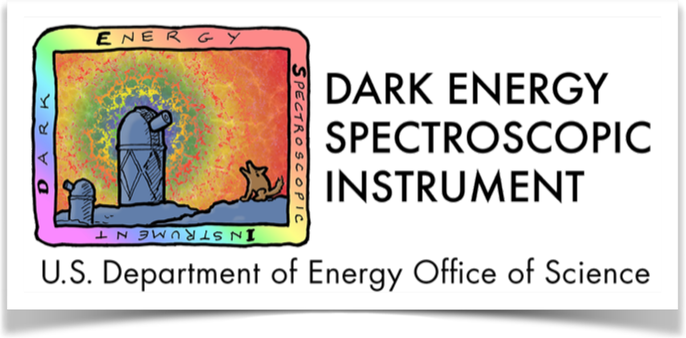
The latest results from the Dark Energy Spectroscopic Instrument (DESI): Is the Standard Cosmological Model in Question?

Davide Bianchi
Università degli Studi di Milano

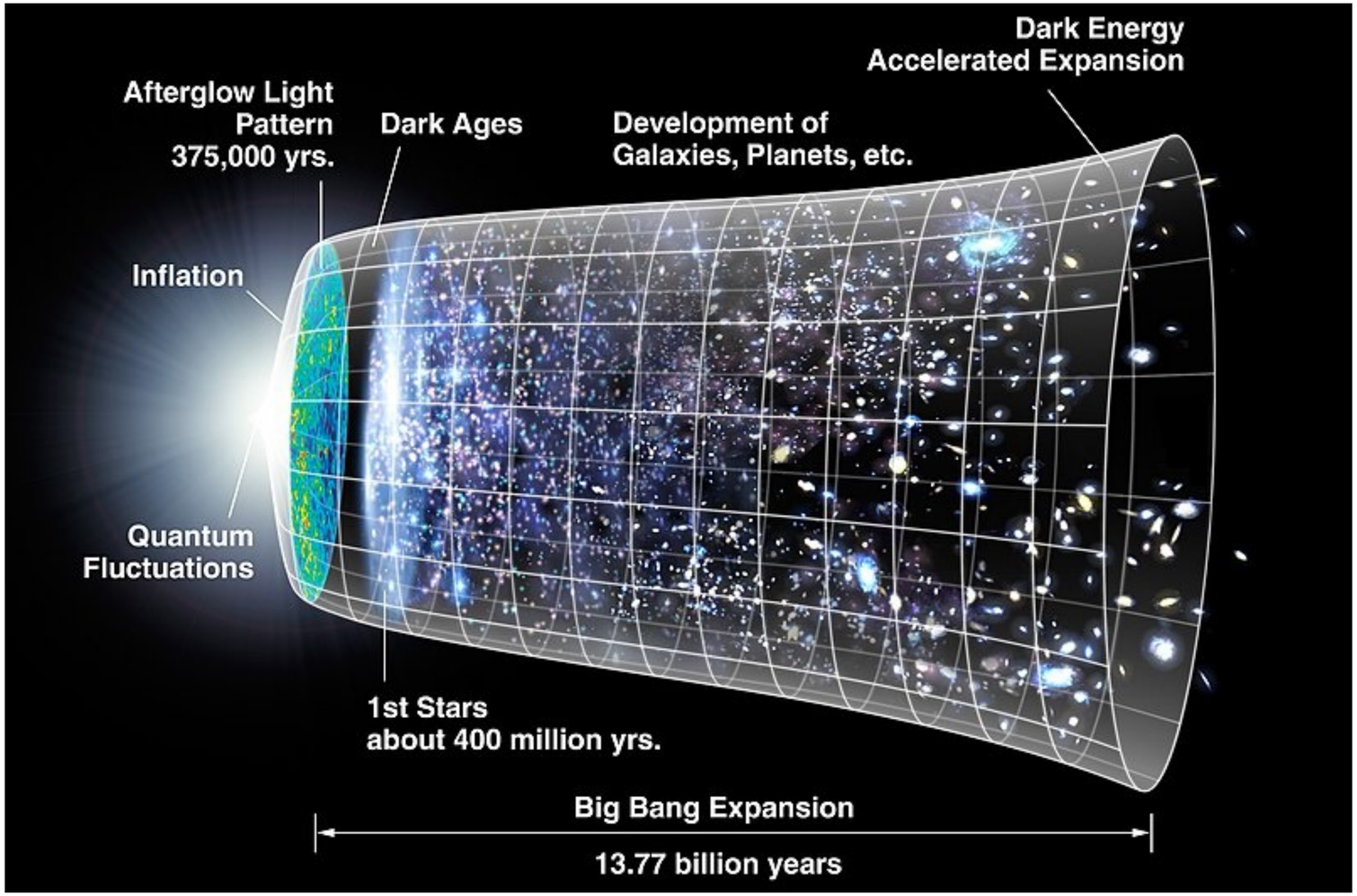


Sapienza
Rome 19/05/2025

Outline

- General introduction
- The DESI experiment
- Baryon acoustic oscillations (BAO)
- Cosmological results

Current understanding of the Universe



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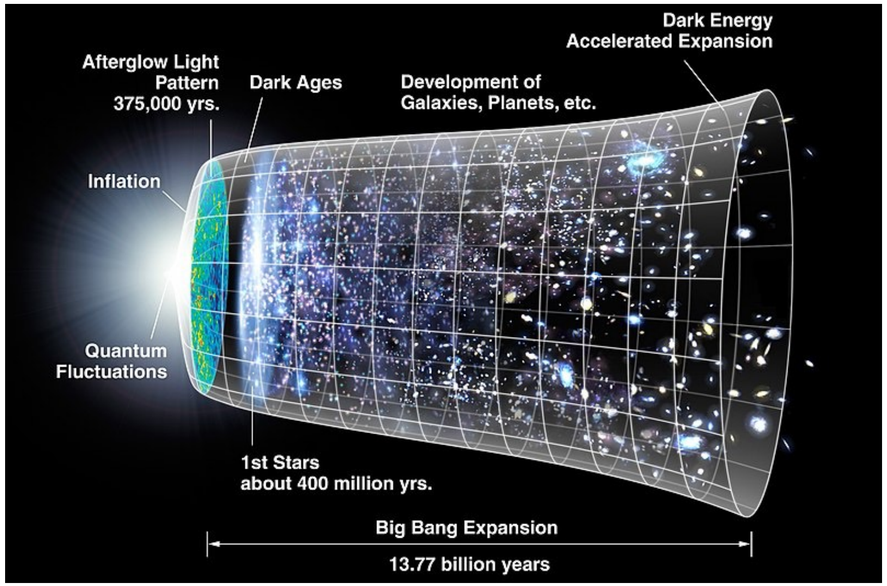


Current understanding of the Universe

Hubble function =
expansion rate of the universe

Redshift

Friedmann equation

$$H(z) = H_0\sqrt{\Omega_\gamma(1+z)^4 + \Omega_{bc}(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\nu\frac{\rho_\nu(z)}{\rho_{\nu,0}} + \Omega_{DE}\frac{\rho_{DE}(z)}{\rho_{DE,0}}}$$

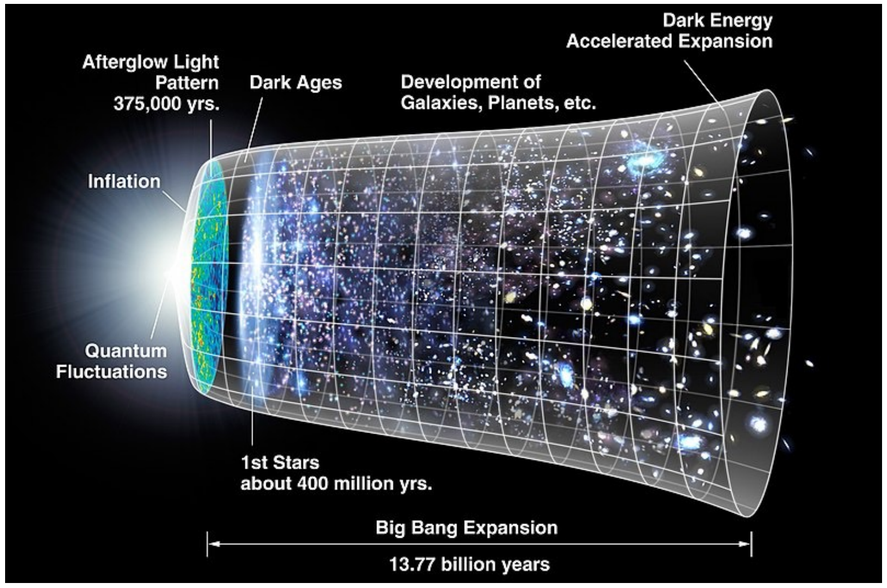
Radiation

Standard Matter
+ Dark Matter

Curvature

Neutrinos

Dark Energy



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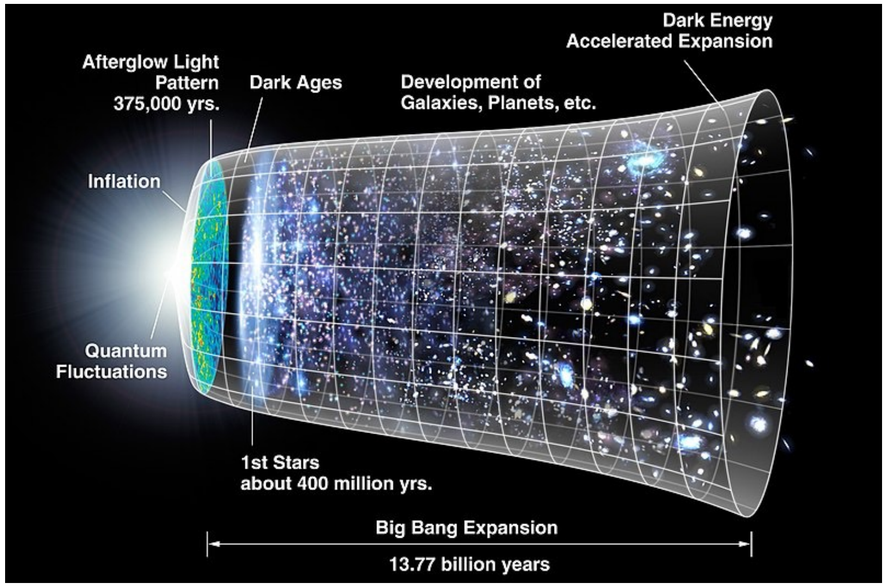

Scale factor

$$a = \frac{1}{1+z}$$

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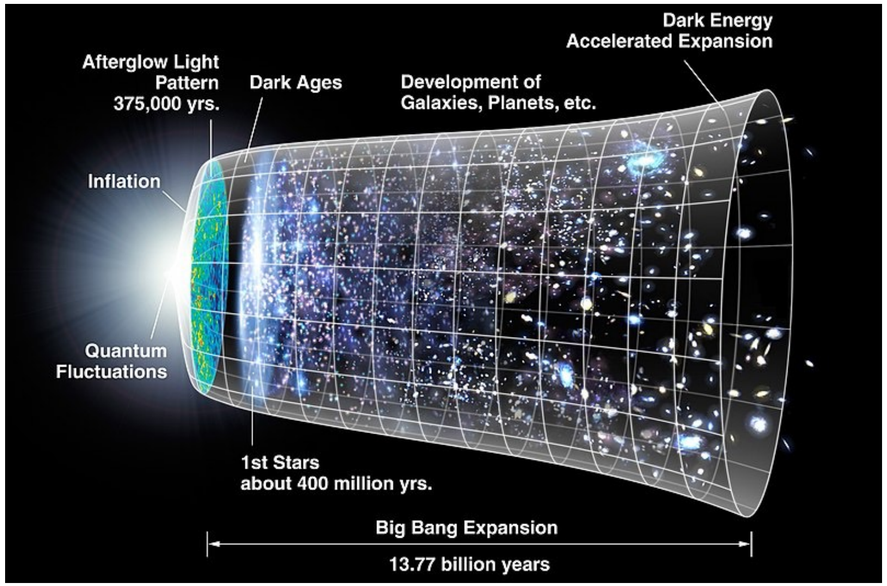

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Equation of state

$$w = \frac{p}{c^2\rho}$$

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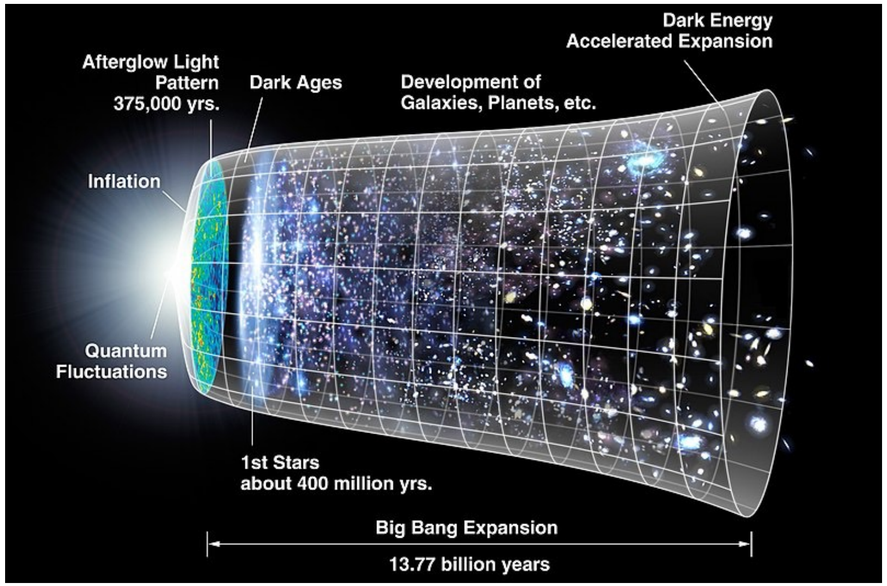
Radiation | Standard Matter + Dark Matter | Curvature | Neutrinos | Dark Energy



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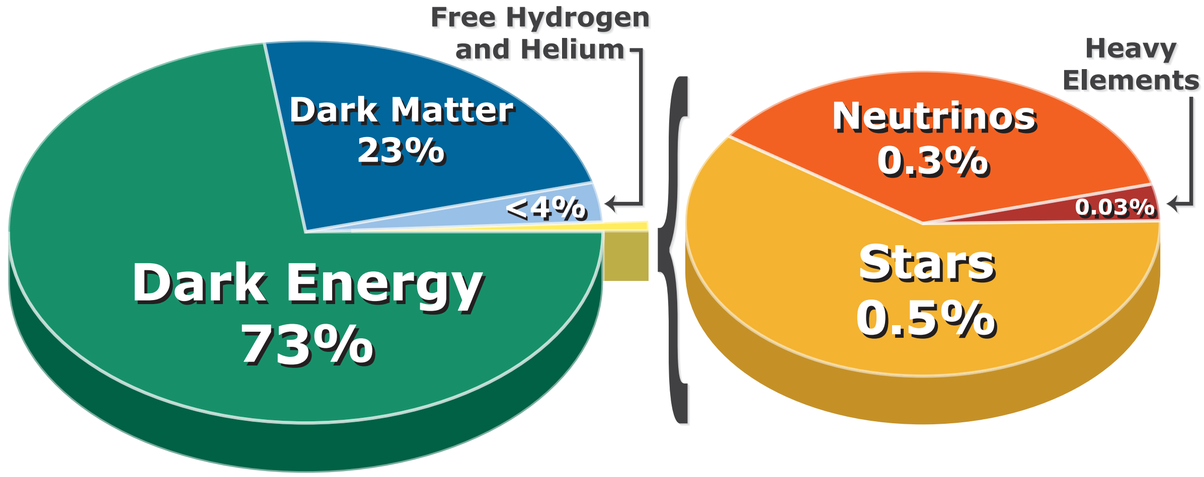
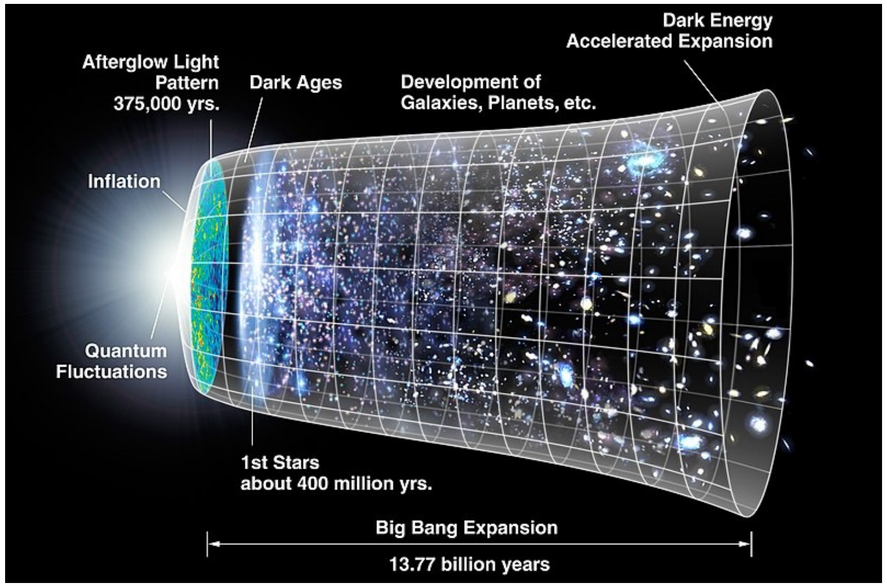


Main cosmological probes



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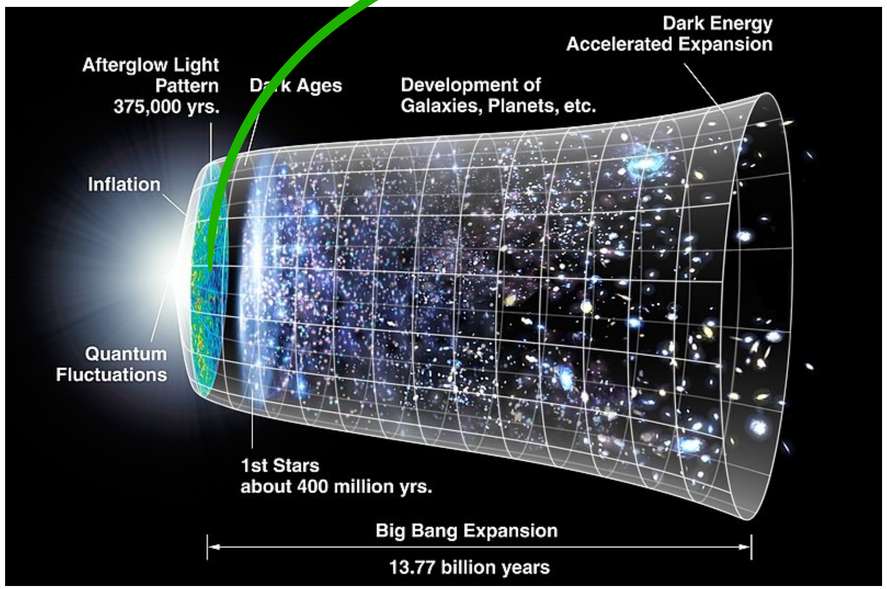
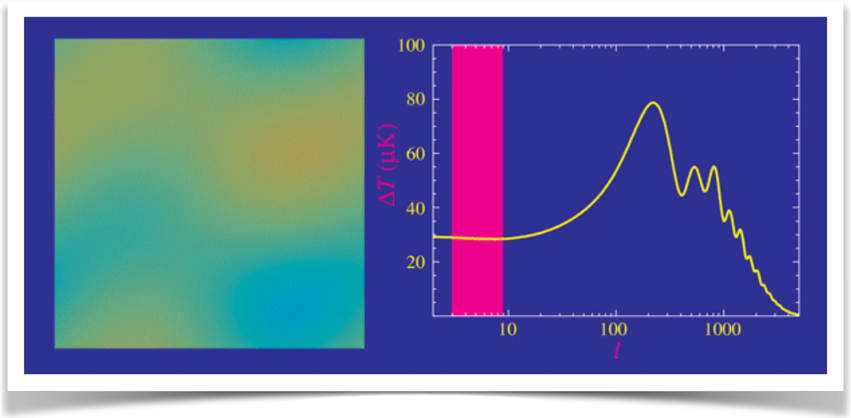


CMB fluctuations



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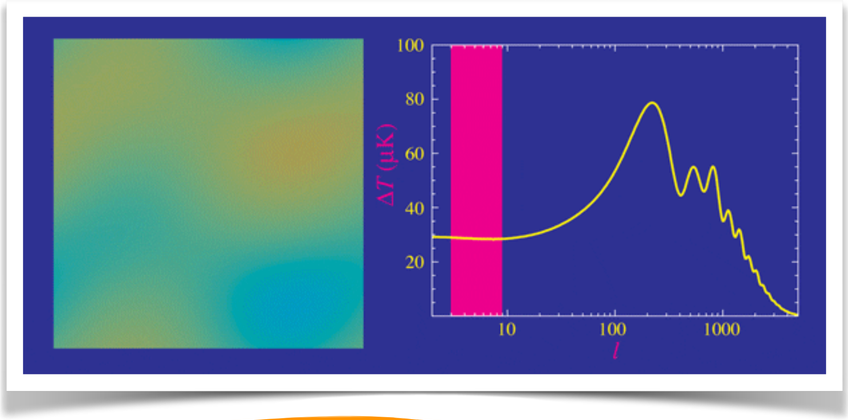
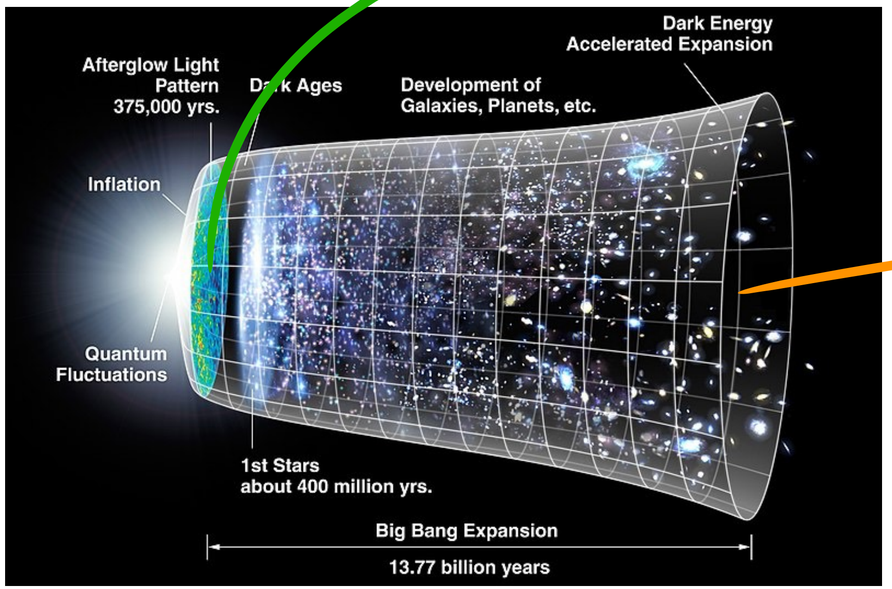
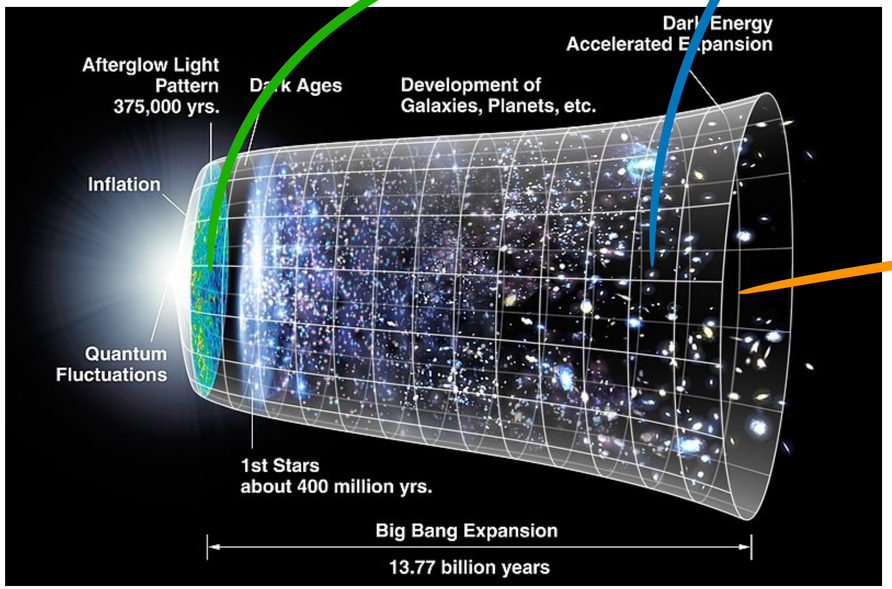




Supernovae type Ia = standard candles

Main cosmological probes



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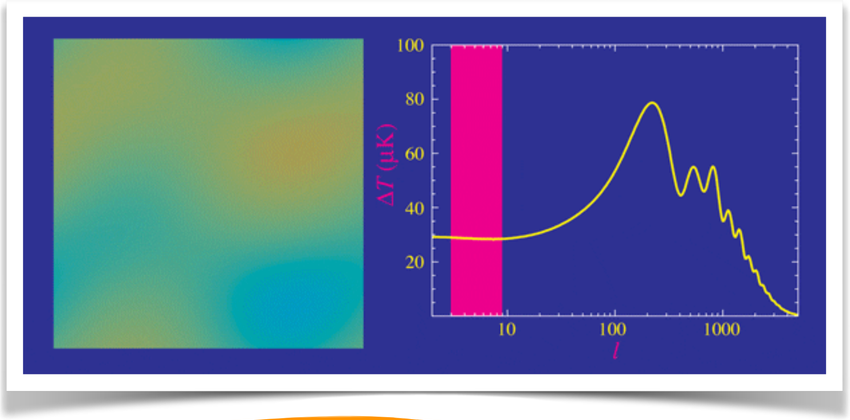
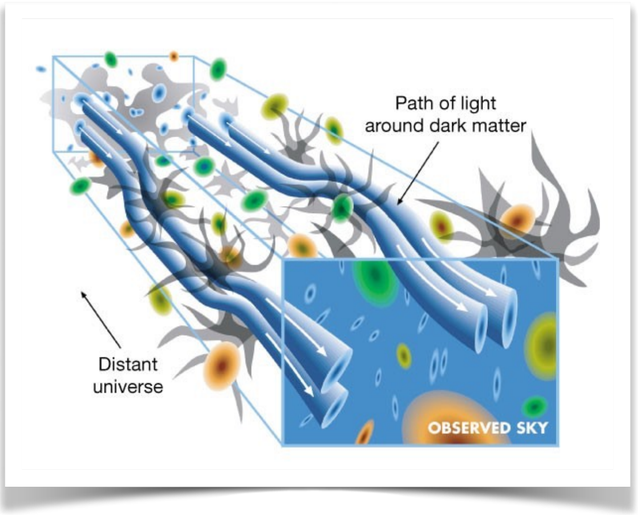


Gravitational lensing



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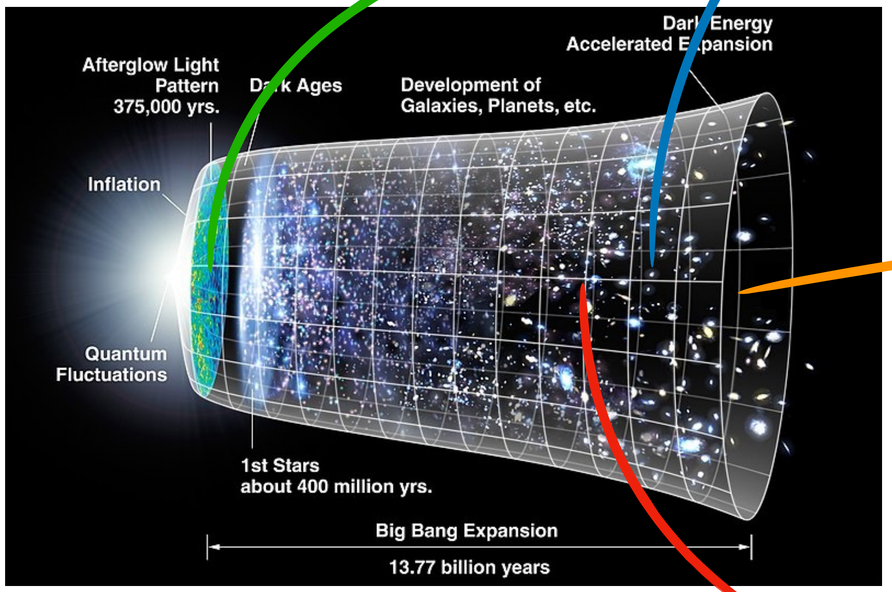

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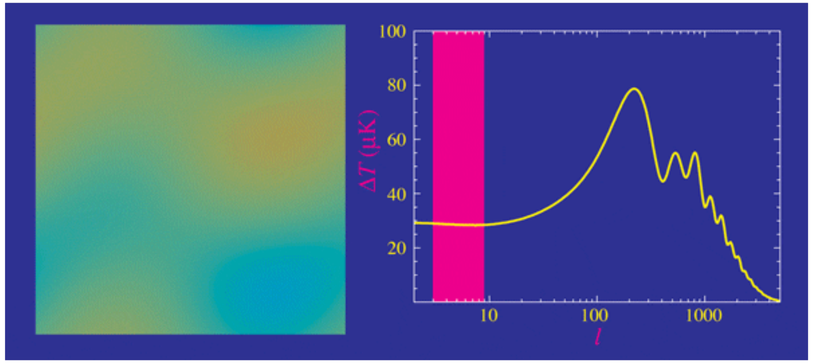

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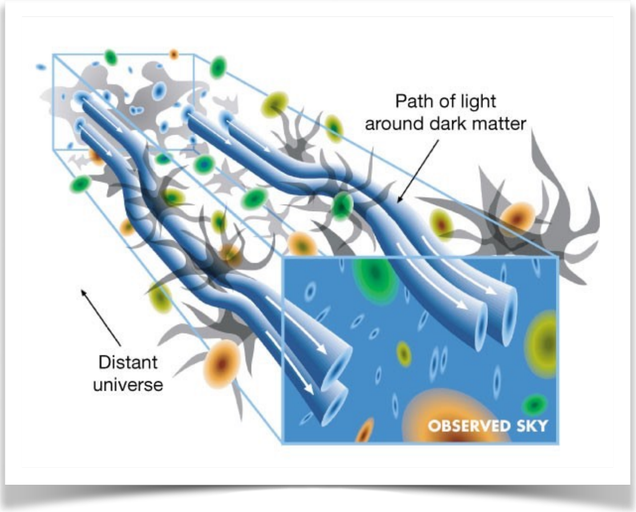
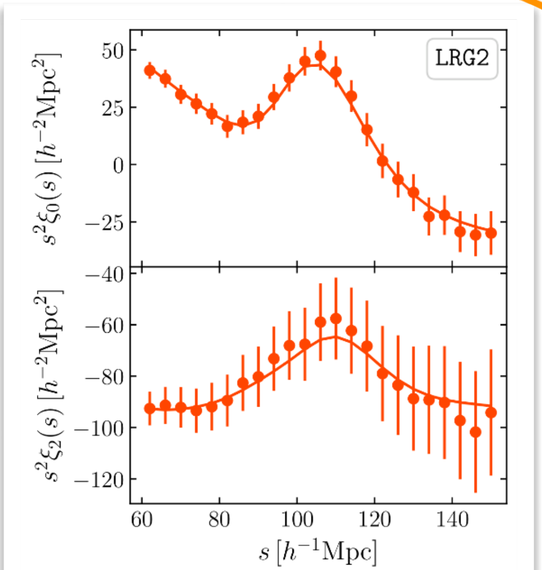


Galaxy clustering



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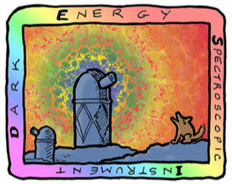

DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

U.S. Department of Energy Office of Science

DESI

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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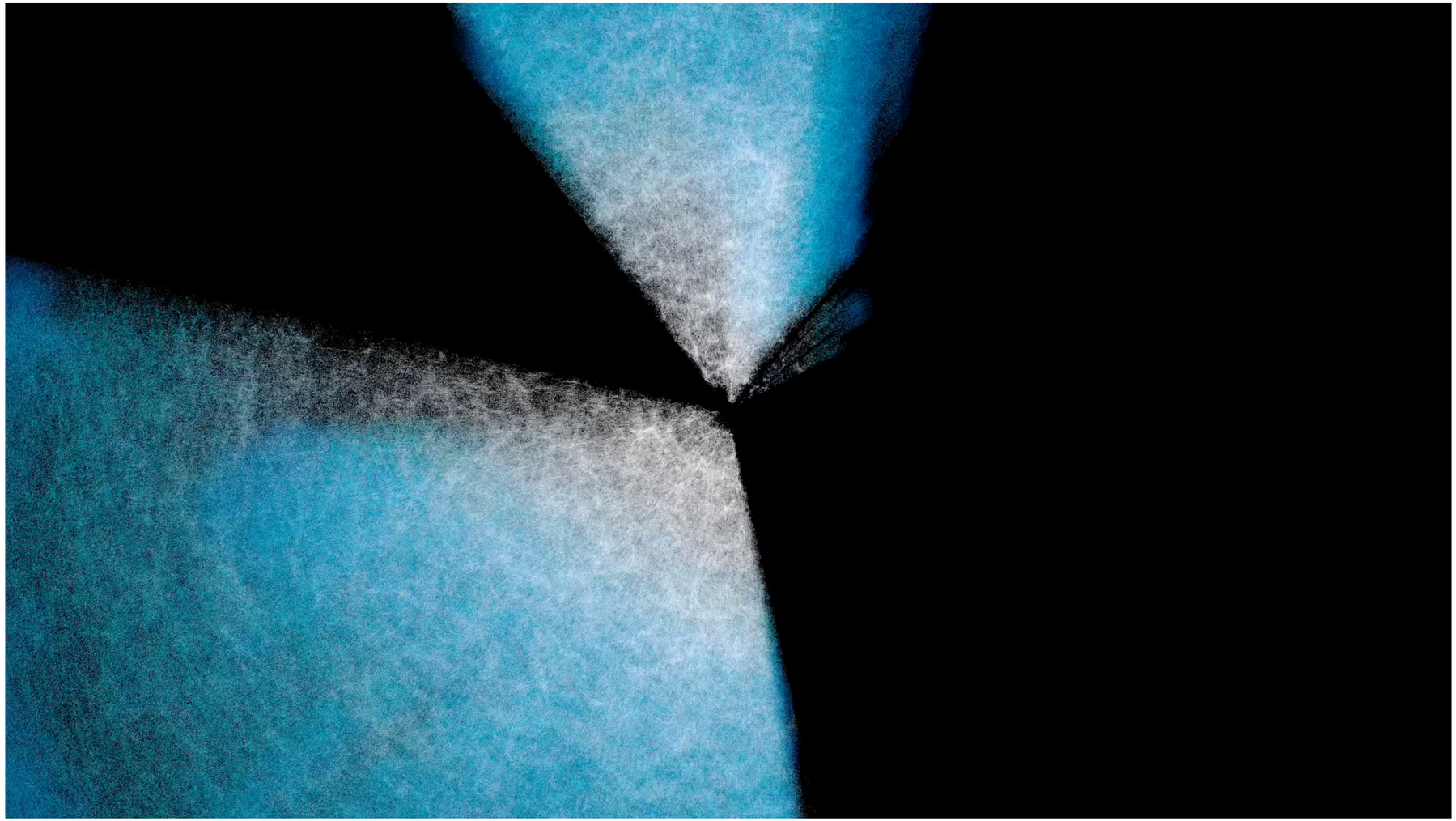
DESI survey



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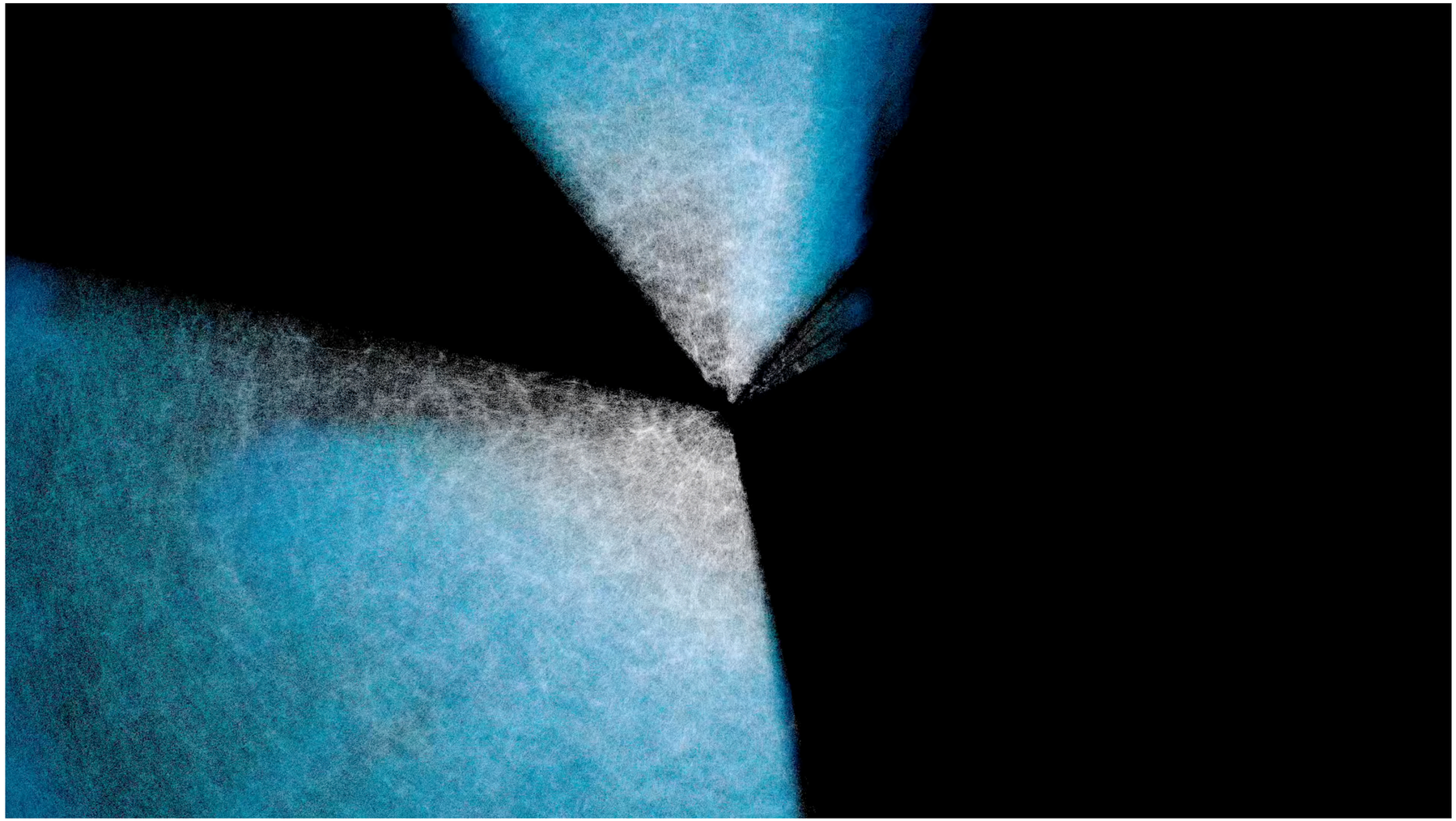

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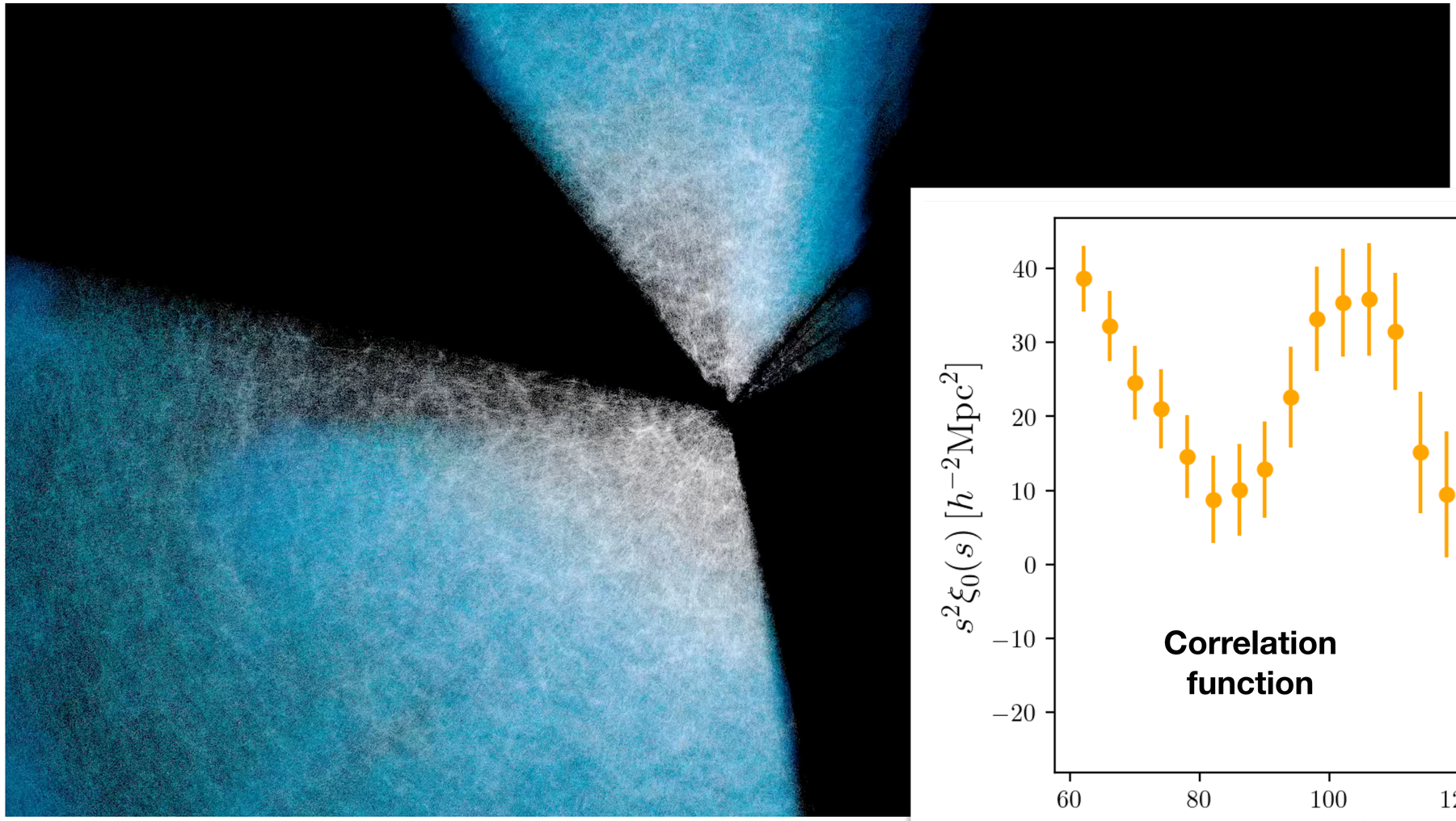
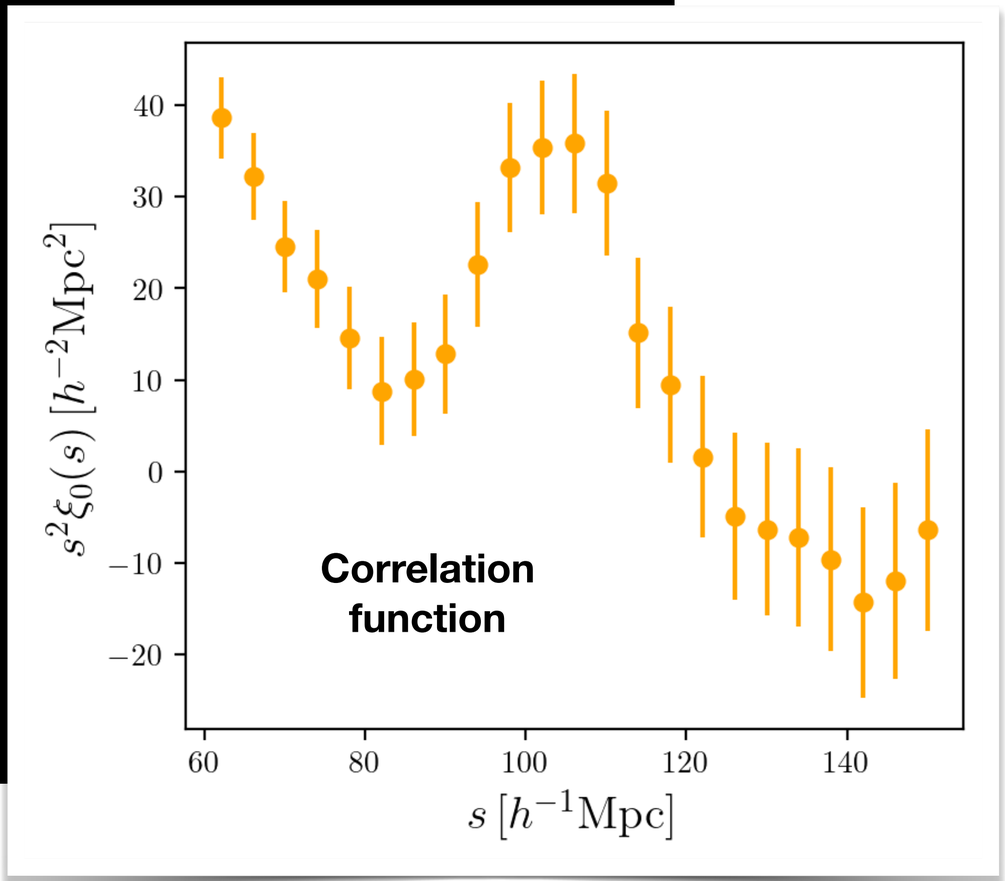
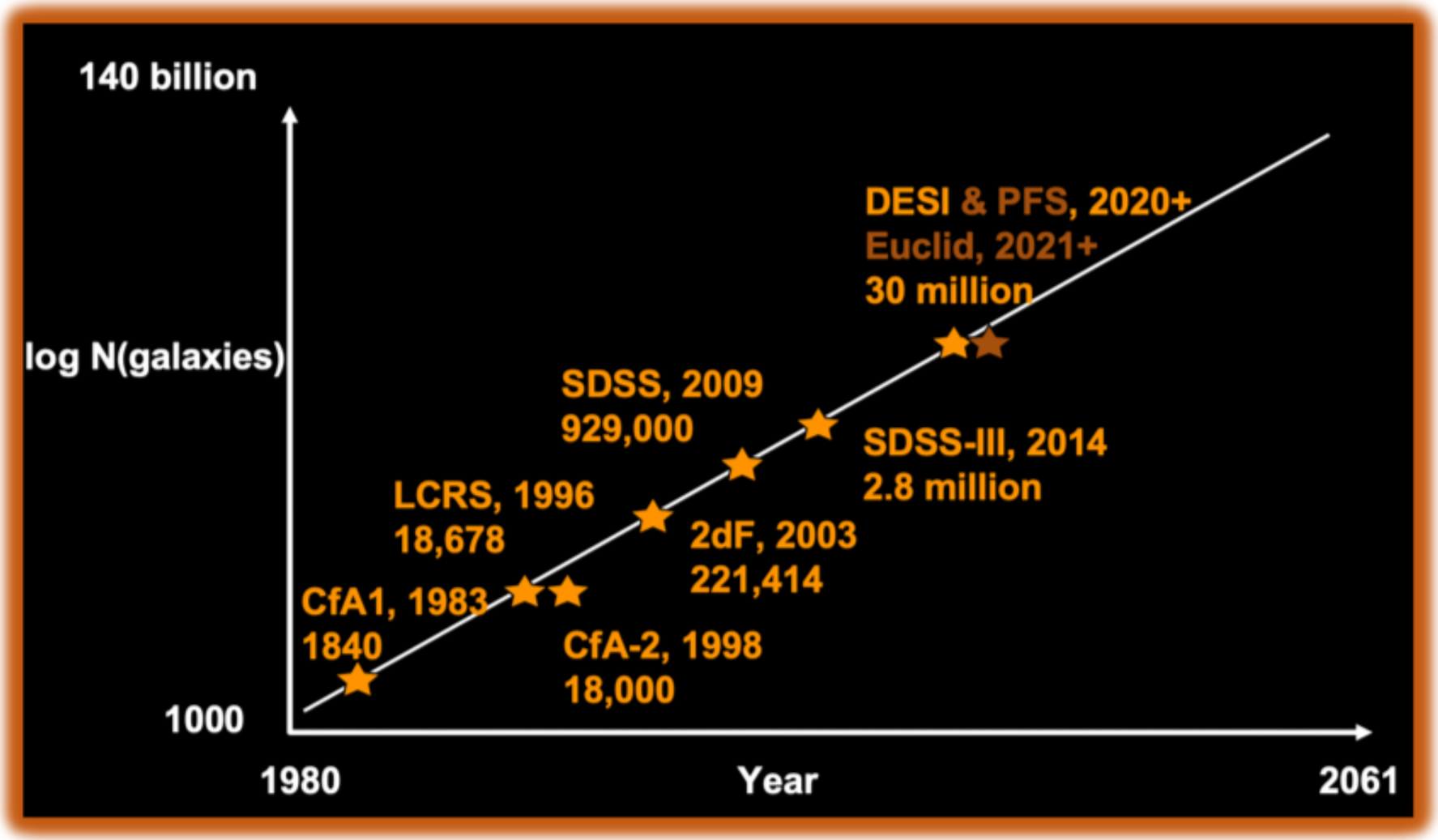




