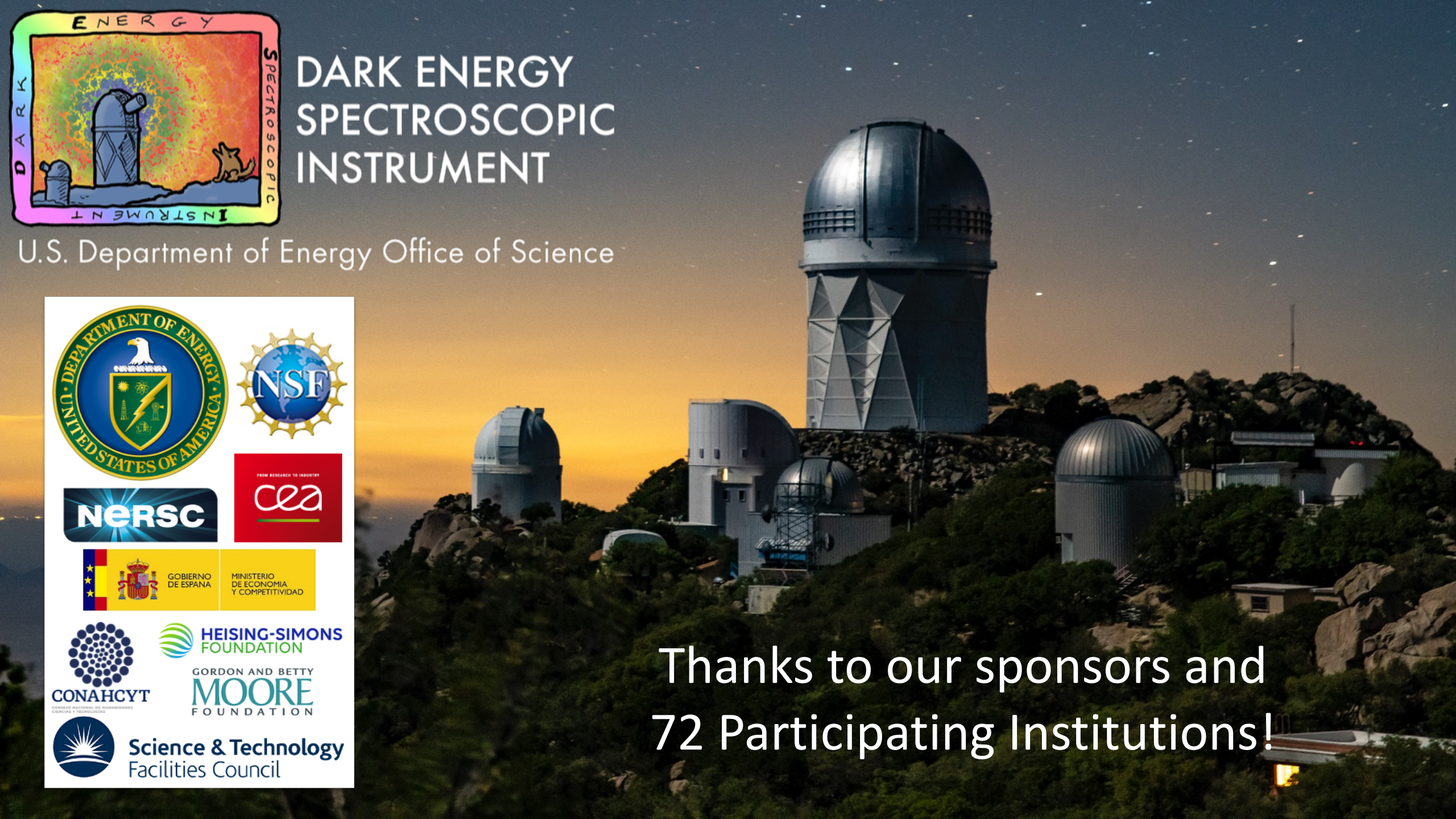
The Dark Energy Spectroscopic Instrument (DESI): An Overview

David Parkinson, Korea Astronomy & Space Science Institute
On behalf of the DESI Collaboration

(slides stolen from many, like Andreu Font-Ribera, Sesh Nadathur, and Kushal Lodha)

Light Dark World International Forum 2024
KAIST, Daejeon, Aug 2024


ENERGY
DARK
SPECTROSCOPIC
INSTRUMENT
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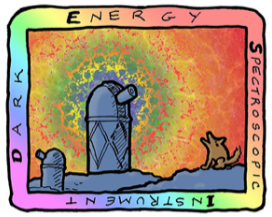

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Outline

- The Dark Energy Spectroscopic Instrument (DESI)
- Introduction to Baryon Acoustic Oscillations (BAO)
- BAO measurements with galaxies and quasars
- Cosmological constraints from DESI BAO
- Other cosmological tests using DESI data

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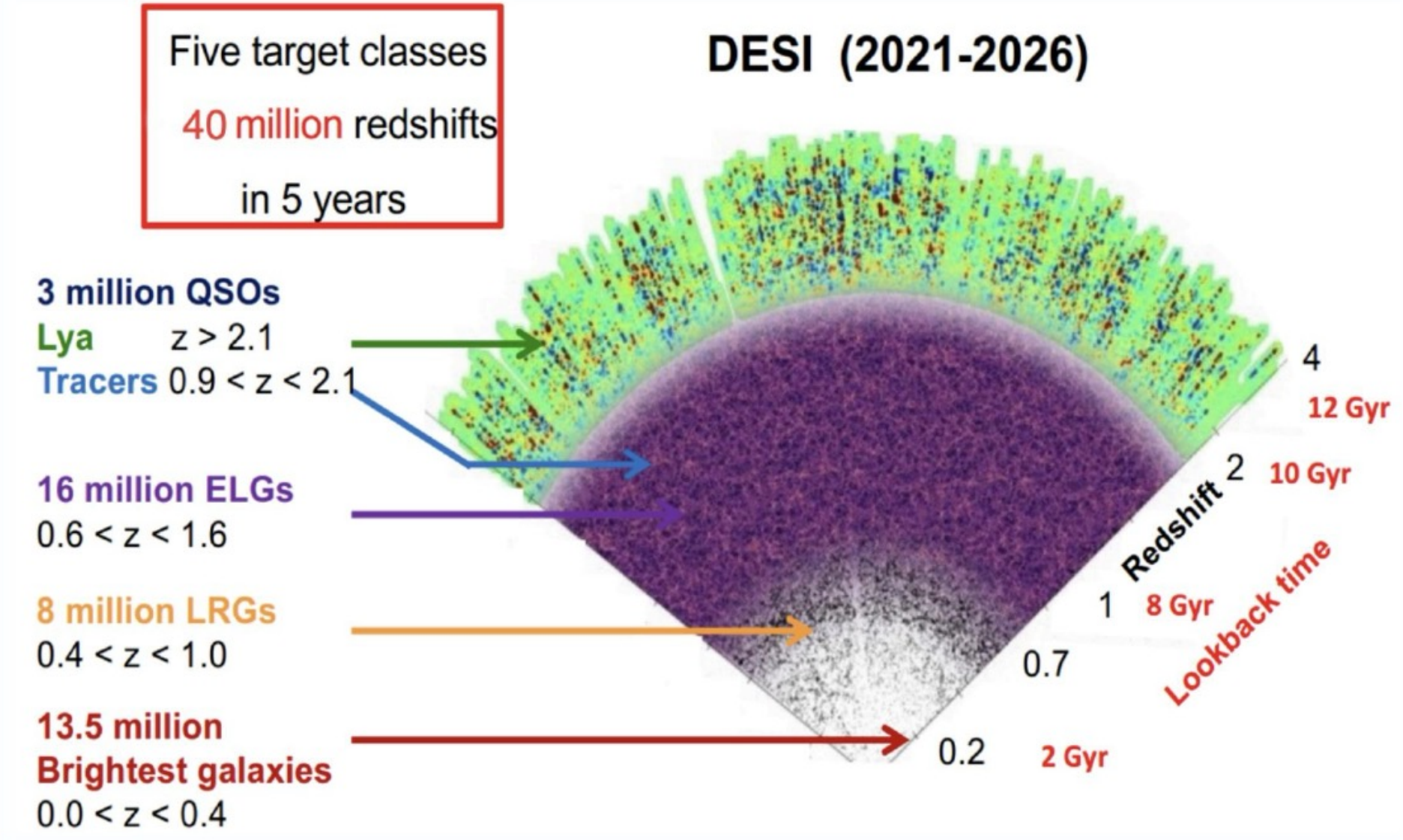
Tracers of the matter distribution



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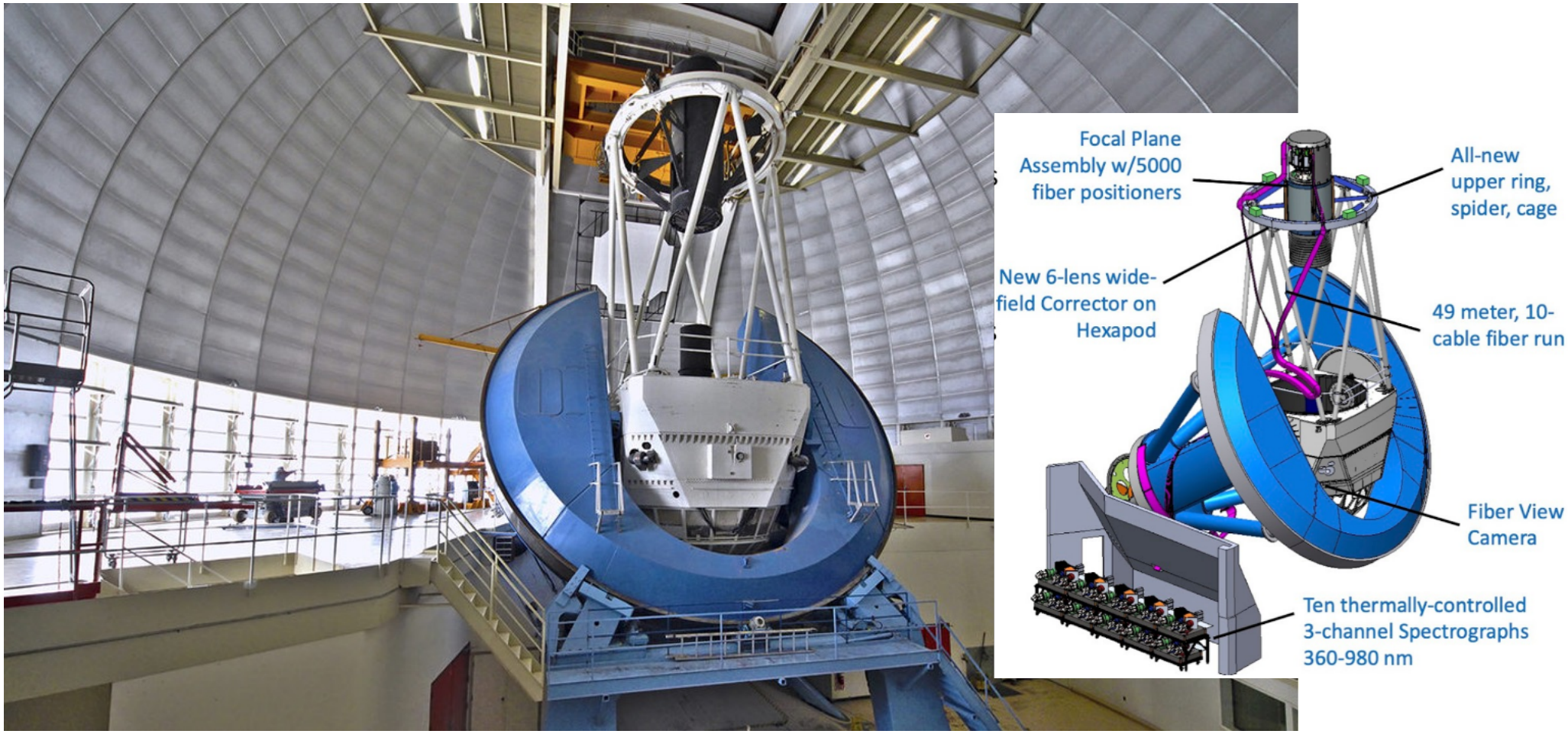
Mayall 4m telescope @ Kitt Peak (AZ)



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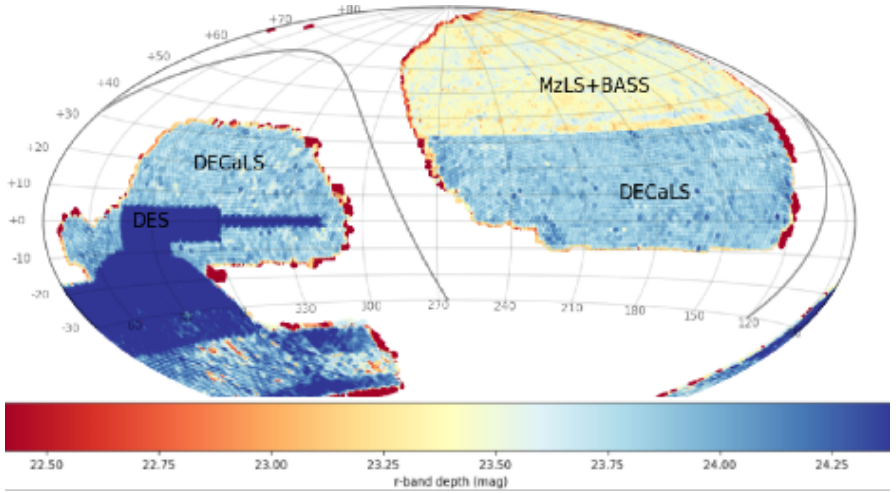
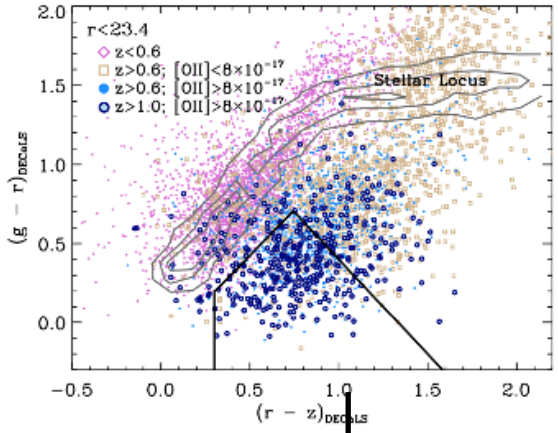
Multi-object Spectroscopy

Imaging surveys (2014-2019)

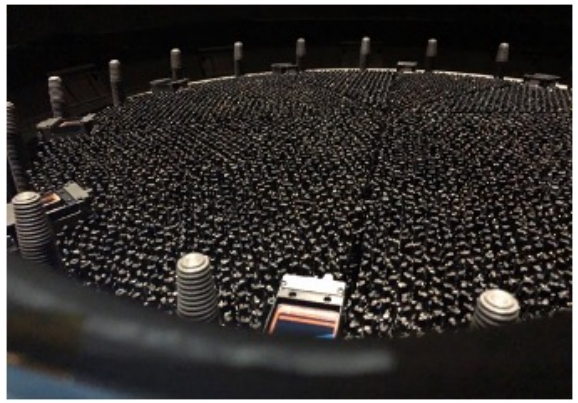


Target selection

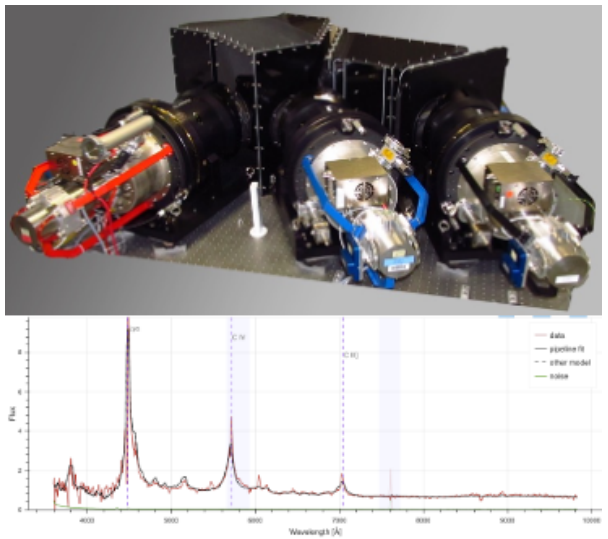


Observation

… of 5000 objects every 20 minutes



and measure their redshift



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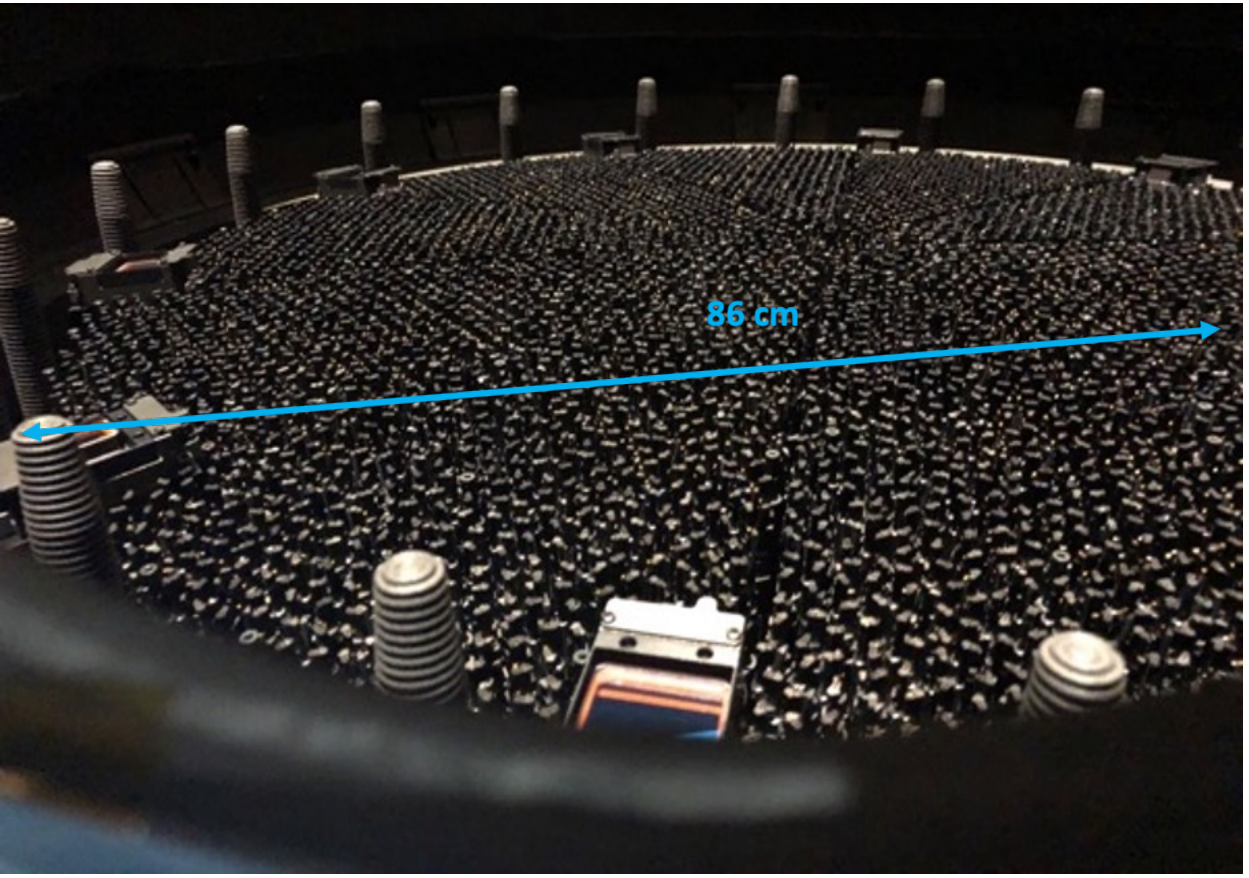
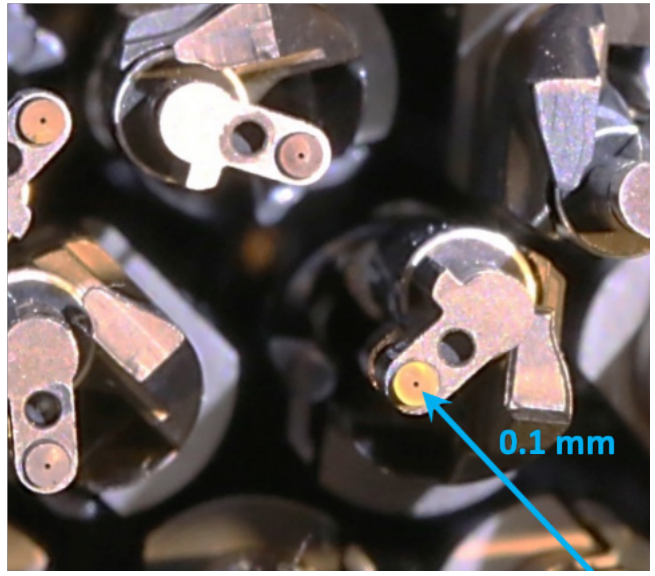
Focal plane – 5000 robotic positioners



- Exposure time (dark) : 1000s
- Configuration of the whole focal plane
- CCD Readout
- Go to next pointing



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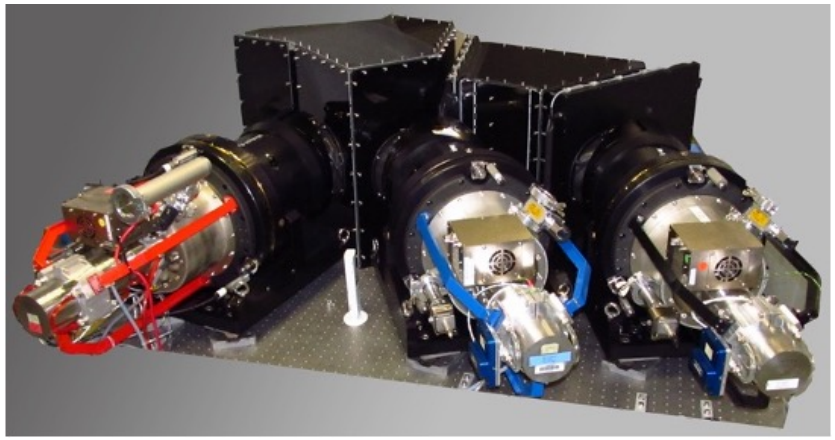
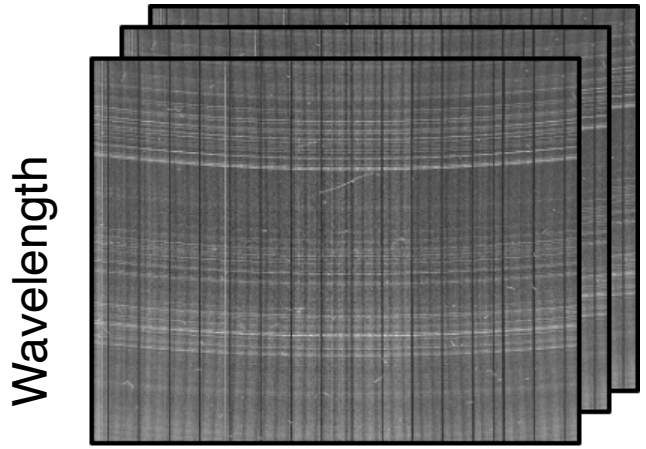
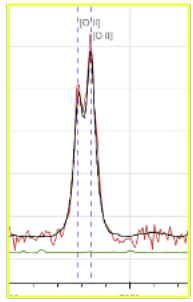
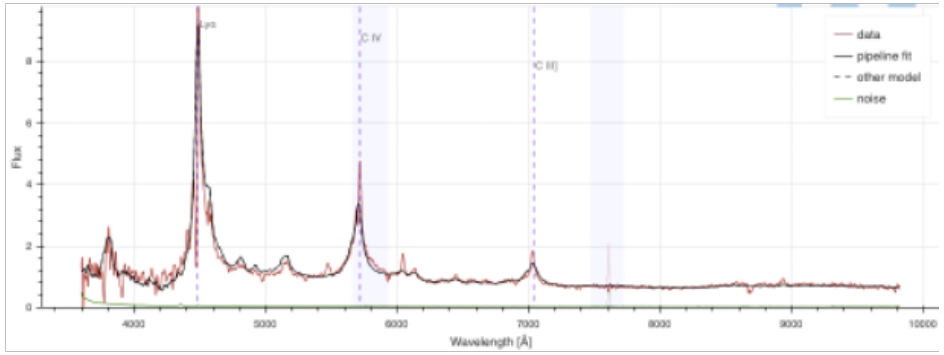
...and Spectra



