Cosmology with galaxy surveys

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Disclaimer

- Cosmology studies the universe as a whole:
  - Its origin, evolution and ultimate fate: expansion, accelerated expansion.
  - Its ultimate components: baryonic matter, neutrinos, dark matter, dark energy.
  - The formation of the structures we see today: galaxies, clusters, filaments…
- Structure formation is the most complex problem in cosmology:
  - Complicated non-linear effects not fully under control.
  - In general, the larger the scale, the easiest the theoretical understanding, but then large surveys are needed to get to large scales (at least 5 Mpc).
- In this talk, I will concentrate on the issue of **dark energy**, arguably the most pressing problem in the whole of fundamental physics.
  - What is causing the current accelerated expansion of the universe?
  - If interpreted as a new component of the universe, DE comprises ~70% of it.

Outline

- Introduction: dark energy and galaxy surveys
- Survey of current and future galaxy surveys
- State of the art: BOSS + Planck
- **Recent results from DES**
- Status of the PAU Survey at ORM
- Multi-messenger astronomy for fundamental physics
- Conclusions

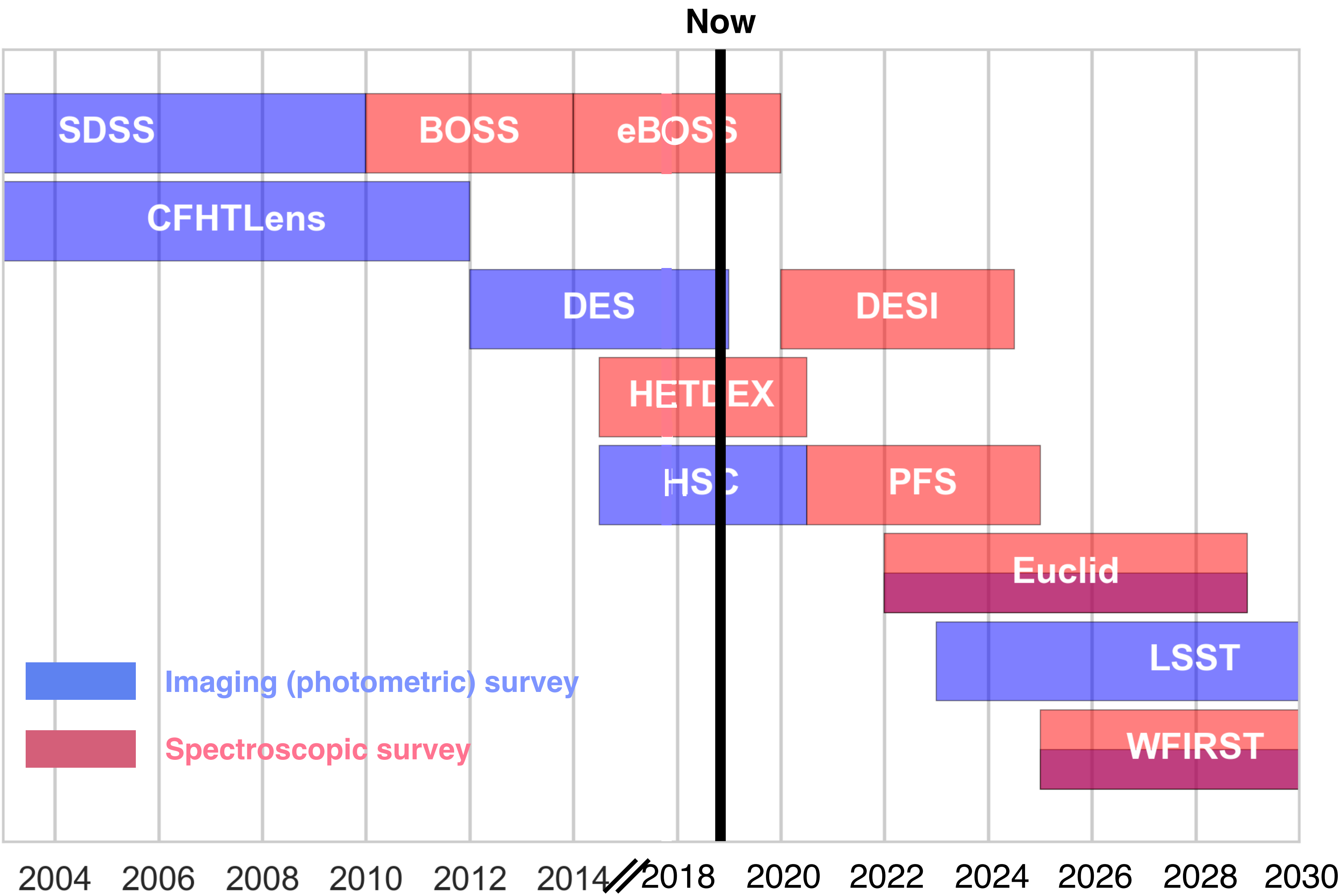
Intro: dark energy and galaxy surveys

- What is causing the acceleration of the expansion of the universe?
  - Einstein's cosmological constant Λ?
  - Some new dynamical field ("quintessence," Higgs-like)?
  - Modifications to General Relativity?

  } "Dark Energy"

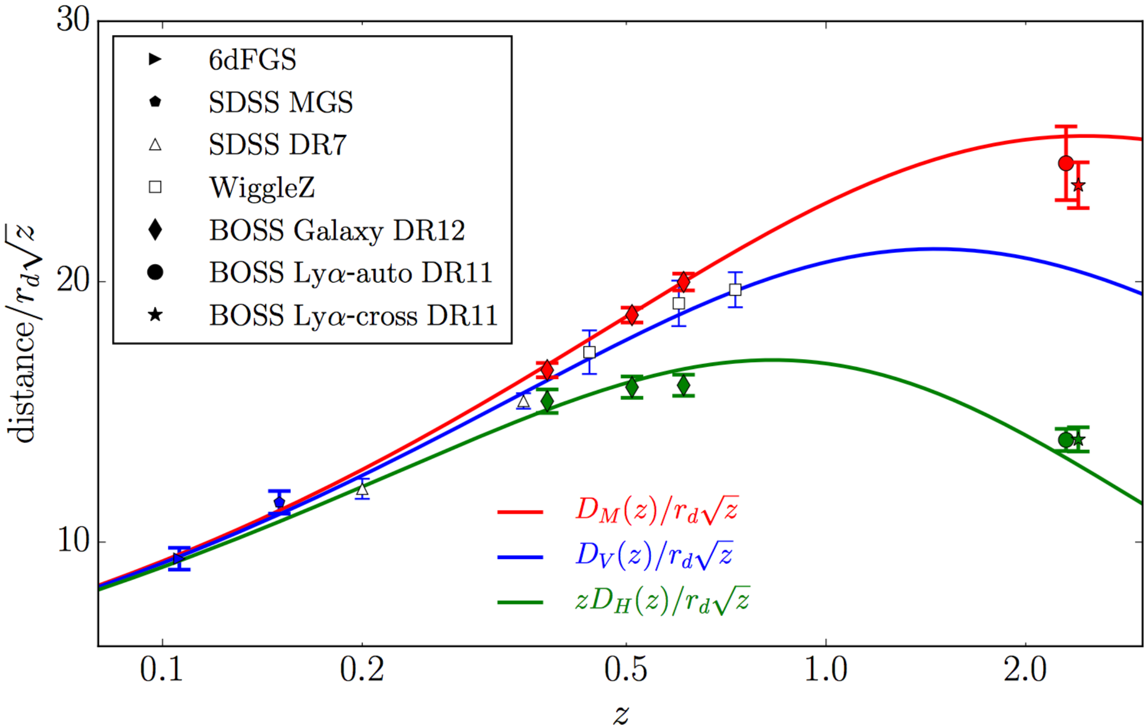
- Dark energy effects can be studied in two main cosmological observables:
  - The history of the expansion rate of the universe: supernovae, weak lensing, baryon acoustic oscillations (BAO), cluster counting, etc.
  - The history of the rate of the growth of structure in the universe: weak lensing, large-scale structure, cluster counting, redshift-space distortions, etc.
- For all probes, **large galaxy surveys are needed**:
  - **Spectroscopic**: 3D (redshift), medium depth, low density, selection effects, **BAO**
  - **Imaging**: "2.5D" (photo-z), deeper, higher density, no selection effects, **WL**

Survey of galaxy surveys

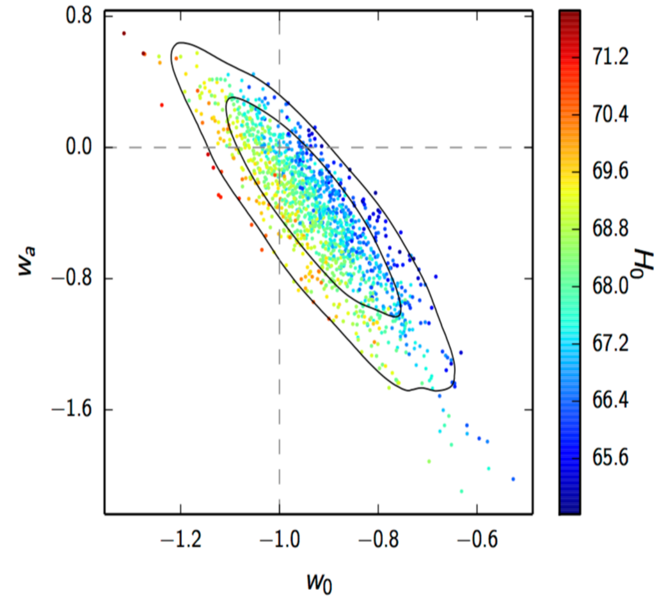


State of the art: BOSS

- BOSS finished data taking in 2014: ~9,400 deg^2
- It measured the BAO scale in galaxies and Ly-α quasars



