Is Dark Energy Weakening?

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June 13, 2024

IJCLab colloquium series, Orsay

Is Dark Energy Weakening?

Probes of the expanding universe

The Dark Energy Spectroscopic Instrument – DESI

DESI First-year BAO results

Expanding Universe

Receding galaxies (Hubble & Lemaître, 1929)

Receding velocity increases with distance

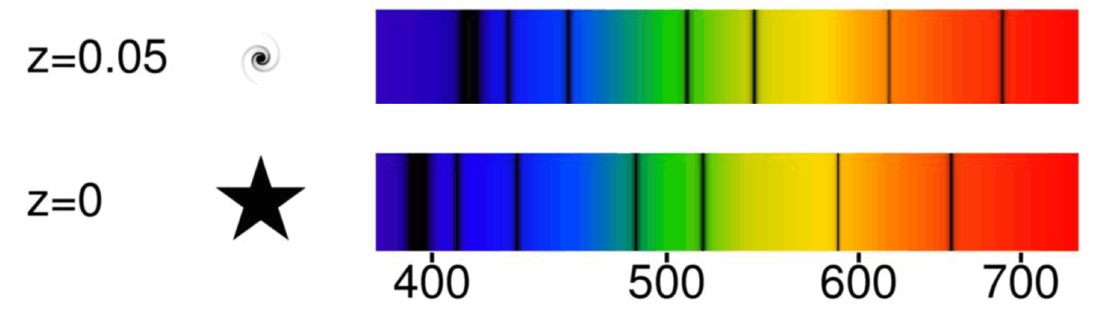
→ Expanding universe

v = H . D

Spectrum

Redshift $z = \frac{\lambda - \lambda_0}{\lambda_0}$

(Doppler effect: $z = v/c$)

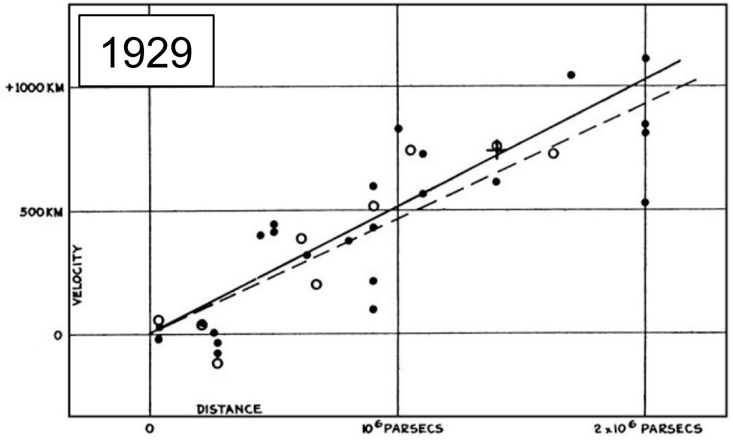


Photometry

Source of known luminosity

(Cepheids: period - luminosity)

$$\mathcal{L}_{\rm obs} \propto \frac{\mathcal{L}_0}{D^2}$$



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Expanding Universe

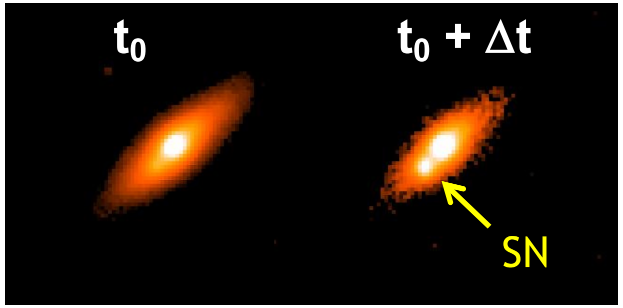
Expanding universe

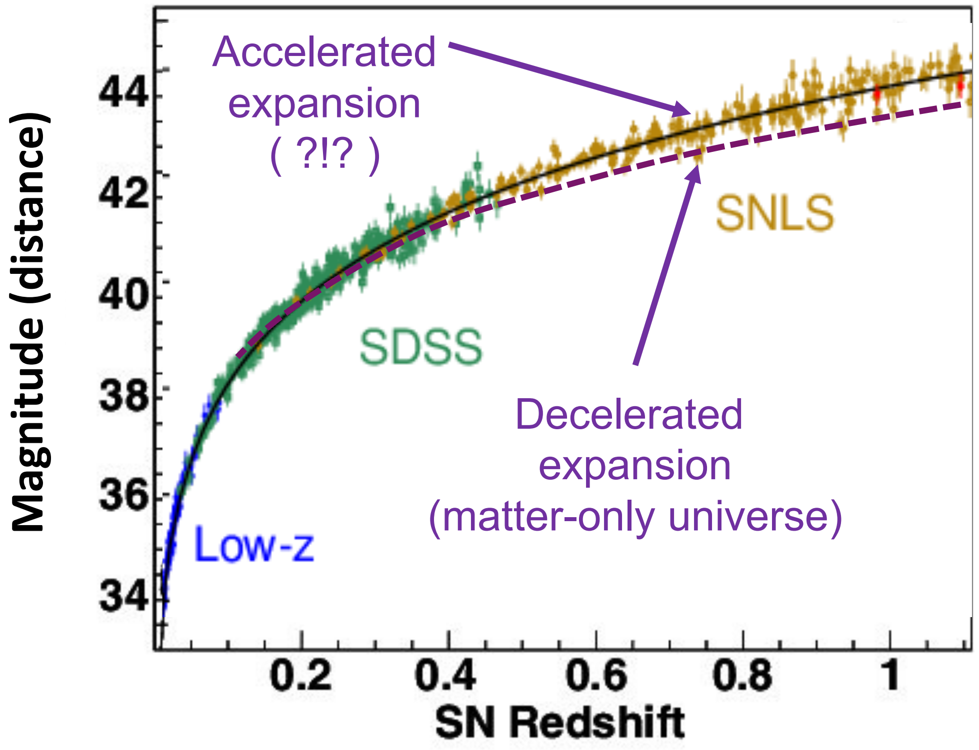
Distance – redshift relation

Supernovae Ia (known intrinsic luminosity)

2011 Nobel Prize

Perlmutter et al., 1998
Riess et al., 1998





SNIa fainter (~20%)
than expected for a given redshift
so further away (~10%)

↓

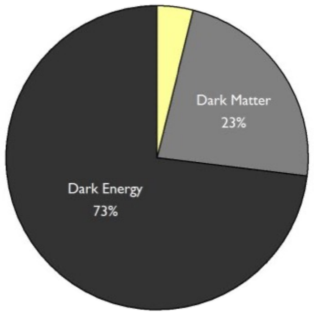
Accelerated expansion

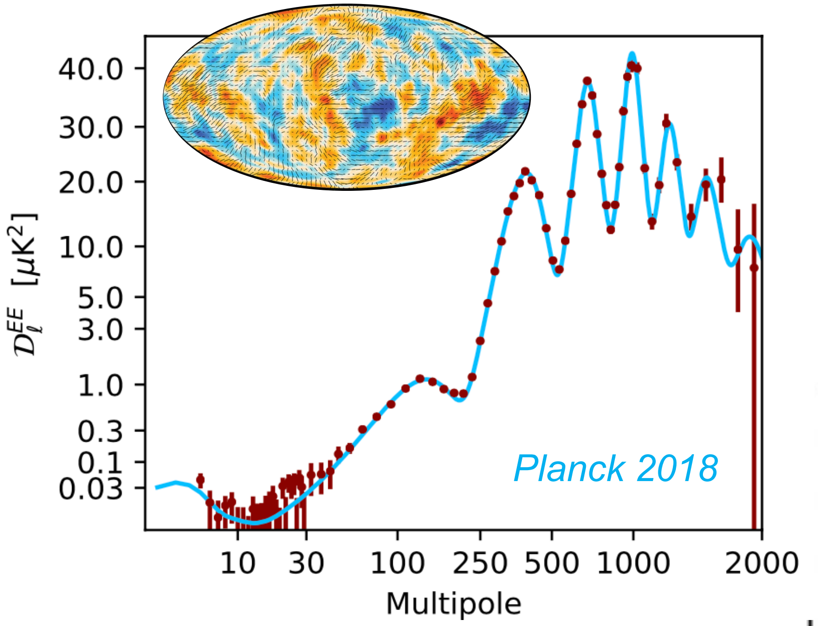
Inconsistent with matter-only universe

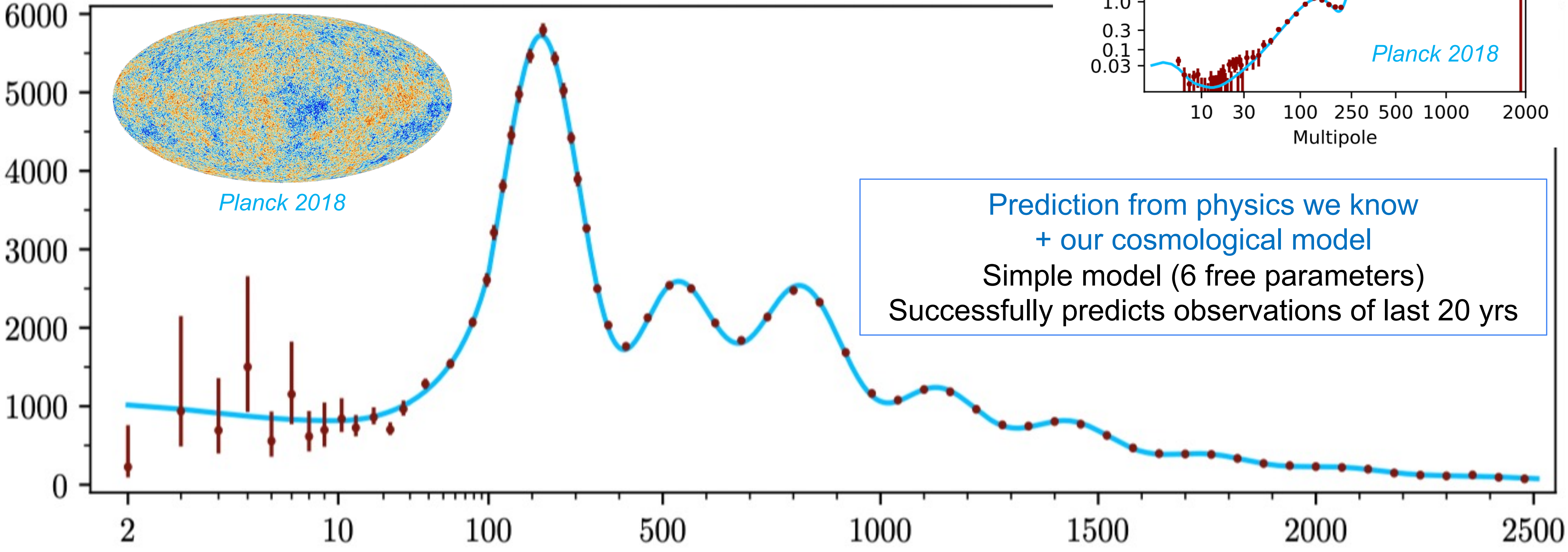
↓

DARK ENERGY!

ΛCDM model







Prediction from physics we know
+ our cosmological model
Simple model (6 free parameters)
Successfully predicts observations of last 20 yrs

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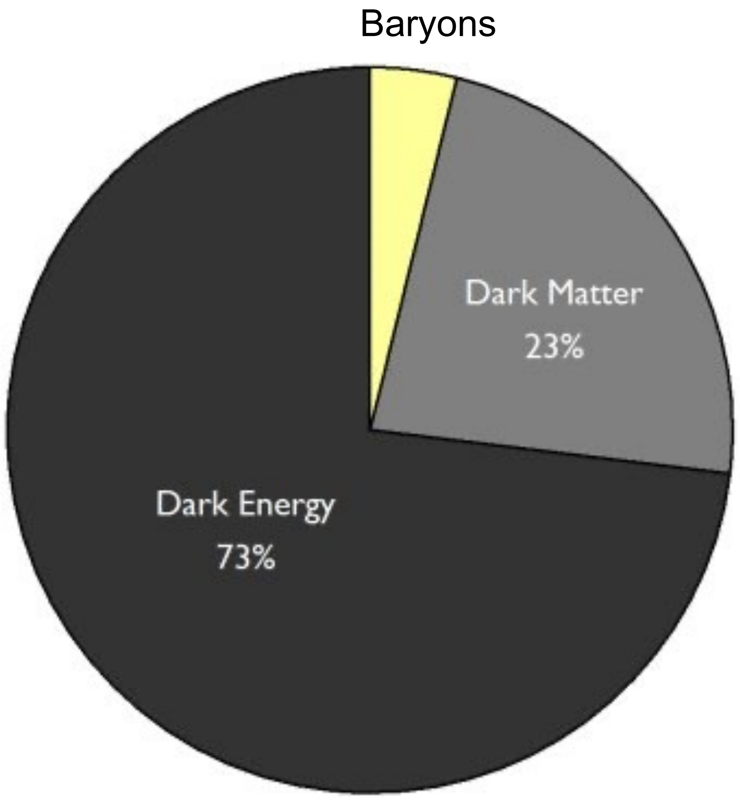
ΛCDM model



Cosmology model based upon

Two components of unknown nature

- **Dark Matter** (galaxy formation, gravitational lensing, rotation curves, …)
- **Dark Energy** (late-time acceleration)

+ Non-yet proven assumption: early-time **inflation?**

Other still-to-be-determined parameters:

- $\Sigma m\nu$
- **Neff (light relics?)**

Dark Energy

$$G_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{4\pi G}{c^4}\, T_{\mu\nu}$$

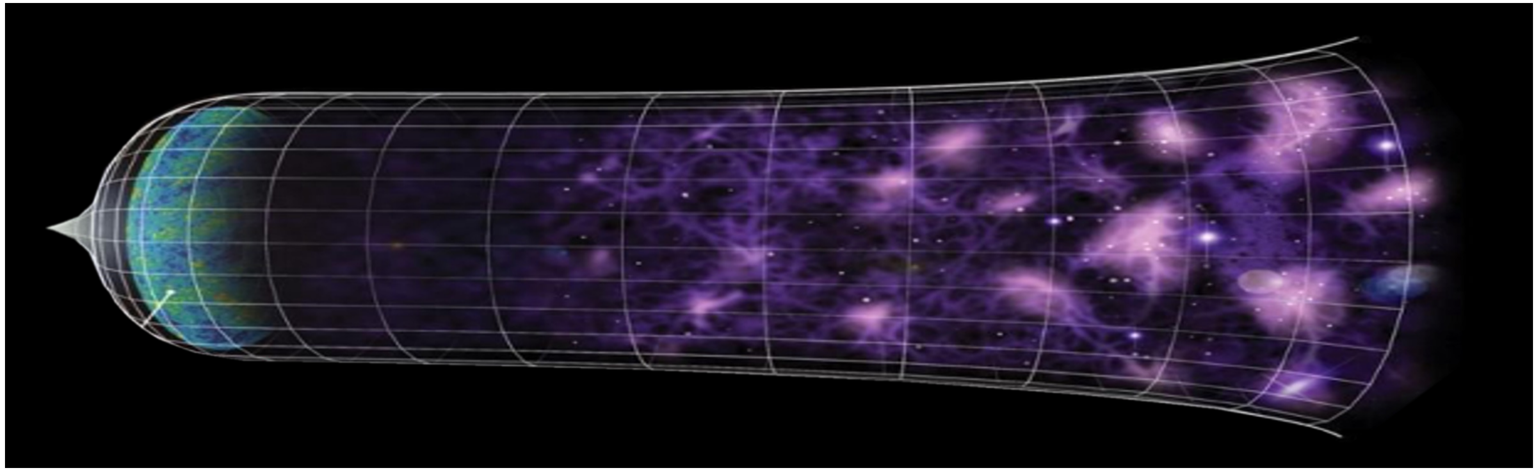
Geometry?
Cosmological constant Λ

Additional fluid (energy content)?

$$w = \frac{p}{\rho}$$

Accelerated expansion

Modified gravity?



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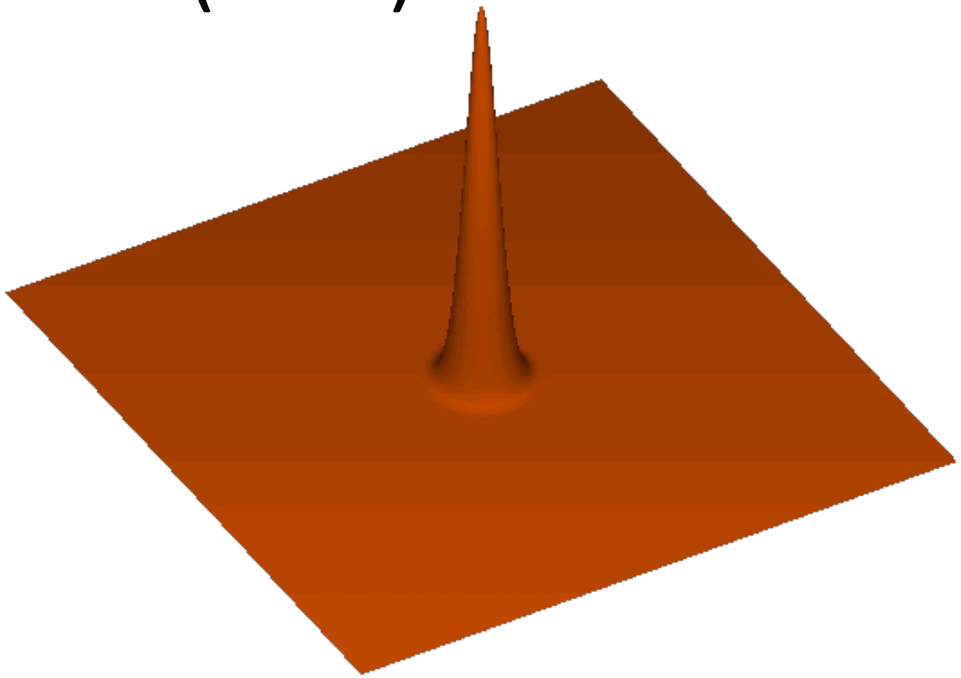
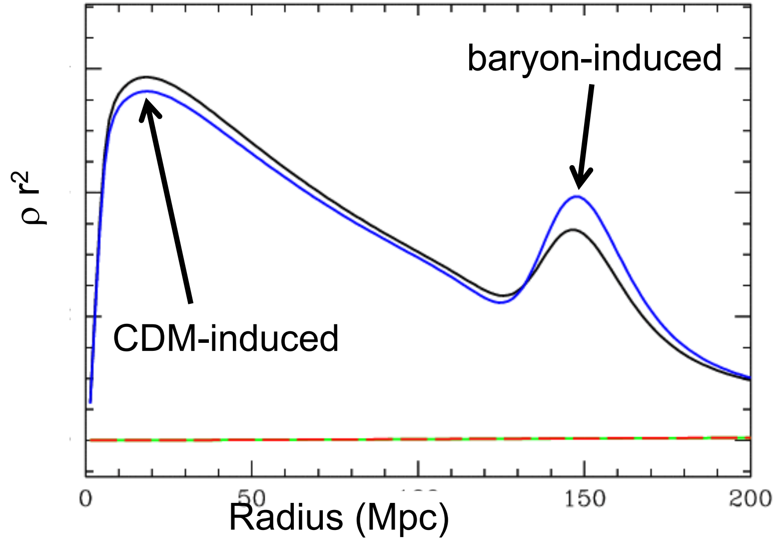
Baryon Acoustic Oscillations (BAO)

Propagation of baryon-photon over-density sound waves in primordial plasma

At recombination (p + e- → H at z~1100)
- Plasma changes to optically thin
- Baryons decouple from photons
- Waves freeze





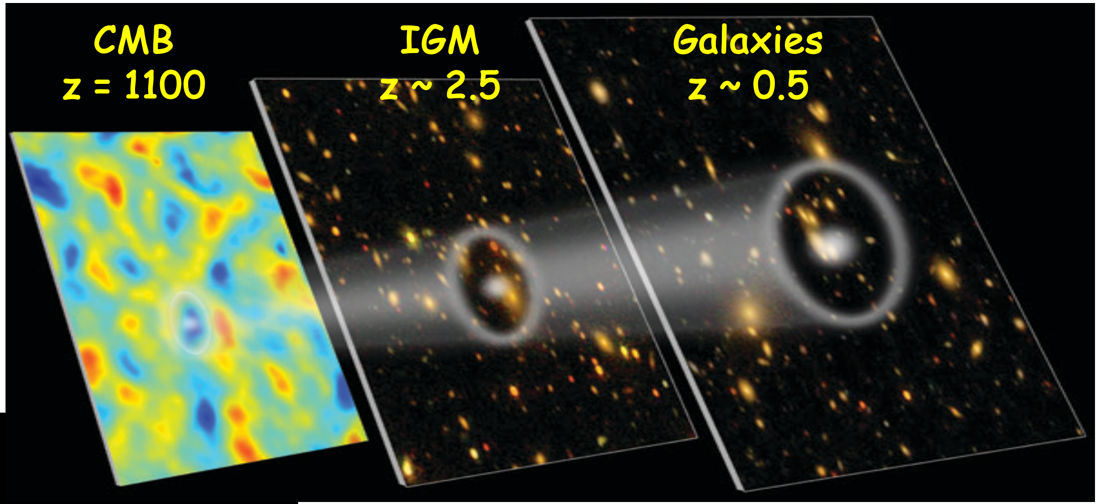
Residual spherical shell ⟶ Peak in clustering of matter

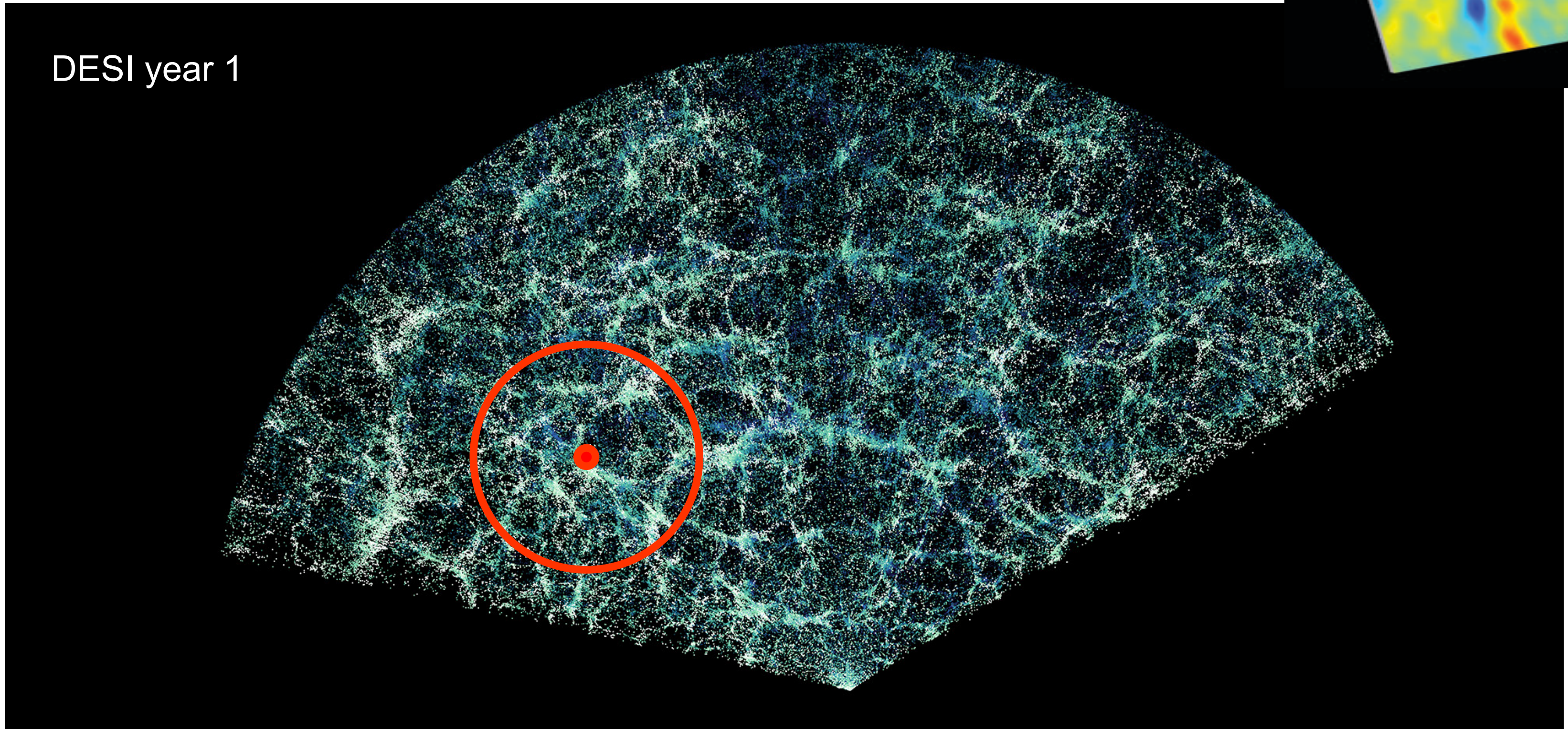
Size of feature = distance sound wave traveled

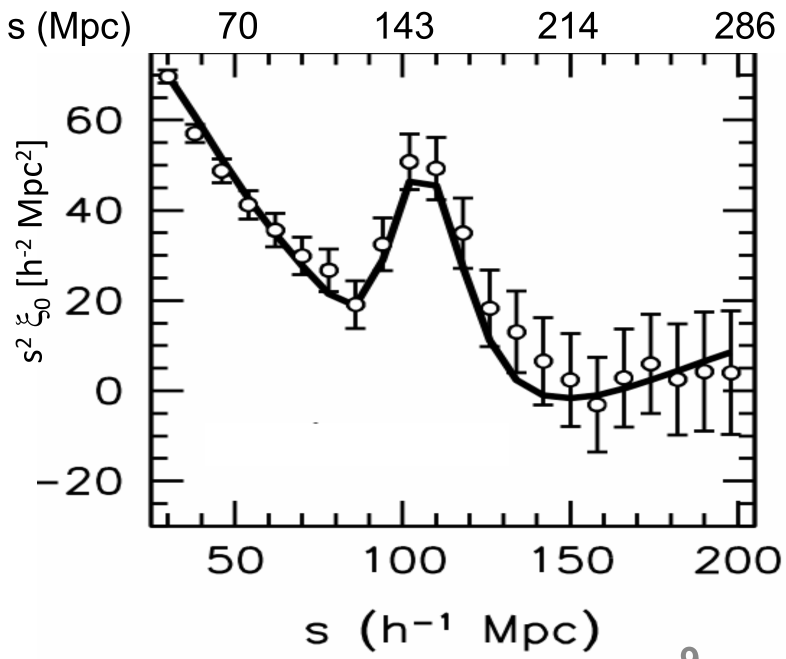
Preferred 3D scale $r_s = c_s \cdot t_{CMB} \sim 150$ kpc (at recombination)
$r_s \sim 150$ Mpc (today)

Baryon Acoustic Oscillations (BAO)

Imprint of fluctuations in primordial plasma
⟶ Standard Ruler to measure distances







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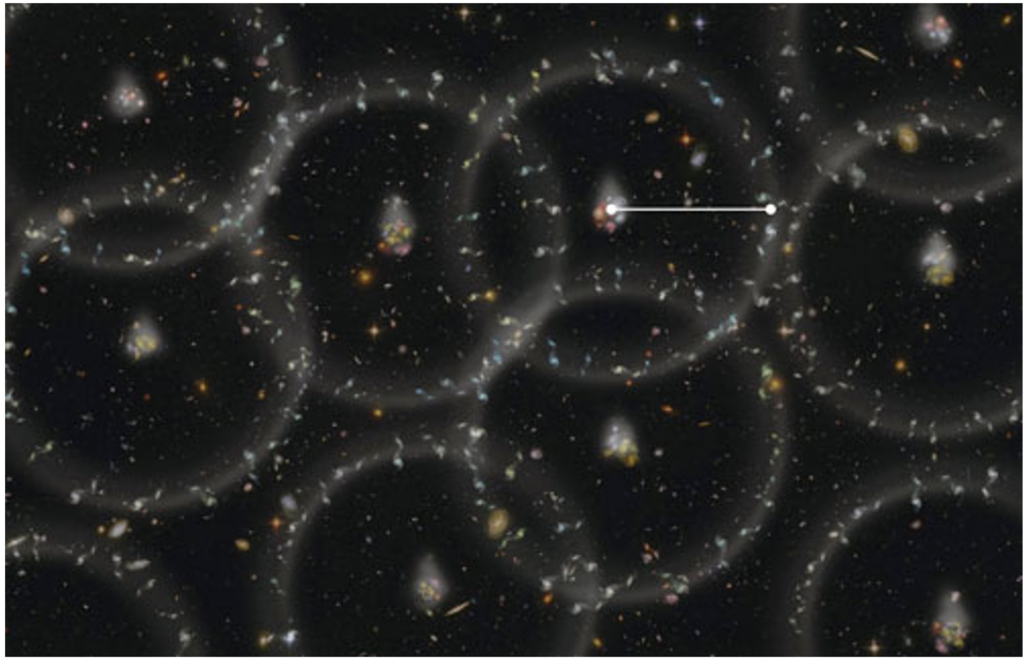
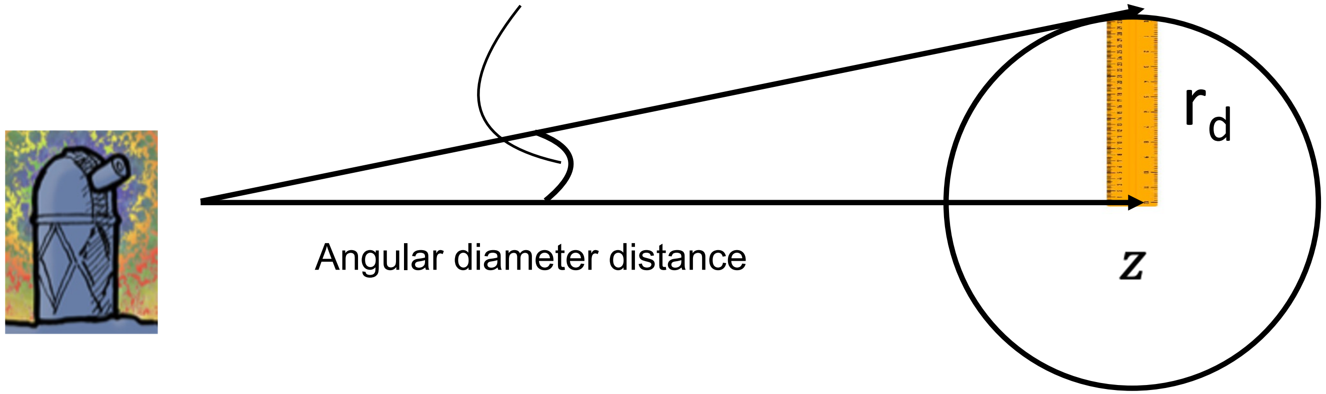
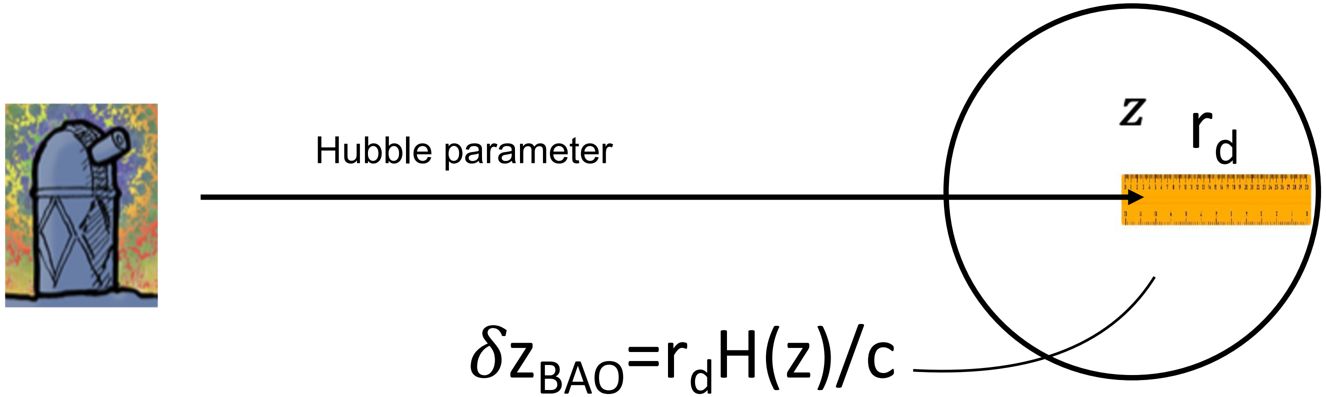
The BAO standard ruler

Artist's view of BAO



$\theta_{BAO} = r_d / D_M(z)$





$\delta z_{BAO} = r_d H(z)/c$

$D_M(z)$ anf H(z) encode expansion history of the Universe

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Probes of the expanding universe

The Dark Energy Spectroscopic Instrument – DESI

DESI First-year BAO results

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DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

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Thanks to our sponsors and 72 Participating Institutions!