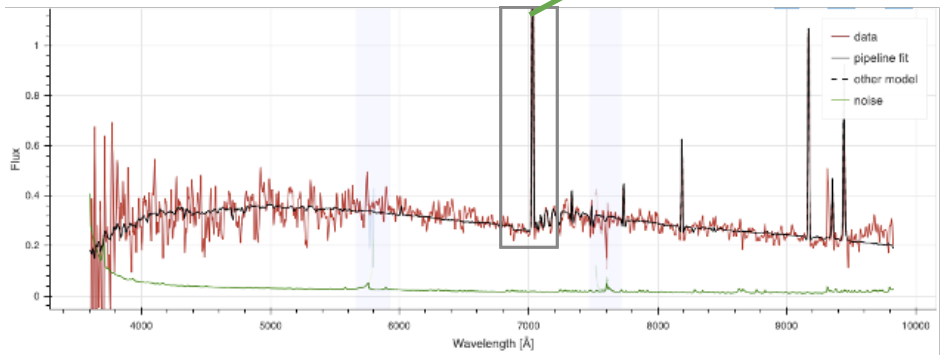


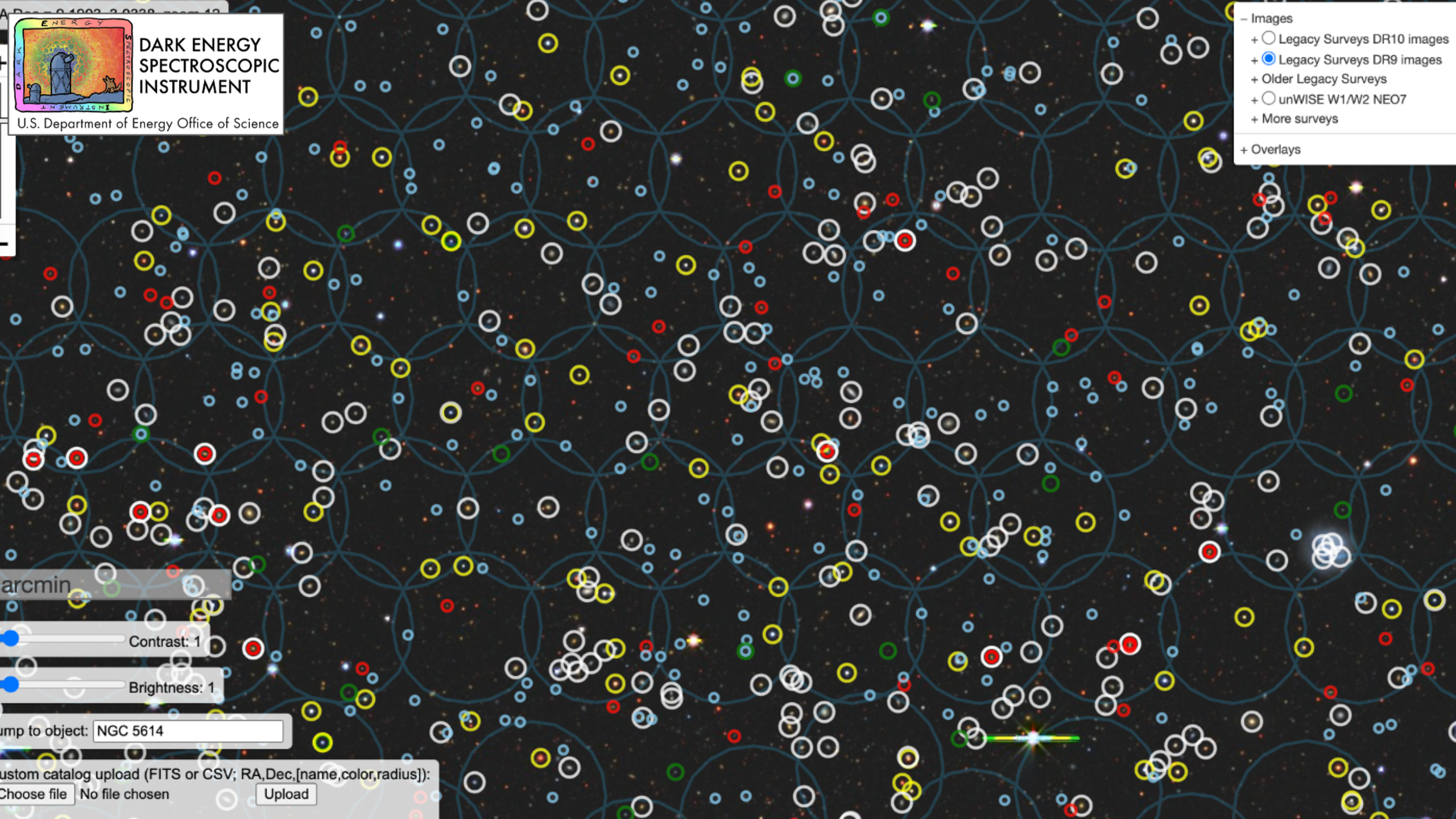


Lyα 121.6 nm
down to z = 2.0



[OII] doublet at 373 nm
up to z = 1.6

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More surveys
Overlays
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Brightness: 1
ump to object: NGC 5614
ustom catalog upload (FITS or CSV; RA,Dec,[name,color,radius]):
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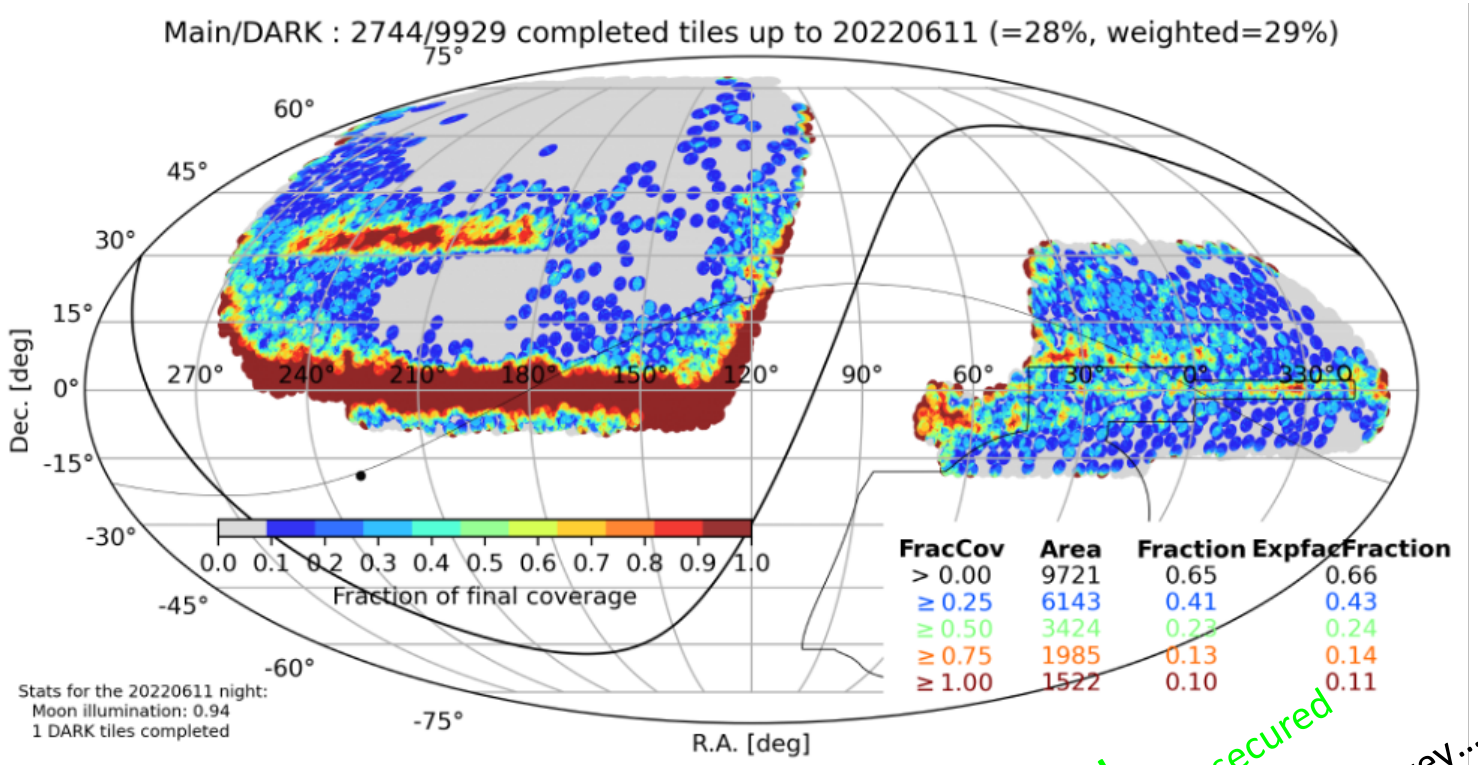
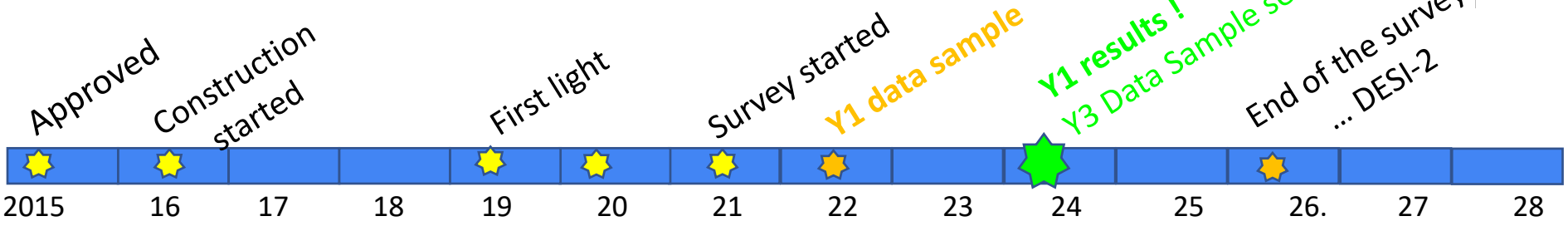
DESI Data Release 1 (DR1)

Full coverage
14,200 deg^2





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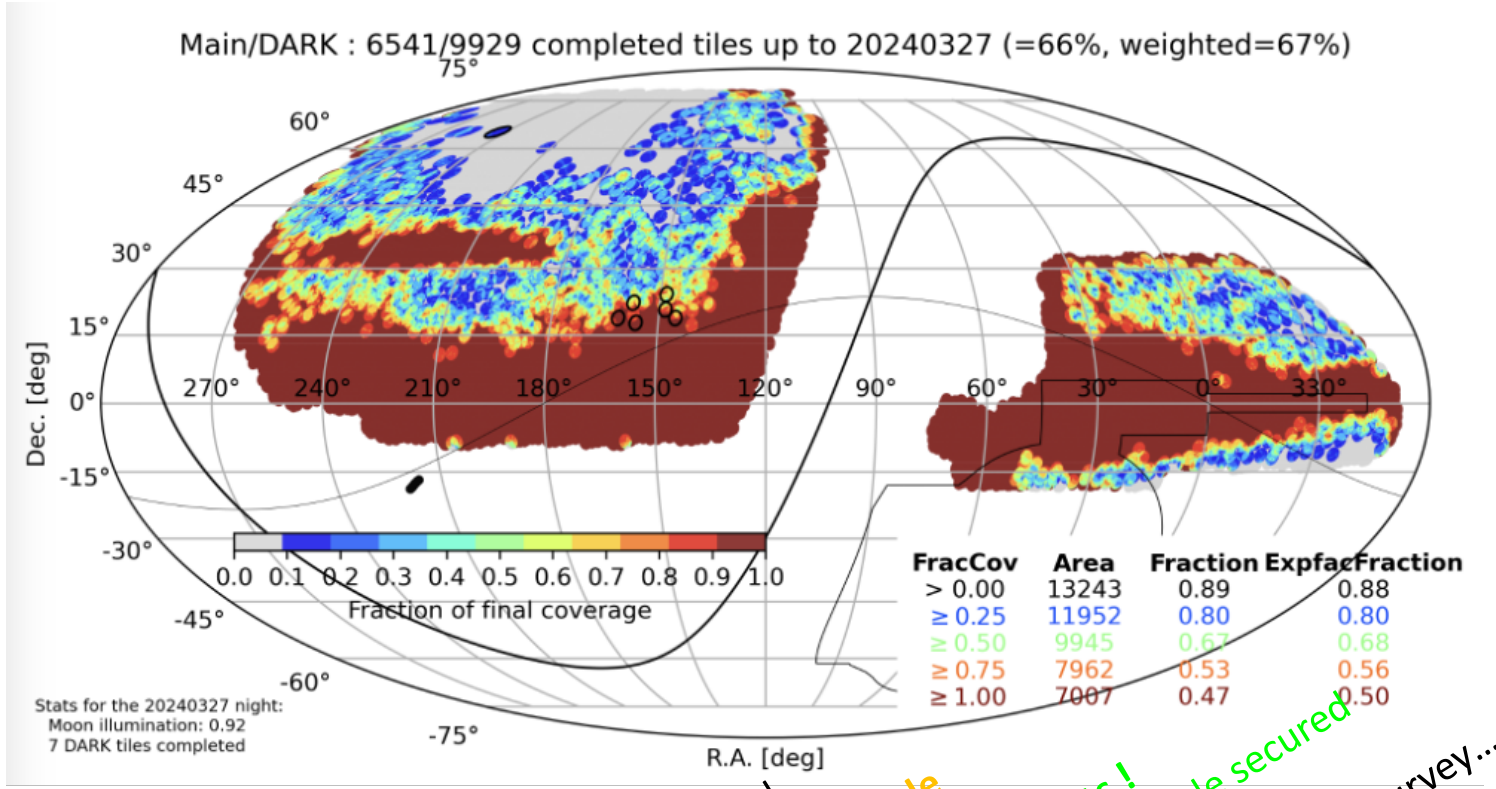
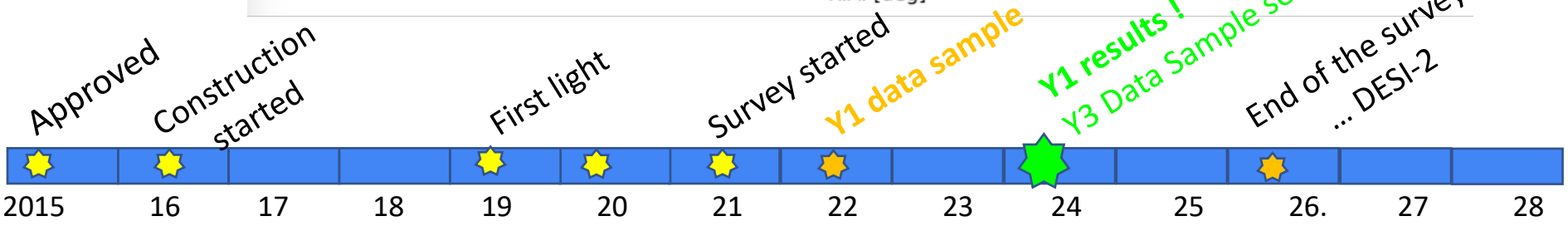
DESI Data Release 2 (DR2)

Full coverage
14,200 deg^2





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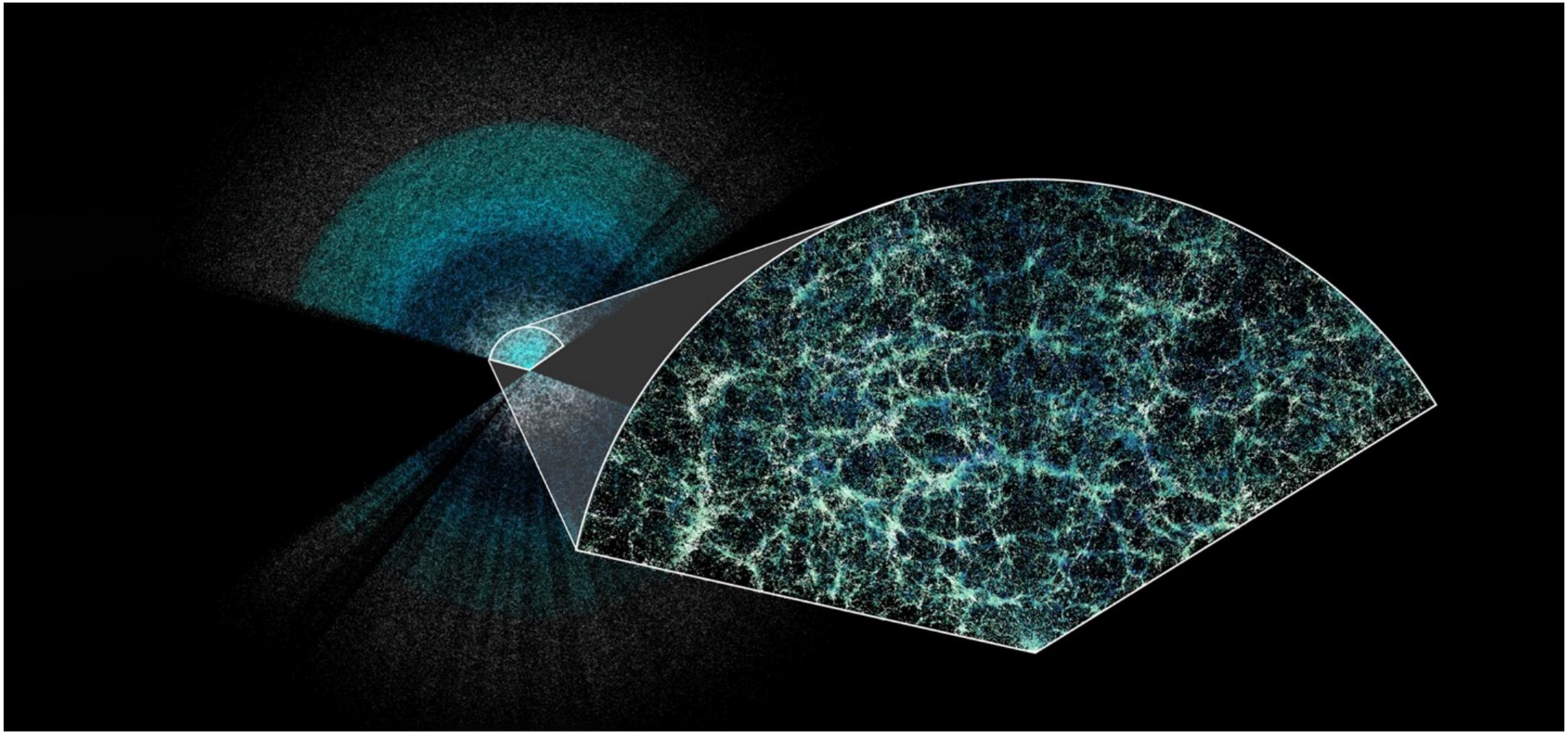
DESI 3D Map of cosmic structures



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Baryon Acoustic Oscillations

The distance-redshift relation can tell us about the nature of Dark Energy

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

Hubble constant (current)

Hubble parameter (expansion rate)

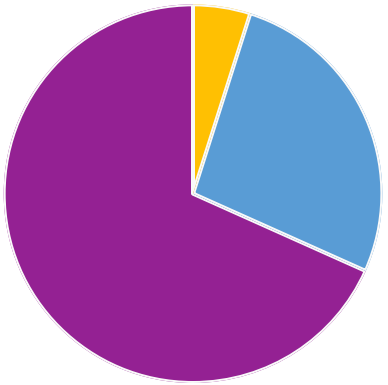
$$\frac{H^2(z)}{H_0^2} = \Omega_r(1+z)^3 + \Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2$$

Radiation

Matter (baryonic or dark)

Dark Energy

Curvature



The expansion will change also if Dark Energy is dynamic (w varies)

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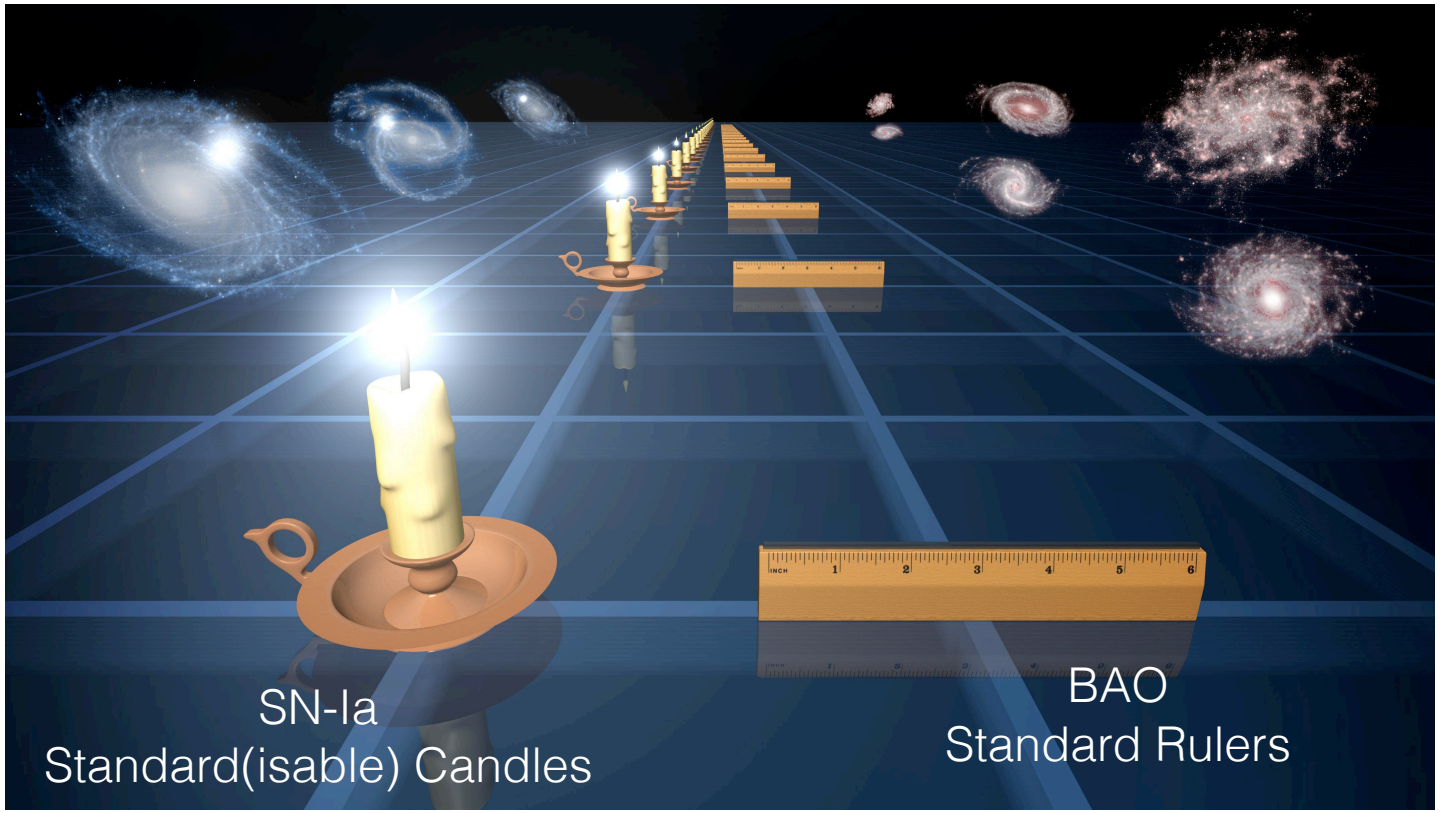
Expansion history

The distance-redshift relation can tell us about the nature of Dark Energy



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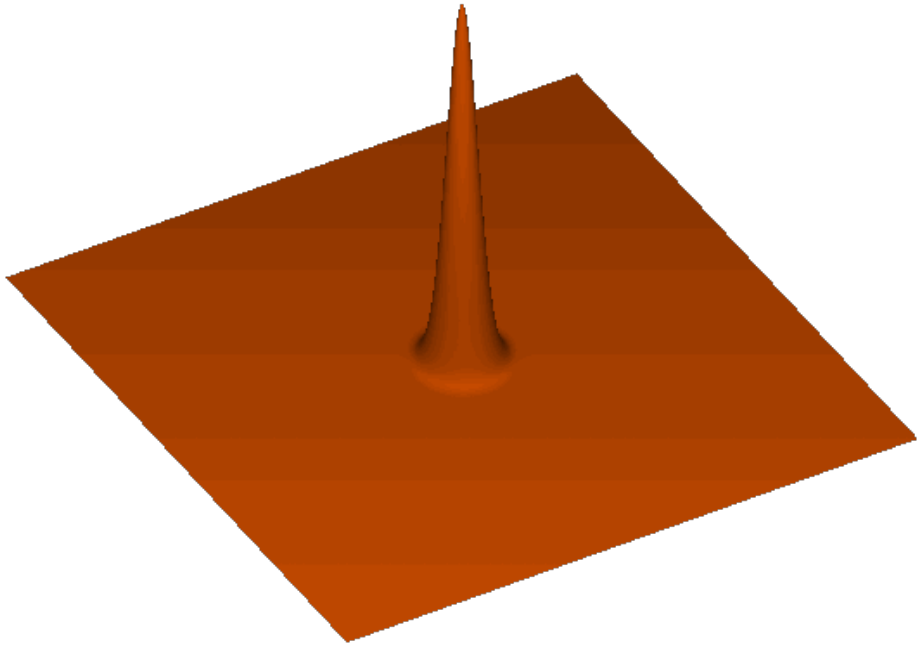
Baryon Acoustic Oscillations

KASI UST

Sound waves in primordial plasma:



Eisenstein, Seo et al. 2007

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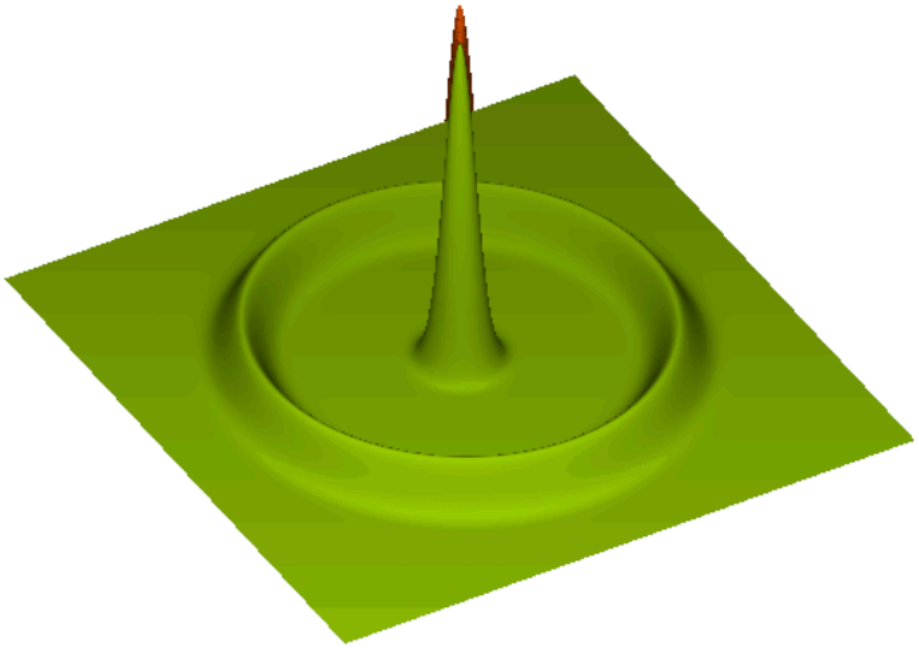
Baryon Acoustic Oscillations

Sound waves in primordial plasma:



Eisenstein, Seo et al. 2007

At recombination ($z \sim 1100$):

- plasma changes to optically thin
- baryons decouple from photons
- sound wave stalls

$\Longrightarrow$ a residual spherical **peak in clustering of galaxies**

size of feature = distance sound wave travelled

= sound horizon scale at recomb.

