Recent Results on Cosmology

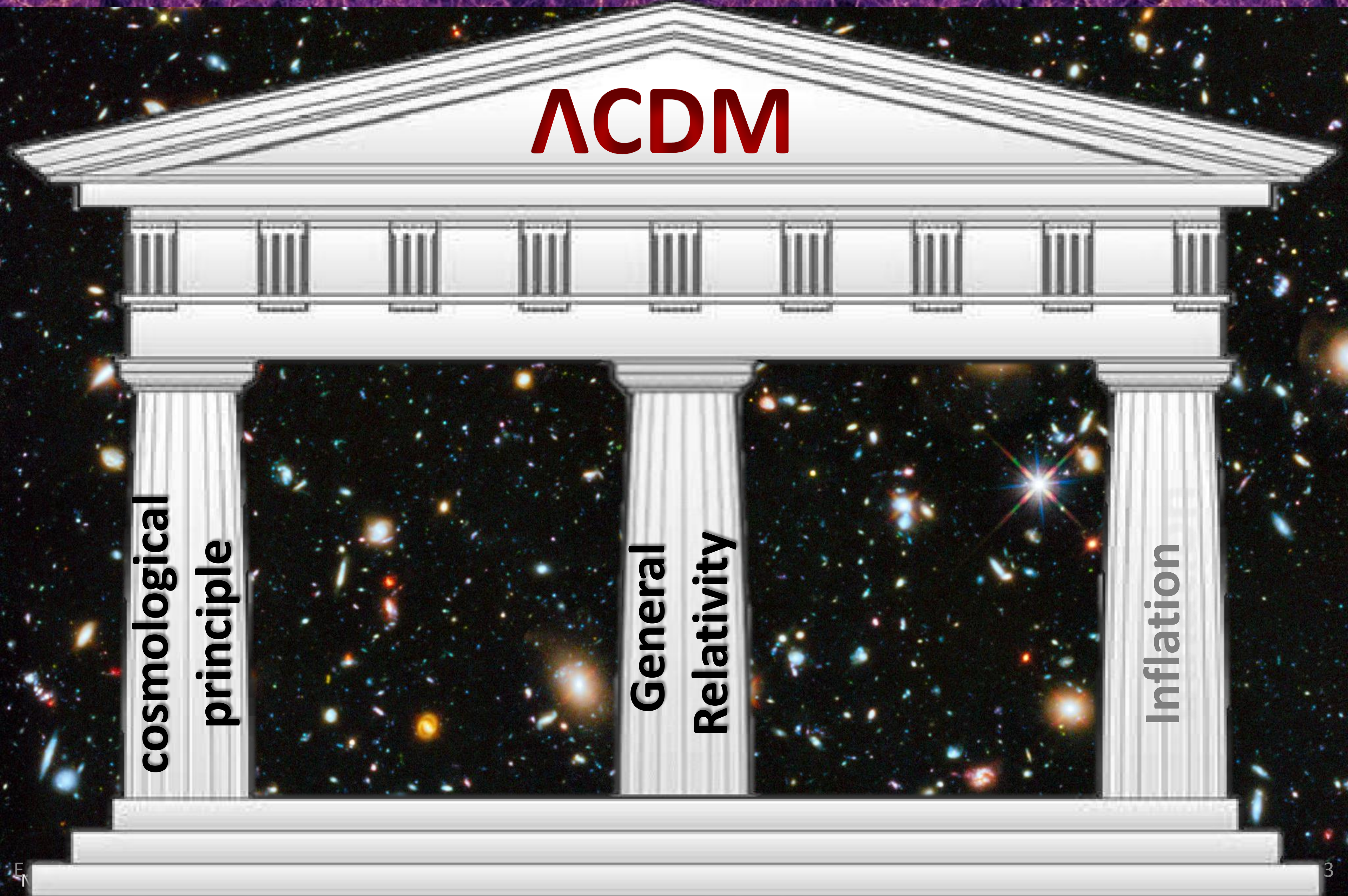
E. Sánchez
CIEMAT

IGWM 2025
June 23th, 2025

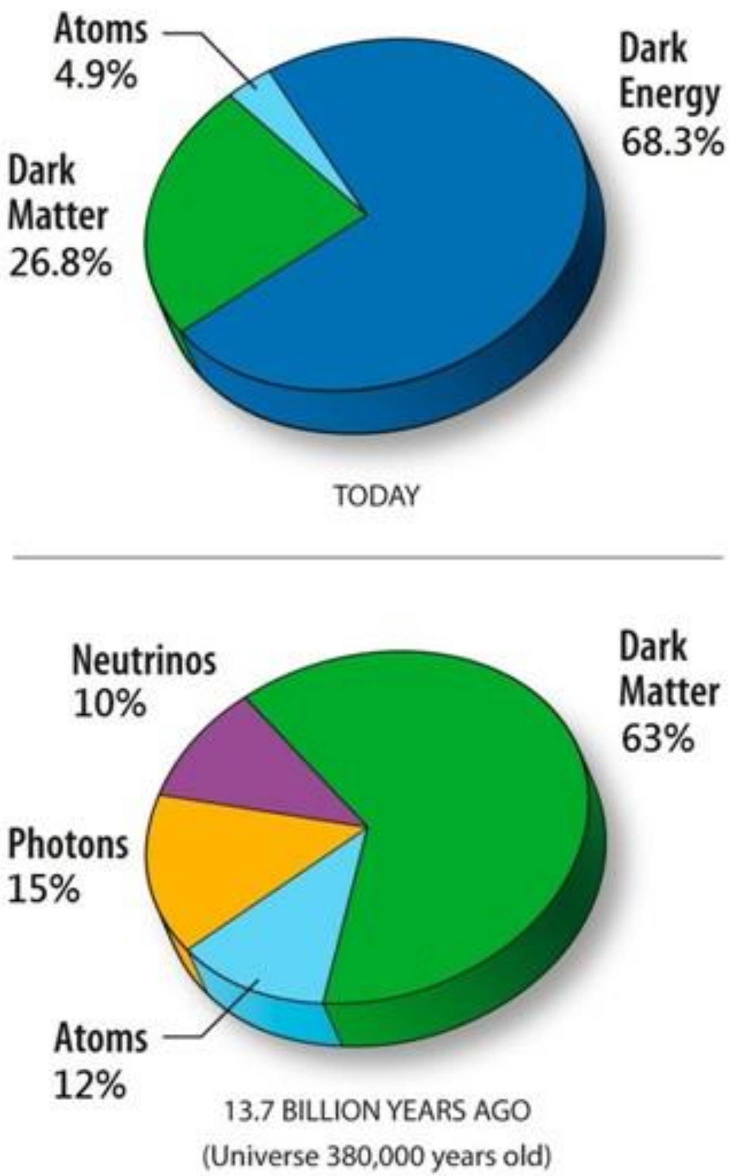
OUTLINE

- **Introduction**. *ΛCDM and Galaxy Surveys*
- **DESI DR2 BAO**. *Latest Results from DESI*
- **DES SNe+BAO.** *Final SNe+BAO DES result*
- **Conclusions**

Cosmology Basis



The Big Bang today: ΛCDM



Dark side:

Flat Universe with the critical density: ~10 hydrogen atoms/m^3

~95% of the matter-energy of the universe is dark:

- *~70% dark energy as the cosmological constant*
- *~25% of cold dark matter with unknown physical nature*
- *~5% baryonic matter*

ΛCDM requires physics beyond the Standard Model of particle physics to explain the early universe (inflation?), baryogenesis, dark components?

Cosmology from Galaxy Surveys

What is causing the acceleration of the expansión of the universe?

Cosmological Constant

New field

Modifications to General Relativity

Two main cosmological observables:

History of the expansion rate of the universe:

SN1a, BAO, weak lensing, cluster counting…

History of the rate of growth structure of the universe:

RSD, weak lensing, LSS, cluster counting…

For all these cosmological probes, LARGE GALAXY SURVEYS ARE NEEDED

Spectroscopic: *3D (redshift), medium depth, low density, preselection*

Imaging: *"2.5D" (photo-z), deeper, higher density, no selection*

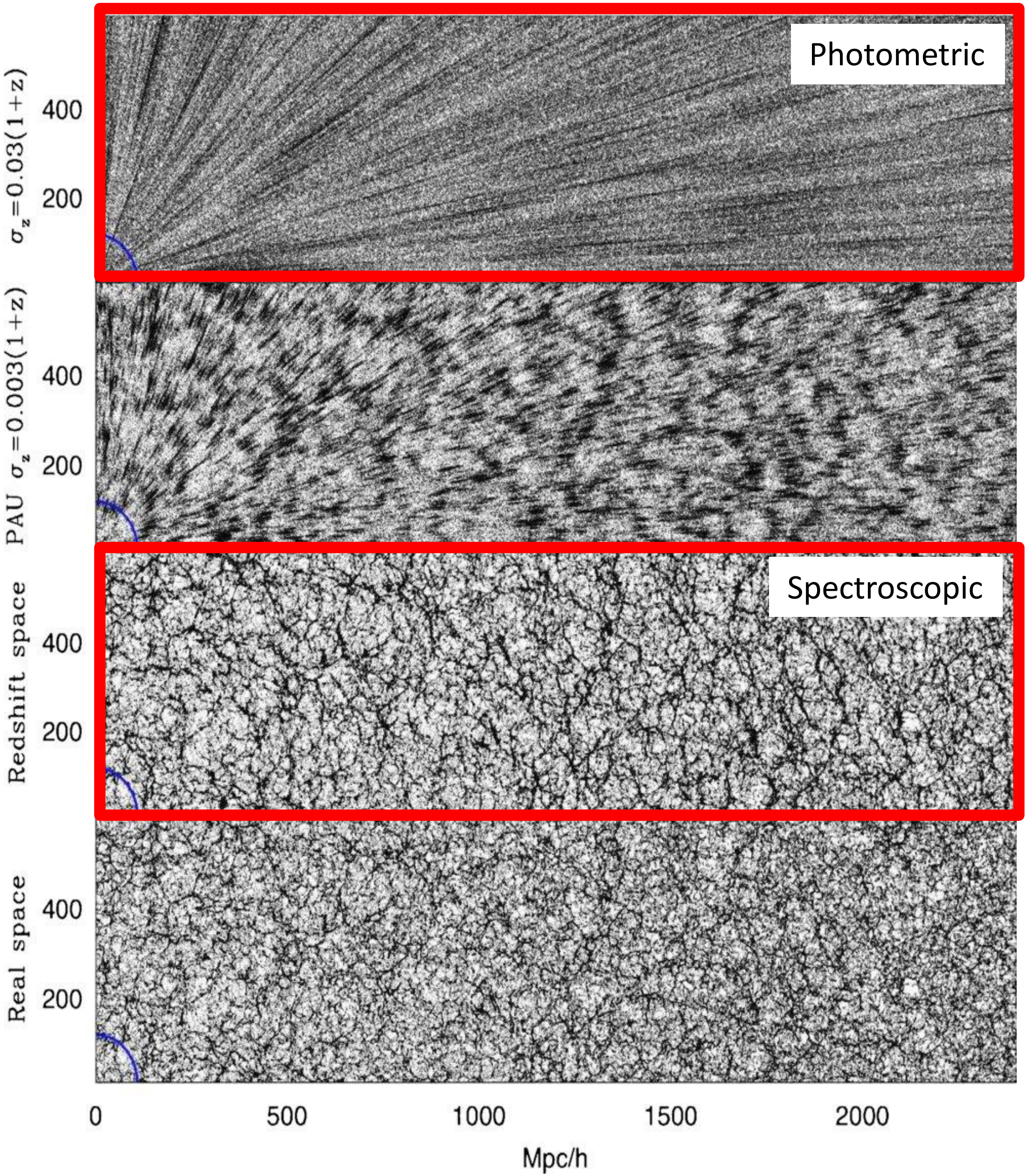
What is a Galaxy Survey

A map of a certain volume of the sky (as large as possible), that locates all its contents. To do this we need big telescopes (to see faint objects), and some method to measure redshifts.

The clustering signal is 3D. However, while angular positions are in general easy to measure, the radial distance is difficult. Two ways to do it:

1) Spectrum of previously selected galaxies
2) Estimate from broadband colours with templates or training samples

Large advance in the last years and bright future, mainly due to technological developments that made possible larger and deeper surveys



Redshift (Spectroscopic) Galaxy Surveys

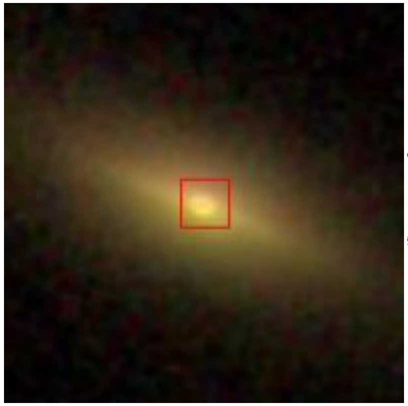
Measure the full 3D structure of Galaxy clustering

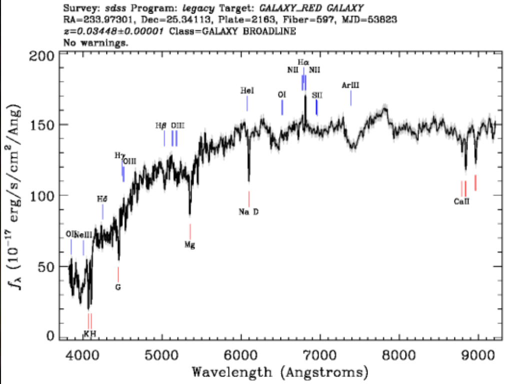
In a 2 step process:

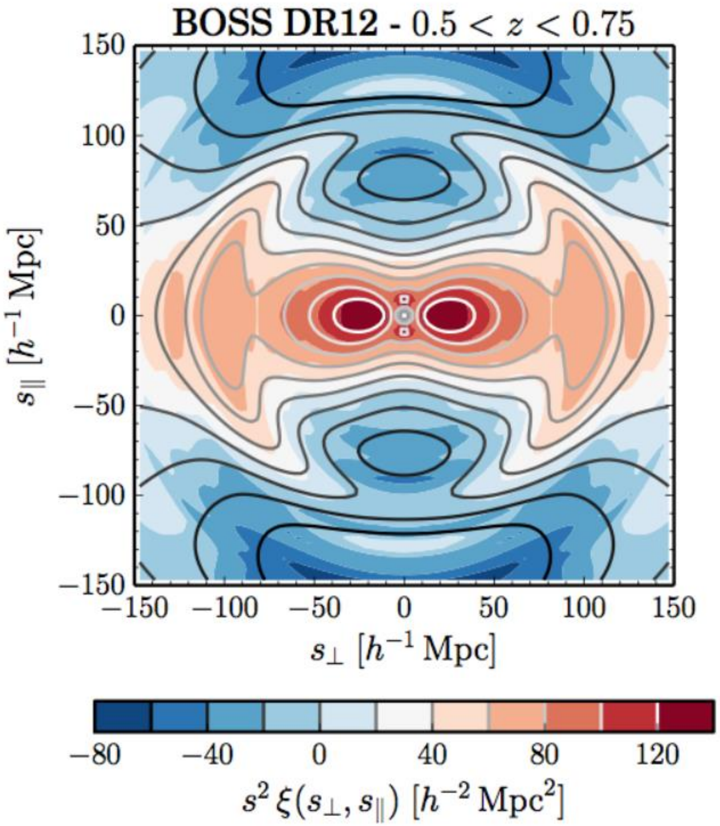
- ***First perform an imaging survey and select targets***
- ***Second, take spectra of the targets***

Main cosmological probes are:

- ***Baryon Acoustic Oscillations Scale***
- ***Redshift Space Distortions***
- ***Galaxy/Quasar Clustering***
- ***Lyman-Alpha Forest***







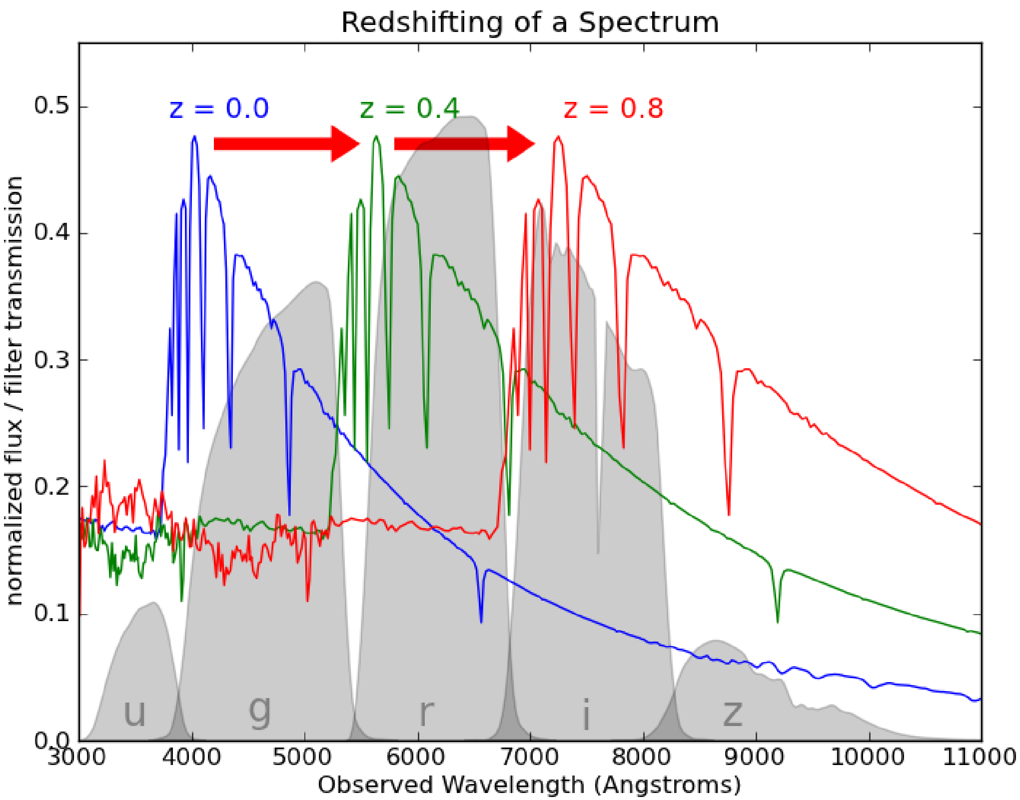
Imaging (Photometric) Galaxy Surveys

Measure the 2D projected structure of Galaxy clustering

Redshift is measured from galaxy fluxes in optical filters (photometric redshifts). Precision is much worse than in spectroscopic surveys, but all galaxies in the field of view are used.

Main cosmological probes are:

- Galaxy Clustering & BAO
- **Weak Gravitational Lensing**
- **Galaxy Clusters**
- SN1a



COSMOLOGY FROM DESI DR2 BAO

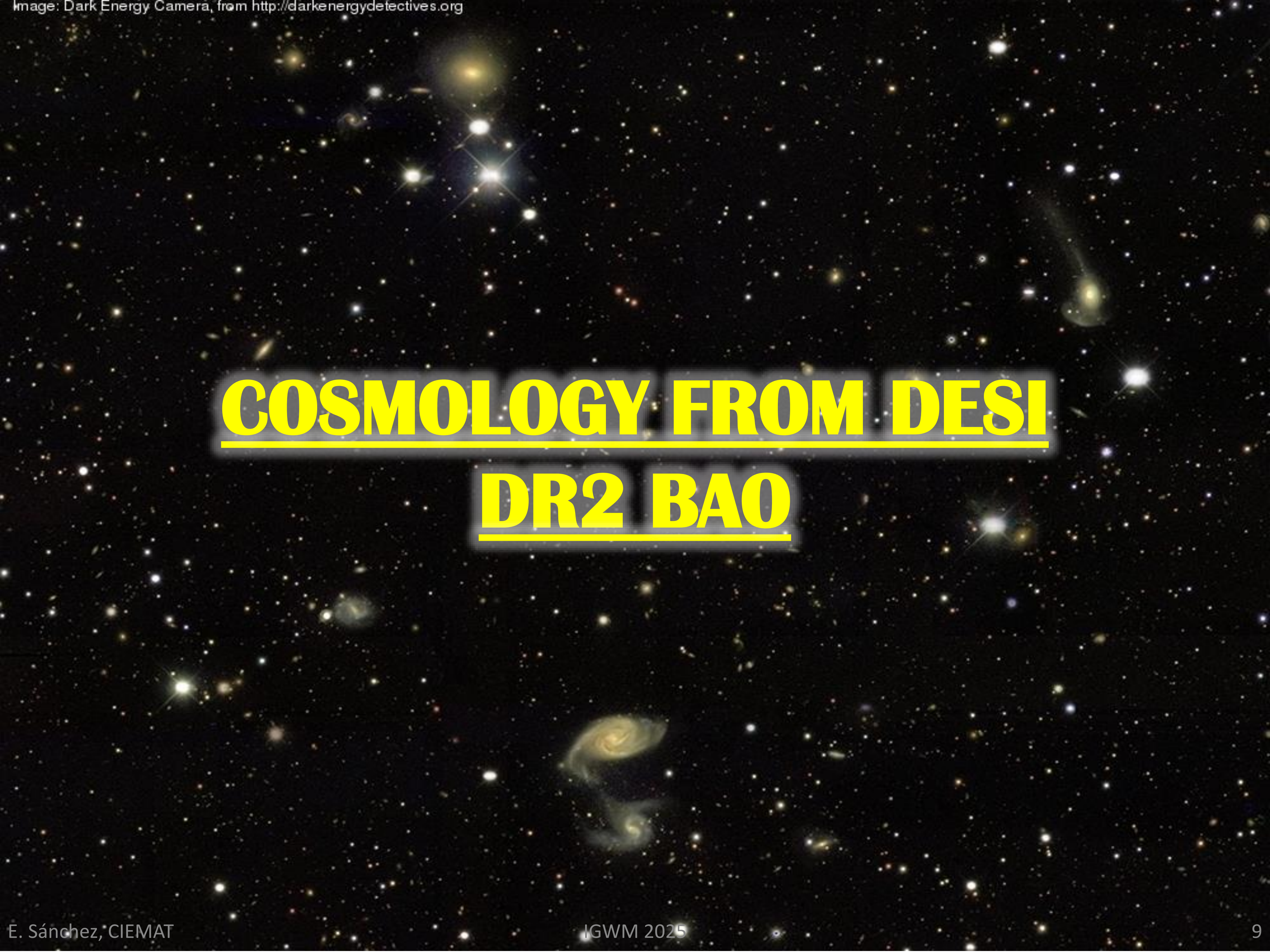
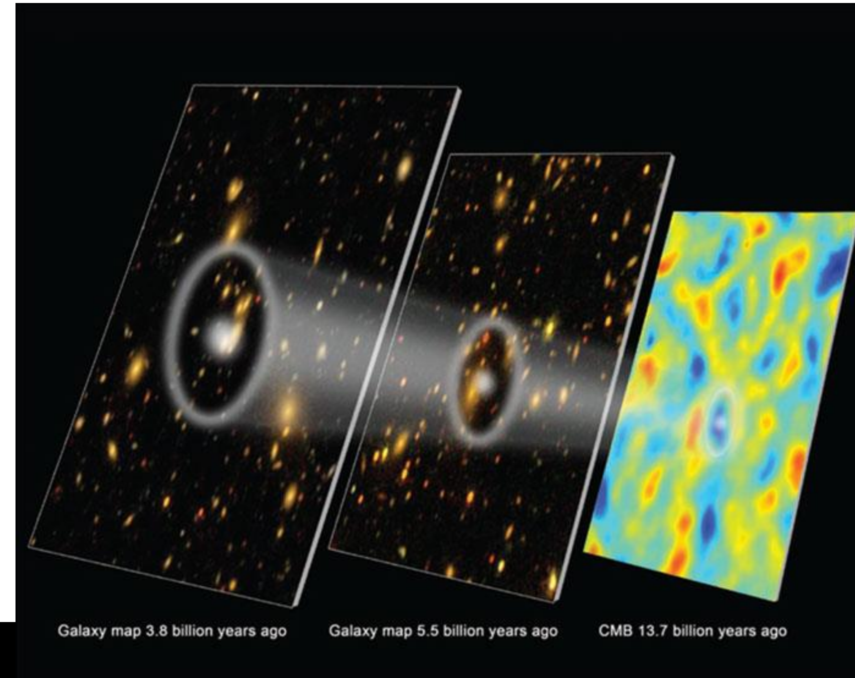


