

Switzerland: Zurich

Spain Consortium: CIEMAT, ICE, IFAE

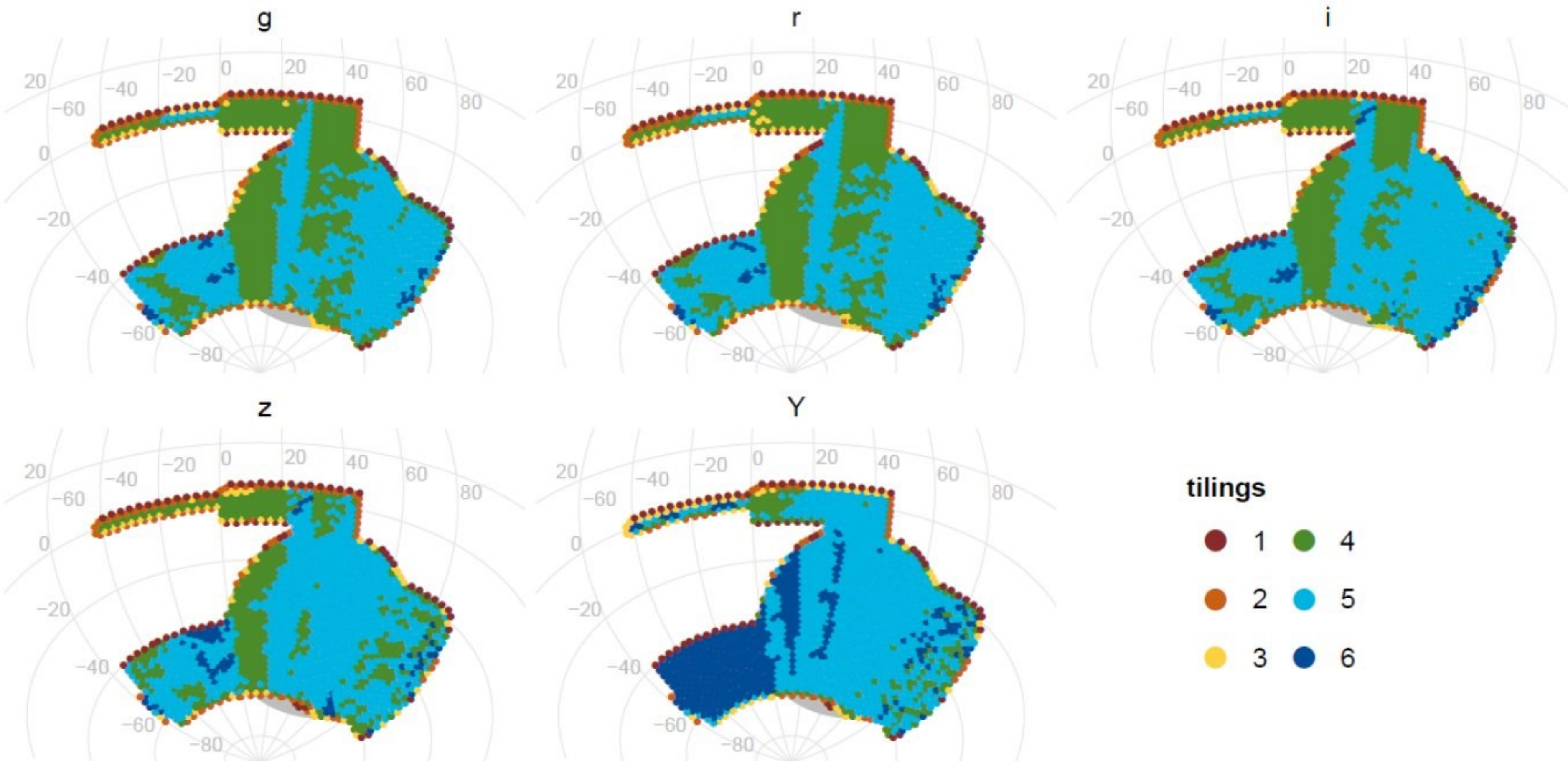
OzDES: CAASTRO, AAO, ANU, Queensland, Swinburne

Brazil Consortium: Observatorio nacional, CBPF, Universidade Federal do Rio de Janeiro, Universidade Federal do Rio Grande do Sul

DES Y3 ended on february 2016

DES is proyected for 5 years , up to 2018

5000 sq-deg already covered, to ~50% of the final projected depth



DES has produced many results already

64 papers: 26 published and 38 submitted

Many different topics: From cosmology using weak lensing to studies of the Milky Way or the Solar System, most of them from the Science Verification data (3% of the total survey)

Y1-Y3 data are in the analysis phase. DES is already the most precise survey ever for many results, and a careful study of systematic errors is required before publications

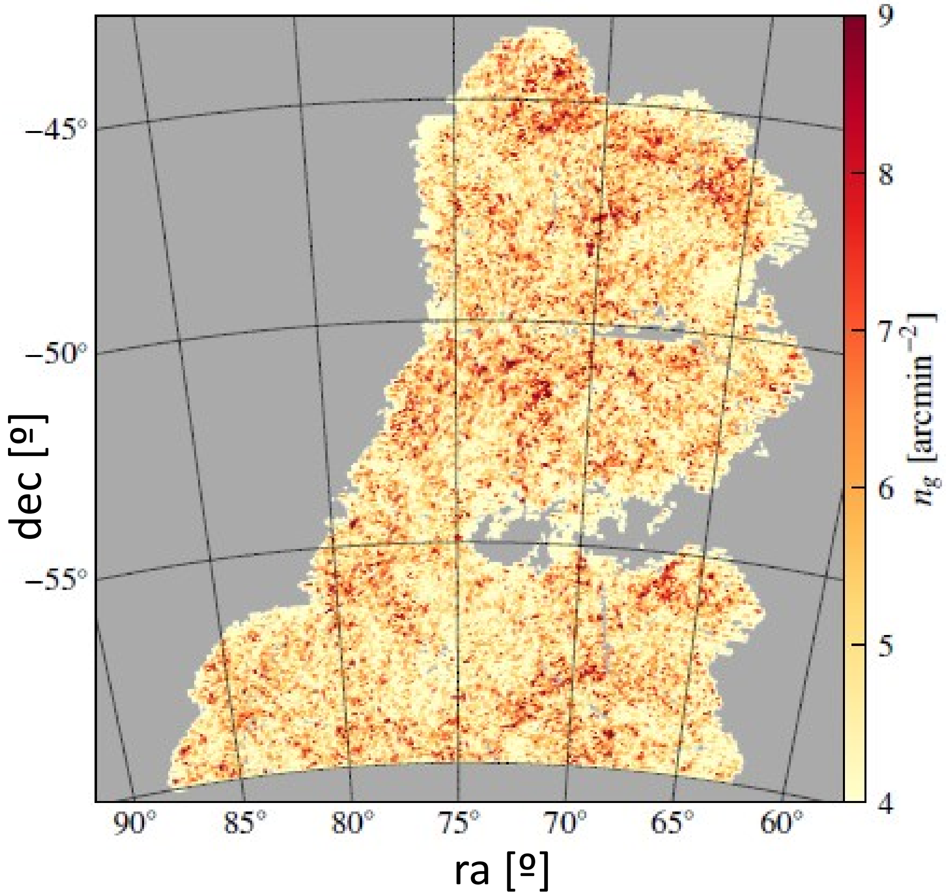
I will flash a few selected results

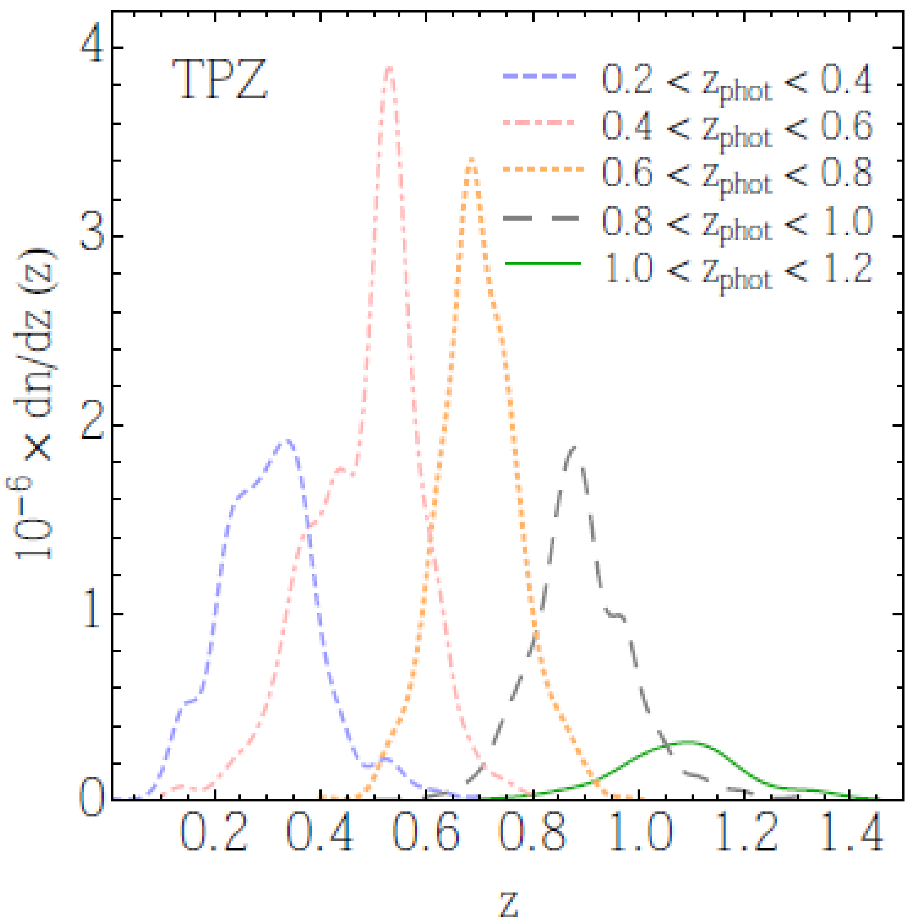
Clustering of Galaxies

Angular 2pt correlation function of 2.3×10^6 galaxies

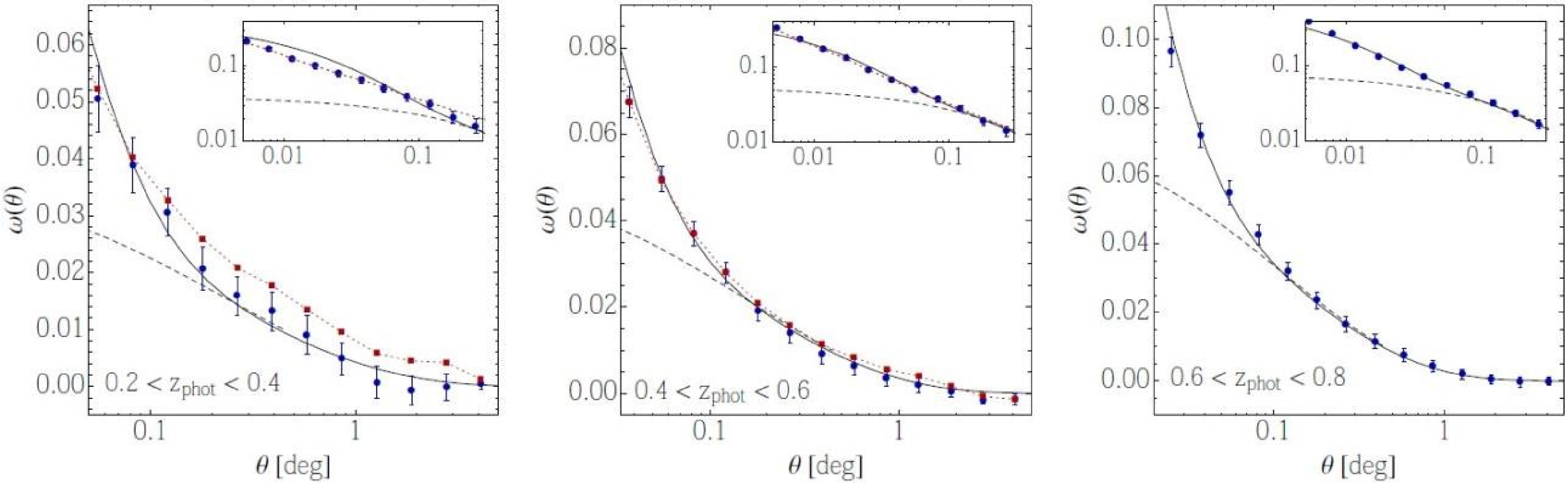
SV data, 116 sq-deg (i<22.5), *Crocce et al. arXiv:1507.05360*

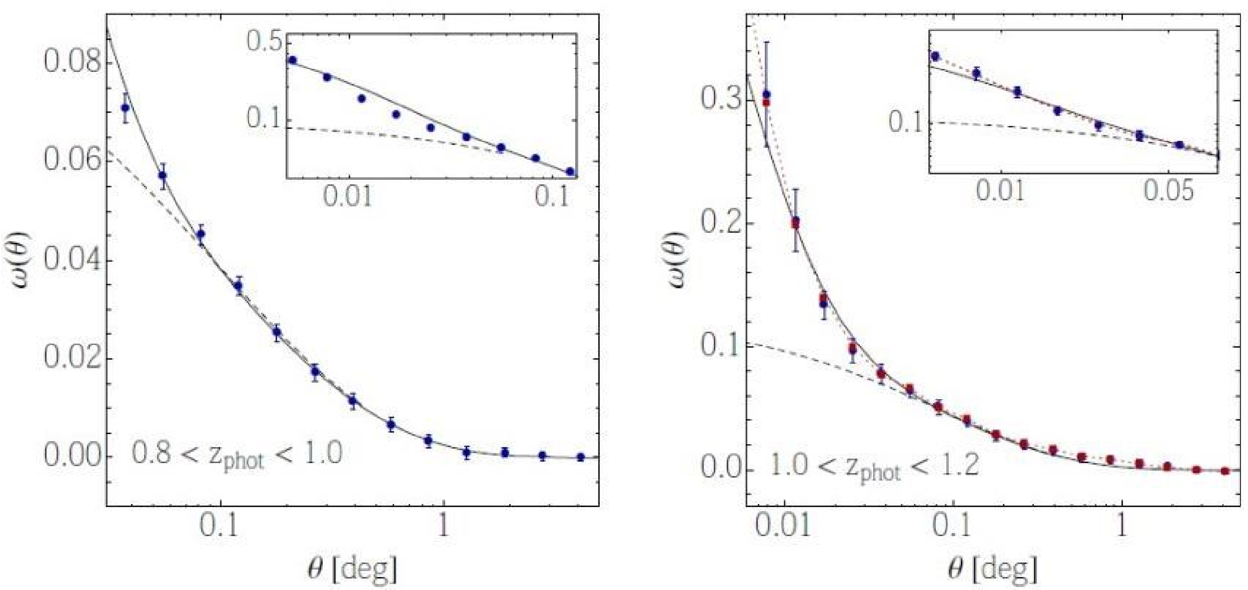
Used to constrain linear bias of the galaxy sample