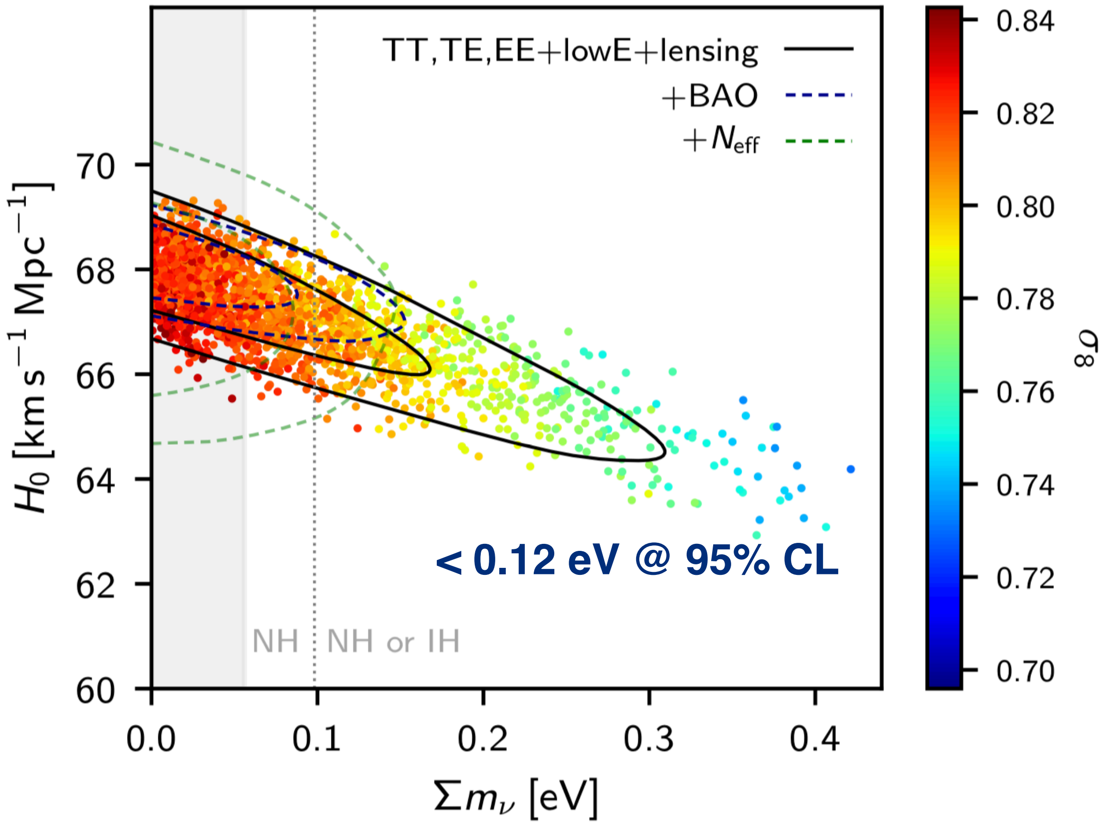
BOSS, MNRAS 470 (2017) 2617



Planck, A&A 594 (2016) A14
(Planck + BAO + SNe)

$w = p / \rho = w_0 + w_a \times (1-a)$, with
$w_0 = w$ (now)
$w_a = - dw / da$ (now)

Neutrino mass



Planck, arXiv:1807.06209

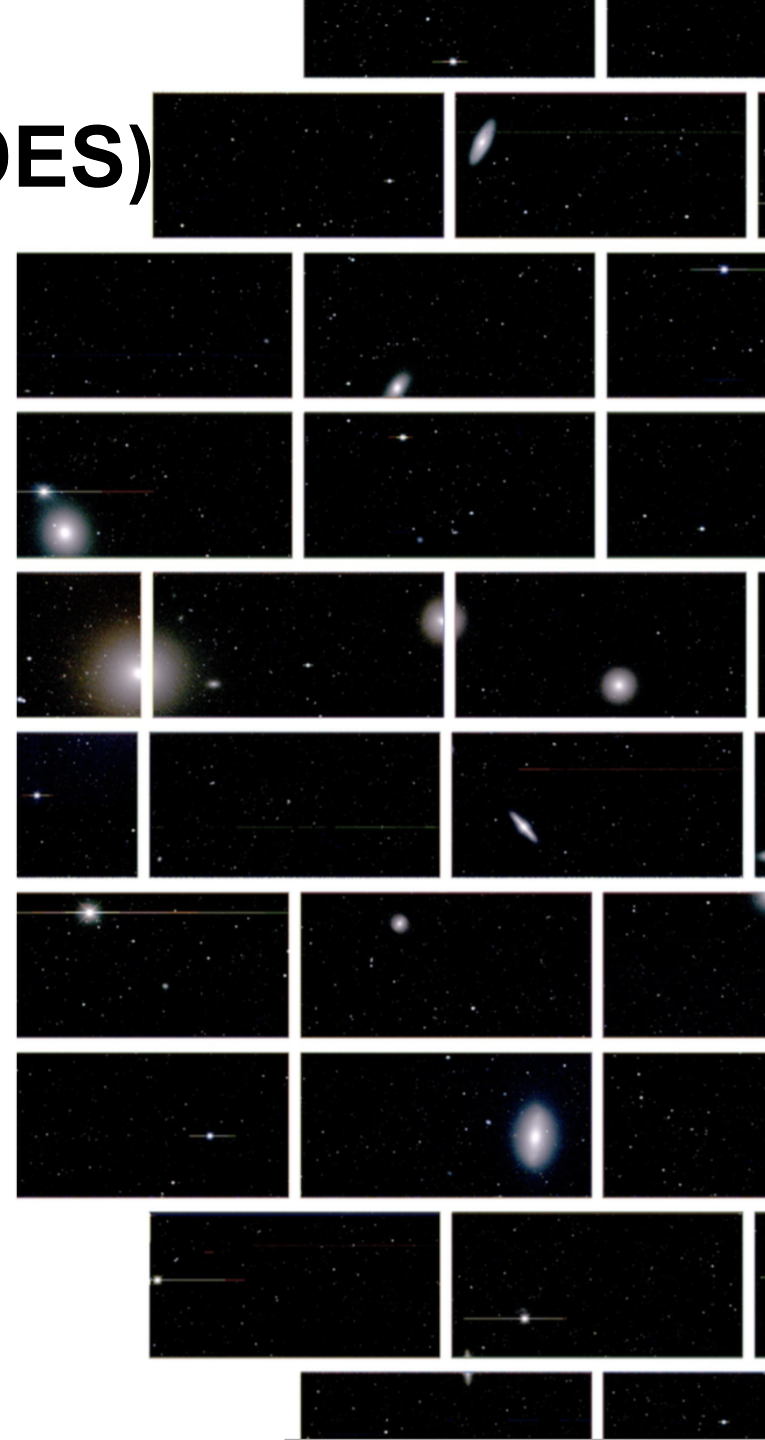
All next generation surveys have the sensitivity to reach a detection

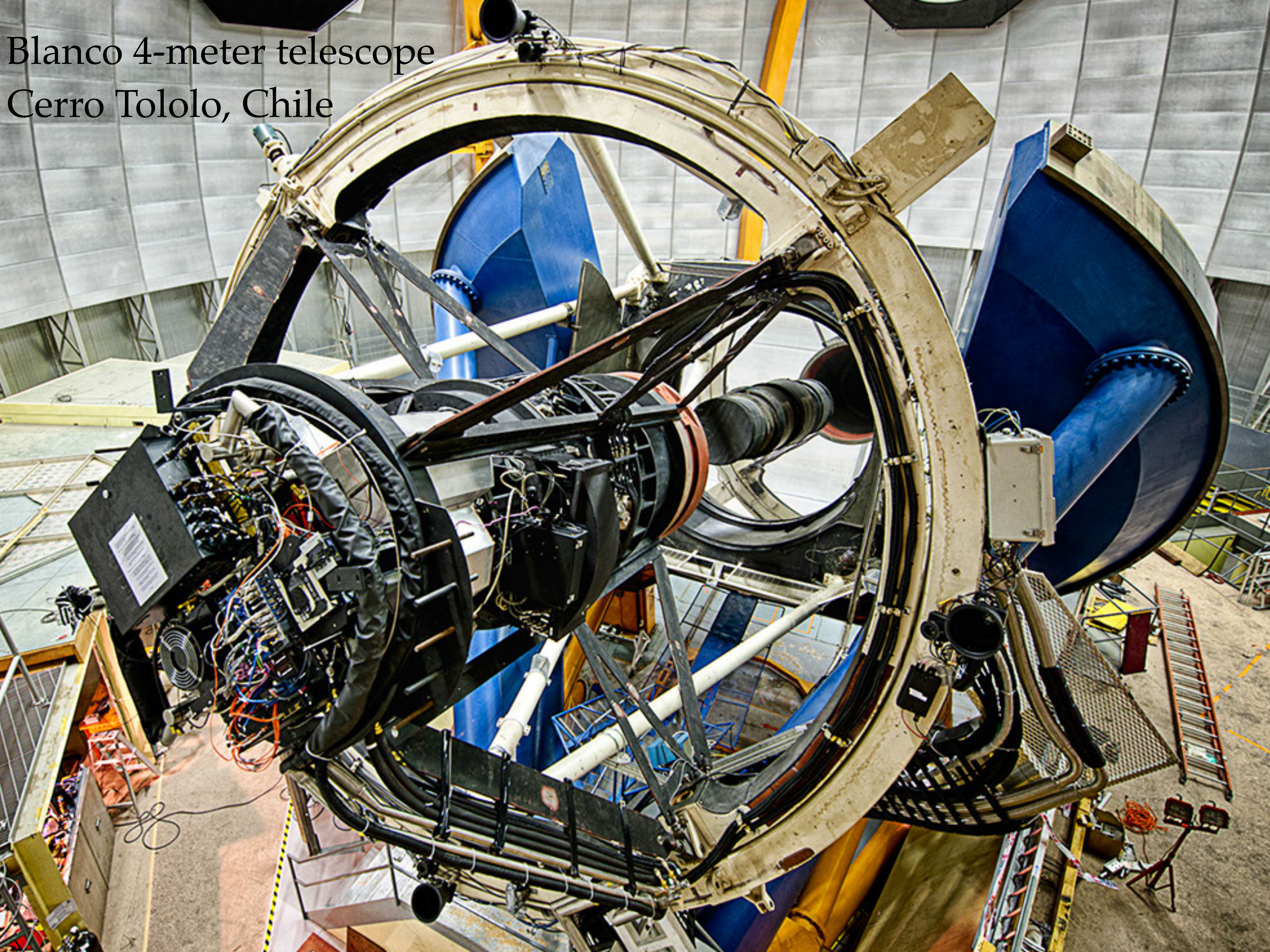
Ex: DESI (+ Planck) forecast a sensitivity ~ 0.02 eV

Dark Energy Survey (DES)