$\simeq 150$ Mpc

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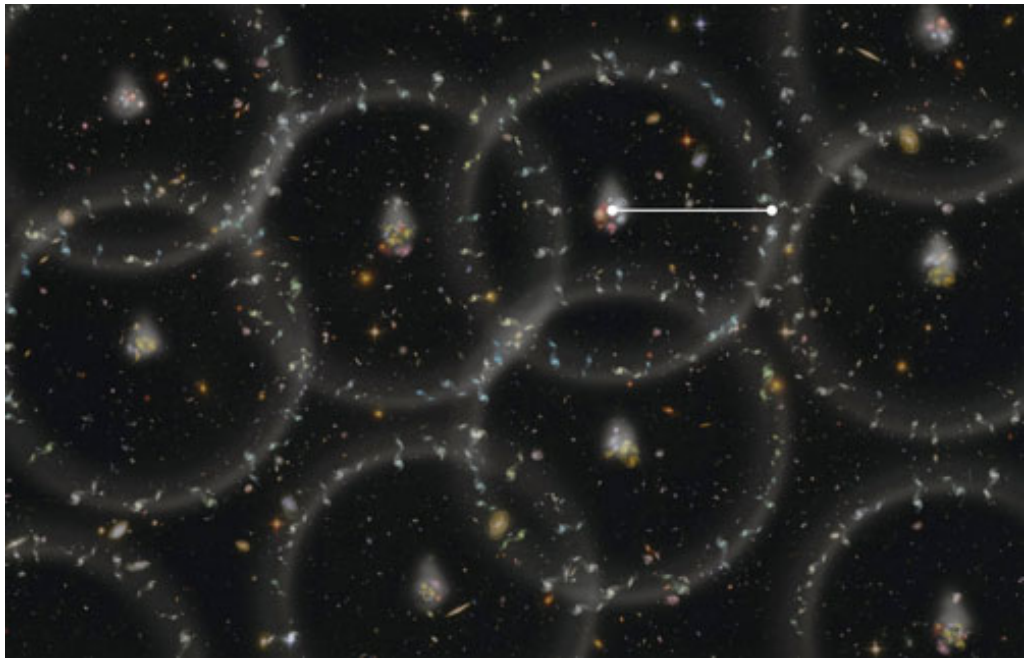
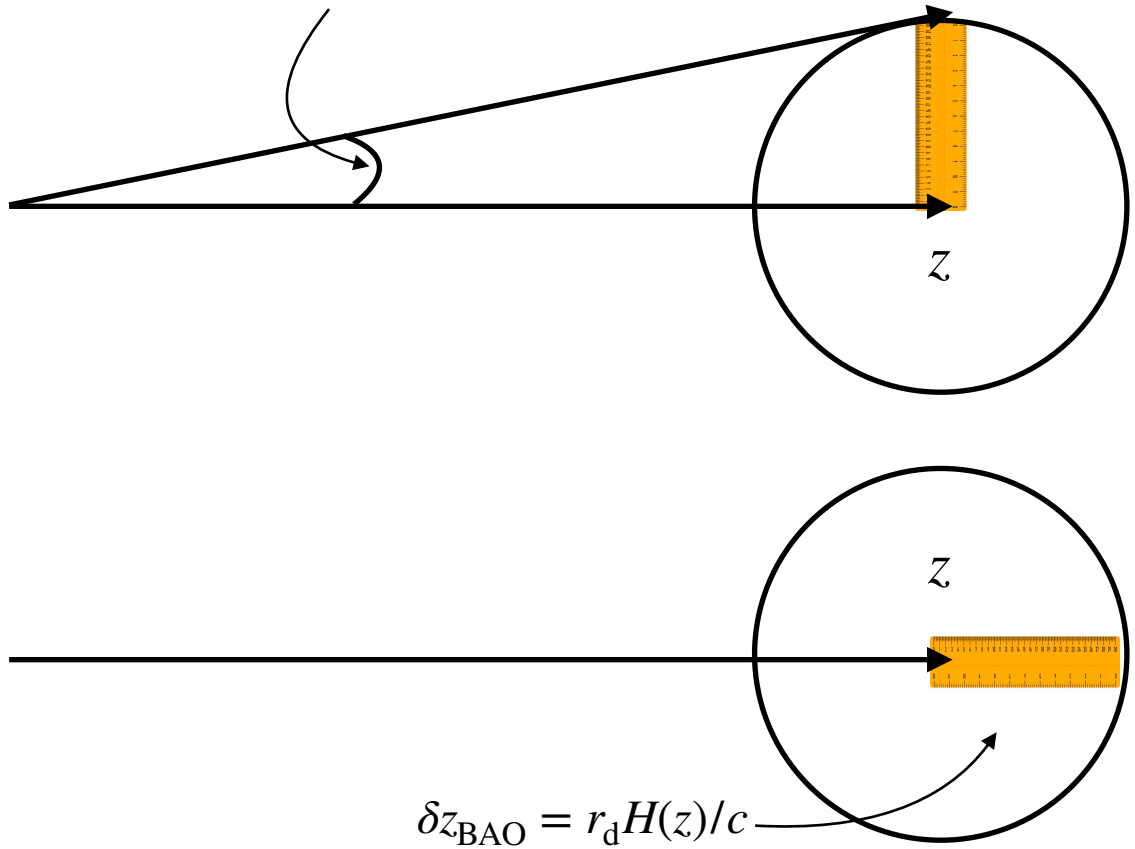
The BAO standard ruler

KASI UST





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

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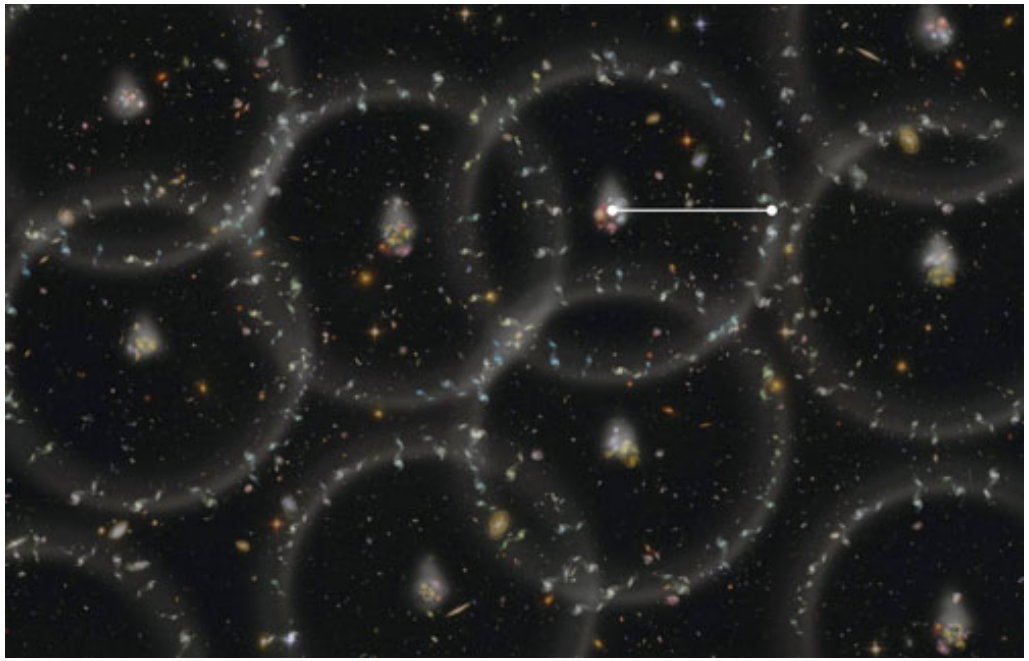
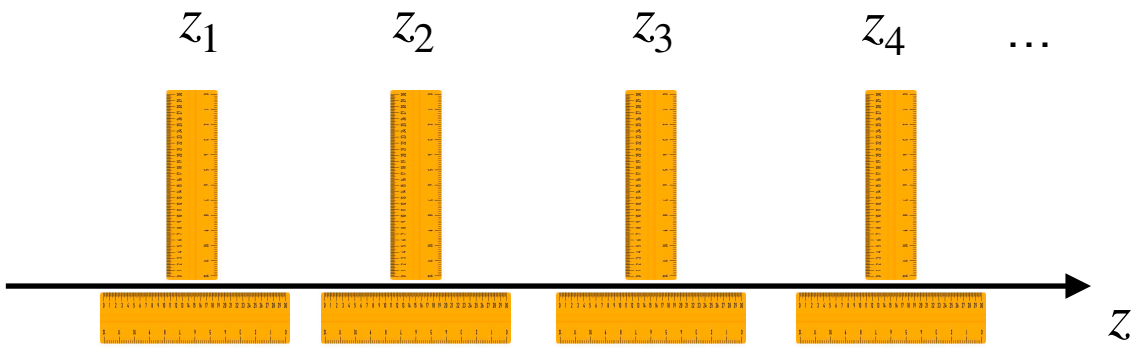
The BAO standard ruler





DESI measures BAO rulers at many times/redshifts

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

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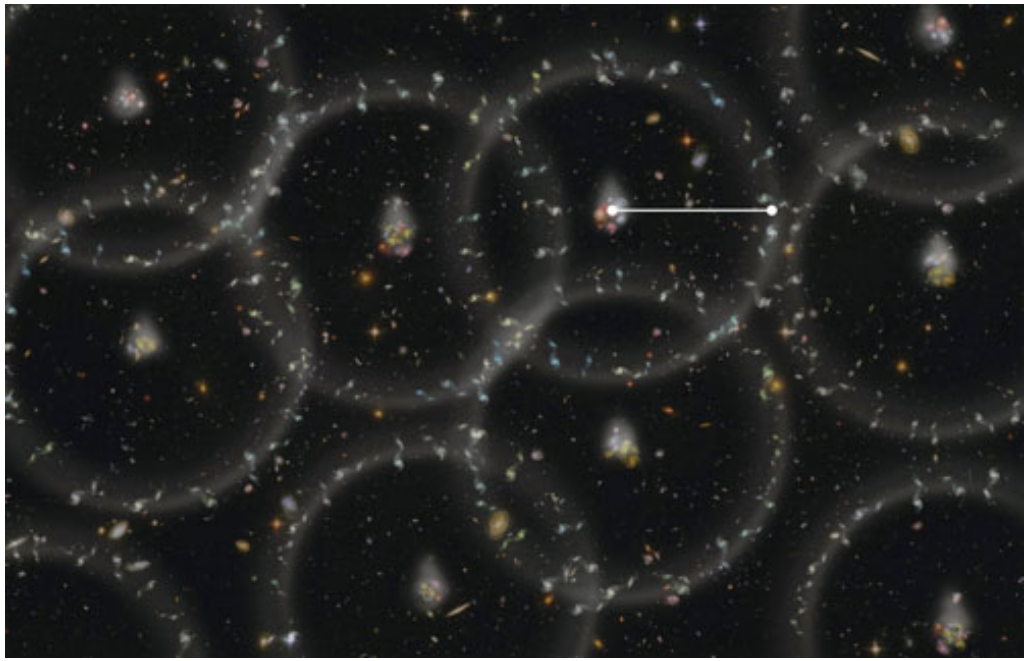
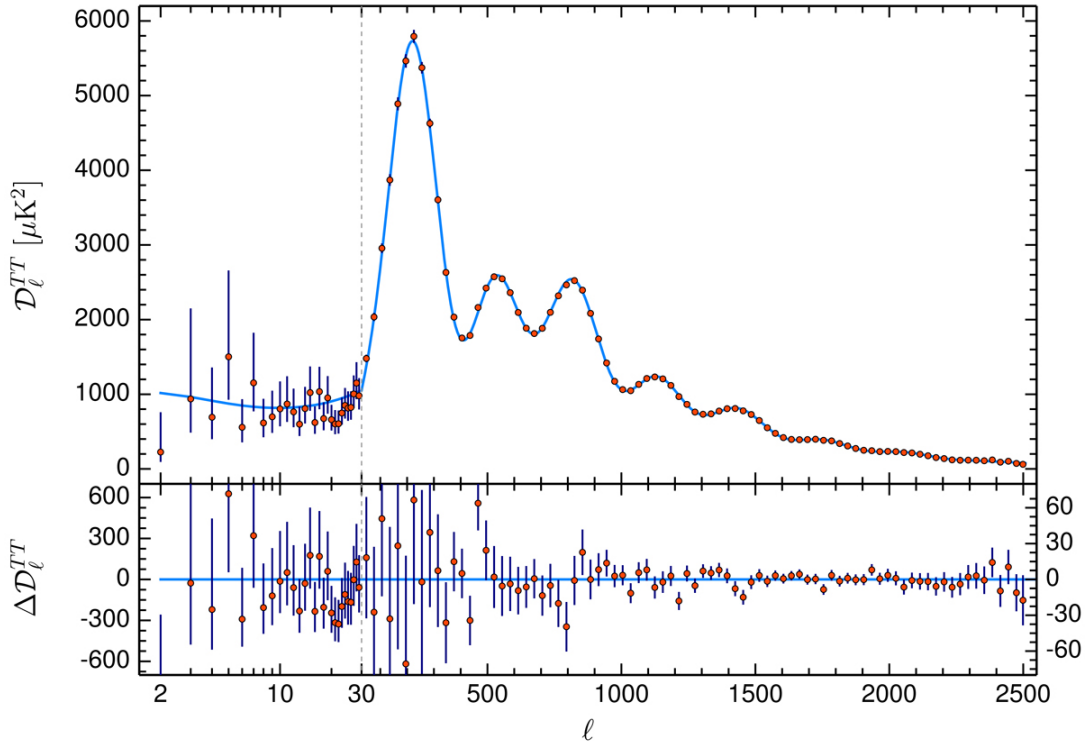
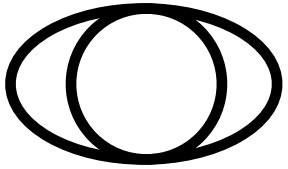
The BAO standard ruler





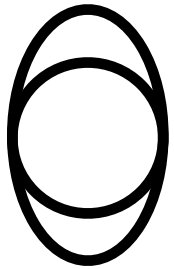
The same BAO features are also measured in the CMB!

Scaling parameters



perpendicular ruler size

$$\alpha_{\perp} = \frac{D_{\mathrm{M}}}{r_{\mathrm{d}}} \frac{r_{\mathrm{d}}^{\mathrm{fid}}}{D_{\mathrm{M}}^{\mathrm{fid}}} \quad \text{and} \quad \alpha_{||} = \frac{D_{\mathrm{H}}}{r_{\mathrm{d}}} \frac{r_{\mathrm{d}}^{\mathrm{fid}}}{D_{\mathrm{H}}^{\mathrm{fid}}}$$



line-of-sight ruler size

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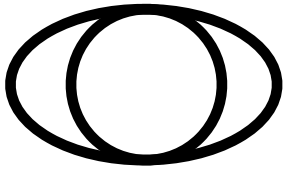
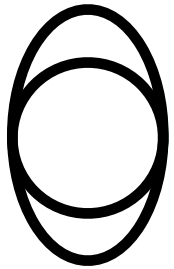
Scaling parameters



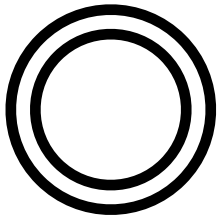
$$\alpha_{\perp} = \frac{D_{\mathrm{M}}}{r_{\mathrm{d}}} \frac{r_{\mathrm{d}}^{\mathrm{fid}}}{D_{\mathrm{M}}^{\mathrm{fid}}} \quad \text{and} \quad \alpha_{||} = \frac{D_{\mathrm{H}}}{r_{\mathrm{d}}} \frac{r_{\mathrm{d}}^{\mathrm{fid}}}{D_{\mathrm{H}}^{\mathrm{fid}}}$$



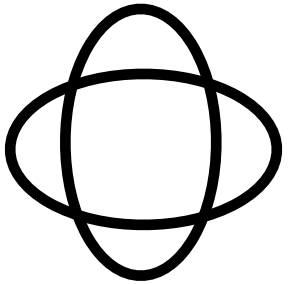
perpendicular ruler size

line-of-sight ruler size

OR



$$\alpha_{\mathrm{iso}} = \left(\alpha_{\perp}^{2} \alpha_{||}\right)^{1/3} \quad \text{and} \quad \alpha_{\mathrm{AP}} = \frac{D_{\mathrm{H}}}{D_{\mathrm{M}}} \frac{D_{\mathrm{M}}^{\mathrm{fid}}}{D_{\mathrm{H}}^{\mathrm{fid}}}$$



overall scale of BAO

anisotropy of BAO

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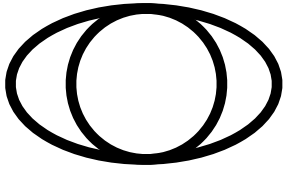
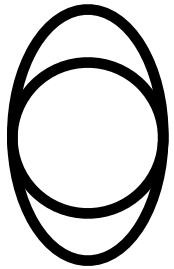
Scaling parameters



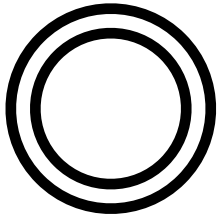
perpendicular ruler size

$$\alpha_{\perp} = \frac{D_{\rm M}}{r_{\rm d}} \frac{r_{\rm d}^{\rm fid}}{D_{\rm M}^{\rm fid}} \quad \text{and} \quad \alpha_{||} = \frac{D_{\rm H}}{r_{\rm d}} \frac{r_{\rm d}^{\rm fid}}{D_{\rm H}^{\rm fid}}$$



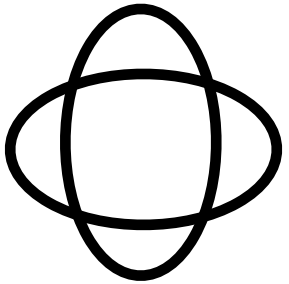
line-of-sight ruler size

OR



overall scale of BAO

$$\alpha_{\rm iso} = \left(\alpha_{\perp}^2 \alpha_{||}\right)^{1/3} \quad \text{and} \quad \alpha_{\rm AP} = \frac{D_{\rm H}}{D_{\rm M}} \frac{D_{\rm M}^{\rm fid}}{D_{\rm H}^{\rm fid}}$$



anisotropy of BAO

OR

just $\alpha_{\rm iso} = \left(\alpha_{\perp}^2 \alpha_{||}\right)^{1/3}$ (if SNR is low)

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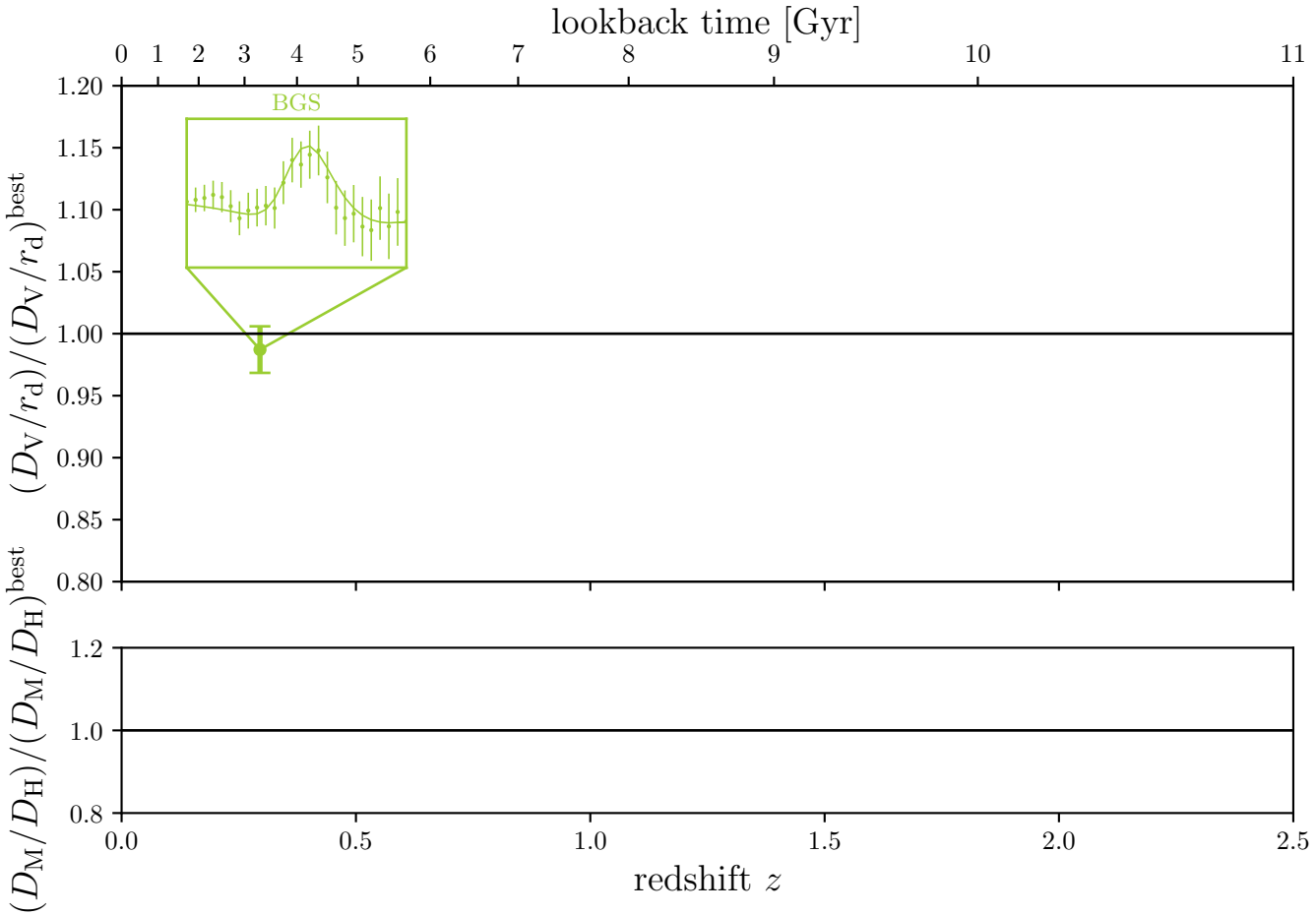
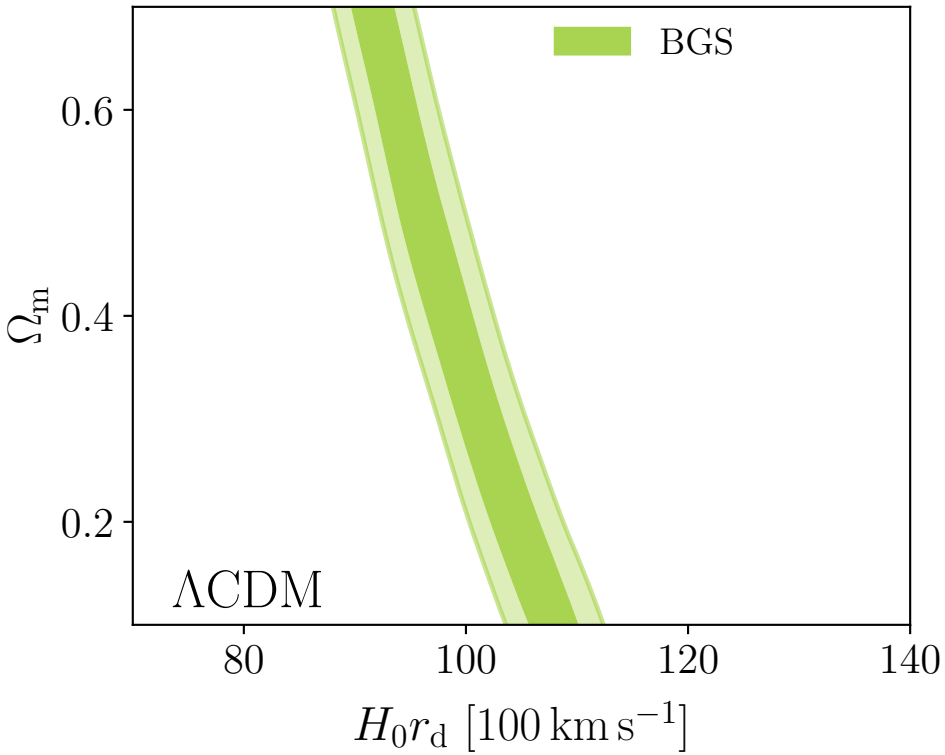
DESI Y1 BAO