Clustering of Galaxies

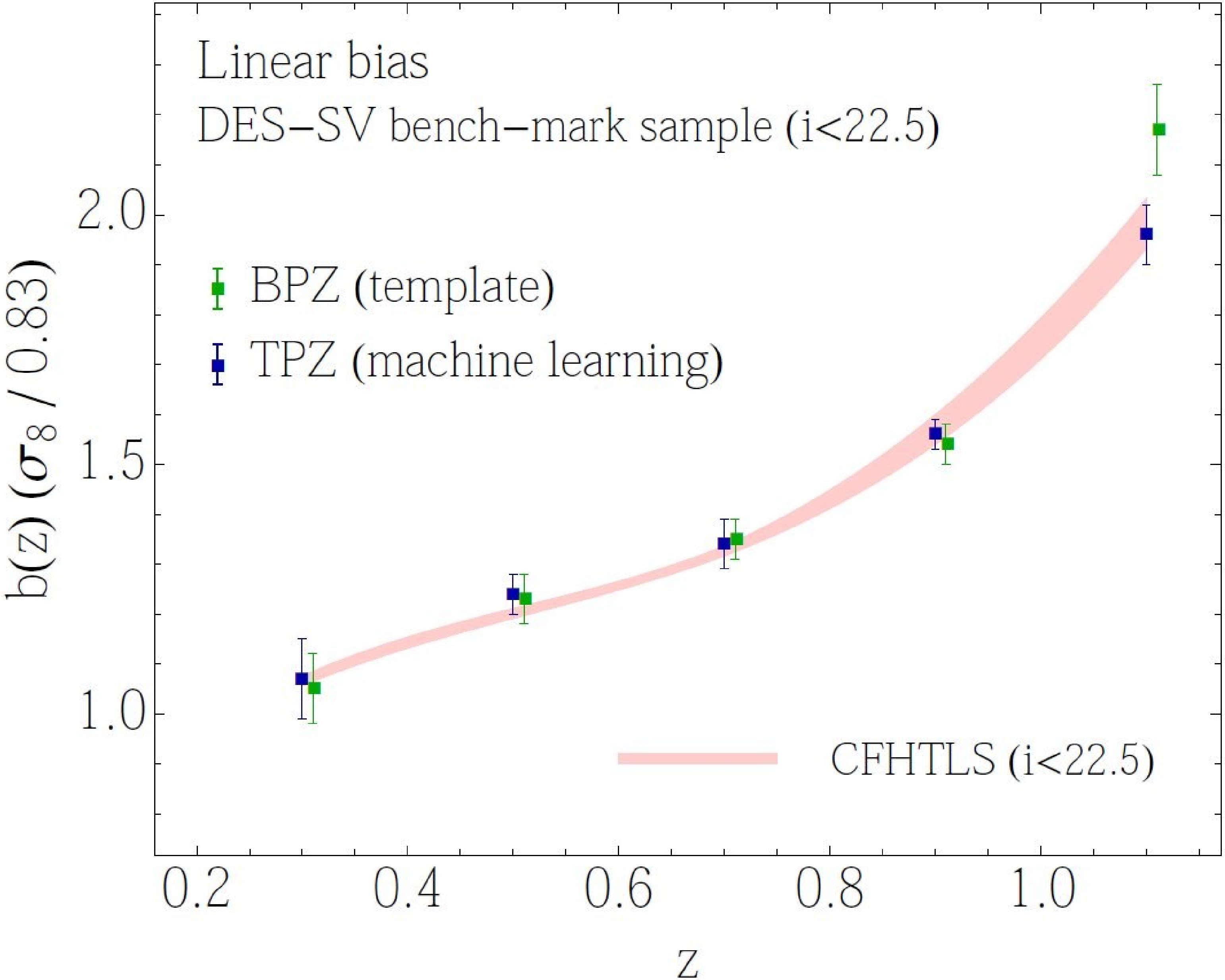




2-pt angular correlation functions in 5 redshift (photoz) bins

- Sys corrected
- Sys uncorrected

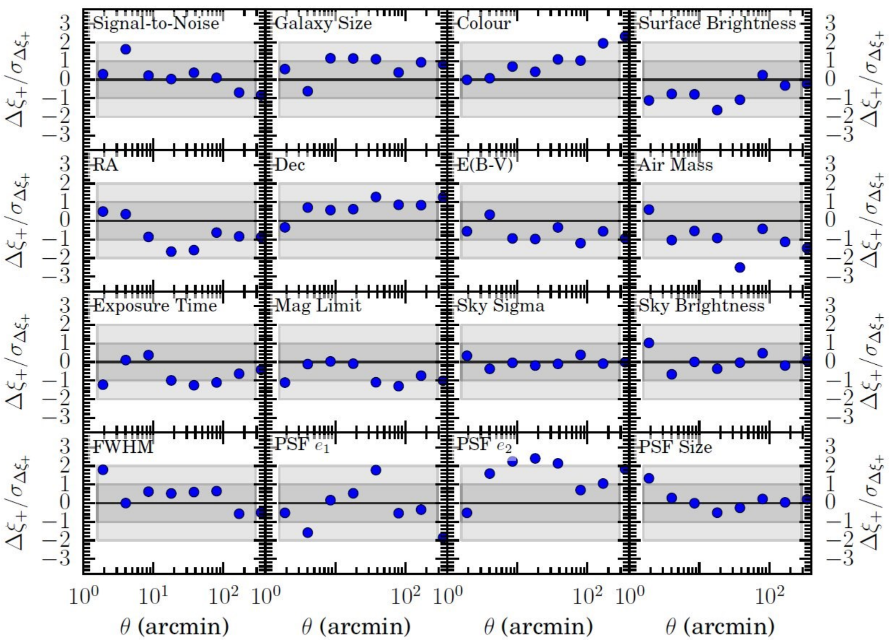
Clustering of Galaxies

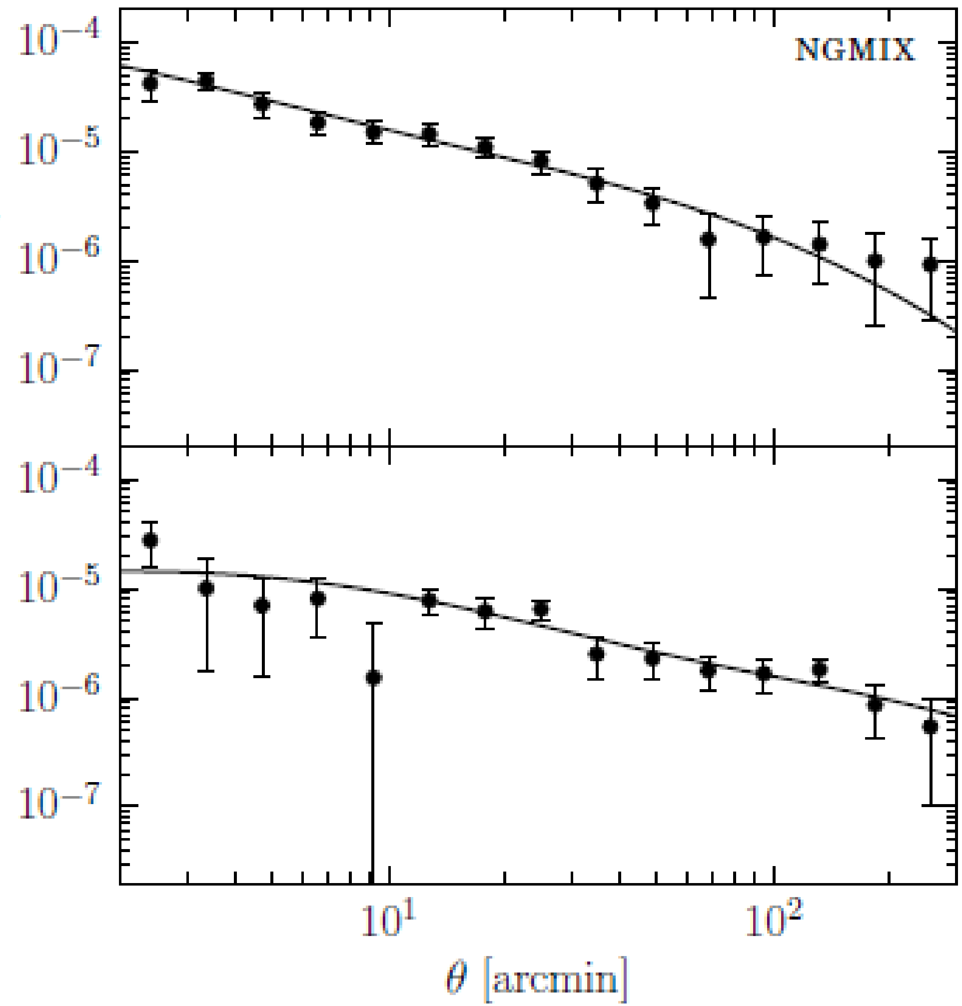


Weak Lensing

Tomographic WL shear 2 pt correlations measurement in 3 redshift bins (Becker et al., arXiv:1507.05598)

SV data: 139 sq-deg





Based on DES SV shear catalog: Jarvis et al. 2015

First Cosmology Results

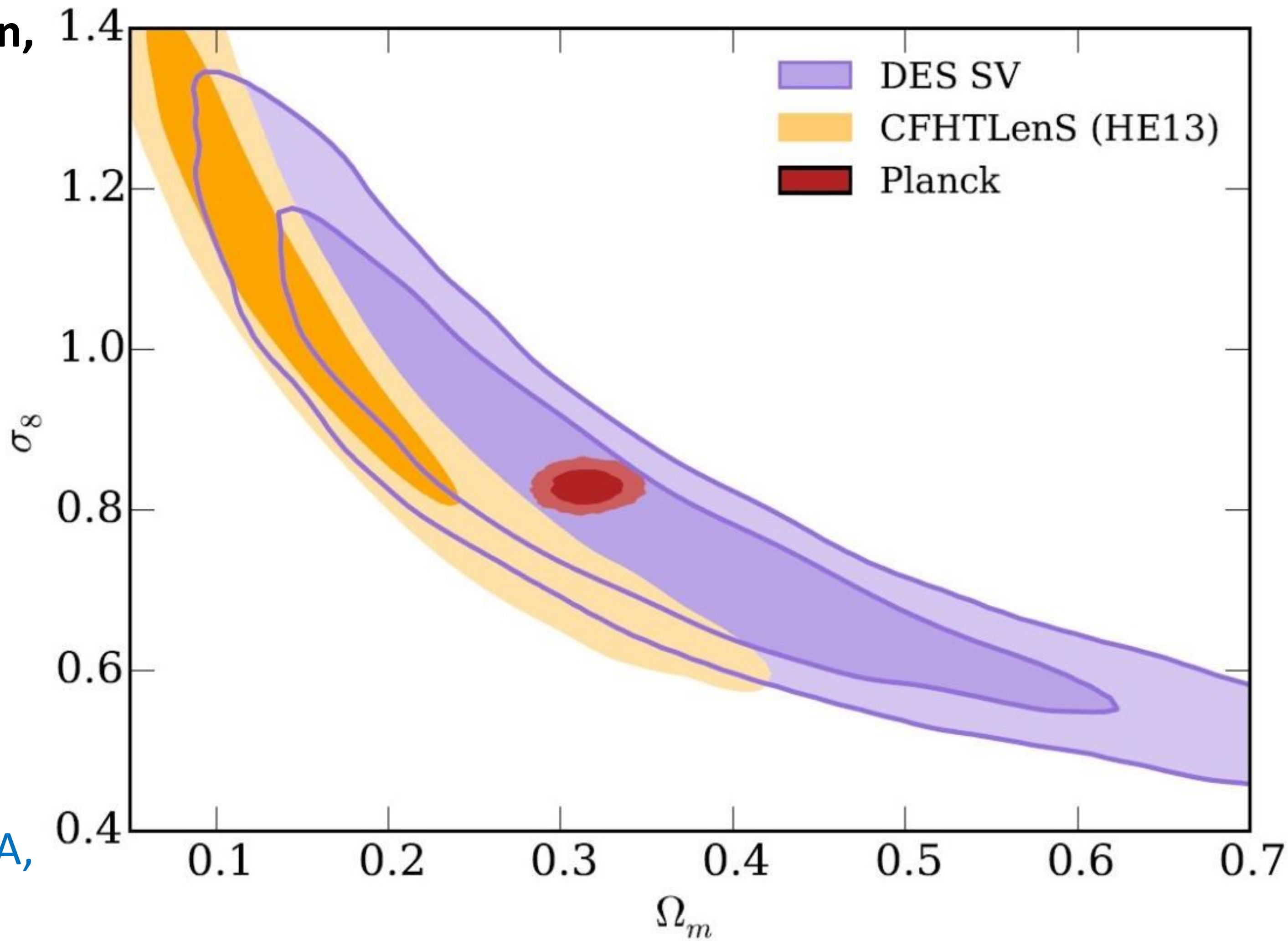
Cosmological parameter estimation, DES Coll. 2015 arXiv: 1507.05552

139 sq-deg

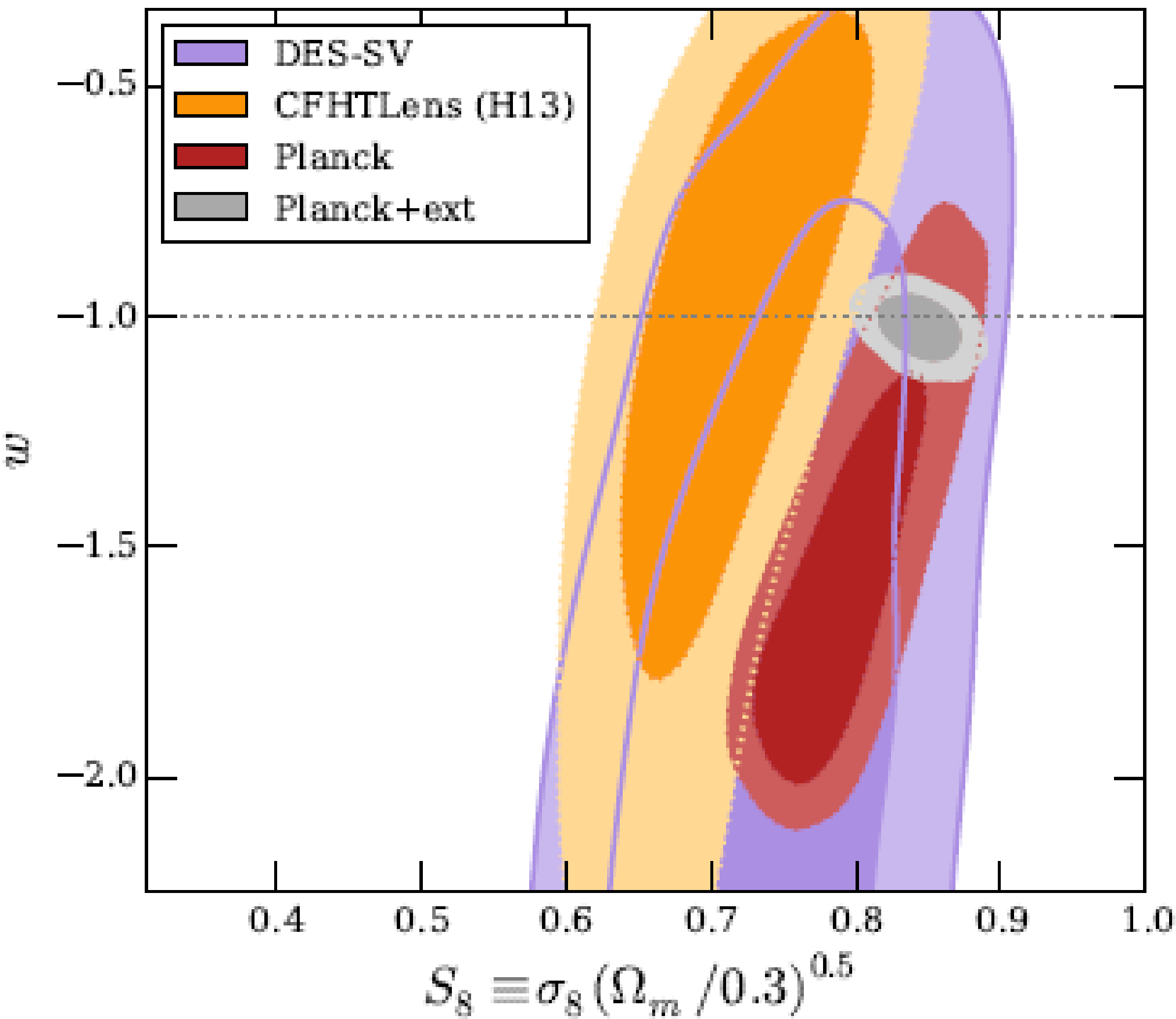
3 redshift bins:
0.30 < z < 0.55
0.55 < z < 0.83
0.83 < z < 1.3

Marginalized over a set of nuisance parameters (shear & photoz calibrations, IA, non-linearities)

Flat priors: 0.2<h<1, 0.01<Ob<0.07, 0.7<nS<1.3



First Cosmology Results



Results from DES in between Planck and CFHTLenS

Not very precise yet, but show that DES is able to measure cosmological parameters from WL