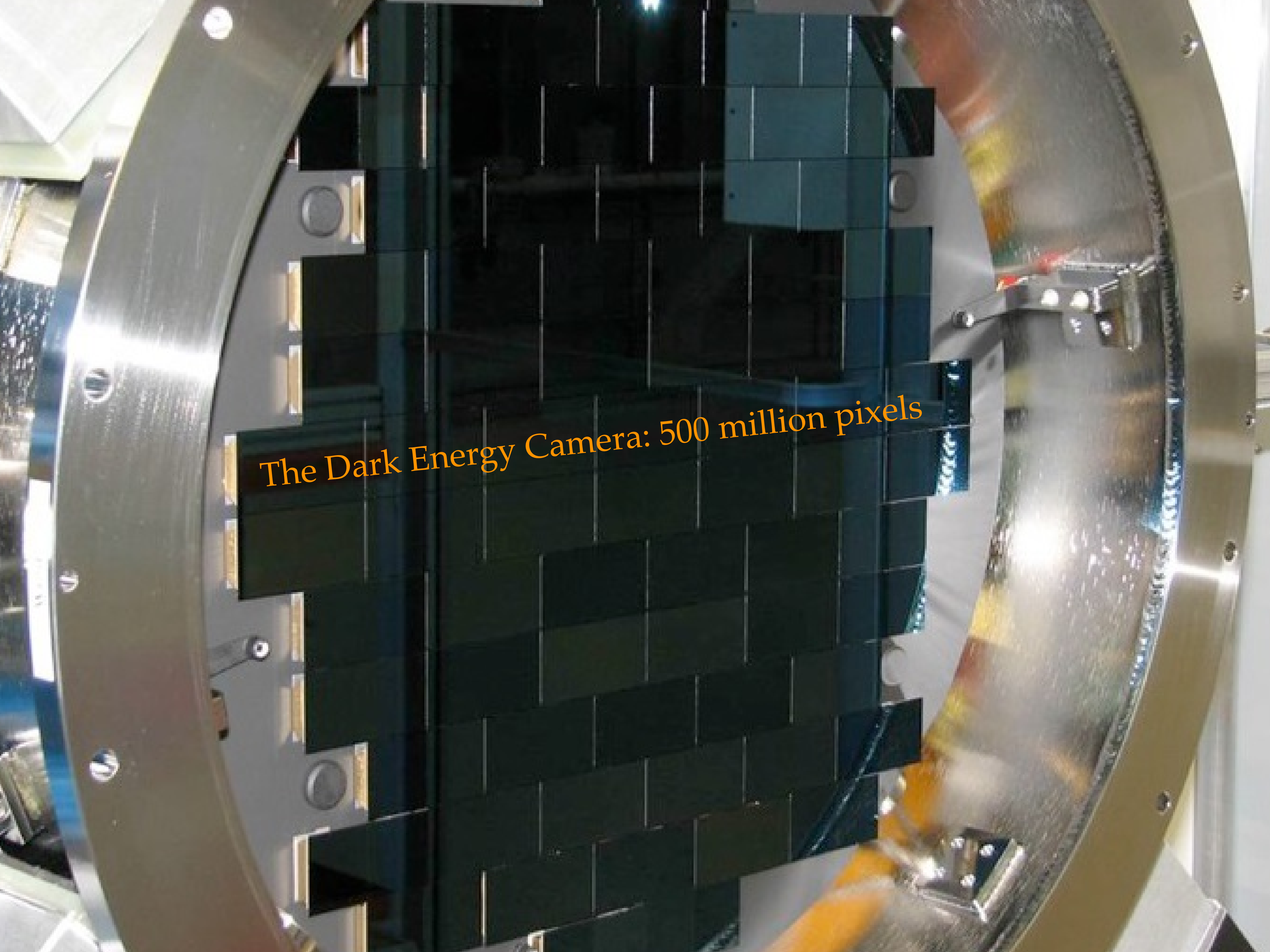
DARK ENERGY SURVEY

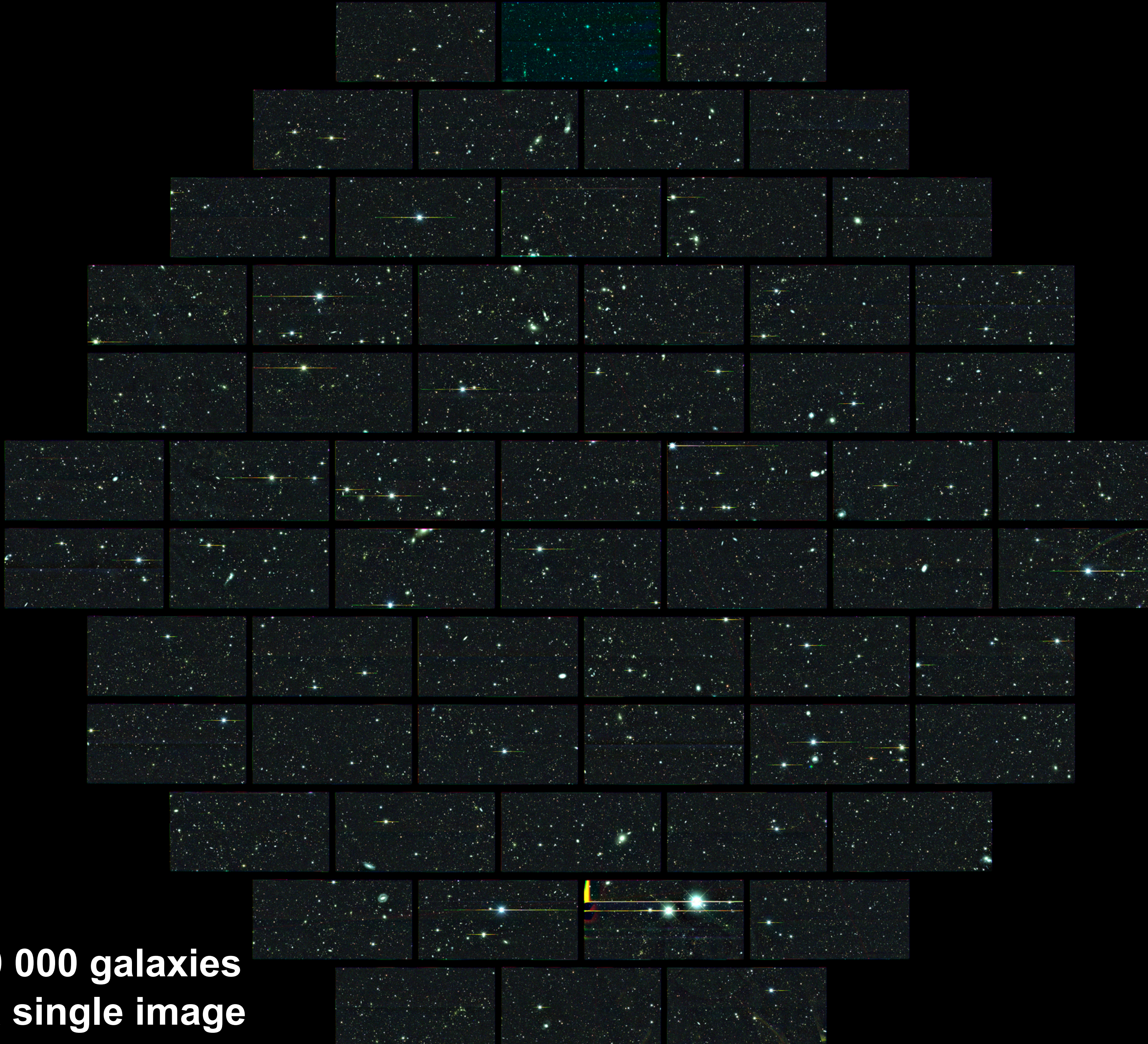
- Imaging galaxy survey on the 4-m Blanco telescope (Chile) to study Dark Energy.
- 350 scientists in 28 institutions in USA, Spain, UK, Brazil, Switzerland, Germany, Australia.
- Is mapping 1/8 of sky (5000 deg^2) to $z \sim 1.3$ in 5 optical bands: 300 million galaxies.
- Started in 2013. 577 nights in 6 seasons.
- Four main dark energy probes:
    - Galaxy cluster counting.
    - Galaxy distribution (including BAO).
    - Type-Ia supernovae.
    - **Weak gravitational lensing.**





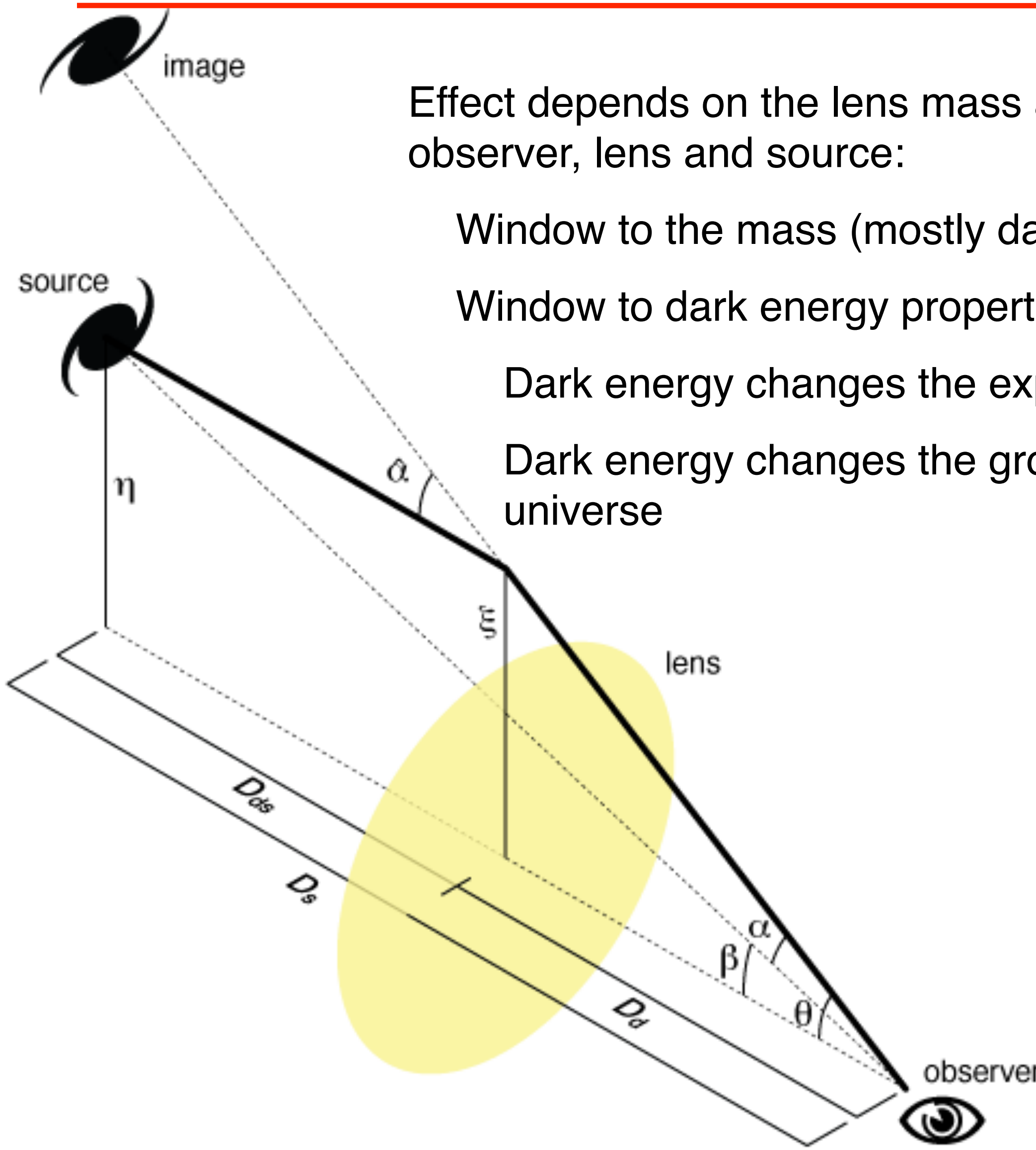
Blanco 4-meter telescope
Cerro Tololo, Chile