Stage-IV Dark Energy Experiment

- Factor 10 on $\sigma_{w0} \cdot \sigma_{wa}$ compared to Stage-II (SNIa) experiments using expansion history (BAO) and growth of structures (RSD)
- Maximize volume **V = A x Δz**
  - Maximize area: 14,000 deg^2
  - Maximize redshift coverage $0.1 < z < 4.2$
- Maximize tracer number density **n**
  - **n**P ~ 1 (beyond which more valuable to increase volume)

$$\frac{\sigma_P}{P} \propto \frac{1}{\sqrt{V}} \times \frac{P + 1/n}{P}$$

clustering power dominates over galaxy shot noise

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DESI targets

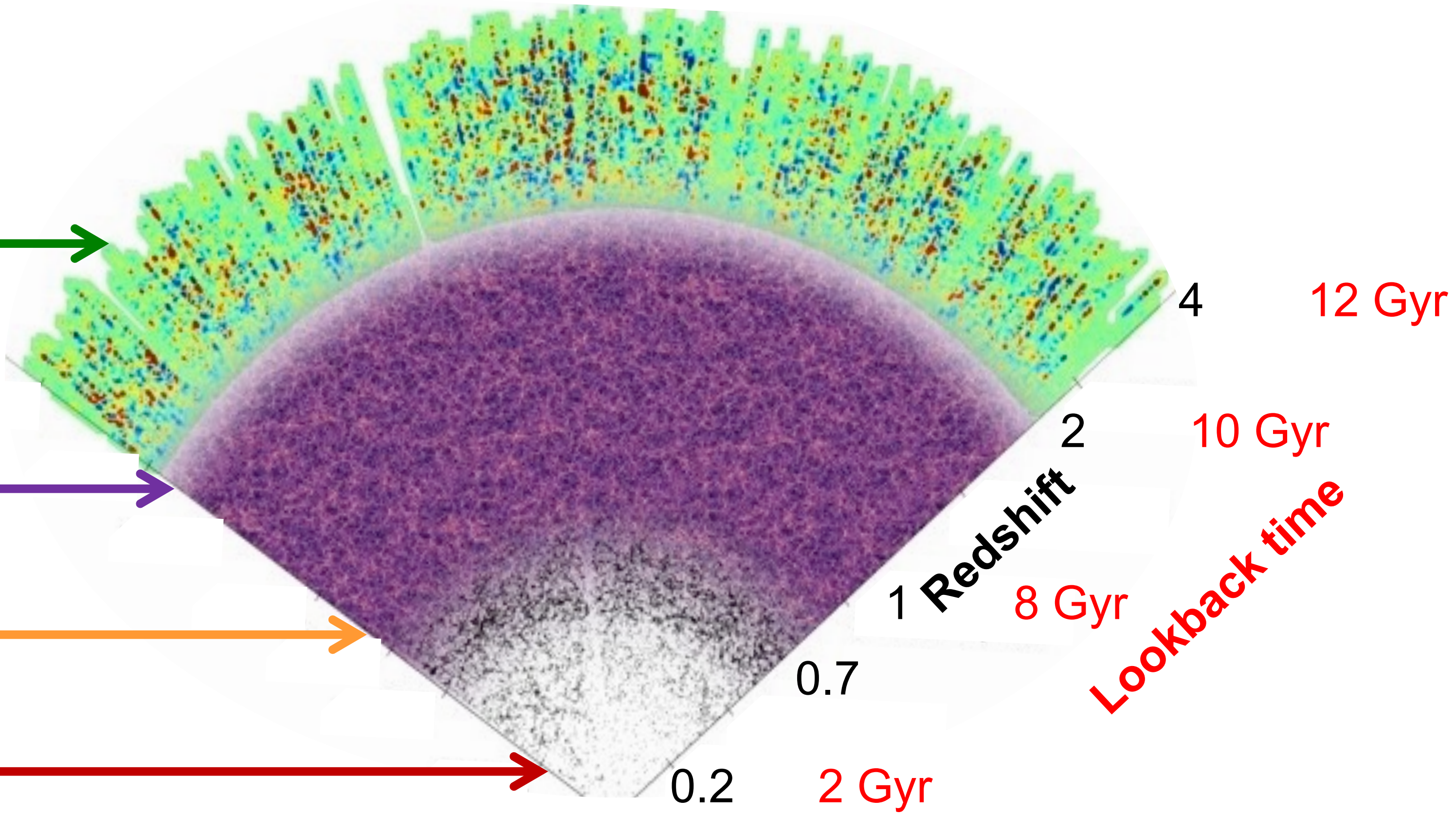
40 million
uninterrupted galaxies and quasars at 0 < z < 4

3 million QSOs
1.0 < z < 4.0

16 million ELGs
0.6 < z < 1.6

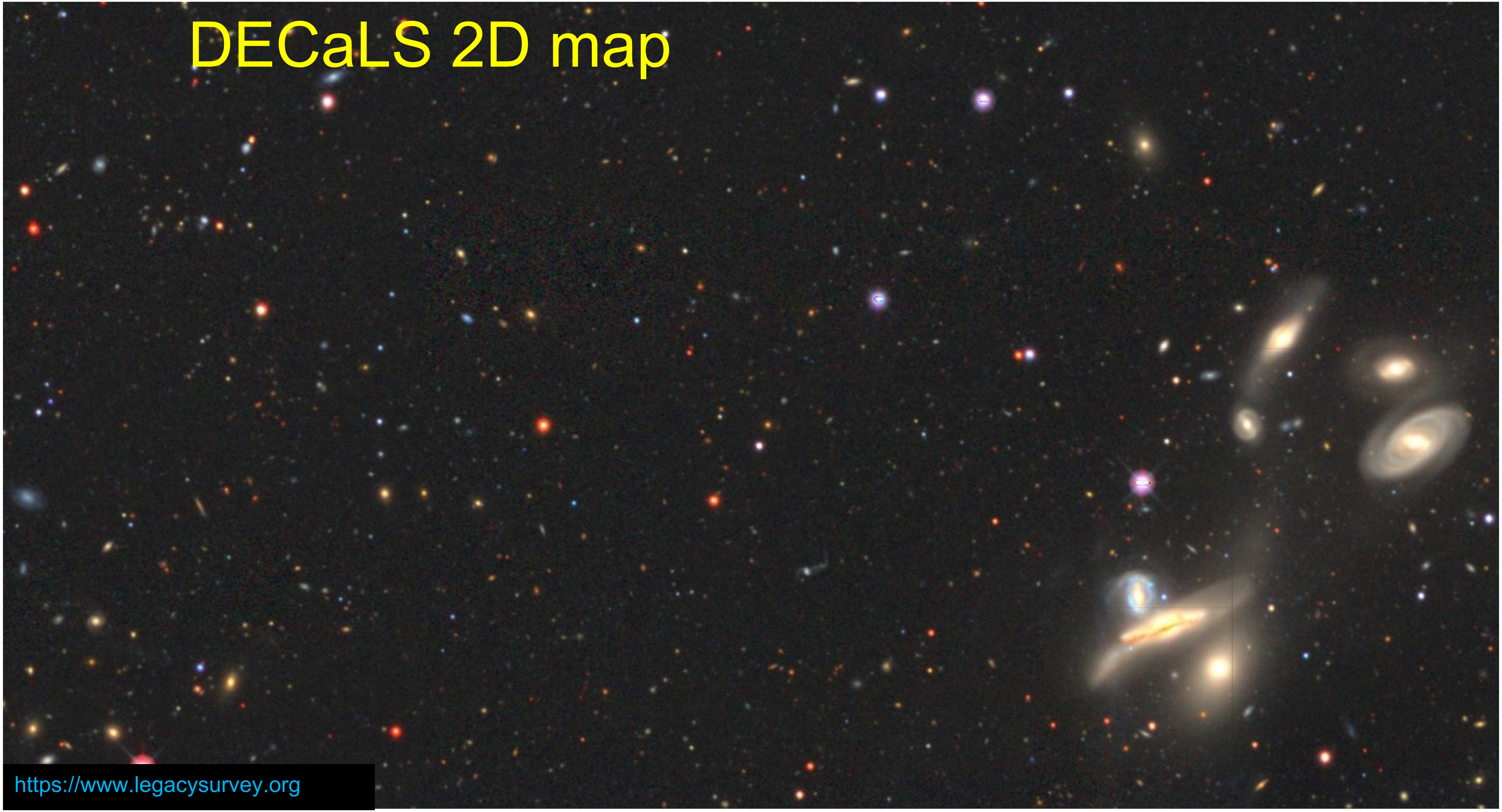
8 million LRGs
0.4 < z < 1.0

13 million Bright galaxies
0.0 < z < 0.4

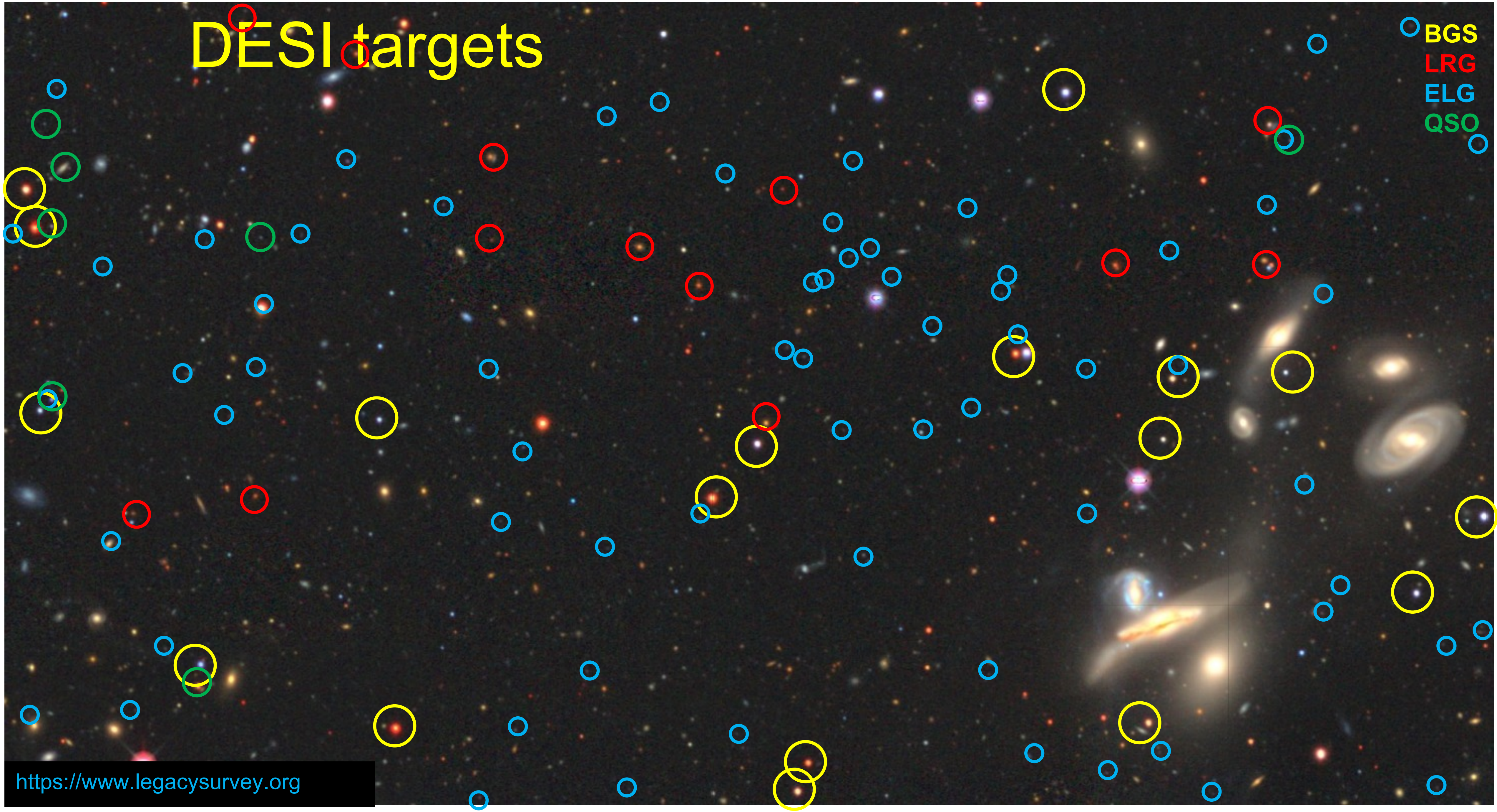


+10 million Milky Way stars

DECaLS 2D map



https://www.legacysurvey.org


DESI targets
BGS
LRG
ELG
QSO
https://www.legacysurvey.org

DESI instrument

Mayall telescope
at Kitt Peak Observatory (AZ)

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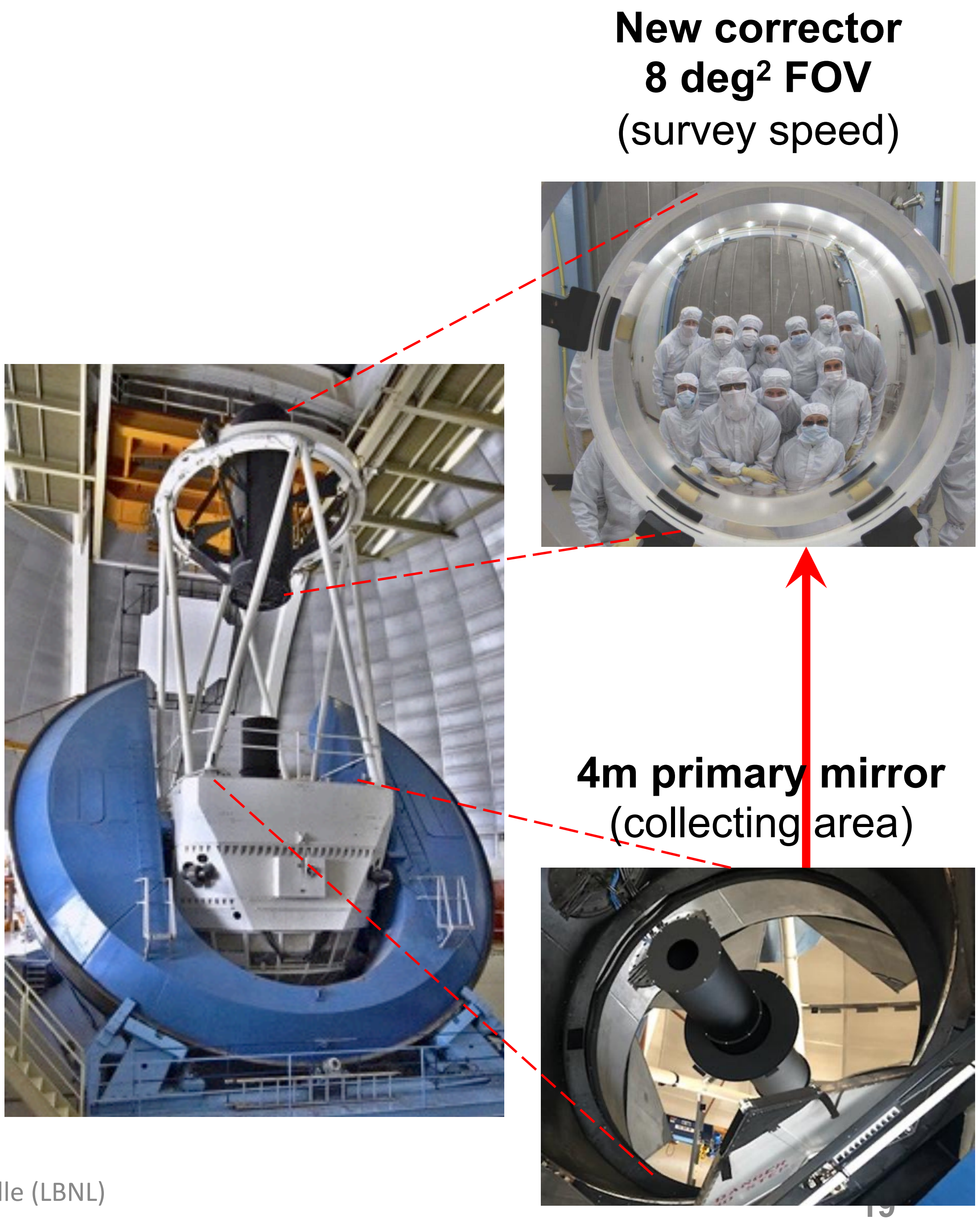
DESI instrument



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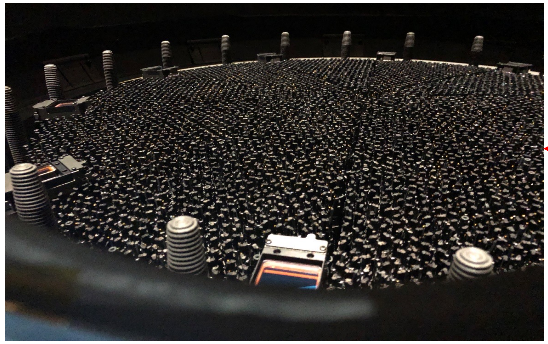
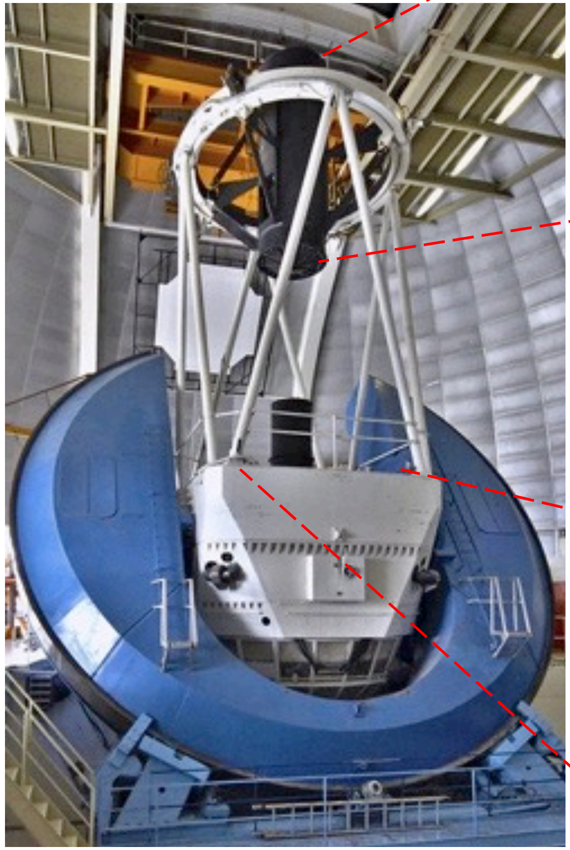
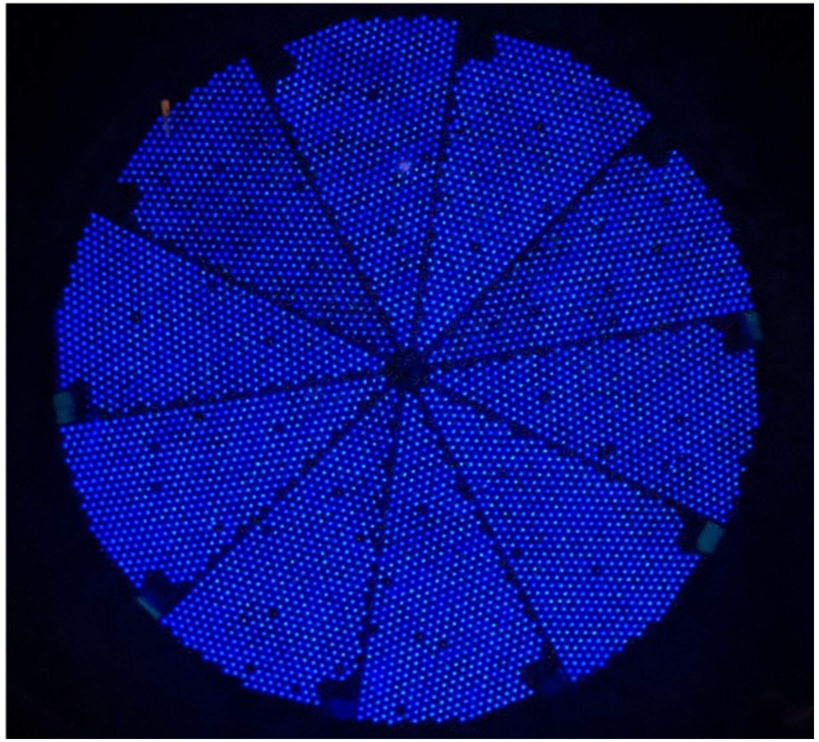
DESI instrument



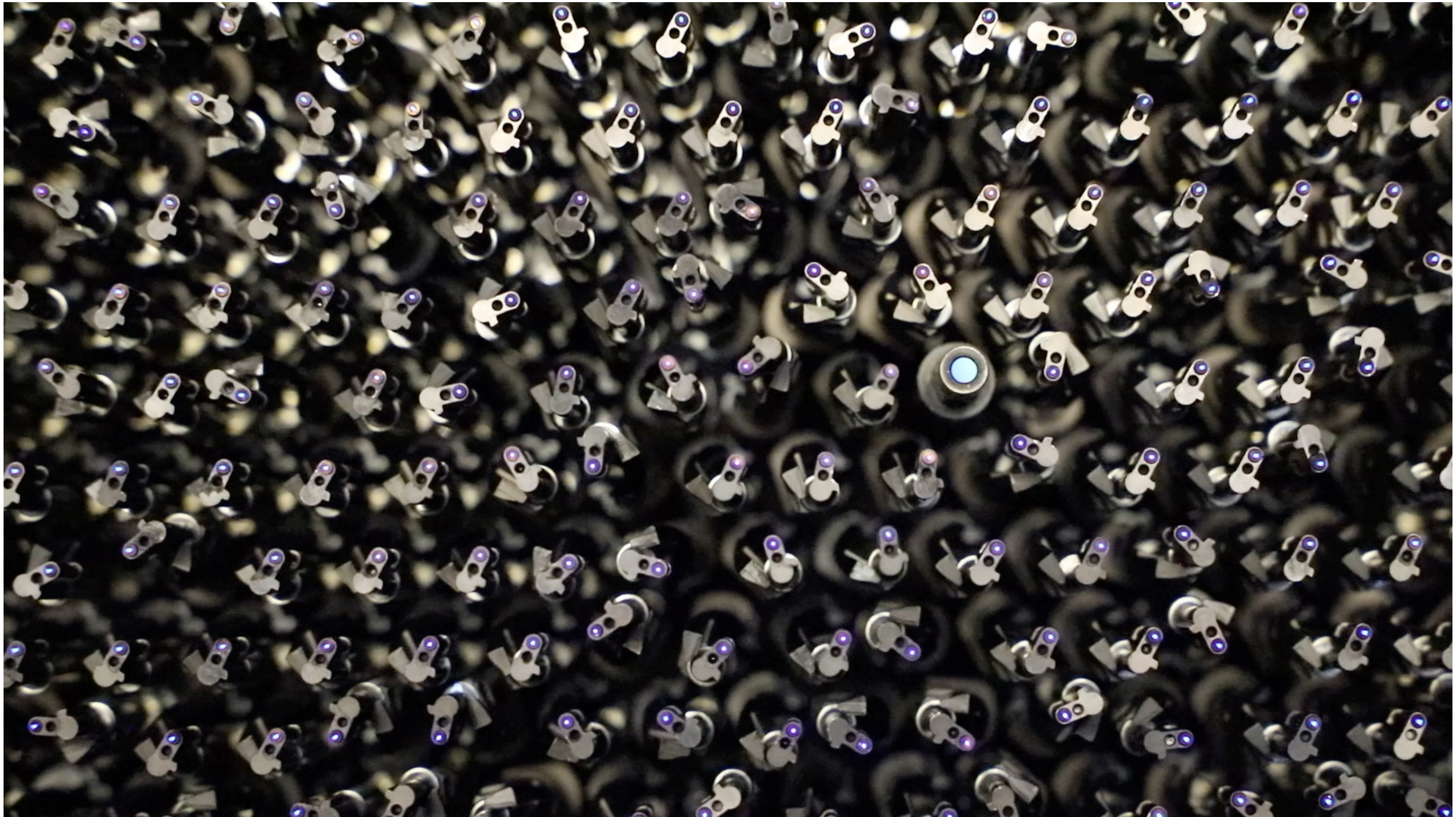




Focal plane:
5000 fiber positioners
(high multiplexing)

