The Dark Energy Spectroscopic Instrument (DESI): First Cosmology Results

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On behalf of the DESI Collaboration

Seminarios Dpto. Investigación Básica
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Dark Energy Spectroscopic Instrument (DESI)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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- **Located at 4-meter 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 measurements
  - 10X improvement to $w_0 w_a$ figure of merit compared with stage-II Type Ia supernovae measurements
- **Comprehensive cosmology program**
  - Redshift Space Distortions
  - Cross-correlations with other surveys
  - Other wider topics

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

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

Lead by LBNL

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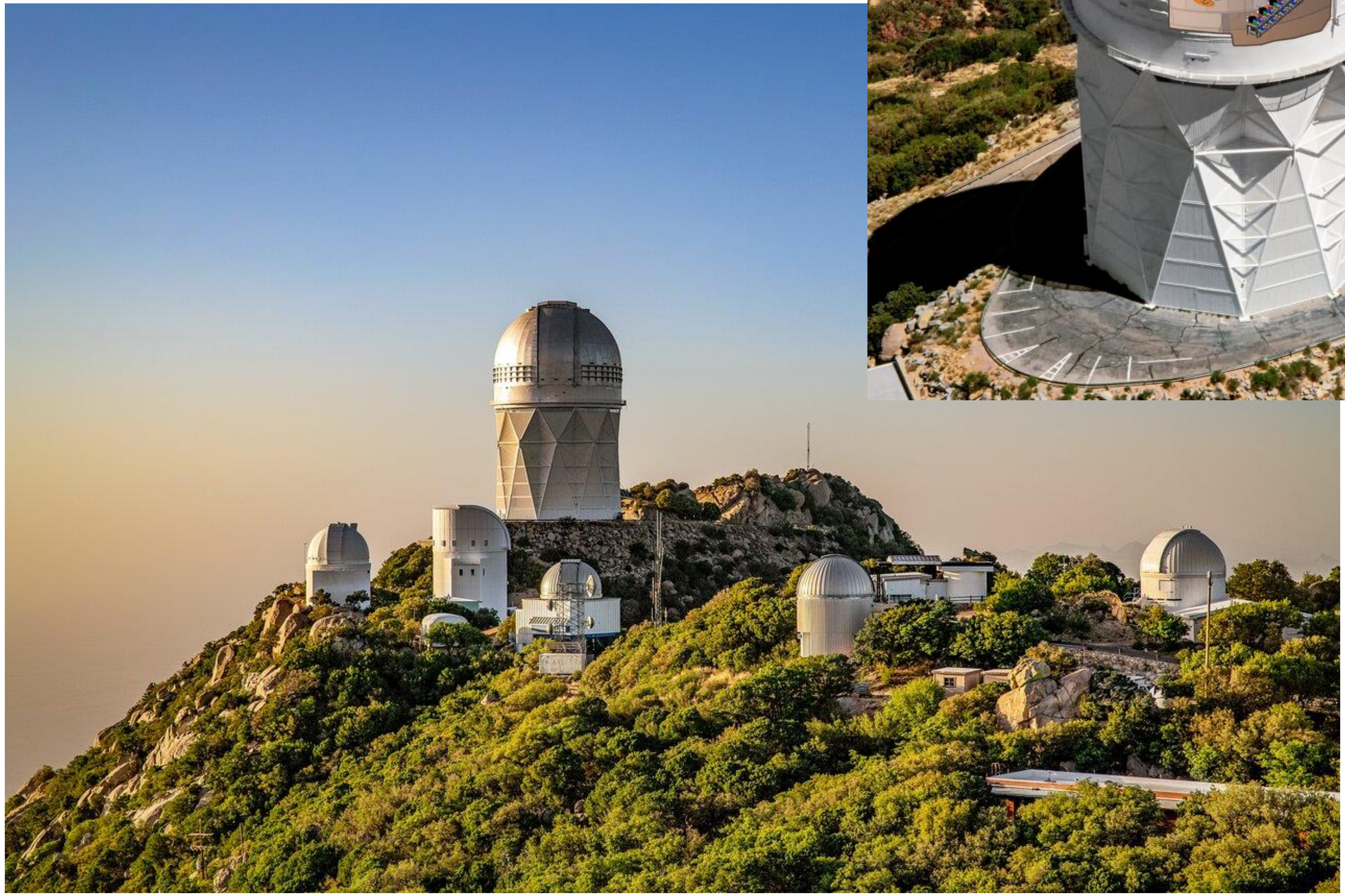
DESI



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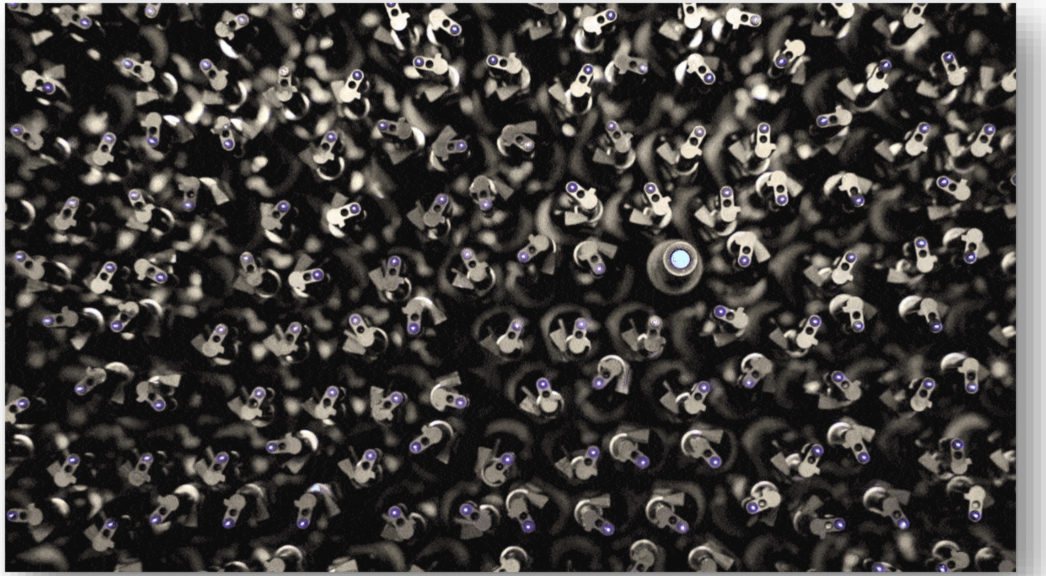
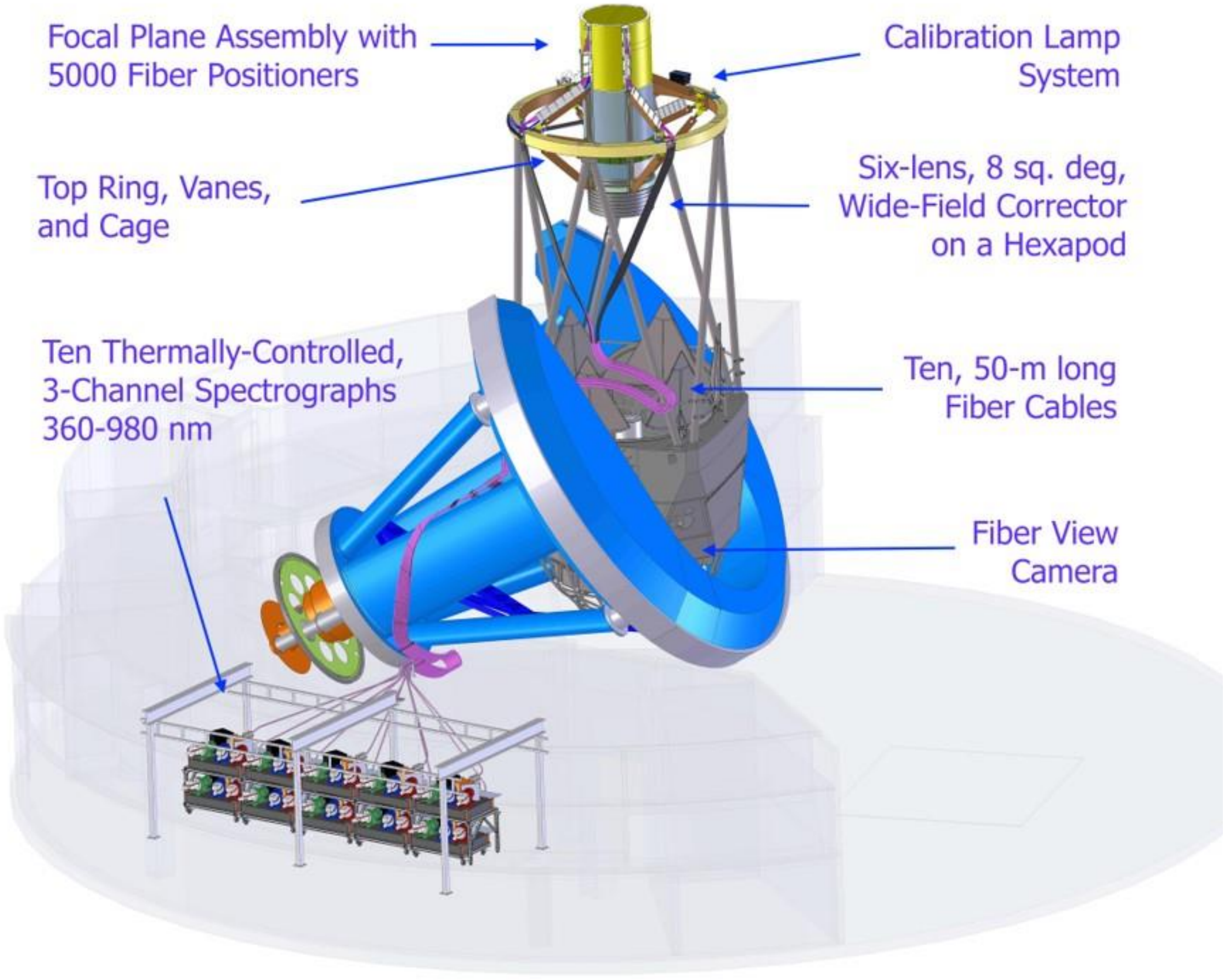
DESI: Massively-multiplexed Spectroscopy

The newest element of DESI are the 5000 fiber positioning robots



~1 minute to position fibers!



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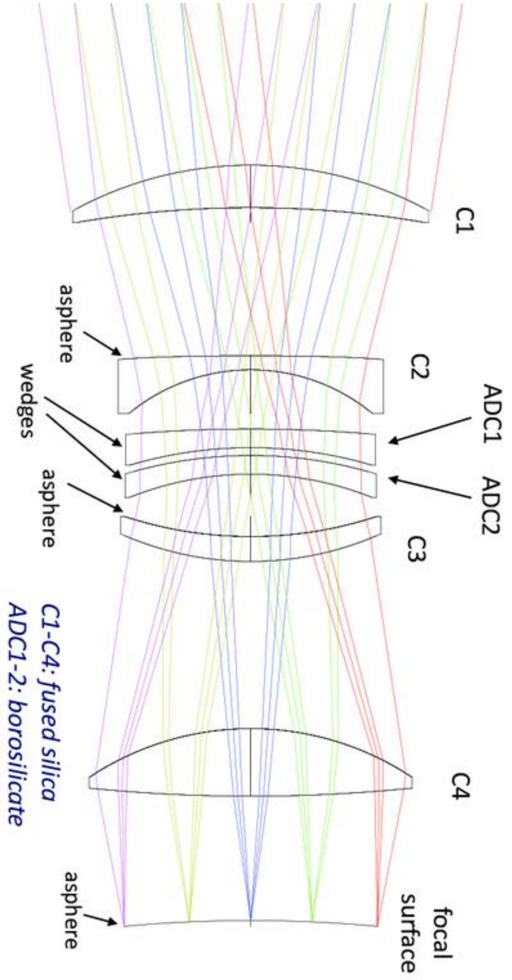
DESI Corrector

DESI Corrector

- 8 deg^2 wide field of view
- 6 lenses, each about a meter in diameter
- Four have all-spherical surfaces and two have an aspheric surface

Performance

- Coatings are superb
- Excellent image quality
- Achieved < 0.6" images



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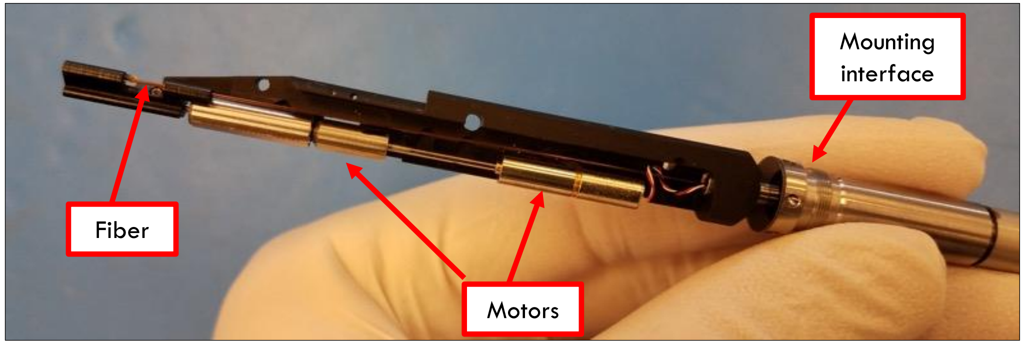
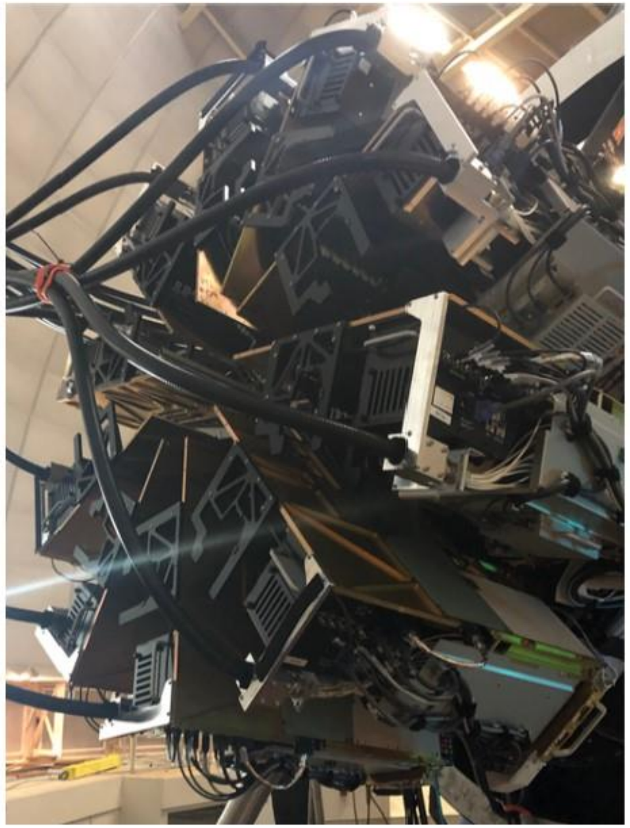
DESI:Focal Plane

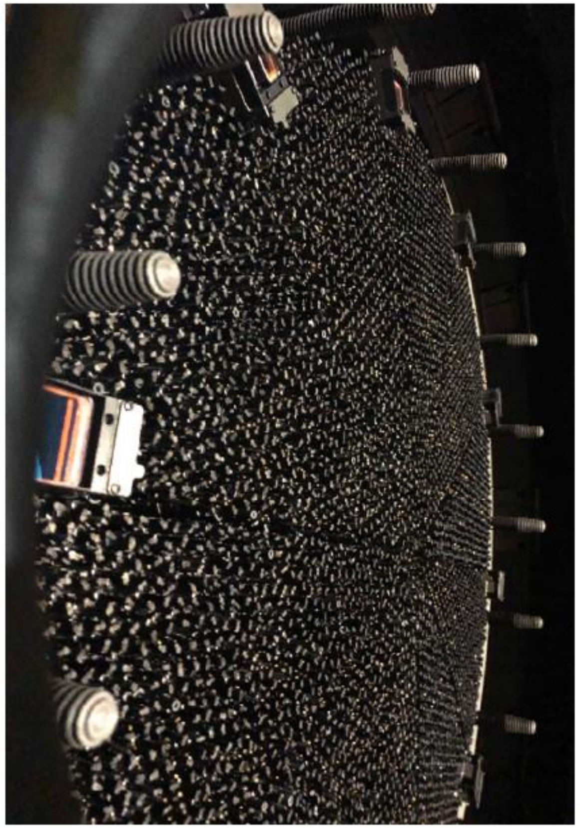


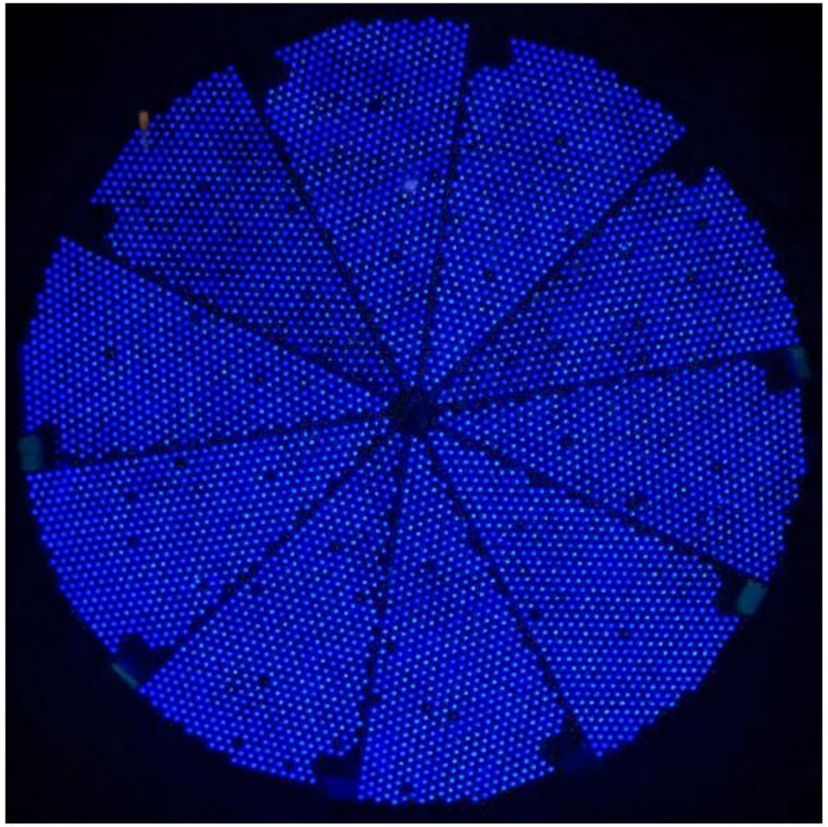
5000 robotic positioners, each holding a fiber-optic cable.

Each one is automatically positioned to fix on a preset sequence of individual galaxies and quasars so that the fibers can collect their light.

The movements of these positioners must be carefully choreographed to avoid collisions.