Evolution of spectroscopic surveys



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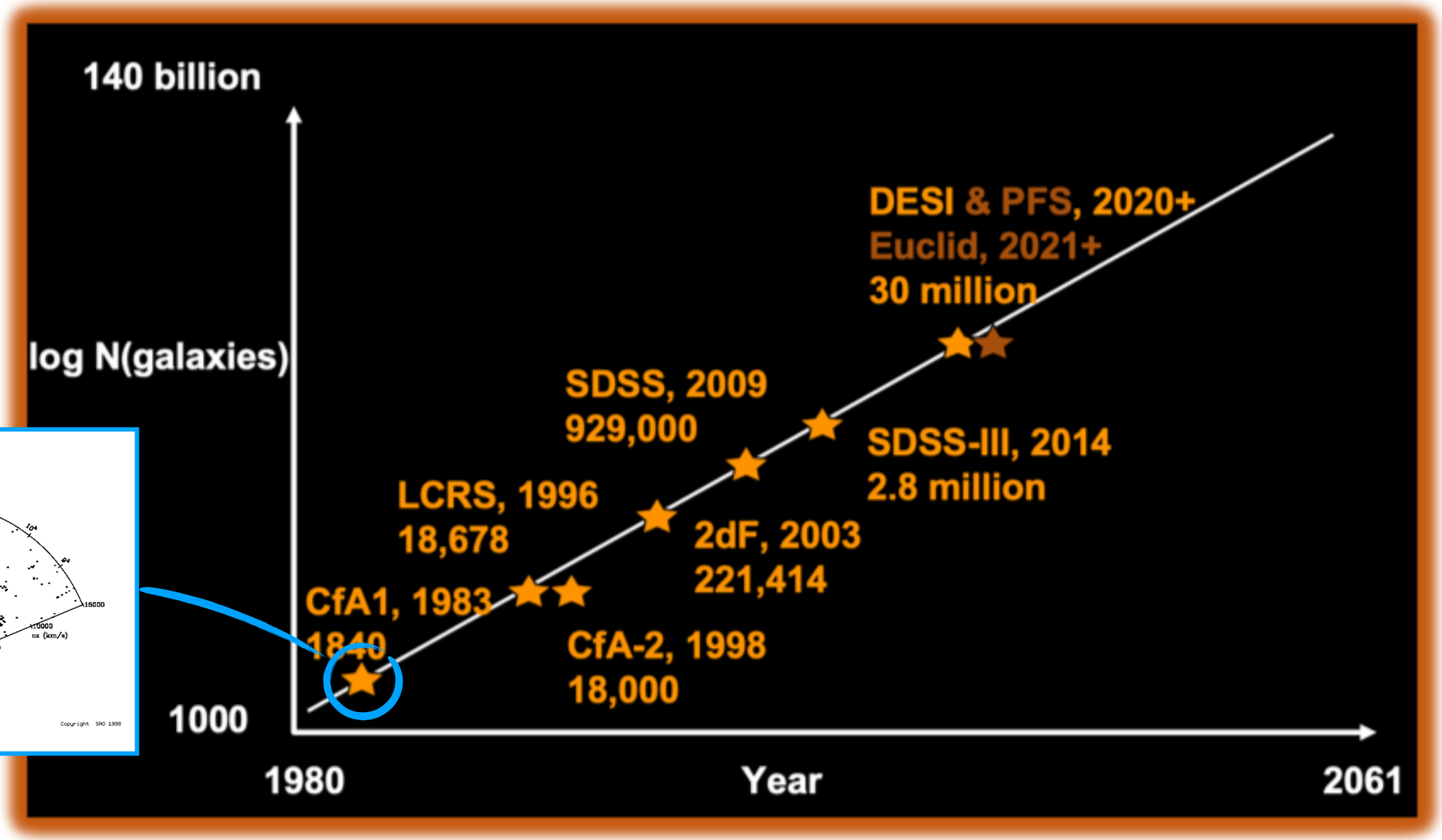

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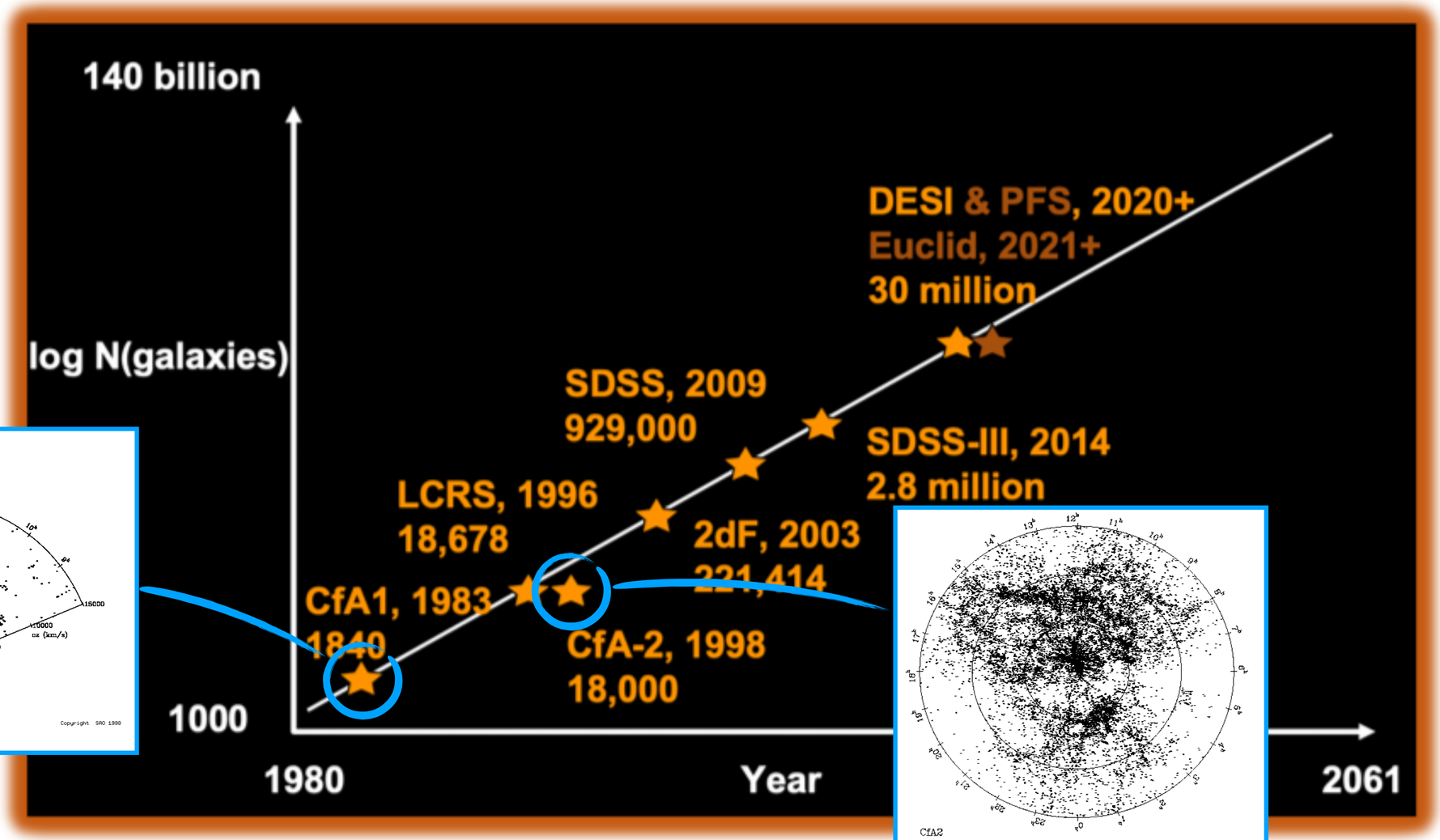

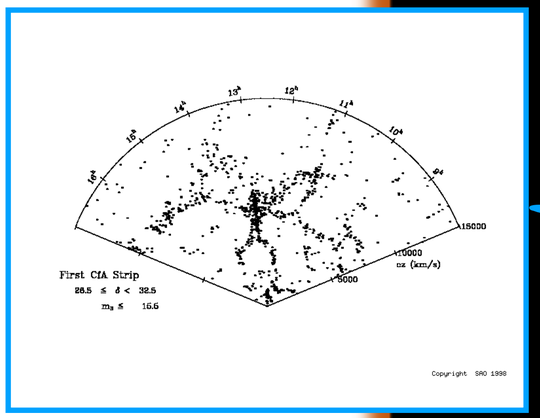

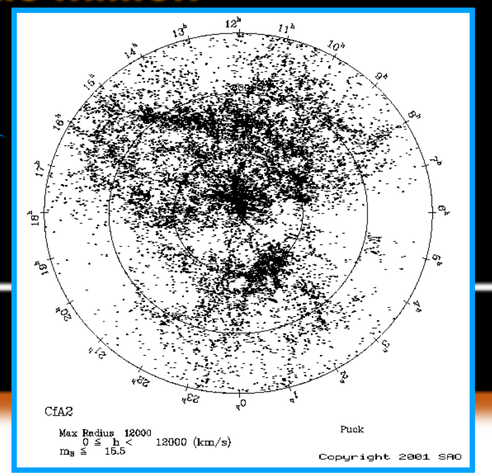

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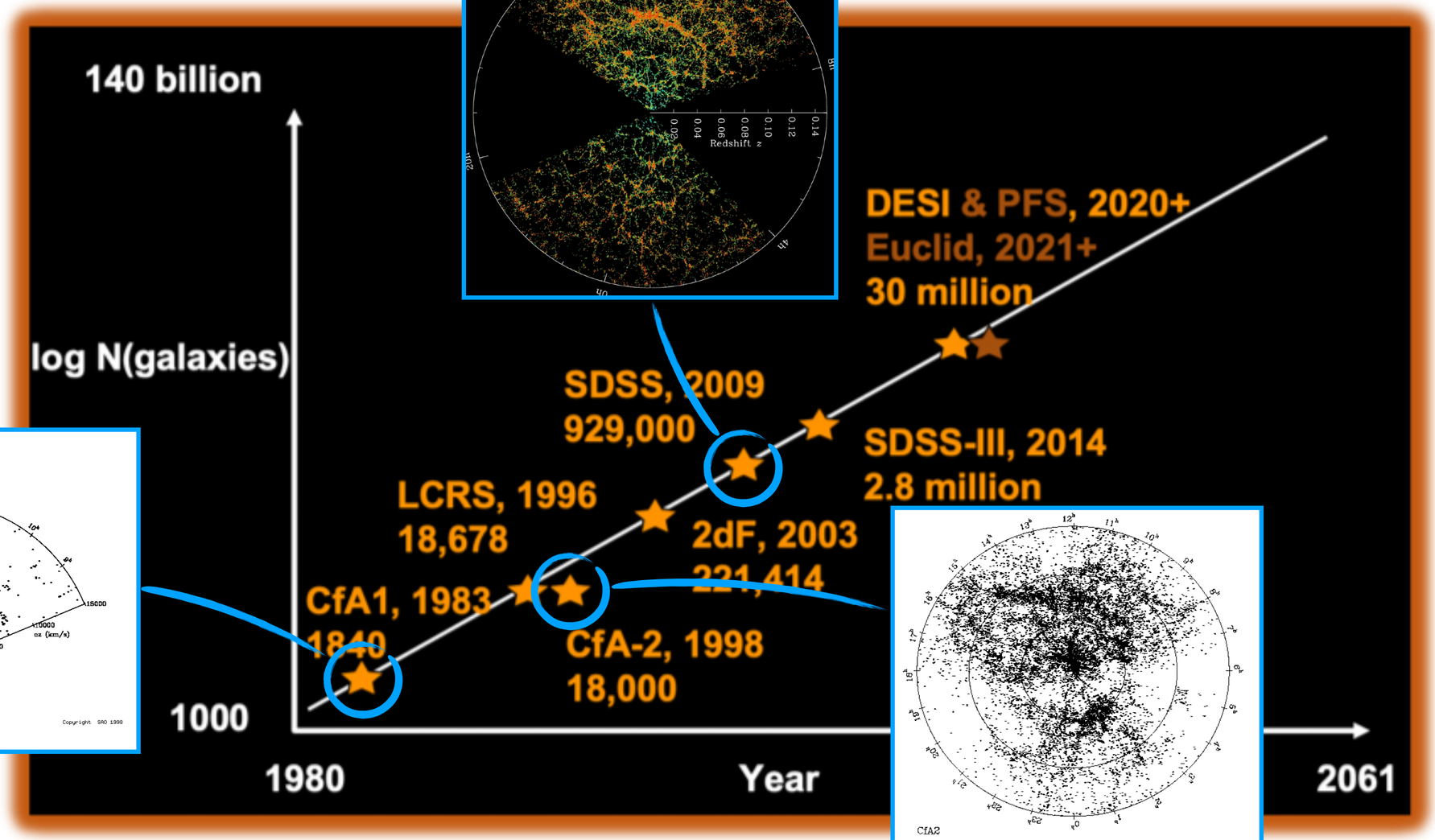

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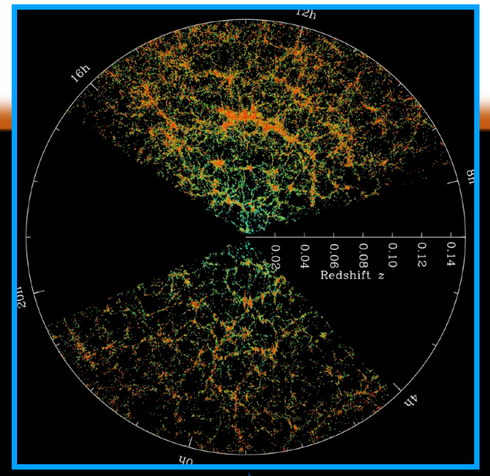


140 billion

log N(galaxies)

1000

1980

Year

2061

DESI & PFS, 2020+
Euclid, 2021+
30 million

SDSS, 2009
929,000

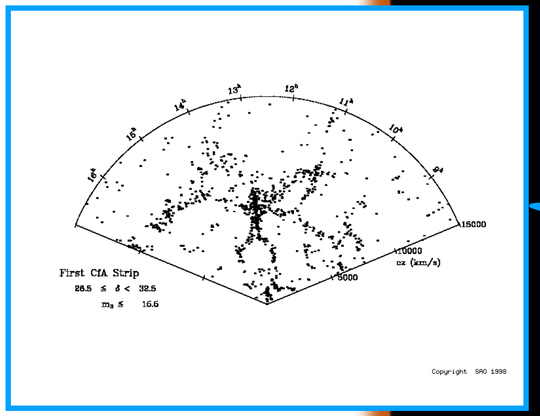
SDSS-III, 2014
2.8 million

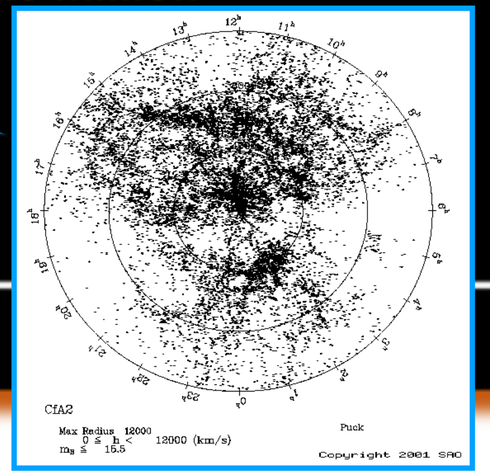
LCRS, 1996
18,678

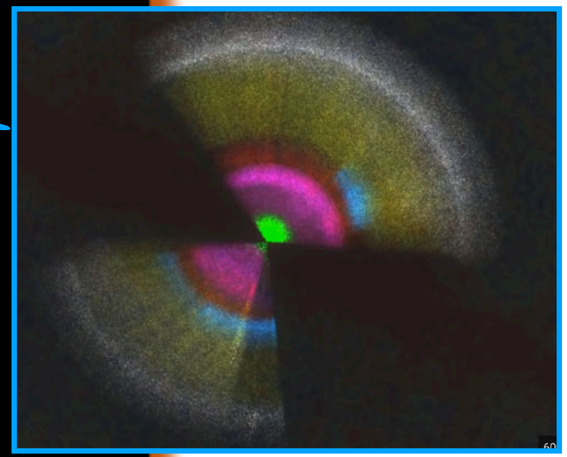
2dF, 2003
221,414

CfA1, 1983
1843

CfA-2, 1998
18,000







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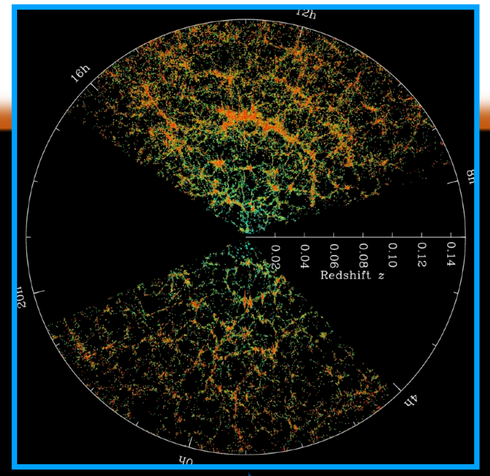

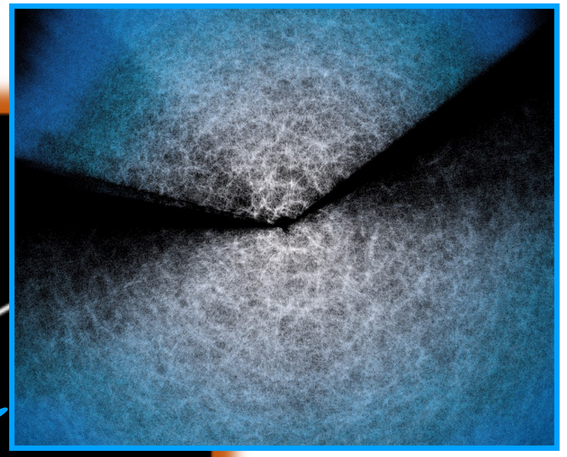

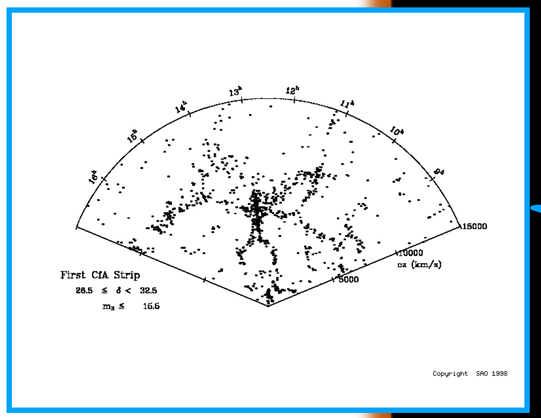

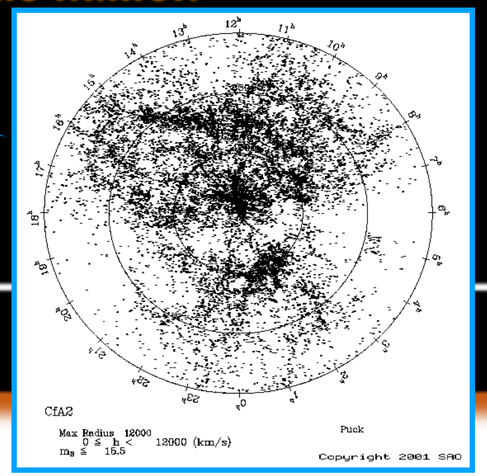

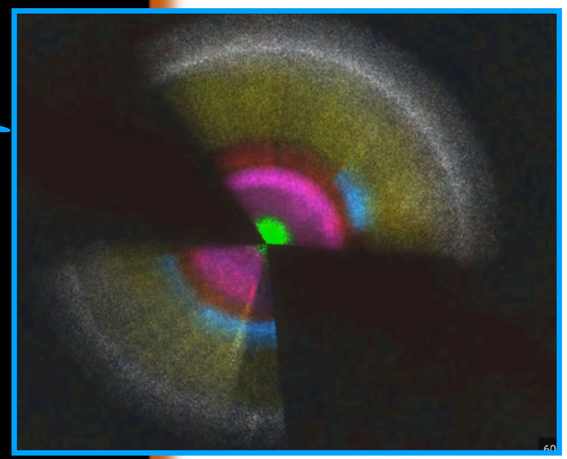

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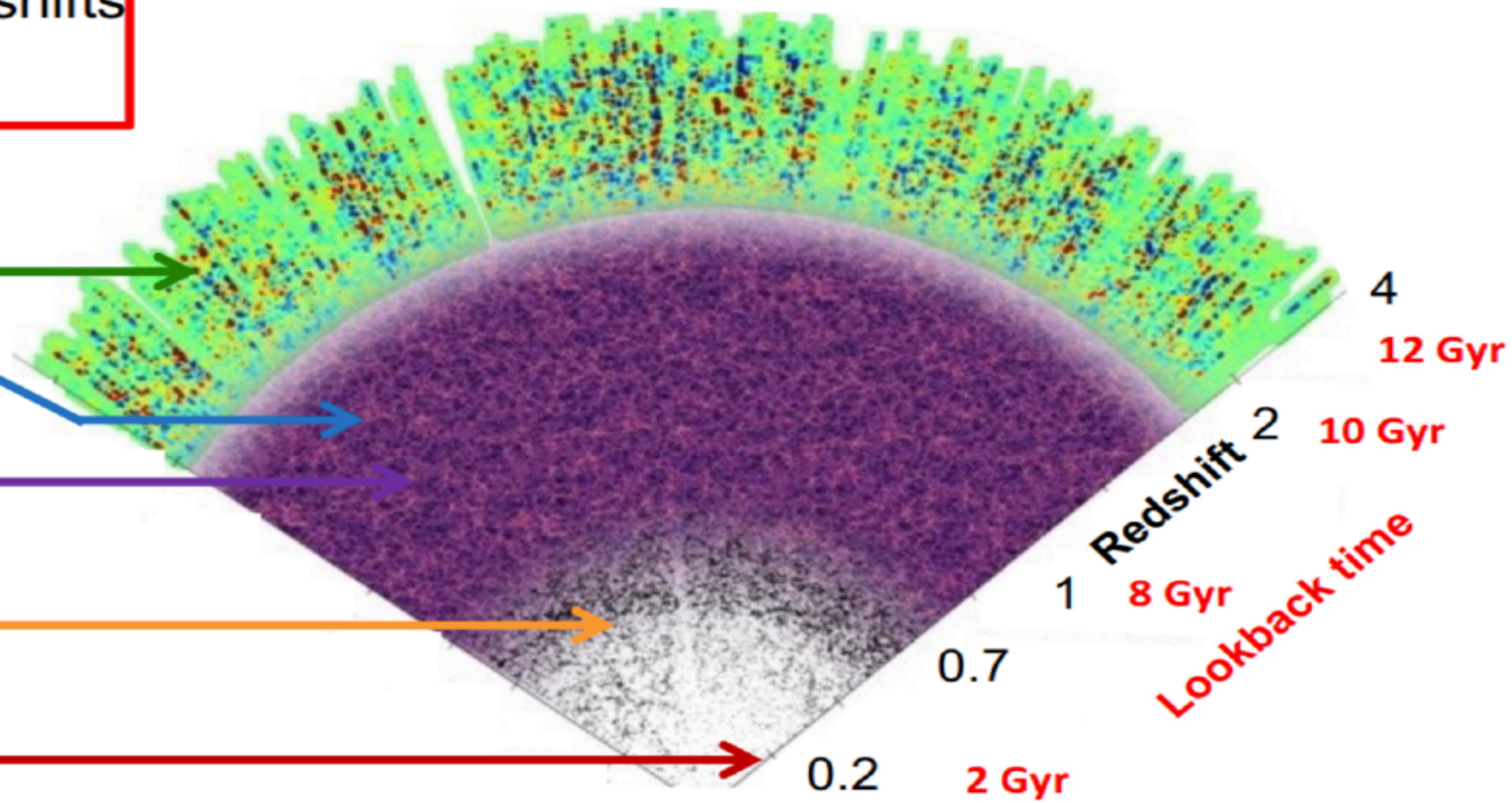
DESI survey

Five target classes

40 million redshifts

in 5 years



3 million QSOs

Lya $z > 2.1$

Tracers $0.9 < z < 2.1$

16 million ELGs

$0.6 < z < 1.6$

8 million LRGs

$0.4 < z < 1.0$

13.5 million Brightest galaxies

$0.0 < z < 0.4$

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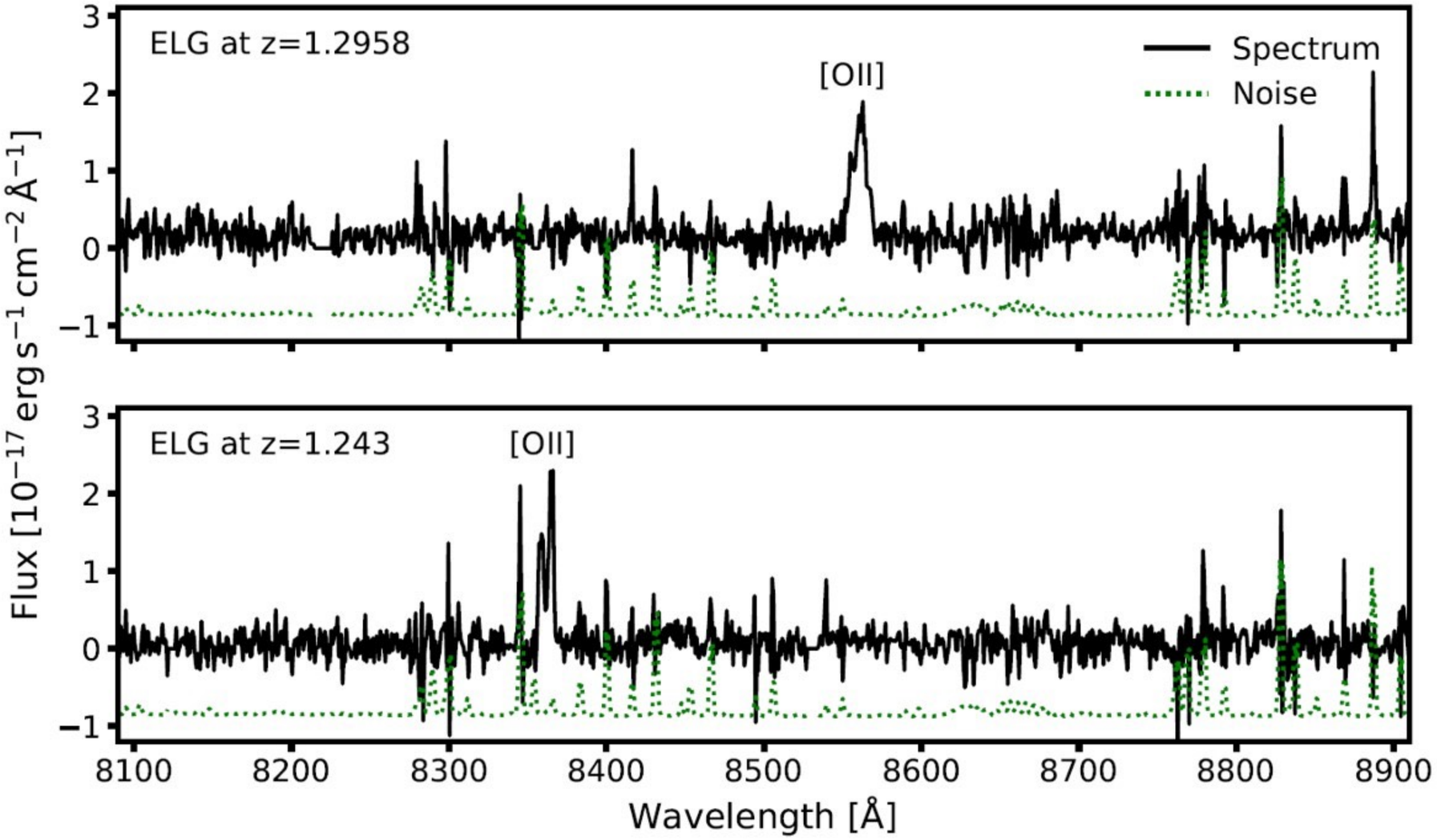
Spectra



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Mayall telescope @ Kitt Peak

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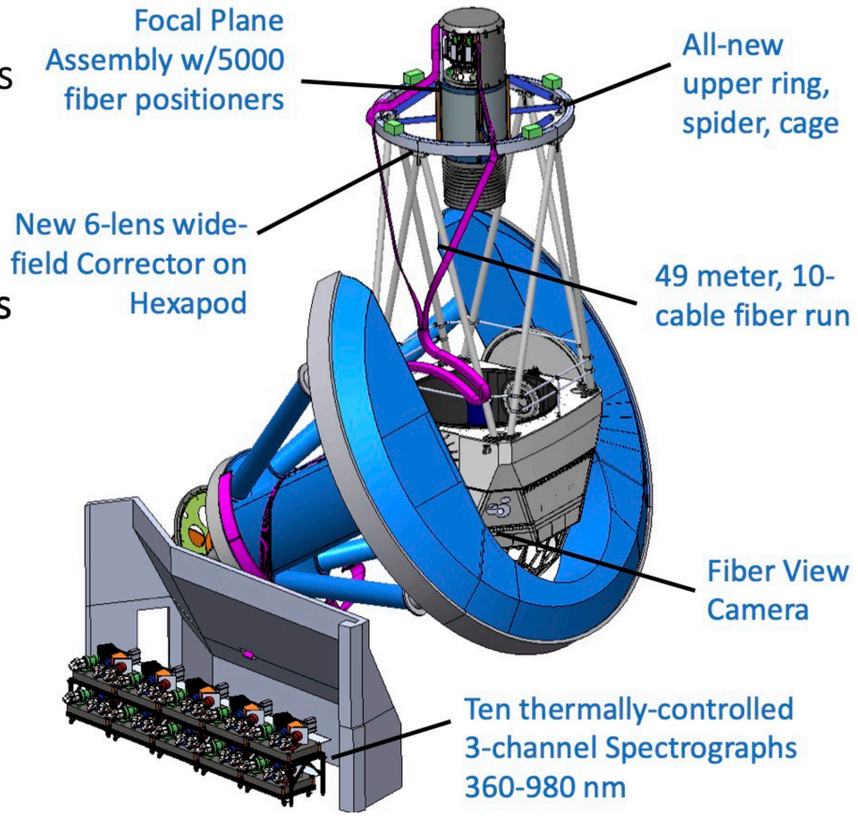
DESI instrument

DESI by the Numbers

- DESI is a Fiber-fed multi-object spectrograph. It uses robotic control to position optical fibers onto the location of a known galaxy
- 5000 fiber positioner robots on the focal plane
- 8 sq. deg. FOV
- Ten 3-channel spectrographs
- Spectra of 35 million galaxies and quasars over 14,000 deg^2 in five years



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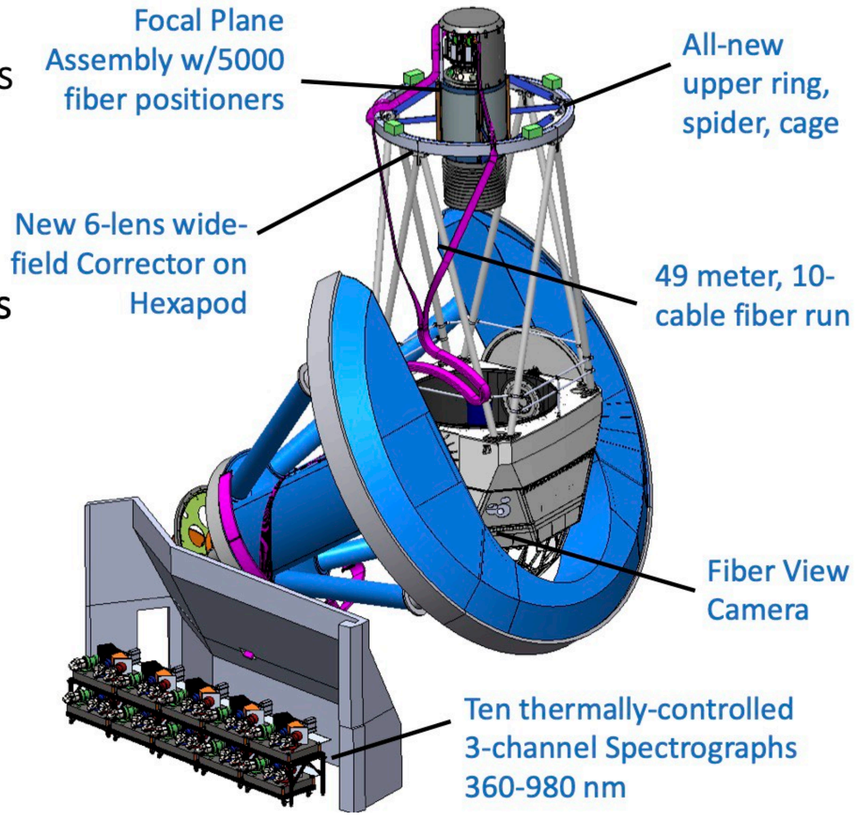

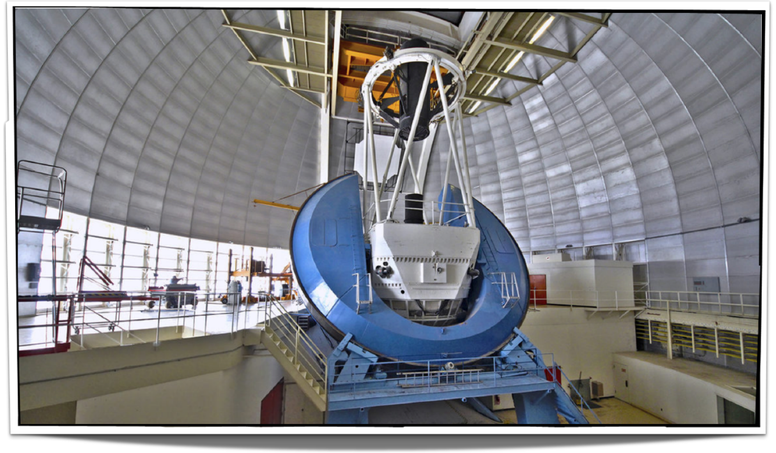

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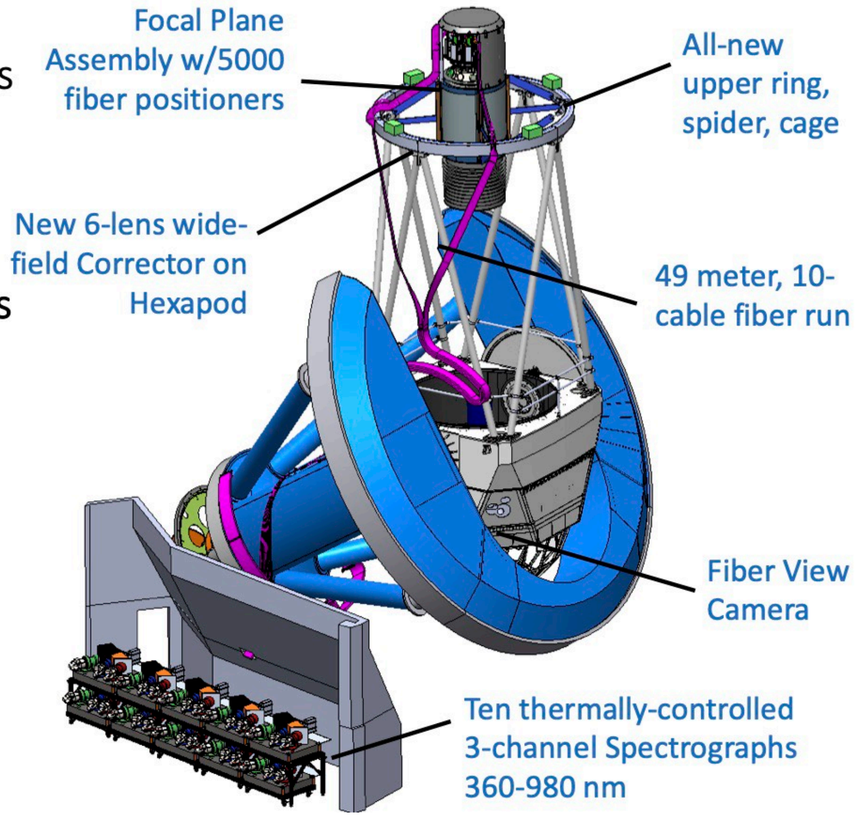

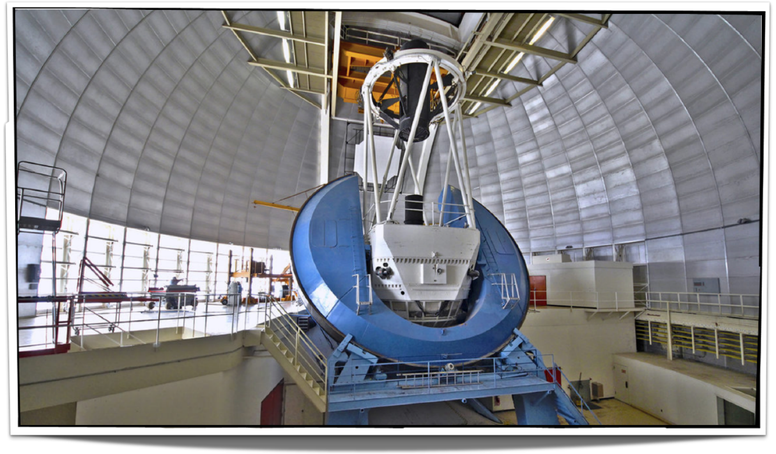

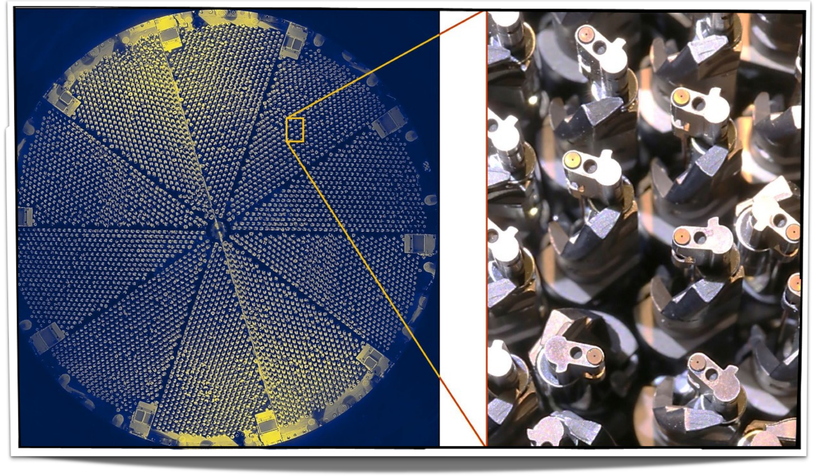

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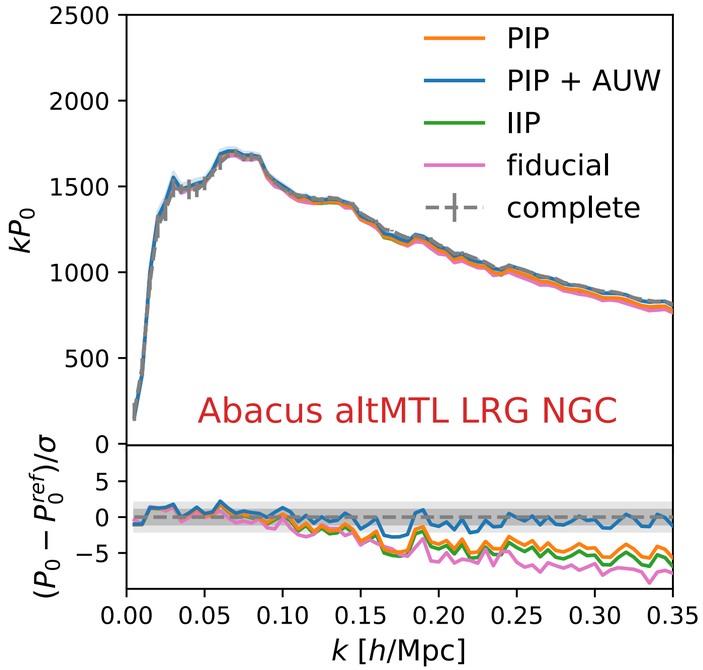
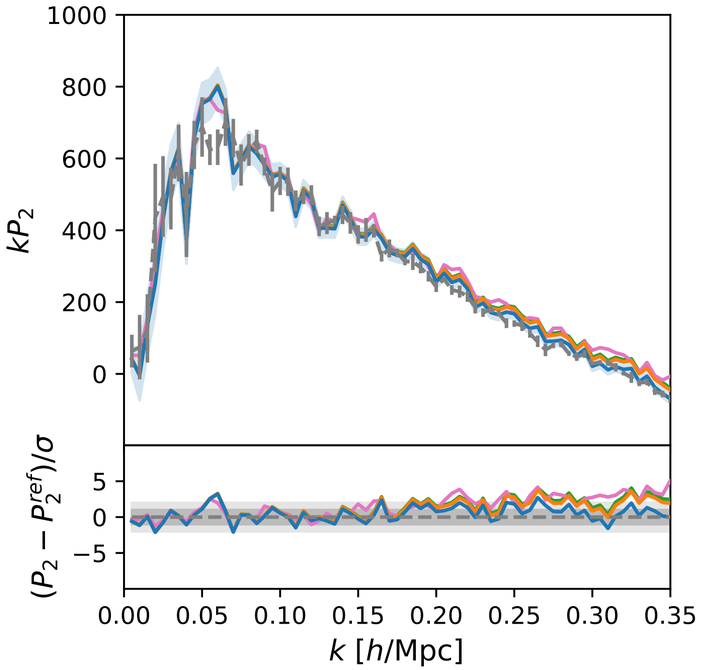
Missing observation: inverse-probability weights

DESI DR1 mocks

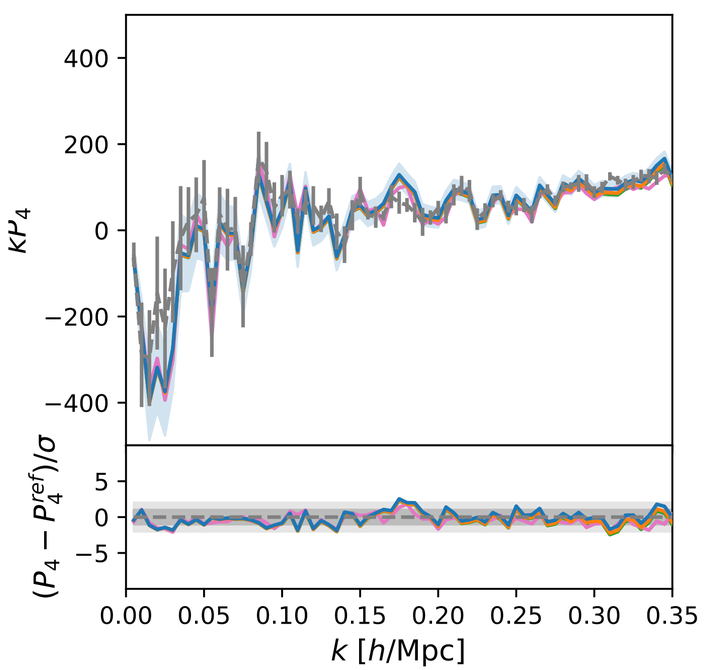
Monopole



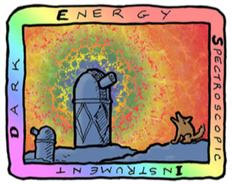
Quadrupole



Hexadecapole



Bianchi D. et al. 2025



DARK ENERGY
SPECTROSCOPIC
INSTRUMENT

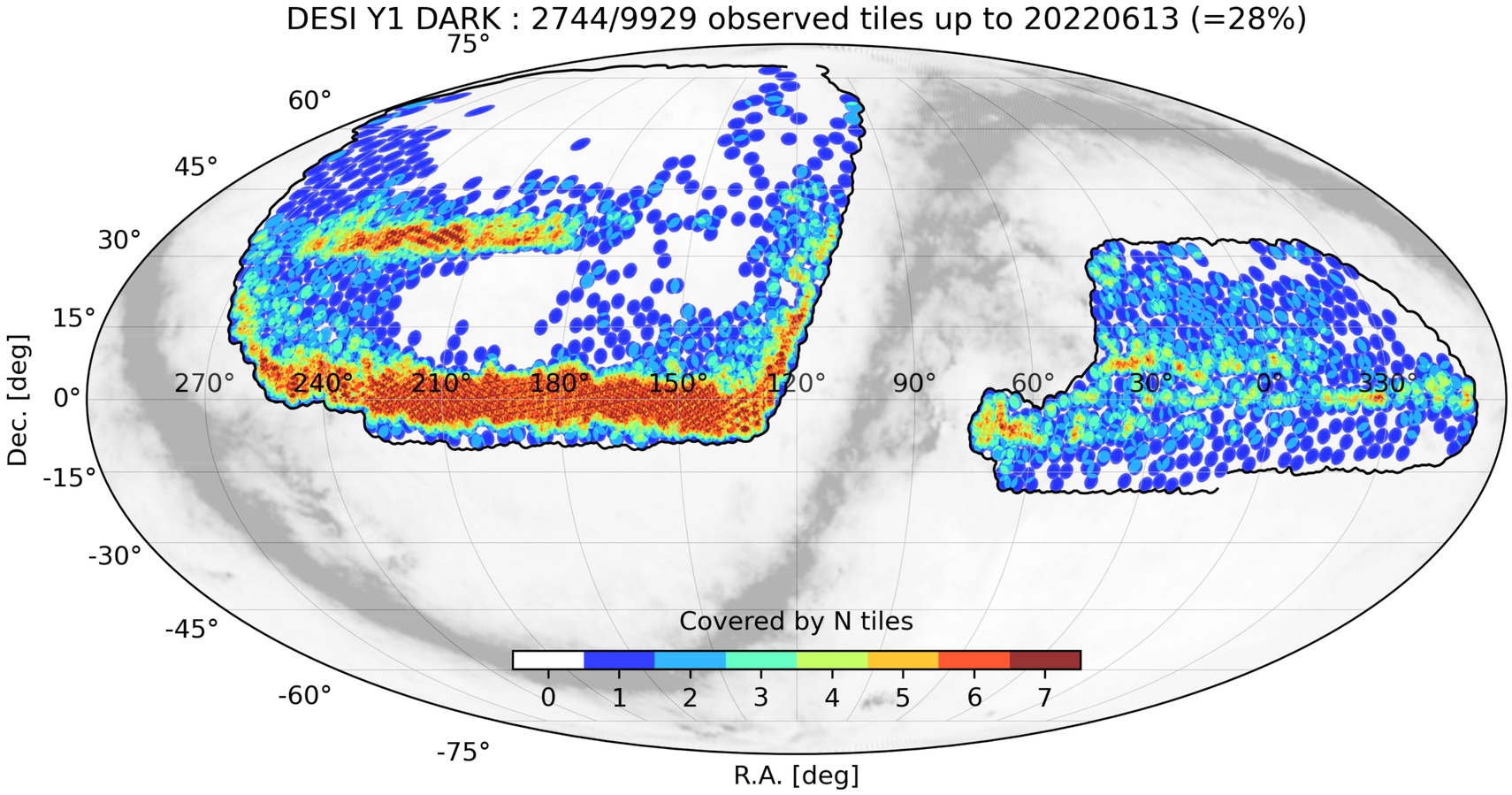
U.S. Department of Energy Office of Science

Data release 2 (DR2)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Data release 2 (DR2) sky coverage



DARK ENERGY SPECTROSCOPIC INSTRUMENT
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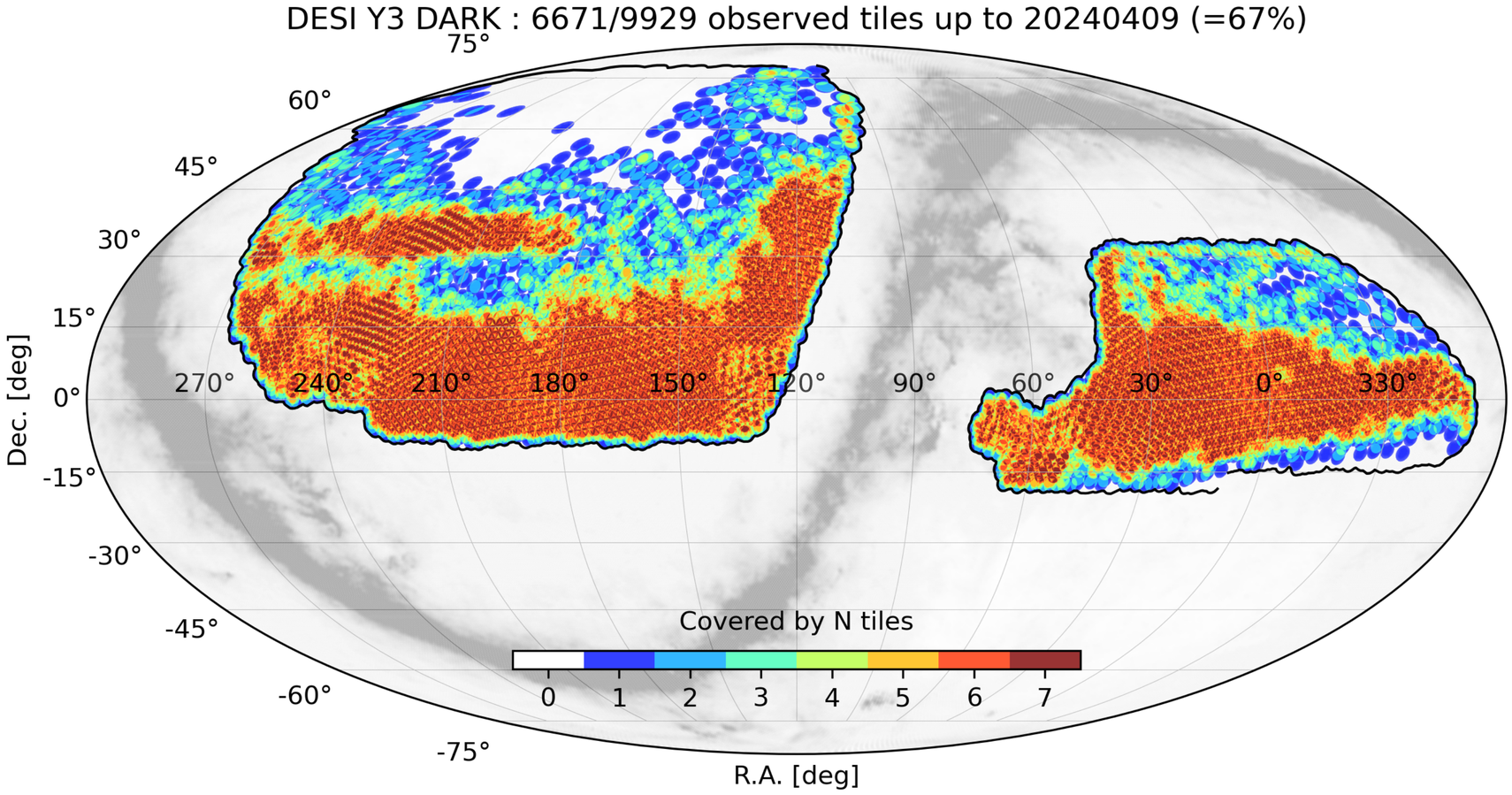
Data release 2 (DR2) sky coverage