DESI INSTRUMENT

Fibers positioned to ~5 micron
(< 0.1 arcsec)
In 2 minutes



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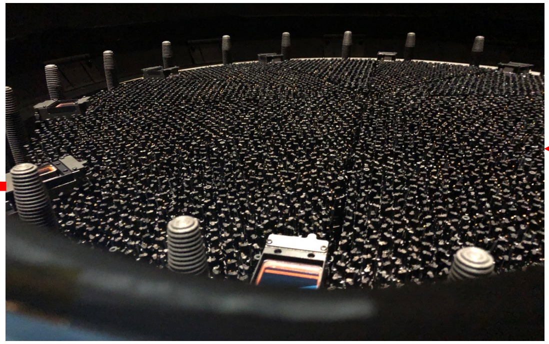
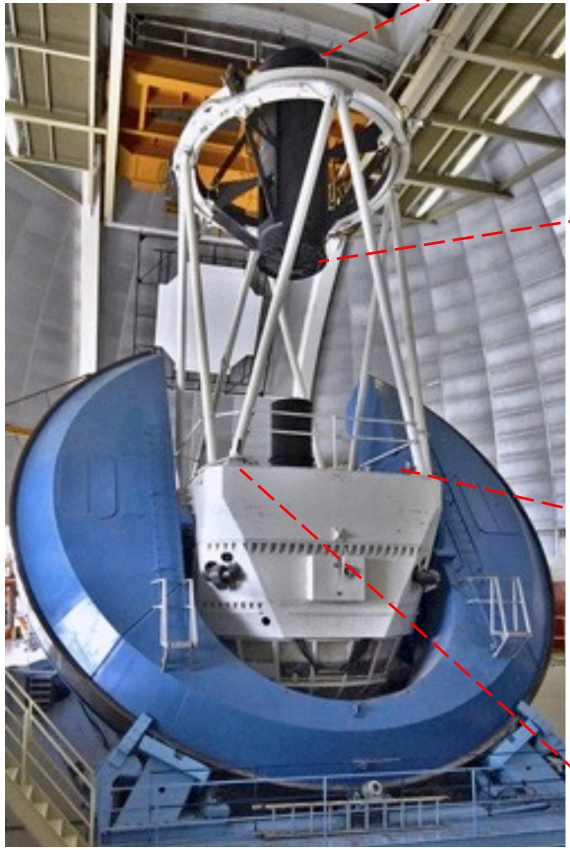
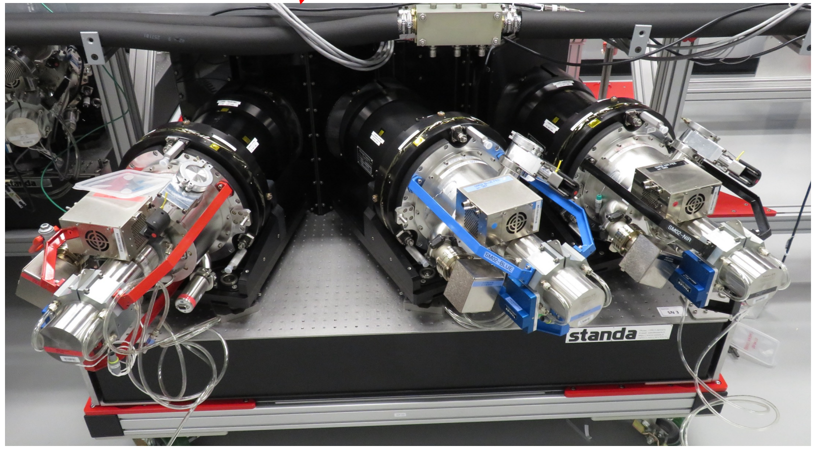
DESI instrument







40m-long optical fibers

10 3-band spectrographs
(high multiplexing)

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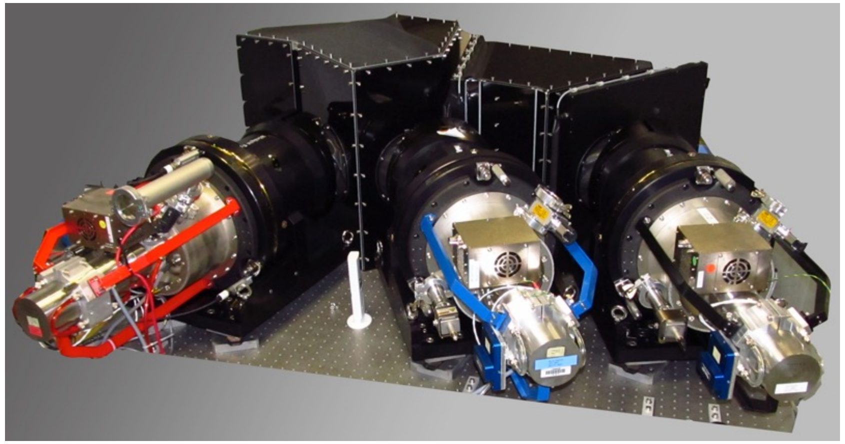
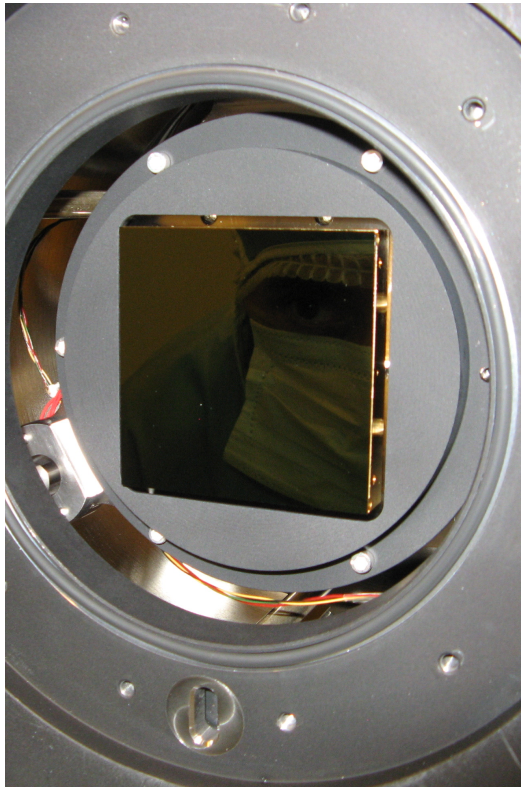
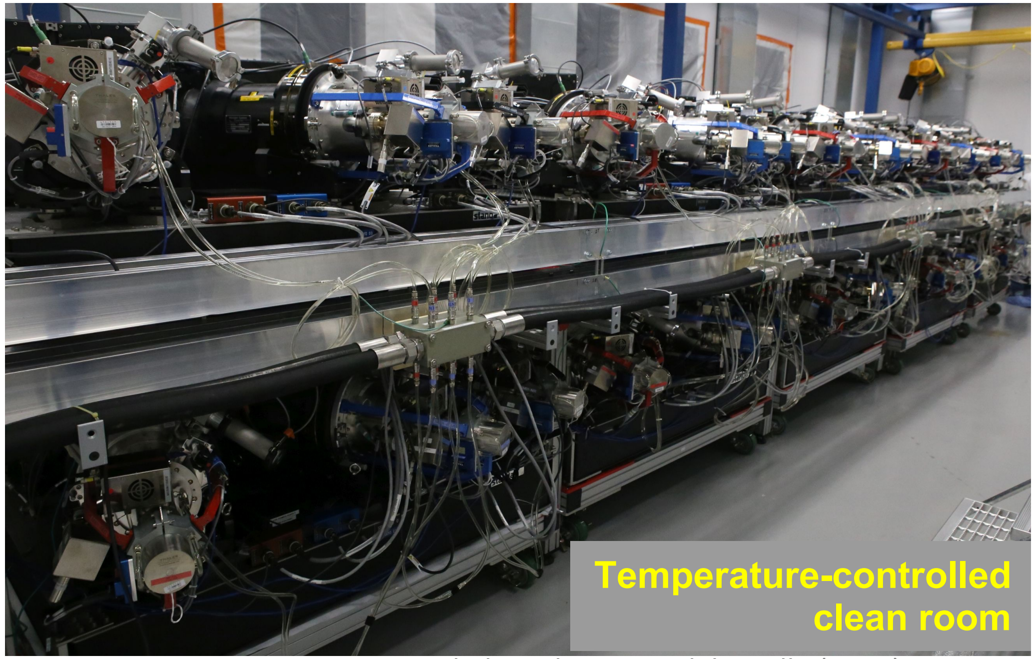
10 3-band spectrographs [360nm – 980nm]
(resolution and spectral coverage)

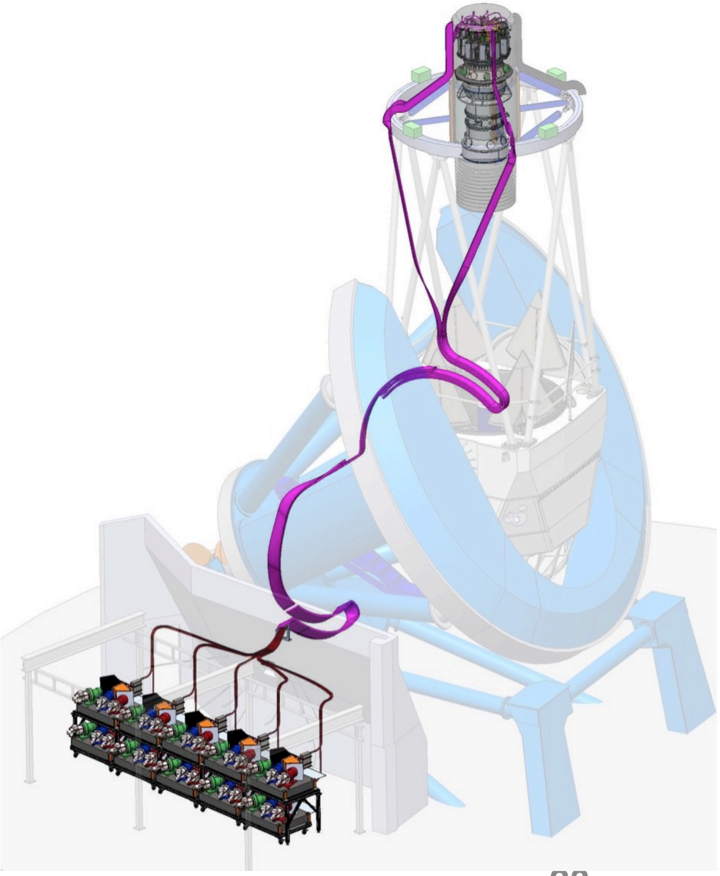
Lyα λ121.6 nm
down to z = 2.0

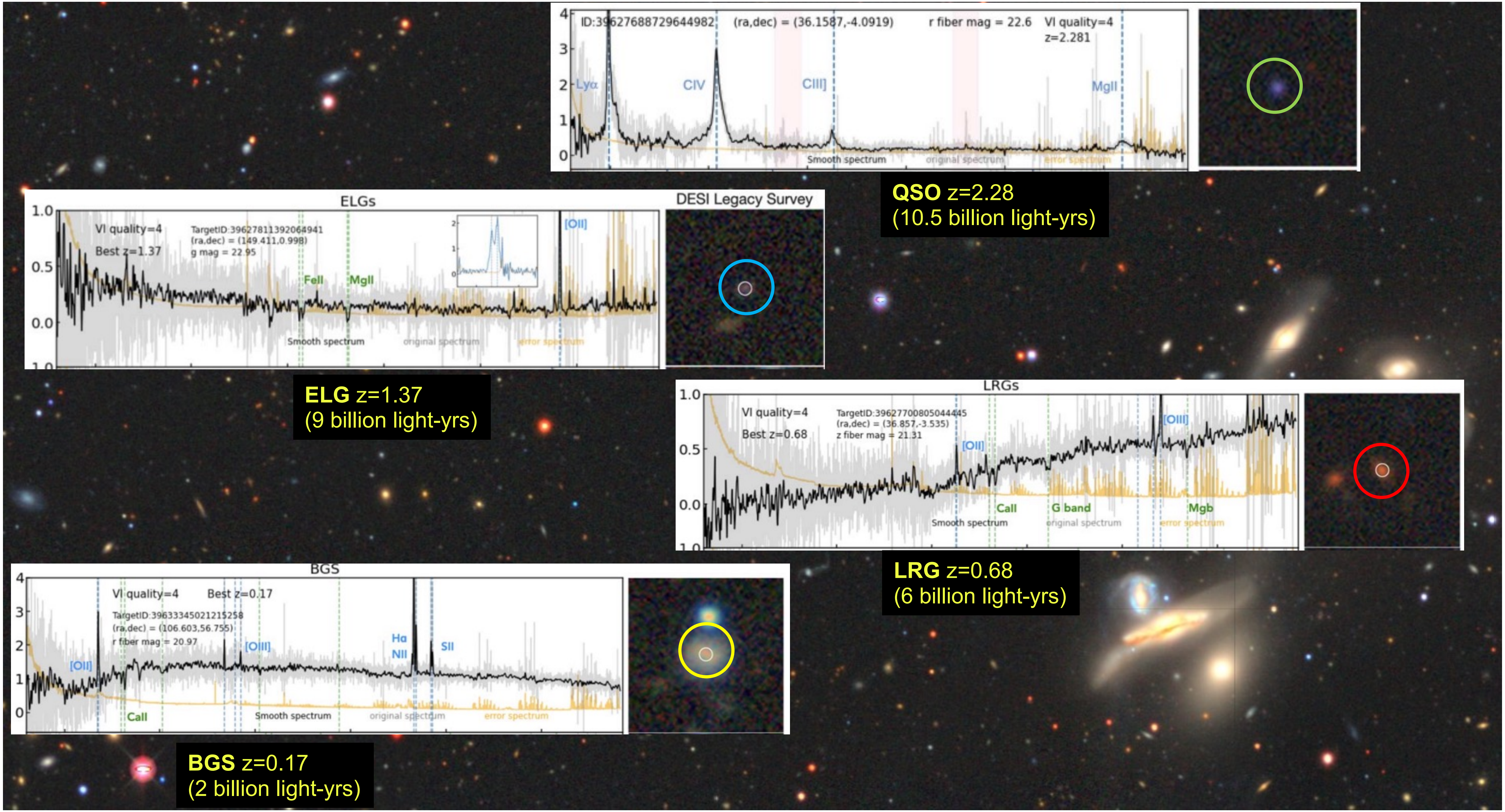
[OII] λ373 nm
up to z = 1.6










ID:39627688729644982
(ra,dec) = (36.1587,-4.0919)
r fiber mag = 22.6
VI quality=4
z=2.281
Lyα
CIV
CIII]
MgII
Smooth spectrum
original spectrum
error spectrum
QSO z=2.28
(10.5 billion light-yrs)
ELGs
DESI Legacy Survey
VI quality=4
Best z=1.37
TargetID:39627811392064941
(ra,dec) = (149.411,0.998)
g mag = 22.95
FeII
MgII
[OII]
ELG z=1.37
(9 billion light-yrs)
LRGs
VI quality=4
Best z=0.68
TargetID:39627700805044445
(ra,dec) = (36.857,-3.535)
z fiber mag = 21.31
[OII]
[OIII]
CaII
G band
Mgb
LRG z=0.68
(6 billion light-yrs)
BGS
VI quality=4
Best z=0.17
TargetID:39633345021215258
(ra,dec) = (106.603,56.755)
r fiber mag = 20.97
[OII]
[OIII]
Hα
NII
SII
CaII
BGS z=0.17
(2 billion light-yrs)

Is Dark Energy Weakening?

Probes of the expanding universe

The Dark Energy Spectroscopic Instrument – DESI

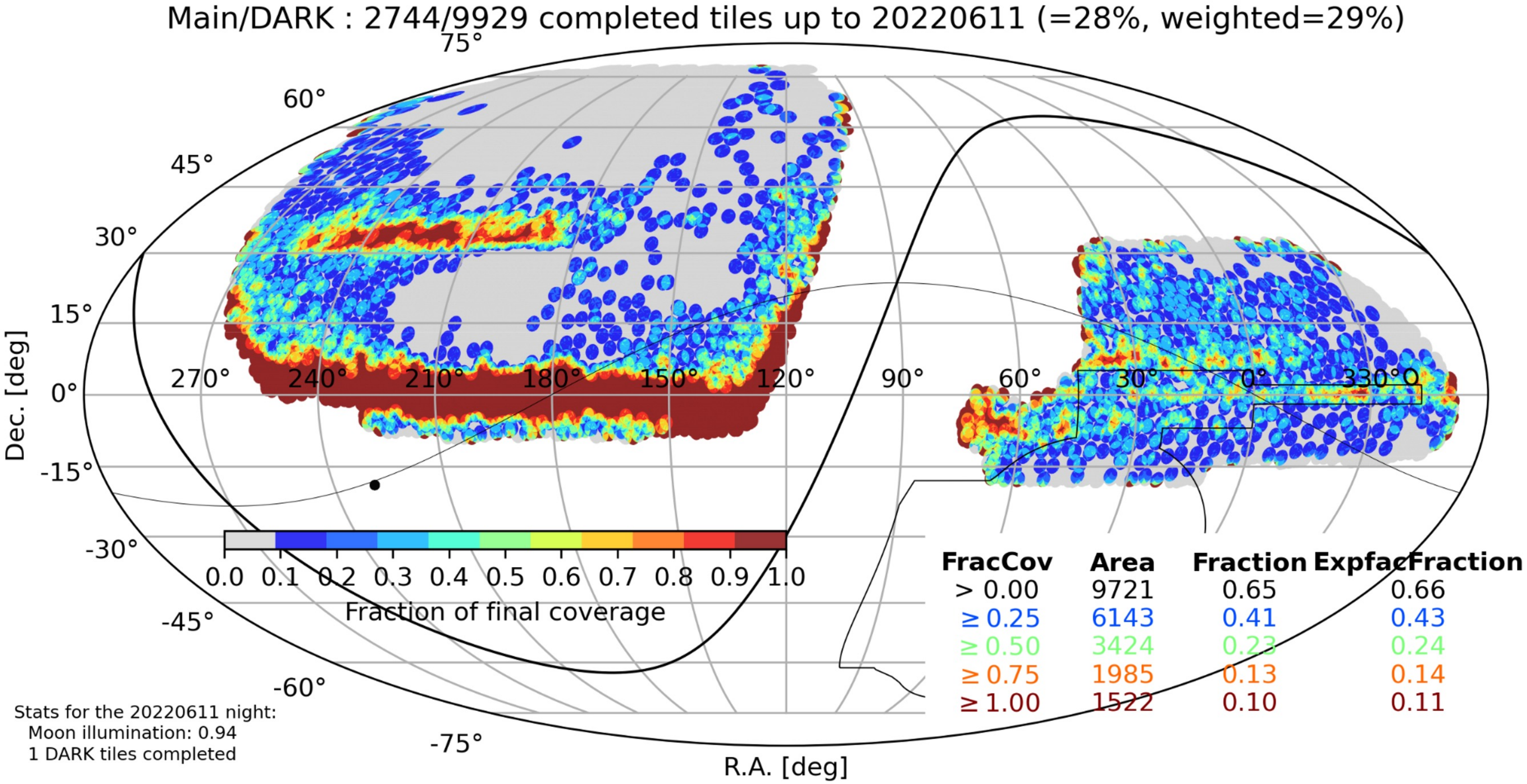
DESI First-year BAO results

BAO analysis on galaxies & quasars

BAO analysis on Lyman-α forest

Cosmological interpretation

DESI Data Release 1 footprint



Year-1 sample – 3x larger than SDSS (20 years)
5.7 million galaxies and quasars
420,000 Lyman-a forests

Year-1 sample is
25% (ELGs) to 45% (QSOs)
of completed survey

Nonlinear evolution of the standard ruler

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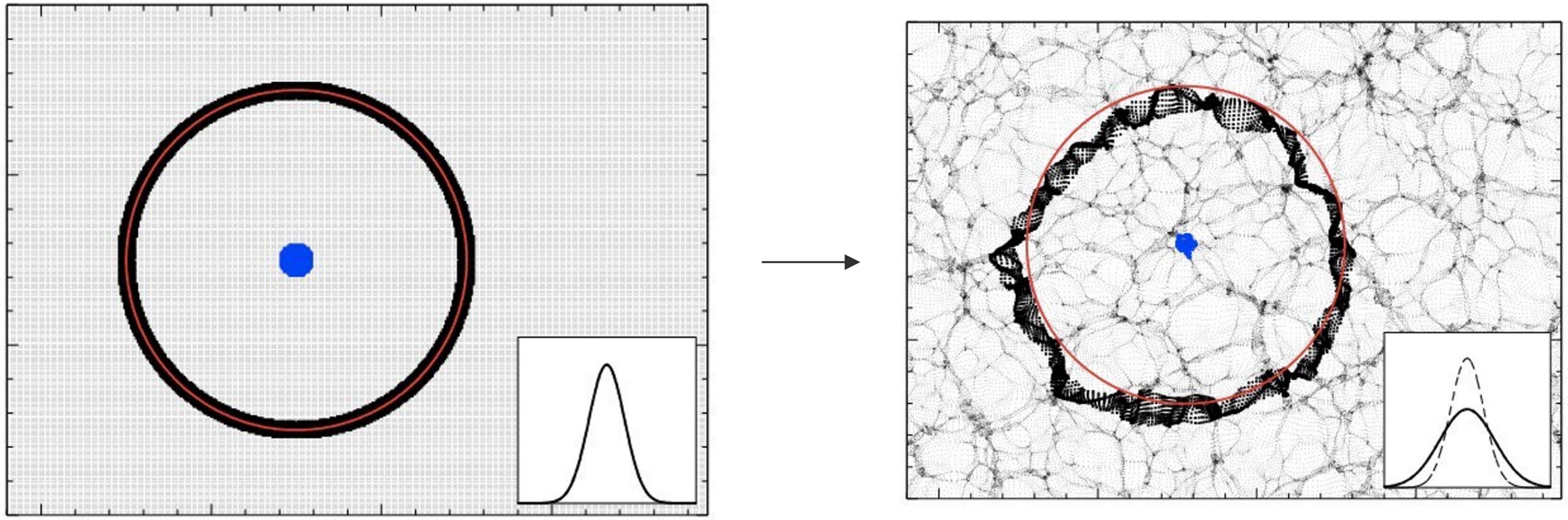
Ruler gets blurred and shrinks due to
- structure growth
- peculiar velocities

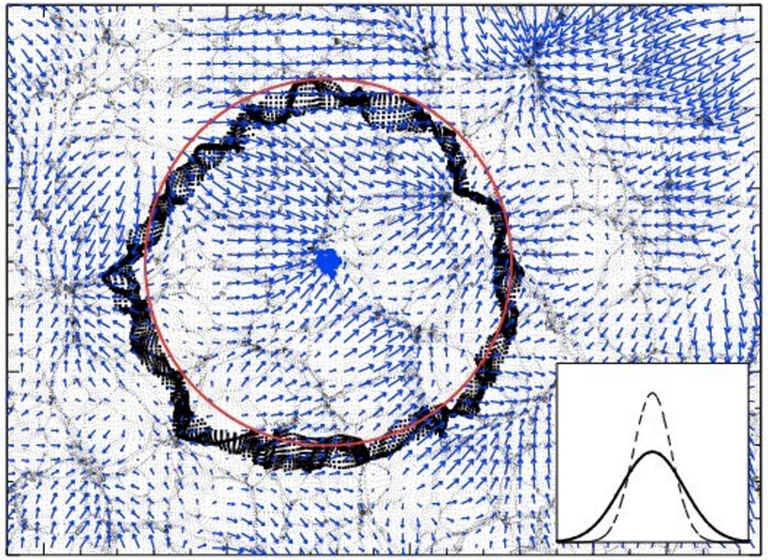


Padmanabhan et al. 2012

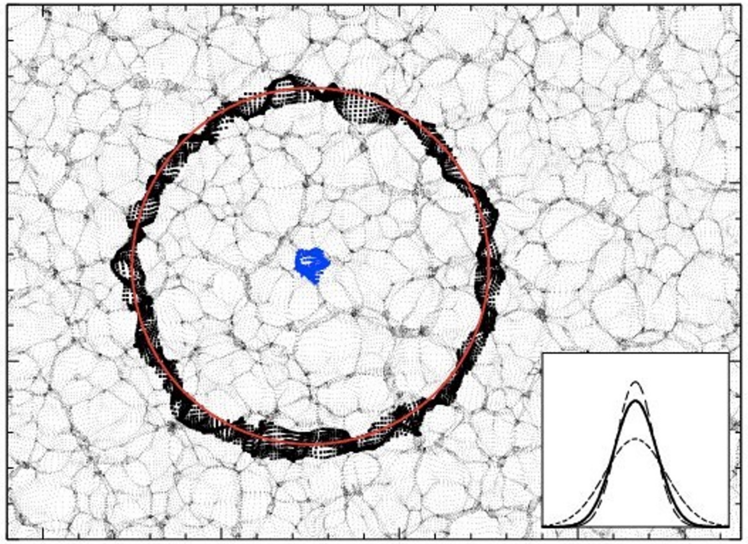
Degrades accuracy and precision of the standard ruler

Density-field reconstruction (Eisenstein et al. 2008)

Refurbishes the ruler!



Reconstruction →



Estimate displacement field applying continuity equation on observed field
→ Reverse the displacement

Improves both precision and accuracy

DESI 2024 galaxy and quasar BAO at z < 2.1

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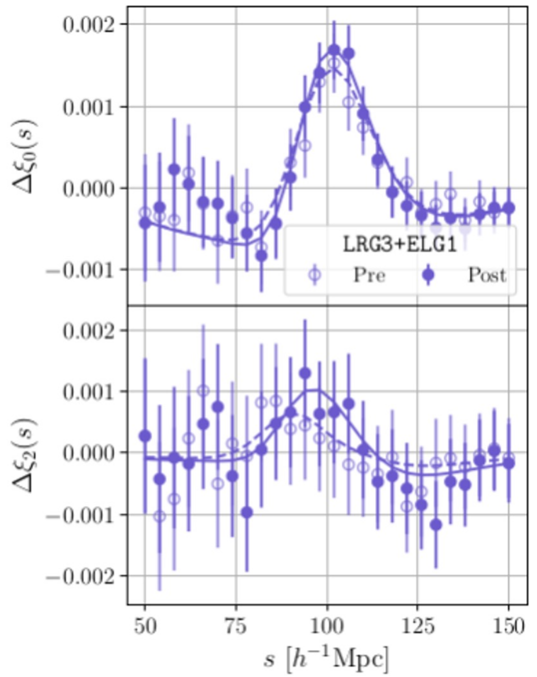
Largest data set in both number and volume
6 independent redshift bins (i.e. epochs)

First catalog-level blinded BAO analysis to mitigate confirmation bias

Systematic uncertainties
None detected for
- observational effects
- reconstruction method
- analytic covariance matrix

0.1 to 0.2% each for
- Galaxy-halo connection
- theoretical modeling
- selection of fiducial cosmology

$\Longrightarrow \sigma_{syst} << \sigma_{stat}$ and $\sigma_{stat + syst} = 1.05\ \sigma_{stat}$



LRG + ELG 0.8<z<1.1

$z_{eff} = 0.93$
9σ detection of BAO
Distance measured at 0.8%

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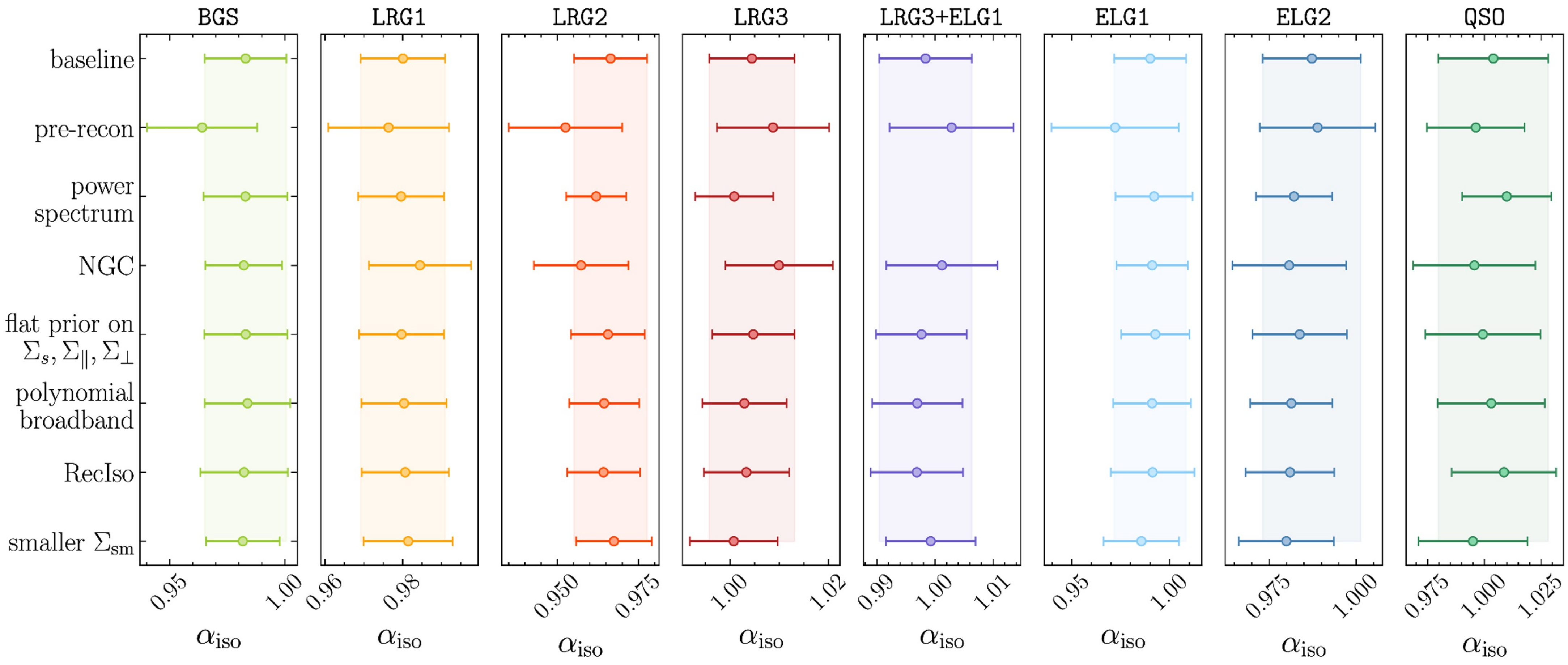
Consistency tests