The Dark Energy Camera: 500 million pixels



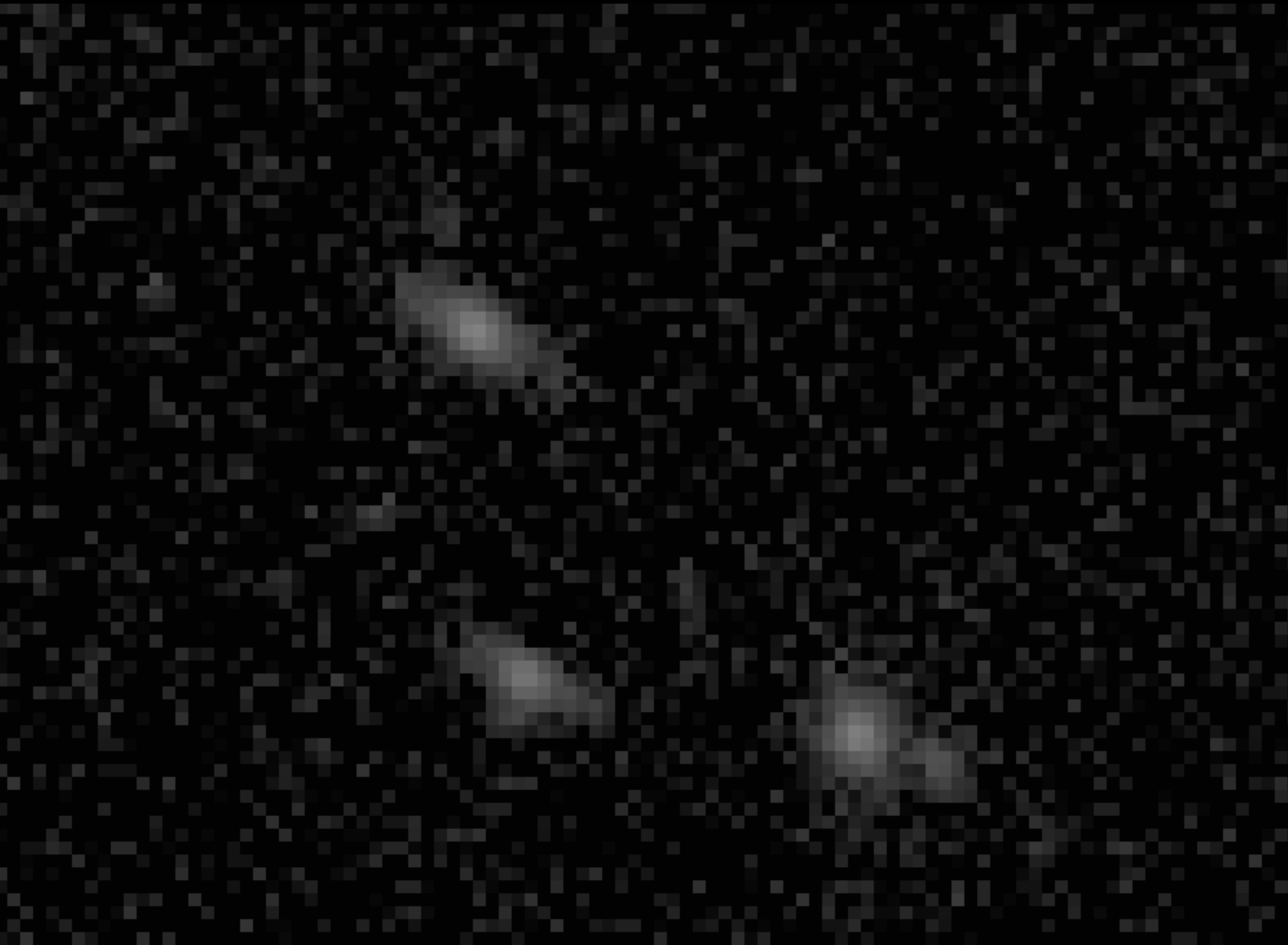
**150 000 galaxies
in a single image**

Weak gravitational lensing



Effect depends on the lens mass and the distances between observer, lens and source:

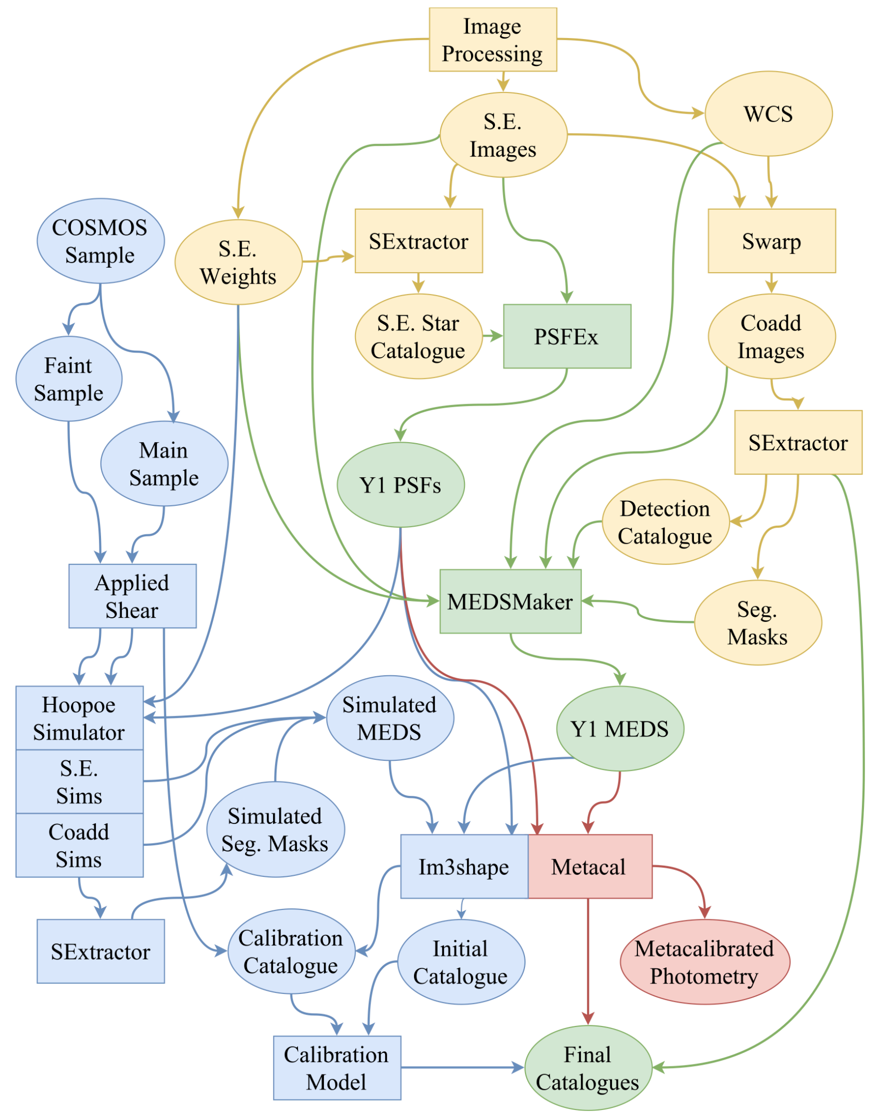
- Window to the mass (mostly dark matter) distribution in the lenses
- Window to dark energy properties:
  - Dark energy changes the expansion rate: distances $\mathbf{D_d}$, $\mathbf{D_s}$, $\mathbf{D_{ds}}$
  - Dark energy changes the growth rate of mass structures in the universe



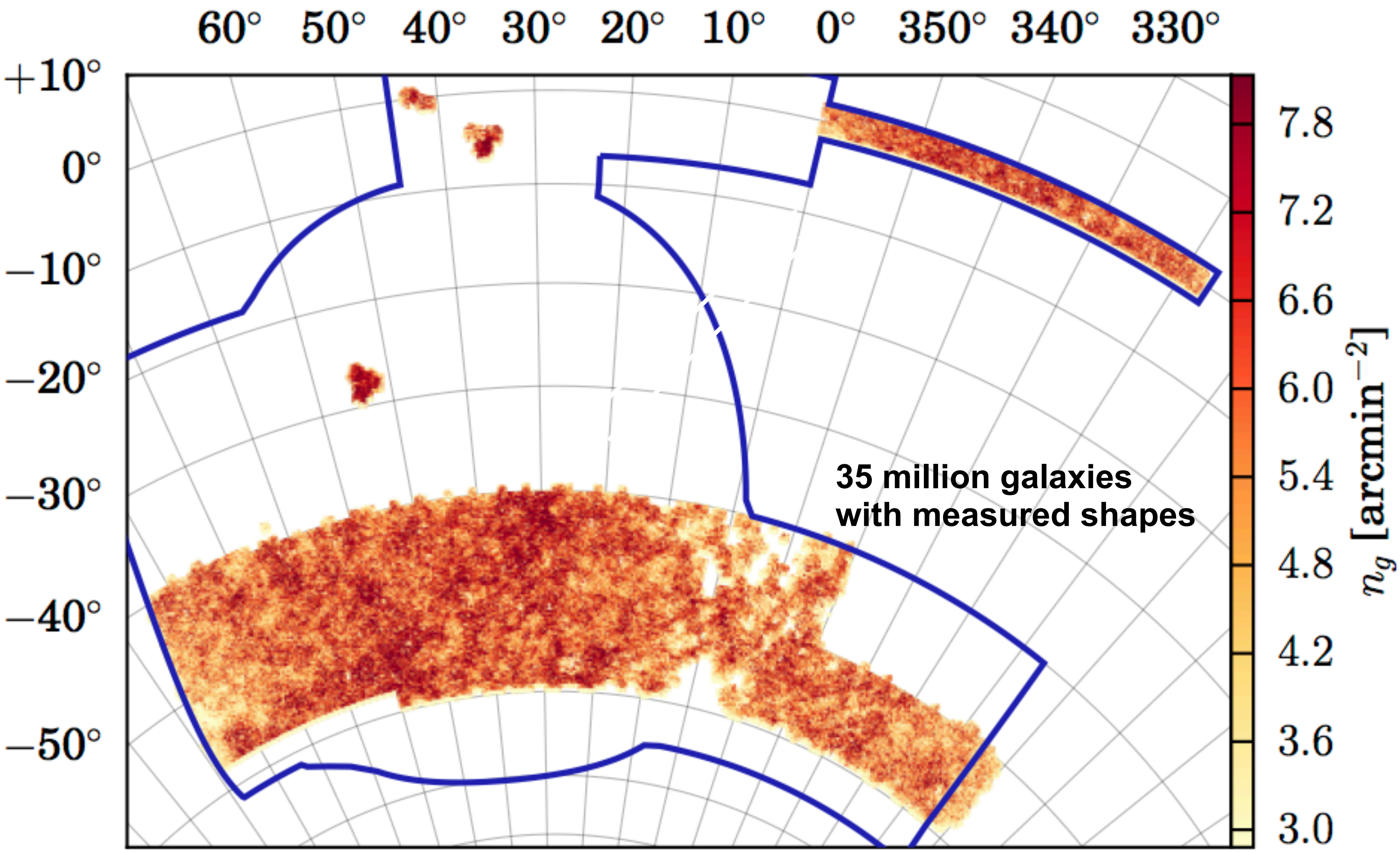
A huge effort!