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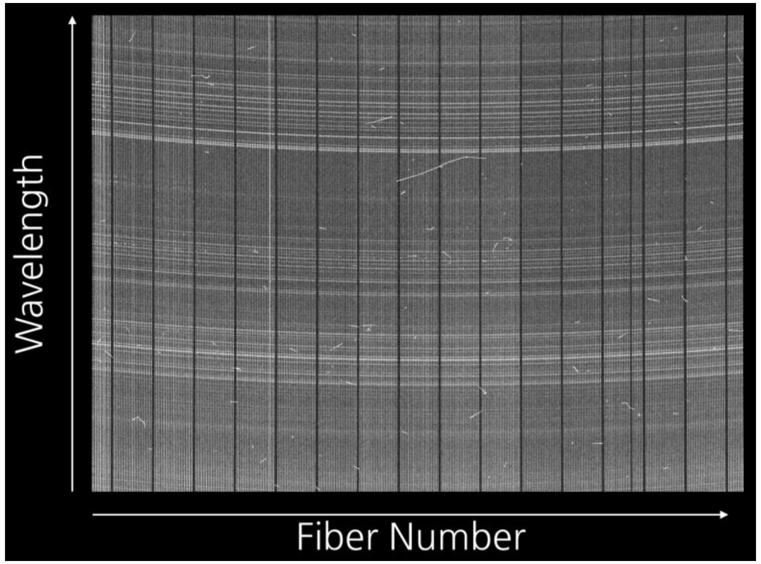
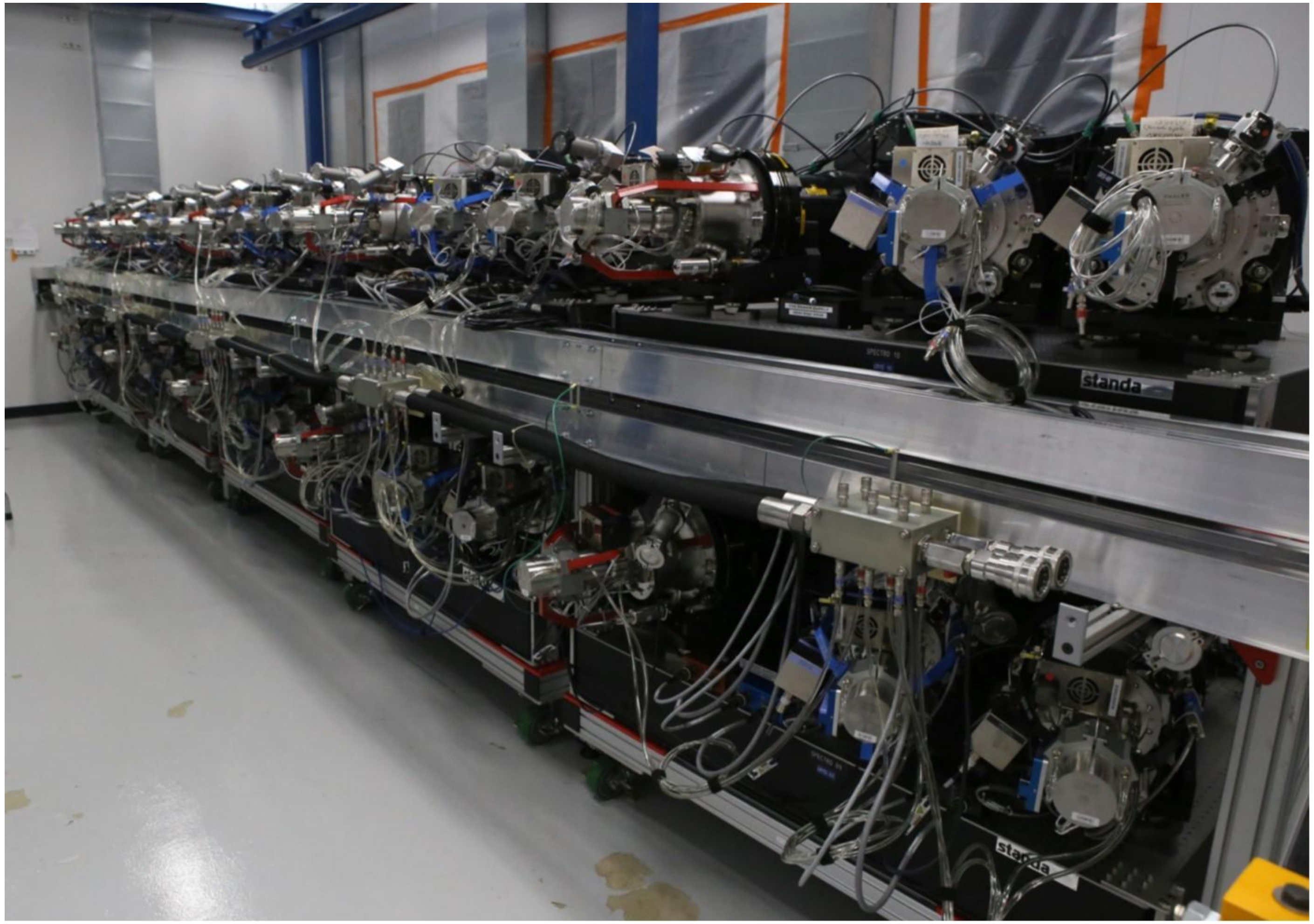
DESI: Spectrographs





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)

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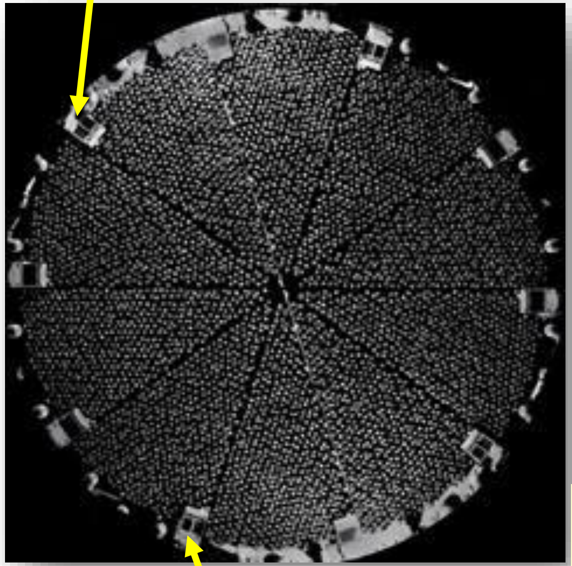
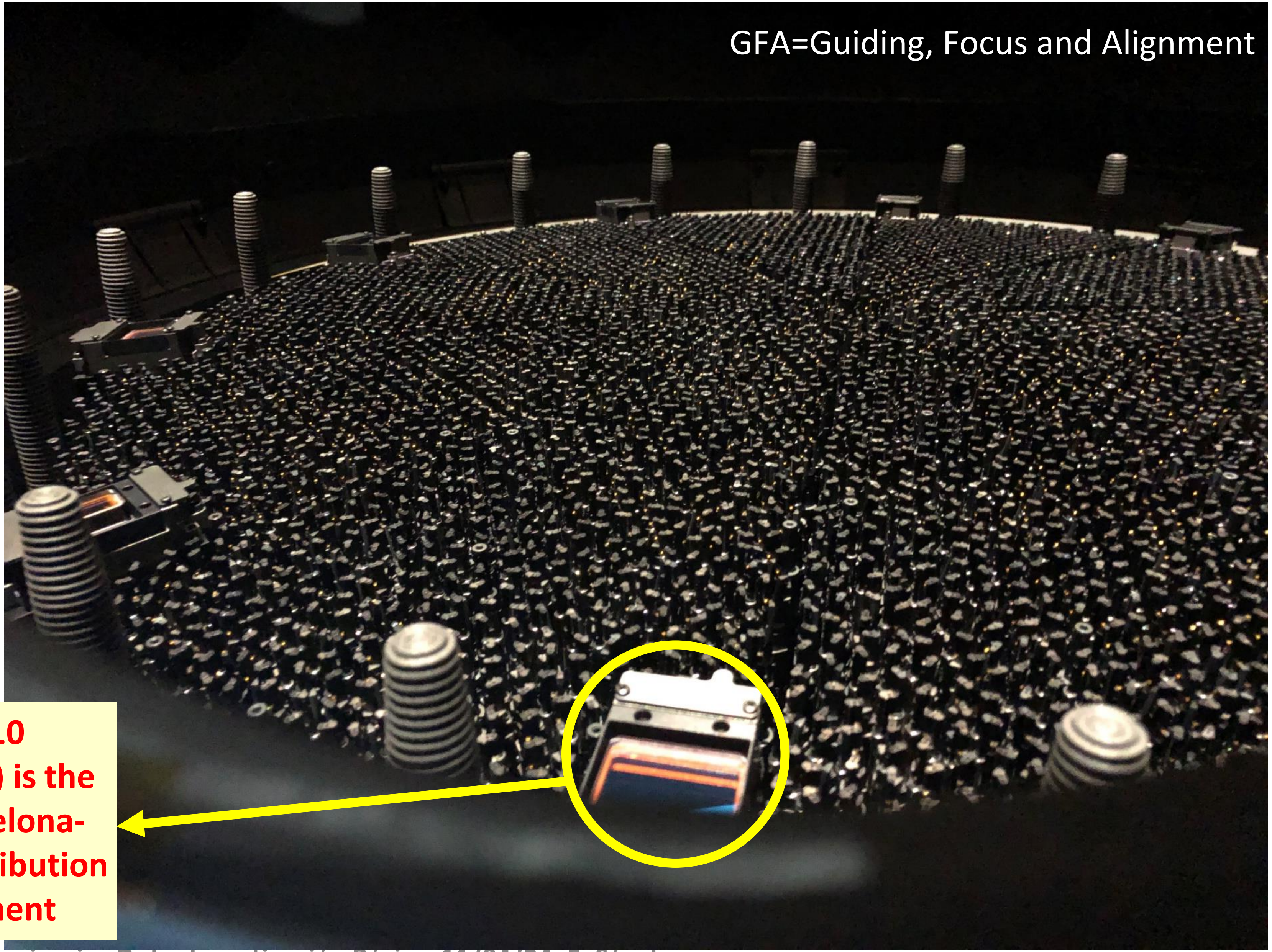
DESI: Fibers and GFA Systems

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

6 Guide Cameras
r filter



4 Wavefront Cameras
r filter, split thickness



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

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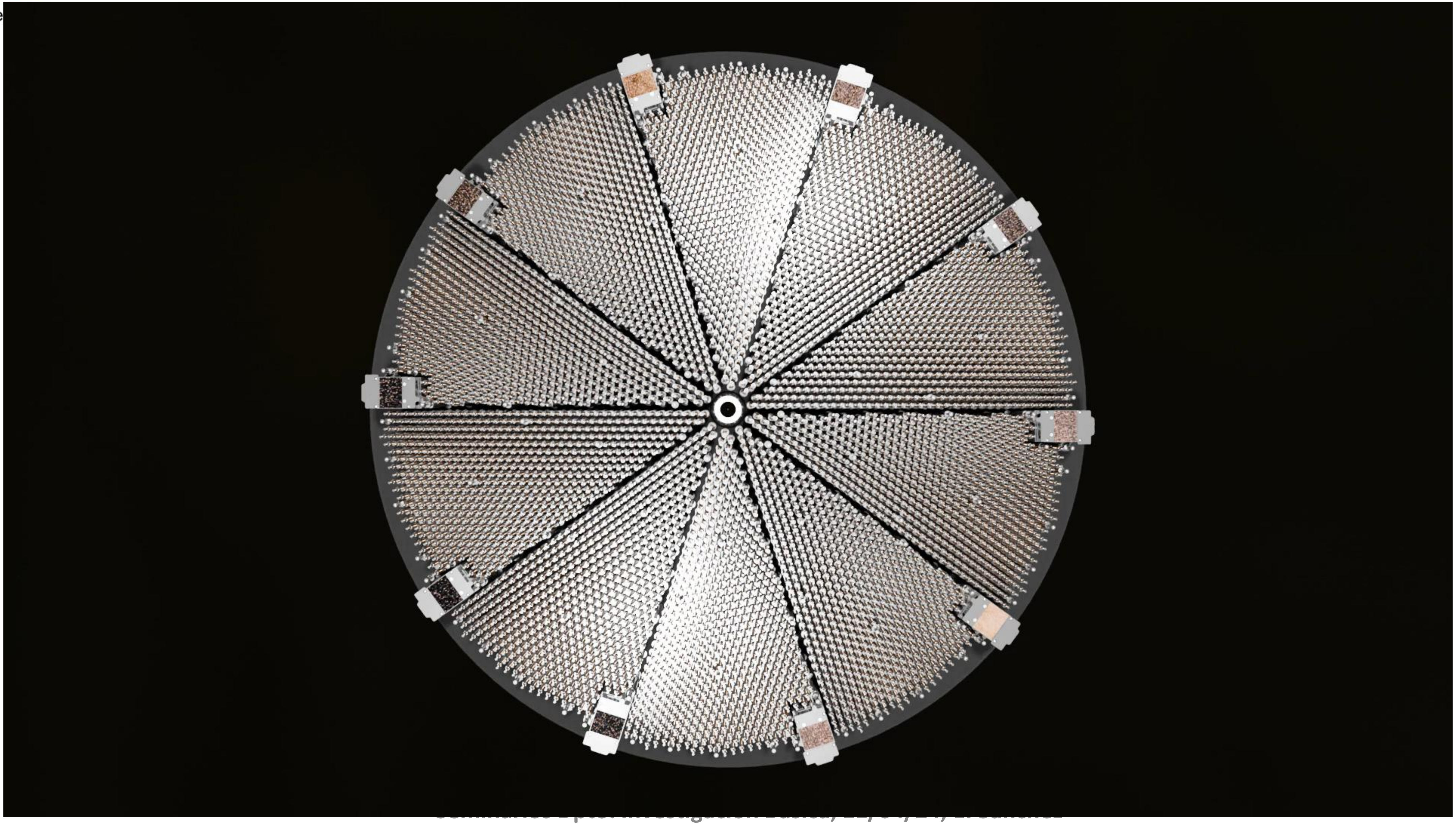
U.S. Departme

DESI: Animation of Robots



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Galaxy and Quasars from 0<z<3.5

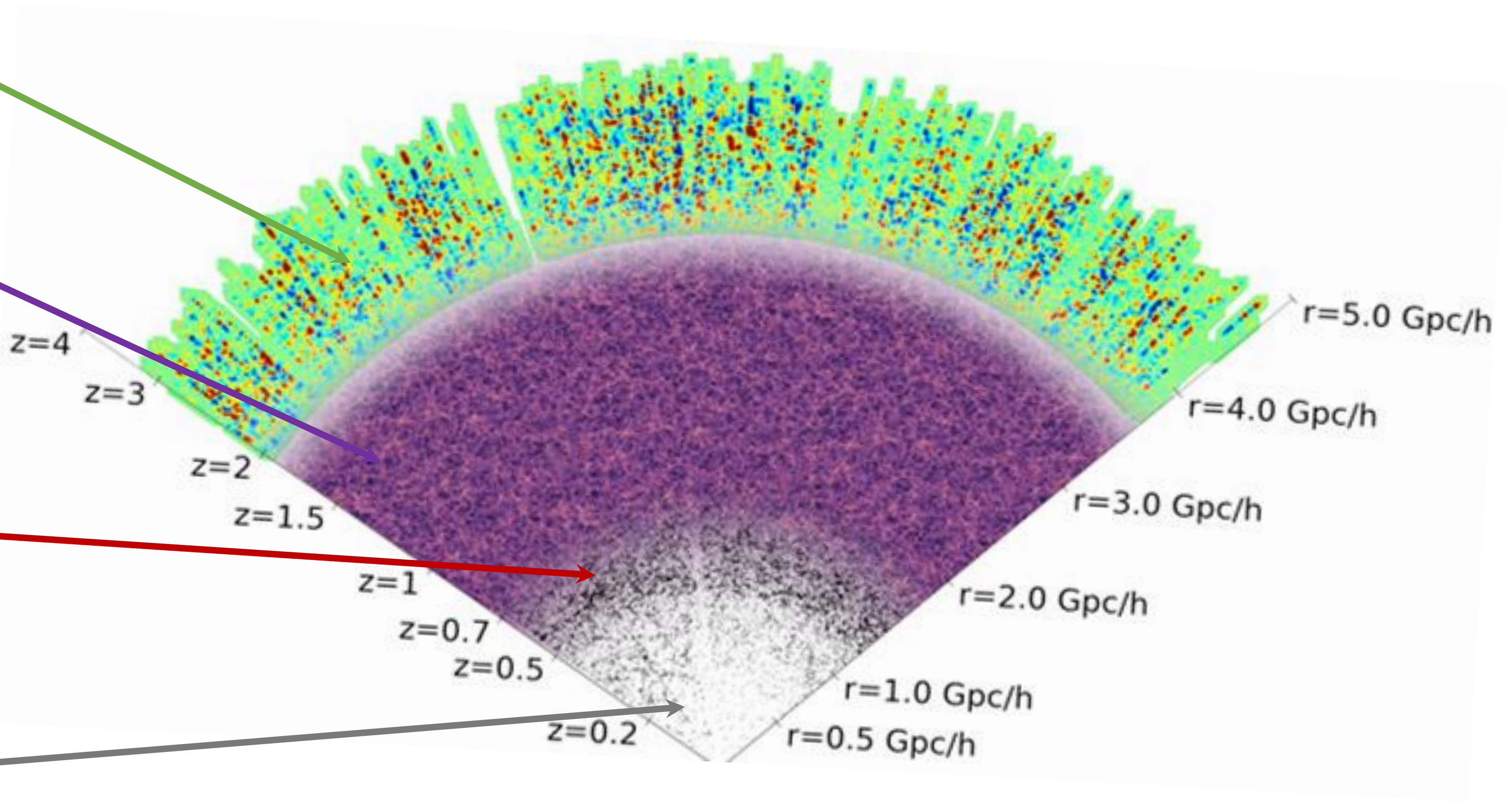
~40 million galaxies+quasars in 5 years

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 ($0.0 < z < 0.4$)



Plus 10 million Milky Way stars

Targets from Legacy Imaging Survey

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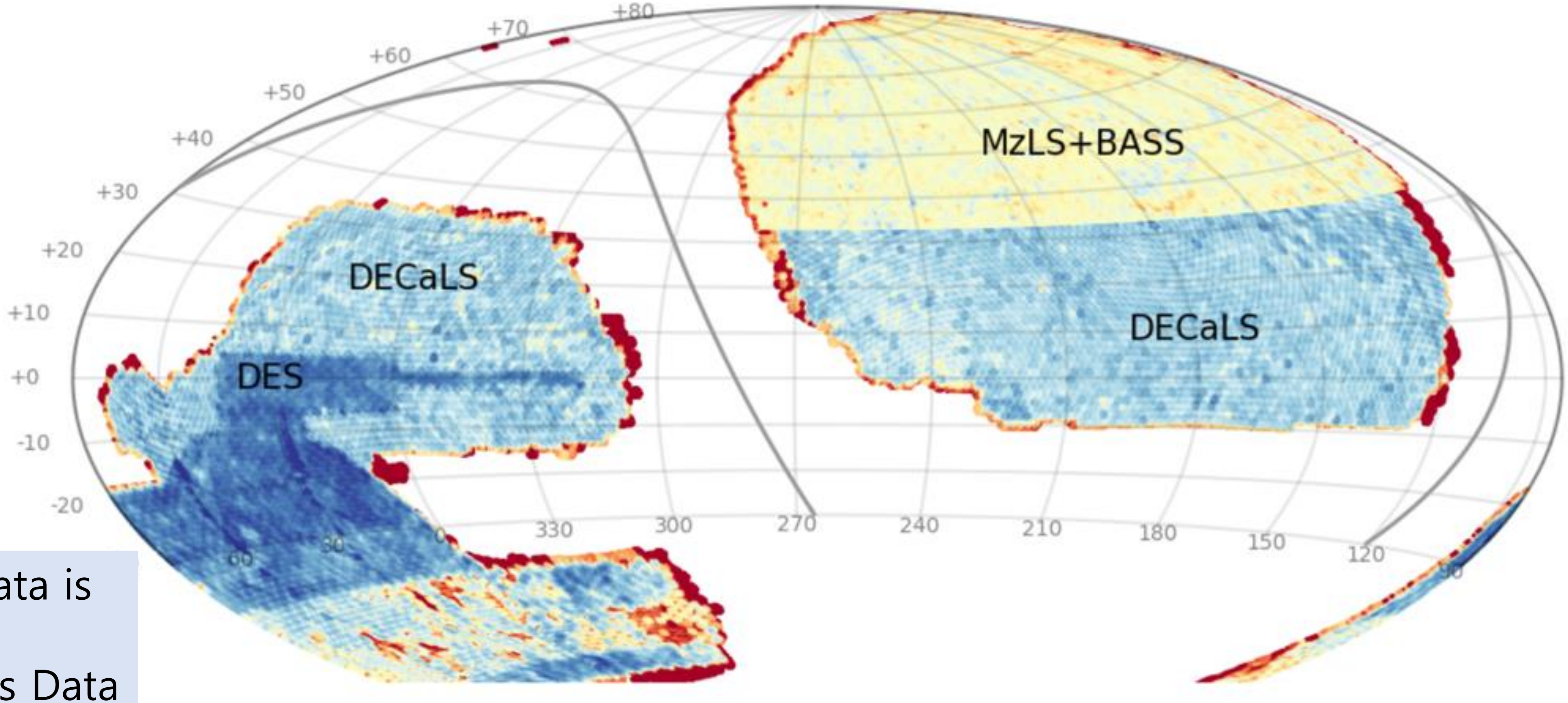
North:
BASS (Beijing Arizona Sky Survey) → g, r bands; 5000 sq-deg
MzLS (Mayall z-band Legacy Survey) → z band, 5000 sq-deg
South (and North):
DECaLS (Dark Energy Camera Legacy Survey) → g, r, z bands; 9000 sq-deg

