DESI DR2 Results: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

Enrique Paillas (on behalf of the DESI Collaboration)
Steward Observatory
University of Arizona

APS Meeting
Anaheim, CA
Mar 2025

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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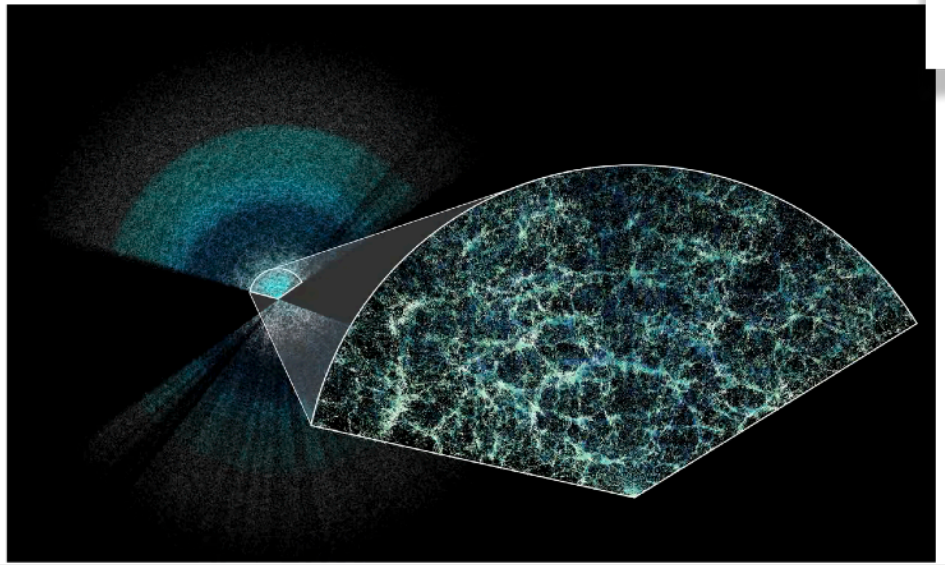
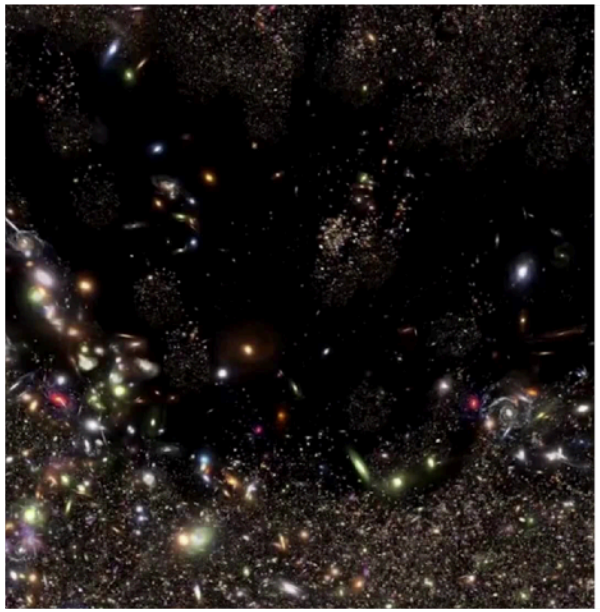
New 3D cosmic map raises questions over future of universe, scientists say

Researchers say findings from map with three times more galaxies than previous efforts could challenge standard idea of dark energy





The New York Times

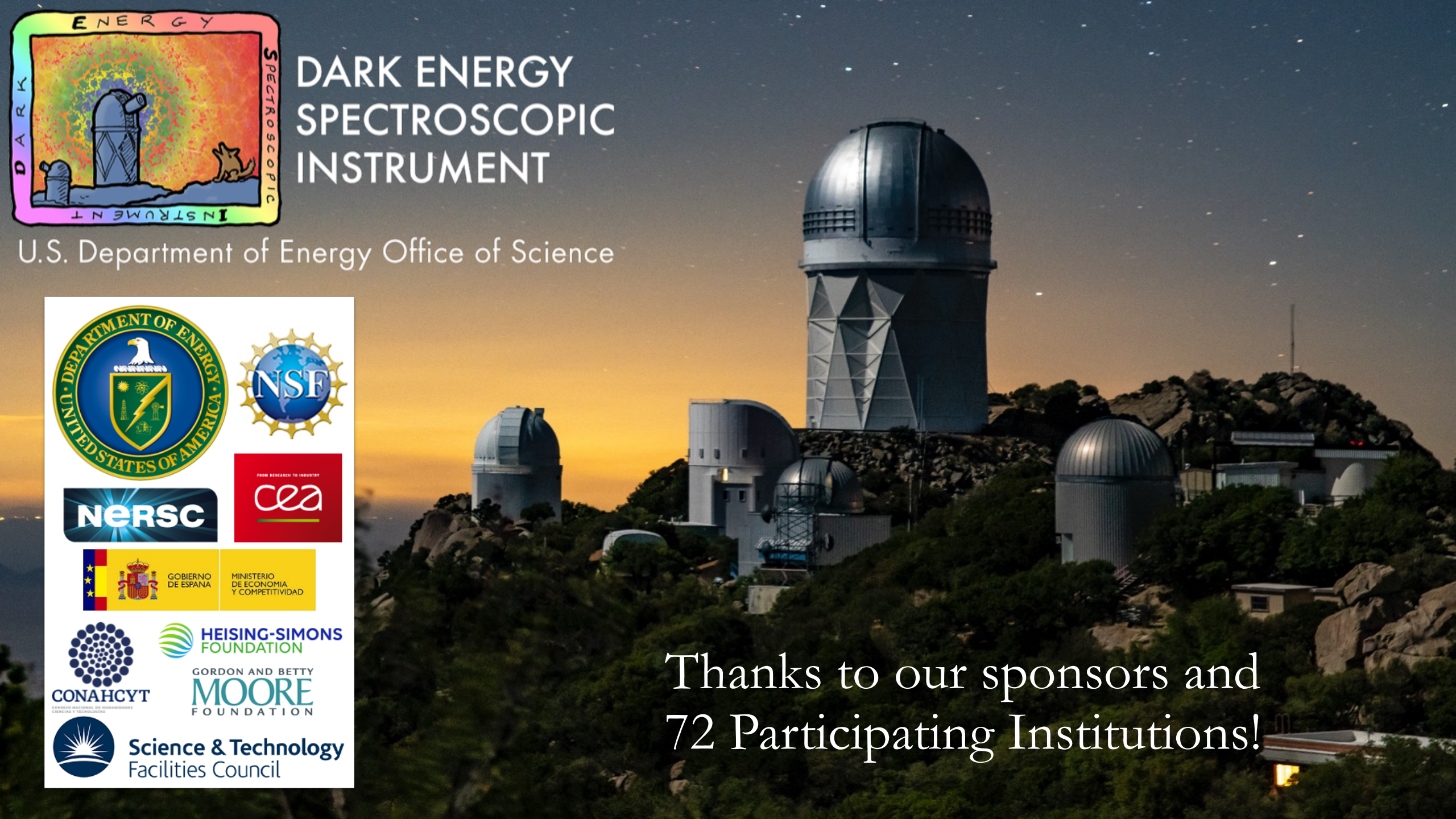
A Tantalizing 'Hint' That Astronomers Got Dark Energy All Wrong

Scientists may have discovered a major flaw in their understanding of that mysterious cosmic force. That could be good news for the fate of the universe.

2024 Biggest Breakthroughs in Physics

16:45

Quanta magazine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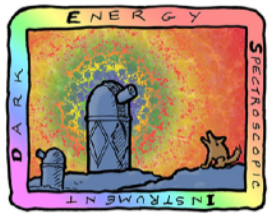

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The DESI DR2 sample

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

Redshifts for the BAO analysis

Tracer	DR1	**DR2**
BGS	300,043	**1,188,526**
LRG	2,138,627	**4,468,483**
ELG	2,432,072	**6,534,844**
QSO	1,223,391	**2,062,839**
Total	6,094,133	**14,254,692**

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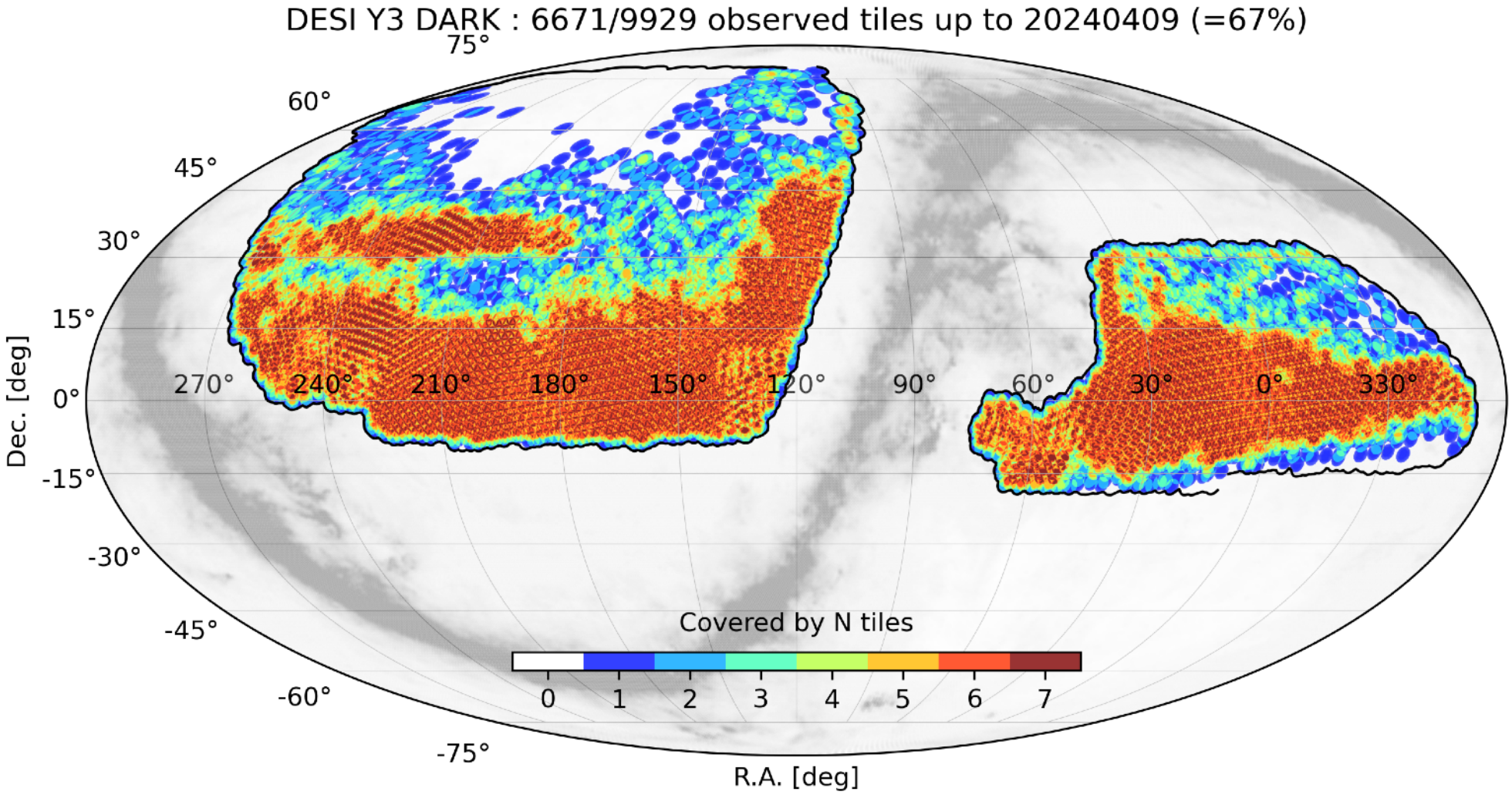
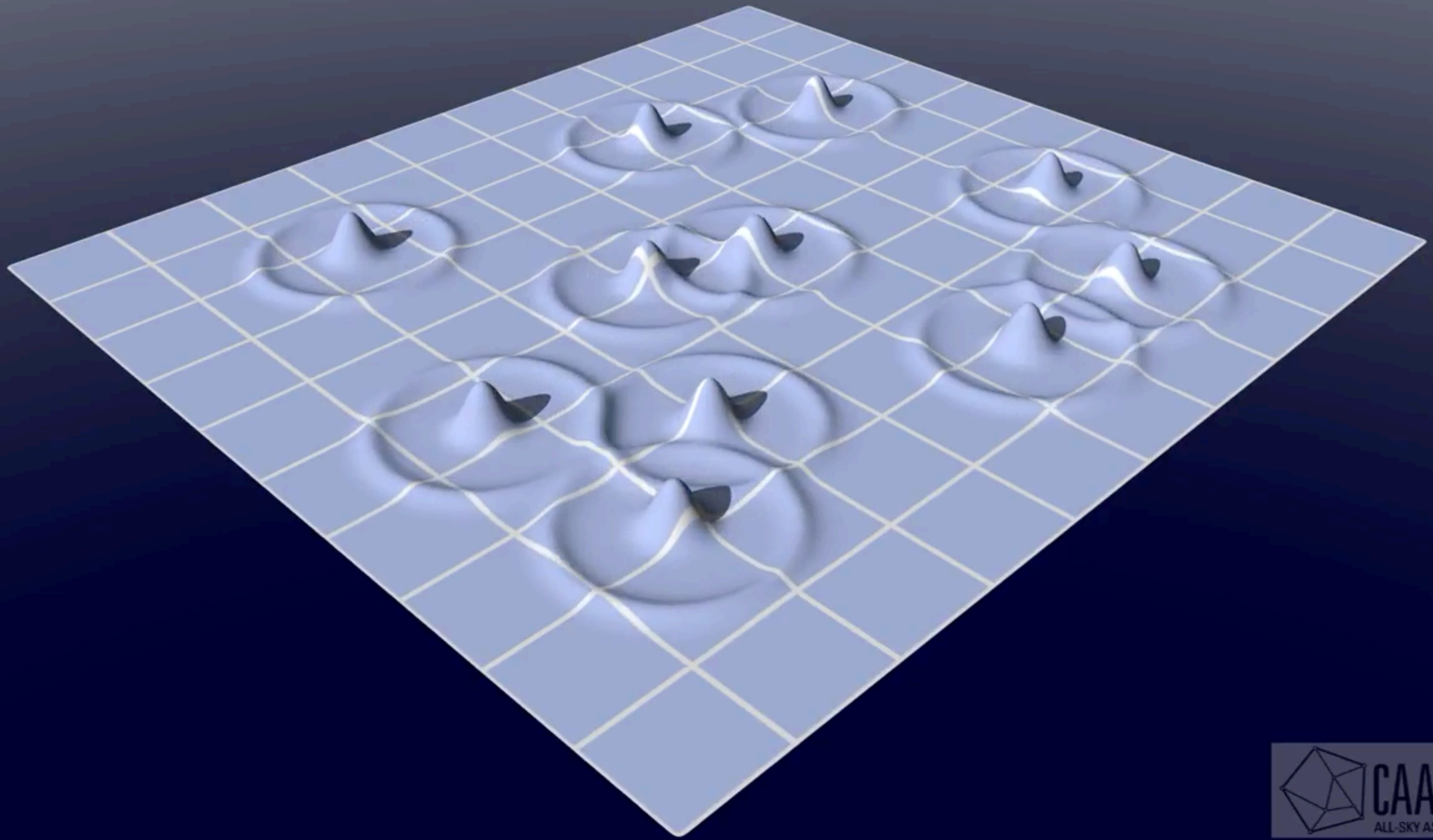
The DESI DR2 sample

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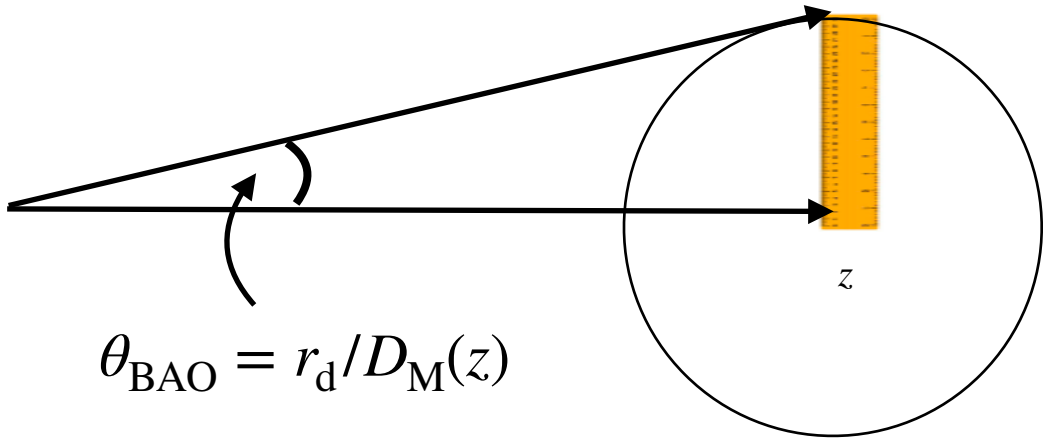
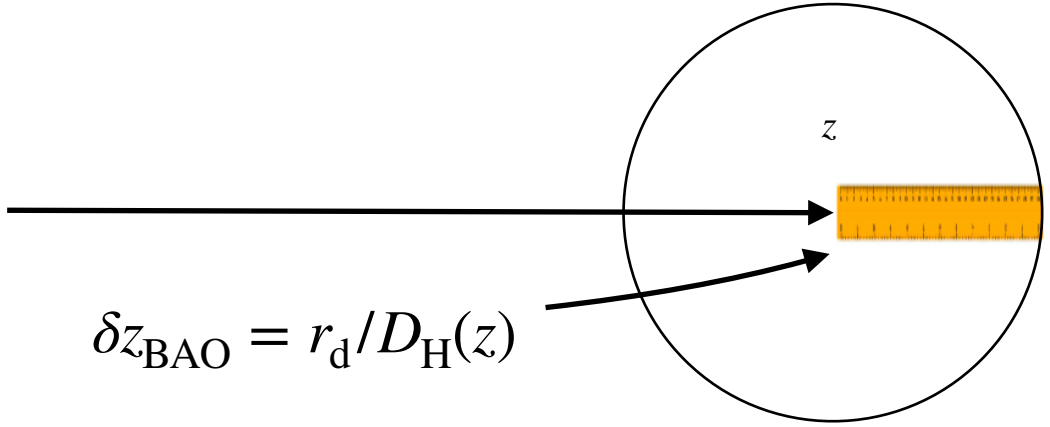
What DESI BAO measures



$$\theta_{\mathrm{BAO}} = r_{\mathrm{d}}/D_{\mathrm{M}}(z)$$



$$\delta z_{\mathrm{BAO}} = r_{\mathrm{d}}/D_{\mathrm{H}}(z)$$

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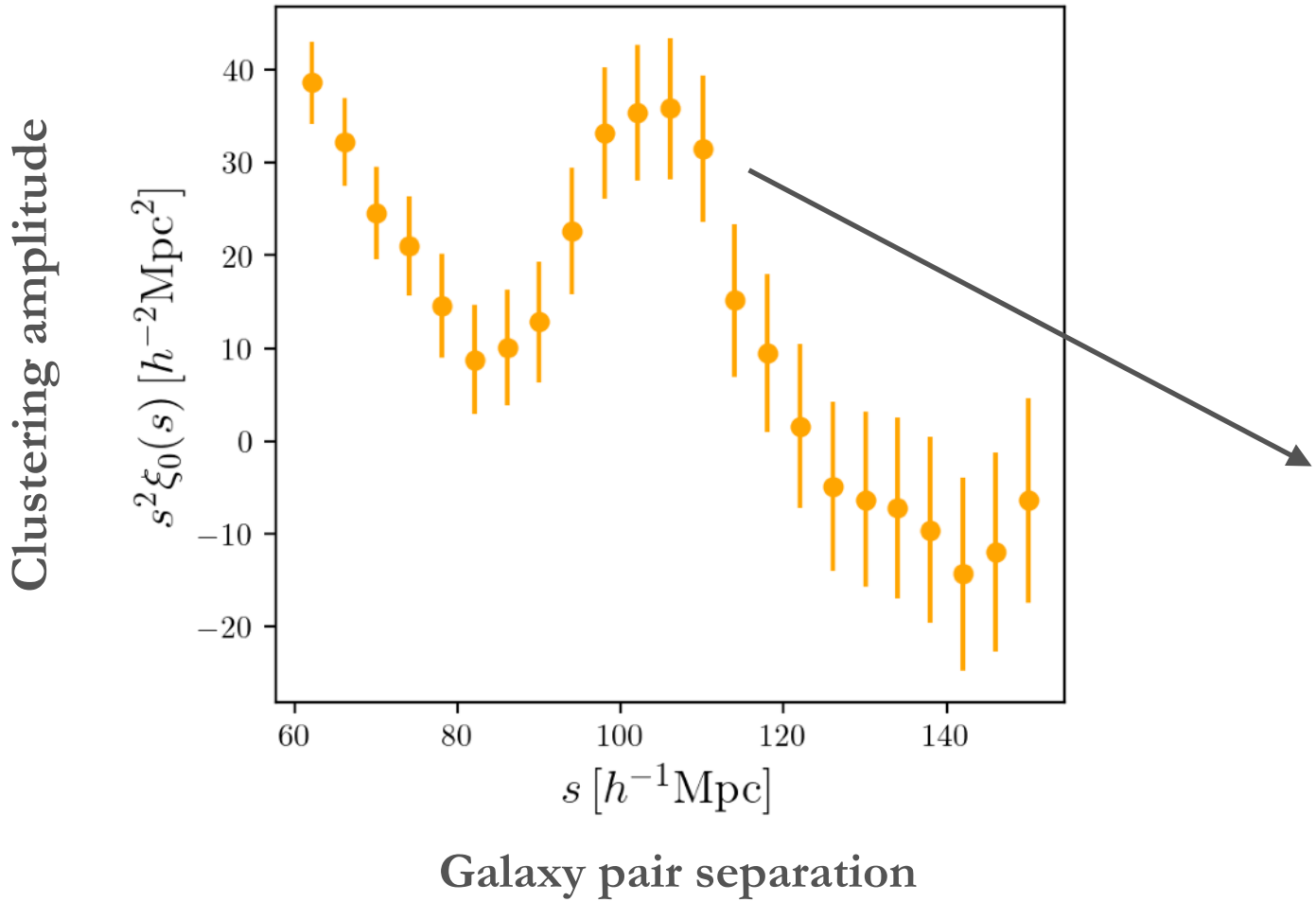
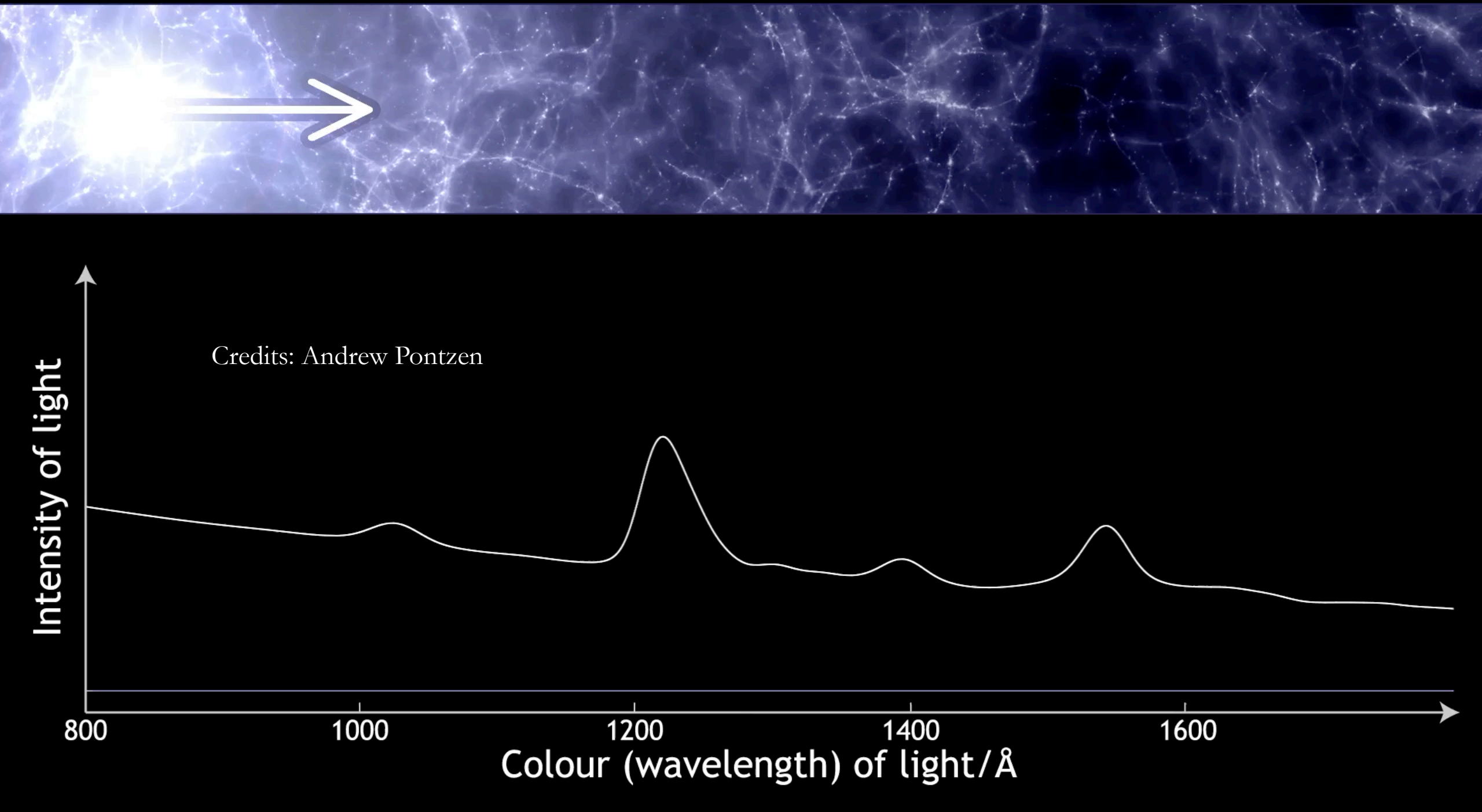
Clustering from galaxies and quasars



- The correlation function measures clustering as a function of scale: $\xi(r) = \langle \delta(x)\, \delta(x+r) \rangle$
- The BAO appears as a distinct peak around $100\,h^{-1}$Mpc (or wiggles in the *power spectrum*).


