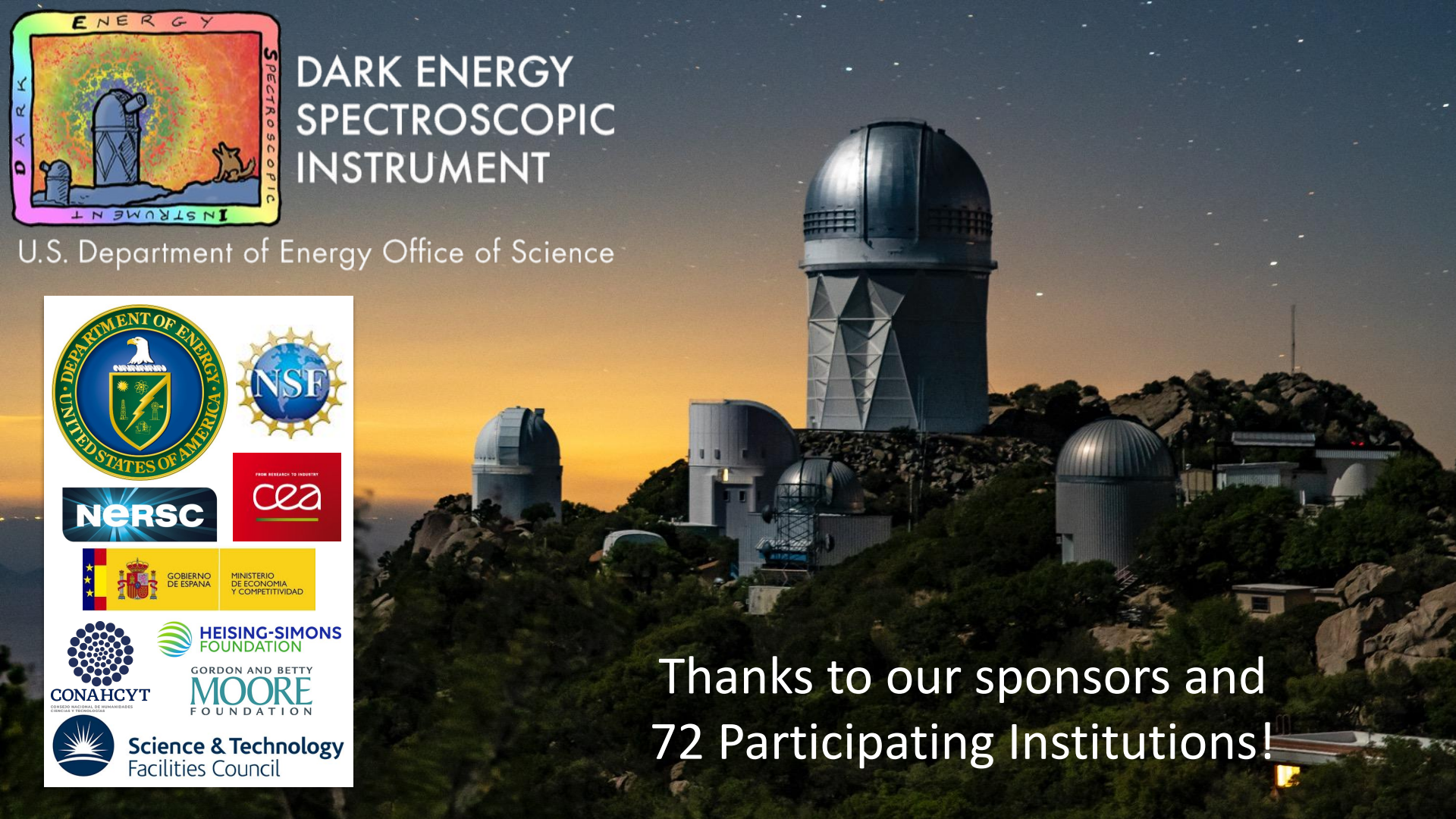
Evidence for evolving dark energy from the DESI DR2 results

Juan Mena-Fernández
On behalf of the DESI collaboration


DARK ENERGY SPECTROSCOPIC INSTRUMENT
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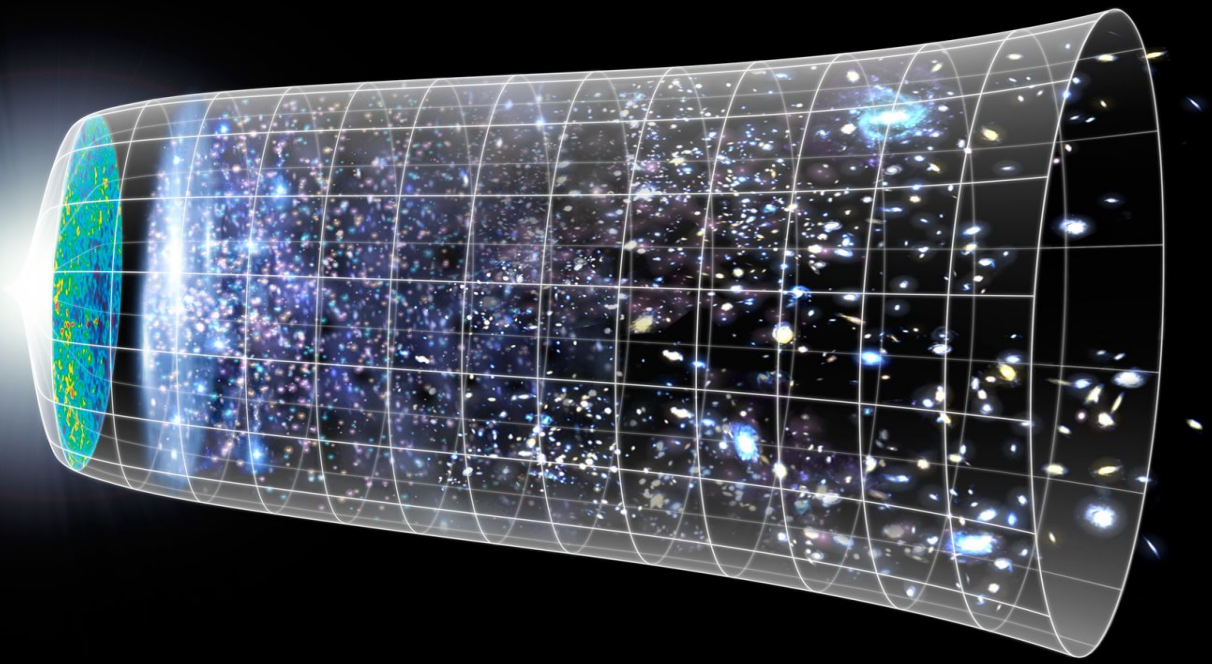
The ΛCDM model



NASA/WMAP Science Team

Pillars of ΛCDM

General relativity

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

"matter tells spacetime how to curve, and curved spacetime tells matter how to move"

The cosmological principle

The spatial distribution of matter in the universe is **isotropic** and **homogeneous** when viewed on a large enough scale

Vast observational basis (CMB, LSS, primordial nucleosynthesis and abundance of light elements)