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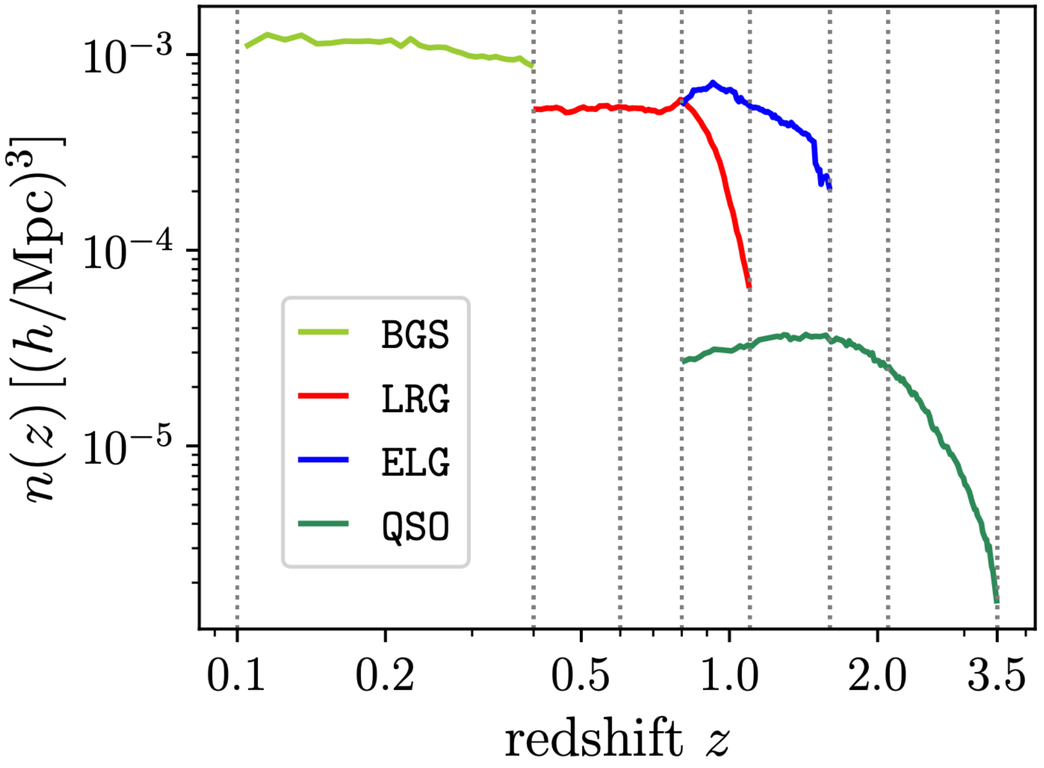
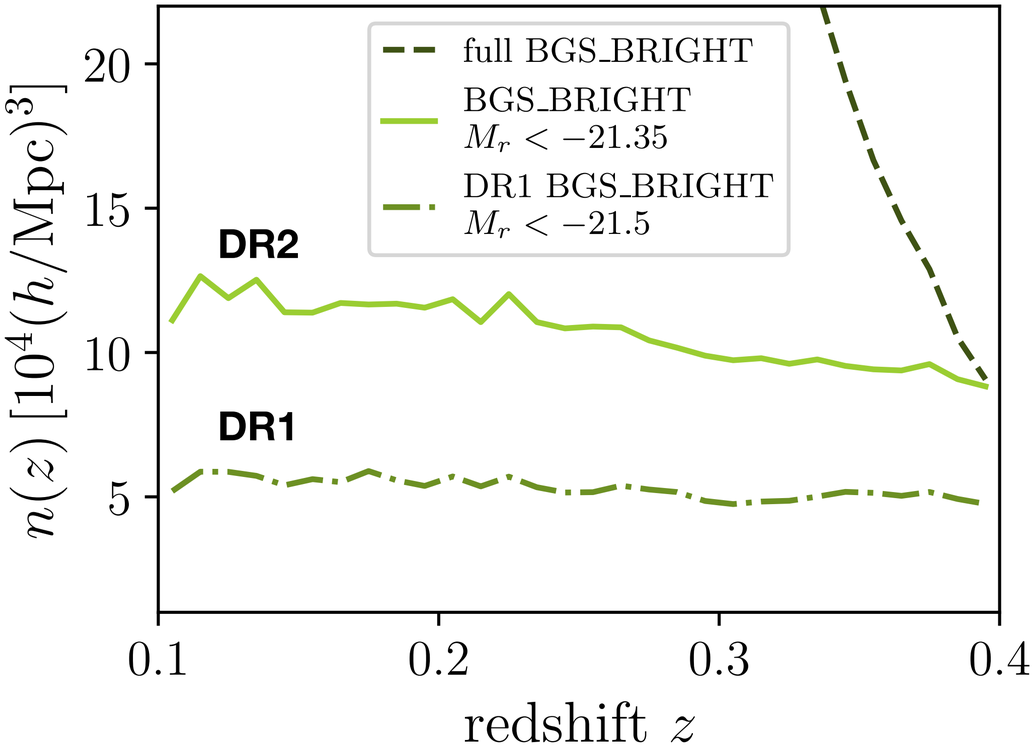
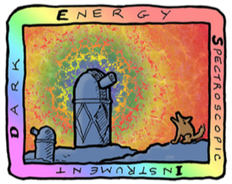
Redshift distribution







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Baryon acoustic oscillations (BAO)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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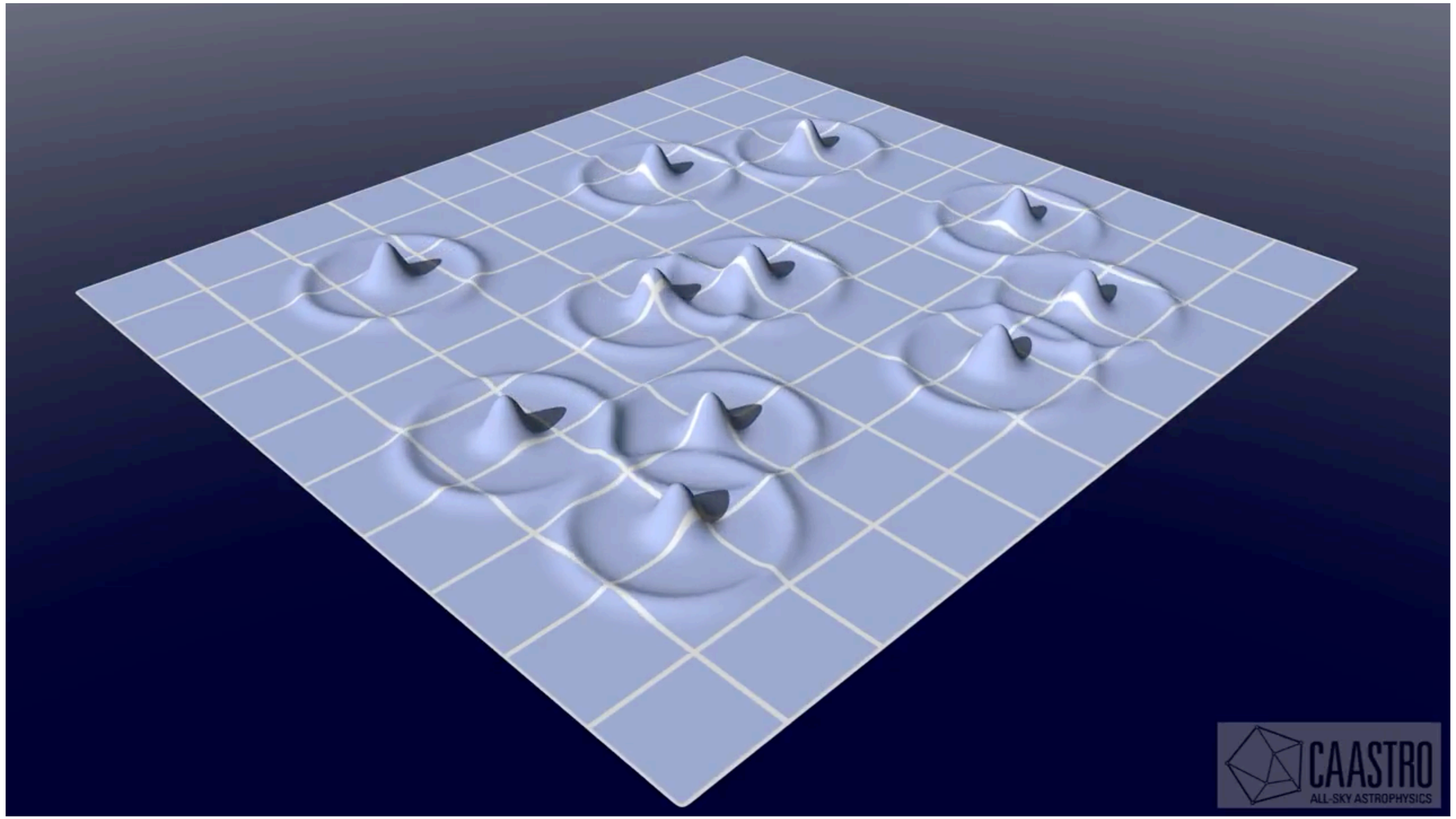
Baryon Acoustic Oscillations (BAO)



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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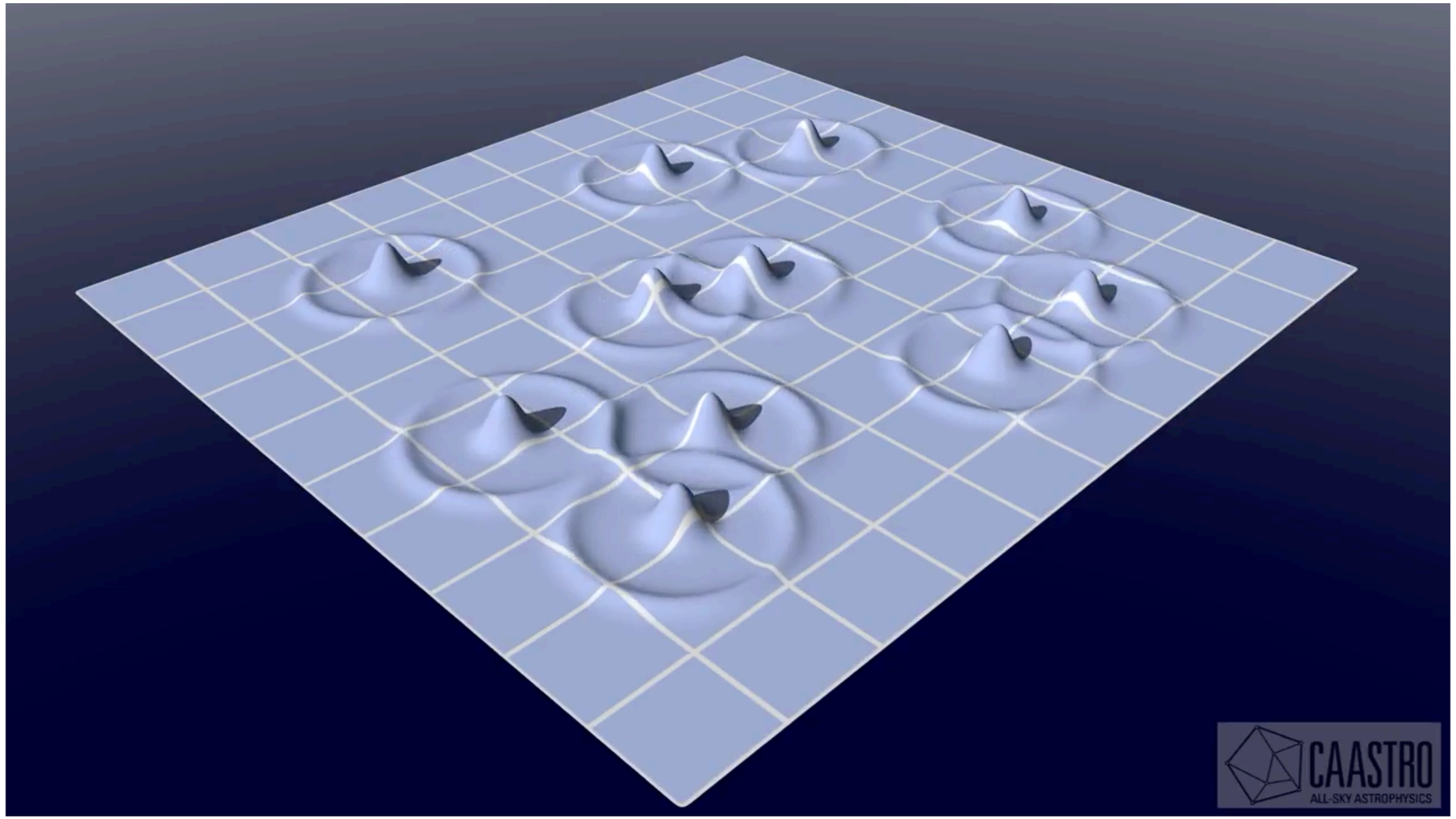
Baryon Acoustic Oscillations (BAO)



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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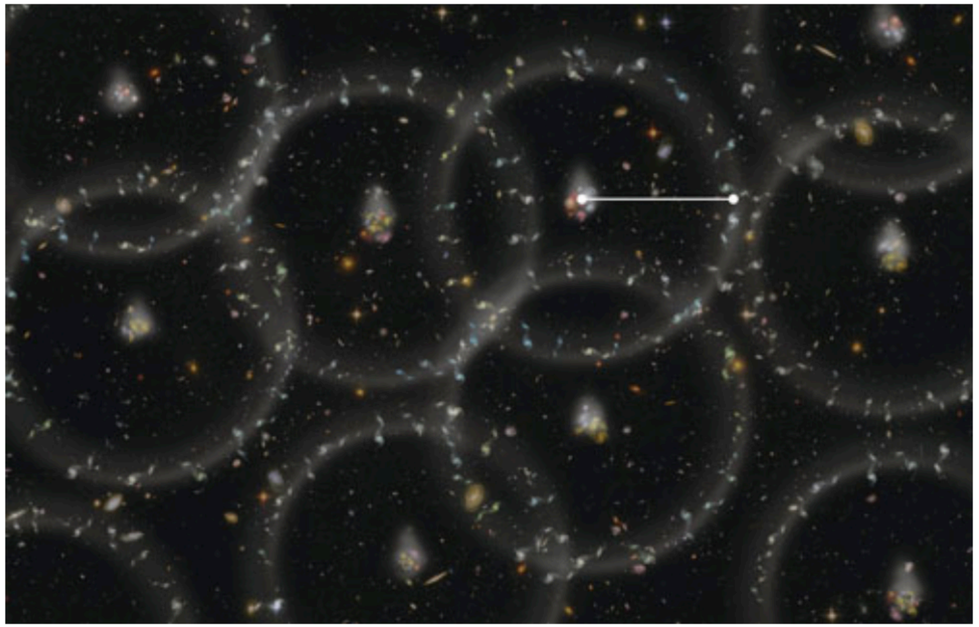
Baryon Acoustic Oscillations (BAO)



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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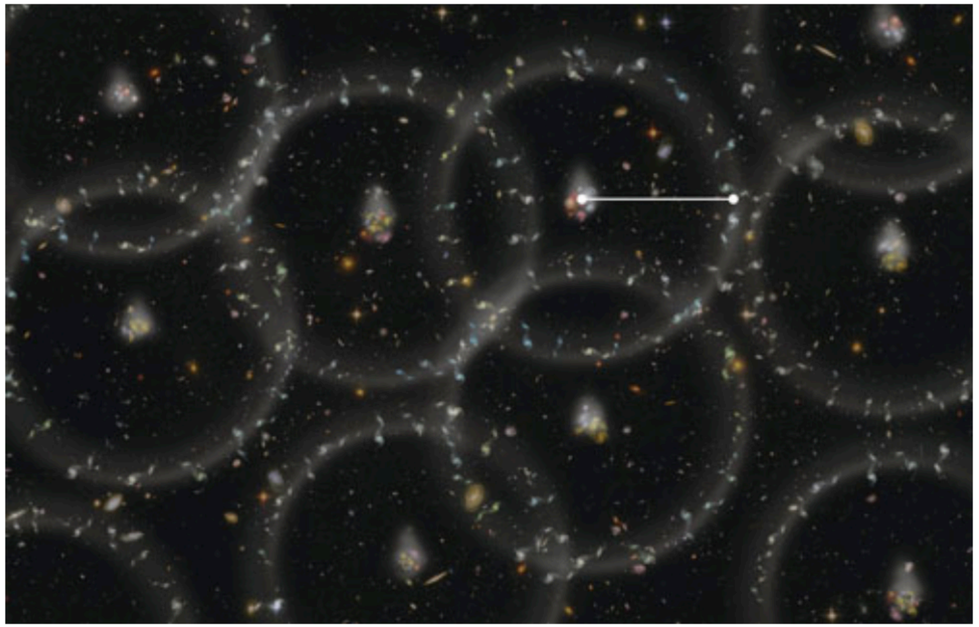
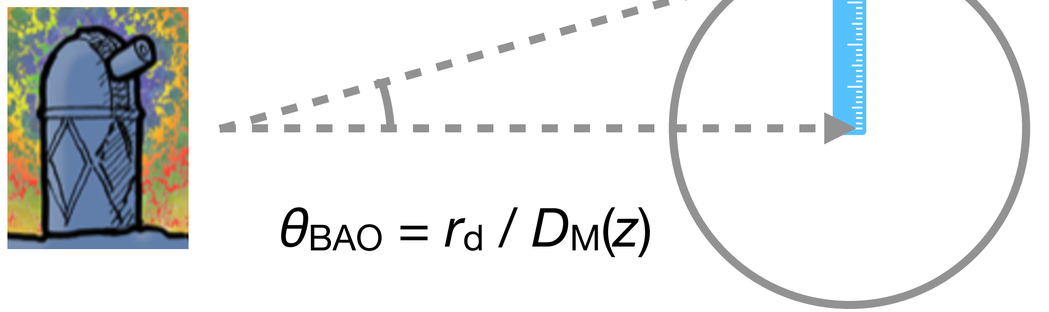
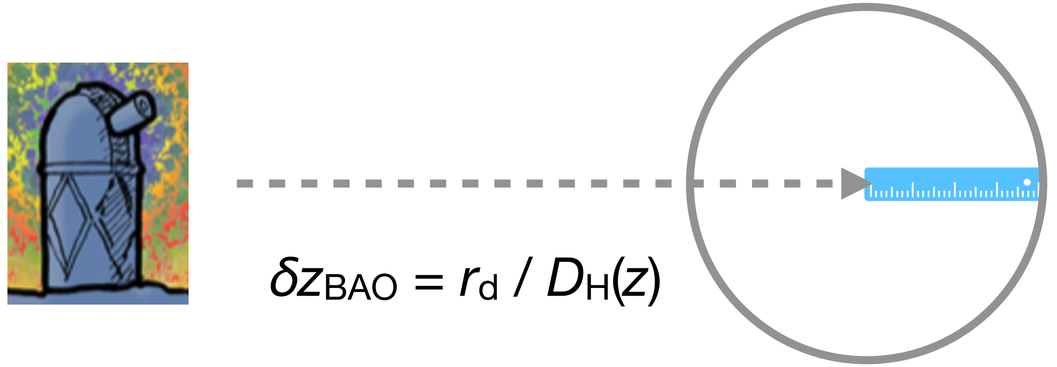
Baryon Acoustic Oscillations (BAO)







$D_M(z)$ and $D_H(z)$ encode the expansion history of the Universe

DARK ENERGY SPECTROSCOPIC INSTRUMENT
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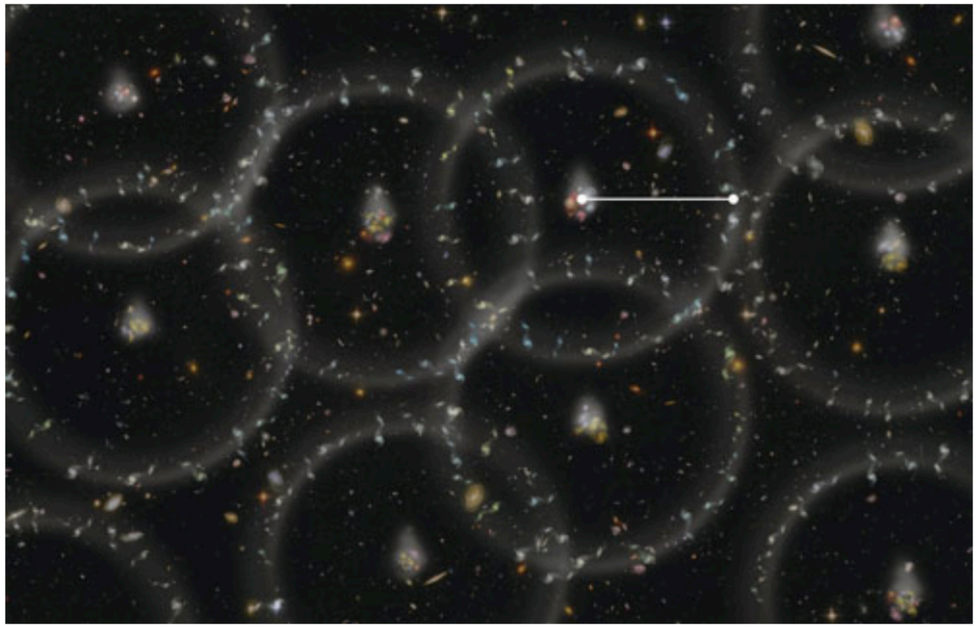
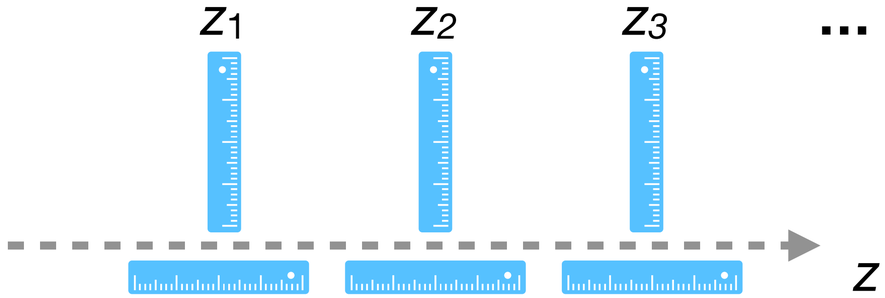
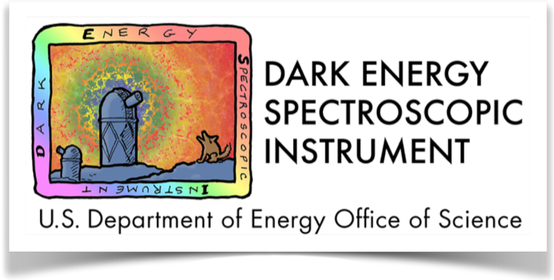
Baryon Acoustic Oscillations (BAO)





$D_M(z)$ and $D_H(z)$ encode the expansion history of the Universe



BAO scaling parameters

2 different compressions for the BAO information

1

2

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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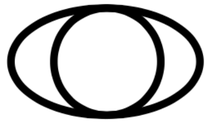
BAO scaling parameters

2 different compressions for the BAO information

1



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

perpendicular std ruler size

line-of-sight std ruler size

2

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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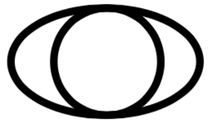
BAO scaling parameters

2 different compressions for the BAO information

1

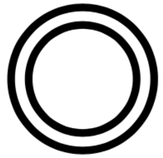


$$\alpha_{\perp} = \frac{D_{\rm M}}{r_{\rm d}} \frac{r_{\rm d}^{\rm fid}}{D_{\rm M}^{\rm fid}} \quad \text{and} \quad \alpha_{||} = \frac{D_{\rm H}}{r_{\rm d}} \frac{r_{\rm d}^{\rm fid}}{D_{\rm H}^{\rm fid}}$$

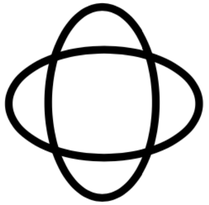
perpendicular std ruler size

line-of-sight std ruler size

2



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



overall scale of std ruler

anisotropy of std ruler

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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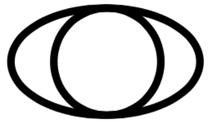
BAO scaling parameters

2 different compressions for the BAO information

1

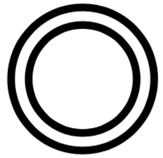


$$\alpha_{\perp} = \frac{D_{\rm M}}{r_{\rm d}} \frac{r_{\rm d}^{\rm fid}}{D_{\rm M}^{\rm fid}} \quad \text{and} \quad \alpha_{||} = \frac{D_{\rm H}}{r_{\rm d}} \frac{r_{\rm d}^{\rm fid}}{D_{\rm H}^{\rm fid}}$$

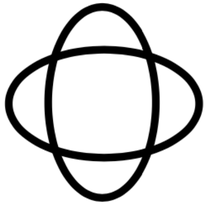
perpendicular std ruler size

line-of-sight std ruler size

2



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



overall scale of std ruler

anisotropy of std ruler

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

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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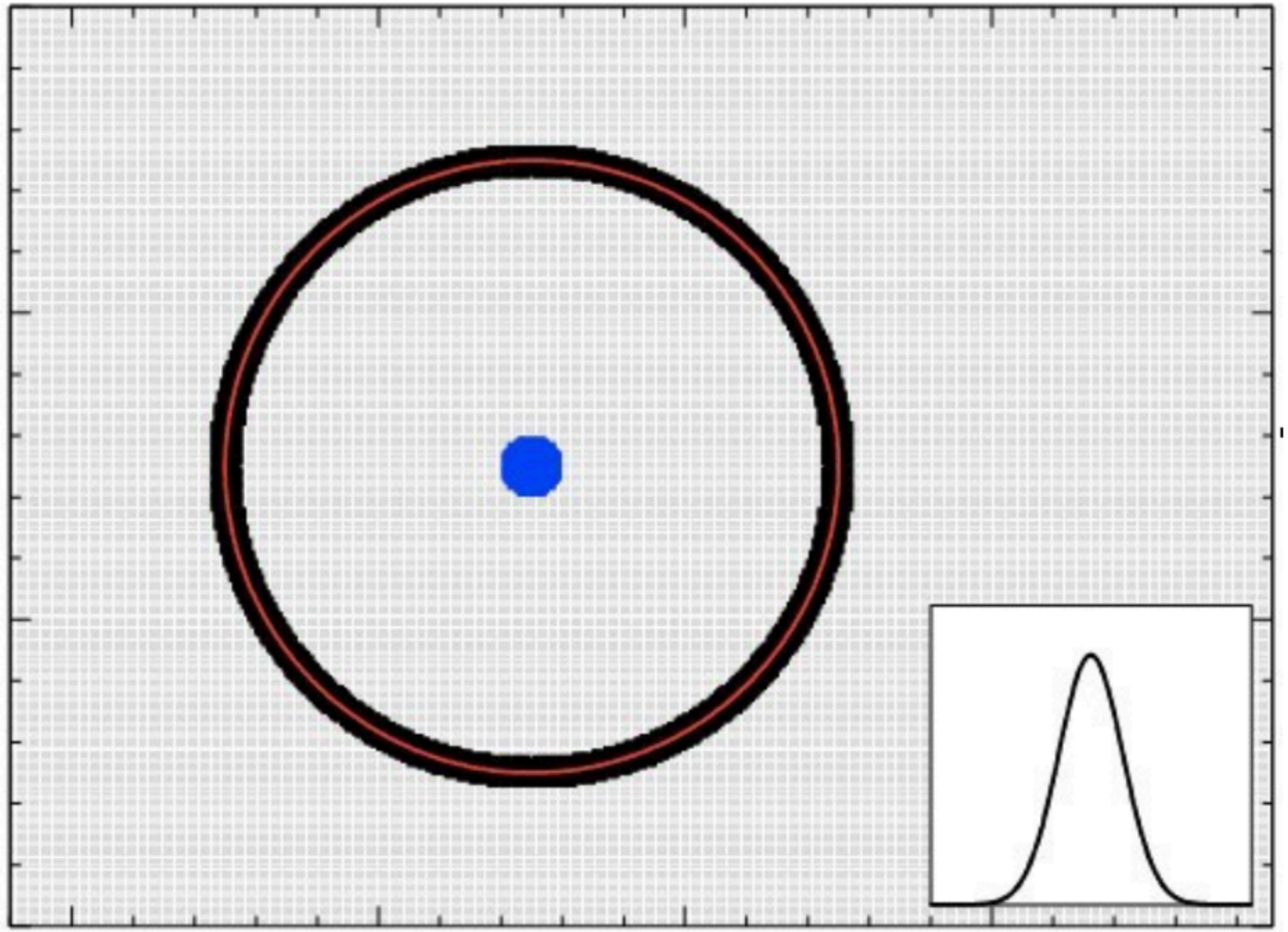
BAO reconstruction



Eisenstein+ 2008,
Padmanabhan+ 2012

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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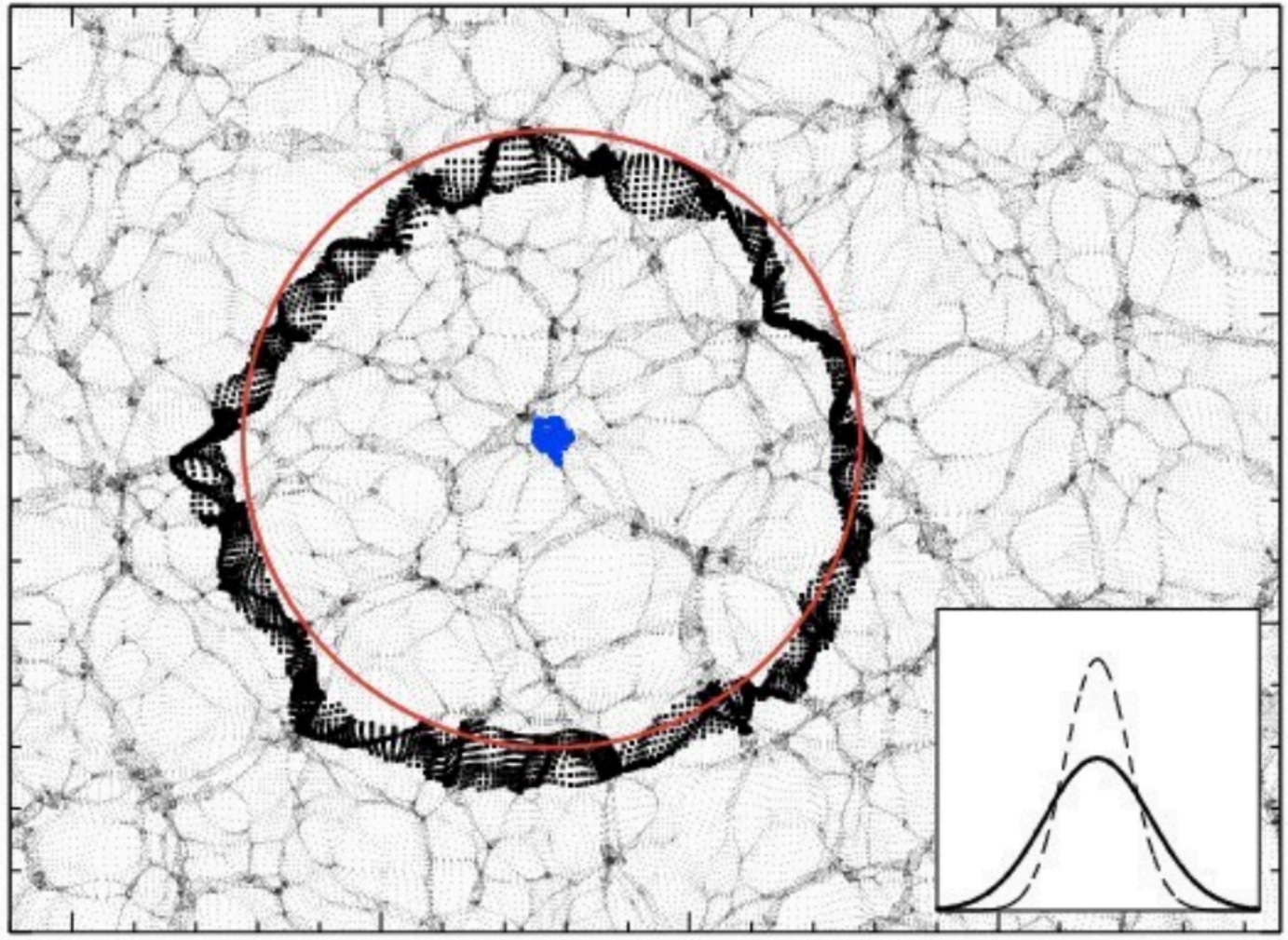
BAO reconstruction



Eisenstein+ 2008,
Padmanabhan+ 2012

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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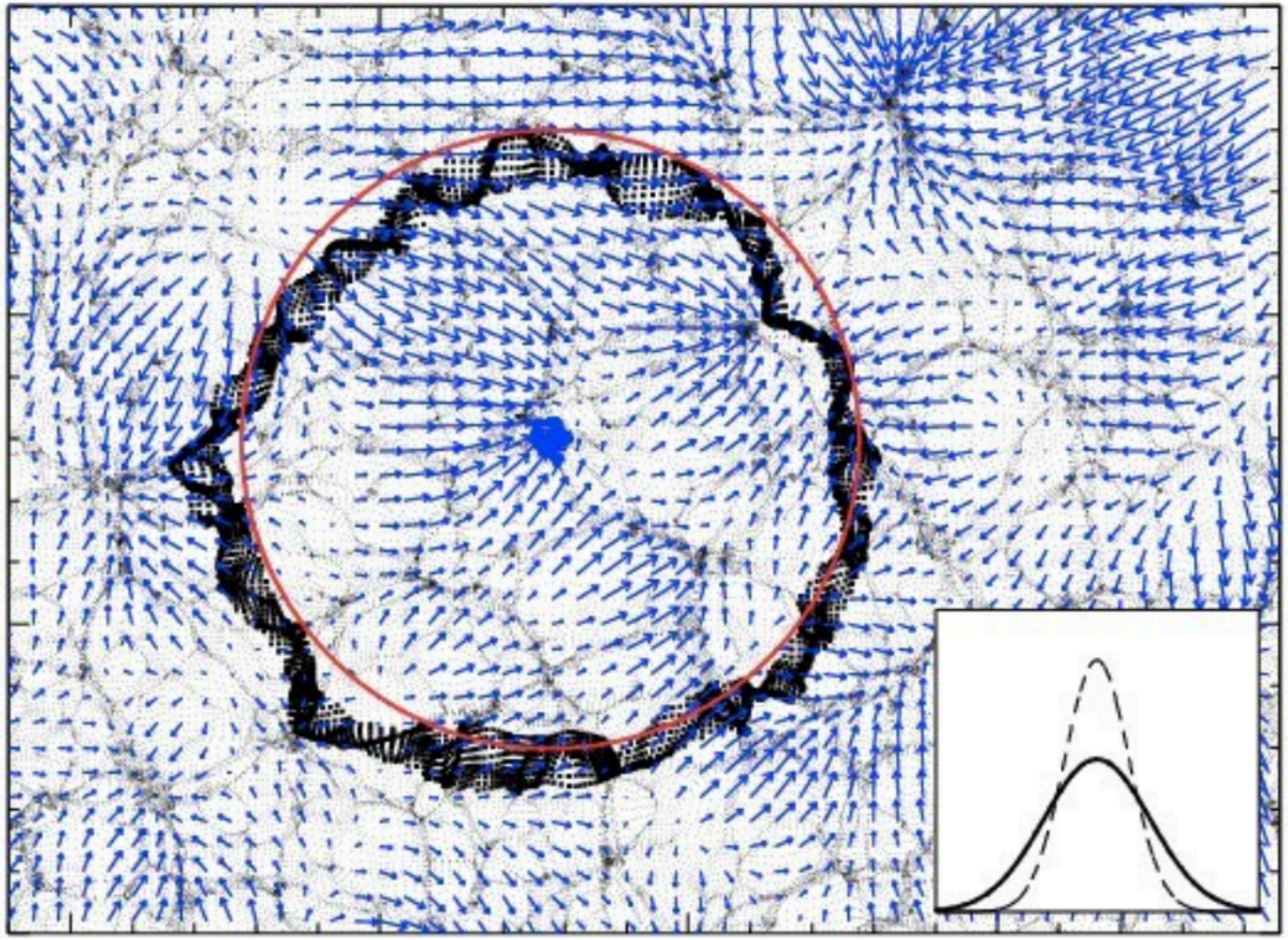
BAO reconstruction



Zeldovich displacement Field

Eisenstein+ 2008,
Padmanabhan+ 2012

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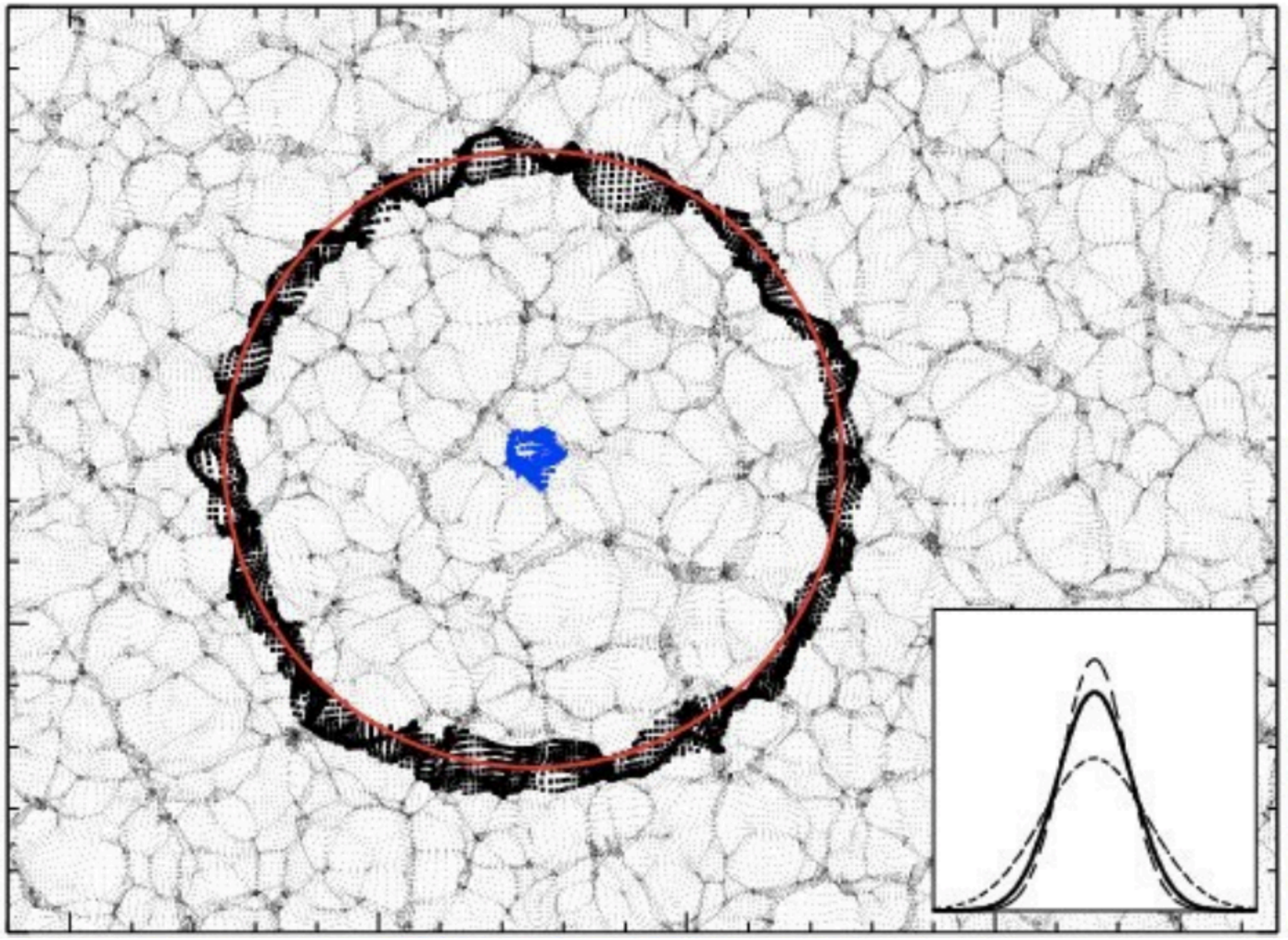
BAO reconstruction



Eisenstein+ 2008,
Padmanabhan+ 2012

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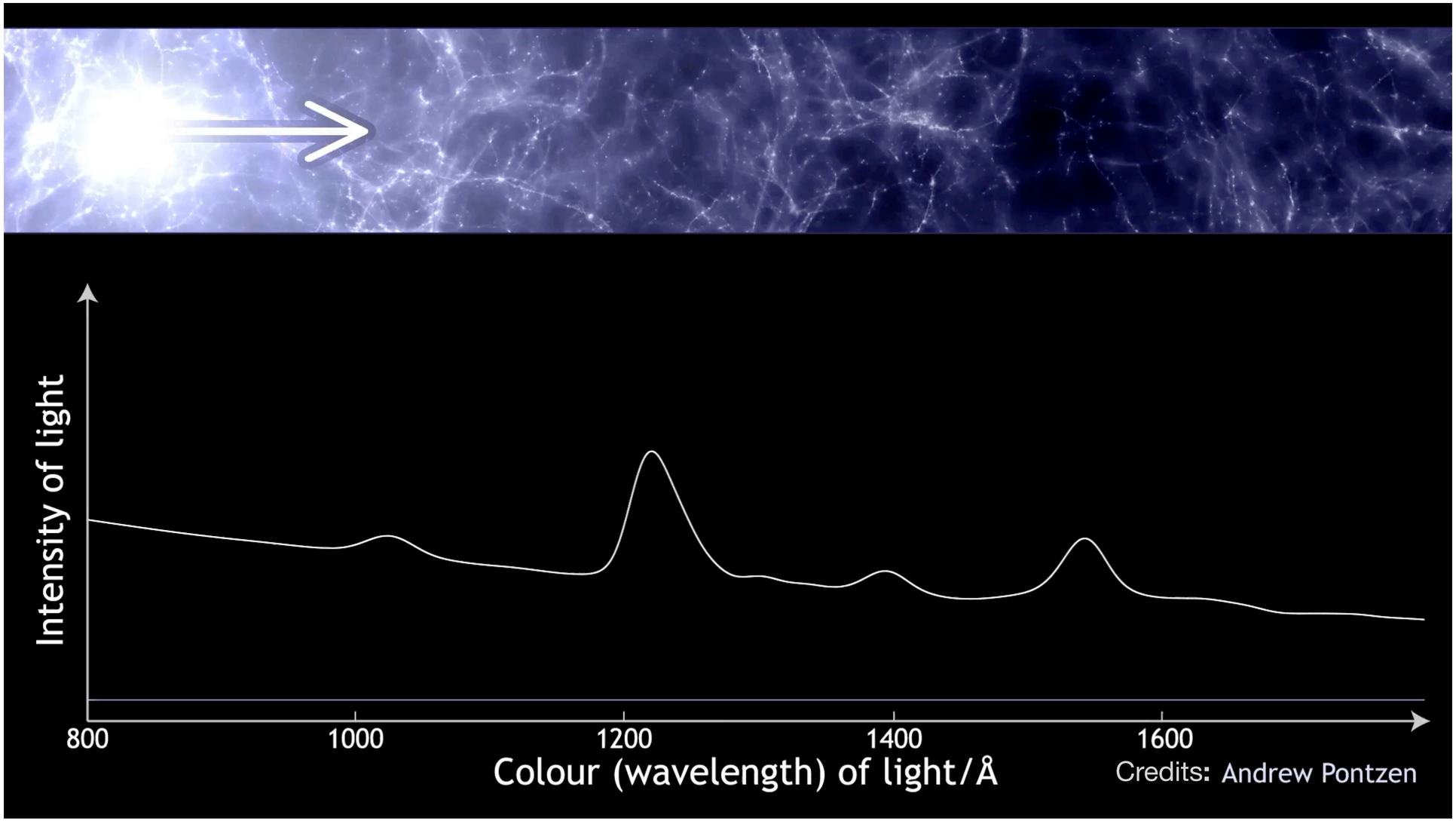
Lyman alpha (Lyα) forest



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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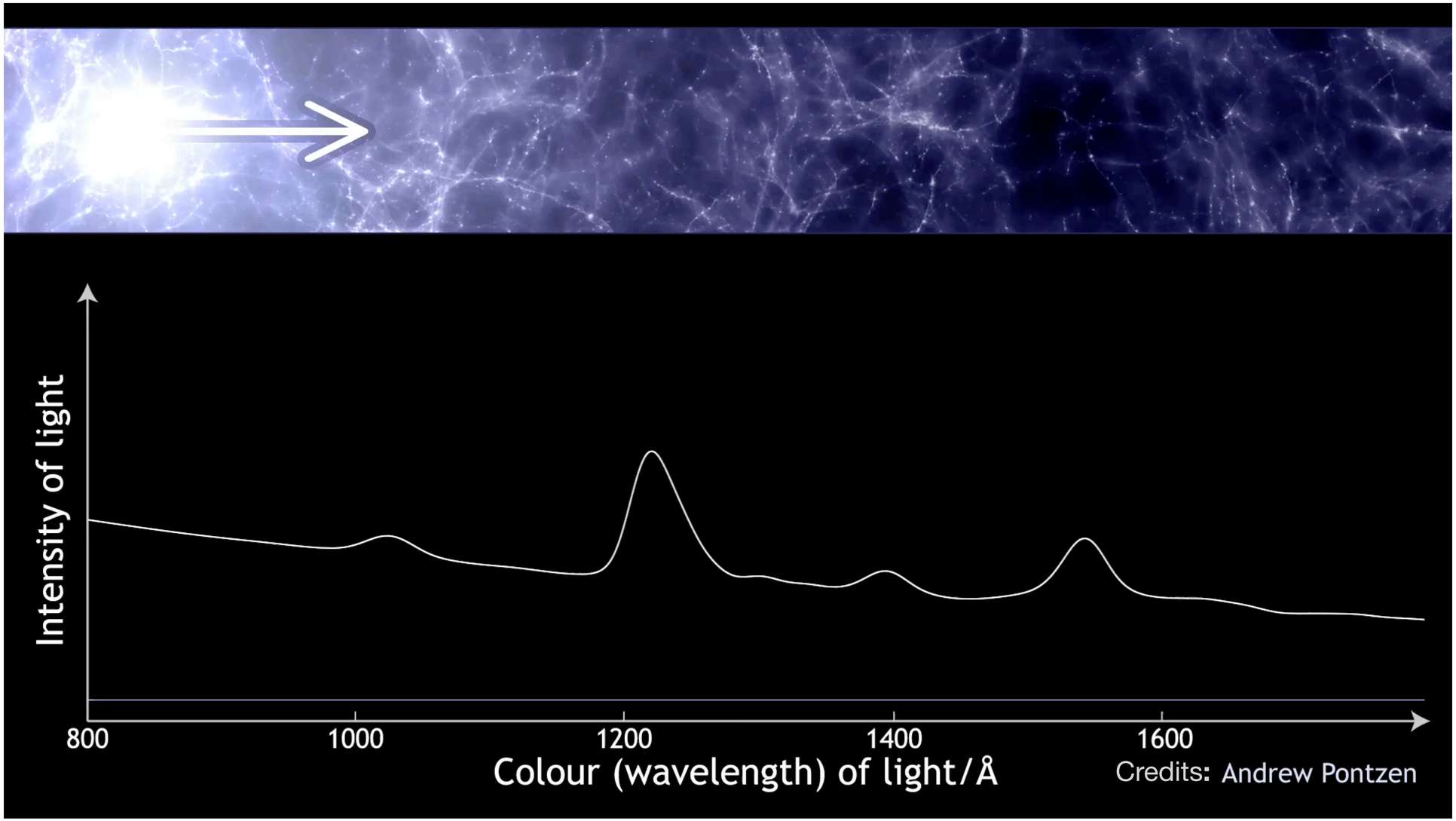
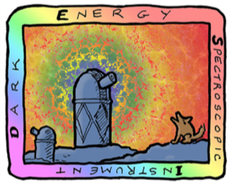
Lyman alpha (Lyα) forest