Credits: Andrew Pontzen
Intensity of light
800
1000
1200
1400
1600
Colour (wavelength) of light/Å

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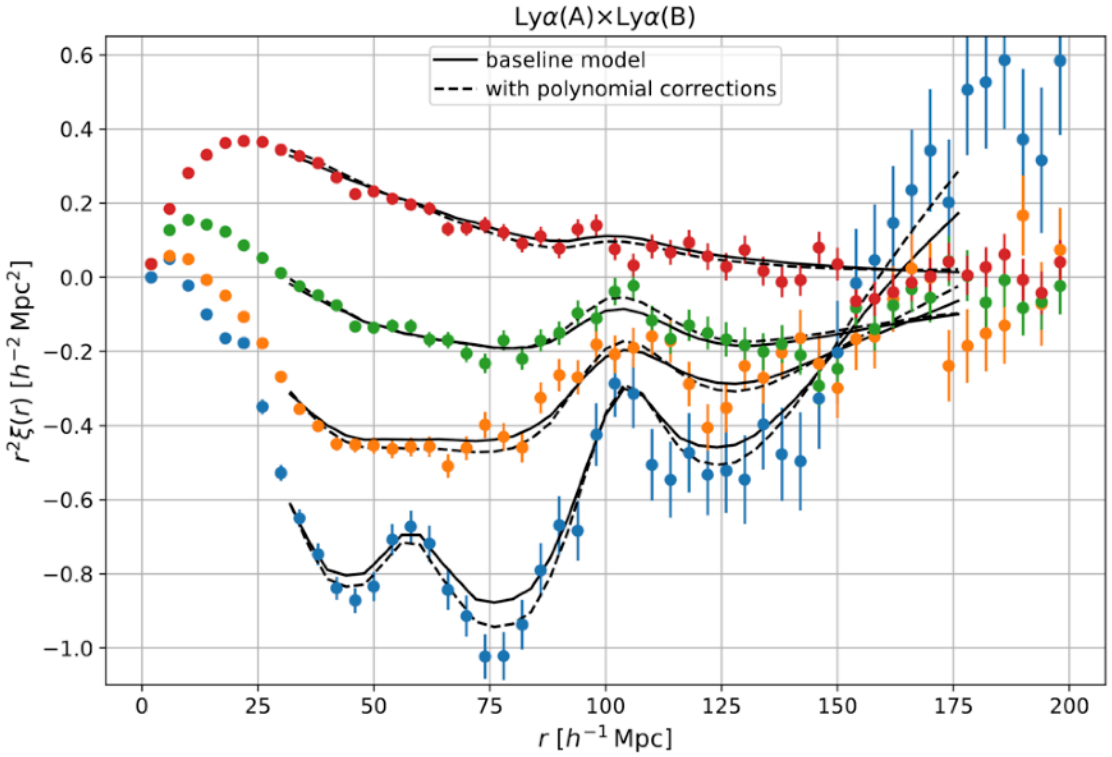
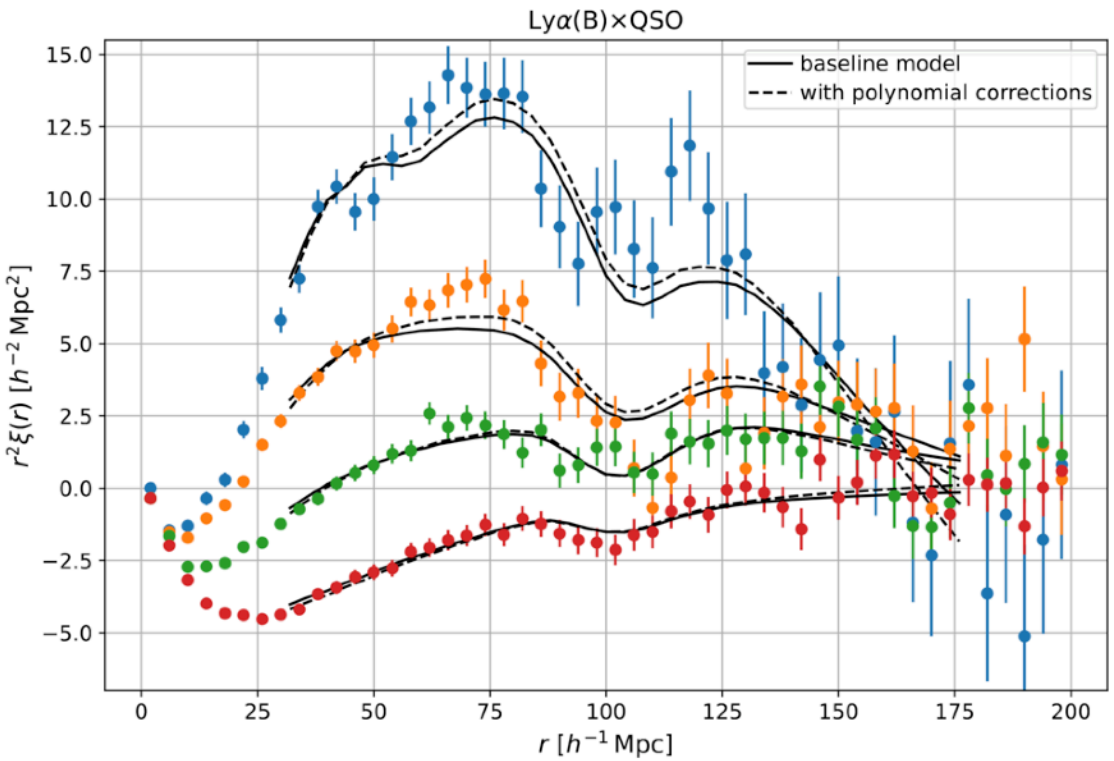
Lyman α Forest Correlations





Lyα forest autocorrelation

$$\xi(r) = \left\langle \delta_F(x)\ \delta_F(x+r) \right\rangle$$

Lyα-QSO cross-correlation

$$\xi(r) = \left\langle \delta_F(x)\ \mathrm{Q}(x+r) \right\rangle$$

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Blinding of the galaxy catalogs

- DESI DR2 BAO measurements were kept blinded during the validation process.
- For galaxies and quasars at $z < 2$: Catalog-level blinding that modifies galaxy redshifts and weights (Andrade++ 2024).
- For the Lyα forest, blinding of the data vector that shifts the BAO peak location (DESI Collaboration 2024).

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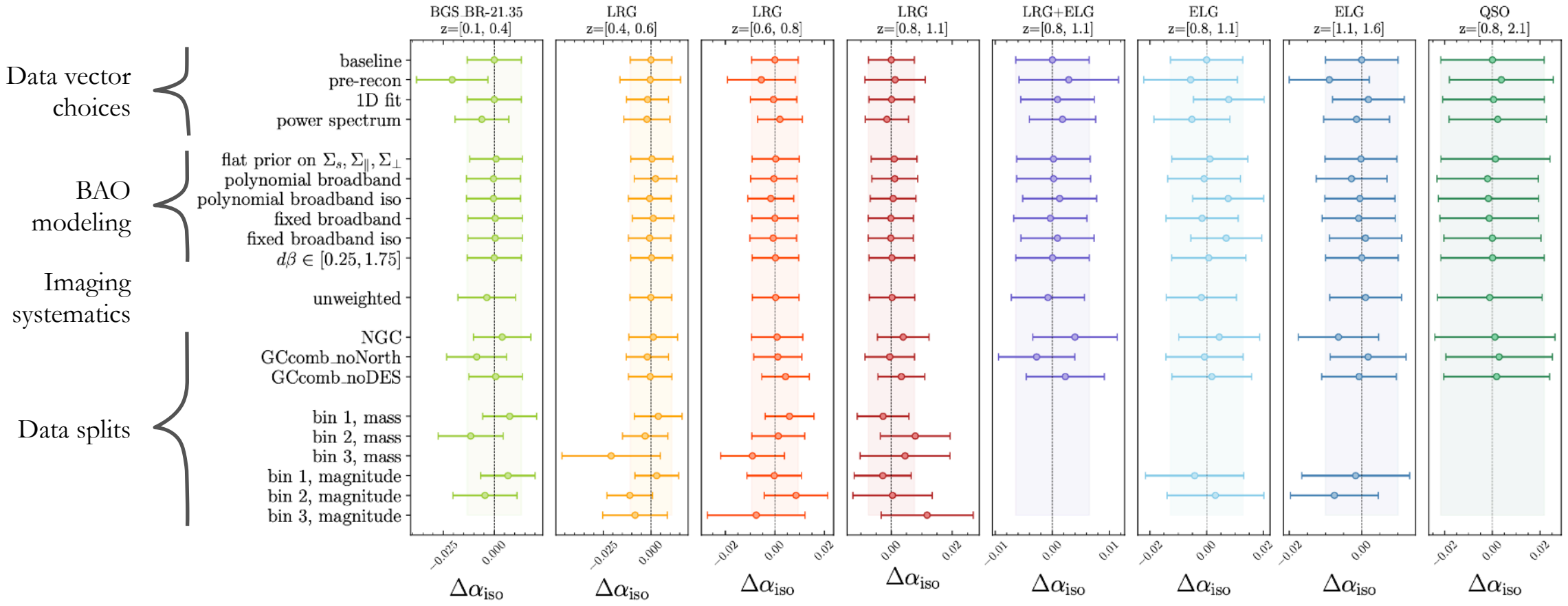
DR2 BAO is robust against different pipeline choices



Differences in the isotropic BAO dilation

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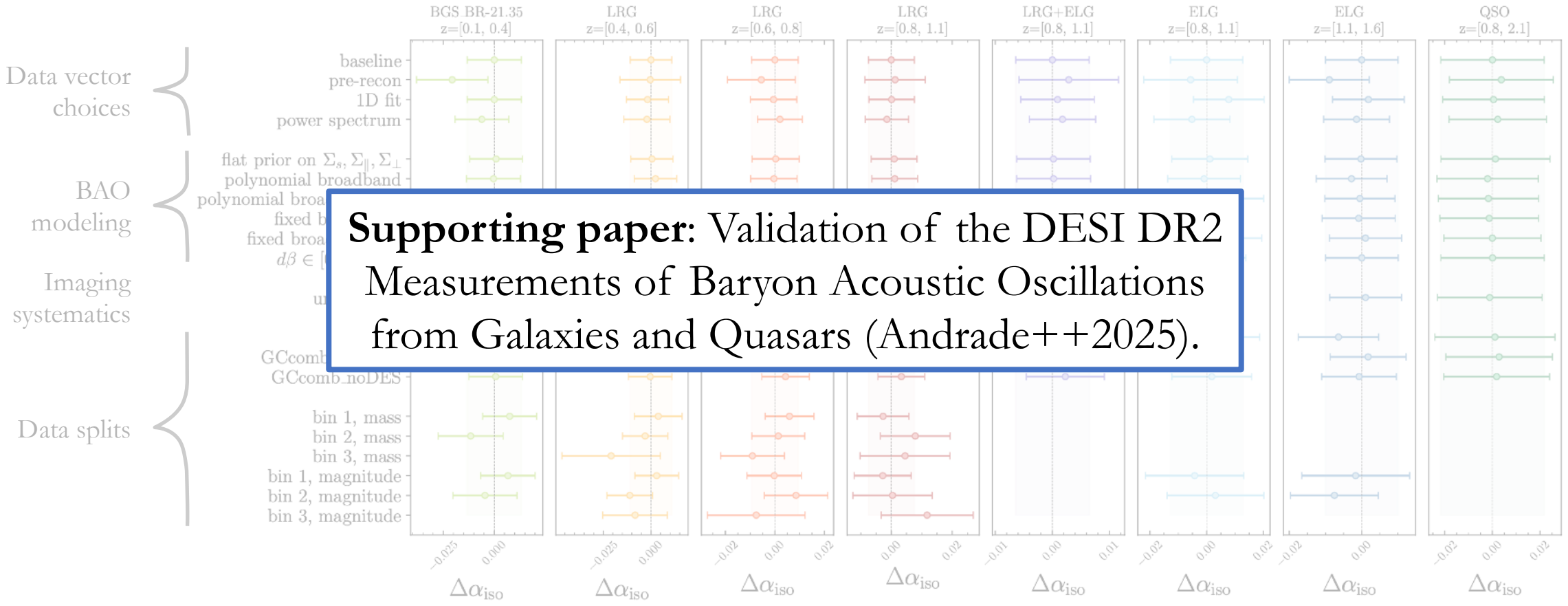
DR2 BAO is robust against different pipeline choices



Supporting paper: Validation of the DESI DR2 Measurements of Baryon Acoustic Oscillations from Galaxies and Quasars (Andrade++2025).

Differences in the isotropic BAO dilation

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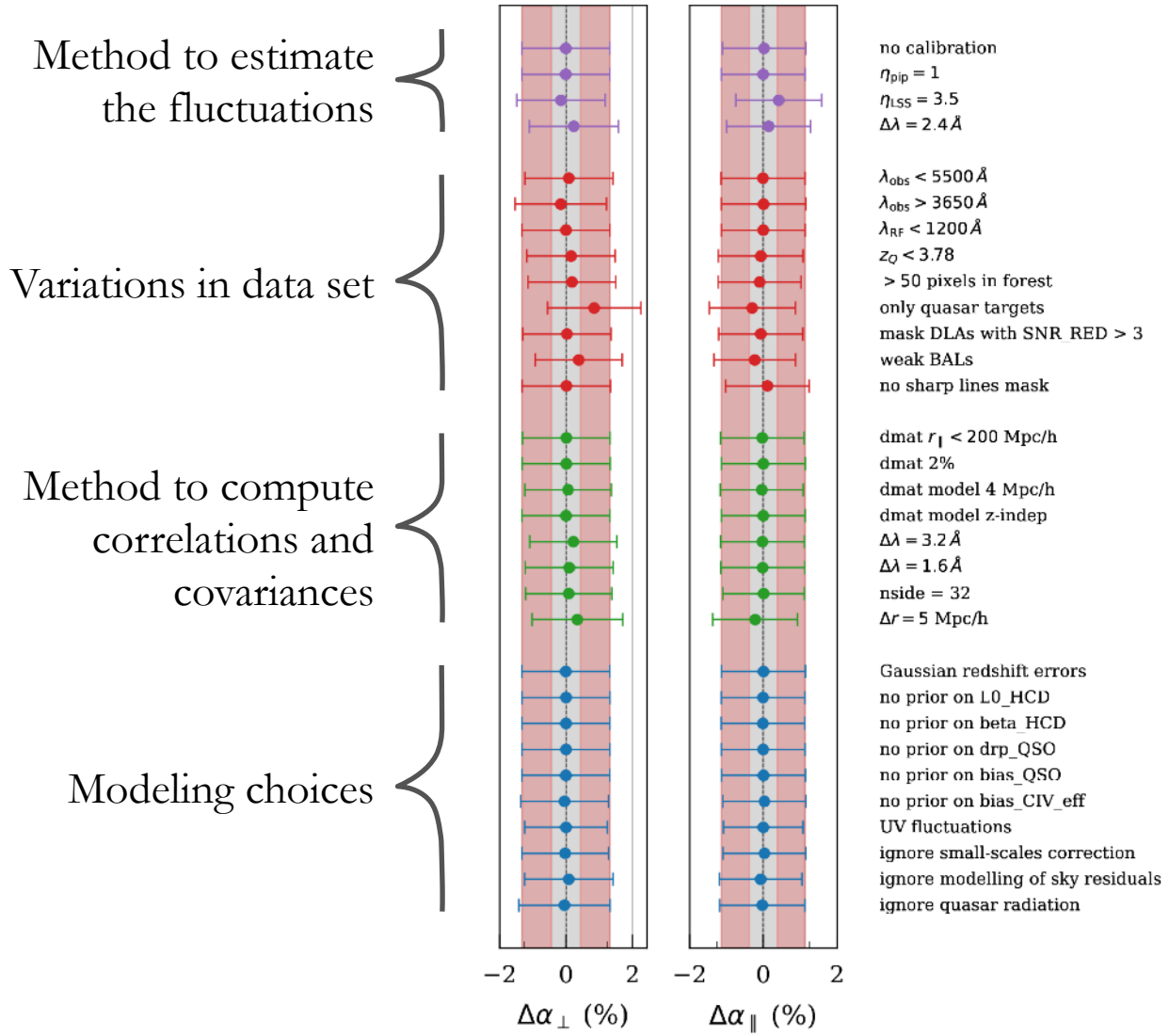
DR2 BAO is robust against different pipeline choices

Key Paper I: Baryon Acoustic Oscillations from the Lyman Alpha Forest (DESI Collaboration).

Supporting paper: Validation of the DESI-Y3 Lyα forest BAO analysis (Casas++2025).

Supporting paper: Construction of the Damped Lyα Absorber Catalog for DESI DR2 Lyα BAO (Brodzeller++2025).



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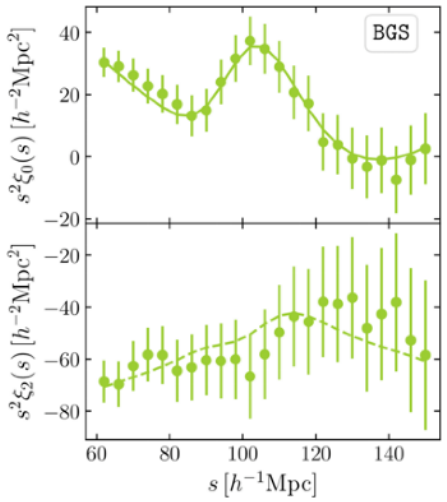
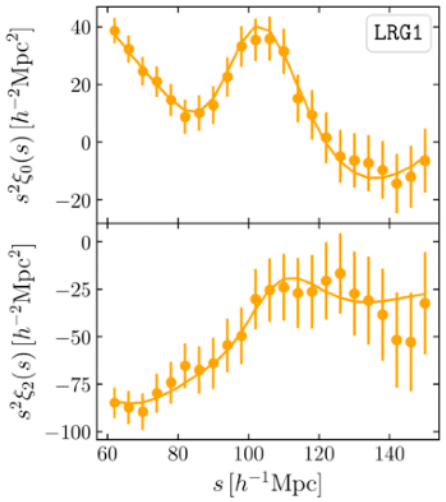
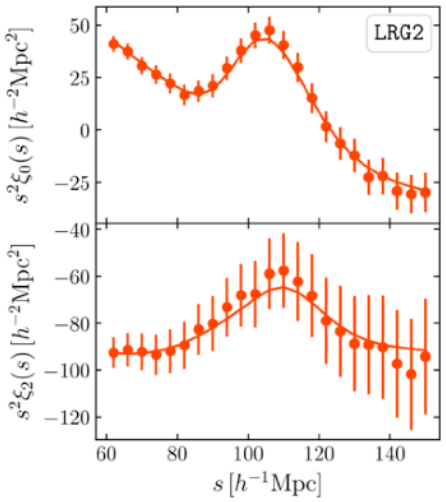
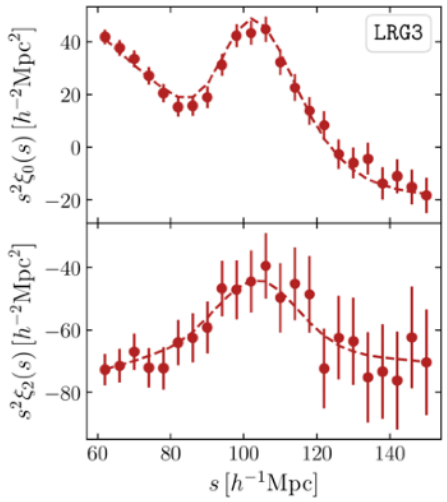
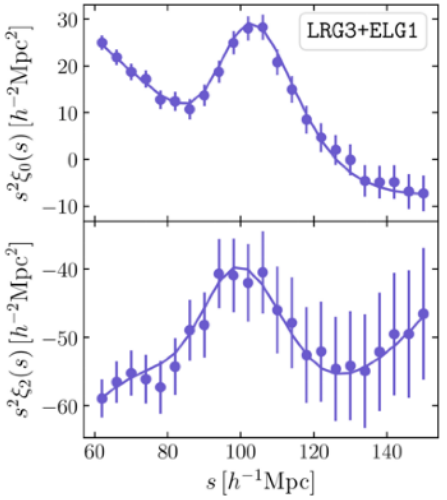
DESI DR2 Clustering Measurements

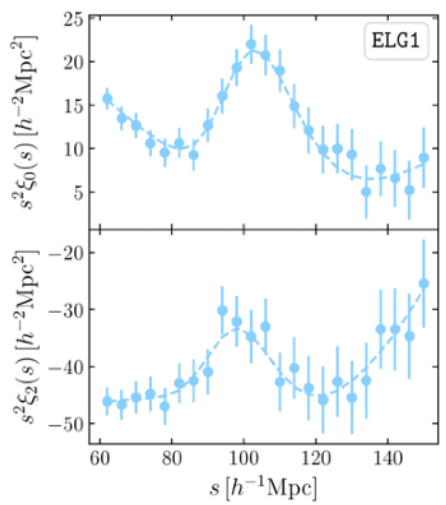


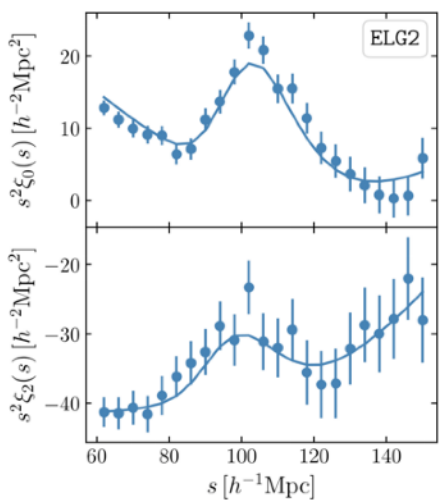


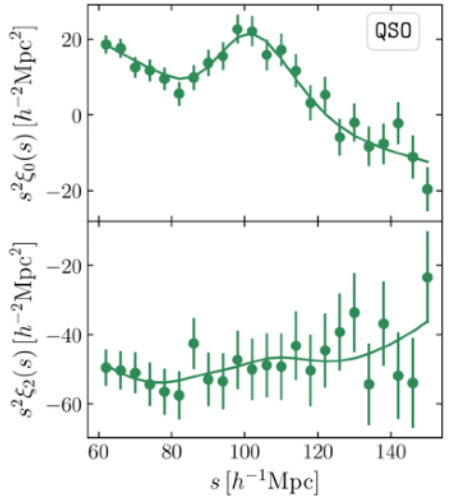


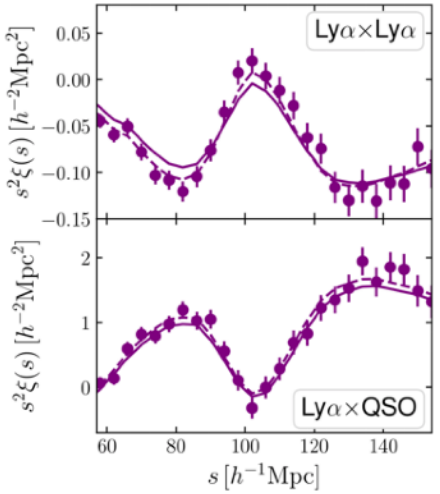












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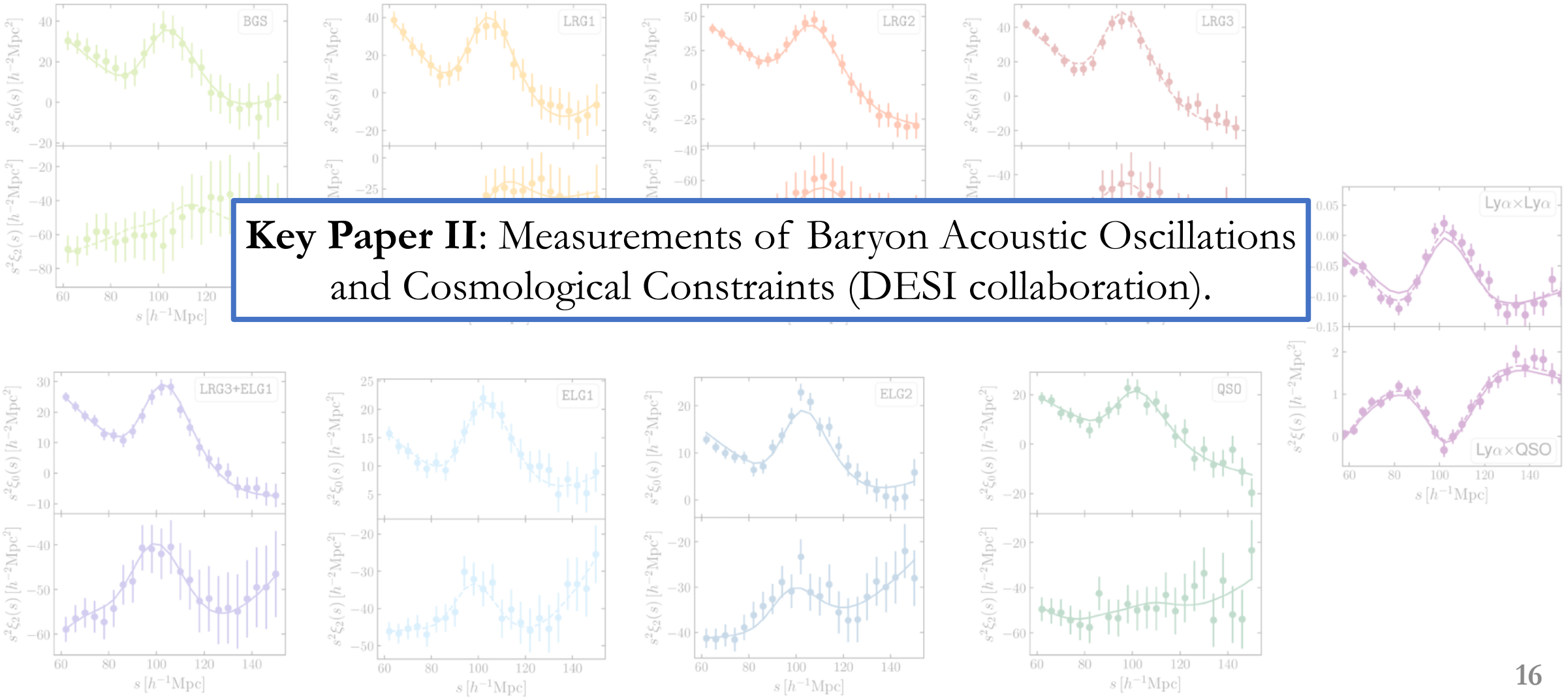
DESI DR2 Clustering Measurements



Key Paper II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints (DESI collaboration).