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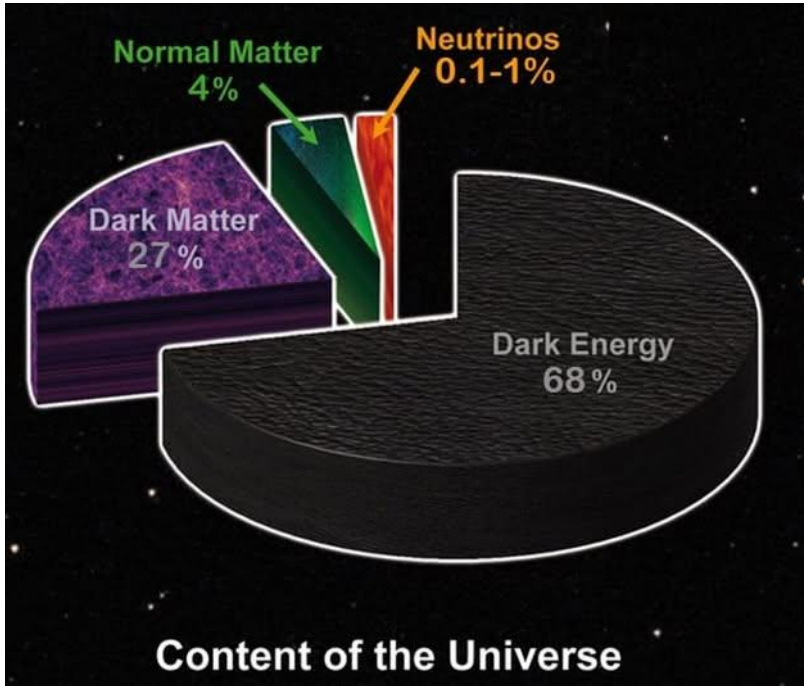
The ΛCDM model

ΛCDM is based upon two main components of **unknown nature**:

- **Dark Energy** (late-time acceleration)
  - Believed to be the **cosmological constant (Λ)**.
- **Dark Matter** (galaxy formation, gravitational lensing, rotation curves, …) - **CDM**.



Dark energy

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

- Causes the **accelerated expansion** of the universe.
- We think it is the **cosmological constant** (the Λ from ΛCDM).
- **~68%** of the energy content of the universe!

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$p = w\rho$$

$$\frac{\rho_{\rm DE}(z)}{\rho_{\rm DE,0}} = \exp\left[3\int_0^z [1 + w(z')]\frac{dz'}{1+z'}\right]$$

- **Cosmological constant (ΛCDM)**

$$w = -1$$

$$\rho_{\rm DE}(z) = \rho_{\rm DE,0}$$

- **Dynamical dark energy (w_0w_aCDM)**

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

$$\rho_{\rm DE}(z) = f(z)$$

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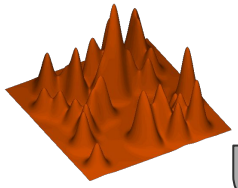
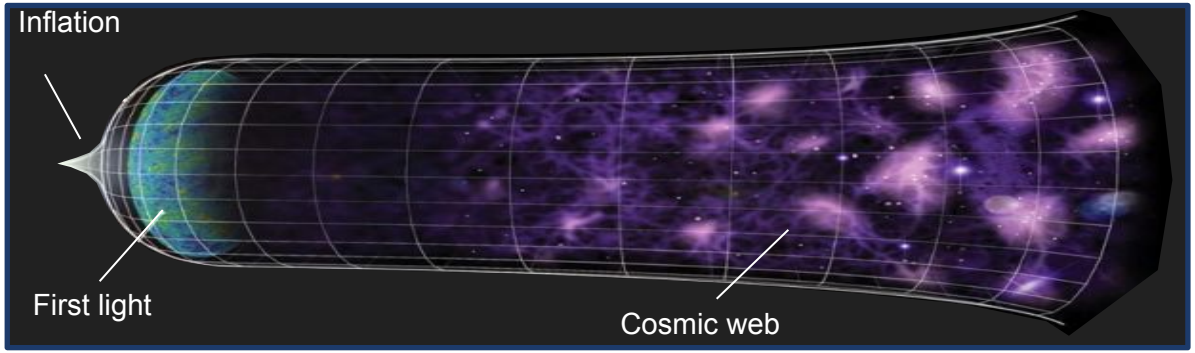
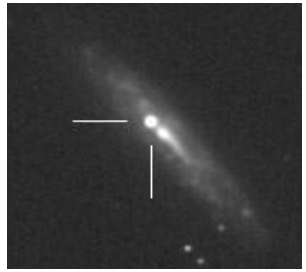
ΛCDM: observational basis

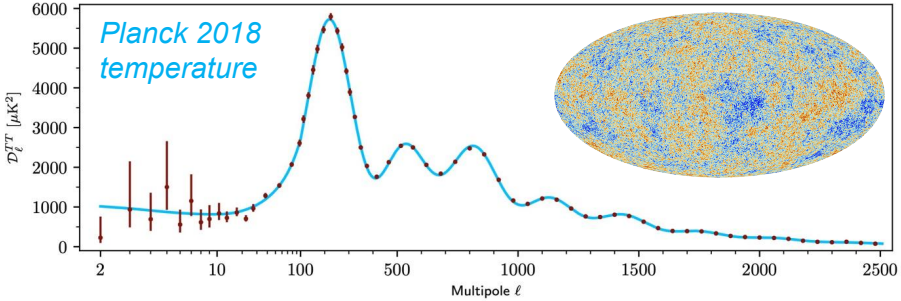


Baryon acoustic oscillations (BAO)





Type Ia supernovae (SN)



Cosmic Microwave Background (CMB)

The physics we know
+ our cosmological model
successfully predict **most observations** of last 20 yrs!

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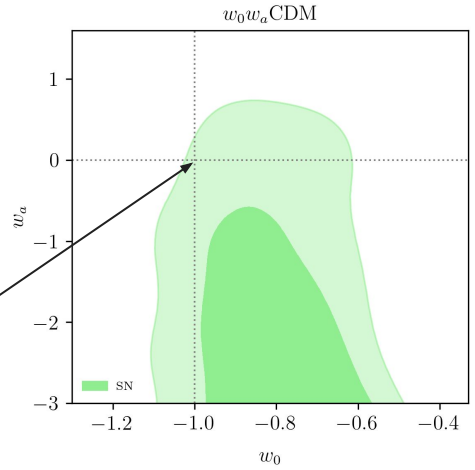
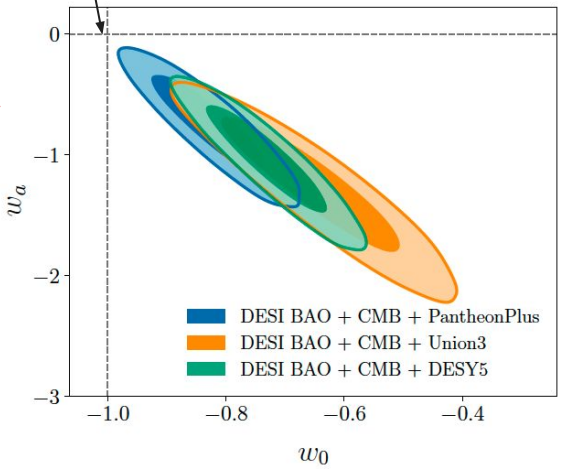
Is DE evolving with time?