Reduction of single-epoch images
Astrometric solution
Photometric calibration
Co-addition into deep images
Object detection
Flux measurement
Star / galaxy separation
PSF extraction from stars
Shape measurement on galaxies

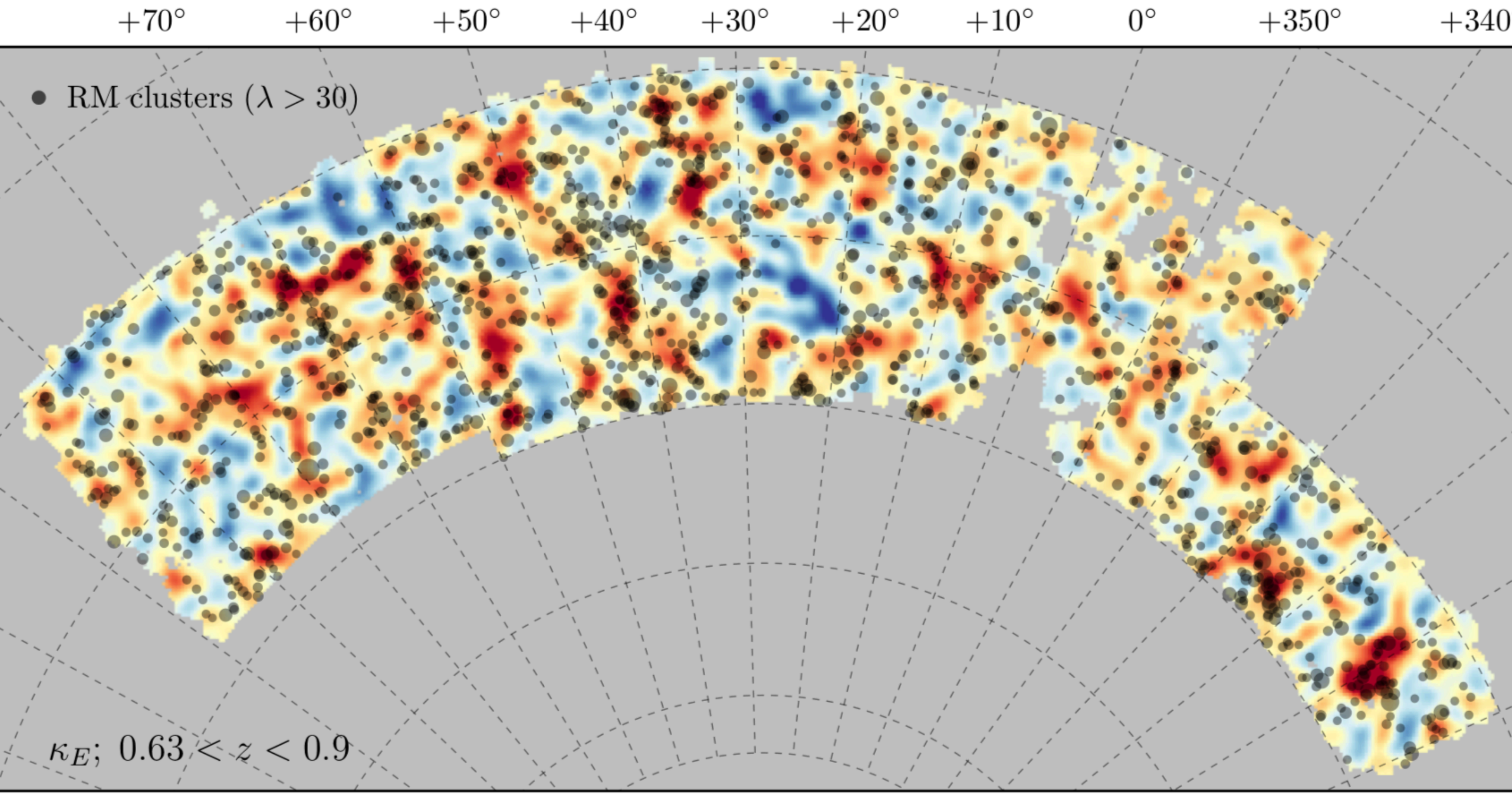
Each bubble can represent months of development and millions of CPU hours.



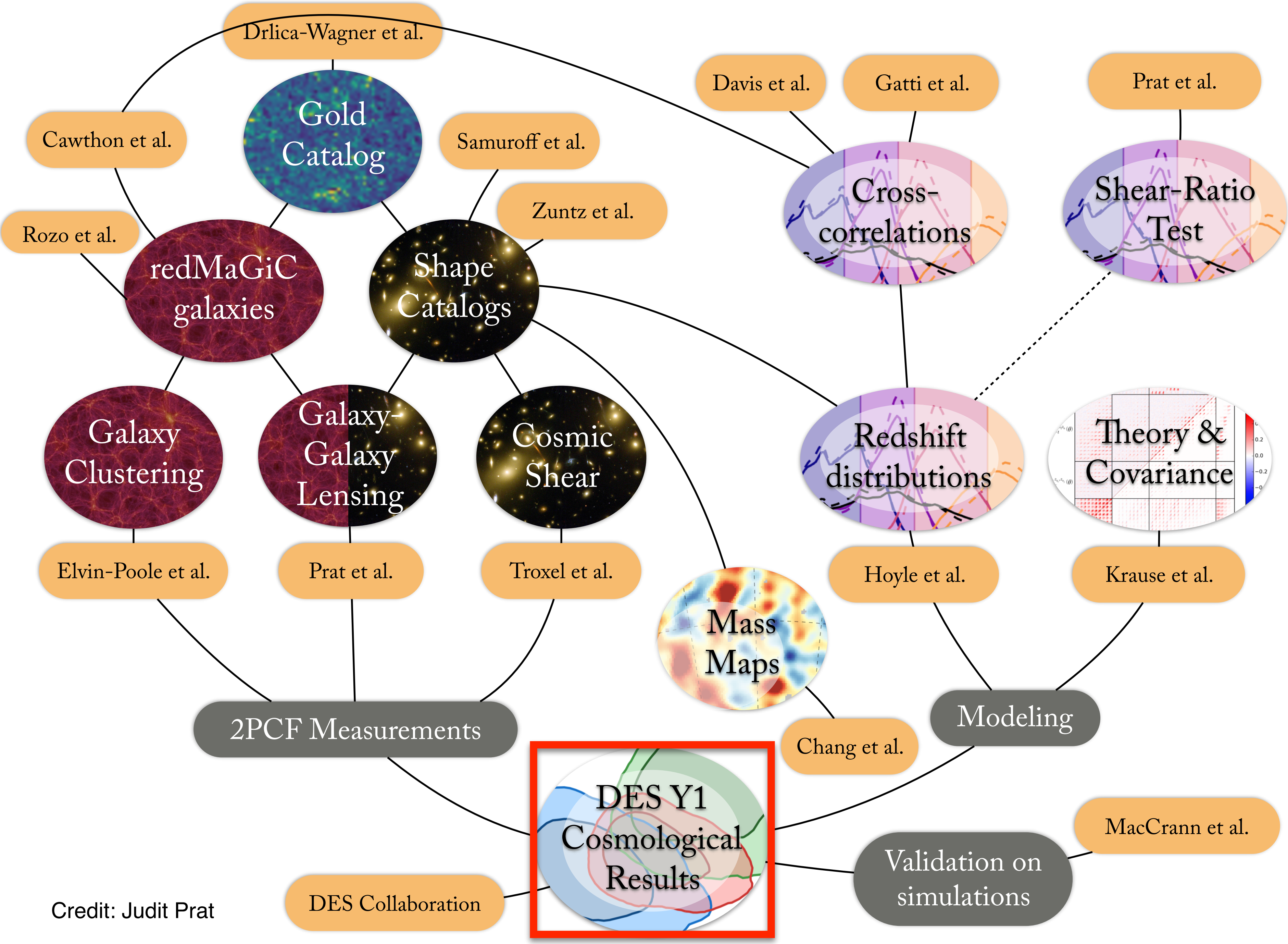
DES Year-1 sample



DES Year-1 mass map



Chang et al. (DES Collaboration), MNRAS 475 (2018) 3165


Drlica-Wagner et al.
Gold Catalog
Cawthon et al.
Samuroff et al.
Davis et al.
Gatti et al.
Prat et al.
Zuntz et al.
Rozo et al.
redMaGiC galaxies
Shape Catalogs
Cross-correlations
Shear-Ratio Test
Galaxy Clustering
Galaxy-Galaxy Lensing
Cosmic Shear
Redshift distributions
Theory & Covariance
Elvin-Poole et al.
Prat et al.
Troxel et al.
Mass Maps
Hoyle et al.
Krause et al.
2PCF Measurements
Chang et al.
Modeling
DES Y1 Cosmological Results
MacCrann et al.
Validation on simulations
DES Collaboration
Credit: Judit Prat