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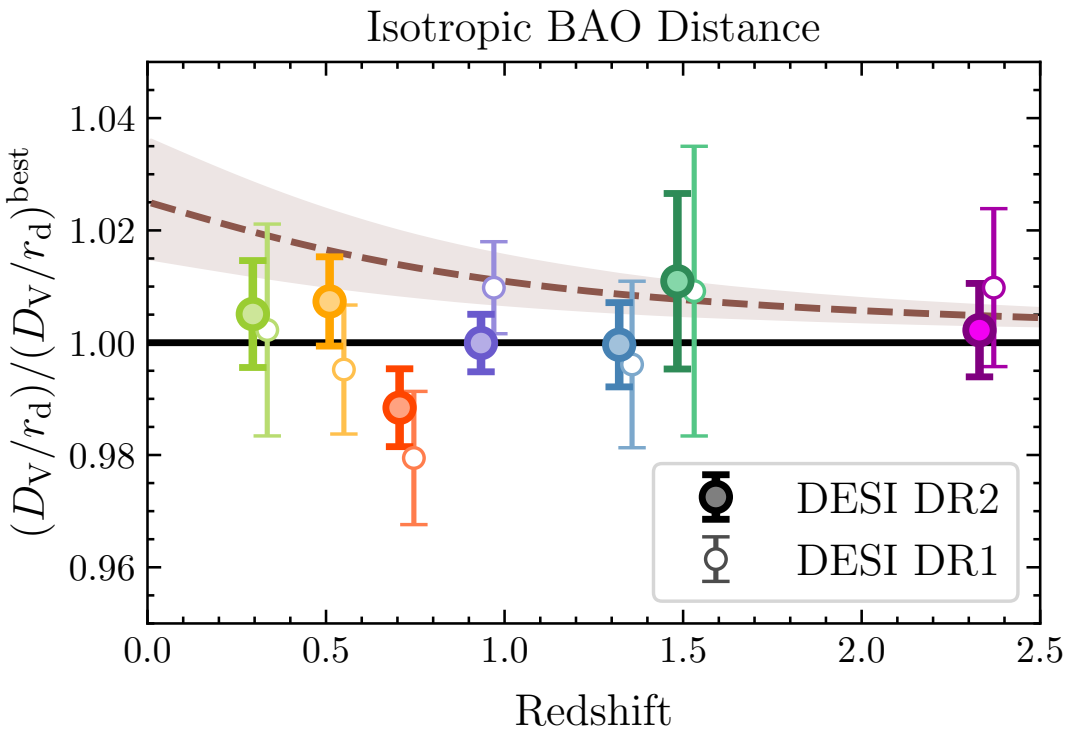
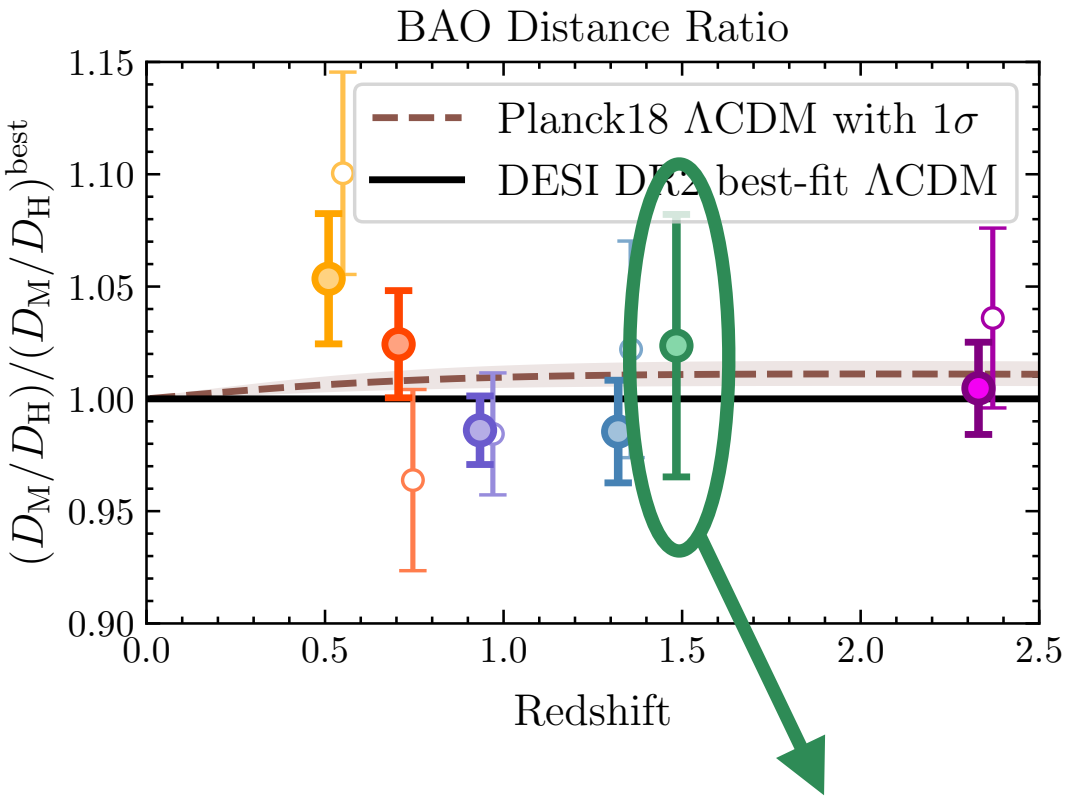
BAO Distance Measurements





New QSO distance ratio measurement

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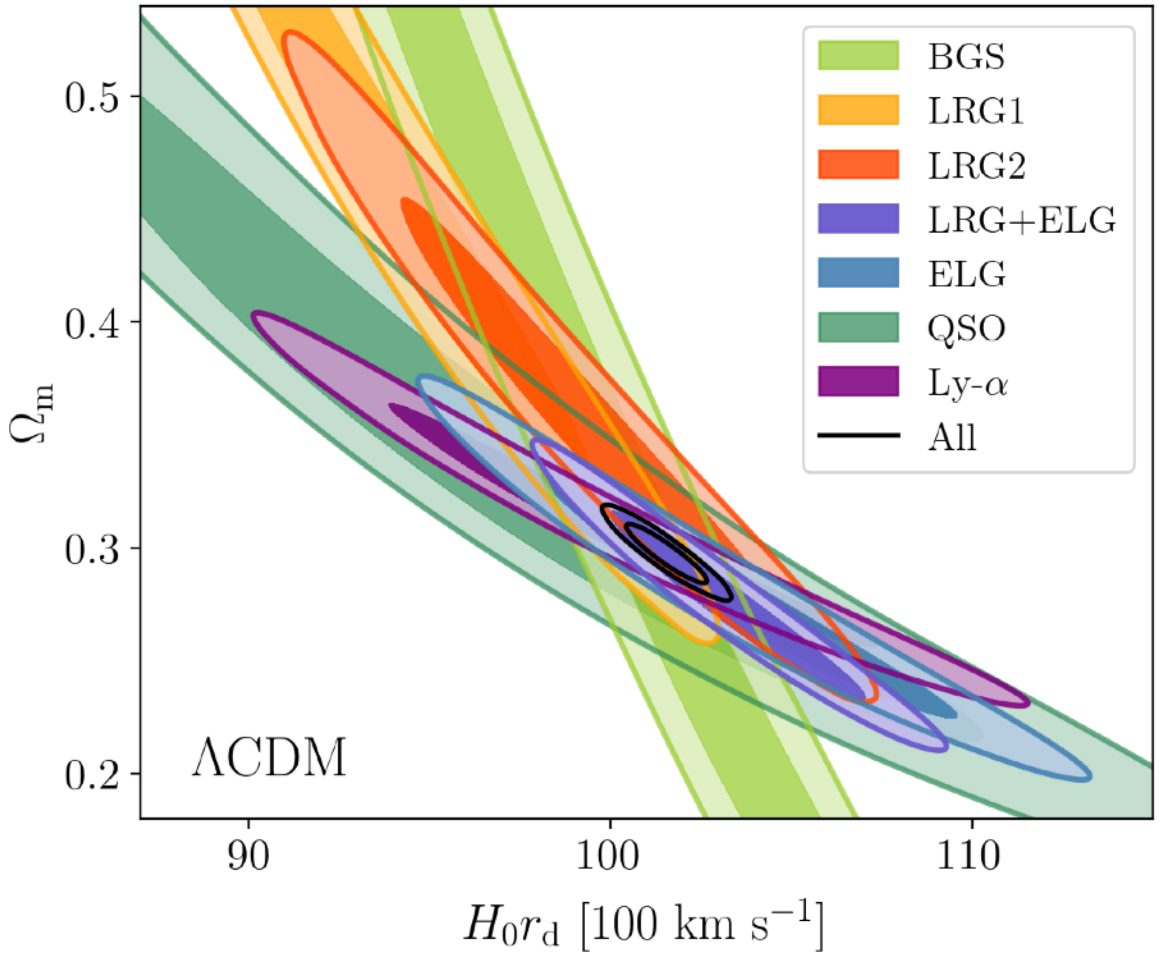
Mutual Consistency of DESI Tracers

- From low to high redshift, the increase on the effective redshift of the sample induces a counter clockwise shift in the degeneracy direction.
- The results from each individual tracer are mutually consistent and complementary in providing tighter constraints.



Main Results

I. Constraints under ΛCDM

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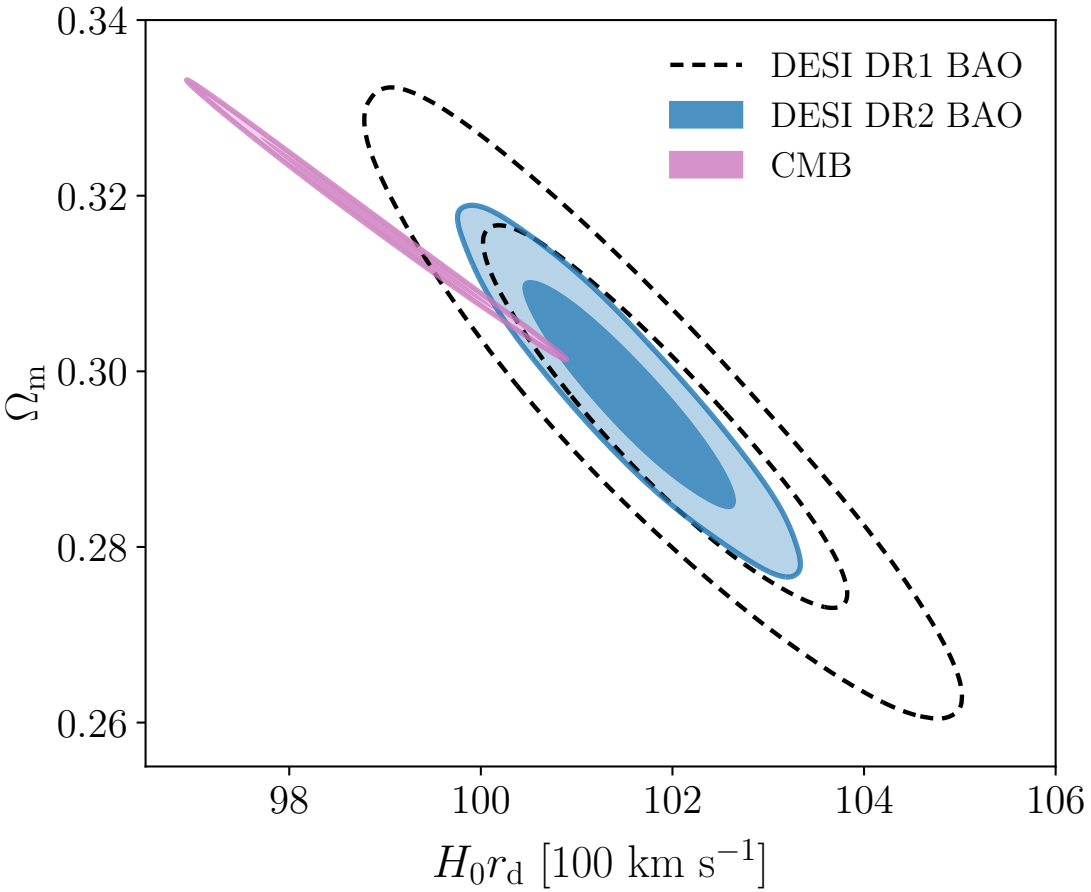
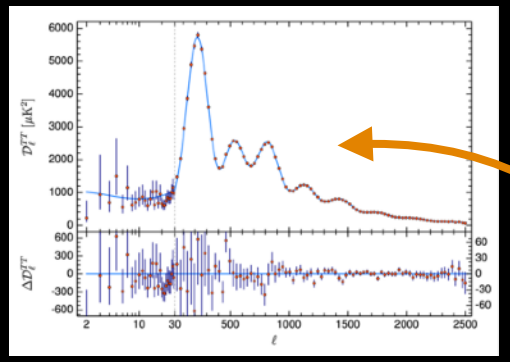
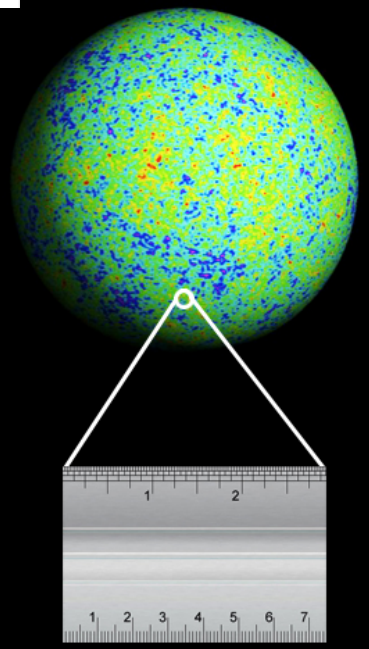
Constraints under ΛCDM

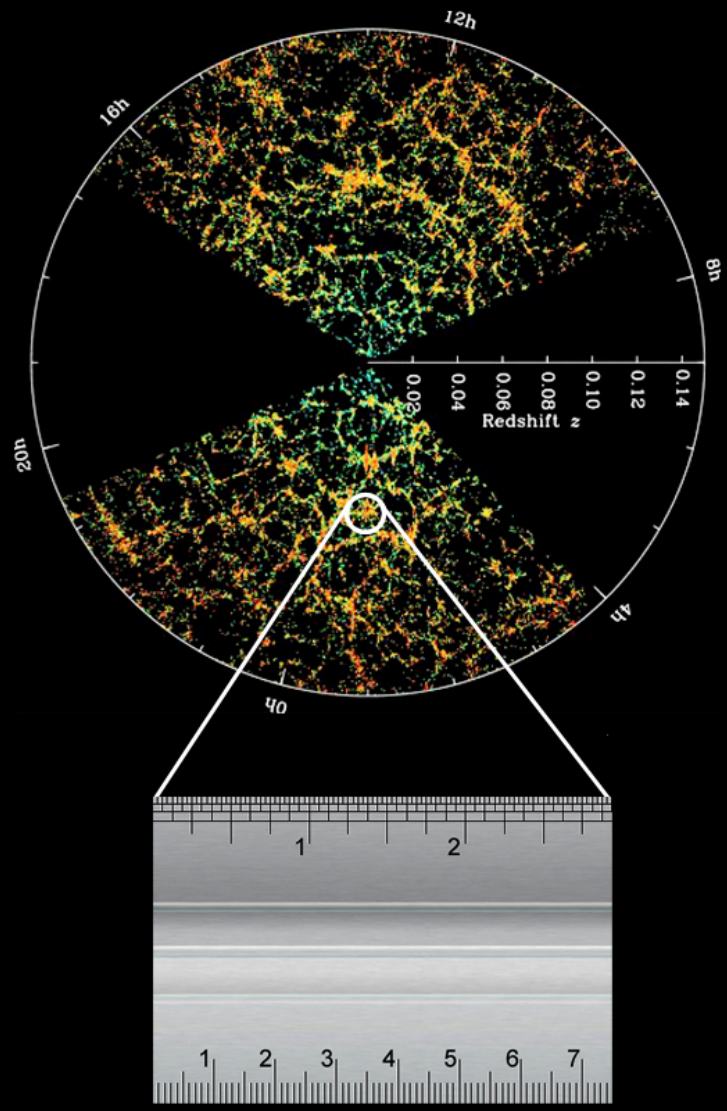


- 40% Improvement in the precision on Ω_m and hr_d compared to DR1.
- Discrepancy between BAO and CMB has increased: 1.9σ (DR1) —> 2.3σ (DR2).

$$\left.\begin{aligned} \Omega_m &= 0.2975 \pm 0.0086, \\ hr_d &= (101.54 \pm 0.73)\ \text{Mpc}, \end{aligned}\right\} \ \text{DESI DR2.}$$







An external calibration on r_d allows us to constrain H_0 with BAO data.

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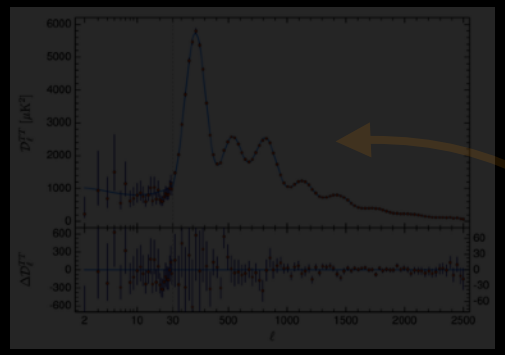
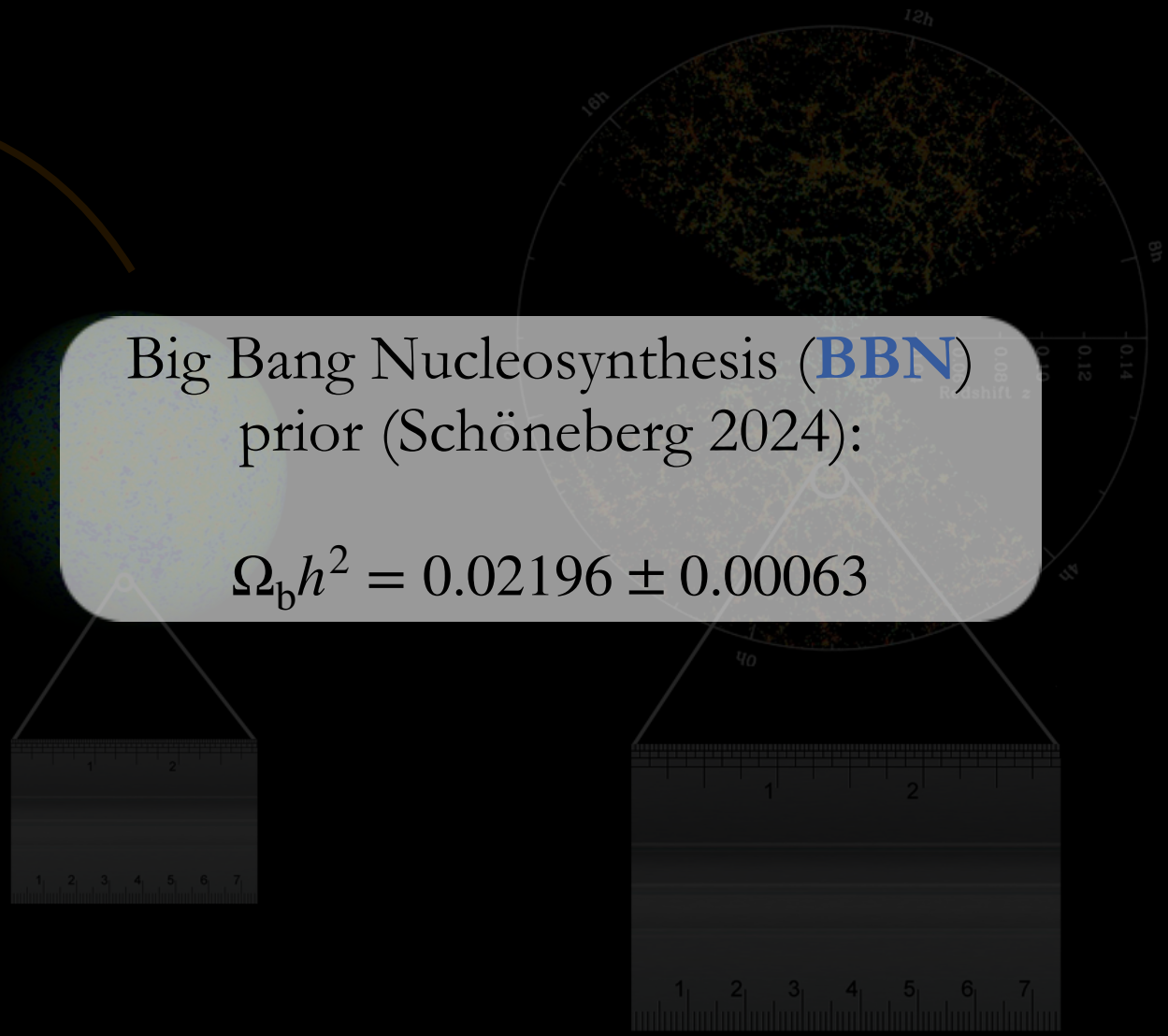
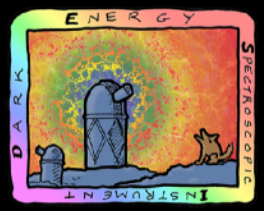


Big Bang Nucleosynthesis (**BBN**) prior (Schöneberg 2024):

$$\Omega_b h^2 = 0.02196 \pm 0.00063$$

An external calibration on r_d allows us to constrain H_0 with BAO data.