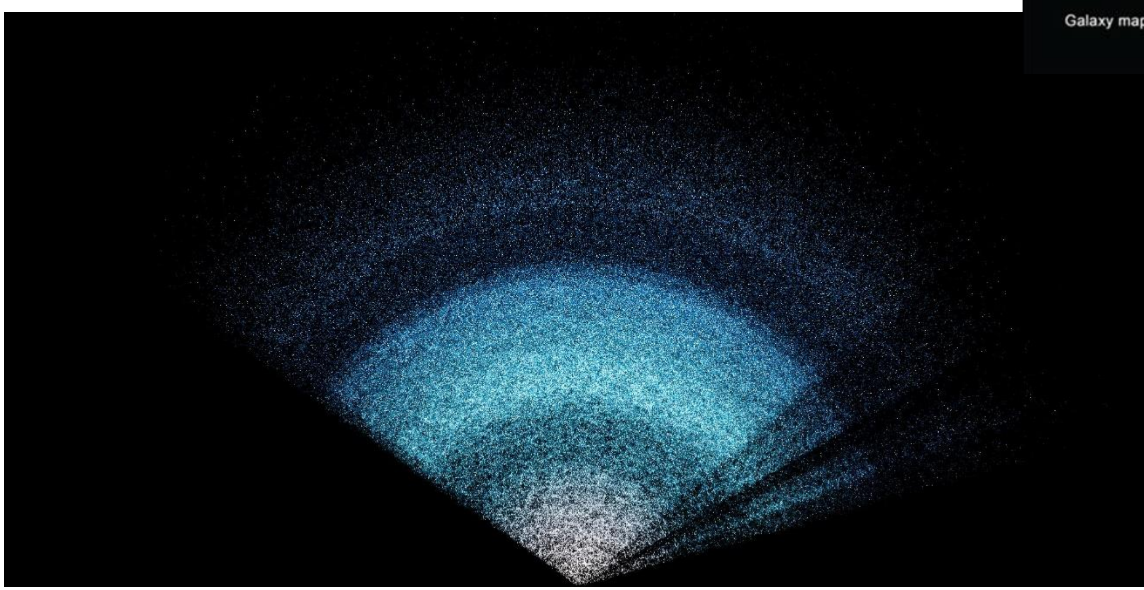
Image: Dark Energy Camera, from http://darkenergydetectives.org

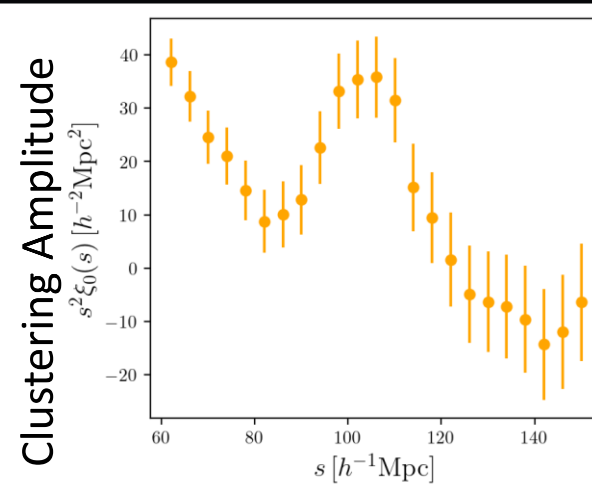
Baryon Acoustic Oscillations (BAO)

BAO scale → Special length: Distance that sound waves were able to travel in the early Universe. → Standard Ruler



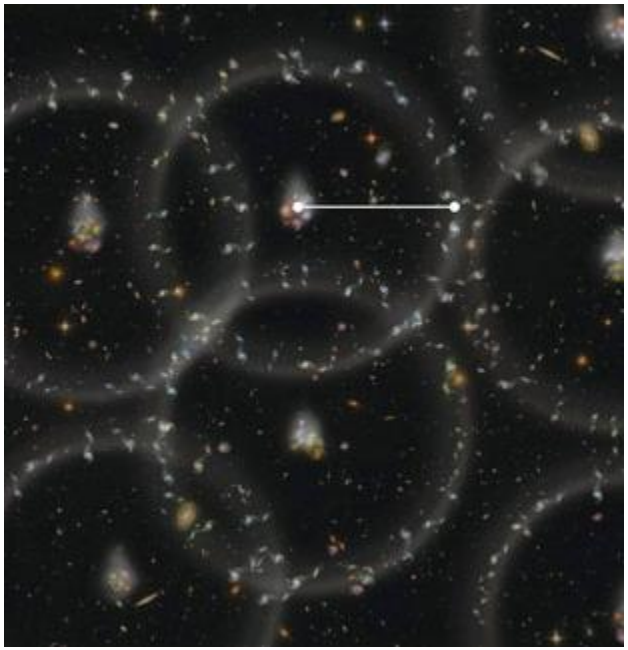
Measured as an accumulation of Galaxy pairs separated by the BAO scale

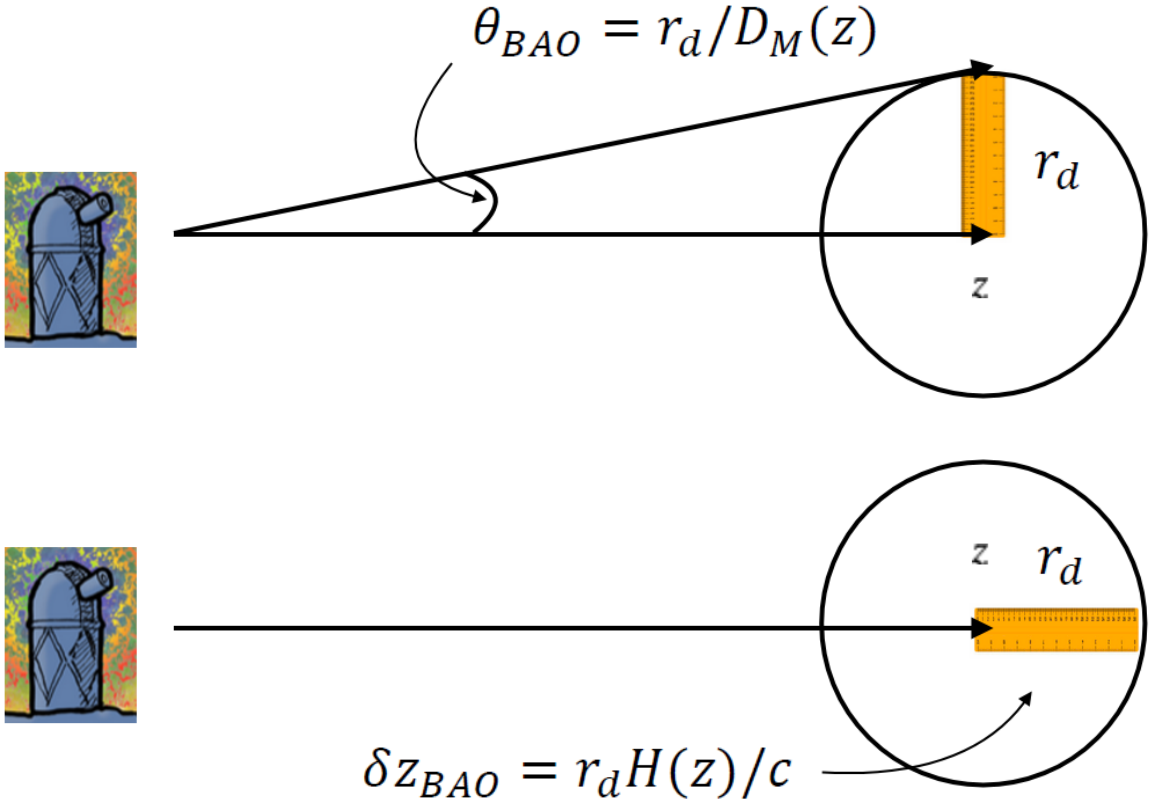




Galaxy Pair separation

BAO scale is a Standard Ruler





$D_M(z)$ and $H(z)$ encode the **expansión history** of the Universe
DESI measures BAO rulers at many redshifts (times)

DESI (Dark Energy Spectroscopic Instrument)

Located at 4-m Mayall Telescope in Arizona
- Upgraded telescope for wide-field spectroscopy
- Now dedicated to multi-object spectroscopy

First Stage-IV Dark Energy Experiment
- **Optimized for BAO measurement**
- 10X improvement to $w_0 w_a$ FoM compared to Stage-II Sne

Comprehensive Cosmology Program
- Redshift Space Distortions
- Cross-correlations with other surveys
- Other wider topics

Large collaboration: More than 900 scientists, 17 countries, 72 institutions

Australia, Canada, China, Colombia, France, Germany, Korea, Mexico, Spain, Switzerland, U.K., and U.S.

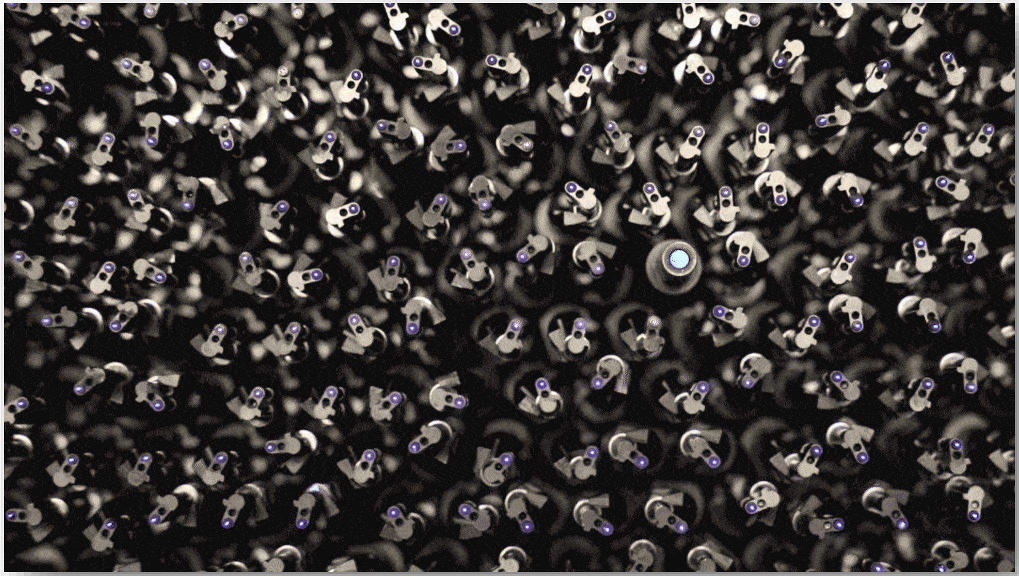
Lead by LBNL

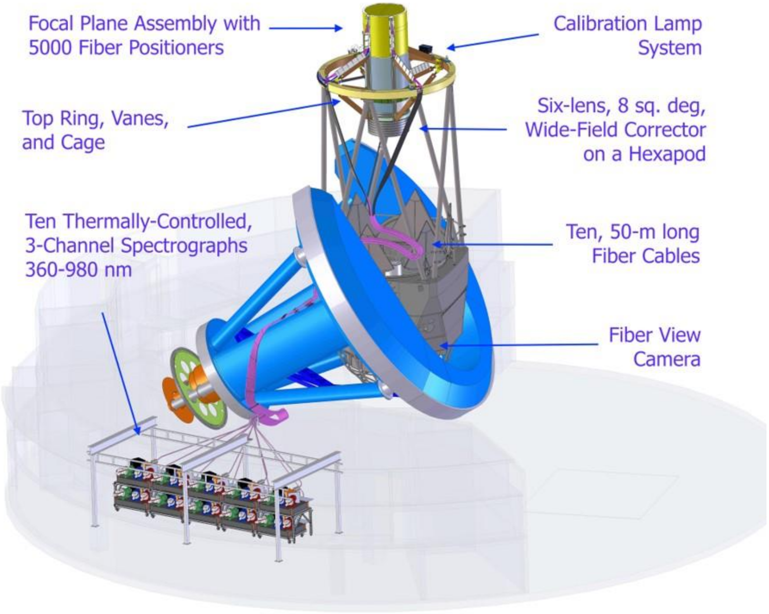
DESI (Dark Energy Spectroscopic Instrument)

DESI (Dark Energy Spectroscopic Instrument)

DESI (Dark Energy Spectroscopic Instrument)

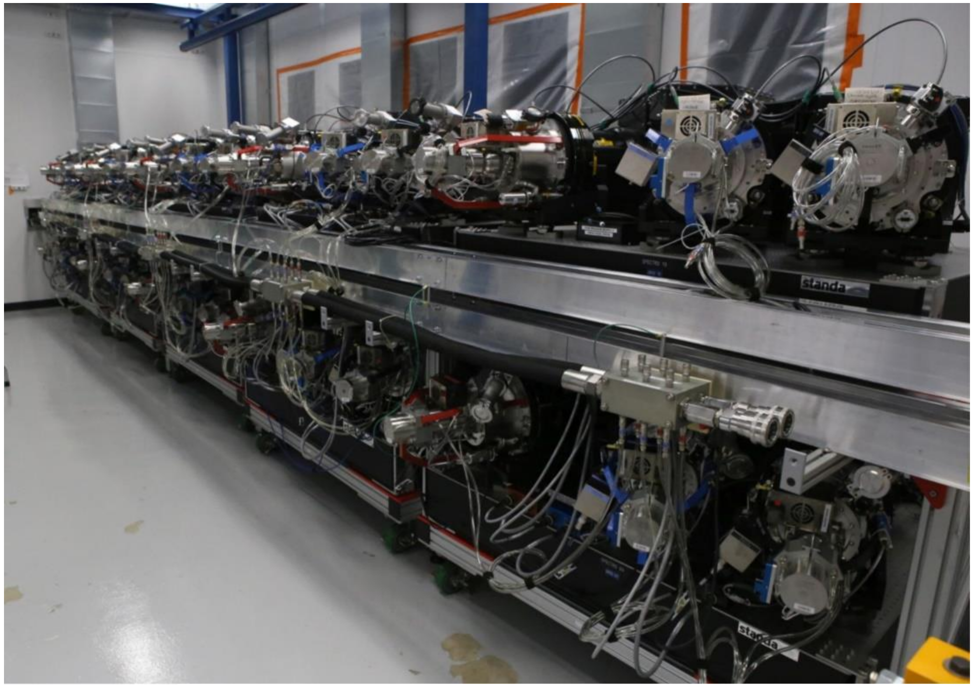
The newest element of DESI are the 5000 fiber positioning robots





~1 minute to position fibers!

DESI (Dark Energy Spectroscopic Instrument)



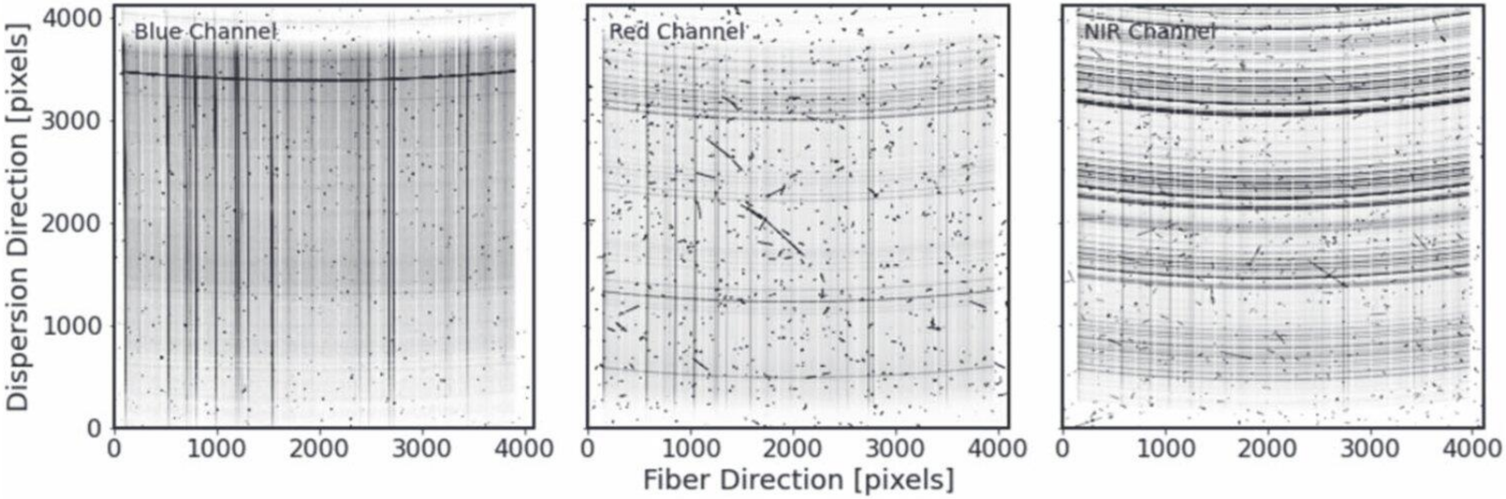
10 Multi-Object Spectrographs:

- Wavelength Range: 360 – 980 nm
- 3 channels with separate optics, CCD, cryostats
- 500 fibers
- Resolution: 2000 (blue) – 5500 (NIR)
- 4kx4k CCDs, 60s readout

Stable PSF: better than 1 % over many days

Low Read out noise: ~ 3 e-

Total Throughput of optical chain is excellent: ~40% at 700 nm (total)



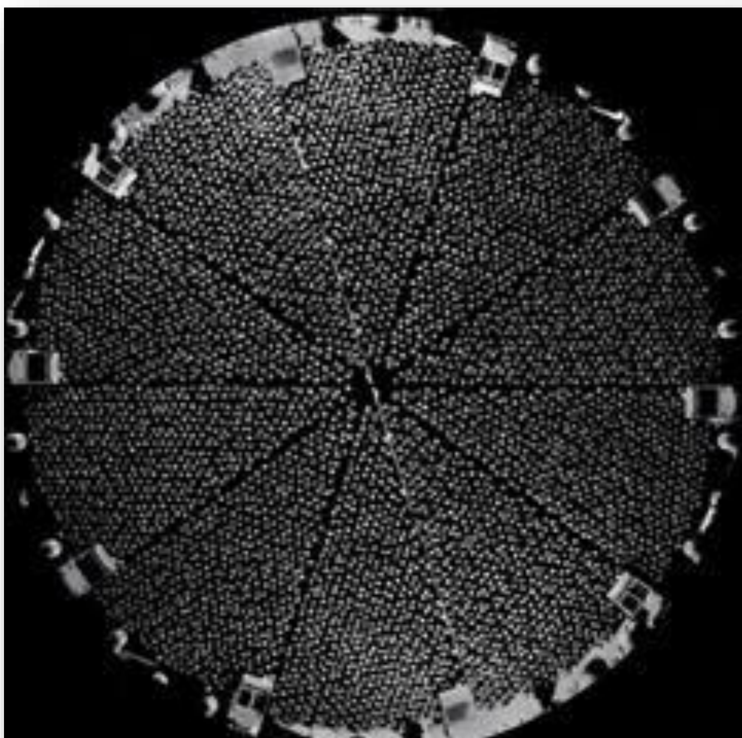
DESI (Dark Energy Spectroscopic Instrument)

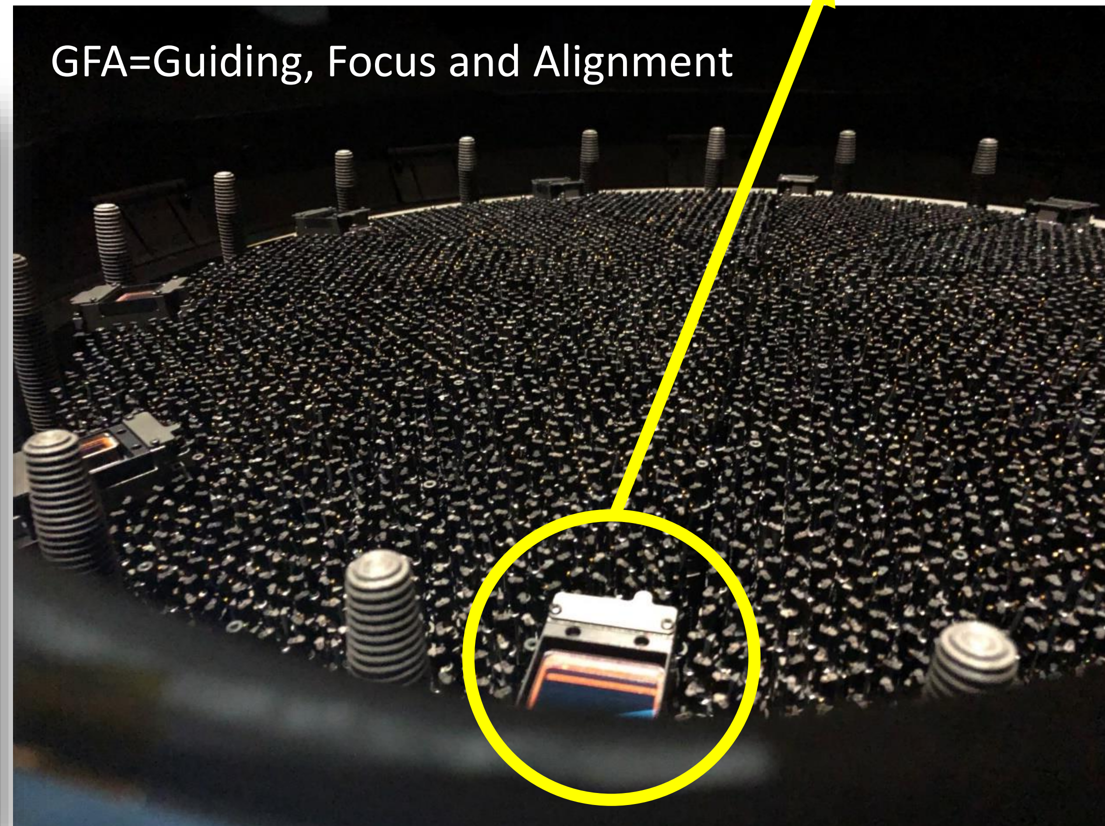
Designed, built and maintained by spanish groups in DESI (RPG-Barcelona-Madrid):
CIEMAT, ICE-CSIC, IFAE, UAM