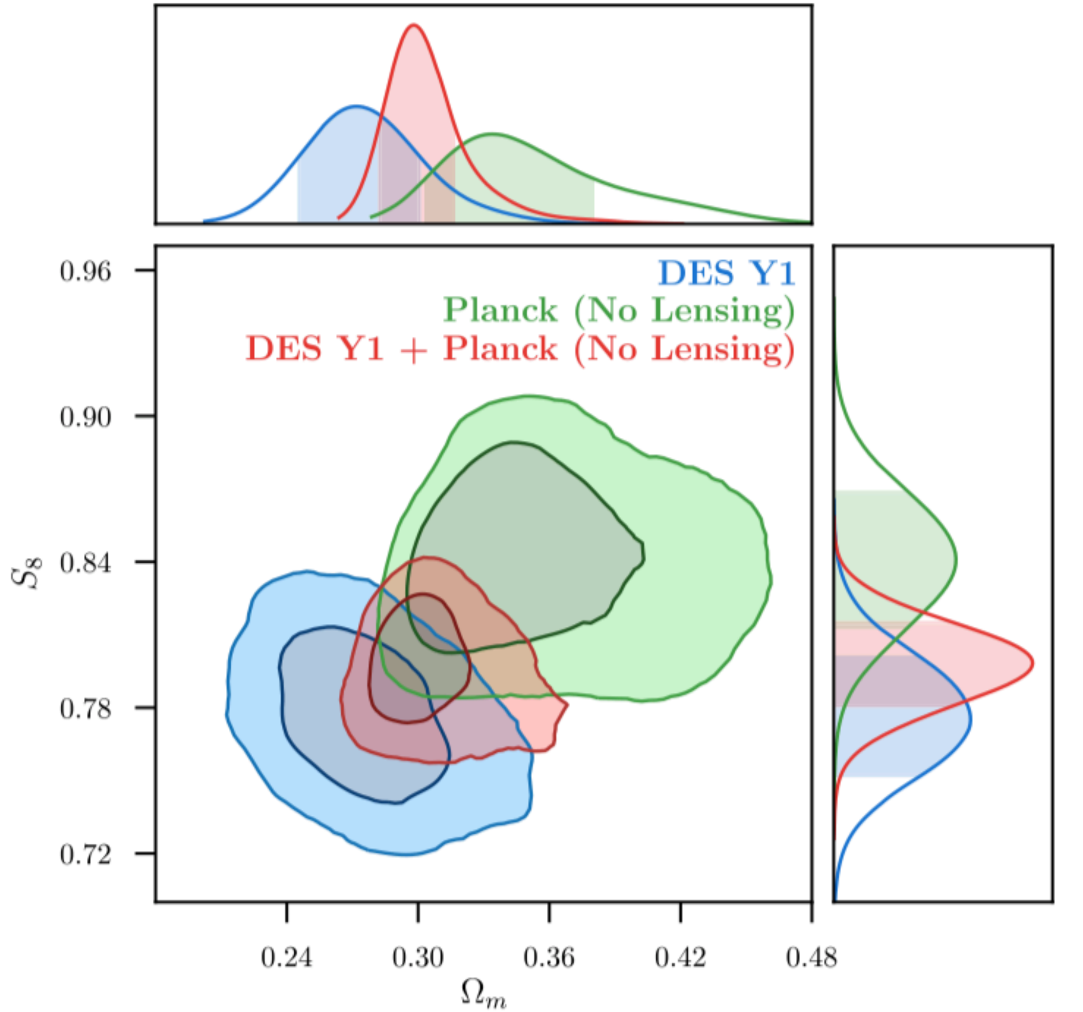
DES-Y1 cosmological results (I)

DARK ENERGY
SURVEY

- $\boldsymbol{S_8} = \sigma_8\,(\Omega_m / 0.3)^{0.5}$ describes the **inhomogeneity of the matter distribution now**: σ_8 is the standard deviation of the matter-density distribution in spheres of radius 8 Mpc/h.

- $\boldsymbol{\Omega_m}$ **: fraction of matter in the total matter-energy of the universe now**.

- First measurement in late universe with **precision comparable to CMB**.

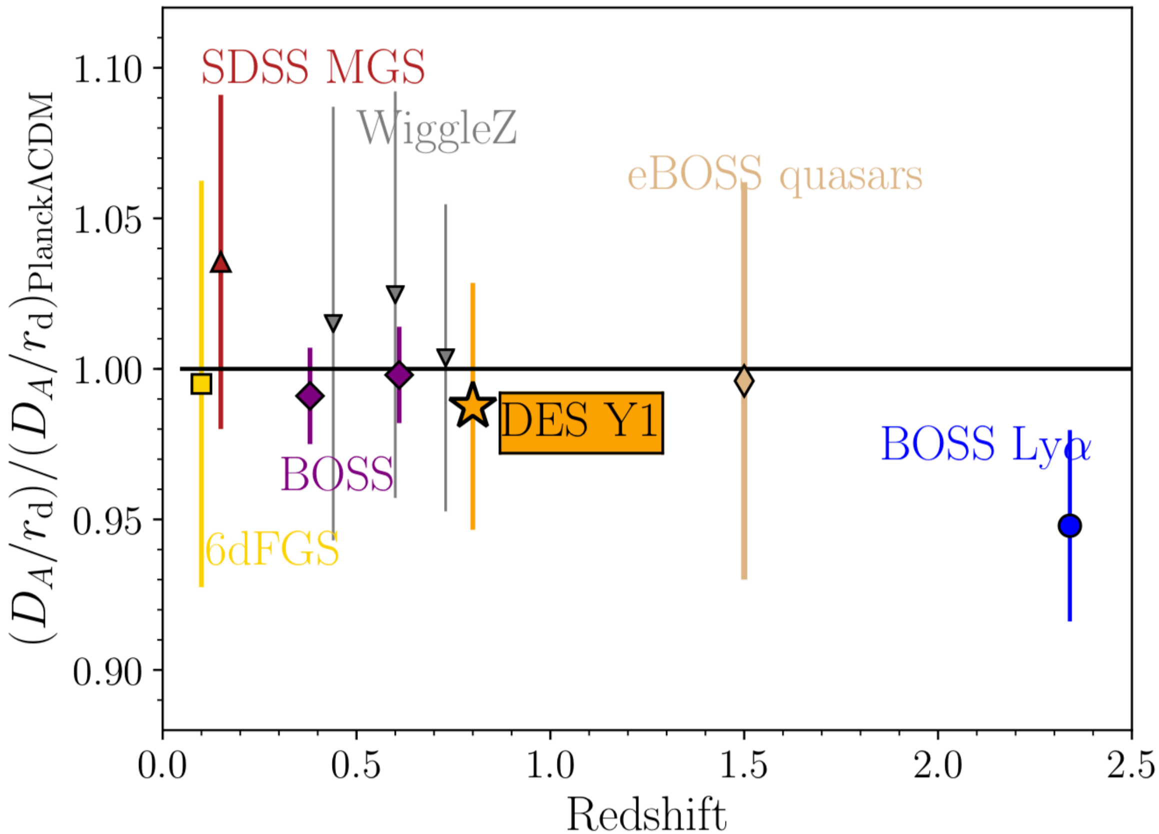


DES Collaboration, Phys. Rev. D98 (2018) 043526

DES-Y1 cosmological results (II)

DARK ENERGY SURVEY

- Measurement of the **BAO** feature in the **angular separation** of a sample of red galaxies.
- This is the highest-redshift **photometric BAO** measurement.
- Very competitive in the region **0.6 < z < 1.0**.

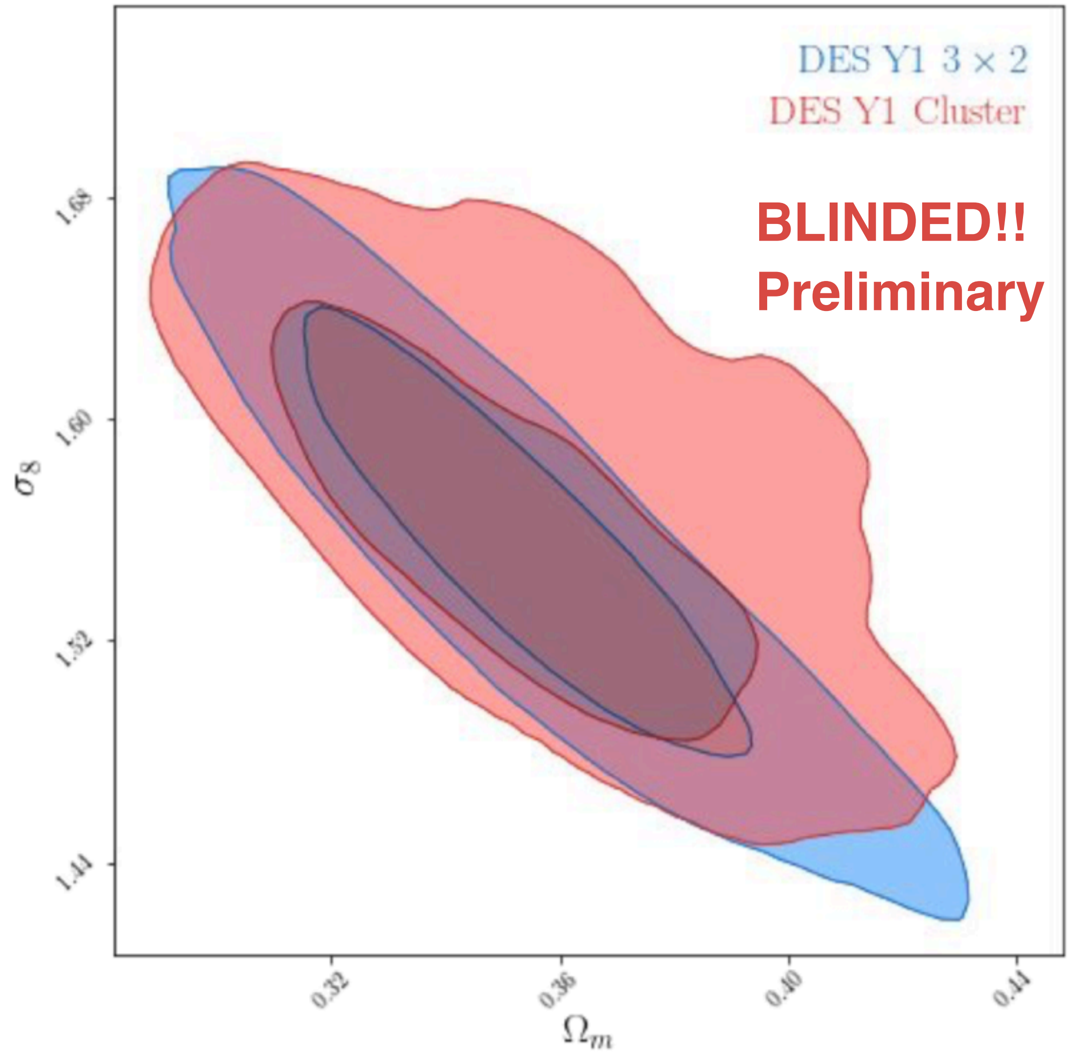


DES Collaboration, arXiv:1712.06209 [astro-ph.CO]

DES-Y1 cosmological results (III)

DARK ENERGY SURVEY

- DES can combine **cluster abundance** as a function of mass and redshift with **WL mass estimates.**
- **6500 clusters** in the redshift range **$0.2 < z < 0.65$**, with mass calibration at 5% level.
- Cosmological constraints are **competitive with those from WL + LSS**.