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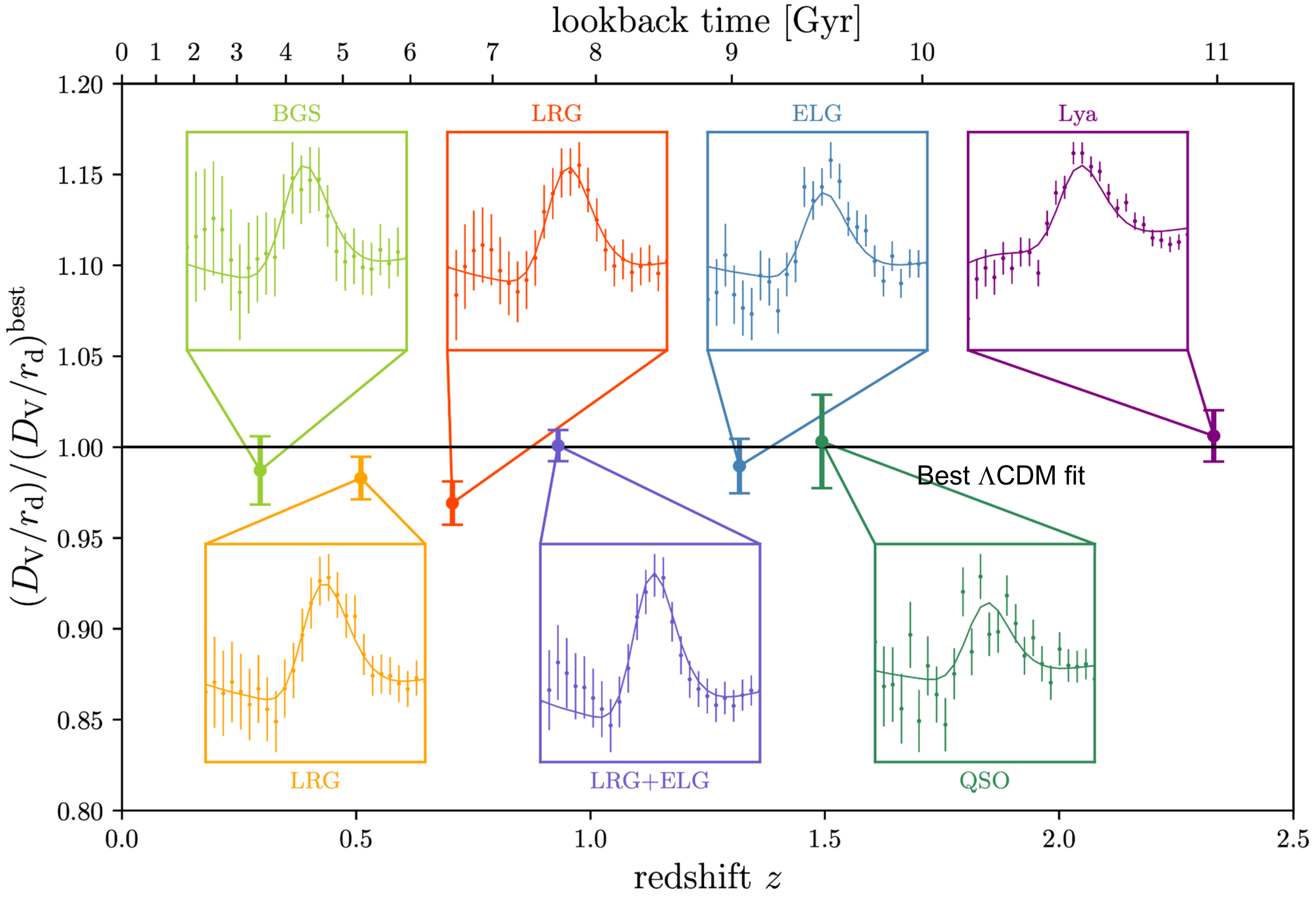
DESI year-1 BAO

BAO data: Δθ and Δz

D_M / r_d D_H / r_d

$$D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$$

Aggregated precision on BAO distance scale from galaxies & quasars ~0.5%



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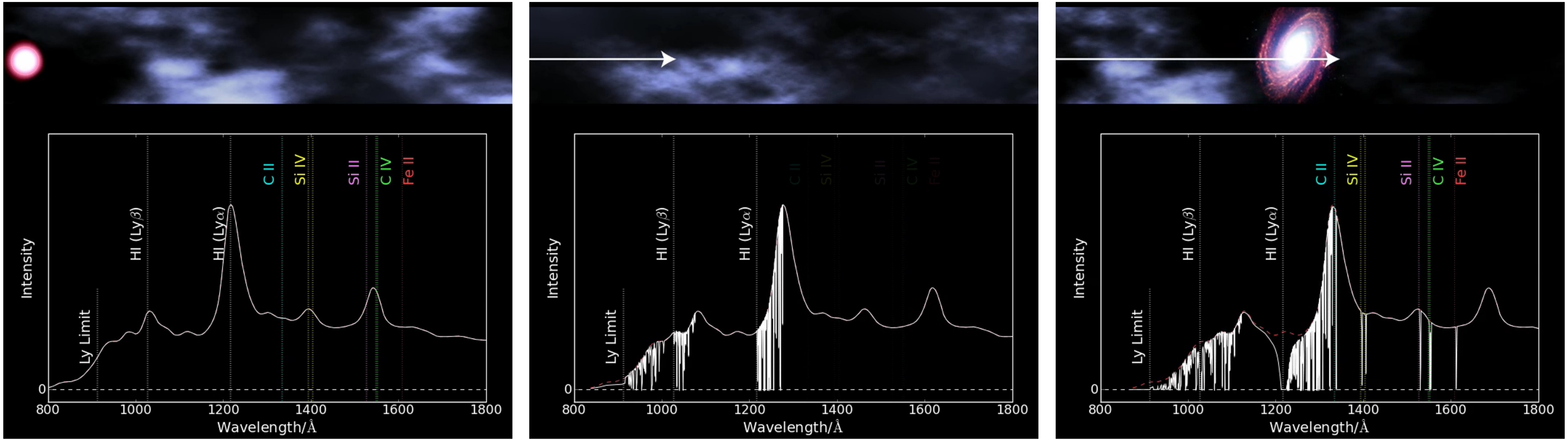
The Lyman-α Forest at z>2.1

credit: Andrew Pontzen



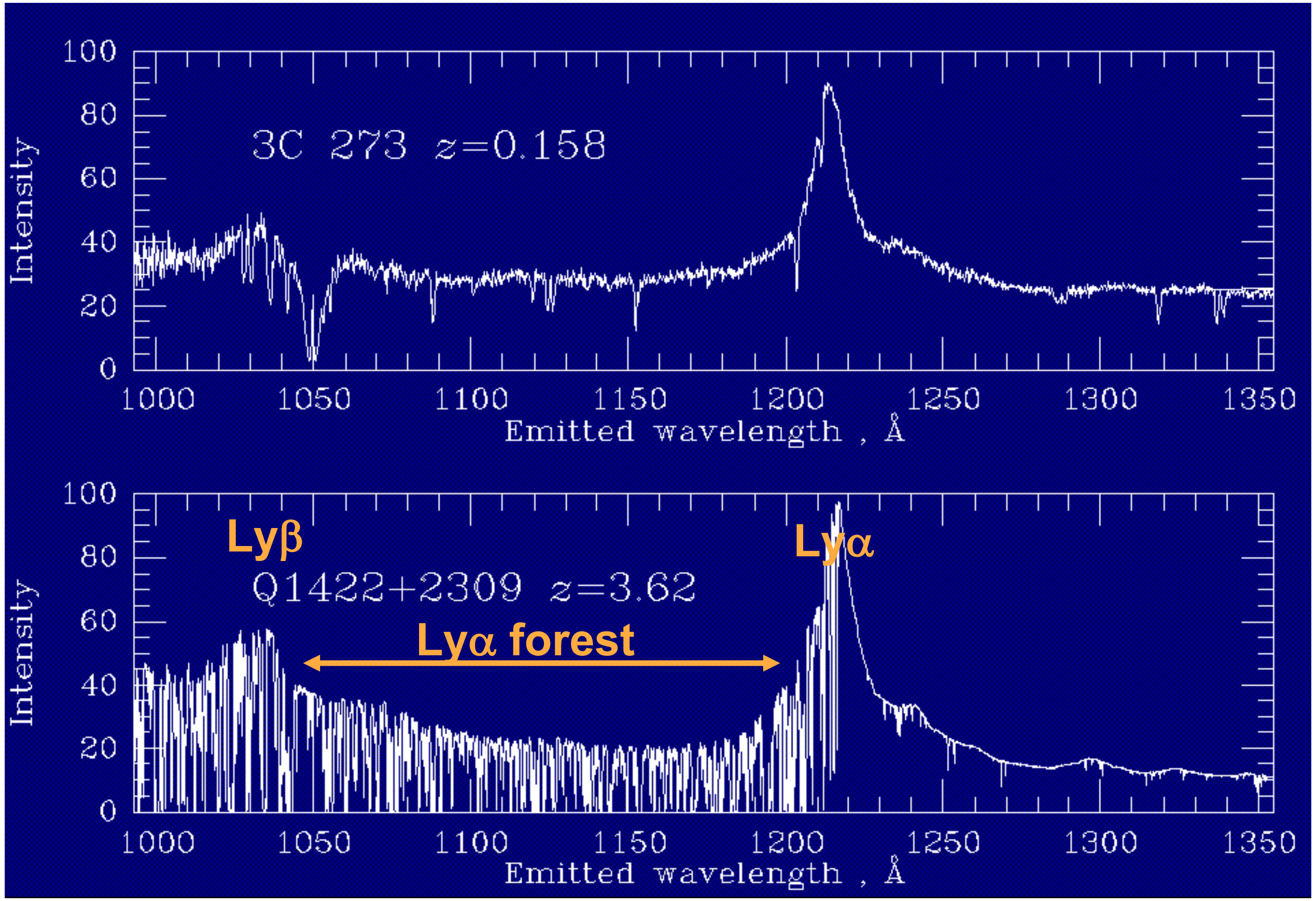
Background quasar —— Intervening gas ——→ Earth

$$F = e^{-\tau}$$

$$\tau \propto n_{HI}$$

- Quasars visible to high redshift (z ~ 5)
- Absorption of Quasar spectrum by neutral H in IGM
- Transmitted flux fraction F used as proxy for neutral H density

The Lyman-alpha forest

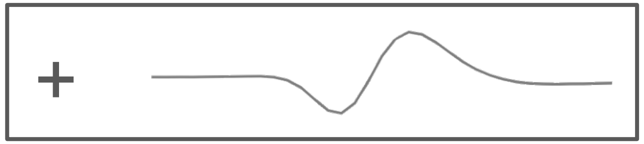


Small density of neutral H
in local Universe
(~fully ionized)

Higher density of neutral H
in distant Universe
(higher neutral H Density)

DESI 2024 Lyman-alpha forest analysis

End-to-end blinded analysis (cosmology-level)
Additive perturbation to correlation function



Tests run before unblinding

1. Validation with mocks (synthetic data sets)
   recover unbiased BAO parameters
   (**< ⅓ of statistical uncertainty**)

2. Data splits on the blinded data set

3. Variation in the choice of analysis parameters

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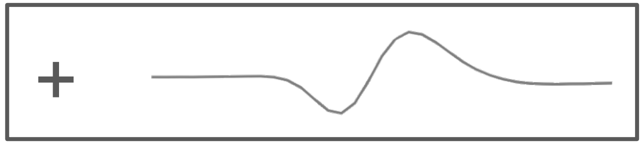

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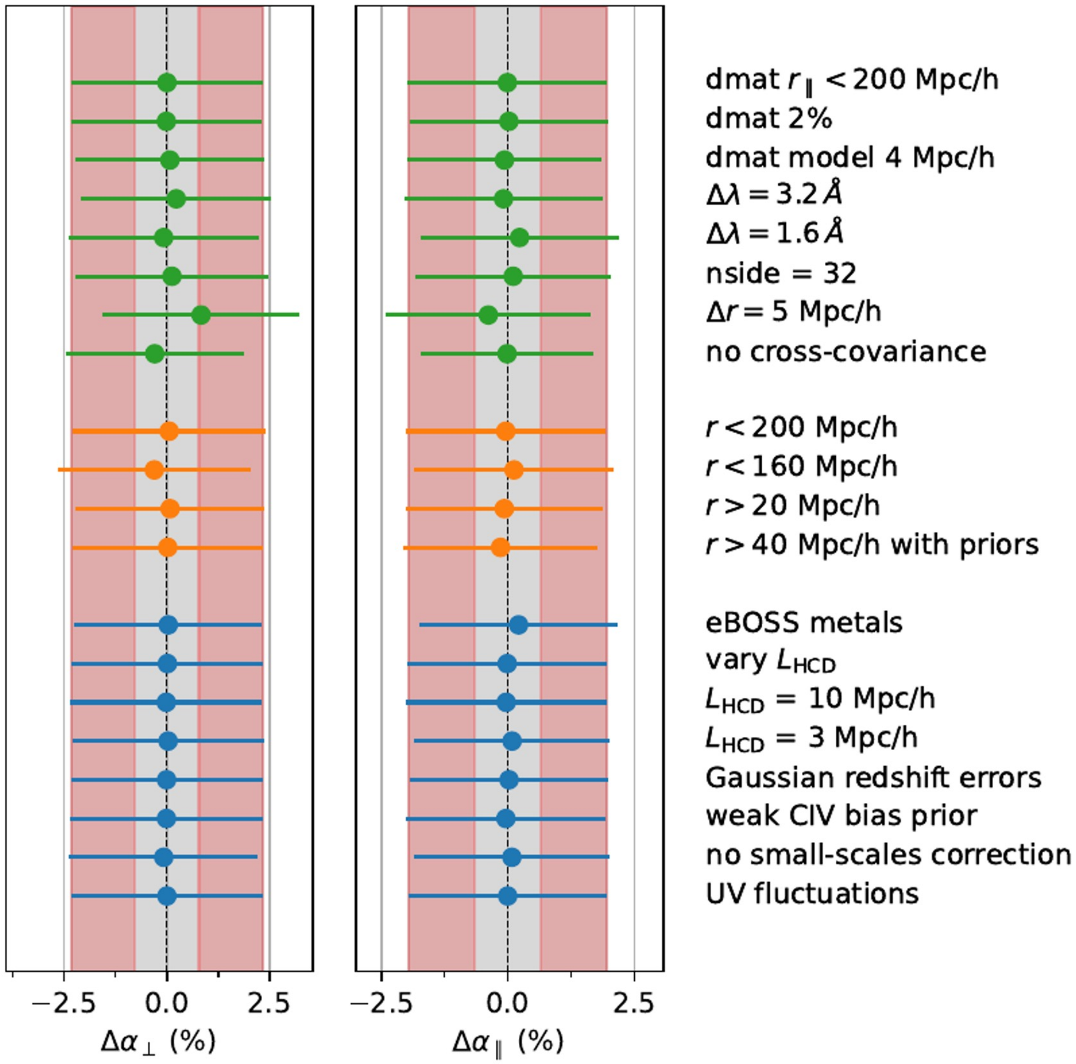
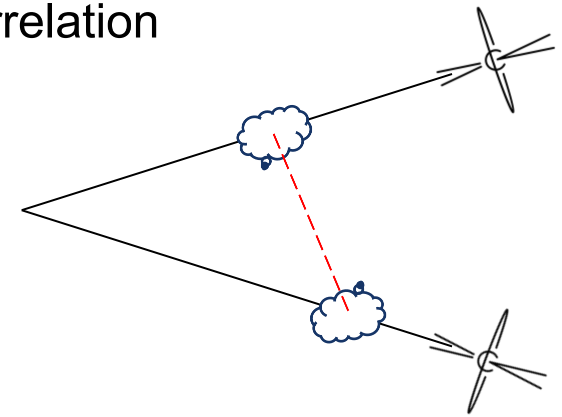
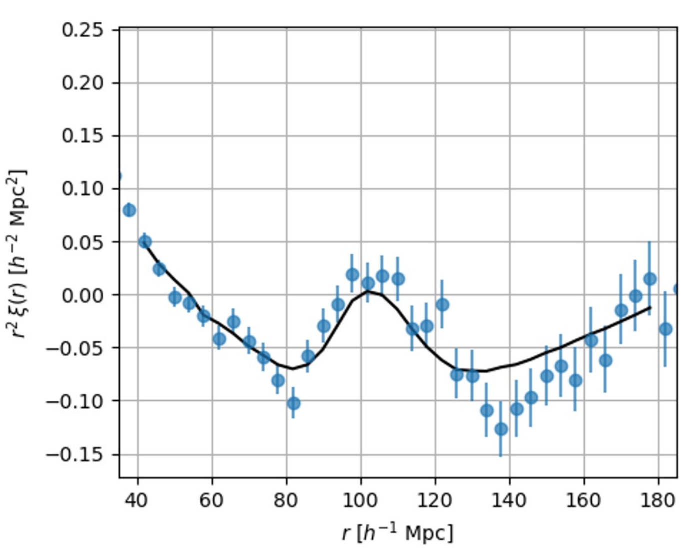
Variations in choice of analysis parameters

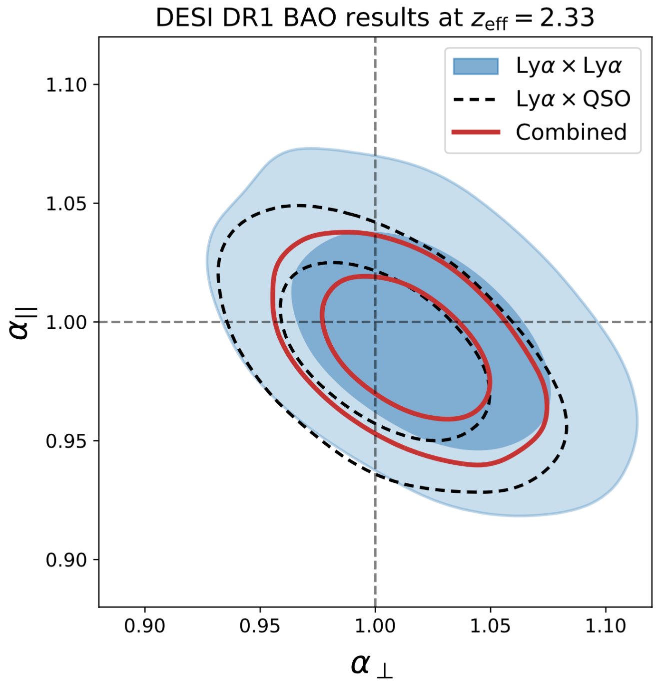


Lyman-alpha forest

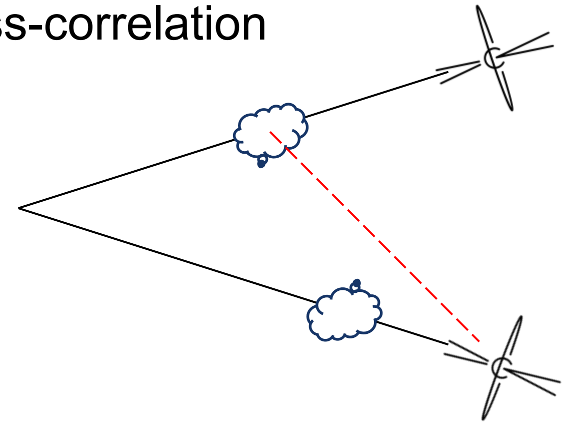
Lya auto-correlation

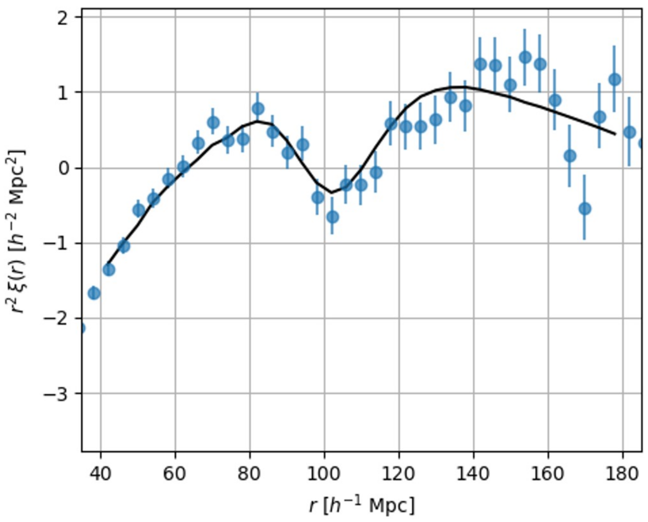






Lya-quasar cross-correlation





1.1% precision on BAO scale at z_{eff}=2.33

Is Dark Energy Weakening?

Probes of the expanding universe

The Dark Energy Spectroscopic Instrument – DESI

DESI First-year BAO results

- BAO analysis on galaxies & quasars
- BAO analysis on Lyman-α forest
- **Cosmological interpretation**

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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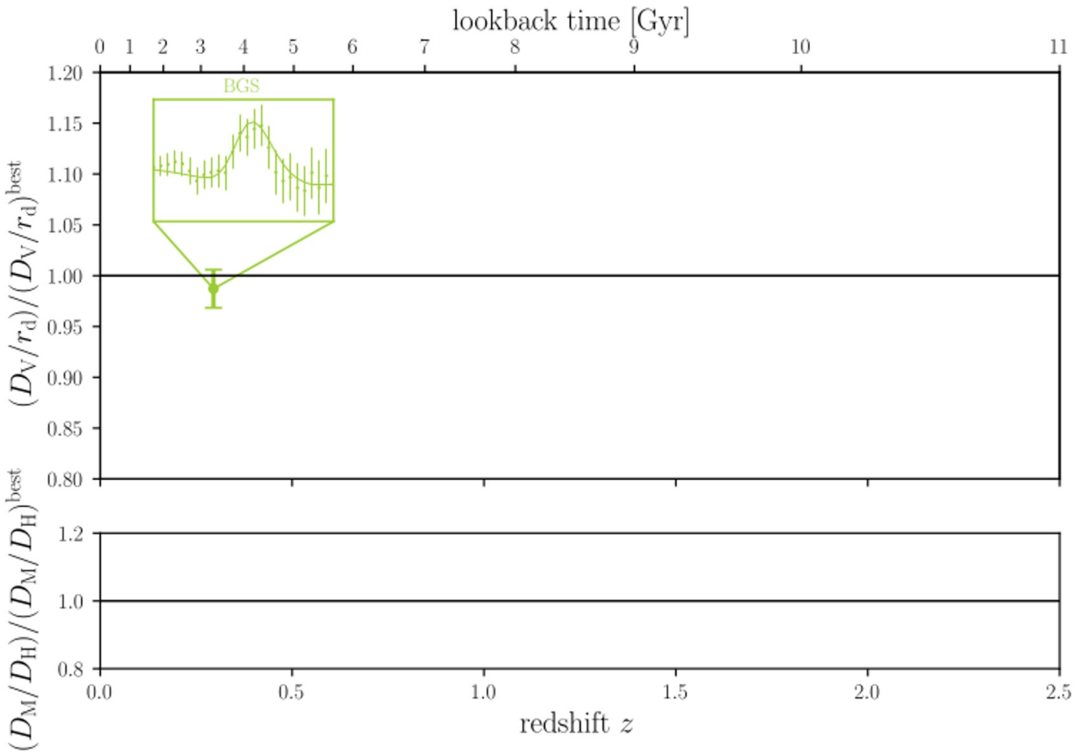
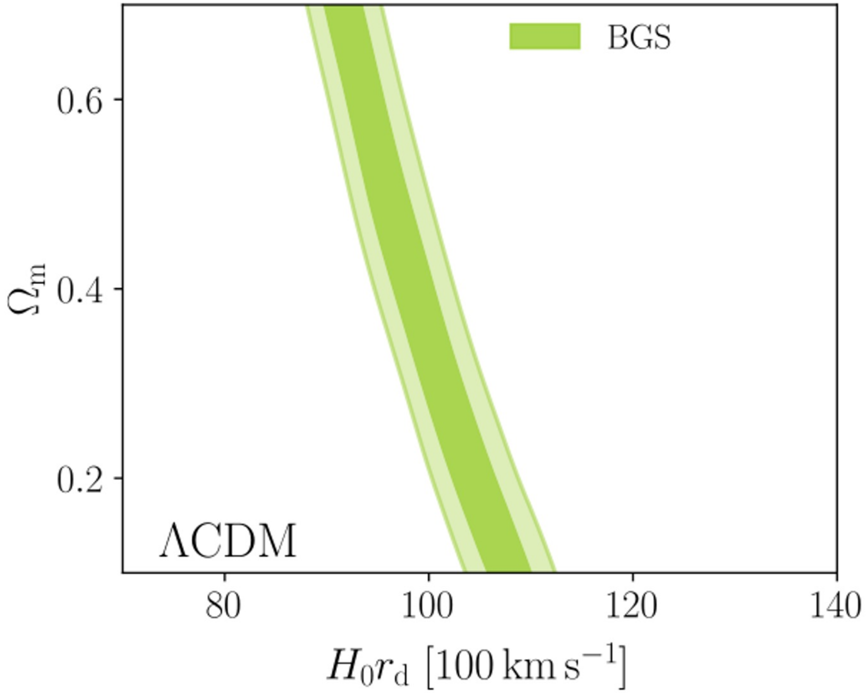
DESI Y1 BAO

D_M / r_d and D_H / r_d ⟶ $D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$

Ω_M and $H_0 r_d$

DESI BAO measurements





DESI Y1 BAO

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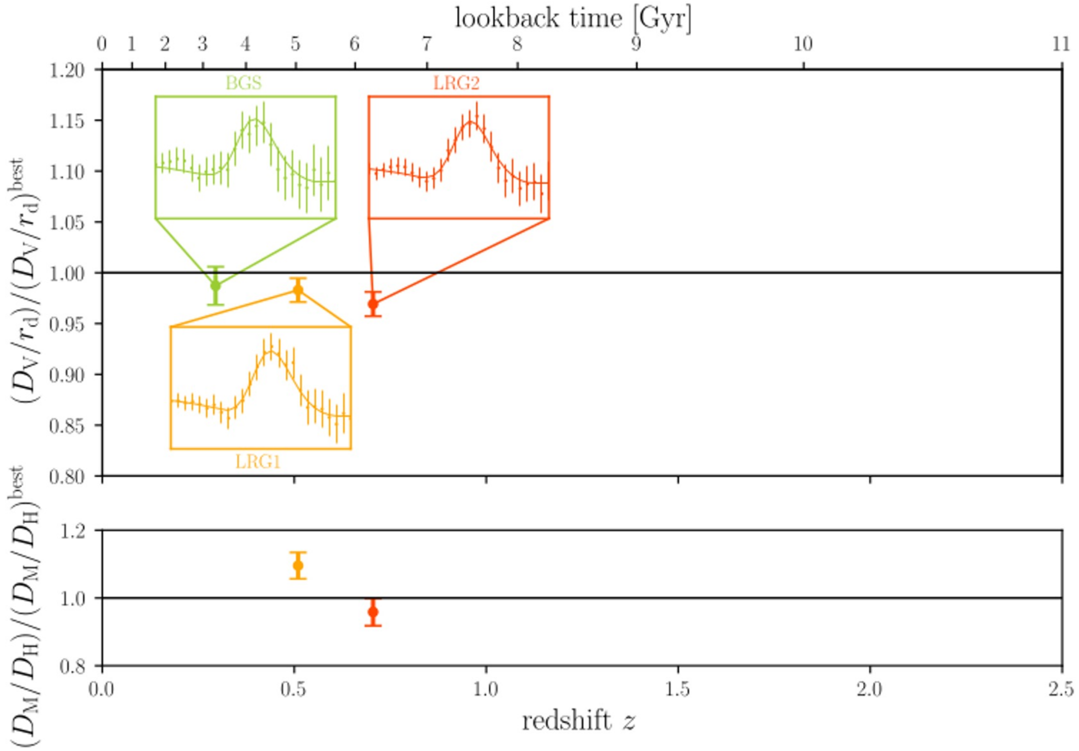
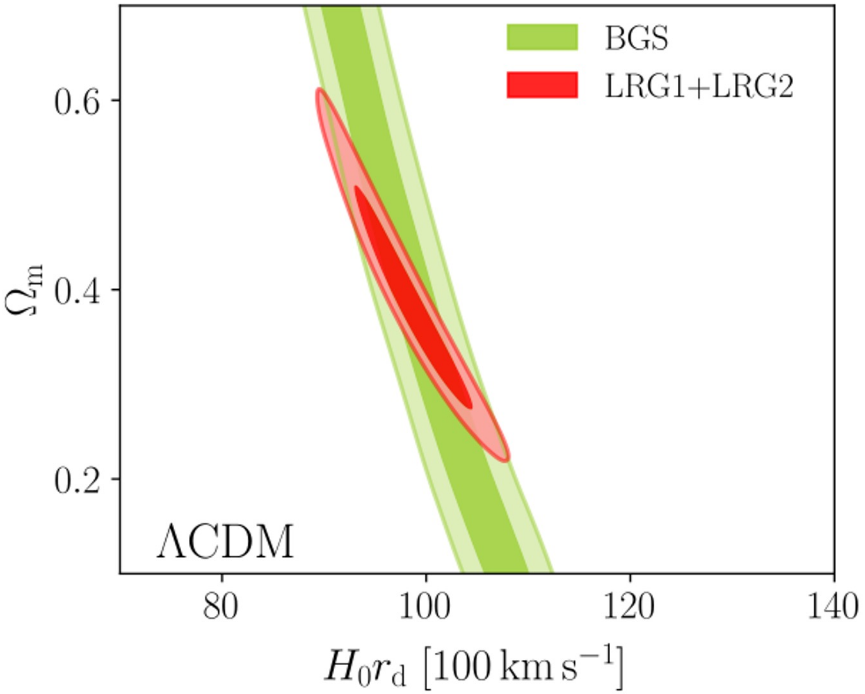
D_M / r_d and D_H / r_d ⟶ $D_V = \left(zD_M(z)^2 D_H(z)\right)^{1/3}$