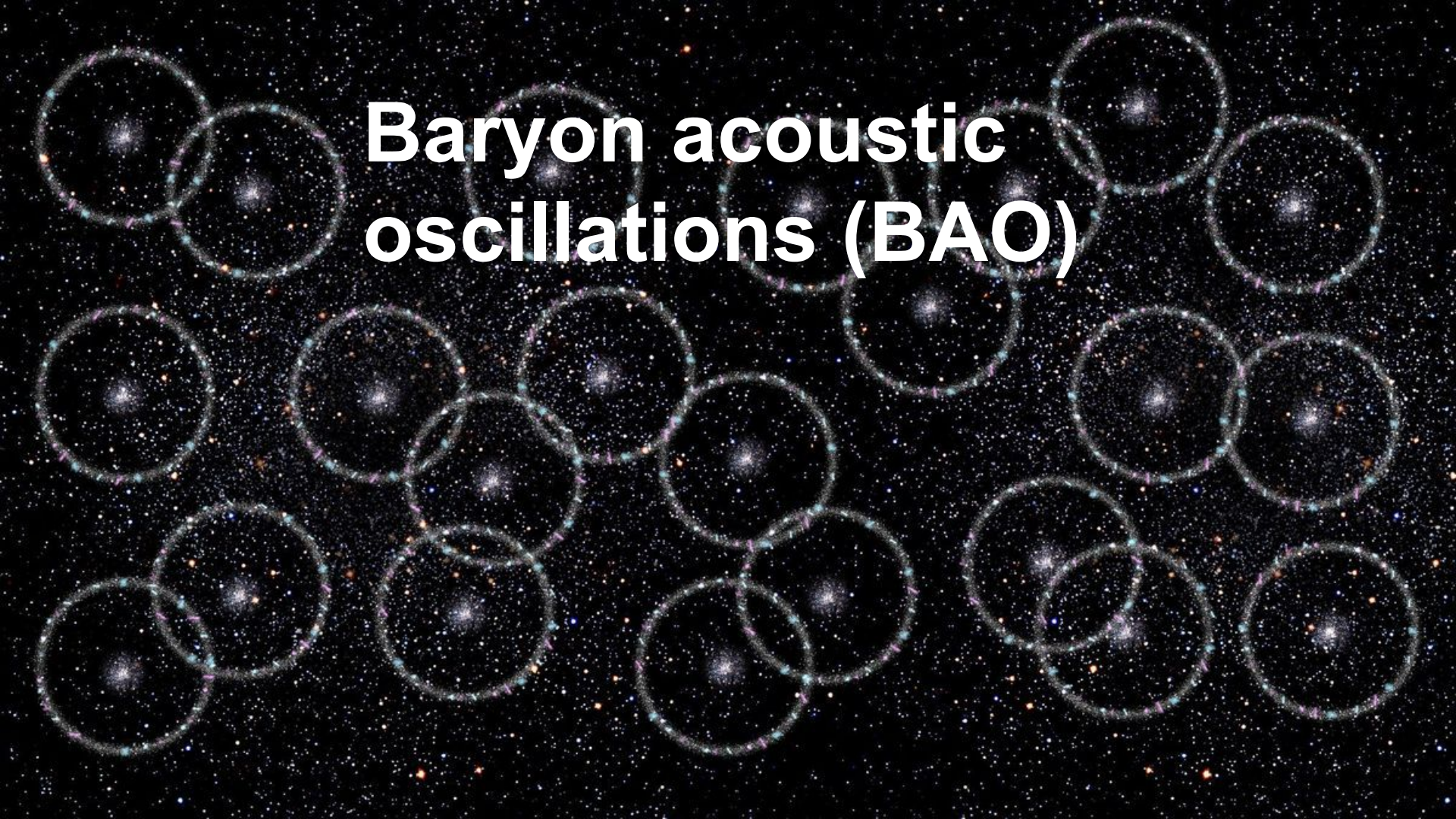
$$w(a) = w_0 + w_a(1-a)$$

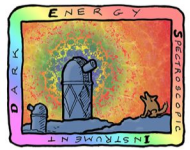
- January 2024: **DES-Y5-SN**:
  ~2σ preference for w_0w_aCDM.
- April 2024: **DESI-DR1-BAO**:
  ~3.9σ preference for w_0w_aCDM when combined with CMB + DES SN.
- March 2025: **DESI-DR2-BAO**
  (this presentation).



ΛCDM




Baryon acoustic
oscillations (BAO)



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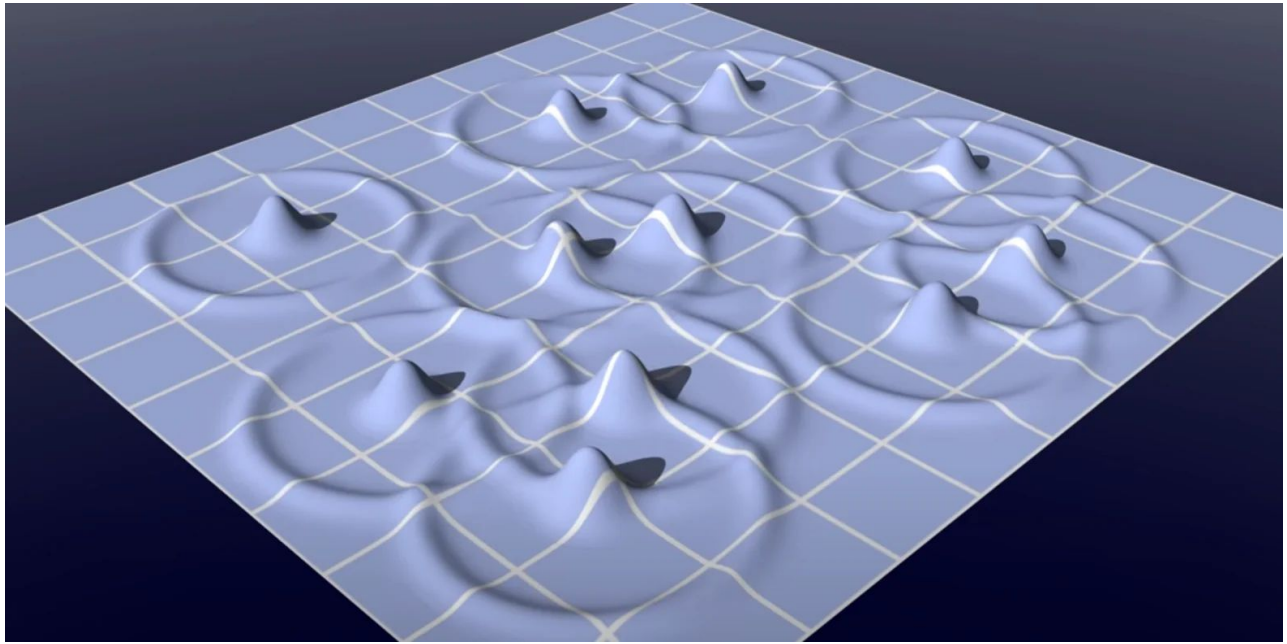
Baryon Acoustic Oscillations (BAO)