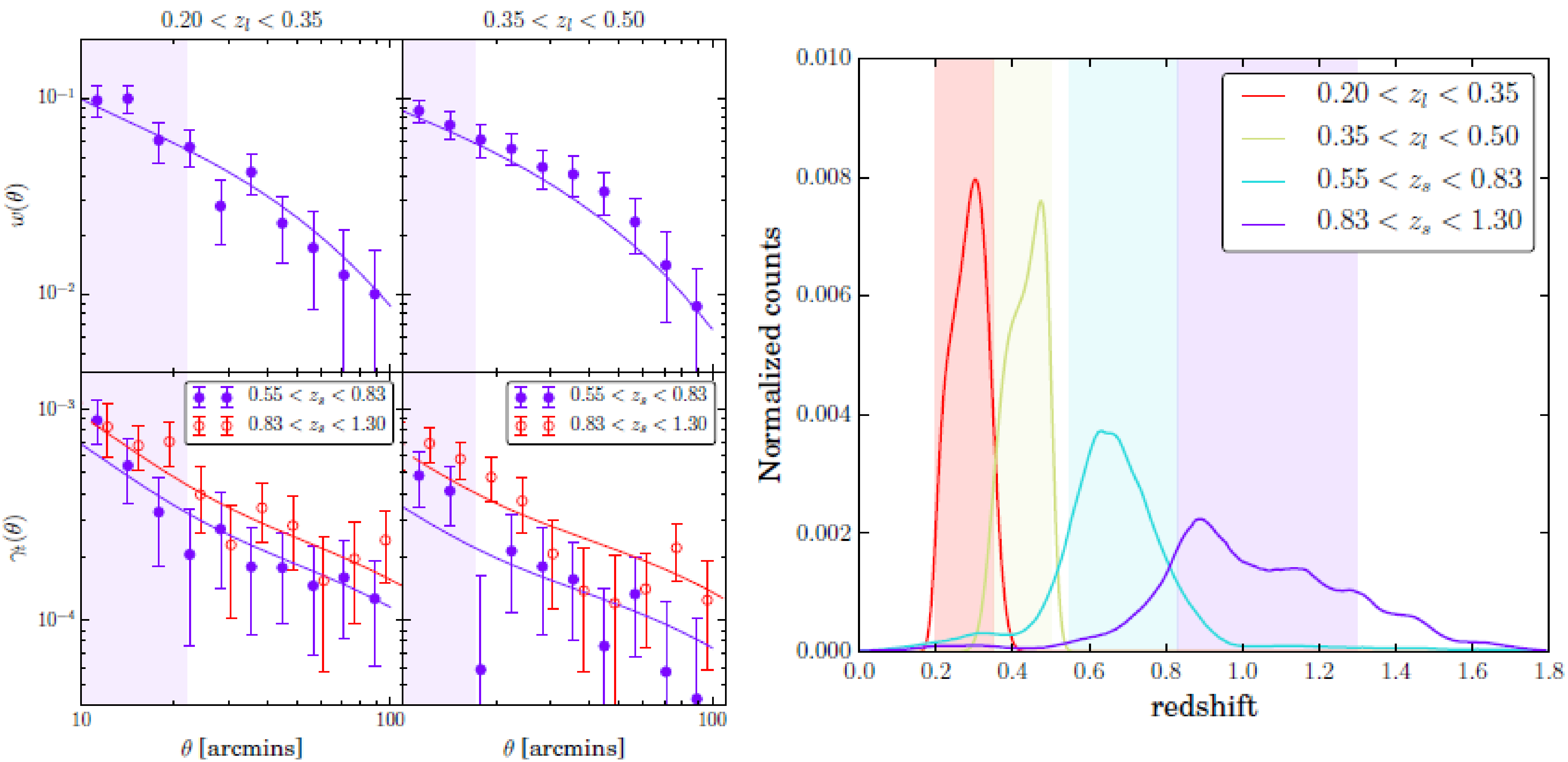
(even if WL image distortions are very smal ~1%, and must be measured to 1% to obtain w at 1%)

To be substantially improved from Y1-Y3 data

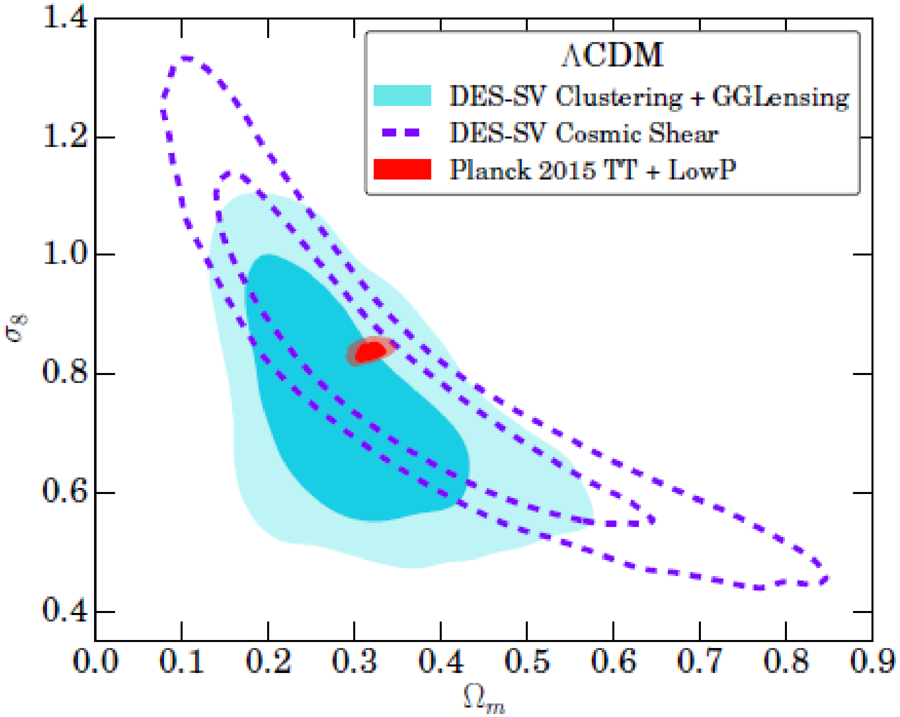
Combination of LSS and WL

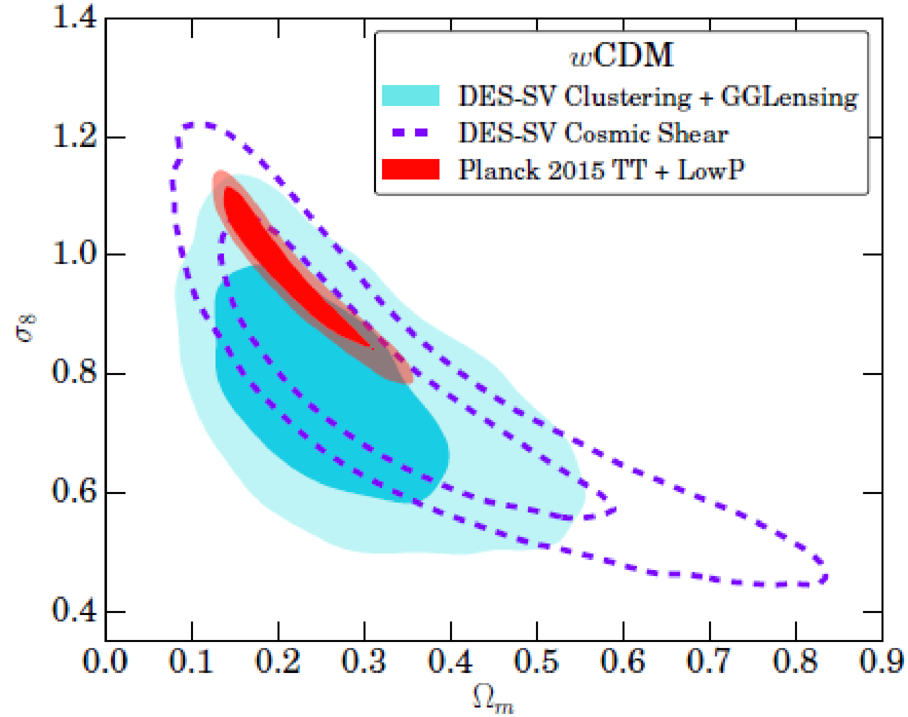
Combined analysis of angular clustering of red galaxies and their cross-correlation with weak gravitational lensing of background galaxies.

DES-SV: 139 sq-deg



Combination of LSS and WL



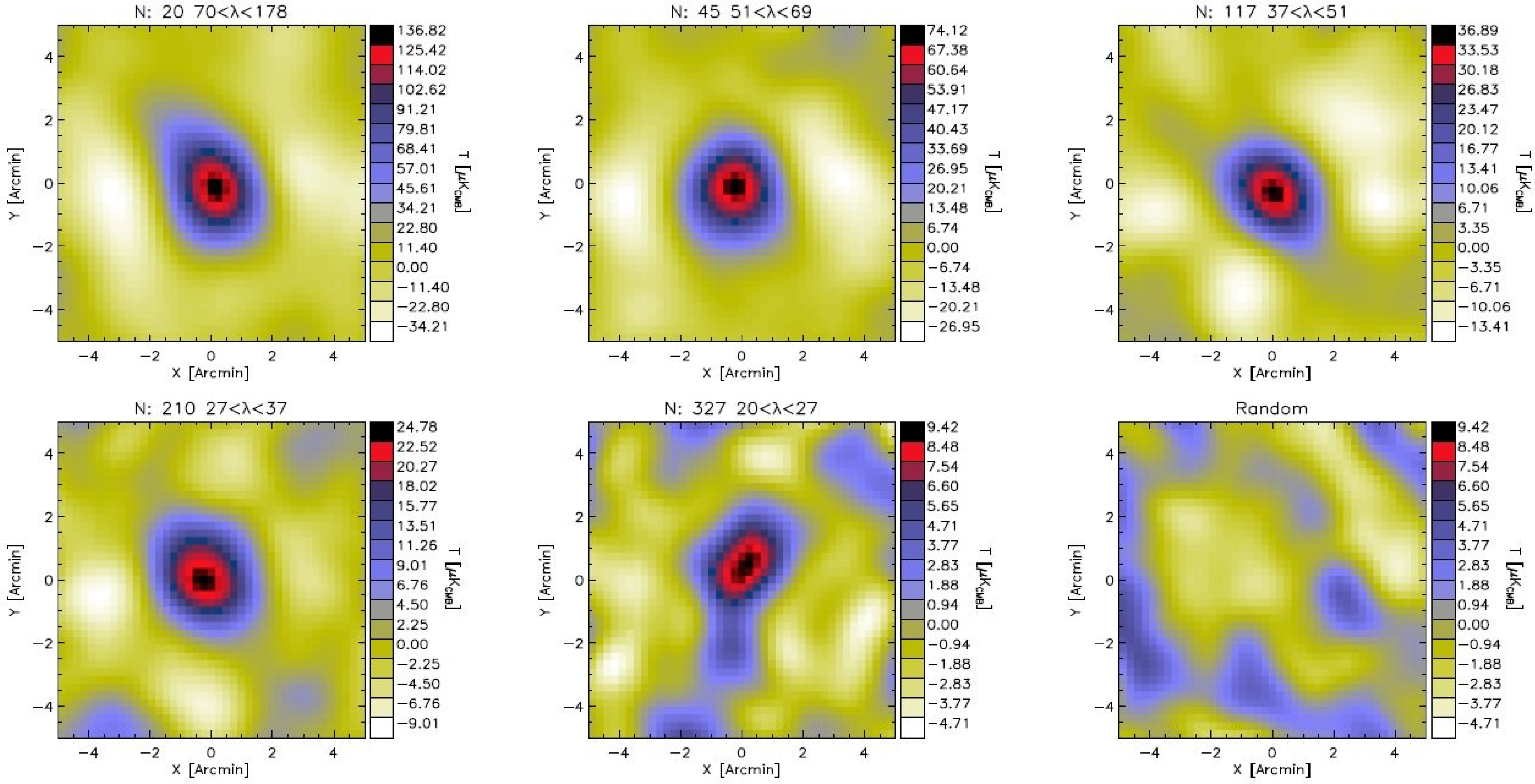


We have placed constraints on the matter density and the amplitude of fluctuations as $\Omega_M = 0.31 \pm 0.09$ and $\sigma_8 = 0.74 \pm 0.13$

Full tomographic analysis with multiple lens bins and a joint analysis with cosmic shear in future DES releases.

Clusters: Detection of the SZ effect in SV

Clear signature of SZ effect in SV data (~125 sq-deg)
719 optically identified clusters



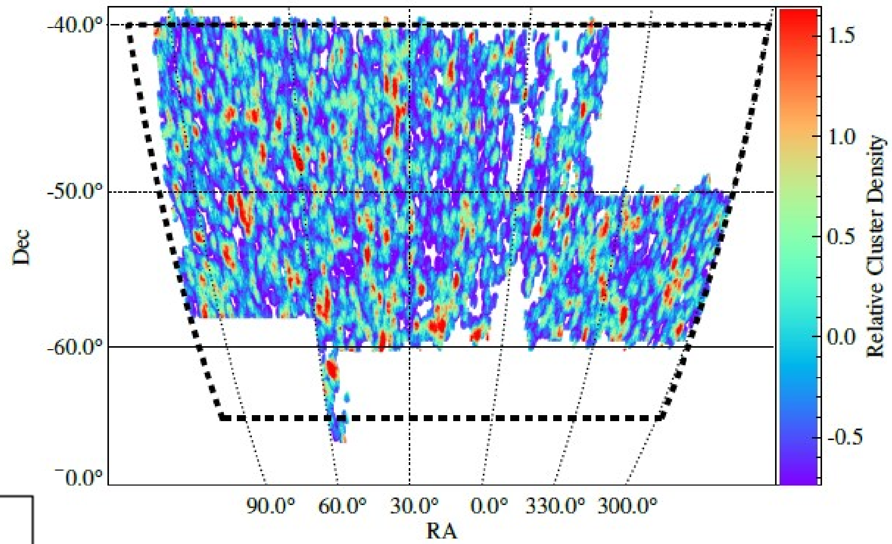
Clusters: Detection of the kSZ effect in Y1