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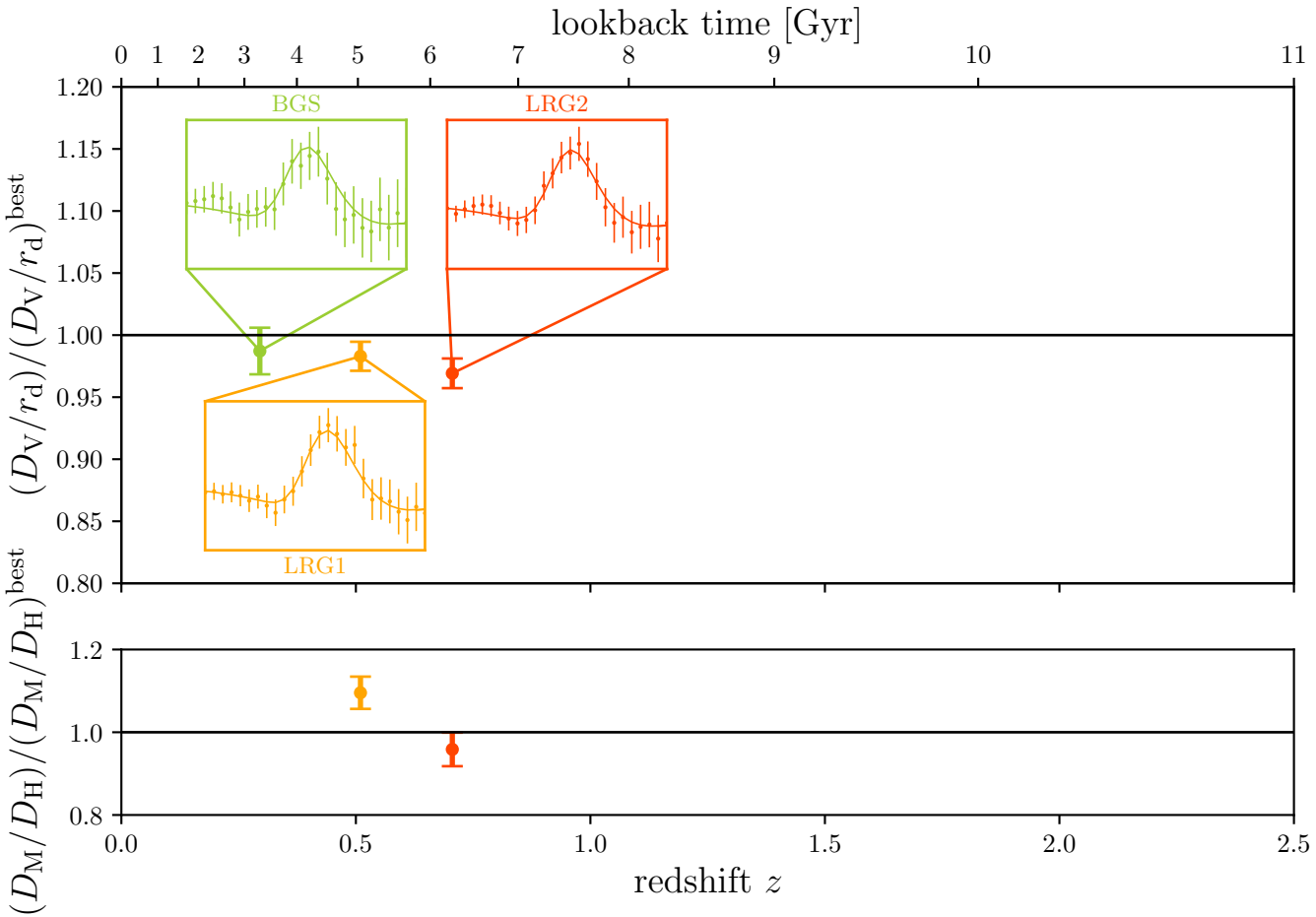
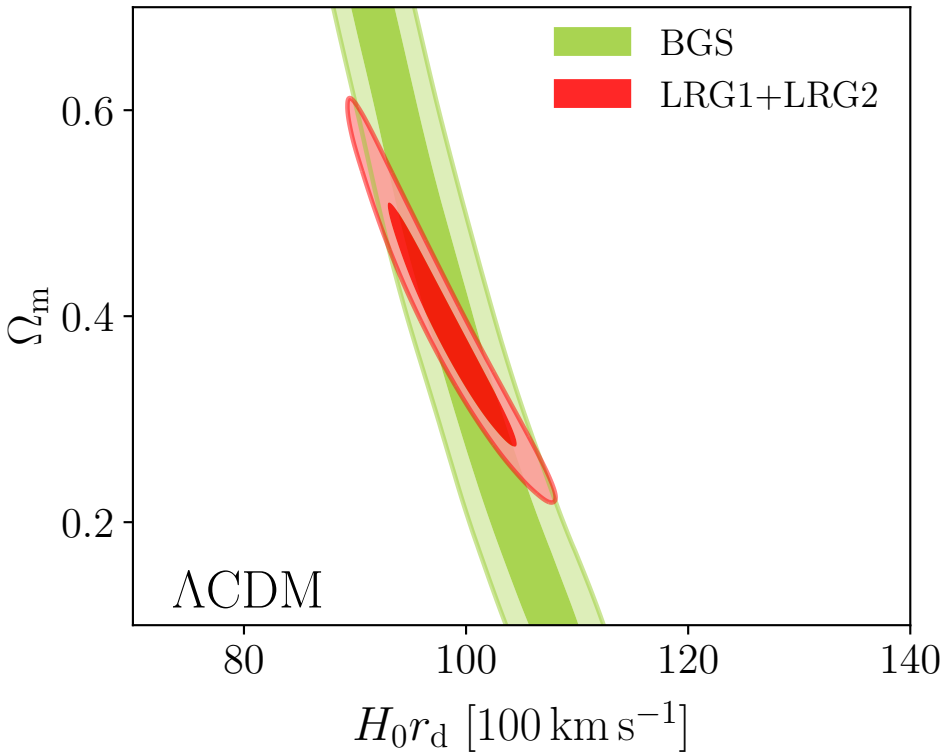
DESI Y1 BAO





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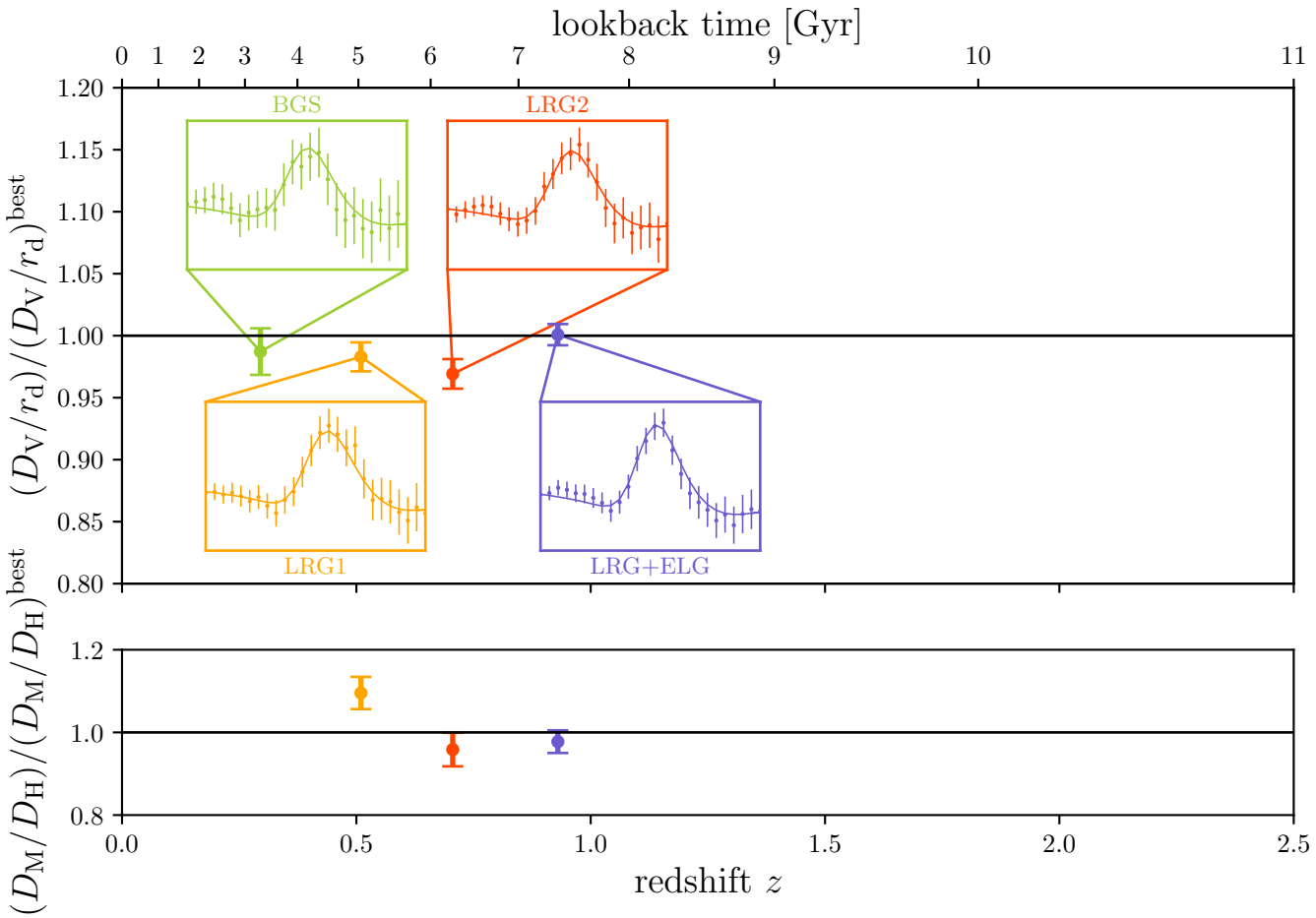
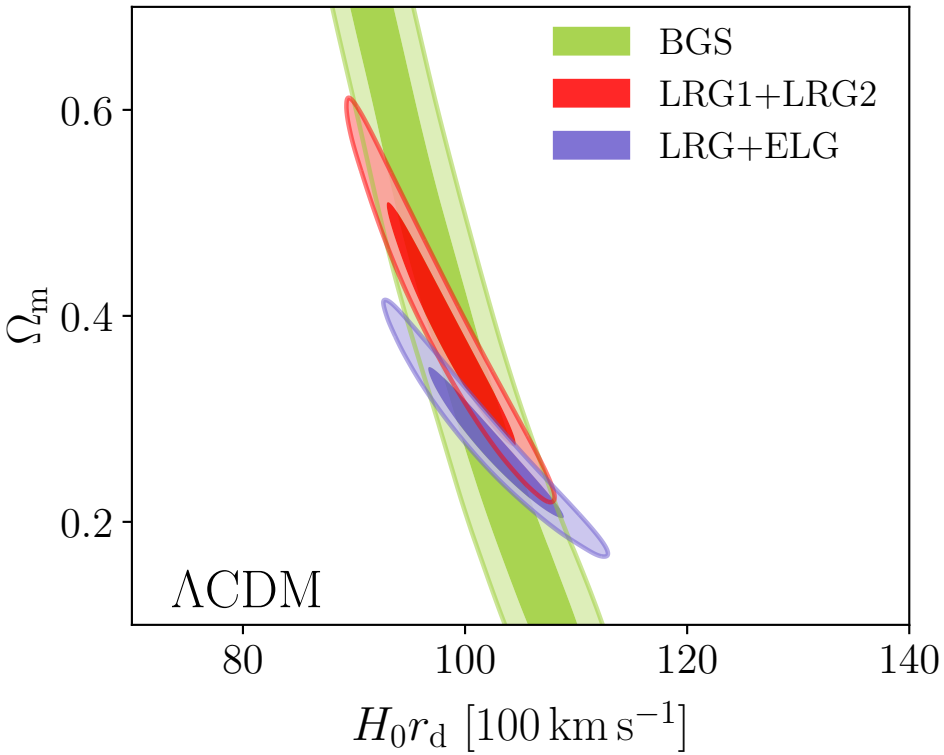
DESI Y1 BAO