6 Guide Cameras
4 Wavefront Cameras

Specification
e2V CCD 230-42
1kx2k, frame transfer
ambient temperature
no shutter
3.4x7.3 arcmin^2 on sky

GFA System (10 mini-cameras) is the spanish (Barcelona-Madrid) contribution to the instrument





DESI (Dark Energy Spectroscopic Instrument)

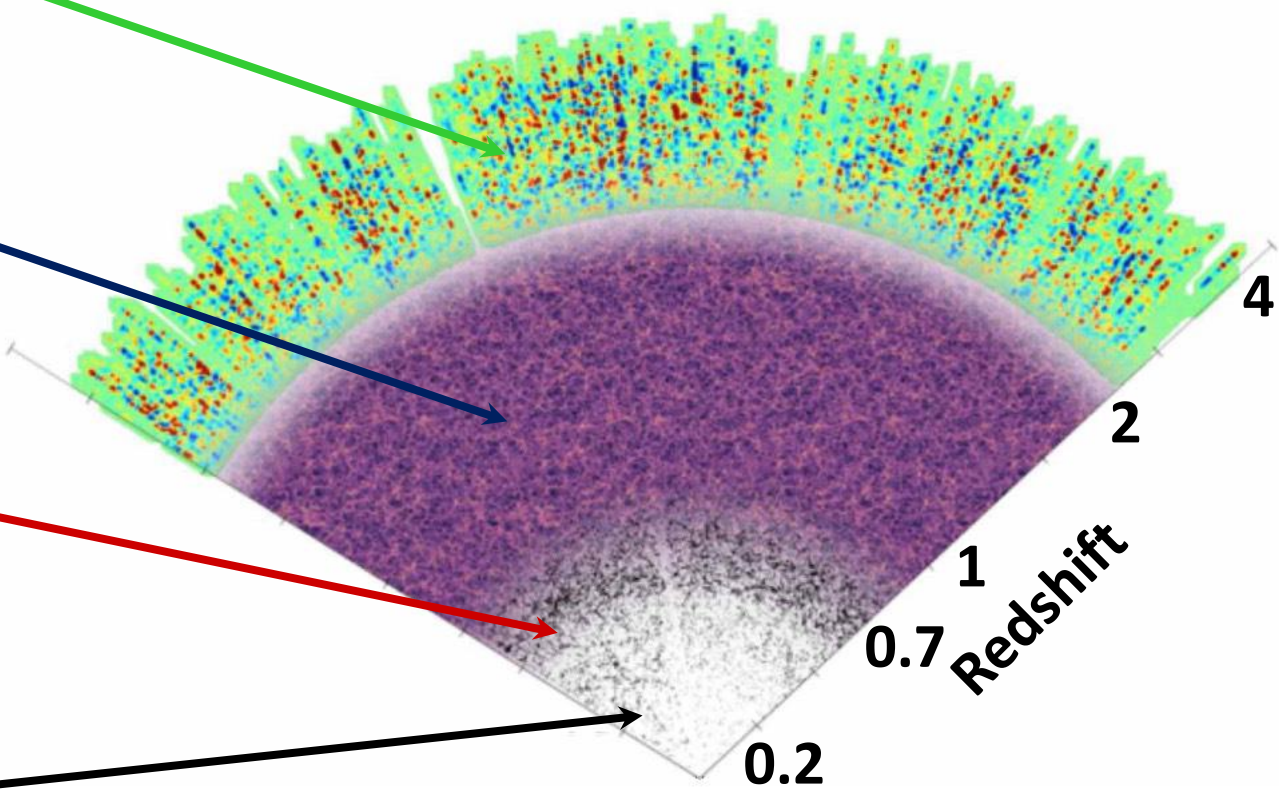
DESI survey covers over 14,000 deg^2 in 5 years!

3 million quasars + Ly-α forest (1 < z < 3.5)

16 million Emission Line Galaxies (0.6 < z < 1.6)

8 million Luminous Red Galaxies (0.4 < z < 1.1)

13 million Bright Galaxies (0.0 < z < 0.4)



+ 10 million Milky Way stars

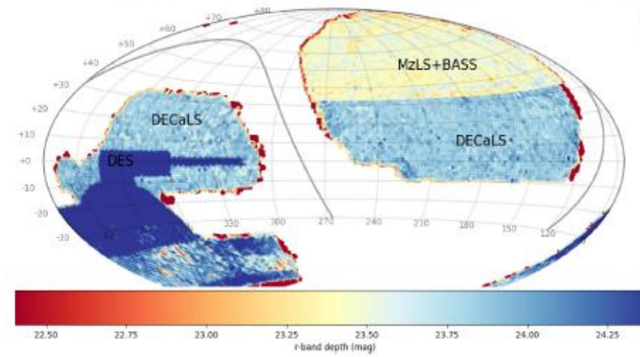
DESI (Dark Energy Spectroscopic Instrument)

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

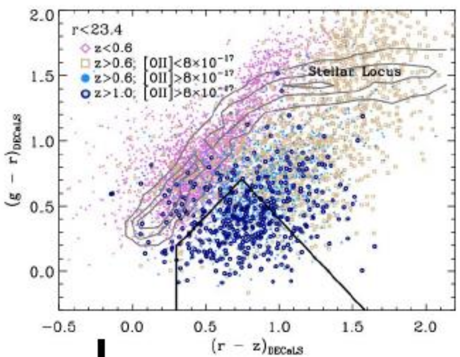
Multi-object Spectroscopy

Imaging Surveys (2014-2019)

+WISE IR sat



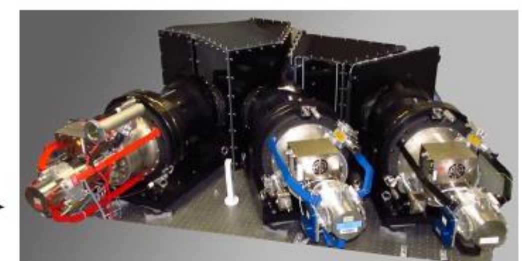
Target Selection

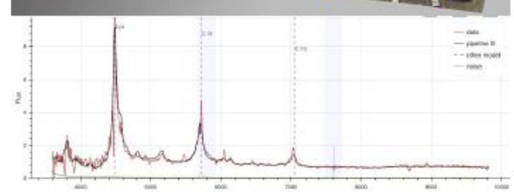


Observation…

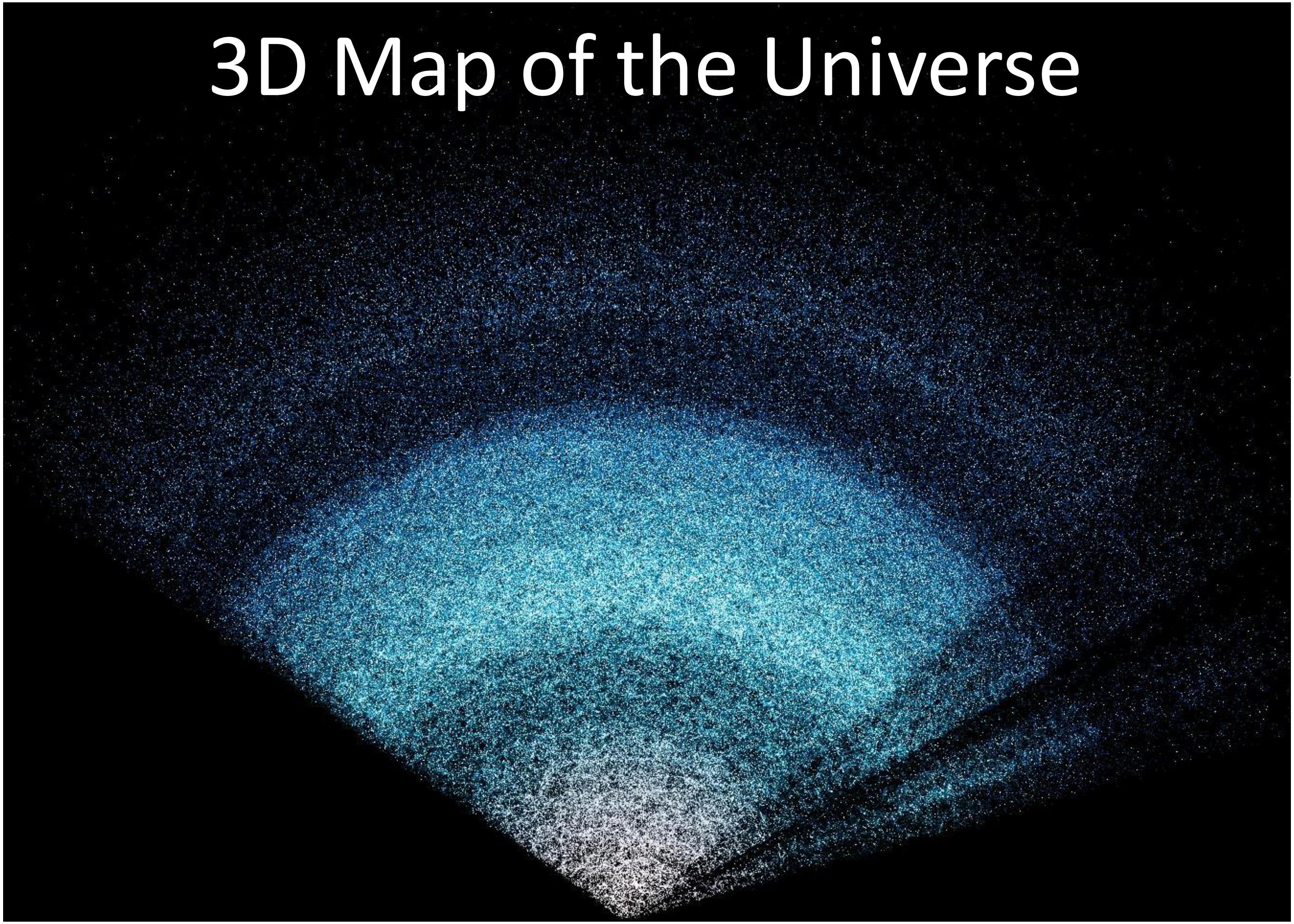
…of 5000 objects every ~20mins…

…and measure their redshift





DESI (Dark Energy Spectroscopic Instrument)

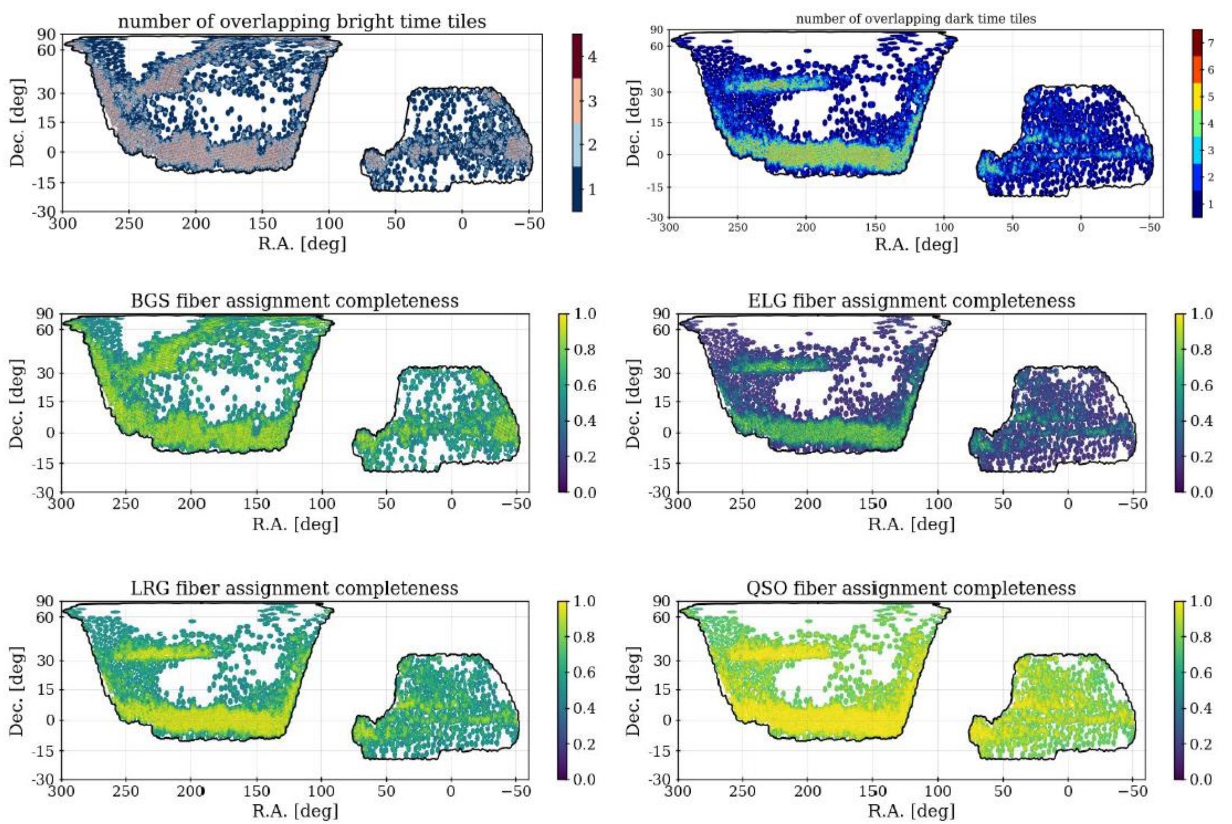


DESI (Dark Energy Spectroscopic Instrument)

Over 30M galaxy and quasar redshifts in 3 years of operation, ~14M of which are used in this analysis.

Compared to DR1 (~6M redshifts), DR2 represents a factor of ~2.4 improvement in data volume.

DR1 Galaxy Sample



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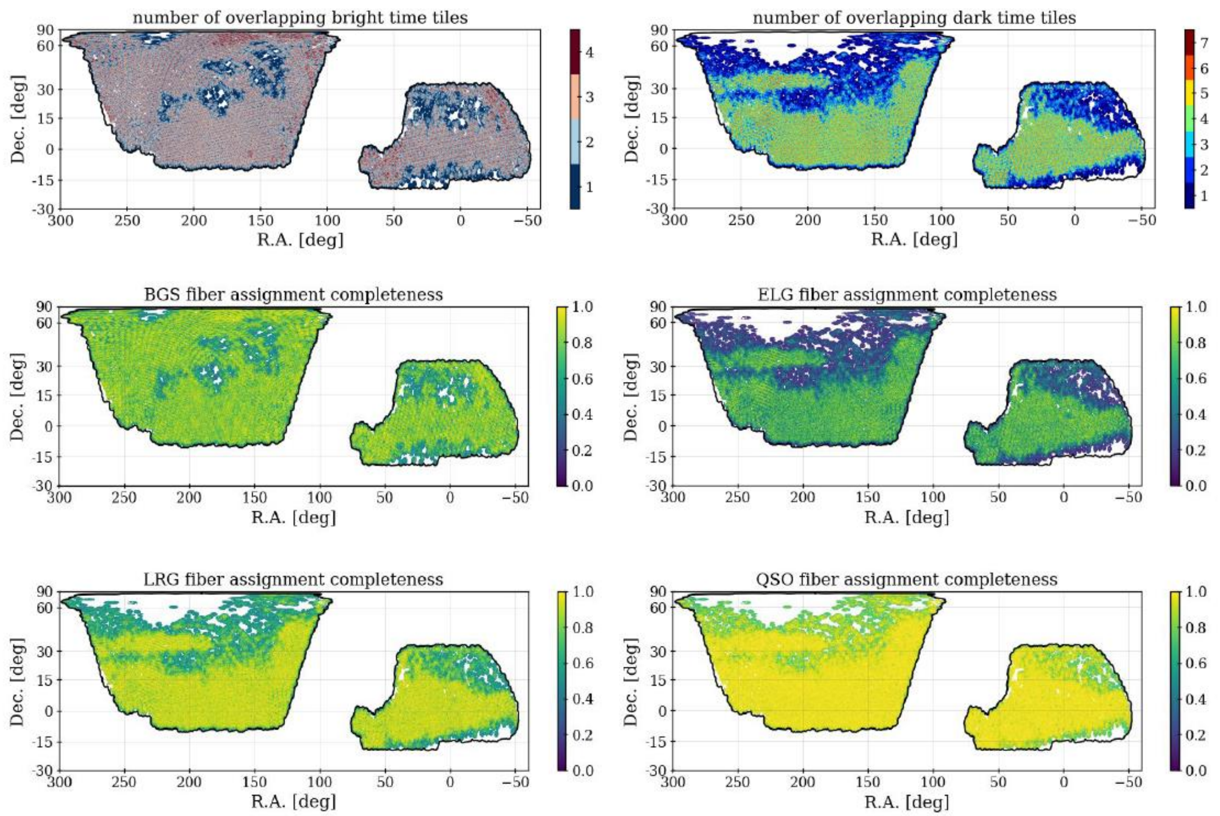
DR2 Galaxy Sample



DESI (Dark Energy Spectroscopic Instrument)

DR2 Galaxy Sample

Tracer	No. of redshifts	Redshift range	zeff	Area [deg^2]	Veff (Gpc^3)
BGS	1,188,526	$0.1<z<0.4$	0.295	12,355	3.8
LRG1	1,052,151	$0.4<z<0.6$	0.510	10,031	4.9
LRG2	1,613,562	$0.6<z<0.8$	0.706	10,031	7.6
LRG3	1,802,770	$0.8<z<1.1$	0.922	10,031	9.8
ELG1	2,737,573	$0.8<z<1.1$	0.955	10,352	5.8
ELG2	3,797,271	$1.1<z<1.6$	1.321	10,352	2.7
QSO	1,461,588	$0.8<z<2.1$	1.484	11,181	2.7

Over 30M galaxy and quasar redshifts in 3 years of operation,
∼14M of which are used in this analysis.
Compared to DR1 (∼6M redshifts),
DR2 represents a factor of ∼2.4 improvement in data volume.

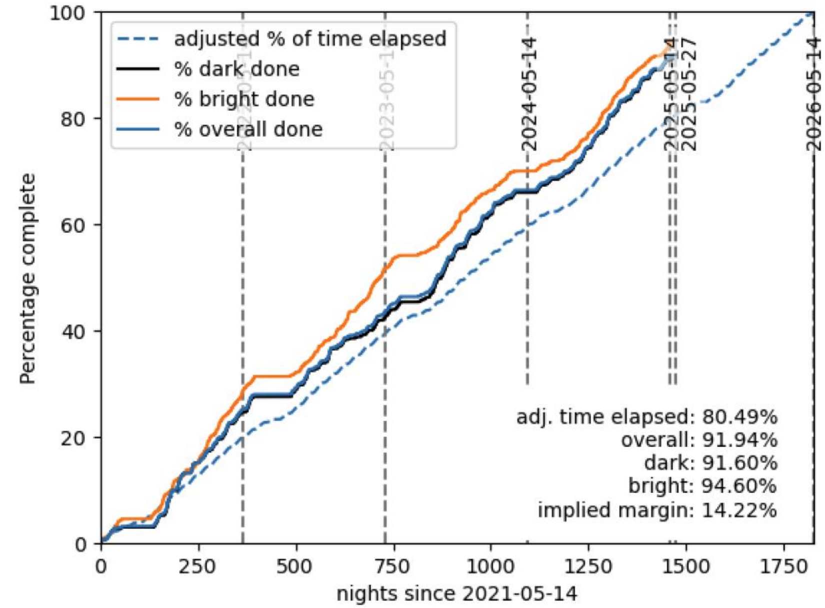
DESI (Dark Energy Spectroscopic Instrument)

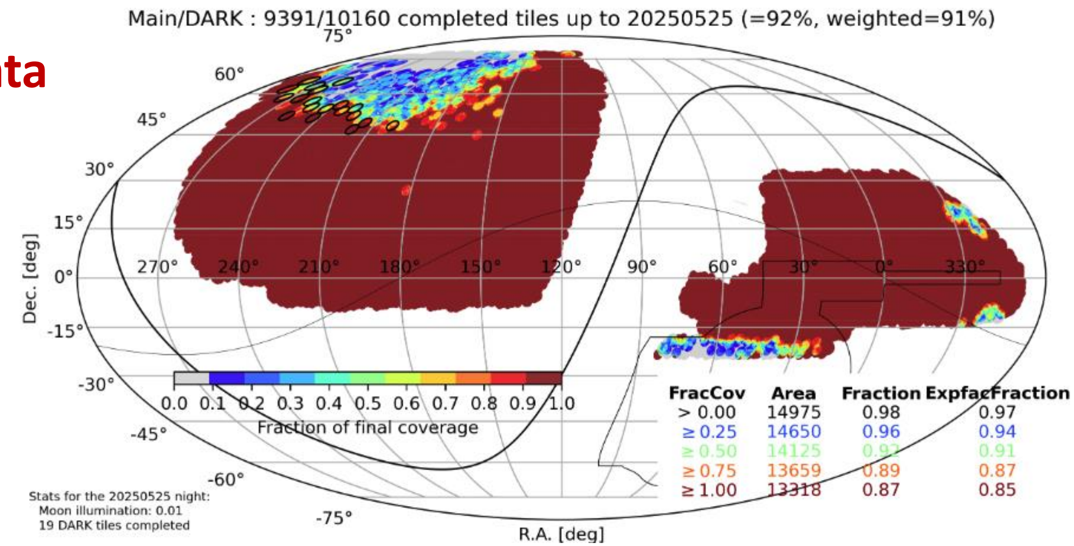
DESI is ahead of schedule!!

And this is achieved even with...
COVID shutdown (03/20-11/20)
Contreras fire shutdown (06/22-09/22)
Hackers attack in 2023

The survey is now more than 90% complete and will continue taking data for 2.5 additional years

Foreseen Data releases
DESI-Y1 (up to June'22) → DR1
DESI-Y3 (up to March'24) → DR2
DESI-Y5 (2026)





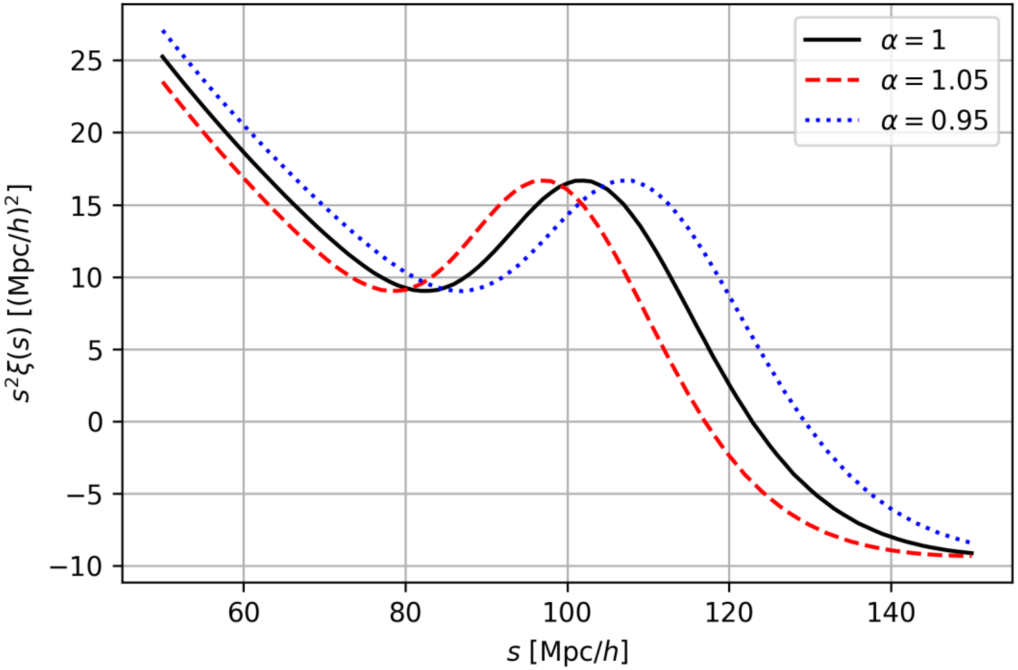
DESI (Dark Energy Spectroscopic Instrument)

How DESI measures BAO

The BAO feature appears as a **peak** in the **galaxy correlation function** or a series of **oscillations** in the **power spectrum**.