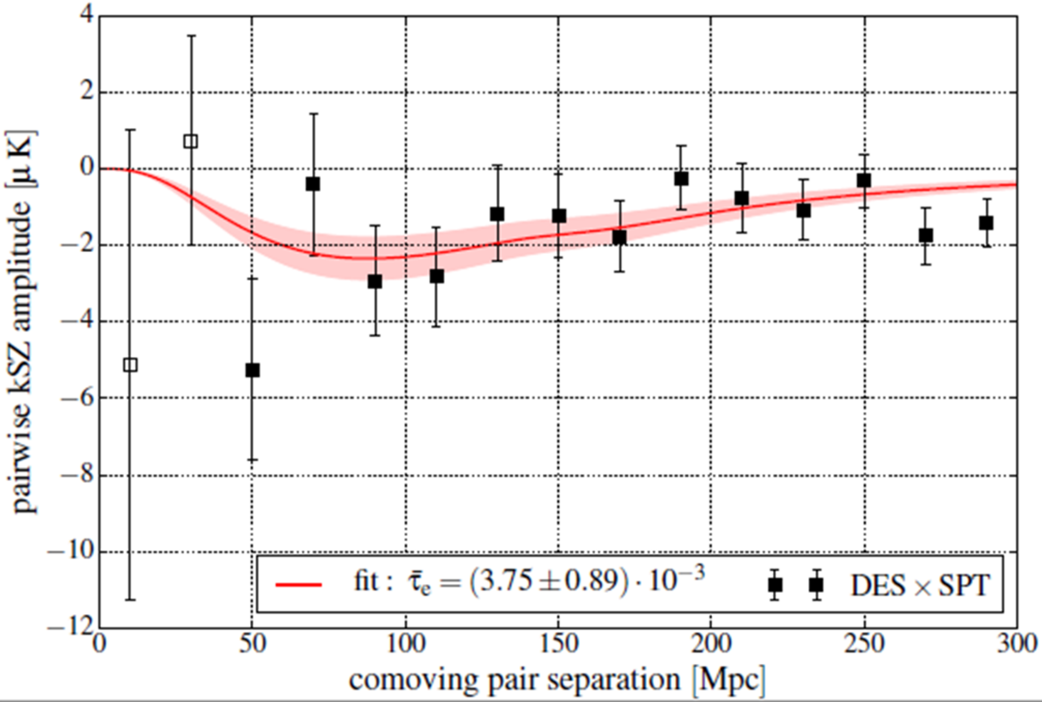
DES Y1 data, ~1200 sq-deg

~6700 clusters with N>20 galaxies

SPT Temperature data

$\sigma_z/(1+z) \sim 0.01\text{-}0.015$





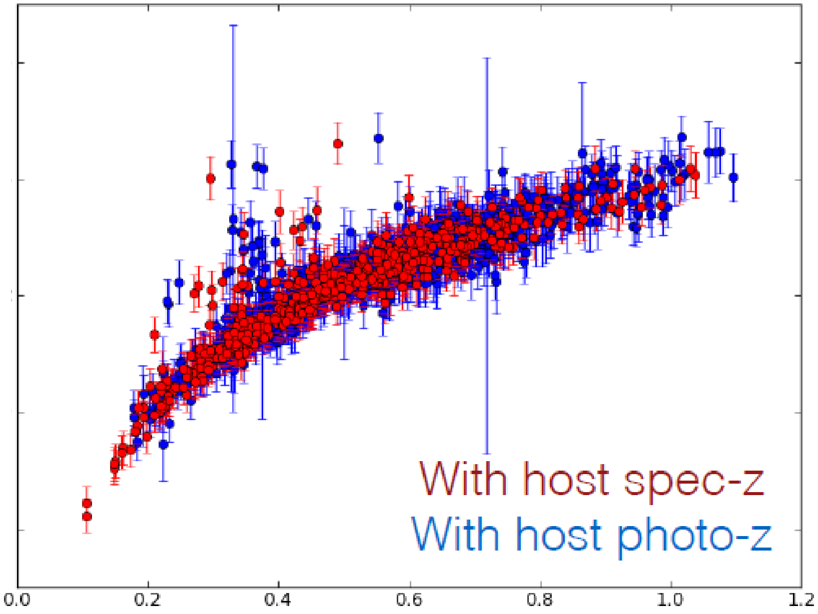
Pairwise estimator of kSZ amplitude

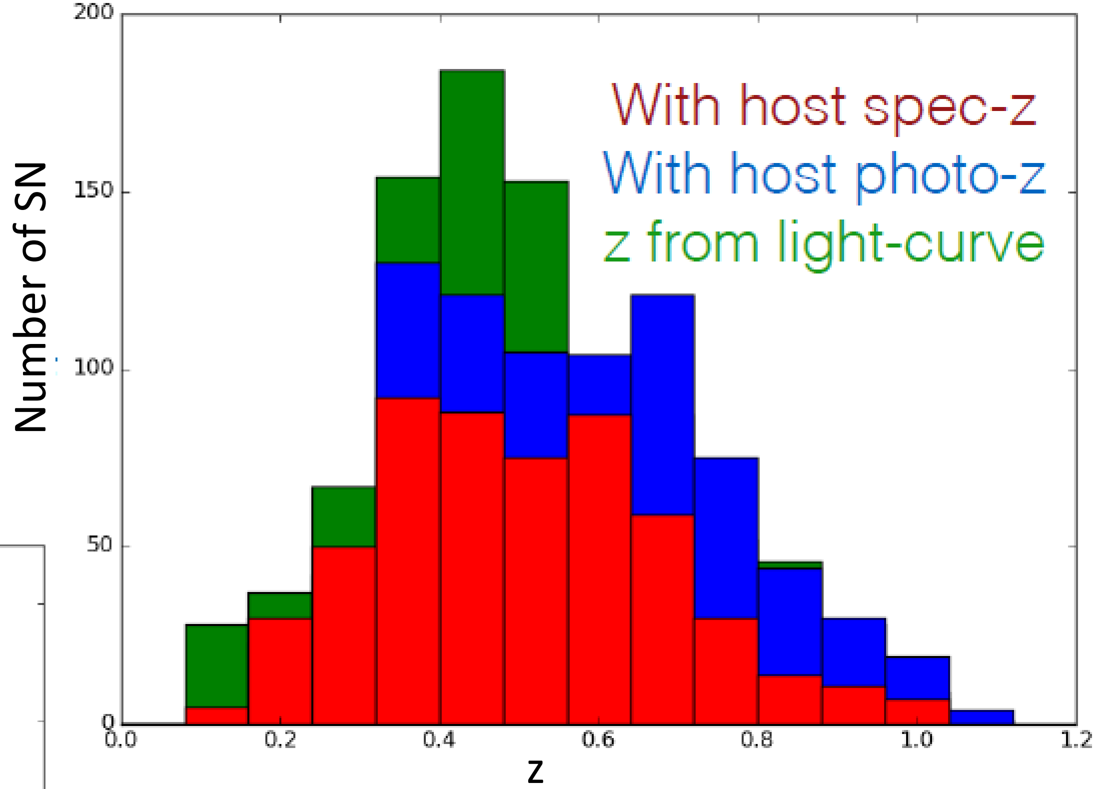
4.2 sigmas detection of the effect

Supernovae

Photometric Classification
-900 (Y1+Y2) likely SNeIa for cosmology, pass rigorous cuts

800 have good host photo-z
530 have host spec-z



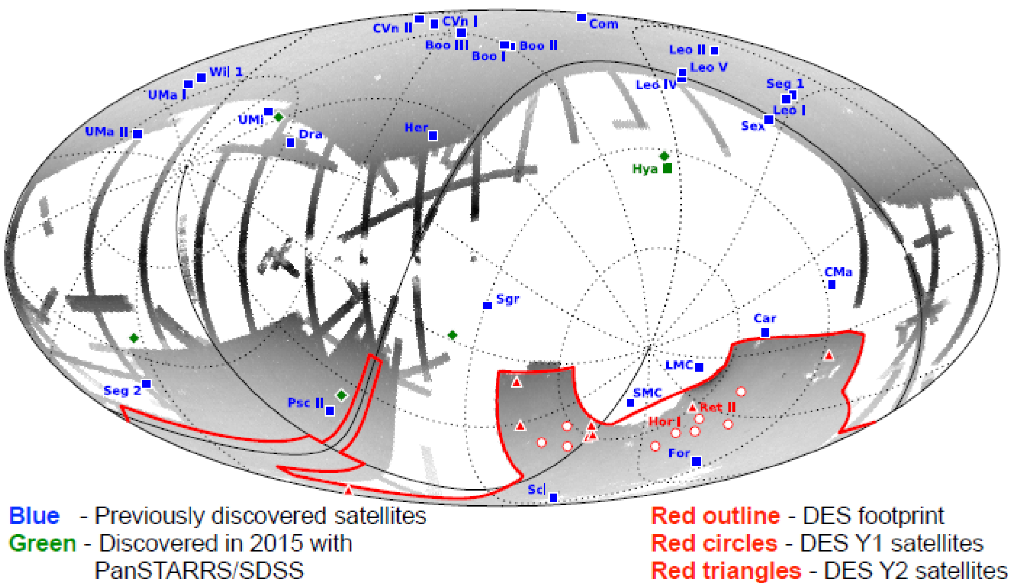


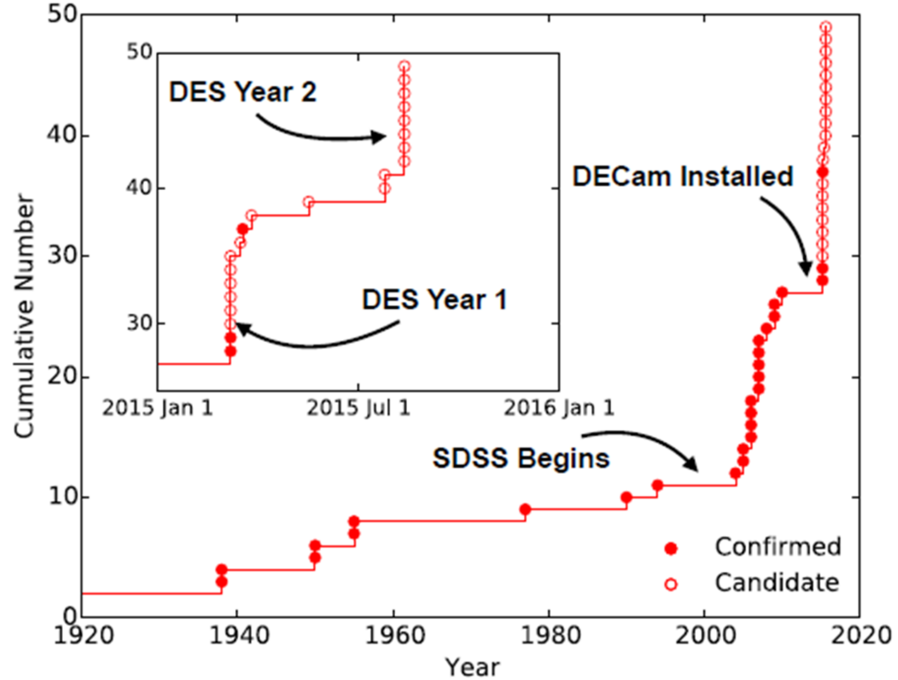
After 3 seasons, largest sample of SNIa

- Redshift distribution 0.2<z<1.2
- New challenges in photometric classification

New Dwarf Satellites of the Milky Way

Drlica-Wagner et al., 2015 , ApJ 813 109
Bechtol et al., 2015 ApJ 807 1





No excess of gamma ray emission (from Fermi-LAT) is detected coming from these objects

No hints of dark matter.

WIMPs with mass<100 GeV are excluded (model dependend)

Summary: DES Status

DES has finished its 3rd year of data taking

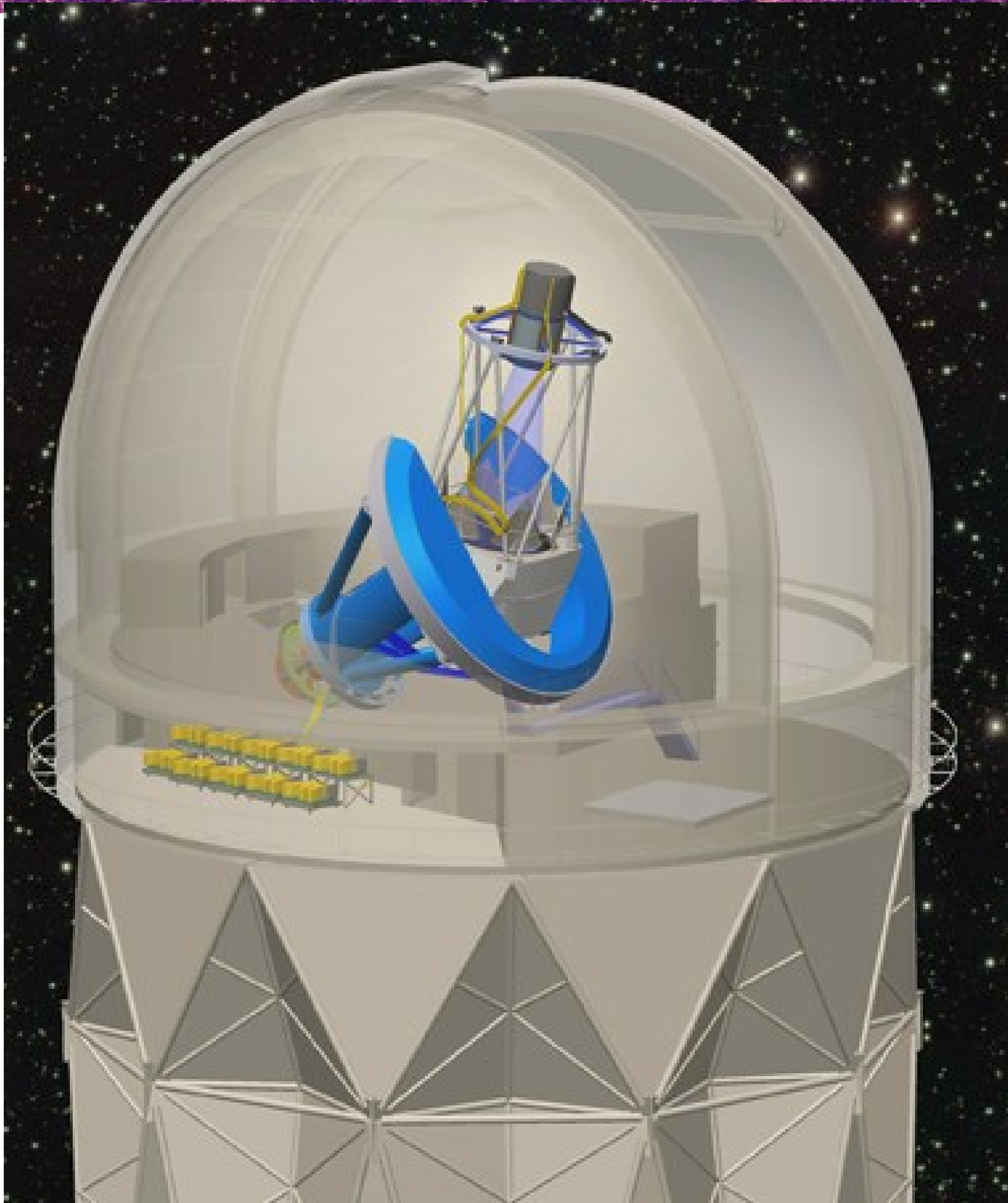
It has already produced many scientific results, mainly from the SV data (3% of the total survey). *DES SV catalogs are now public*.

Many DES results not covered in this talk: More WL measurements, Cluster catalog, strong lensing, non-cosmology results (trans-neptunian objects and Planet 9, Milky Way, GW follow-up, galaxy evolution, quasars…)

Y1-Y3 data are being analysed. DES will already be the best survey ever for many of these results. Careful control of systematics required

First dark energy results expected for this year.

DESI



DESI, the Dark Energy Spectroscopic Instrument, is a new instrument currently under construction.

It is designed to improve our understanding of the role of dark energy in the expansion history of the universe.

It will do this by measuring the redshifts of more than 30 million galaxies and quasars, with unprecedented precision.

DESI Science Goals

Is cosmic expansion accelerating because of a breakdown of General Relativity (GR) on cosmological scales or because of a new energy component that exerts repulsive gravity within GR?

If the latter, is it consistent with a cosmological constant or does it evolve in time?

Any answers to this will point to new physics!

Measure the expansion rate of the Universe

The distance-redshift relation $D_A(z)$

Directly measure $H(z)$

Measure the rate at which structures grow in the Universe

Growth function and its derivatives

DESI will do both in one survey

DESI Science Goals

Use BAO to measure the distance scale of the universe over nearly the whole northern sky and nearly the entire age of the universe (out to z~3.5, 12 billion years ago)

Test modifications of gravity by measuring the growth rate of structures with RSD

Measure the mass of the neutrino through the suppression of small-scale clustering (~20 meV precision on the measurement of the sum of neutrino masses)

Test inflation by measuring non-Gaussianity and spectral shape of inflationary perturbations

DESI Survey Data Set

These measurements can be achieved by means of 5 populations that should give the easiest redshifts over a broad redshift range:

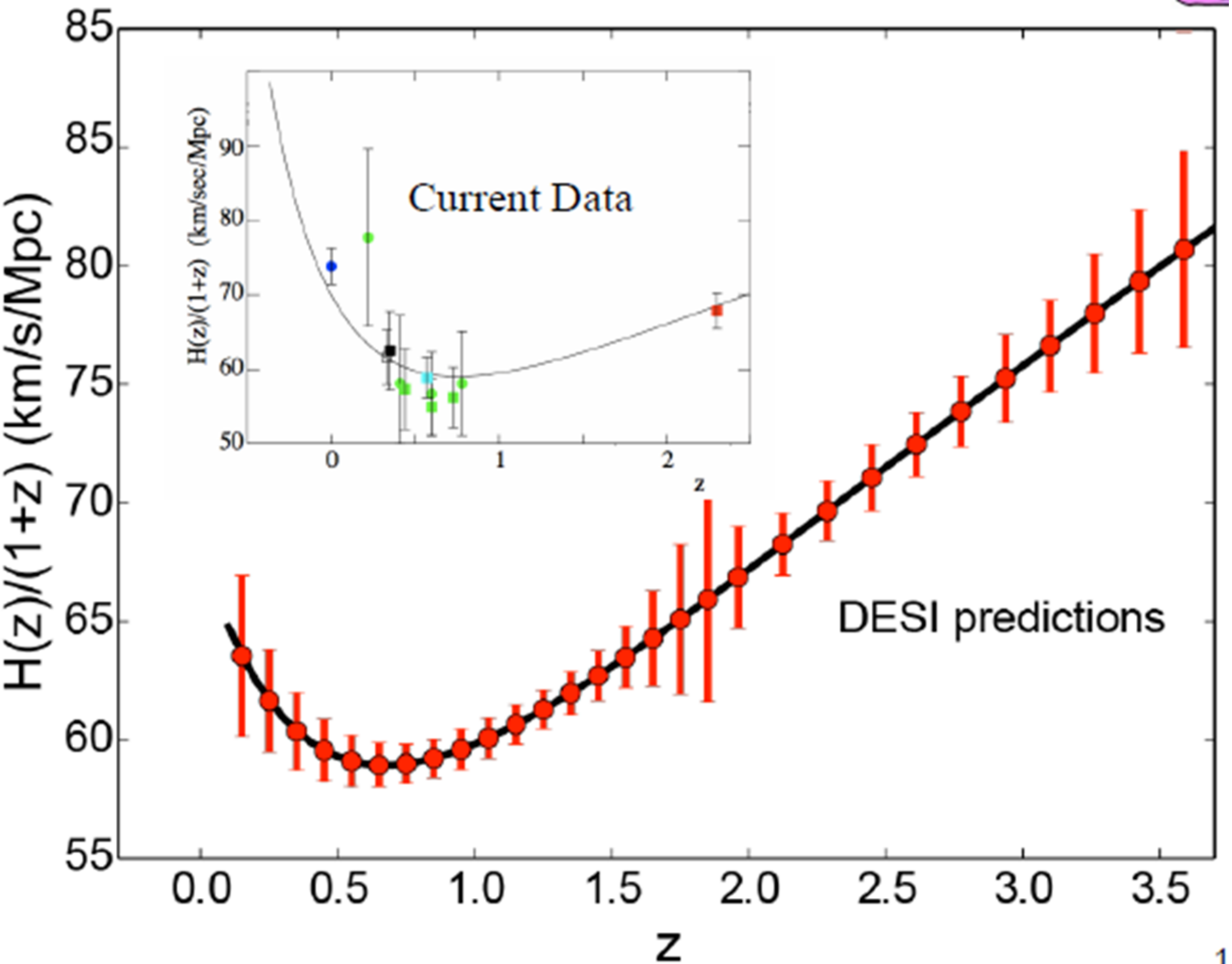
- Bright Galaxies (BG) (0<z<0.4)
- Luminous Red Galaxies (LRG) (0.4<z<1)
- Emission Line Galaxies (ELG) (0.6<z<1.6)
- Tracer Quasars (QSO) (1<z<2.1)
- High Redshift Quasars (Ly-α forest) (z>2.1)