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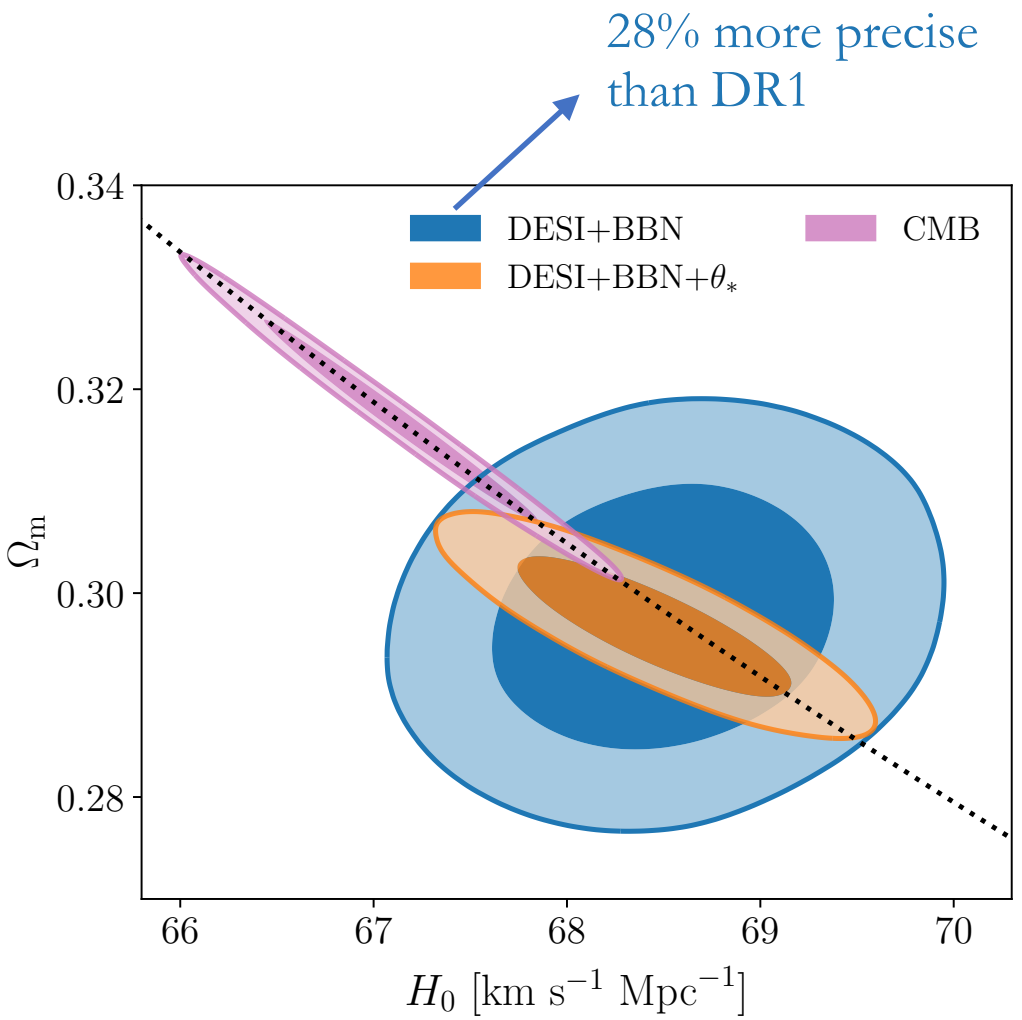
Constraints under ΛCDM

- By calibrating the BAO relative distance measurements using a BBN prior on ω_b, we obtain

$$H_0 = (68.51 \pm 0.58)\ \mathrm{km\,s^{-1}\,Mpc^{-1}} \quad \text{(DESI+BBN)}$$

- Adding a prior on the angular acoustic scale θ_* :

$$H_0 = (68.45 \pm 0.47)\ \mathrm{km\,s^{-1}\,Mpc^{-1}} \quad \text{(DESI+BBN+}\theta_*\text{)}$$



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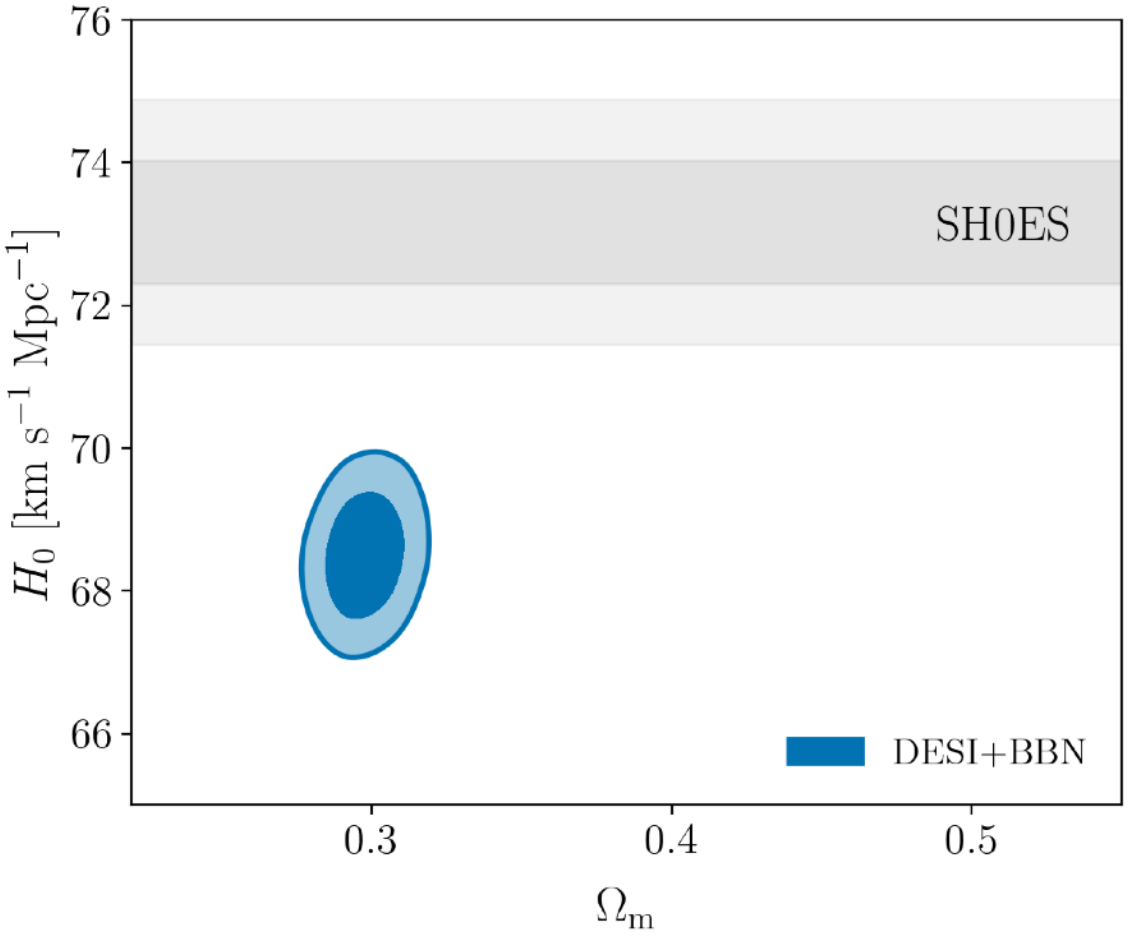
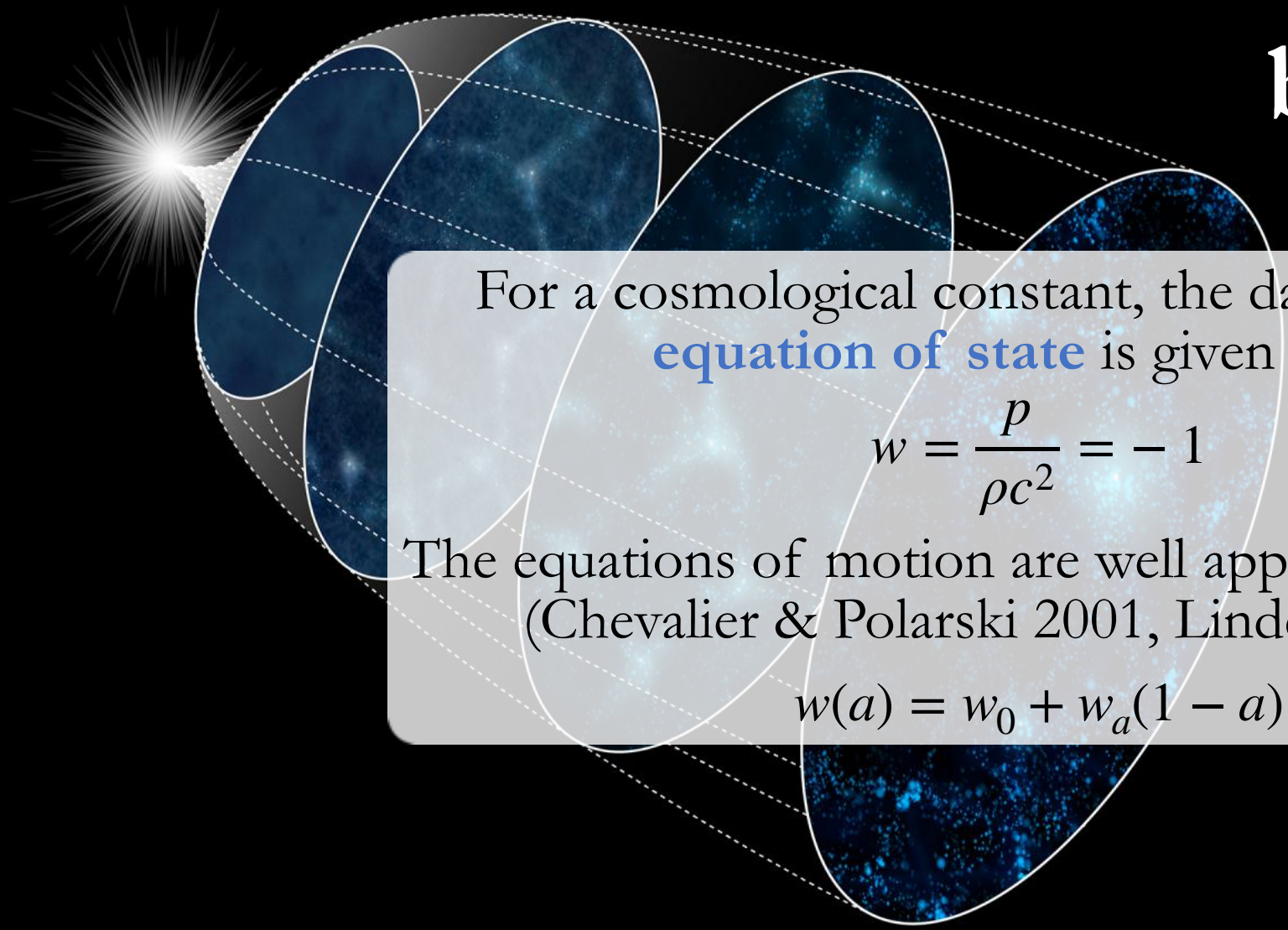
Constraints under ΛCDM



In ΛCDM, the tension between the DESI+BBN and SH0ES H_0 (Breuval++2024) now stands at 4.5σ, independent of the CMB.

II. Dark Energy beyond ΛCDM

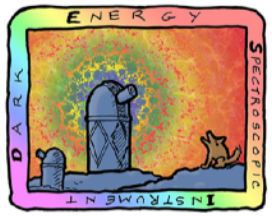


For a cosmological constant, the dark energy **equation of state** is given by

$$w = \frac{p}{\rho c^2} = -1$$

The equations of motion are well approximated by (Chevalier & Polarski 2001, Linder 2003)

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



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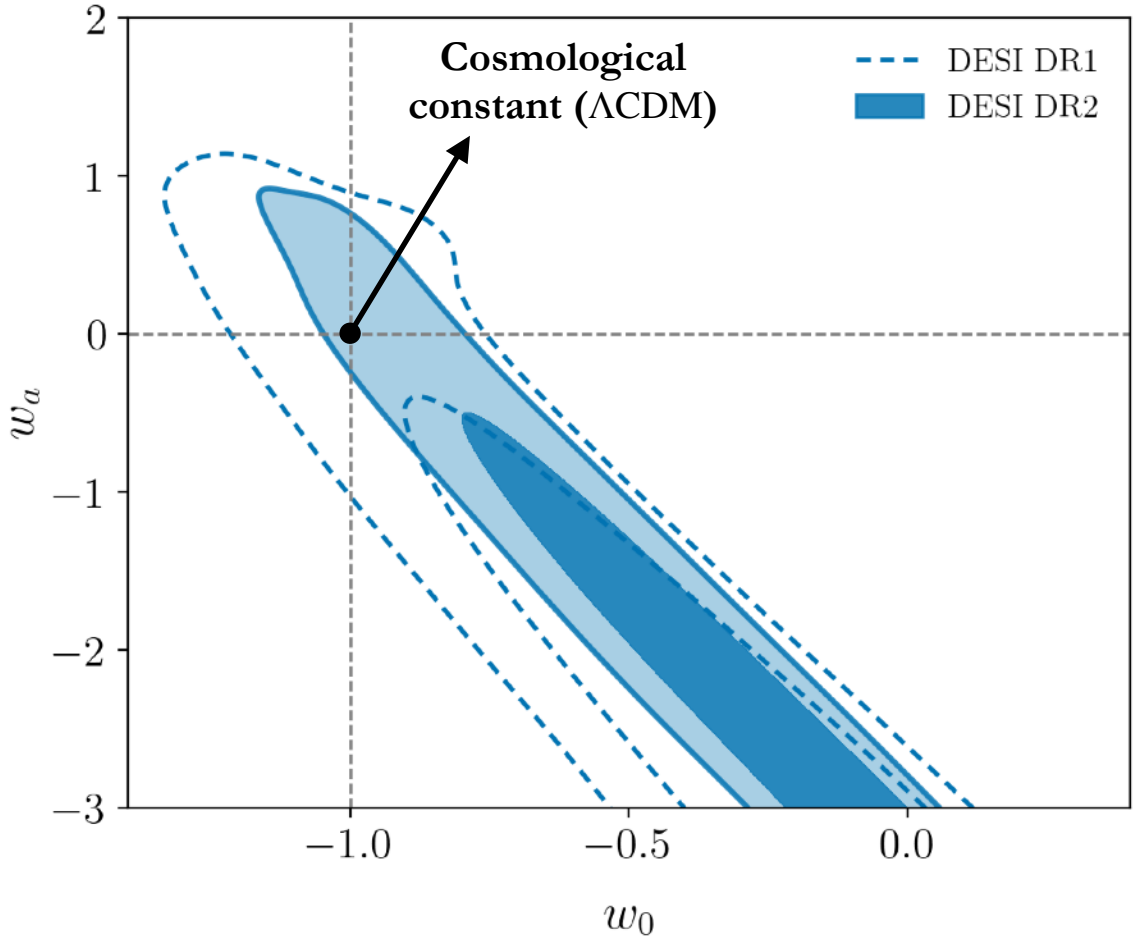
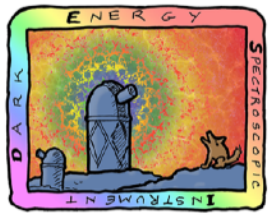
Dynamical Dark Energy

- BAO data define a degeneracy direction in the w_0-w_a plane.
- BAO data by itself does not rule out the cosmological constant, but its combination with more data sets leads to tight constraints.





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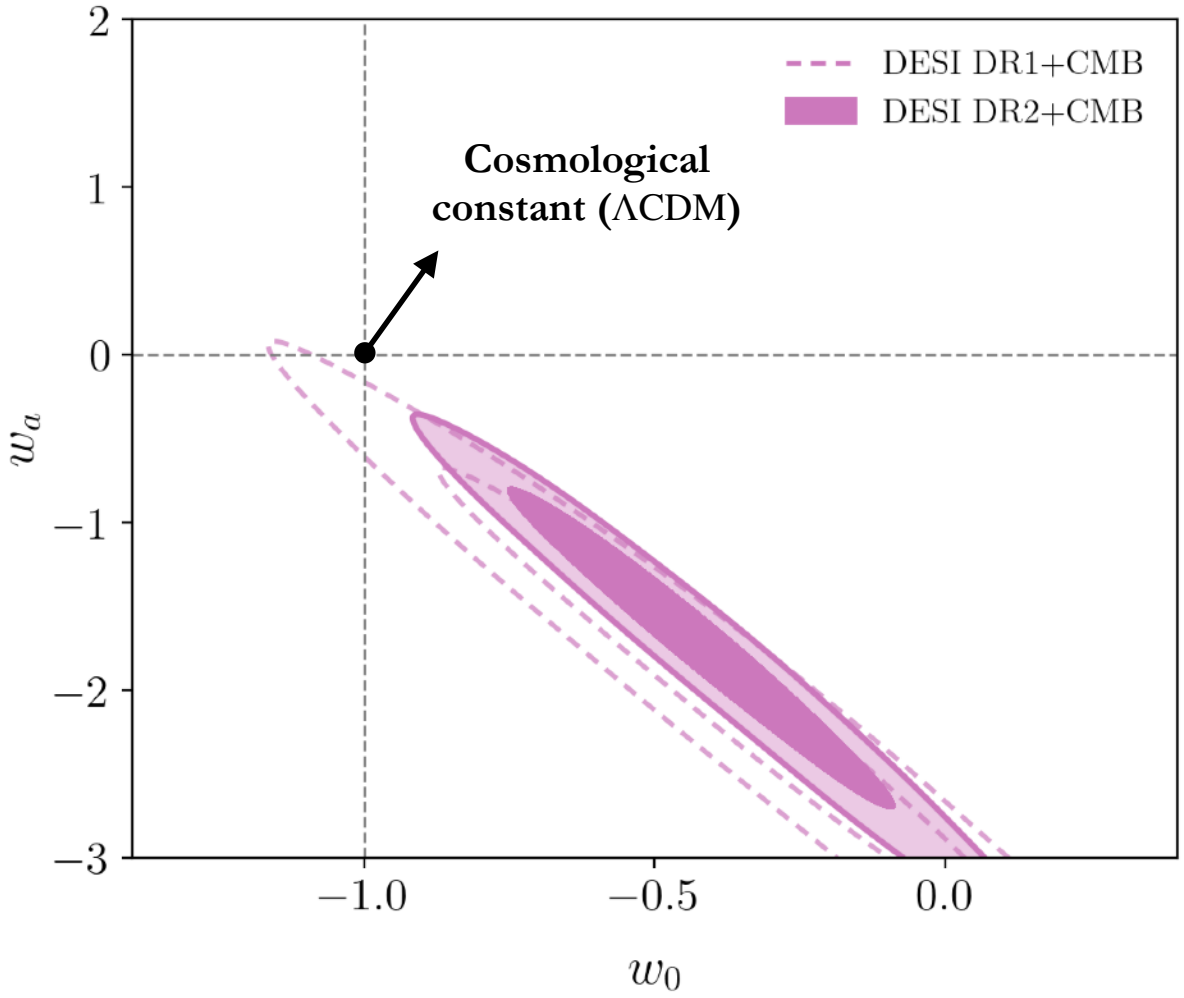
Dynamical Dark Energy

- Last year: 2.6σ preference for evolving dark energy from DESI BAO+CMB

—> 3.1σ in DR2

$$\left.\begin{aligned} w_0 &= -0.42 \pm 0.21 \\ w_a &= -1.75 \pm 0.58 \end{aligned}\right\} \text{ DESI+CMB}$$



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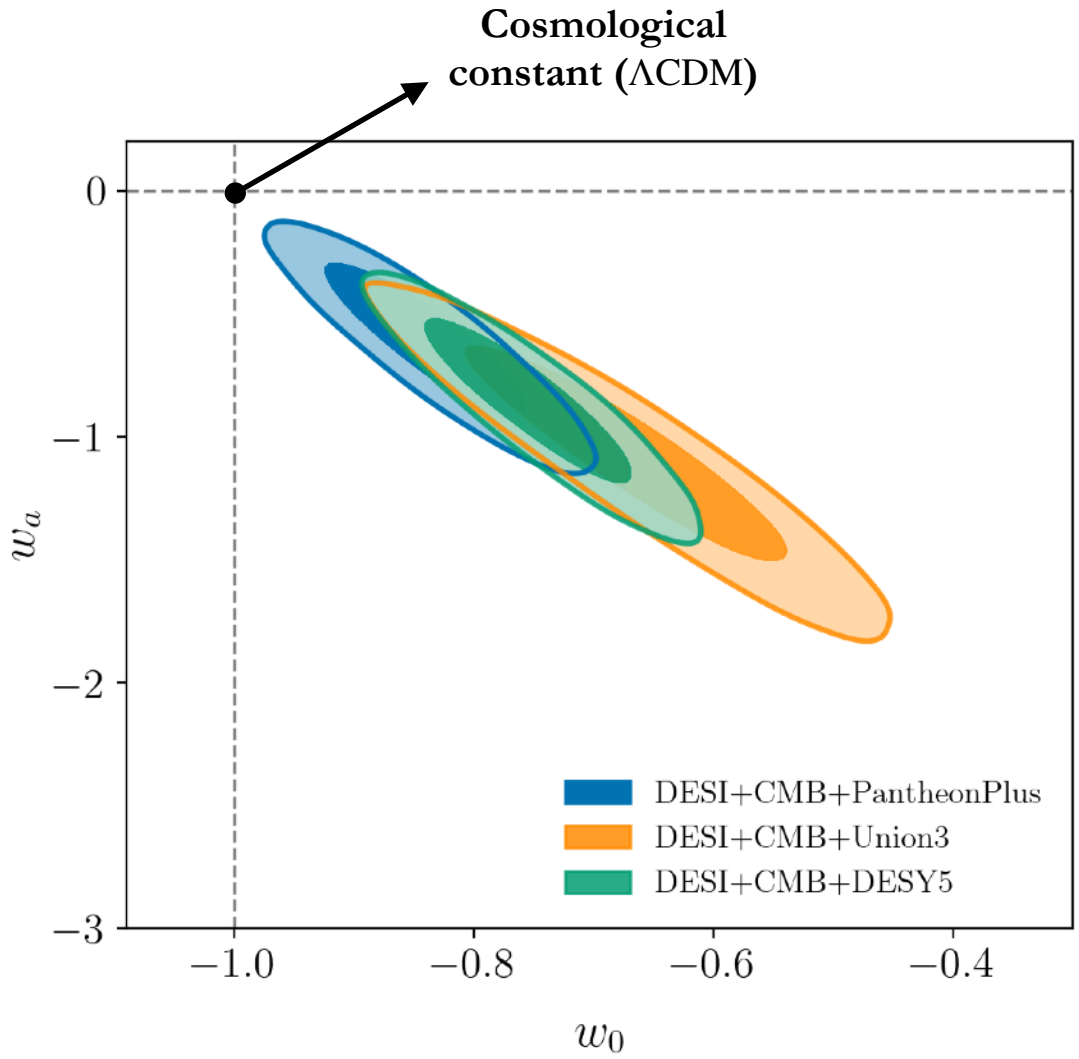
Dynamical Dark Energy

- Significance of rejection of ΛCDM:
  - DESI+CMB+Pantheon+: 2.8σ
  - DESI+CMB+Union3 : 3.8σ
  - DESI+CMB+DESY5: 4.2σ



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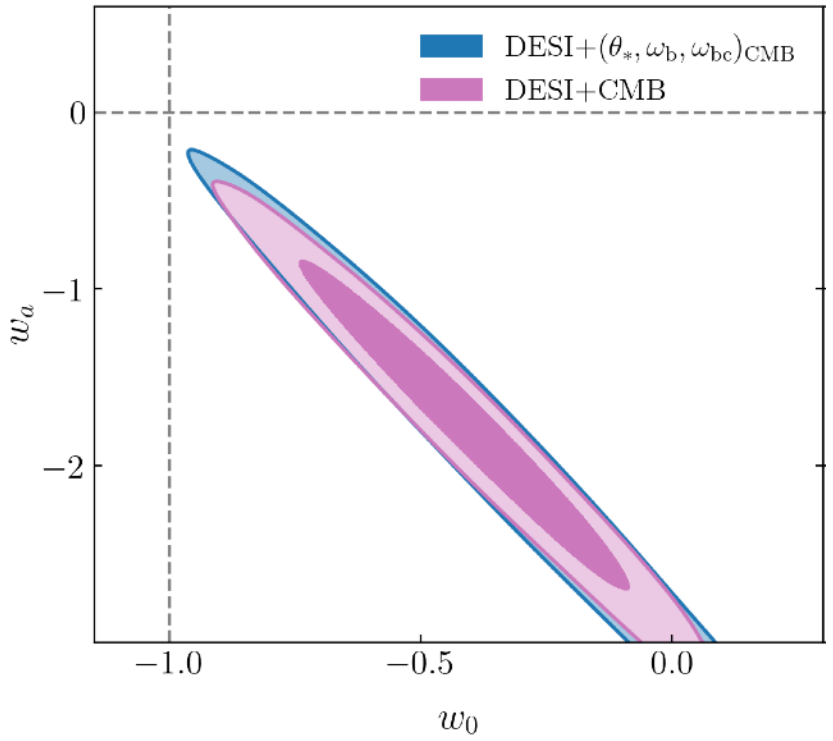
Dynamical Dark Energy



- Combining DESI with **early-Universe priors** on $(\theta_*, \omega_b, \omega_{bc})$ derived from the CMB shows preference for evolving dark energy at the 2.4σ level.