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Cosmological results

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DESI DR2 blinding

BAO measurements were kept blinded during validation process

Galaxies: catalog-level blinding that modifies redshifts and weights

Lyα forest: data-vector blinding that shifts BAO peak

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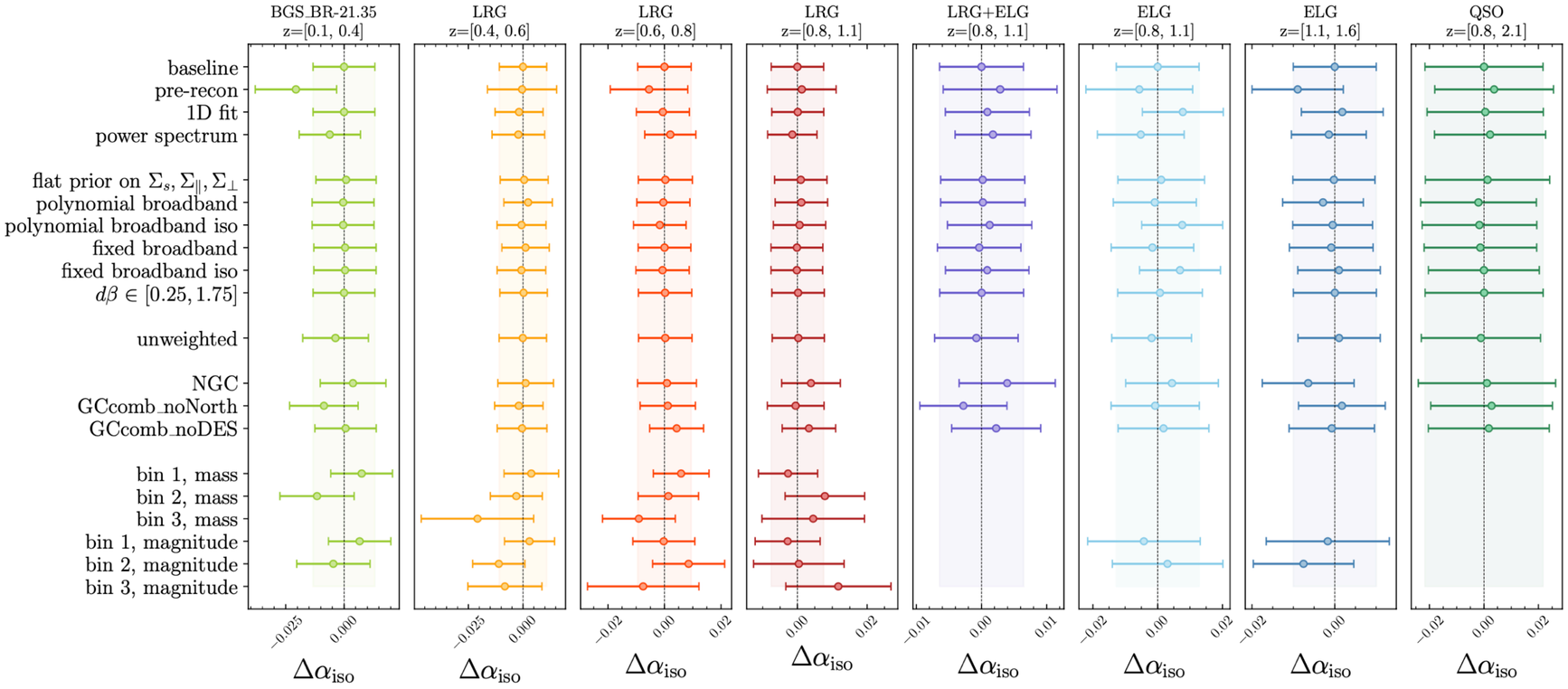
DR2 BAO robustness



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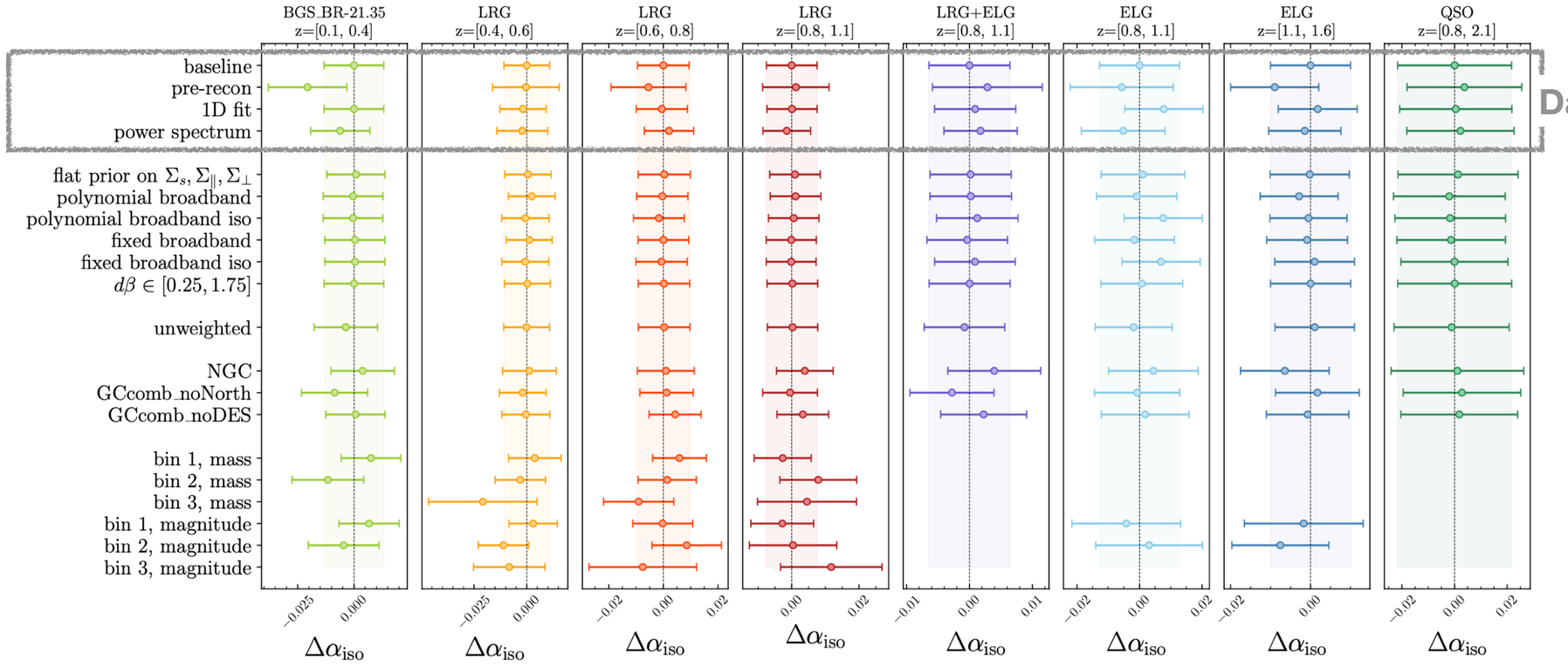
DR2 BAO robustness



Data vector choices

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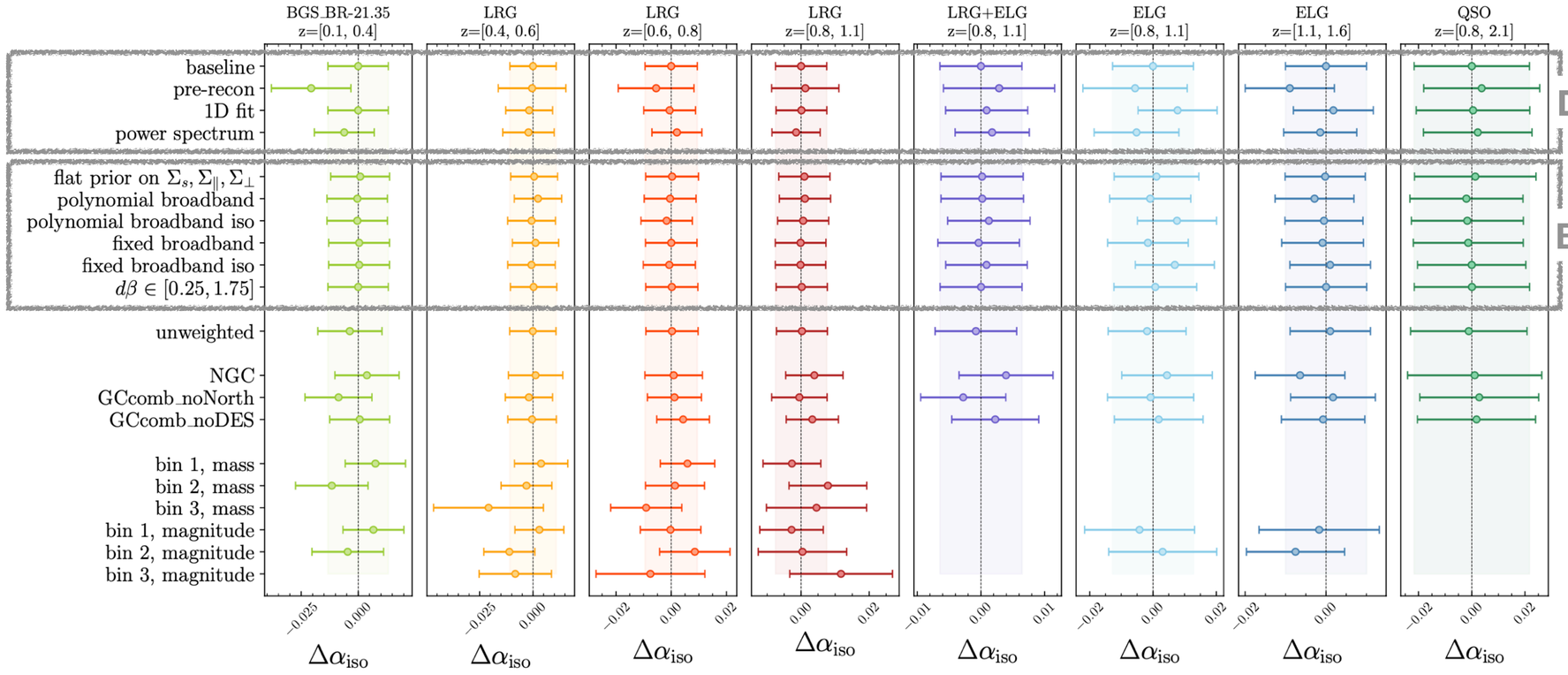
DR2 BAO robustness



Data vector choices

BAO modelling

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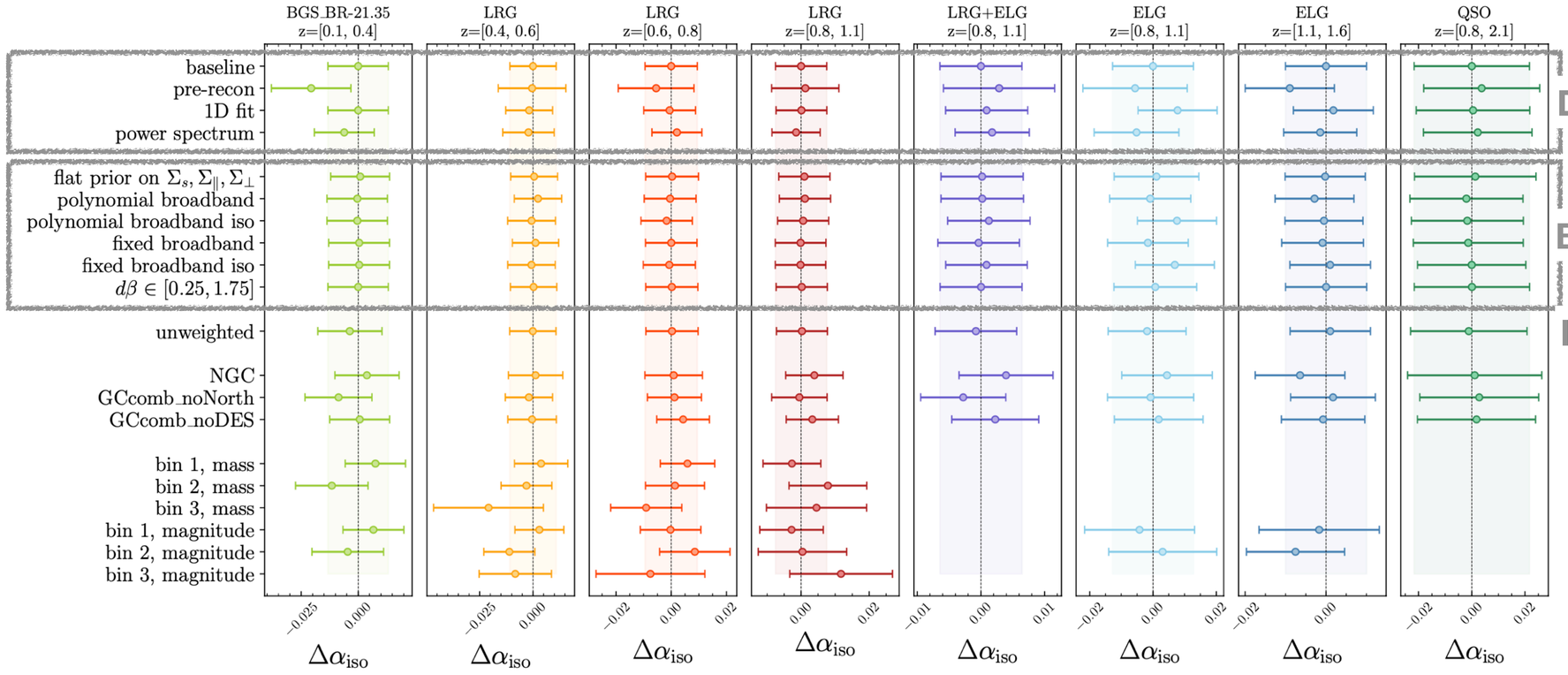
DR2 BAO robustness



Data vector choices

BAO modelling

Imaging systematics

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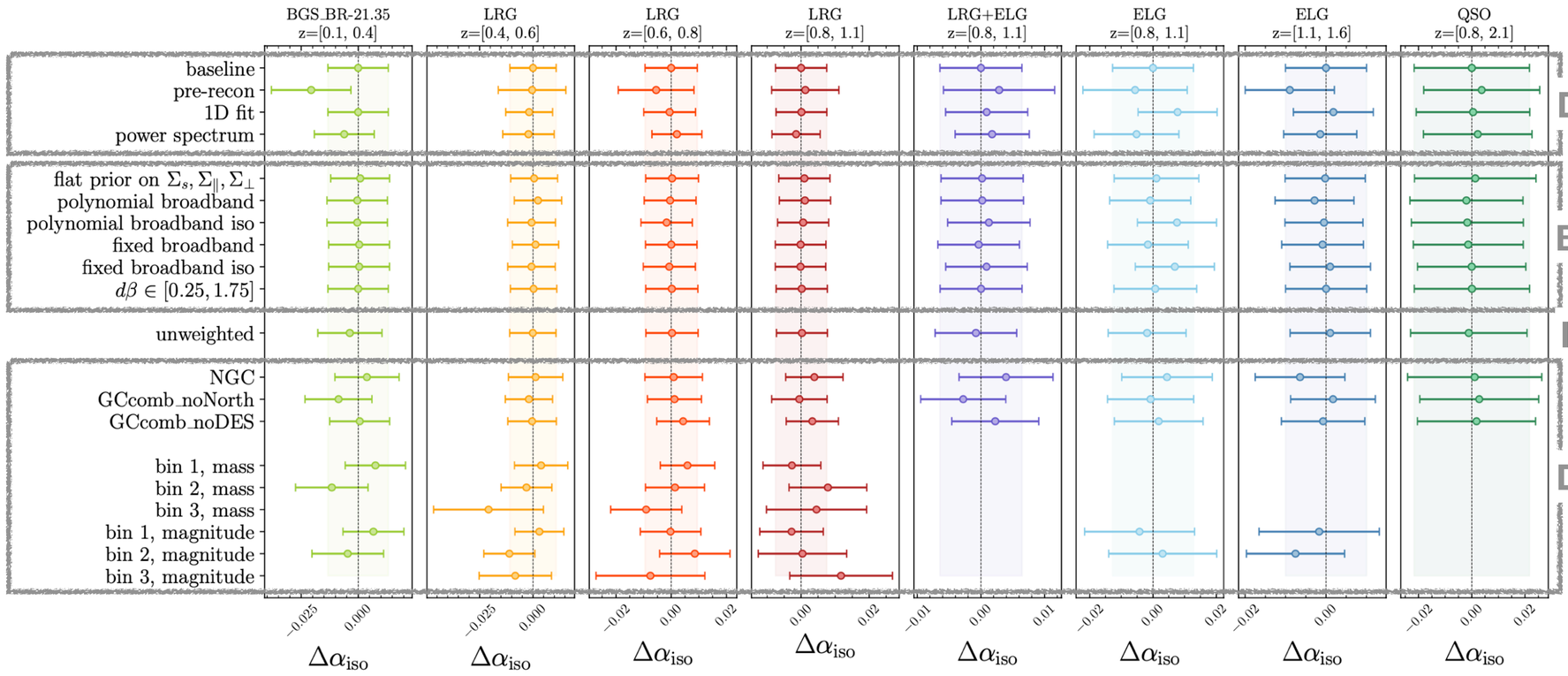
DR2 BAO robustness



Data vector choices

BAO modelling

Imaging systematics

Data splits

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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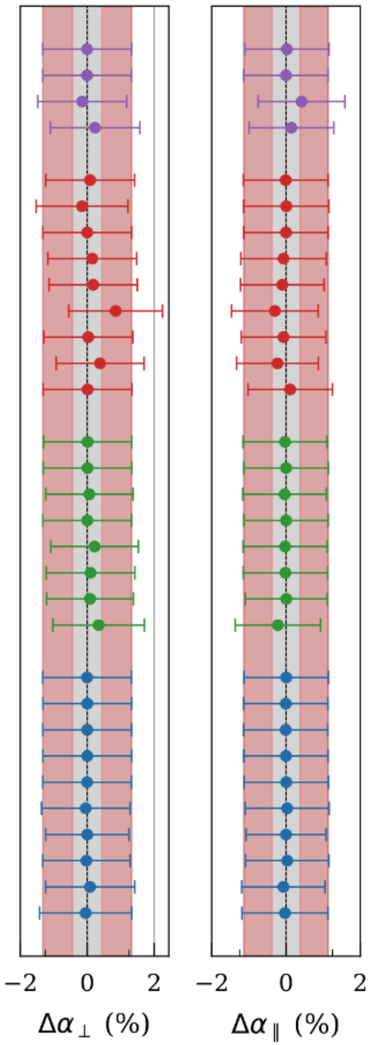
DR2 Lyα BAO robustness



no calibration
$\eta_{\rm pip} = 1$
$\eta_{\rm LSS} = 3.5$
$\Delta\lambda = 2.4\,Å$

$\lambda_{\rm obs} < 5500\,Å$
$\lambda_{\rm obs} > 3650\,Å$
$\lambda_{\rm RF} < 1200\,Å$
$z_Q < 3.78$
> 50 pixels in forest
only quasar targets
mask DLAs with SNR_RED > 3
weak BALs
no sharp lines mask

dmat $r_\parallel < 200$ Mpc/h
dmat 2%
dmat model 4 Mpc/h
dmat model z-indep
$\Delta\lambda = 3.2\,Å$
$\Delta\lambda = 1.6\,Å$
nside = 32
$\Delta r = 5$ Mpc/h

Gaussian redshift errors
no prior on L0_HCD
no prior on beta_HCD
no prior on drp_QSO
no prior on bias_QSO
no prior on bias_CIV_eff
UV fluctuations
ignore small-scales correction
ignore modelling of sky residuals
ignore quasar radiation

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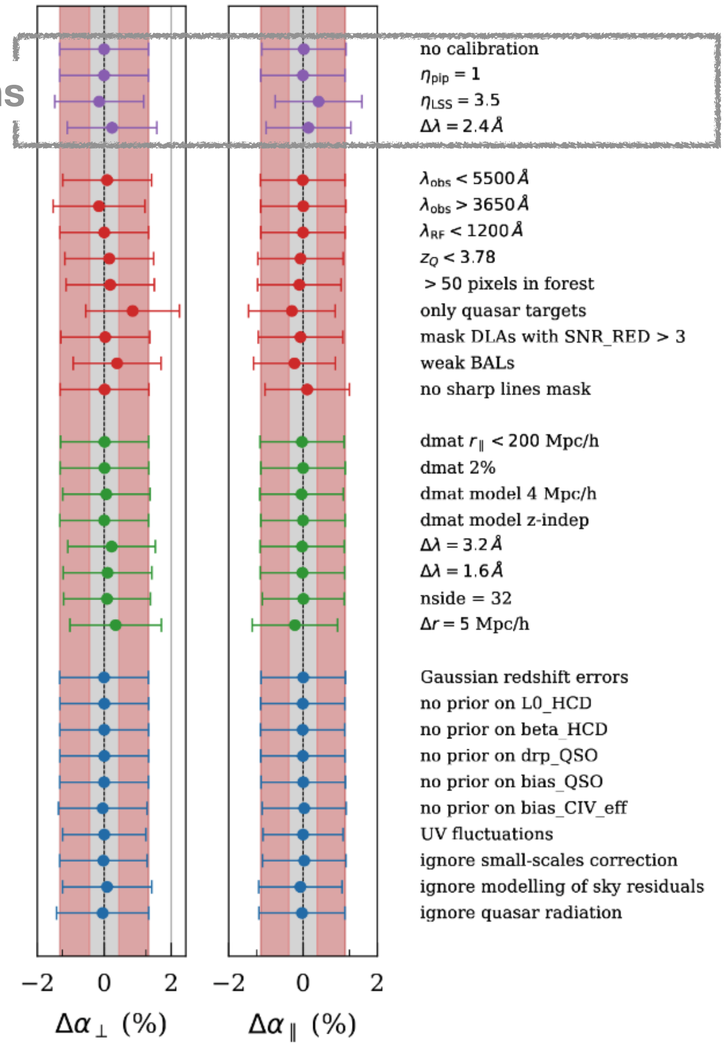
DR2 Lyα BAO robustness

Method to estimate the fluctuations



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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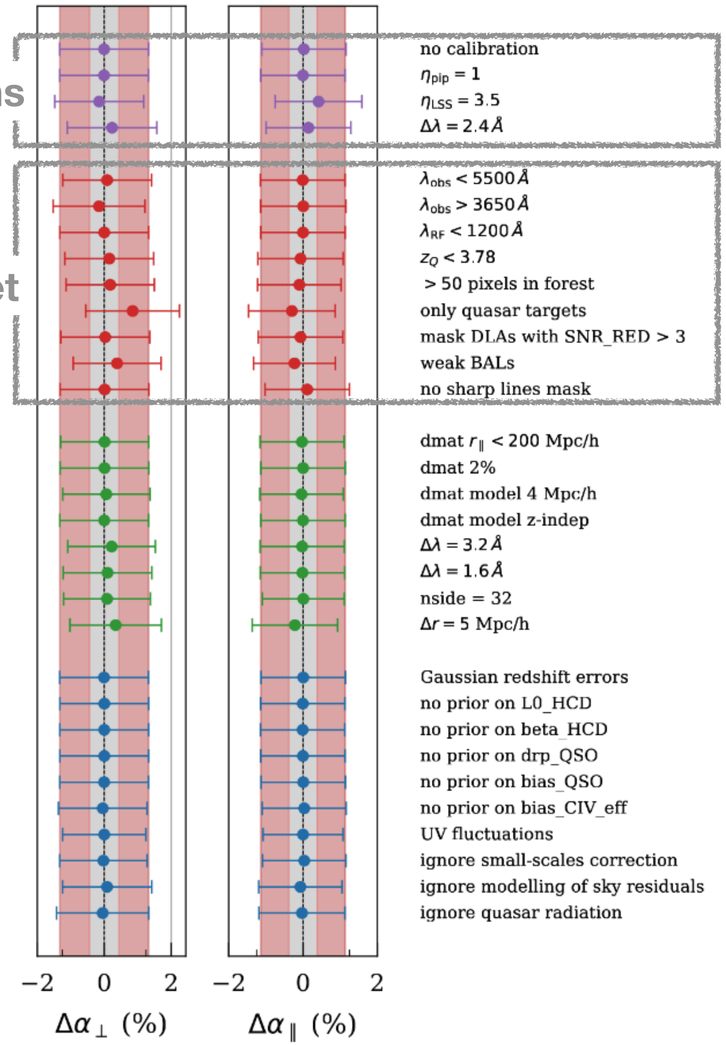
DR2 Lyα BAO robustness

Method to estimate the fluctuations

Variations in dataset



DARK ENERGY SPECTROSCOPIC INSTRUMENT
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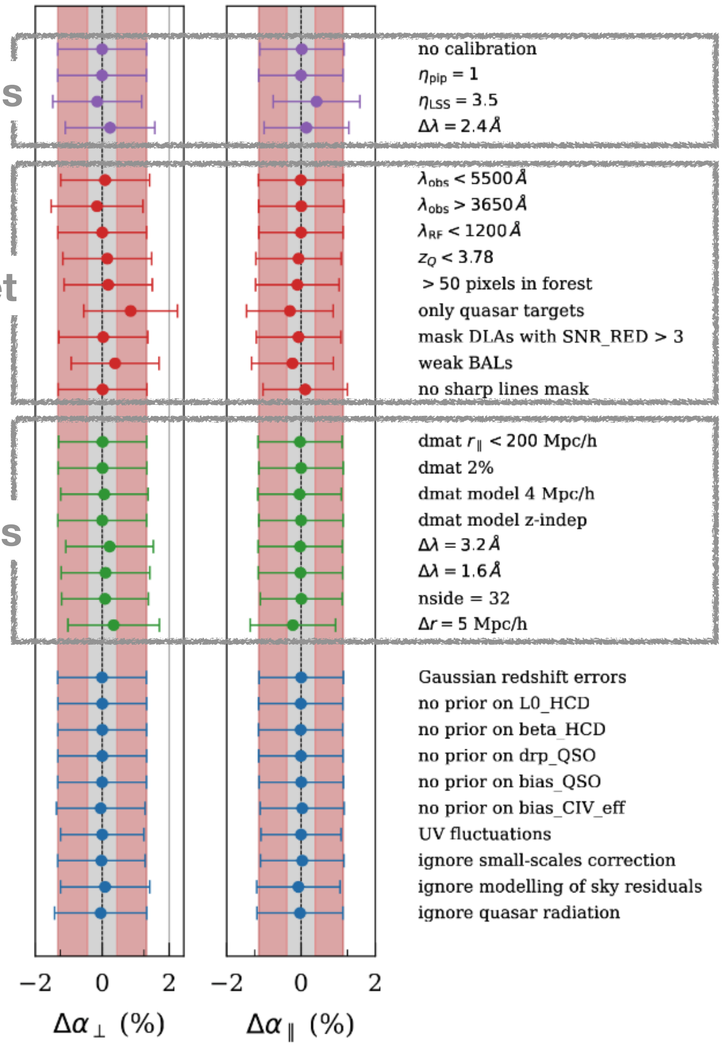
DR2 Lyα BAO robustness

Method to estimate the fluctuations

Variations in dataset

Method to compute correlations and covariances



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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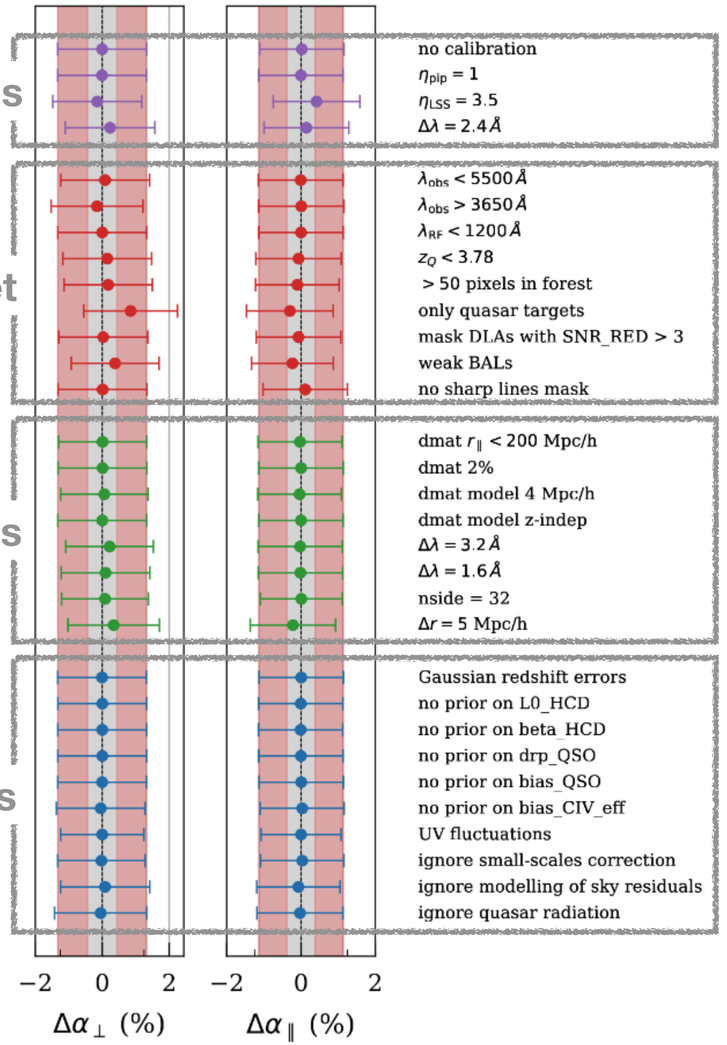
DR2 Lyα BAO robustness

Method to estimate the fluctuations

Variations in dataset

Method to compute correlations and covariances

Modelling choices



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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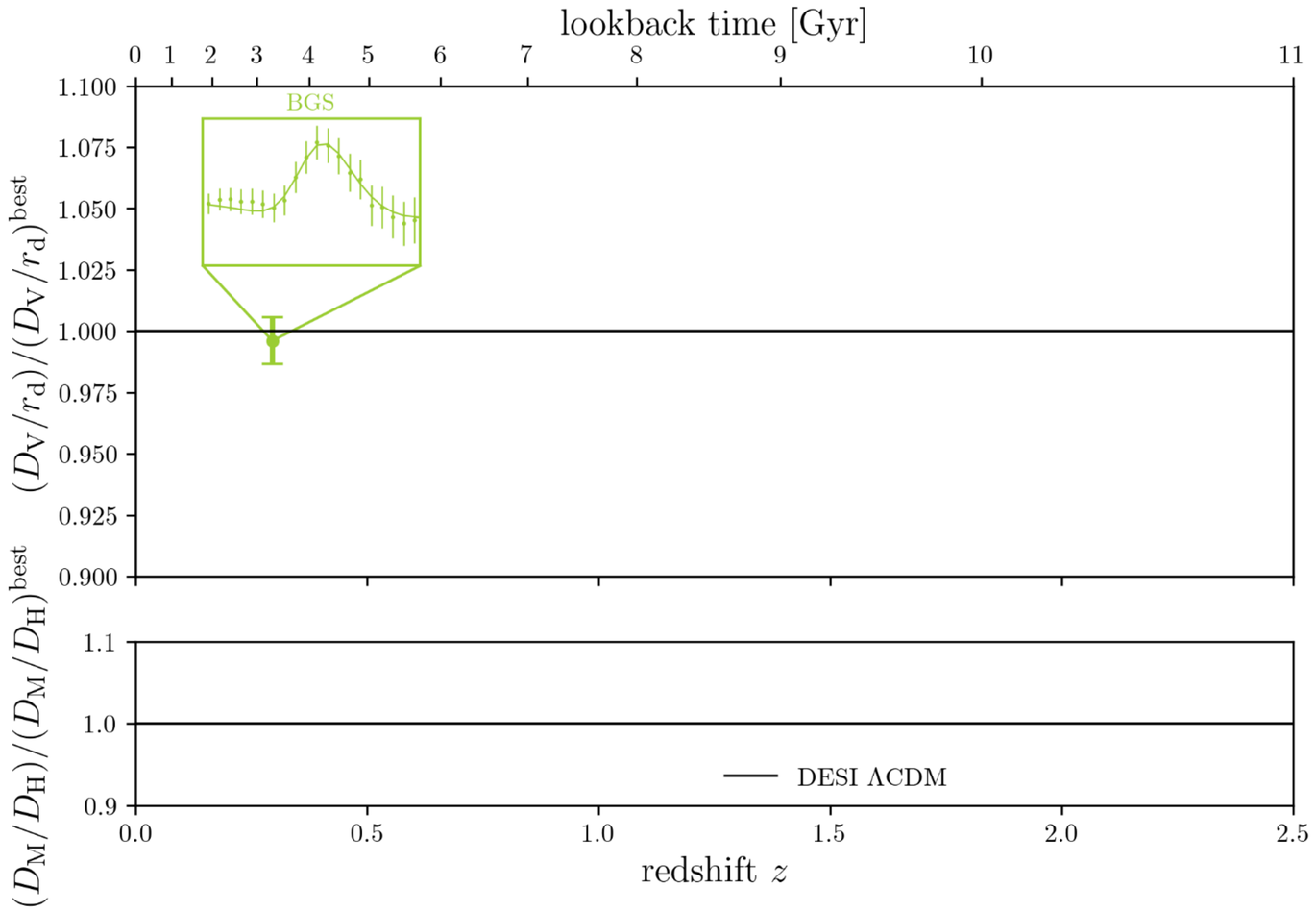
DESI DR2 BAO results



Overall size

Anisotropy

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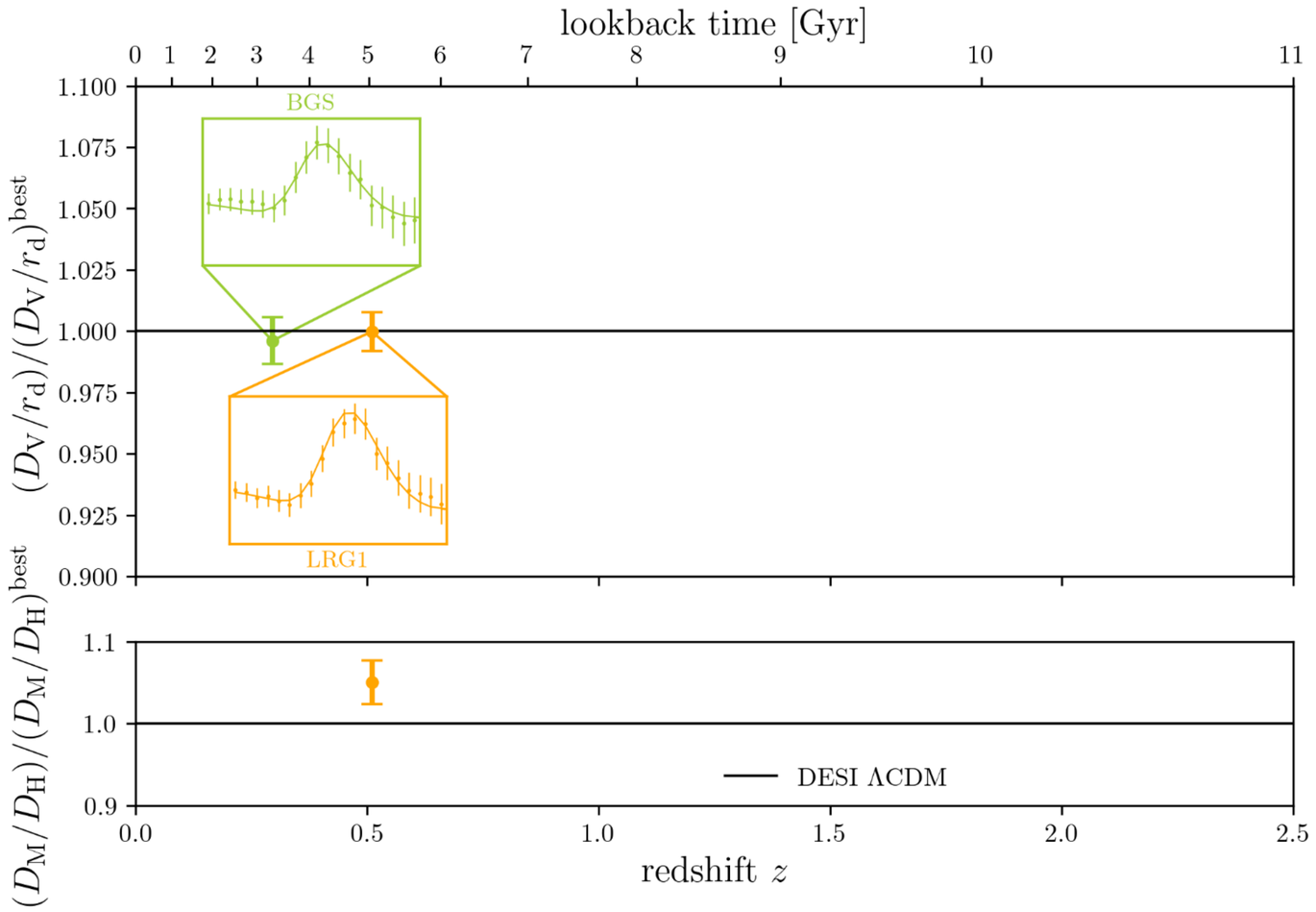
DESI DR2 BAO results



Overall size

Anisotropy

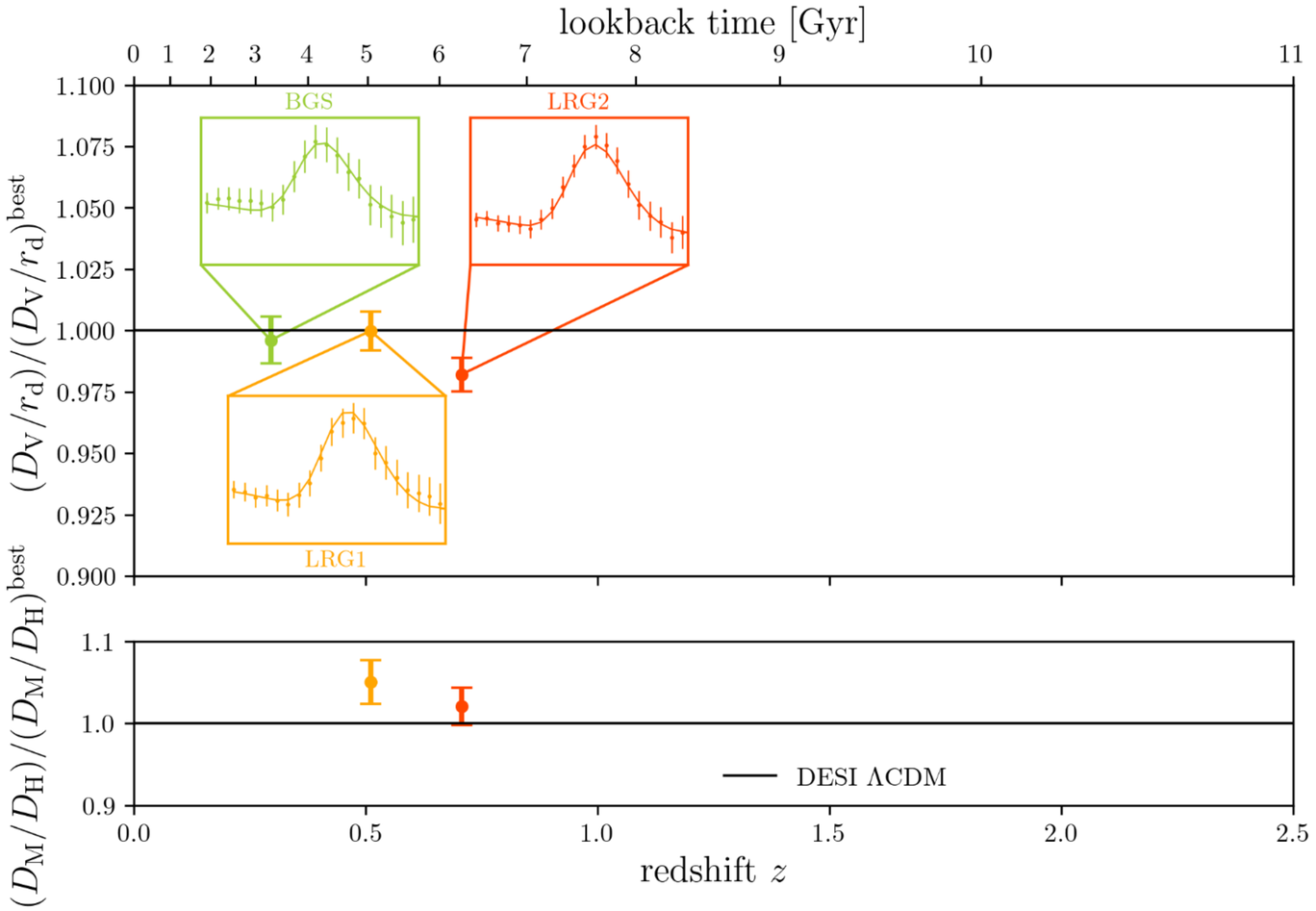
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI DR2 BAO results

Overall size

Anisotropy



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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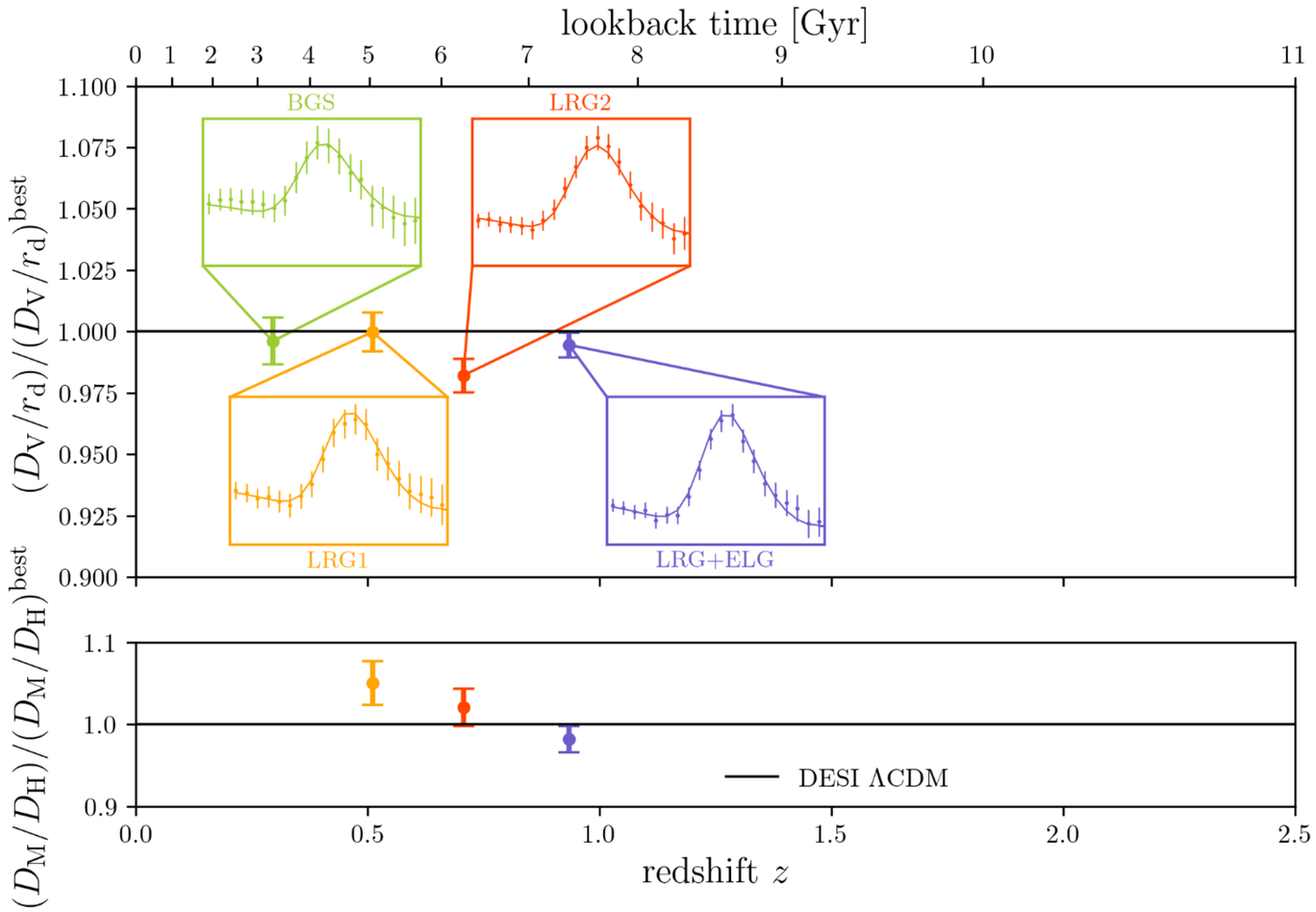
DESI DR2 BAO results



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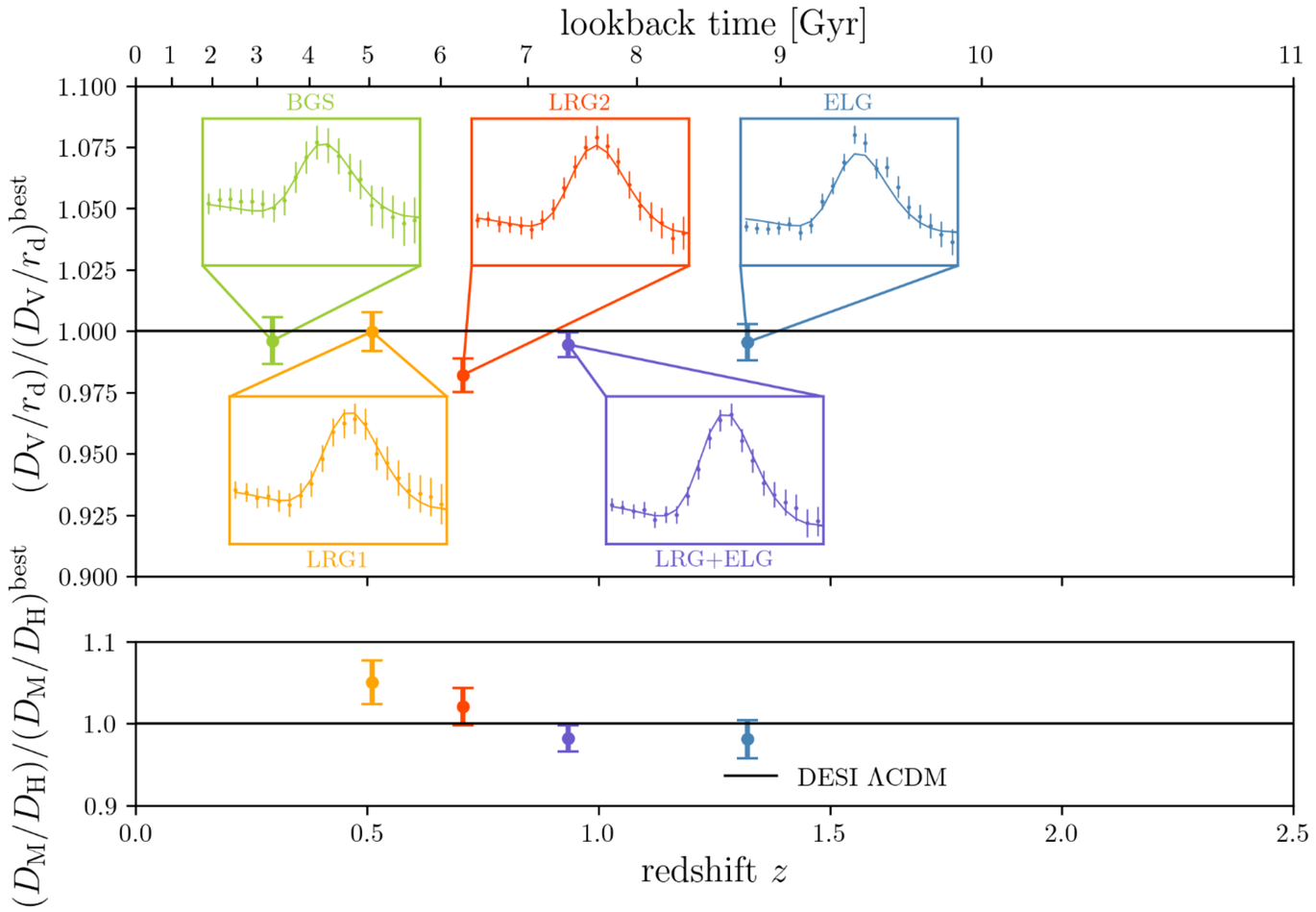
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI DR2 BAO results



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DARK ENERGY SPECTROSCOPIC INSTRUMENT

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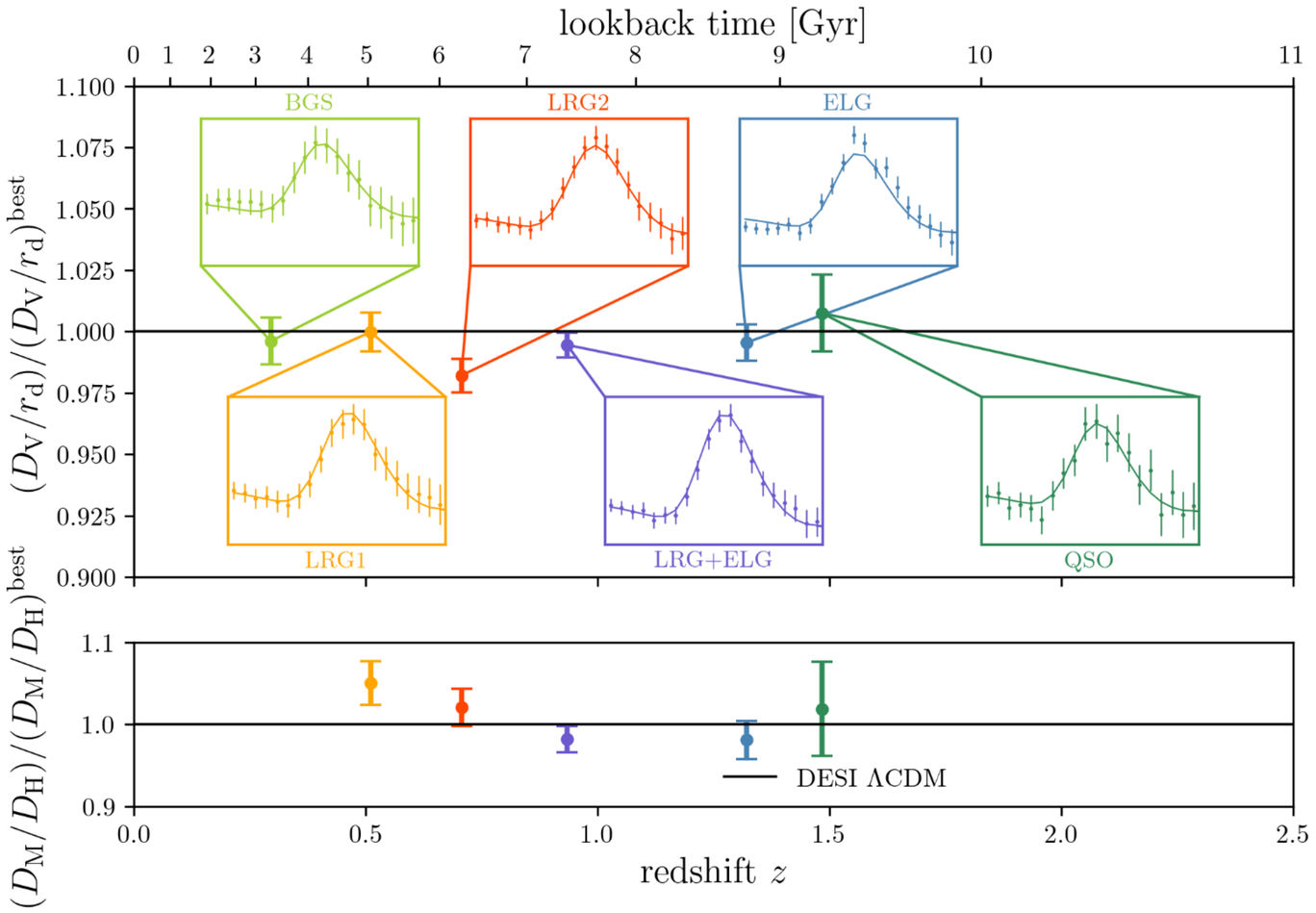
DESI DR2 BAO results