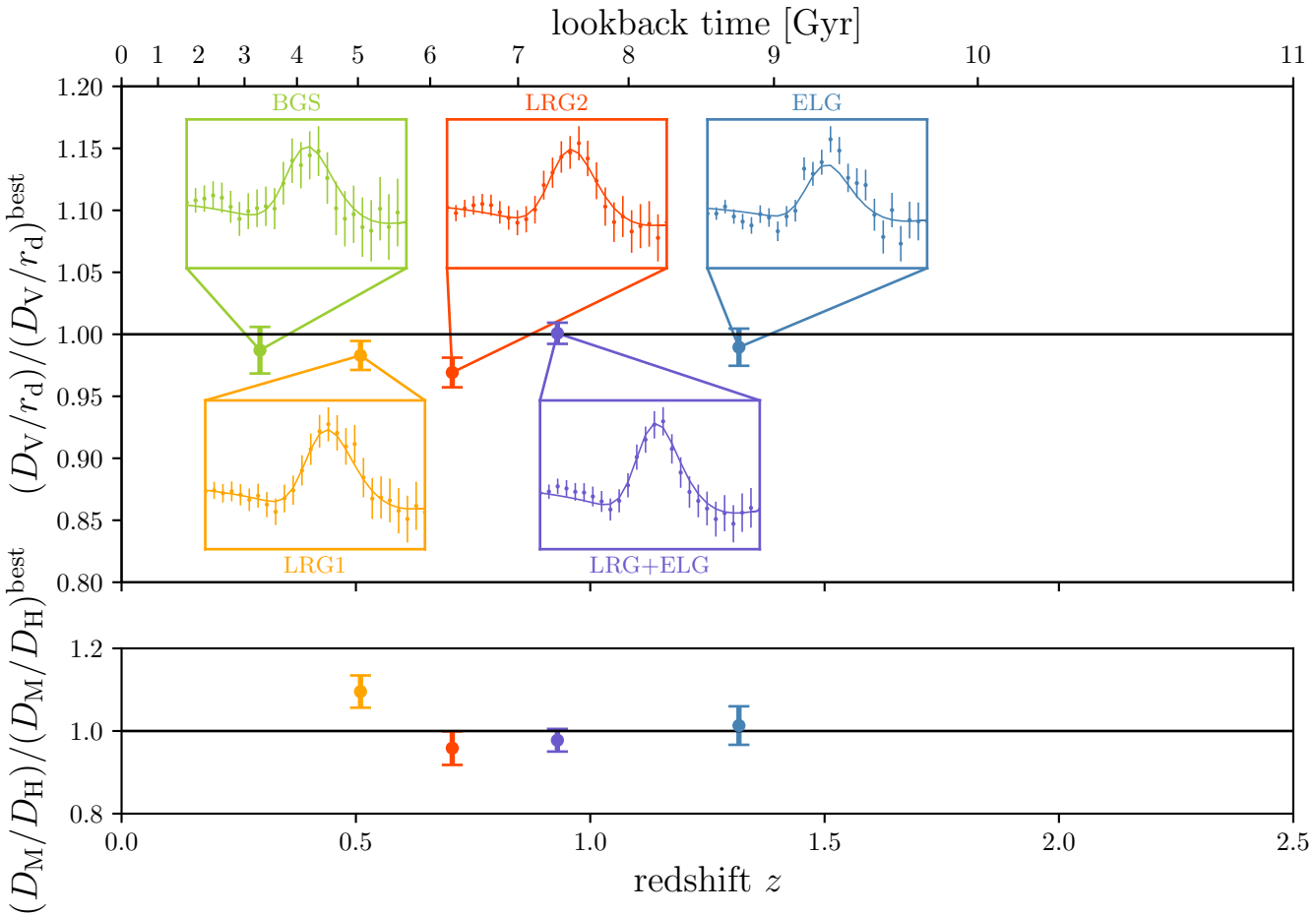


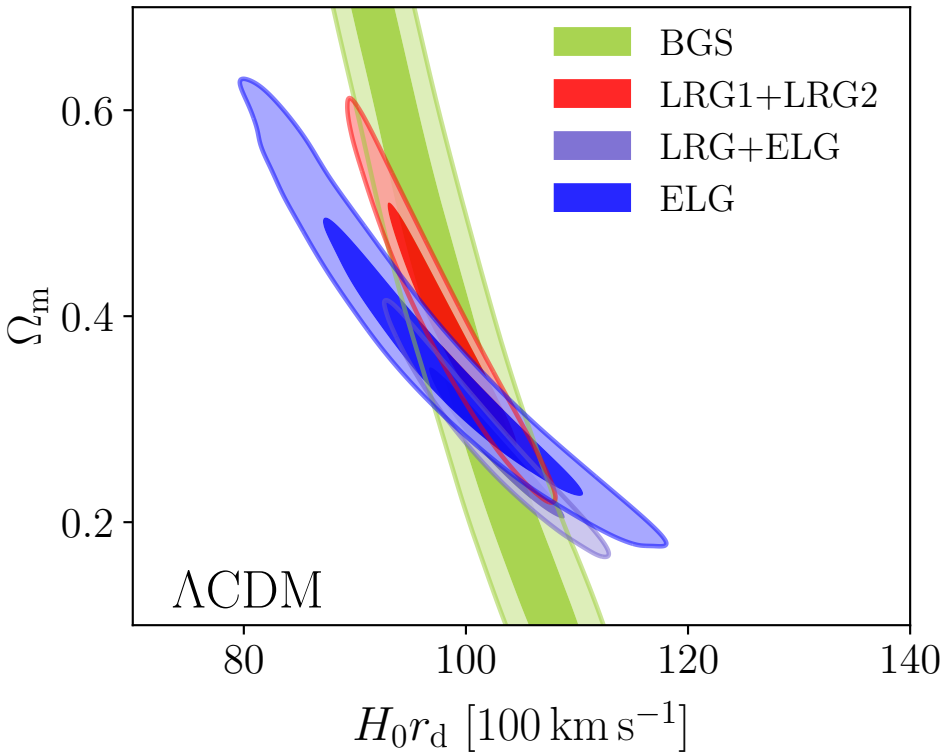


DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Y1 BAO

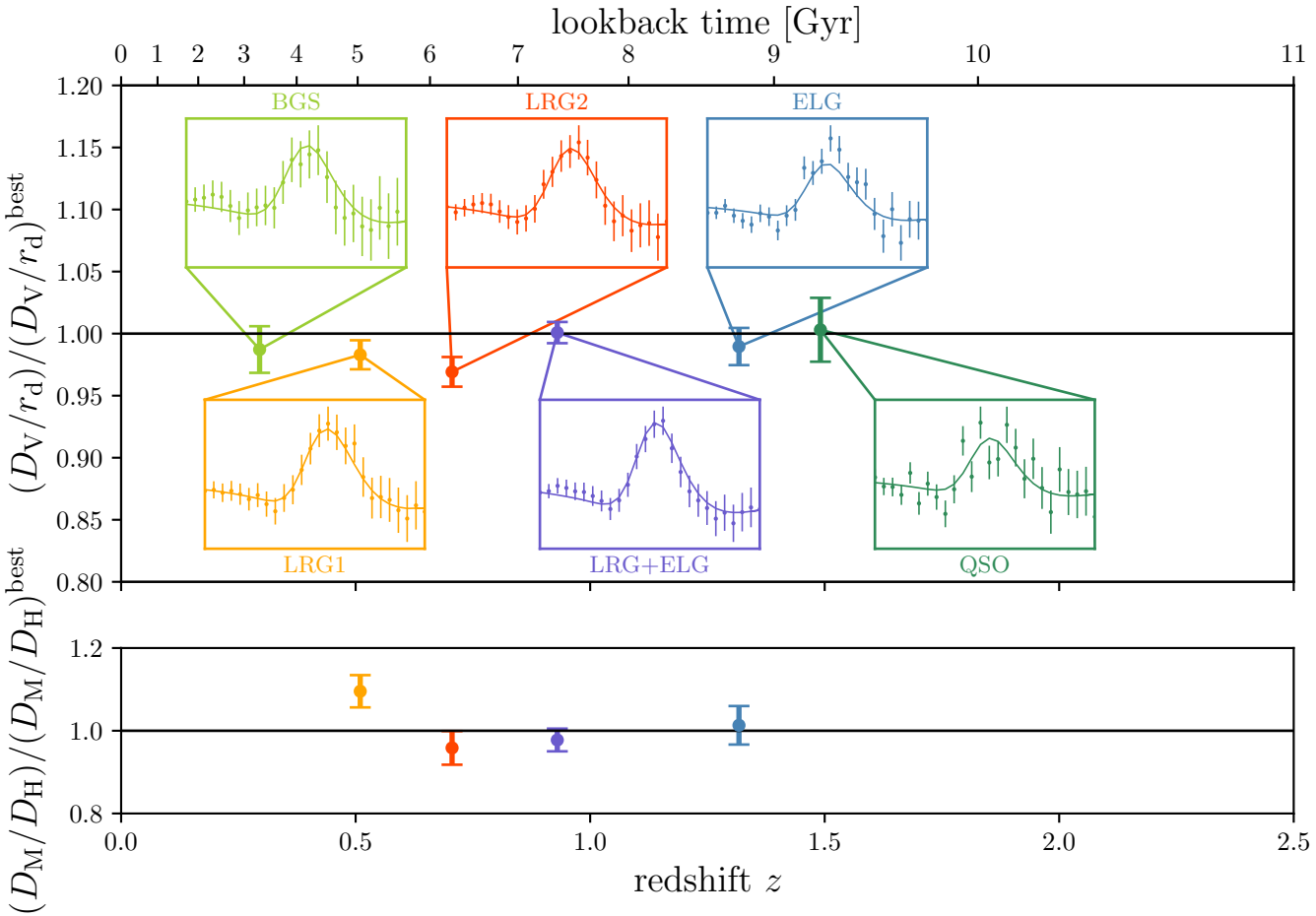


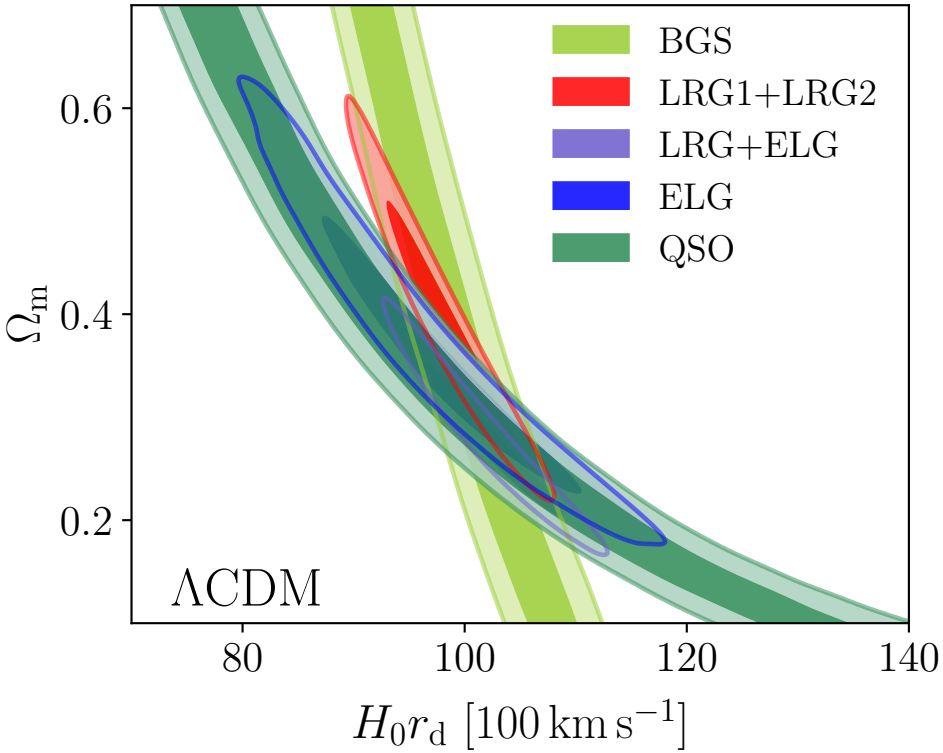


DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI Y1 BAO

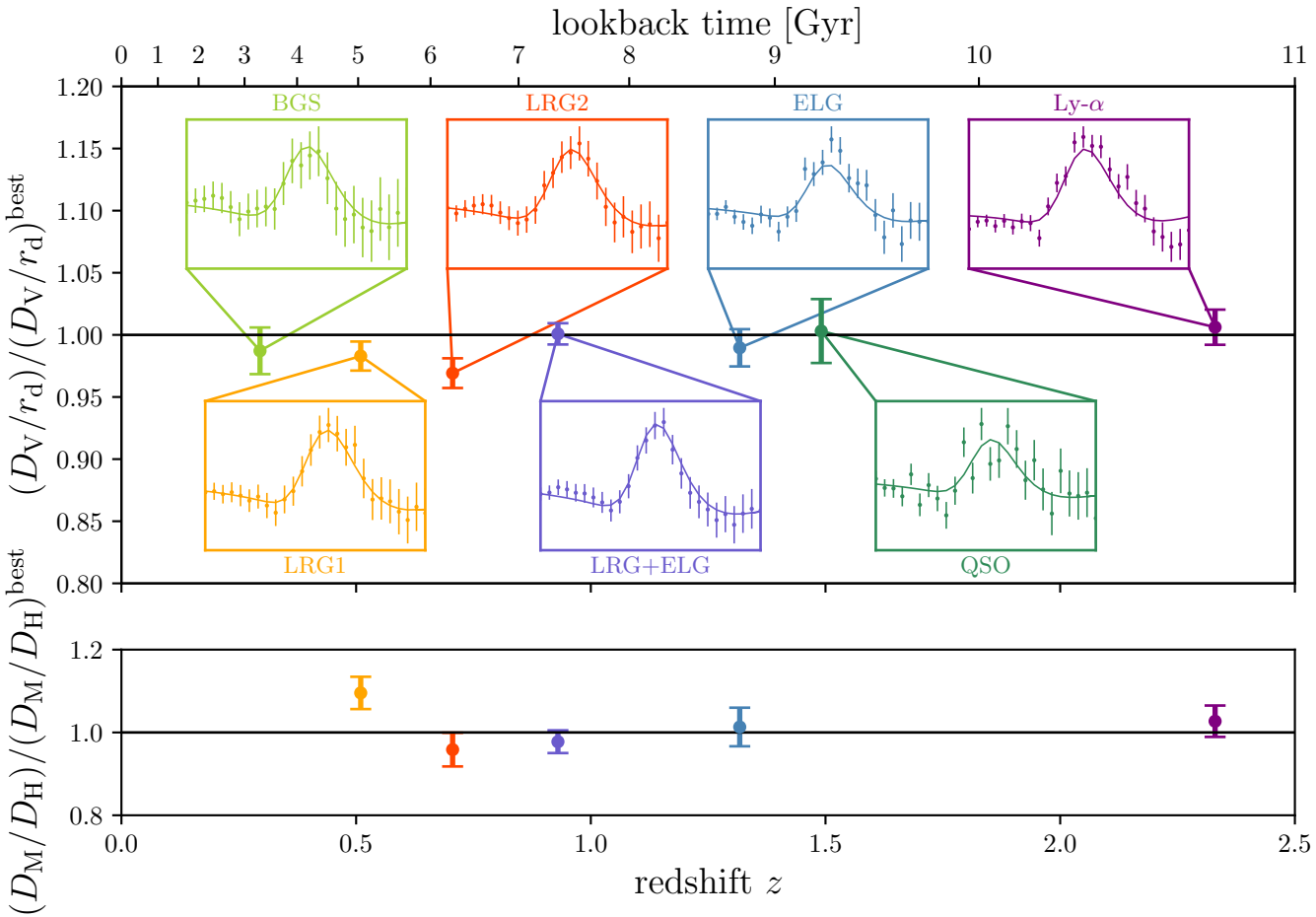


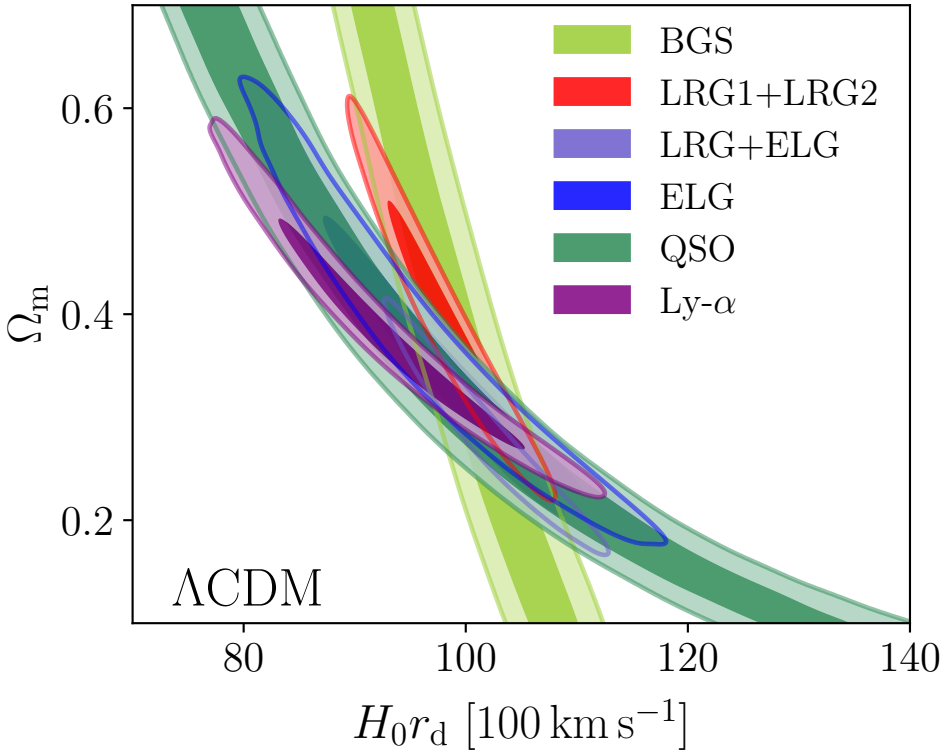


DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

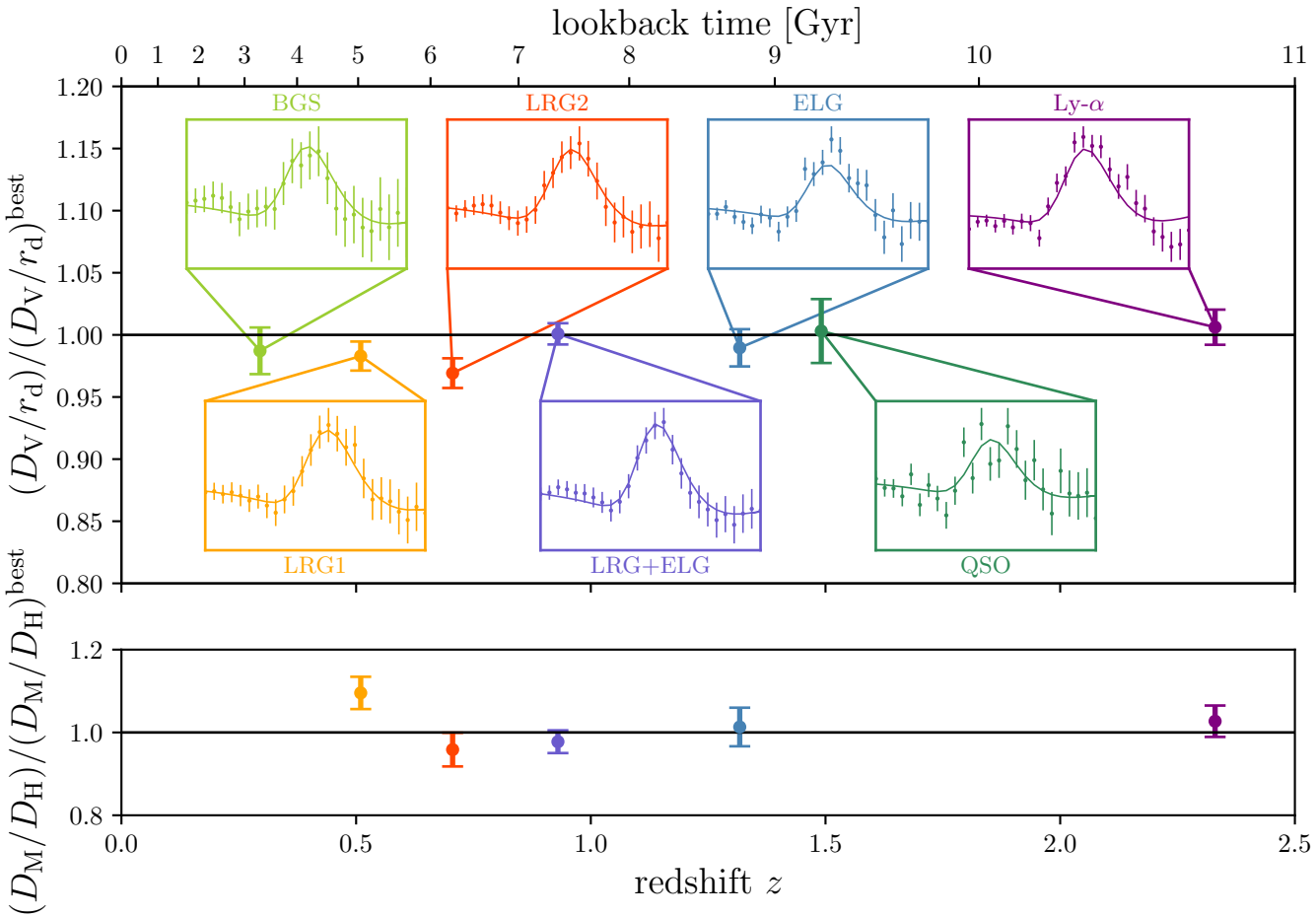
DESI Y1 BAO

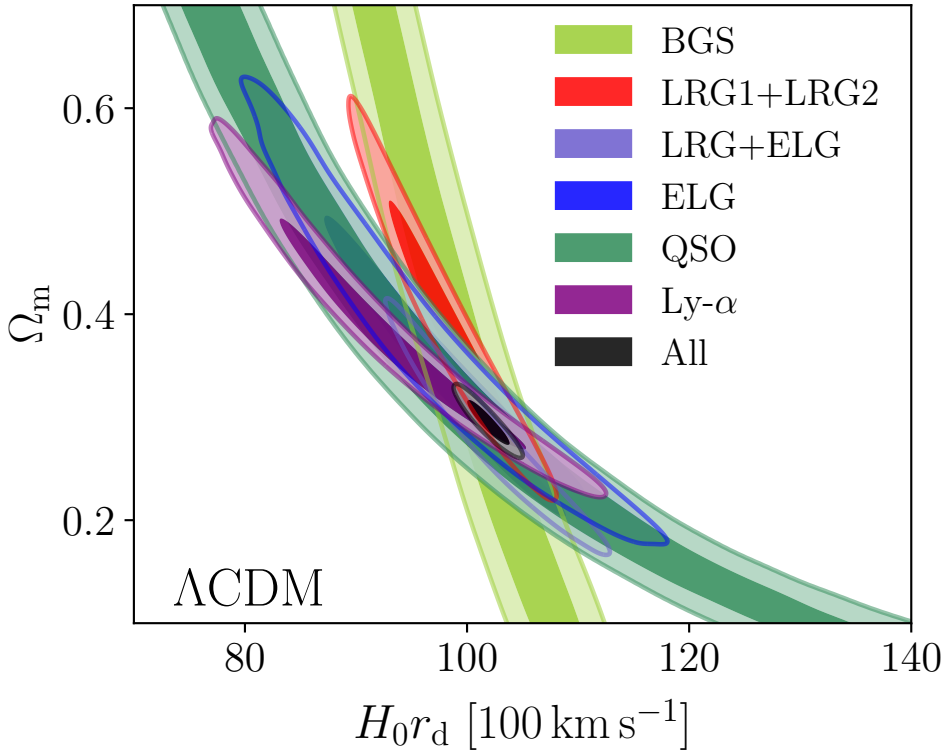




DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

DESI Y1 BAO





DARK ENERGY SPECTROSCOPIC INSTRUMENT
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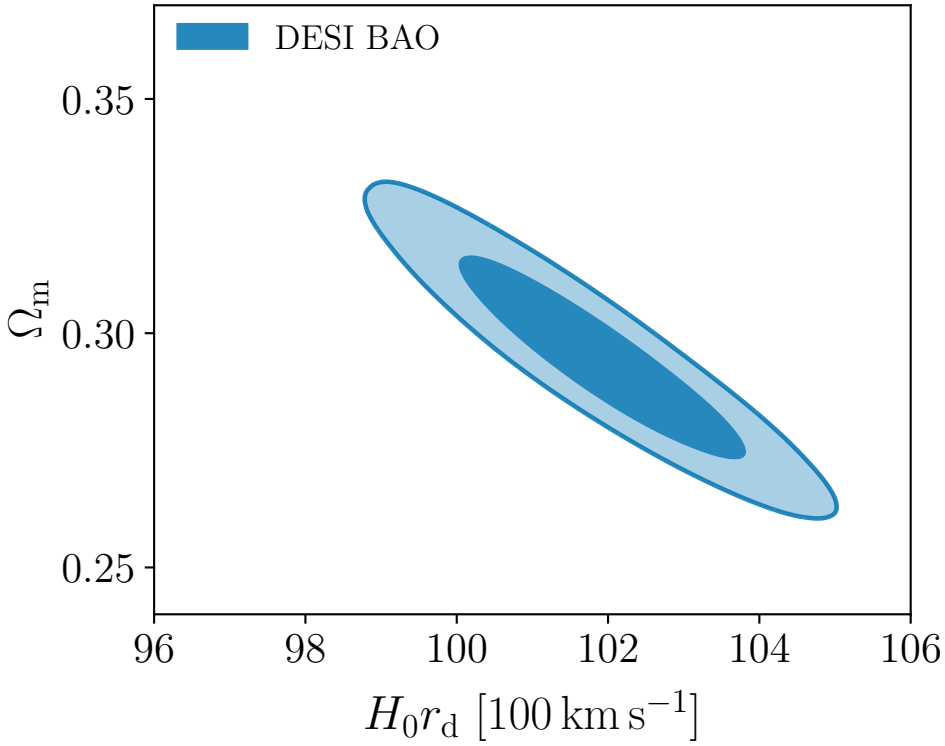
Consistency with other probes

DESI Y1 BAO consistent with:

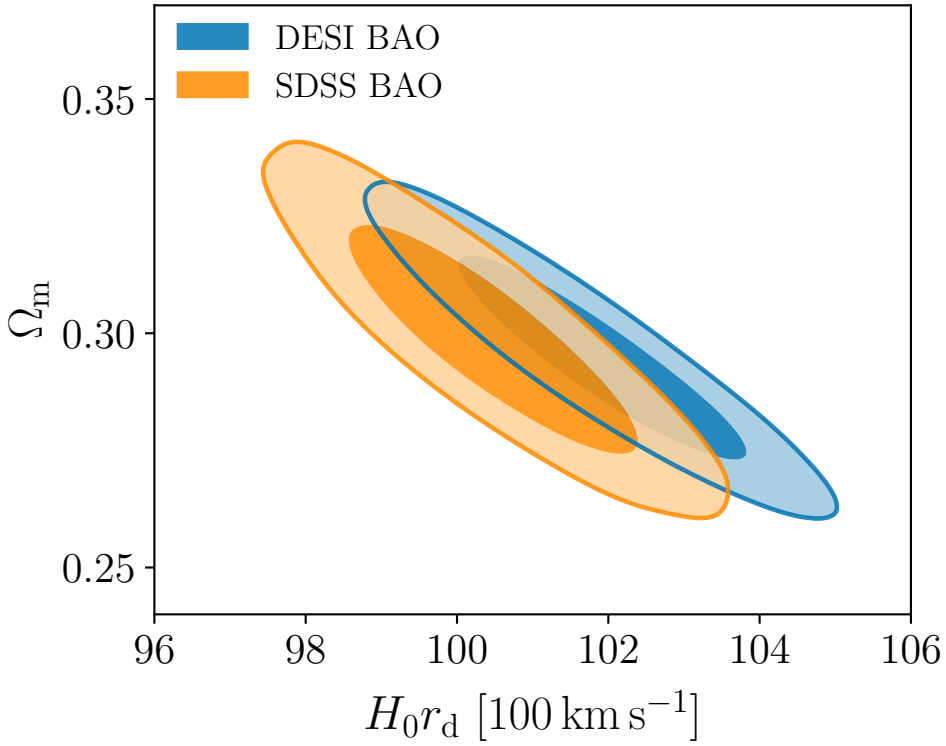


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Consistency with other probes

DESI Y1 BAO consistent with:

- SDSS (eBOSS Collaboration, 2020)



DARK ENERGY SPECTROSCOPIC INSTRUMENT
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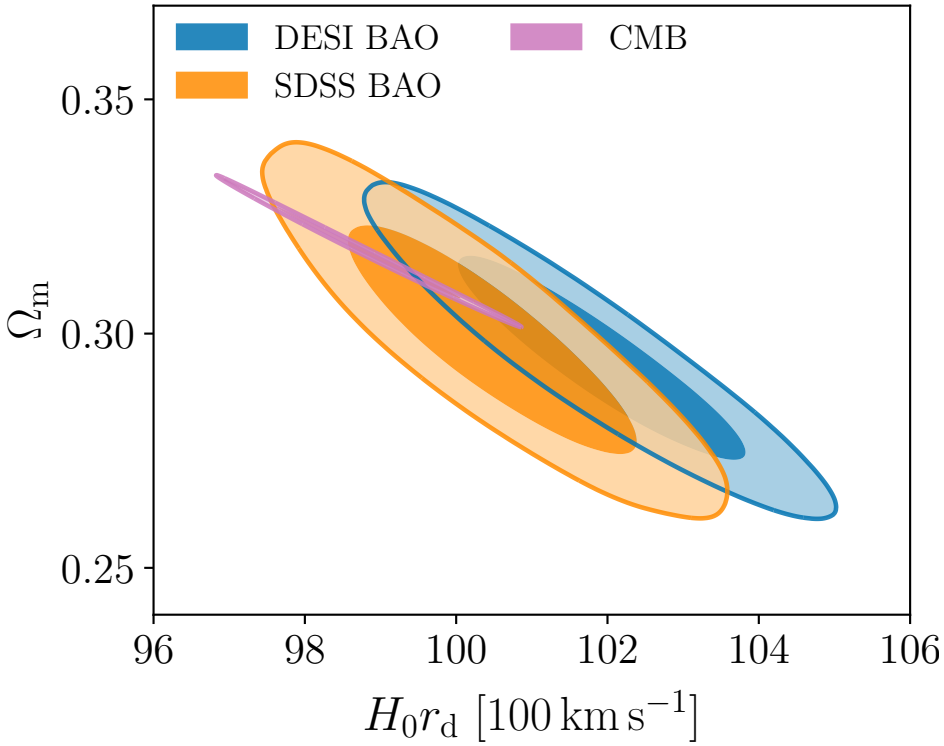
Consistency with other probes

DESI Y1 BAO consistent with:

- SDSS (eBOSS Collaboration, 2020)
- primary CMB: Planck Collaboration, 2018 and CMB lensing: Planck PR4 + ACT DR6 lensing ACT Collaboration, 2023, Carron, Mirmelstein, Lewis, 2022



DARK ENERGY SPECTROSCOPIC INSTRUMENT
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Consistency with other probes

KASI UST

DESI Y1 BAO consistent with:

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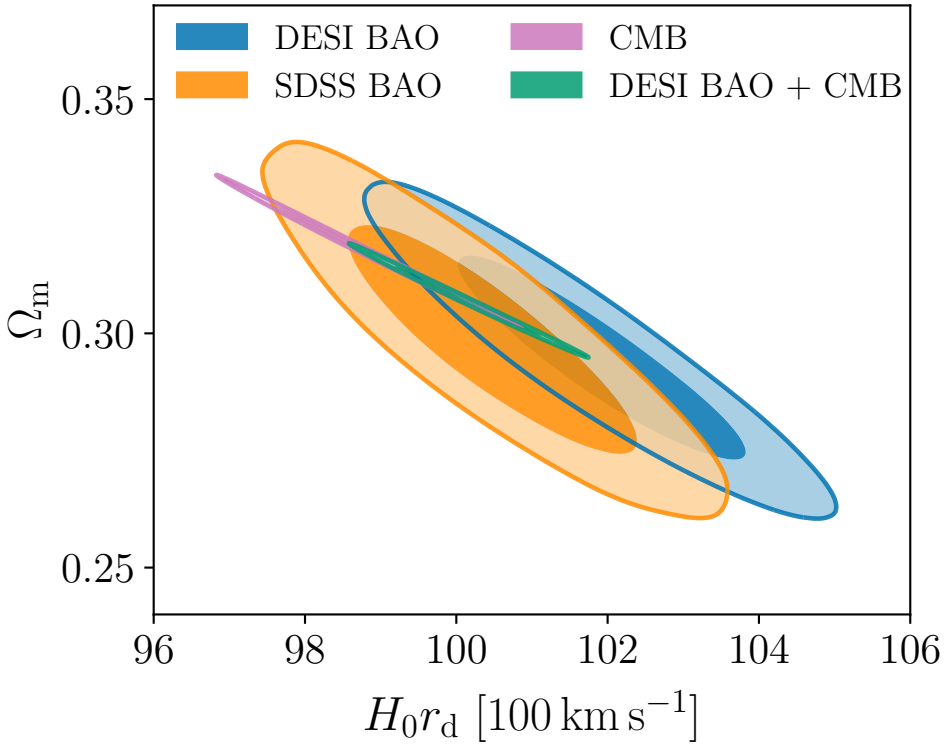
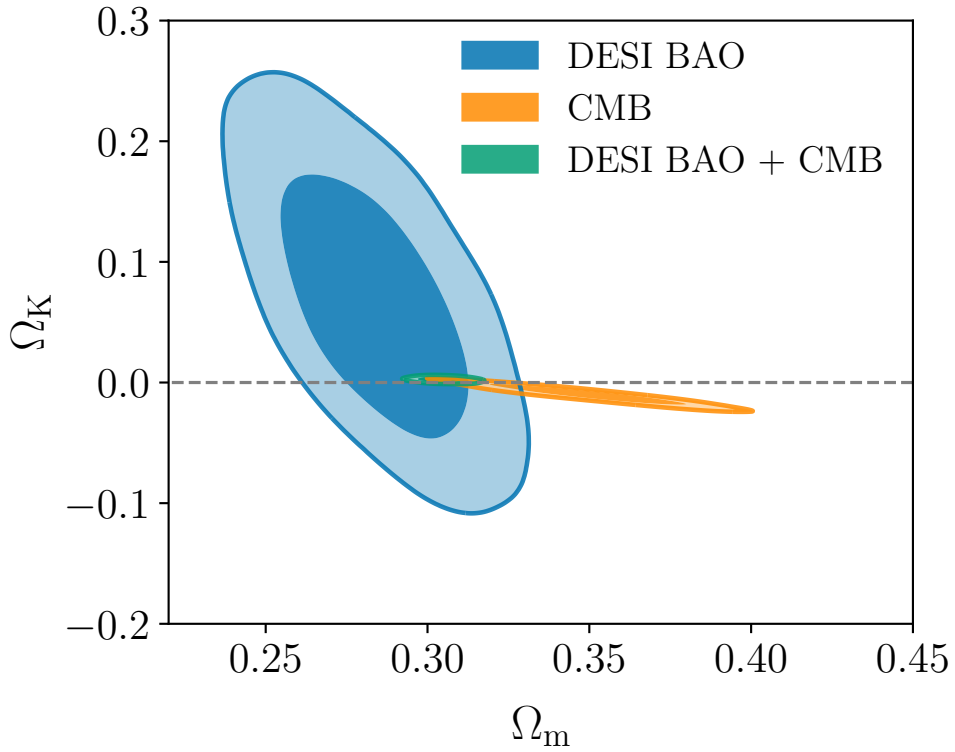


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Spatial curvature

DESI + CMB measurements favour a flat Universe

$$\Omega_K = 0.0024 \pm 0.0016$$ (DESI + CMB)



DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

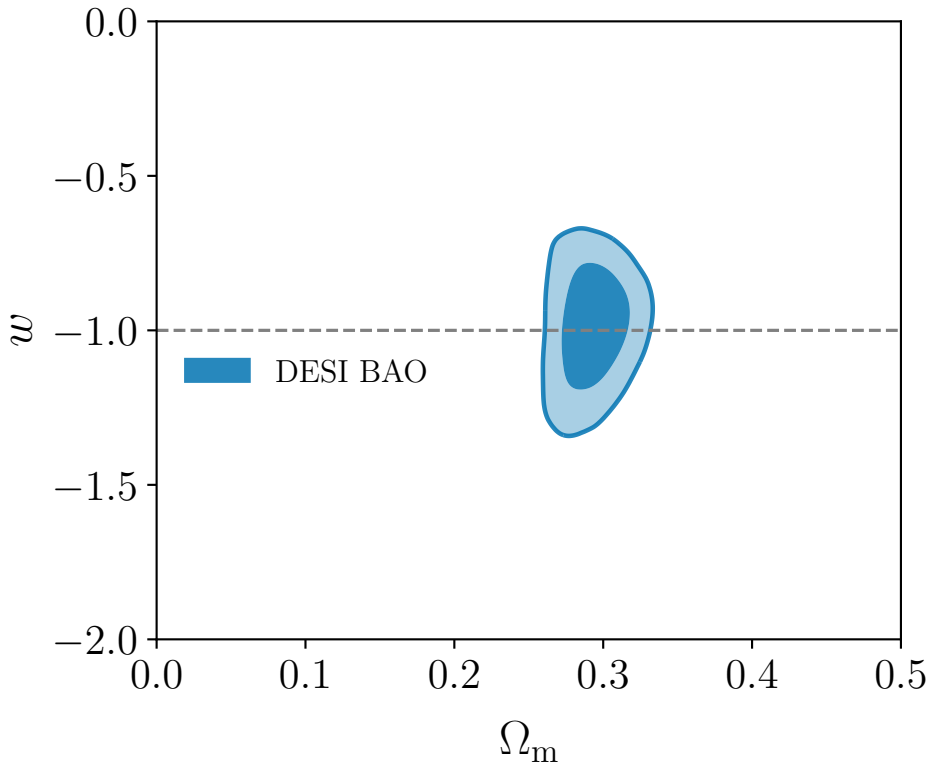
Dark Energy Equation of State

DESI

Constant EoS parameter w

$$\Omega_m = 0.293 \pm 0.015$$

$$w = -0.99^{+0.15}_{-0.13}$$



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

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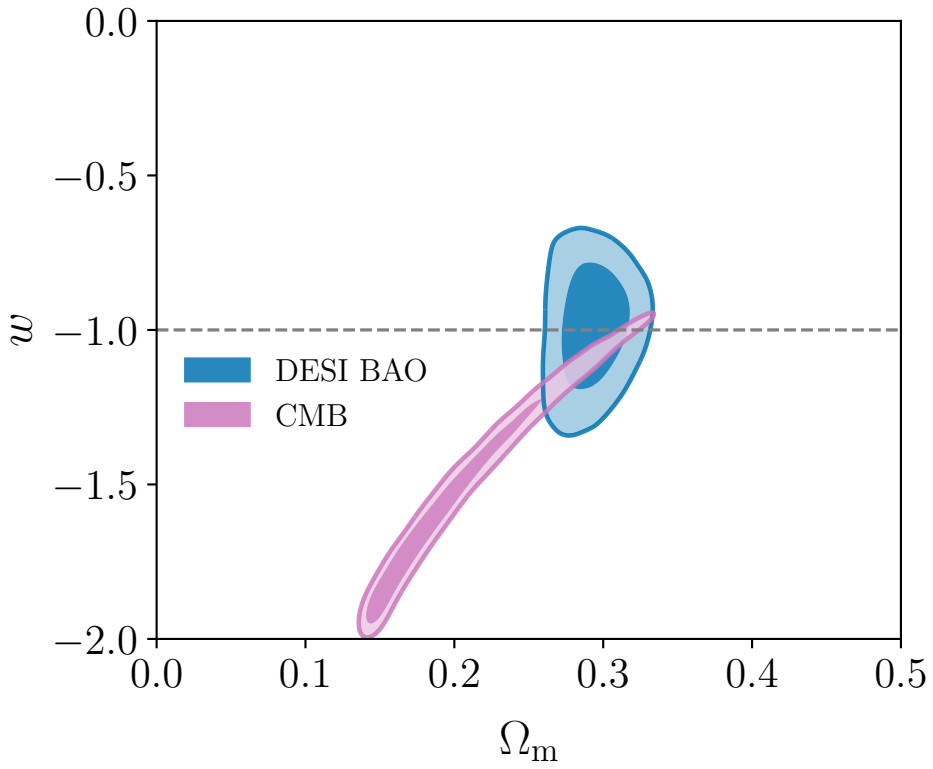


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Dark Energy Equation of State

DESI

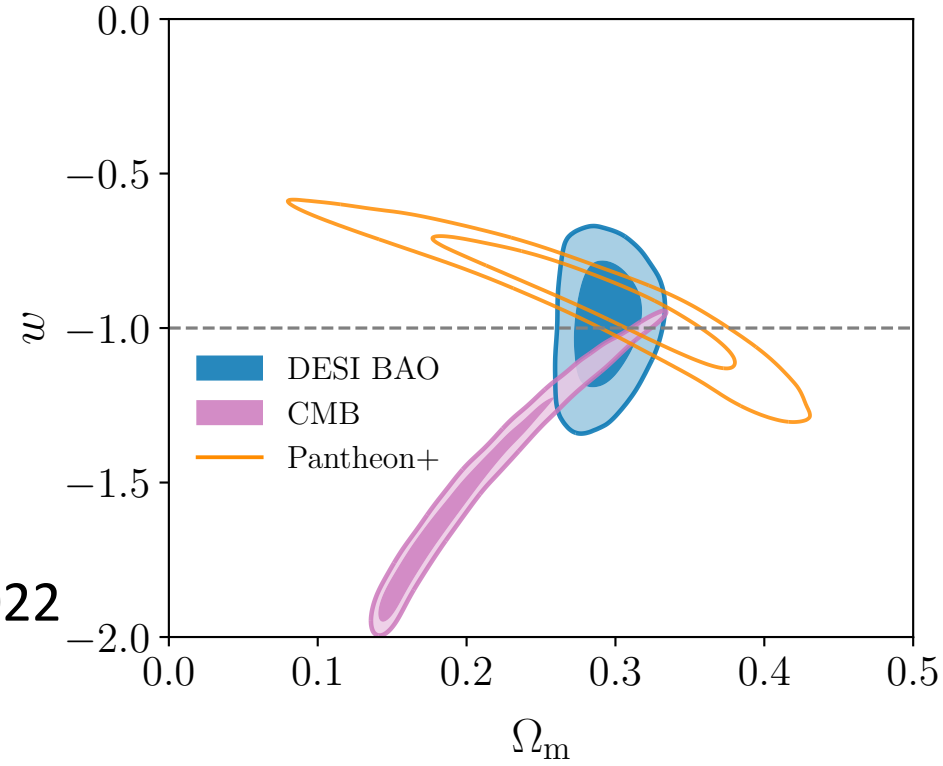
Constant EoS parameter w

$$\Omega_m = 0.293 \pm 0.015$$

$$w = -0.99^{+0.15}_{-0.13}$$

SNe:

- Pantheon+ Brout, Scolnic, Popovic et al., 2022



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

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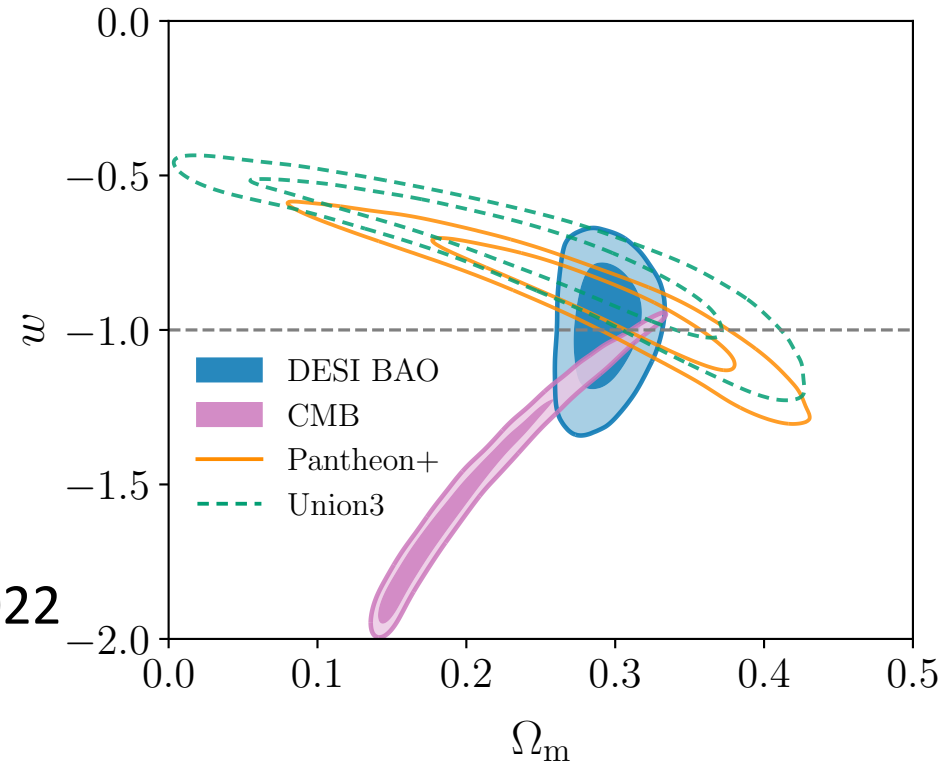

SNe:

- Pantheon+ Brout, Scolnic, Popovic et al., 2022
- Union3 Rubin, Aldering, Betoule et al. 2023

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

Dark Energy Equation of State

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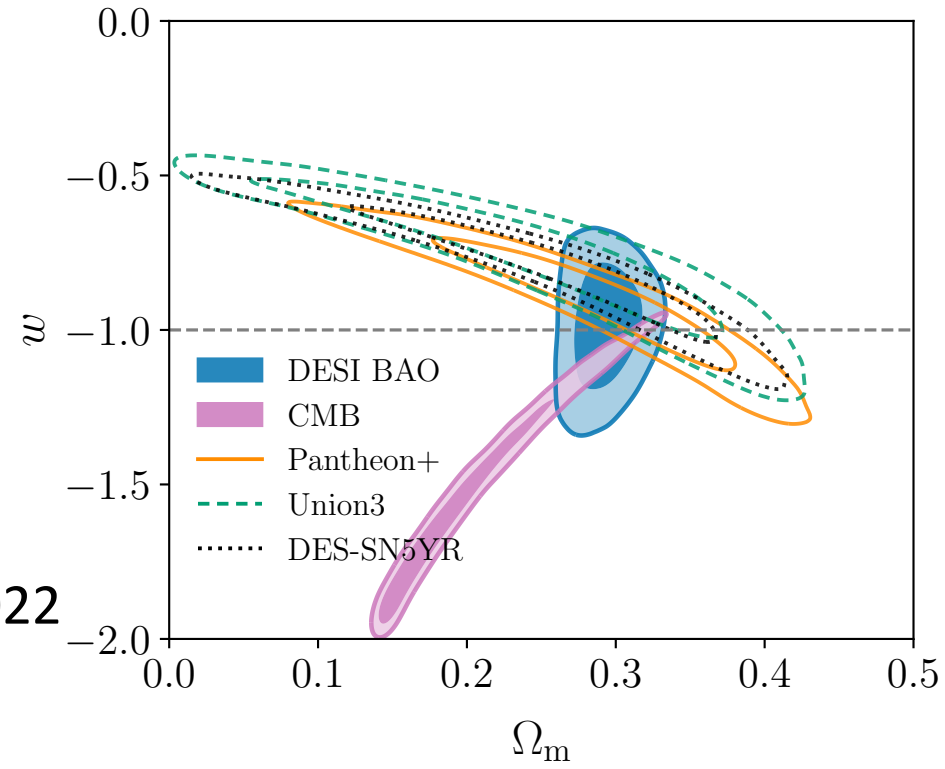


SNe:

- Pantheon+ Brout, Scolnic, Popovic et al., 2022
- Union3 Rubin, Aldering, Betoule et al. 2023
- DES-SN5YR DES Collaboration et al. 2024

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

Dark Energy Equation of State

DESI

Constant EoS parameter w

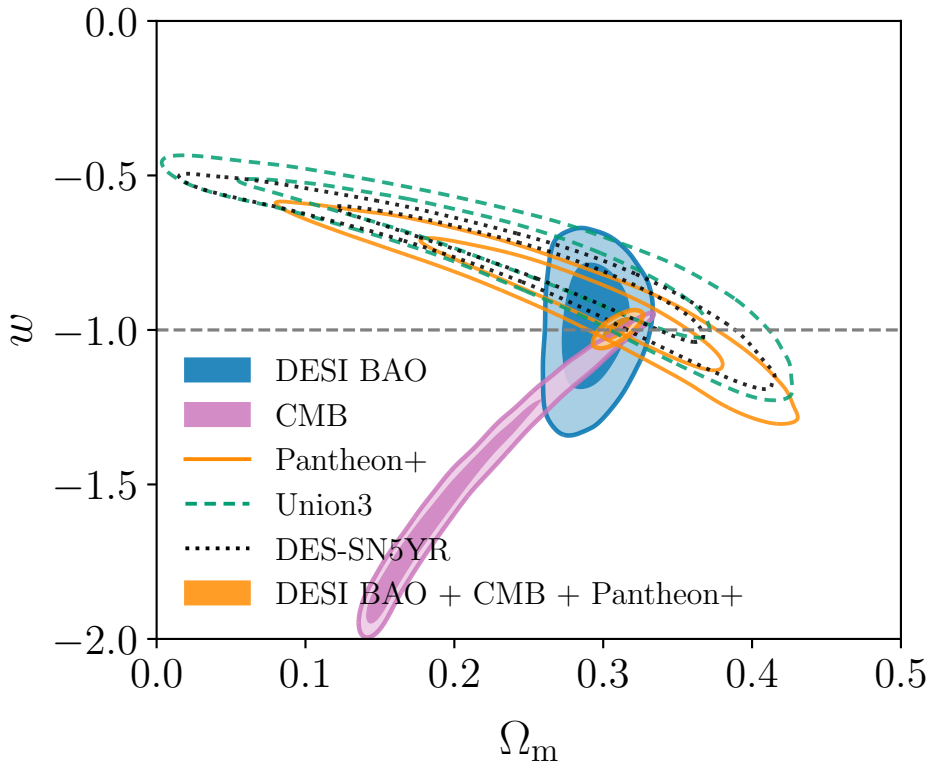
$$\Omega_m = 0.293 \pm 0.015$$

$$w = -0.99^{+0.15}_{-0.13}$$

DESI + CMB + Pantheon+

$$\Omega_m = 0.2095 \pm 0.0065$$

$$w = -0.997 \pm 0.025$$



Assuming a constant EoS, DESI BAO fully compatible with a cosmological constant...

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

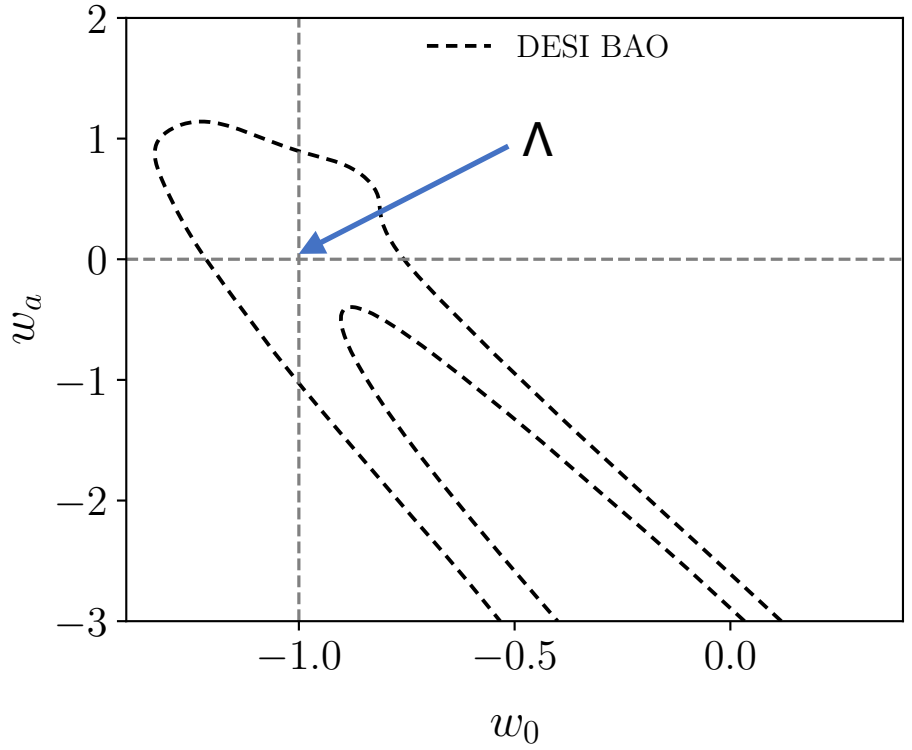
Dark Energy Equation of State

KASI UST

Varying EoS

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

$$w_0 = -0.55^{+0.39}_{-0.21} \qquad w_a < -1.32$$



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

Dark Energy Equation of State

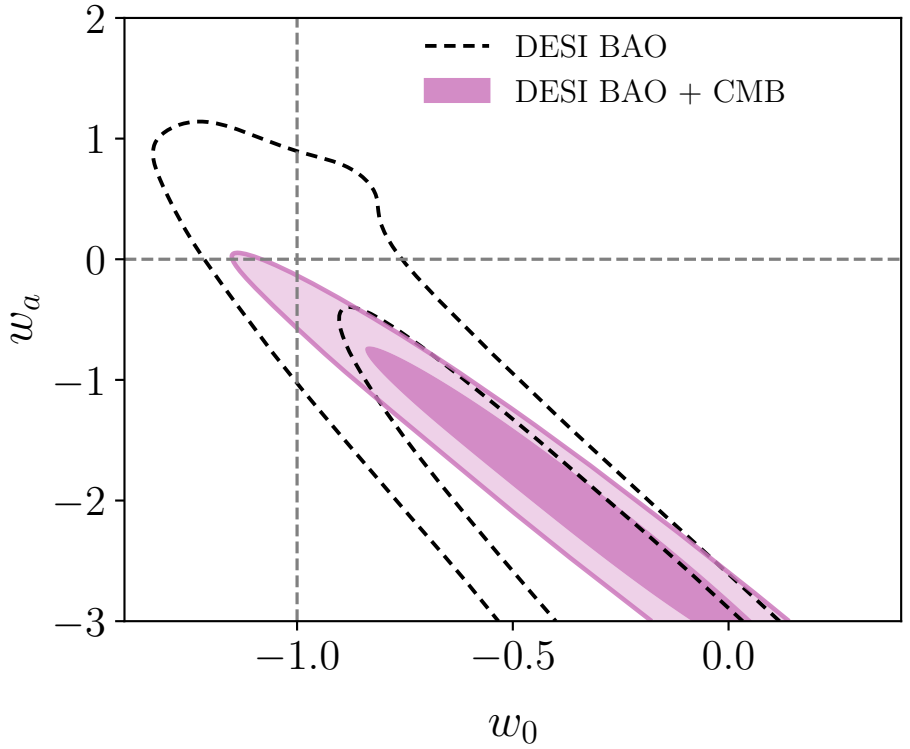
KASI UST

Varying EoS

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

DESI + CMB ⟹ 2.6σ

$$w_0 = -0.45^{+0.34}_{-0.21} \qquad w_a = -1.79^{+0.48}_{-1.0}$$



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

Dark Energy Equation of State

KASI UST

Varying EoS

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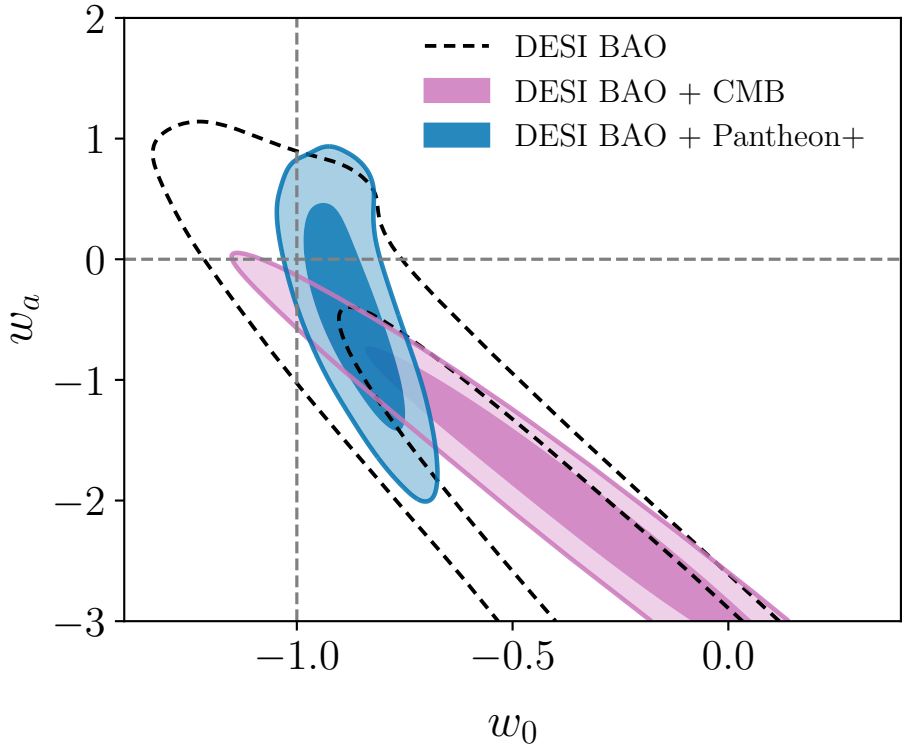

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Dark Energy Equation of State

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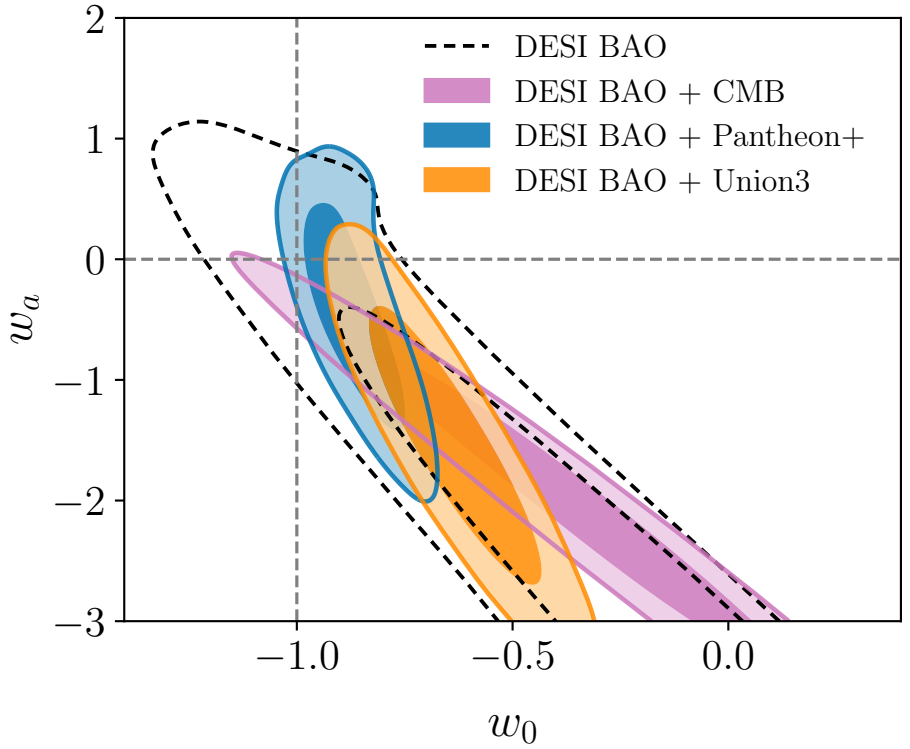

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Dark Energy Equation of State