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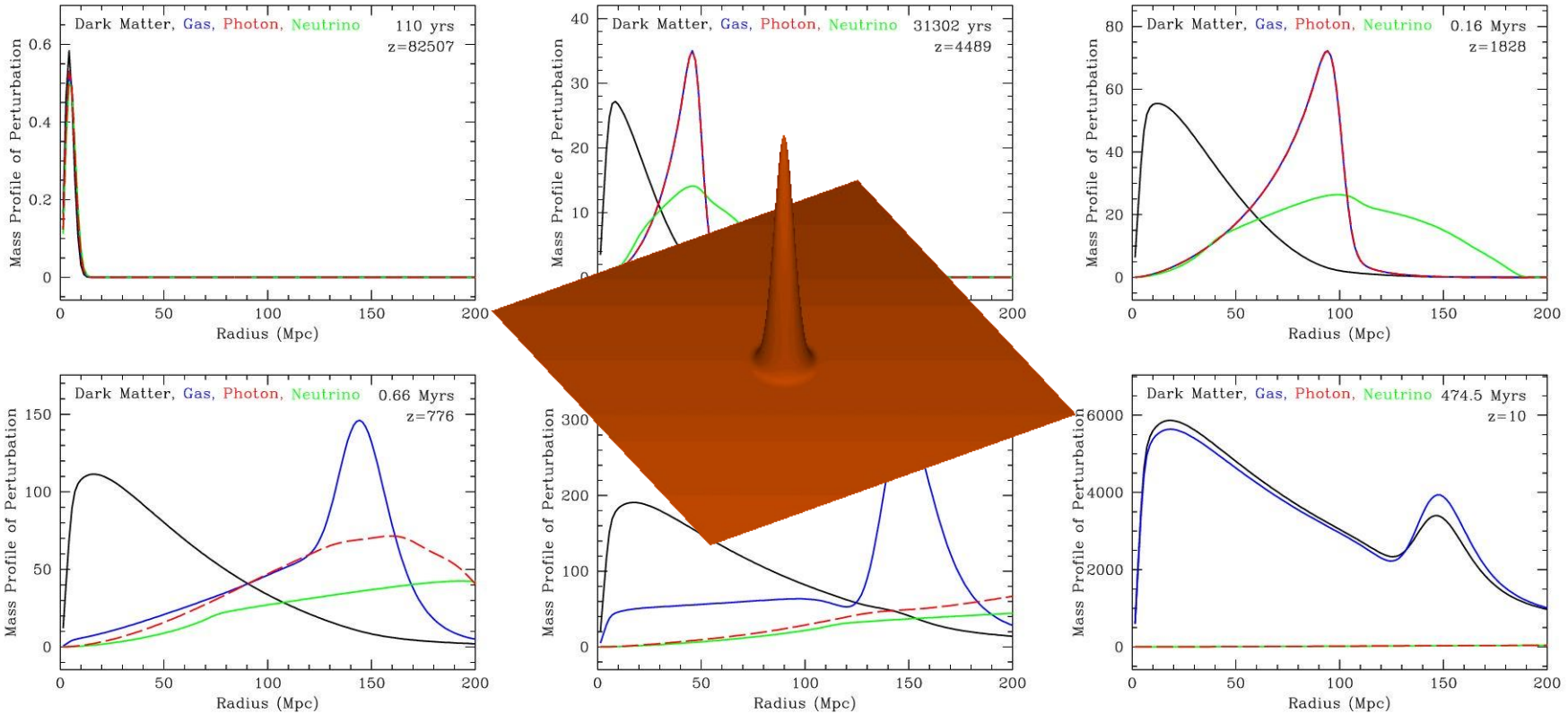
Baryon Acoustic Oscillations (BAO)



Sound horizon scale at recombination (r_d~150 Mpc)

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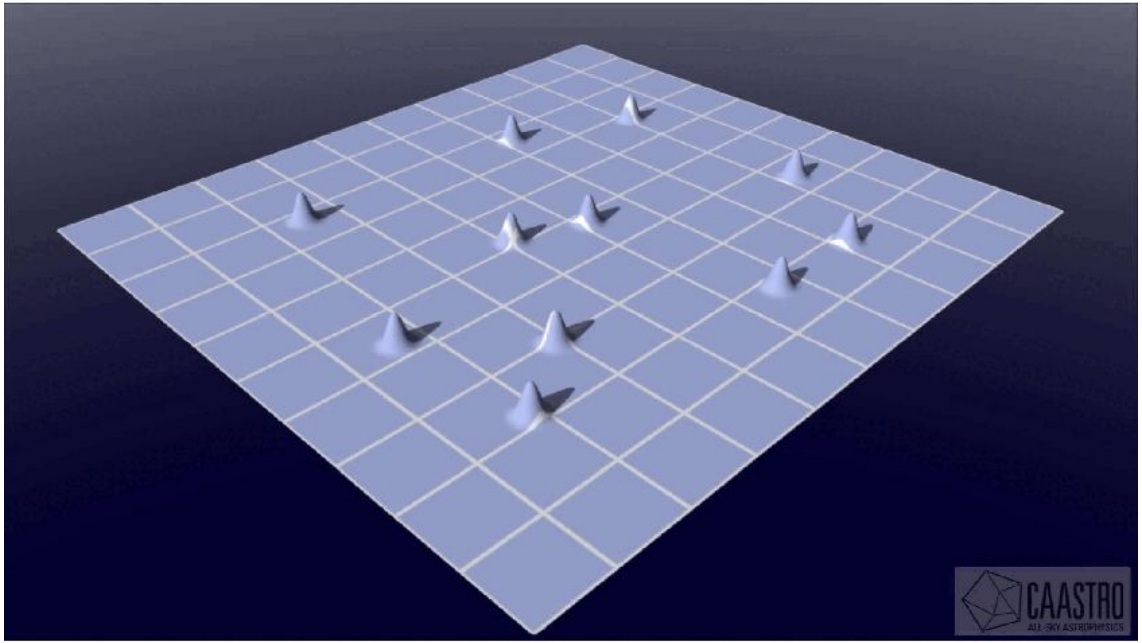
Baryon Acoustic Oscillations (BAO)



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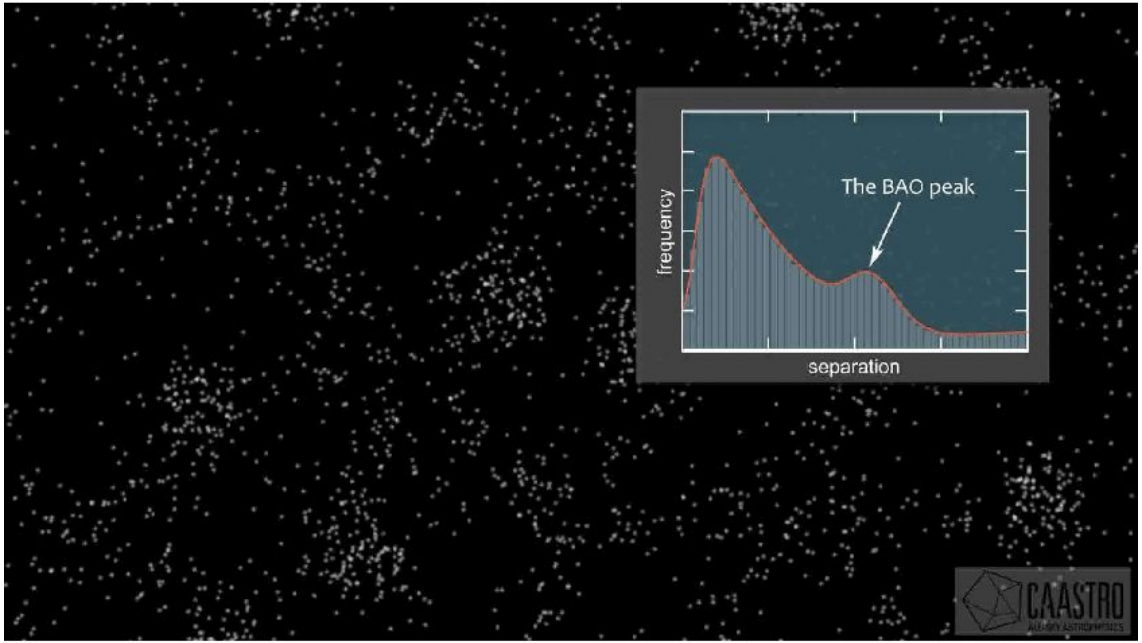
Baryon Acoustic Oscillations (BAO)