⟶ Ω_M and $H_0 r_d$

DESI BAO measurements





DESI Y1 BAO

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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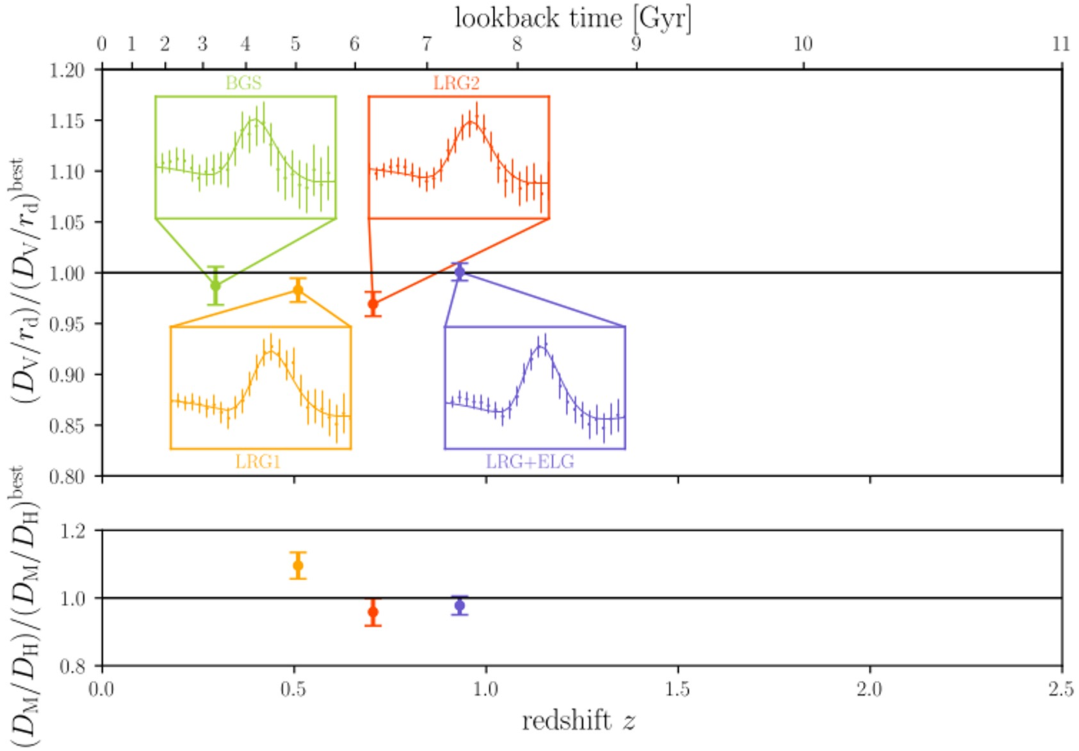
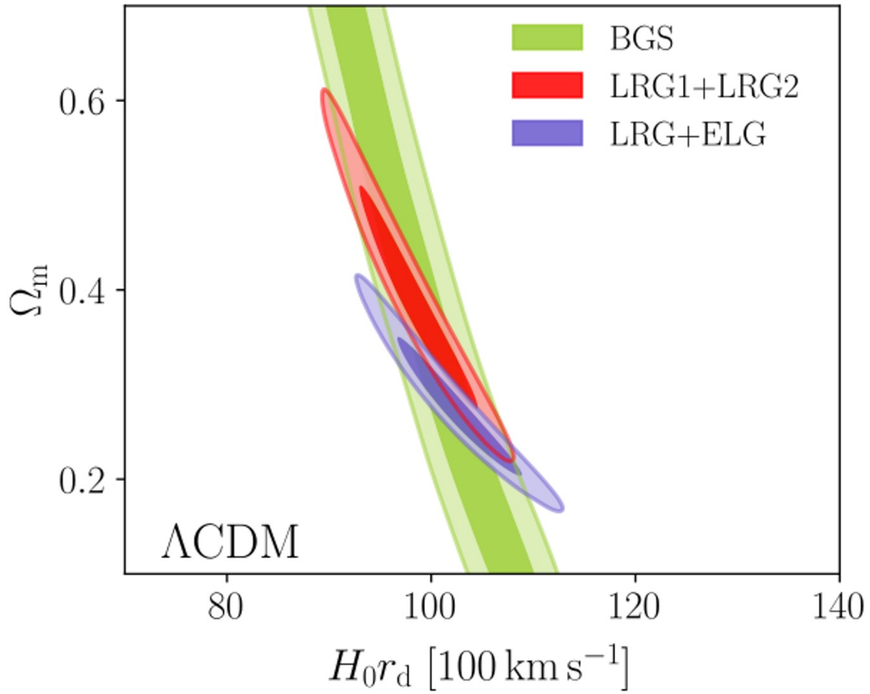
D_M / r_d and D_H / r_d ⟶ $D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$

Ω_M and $H_0 r_d$

DESI BAO measurements





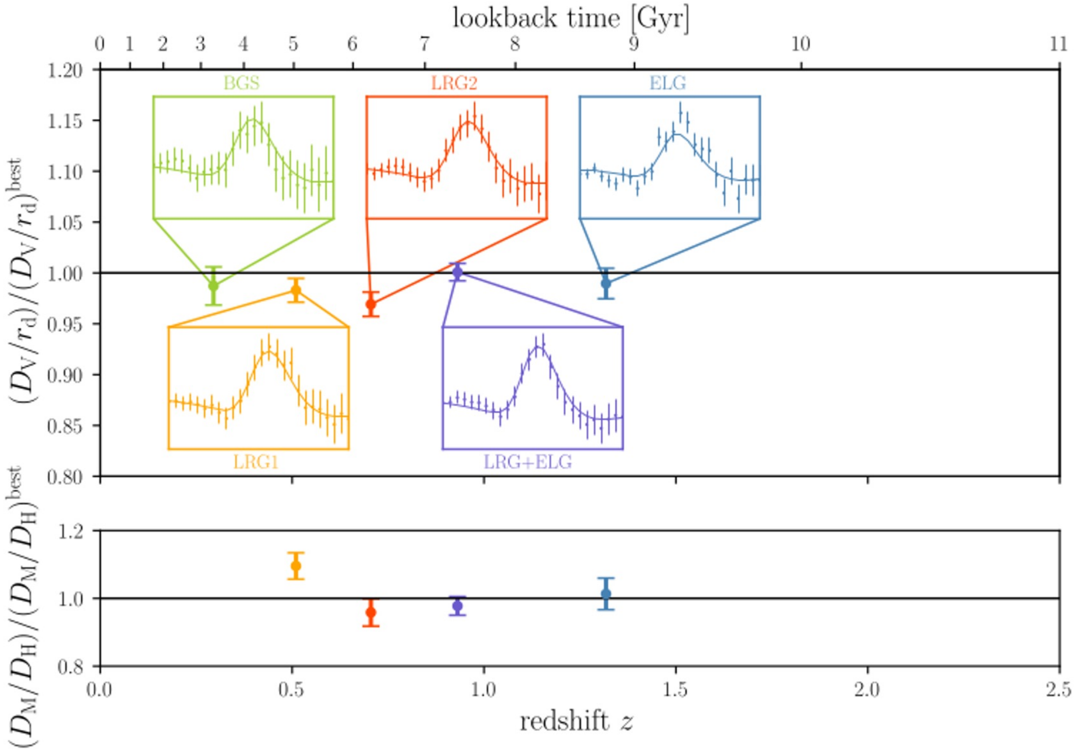
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
U.S. Department of Energy Office of Science

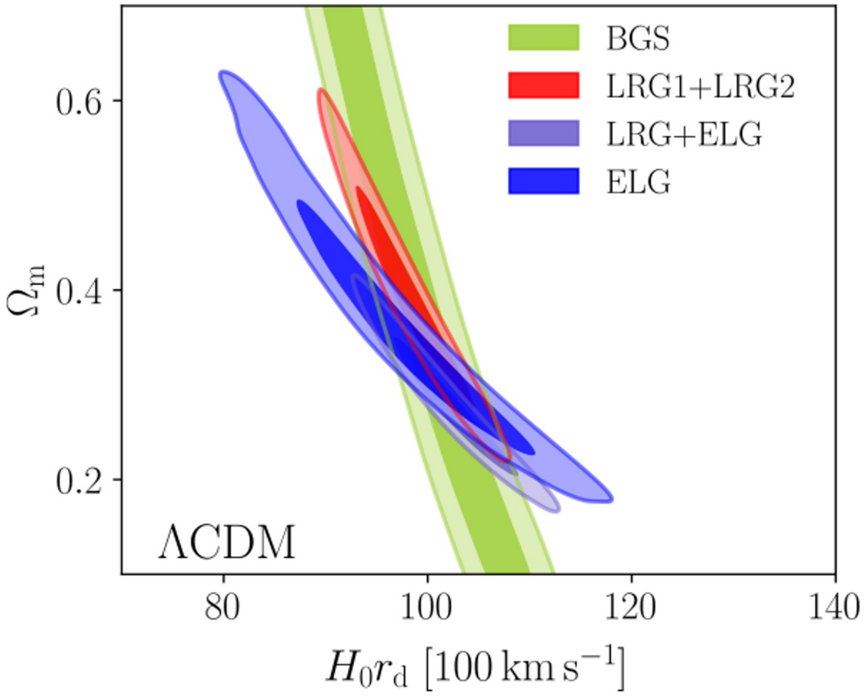
DESI Y1 BAO

D_M / r_d and D_H / r_d ⟶ $D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$

Ω_M and $H_0 r_d$

DESI BAO measurements





DARK ENERGY SPECTROSCOPIC INSTRUMENT

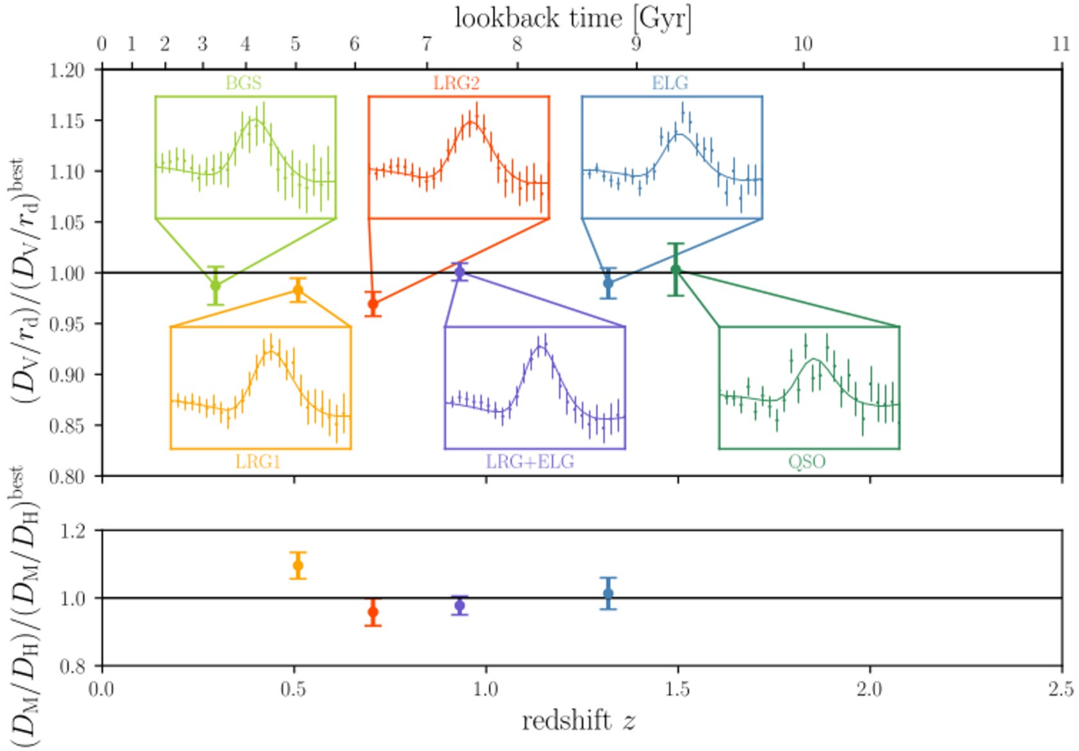
U.S. Department of Energy Office of Science

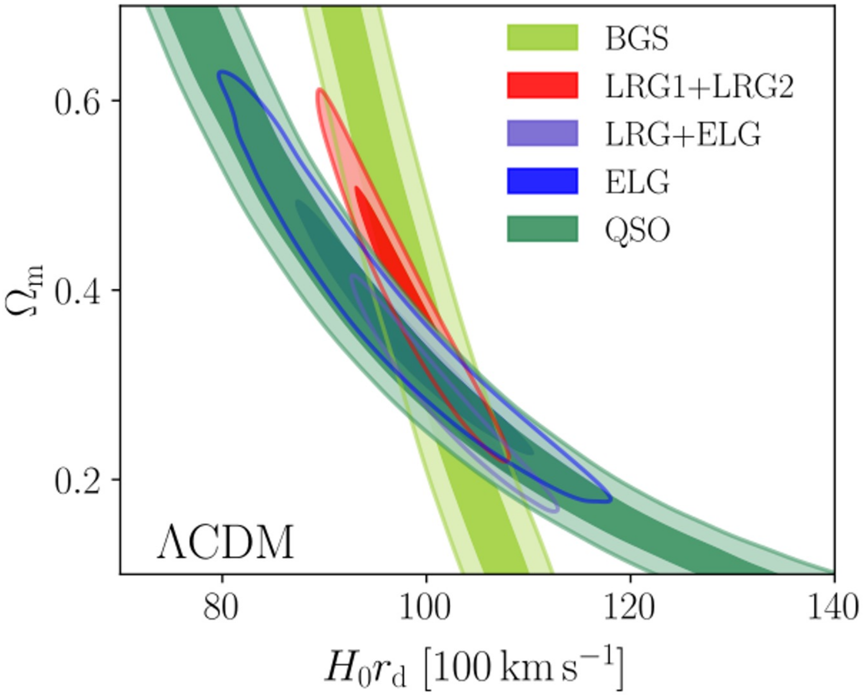
DESI Y1 BAO

D_M / r_d and D_H / r_d ⟶ $D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$

Ω_M and $H_0 r_d$

DESI BAO measurements





DESI Y1 BAO

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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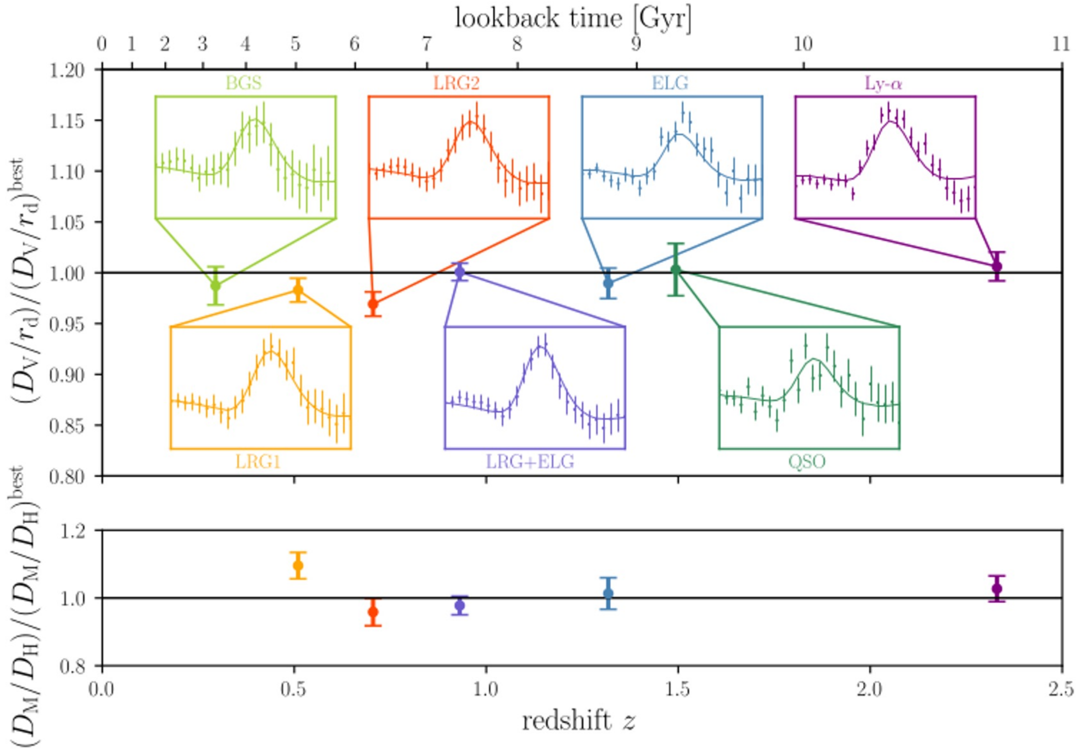
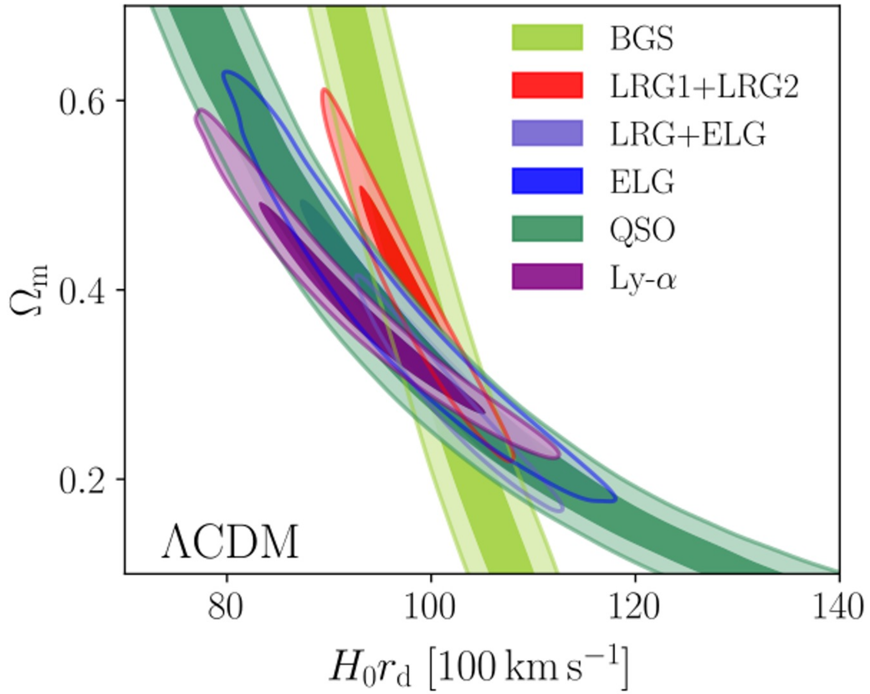
D_M / r_d and D_H / r_d ⟶ $D_V = \left(zD_M(z)^2 D_H(z)\right)^{1/3}$

Ω_M and $H_0 r_d$

DESI BAO measurements





DARK ENERGY SPECTROSCOPIC INSTRUMENT

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DESI Y1 BAO

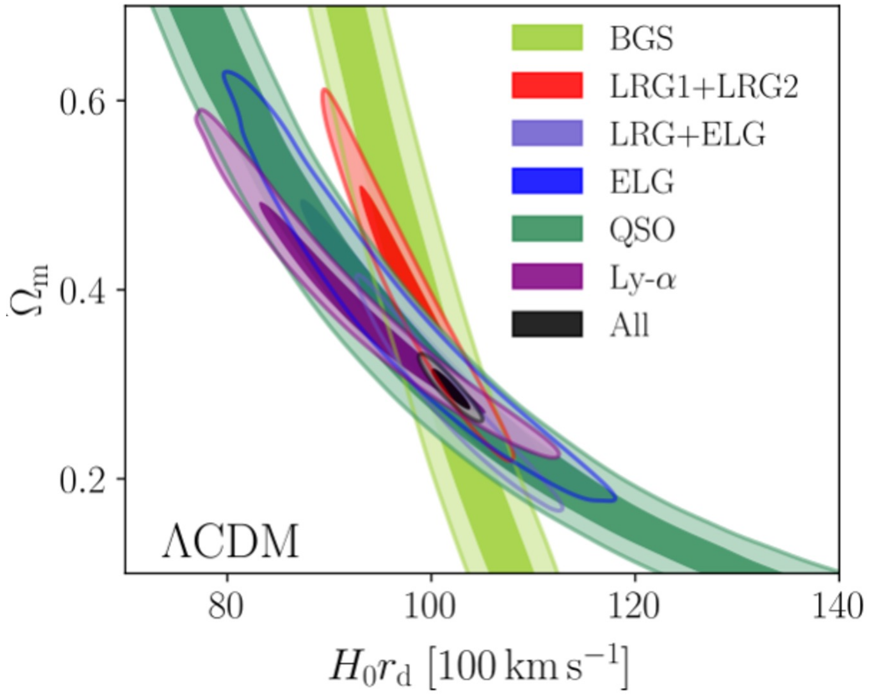
D_M / r_d and D_H / r_d ⟶ $D_V = \left(z D_M(z)^2 D_H(z)\right)^{1/3}$

→ Ω_M and $H_0 r_d$

DESI BAO measurements

Consistent with each other, and complementary

$$\underbrace{\begin{array}{lr} \Omega_{\rm m} = 0.295 \pm 0.015 & \mathbf{(5.1\%)} \\ H_0 r_{\rm d} = (101.8 \pm 1.3)\,[100\,{\rm km\,s^{-1}}] & \mathbf{(1.3\%)} \end{array}}_{\rm DESI}$$



chi2 = 12.66 for 12 data points and 2 parameters

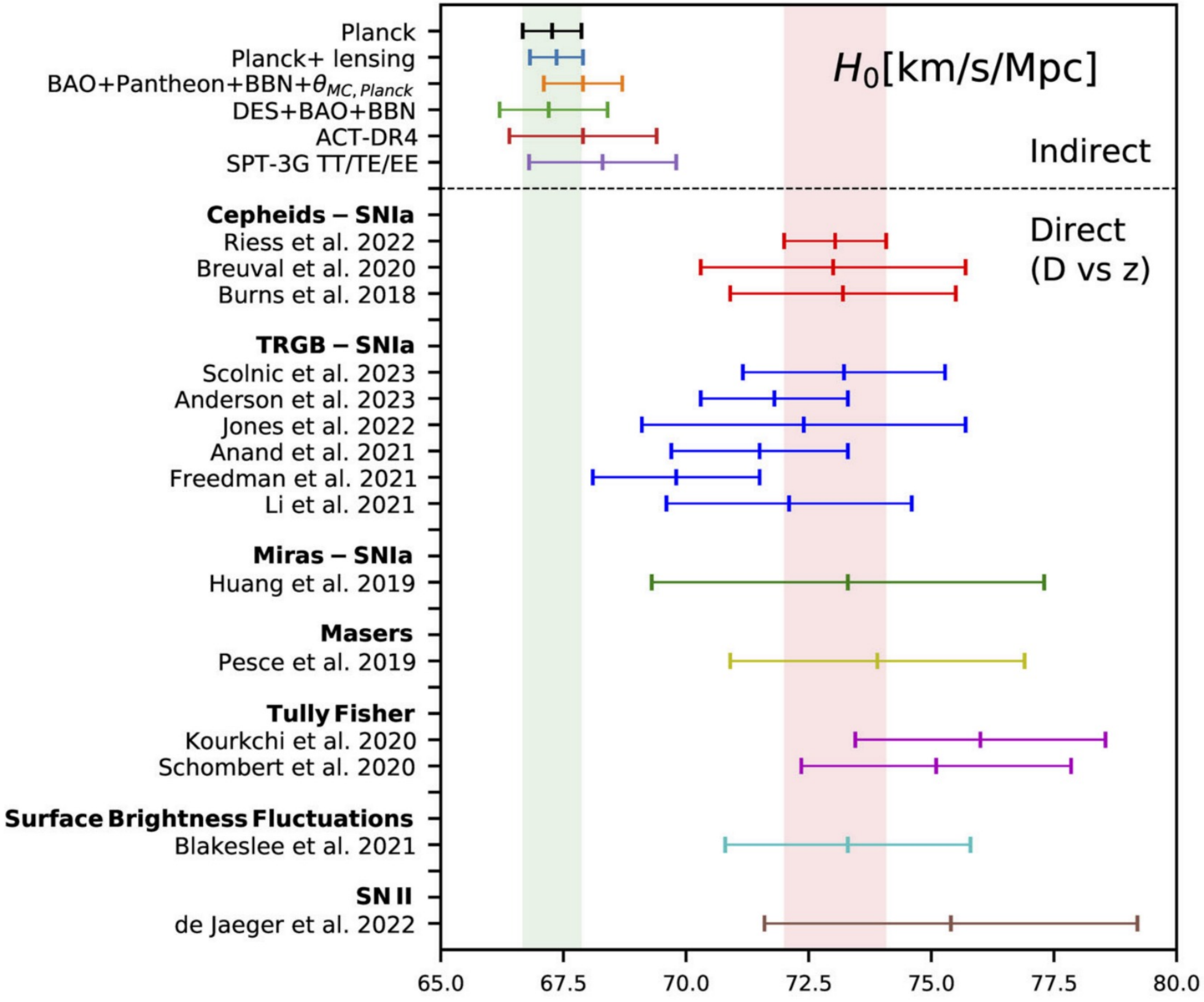
H_0

Extrapolation to z=0 of fit to early-universe data

Distance-ladder calibration approach

Early-time

Late-time Universe



Riess & Breuval 2023

H_0

BAO data $\Delta\theta$ and $\Delta z \rightarrow D_M / r_d$ and D_H / r_d ⟹ Ω_M and $H_0 r_d$

Need r_d from other probe

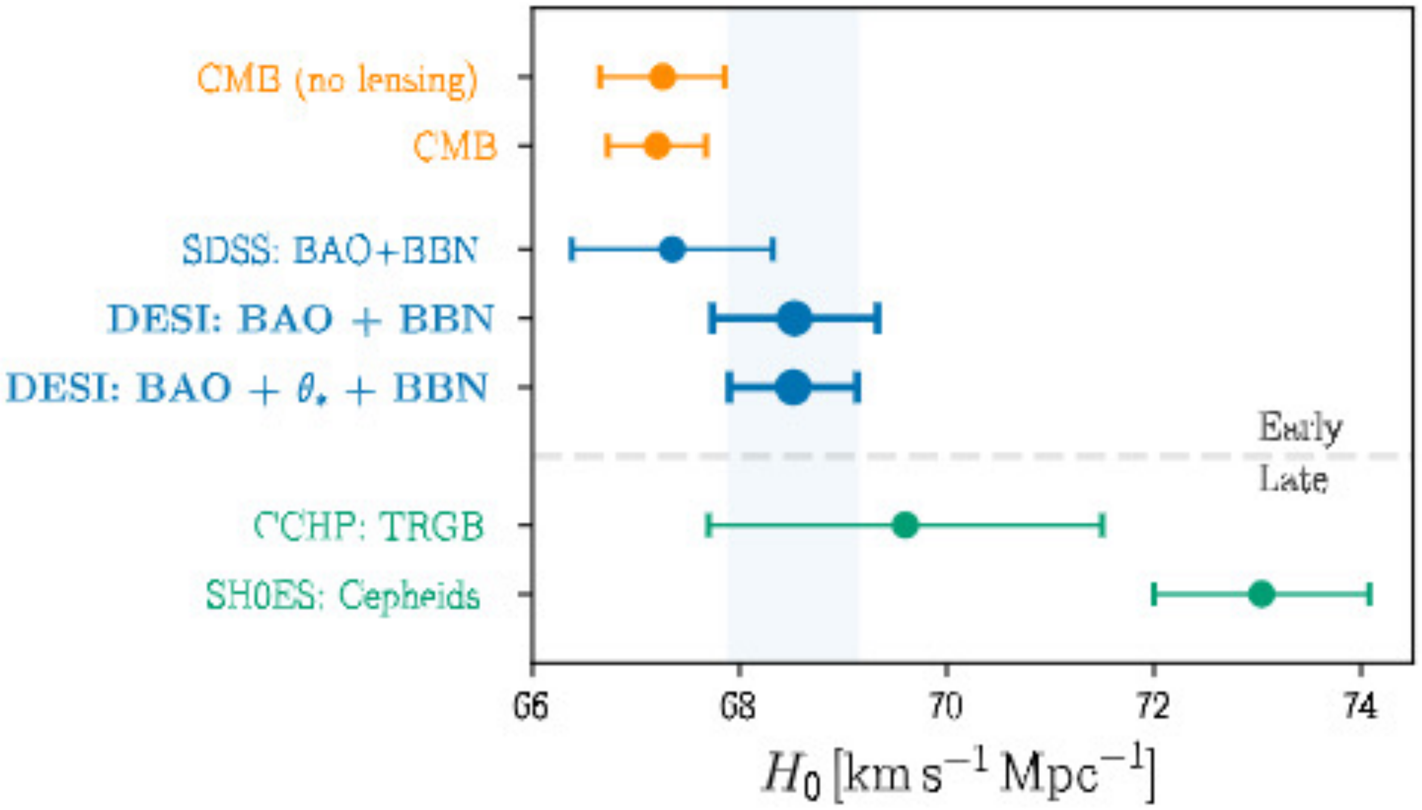
$H_0 = (68.53 \pm 0.80)$ km s^{-1} Mpc^{-1} → **1.2%**