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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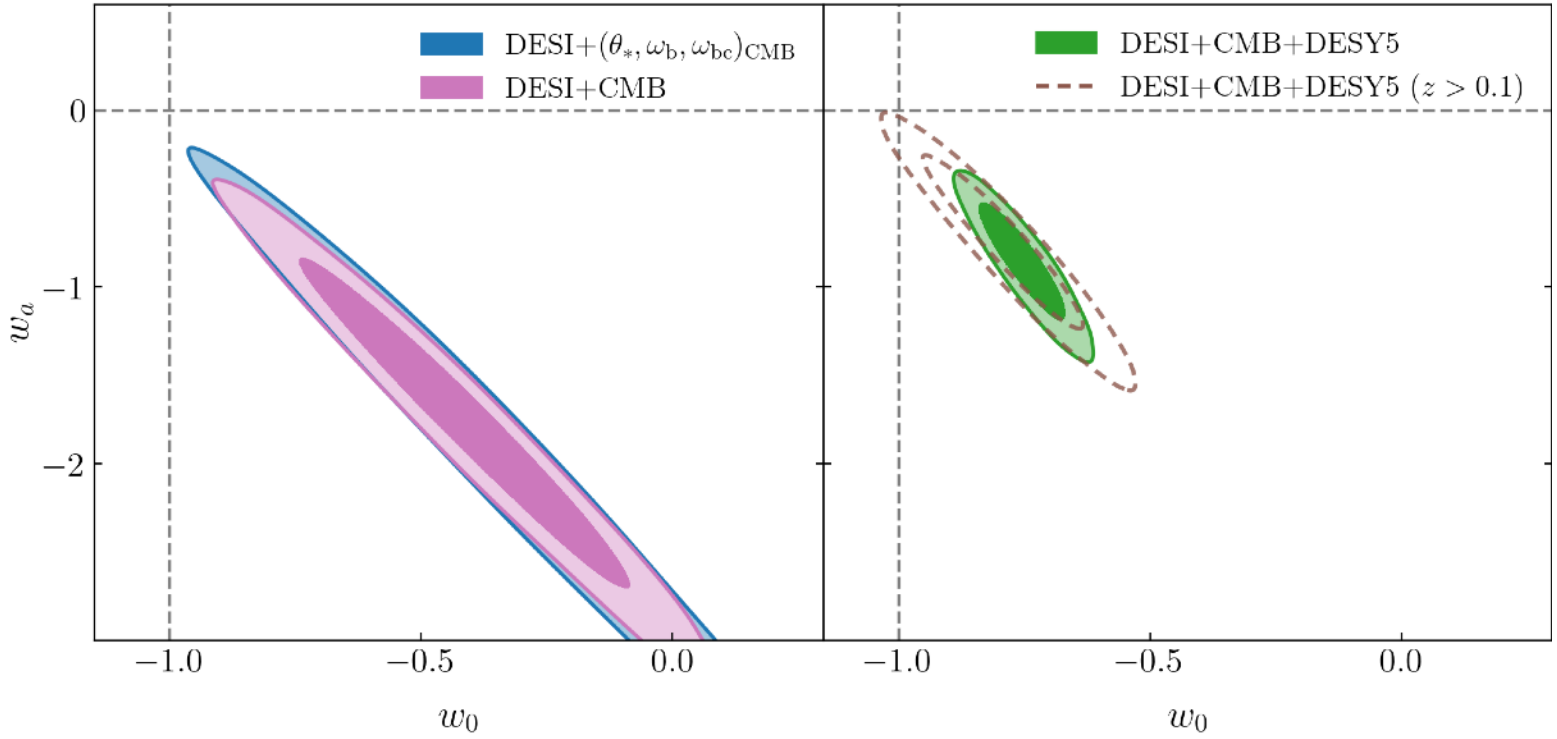
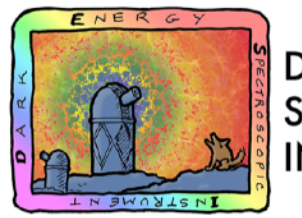
Dynamical Dark Energy



- **Excluding z < 0.1 SNe** reduces the statistical significance of the dynamical DE detection, but the best-fit values for w_0, w_a remain far from ΛCDM.



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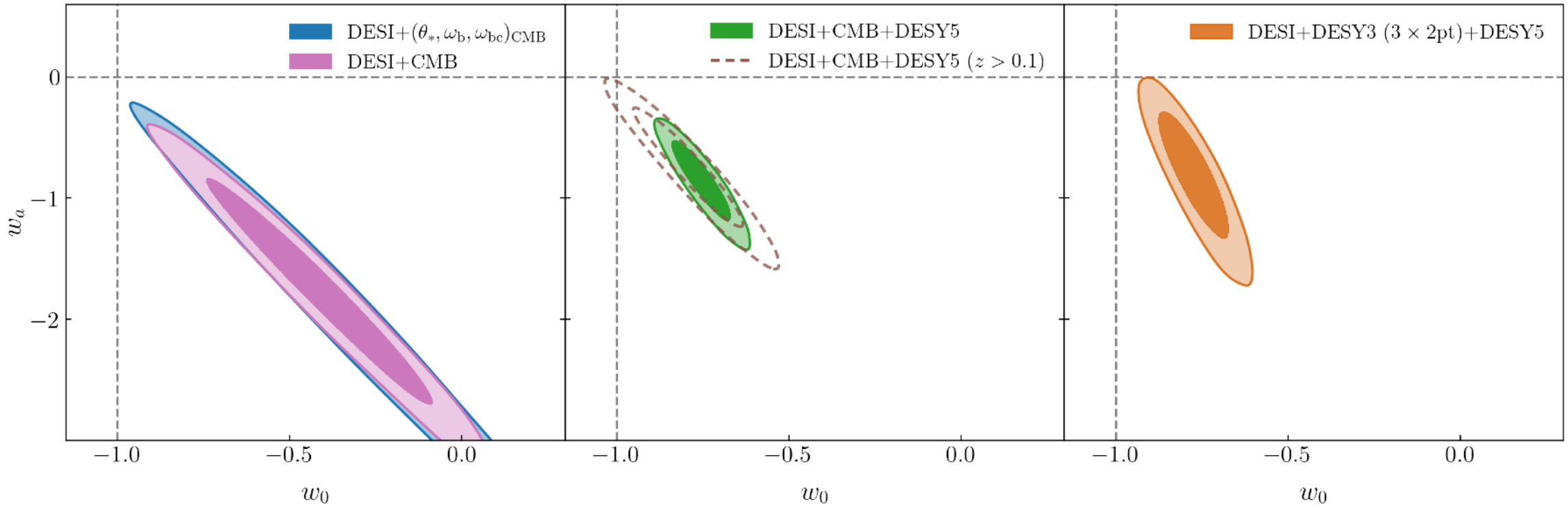
Dynamical Dark Energy



- **Replacing the CMB with DESY3 3x2pt** (weak lensing), we obtain a constraint coming entirely from low-redshift cosmological probes (BAO, weak lensing, SNe).

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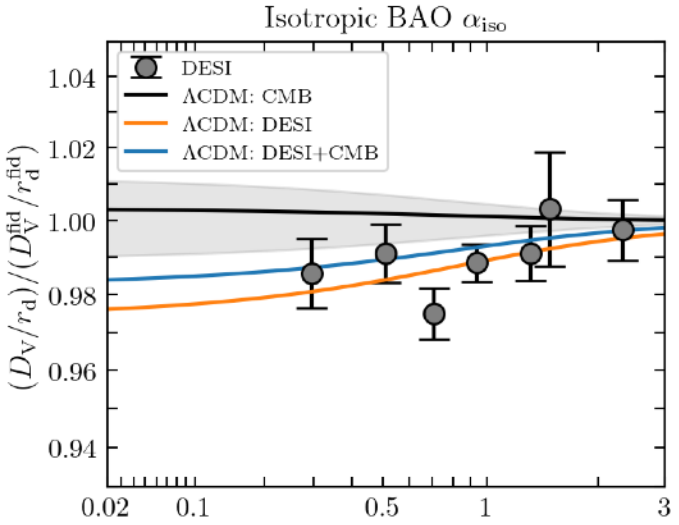
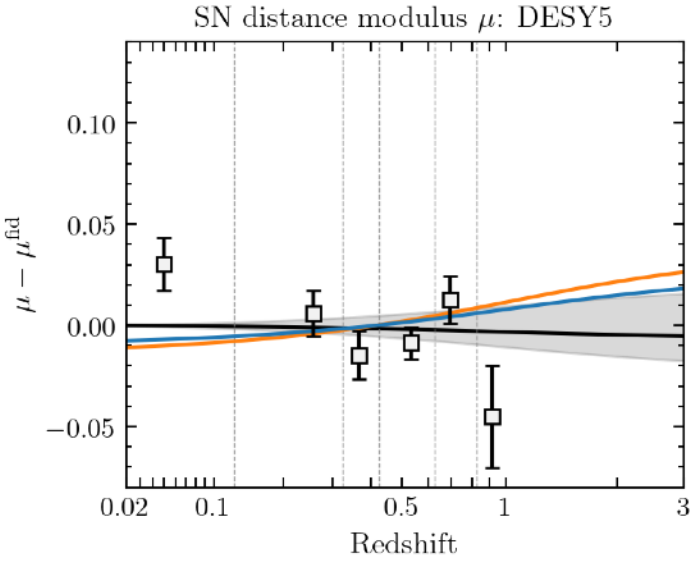
Dynamical Dark Energy

Isotropic BAO distance measurement



Supernovae distance modulus



- There are ΛCDM models that each dataset prefer, but they are inconsistent in their Ω_m values.

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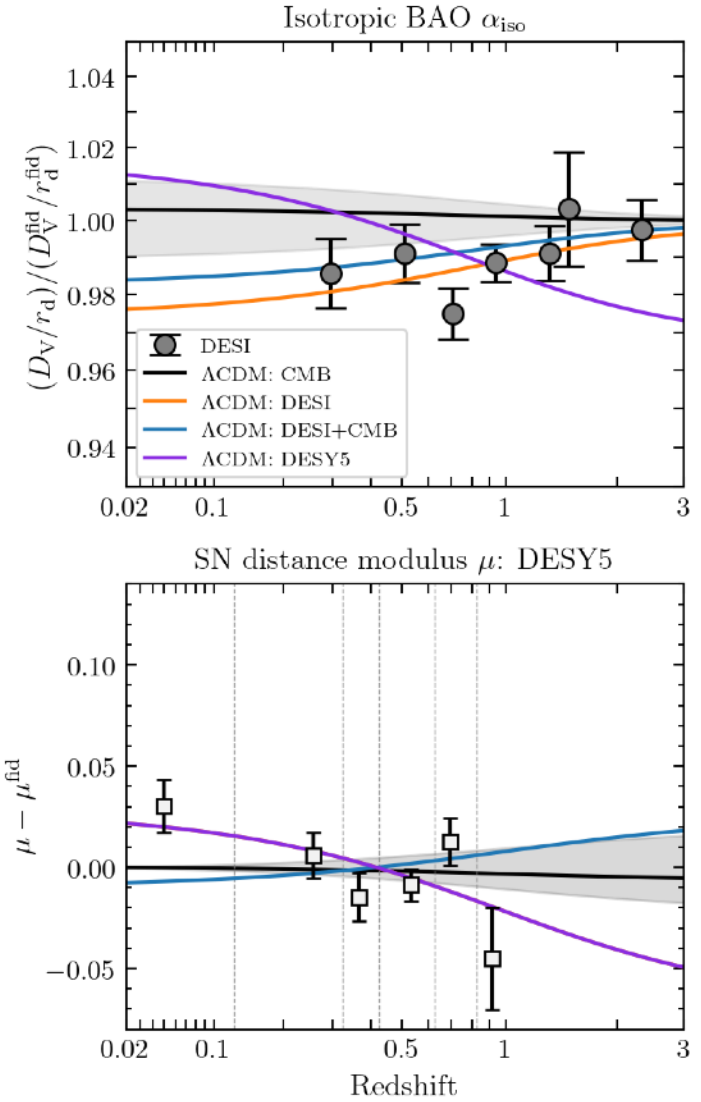
Dynamical Dark Energy



- There are ΛCDM models that each dataset prefer, but they are inconsistent in their Ω_m values.
- ΛCDM does not provide a good fit to all data simultaneously.

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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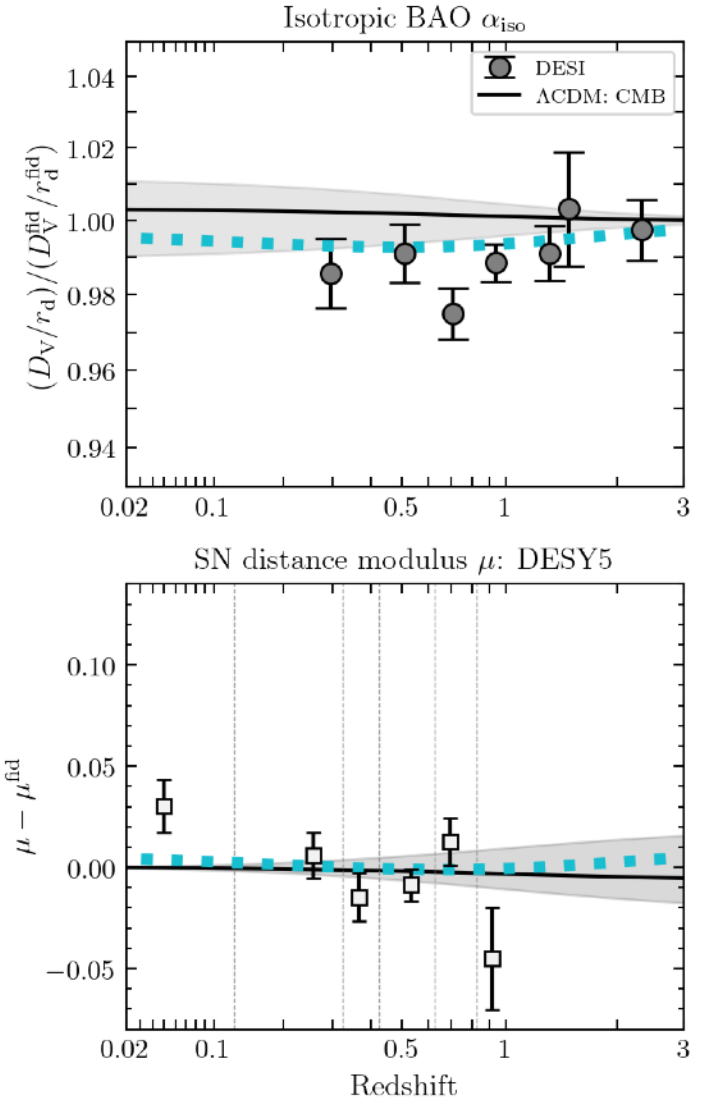
Dynamical Dark Energy



- *w*CDM model: constant equation of state $P/(\rho c^2)$, but not necessarily equal to -1.
- *w*CDM does not have enough freedom in the expansion history to fit BAO, CMB, and SNe simultaneously.

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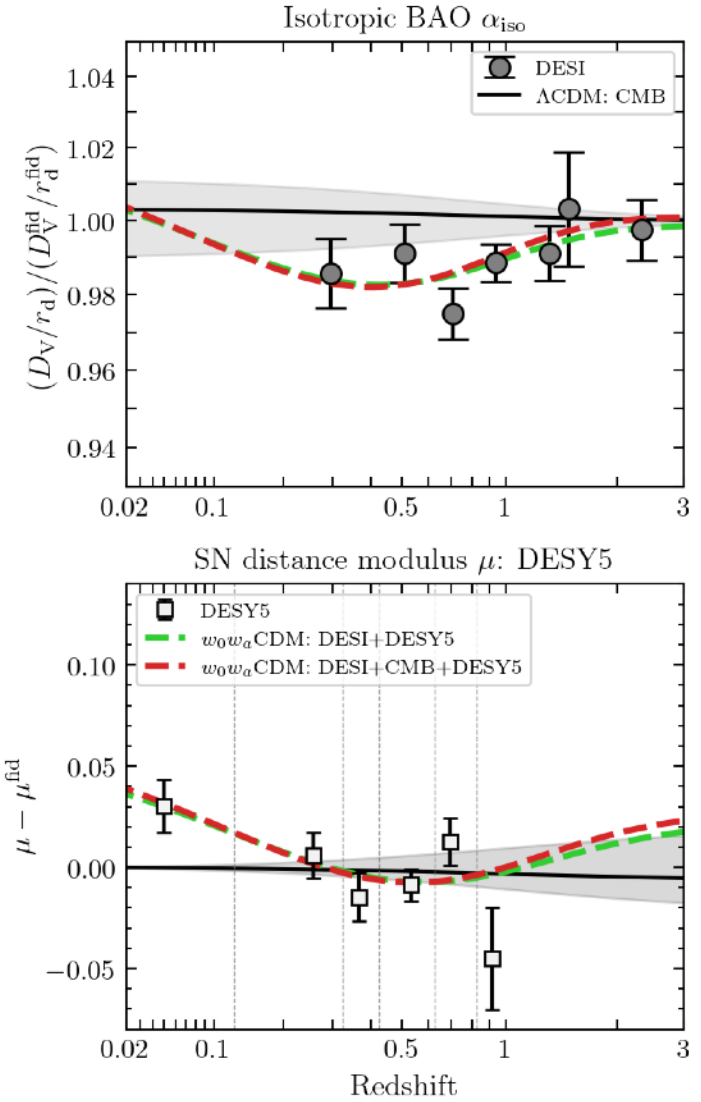
Dynamical Dark Energy



- w_0w_aCDM has sufficient flexibility to simultaneously achieve good fits to all three datasets.
- Resolves the mismatch in Ω_m between DESI and CMB.

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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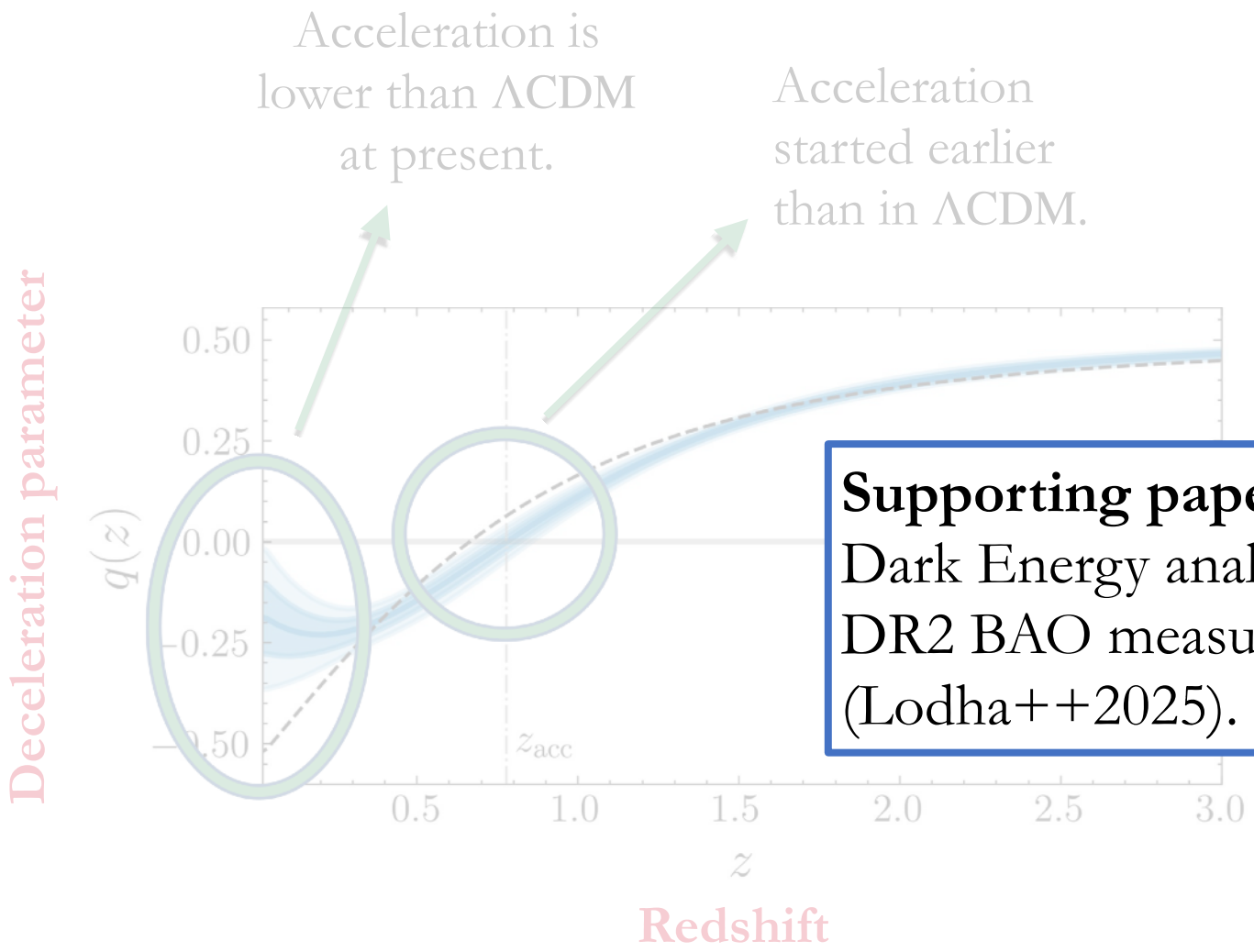
Dynamical Dark Energy



Supporting paper: Extended Dark Energy analysis using DESI DR2 BAO measurements (Lodha++2025).