We measure the BAO scale by analyzing the clustering pattern of galaxies

Density field reconstruction helps recover the initial BAO signal by undoing the effects of nonlinear evolution, sharpening the BAO peak

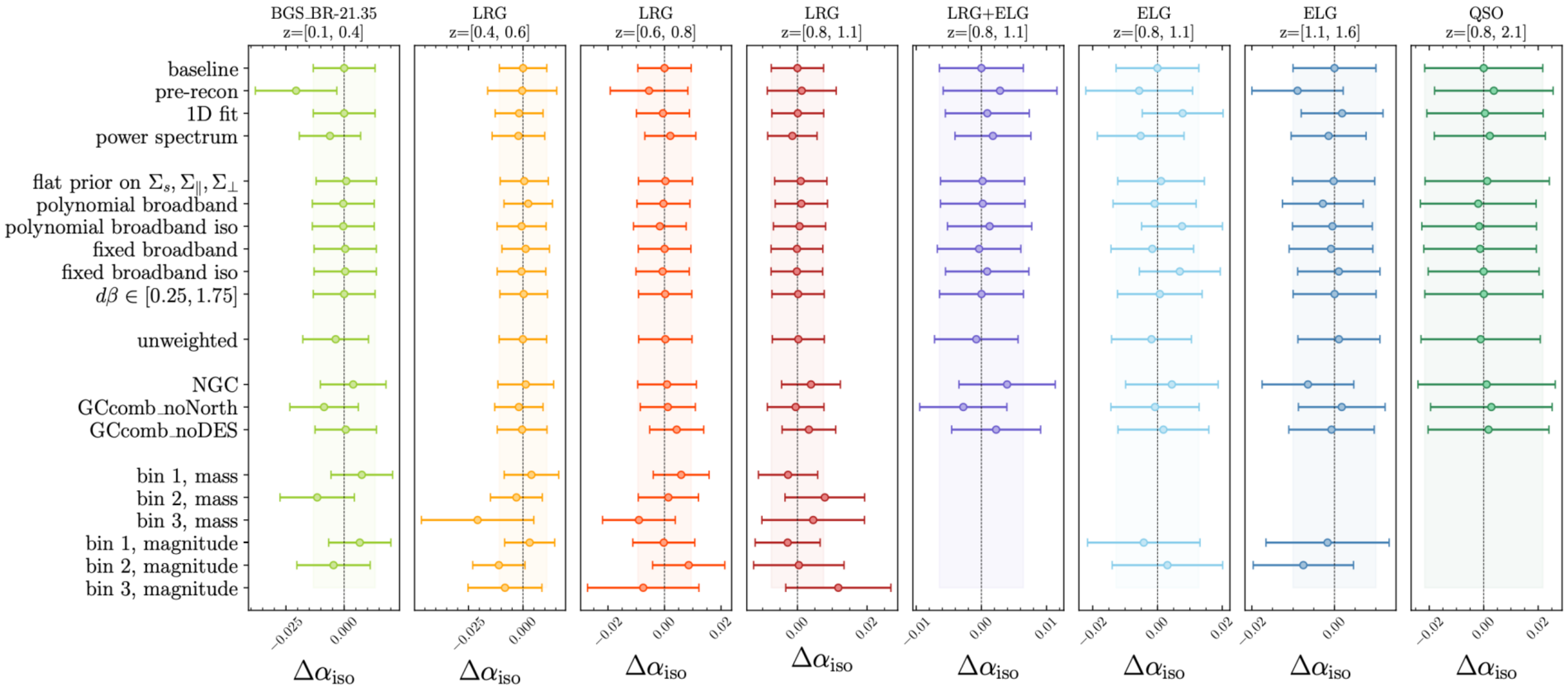


$$\alpha_{\rm iso}(z) = \frac{D_V(z) r_s^{\rm fid}(z_d)}{D_V^{\rm fid}(z) r_s(z_d)}$$

$$\alpha_{\rm AP}(z) = \frac{H(z)^{\rm fid} D_A(z)^{\rm fid}}{H(z) D_A(z)}$$

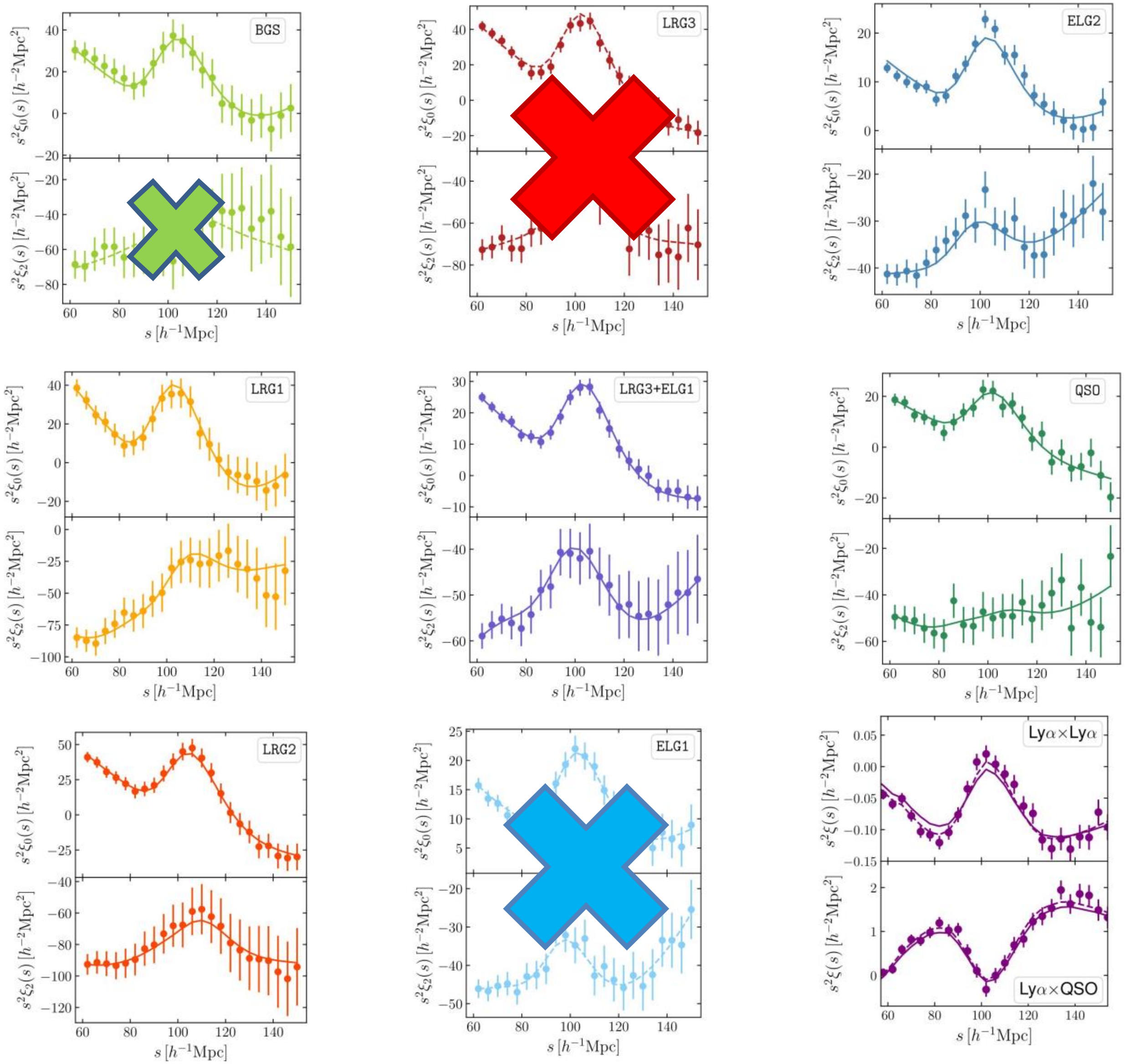
DESI (Dark Energy Spectroscopic Instrument)

BAO measurement is robust → Low systematic error



systematic error clearly below 1% **(between 0.14% and 0.33%)**

DESI (Dark Energy Spectroscopic Instrument)

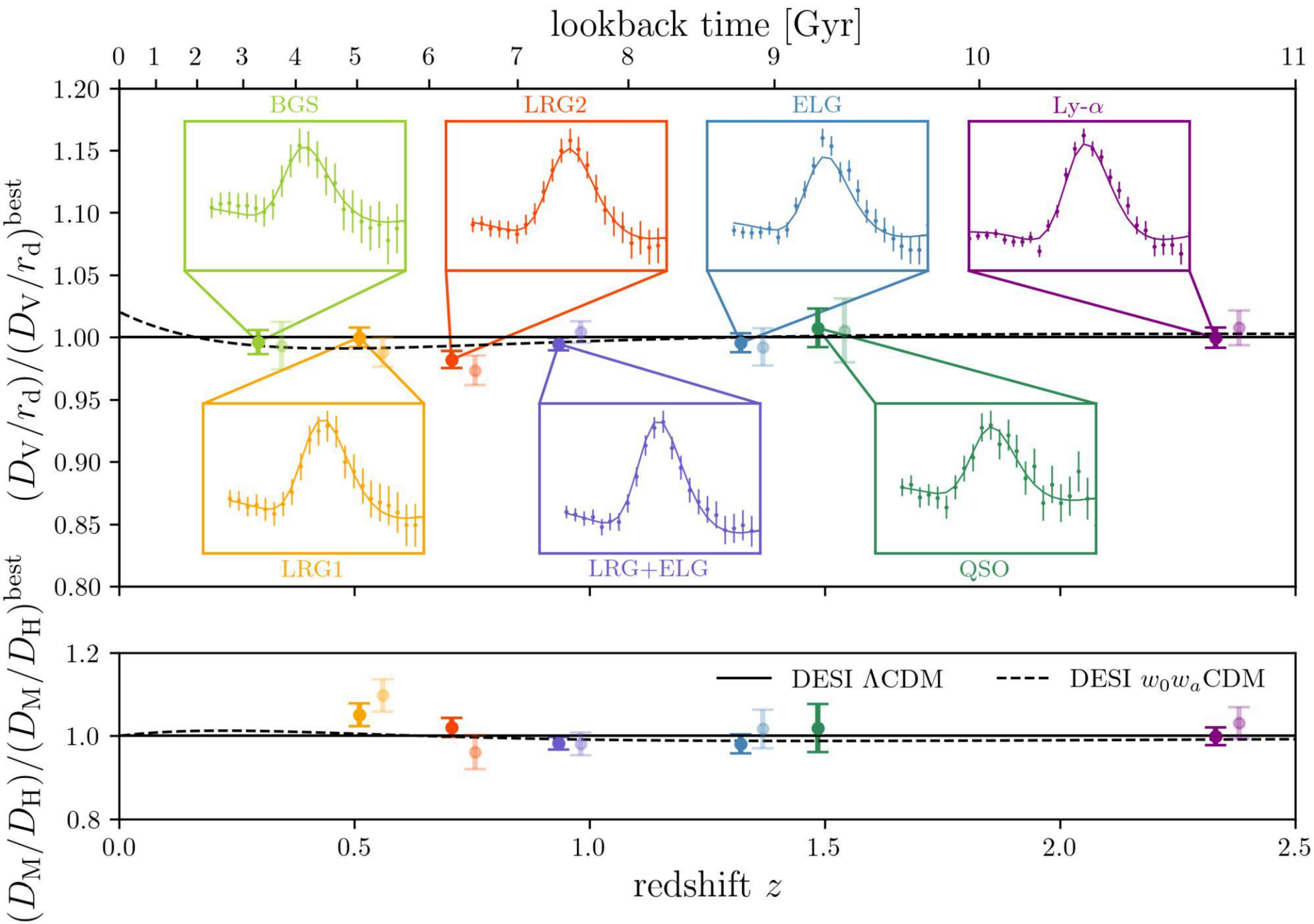


For BGS, only the isotropic fit is used (signal to noise is not enough for the LOS fit).

LRG3 and ELG1 are combined for the cosmology fit, given the tightest BAO measurement when combined

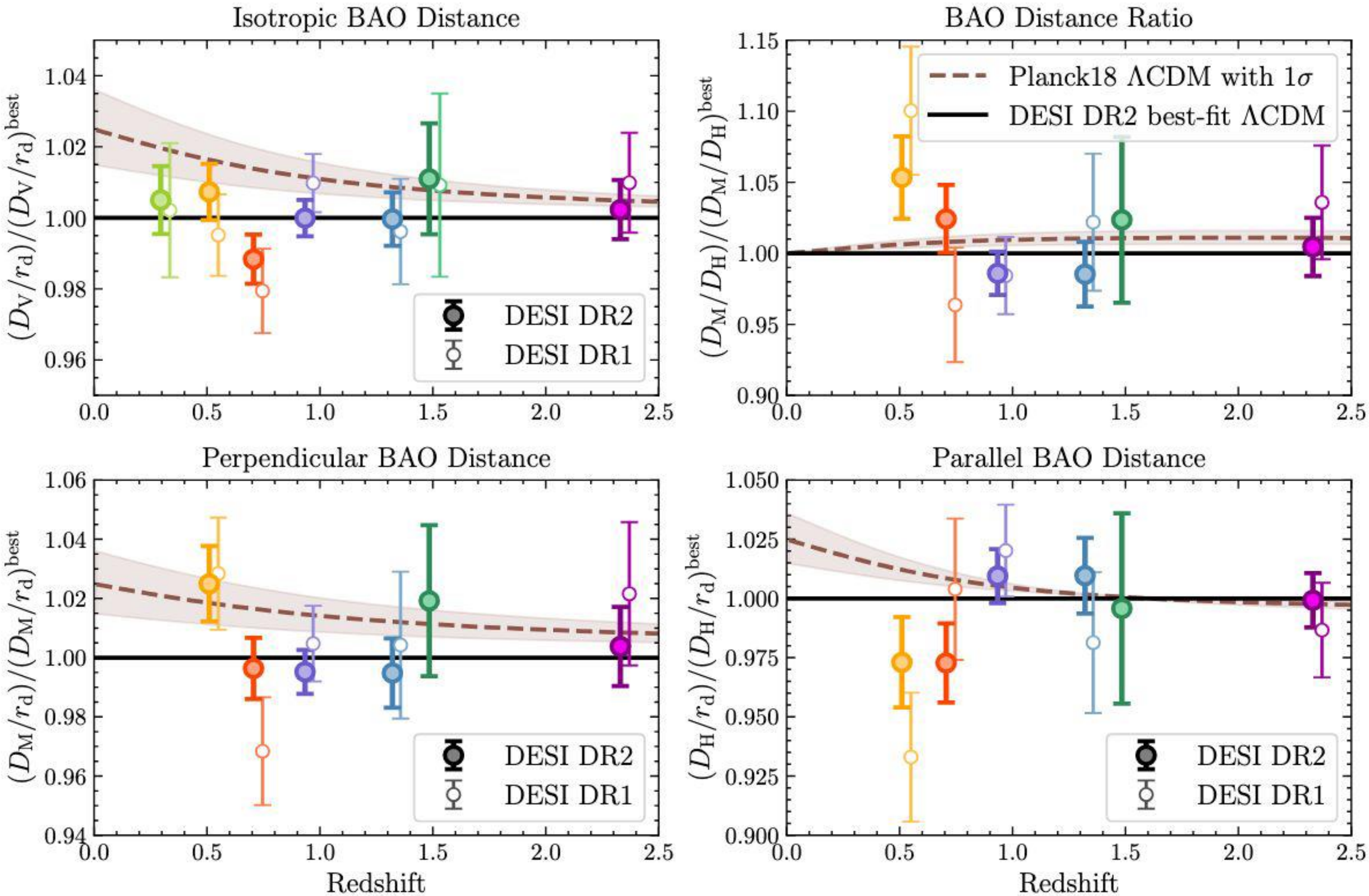
DESI (Dark Energy Spectroscopic Instrument)

DESI DR2 clustering measurements



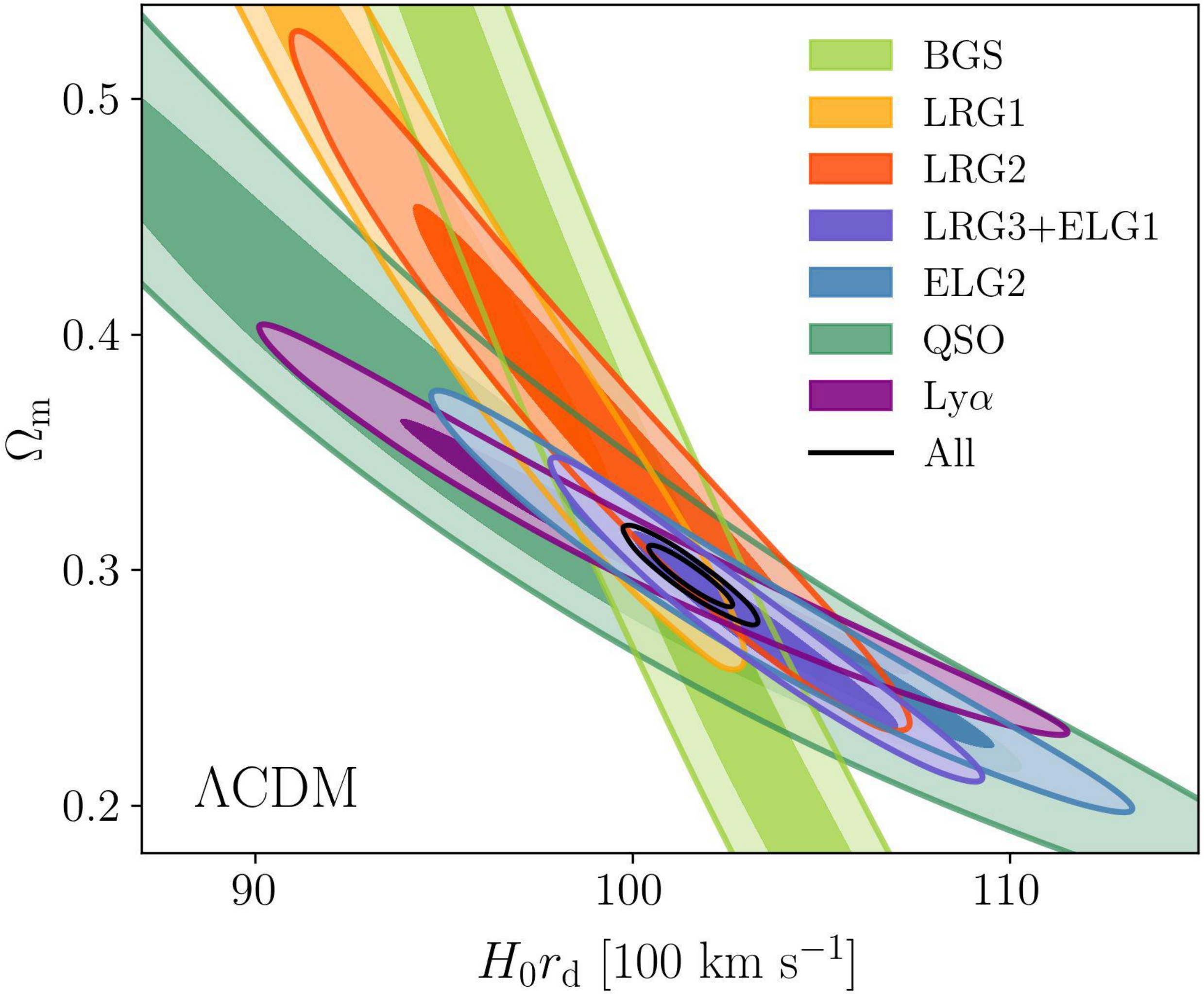
DESI (Dark Energy Spectroscopic Instrument)

BAO measurements



DESI (Dark Energy Spectroscopic Instrument)

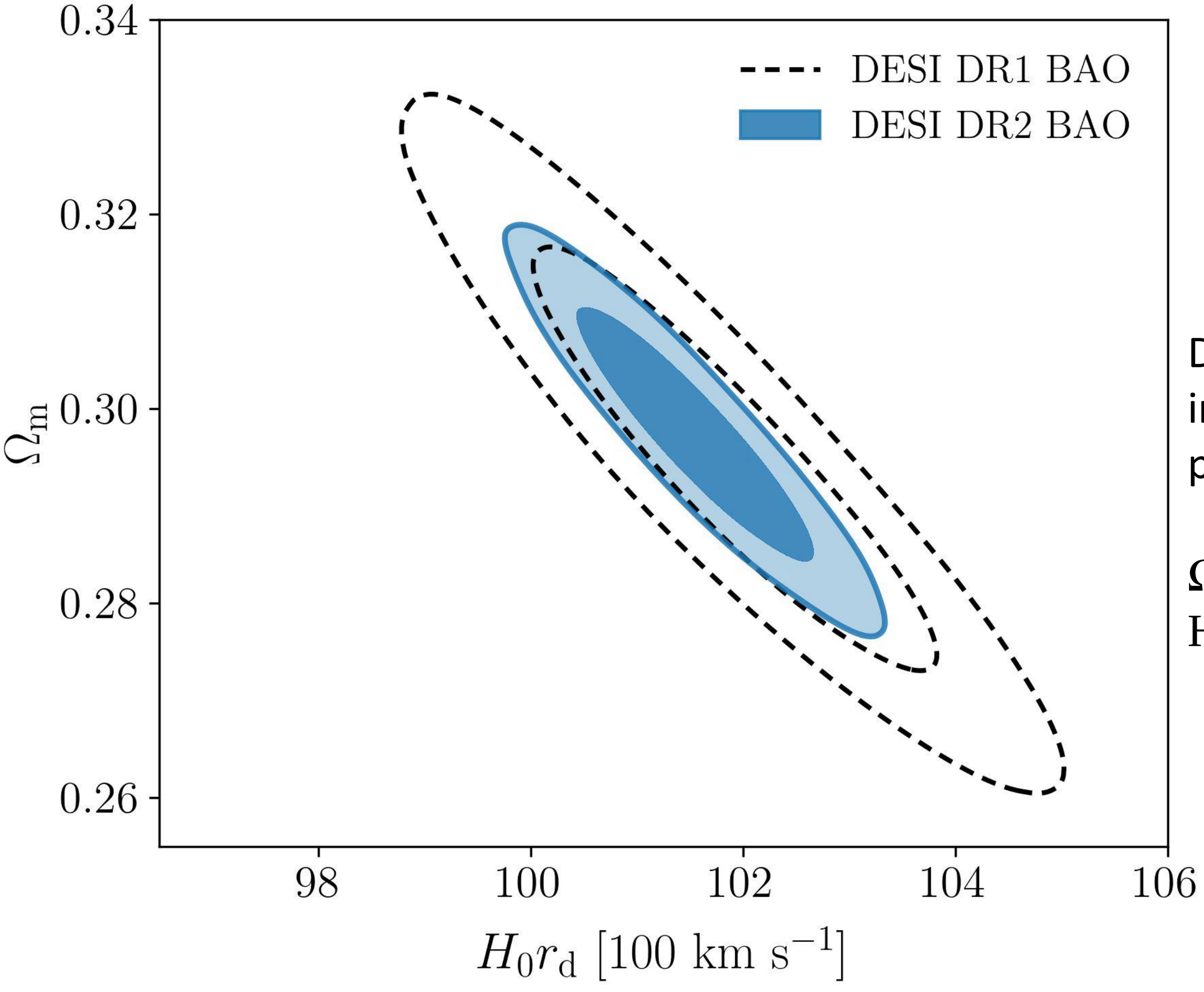
COSMOLOGICAL CONSTRAINTS UNDER ΛCDM



Tracers give consistent results

DESI (Dark Energy Spectroscopic Instrument)