DESI + BBN ($\Omega_b \rightarrow r_d$)

$H_0 = (68.52 \pm 0.62)$ km s^{-1} Mpc^{-1} → **0.9%**

DESI + BBN + θ⋆ (Planck angular acoustic scale)

- Consistent with SDSS
- In agreement with CMB
- In **3.7σ** tension with SH0ES



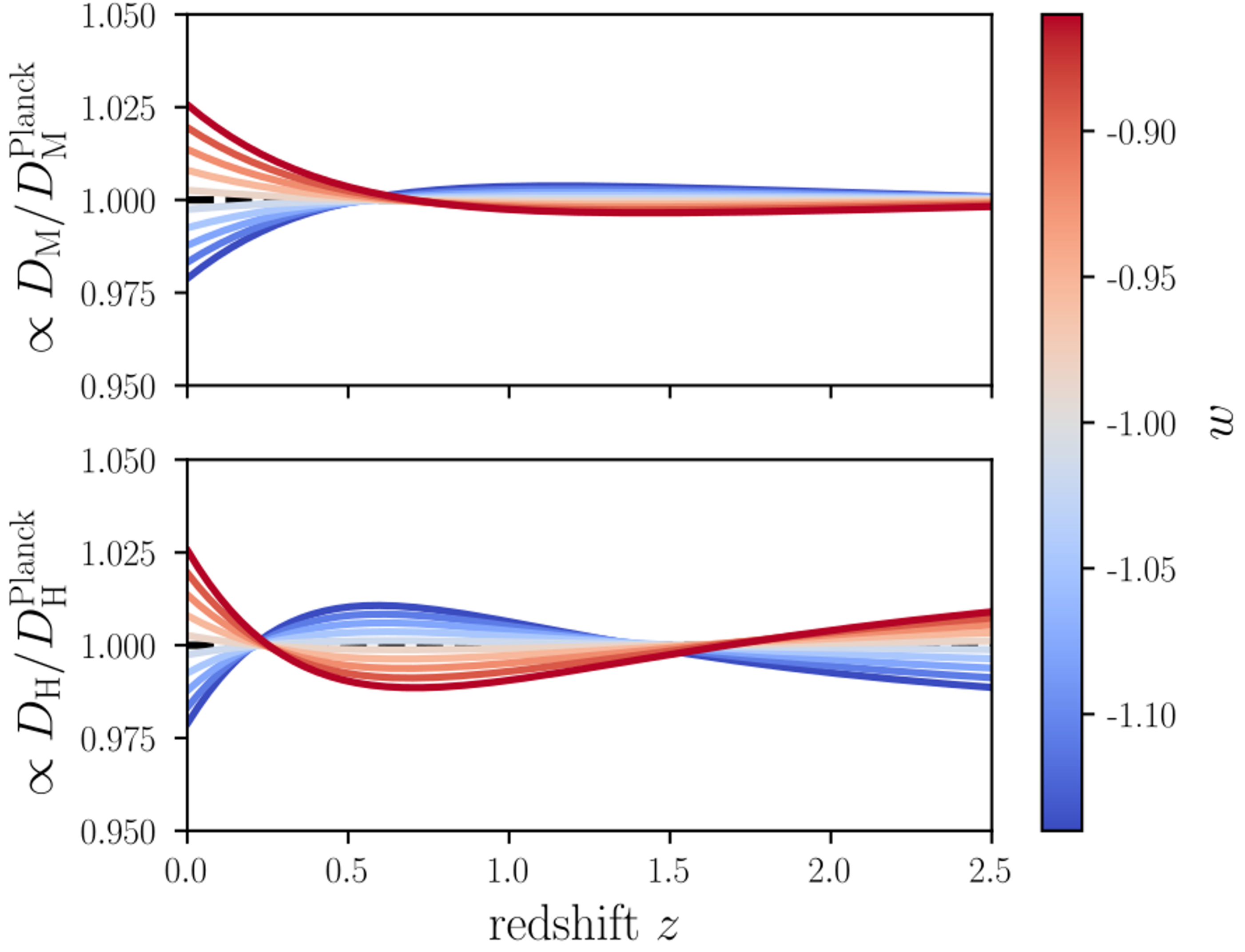
Dark Energy

Dark energy equation of state:

$$P = w\rho$$

- w = constant

w=-1 for ΛCDM
(cosmological constant)



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Dark Energy – Equation of State w=p/ρ

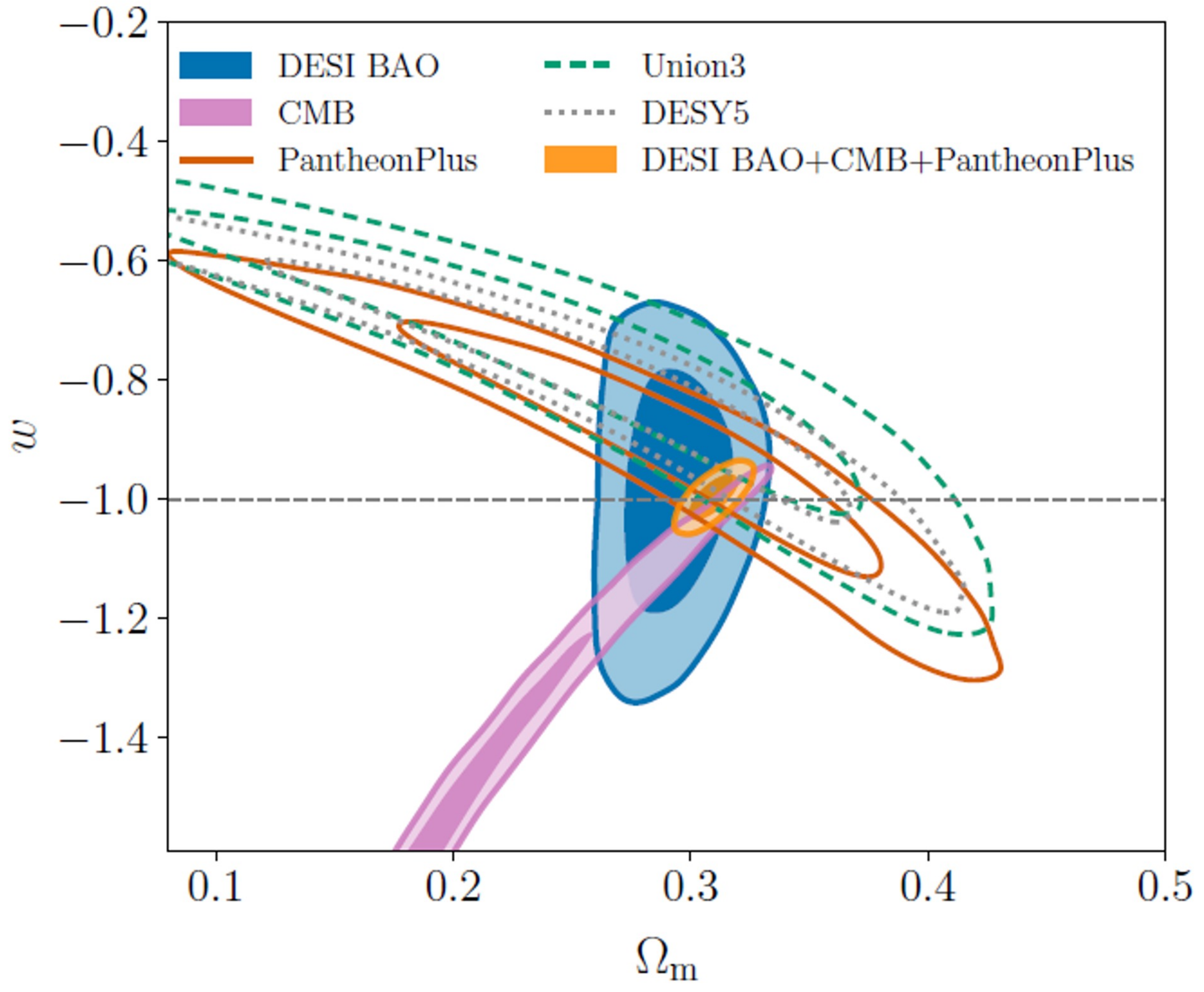
DESI only:

Ω_m = 0.293 ± 0.015 (**5.1%**)
w = -0.99 ± 0.15 (**15.2%**)

DESI+CMB+SN (e.g. PantheonPlus):

Ω_m = 0.3095 ± 0.0065 (**2.1%**)
w = −0.997 ± 0.025 (**2.5%**)

Assuming a **constant** EoS, DESI BAO compatible with a cosmological constant
but …



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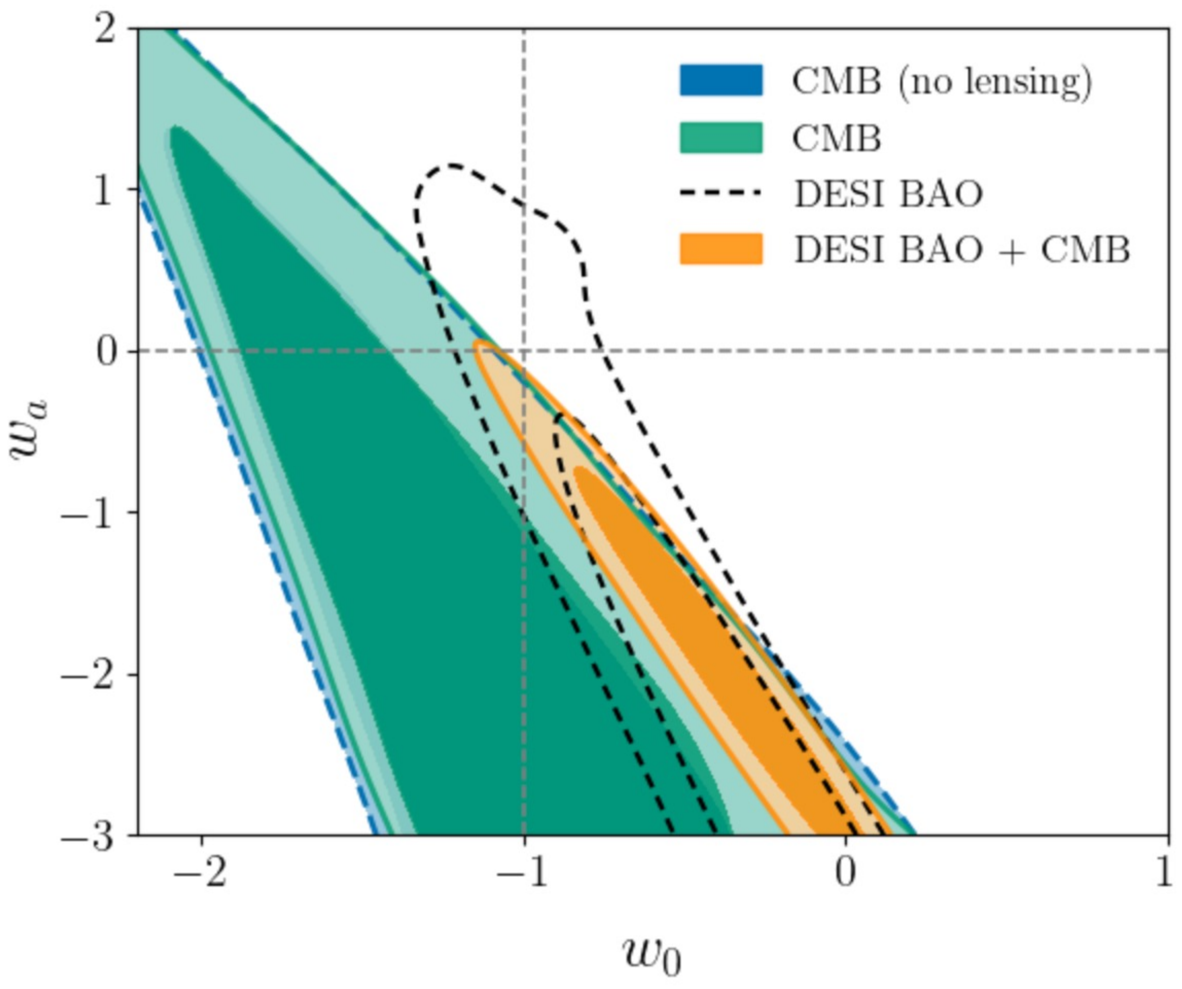
Dark Energy – w_0 w_a

CMB = Planck (Temp. & Polar/) & Planck + ACT DR6 lensing

Varying EoS (CPL) $w(a) = w_0 + (1 - a)w_a$

$$\underbrace{w_0 = -0.45^{+0.34}_{-0.21} \qquad w_a = -1.79^{+0.48}_{-1.00}}$$

DESI + CMB ⟹ 2.6σ



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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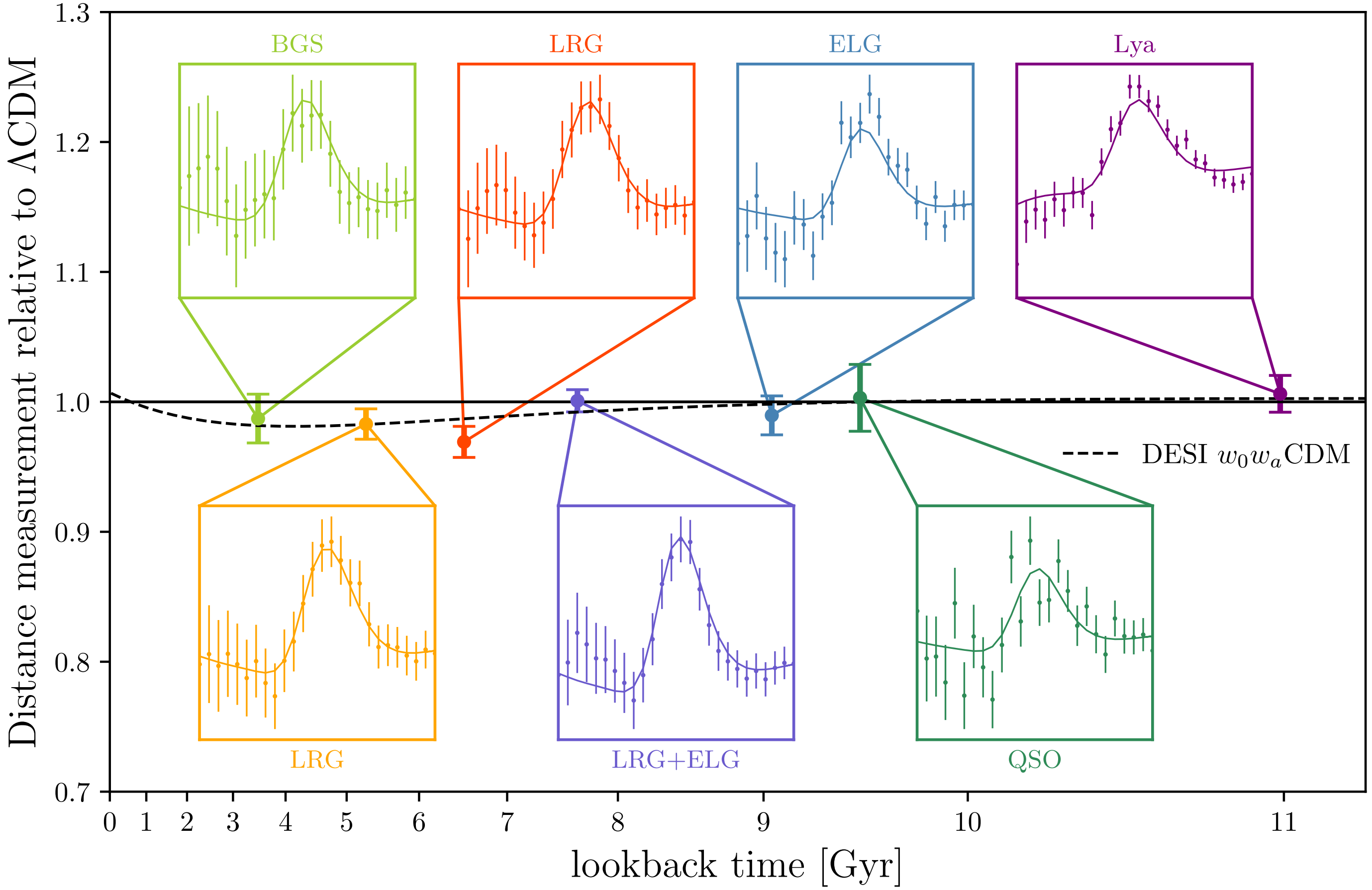
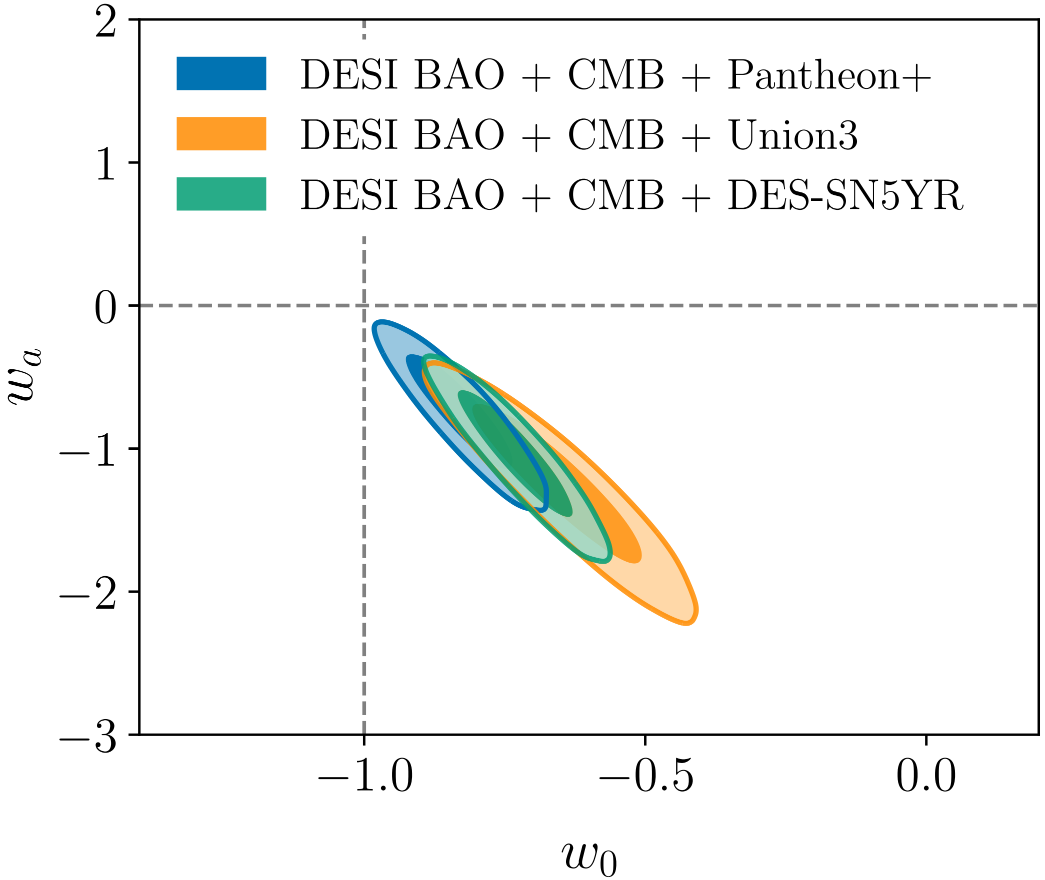
Dark Energy – w_0 w_a





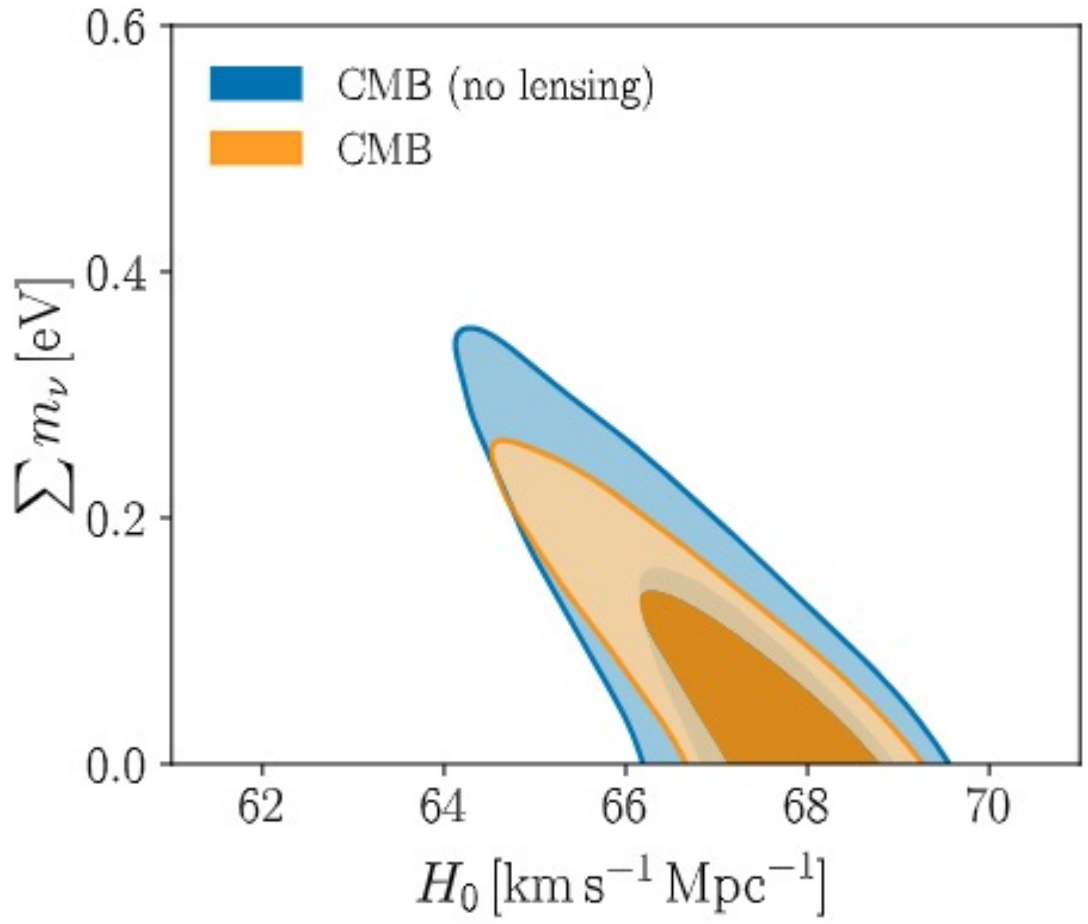
Pantheon+: 2.5σ

Union3: 3.5σ

DES-SN5Yr: 3.9σ

Neutrino masses

Internal CMB degeneracies limiting sensitivity to neutrino masses



Neutrino masses

DARK ENERGY SPECTROSCOPIC INSTRUMENT
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Internal CMB degeneracies limiting sensitivity to neutrino masses

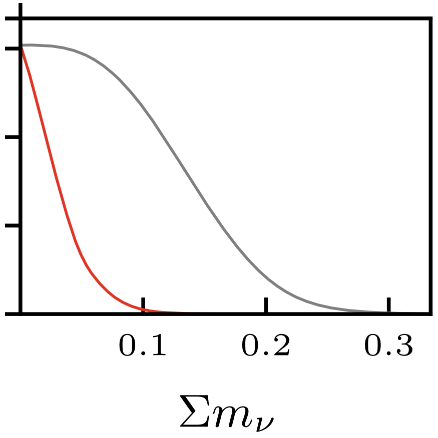
broken by BAO, especially through H_0

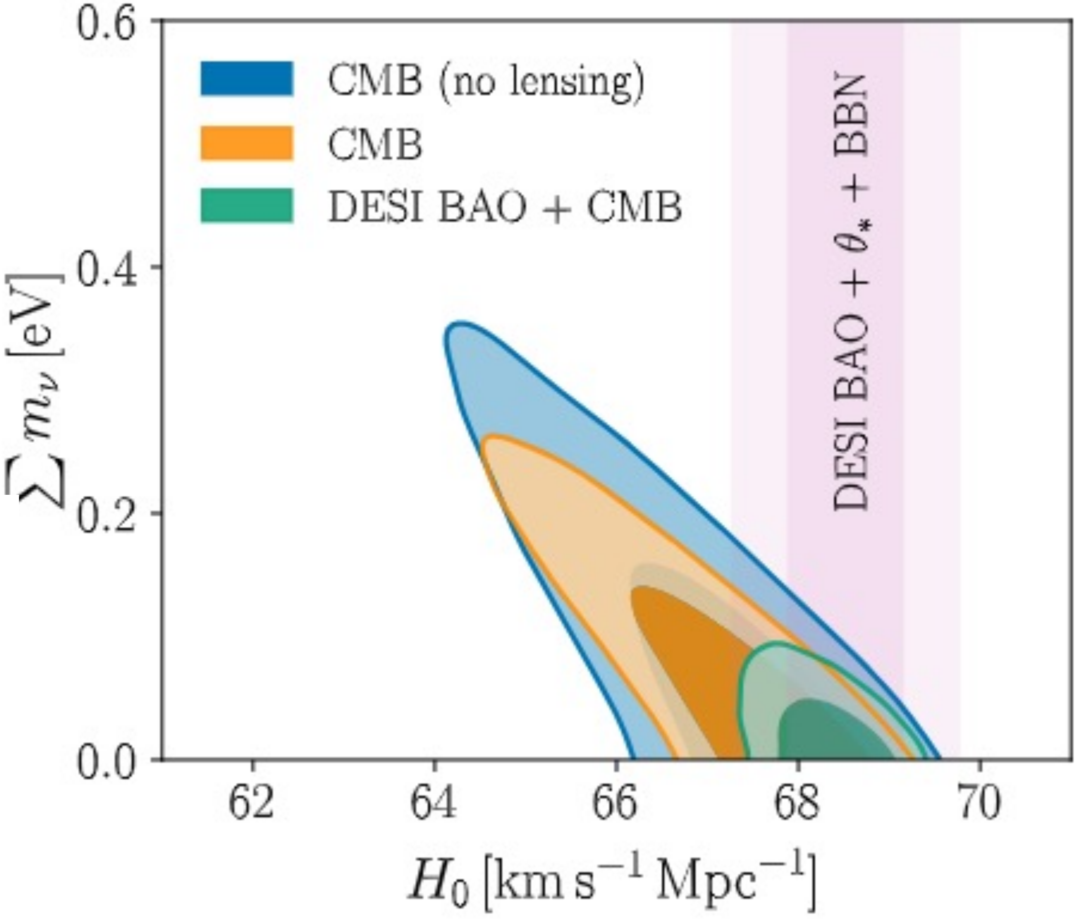
DESI prefers high values of H_0, yielding

$\sum m_\nu < 0.072\,\mathrm{eV}$ (95%, DESI+CMB)

Limit relaxed for extensions to ΛCDM

$\sum m_\nu < 0.195\,\mathrm{eV}$ for w_0w_aCDM





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Beyond DESI Year 1 BAO

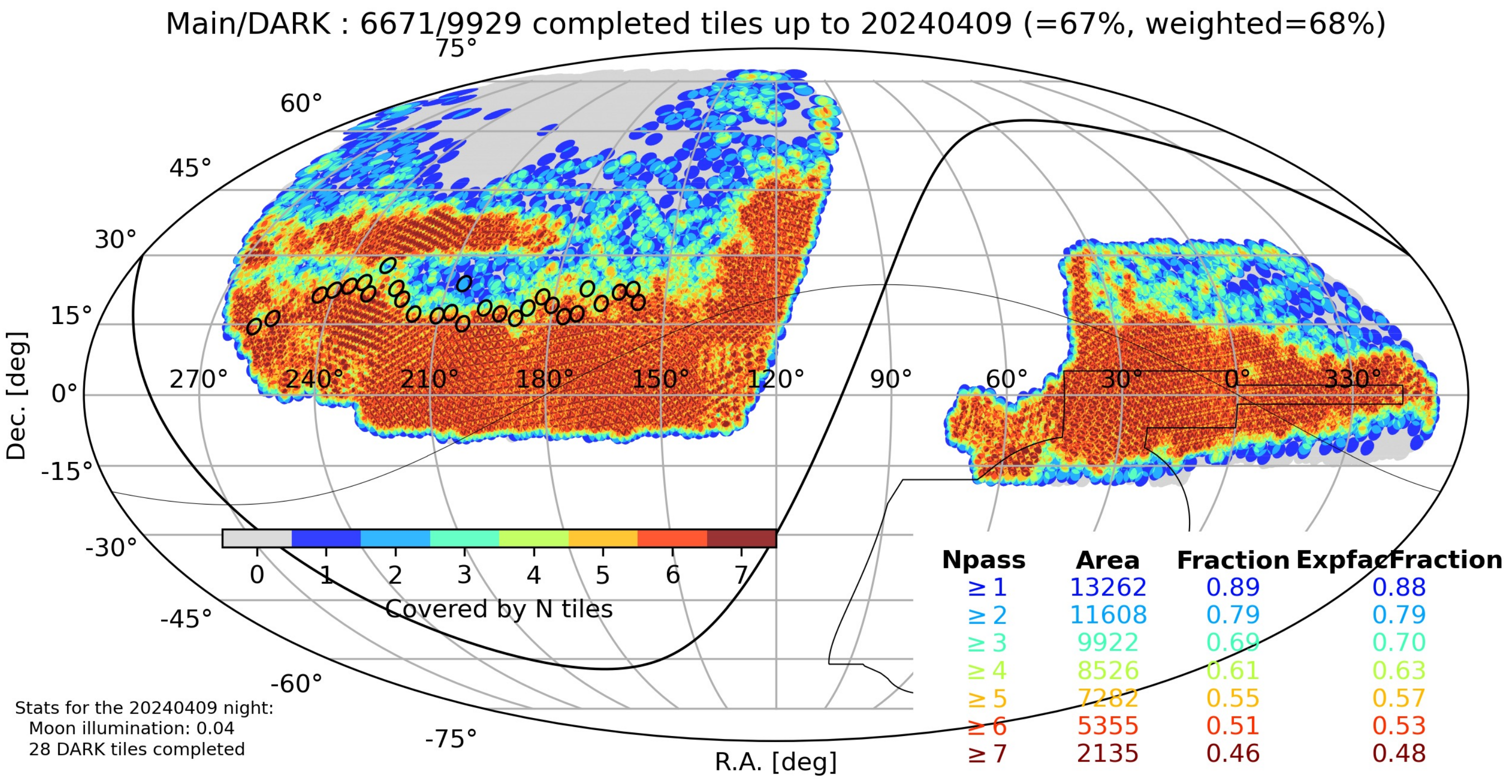
Year 3 sample already in hand!