All Sky:
WISE (Wide Field IR Survey Explorer),
NASA satélite → W1, W2 bands



- DESI imaging data is fully public
- DESI survey uses Data Release 9

DESI: 3D Map of te Universe

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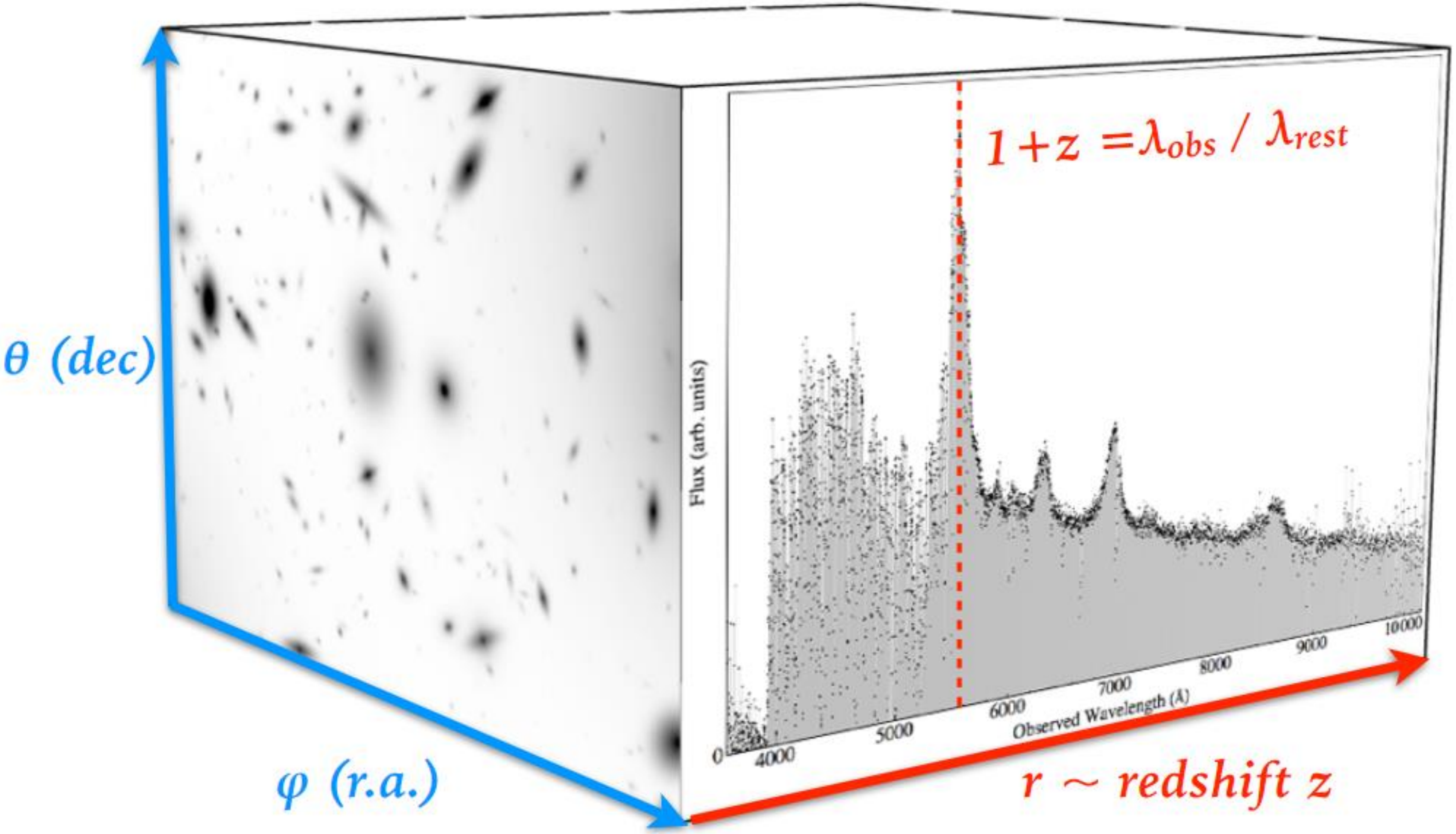

The optical sky is a data cube: $\theta \times \varphi \times r$

3D Map of the Universe

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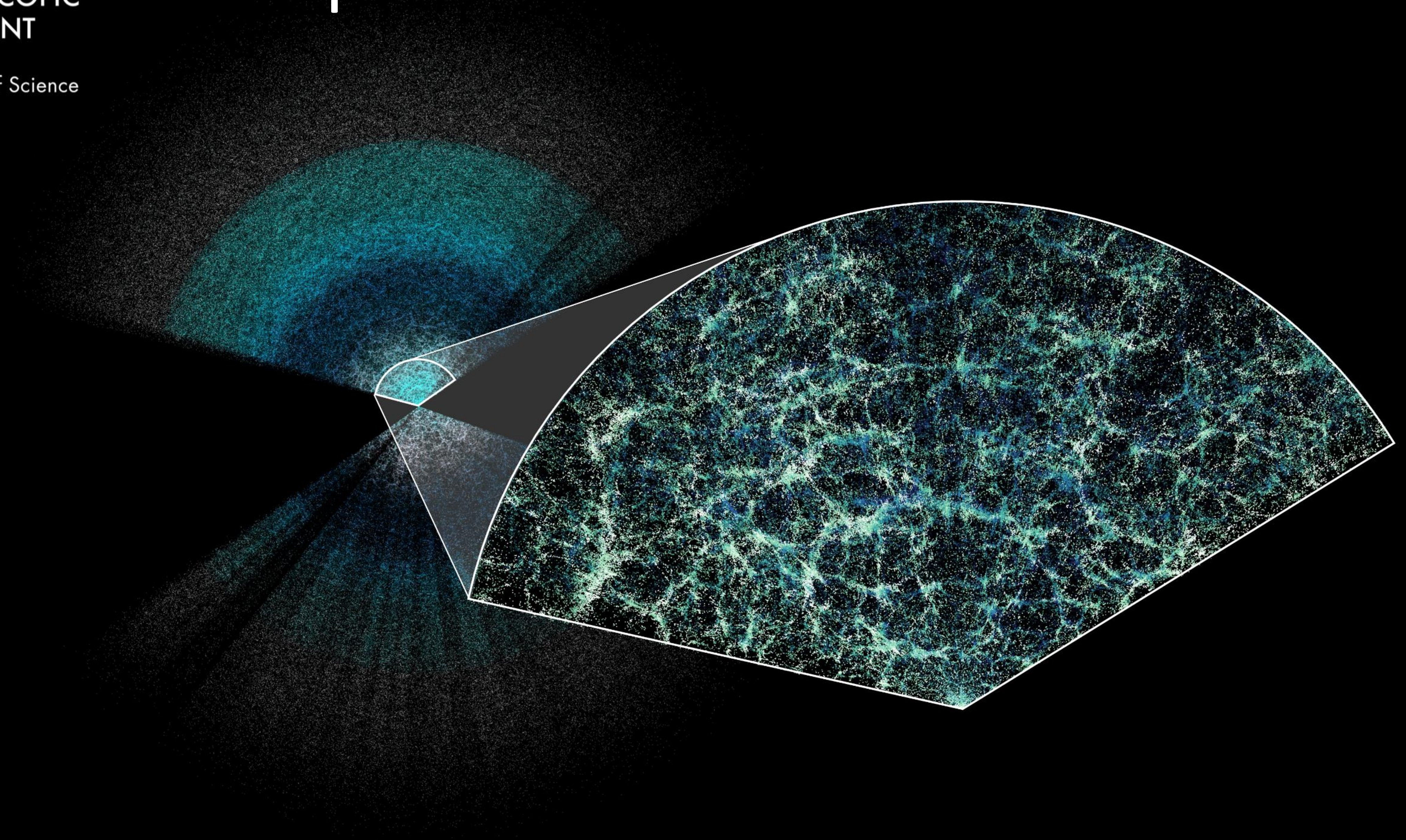

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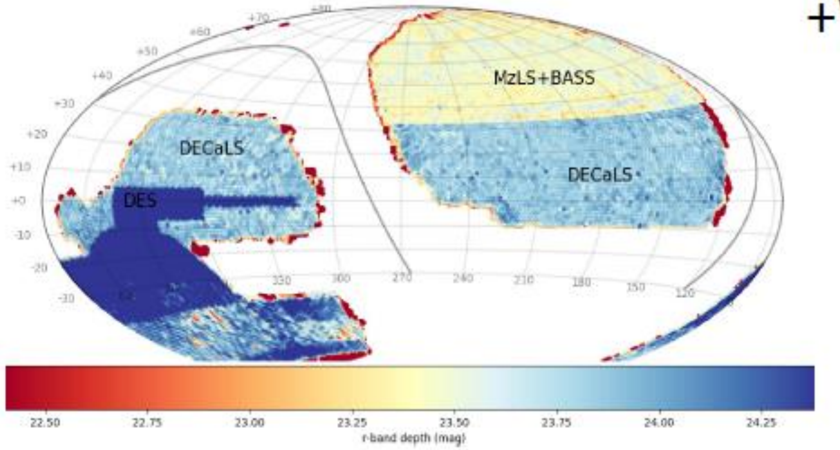
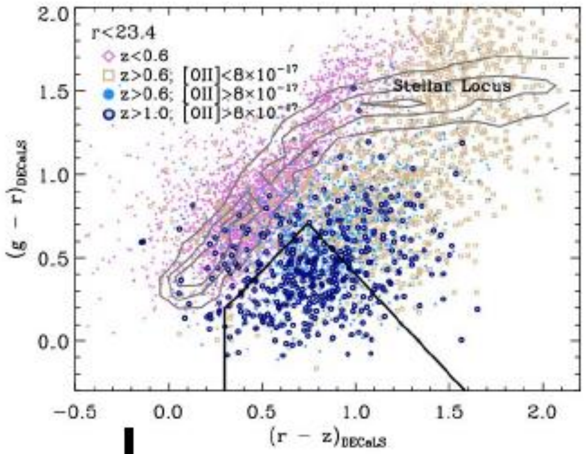
Multi-object Spectroscopy

Imaging Surveys (2014-2019)

+WISE IR sat

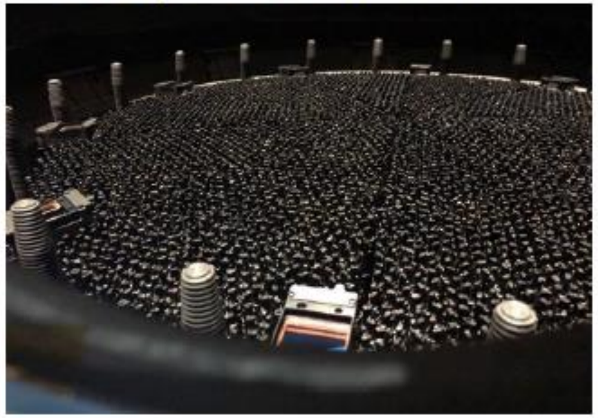


Target Selection

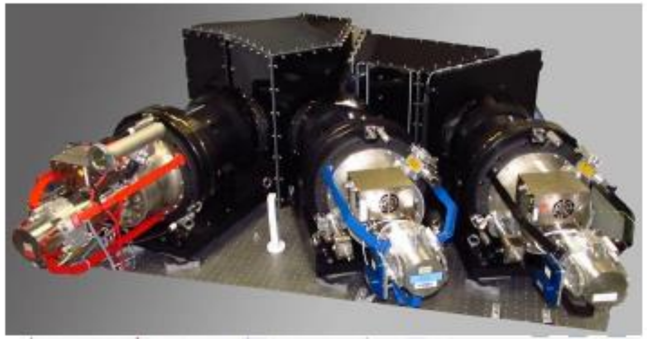


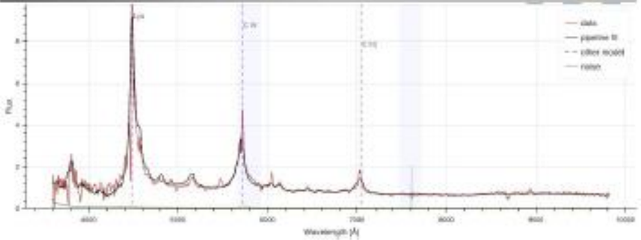
Observation…

…of 5000 objects every ~20mins…



…and measure their redshift





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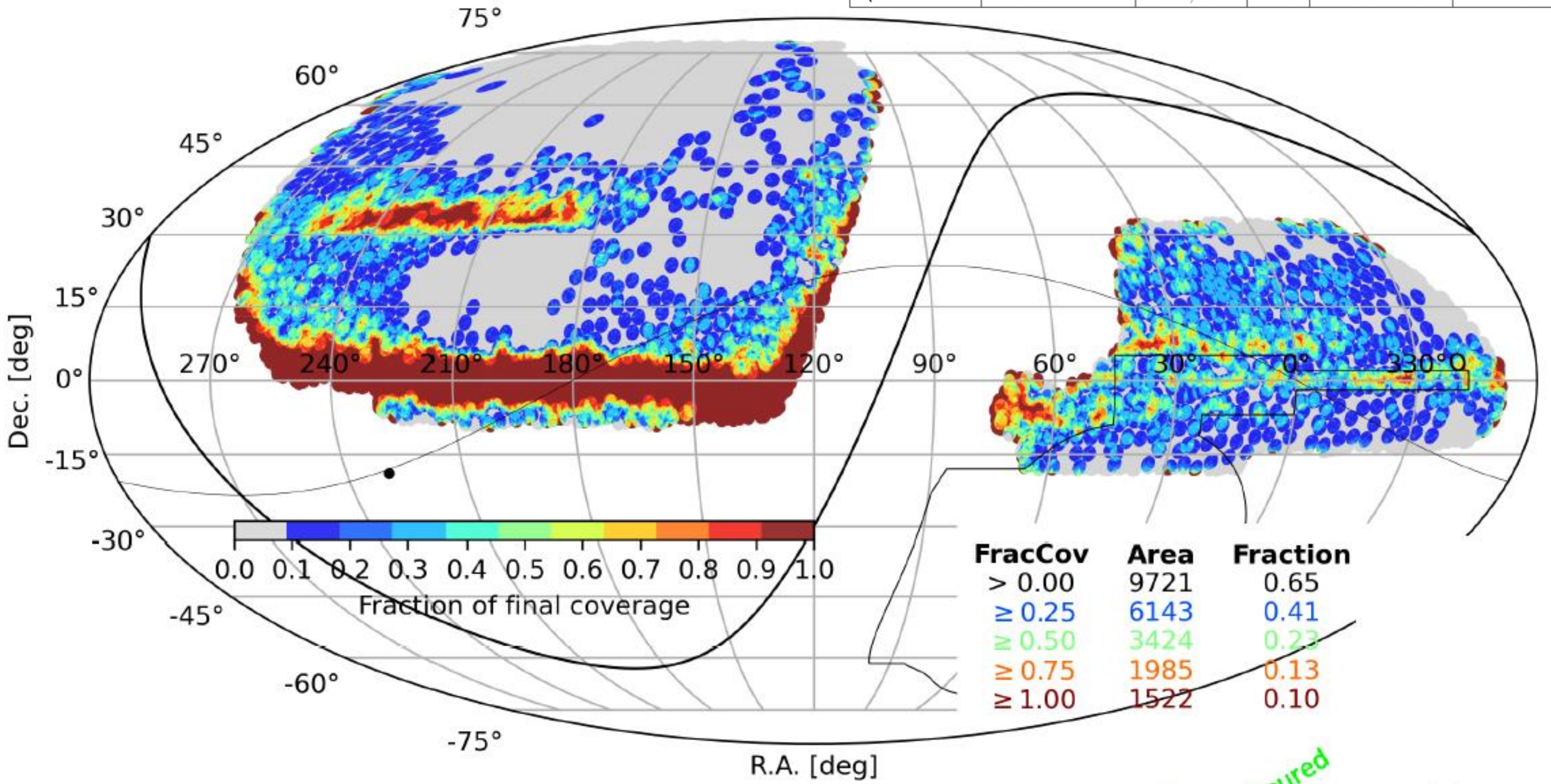
Y1 Sample

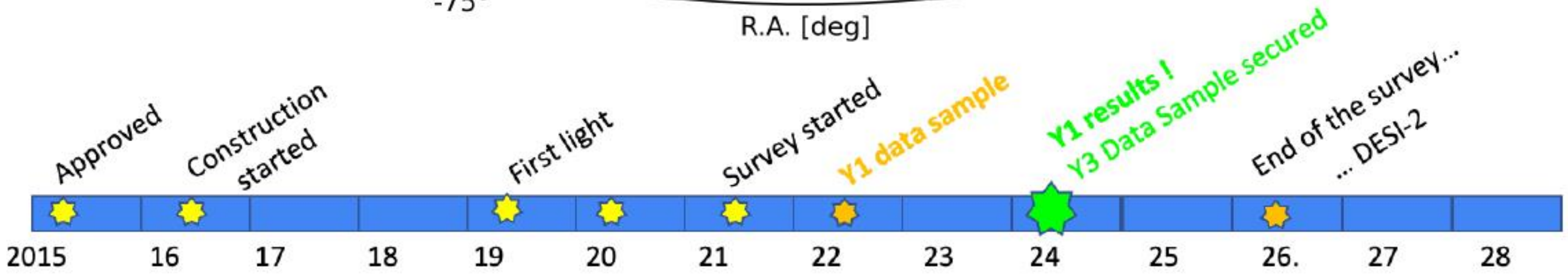
Tracer	redshift range	$N_{\rm tracer}$	$z_{\rm eff}$	$P_0(k=0.14)$	$V_{\rm eff}$ (Gpc^3)
BGS	$0.1-0.4$	300,017	0.30	$\sim 9.2\times10^3$	1.7
LRG1	$0.4-0.6$	506,905	0.51	$\sim 8.9\times10^3$	2.6
LRG2	$0.6-0.8$	771,875	0.71	$\sim 8.9\times10^3$	4.0
LRG3	$0.8-1.1$	859,824	0.92	$\sim 8.4\times10^3$	5.0
ELG1	$0.8-1.1$	1,016,340	0.95	$\sim 2.6\times10^3$	2.0
LRG3+ELG1	$0.8-1.1$	1,876,164	0.93	$\sim 5.9\times10^3$	6.5
ELG2	$1.1-1.6$	1,415,687	1.32	$\sim 2.9\times10^3$	2.7
QSO	$0.8-2.1$	856,652	1.49	$\sim 5.0\times10^3$	1.5

DESI DR1 includes data taken from May 14th (2021) to June 12th (2022)

- BGS (0.1<z<0.4) , 300.017 galaxies
- LRG (0.4<z<1.1), 2.138.600 galaxies
- ELG(1.1<z<1.6), 2.432.022 galaxies
- LRG+ELG in (0.8<z<1.1)
- QSO (0.8<z<2.1) 856.652 QSOs
- Lyα (1.77<z<4.56) 709.565 QSOs

~6 millions unique redshifts → more than twice all the previous spectroscopic surveys together