COSMOLOGICAL CONSTRAINTS UNDER ΛCDM

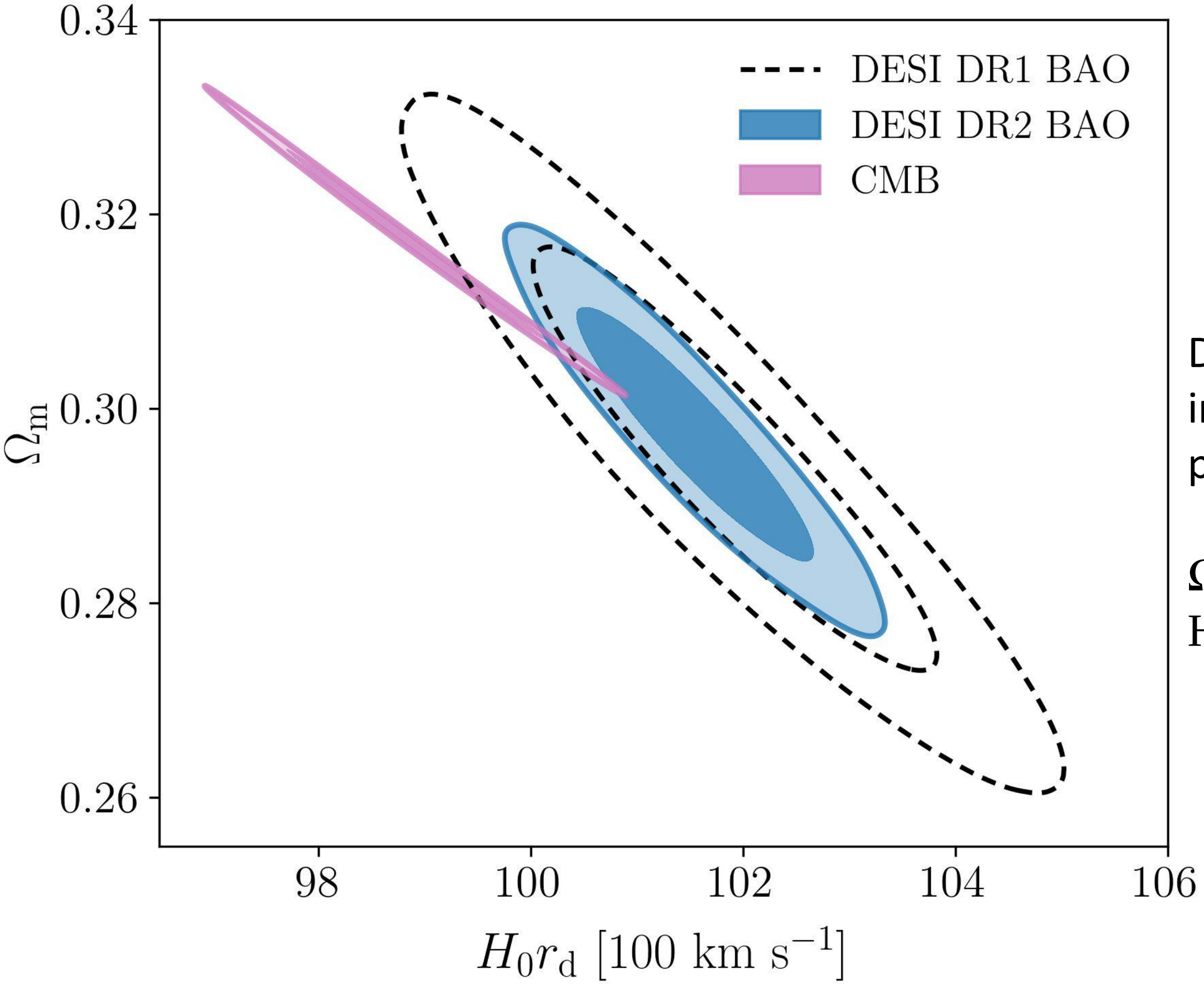


DESI DR2 gives around a 40% improvement in constraints precisión with respect to DR1

$\Omega_m = 0.2975 \pm 0.0086$
$H_0 r_d = 101.54 \pm 0.73$ [100 km s^{-1}]

DESI (Dark Energy Spectroscopic Instrument)

COSMOLOGICAL CONSTRAINTS UNDER ΛCDM



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DESI (Dark Energy Spectroscopic Instrument)

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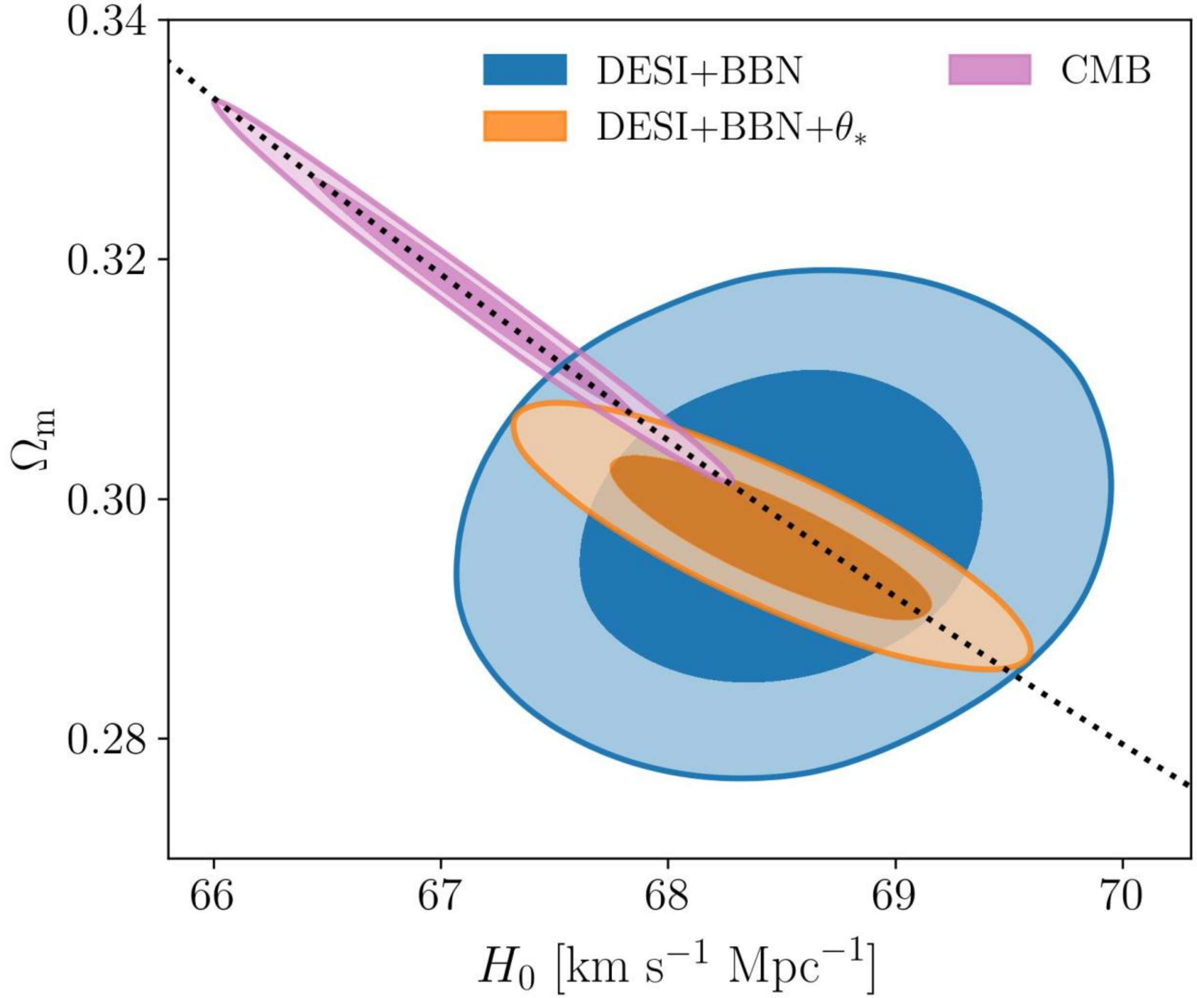


Use BBN to calibrate BAO data and set constraints on H_0

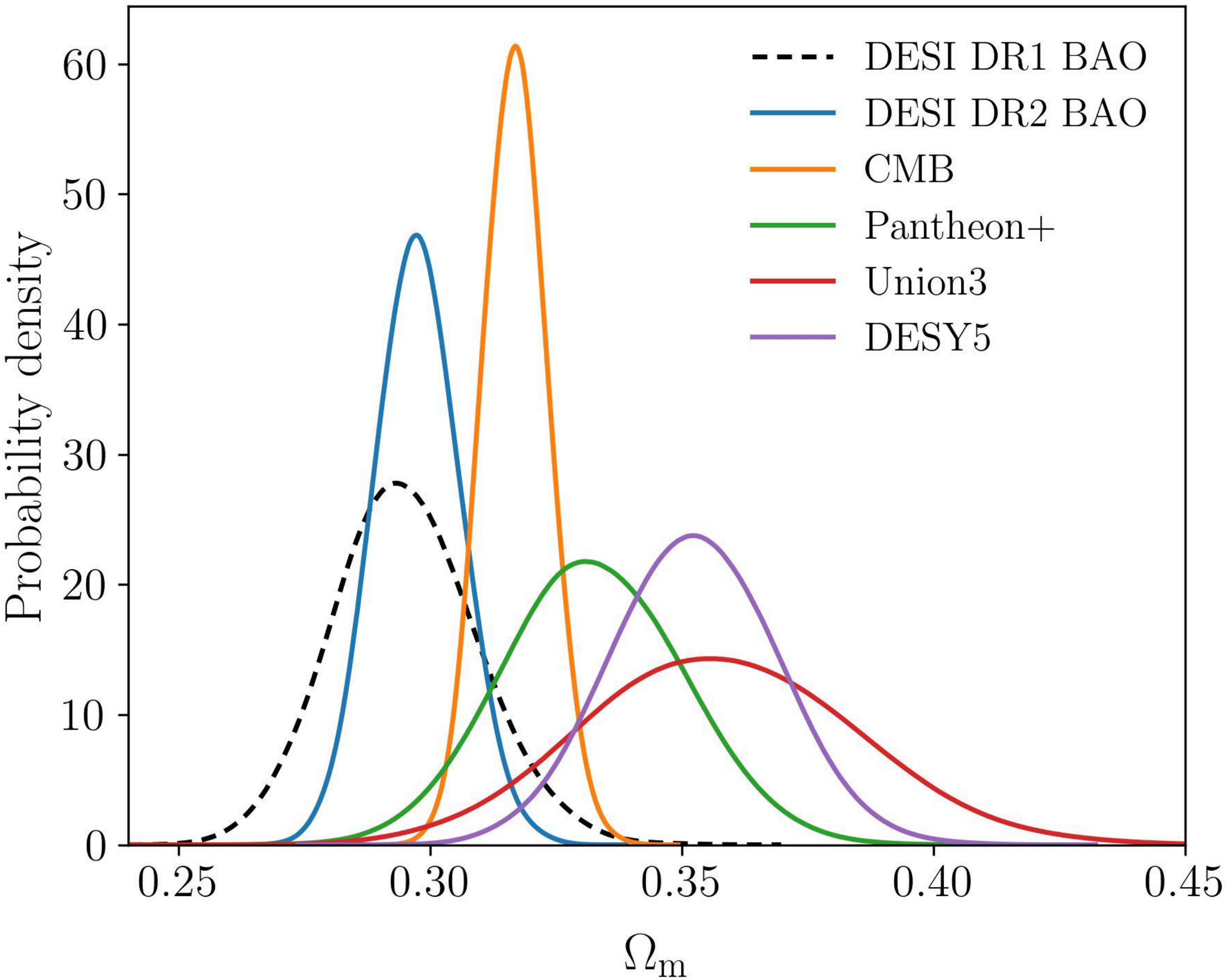
DESI+BBN:
H_0=(68.51 ± 0.58) km s^{-1} Mpc^{-1}

DESI+BBN+θ* :
H_0=(68.45 ± 0.47) km s^{-1} Mpc^{-1}

4.5σ tensión with SH0ES

DESI (Dark Energy Spectroscopic Instrument)

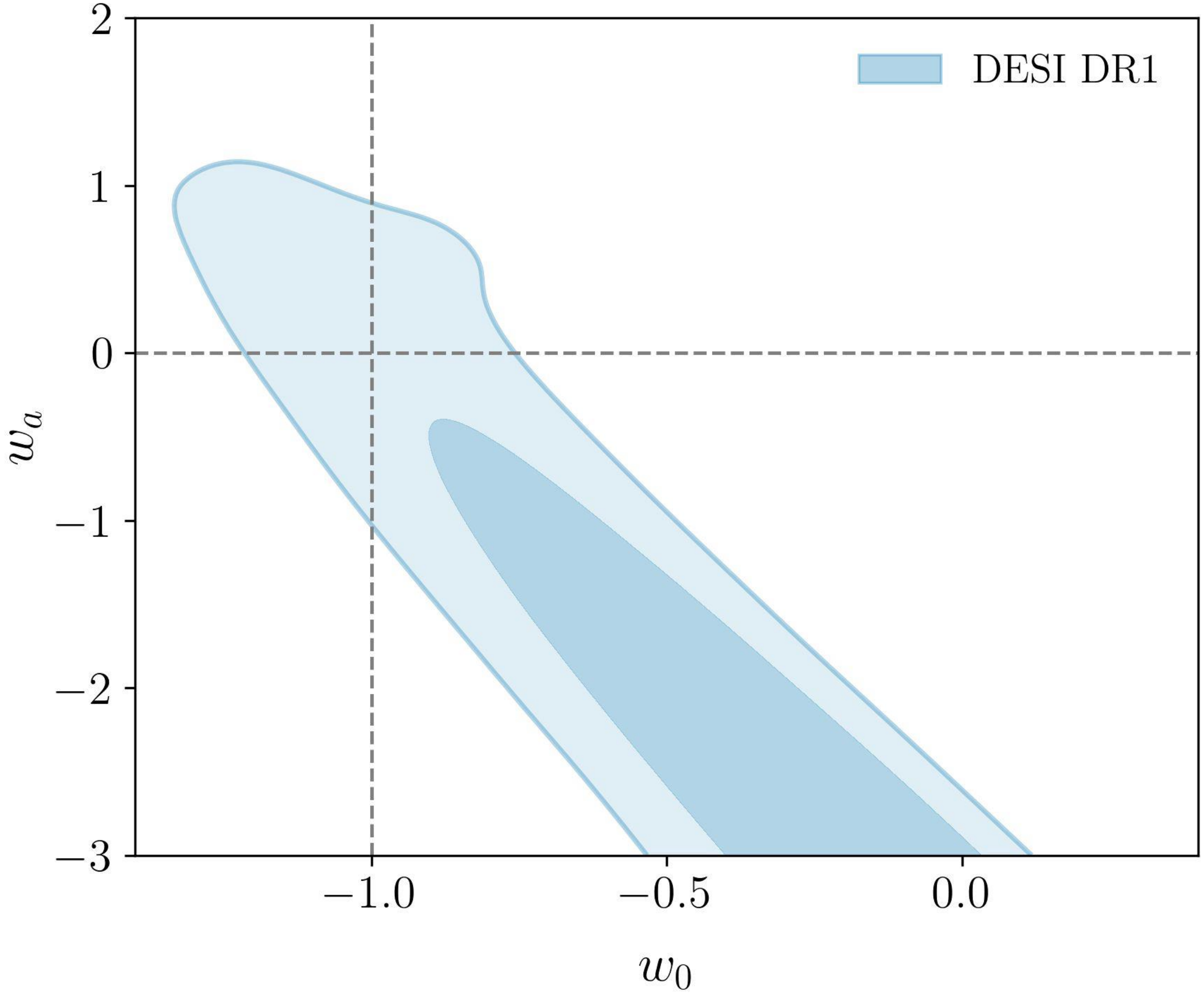
COSMOLOGICAL CONSTRAINTS UNDER ΛCDM



Matter Content

DESI (Dark Energy Spectroscopic Instrument)

DARK ENERGY

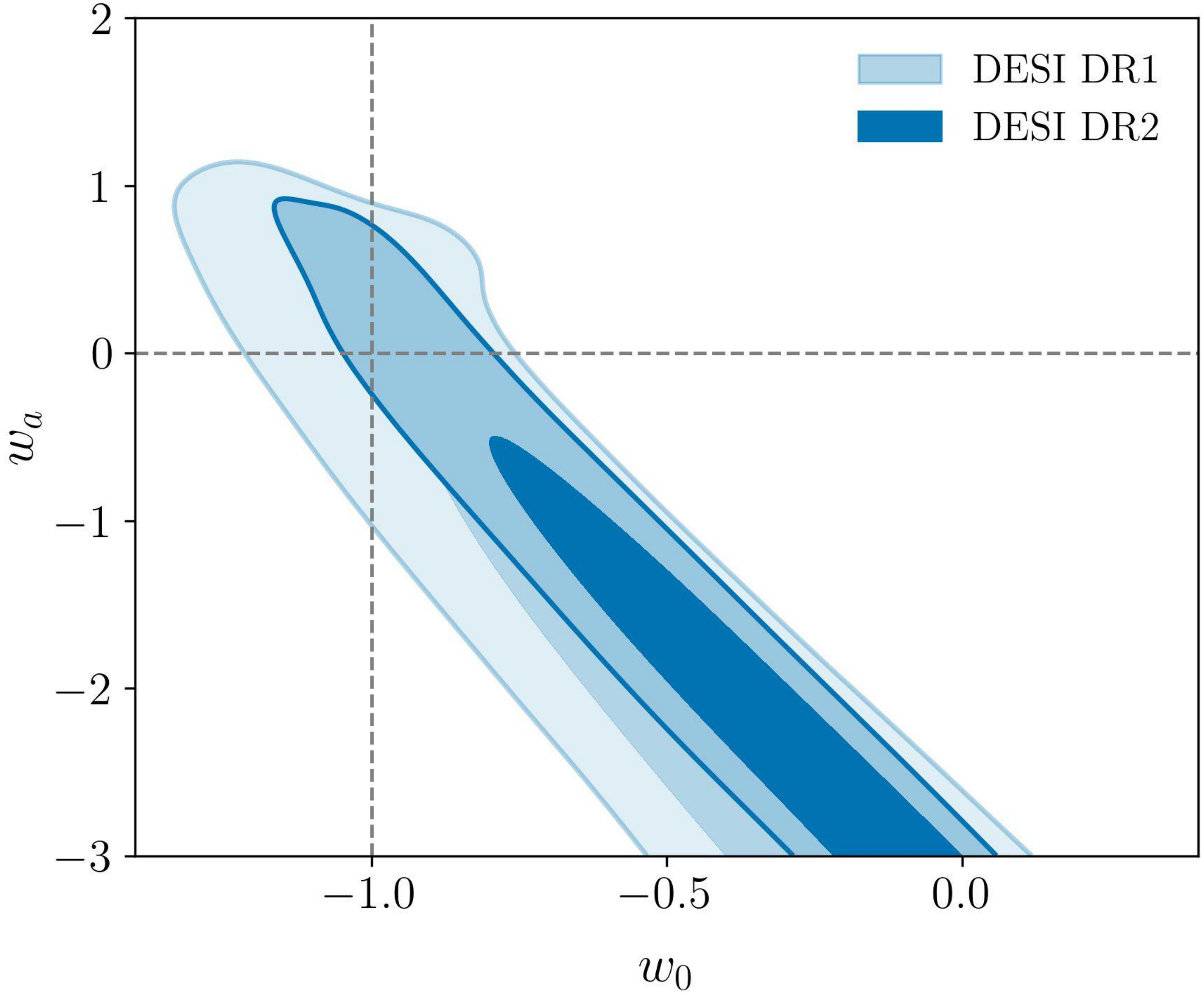


We model evolving dark energy through:

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

DESI (Dark Energy Spectroscopic Instrument)