KASI UST

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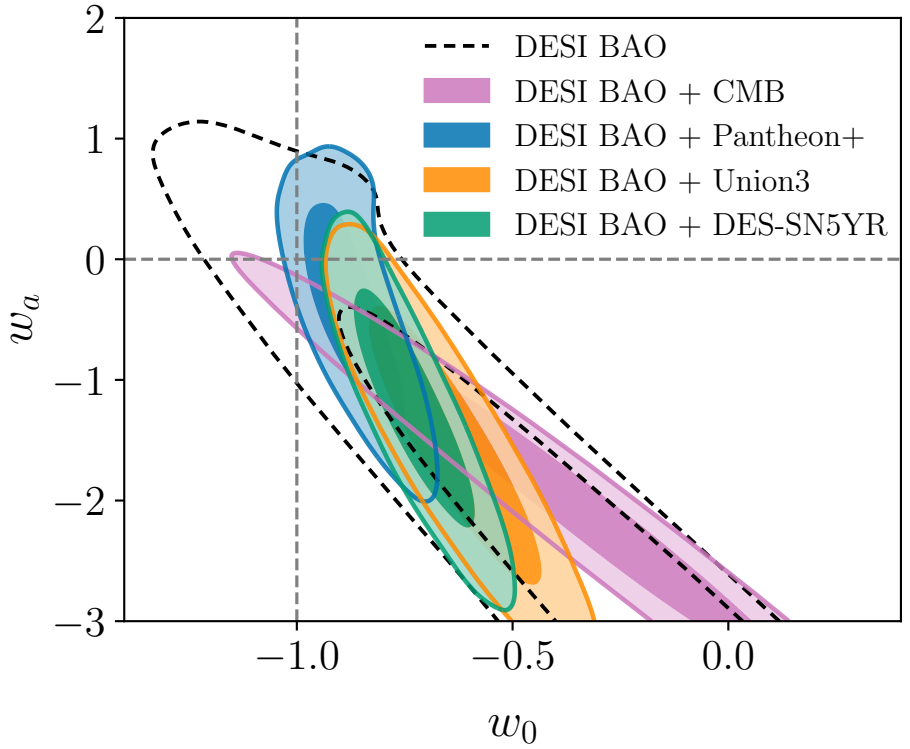


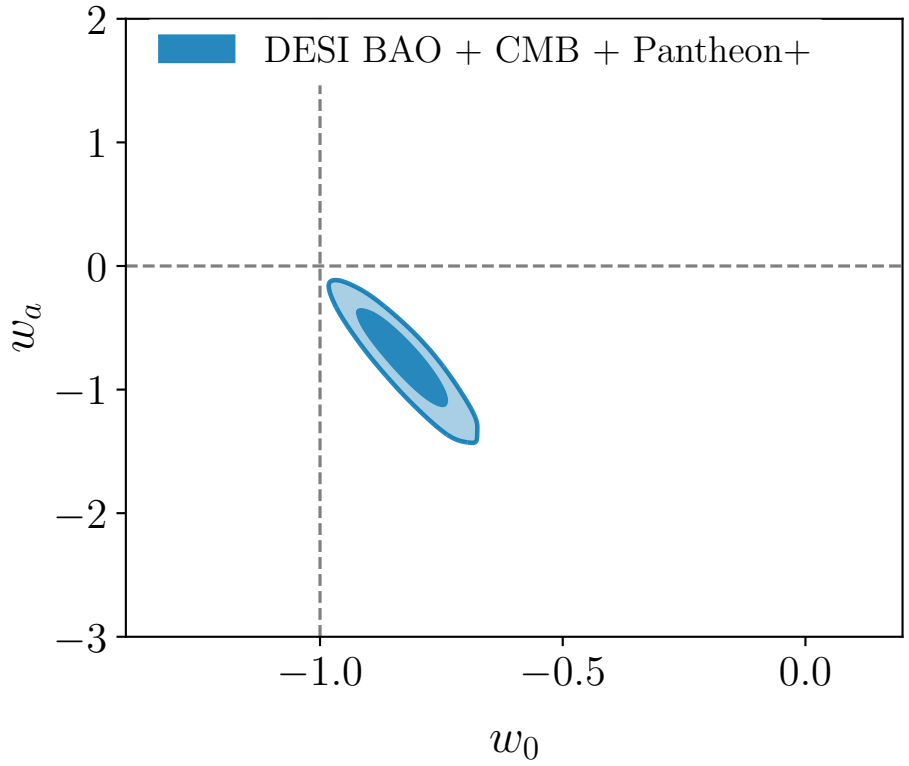
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Dark Energy Equation of State

Combining all DESI + CMB + SN

DESI + CMB + Pantheon+ $\Longrightarrow 2.5\sigma$

$$w_0 = -0.827 \pm 0.063 \qquad w_a = -0.75^{+0.29}_{-0.25}$$



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

Dark Energy Equation of State

KASI UST

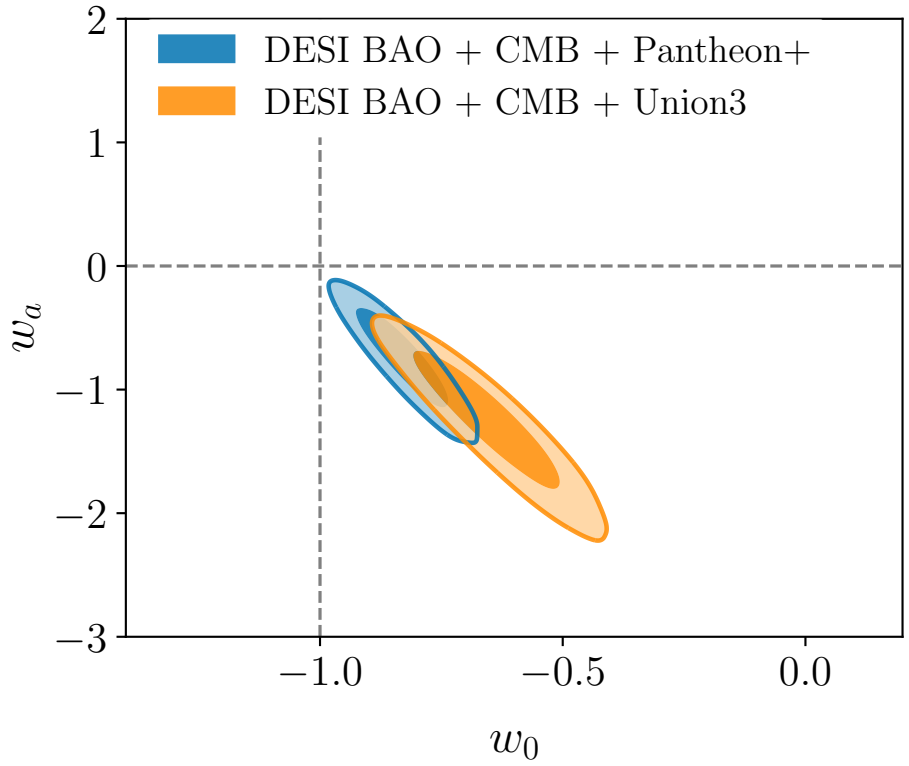
Combining all DESI + CMB + SN

DESI + CMB + Pantheon+ $\Longrightarrow$ 2.5σ

$w_0 = -0.827 \pm 0.063 \qquad w_a = -0.75^{+0.29}_{-0.25}$

DESI + CMB + Union3 $\Longrightarrow$ 3.5σ

$w_0 = -0.64 \pm 0.11 \qquad w_a = -1.27^{+0.40}_{-0.34}$



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

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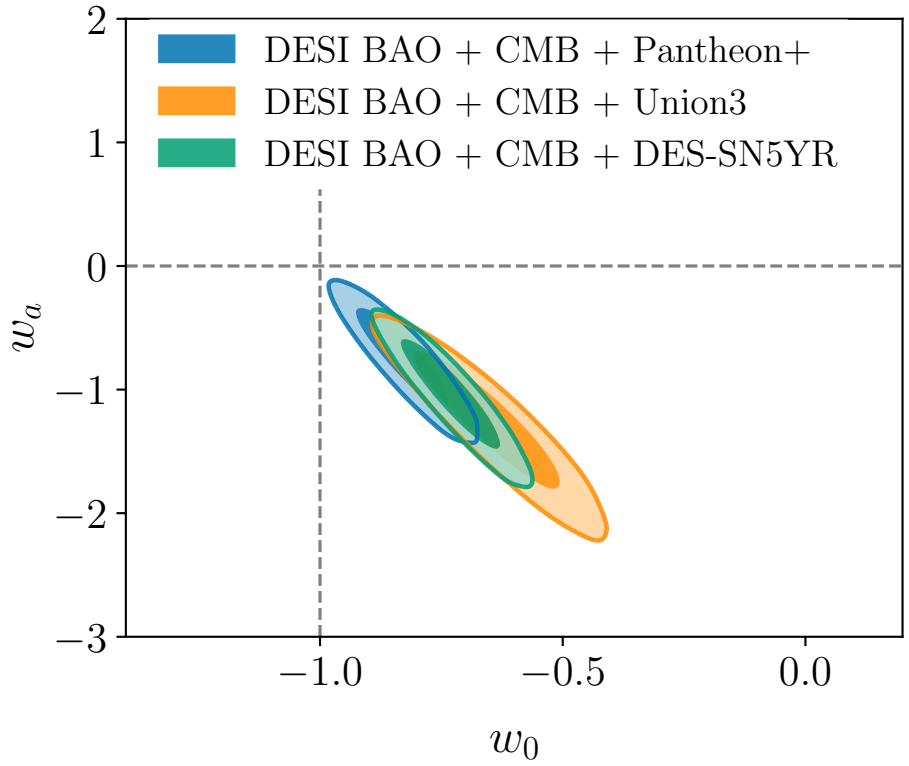


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Dark Energy Equation of State

Combining all DESI + CMB + SN

DESI + CMB + Pantheon+ $\Longrightarrow$ 2.5σ

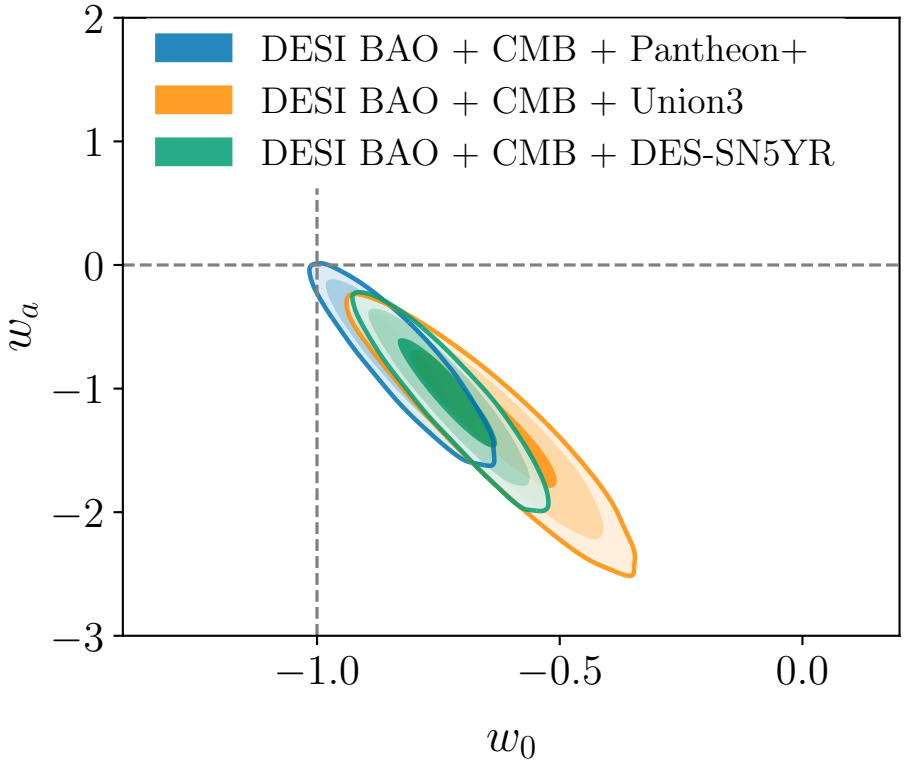
$w_0 = -0.827 \pm 0.063 \qquad w_a = -0.75^{+0.29}_{-0.25}$

DESI + CMB + Union3 $\Longrightarrow$ 3.5σ

$w_0 = -0.64 \pm 0.11 \qquad w_a = -1.27^{+0.40}_{-0.34}$

DESI + CMB + DES-SN5YR $\Longrightarrow$ 3.9σ

$w_0 = -0.727 \pm 0.067 \qquad w_a = -1.05^{+0.31}_{-0.27}$



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Dark Energy beyond w_0w_a

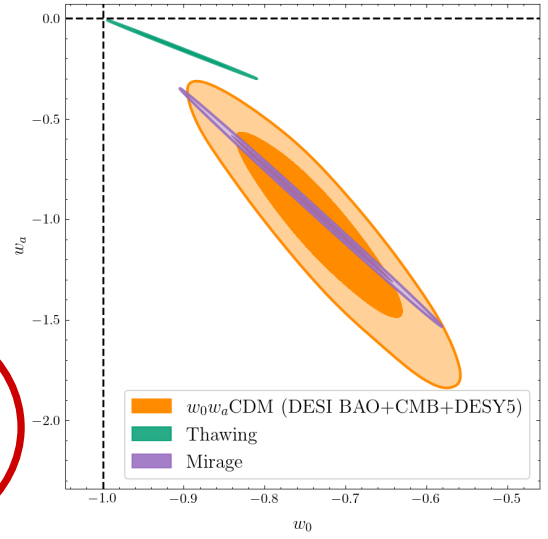
Less DOF (1) → More DOF

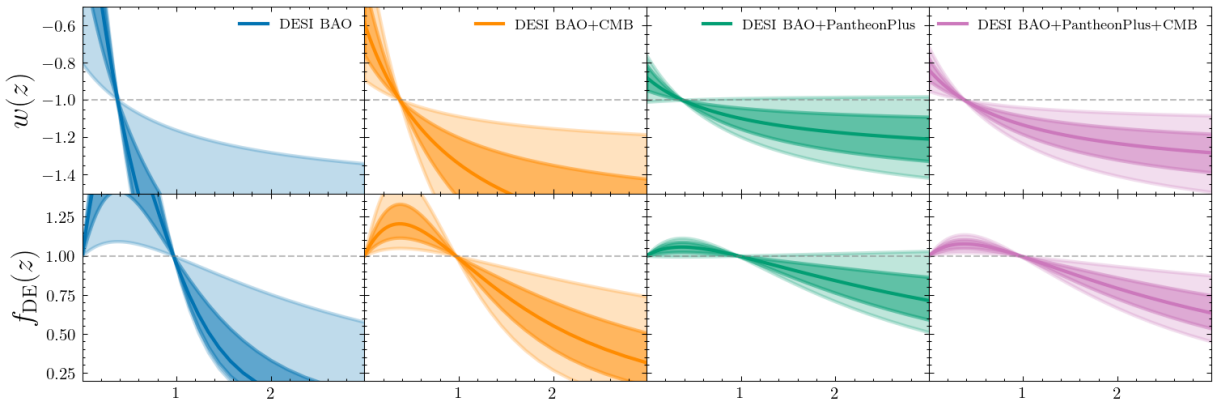
Reconstruction

$$w(z) = w_0 \sum_{i=0}^{M} C_i T_i(x)$$

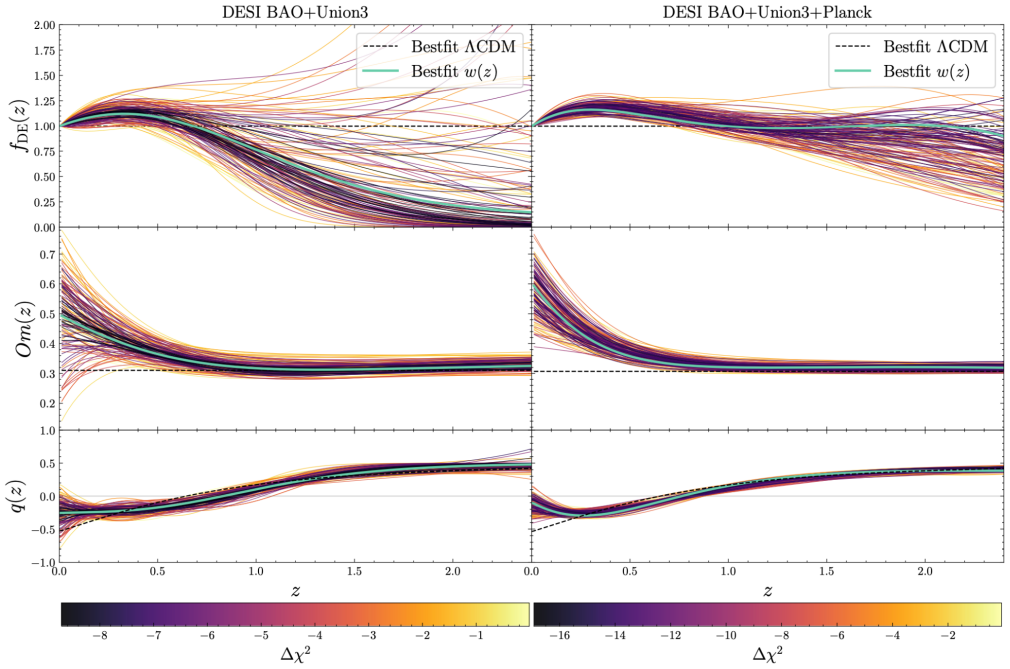
- Three '**Physics-focused**' classes of DE
  - Thawing
  - Emergent
  - Mirage

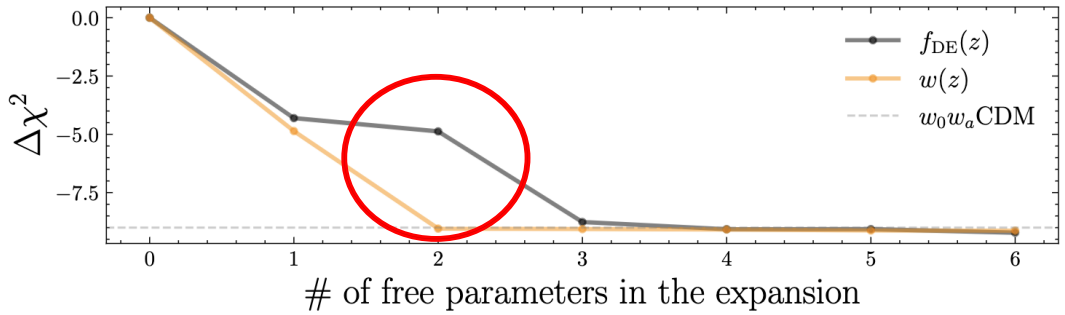
Data - $\ln B_{21}$	Mirage	w_0w_a
DESI+CMB+PantheonPlus	2.8	0.65
DESI+CMB+Union3	4.2	2.4
DESI+CMB+DES-SN5YR	6.4	2.8





K. Lodha, A. Shafieloo, R.Calderón, E. V. Linder ++ 2024 [2405.13588]

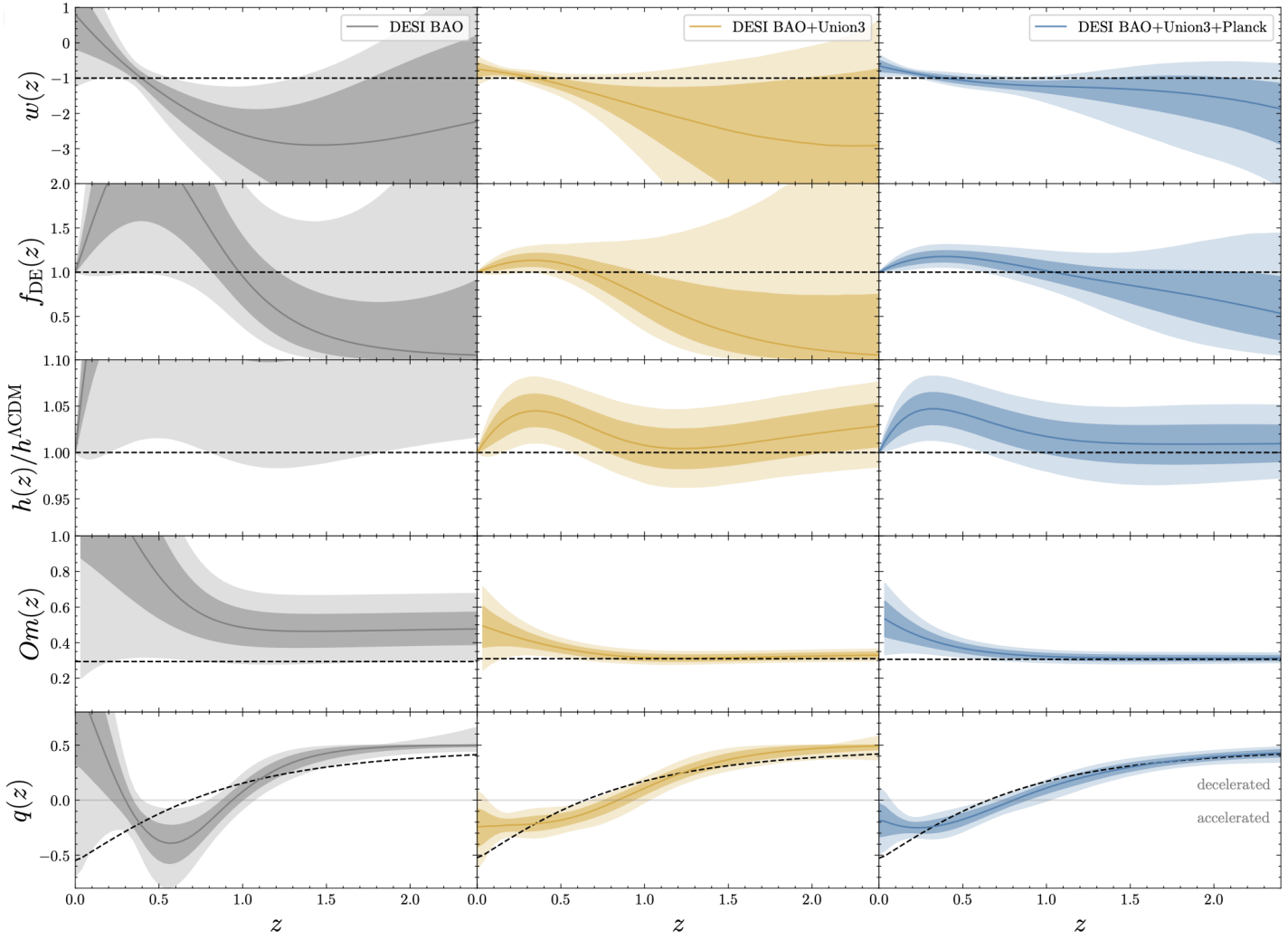




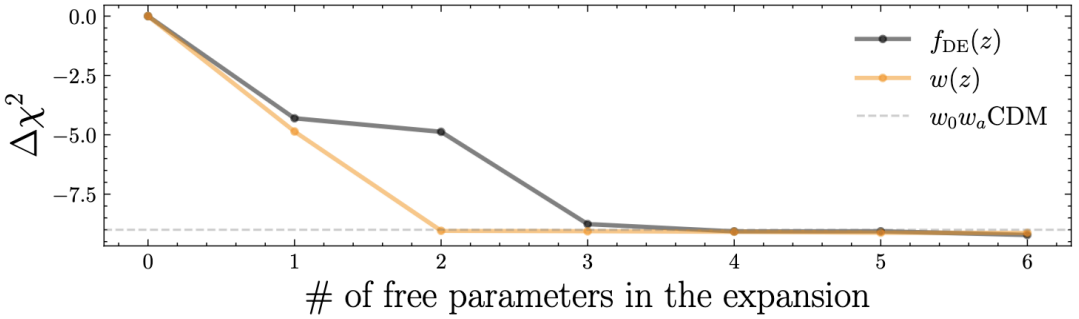
R.Calderón, K. Lodha, A. Shafieloo, E. V. Linder ++ 2024 [2405.04216]

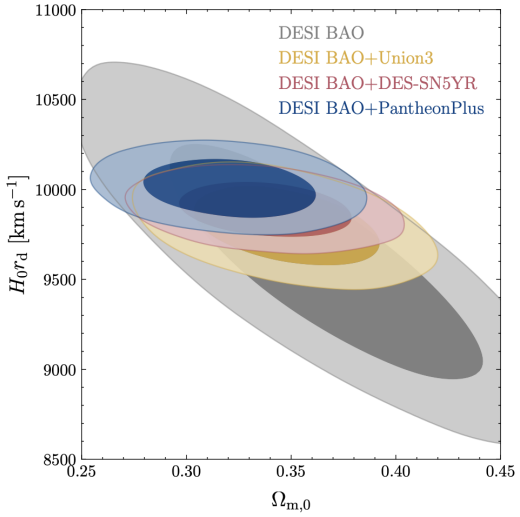
Dark Energy Reconstructions

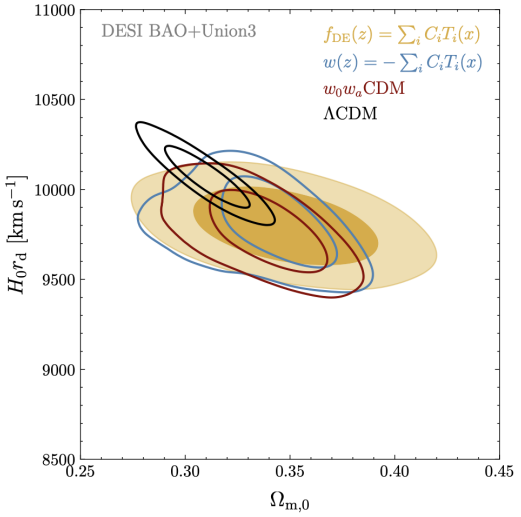
DARK ENERGY SPECTROSCOPIC INSTRUMENT



$$w(z) = w_0 \sum_{i=0}^{M} C_i T_i(x)$$





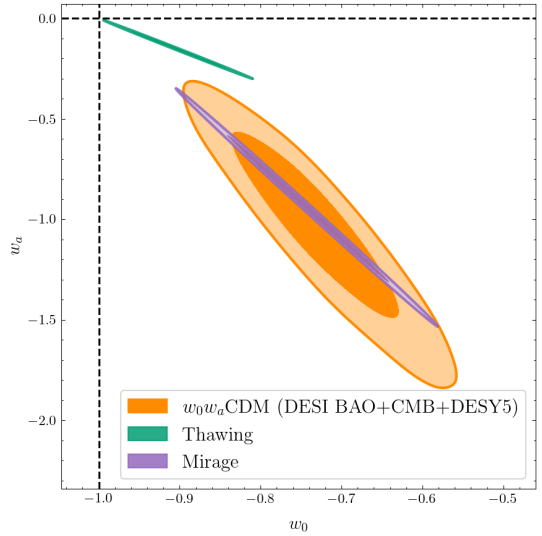


R.Calderón, K. Lodha, A. Shafieloo, E. V. Linder ++ 2024 (submitted to JCAP)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Physics-Focused Aspects of DE