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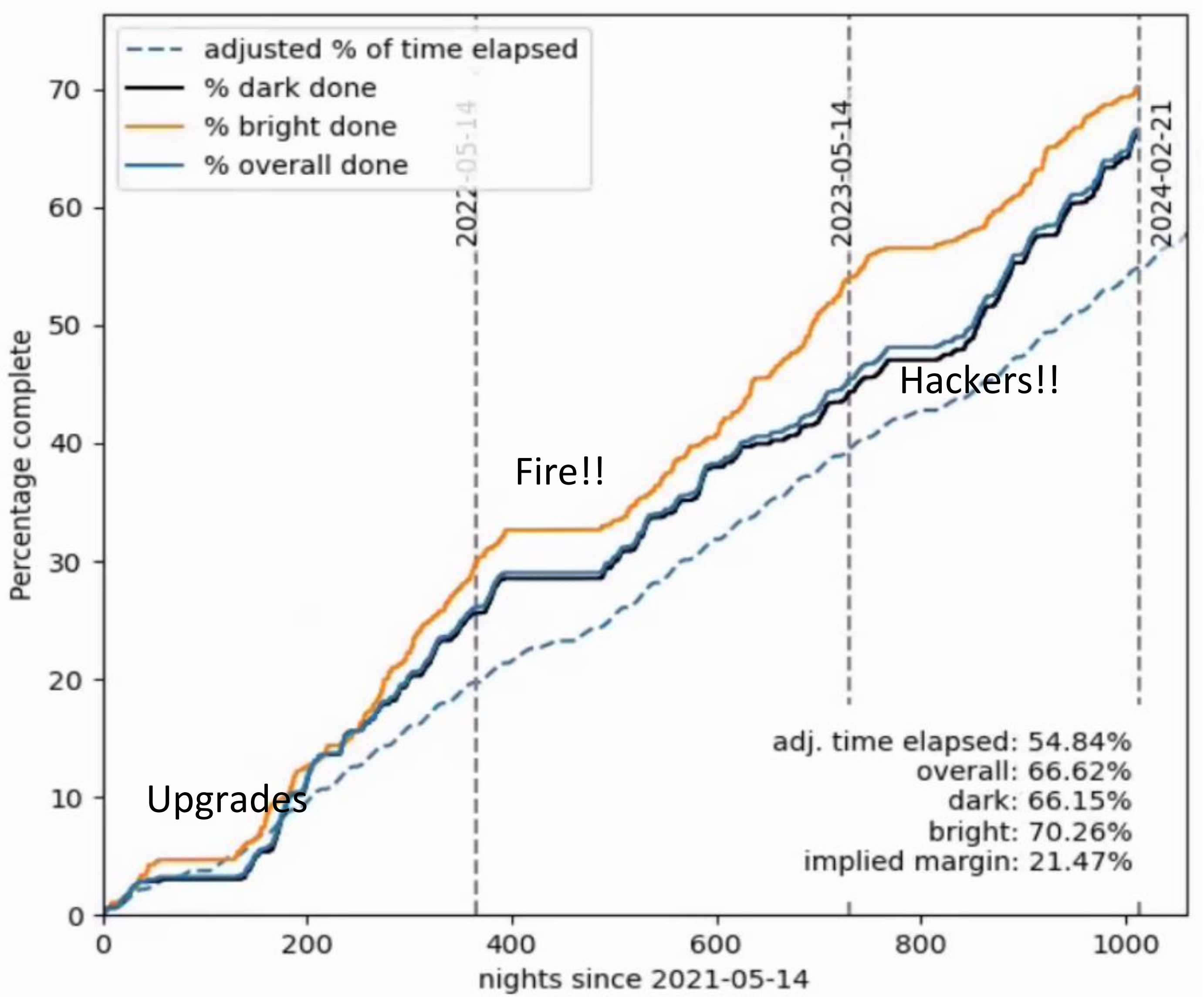
DESI is ahead of schedule!!

And this is achieved even with...
COVID shutdown (March 2020-November 2020)
Contreras fire shutdown (June 2022-September 2022)
Hackers attack in 2023

The survey is now more than 60% complete
Y3 sample is already taken → Analysis starting now!!

Foreseen Data releases
✓ DESI-Y1 (up to June'22)
DESI-Y3 (up to March'24)
DESI-Y5 (final, 2026)



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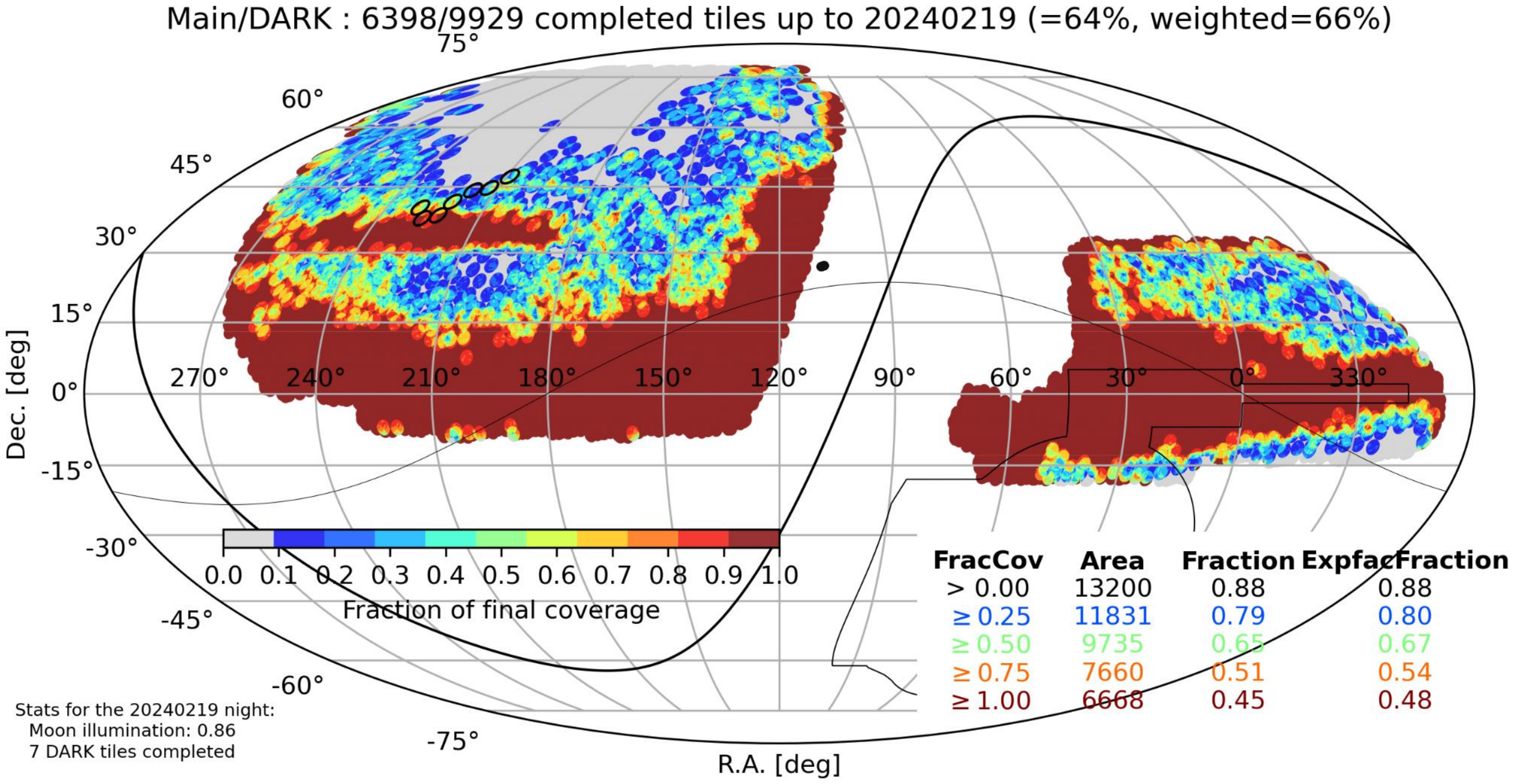
Current Sky Area Coverage



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Y1 BAO Results

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:

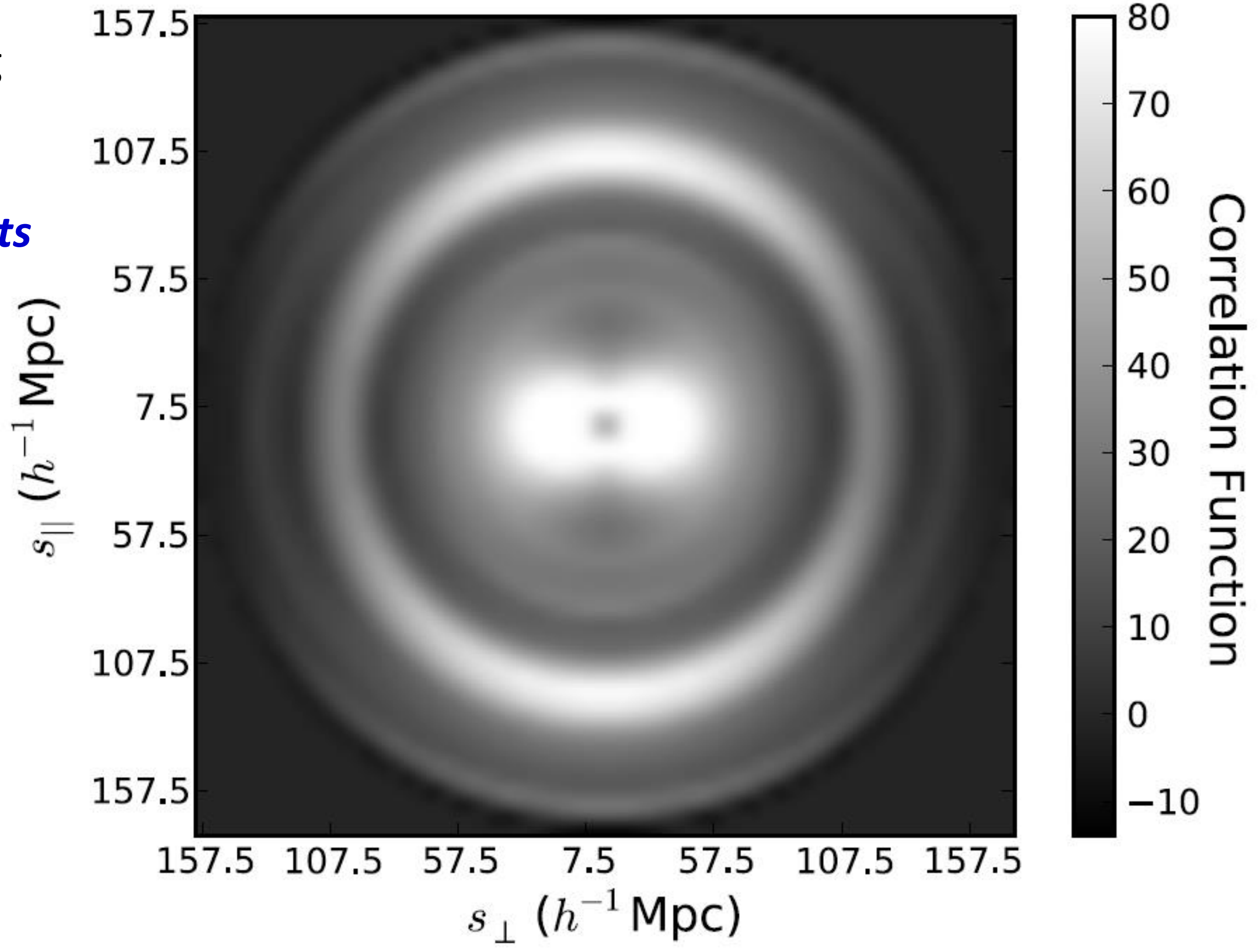
Galaxy/Quasar Clustering

Lyman-Alpha Forest

To measure (as a function of redshift):

Baryon Acoustic Oscillations Scale

Redshift Space Distortions



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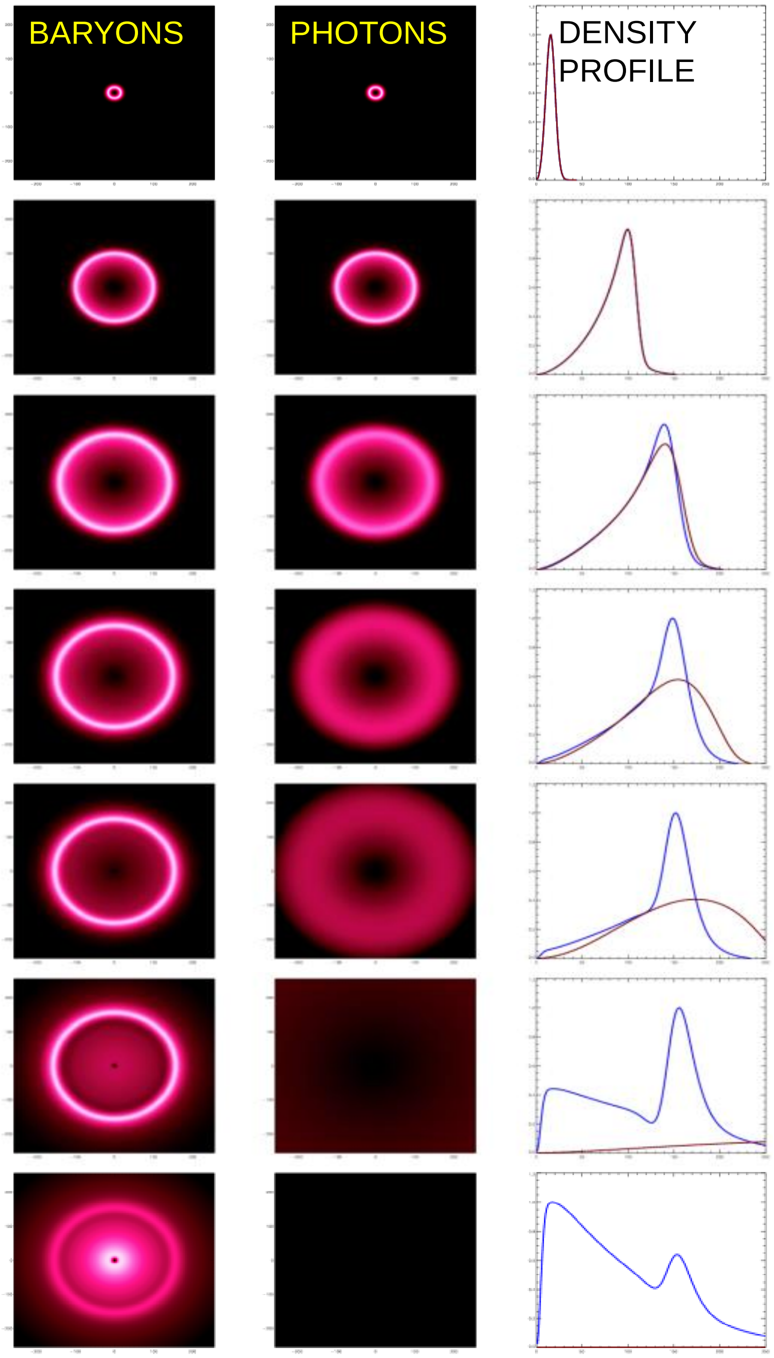
Cosmology from BAO Scale



At *z*>>1000 the universe was a strongly coupled gas of photons and charged particles (and neutrinos and dark matter)

Overdensities make overpressures and a sound wave in the gas, wich propagates with velocity $\sim c/\sqrt{3}$

At *z* ~ 1100 (*t* ~ 350 000 yr), temperature is low enough (3000 K) for the formation of hydrogen. Photons decouple and propagate freely (CMB)

Photons quickly stream away, leaving the baryon peak stalled at ~150 Mpc.

There is a special separation between galaxies:
150 Mpc, that can be used as a <u>STANDARD RULER</u>

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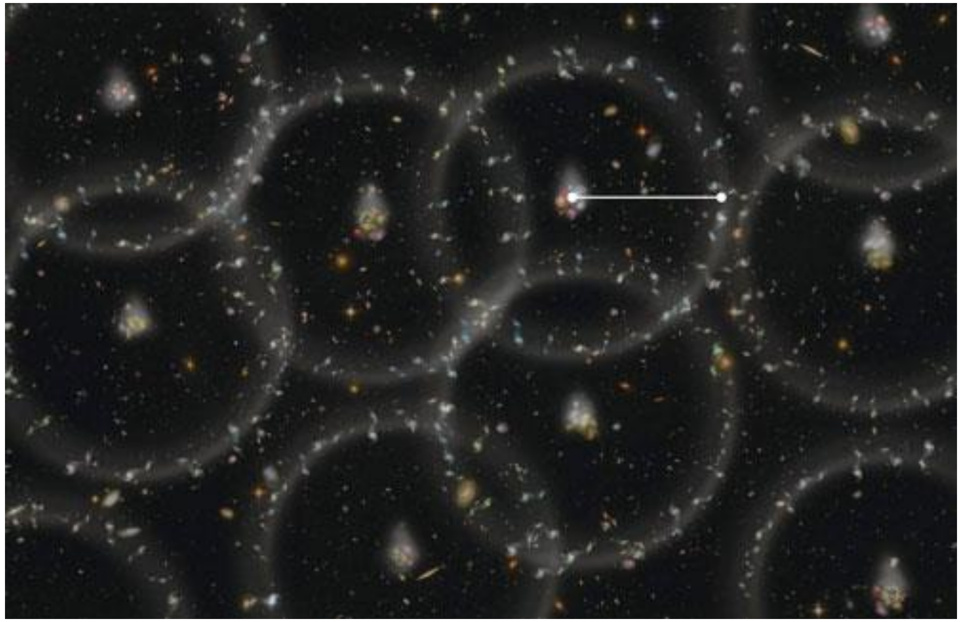
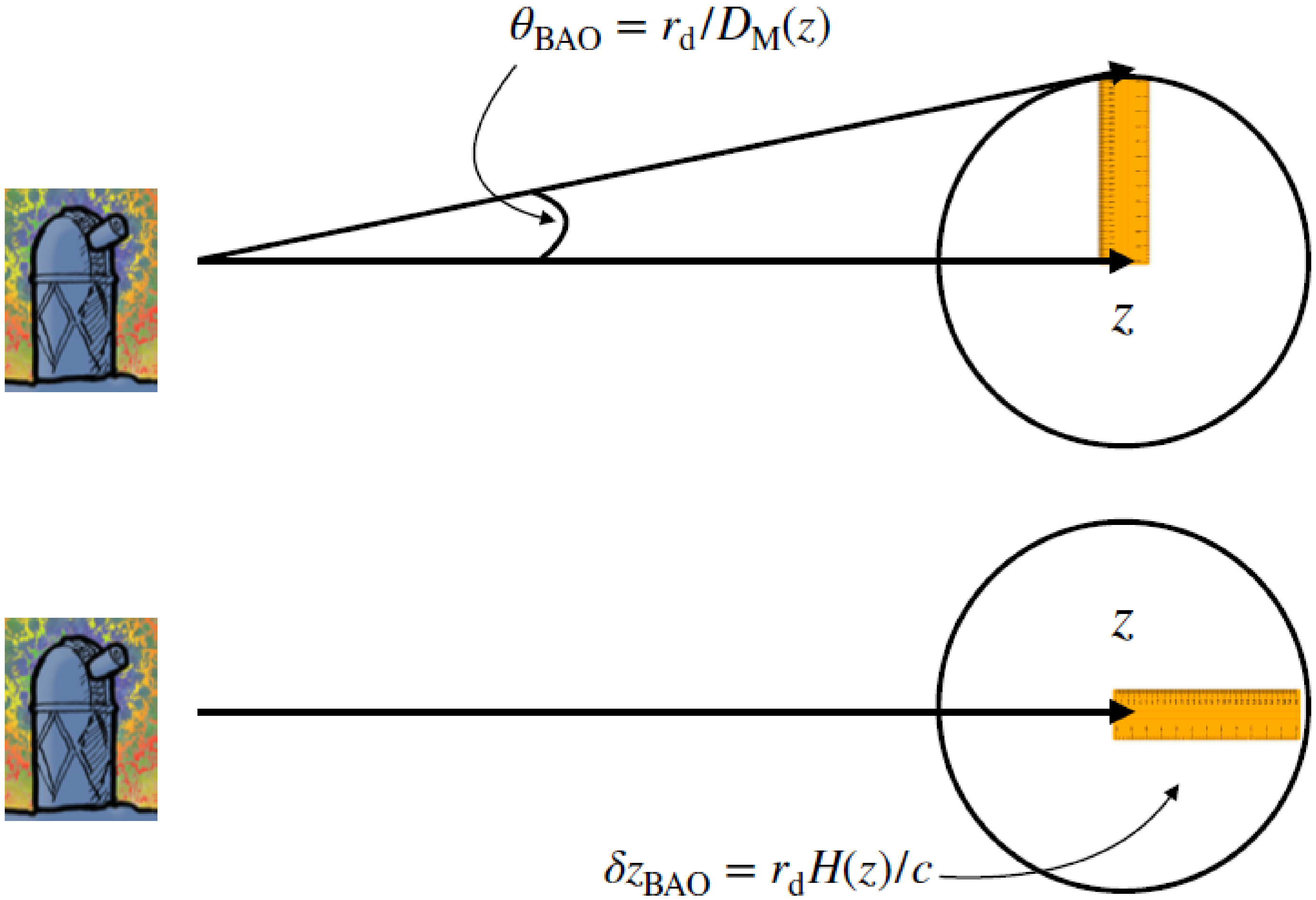
BAO Standard Ruler