III. Massive Neutrinos

Image: Super Kamiokande Neutrino Observatory
Credit: Jordy Meow

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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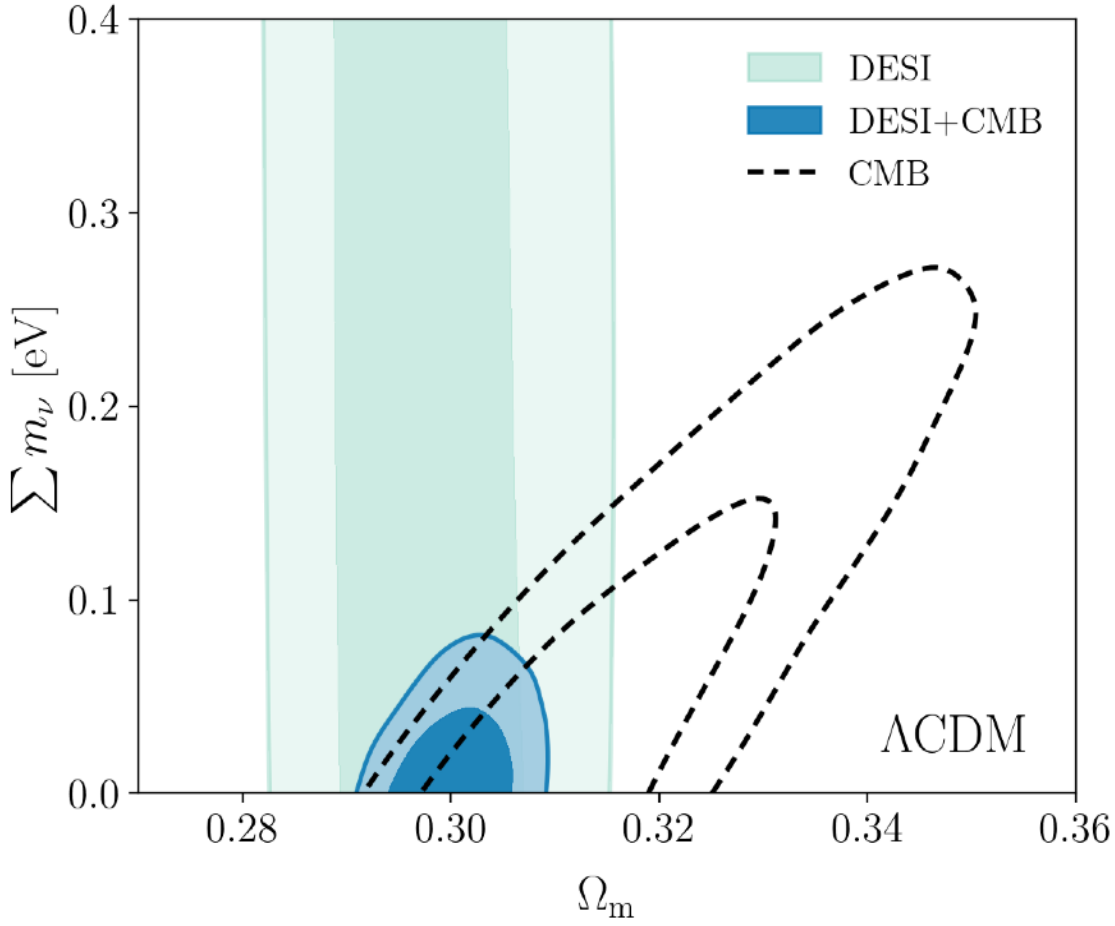
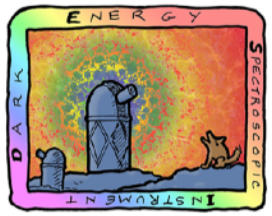
Massive Neutrinos

- Massive neutrinos change the angular diameter distance to last scattering, which is degenerate with the effects of other cosmological parameters in CMB fits.

- DESI BAO helps to break this geometric degeneracy, leading to a tight joint constraint, given the preference for lower Ω_m values from DESI.





DARK ENERGY SPECTROSCOPIC INSTRUMENT

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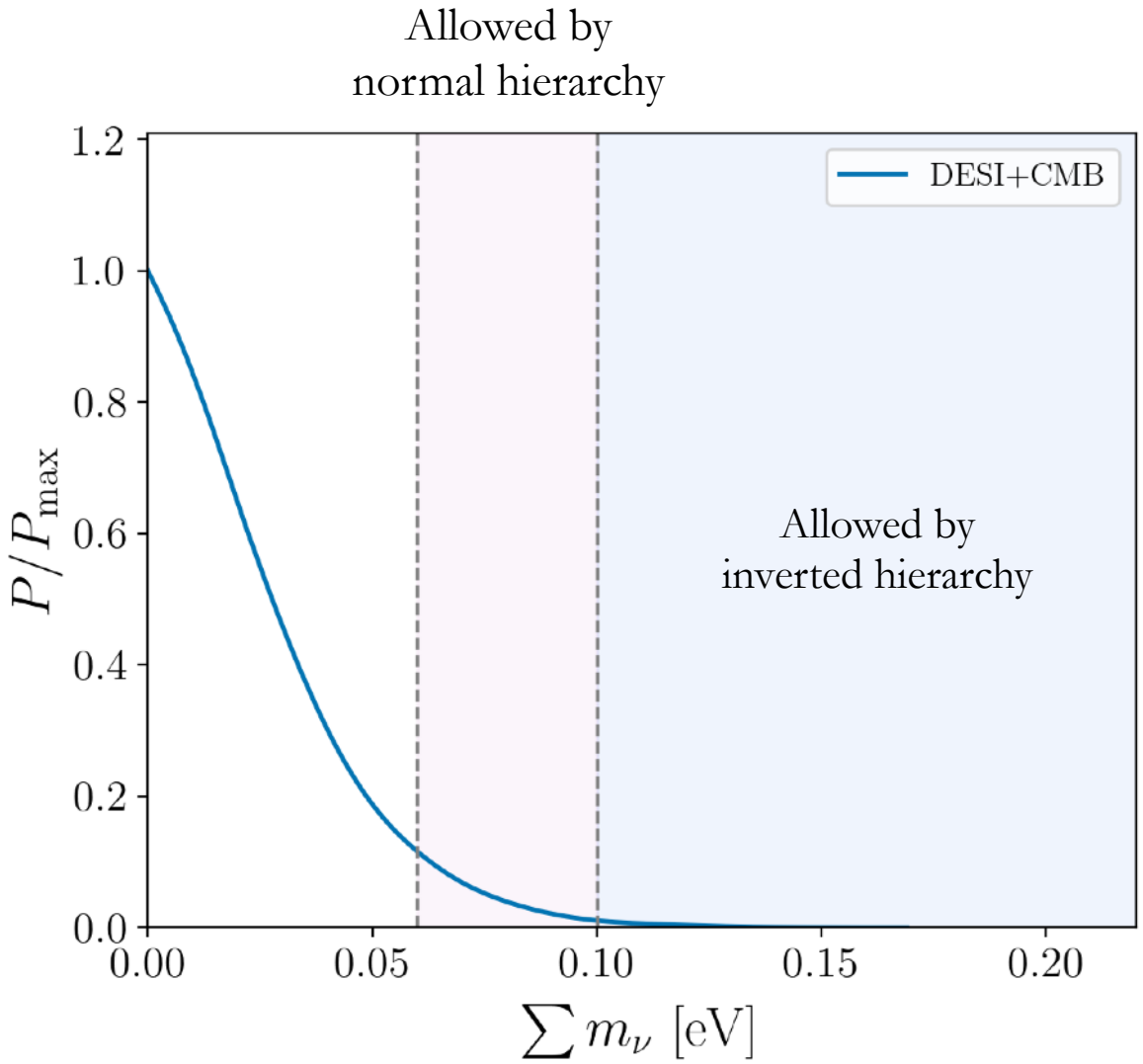
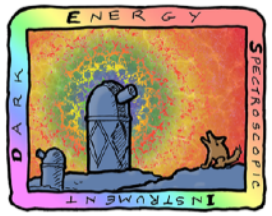
Massive Neutrinos

- Assuming a ΛCDM background, we find

$\sum m_\nu < 0.0642\,\mathrm{eV}$ (95%, DESI+CMB)

- Close to 20 % higher precision compared to DR1 (when using the same CMB likelihood).





DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Massive Neutrinos

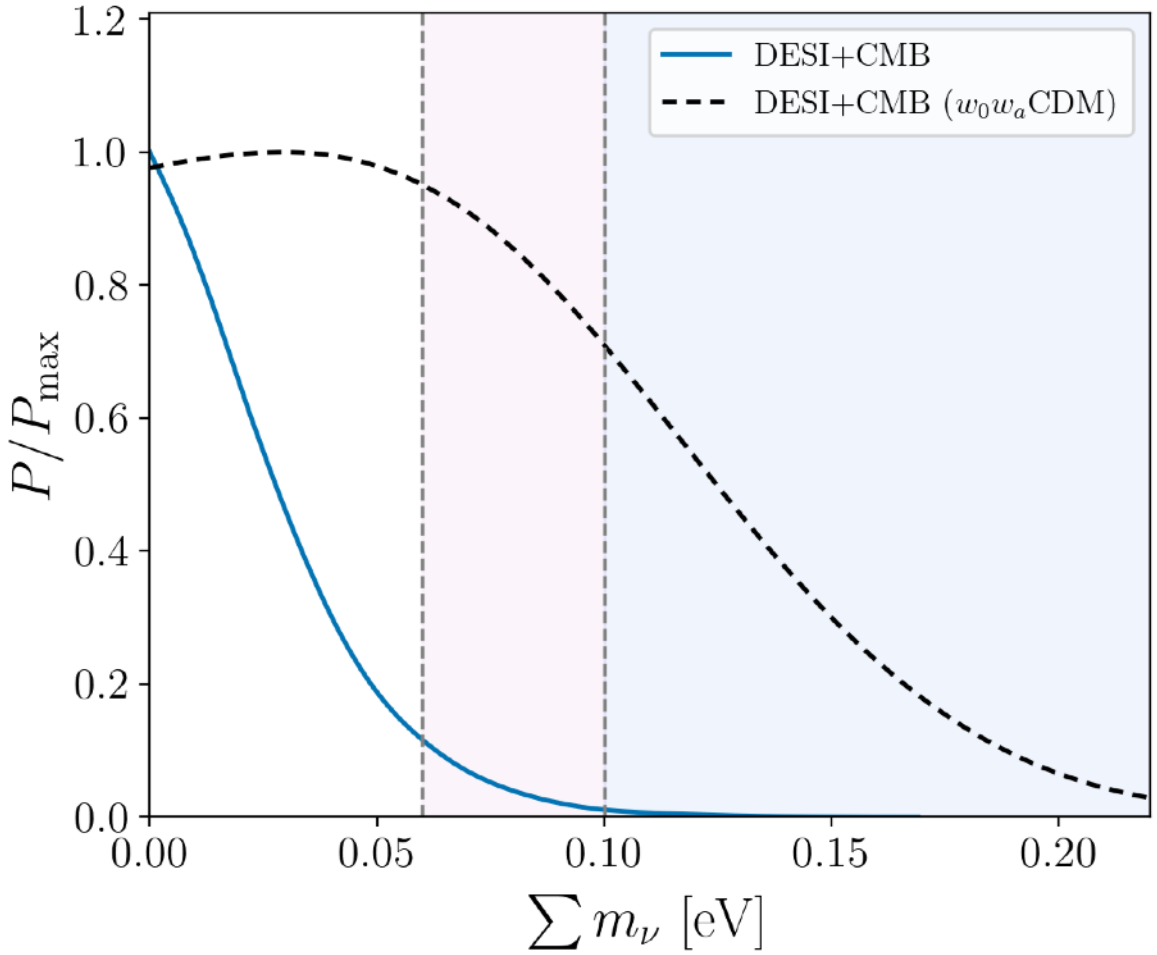
- Assuming a ΛCDM background, we find

$\sum m_\nu < 0.0642\,\mathrm{eV}$ (95%, DESI+CMB)

- Close to 20 % higher precision compared to DR1 (when using the same CMB likelihood).

- This constraint is significantly relaxed for a $w_0 w_a$CDM model:

$\sum m_\nu < 0.163\,\mathrm{eV}$ (95%, DESI+CMB)

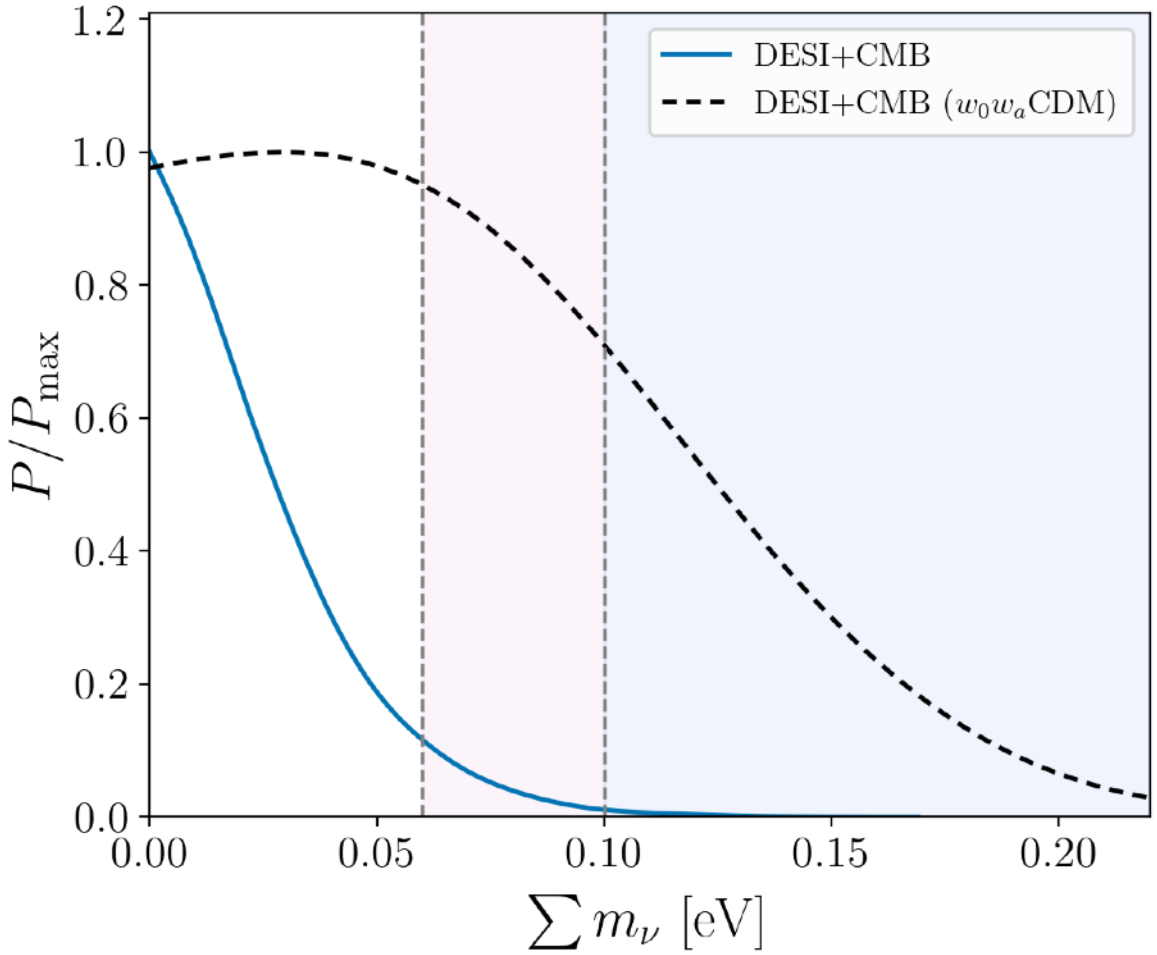


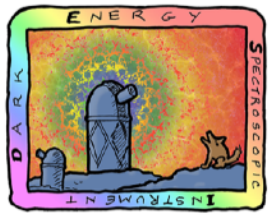
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

Massive Neutrinos

Supporting paper: Constraints on Neutrino Physics from DESI DR2 BAO and DR1 Full Shape (Elbers++2025).





DARK ENERGY SPECTROSCOPIC INSTRUMENT

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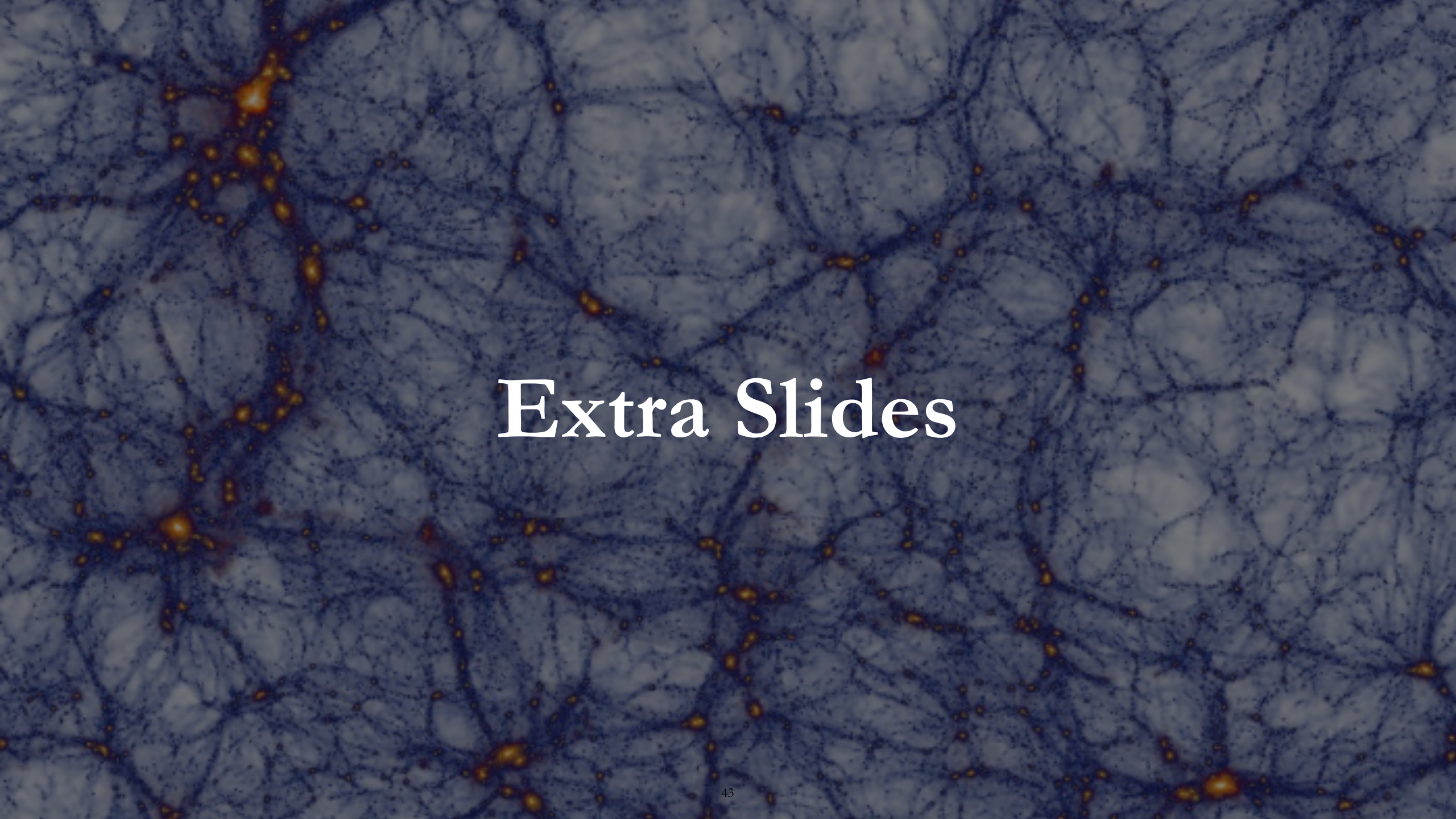
Conclusions

- Discrepant results between DESI+BBN and CMB in the Ω_m-H_0 plane within ΛCDM. Also, DESI is somewhat in tension with the high Ω_m values preferred by SNe, which—contrary to DESI— prefer larger Ω_m than Planck.
- Assuming a ΛCDM background, the combination of DESI and CMB data give the tightest upper bounds for the sum of neutrino masses to date, in increasing tension with the lower bounds from terrestrial experiments.
- The points above hint at a growing incompatibility between different datasets when interpreted in the ΛCDM model.
- Evidence for evolving dark energy has increased with the DR2 BAO data (3.1σ from DESI+CMB alone), 2.8σ to 4.2σ when also including SNe. This also reconciles the discrepancies between datasets mentioned above.


Extra Slides

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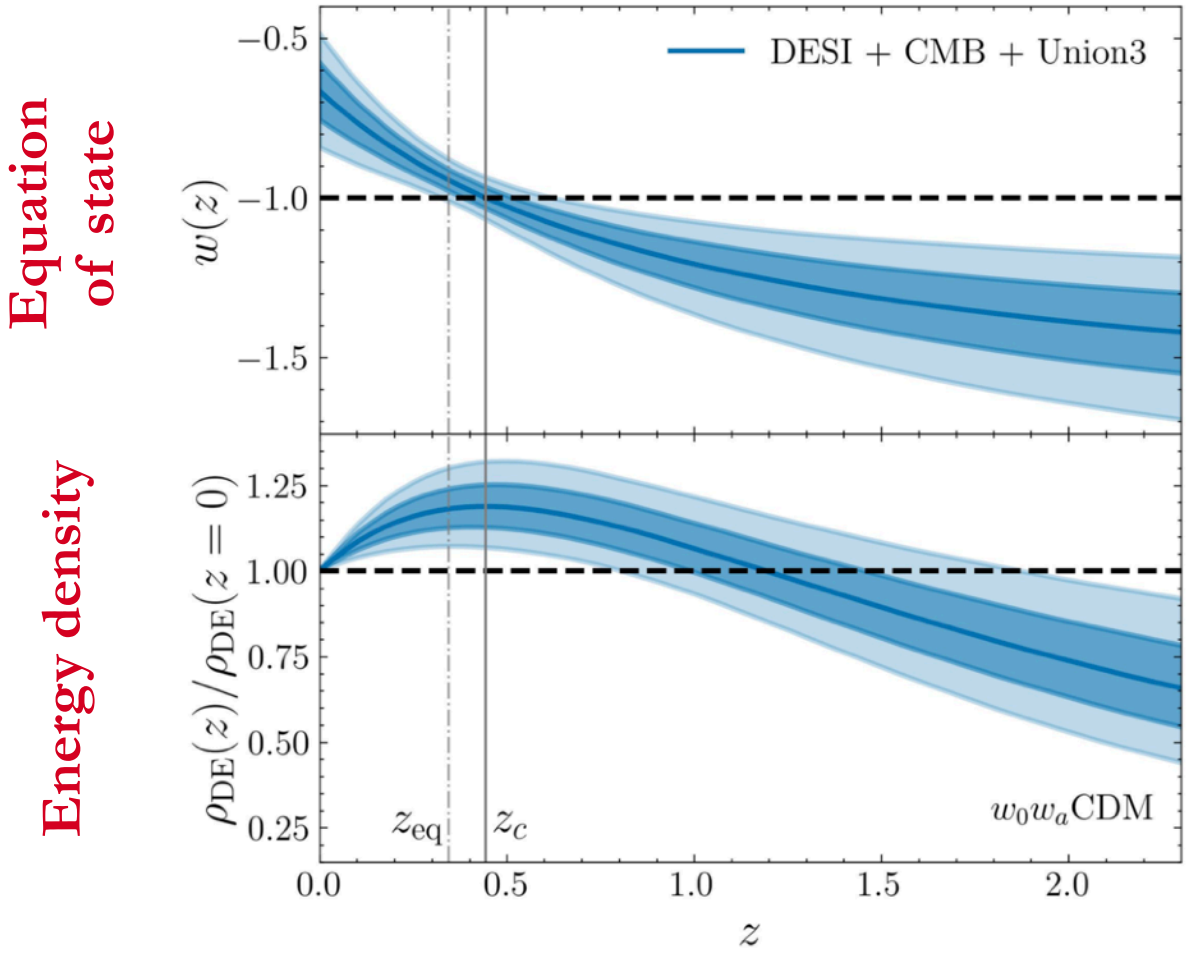
Dynamical Dark Energy



- Maximum dark energy density reached at $z \approx 0.45$ (phantom crossing).
- The phantom crossing could indicate significantly more complex dark sector than traditionally assumed.

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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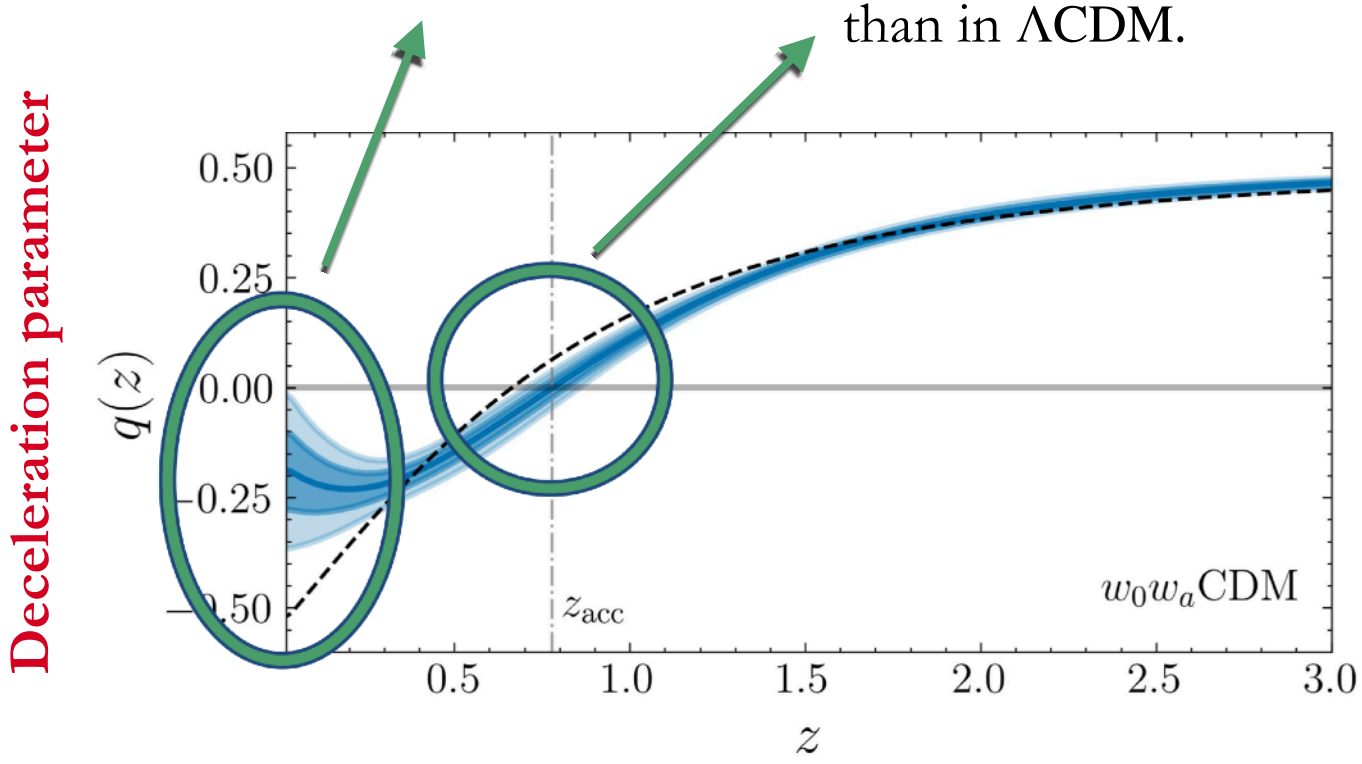
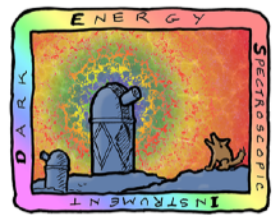
Dynamical Dark Energy

Acceleration is lower than ΛCDM at present.