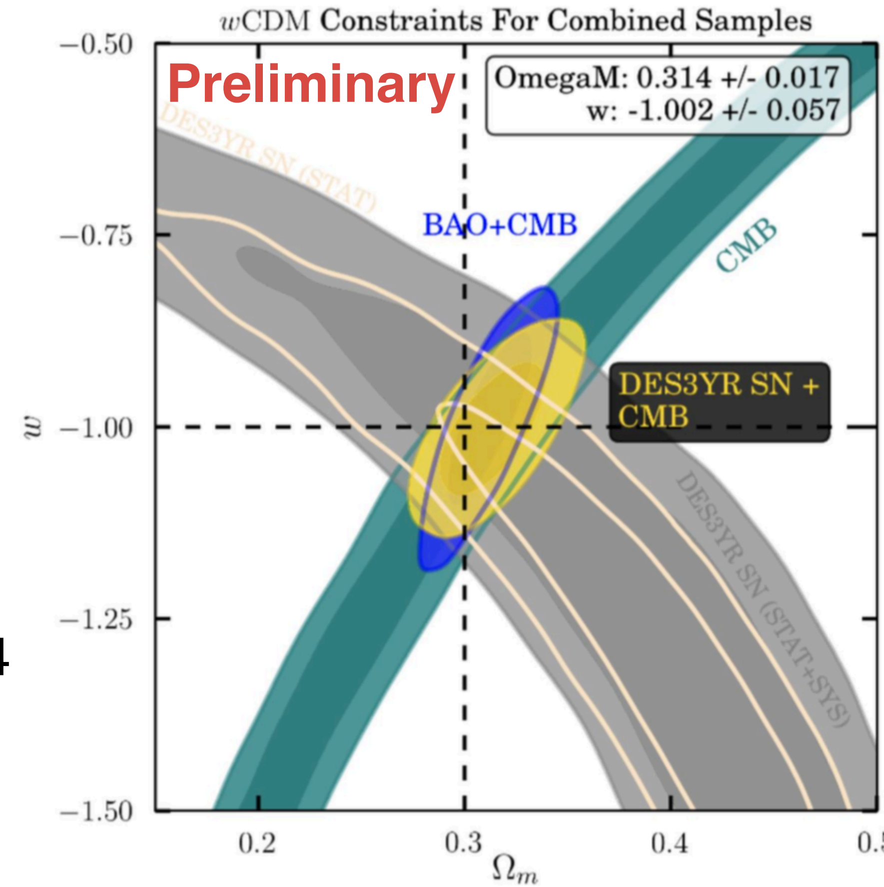


DES Collaboration 2018, in preparation

DES-Y3 SNe cosmological results

DARK ENERGY SURVEY

- **206 new spectroscopic type-Ia SNe** from DES Y1-Y3 in the range **0.02 < z < 0.85**, together with 128 external low-z SNe.
- We are able to measure **distances with 4% precision** and determine the dark-energy equation of state **w with a ± 0.057 precision** (cf. ± 0.054 in JLA (2014) with 740 SNe.



DES Collaboration 2018, in preparation

The PAU Survey at the ORM

- PAUCam built by Spanish consortium (Consolider-2010 project) led by IFAE.
- 40 narrow-band filters provide very precise redshifts.
- >100-night survey at WHT, including partners from Bonn, Leiden, ETH Zurich, Durham, UCL:
  - Redshift-space distortions.
  - Weak-lensing magnification.
  - Intrinsic galaxy alignments.
  - Photo-z calibration for DES, Euclid, LSST…
- Commissioning took place in 2015; science verification in spring 2016; survey started in fall 2016.
- First papers just appeared in the arXiv.

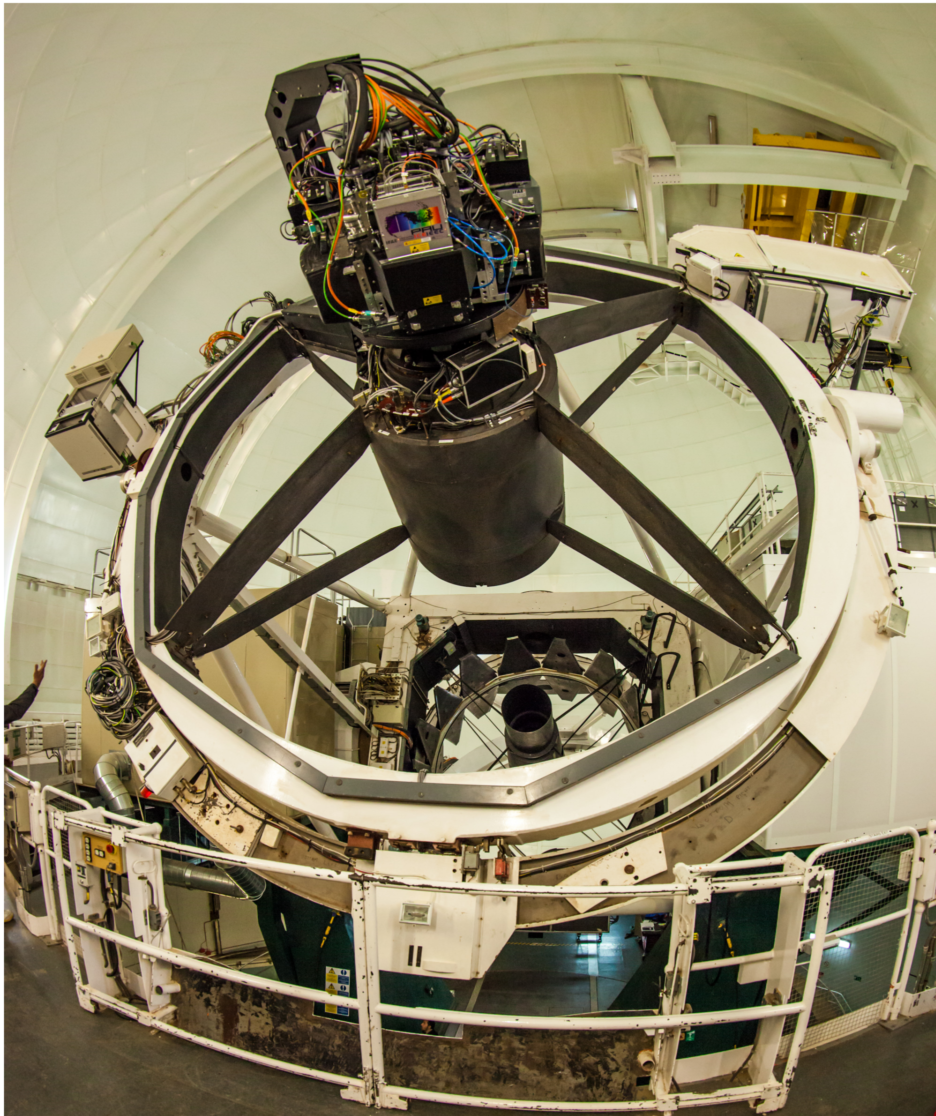
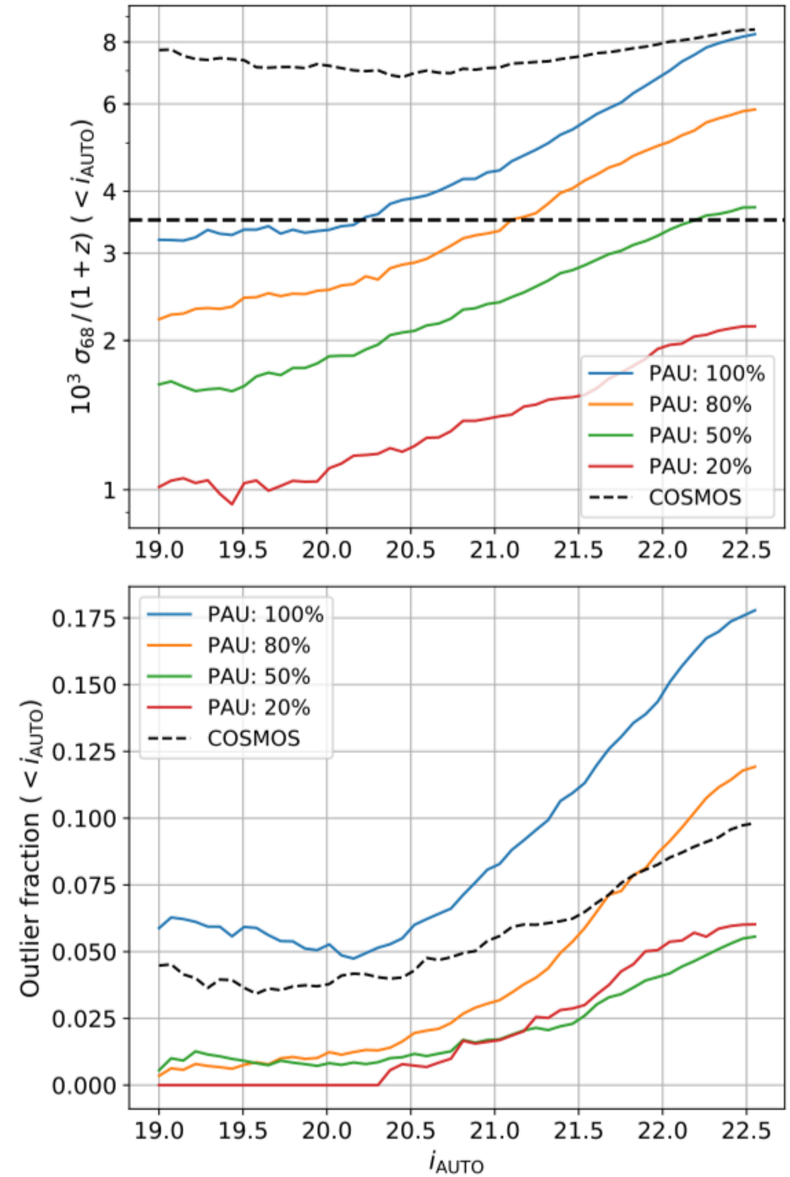


Photo-z measurements

- First results obtained using a sample of galaxies matched to those in the COSMOS field with spectroscopic redshifts.
- Using a quality cut that keeps 50% of the galaxies in the sample, we match the expectations from simulations:

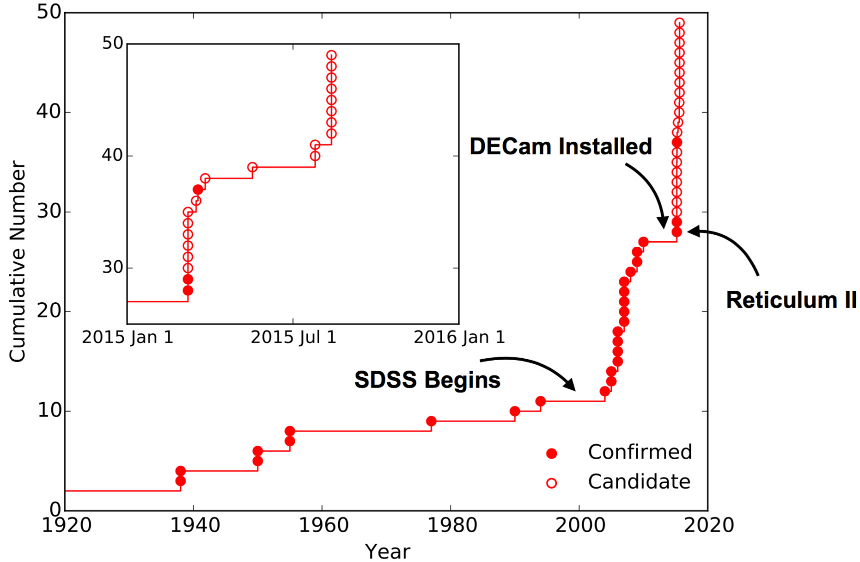
$$\sigma_{68}(z) \lesssim 0.0035 \times (1+z)$$