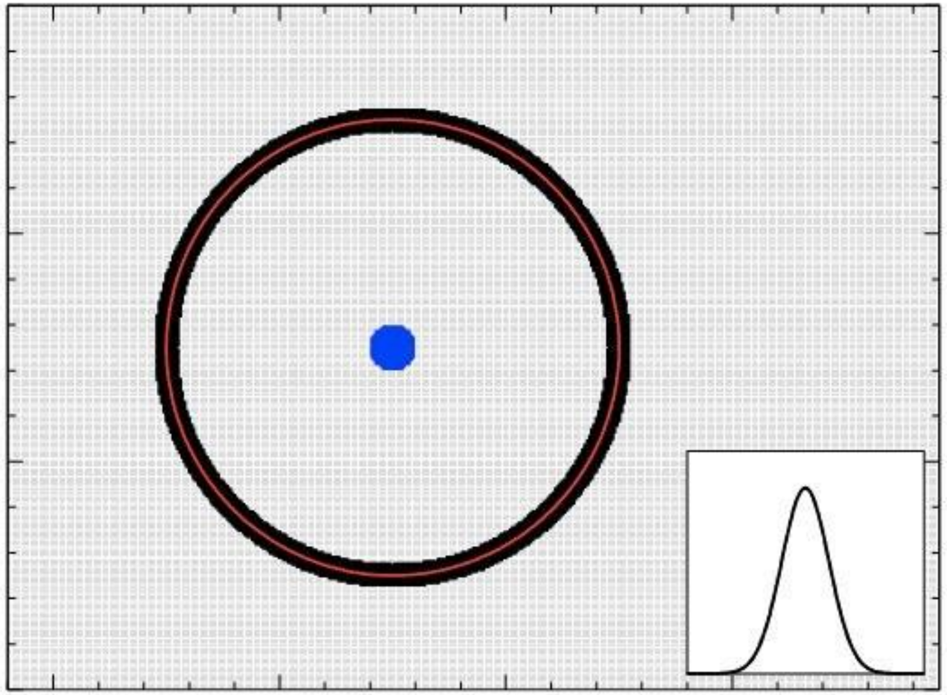


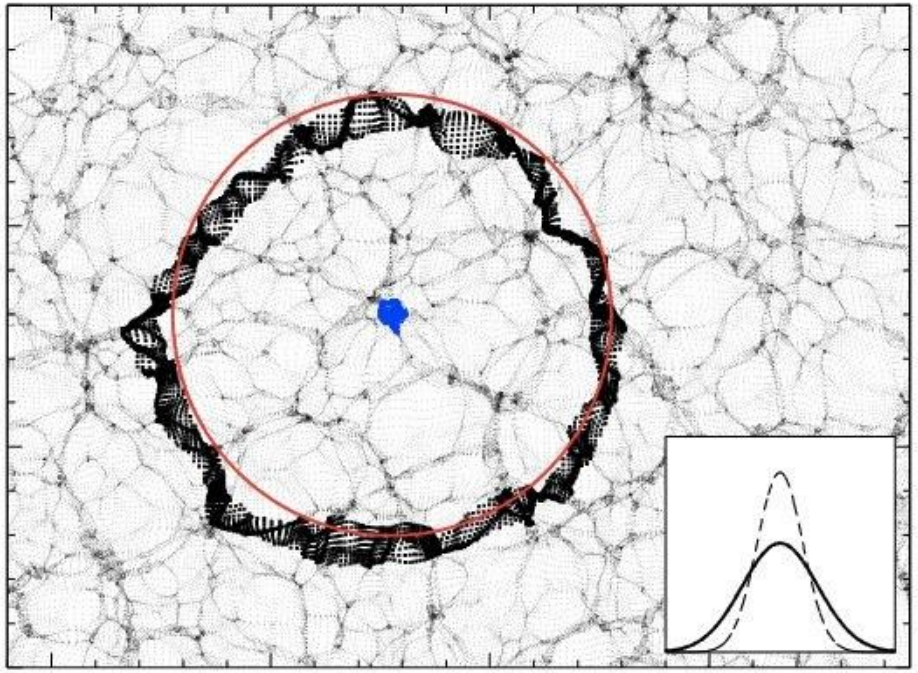


$D_{\mathrm{M}}(z)$ and $H(z)$ encode the **expansion history** of the Universe

Non-linear evolution

Structure growth and peculiar velocities **blur** and **shrink** the ruler, and degrades the precision of the cosmological test





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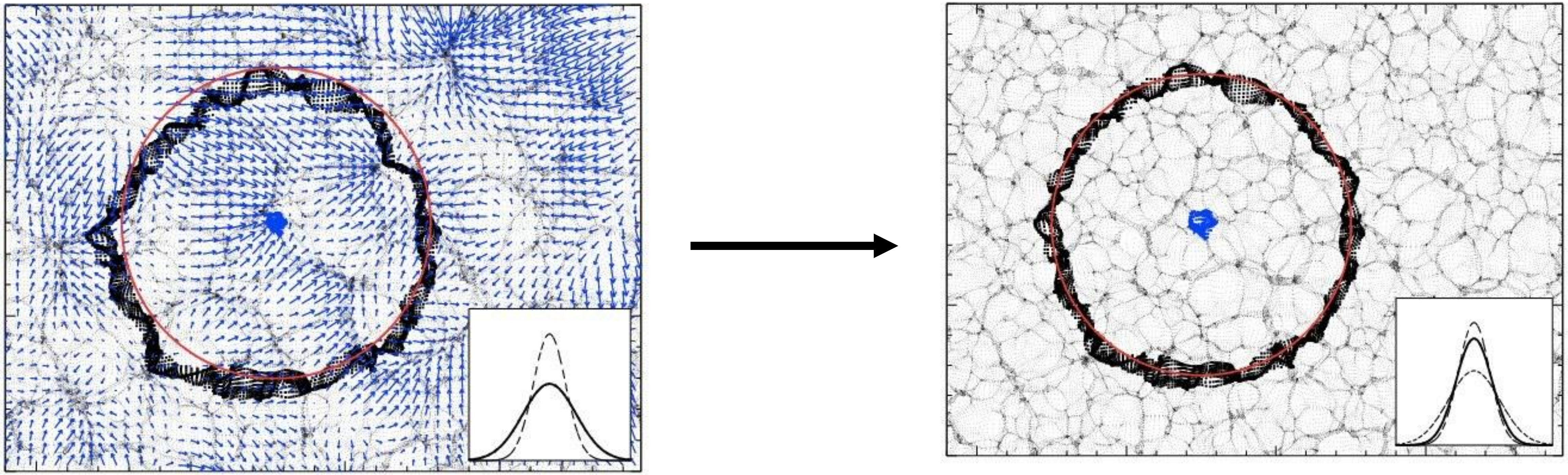
Density field reconstruction

Estimates Zeldovich displacement from observed field, and undoes displacement

Refurbishes the ruler – **improves both precision and accuracy**



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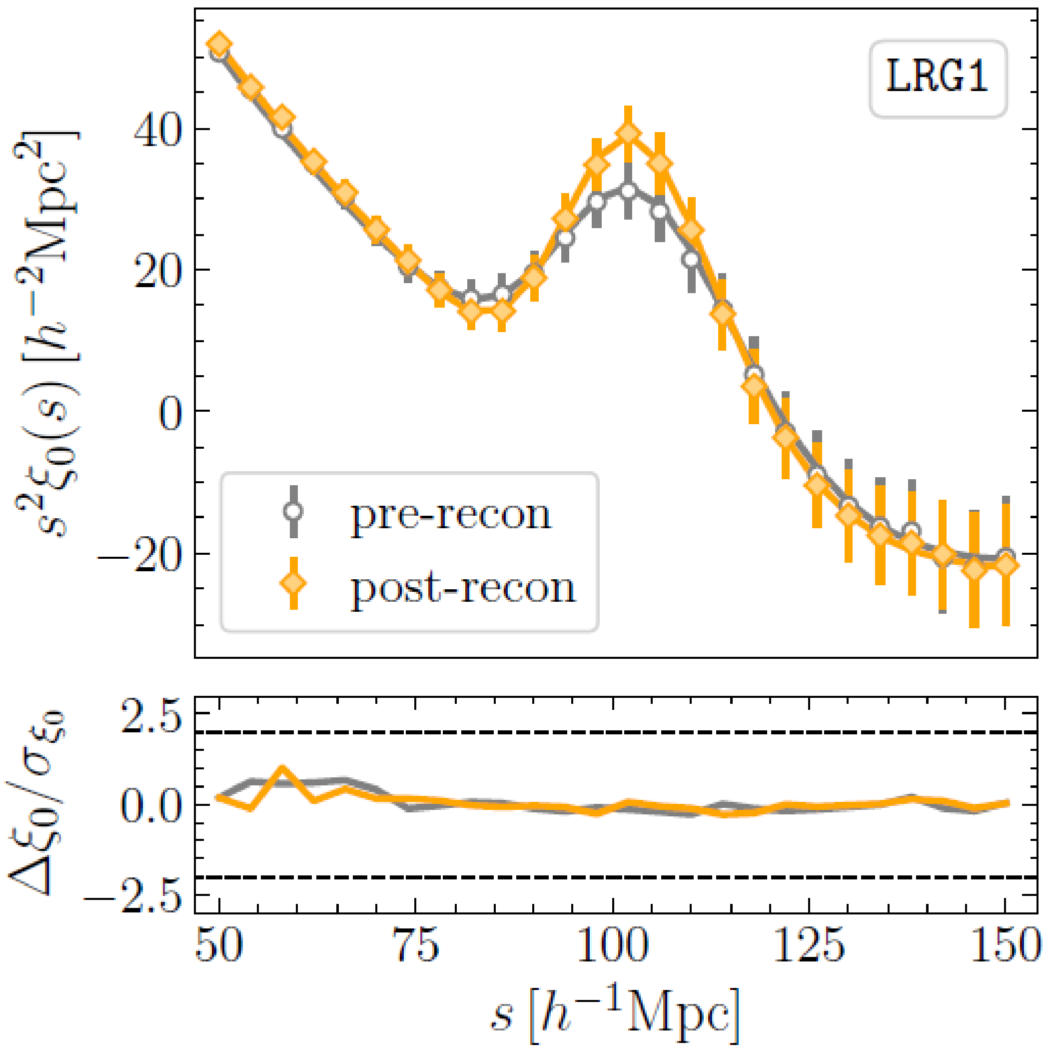
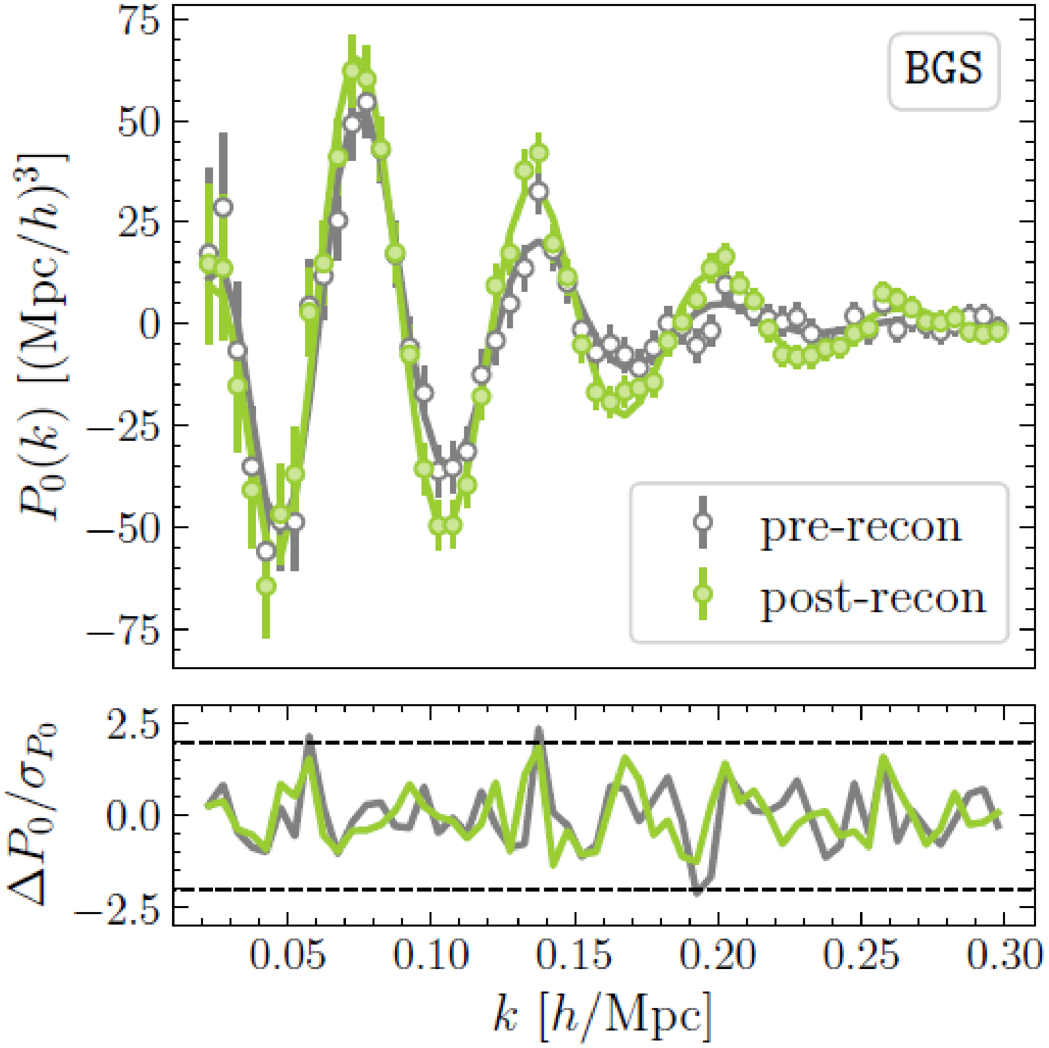
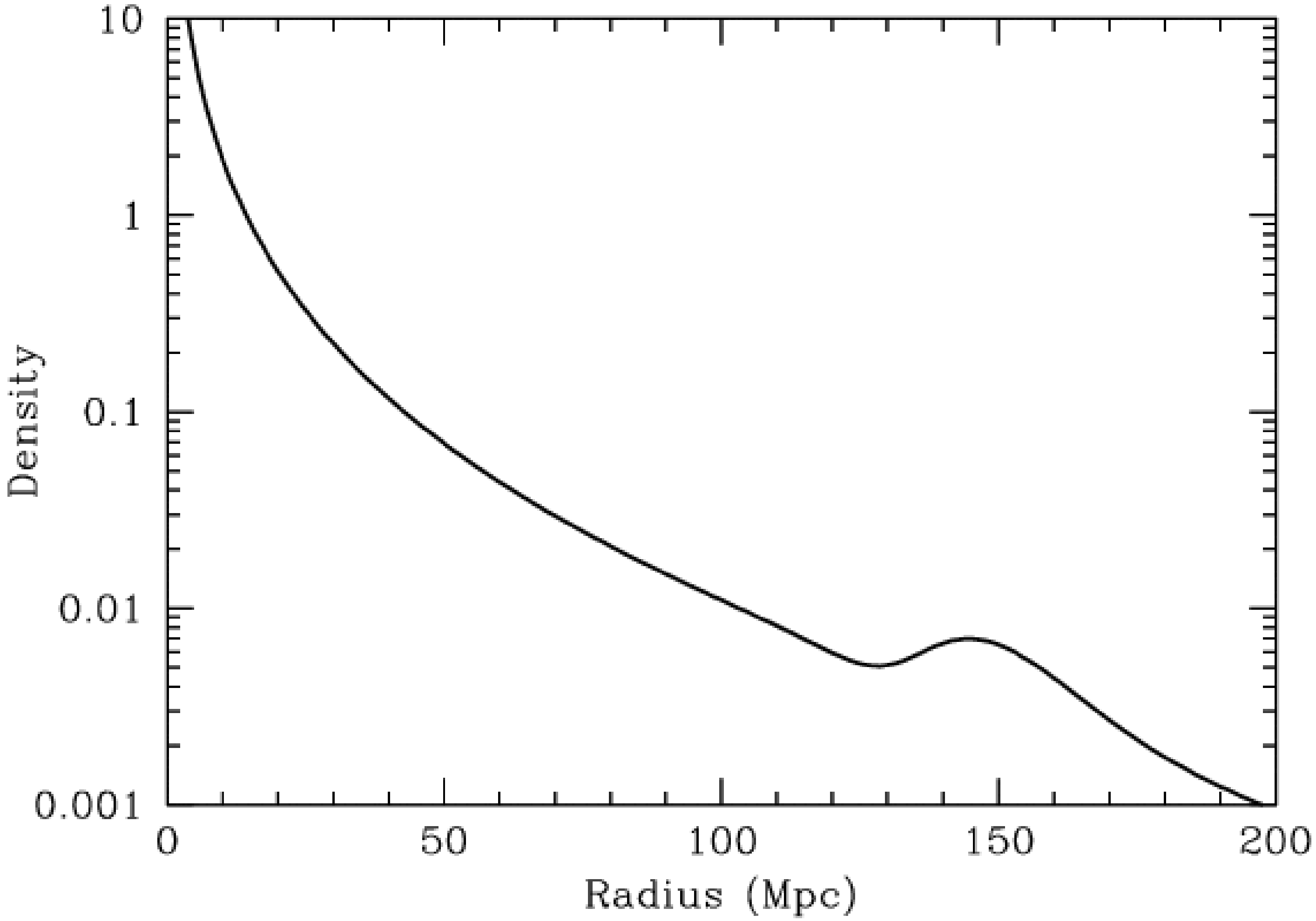
Effect of reconstruction





Localize the BAO peak

Plotting the density profile we see that the peak is indeed very weak, but measurable



Galaxies form in the overdense regions. Mostly, where the initial overdensities were. However, there is a 1% enhancement in the regions 150 Mpc away from these initial overdensities.

Hence, there should be a small **excess of galaxies 150 Mpc** away from other galaxies, as opposed to 120 or 180 Mpc.