Acceleration started earlier than in ΛCDM.





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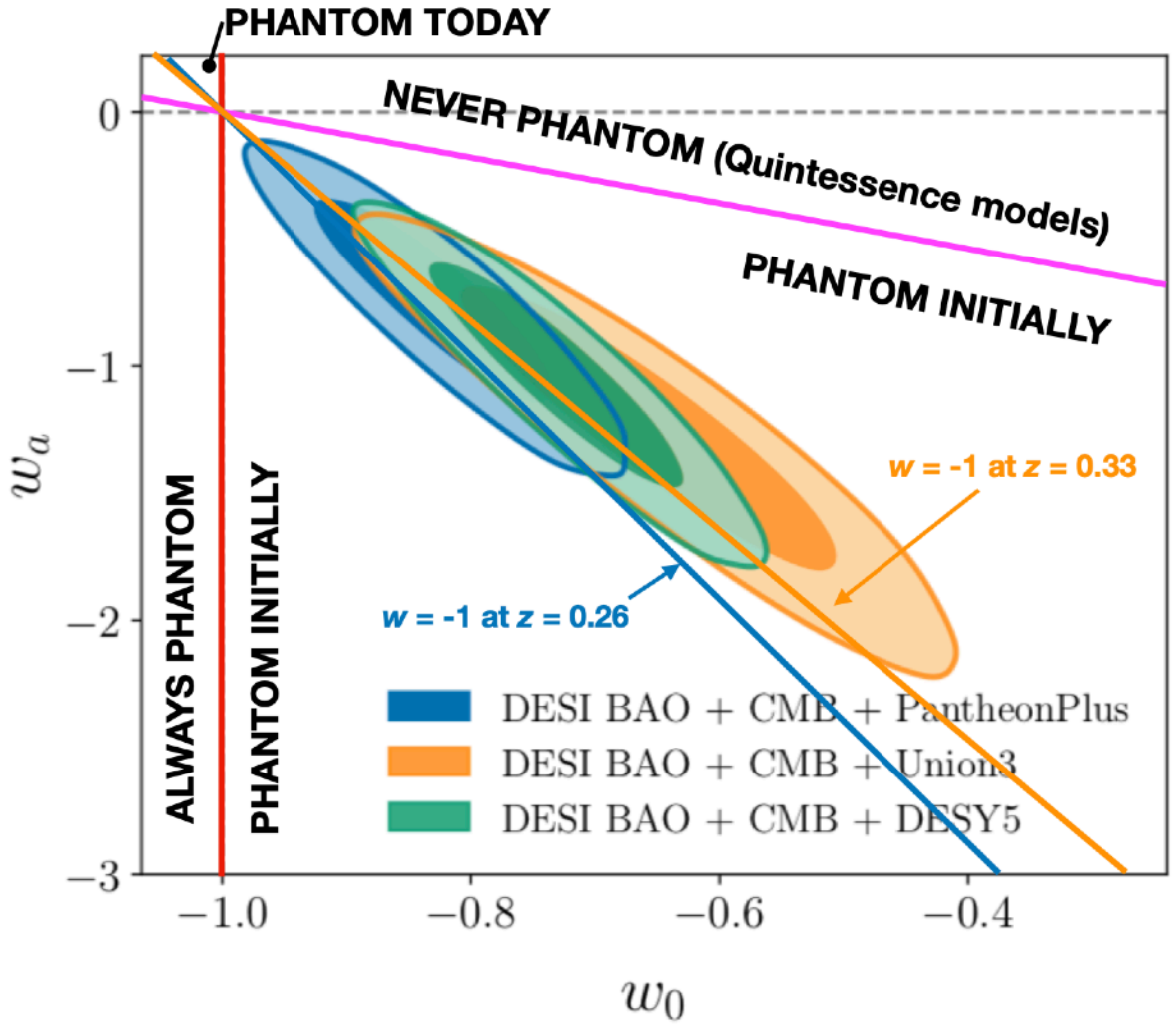
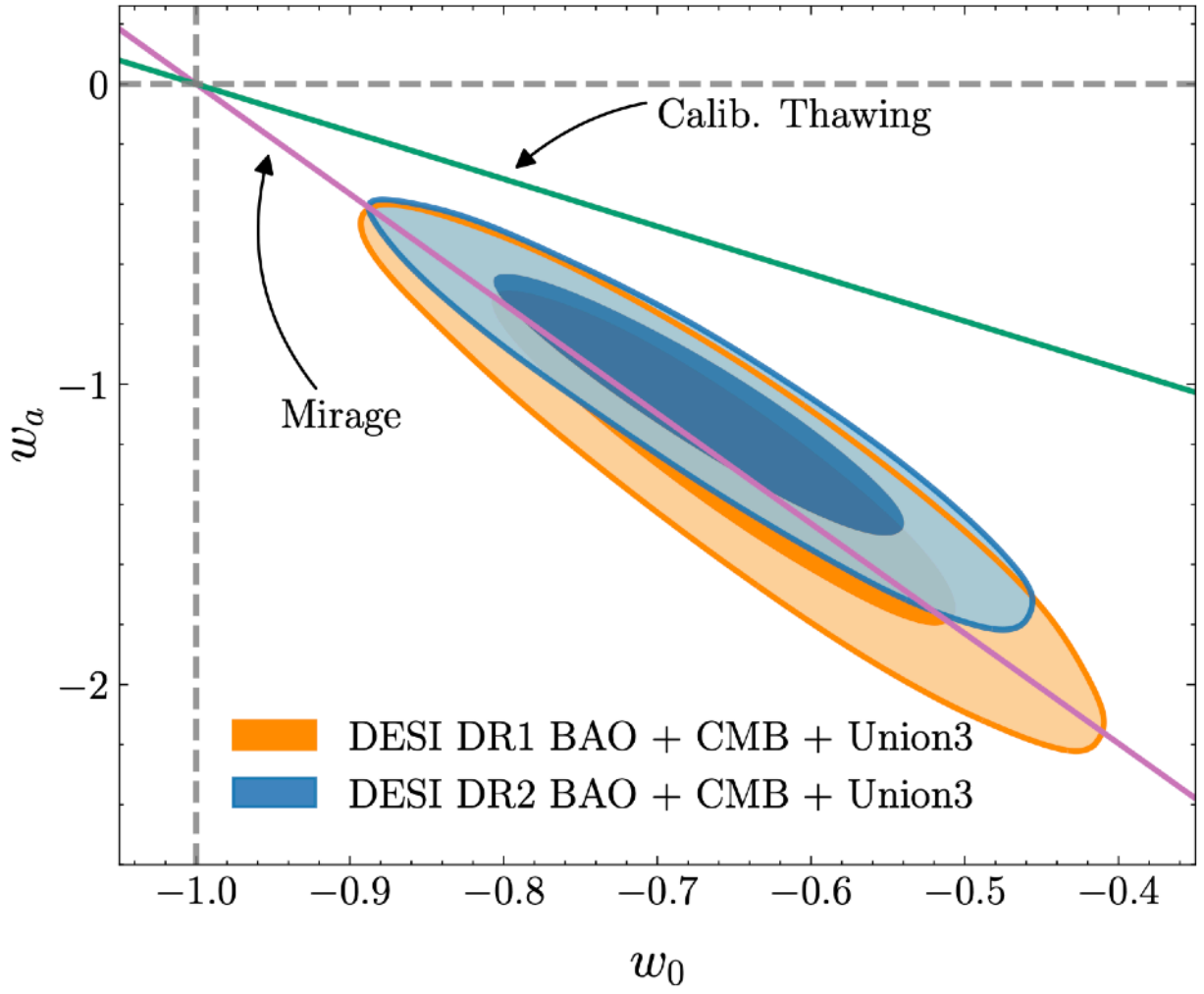
Cortês & Liddle (2024)



Lodha++2025


0
−1
−2
w_a
Calib. Thawing
Mirage
DESI DR1 BAO + CMB + Union3
DESI DR2 BAO + CMB + Union3
−1.0
−0.9
−0.8
−0.7
−0.6
−0.5
−0.4
w_0

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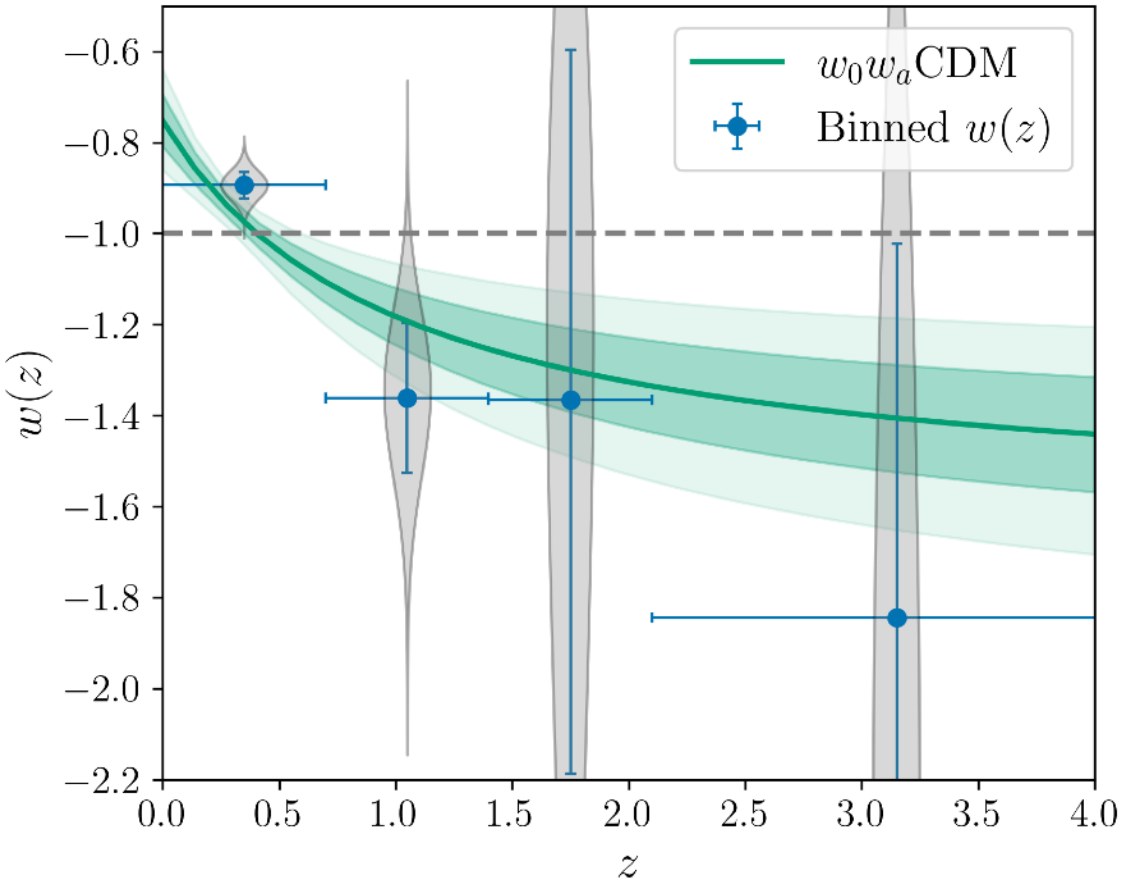
Dynamical Dark Energy



- Binned reconstruction of $w(z)$ without assuming a functional form for the equation of state.
- Consistent with our w_0w_aCDM results.

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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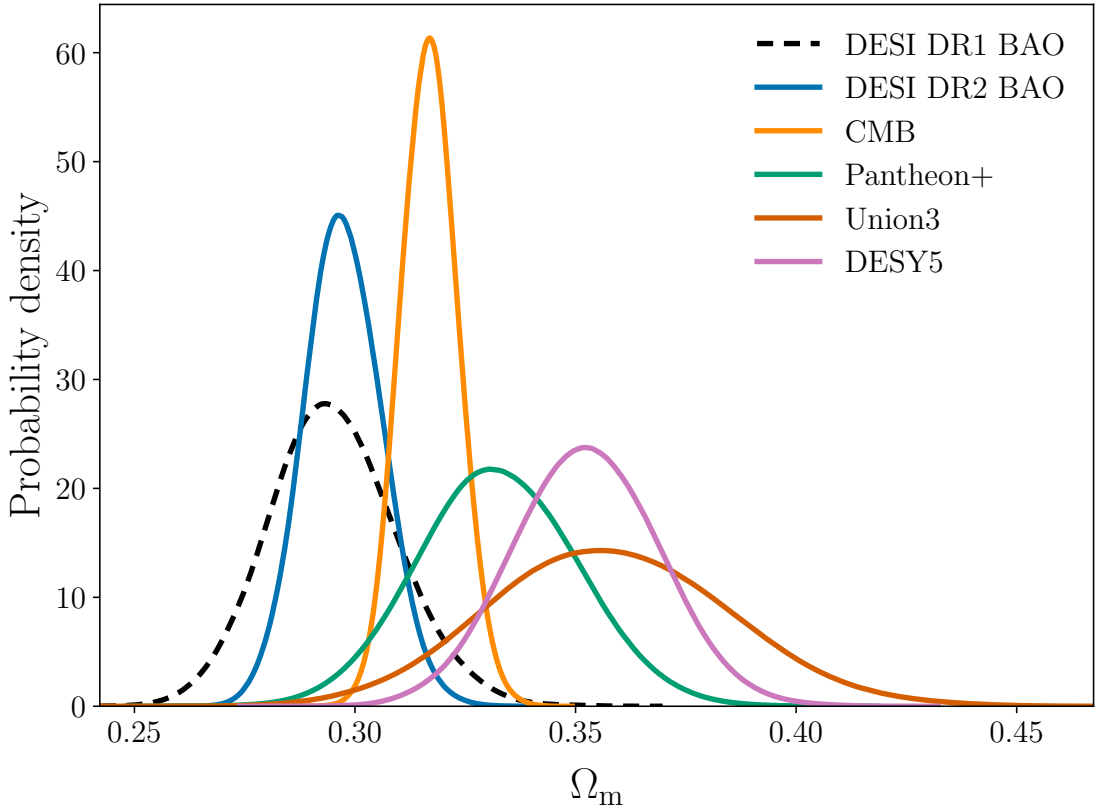
Constraints under ΛCDM

- Mild to moderate discrepancy between the recovered values of Ω_m from DESI and SNe under ΛCDM.

- Might indicate that DESI and at least some of the SNe datasets cannot be consistently fit except with models that have greater freedom in the background evolution.



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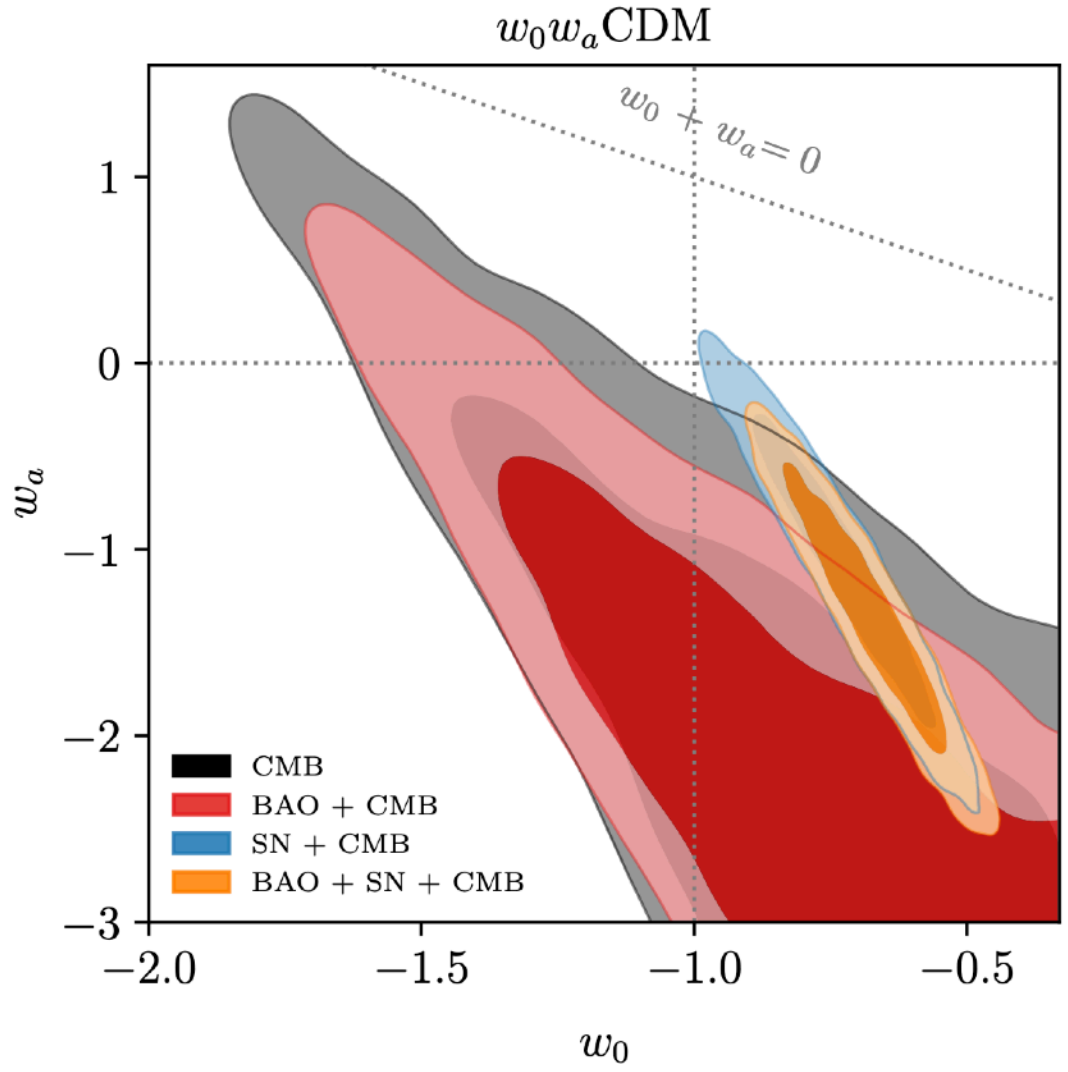
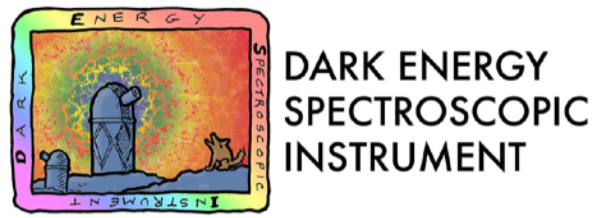
DES Collaboration (2025)





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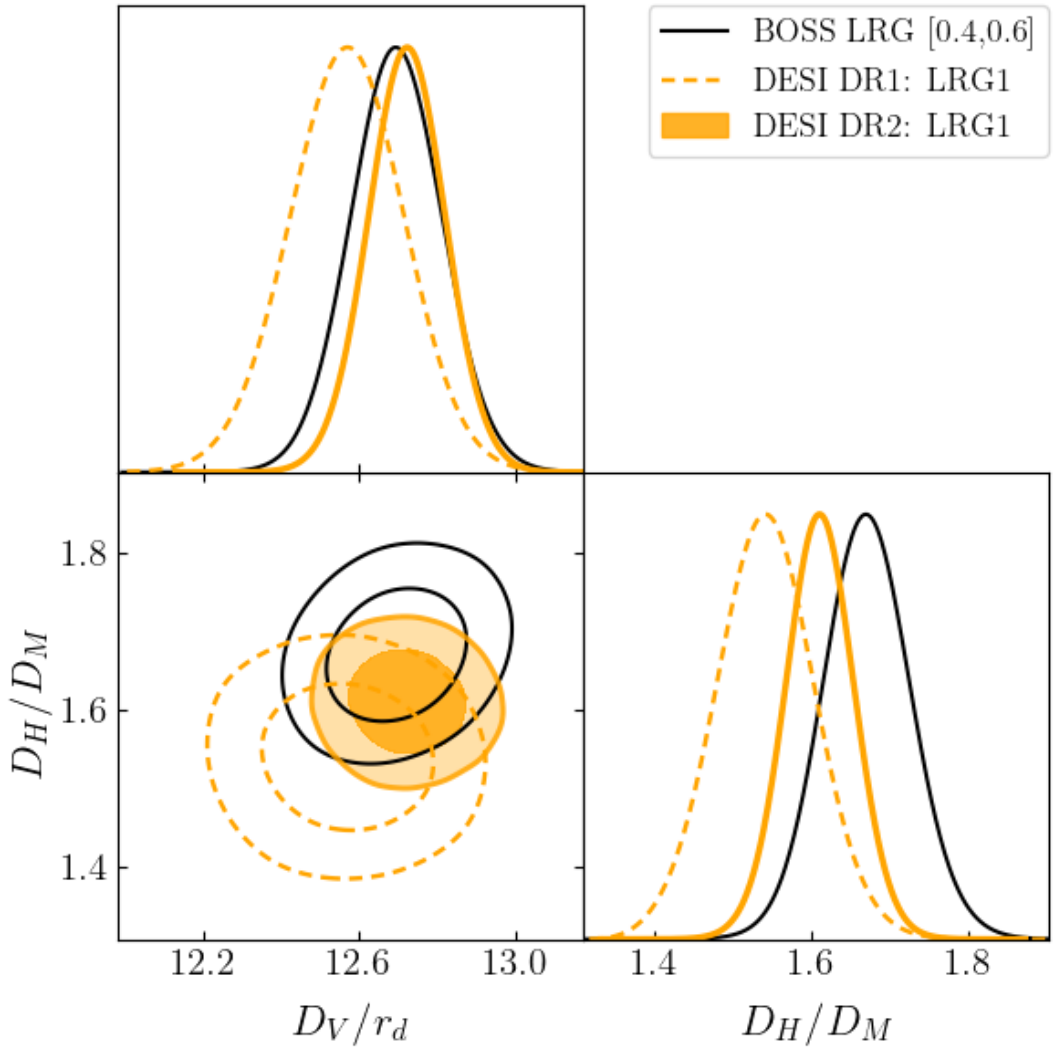
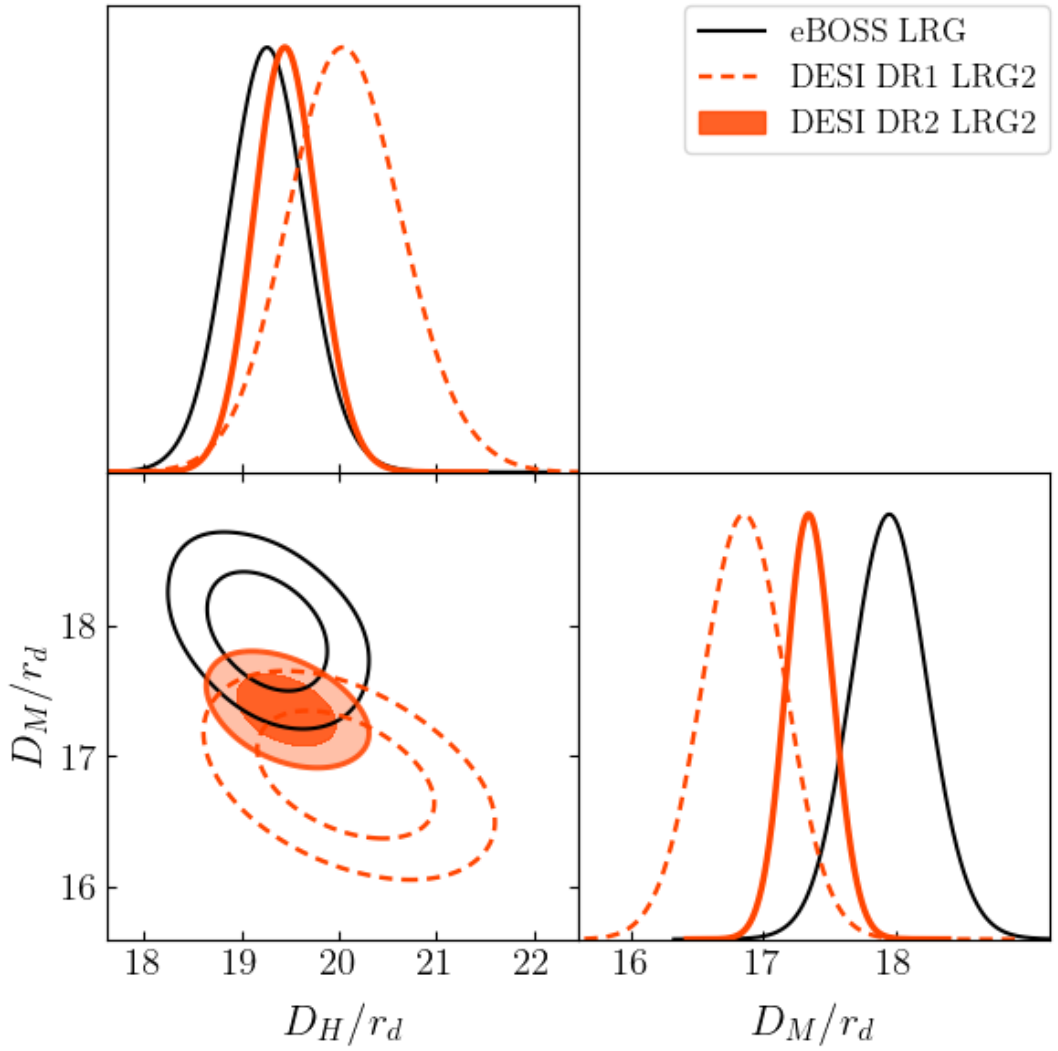
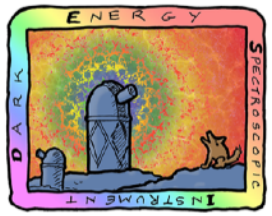
Agreement with SDSS







DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Detection significance

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 $\Delta({\rm DIC}) = {\rm DIC}_{w_0w_a{\rm CDM}} - {\rm DIC}_{\Lambda{\rm CDM}}$. 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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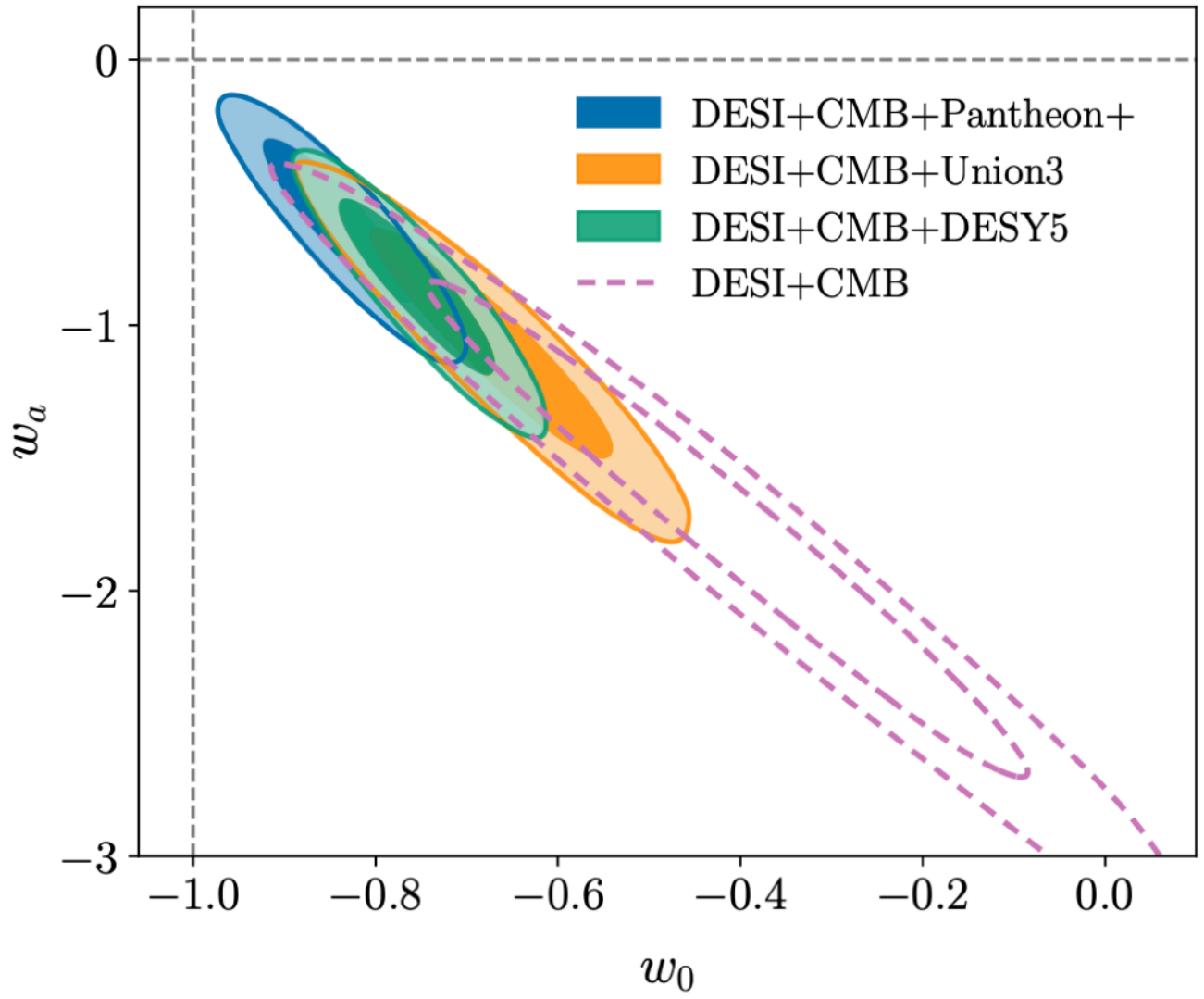
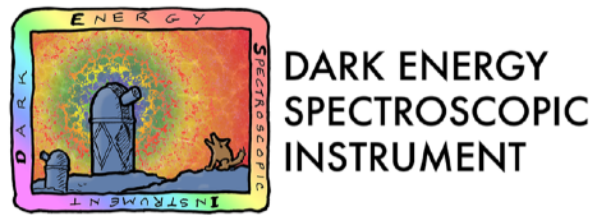
Dark Energy Constraints





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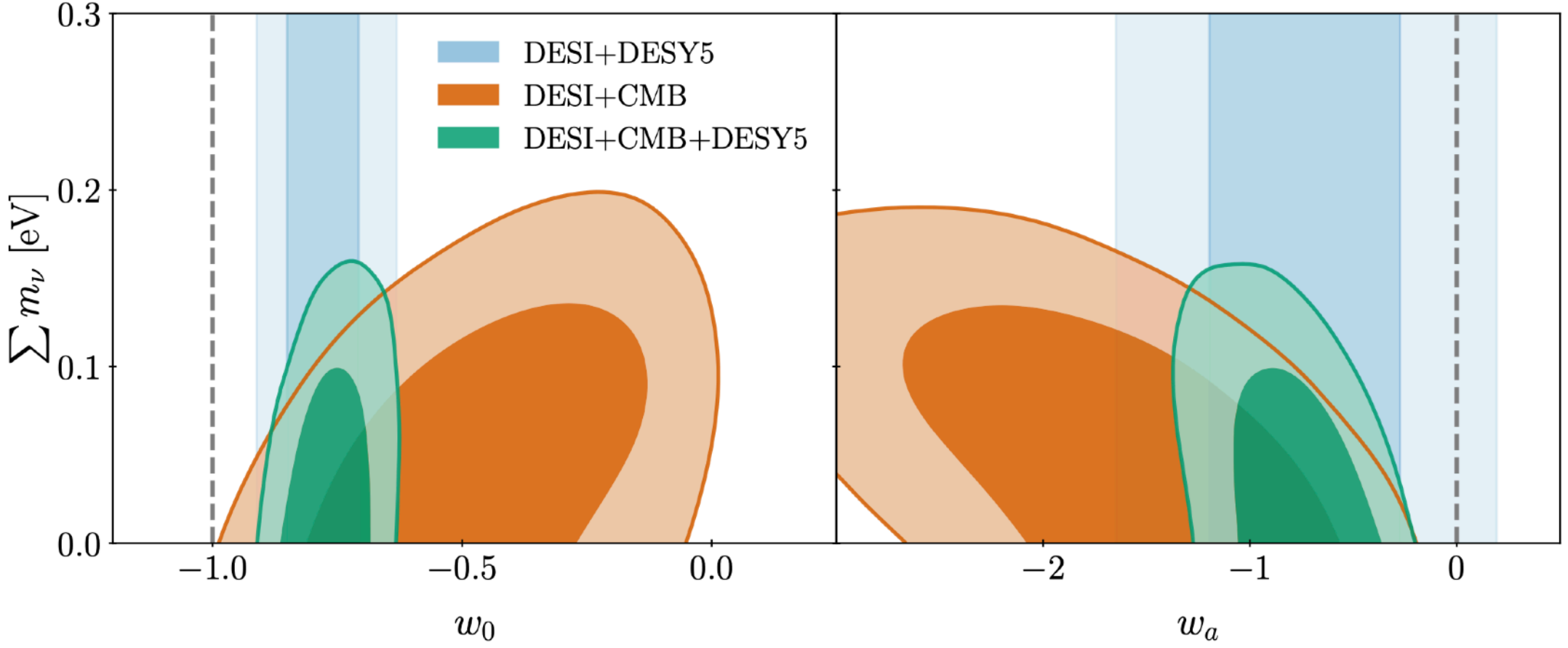
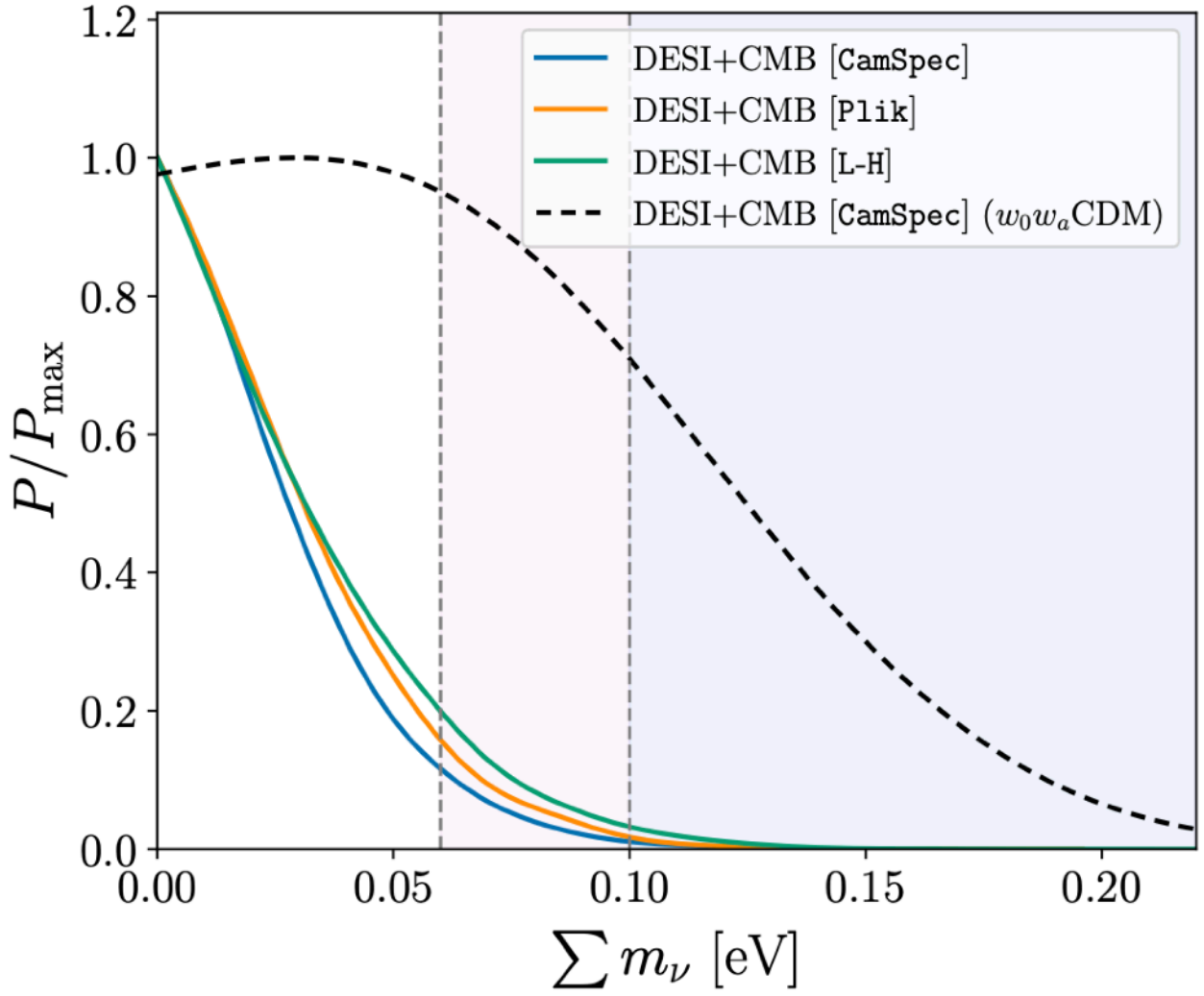
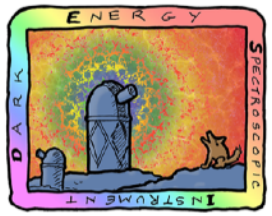
Neutrinos under w0wa



Neutrinos for different Planck likelihoods





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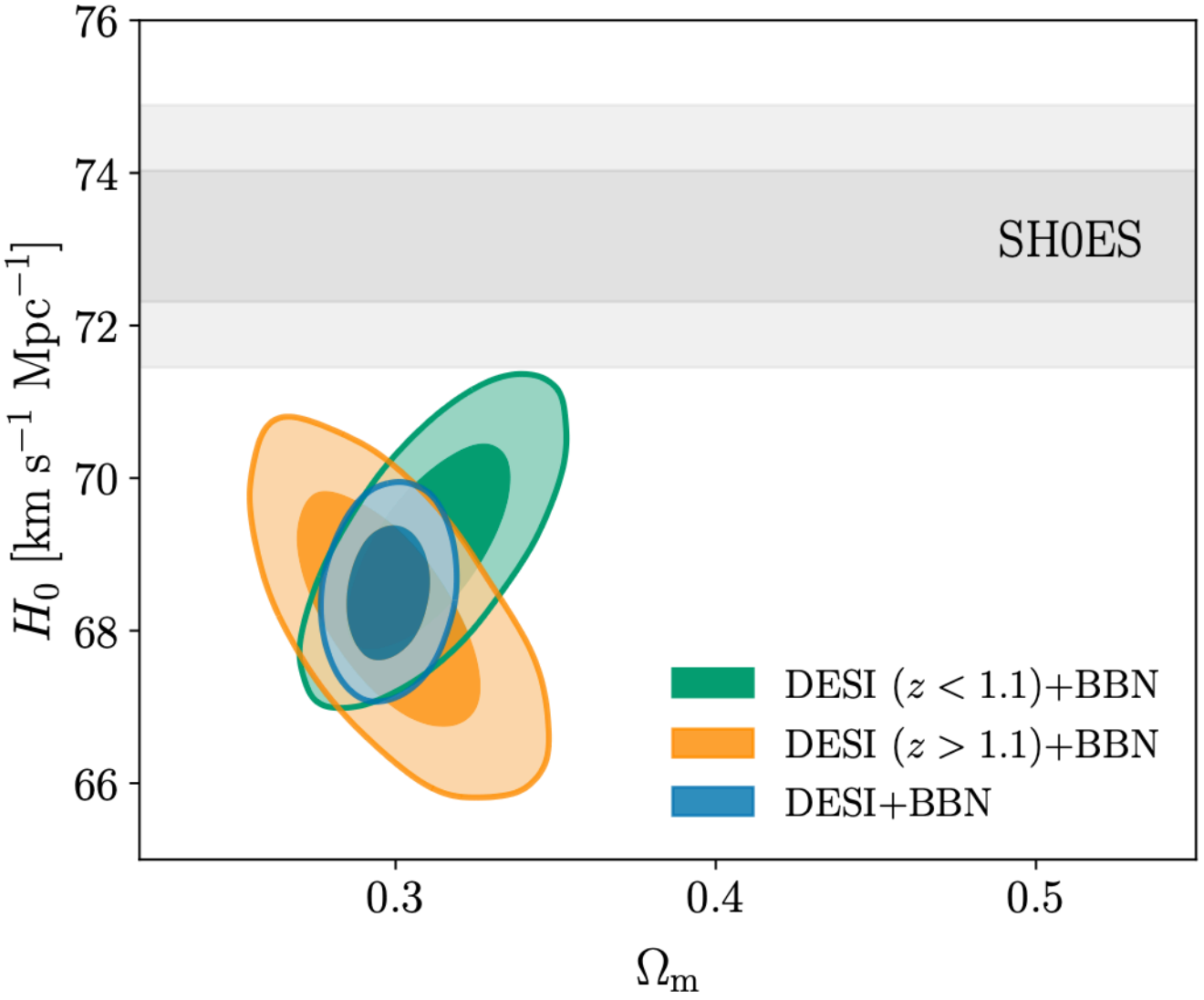
Hubble Tension



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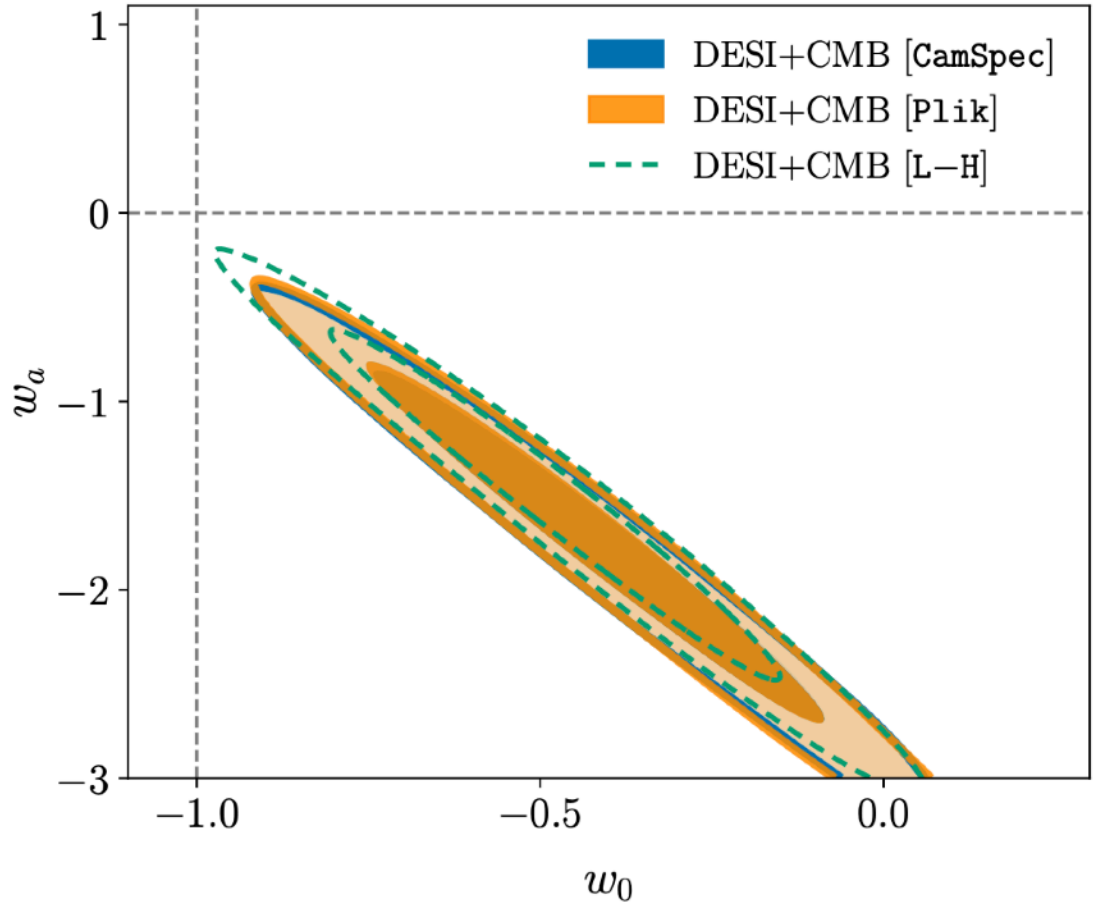
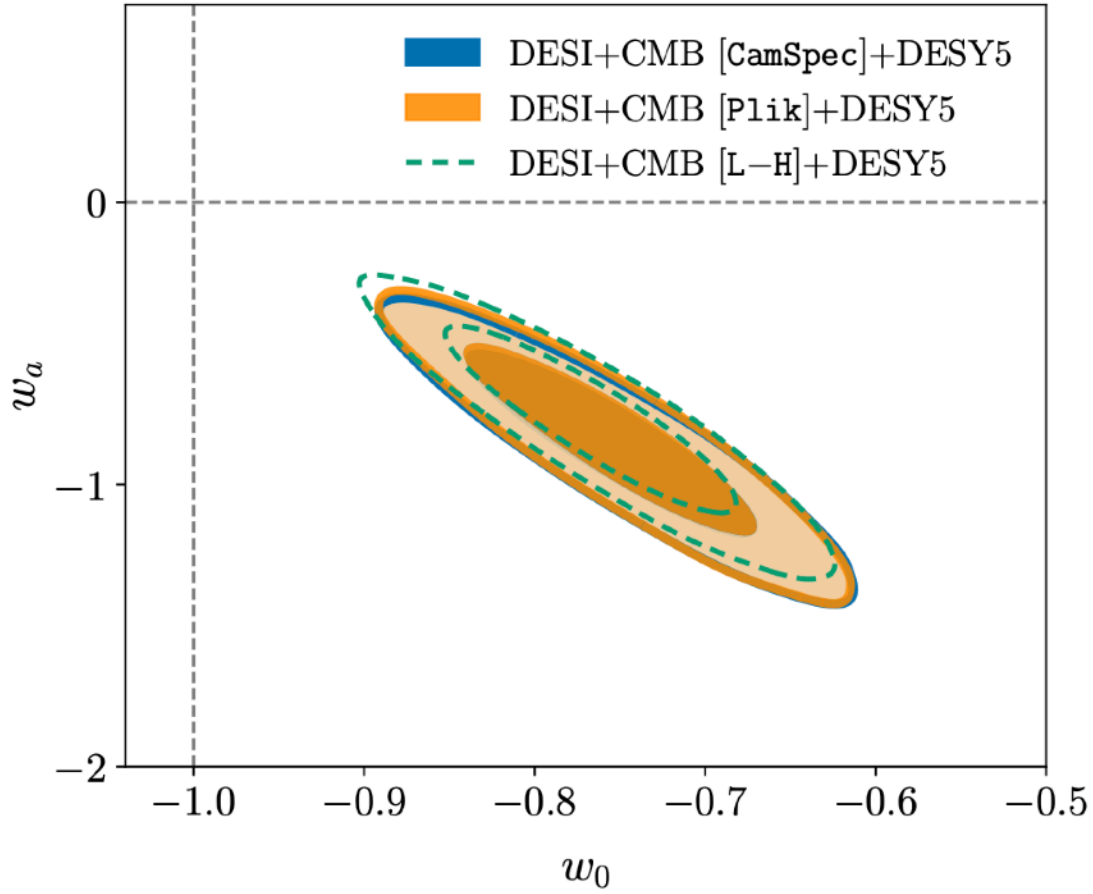
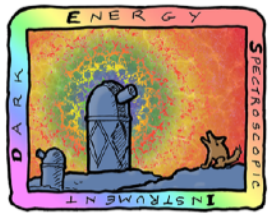
w0wa for different Planck likelihoods







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Neutrinos for different data combinations