Overall size

Anisotropy



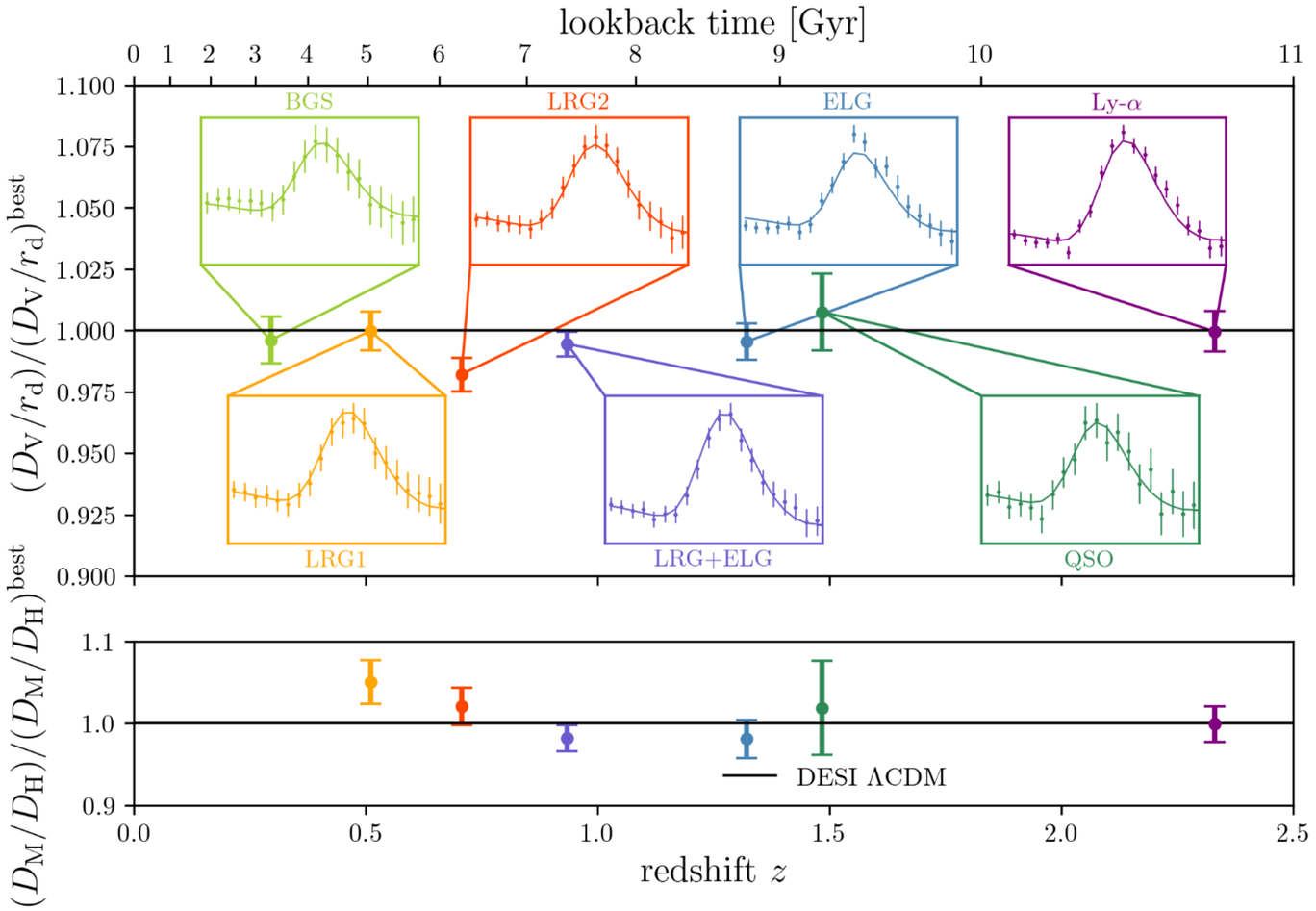
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DESI DR2 BAO results

Overall size

Anisotropy



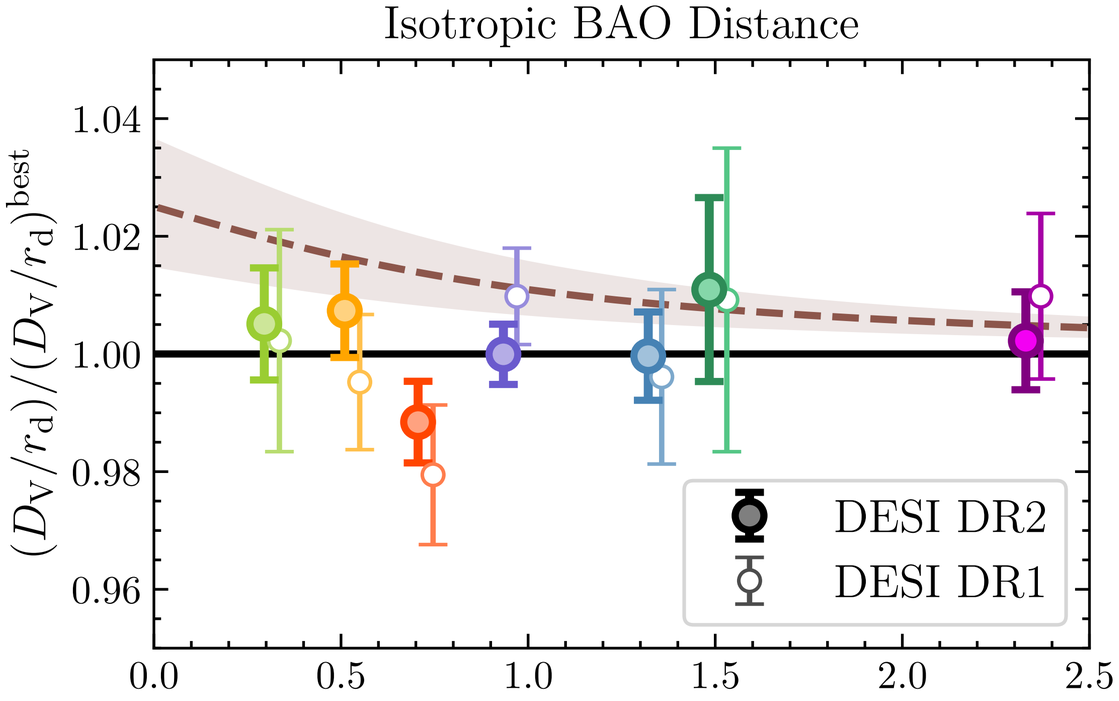
DARK ENERGY SPECTROSCOPIC INSTRUMENT

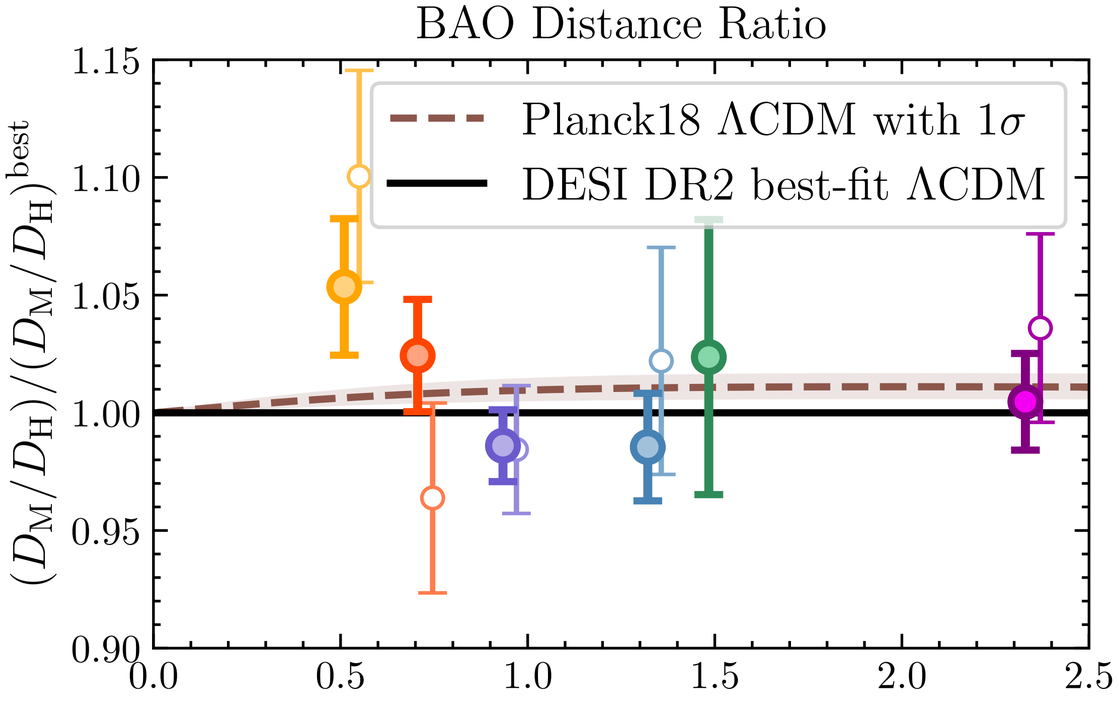
U.S. Department of Energy Office of Science

DESI DR2 BAO results vs Planck

Overall size

Anisotropy





DARK ENERGY SPECTROSCOPIC INSTRUMENT

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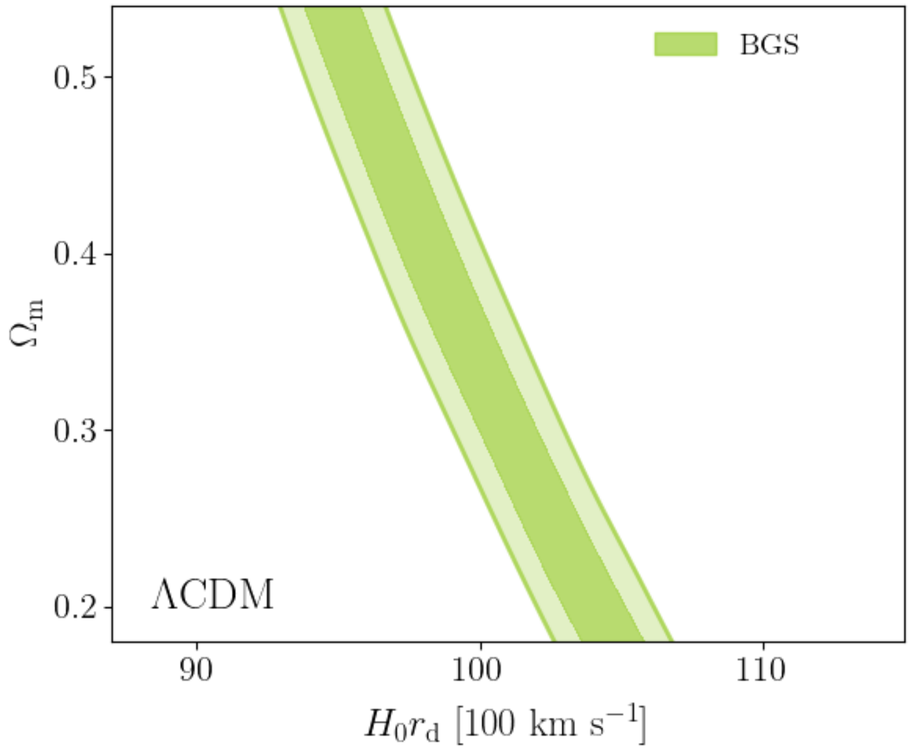
Cosmological parameters (ΛCDM)



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U.S. Department of Energy Office of Science

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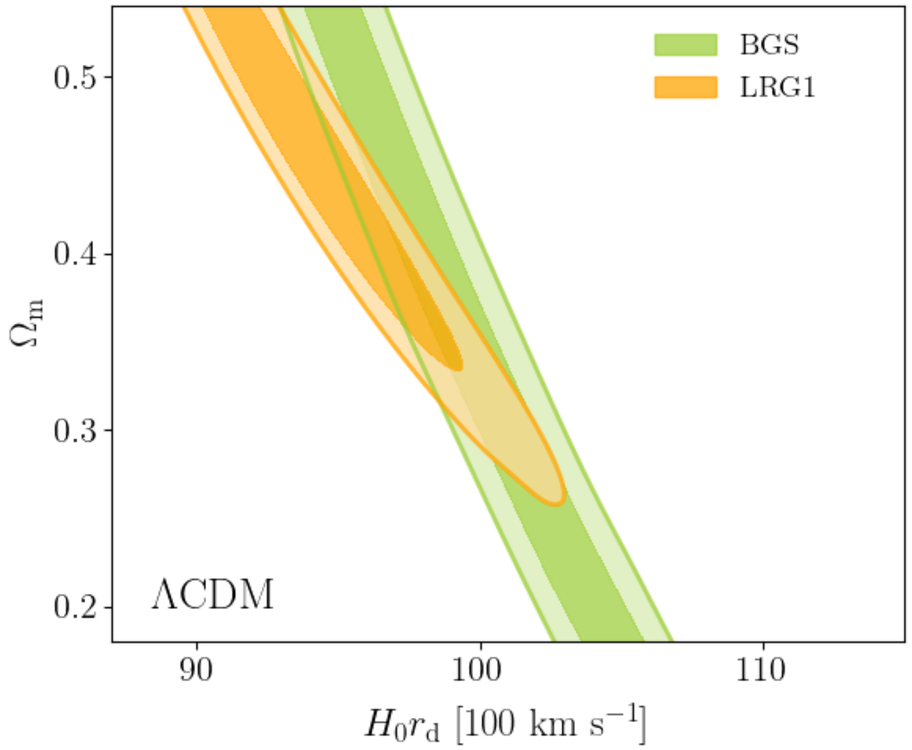

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U.S. Department of Energy Office of Science

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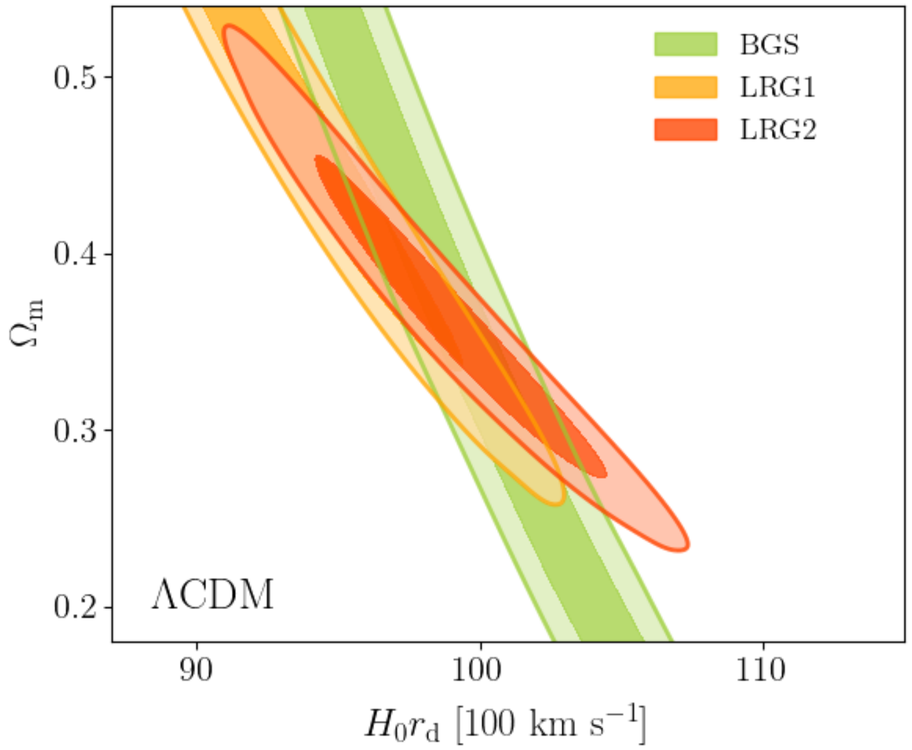

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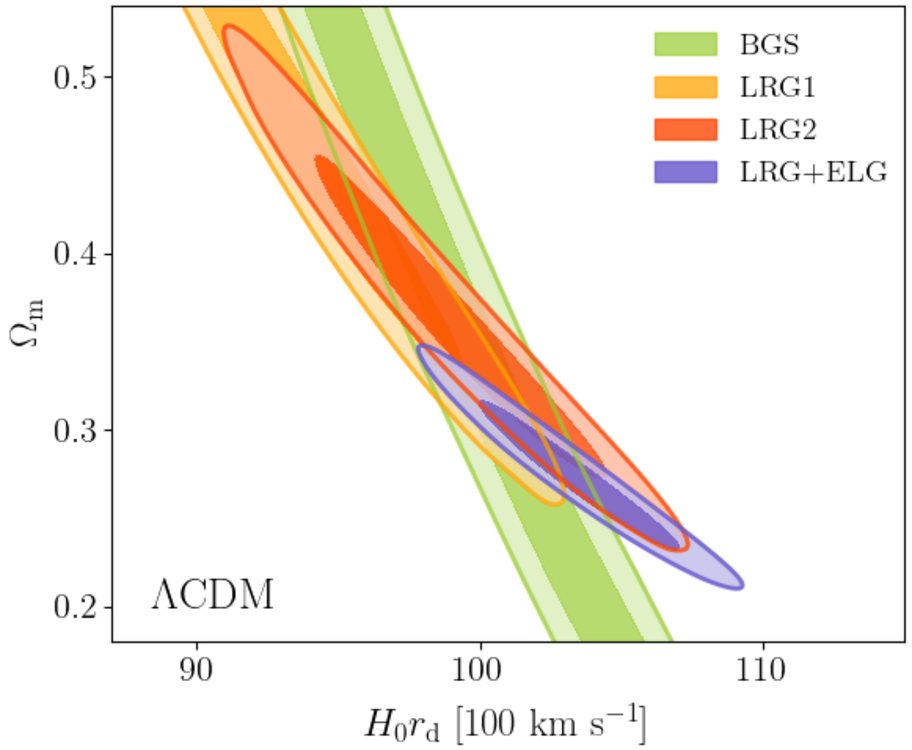

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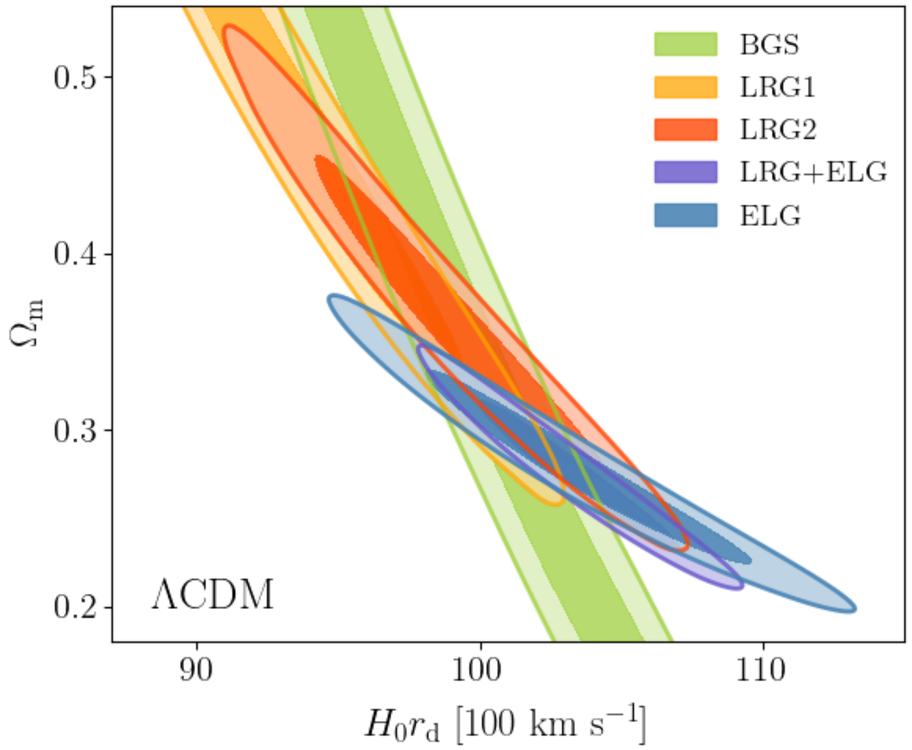

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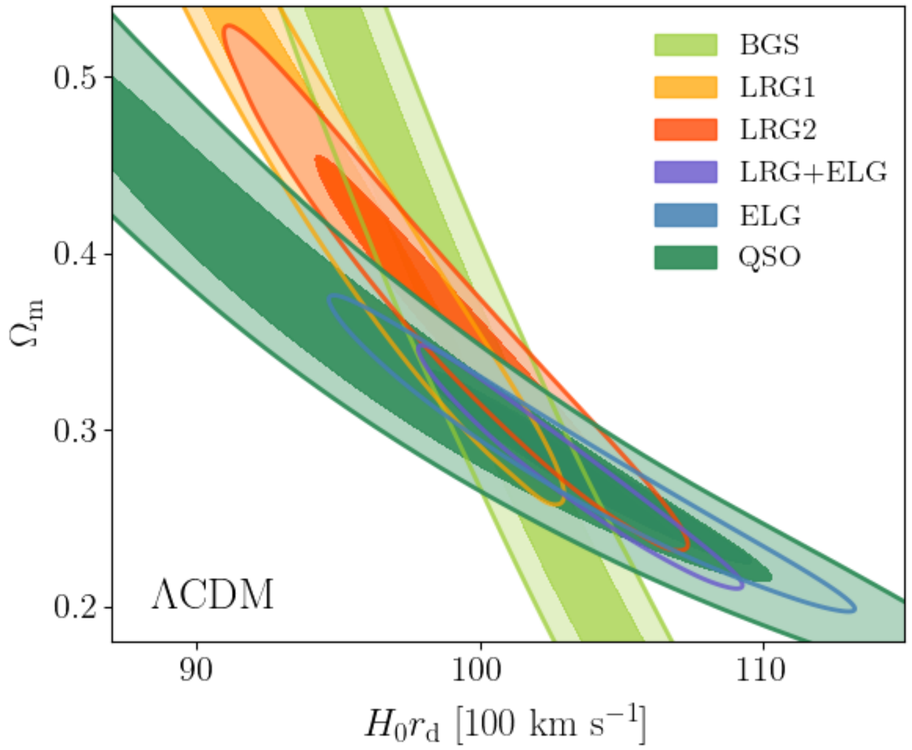

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U.S. Department of Energy Office of Science

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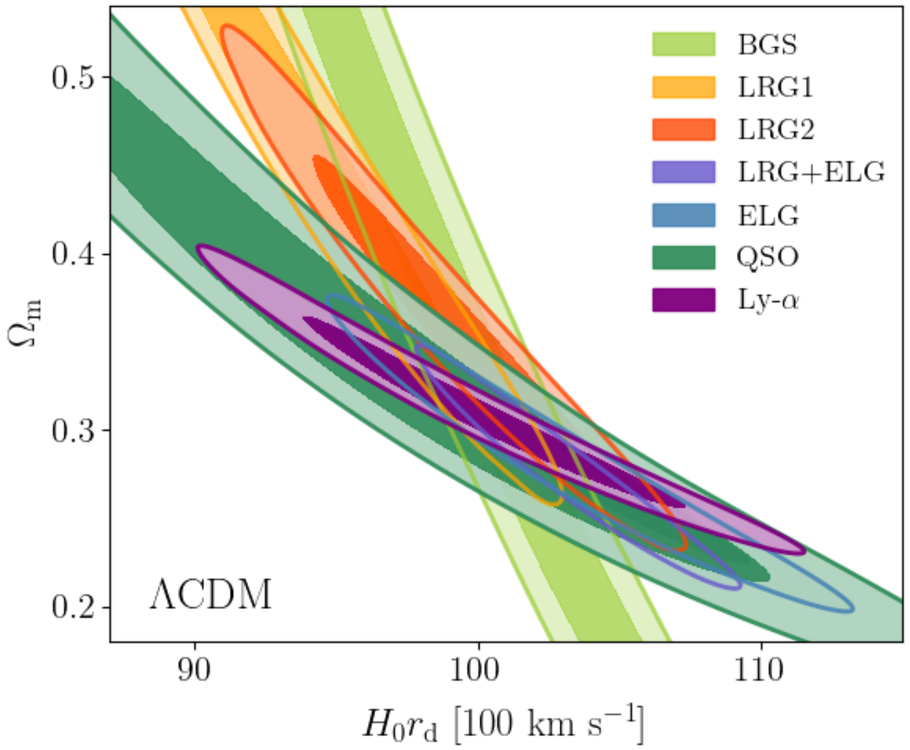

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

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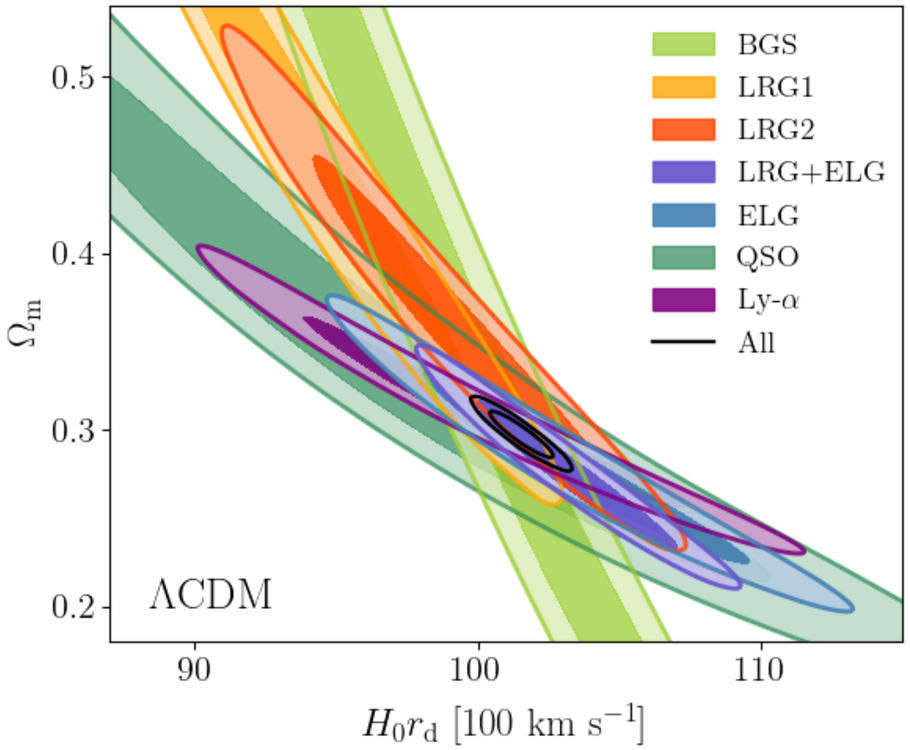

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

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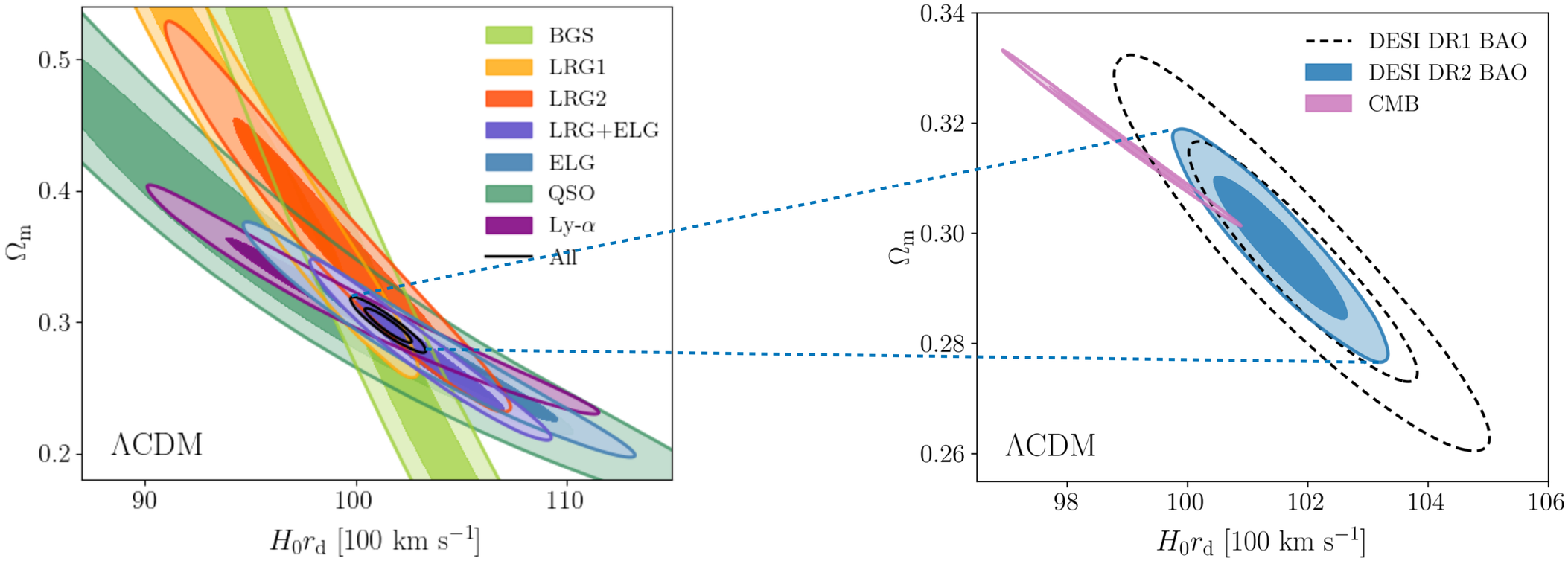

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

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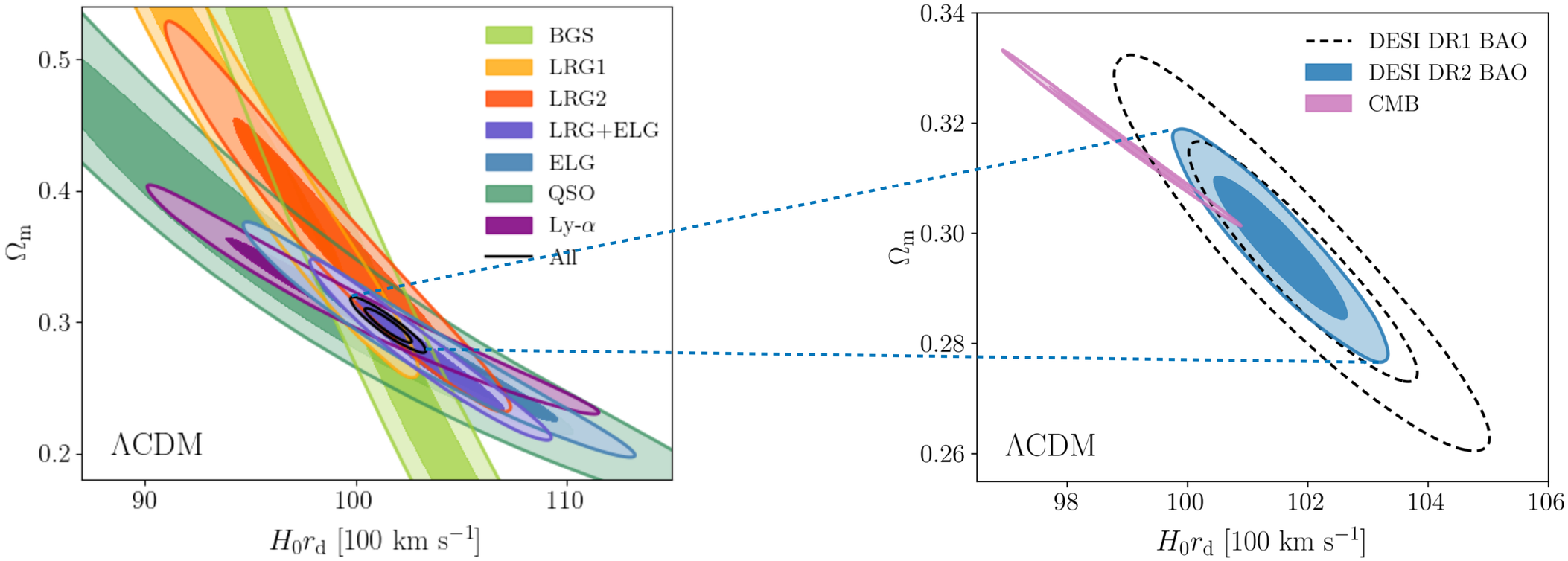

Discrepancy between BAO and CMB:
1.9σ in DR1 → 2.3σ in DR2

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

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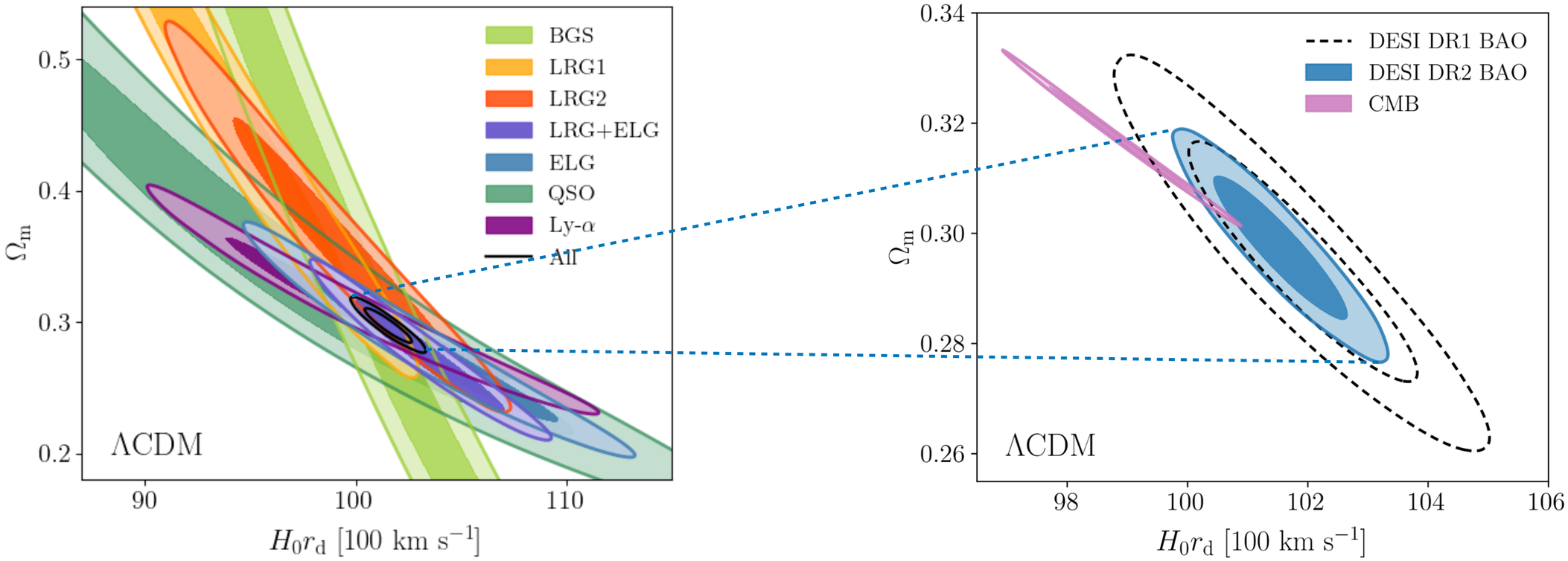


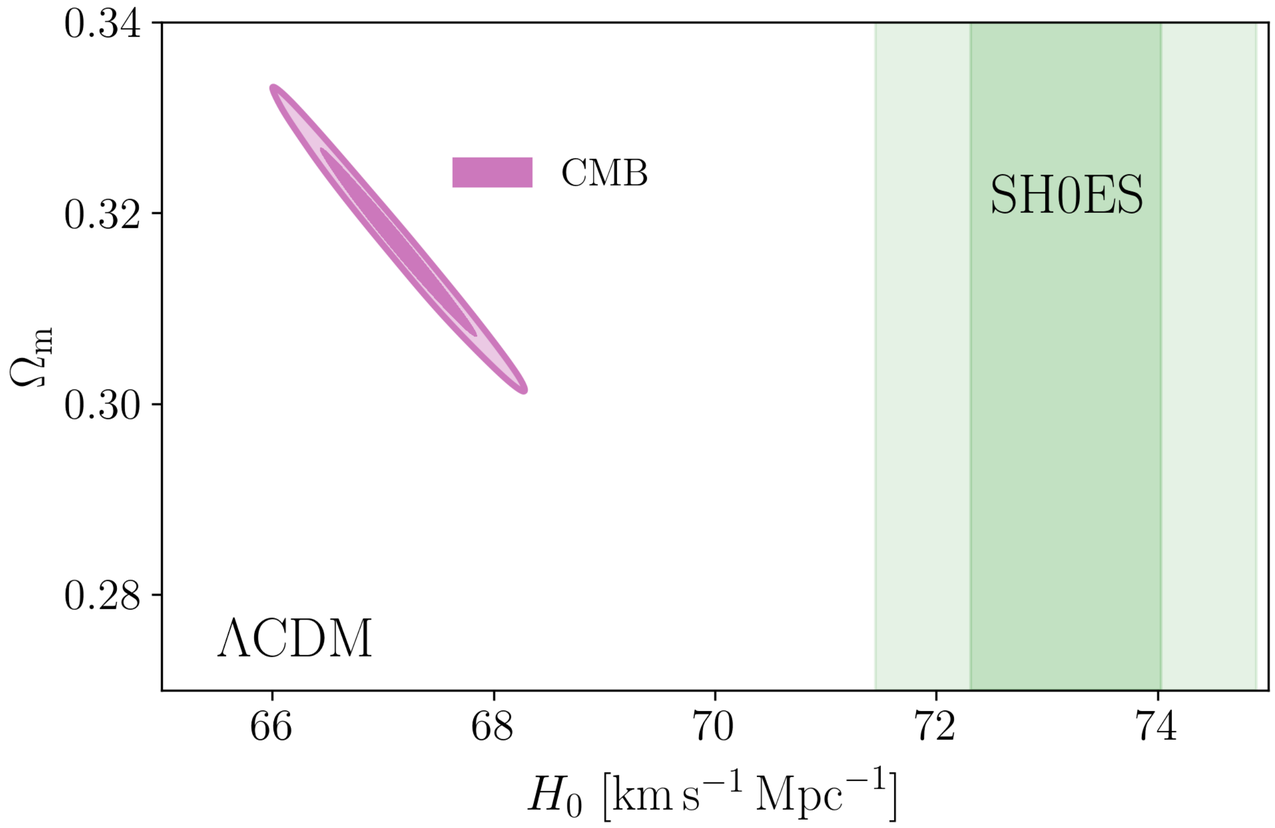
Discrepancy between BAO and CMB:
1.9σ in DR1 → 2.3σ in DR2

$\Omega_m = 0.2975 \pm 0.0086$
$H_0 r_d = 101.54 \pm 0.73$ Mpc

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Hubble tension

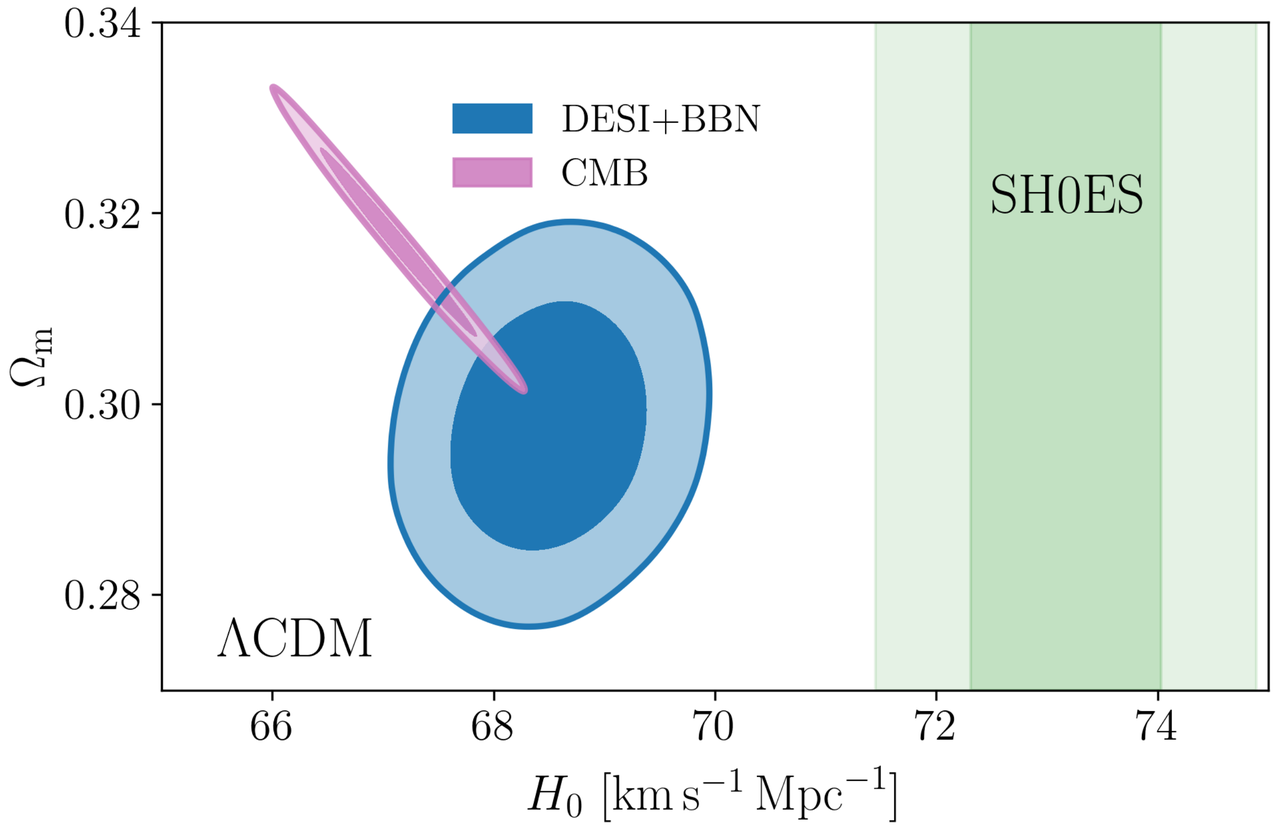


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Hubble tension

DESI + BBN

$H_0 = 68.51 \pm 0.58$ km s^{-1} Mpc^{-1}

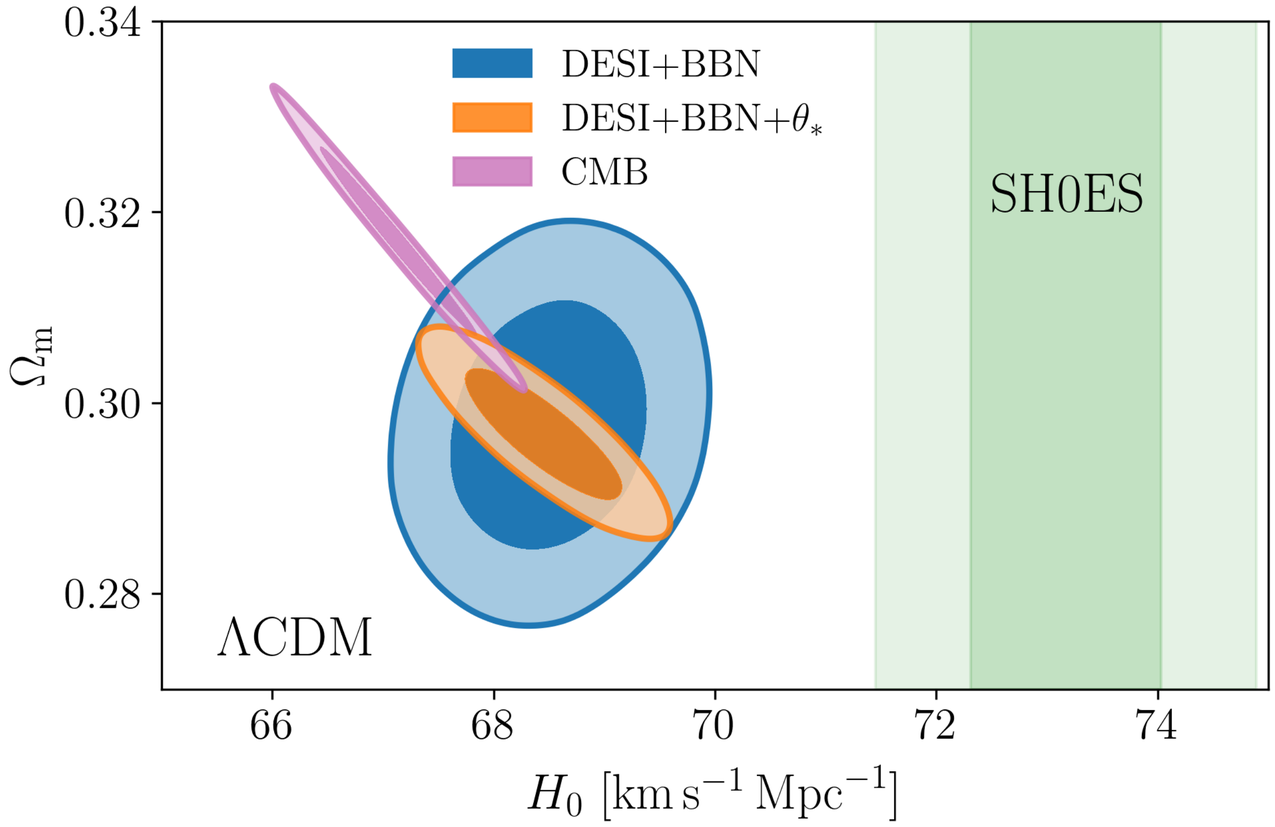


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Hubble tension

DESI + BBN
$H_0 = 68.51 \pm 0.58$ km s^{-1} Mpc^{-1}

DESI + θ_* + BBN
$H_0 = 68.45 \pm 0.47$ km s^{-1} Mpc^{-1}



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

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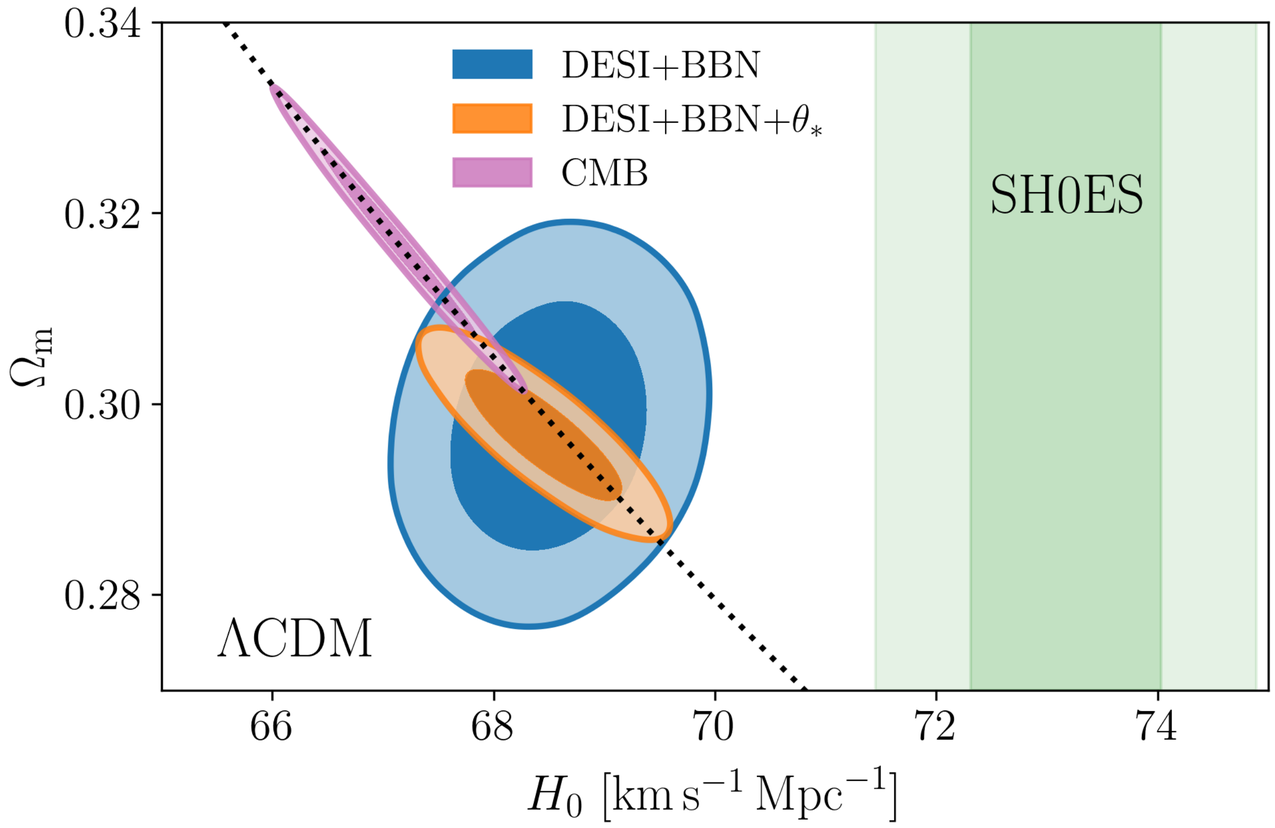
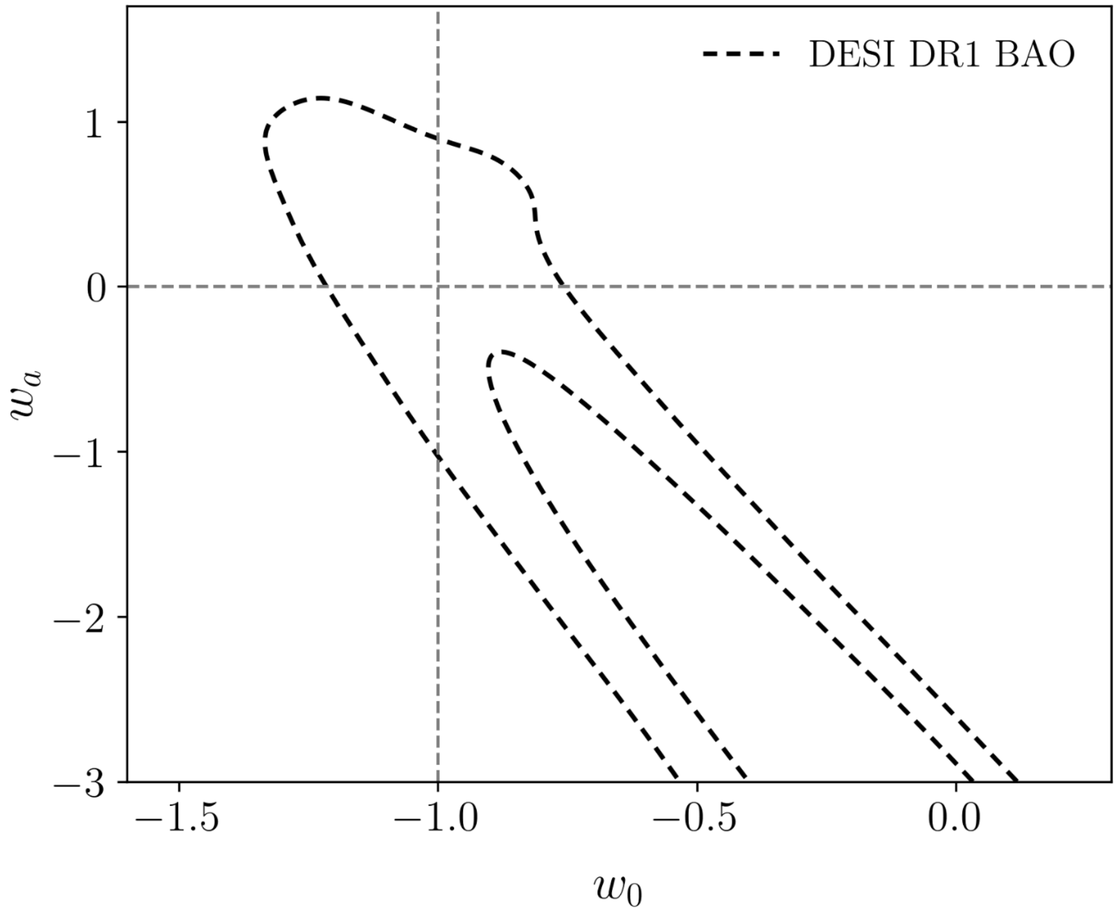