We can see this as a **single *acoustic peak* in the correlation function of galaxies**.

https://www.cfa.harvard.edu/~deisenst/acousticpeak/acoustic_physics.htm

Analysis Procedure

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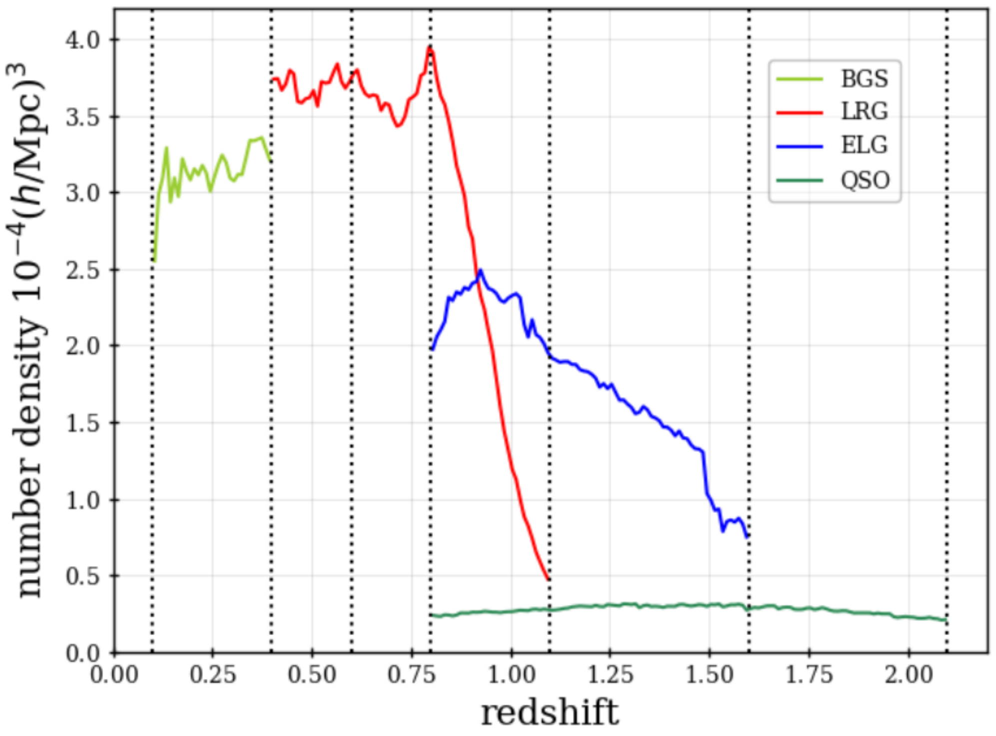
Measure position and redshift of the galaxies, compute the correlation function (or power spectrum) and locate the excess

Very robust technique. Not affected by astrophysical systematic effects.

What is new in DESI?



The data! – **biggest ever BAO dataset**
~6 million unique redshifts
Effective volume: 18 Gpc3. 3 times bigger than SDSS
Improvements in modelling
Fully blinded analysis:

$$(\mathrm{ra}, \mathrm{dec}, z) \xrightarrow[\text{fiducial cosmology}]{} (X, Y, Z) \xrightarrow[\substack{\textbf{blind}\text{ cosmology } w_0,\, w_a,\, \Omega_m \\ \text{(not revealed!)}}]{} (\mathrm{ra}, \mathrm{dec}, z')$$

+ change to peculiar velocity contributions to redshift to blind growth rate

+ weights-based blinding for primordial non-Gaussianity f_{NL}

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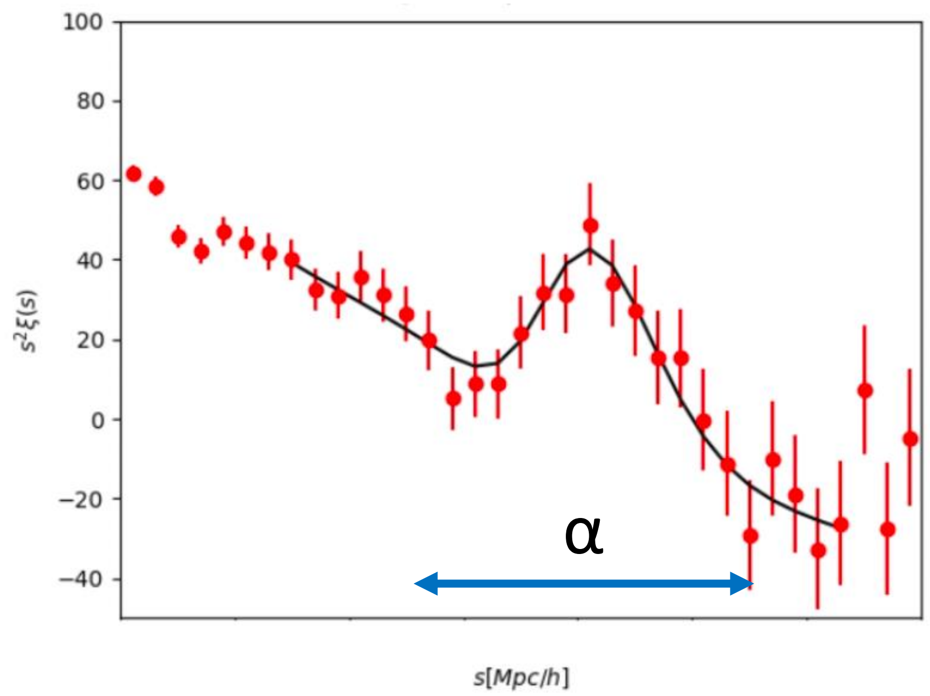
Fitting BAO

Fit data to the correlation function of a fiducial (model) by rescaling it using alpha parameters

$$\alpha_\perp = \frac{D_A(z) r_d^{\rm fid}}{D_A^{\rm fid}(z) r_d} \quad \alpha_{||} = \frac{H^{\rm fid}(z) r_d^{\rm fid}}{H(z) r_d} \quad \text{or} \quad \alpha_{\rm iso} = (\alpha_\parallel \alpha_\perp^2)^{1/3} \quad \alpha_{\rm AP} = \alpha_\parallel / \alpha_\perp$$



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Analysis of Systematic Errors

Systematic errors below statistical errors ($\sigma_{SYS} < \sigma_{STAT}$). Not a limitation for Y1 results

Possible sources of systematic error:

- observational effects in data (imaging, fiber assignment etc)
- reconstruction algorithm
- covariance matrix construction
- incomplete theory modelling
- choice of fiducial cosmology
- galaxy-halo (HOD) model uncertainties

	Tracer	σ_{BGS}	$\sigma_{\mathrm{LRGs,ELGs}}$		σ_{QSO}
Space	Source	α_{iso} (%)	α_{iso} (%)	α_{AP} (%)	α_{iso} (%)
$\xi(r)$	Theory (Table 7)	0.1	0.1	0.2	0.1
$\xi(r)$	HOD (Table 8)	0.2	0.2	0.2	0.2
$\xi(r)$	Fiducial (Table 11)	0.1	0.1	0.1	0.1
$\xi(r)$	Total	0.245	0.245	0.3	0.245
$P(k)$	Theory (Table 7)	0.1	0.1	0.2	0.1
$P(k)$	HOD (Table 8)	0.2	0.1	0.1	0.12
$P(k)$	Fiducial (Table 11)	0.1	0.1	0.1	0.1
$P(k)$	Total	0.245	0.18	0.245	0.19

Systematic Errors

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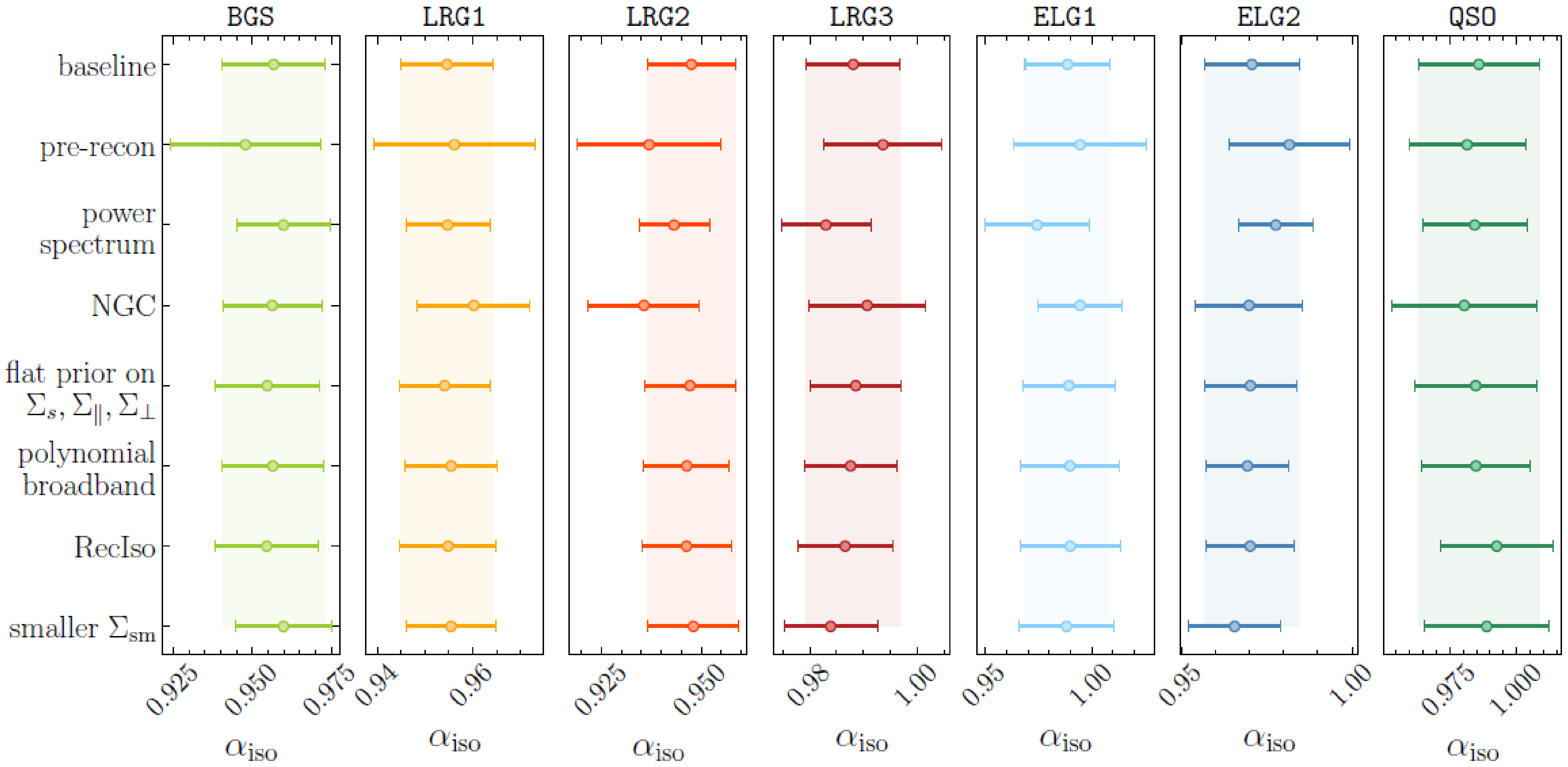

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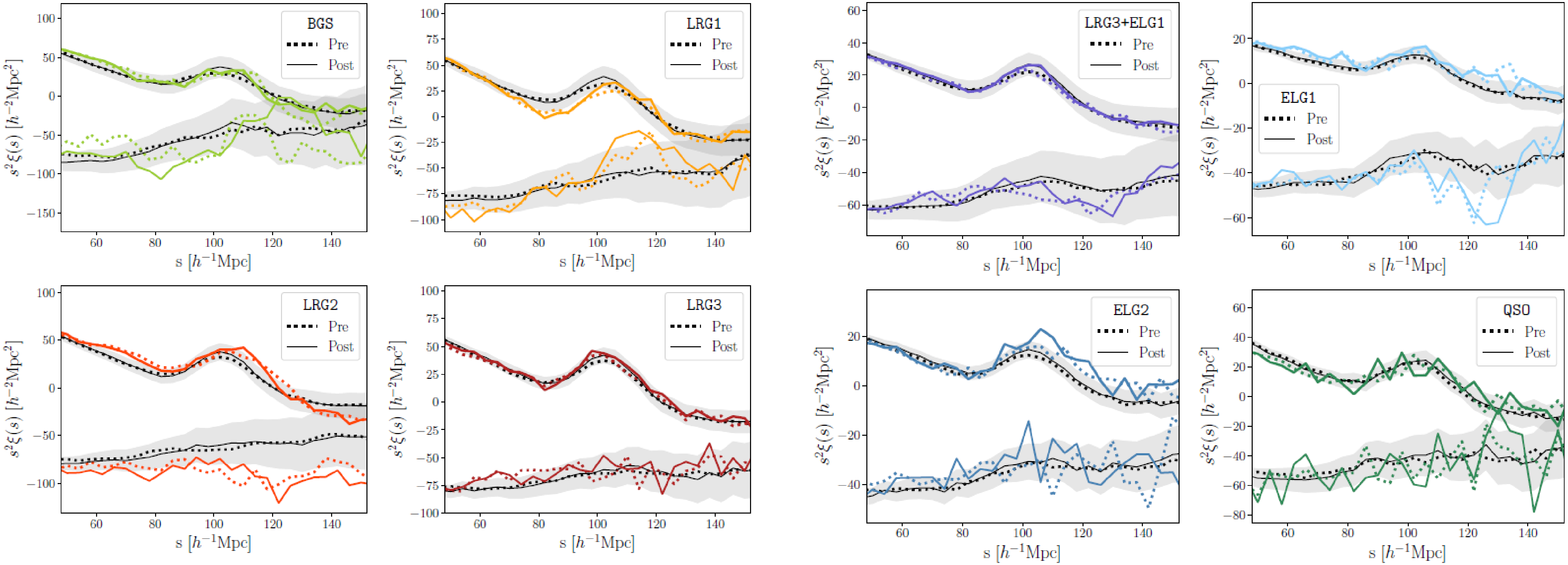
Measured Correlation Functions



Lyman-Alpha Forest

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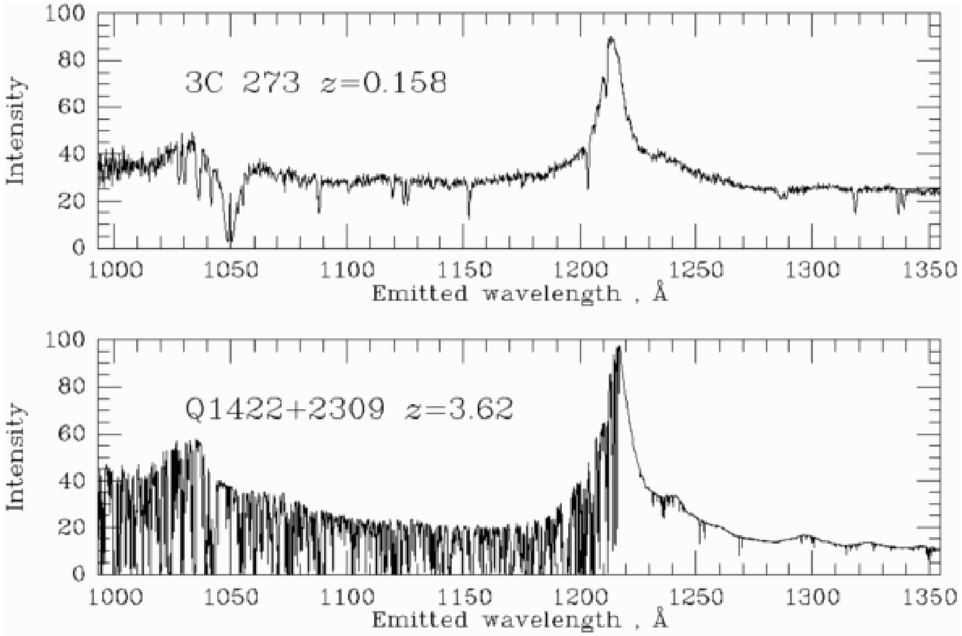
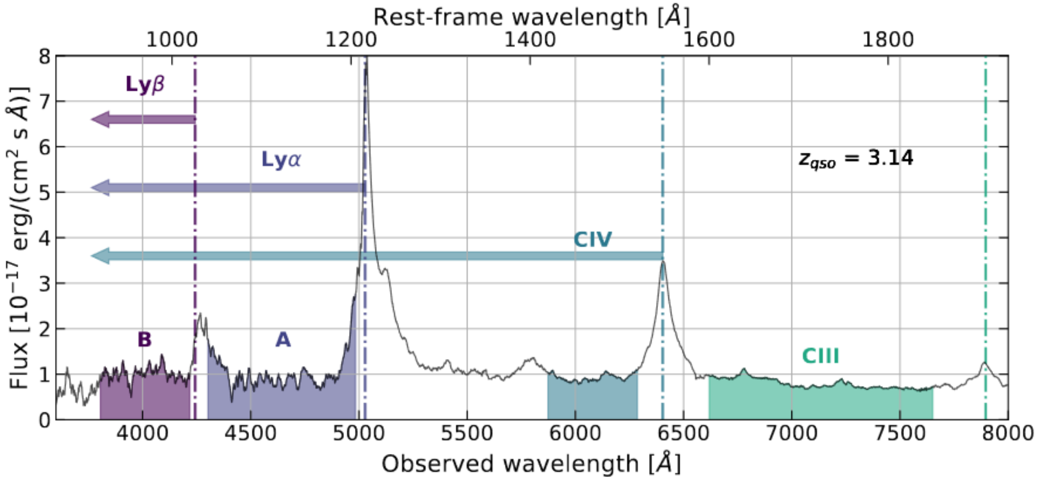
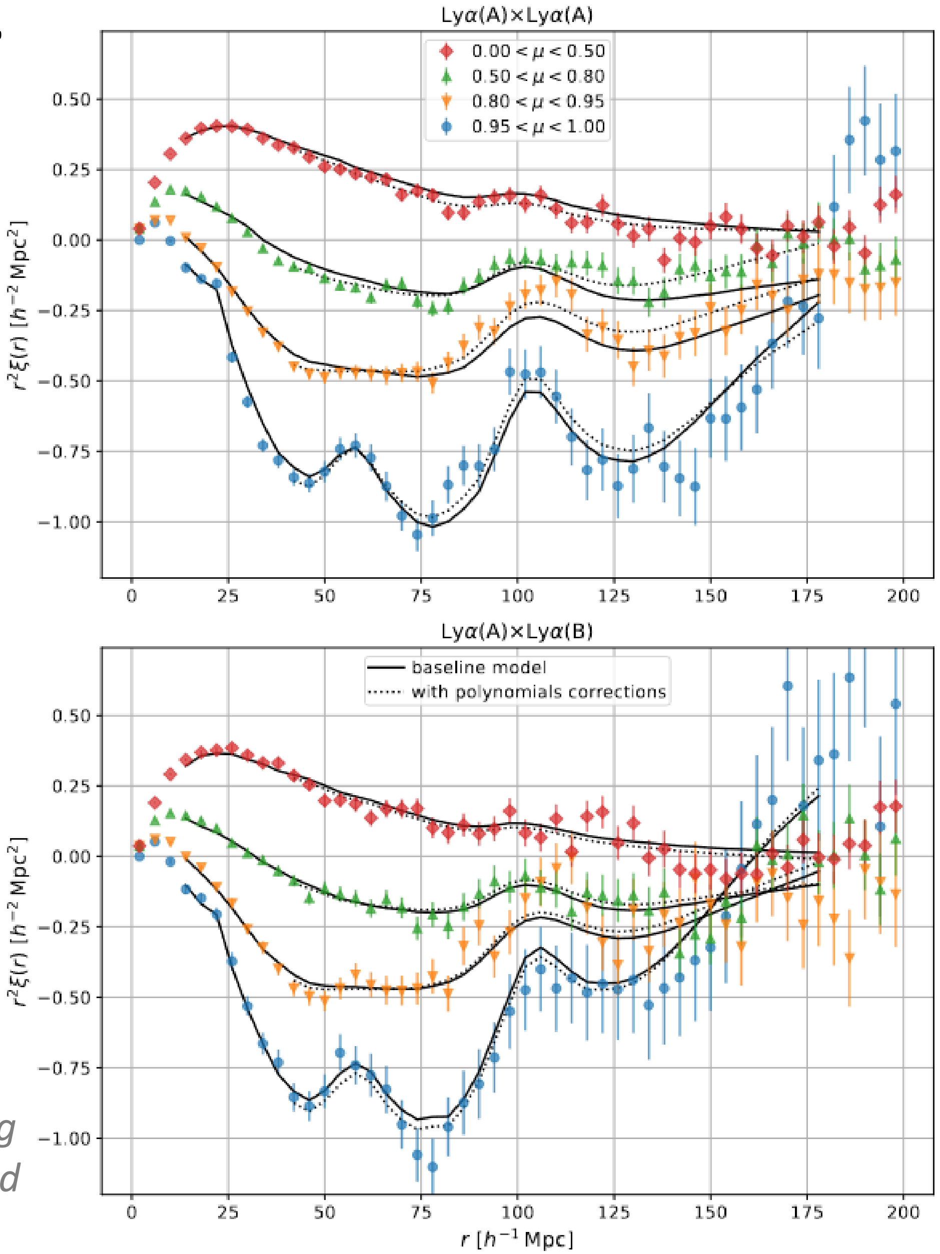
Use absorption lines due to hydrogen clouds between QSO and observer.