31M galaxies & quasars

11M stars

Survey about 70% complete

(3 months ahead of schedule)



Enhanced science goal

- Improved precision from additional approaches (higher-order statistics, Alcock-Paczynski in Lyman-α)
- Enhanced structure growth (cross-correlations with CMB lensing or galaxy lensing, in addition to RSD)
- Mass profile of Milky Way and constraints on dark matter models

Conclusions

DESI Year 1 data set (vs. 20 years of SDSS)

- 3x SDSS with 5.7 million galaxies/quasars at $z<2.1$
- 2x SDSS with 420,000 Lyman-alpha forests at $z>2.1$

Most precise BAO measurement to date

- 0.5% for $z < 2.1$
- 1.1% for $z > 2.1$

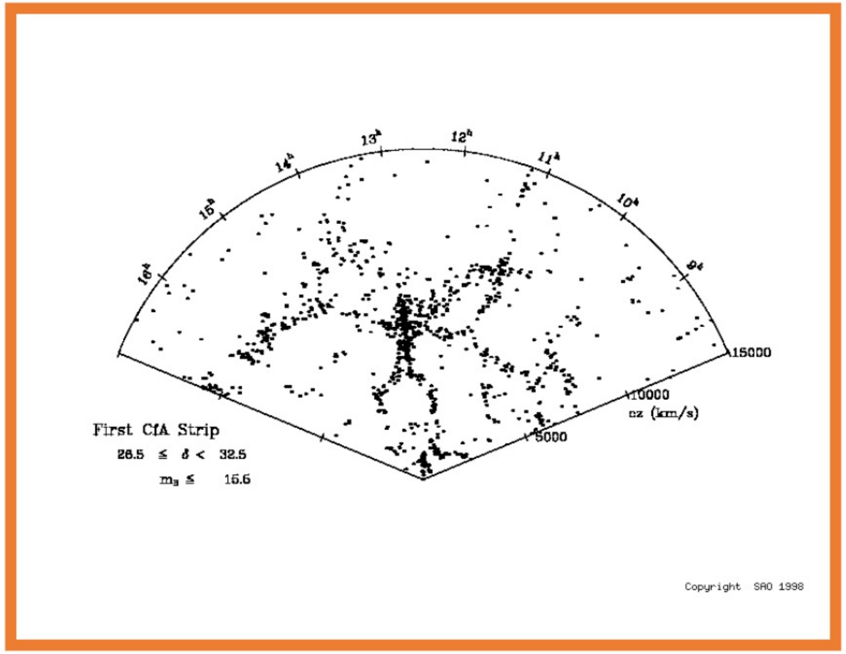
Result highlights

- 1% measurement of H0 from DESI + BBN (+ θ^*) in tension with local value (SH0ES)
- DESI consistent with ΛCDM or w=-1 if assumed constant
- Hint for varying dark energy, at 2.6σ (DESI+CMB) and 2.5σ to 3.9σ (DESI+CMB+SN)

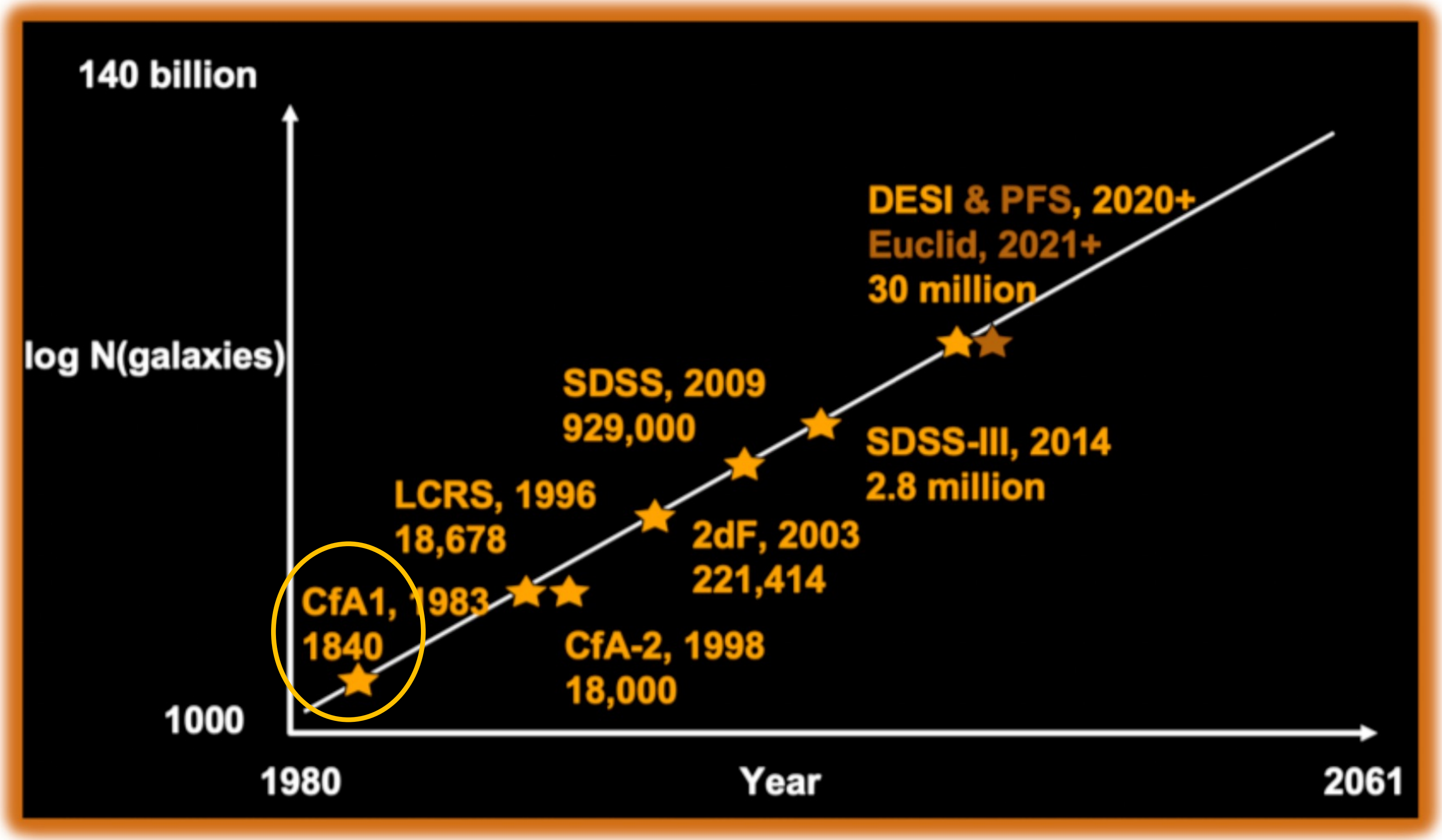
Thank you!

Large-scale structures over the years

CfA (1998)
1k spectra

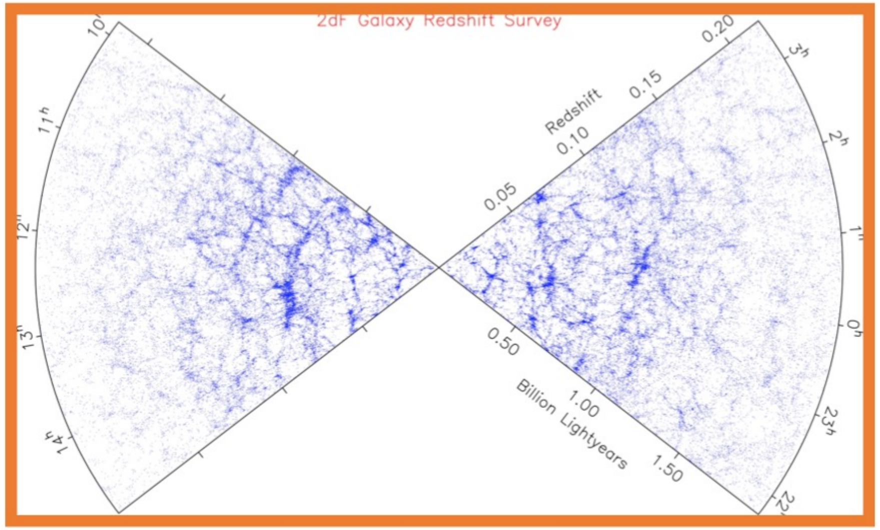


CDM simulations

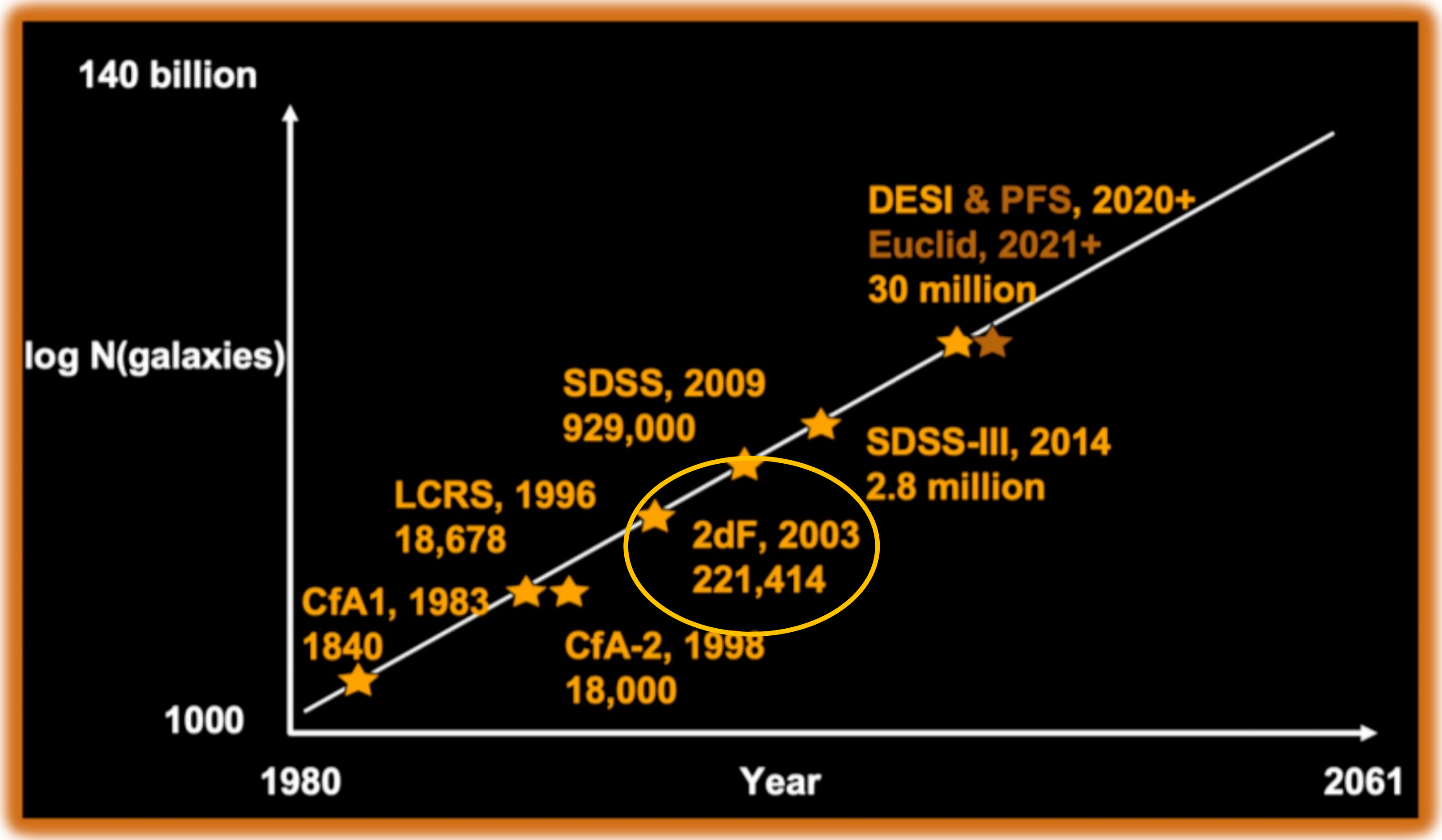


Large-scale structures over the years

2dF (2003)
200k spectra

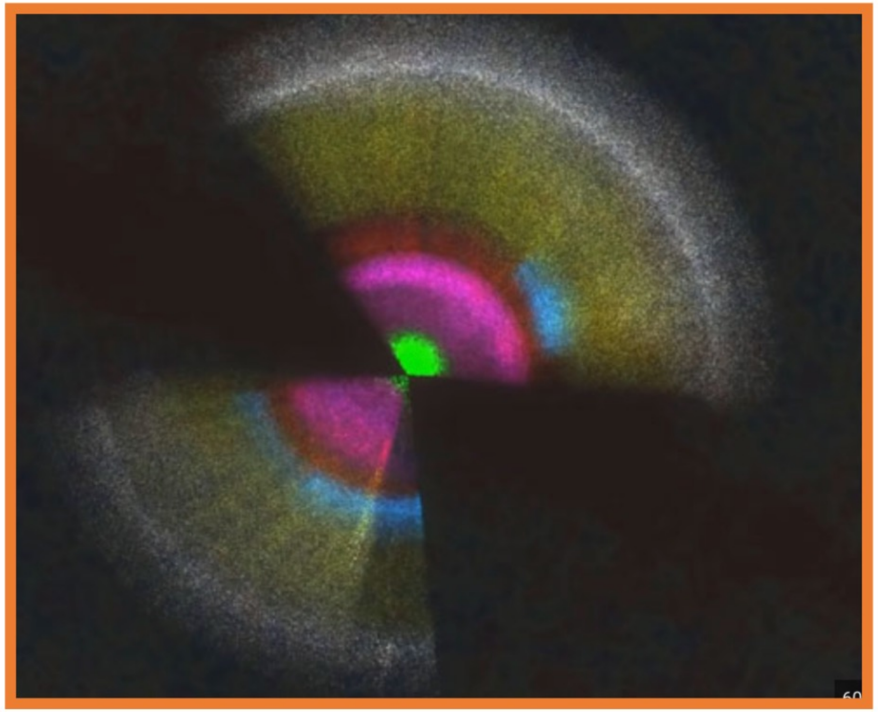


First statistical studies

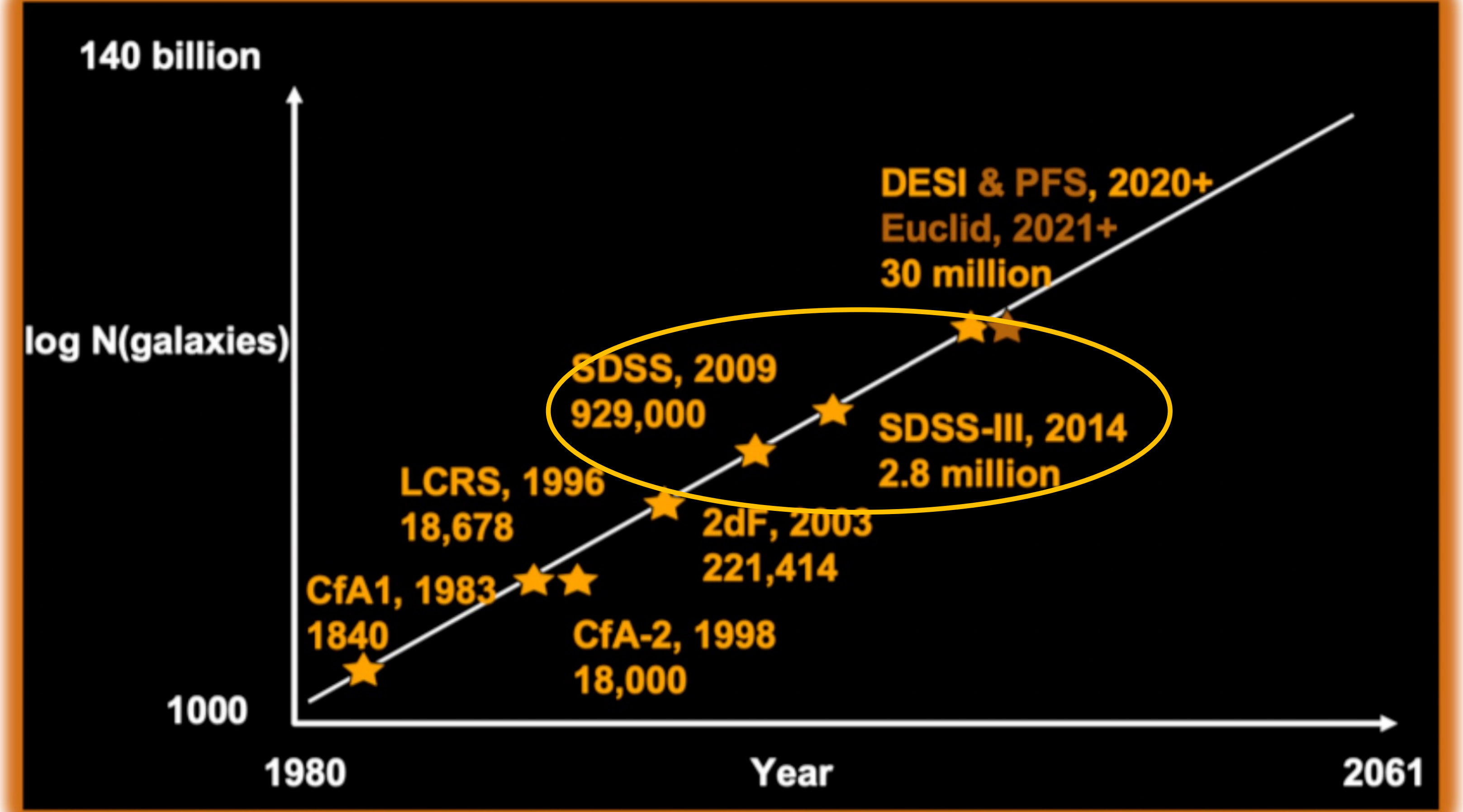


Large-scale structures over the years

SDSS BOSS/eBOSS (2009-2020)
2.8M spectra

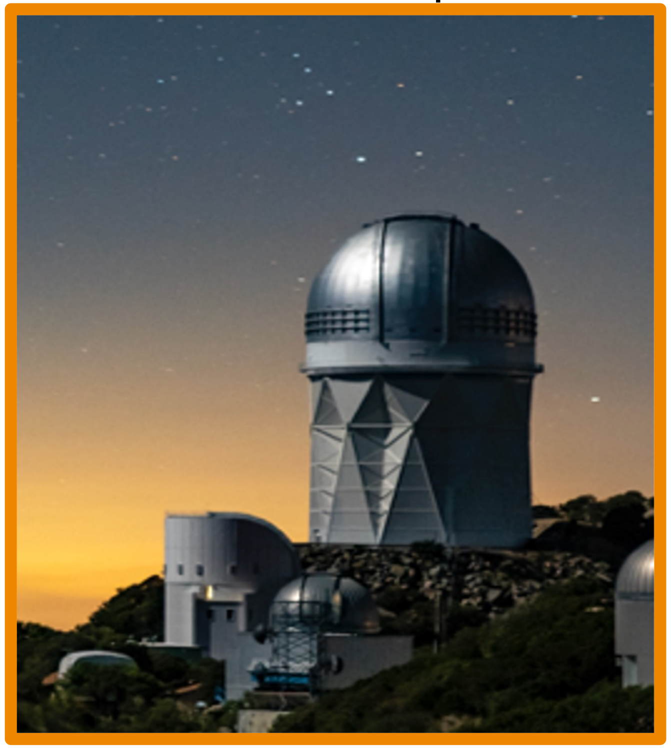


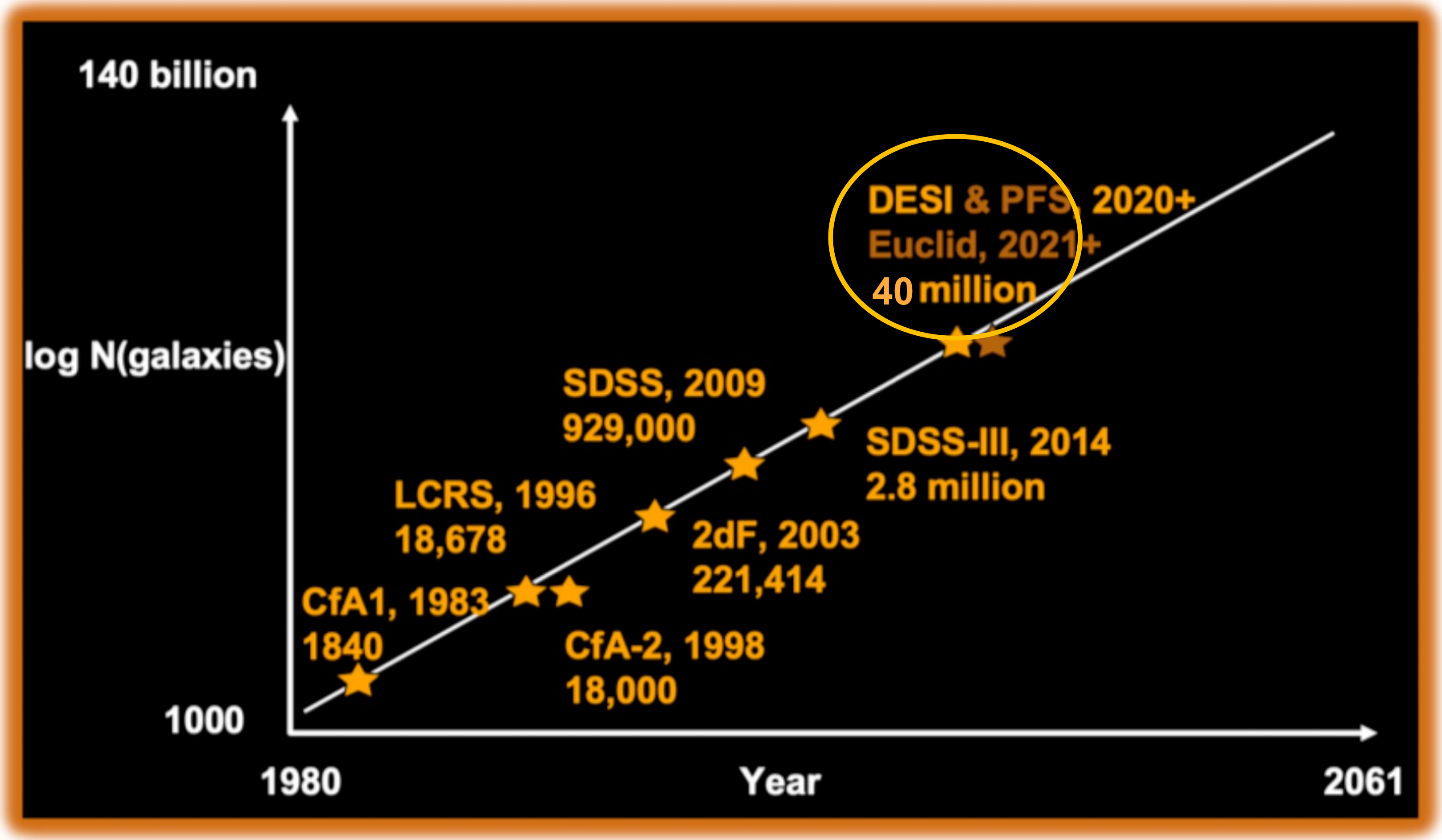
LSS precision cosmology



Large-scale structures over the years

DESI (2020)
Towards 40M spectra

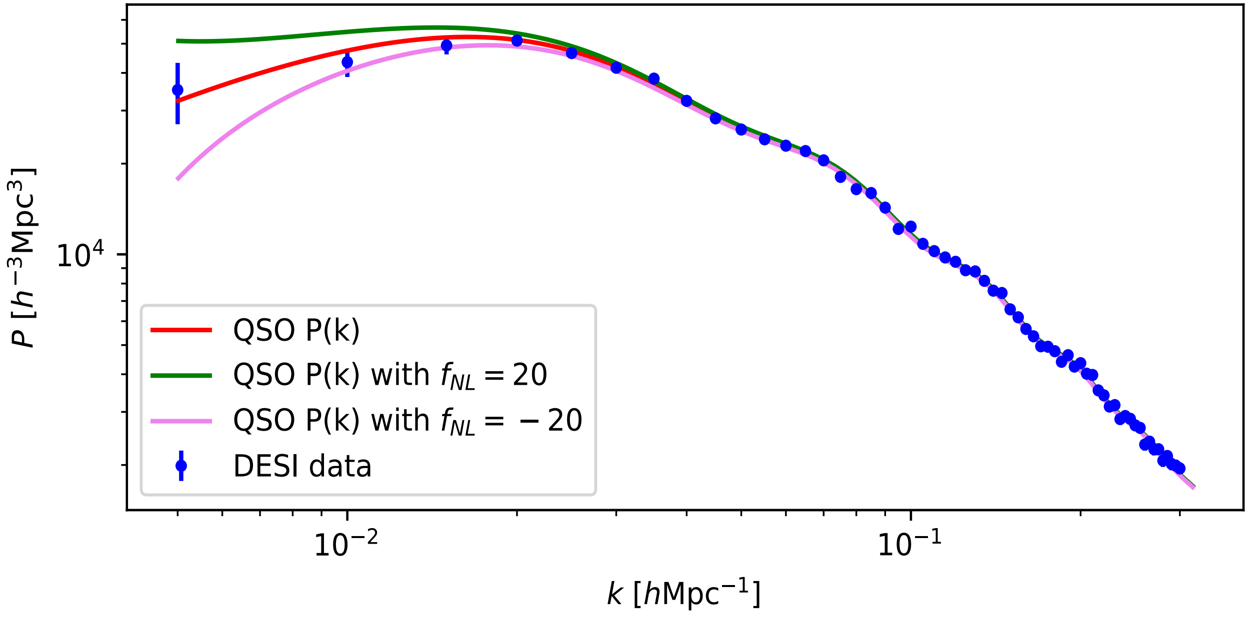




DESI – additional goals

Data	$\sigma_{\Sigma m_\nu}$ [eV]
Planck	0.56
Gal ($k_{\rm max} = 0.1h\,{\rm Mpc}^{-1}$)	0.030
Gal ($k_{\rm max} = 0.2h\,{\rm Mpc}^{-1}$)	0.021
Ly-α forest	0.041
Ly-α forest + Gal ($k_{\rm max} = 0.2$)	0.020

Neutrino mass at 3σ
if normal hierarchy



Sensitivity to small scales: **Neutrino mass**
→ Low noise
→ Good redshift / wavelength resolution

Sensitivity to large scales: **primordial non-Gaussianity**
→ large volume
→ low angular and radial systematics