Successful z object density/sq-deg

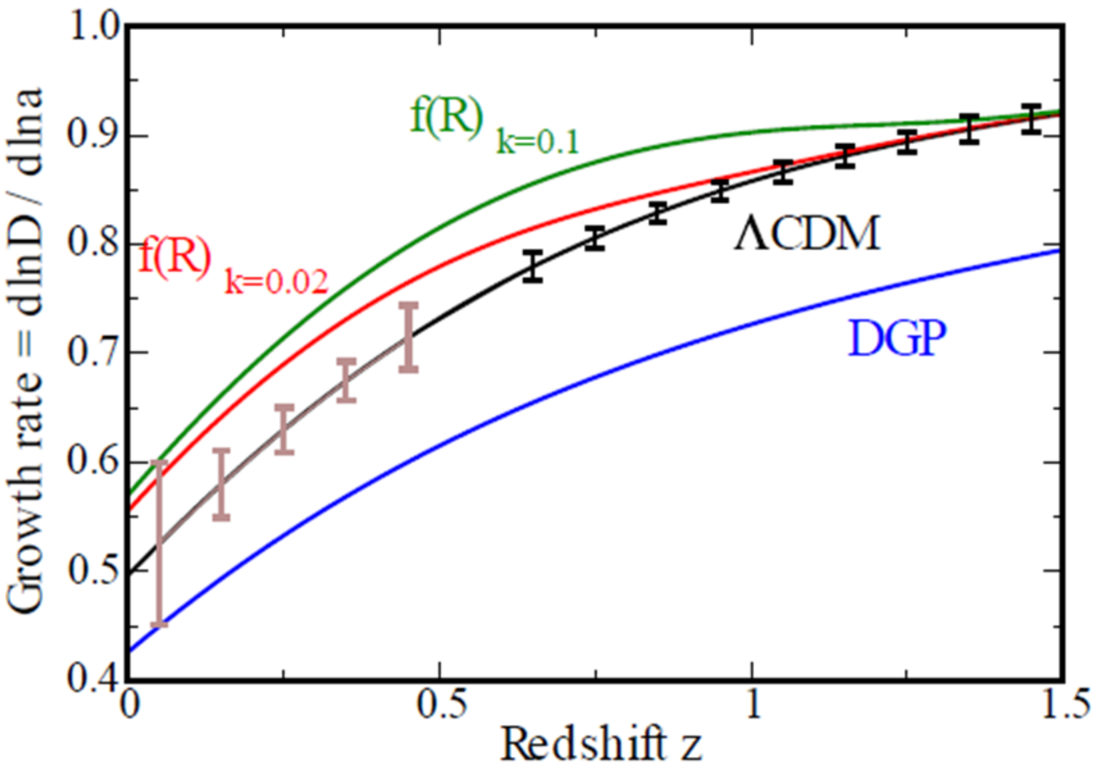
- BGs > 700
- LRGs>300
- ELGs>1280
- QSOs>120
- Ly-α>50

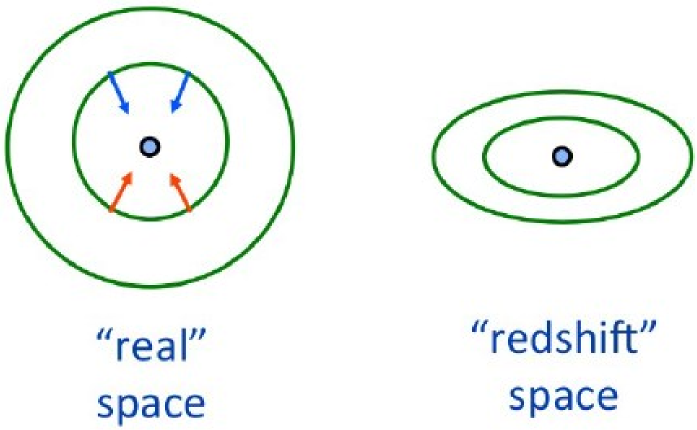
Number of redshifts ~34 M

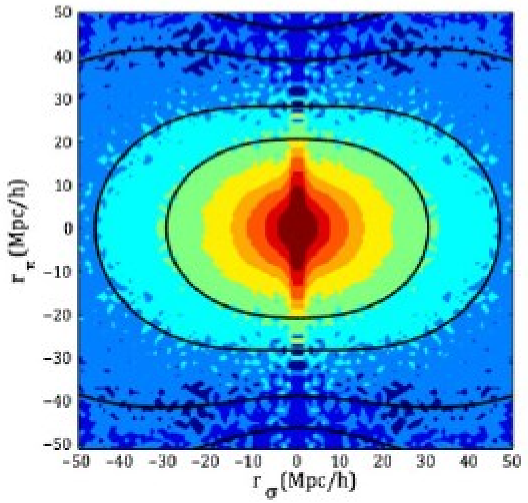
DESI Survey Data Set



DESI Survey Data Set





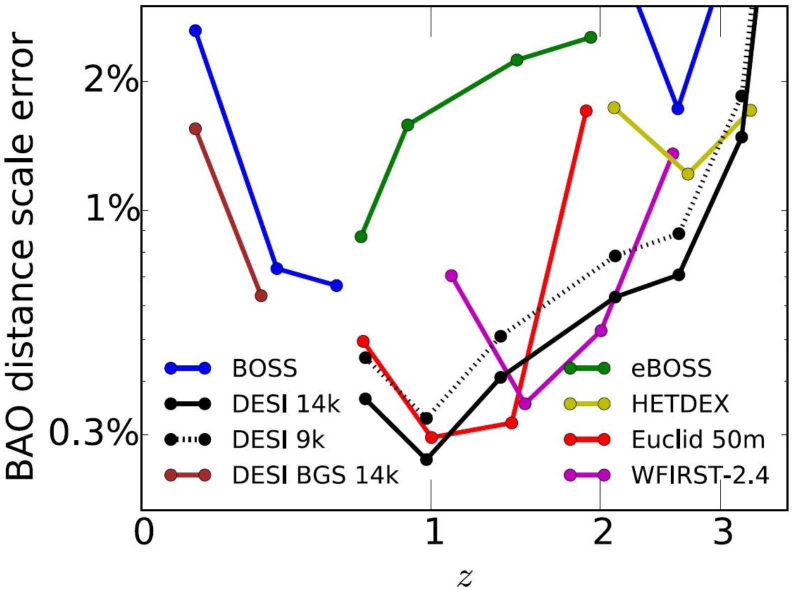


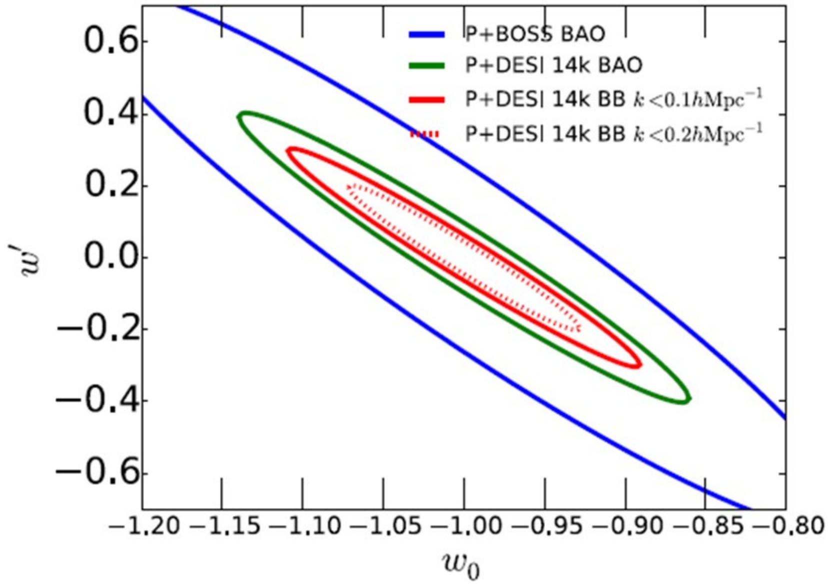
RSD observed in BOSS

RSD constrain the growth rate → Test of GR

DESI will measure the growth rate with precision <1% over 0.5<z<1.4

DESI Survey Data Set





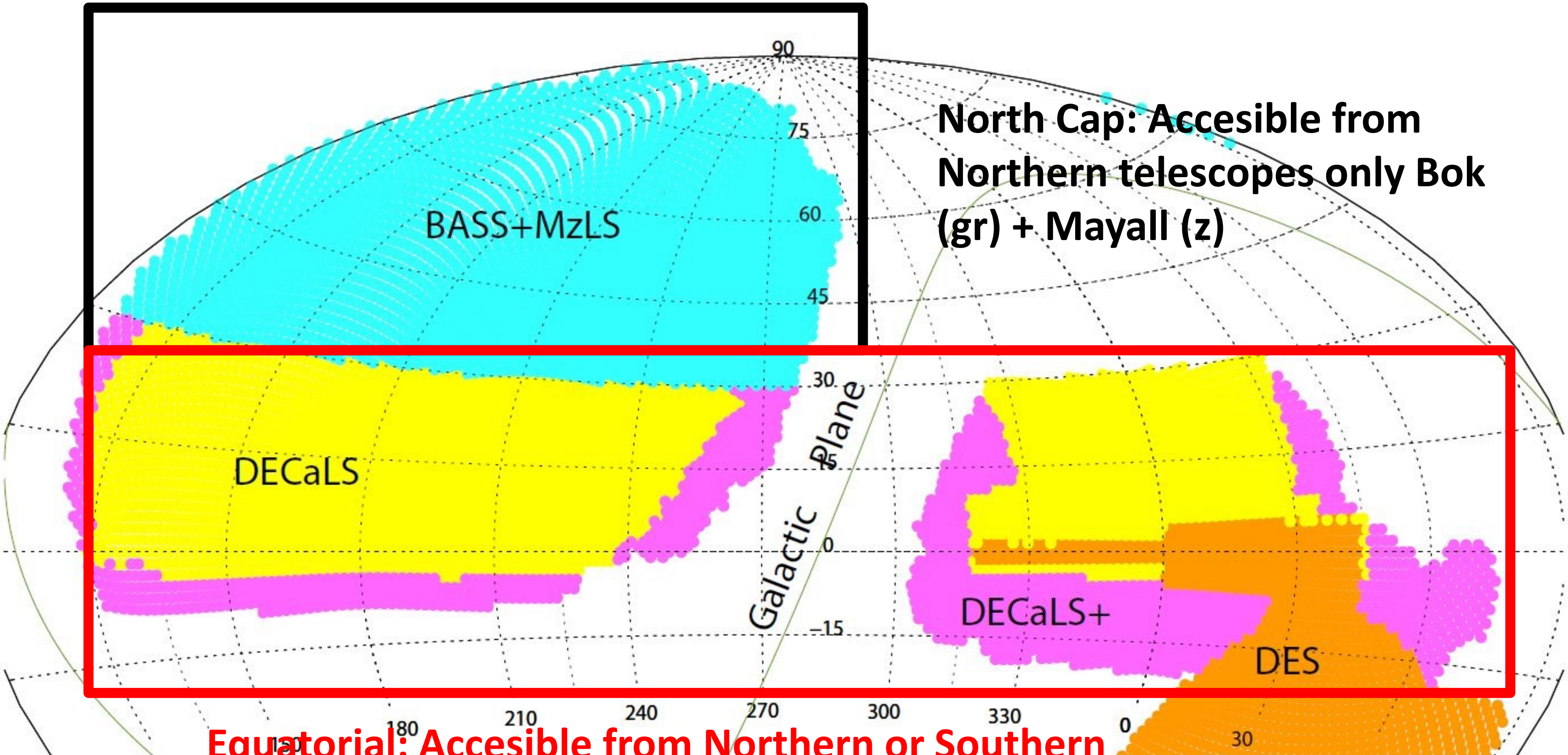
Will measure distance scale to better than 0.3% statistical errors. Figure of Merit (FoM) surpasses definition of a Stage-IV Dark Energy Experiment with margin

Surveys	FoM
BOSS BAO	37
DESI 14k galaxy BAO	133
DESI 14k galaxy and Ly-α forest BAO	169
DESI 14k BAO + gal. broadband to $k < 0.1\ h\ \mathrm{Mpc}^{-1}$	332
DESI 14k BAO + gal. broadband to $k < 0.2\ h\ \mathrm{Mpc}^{-1}$	704

DESI Survey Data Set

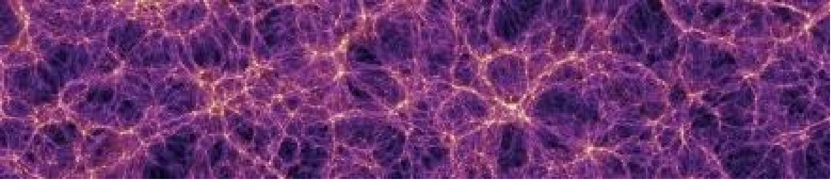
14000 sq-deg footprint

DESI targeting requires new imaging over this area



North Cap: Accesible from Northern telescopes only Bok (gr) + Mayall (z)