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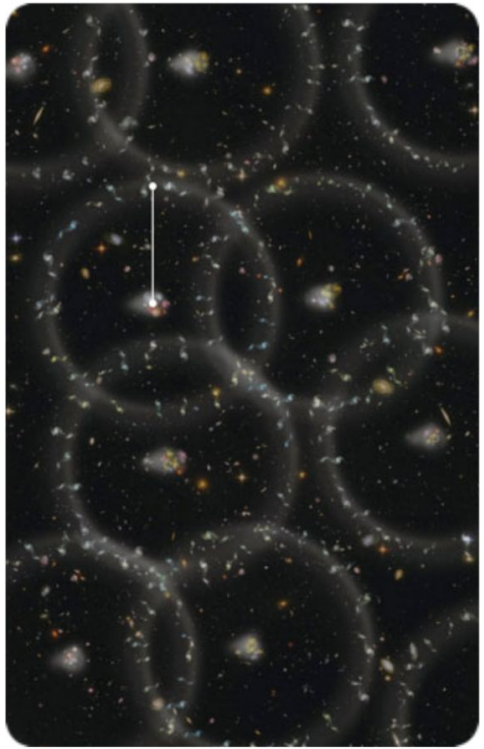
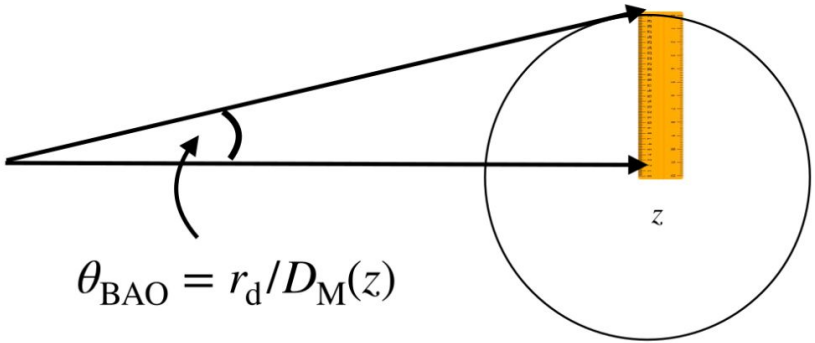
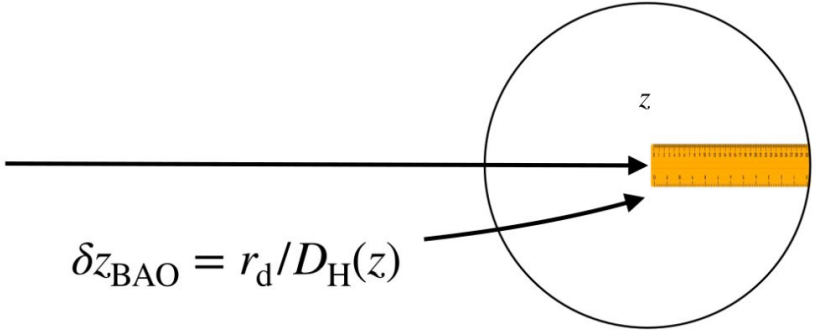
Standard ruler to measure distances





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

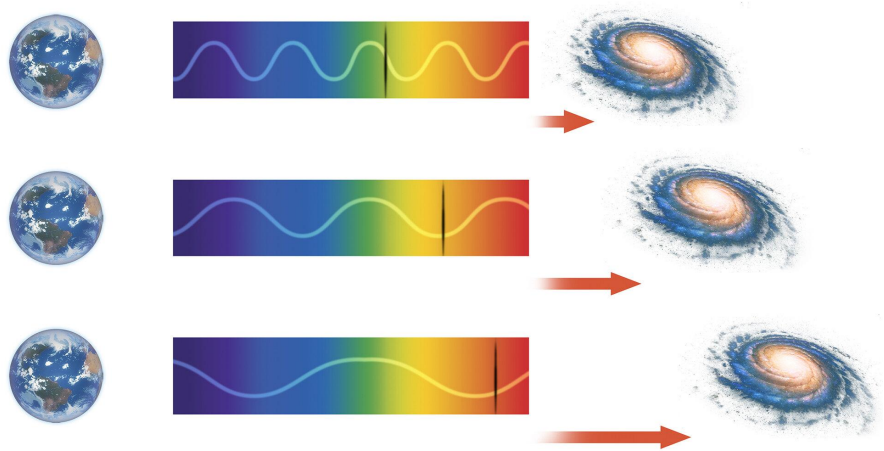


$$\delta z_{\mathrm{BAO}} = r_{\mathrm{d}}/D_{\mathrm{H}}(z)$$

The Dark Energy Spectroscopic Instrument (DESI)

Dark Energy Spectroscopic Instrument

- DESI is a spectroscopic galaxy redshift survey: it measures the **redshift** from the spectra of galaxies.



$$1 + z_{\rm obs} = (1 + z_{\rm cos})(1 + z_{\rm pec})$$

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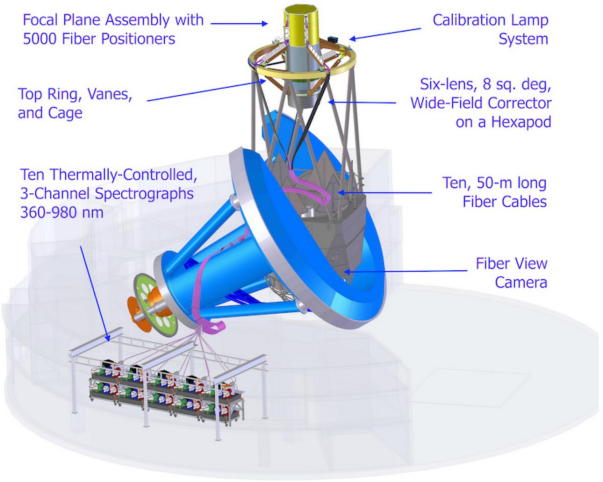
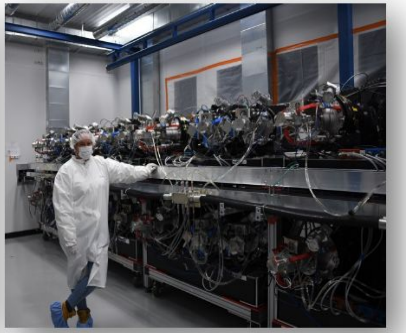
Dark Energy Spectroscopic Instrument



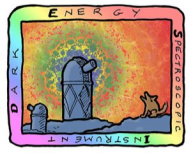
Wide Field Corrector

Focal Plane with 5,000 Fiber Positioners



10 Multi-Object Spectrographs

- Mayall 4m telescope at Kitt Peak National Observatory (Arizona, US).
- Each fiber positioner controls an optical fiber that extends to the spectrographs.
- Spectral range: (360, 980) nm.



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Dark Energy Spectroscopic Instrument

Five target classes

40 million redshifts

in 5 years

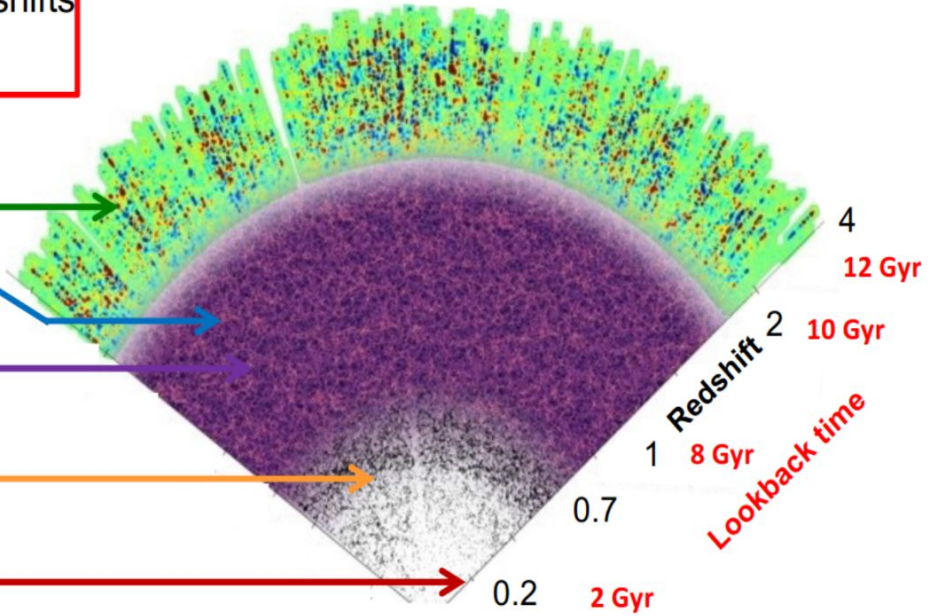
DESI (2021-2026)

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



This talk: analysis of the **first 3 years** of data (2021-2024).