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Time-dependent dark energy (DESI alone)

Dark energy eq. of state
$w = p / (\rho c^2)$

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



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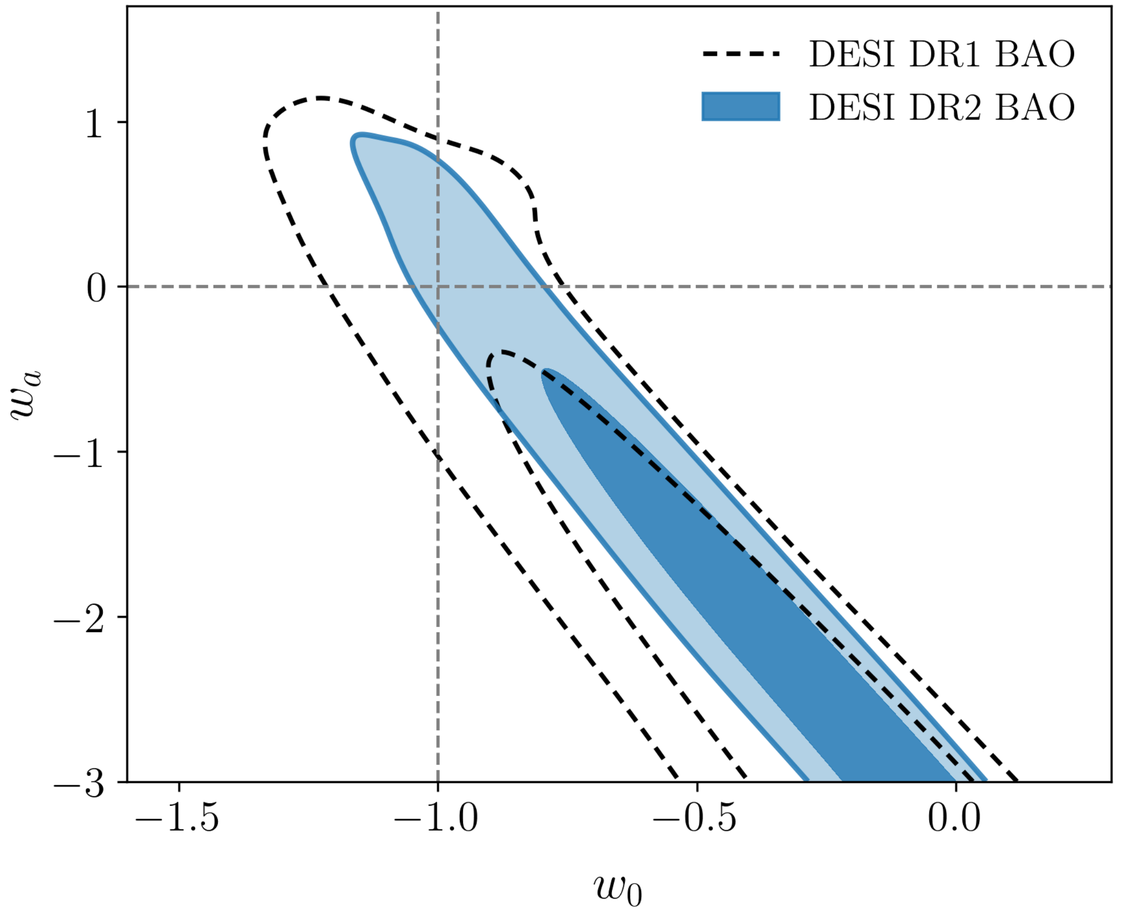
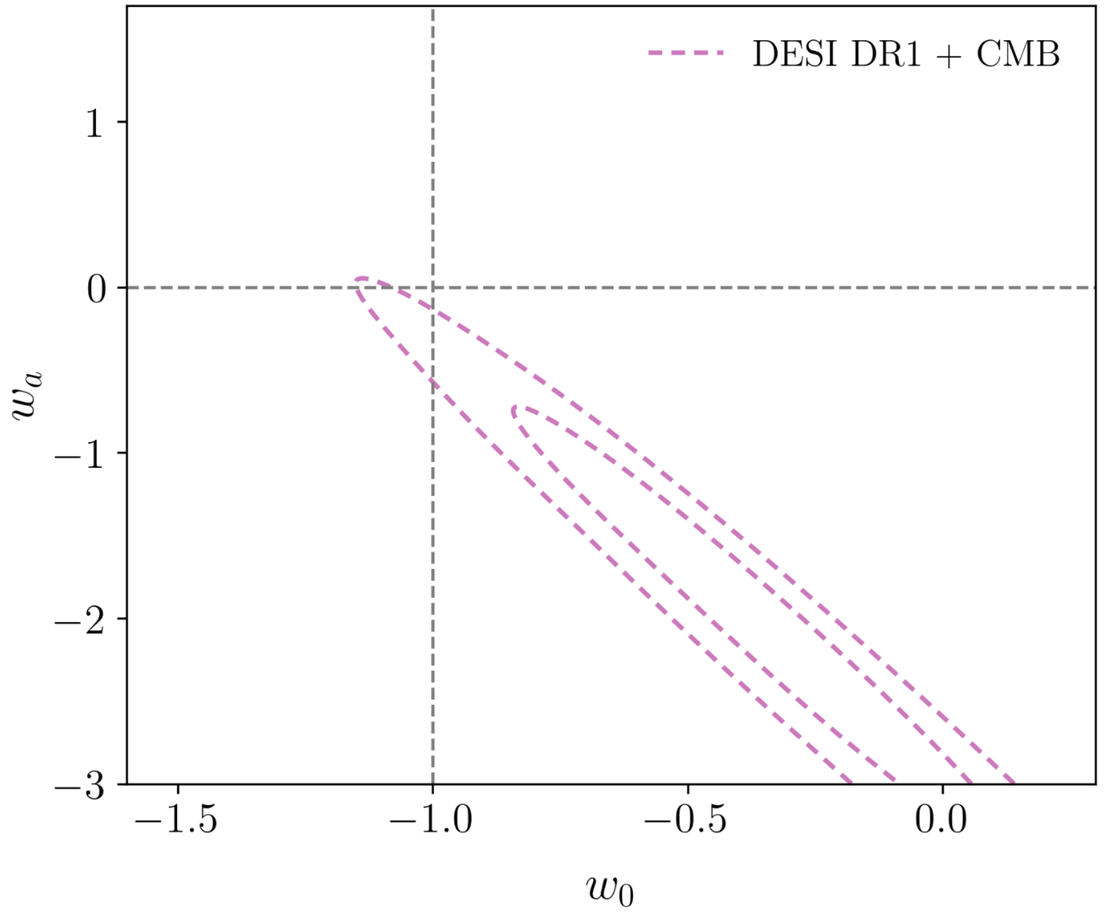


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Time-dependent dark energy (DESI + CMB)

Dark energy eq. of state
$w = p / (\rho c^2)$

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



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

Time-dependent dark energy (DESI + CMB)

Dark energy eq. of state
$w = p / (\rho c^2)$

CPL parametrisation
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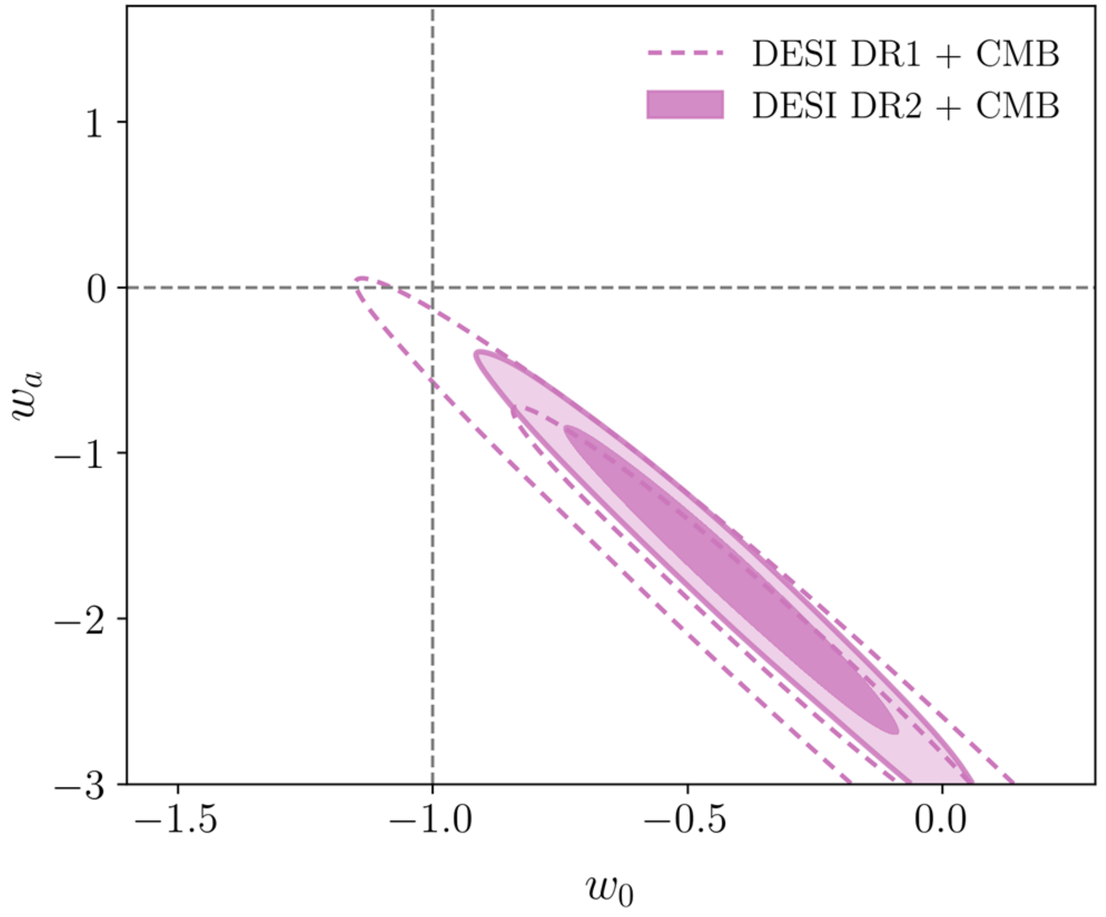
Levels of tension with ΛCDM
DESI BAO + CMB:
2.5σ in DR1 → 3.1σ in DR2

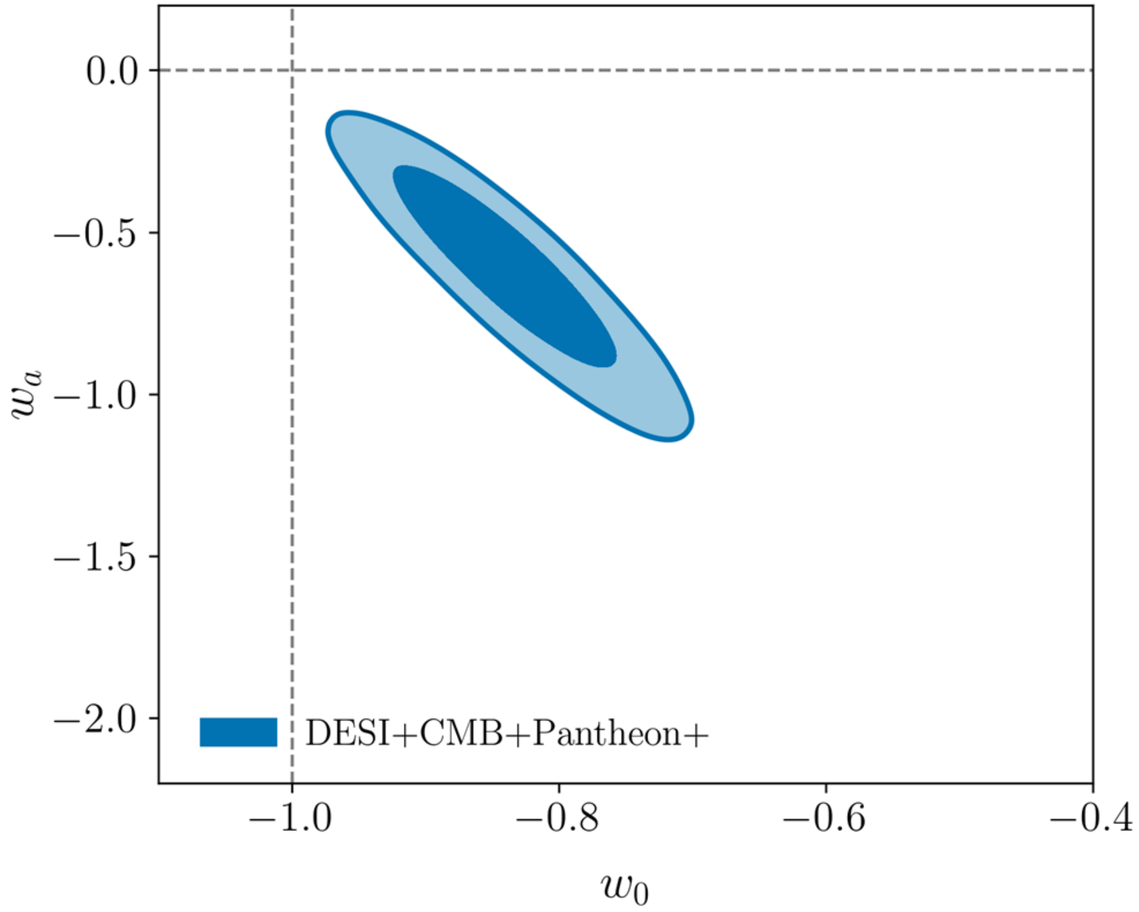


DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Time-dependent dark energy (DESI + CMB + SNe)

Dark energy eq. of state
$w = p / (\rho c^2)$

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



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

Time-dependent dark energy (DESI + CMB + SNe)

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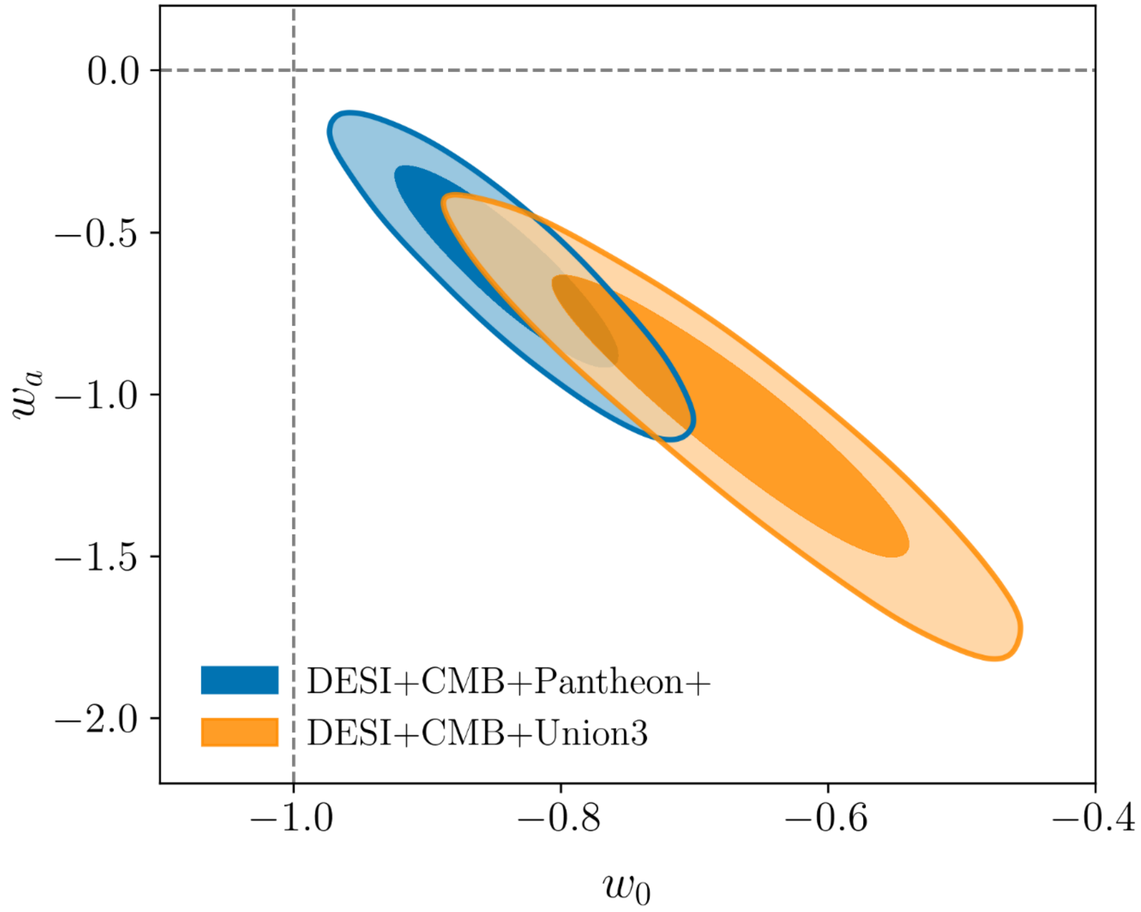

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

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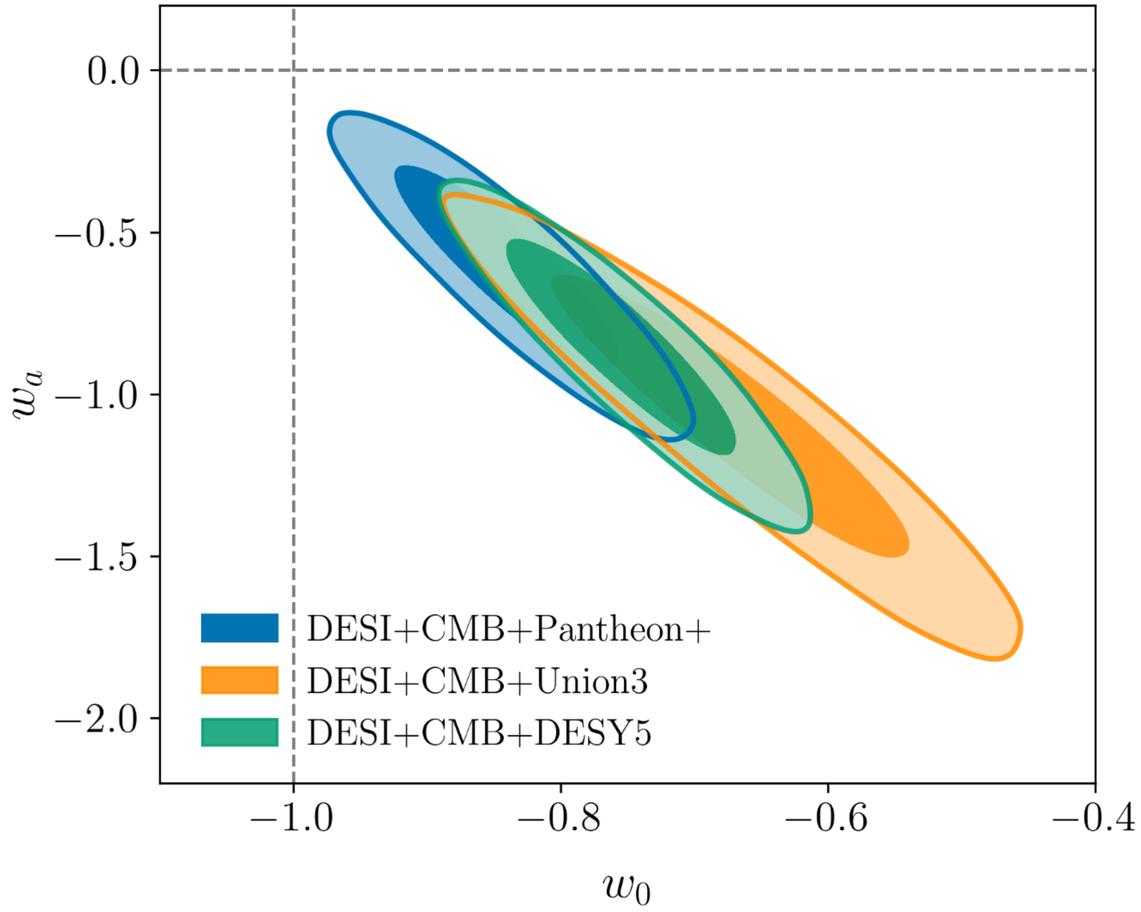


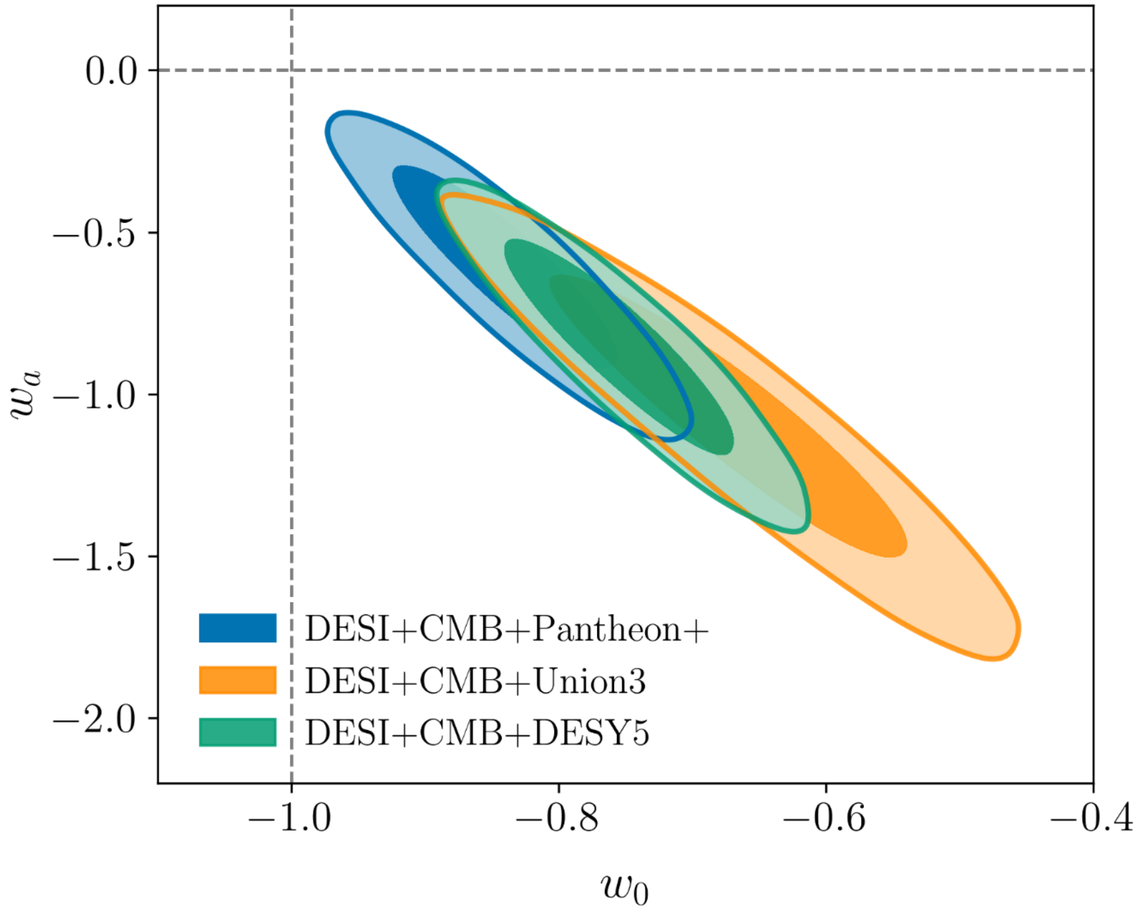
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Time-dependent dark energy (DESI + CMB + SNe)

Dark energy eq. of state
$w = p / (\rho c^2)$

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

Levels of tension with ΛCDM
DESI BAO + CMB +
- Pantheon+: 2.8σ
- Union3: 3.8σ
- DES-SN5YR: 4.2σ



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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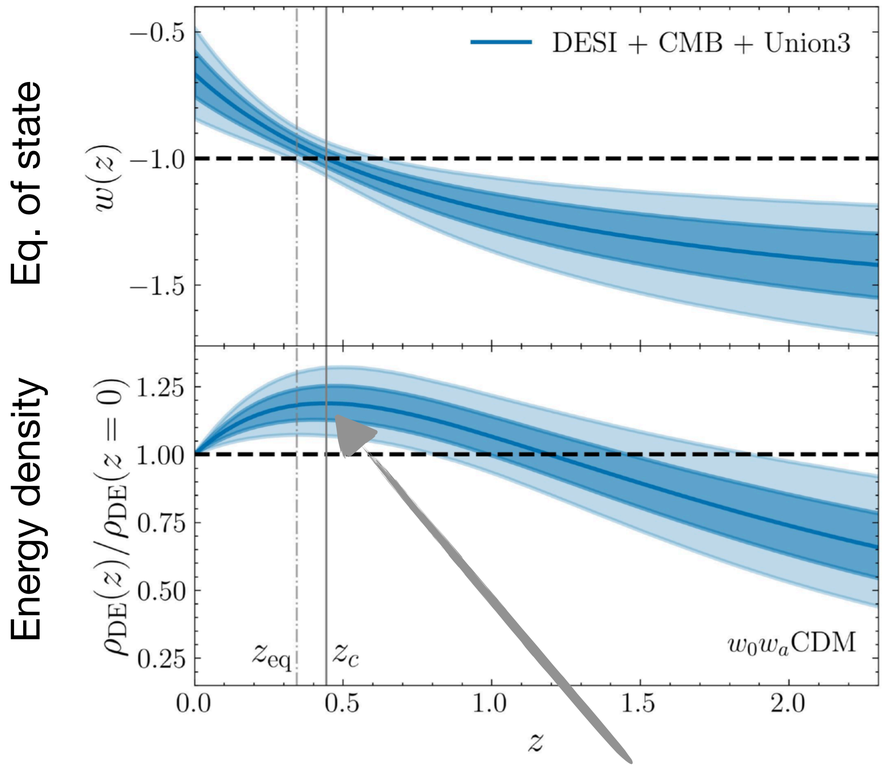
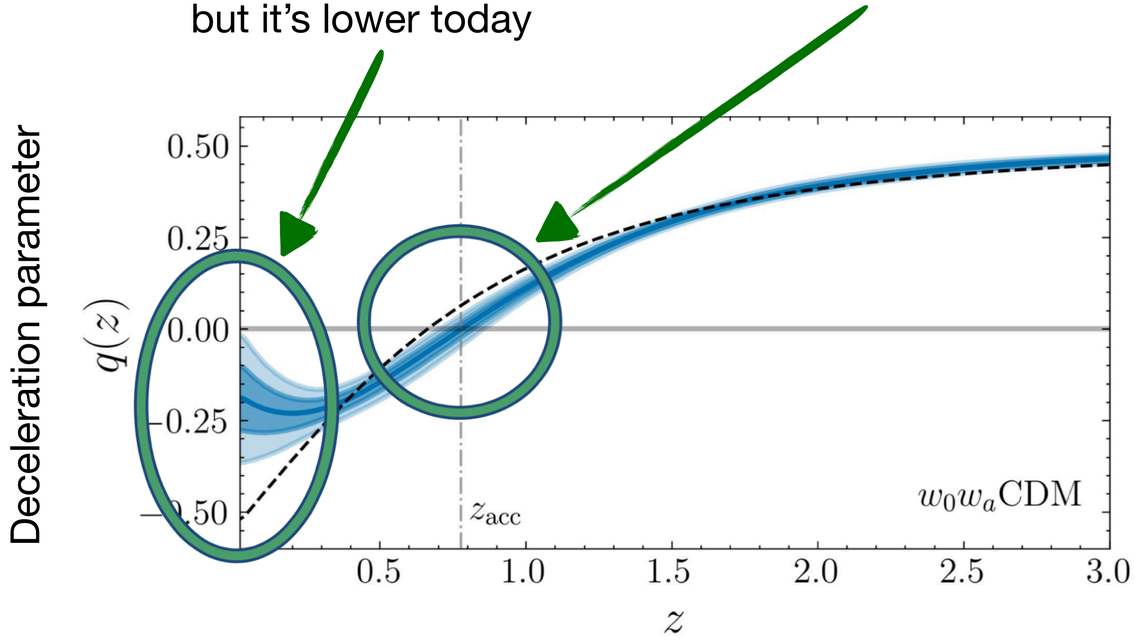
Time-dependent dark energy (phantom crossing)



Compared to ΛCDM acceleration started earlier but it's lower today



Max dark energy density at z ≈ 0.45 (phantom crossing)

Phantom crossing could indicate more complex dark sector than traditionally assumed

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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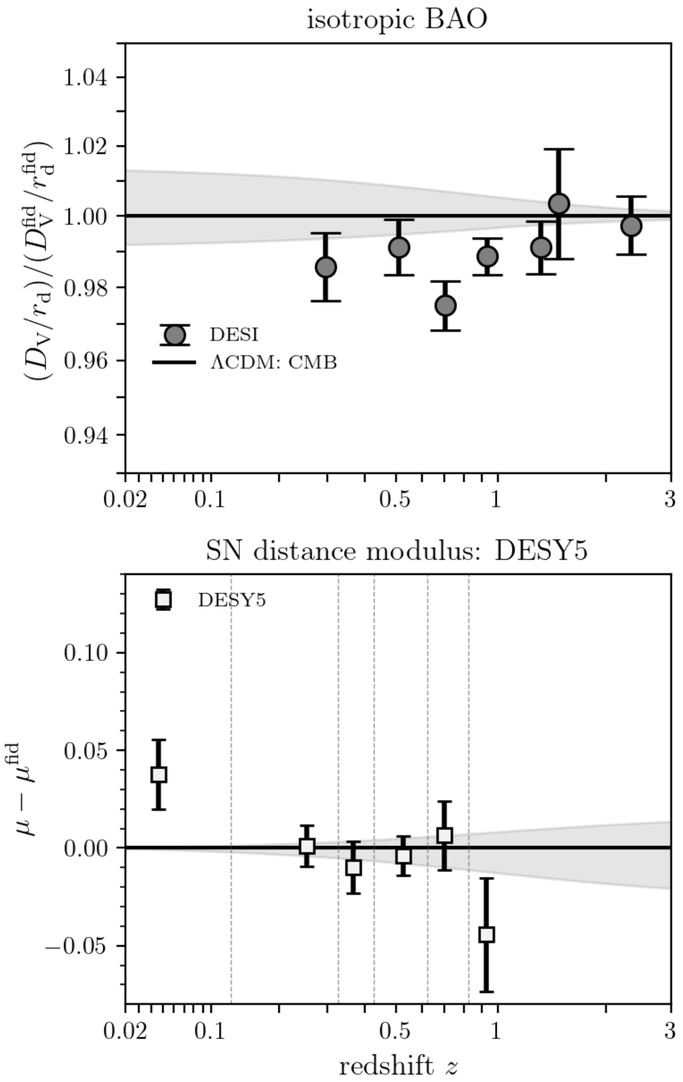
Time-dependent dark energy (what drives it?)



DARK ENERGY SPECTROSCOPIC INSTRUMENT
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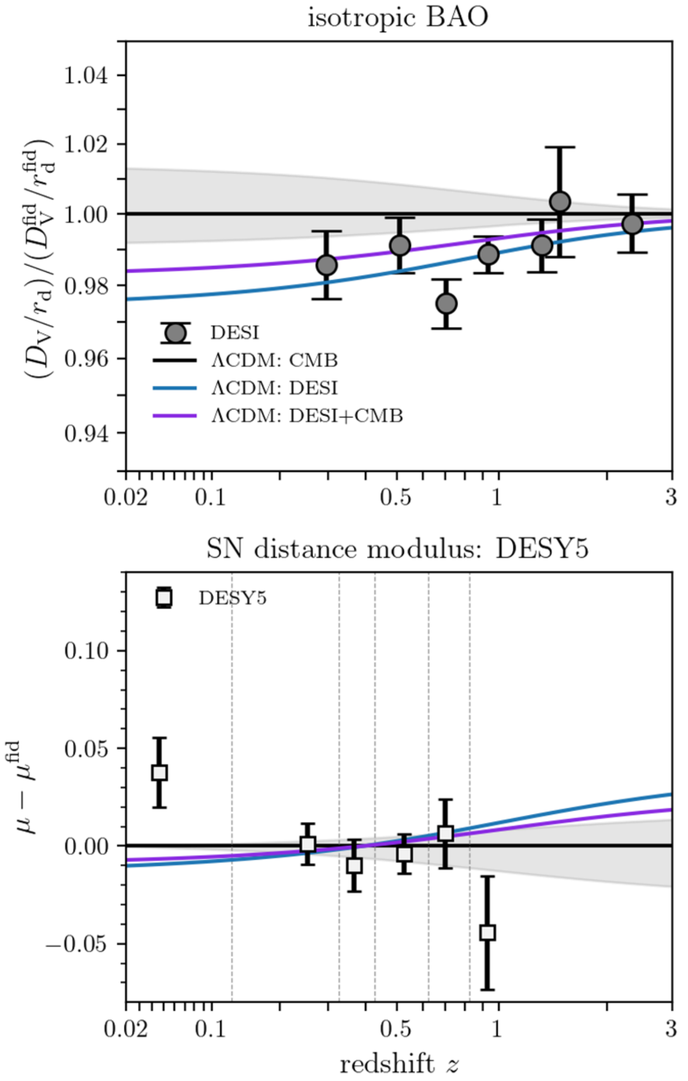
Time-dependent dark energy (what drives it?)

Each individual dataset (BAO, CMB, SNe) is still compatible with ΛCDM, but the corresponding Ω_m values are inconsistent

ΛCDM does not provide a good fit to all data simultaneously



DARK ENERGY SPECTROSCOPIC INSTRUMENT
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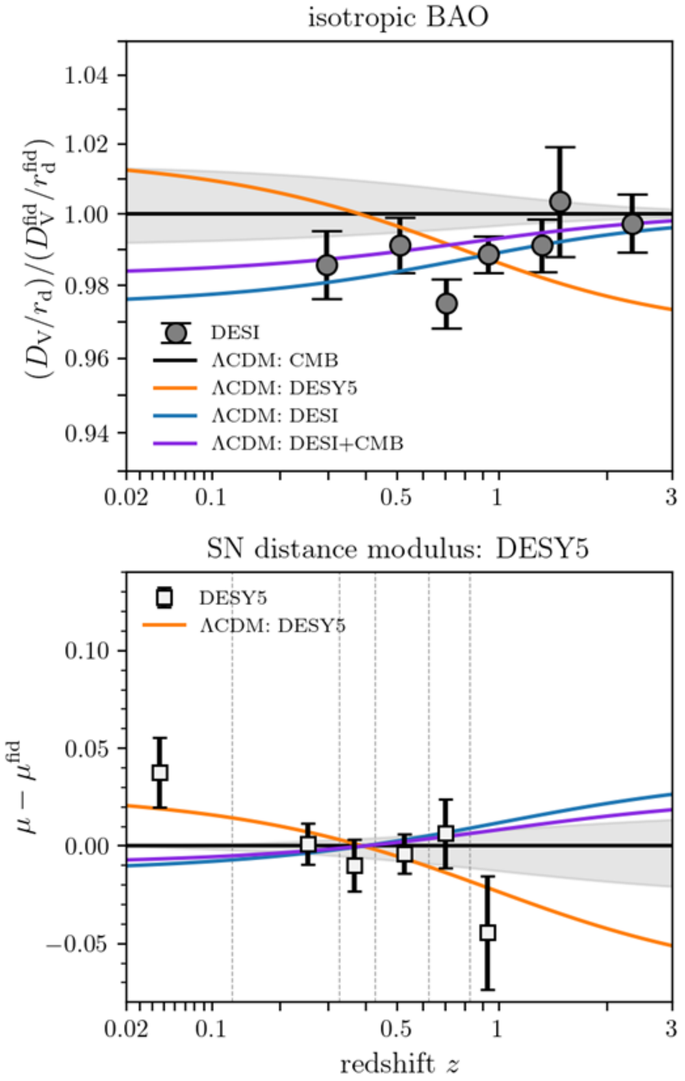

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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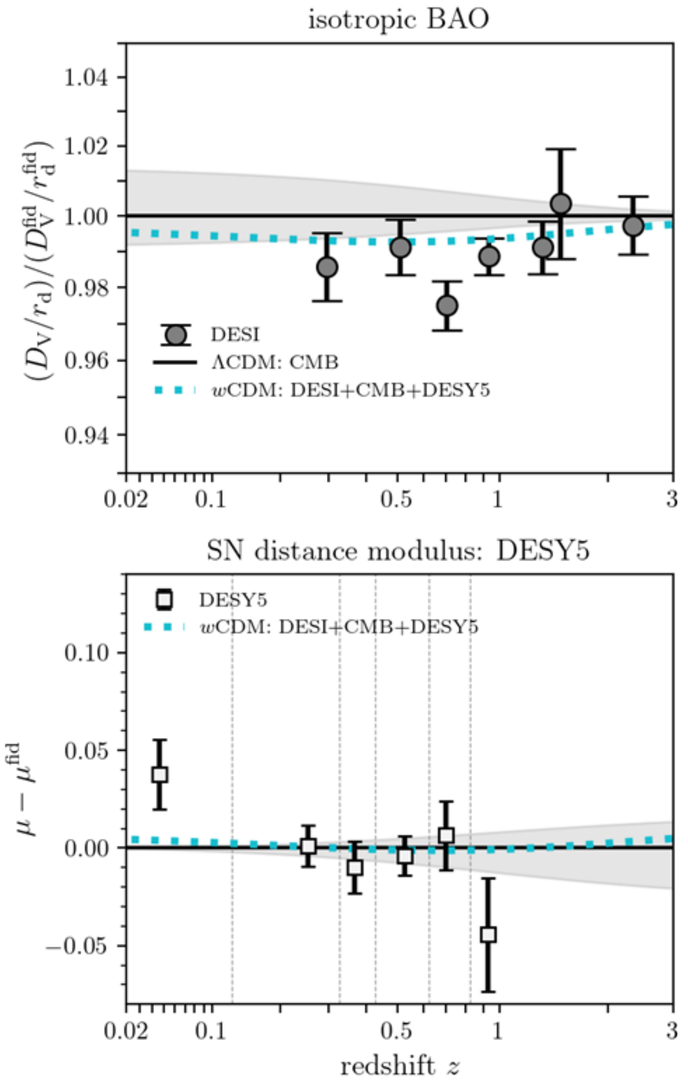
Time-dependent dark energy (what drives it?)

Each individual dataset (BAO, CMB, SNe) is still compatible with ΛCDM, but the corresponding Ω_m values are inconsistent

ΛCDM does not provide a good fit to all data simultaneously

*w*CDM model: constant eq. of state but not necessarily equal to -1

*w*CDM does not have enough freedom in the expansion history to fit BAO, CMB, and SNe simultaneously



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Time-dependent dark energy (what drives it?)

Each individual dataset (BAO, CMB, SNe) is still compatible with ΛCDM, but the corresponding Ω_m values are inconsistent

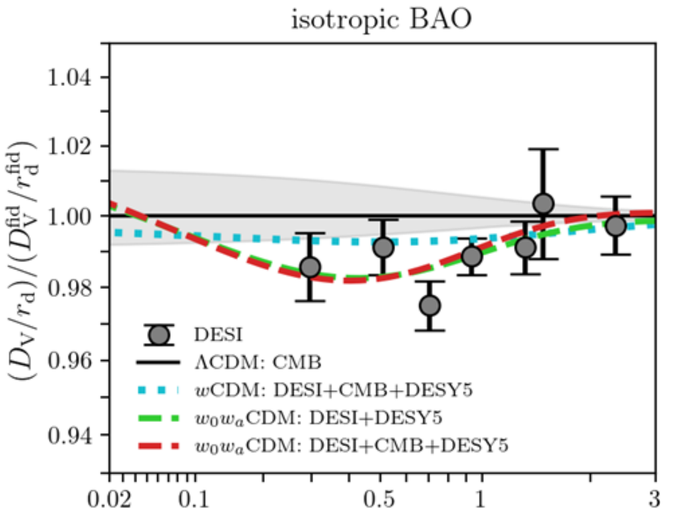
ΛCDM does not provide a good fit to all data simultaneously

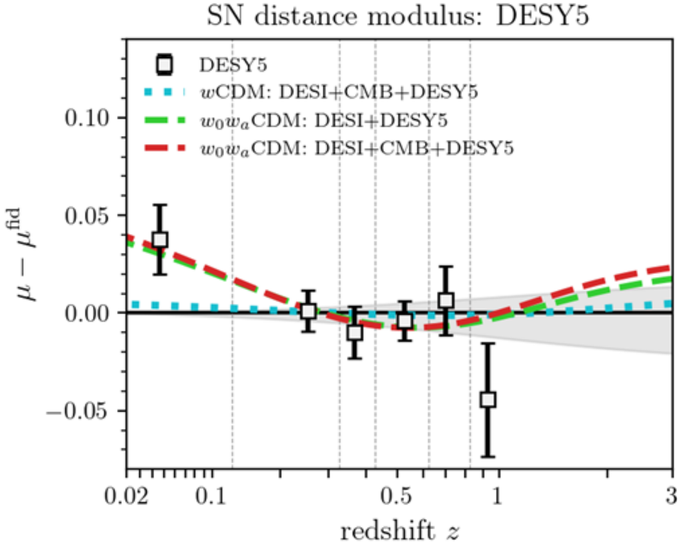
*w*CDM model: constant eq. of state but not necessarily equal to -1

*w*CDM does not have enough freedom in the expansion history to fit BAO, CMB, and SNe simultaneously

w_0w_aCDM has sufficient flexibility to simultaneously achieve good fits to all 3 datasets

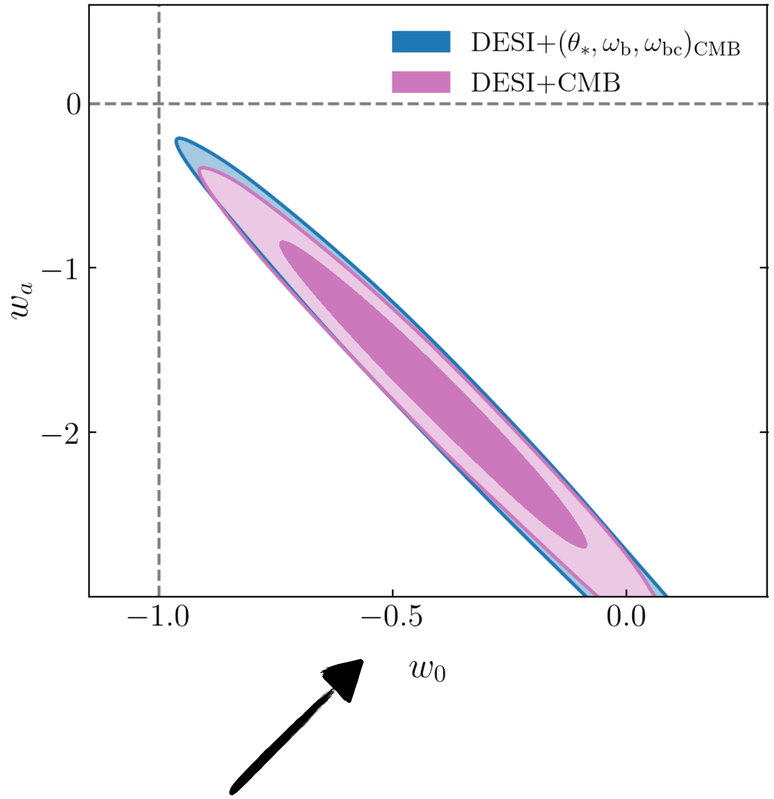
Resolves the mismatch in Ω_m between DESI and CMB





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

Time-dependent dark energy (early- vs late-time probes)



Just early universe info + DESI

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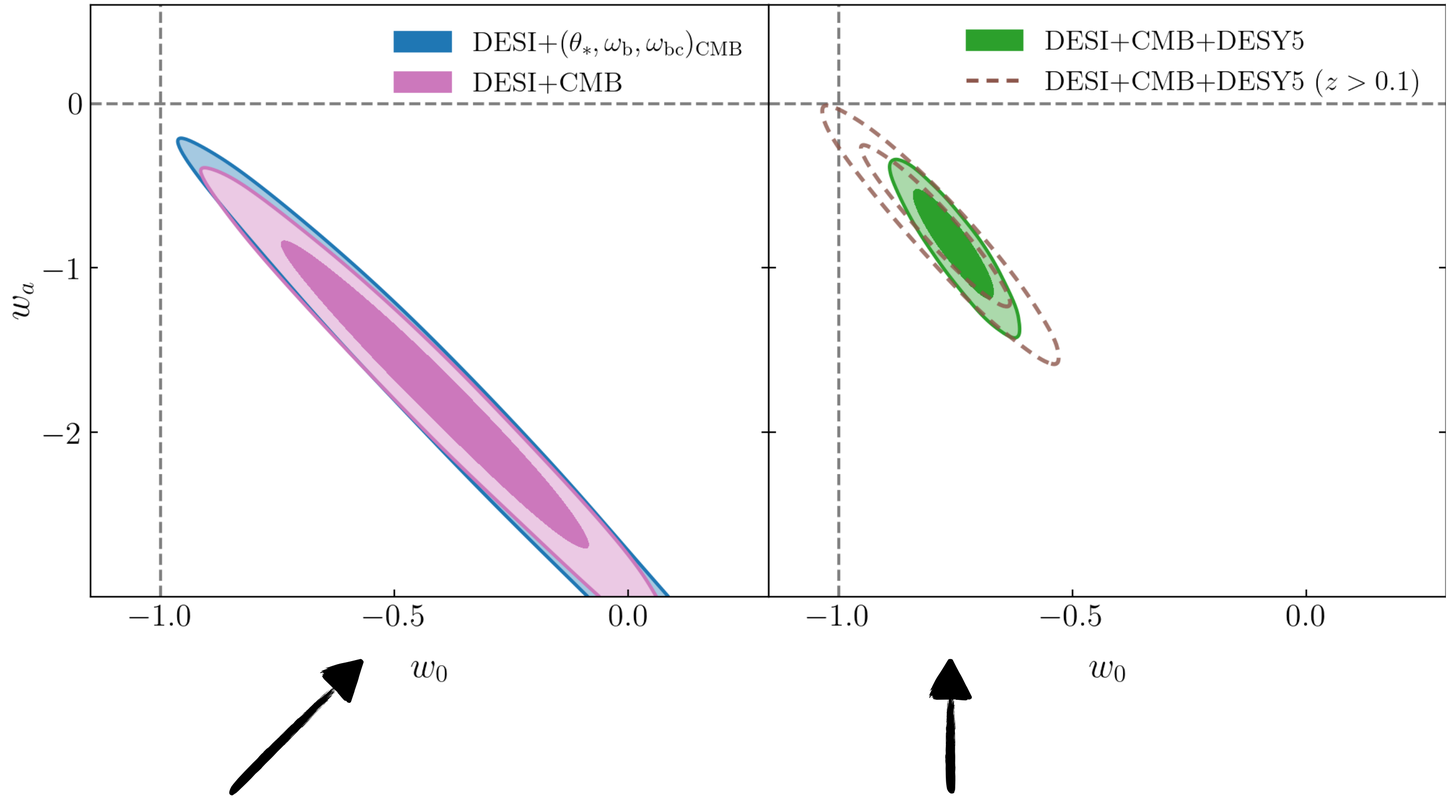
U.S. Department of Energy Office of Science

Time-dependent dark energy (early- vs late-time probes)