Equatorial: Accesible from Northern or Southern telescopes



DESI

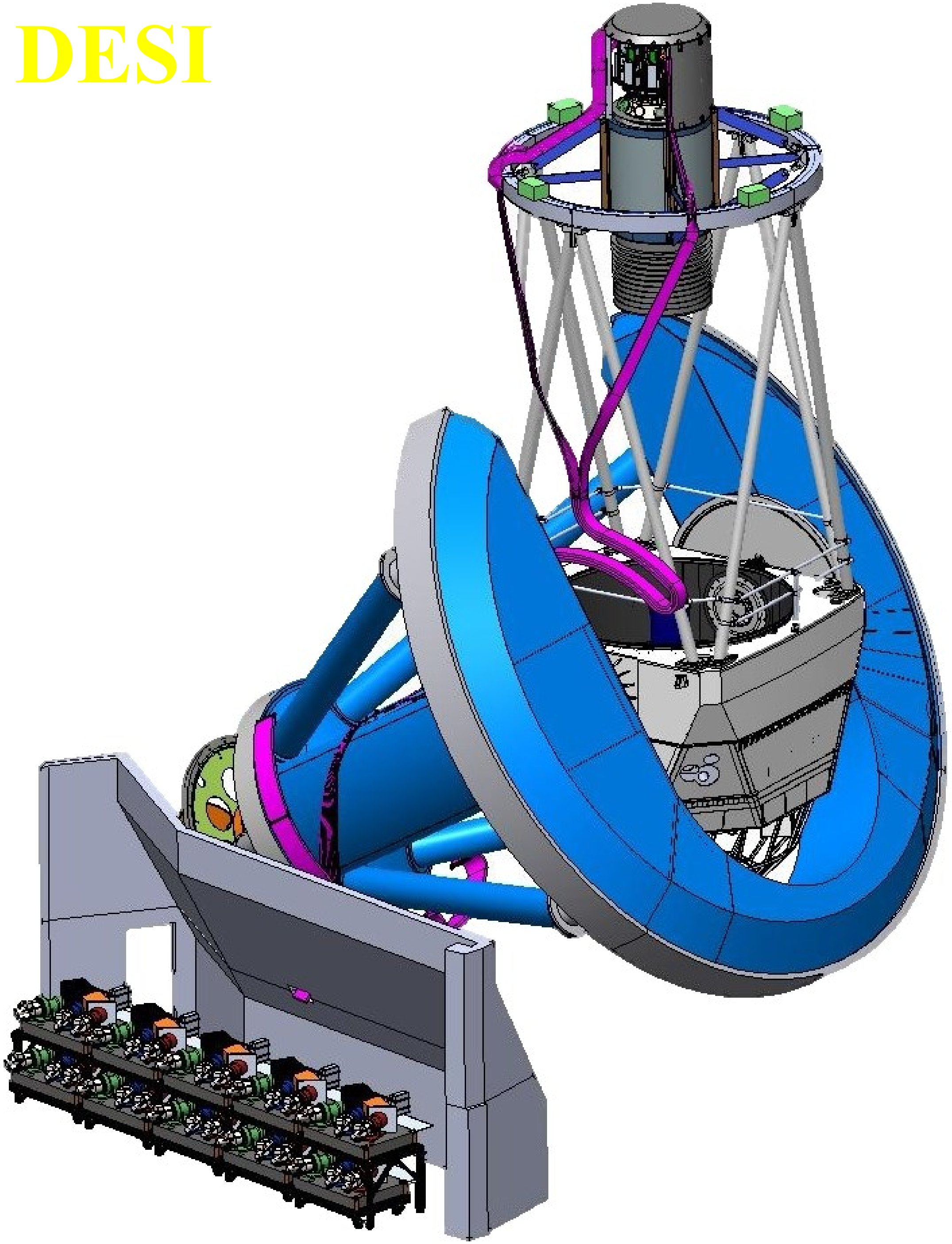
To achieve these measurements, we need:

4m telescope: Mayall @ Kitt Peak

8 sq-deg field of view optics

5000 fibers in robotic actuators

10 spectrographs x 3 bands (blue, red and NIR; 360-1020 nm)



DESI Instrument

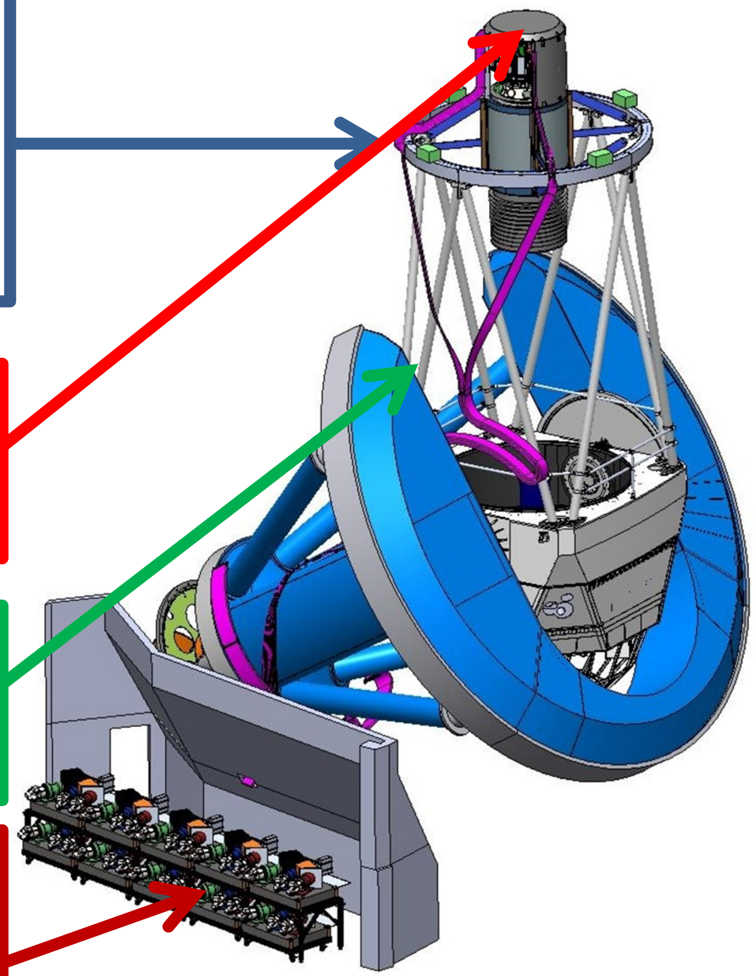
The DESI project will build:

A new corrector for the telescope (creating a 8 deg2 FOV)
A new top ring and cage, barrel and hexapod assembly

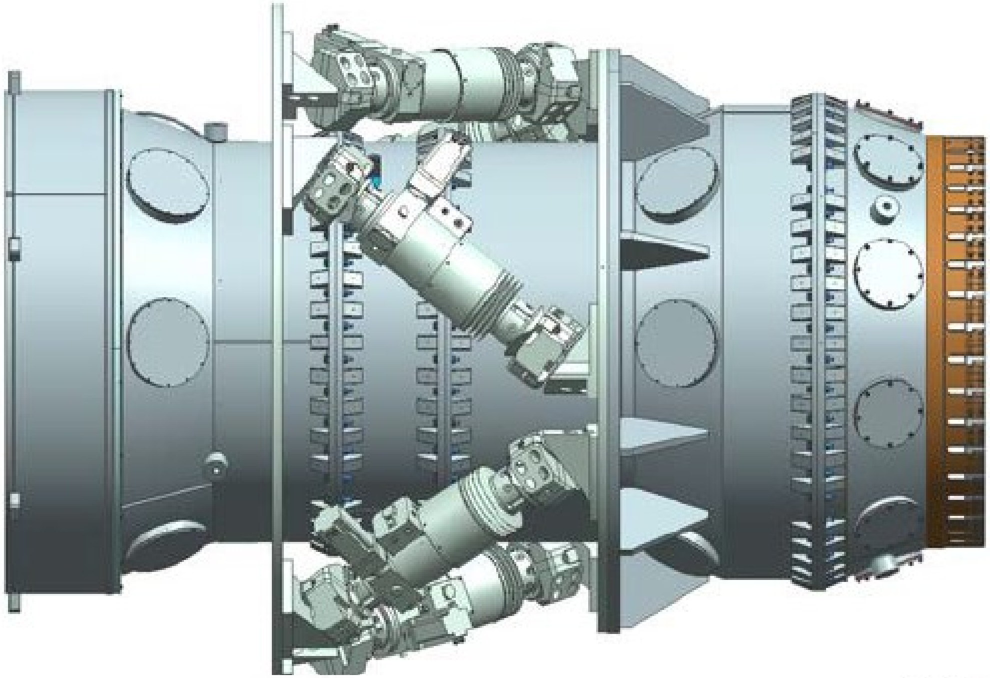
A focal plane with 5000 fiber positioner robots in 10 petals

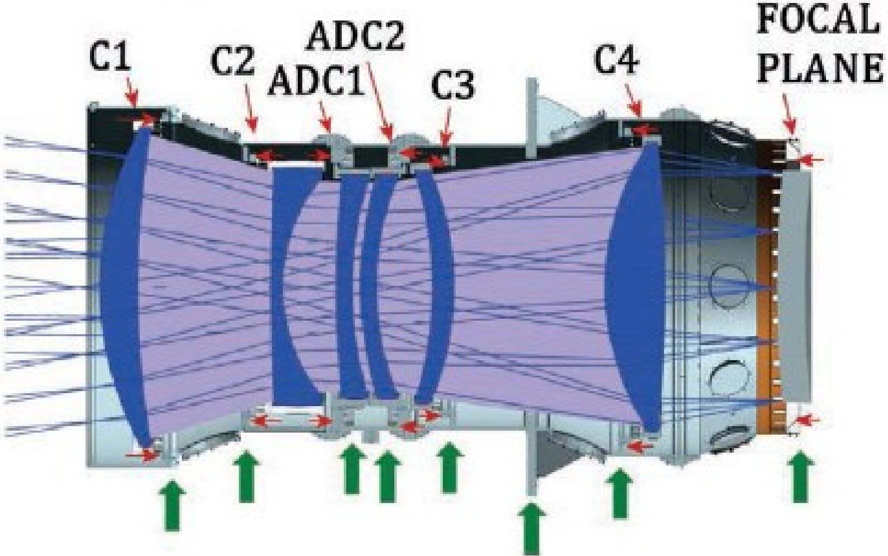
A fiber optic system to transport the light to spectrographs

Ten 3-arm spectrographs based upon the BOSS design
Instrument controls and data processing



DESI Instrument: New Corrector

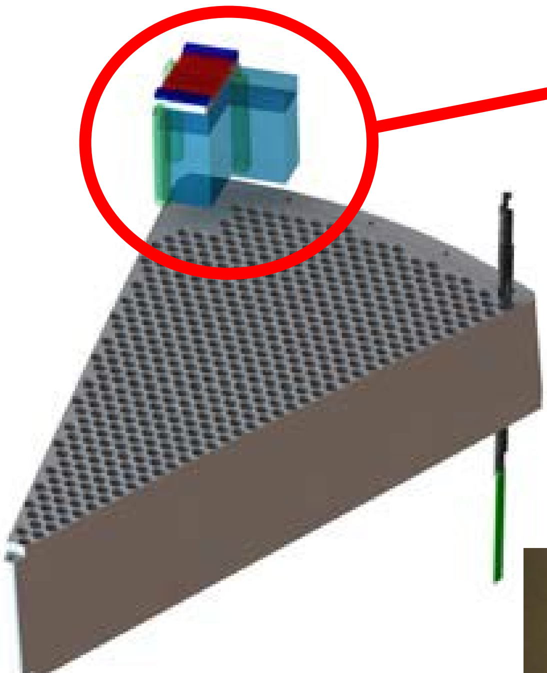




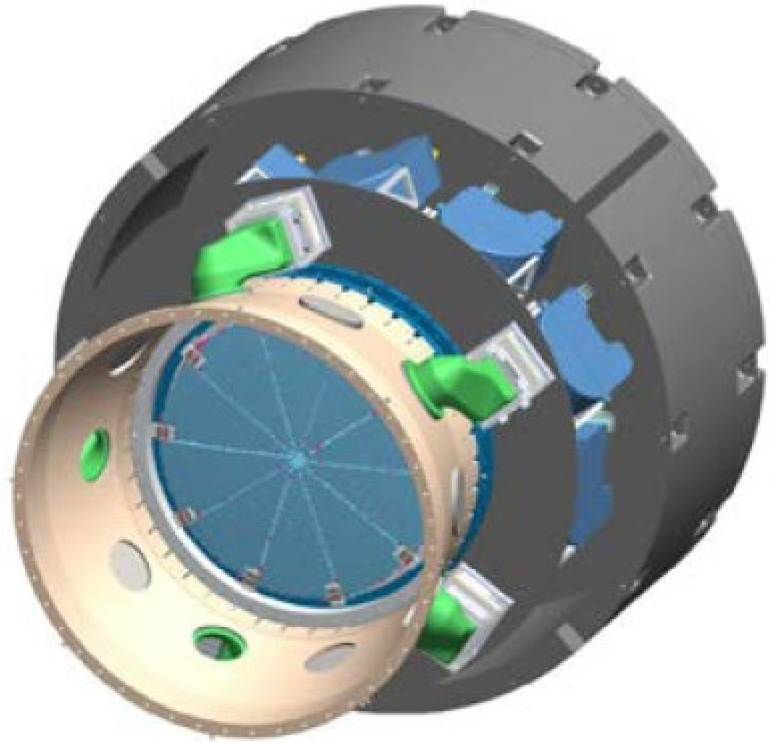
C4 Lens, ~1m diameter!!!!

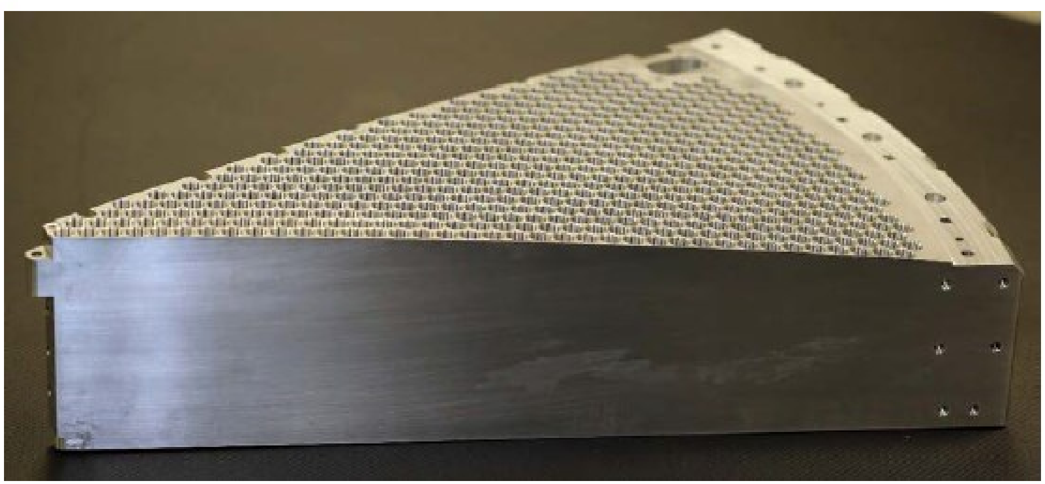
DESI Instrument: Focal Plane

10 Petals. Each one contains 500 optical fiber positioners and one GFA camera

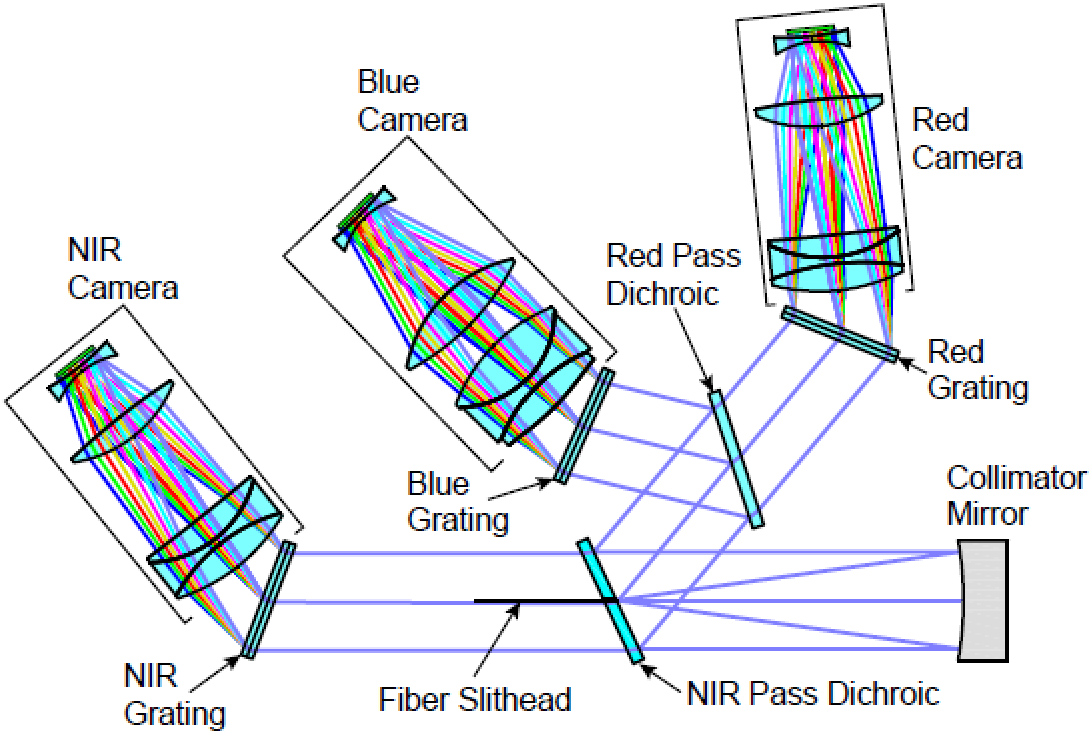


Responsibility of BCN-MAD





DESI Instrument: Spectrographs



Schematic of a spectrograh. DESI will have 10 spectrographs with 3 bands each (Blue, Red, NIR)