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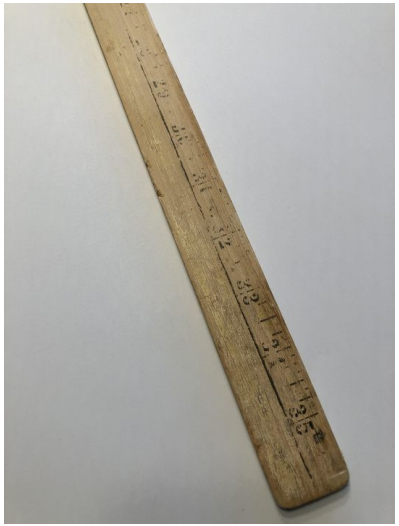
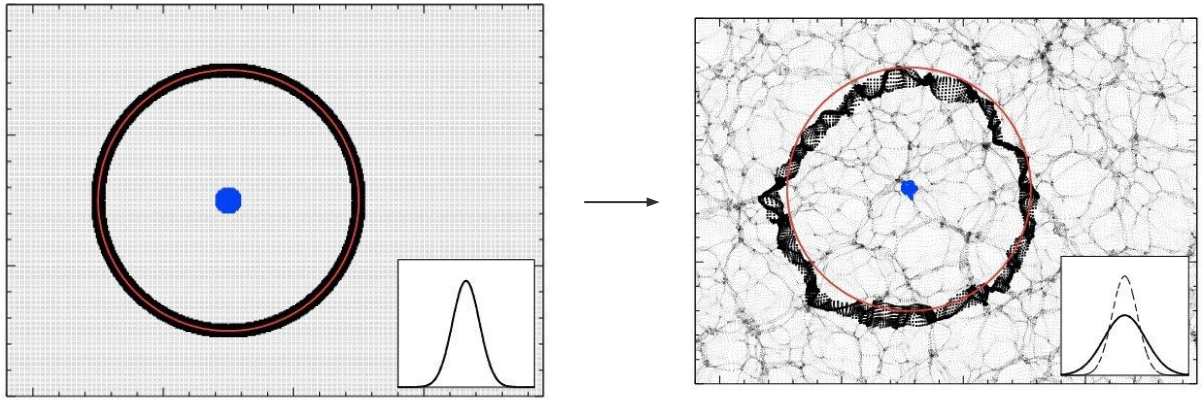
Nonlinear evolution of the standard ruler



The ruler gets blurred and shrinks during the **structure growth** and also due to the distortions by **peculiar velocities**.

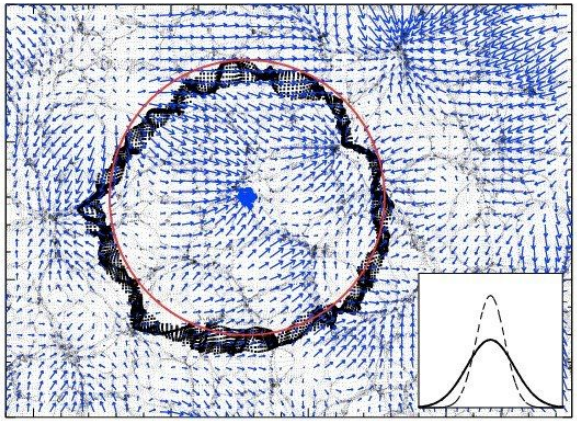


Padmanabhan et al. 2012

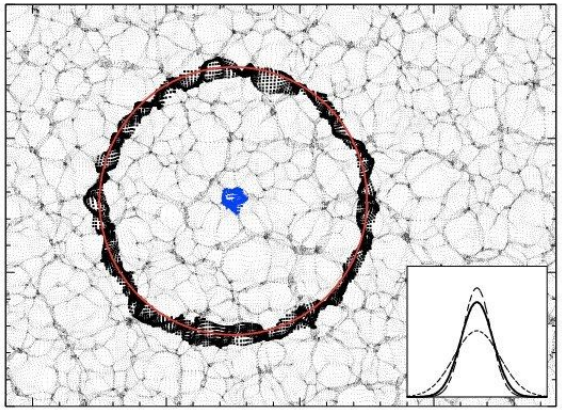
This degrades the accuracy and precision of the standard ruler test…

Density-field reconstruction

Refurbishes the ruler!



Reconstruction



We estimate the displacement field applying the continuity equation on the observed field and reverse it

Improves both precision and accuracy!

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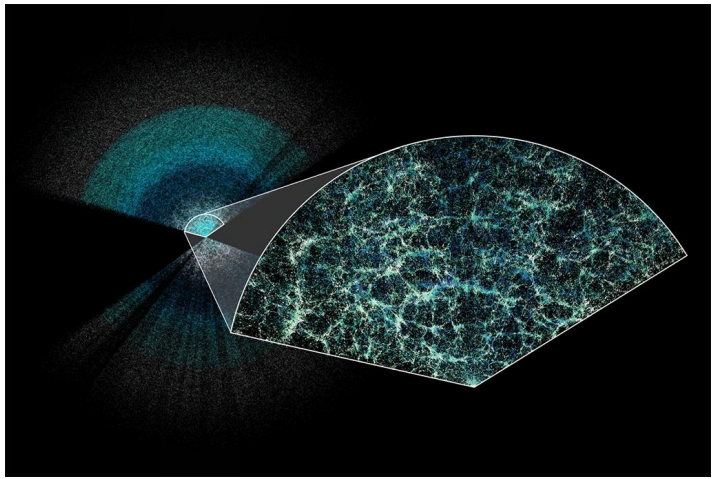
Blind analysis

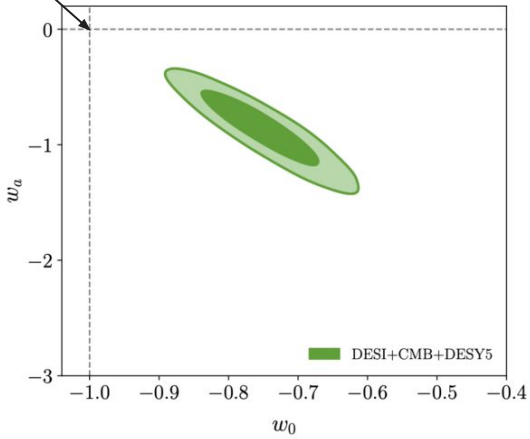
Galaxy catalogs (RA, Dec, z)



Scientific pipeline

ΛCDM

Cosmo. parameters



We get an **unexpected result**: a new systematic? Issue with the baseline pipeline settings?