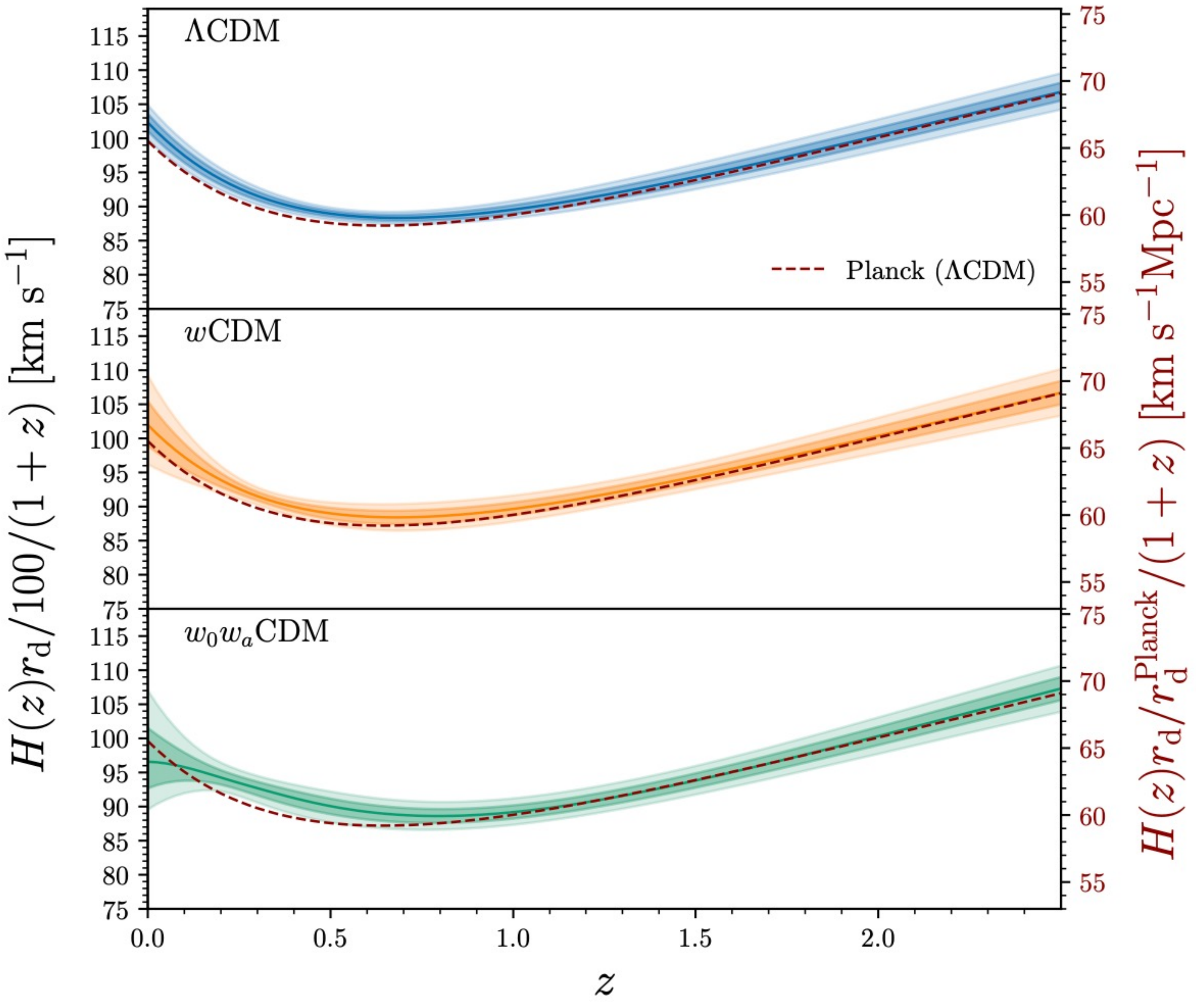
Dark Energy

Varying EoS (CPL)

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

$w_0 > -1$ and $w_a < 0$

Slightly favored in all data combinations



Mnu

model / dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	Σm_ν [eV]	N_eff
ΛCDM+$\sum m_\nu$				
DESI+CMB	0.3037 ± 0.0053	68.27 ± 0.42	< 0.072	—
ΛCDM+N_eff				
DESI+CMB	0.3058 ± 0.0060	68.3 ± 1.1	—	3.10 ± 0.17
wCDM+$\sum m_\nu$				
DESI+CMB	0.282 ± 0.013	$71.1^{+1.5}_{-1.8}$	< 0.123	—
DESI+CMB+Panth.	0.3081 ± 0.0067	67.81 ± 0.69	< 0.079	—
DESI+CMB+Union3	0.3090 ± 0.0082	67.72 ± 0.88	< 0.078	—
DESI+CMB+DESY5	0.3152 ± 0.0065	67.01 ± 0.64	< 0.073	—
wCDM+N_eff				
DESI+CMB	0.281 ± 0.013	$71.0^{+1.6}_{-1.8}$	—	2.97 ± 0.18
DESI+CMB+Panth.	0.3090 ± 0.0068	67.9 ± 1.1	—	3.07 ± 0.18
DESI+CMB+Union3	0.3097 ± 0.0084	67.8 ± 1.2	—	3.06 ± 0.18
DESI+CMB+DESY5	0.3163 ± 0.0067	67.2 ± 1.1	—	3.09 ± 0.18
w_0w_aCDM+$\sum m_\nu$				
DESI+CMB	$0.344^{+0.032}_{-0.026}$	$64.7^{+2.1}_{-3.2}$	< 0.195	
DESI+CMB+Panth.	0.3081 ± 0.0069	68.07 ± 0.72	< 0.155	—
DESI+CMB+Union3	0.3240 ± 0.0098	66.48 ± 0.94	< 0.185	—
DESI+CMB+DESY5	0.3165 ± 0.0069	67.22 ± 0.66	< 0.177	—
w_0w_aCDM+N_eff				
DESI+CMB	$0.346^{+0.032}_{-0.026}$	$63.9^{+2.2}_{-3.3}$	—	2.89 ± 0.17
DESI+CMB+Panth.	0.3093 ± 0.0069	67.5 ± 1.1	—	2.93 ± 0.18
DESI+CMB+Union3	0.3245 ± 0.0098	65.9 ± 1.3	—	2.91 ± 0.18
DESI+CMB+DESY5	0.3172 ± 0.0067	66.6 ± 1.1	—	2.92 ± 0.18

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model/dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_K$	w or w_0	w_a
Flat ΛCDM					
DESI	0.295 ± 0.015	—	—	—	—
DESI+BBN	0.295 ± 0.015	68.53 ± 0.80	—	—	—
DESI+BBN+θ_*	0.2948 ± 0.0074	68.52 ± 0.62	—	—	—
DESI+CMB	0.3069 ± 0.0050	67.97 ± 0.38	—	—	—
ΛCDM+Ω_K					
DESI	0.284 ± 0.020	—	65^{+68}_{-78}	—	—
DESI+BBN+θ_*	0.296 ± 0.014	68.52 ± 0.69	$0.3^{+4.8}_{-5.4}$	—	—
DESI+CMB	0.3049 ± 0.0051	68.51 ± 0.52	2.4 ± 1.6	—	—
***w*CDM**					
DESI	0.293 ± 0.015	—	—	$-0.99^{+0.15}_{-0.13}$	—
DESI+BBN+θ_*	0.295 ± 0.014	$68.6^{+1.8}_{-2.1}$	—	$-1.002^{+0.091}_{-0.080}$	—
DESI+CMB	0.281 ± 0.013	$71.3^{+1.5}_{-1.8}$	—	$-1.122^{+0.062}_{-0.054}$	—
DESI+CMB+Panth.	0.3095 ± 0.0069	67.74 ± 0.71	—	-0.997 ± 0.025	—
DESI+CMB+Union3	0.3095 ± 0.0083	67.76 ± 0.90	—	-0.997 ± 0.032	—
DESI+CMB+DESY5	0.3169 ± 0.0065	66.92 ± 0.64	—	-0.967 ± 0.024	—
w_0w_aCDM					
DESI	$0.344^{+0.047}_{-0.026}$	—	—	$-0.55^{+0.39}_{-0.21}$	< -1.32
DESI+BBN+θ_*	$0.338^{+0.039}_{-0.029}$	$65.0^{+2.3}_{-3.6}$	—	$-0.53^{+0.42}_{-0.22}$	< -1.08
DESI+CMB	$0.344^{+0.032}_{-0.027}$	$64.7^{+2.2}_{-3.3}$	—	$-0.45^{+0.34}_{-0.21}$	$-1.79^{+0.48}_{-1.0}$
DESI+CMB+Panth.	0.3085 ± 0.0068	68.03 ± 0.72	—	-0.827 ± 0.063	$-0.75^{+0.29}_{-0.25}$
DESI+CMB+Union3	0.3230 ± 0.0095	66.53 ± 0.94	—	-0.65 ± 0.10	$-1.27^{+0.40}_{-0.34}$
DESI+CMB+DESY5	0.3160 ± 0.0065	67.24 ± 0.66	—	-0.727 ± 0.067	$-1.05^{+0.31}_{-0.27}$
w_0w_aCDM+Ω_K					
DESI	0.313 ± 0.049	—	87^{+100}_{-85}	$-0.70^{+0.49}_{-0.25}$	< -1.21
DESI+BBN+θ_*	$0.346^{+0.042}_{-0.024}$	$65.8^{+2.6}_{-3.5}$	$5.9^{+9.1}_{-6.9}$	$-0.52^{+0.38}_{-0.19}$	< -1.44
DESI+CMB	$0.347^{+0.031}_{-0.025}$	$64.3^{+2.0}_{-3.2}$	-0.9 ± 2	$-0.41^{+0.33}_{-0.18}$	< -1.61
DESI+CMB+Panth.	0.3084 ± 0.0067	68.06 ± 0.74	0.3 ± 1.8	-0.831 ± 0.066	$-0.73^{+0.32}_{-0.28}$
DESI+CMB+Union3	$0.3233^{+0.0089}_{-0.010}$	66.45 ± 0.98	-0.4 ± 1.9	-0.64 ± 0.11	$-1.30^{+0.45}_{-0.39}$
DESI+CMB+DESY5	0.3163 ± 0.0065	67.19 ± 0.69	-0.2 ± 1.9	-0.725 ± 0.071	$-1.06^{+0.35}_{-0.31}$

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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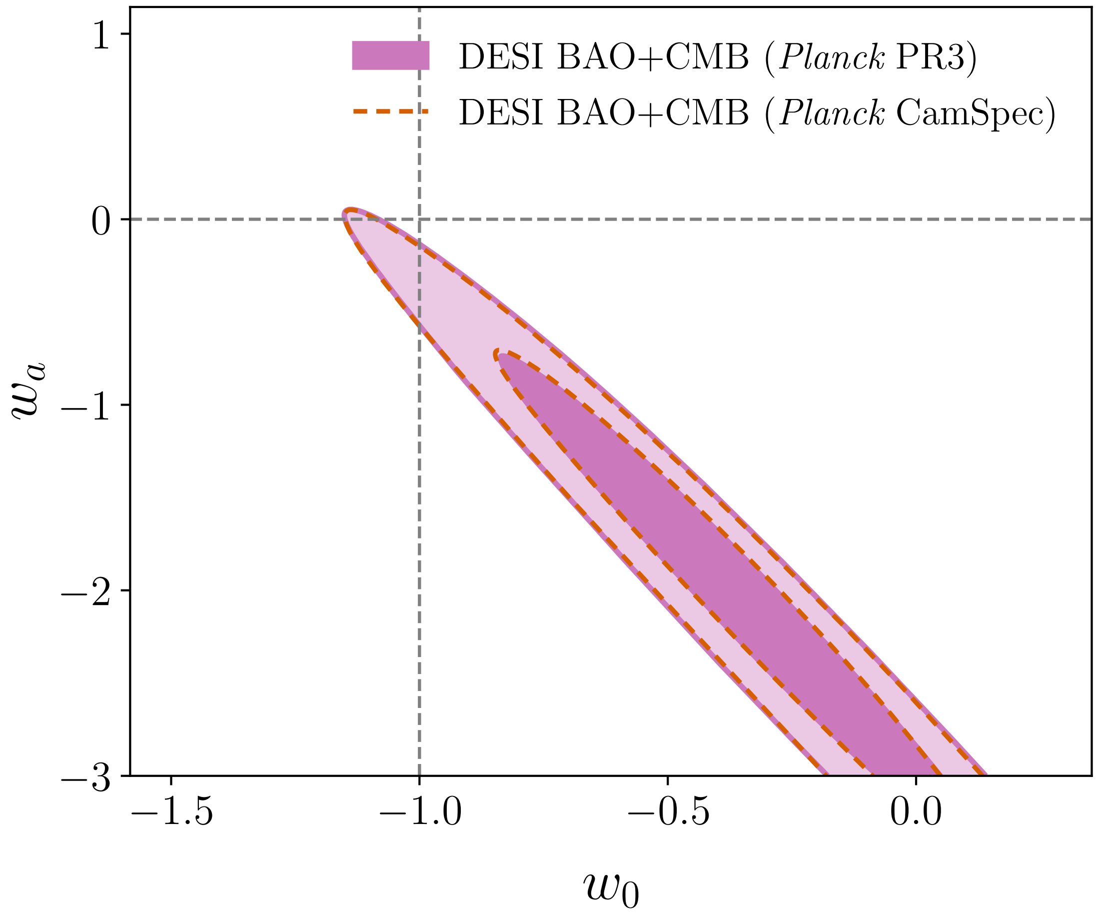
Dependance on Planck likelihood



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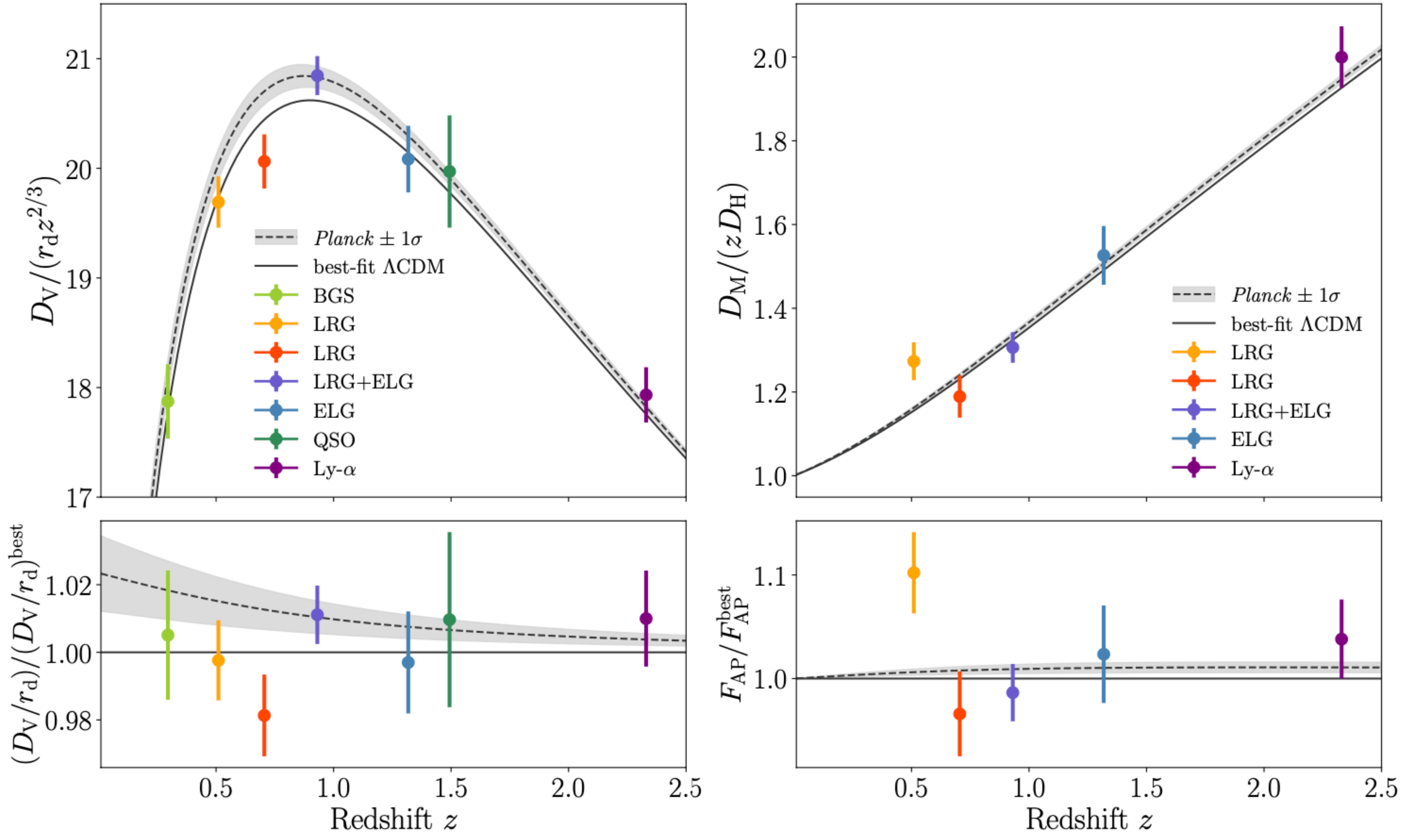
$F_{AP} = D_M / DH$



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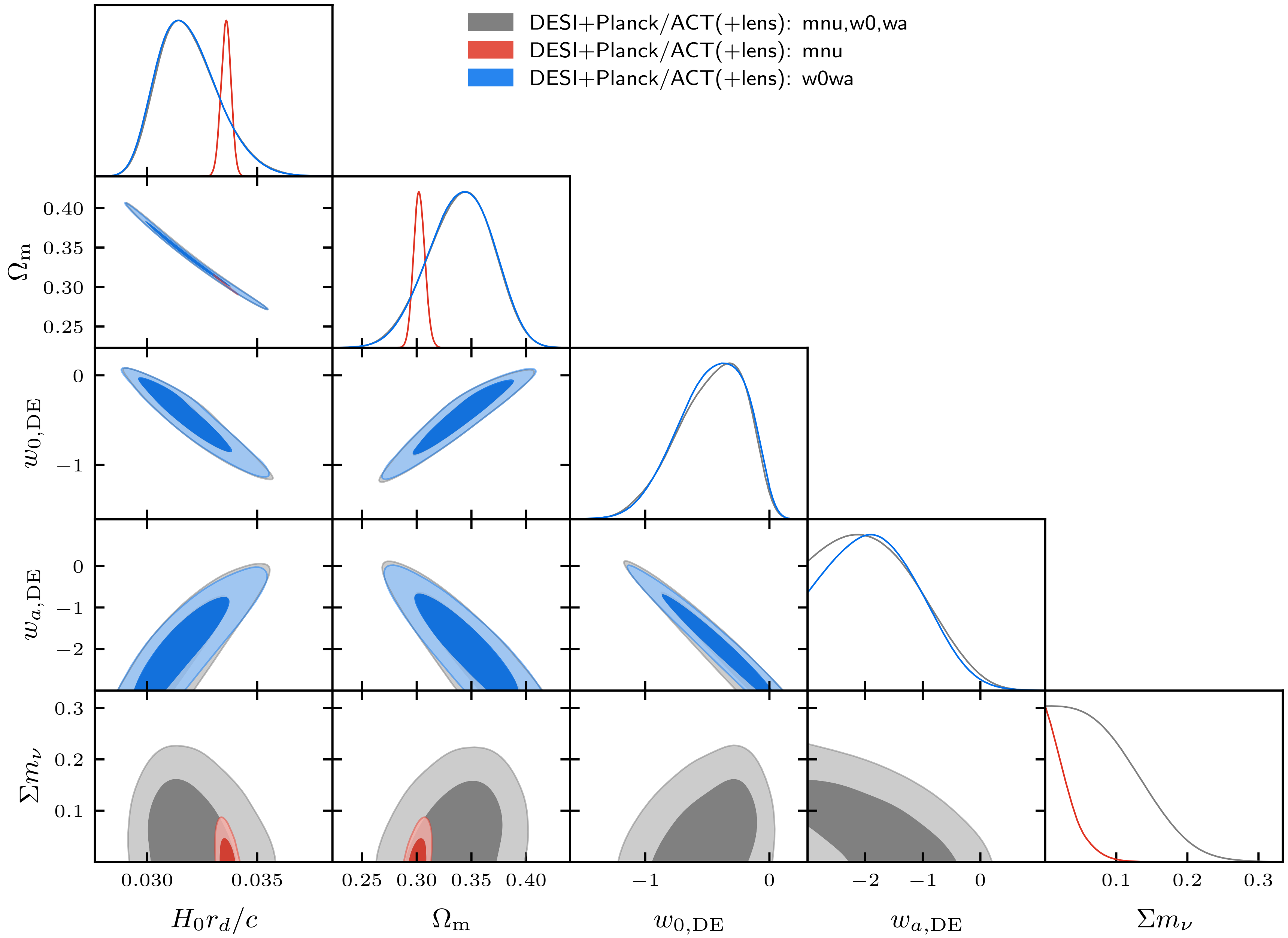
Mnu

With w_0, w_a



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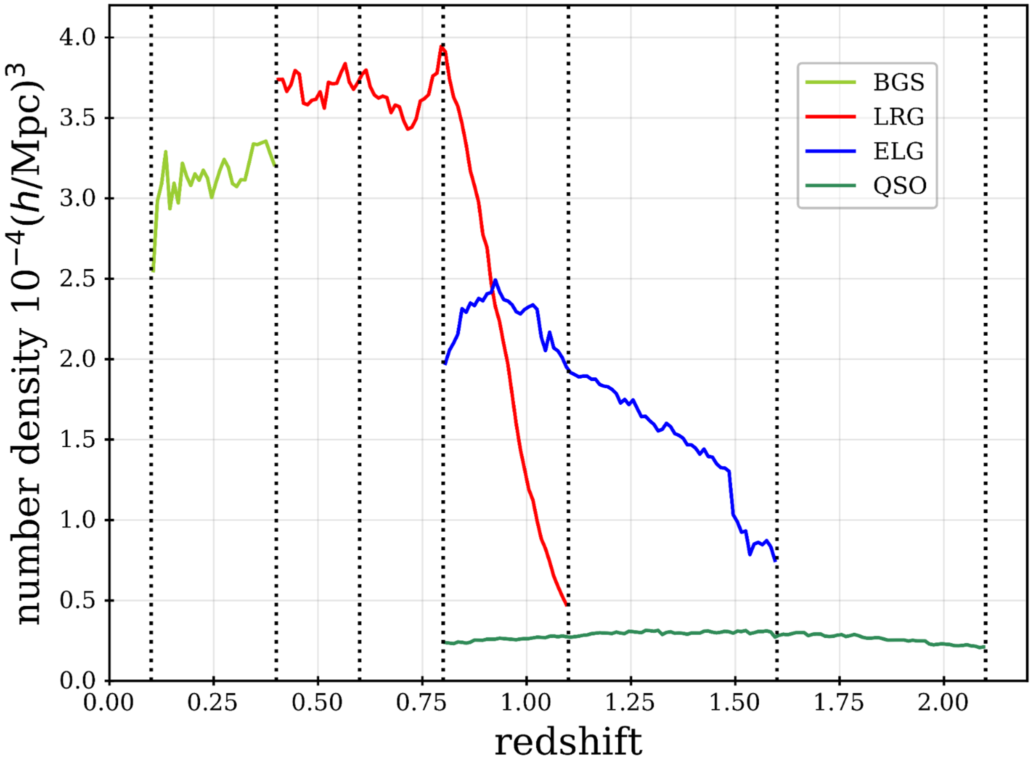
DESI 2024 galaxy and quasar BAO at z < 2.1



5.7 million unique redshifts with the effective cosmic volume of **18 Gpc^3**

A factor of 3 times bigger than SDSS.

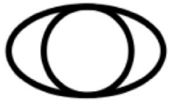
Split into six redshift bins
→ expansion history as a function of lookback time.

BAO measurement

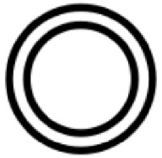
- Correlation function model decomposed into a smooth and a peak component
- Peak component stretched with BAO parameters

$$\xi(r_{||}, r_{\perp}) = \hat{\xi}_{\mathrm{s}}(r_{||}, r_{\perp}) + \hat{\xi}_{\mathrm{p}}(\alpha_{||} r_{||}, \alpha_{\perp} r_{\perp})$$

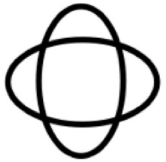
$$\alpha_{||} = \frac{D_H(z_{\mathrm{eff}})/r_d}{[D_H(z_{\mathrm{eff}})/r_d]_{\mathrm{fid}}}$$



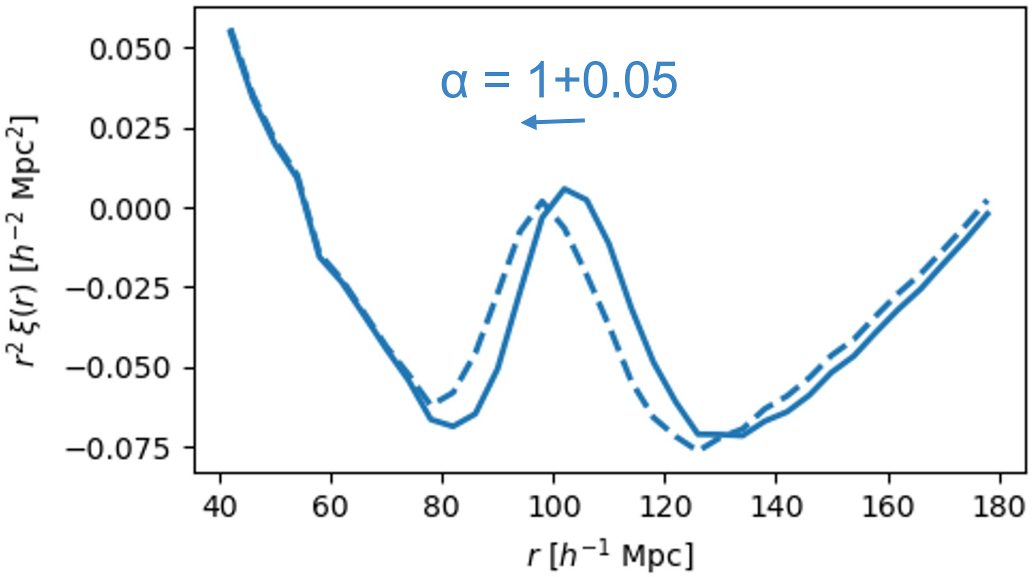
$$\alpha_{\perp} = \frac{D_M(z_{\mathrm{eff}})/r_d}{[(D_M(z_{\mathrm{eff}})/r_d]_{\mathrm{fid}}}$$



$$\alpha_{\mathrm{iso}} = (\alpha_{\perp}^2 \alpha_{||})^{1/3}$$



$$\alpha_{\mathrm{AP}} = \frac{D_H}{D_M} \frac{D_M^{\mathrm{fid}}}{D_H^{\mathrm{fid}}}$$



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Beyond DESI:

2022 Snowmass report

"Continue operation of DESI (via a new DESI-II program) to constrain dark energy in new domains and as a step towards a Stage V spectroscopic facility (Spec-S5)."

DESI-II

Extended science scope, same instrument

- Dedicated high-z survey for early dark energy: ~DESI sensitivity in different regime
- Support for Rubin cosmology

Limited upgrades

- Improved performance
- Segue to Spec-S5

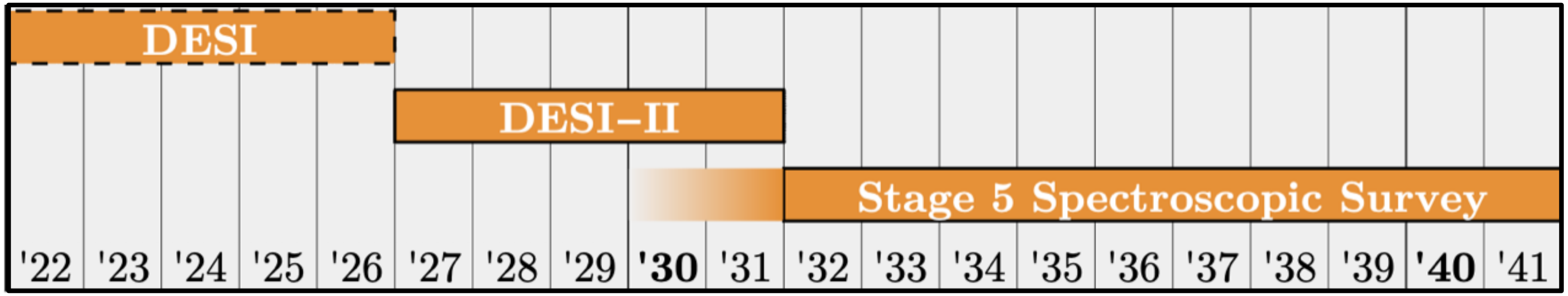
Spec-S5

New science scope, new instrument

- Ultimate dark energy survey + primordial physics, neutrino mass, unknown particles
- New tracers of matter

Instrument upgrades

New facility (several options considered)



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Beyond DESI Year 1 BAO

- **RSD analysis (full shape clustering)**
  - $f\sigma_8(z)$

    → Modified gravity

- **Full shape measurement on large scales**
  - Non-Gaussianity f_{NL}

    → Inflation

Currently still blinded