DARK ENERGY



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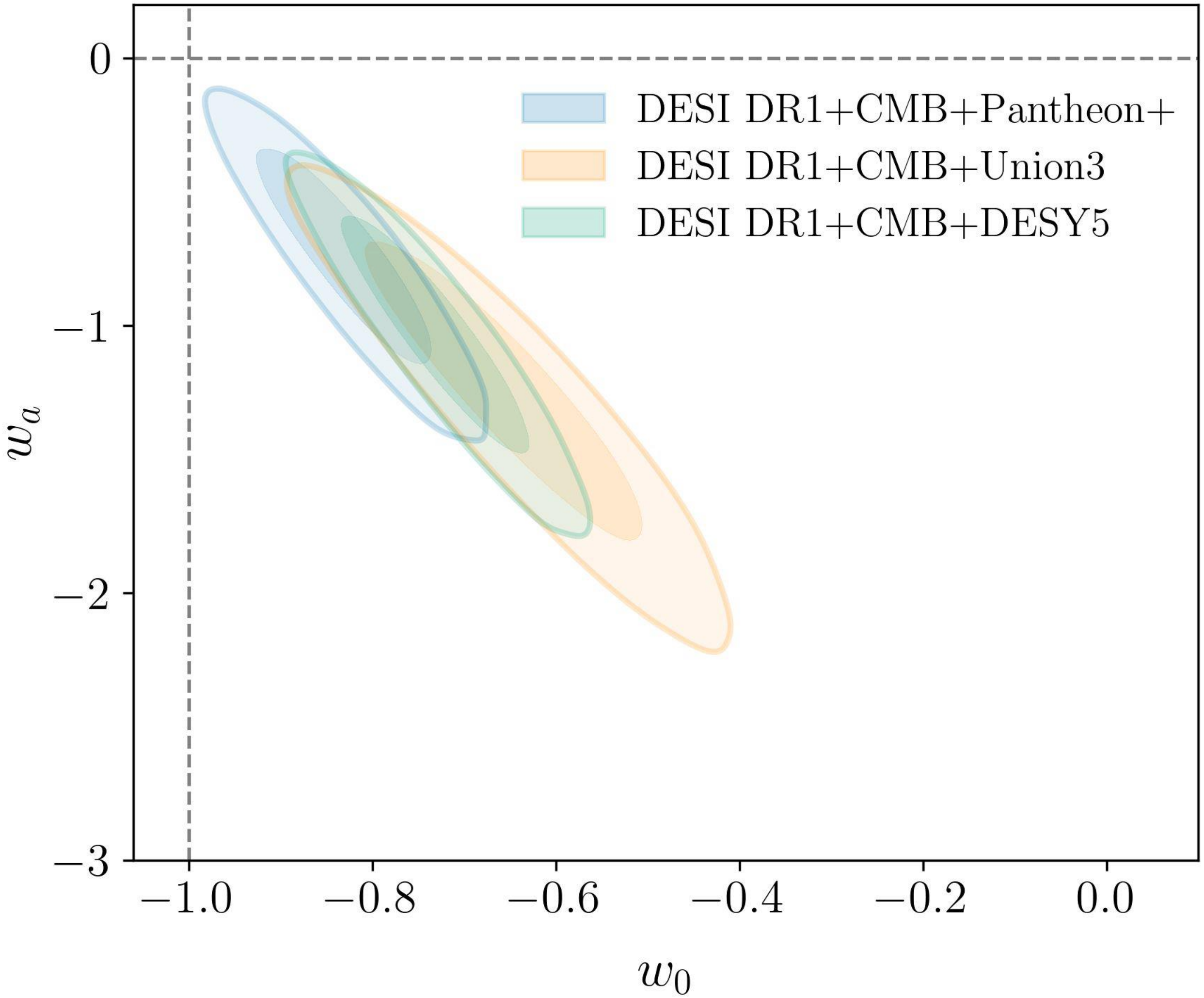

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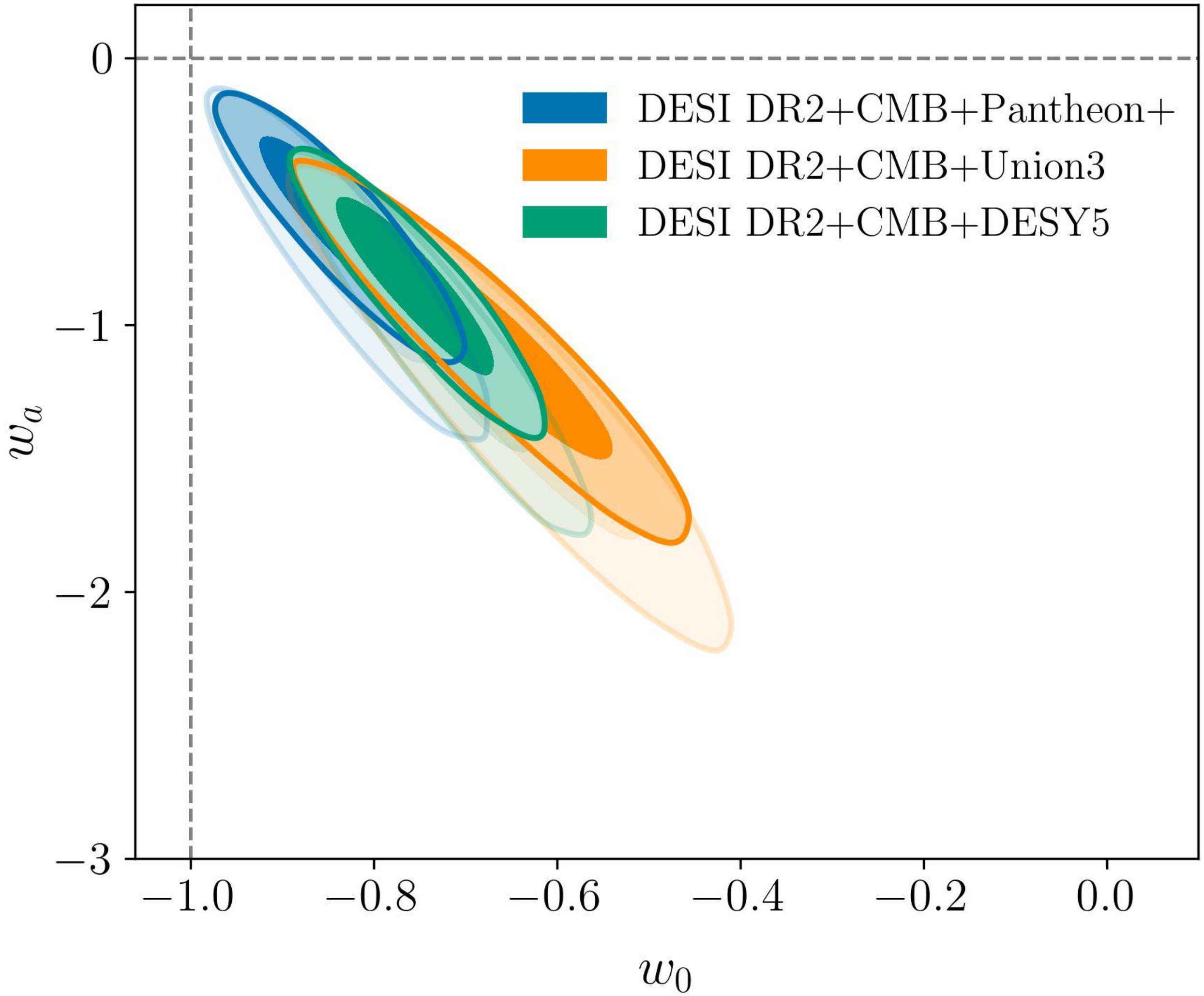
DESI (Dark Energy Spectroscopic Instrument)

DARK ENERGY



We model evolving dark energy through:

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

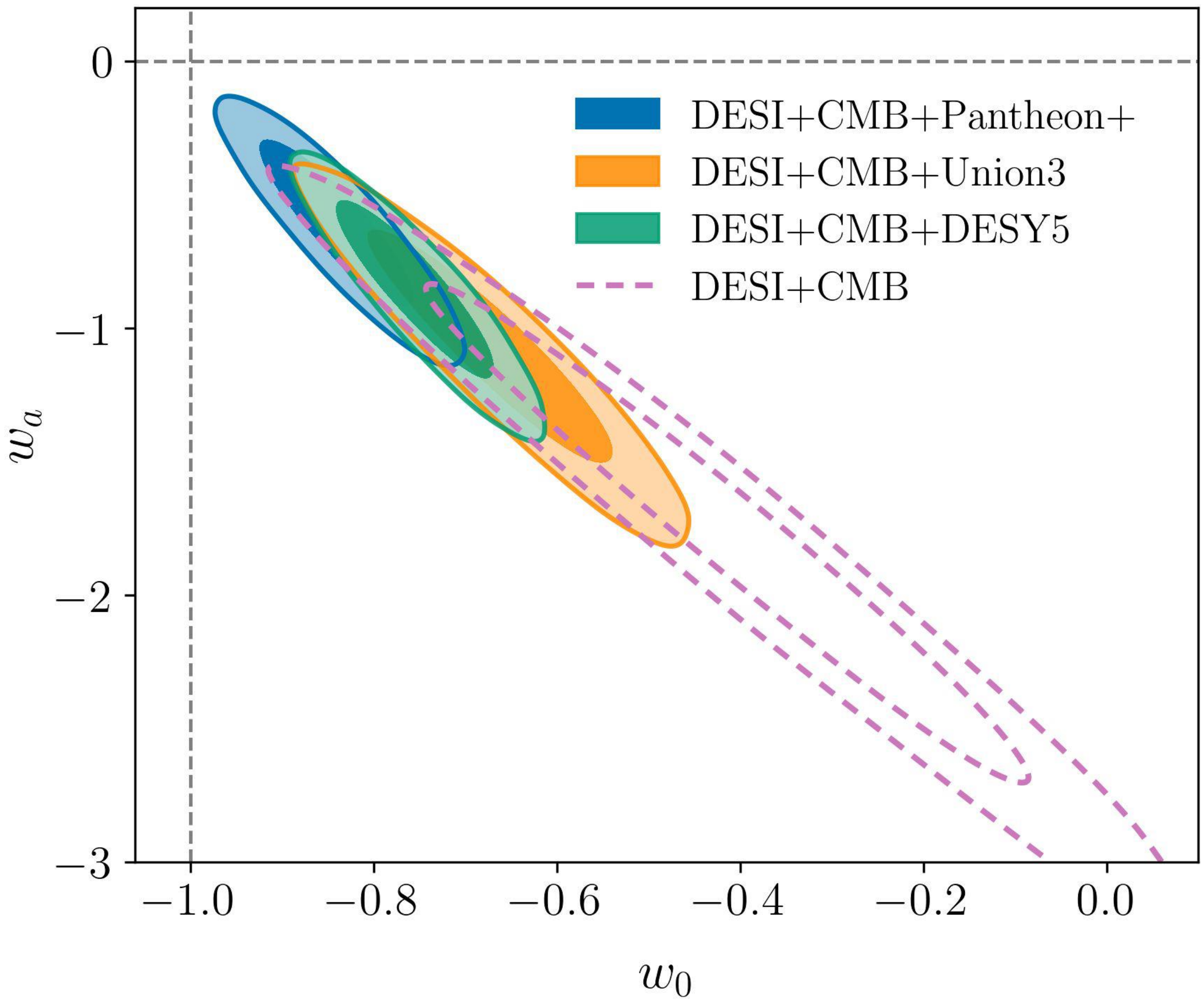
Tensions have marginally increased by 0.3σ with respect to DESI DR1

Tension with cosmological constant, DESI+CMB+ :

Pantheon+: 2.8σ
Union 3: 3.8σ
DES-Y5: 4.2σ

DESI (Dark Energy Spectroscopic Instrument)

DARK ENERGY



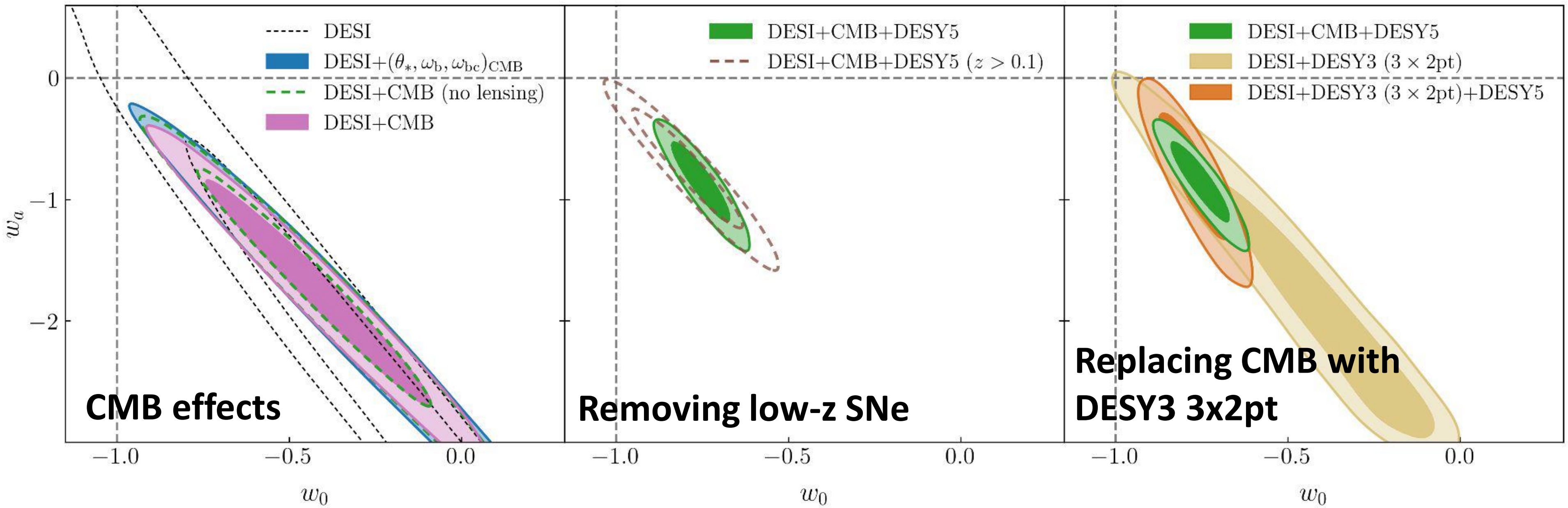
We model evolving dark energy through:

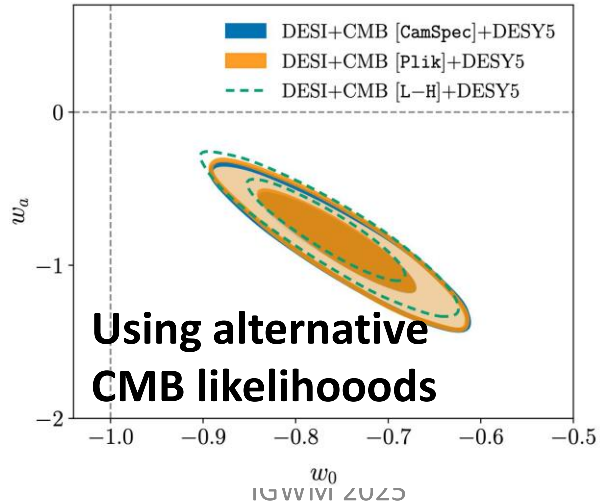
$$w(a) = w_0 + w_a(1 - a)$$

DESI+CMB by itself is now showing a 3.1σ tensión with ΛCDM

DESI (Dark Energy Spectroscopic Instrument)

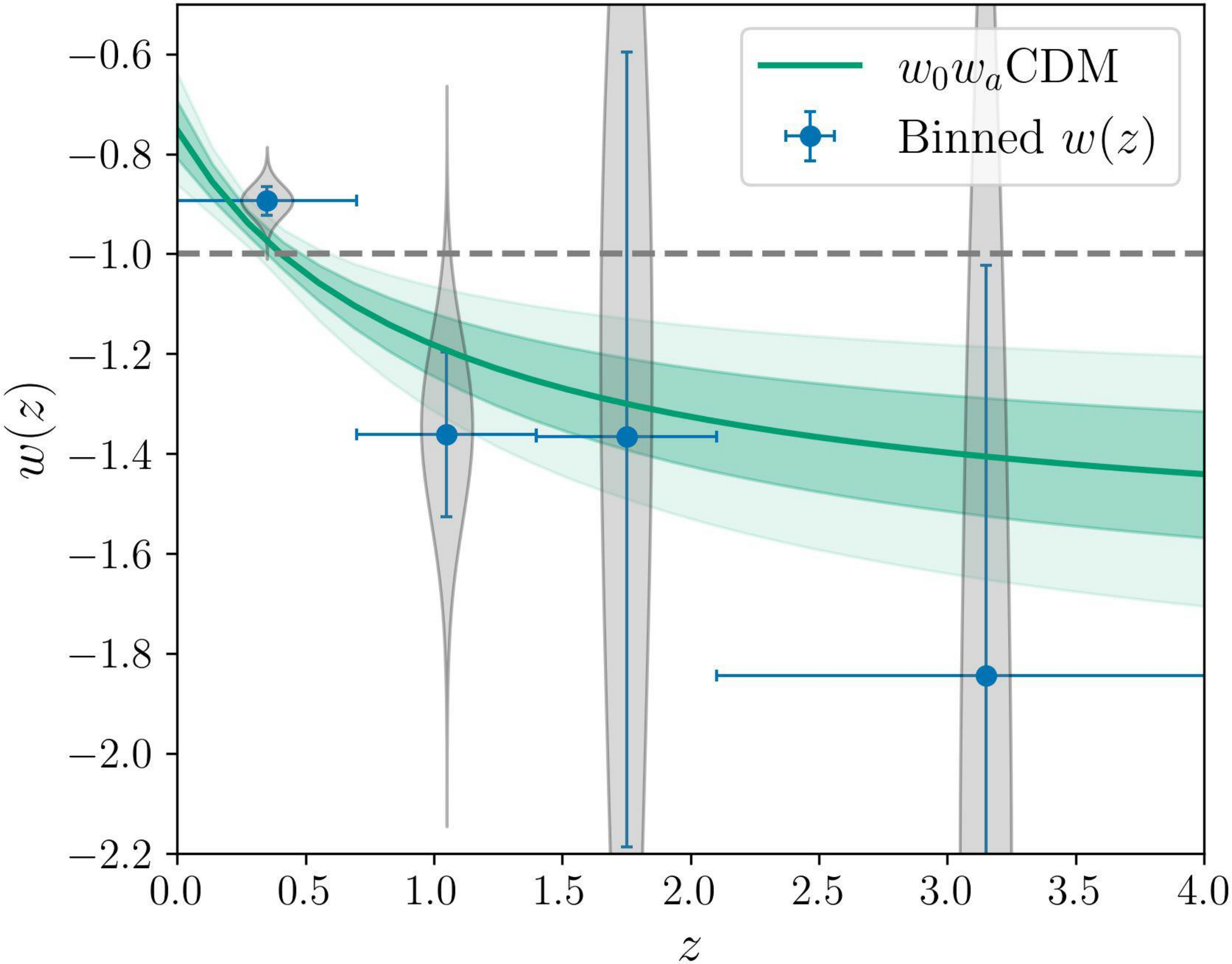
Robustness of DARK ENERGY results





DESI (Dark Energy Spectroscopic Instrument)

Binning the DE EoS

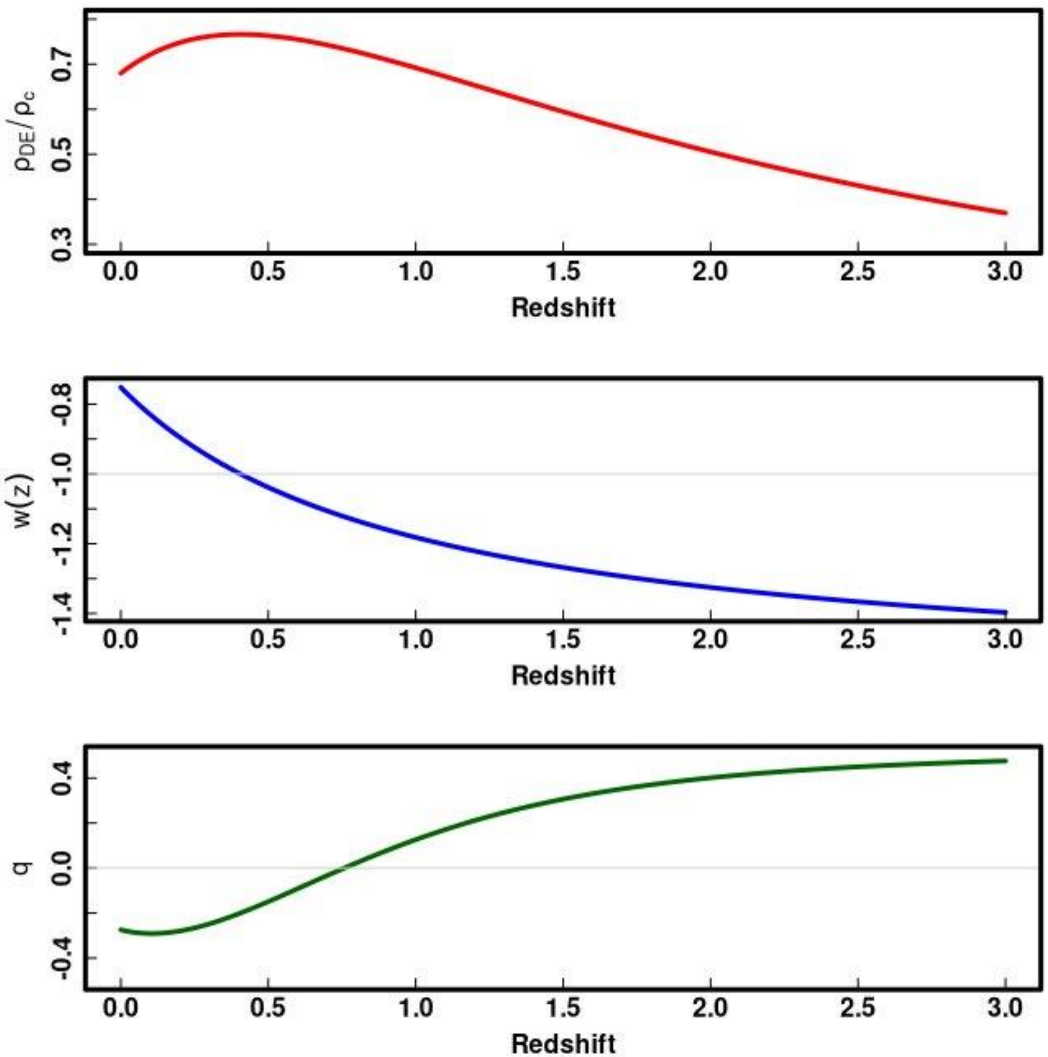


Consistent picture between binning w(z) and CPL!