Eriksen et al., arXiv:1809:04375

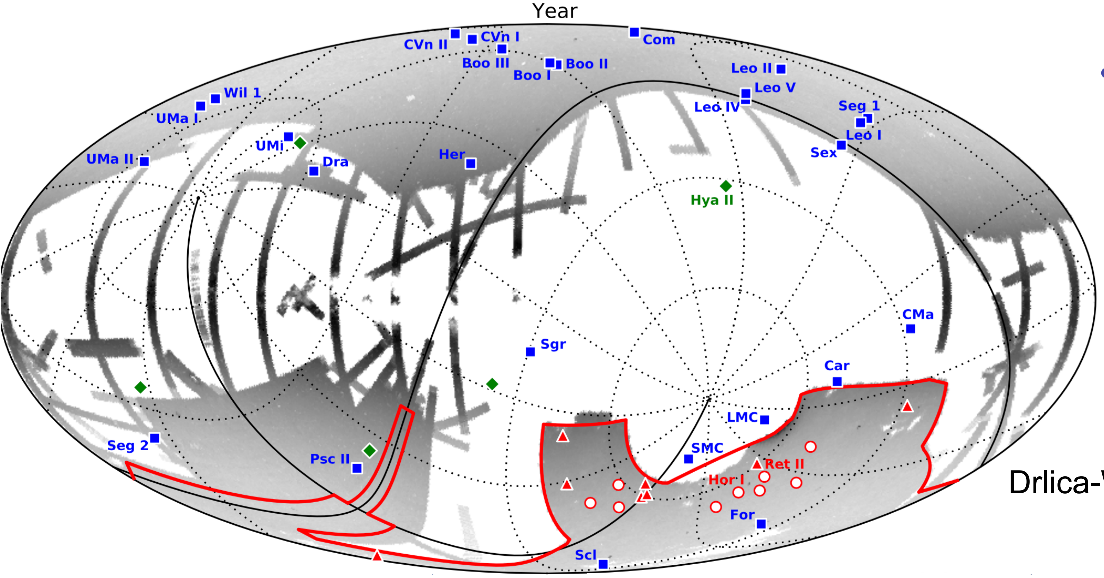


DARK ENERGY SURVEY

Milky Way satellite galaxies



- ΛCDM predicts 100s of MW satellite galaxies
- These are very rich in dark matter (mass to light ratio > 100)
  - Excellent targets for indirect dark matter searches
- Spectroscopic campaigns confirmed candidates and measured J-factors
- Then, gamma-ray observations of confirmed dwarf galaxies



Red outline: DES footprint

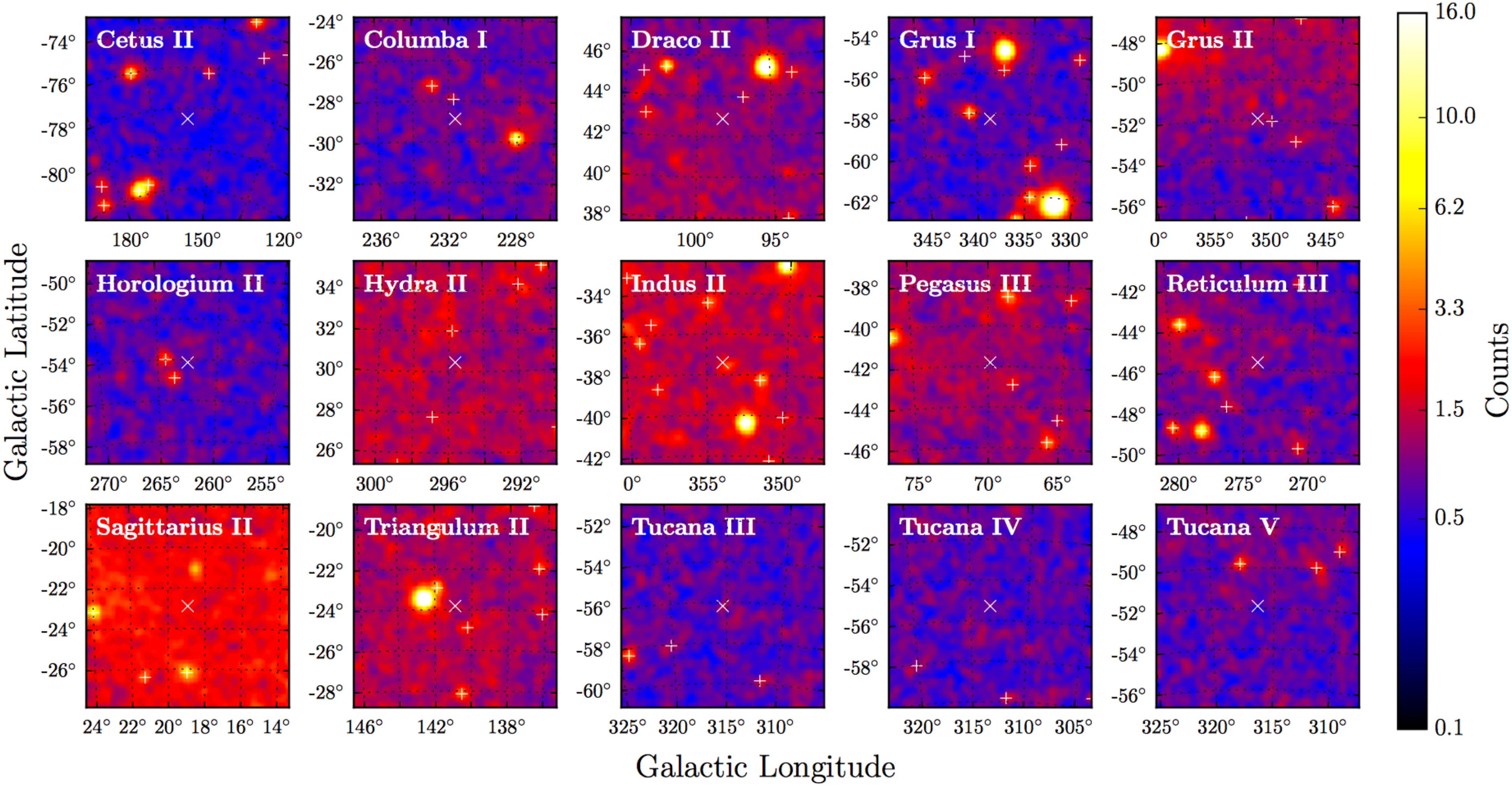
○ : DES Y1 satellites

▲ : DES Y2 satellites

Drlica-Wagner et al. (DES Collaboration), ApJ 813 (2015) 109

Gamma ray searches in dwarf galaxies

DARK ENERGY SURVEY

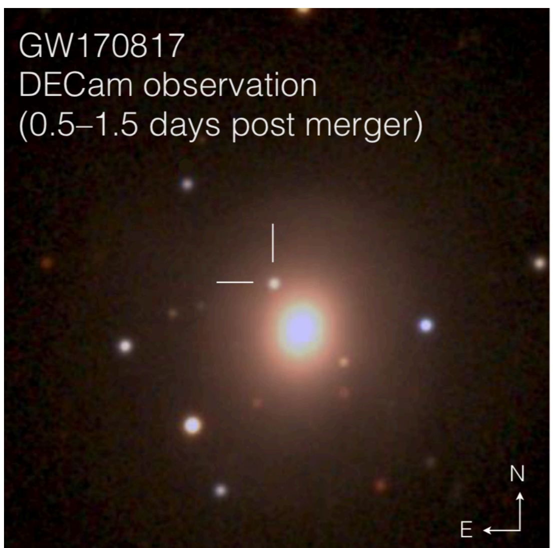


Albert et al. (Fermi-LAT and DES), ApJ 834 (2017) 110

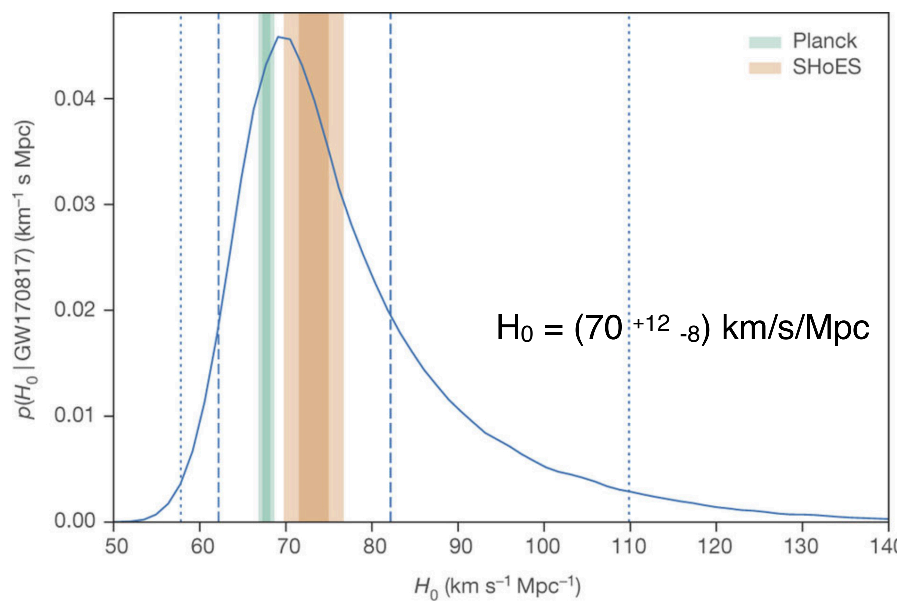
Gravitational waves from NS-NS

DARK ENERGY SURVEY

- Neutron star-neutron star mergers are “standard sirens”: one can determine accurately the **distance** to the event from the GW signal.
- Since NS-NS mergers have optical counterparts, one can determine the host galaxy and its **redshift ➡ Hubble diagram**.
- From the one local event GW170817, one can already determine H_0.



z = 0.0098



Soares-Santos et al., ApJ 848 (2017) L16

Abbott et al. (LIGO, Virgo, DES et al.), Nature 551 (2017) 85

Conclusions

- Dark Energy is a profound mystery that deserves the attention is receiving.
- Imaging/Spectroscopy, Ground/Space are complementary and synergistic:
  - Imaging: efficient; deep; 2.5D for many methods; allows weak lensing.
  - Spectroscopy: 3D info for BAO, RSD.
  - Space: exquisite, stable PSF for lensing; access to near-infrared.
  - Ground: larger telescopes allow fast, wide, deep surveys.
- DES-Y1 results represent a first powerful test of ΛCDM in the local universe.
- DES-Y3 (2019) and DES-Y6 (2021) will combine all probes and provide unprecedented constraints on the cosmological parameters.
- In the next decade, DESI, Euclid, and LSST will increase the precision on the dark energy parameters by an order of magnitude.
- Multi-messenger astronomy is starting to fulfill its promise, providing unique information on fundamental physics problems.