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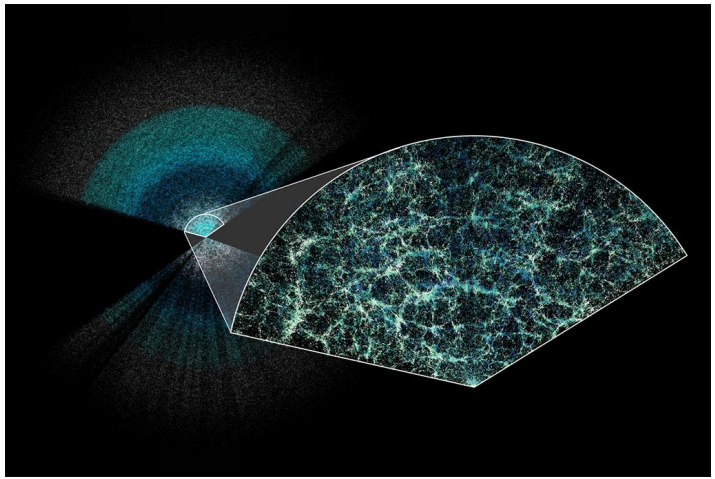
Blind analysis

Galaxy catalogs (RA, Dec, z)

Blinded catalogs
(z → z')



Scientific pipeline

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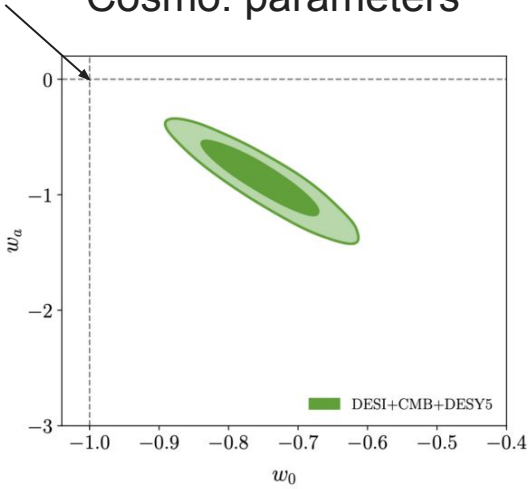
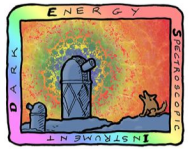


Goal: mitigate confirmation bias by concealing information (in our case, the redshift).



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When do we unblind?

- The base pipeline methods need to be determined (tests on simulations).
- The upper limit of the systematics needs to be set.
- Pre-unblinding tests need to be passed.
- Pre-define what is allowed to change after unblinding.

The DESI DR2 analysis

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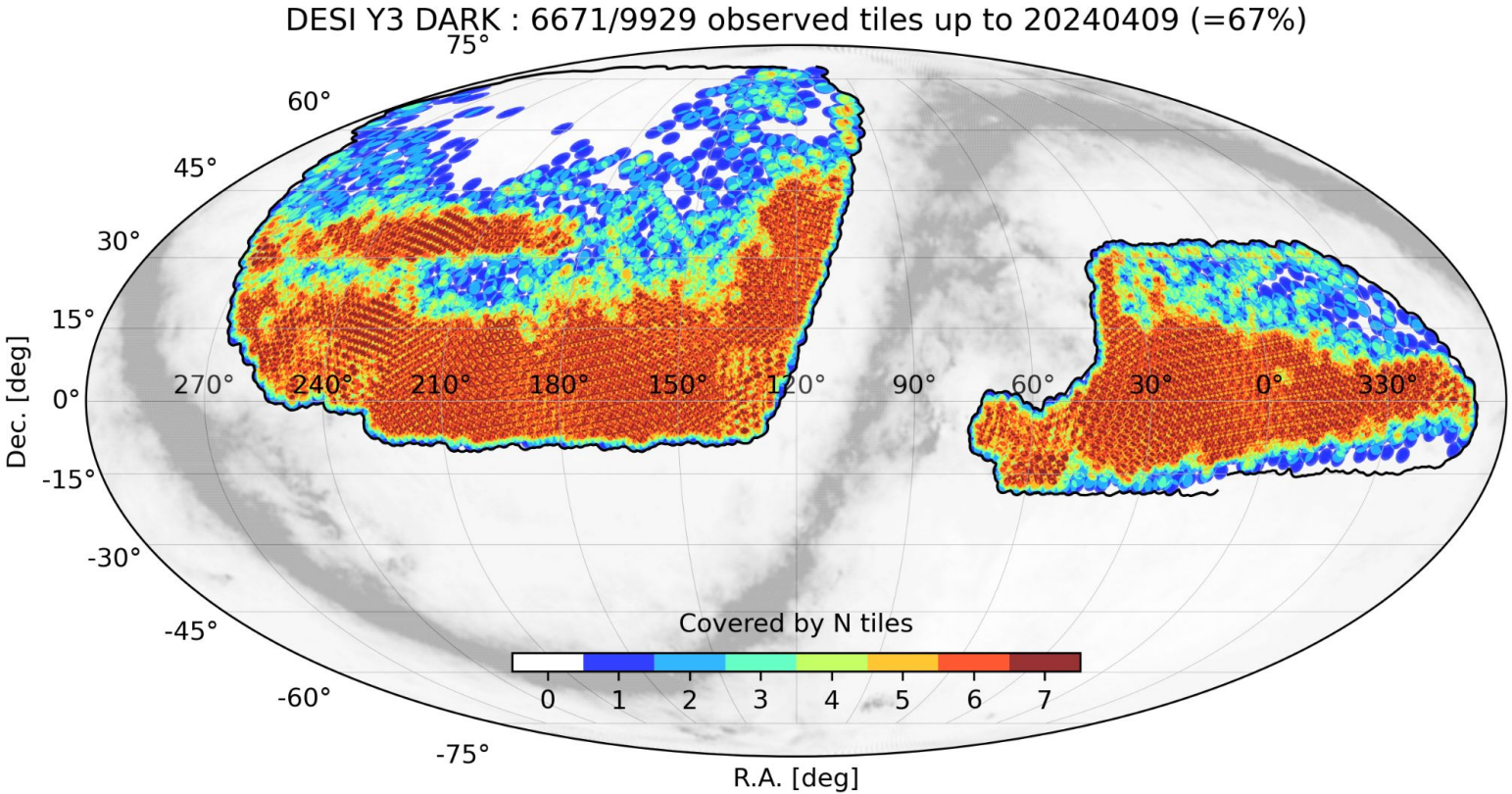
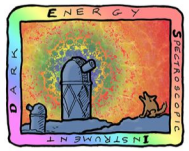
DESI Data Release 2 footprint





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DESI DR2 galaxy and quasar BAO at z < 2.1

- 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**

The DESI DR1 data (~6M redshifts) is **already public**!

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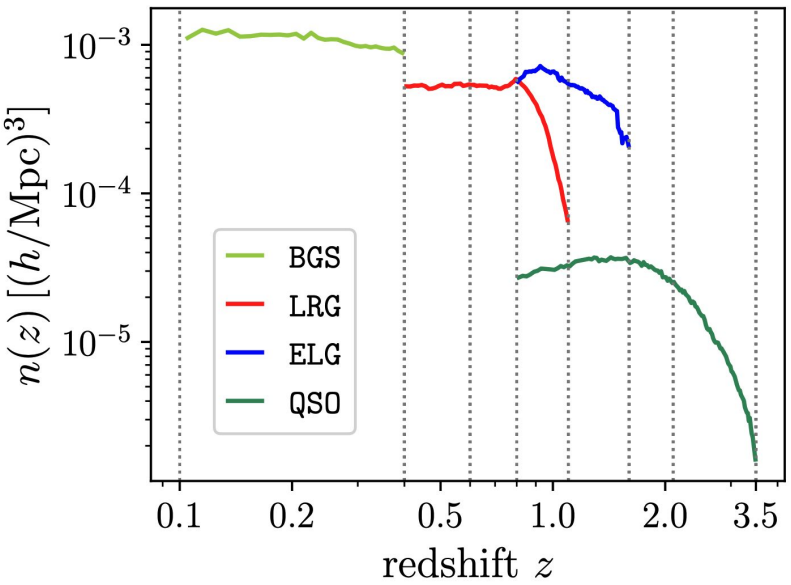
DESI DR2 galaxy and quasar BAO at z < 2.1



- Four different large-scale tracers.
- **14 million** unique redshifts with the effective cosmic volume of **42 Gpc^3**.
- Split into **six redshift bins** to probe the expansion history as a function of lookback time.