Allows to measure higher redshifts

Correlate several samples







Second Peak (~60 Mpc/h) caused by Silicon lines along the line of sight. Understood and not due to BAO

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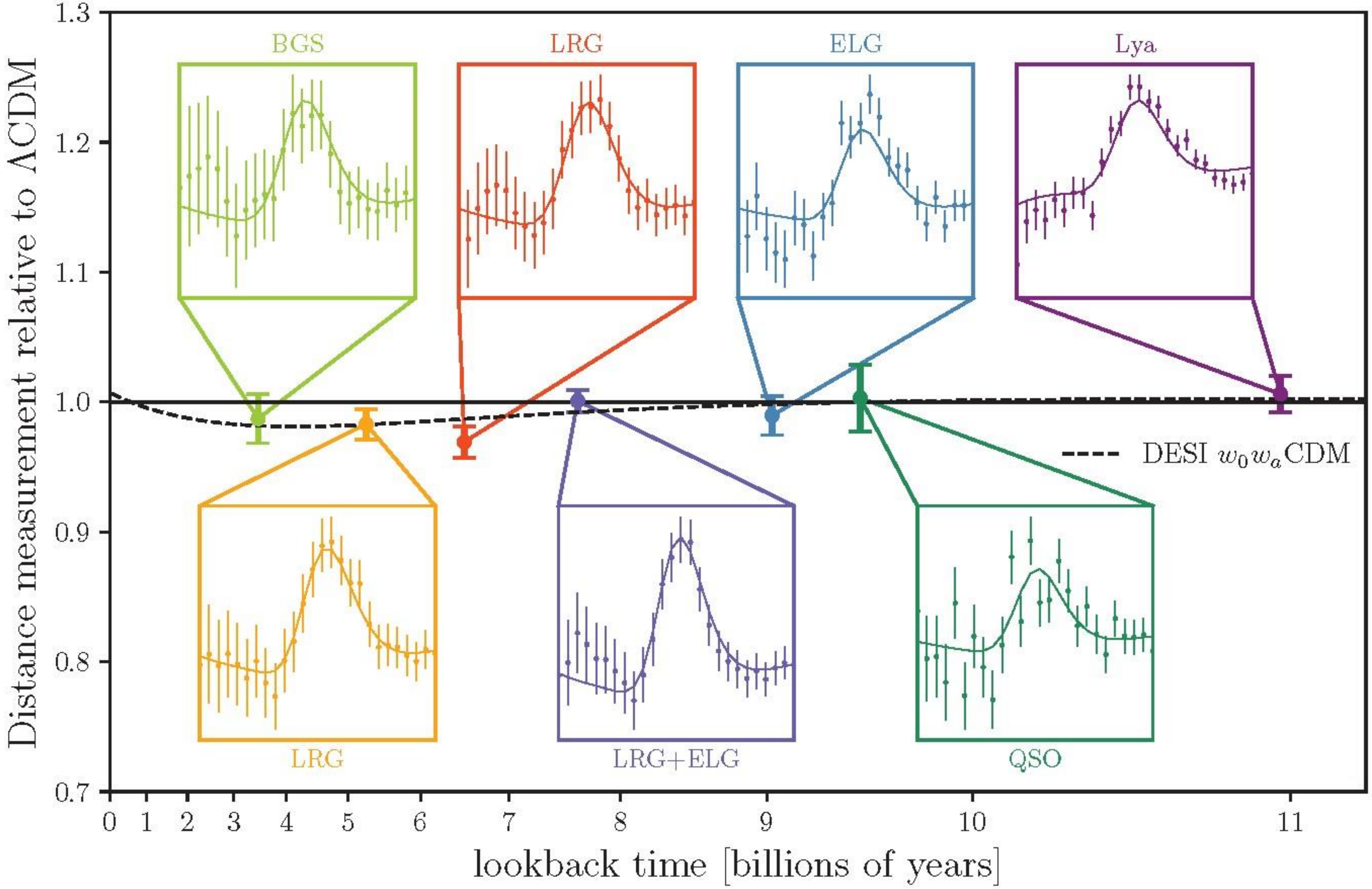
Results for the Standard Ruler

Measured BAO as a function of redshift (lookback time)

ΛCDM

$w_0 w_a$



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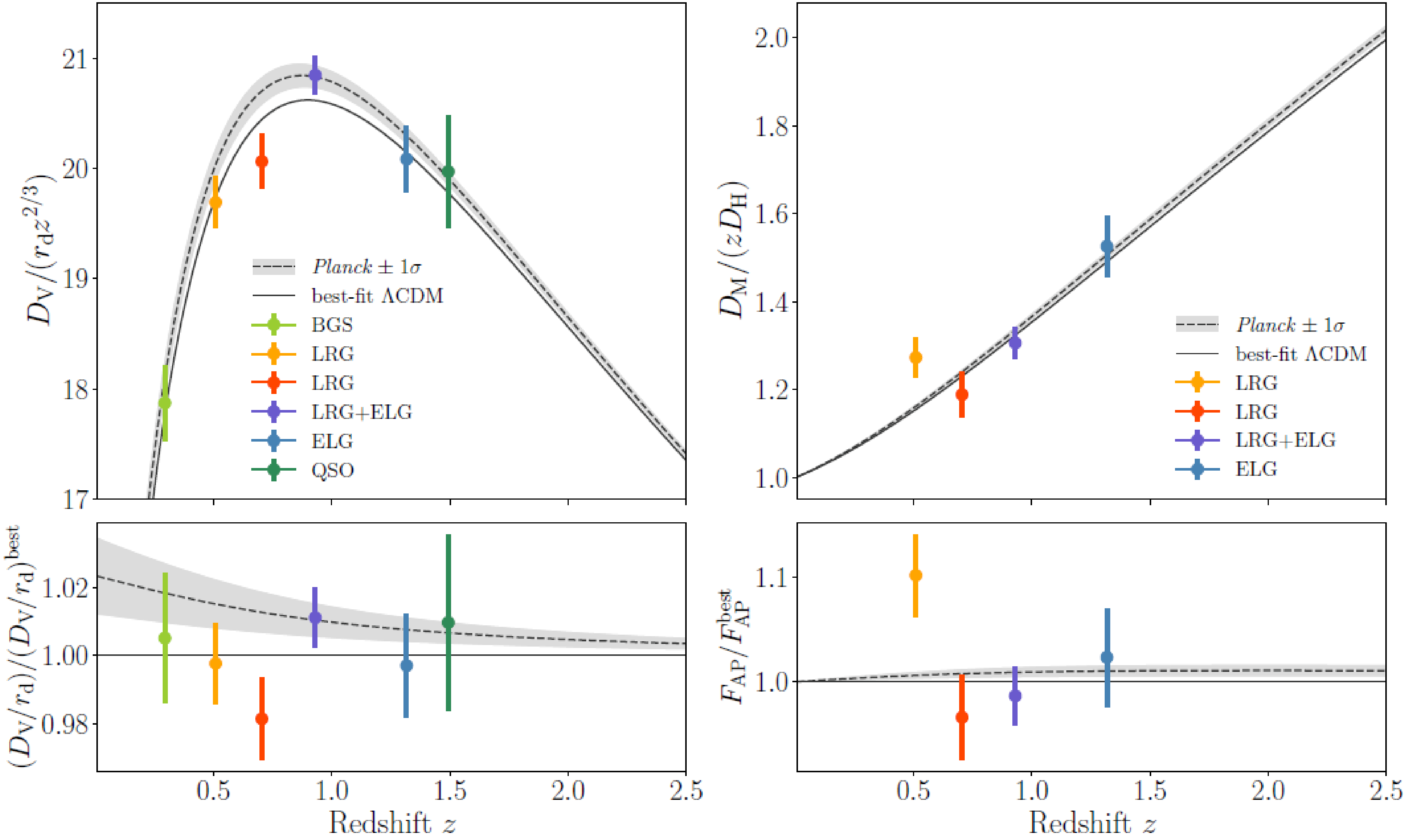
BAO Results



Cosmology from BAO

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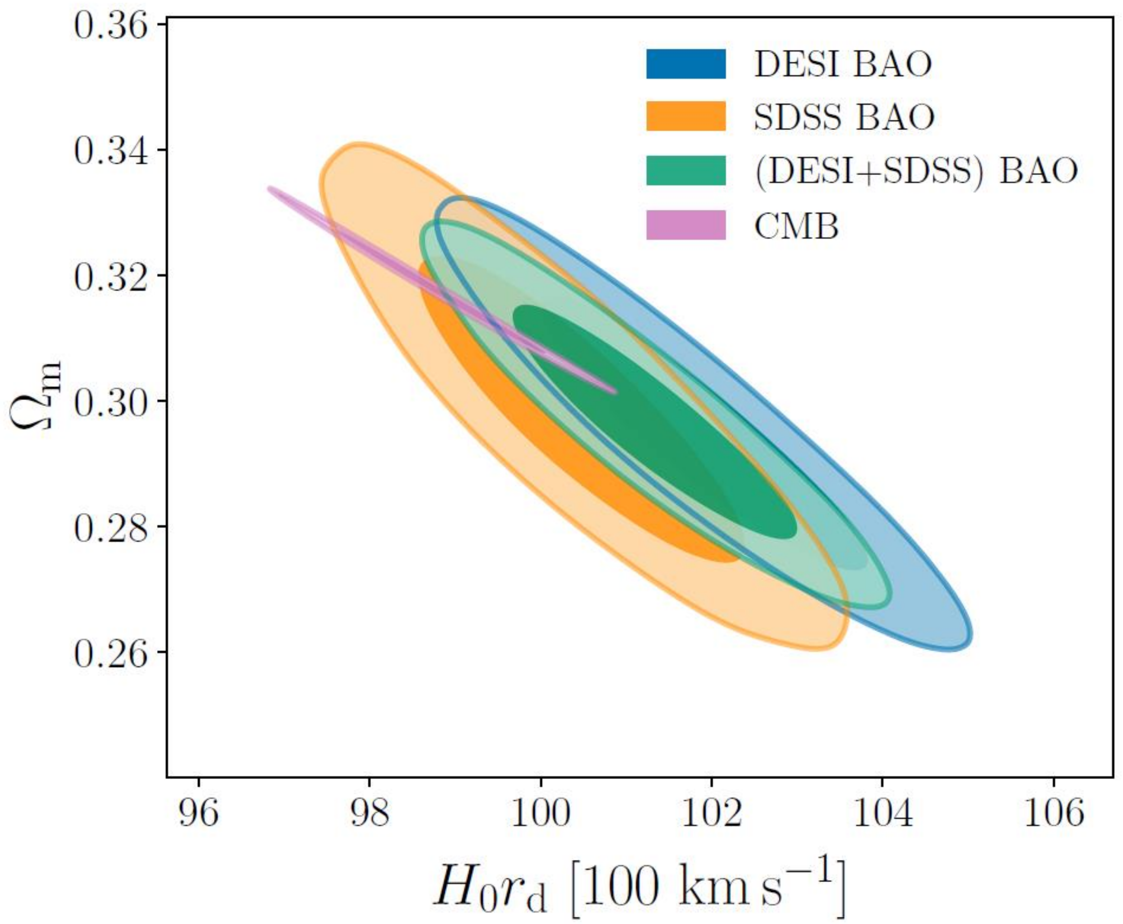
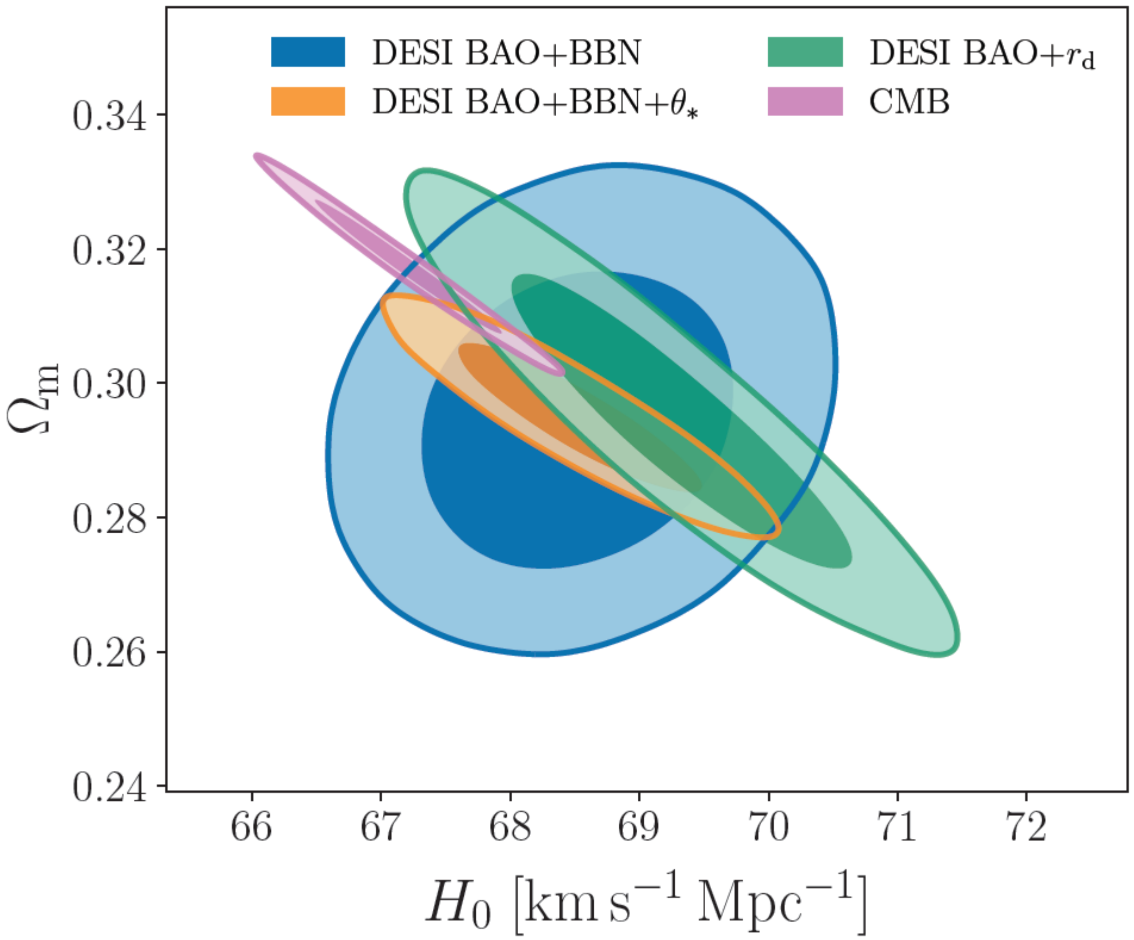
ΛCDM: Consistent with CMB, slightly higher $H_0 r_d$



ΛCDM: Esternal r_d → slightly larger H_0 but still conisstent with CMB



Hubble Tension

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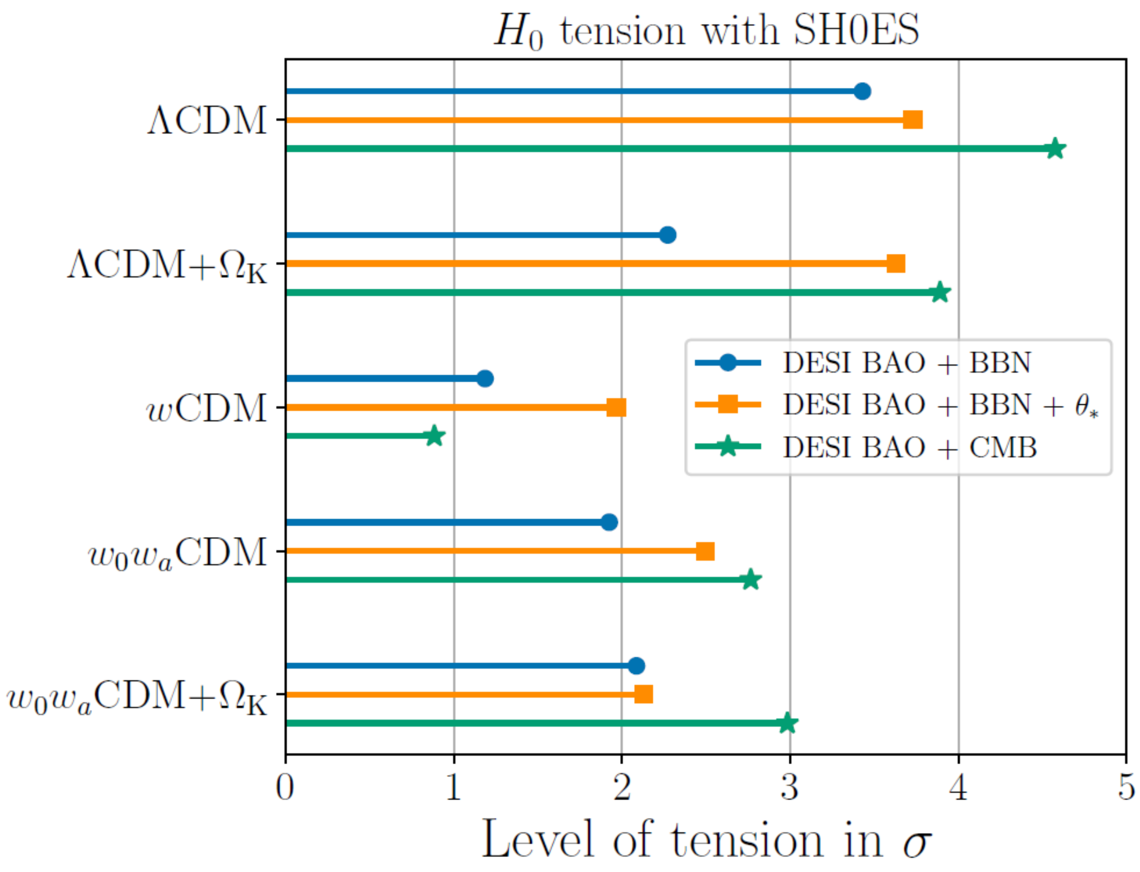
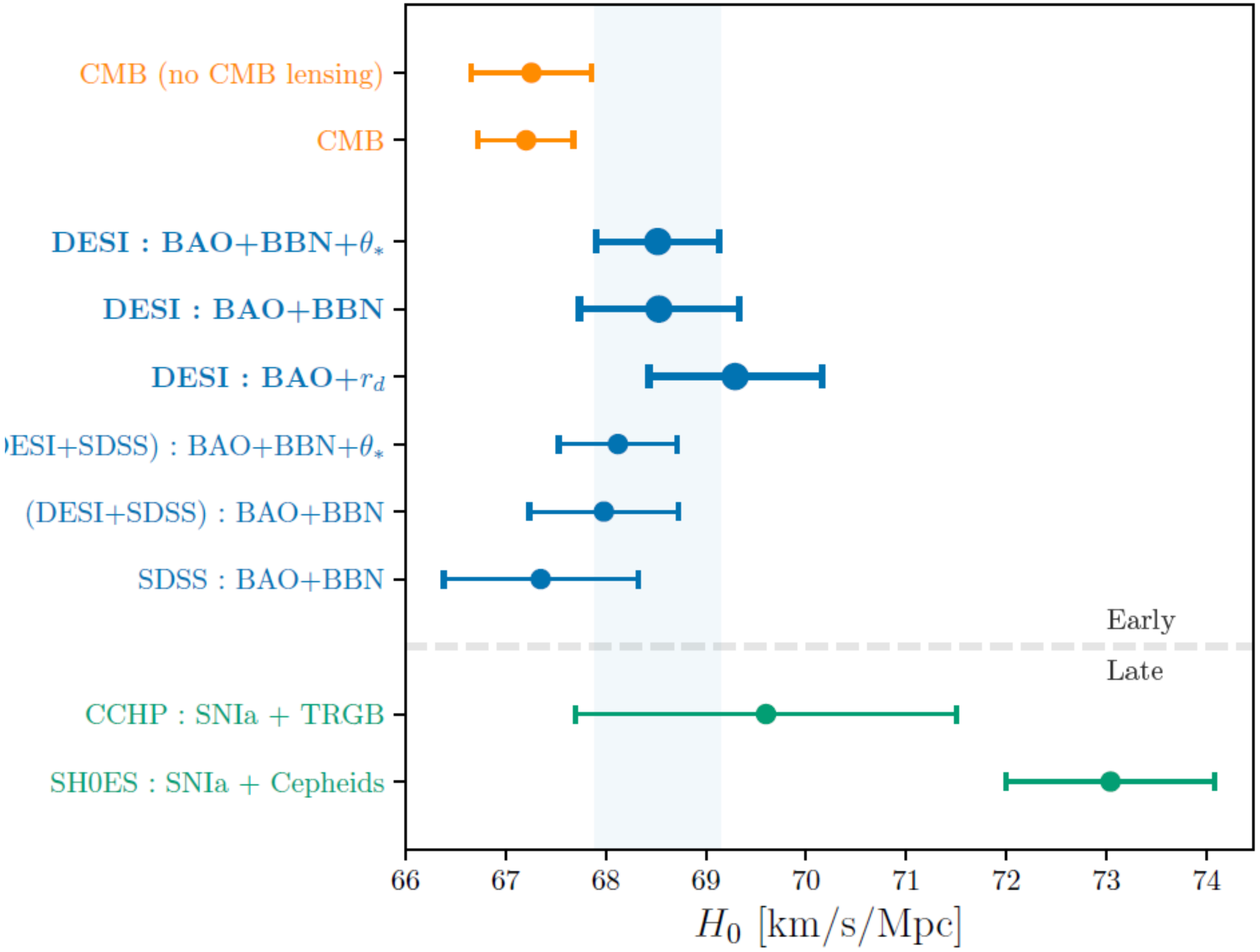
DESI + CMB: 67.97 ± 0.38 km/s/Mpc