Some of the spectrograph cameras

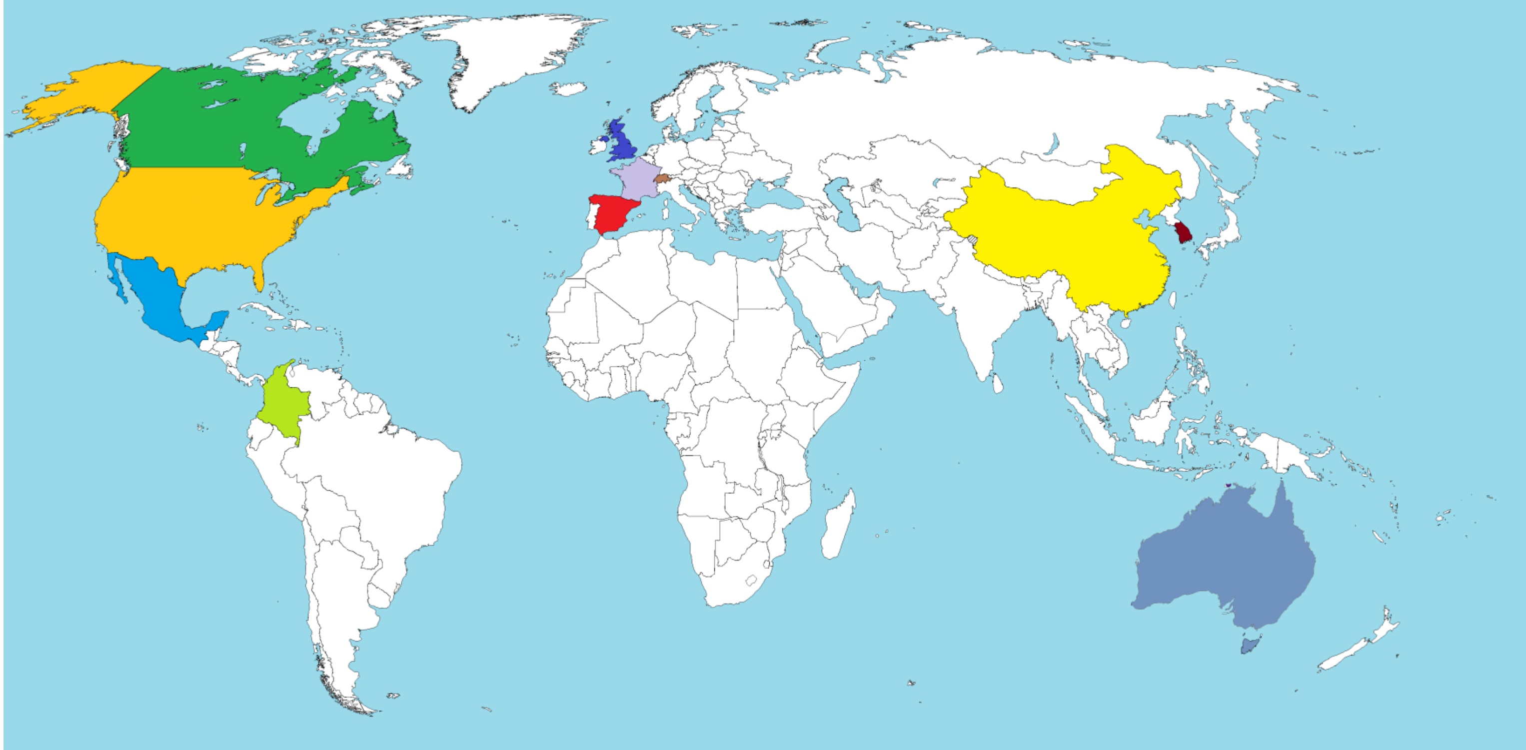
The DESI Collaboration

The DESI Collaboration has ~200 Participants from ~40 institutions

Project Director: **M. Levi (LBNL)**

Spokespersons: **D. Eisenstein (Harvard), R. Wechsler (SLAC)**

USA (ANL, Arizona, BNL, BU, CMU, Cornell, FNAL, Harvard, Irvine, **LBNL**, LLNL, Michigan, NOAO, OSU, Ohio, Pennsylvania, Pittsburgh, Siena, SLAC, SMU, UCB, UCSC, Utah, Yale), Australia (Queensland, Swinburne), **Canada** (Toronto) , **China** (NAOC RPG) , **Colombia** (Andes) , **France** (CEA, CPPM, LAM, LPNHE, OHP) , **Korea** (KASI,KIAS) , **Mexico** , **Spain** (BCN-MAD RPG, GMT RPG) , **Switzerland** (EPFL, ETHZ) , **UK** (Durham, Portsmouth, UCL, RPG)



Summary: DESI Status

- Dark energy is one of the most important puzzles of fundamental physics. Baryon Acoustic Oscillations and Redshift Space Distortions are key probes of Dark Energy, complementary to other probes with low systematics

- DESI is a massive spectroscopic survey, which will use those probes with impressive forecast. DESI will be the final measurement of BAO up to $z<2$.

- The project is funded and construction has started.

- On track for on-sky commissioning <4 years from now in 2019 and start of the survey in second-half of 2019!

- BCN-MAD RPG is actively involved in the collaboration

Conclusions

- **Dark energy is one of the most important puzzles of fundamental physics. Progress on its understanding will come from current and future galaxy surveys**

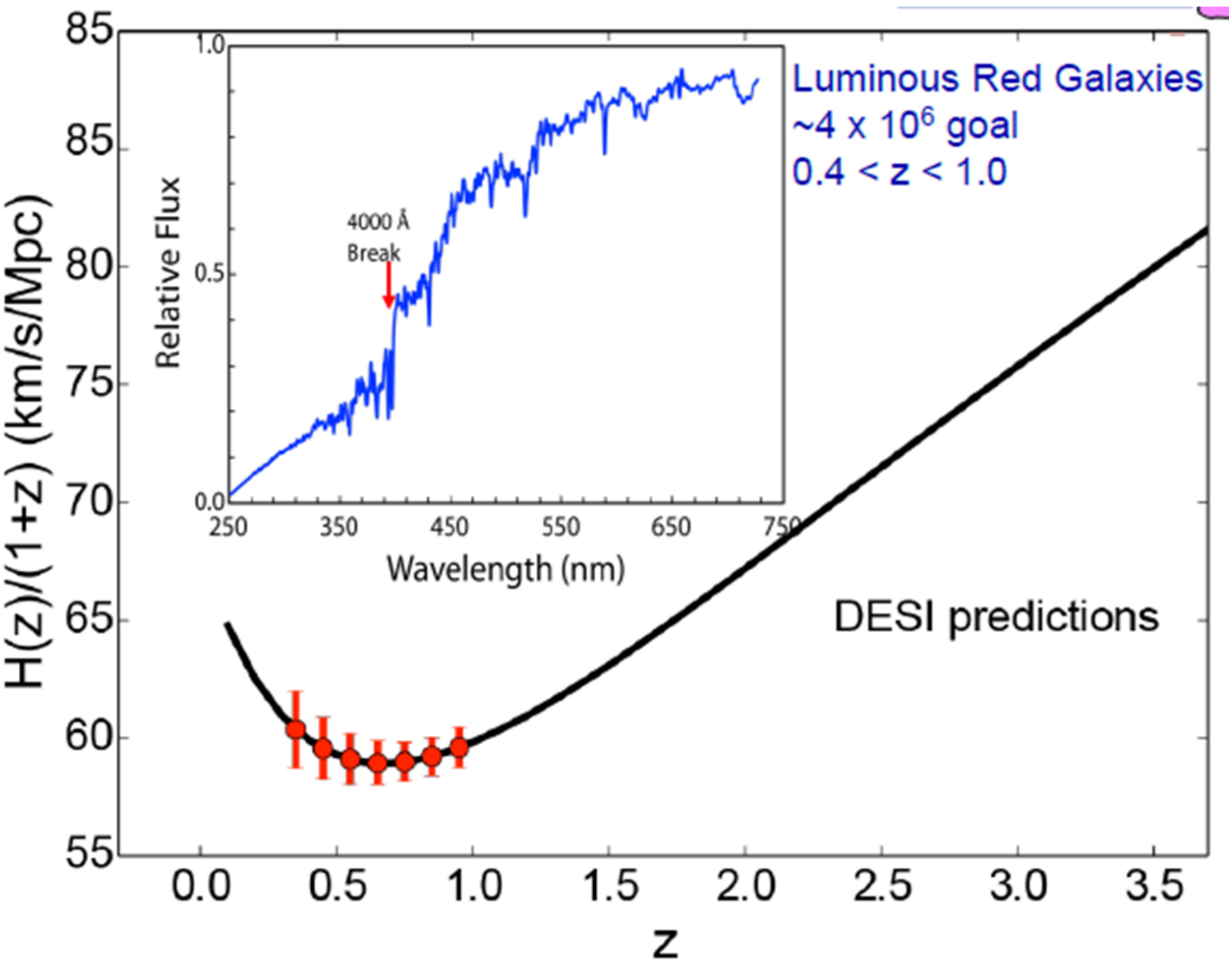
- **DES is taking data and already producing science. Its first competitive results on dark energy are expected for this year**

- **DESI is on track to start the survey before the end of 2019**

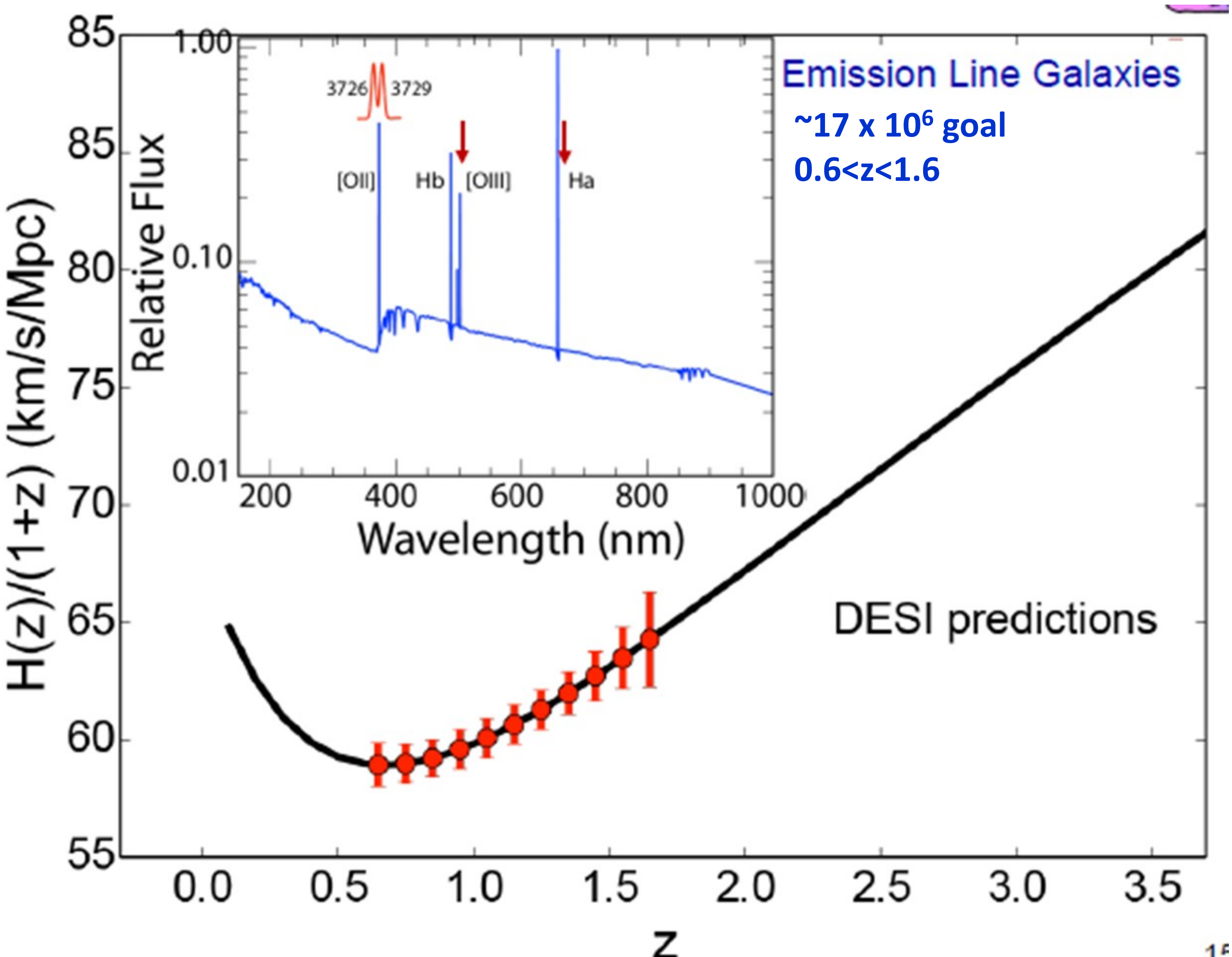
- **This is a very active scientific area, where there is room for discoveries.**