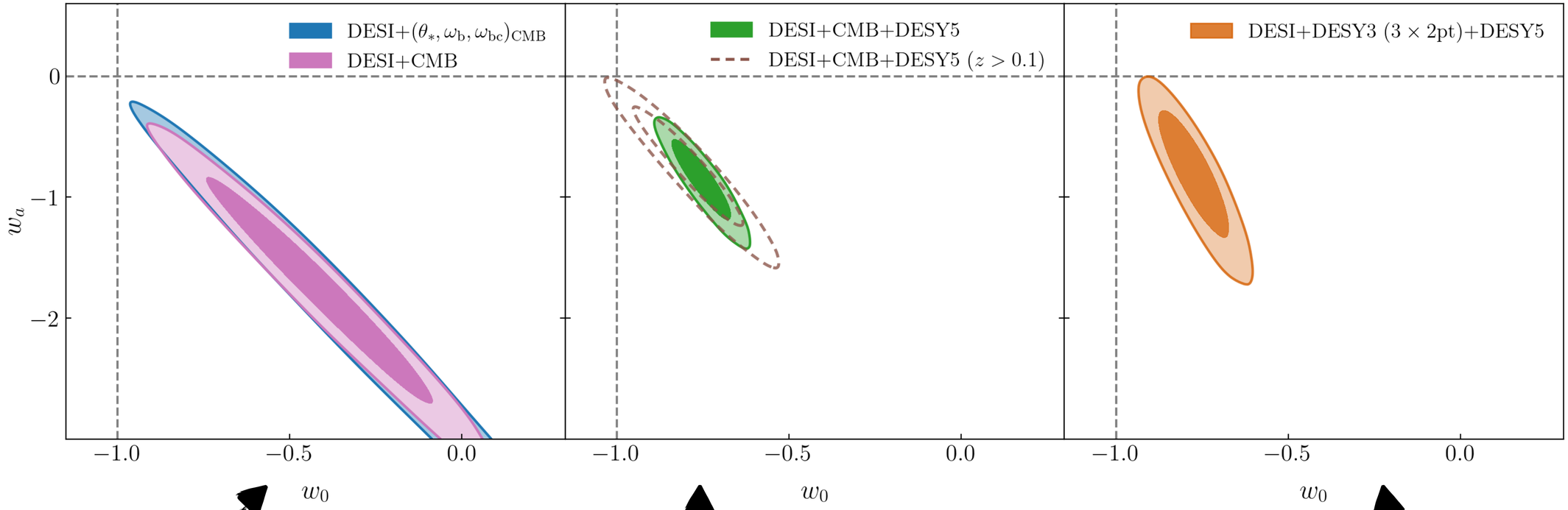


Just early universe info + DESI

Removing SN lowest z-bin

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

Time-dependent dark energy (early- vs late-time probes)



Just early universe info + DESI

Removing SN lowest z-bin

Just low-z info

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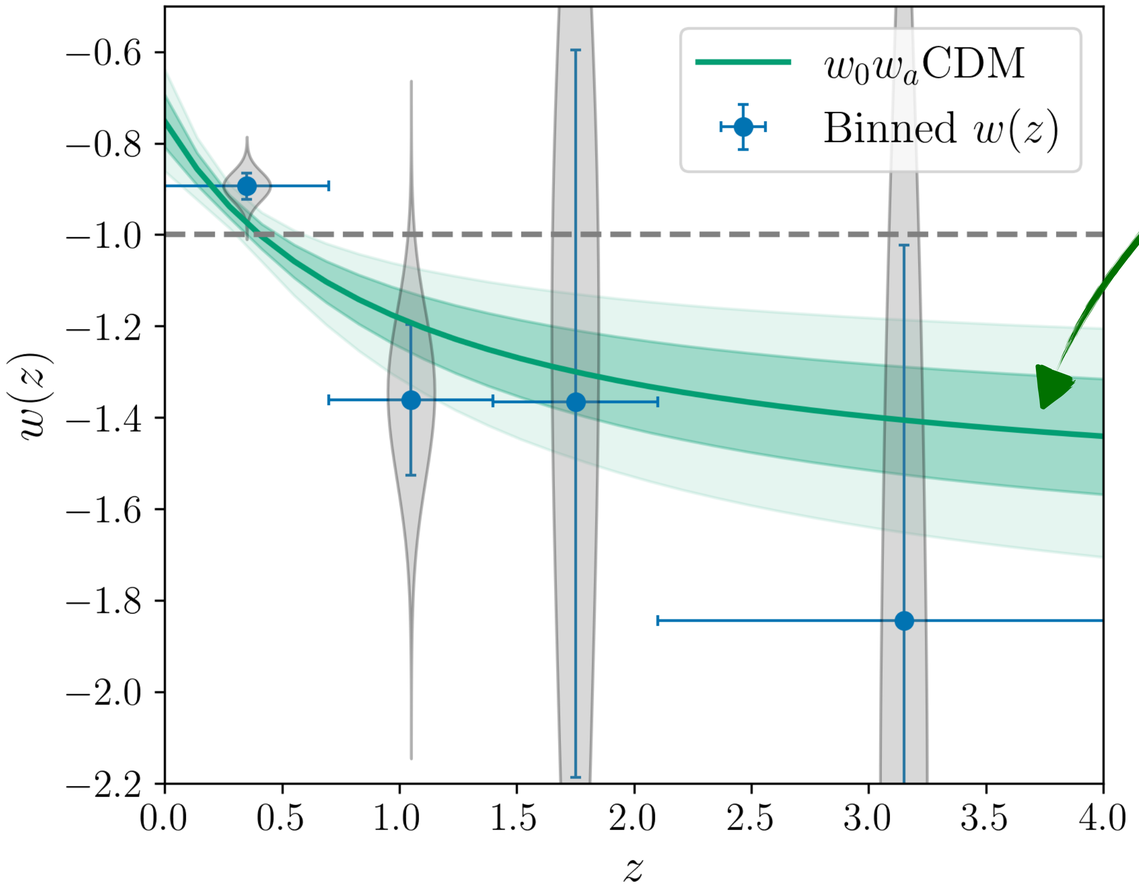
Time-dependent dark energy (CPL param. vs binned eq. of state)



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

Binned reconstruction of w(z) without assuming a functional form for the eq. of state

Consistent with our w_0w_aCDM results

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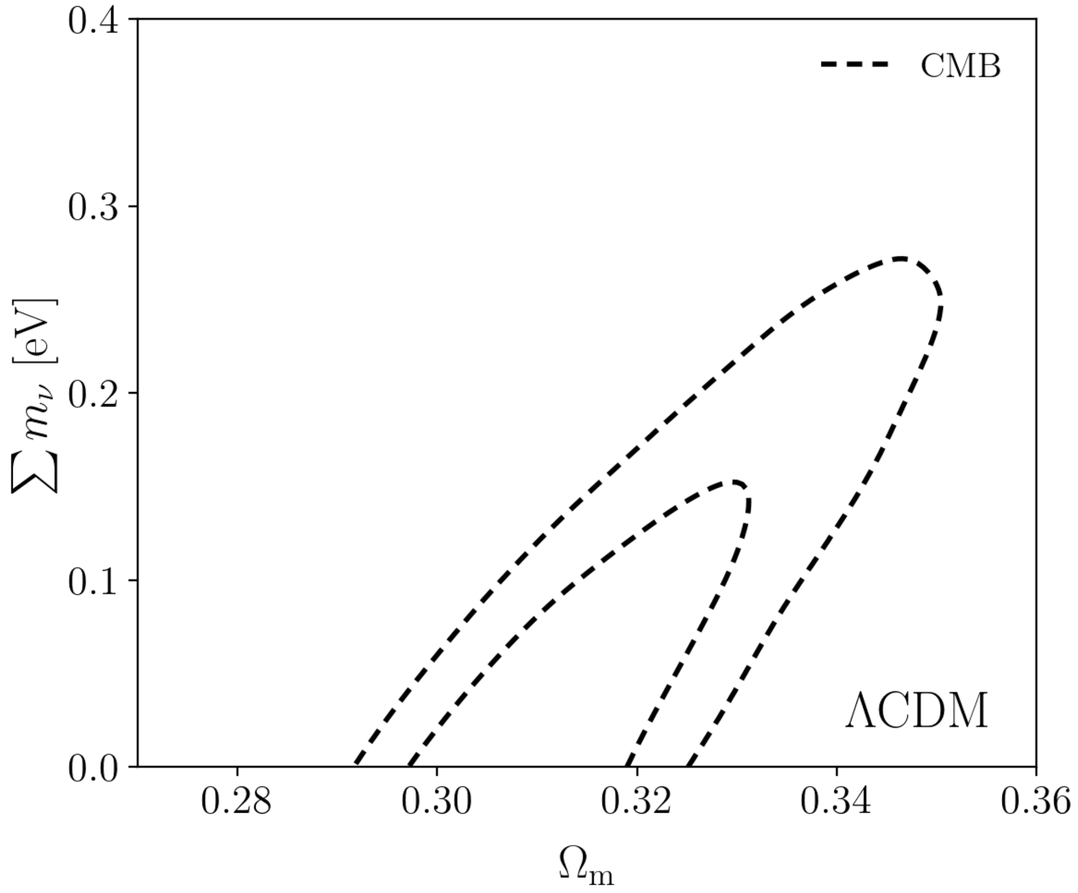
Neutrino mass (ΛCDM)

Massive neutrinos influence the angular diameter distance to last scattering but so do other cosmological parameters



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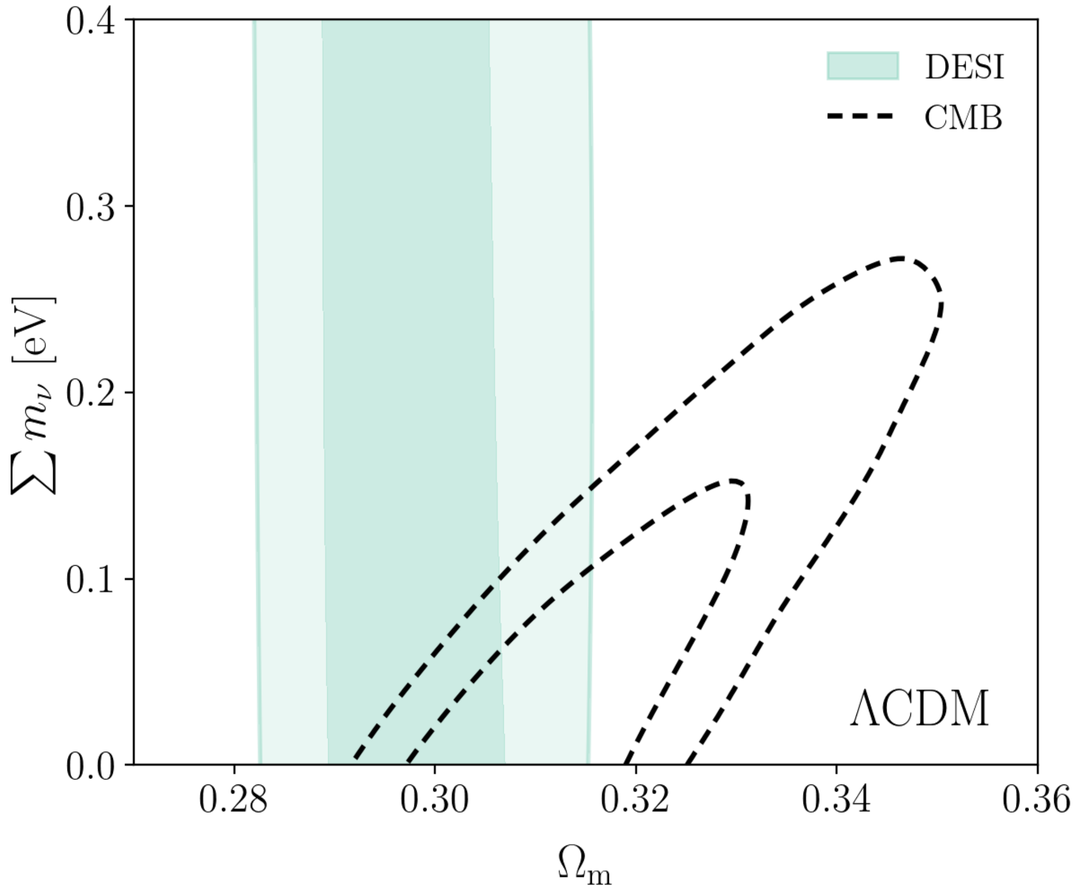
Neutrino mass (ΛCDM)

Massive neutrinos influence the angular diameter distance to last scattering but so do other cosmological parameters

DESI BAO help breaking these degeneracies



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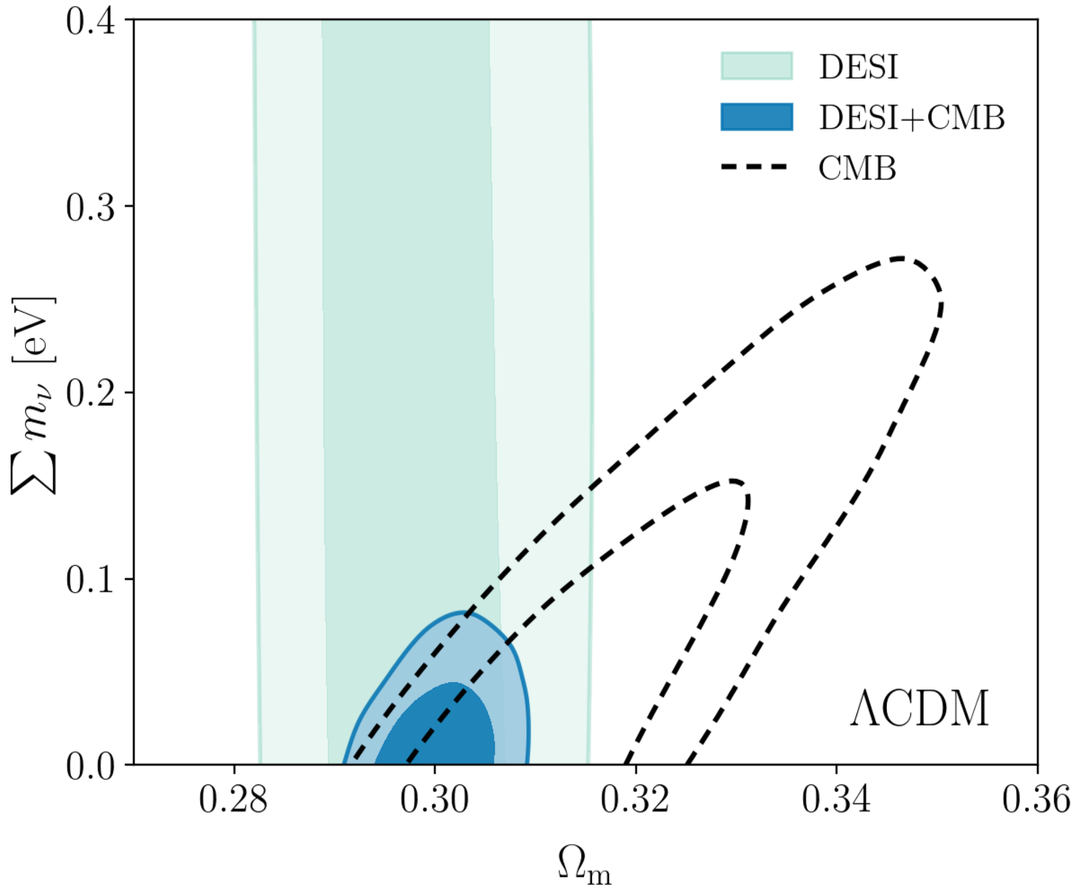

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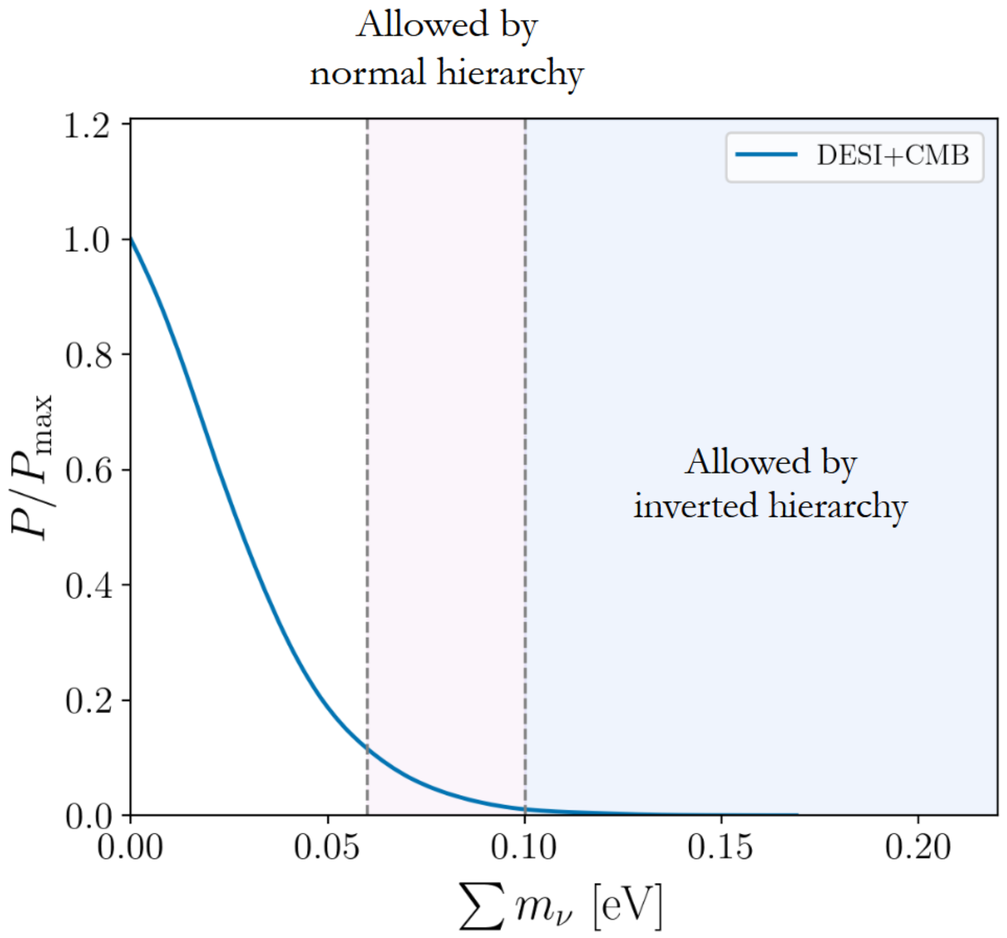
Neutrino mass (w_0w_aCDM)

Assuming ΛCDM:

$\Sigma m_\nu = 0.0642$ eV



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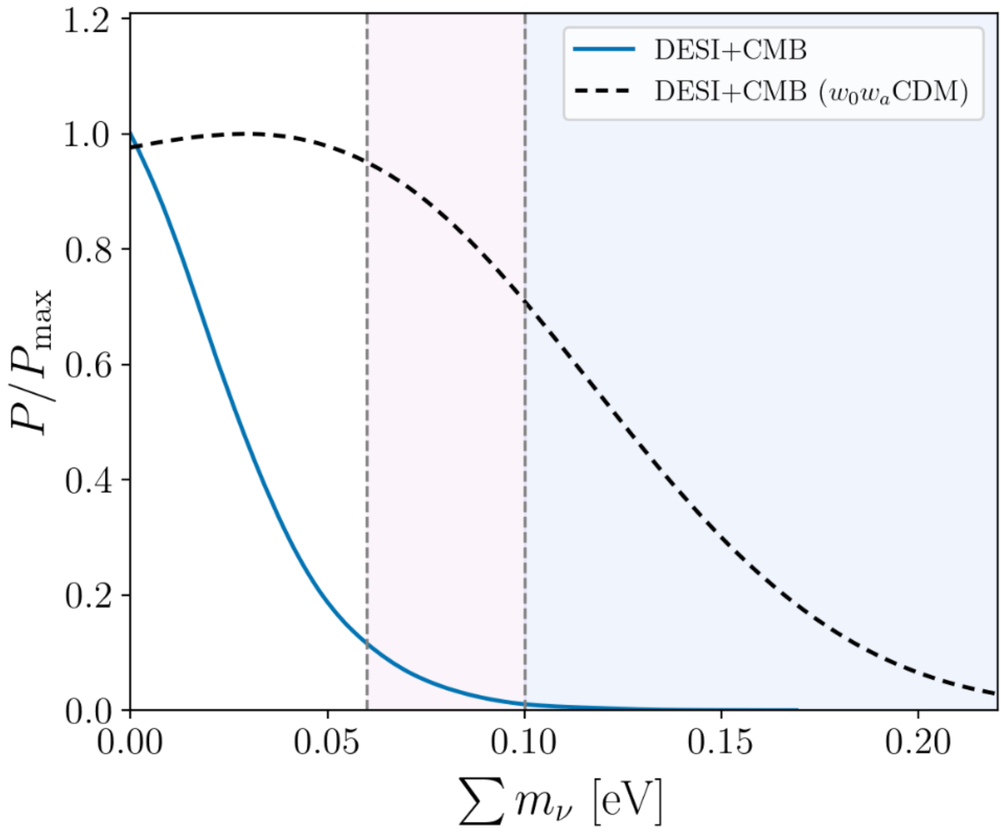
Neutrino mass (w_0w_aCDM)

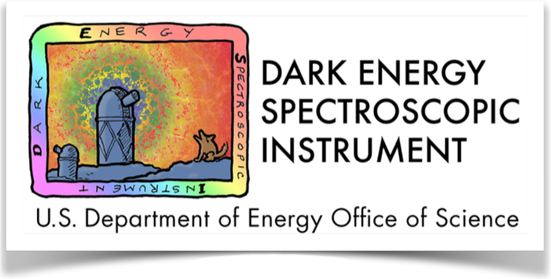
Assuming ΛCDM:

$\Sigma m_\nu = 0.0642$ eV

Assuming w_0w_aCDM:

$\Sigma m_\nu = 0.163$ eV





Summary

- Discrepant results between DESI+BBN and CMB in the Ω_m-H_0 plane within ΛCDM. In addition, DESI is in tension with the Ω_m values measured with SNe, which are larger than that preferred by CMB.
- Assuming ΛCDM, DESI + CMB yield the tightest constraints on the sum of neutrino masses, in increasing tension with lower bounds from terrestrial oscillation experiments
- These points hint at growing incompatibility between different datasets when interpreted using the ΛCDM model
- With DR2 BAO the evidence for evolving dark energy has increased to 3.1σ from DESI+CMB alone, and to between 2.8σ and 4.2σ when including SNe. This additional freedom reconciles the discrepancies between dataset mentioned above

What’s next?

What’s next?

1. ~ 4 more years of DESI/Euclid data (+ PFS, Roman, …)

What’s next?

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2. DESI-2

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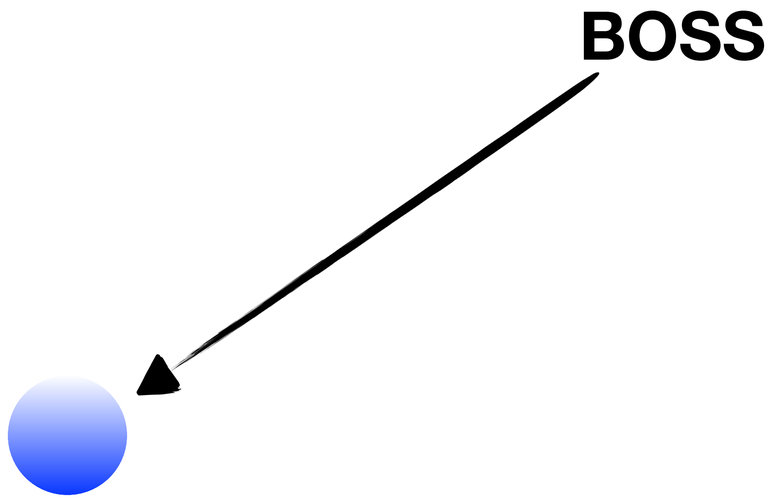

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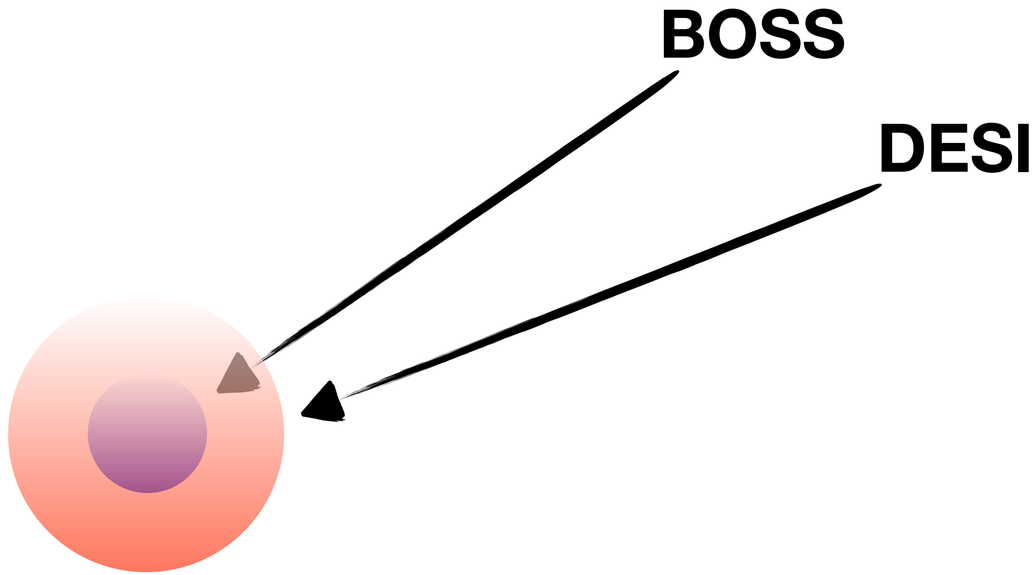

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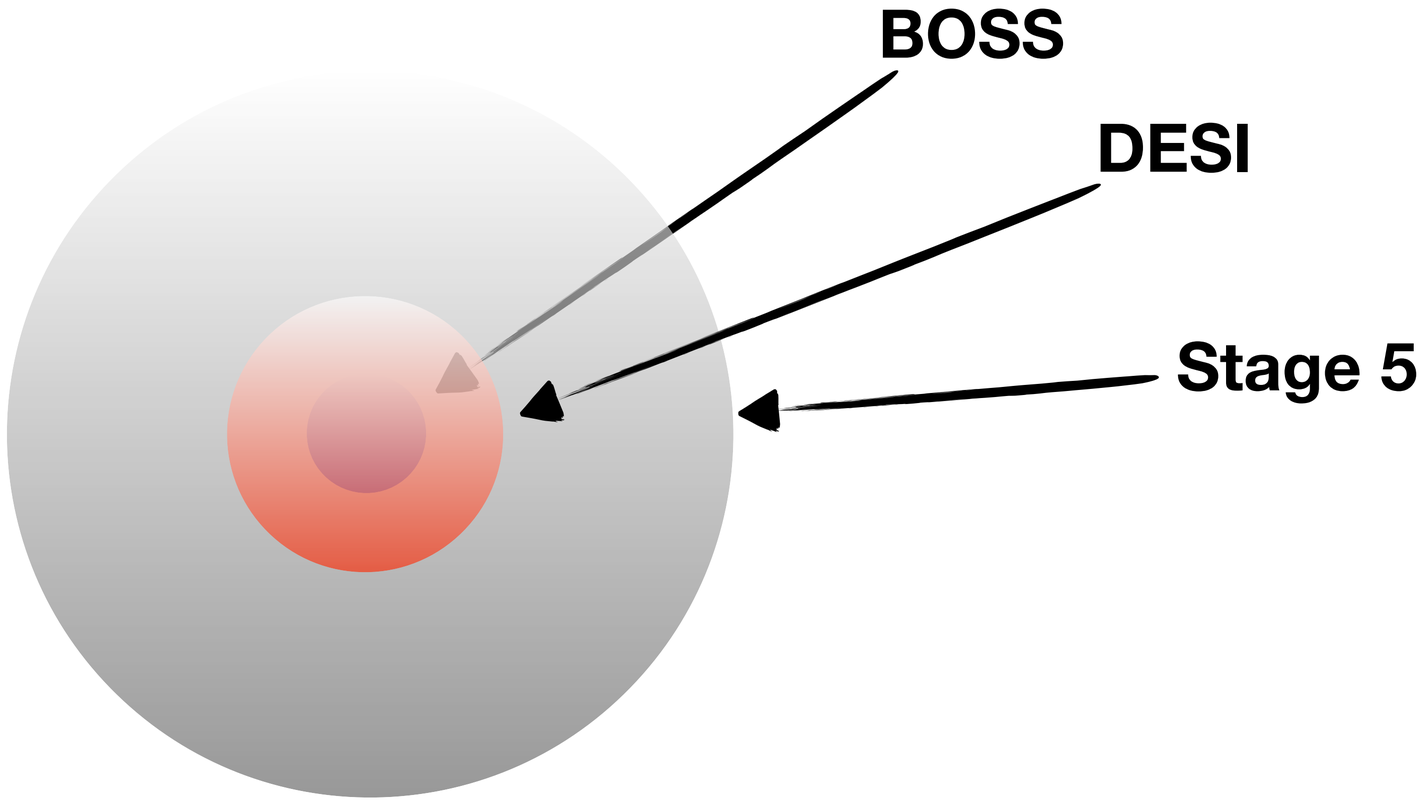

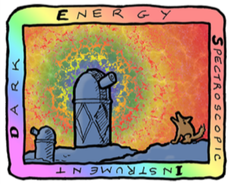

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Extra slides

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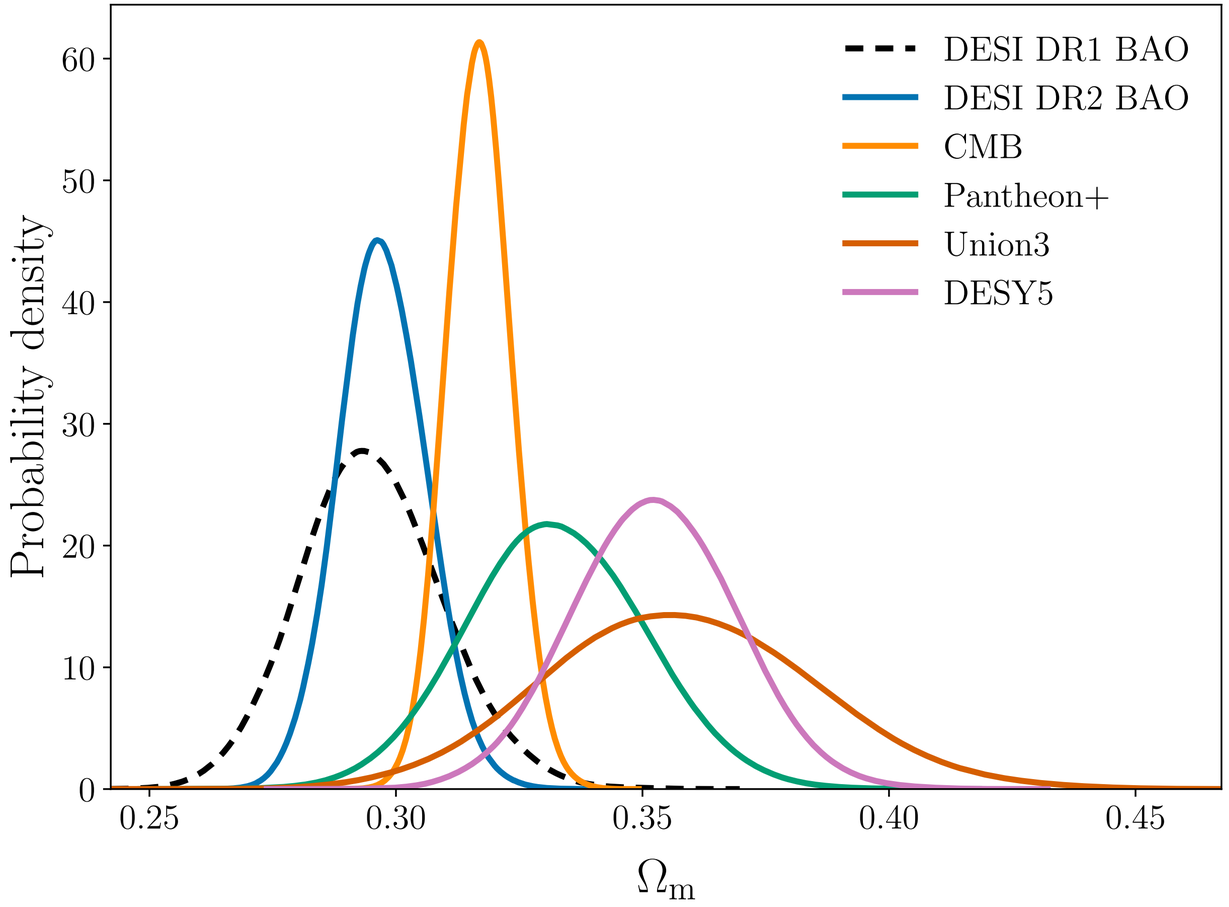
Ω_m comparison under ΛCDM

Mild to moderate discrepancy between DESI and SNe

Might indicate that DESI and SNe can be fitted together only with models with greater freedom in background evolution



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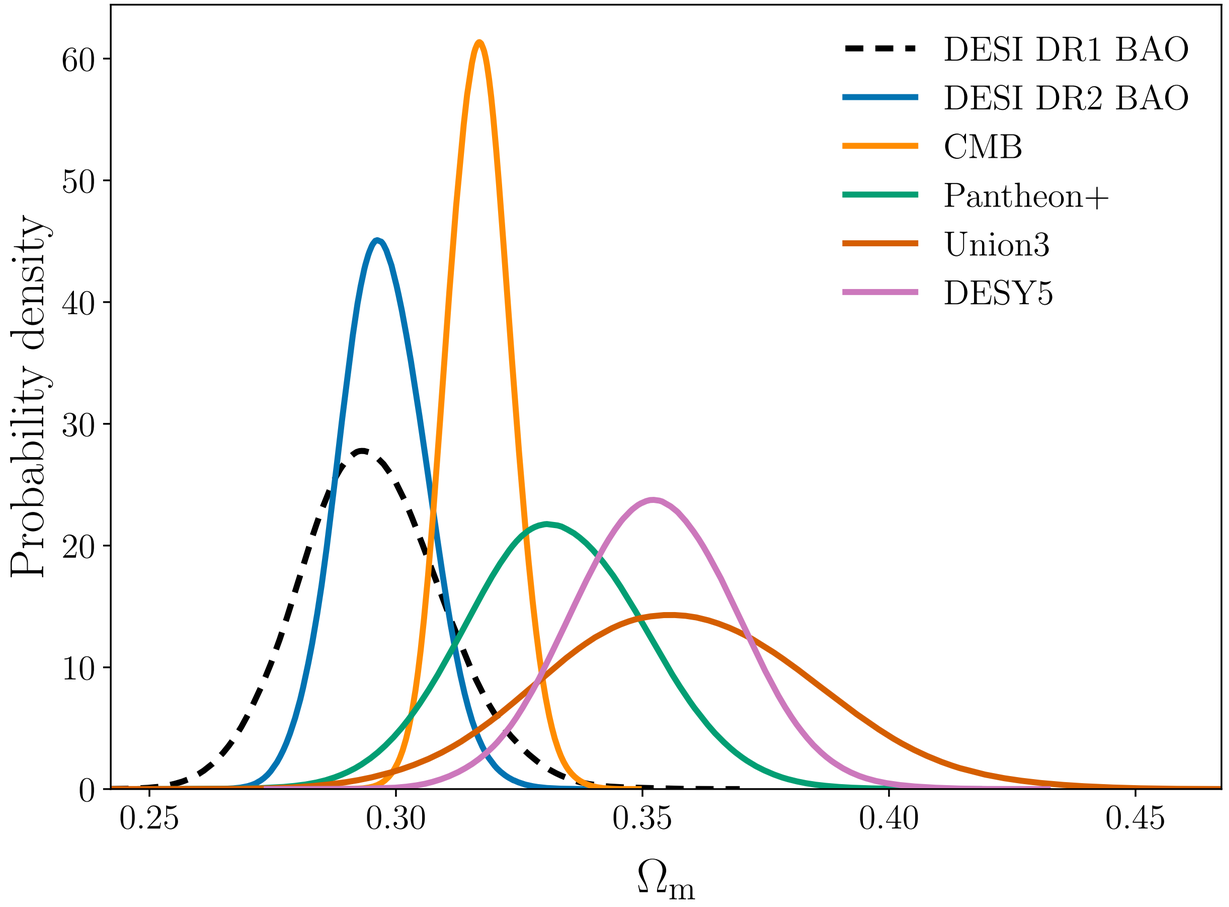

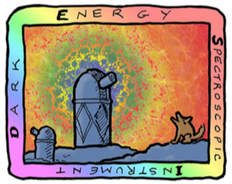

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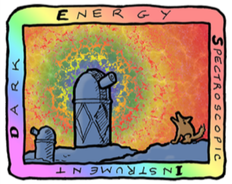
DR2 parameter table

Model/Dataset	$\Omega_{\rm m}$	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_{\rm K}$	w or w_0	w_a
ΛCDM					
CMB	0.3169 ± 0.0065	67.14 ± 0.47	—	—	—
DESI	0.2975 ± 0.0086	—	—	—	—
DESI+BBN	0.2977 ± 0.0086	68.51 ± 0.58	—	—	—
DESI+BBN+θ_*	0.2967 ± 0.0045	68.45 ± 0.47	—	—	—
DESI+CMB	0.3027 ± 0.0036	68.17 ± 0.28	—	—	—
ΛCDM+$\Omega_{\rm K}$					
CMB	$0.354^{+0.020}_{-0.023}$	63.3 ± 2.1	$-10.7^{+6.4}_{-5.3}$	—	—
DESI	0.293 ± 0.012	—	25 ± 41	—	—
DESI+CMB	0.3034 ± 0.0037	68.50 ± 0.33	2.3 ± 1.1	—	—



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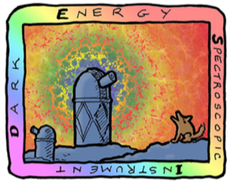
DR2 parameter table

Model/Dataset	$\Omega_{\rm m}$	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_{\rm K}$	w or w_0	w_a
wCDM					
CMB	$0.203^{+0.017}_{-0.060}$	85^{+10}_{-6}	—	$-1.55^{+0.17}_{-0.37}$	—
DESI	0.2969 ± 0.0089	—	—	-0.916 ± 0.078	—
DESI+Pantheon+	0.2976 ± 0.0087	—	—	-0.914 ± 0.040	—
DESI+Union3	0.2973 ± 0.0091	—	—	-0.866 ± 0.052	—
DESI+DESY5	0.2977 ± 0.0091	—	—	-0.872 ± 0.039	—
DESI+CMB	0.2927 ± 0.0073	69.51 ± 0.92	—	-1.055 ± 0.036	—
DESI+CMB+Pantheon+	0.3047 ± 0.0051	67.97 ± 0.57	—	-0.995 ± 0.023	—
DESI+CMB+Union3	0.3044 ± 0.0059	68.01 ± 0.68	—	-0.997 ± 0.027	—
DESI+CMB+DESY5	0.3098 ± 0.0050	67.34 ± 0.54	—	-0.971 ± 0.021	—



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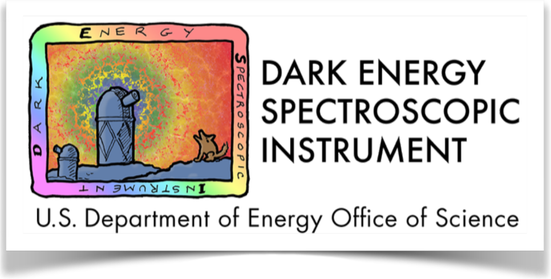
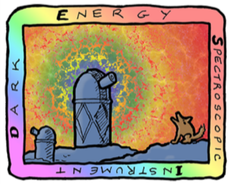
DR2 parameter table

Model/Dataset	$\Omega_{\rm m}$	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_{\rm K}$	w or w_0	w_a
w_0w_aCDM					
CMB	$0.220^{+0.019}_{-0.078}$	83^{+20}_{-6}	—	$-1.23^{+0.44}_{-0.61}$	< -0.504
DESI	$0.352^{+0.041}_{-0.018}$	—	—	$-0.48^{+0.35}_{-0.17}$	< -1.34
DESI+Pantheon+	$0.298^{+0.025}_{-0.011}$	—	—	$-0.888^{+0.055}_{-0.064}$	-0.17 ± 0.46
DESI+Union3	$0.328^{+0.019}_{-0.014}$	—	—	-0.70 ± 0.11	-0.99 ± 0.57
DESI+DESY5	$0.319^{+0.017}_{-0.011}$	—	—	$-0.781^{+0.067}_{-0.076}$	-0.72 ± 0.47
DESI+$(\theta_*, \omega_{\rm b}, \omega_{\rm bc})_{\rm CMB}$	0.353 ± 0.022	$63.7^{+1.7}_{-2.2}$	—	-0.43 ± 0.22	-1.72 ± 0.64
DESI+CMB (no lensing)	0.352 ± 0.021	$63.7^{+1.7}_{-2.1}$	—	-0.43 ± 0.21	-1.70 ± 0.60
DESI+CMB	0.353 ± 0.021	$63.6^{+1.6}_{-2.1}$	—	-0.42 ± 0.21	-1.75 ± 0.58
DESI+CMB+Pantheon+	0.3114 ± 0.0057	67.51 ± 0.59	—	-0.838 ± 0.055	$-0.62^{+0.22}_{-0.19}$
DESI+CMB+Union3	0.3275 ± 0.0086	65.91 ± 0.84	—	-0.667 ± 0.088	$-1.09^{+0.31}_{-0.27}$
DESI+CMB+DESY5	0.3191 ± 0.0056	66.74 ± 0.56	—	-0.752 ± 0.057	$-0.86^{+0.23}_{-0.20}$
DESI+DESY3 (3×2pt)+Pantheon+	0.3140 ± 0.0091	—	—	-0.870 ± 0.061	$-0.46^{+0.33}_{-0.29}$
DESI+DESY3 (3×2pt)+Union3	0.333 ± 0.012	—	—	-0.68 ± 0.11	$-1.09^{+0.48}_{-0.39}$
DESI+DESY3 (3×2pt)+DESY5	0.3239 ± 0.0092	—	—	-0.771 ± 0.068	$-0.82^{+0.38}_{-0.32}$



DR2 parameter table

Model/Dataset	$\Omega_{\rm m}$	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_{\rm K}$	w or w_0	w_a
$\boldsymbol{w_0w_a}$**CDM+**$\boldsymbol{\Omega_{\rm K}}$					
DESI	$0.357^{+0.041}_{-0.030}$	—	-2 ± 56	$-0.45^{+0.33}_{-0.17}$	< -1.43
DESI+CMB+Pantheon+	0.3117 ± 0.0056	67.62 ± 0.60	1.1 ± 1.3	-0.853 ± 0.057	-0.54 ± 0.22
DESI+CMB+Union3	0.3273 ± 0.0086	65.98 ± 0.86	0.6 ± 1.3	-0.678 ± 0.092	$-1.03^{+0.33}_{-0.29}$
DESI+CMB+DESY5	0.3193 ± 0.0056	66.82 ± 0.58	0.8 ± 1.3	-0.762 ± 0.060	-0.81 ± 0.24



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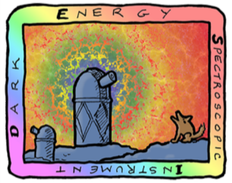
DR2 parameter table (neutrinos)

Model/Dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$H_0 r_d$ [100 km s^{-1}]	$\sum m_\nu$ [eV]	w or w_0	w_a
ΛCDM+$\sum m_\nu$						
DESI BAO+CMB [Camspec]	0.3009 ± 0.0037	68.36 ± 0.29	100.96 ± 0.48	< 0.0642	—	—
DESI BAO+CMB [L-H]	0.2995 ± 0.0037	68.48 ± 0.30	101.16 ± 0.49	< 0.0774	—	—
DESI BAO+CMB [Plik]	0.2998 ± 0.0038	68.56 ± 0.31	101.09 ± 0.50	< 0.0691	—	—
wCDM+$\sum m_\nu$						
DESI BAO+CMB	0.2943 ± 0.0073	69.28 ± 0.92	102.3 ± 1.3	< 0.0851	-1.039 ± 0.037	—
DESI BAO+CMB+Pantheon+	0.3045 ± 0.0051	67.94 ± 0.58	100.35 ± 0.84	< 0.0653	-0.985 ± 0.023	—
DESI BAO+CMB+Union3	0.3047 ± 0.0059	67.93 ± 0.69	100.33 ± 0.99	< 0.0649	-0.985 ± 0.028	—
DESI BAO+CMB+DESY5	0.3094 ± 0.0049	67.34 ± 0.53	99.49 ± 0.78	< 0.0586	-0.961 ± 0.021	—
$w_0 w_a$CDM+$\sum m_\nu$						
DESI BAO+CMB	0.353 ± 0.022	$63.7^{+1.7}_{-2.2}$	$93.8^{+2.5}_{-3.2}$	< 0.163	$-0.42^{+0.24}_{-0.21}$	-1.75 ± 0.63
DESI BAO+CMB+Pantheon+	0.3109 ± 0.0057	67.54 ± 0.59	99.62 ± 0.86	< 0.117	-0.845 ± 0.055	$-0.57^{+0.23}_{-0.19}$
DESI BAO+CMB+Union3	0.3269 ± 0.0088	65.96 ± 0.84	97.3 ± 1.2	< 0.139	-0.674 ± 0.090	$-1.06^{+0.34}_{-0.28}$
DESI BAO+CMB+DESY5	0.3188 ± 0.0058	66.75 ± 0.56	98.43 ± 0.83	< 0.129	-0.758 ± 0.058	$-0.82^{+0.26}_{-0.21}$



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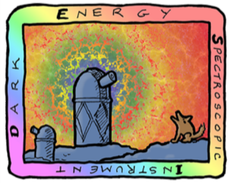
DR2 evidence table

Datasets	$\Delta\chi^2_{\rm MAP}$	Significance	Δ(DIC)
DESI	-4.7	1.7σ	-0.8
DESI+$(\theta_*, \omega_{\rm b}, \omega_{\rm bc})_{\rm CMB}$	-8.0	2.4σ	-4.4
DESI+CMB (no lensing)	-9.7	2.7σ	-5.9
DESI+CMB	-12.5	3.1σ	-8.7
DESI+Pantheon+	-4.9	1.7σ	-0.7
DESI+Union3	-10.1	2.7σ	-6.0
DESI+DESY5	-13.6	3.3σ	-9.3
DESI+DESY3 (3×2pt)	-7.3	2.2σ	-2.8
DESI+DESY3 (3×2pt)+DESY5	-13.8	3.3σ	-9.1
DESI+CMB+Pantheon+	-10.7	2.8σ	-6.8
DESI+CMB+Union3	-17.4	3.8σ	-13.5
DESI+CMB+DESY5	-21.0	4.2σ	-17.2

TABLE VI. Summary of the difference in the effective $\chi^2_{\rm MAP}$ value (defined as twice the negative log posterior at the maximum posterior point) for the best-fit w_0w_aCDM model relative to the best ΛCDM model with $w_0 = -1$, $w_a = 0$, for fits to different combinations of datasets as indicated. The third column lists the corresponding (frequentist) significance levels given 2 extra free parameters, and the final column shows the results for $\Delta(\text{DIC}) = \text{DIC}_{w_0w_a\text{CDM}} - \text{DIC}_{\Lambda\text{CDM}}$. As a rule of thumb, Δ(DIC) values < -5 indicate a 'strong' preference for w_0w_aCDM and values < -10 a 'decisive' preference [144].