Closer to Planck than to the local value





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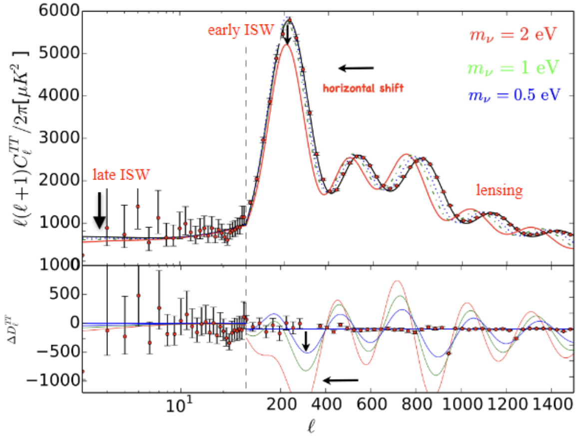
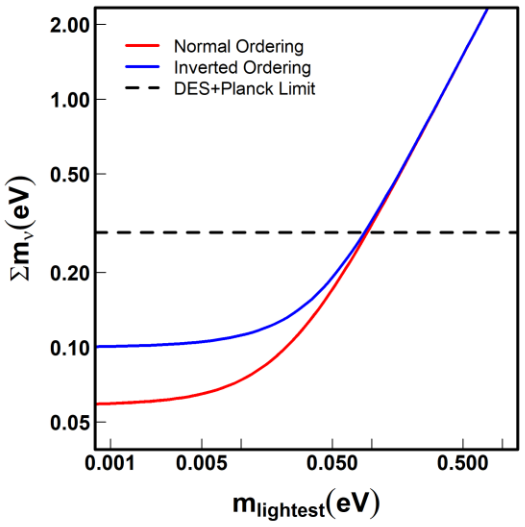
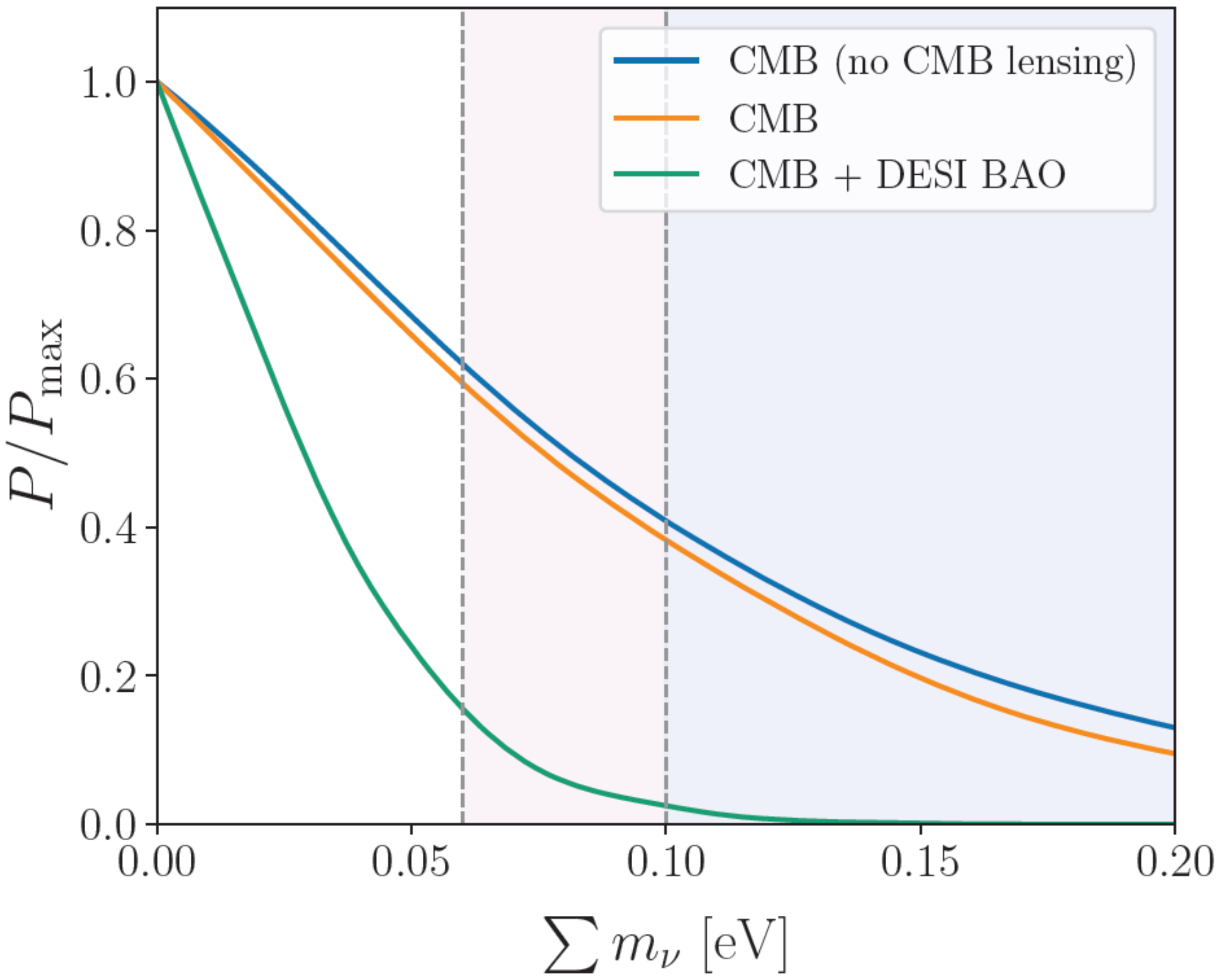
Neutrino mass

$\omega_M = \omega_b + \omega_{CDM} + (\Sigma m_\nu) / 93.14$ eV







BAO breaks CMB degeneracy between H_0 and Σm_ν

DESI+CMB: $\Sigma m_\nu < 0.072$ eV (95% C.L.)

If allowing for w(a): $\Sigma m_\nu < 0.195$ eV (95%)

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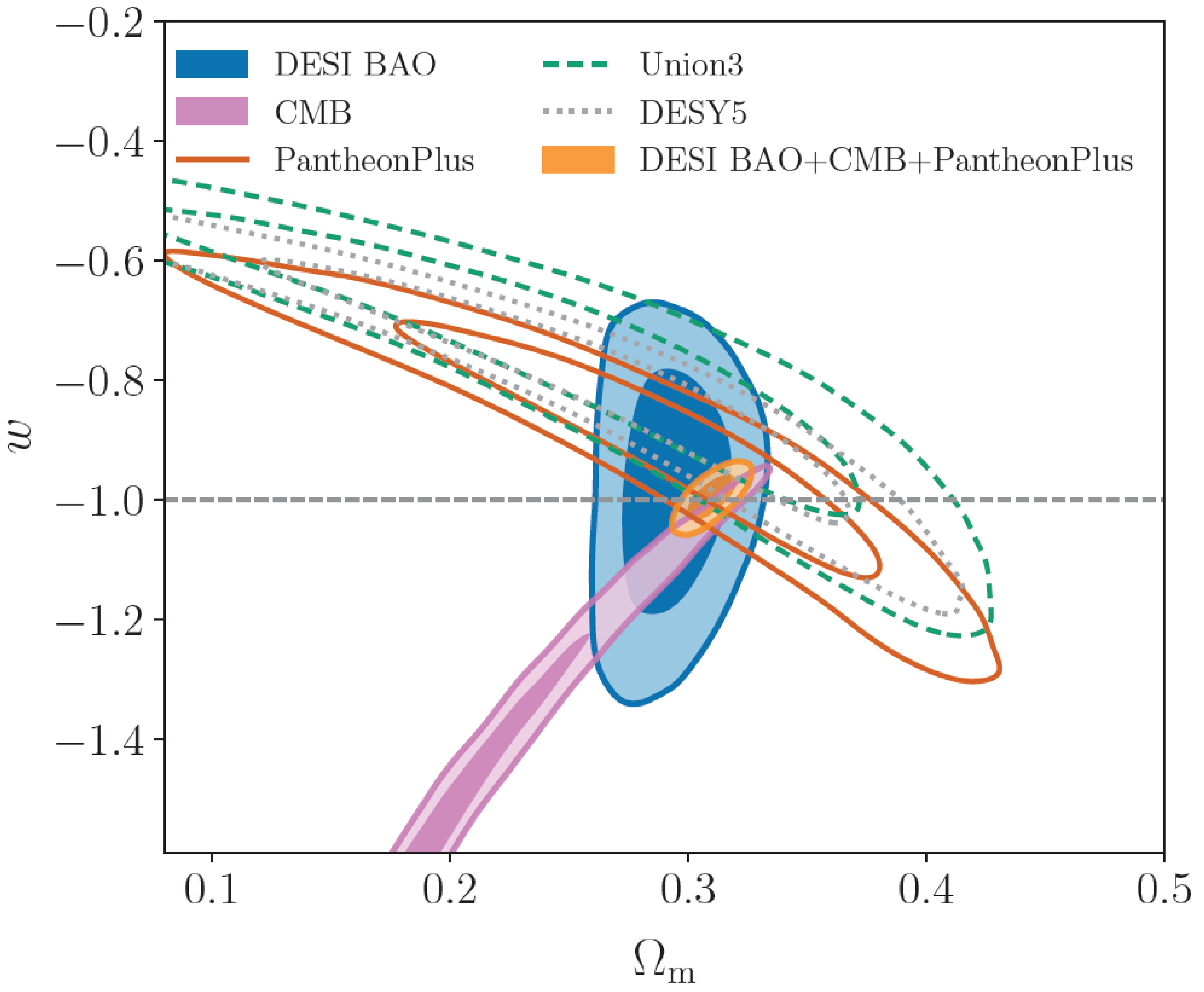
Dark Energy

$$\left.\begin{aligned}\Omega_\mathrm{m} &= 0.3095 \pm 0.0069,\\ w &= -0.997 \pm 0.025,\end{aligned}\right\} \quad \begin{array}{l}\text{DESI+CMB}\\ \text{+PantheonPlus.}\end{array}$$



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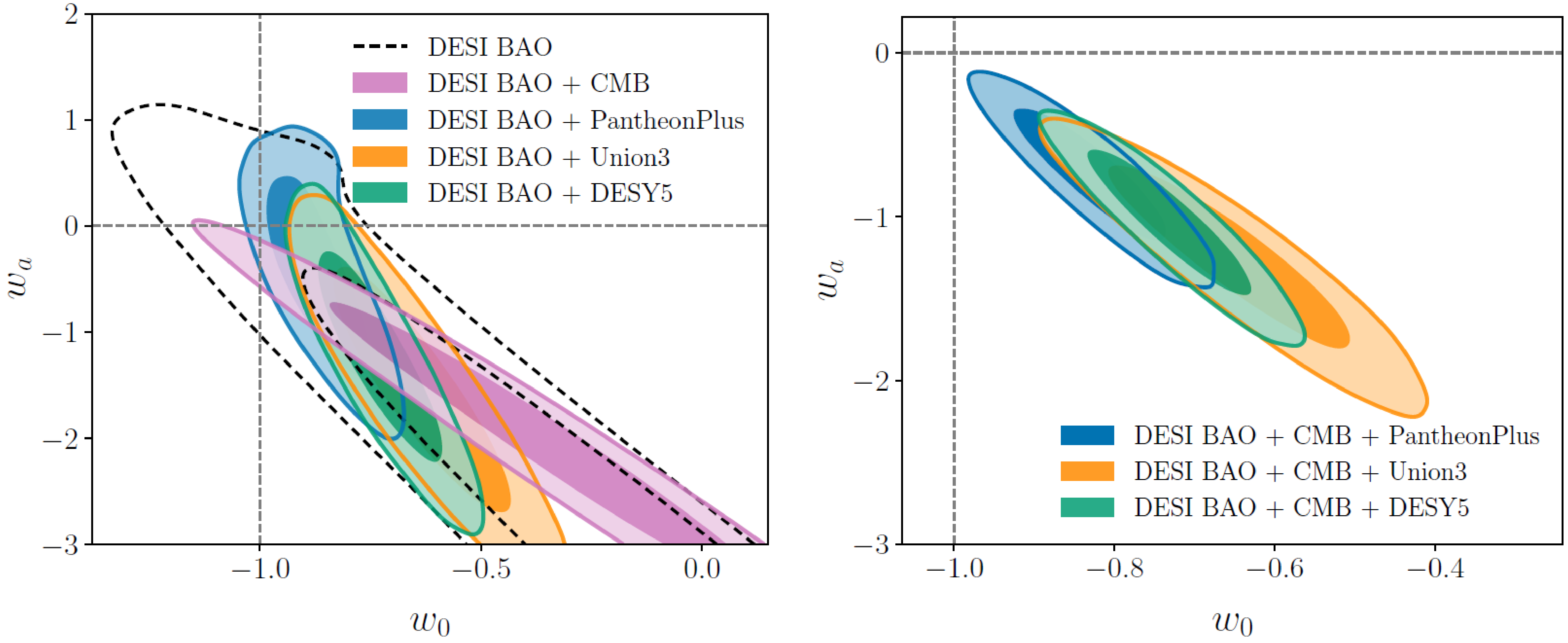
Dark Energy



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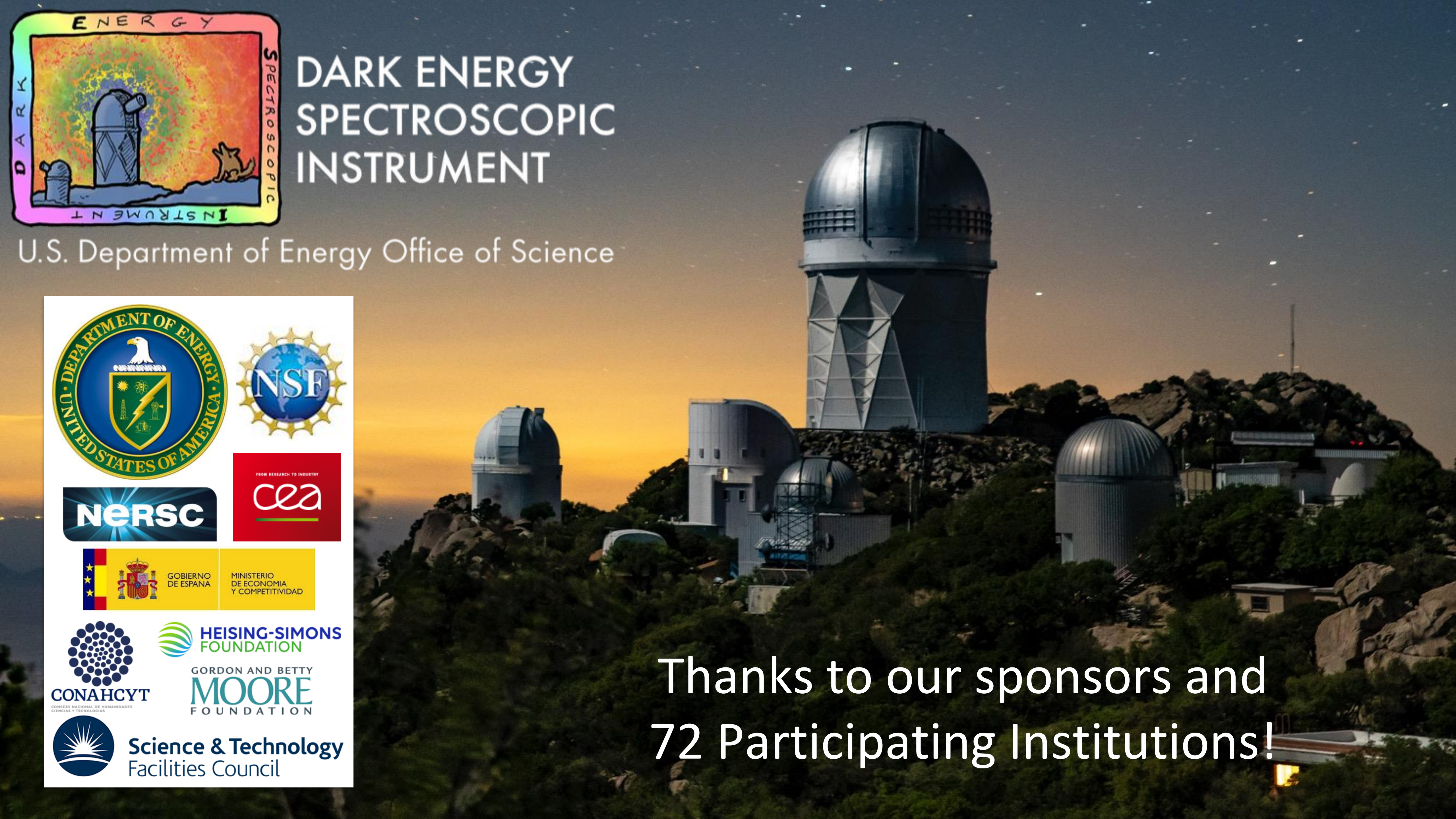
Summary

- **DESI already has the most precise BAO measurements ever**
- **DESI BAO + external priors give ~1% precisión on H_0**
- **Consistent with CMB and flat ΛCDM**
- **Neutrino mass constraints close to exclusion of inverted ordering**
- **Hints of time-varying EoS of the dark energy**

Still to come

- Full shape measurements of correlation function (power spectrum)
  → Soon! (in a few months)
- DR2 data (Y3) has been already collected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