Backup Slides

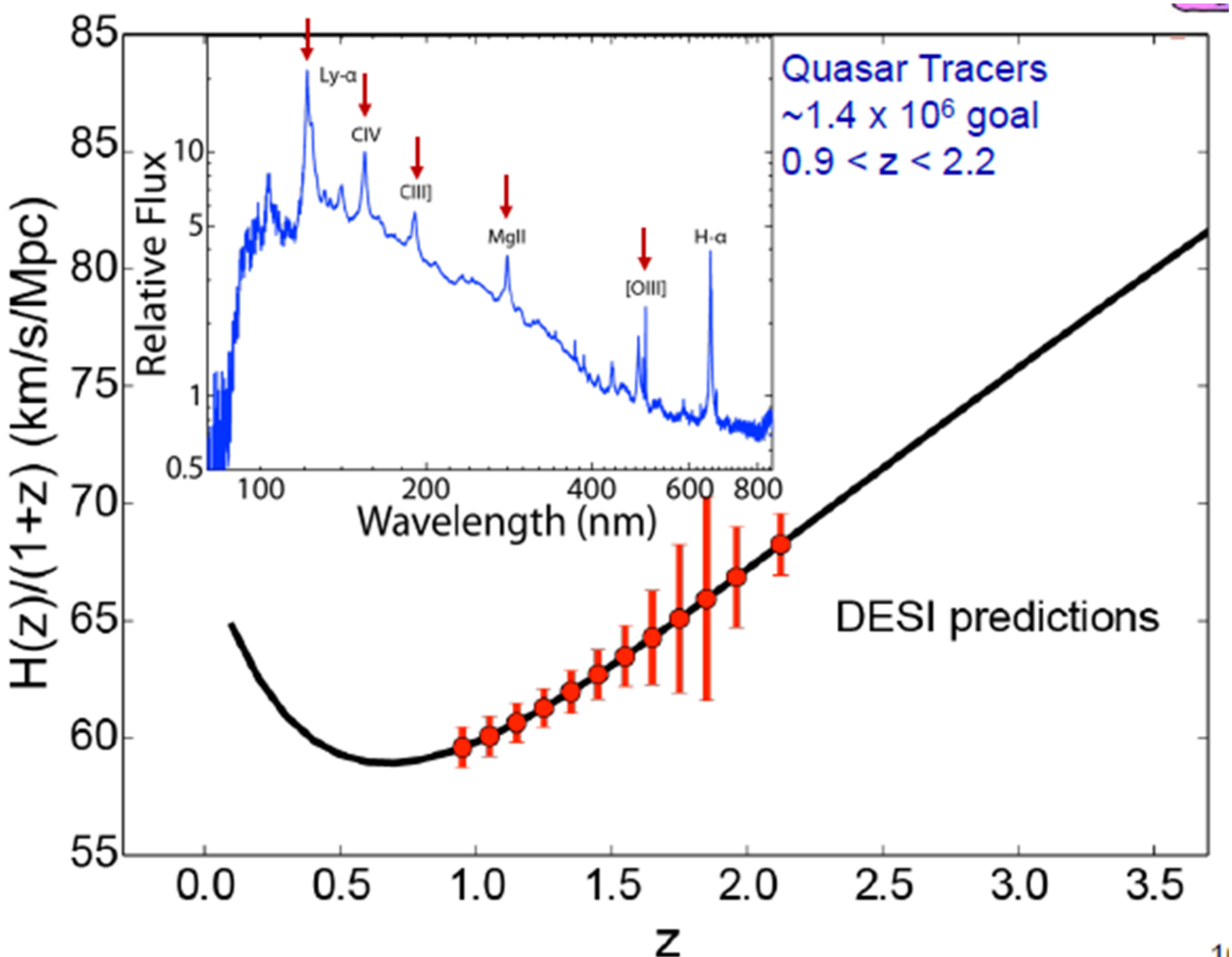
DESI Survey Data Set



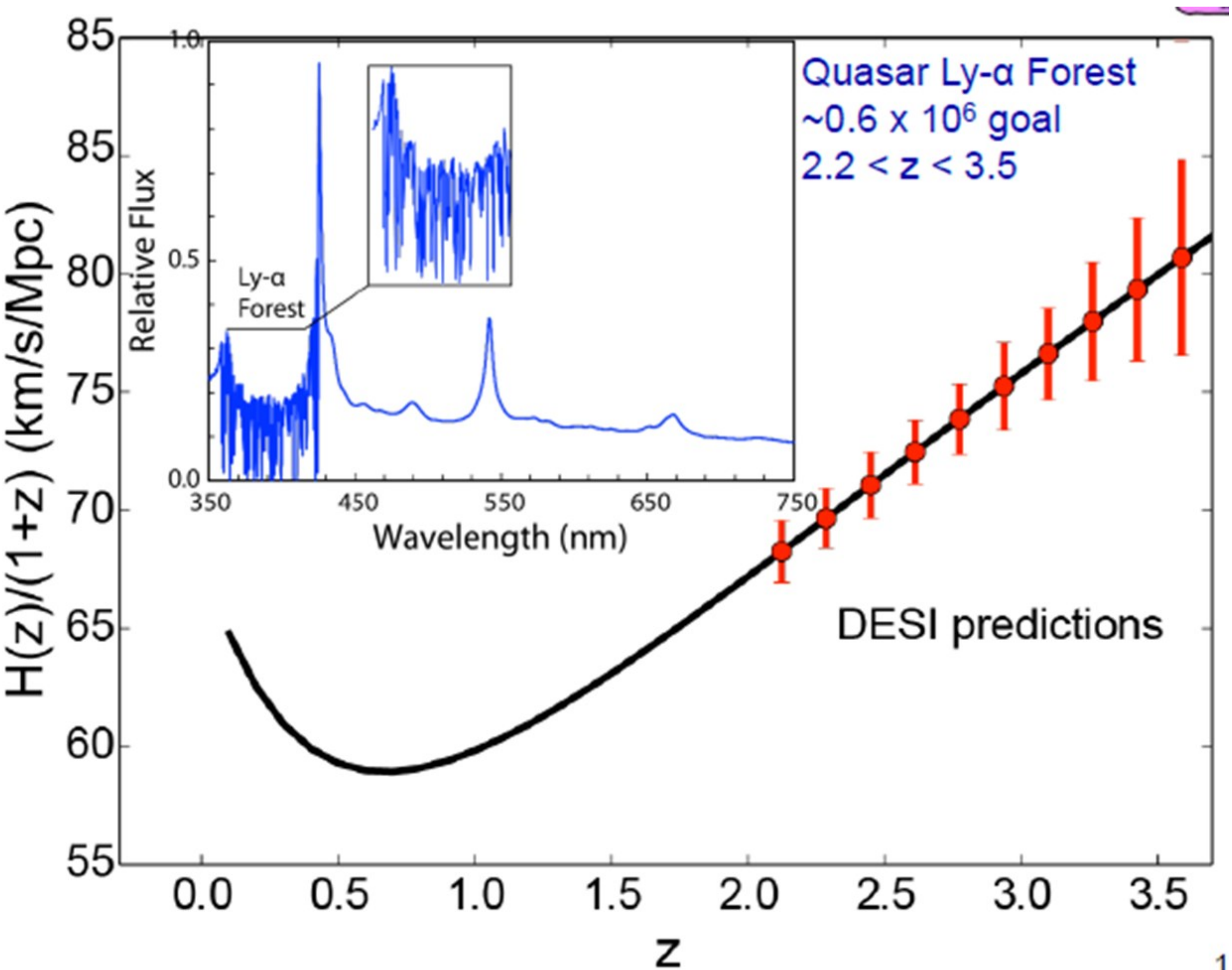
DESI Survey Data Set



DESI Survey Data Set



DESI Survey Data Set



DESI Funding

- Office of High Energy Physics of the U.S. Department of Energy,
- U.S. National Science Foundation,
- Science and Technologies Facilities Council of the United Kingdom,
- Gordon and Betty Moore Foundation,
- Heising-Simons Foundation,
- National Council of Science and Technology of Mexico,
- DESI Member Institutions (Spanish from Plan Nacional)

DESI: Spanish Contribution

2 spanish RPGs + some individuals

Barcelona-Madrid Regional Participation Group Institutions

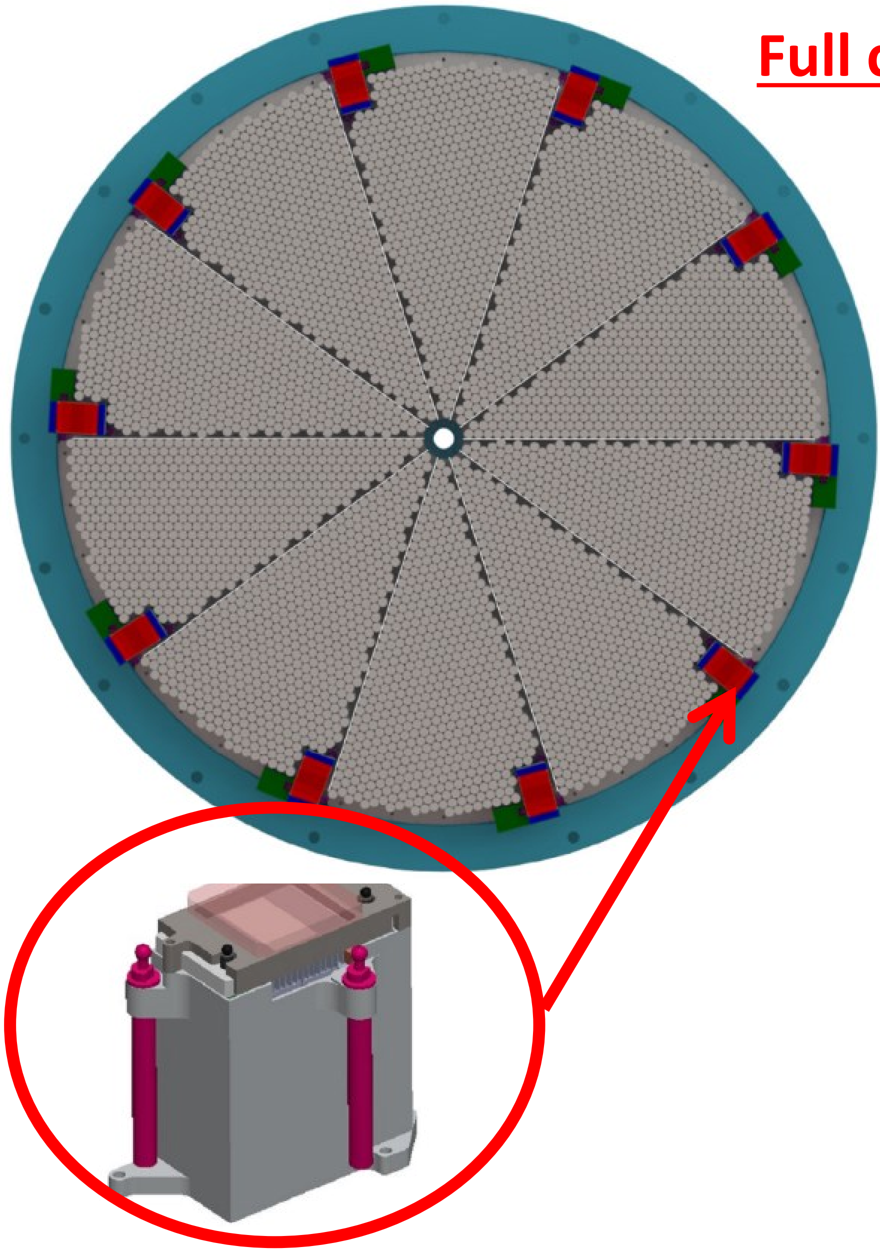
ICE, IEEC/CSIC, IFAE, CIEMAT, IFT/UAM

- **Instrumentation**
  - Guide Focus and Alignment Units
  - Guiding software
- **Science**
  - Working Group participation
  - Leading image validation task force
- **Management**
  - Part of Institutional Board
  - Member of several committees

GMT Regional Participation Group Institutions

CEI/UAM+CSIC, IAA, IAC

DESI Instrument: Spanish Contribution



Full construction of the Guiding, Focus and Alignment (GFA) System

- Focal Plane composed of 10 petals

- Each petal contains a GFA camera (There are 10 cameras)

- GFA of two types:
  - 6 for guiding and field acquisition
  - 4 for focus and alignment
  - Identical except for optical filter

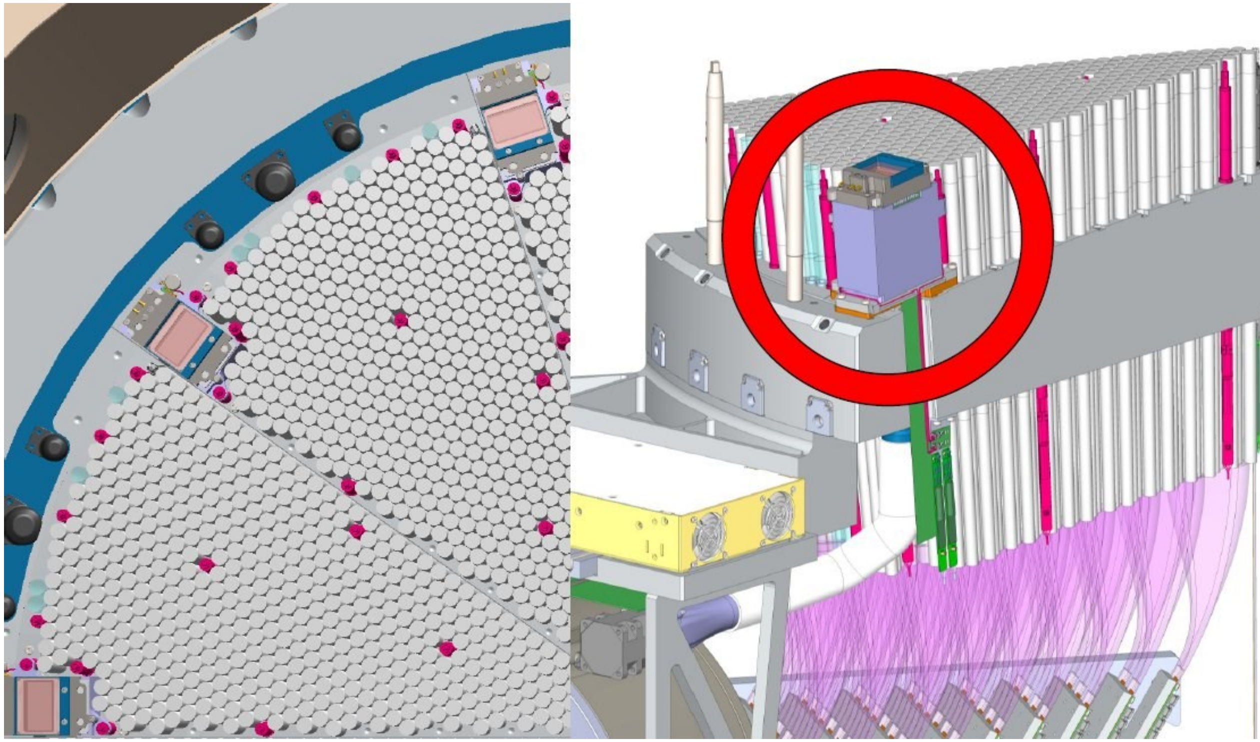
- The only imaging systems in DESI

- GFA cameras use stars to provide the guide signal and measure focus and alignment

DESI Instrument: Spanish Contribution

The GFA cameras have to operate at ambient temperature to minimize local heating near the focal surface

The GFA camera footprint has to be such as to minimize the number of science fibers displaced



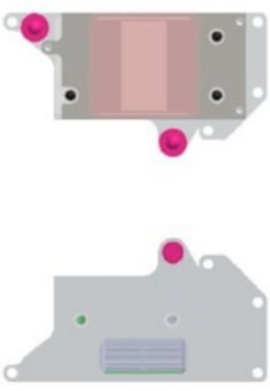
GFA system requiremets:

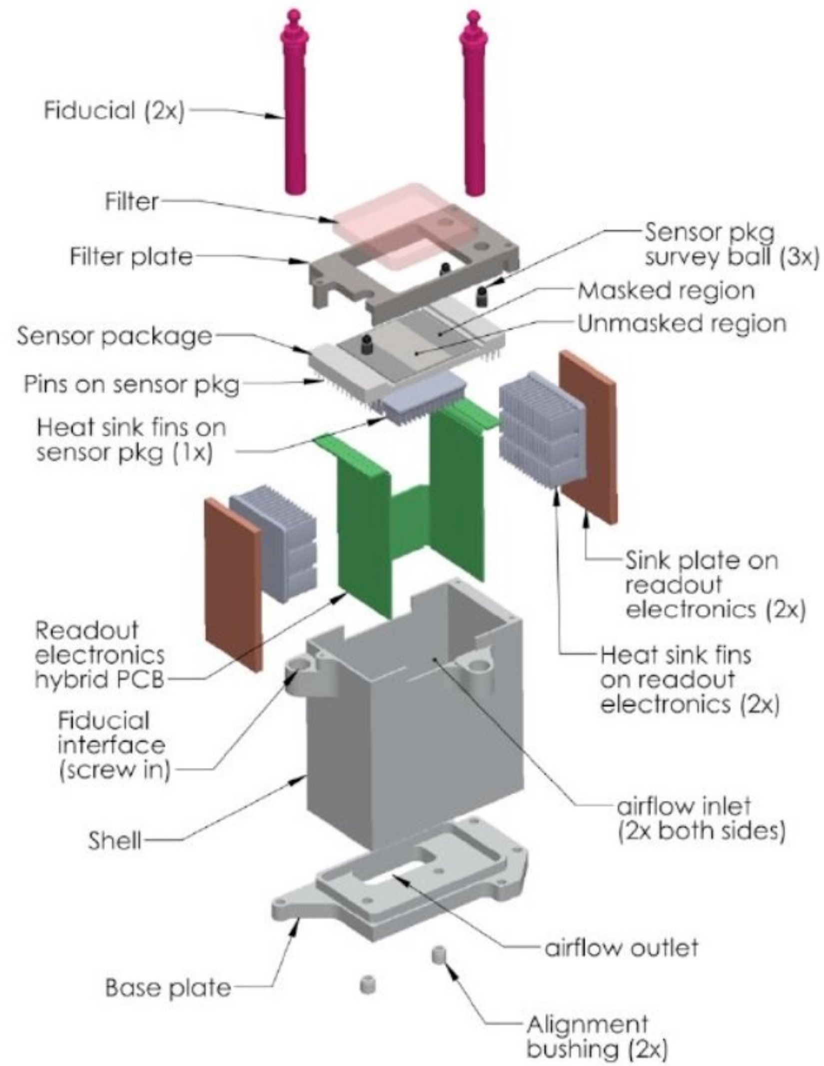
- Provide imaging data during commissioning of the instrument
- Determine the current telescope pointing within 20 seconds after telescope slew
- Determine focal plane scale, rotation and astrometric solution
- Monitor the intensity and PSF of stars during observations to provide feedback on observing conditions
- Provide guide signals to the telescope at 1Hz to a precision of <30 mas
- Determine the wavefront error in focus, decenter, tip and tilt, and provide corrective information to the hexapod system

DESI Instrument: Spanish Contribution

Each 10 GFA camera contains a single CCD sensor, mounted and operated as a standalone instrument

Each camera contains all CCD readout electronics and all controls, and requires only DC power and a Gigabit Ethernet connection





DESI Instrument: Spanish Contribution

GFA System Status:

Design has been finalized and is ready for fabrication

Mechanics: Prototype built and tested

Electronics Schematics defined, Layout finished

Software: Designed and being written

CCDs have been selected, in process of purchasing

Characterization and test setups for CCDs (BCN) and filters (MAD) are ready

The plan is to have the GFA completed by the end of 2017