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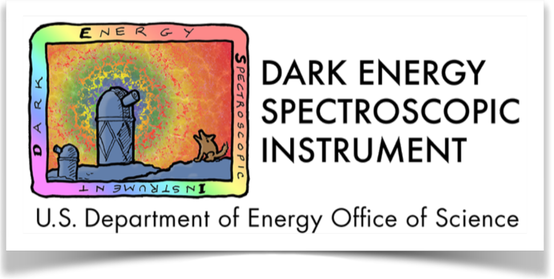
DR2 BAO z-bins

Tracer	No. of redshifts	Redshift range	$z_{\rm eff}$	Area [deg^2]	$P_0(k=0.14)$	$V_{\rm eff}$ (Gpc^3)
BGS	1,188,526	$0.1 < z < 0.4$	0.295	12,355	7000	3.8
LRG1	1,052,151	$0.4 < z < 0.6$	0.510	10,031	10000	4.9
LRG2	1,613,562	$0.6 < z < 0.8$	0.706	10,031	10000	7.6
LRG3	1,802,770	$0.8 < z < 1.1$	0.922	10,031	10000	9.8
ELG1	2,737,573	$0.8 < z < 1.1$	0.955	10,352	4000	5.8
ELG2	3,797,271	$1.1 < z < 1.6$	1.321	10,352	4000	2.7
QSO	1,461,588	$0.8 < z < 2.1$	1.484	11,181	6000	2.7



DESI targets

Galaxy type	Redshift range	Bands used	Targets per deg^2	Exposures per deg^2	Good z's per deg^2	Baseline sample
LRG	0.4–1.0	r,z,$W1$	350	580	285	4.0 M
ELG	0.6–1.6	g,r,z	2400	1870	1220	17.1 M
QSO (tracers)	< 2.1	g,r,z,$W1$,$W2$	170	170	120	1.7 M
QSO (Ly-α)	> 2.1	g,r,z,$W1$,$W2$	90	250	50	0.7 M
Total in dark time			**3010**	**2870**	**1675**	**23.6 M**
BGS	0.05–0.4	r	700	700	700	9.8 M
Total in bright time			**700**	**700**	**700**	**9.8 M**

DESI collaboration arXiv:1611.00036

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DESI spectrograph

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10 Multi-Object Spectrographs:

- 360 - 980 nm range over 3 channels
- Resolution: 2000 (blue) – 5500 (NIR)
- 500 fibers per spectrograph
- 4kx4k CCDs, 60s readout

Stable PSF

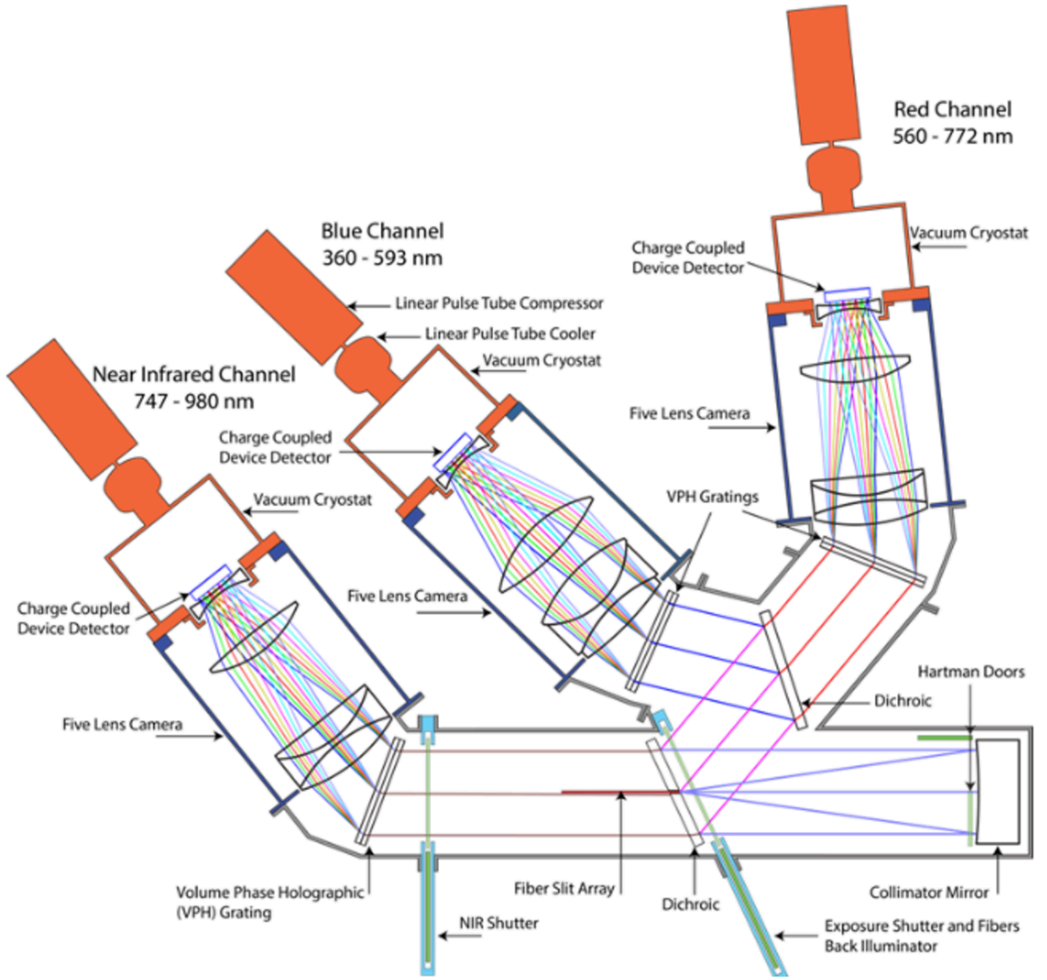
better than 1 % over many days

Low Read out noise

~ 3 e-

Throughput of optical chain is excellent

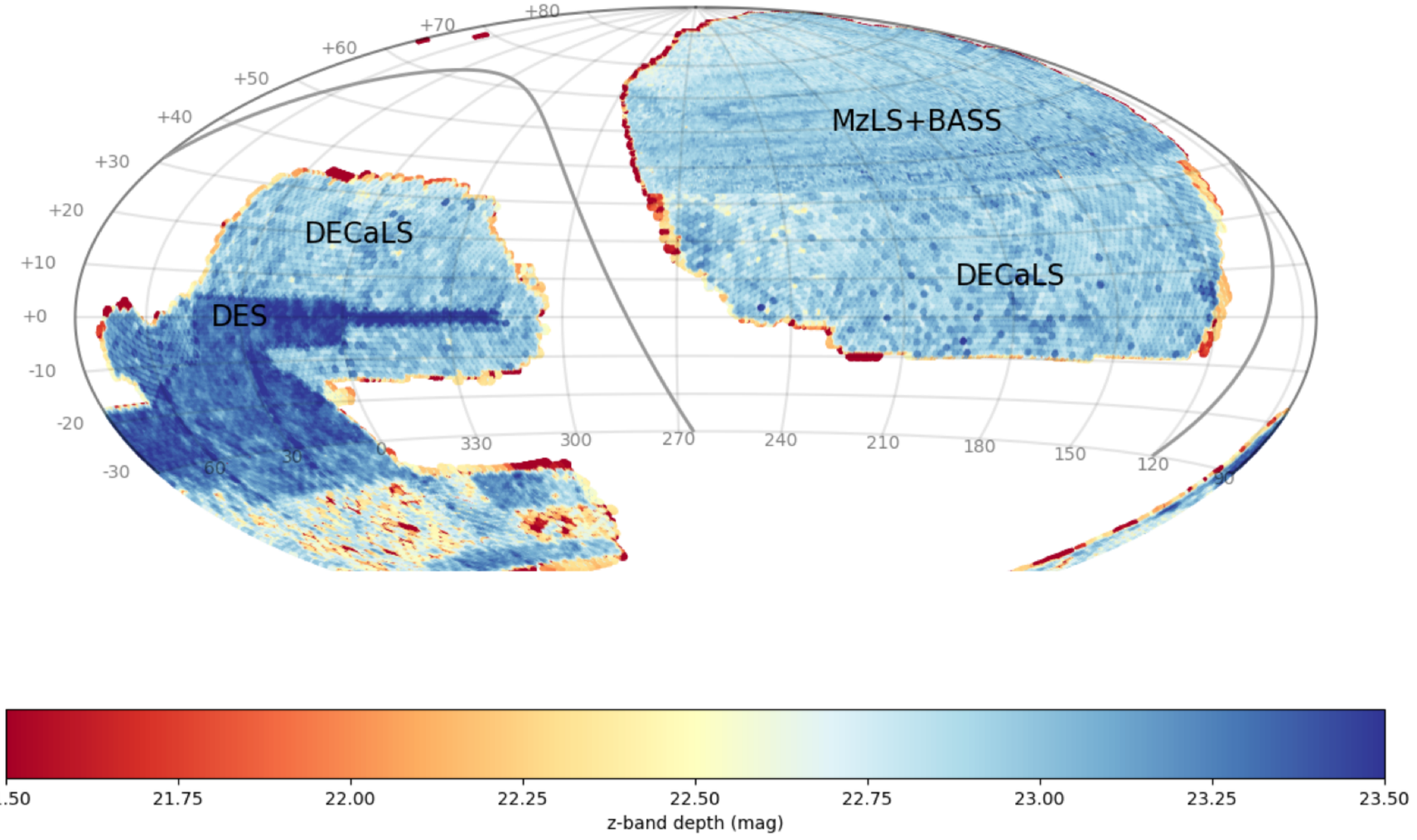
~40% at 700 nm (total)



DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

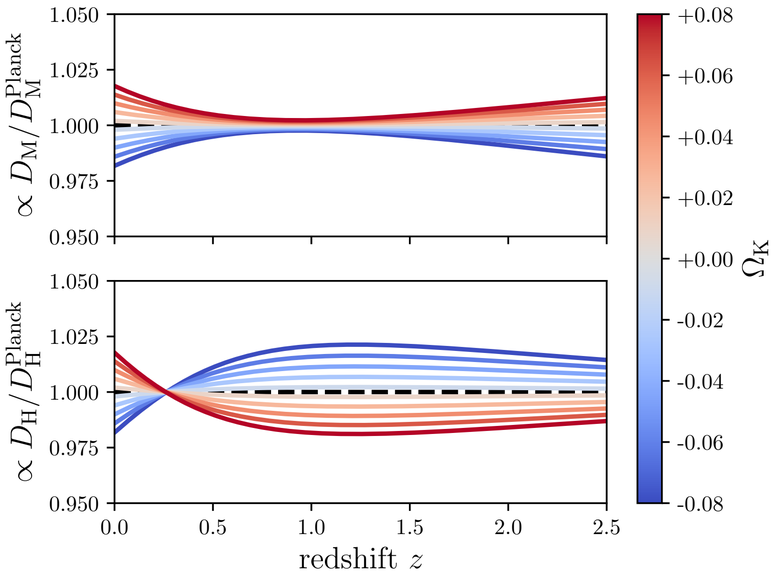
Parent (imaging) surveys

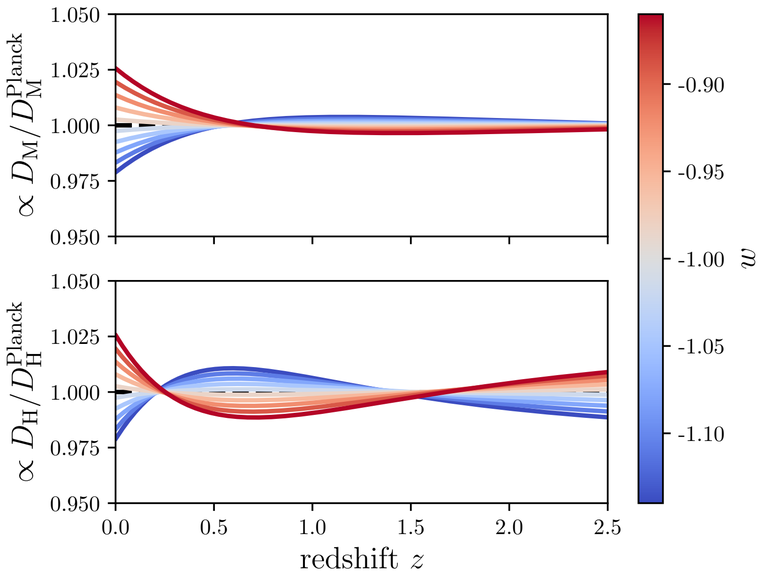


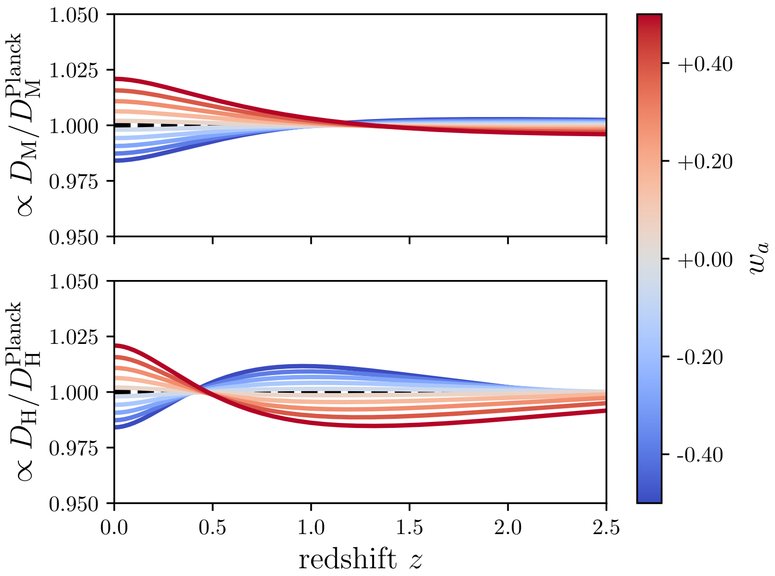
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

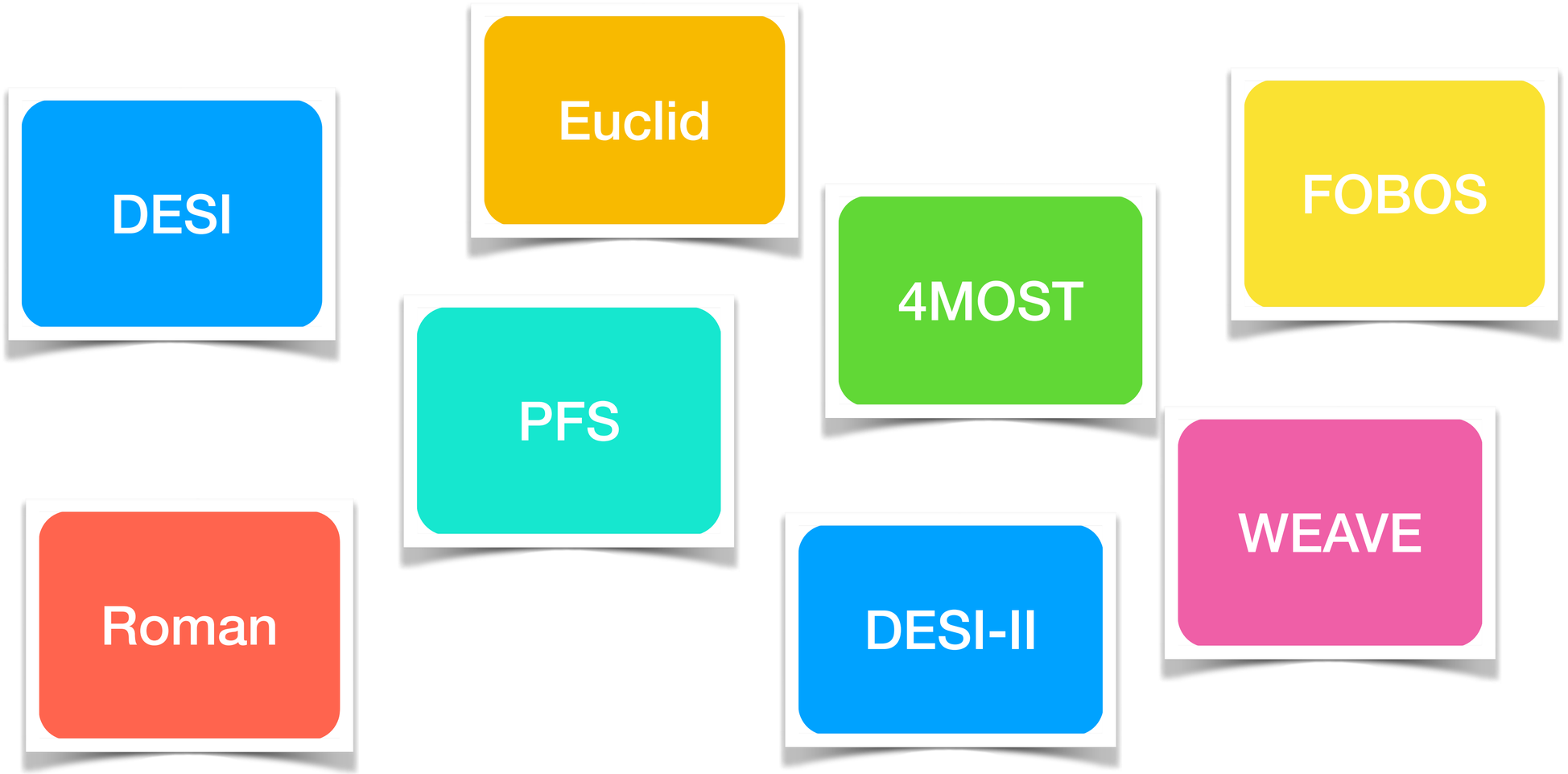
BAO evolution for different cosmo params





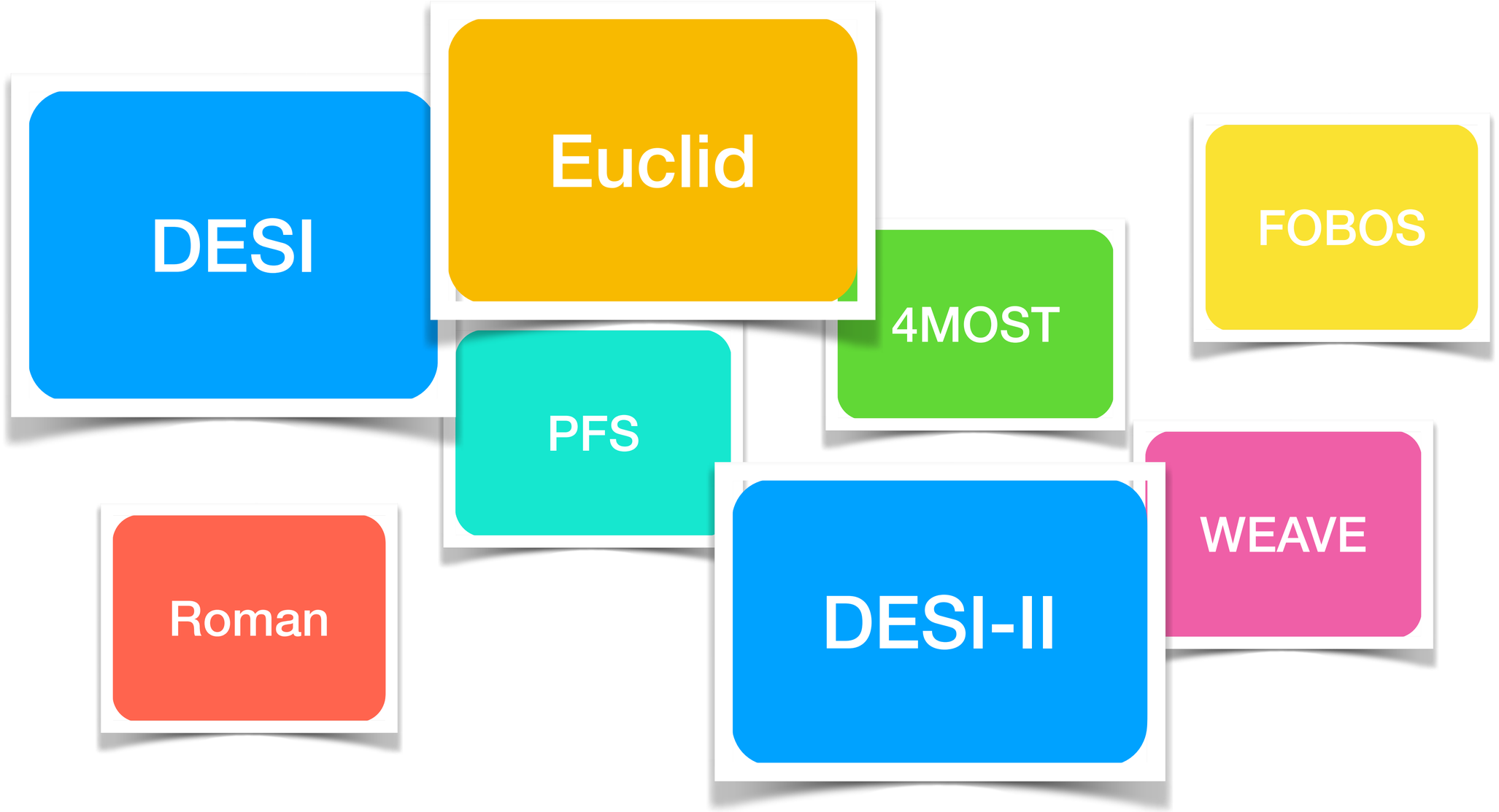


Spectroscopic zoo



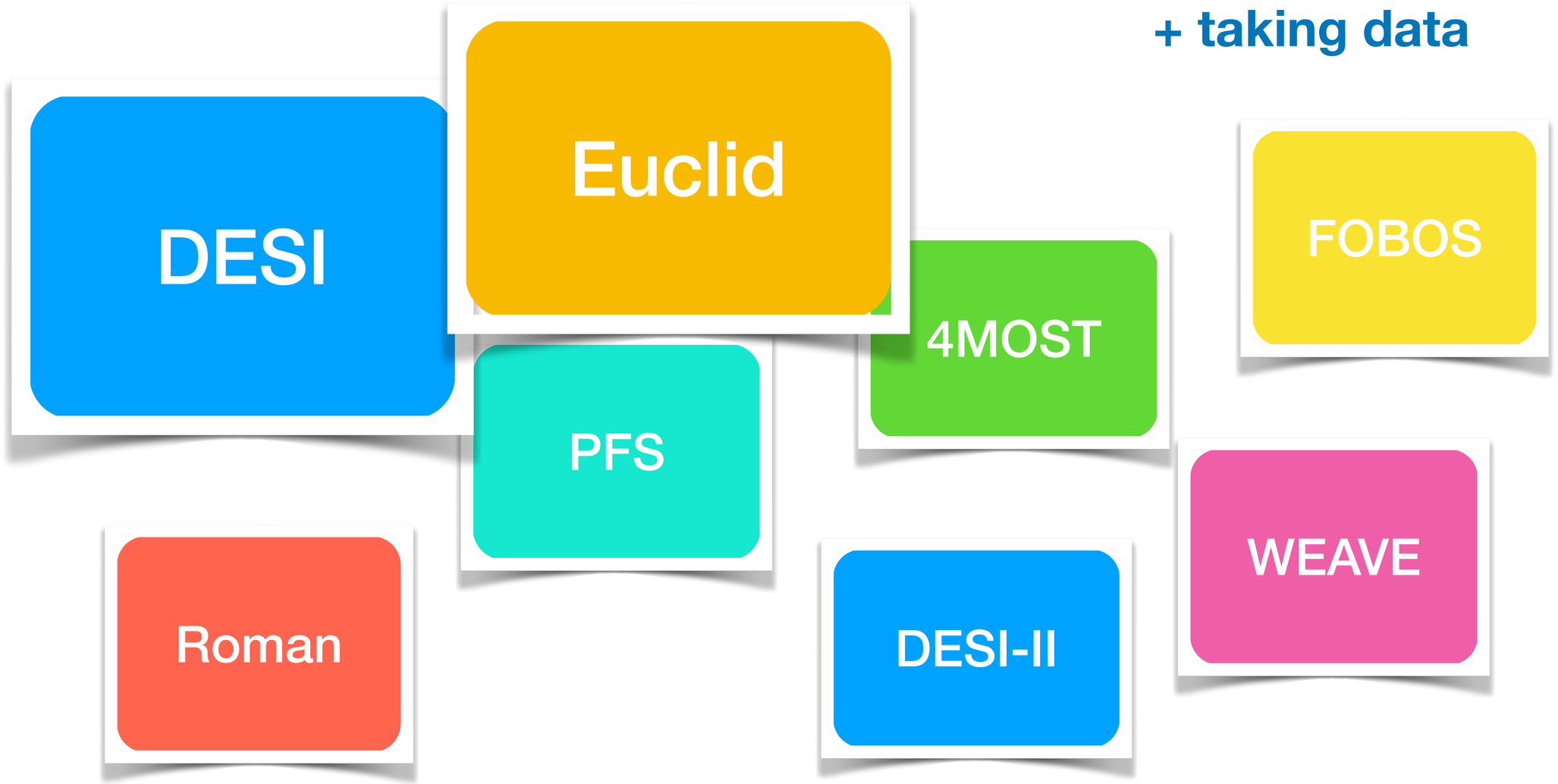
Spectroscopic zoo

Purely focused on cosmology



Spectroscopic zoo

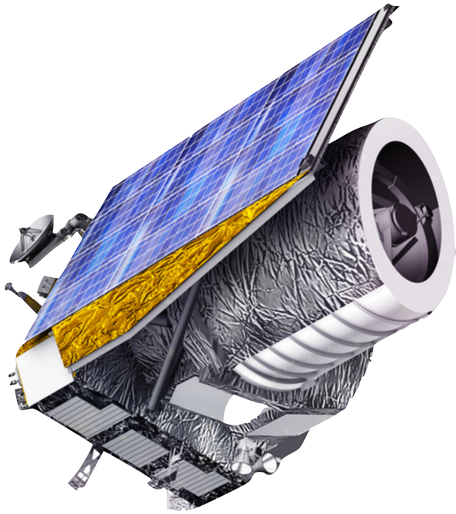
Purely focused on cosmology
+ taking data



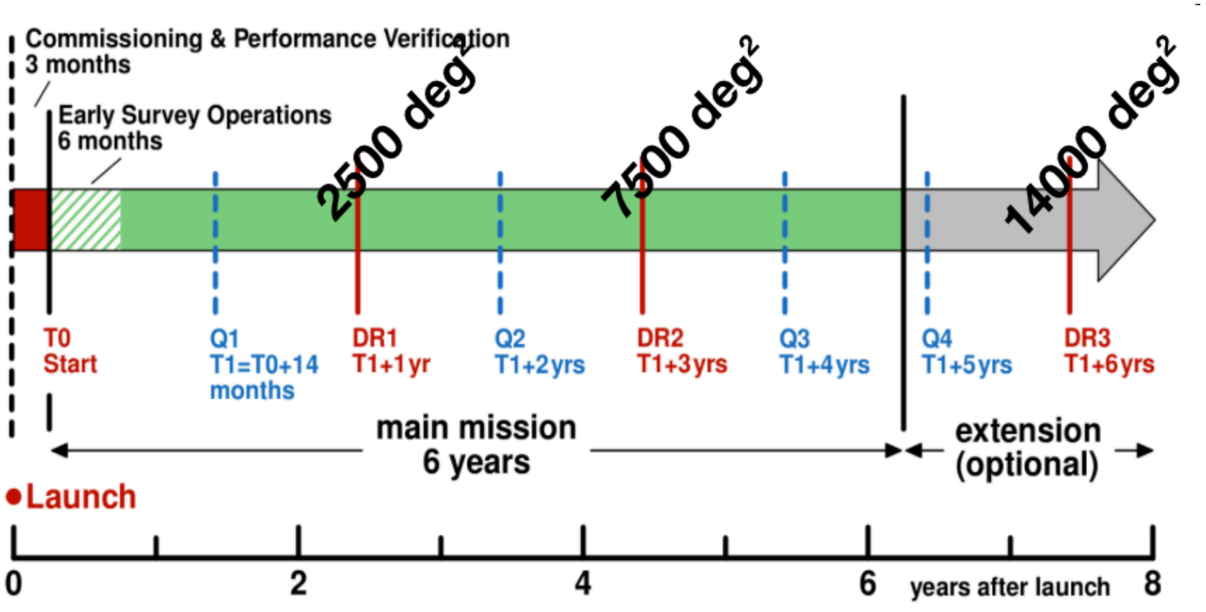
Euclid

14 000 deg² survey over 6 year mission

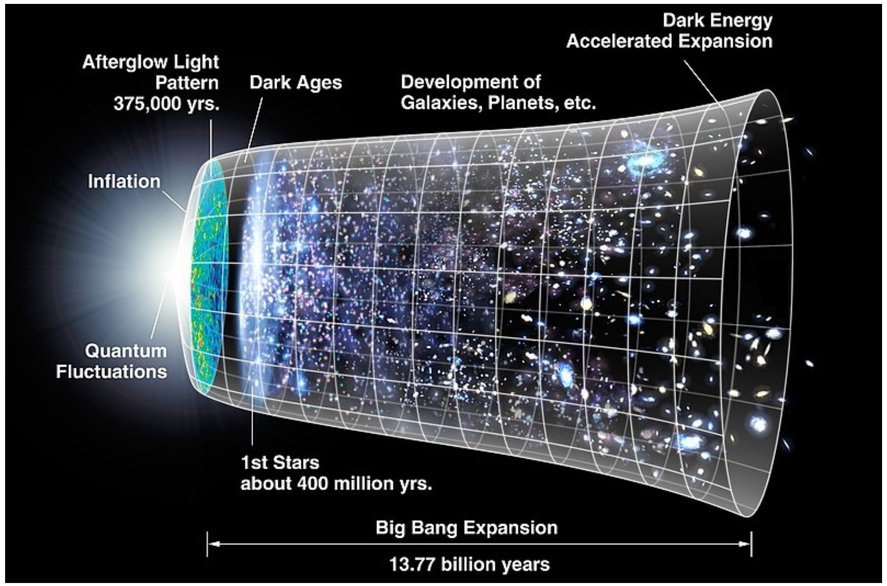
High resolution optical imaging
and Near IR imaging and spectroscopy



Launched on 1st July 2023, from Cape Canaveral
(Credits: ESA, NASA & Space-X)



Current understanding of the Universe



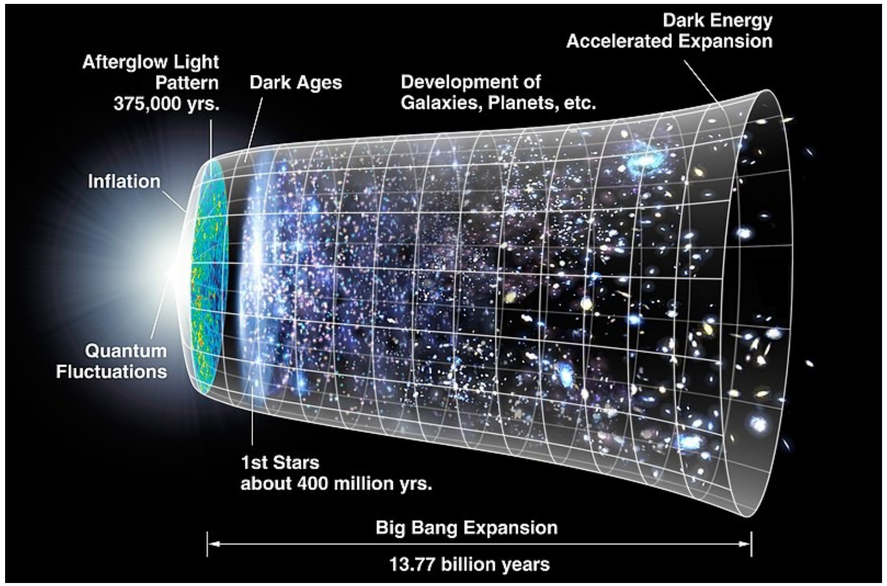
Current understanding of the Universe

Friedmann equation

Expansion rate of the universe

$$H(z) = H_0\sqrt{\Omega_\gamma(1+z)^4 + \Omega_{bc}(1+z)^3 + \Omega_K(1+z)^2 + \Omega_\nu\frac{\rho_\nu(z)}{\rho_{\nu,0}} + \Omega_{DE}\frac{\rho_{DE}(z)}{\rho_{DE,0}}}$$

Radiation | Standard Matter + Dark Matter | Curvature | Neutrinos | Dark Energy



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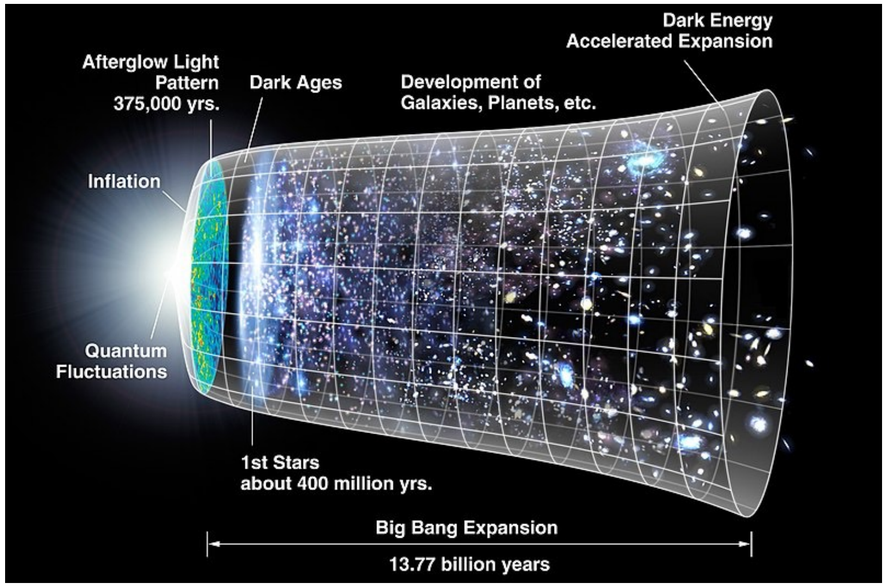

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$$a = \frac{1}{1+z}$$

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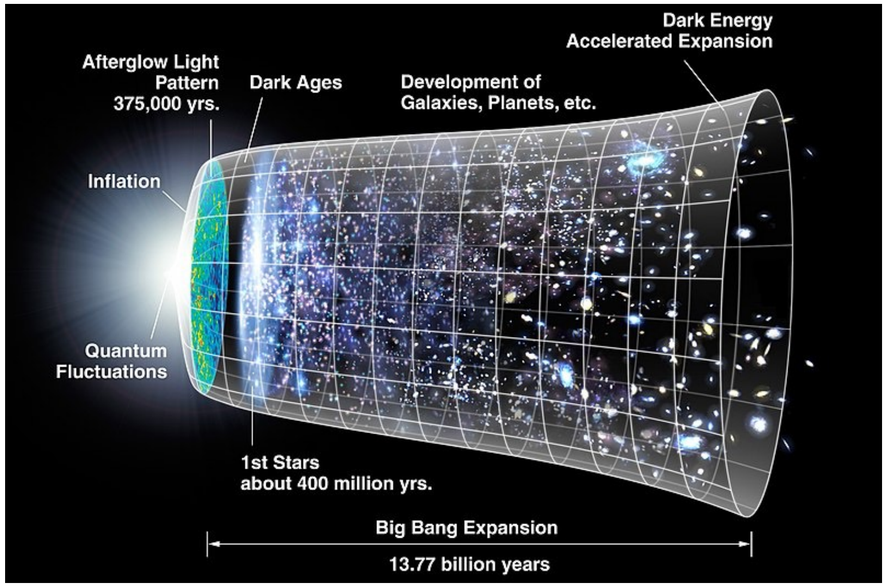

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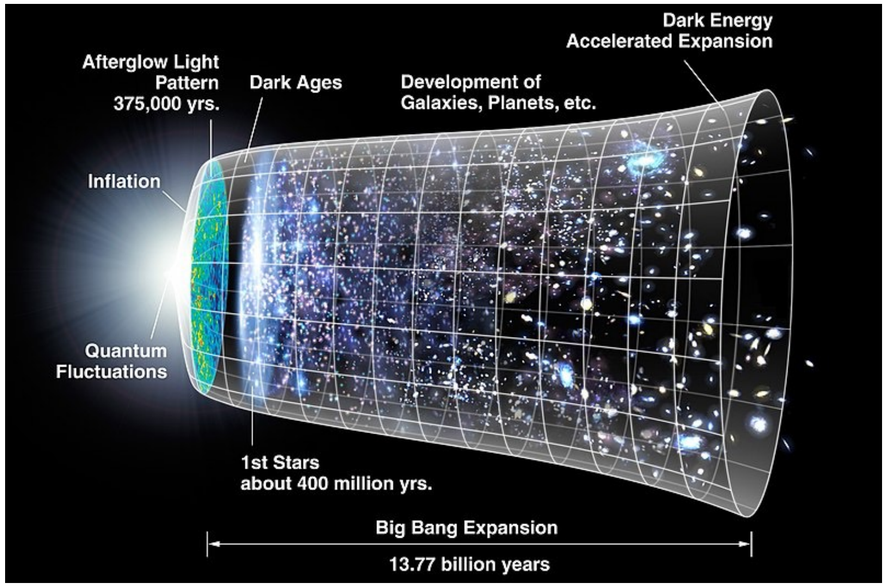

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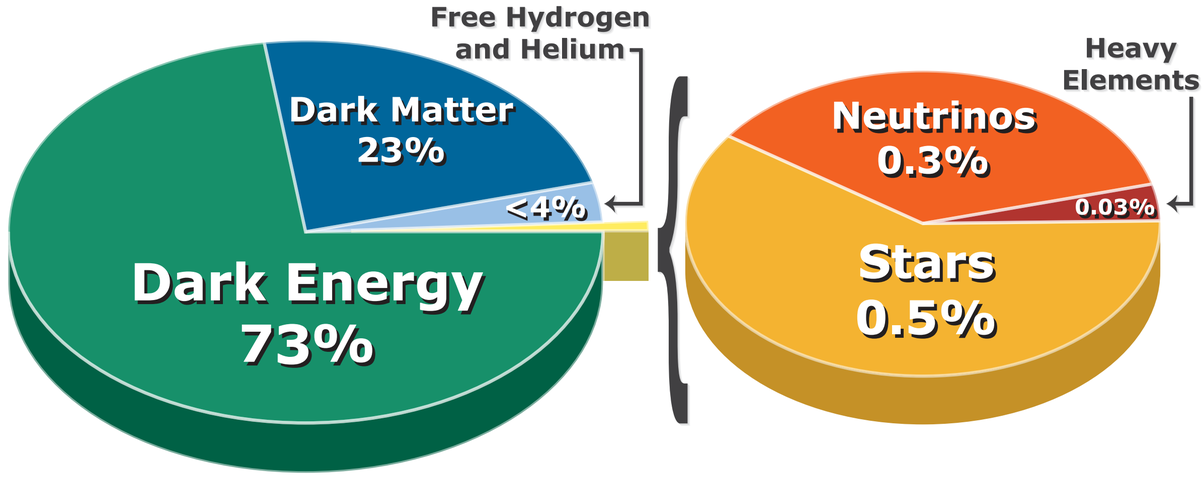

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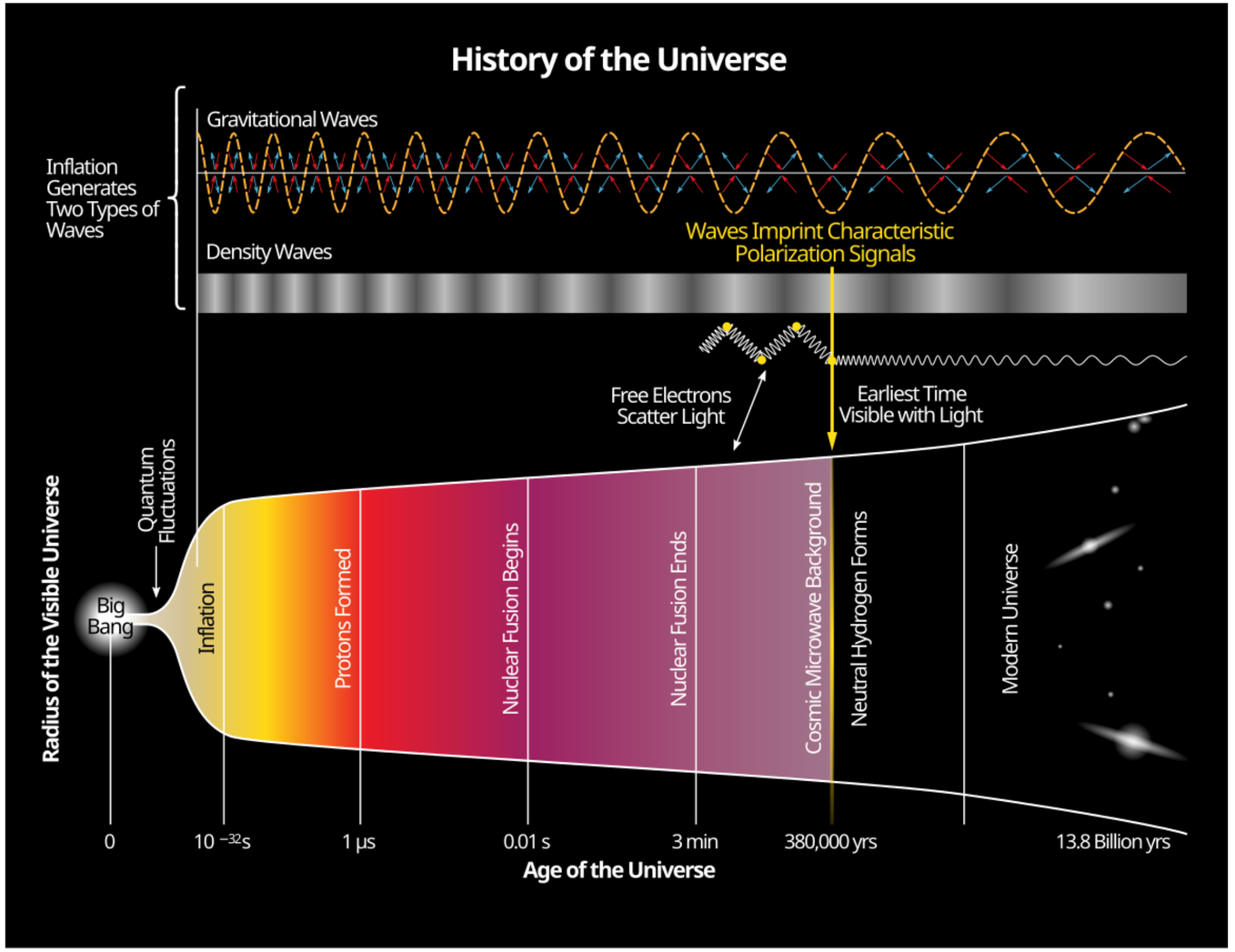

Spectroscopic galaxy surveys:
State of the art

Why measuring tens of millions galaxy spectra?

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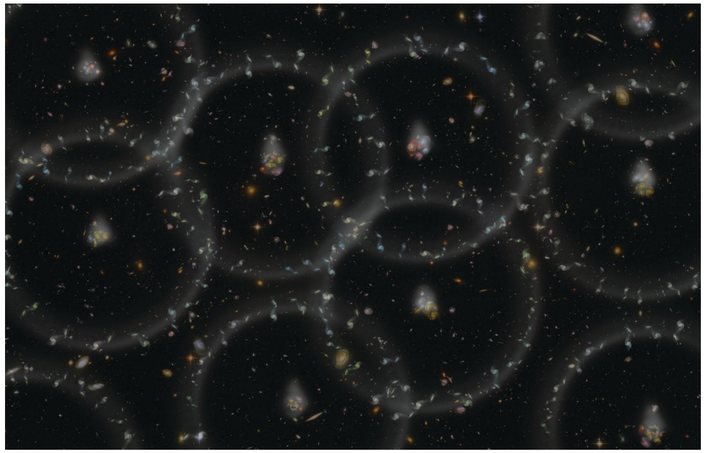
- **Baryon Acoustic Oscillations (BAO)**
  - Preferred scale in clustering of galaxies
  - Direct expansion measurement

Artist rendition of BAO



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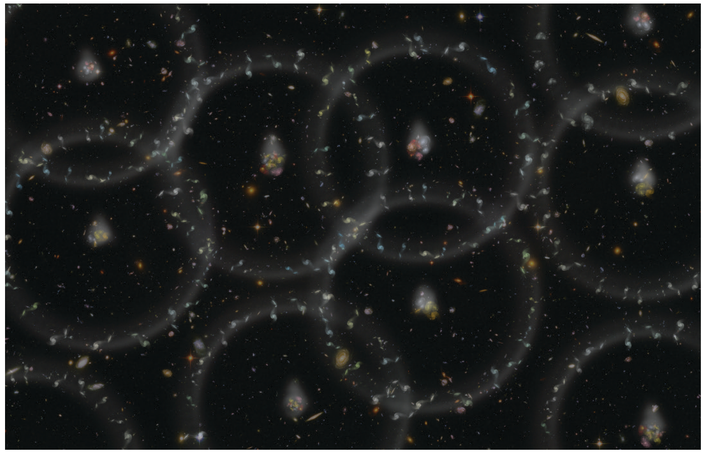
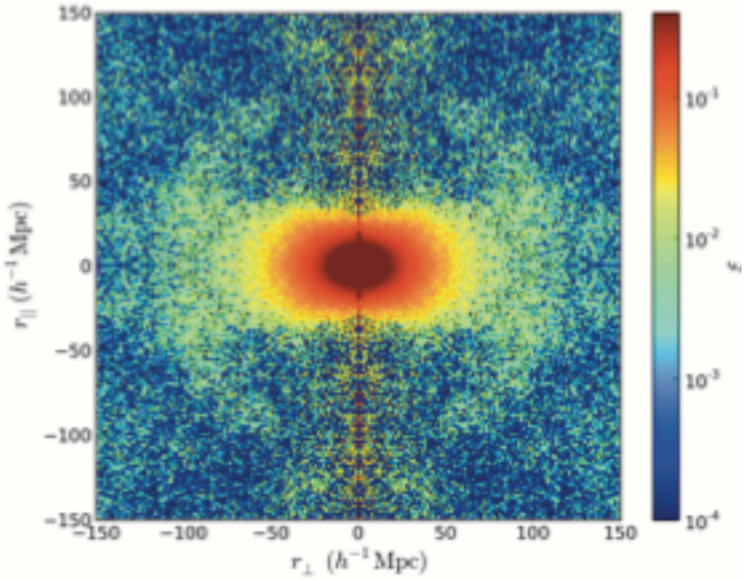


Galaxy correlation function



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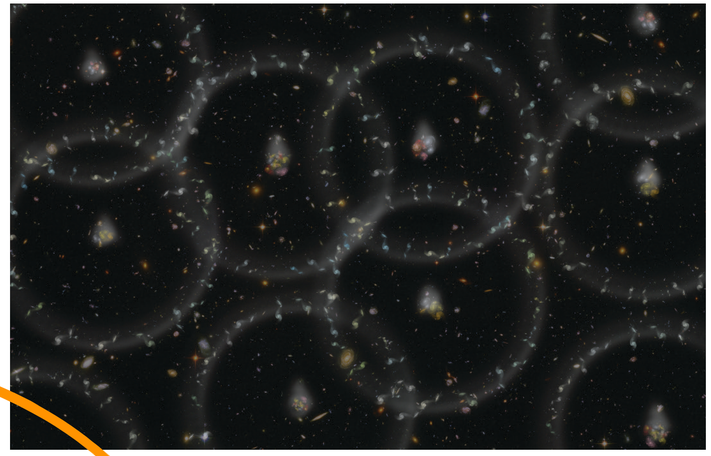

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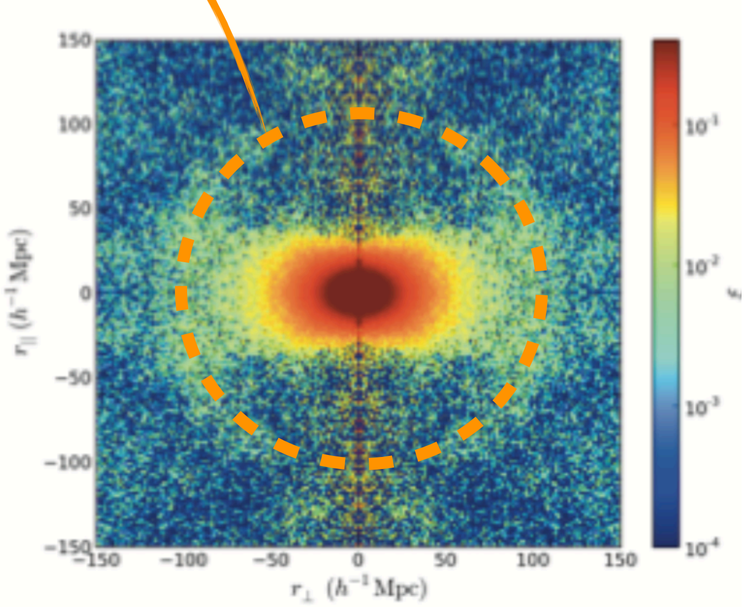

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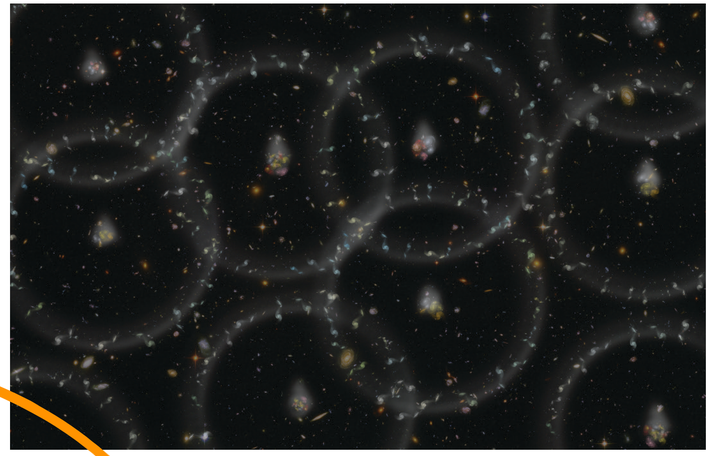

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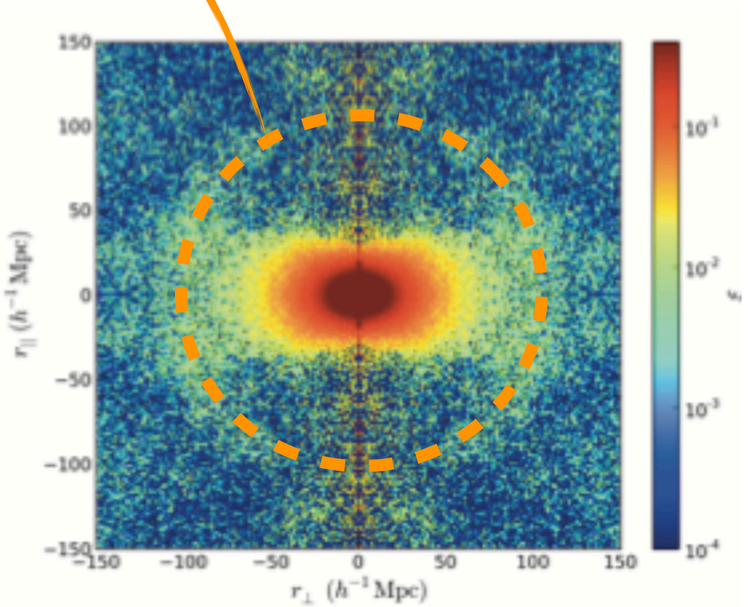

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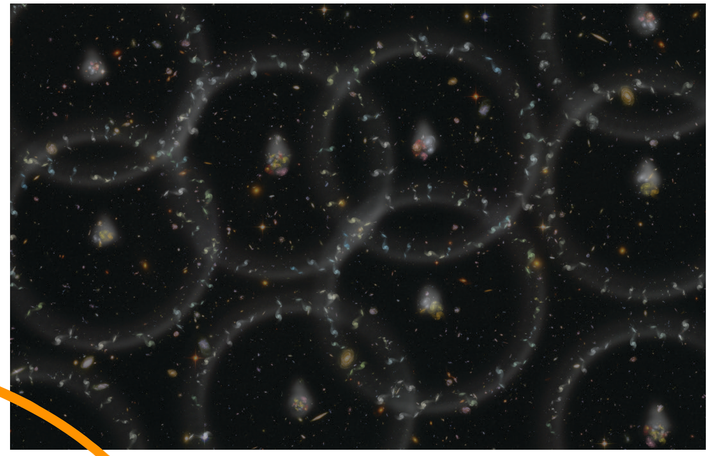

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