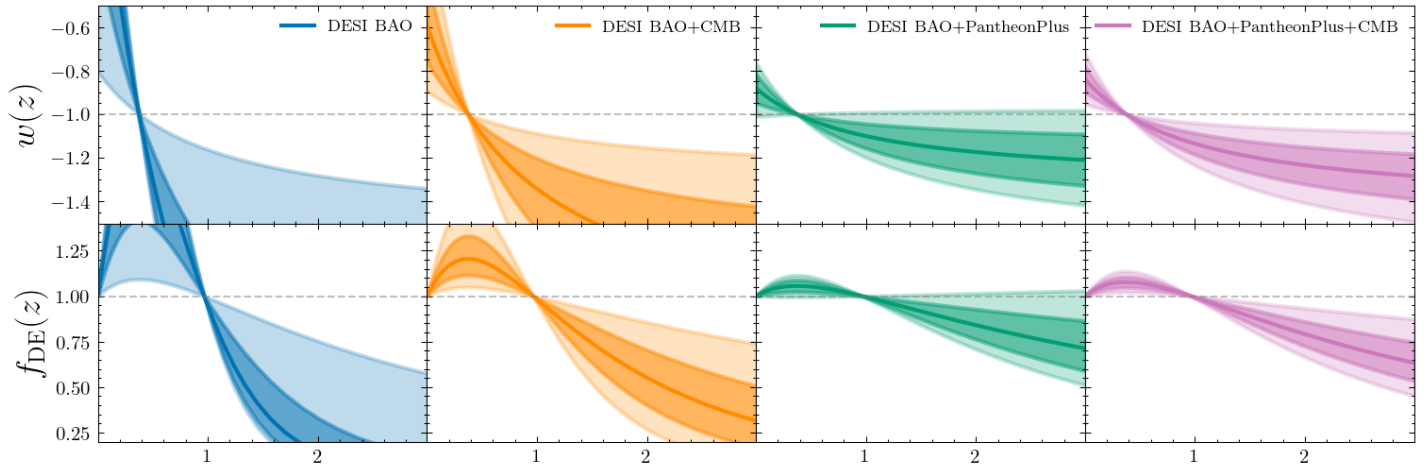


- Three 'Physics-focused' classes of DE
  - Thawing
  - Emergent
  - Mirage

- **Strong** Bayesian Evidence for Mirage class (Jeffrey's scale)

  w0waCDM
  - Pantheon+ : **2.8** [0.65]
  - Union3: **4.2** [2.4]
  - DES-SN5YR: **6.4** [2.8]

Data	$\Delta\chi^2_{\rm Thawing}$	$\Delta\chi^2_{\rm GEDE}$	$\Delta\chi^2_{\rm Mirage}$	$\Delta\chi^2_{w_0w_a}$
+CMB+PantheonPlus	−0.6	−1.7	−9.0	−9.6
+CMB+Union3	−3.0	−3.2	−15.2	−15.6
+CMB+DES-SN5YR	−5.0	−4.8	−17.7	−18.3



K. Lodha, A. Shafieloo, R.Calderón, E. V. Linder ++ 2024 (submitted to JCAP)

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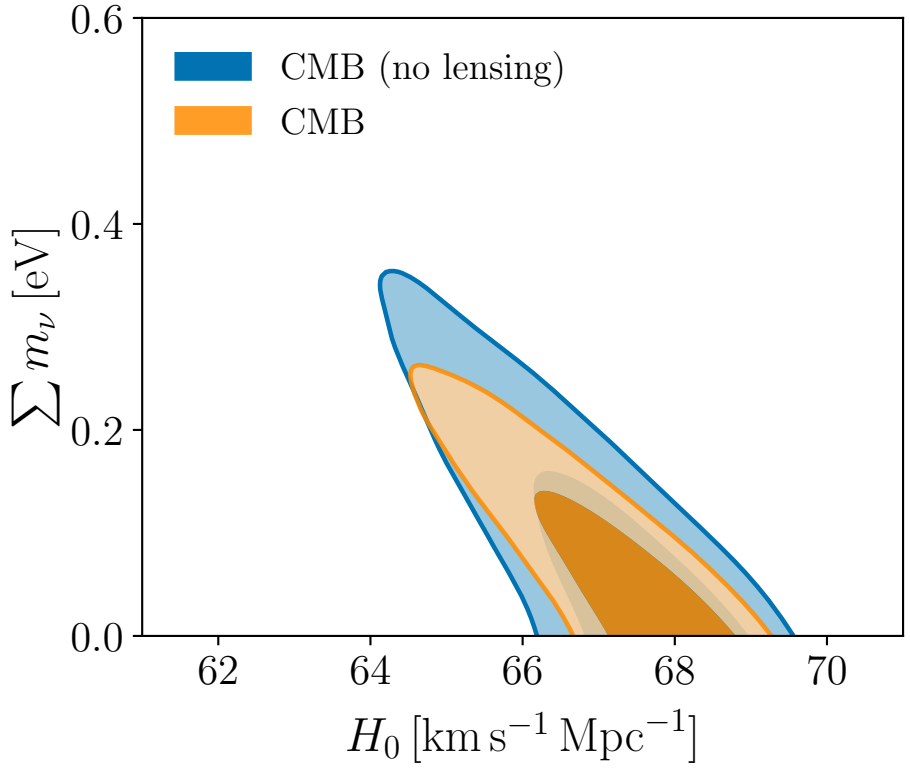
Sum of neutrino Mass

Internal CMB degeneracies limiting precision on the sum of neutrino masses



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Sum of neutrino Mass

Internal CMB degeneracies limiting precision on the sum of neutrino masses

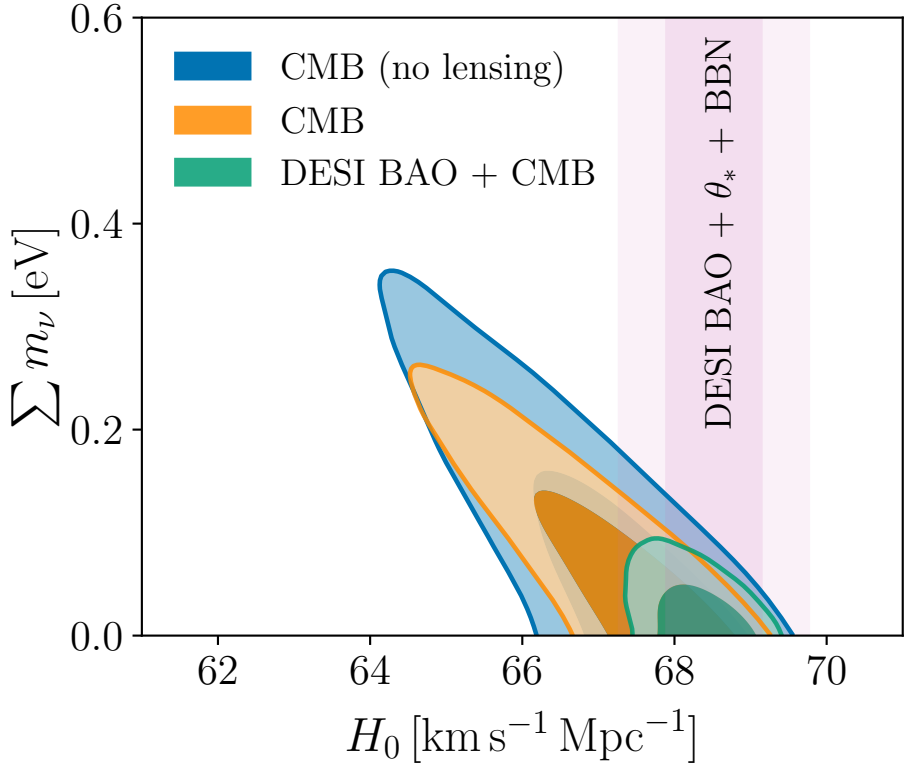
Broken by BAO, especially through H_0 constraint

Low preferred value of H_0 yields

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

Limit relaxed for extensions to ΛCDM

$\sum m_\nu < 0.195\text{eV}$ for $w_0 w_a$CDM



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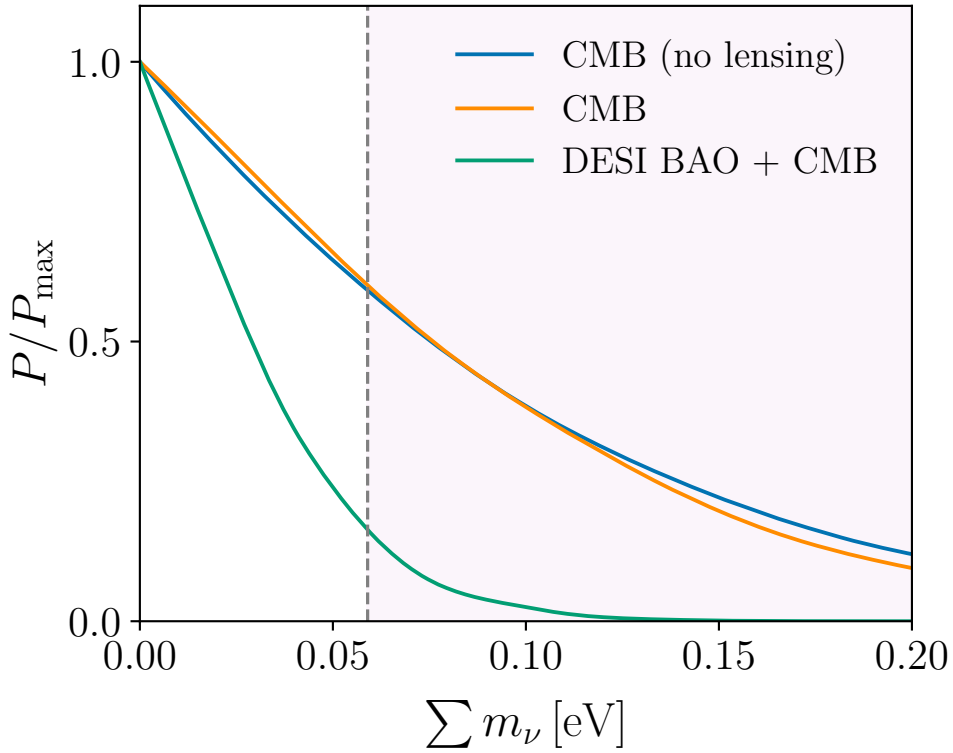
Neutrino mass hierarchies

With $> 0.059\text{eV}$ prior (NH)

$\sum m_\nu < 0.113\text{eV}$ (95%, DESI+CMB)



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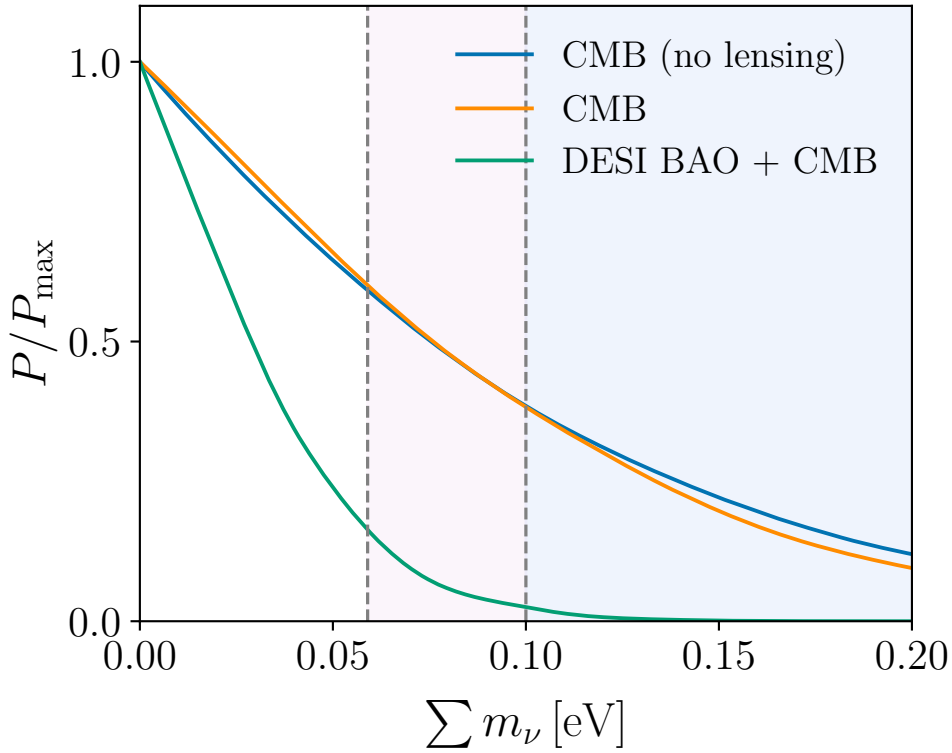
Neutrino mass hierarchies

With $> 0.059\text{eV}$ prior (NH)

$\sum m_\nu < 0.113\text{eV}$ (95%, DESI+CMB)

With $> 0.1\text{eV}$ prior (IH)

$\sum m_\nu < 0.145\text{eV}$ (95%, DESI+CMB)



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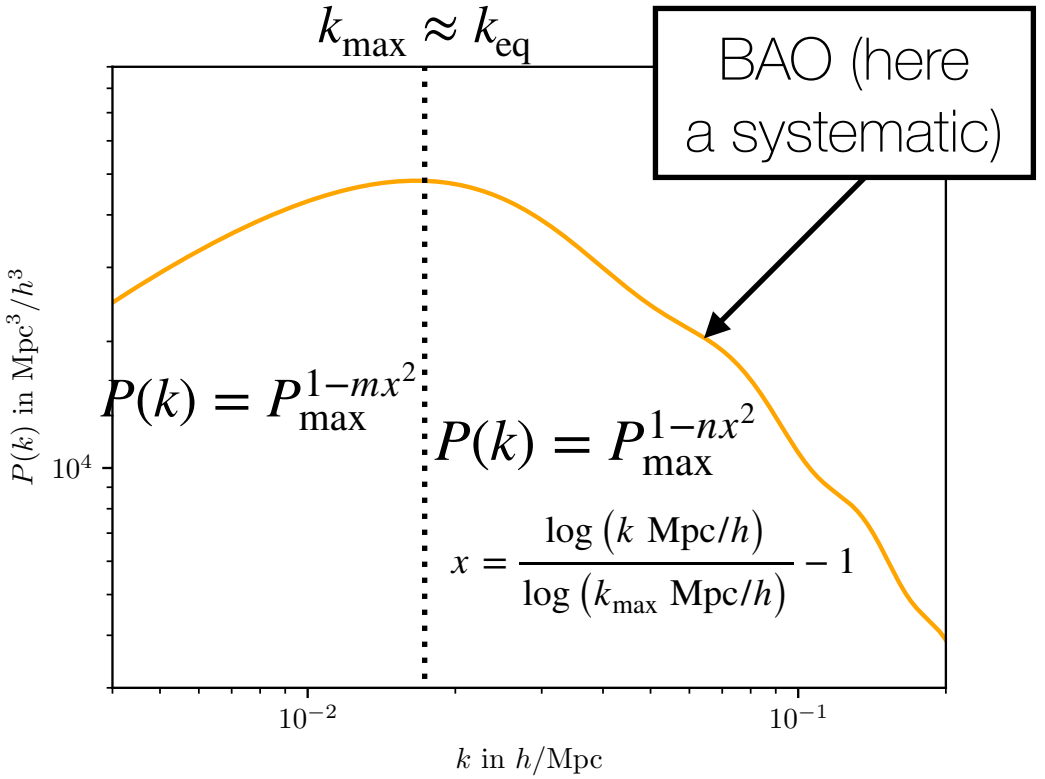
Power spectrum turnover

- The power spectrum peak is fixed by a physical scale: the matter-radiation equality scale
- Density fluctuations in early universe grow at different rates depending on the details of the expansion (dominant component)
  - During Radiation Domination: Pressure stabilises sub-horizon perturbations, and they do not grow
  - During Matter Domination: Perturbations grow as $\delta_m \propto a$
- Change over leads to peak: scales that enter horizon at matter-radiation equality epoch
- Measure the position of the power spectrum peak to use as a standard ruler, similar to the BAO



$$a_{\rm eq} = \rho_{\rm rel}/\rho_{\rm mat}$$

$$r_{\rm H} = \frac{2c\left(\sqrt{2}-1\right)\sqrt{a_{\rm eq}}}{H_0\sqrt{\Omega_m}}$$

$$k_{\rm eq} = \left(4-2\sqrt{2}\right) r_{\rm H}^{-1}$$

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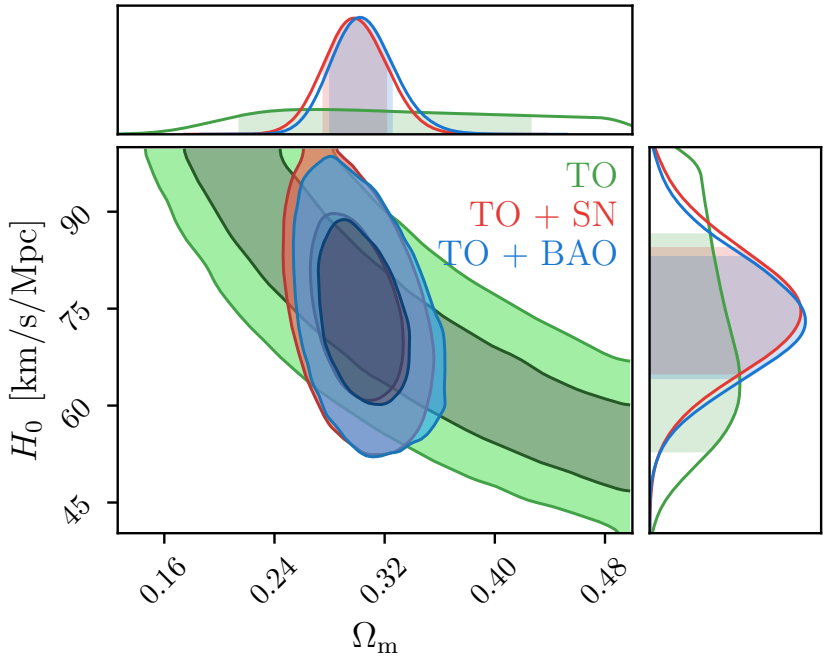
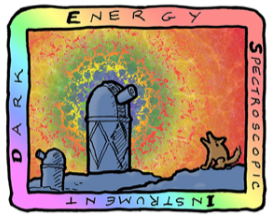
Turnover and H_0

- Measured peak from eBOSS, and used as ruler
- Combine the turnover position with uncalibrated BAO or SN-Ia
  - Without calibrator (Cepheids for SN-Ia or the CMB for BAO) these distances are insensitive to H_0 and only measure the density parameters, such as Ω_m
- We find:
  - $H_0 = \left(74.7 \pm 9.6\right)$ km/s/Mpc (with Pantheon) and
  - $H_0 = \left(72.9^{+10.0}_{-8.6}\right)$ km/s/Mpc (with eBOSS LRG and Ly BAO)
- Results seem to prefer higher value of H0 than Planck+BAO results, more in line with SH0ES Cepheid+SN-Ia results
- DESI analysis in progress



No sound horizon information included (marginalise over $\Omega_b h^2$ w/o prior, and parameter is poorly constrained)



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Summary

- DESI already has the most precise BAO measurements ever
- BAO measurements, in combination with CMB data, favour zero spatial curvature
- Dark energy EoS consistent with w = –1 when assumed constant
- When allowing EoS (w) to vary, DESI combined with CMB: 2.6σ and SN: 2.5 to 3.9σ tension with Λ prediction $(w_0, w_a) = (-1, 0)$
- Limit on $\sum m_\nu$ improves to < 0.072 eV (95%, ΛCDM), < 0.195 eV (95%, w_0w_aCDM)

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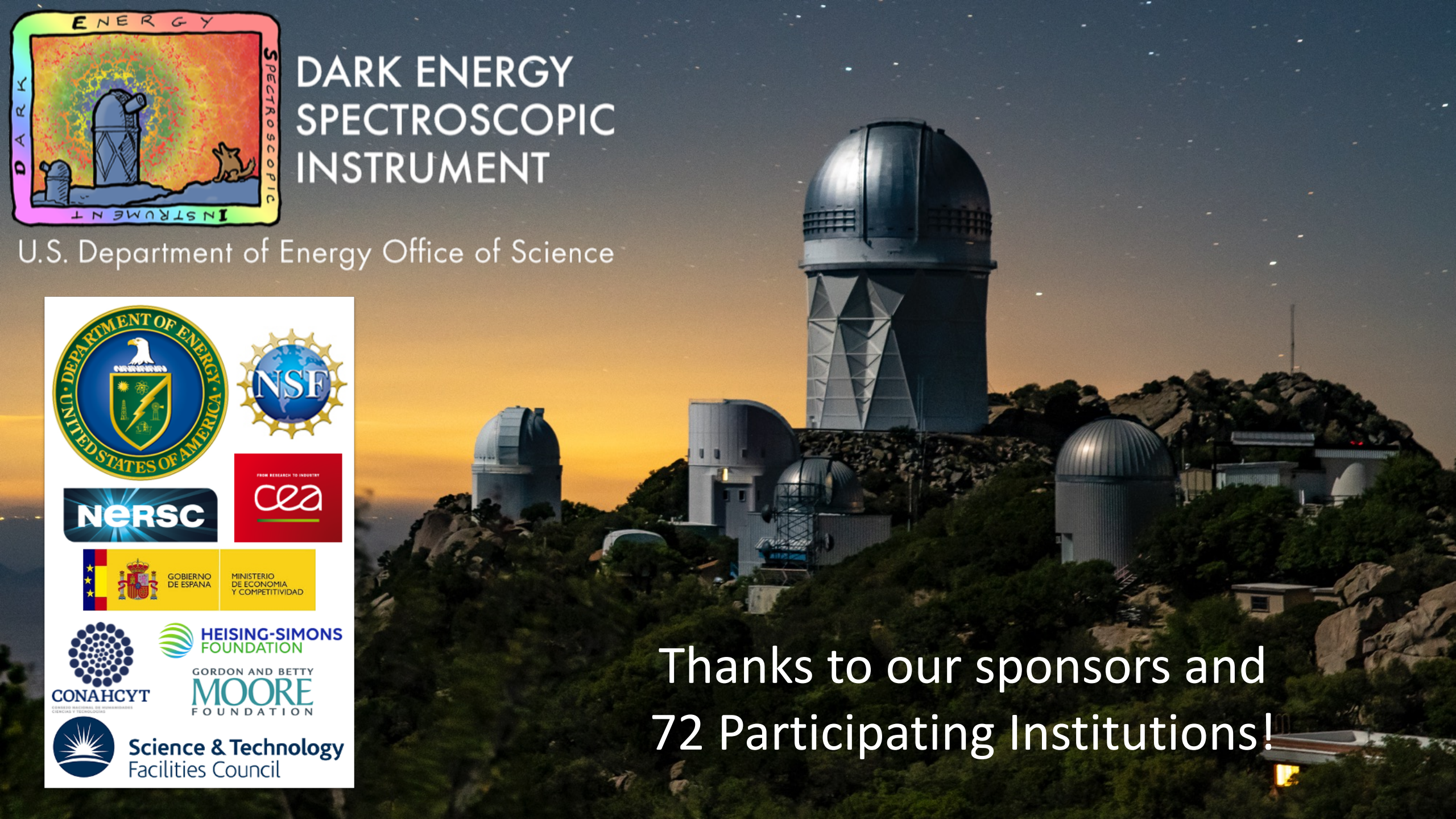
What's to come?

- "Full-shape" results – soon!
- DR2 data (Y3 > Y1) – data collection just completed
- Final DESI dataset (DR3) will be ~3x larger than current – 2026 onwards
- DESI-2, Spec-S5 …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