Phantom crossing at z~0.5

DESI (Dark Energy Spectroscopic Instrument)

Properties of the Dark Energy



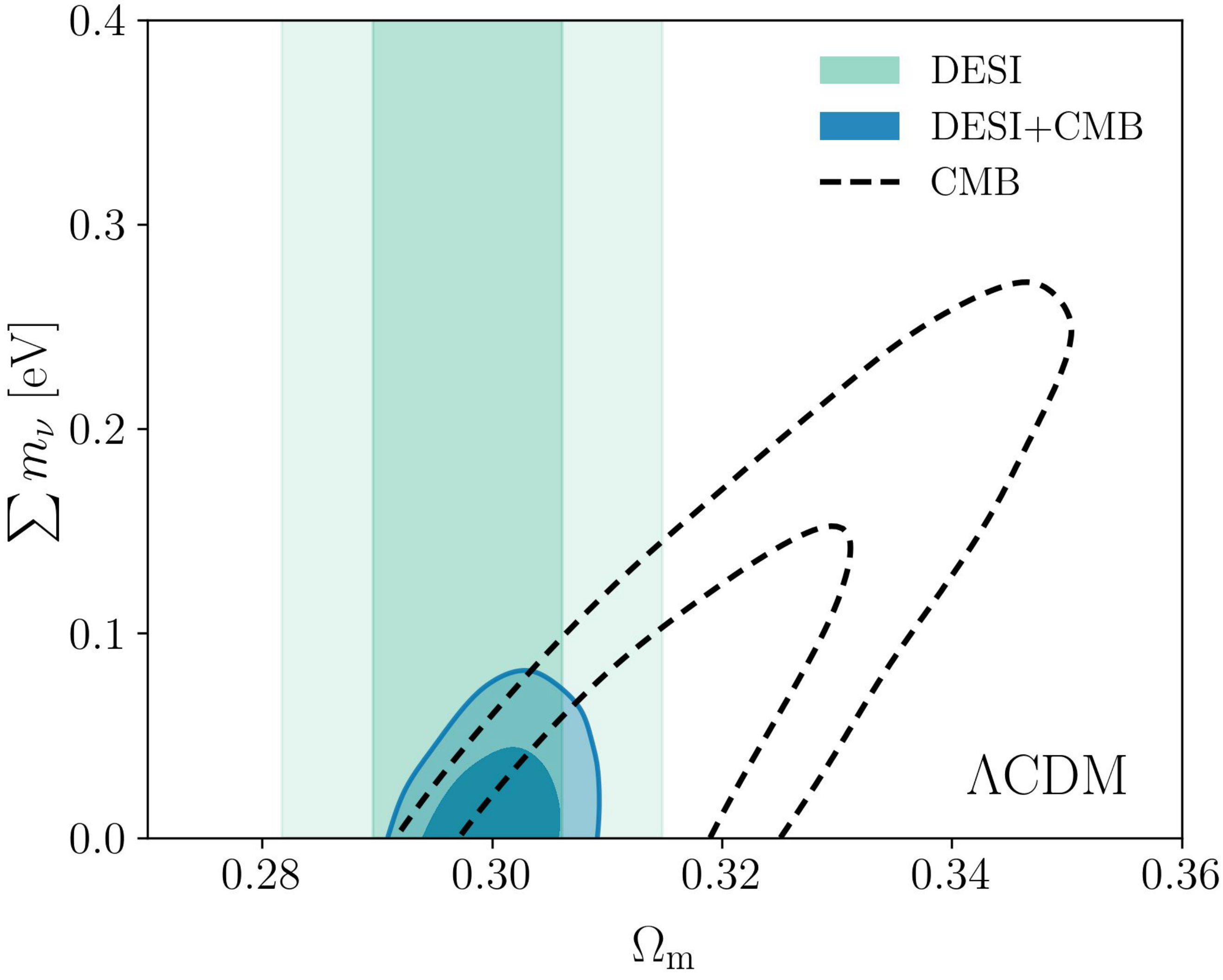
With the measured w_0 and w_a, the dark energy crosses the phantom divide at z~0.5

$$\boldsymbol{w_0 = -0.752 \pm 0.057}$$
$$\boldsymbol{w_a = -0.86^{+0.23}_{-0.20}}$$

DESI+CMB+DESY5

DESI (Dark Energy Spectroscopic Instrument)

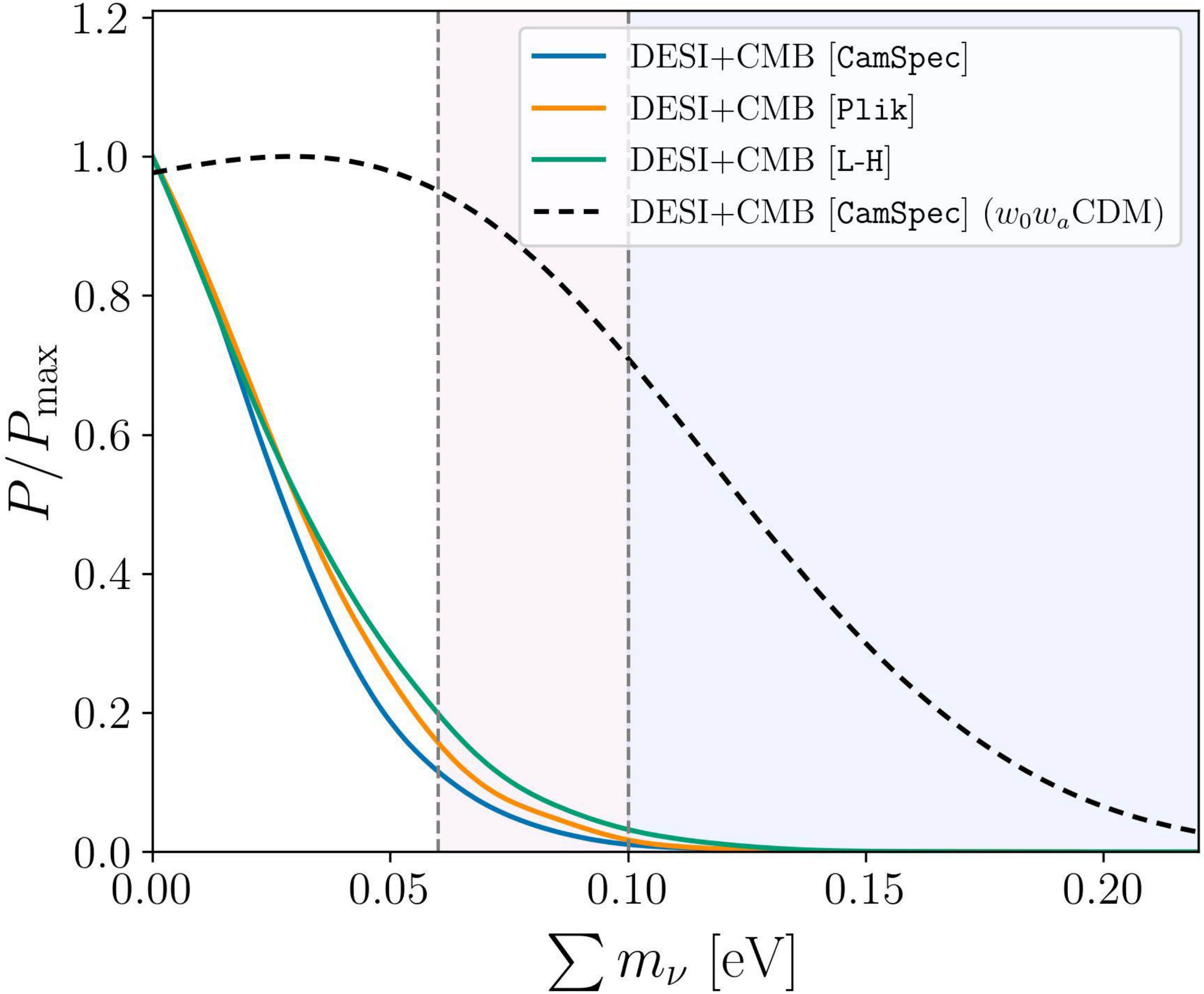
Neutrinos



Matter content disagreement implies very low neutrino mass

DESI (Dark Energy Spectroscopic Instrument)

Neutrinos



DESI+CMB:

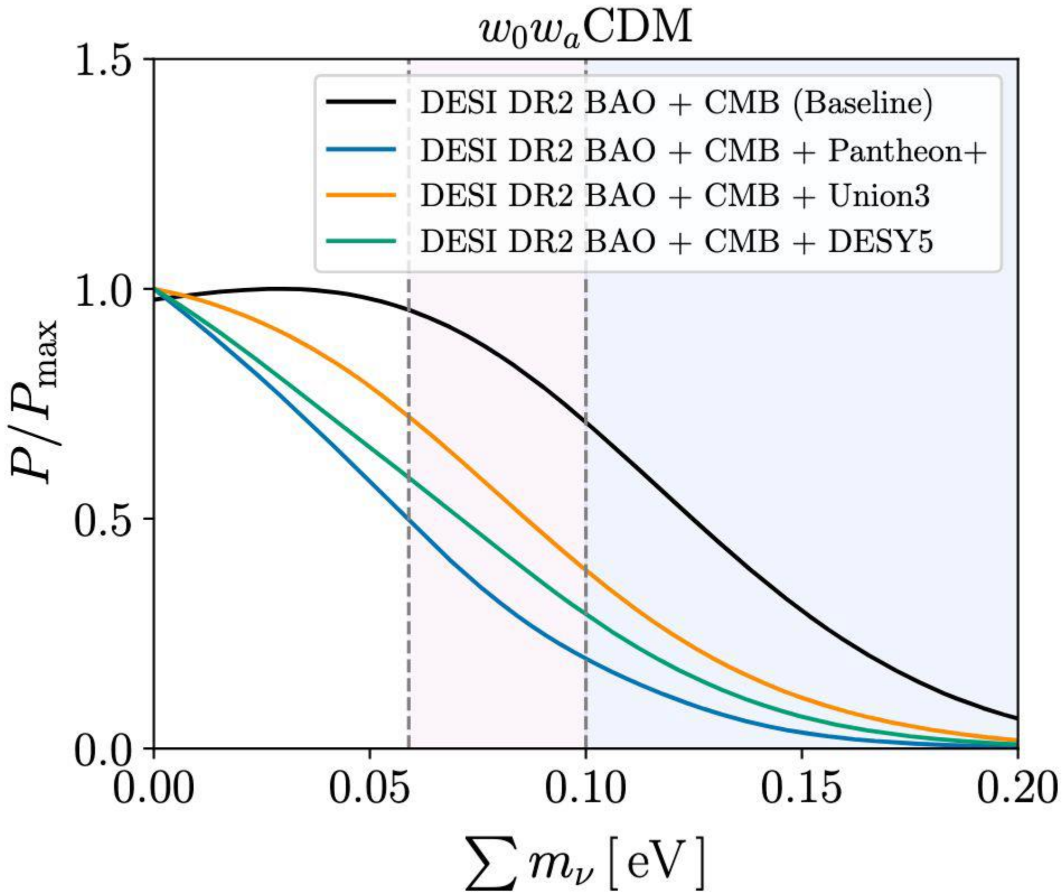
ΛCDM:
$\Sigma m_\nu < 0.0642$ eV (95%)
$\Sigma m_\nu < 0.0774$ eV (95%, using L-H)

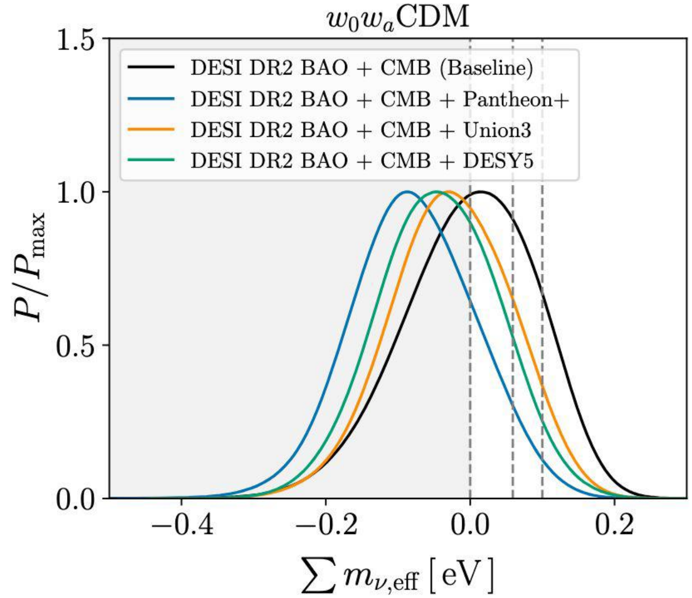
w_0w_aCDM:
$\Sigma m_\nu < 0.163$ eV (95%)

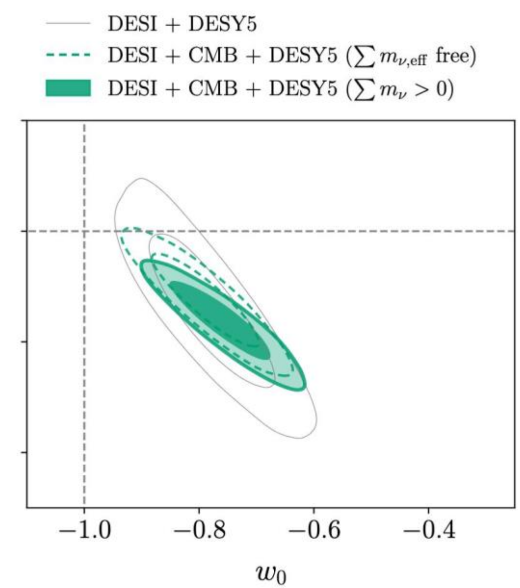
DESI (Dark Energy Spectroscopic Instrument)

Neutrinos

DESI+CMB+SNe







DESI (Dark Energy Spectroscopic Instrument)

The Future

- **DESI (primarily z<1.5)**
  - Five year survey + 2.5 year extension aimed at Dark Energy with BAO and RSD
  - Many more DR2 results on the horizon, including full shape analysis, then DR3, …

- **DESI-II (primarily z>2)**
  - Focused on z>2. Aim for a six year survey with some instrument upgrades
  - Early dark energy and growth of structure in the matter-dominated regime
  - Synergies with other Cosmic Frontier experiments (Rubin, CMB S-4)

- **Spec-S5 (Spectroscopic Stage 5, where DESI is 'Stage 4")**
  - New facility or facilities and new instrumentation

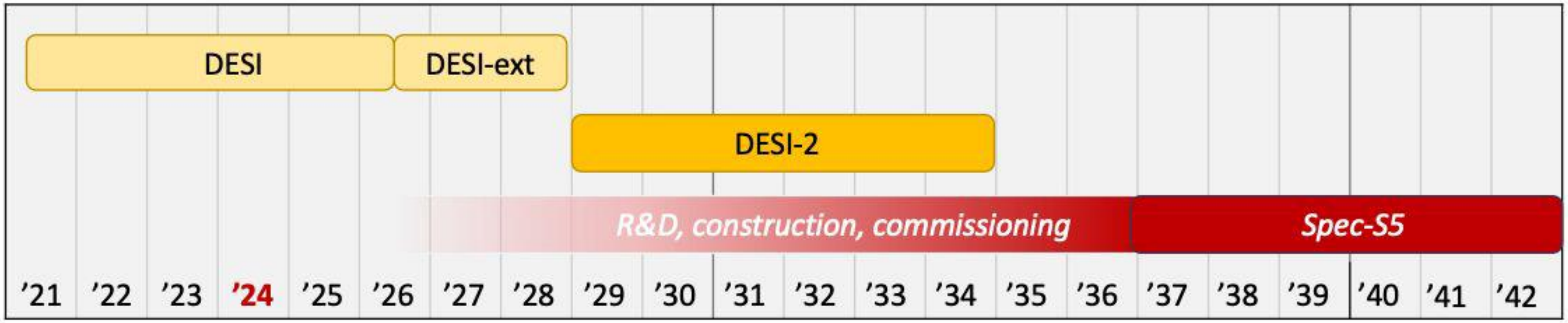
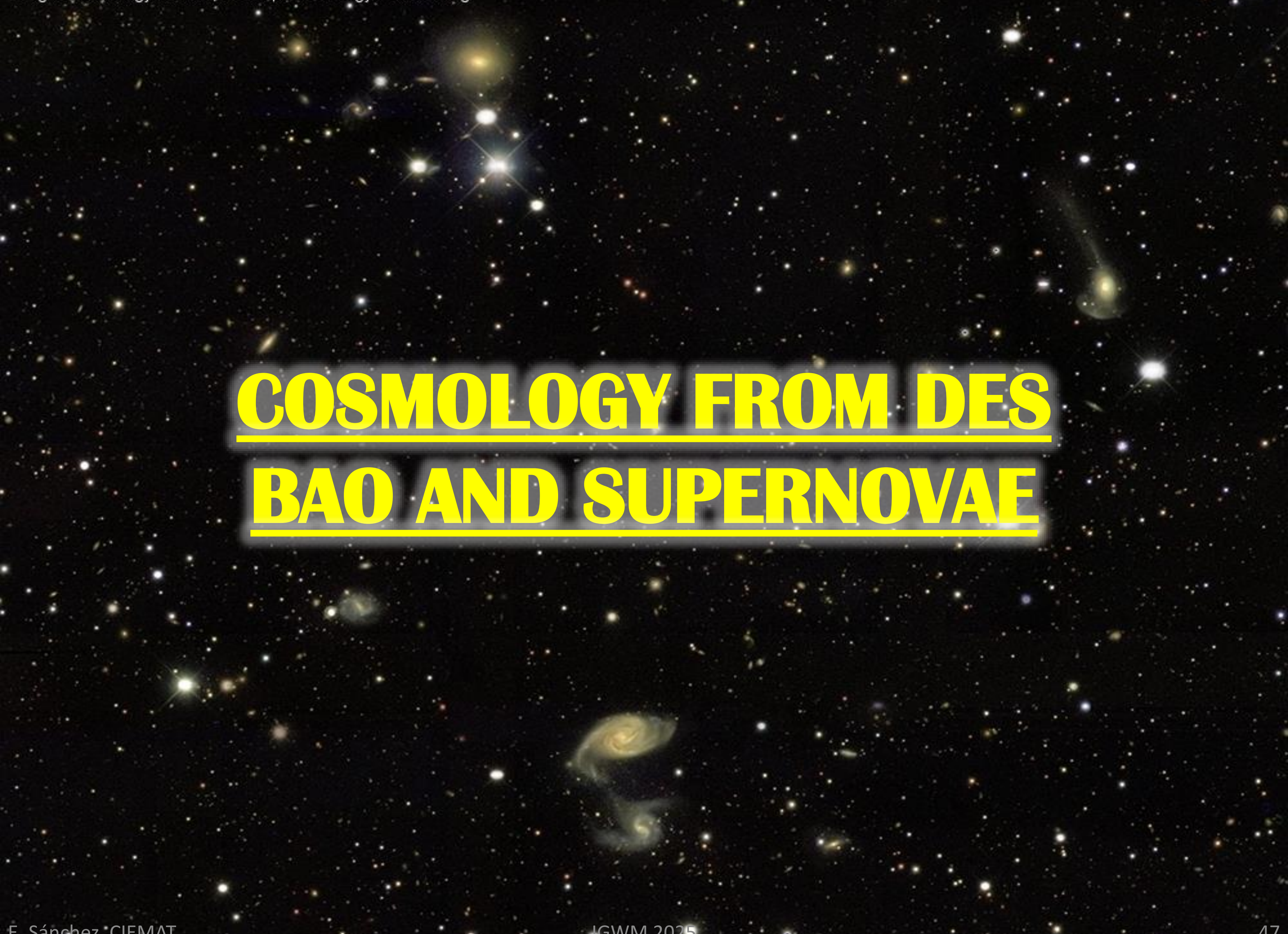


Image: Dark Energy Camera, from http://darkenergydetectives.org



COSMOLOGY FROM DES BAO AND SUPERNOVAE

DES (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
+ 30 sq-deg time-domain griz (SNe)

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

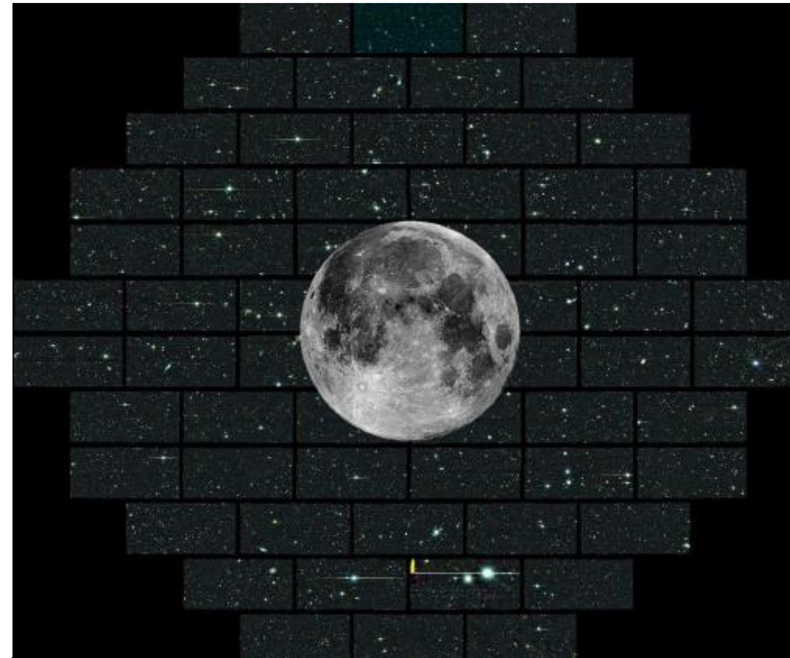
570 Mpx camera with 3 sq-deg FoV, DECam

DES (Dark Energy Survey)

Camera installed on Blanco since 2012

Took data from 2013 to 2019
Currently in the final phase of scientific data. Full final results this year.

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)



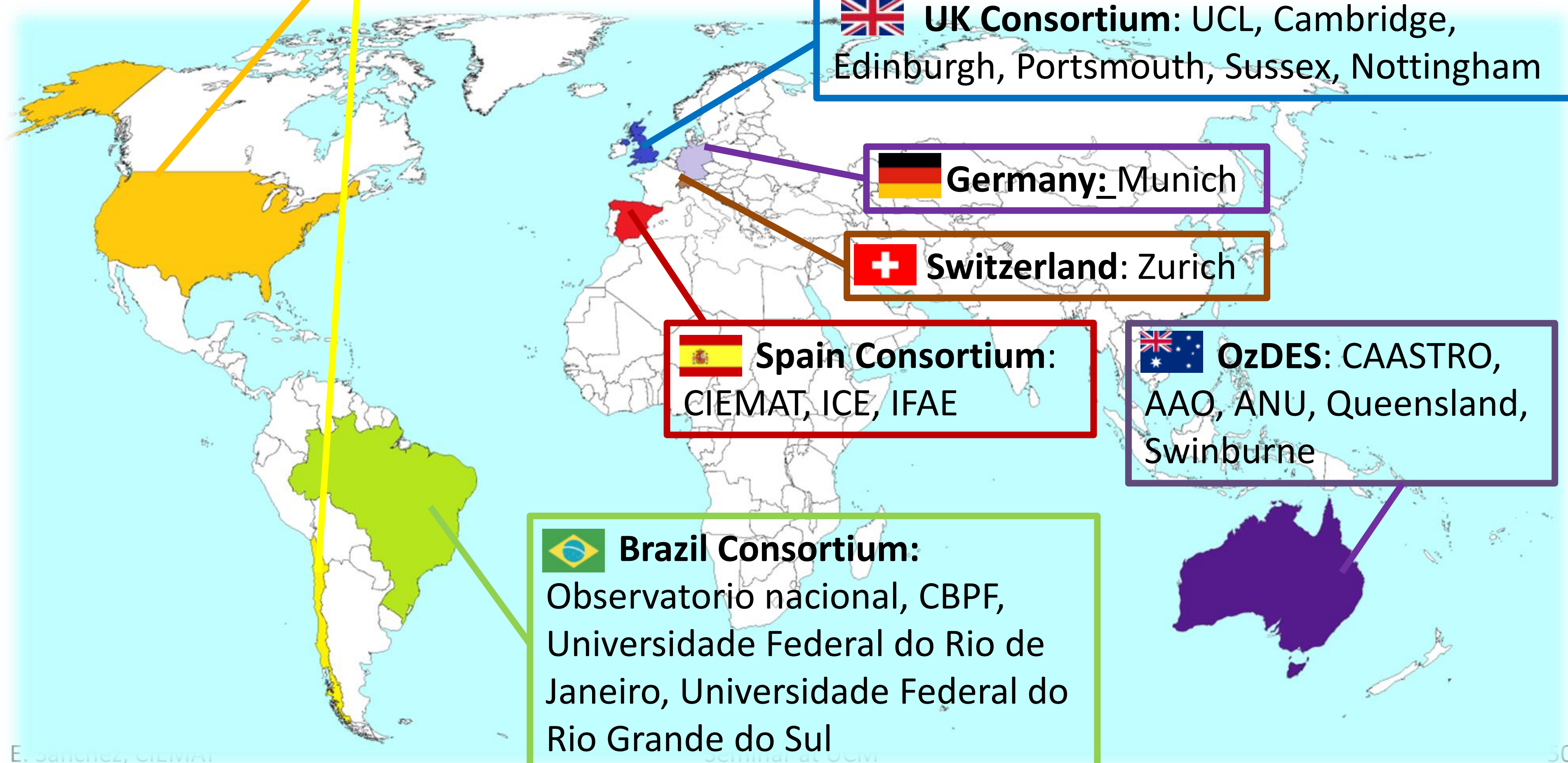
DES (Dark Energy Survey)

DARK ENERGY SURVEY

~500 scientists from 25 institutions

darkenergysurvey.org

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 (Dark Energy Survey)

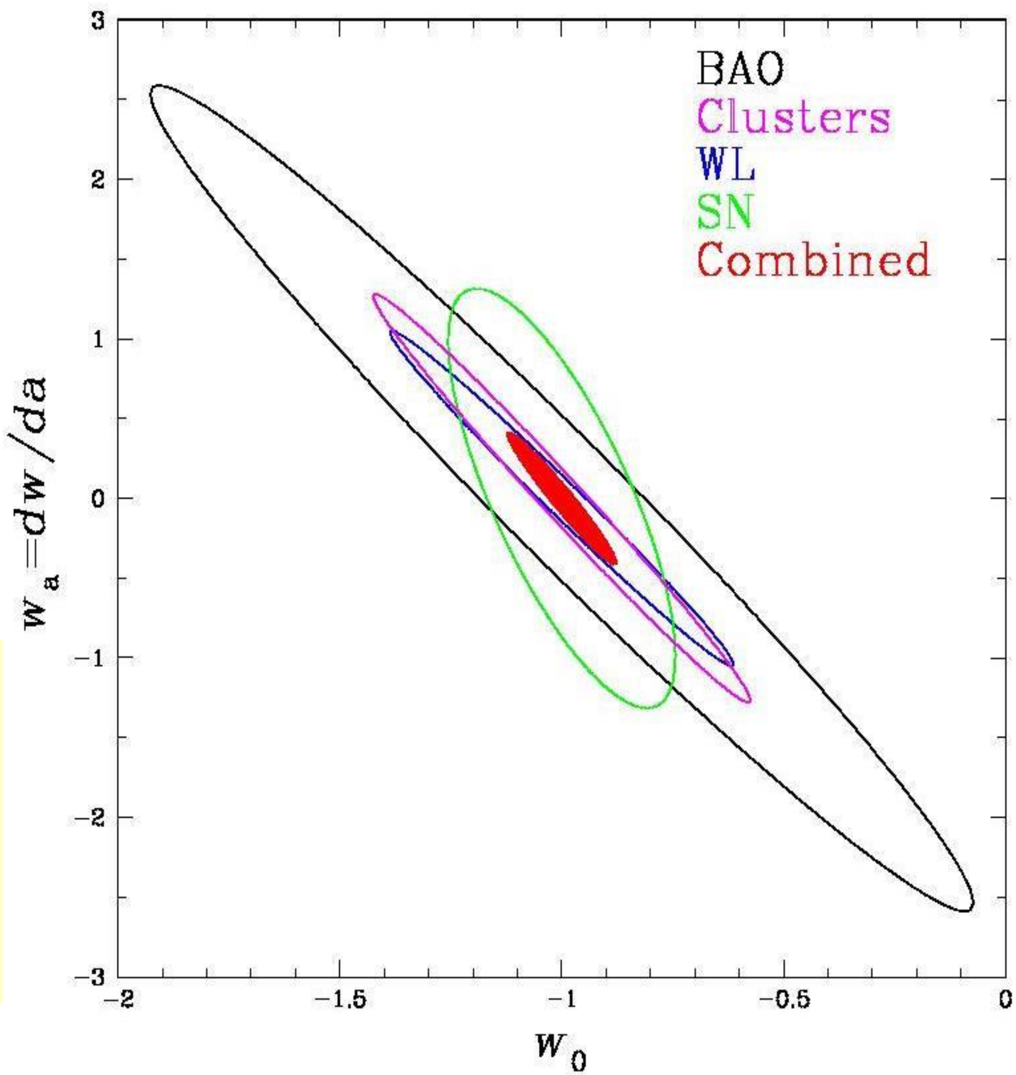
4 Probes of Dark Energy

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

Galaxy Clustering (struct) and its Baryon Acoustic Oscillations (dist)
300 million galaxies to z~1.4

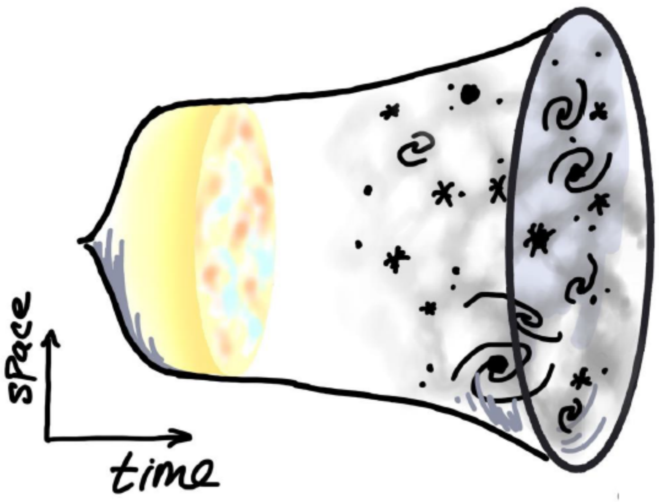
Supernovae (dist)
3500 well-sampled Sne Ia to z~1



DES (Dark Energy Survey)

We probe physics with the Dark Energy Survey by observing:

Background expansion



Focus of this talk!

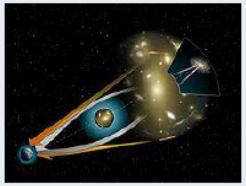
Galaxy clustering

Supernovae

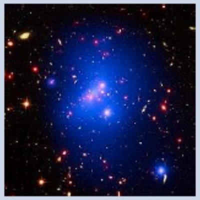
Structure growth

Galaxy clustering

Weak lensing



Galaxy clusters



Results about the growth of structure with the full DES sample will be published later this year

And more! Milky Way structure, galaxy evolution, QSOs, strong lensing, GW follow-up, solar system objects (TNO, comets)

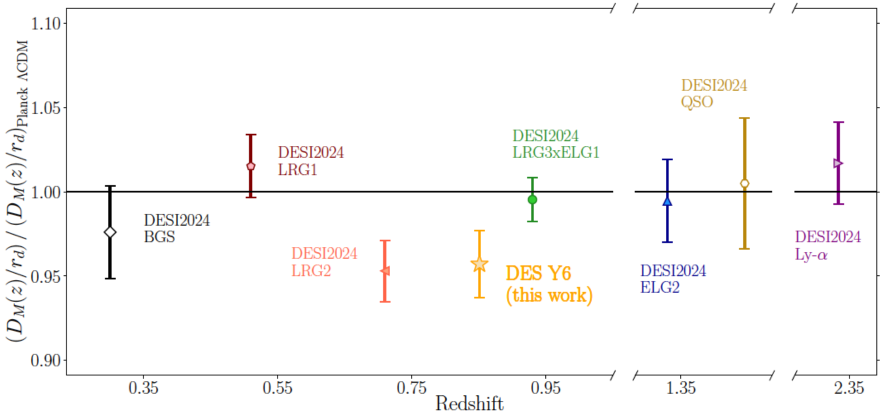
DES (Dark Energy Survey)

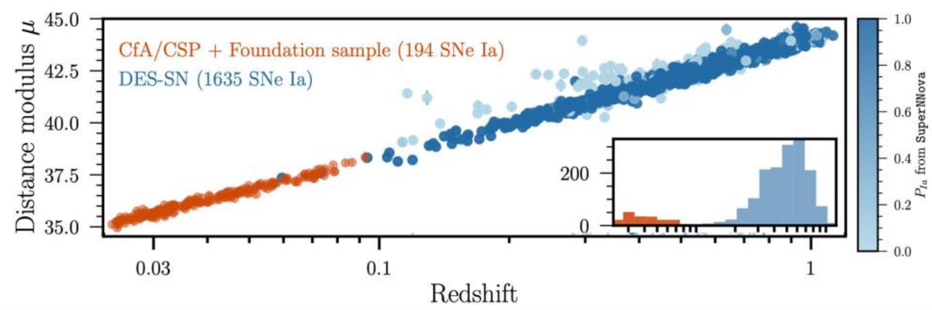
Using DES project galaxy clustering, we measured the BAO scale was measured to 2.1% accuracy

4.3% and 2.1σ below Planck ΛCDM

DES SNe is the largest and deepest supernova sample ever compiled from a single telescope

1635 SN 1a photometrically classified
Combined with 194 SN 1a at low redshift from other projects

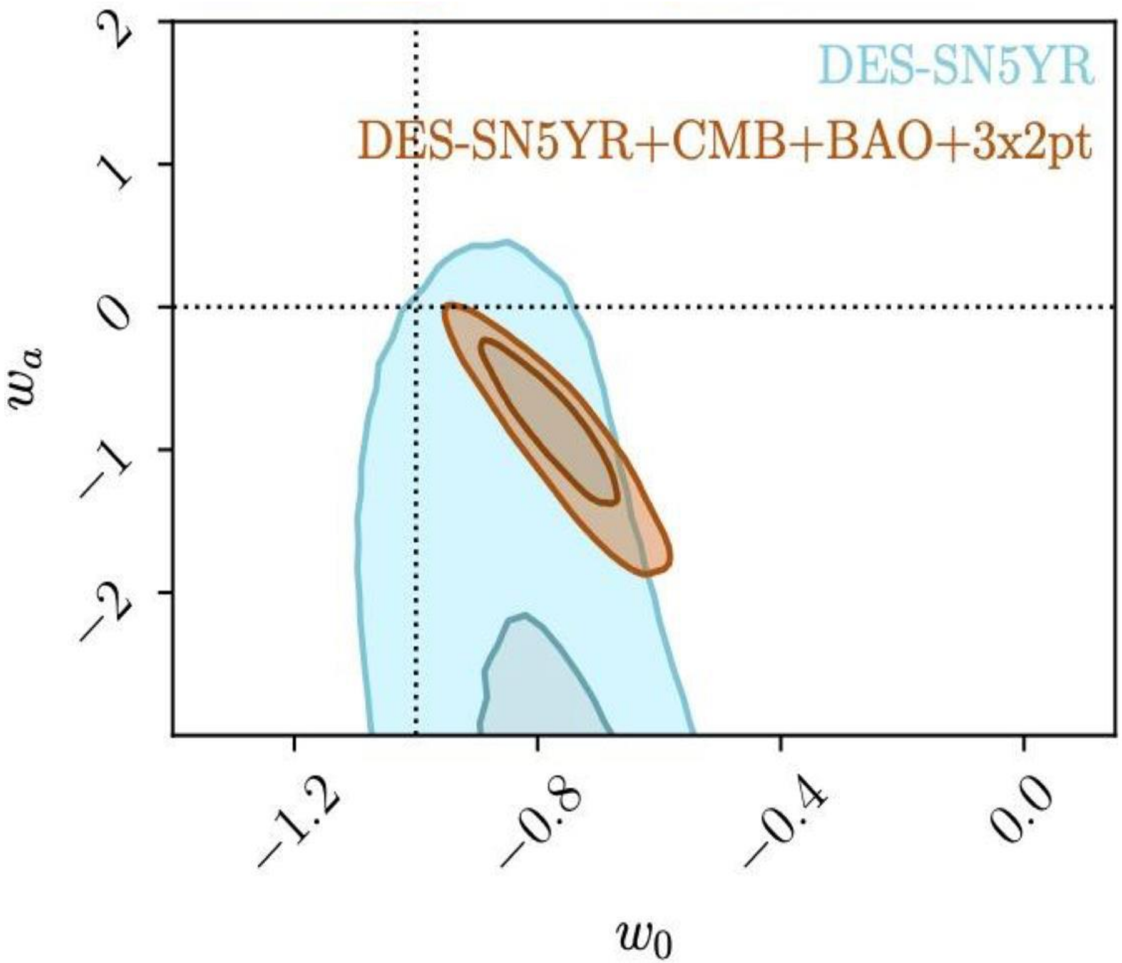




These are the final results from DES for cosmological probes about the expansión history of the Universe

DES (Dark Energy Survey)

Combining both probes…



When combining DES BAO with DES SNe and the CMB, we find a parameter shift of 3.2σ away from ΛCDM

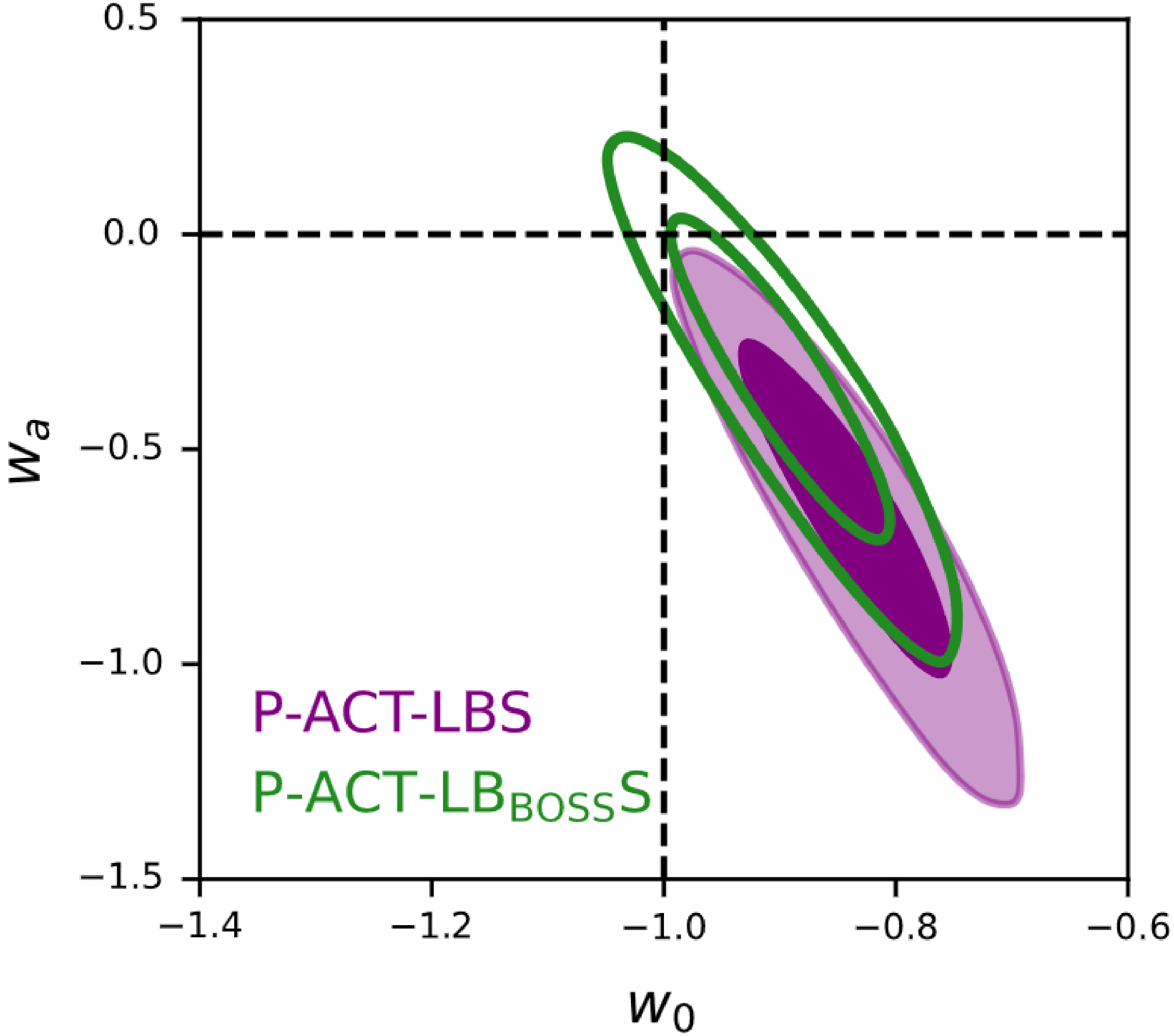
Similar but lower significance than DESI results

Image: Dark Energy Camera, from http://darkenergydetectives.org

ADDITIONAL DATA: ACT

ACT (Atacama Cosmology Telescope)

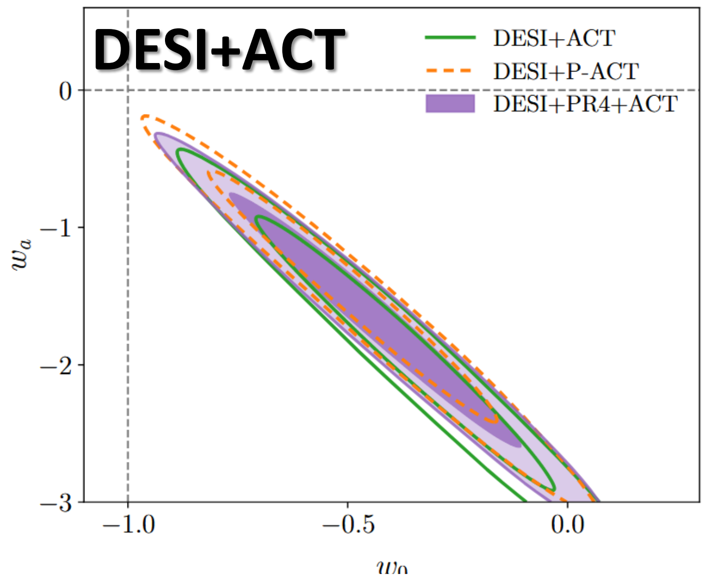
Just to make more noise…

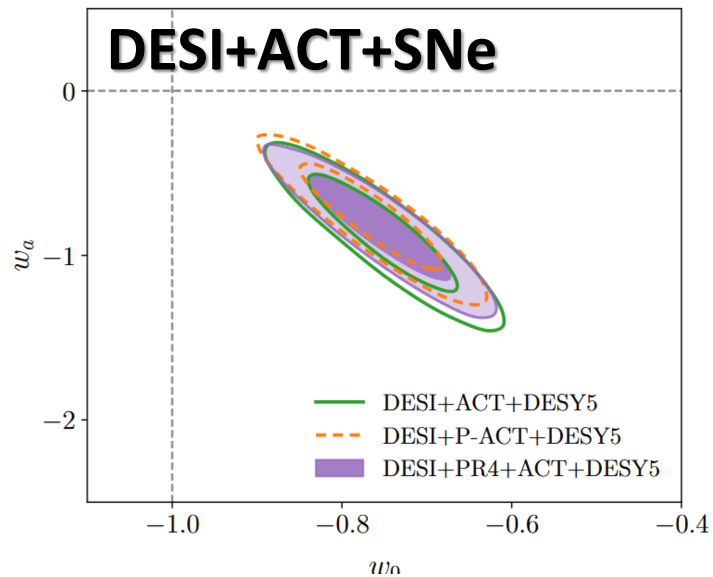


P-ACT-LBS: Planck + ACT + Planck Lensing + DESI Y1 BAO + Pantheon+ SN

B$_{BOSS}$ uses BOSS BAO instead of DESI-Y1 BAO

DESI + ACT


DESI+ACT
DESI+ACT
DESI+P-ACT
DESI+PR4+ACT
w_a
w_0


DESI+ACT+SNe
DESI+ACT+DESY5
DESI+P-ACT+DESY5
DESI+PR4+ACT+DESY5
w_a
w_0

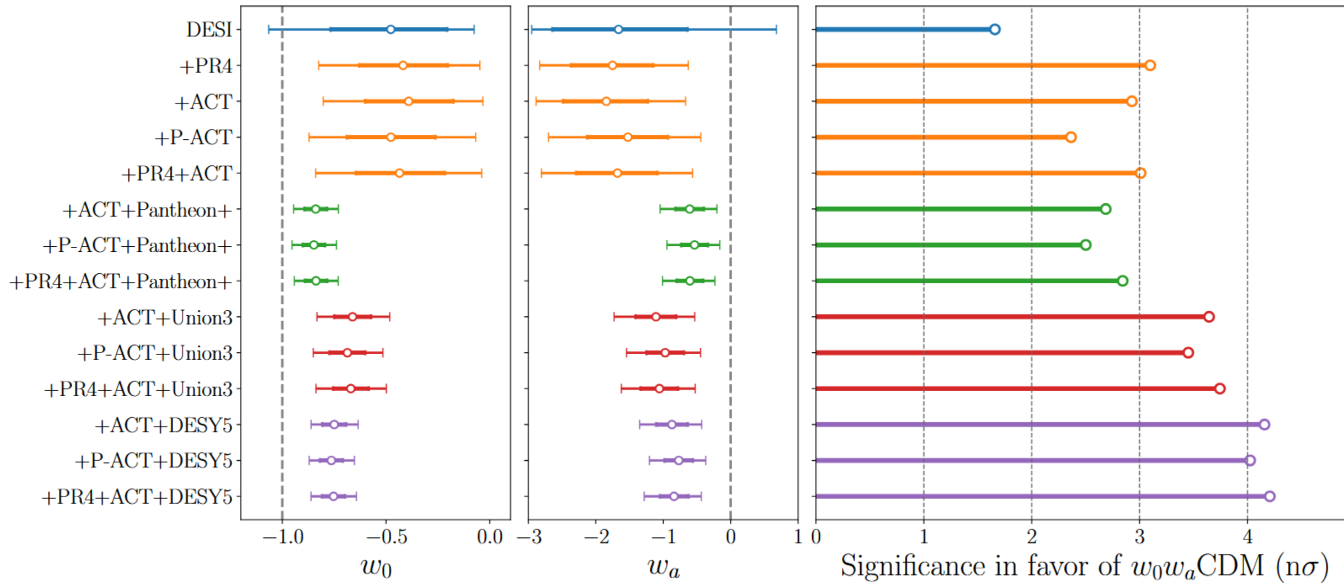

DESI
+PR4
+ACT
+P-ACT
+PR4+ACT
+ACT+Pantheon+
+P-ACT+Pantheon+
+PR4+ACT+Pantheon+
+ACT+Union3
+P-ACT+Union3
+PR4+ACT+Union3
+ACT+DESY5
+P-ACT+DESY5
+PR4+ACT+DESY5
w_0
w_a
Significance in favor of w_0w_aCDM ($n\sigma$)

Image: Dark Energy Camera, from http://darkenergydetectives.org

CONCLUSIONS

CONCLUSIONS

- New measurement of BAO from DESI with 14 million galaxies
- Precision well below 1% at all redshifts
- DESI DR2 is fully consistent with DESI DR1
    - ***DESI+CMB+SNe prefer w_0w_a over ΛCDM more than DR1***
    - ***DESI BAO+CMB prefer dynamical dark energy at 3.1σ***
    - ***DESI BAO+CMB+SN prefer dynamical dark energy at 2.8σ–4.2σ***
- ***$\Sigma m_\nu < 0.064$ eV in ΛCDM , $\Sigma m_\nu < 0.16$ eV in w_0w_aCDM***
- More and better data are coming
- Final DES results about expansión history are compatible with DESI. Final DES results on growth of structure coming this year as well.
- ACT is also finding compatible results

- If this is correct, it would be the most important discovery since DE itself