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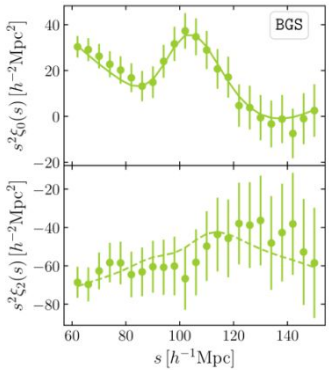
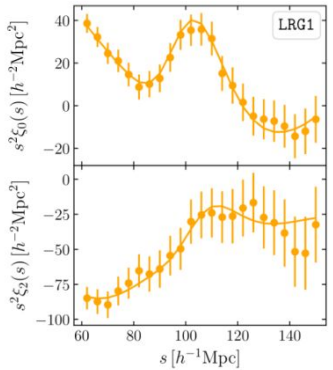
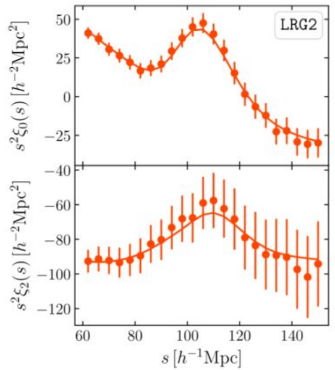
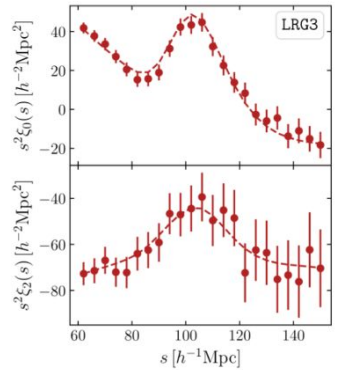
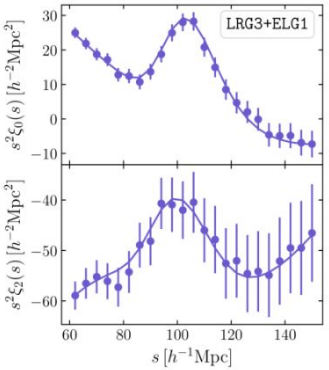
DESI DR2 clustering measurements

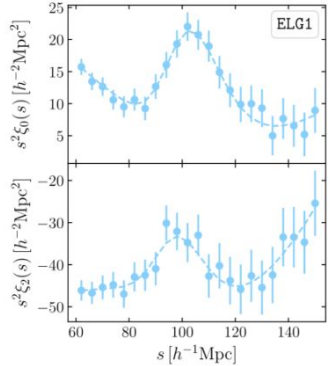


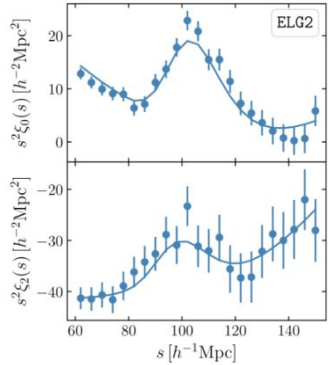


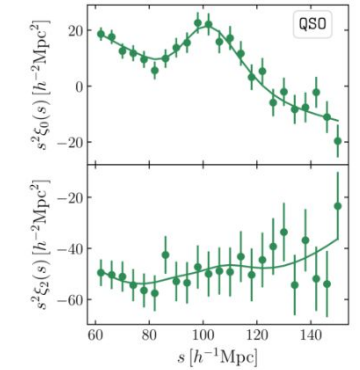


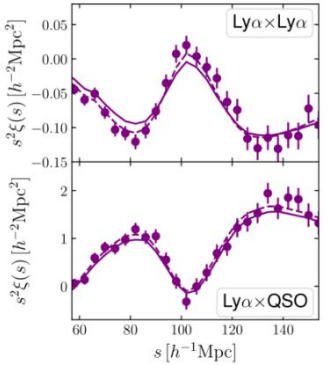












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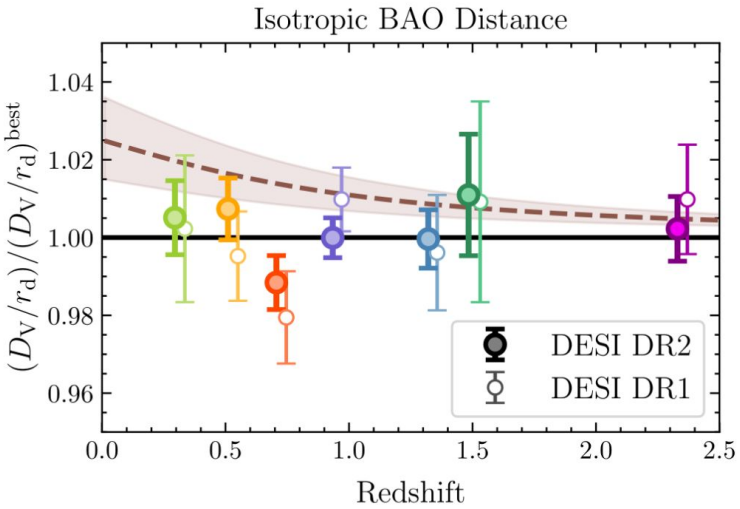
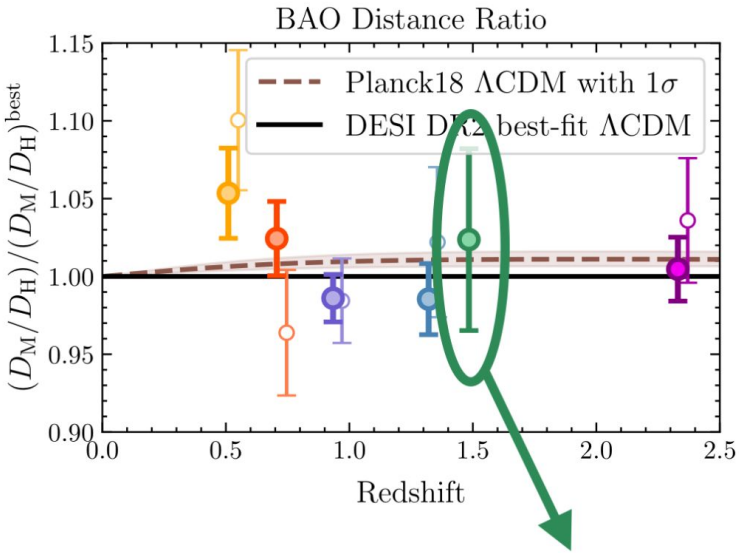
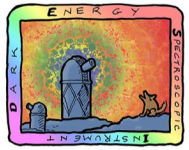
DESI DR2 BAO distance measurements





New QSO distance ratio measurement

Main results
I. Constraints under ΛCDM



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Parameters to keep in mind

- H_0: Hubble constant. Present-day rate of expansion of the Universe.
- Ω_m: total matter density parameter.
- r_d: sound horizon scale (~150 Mpc).

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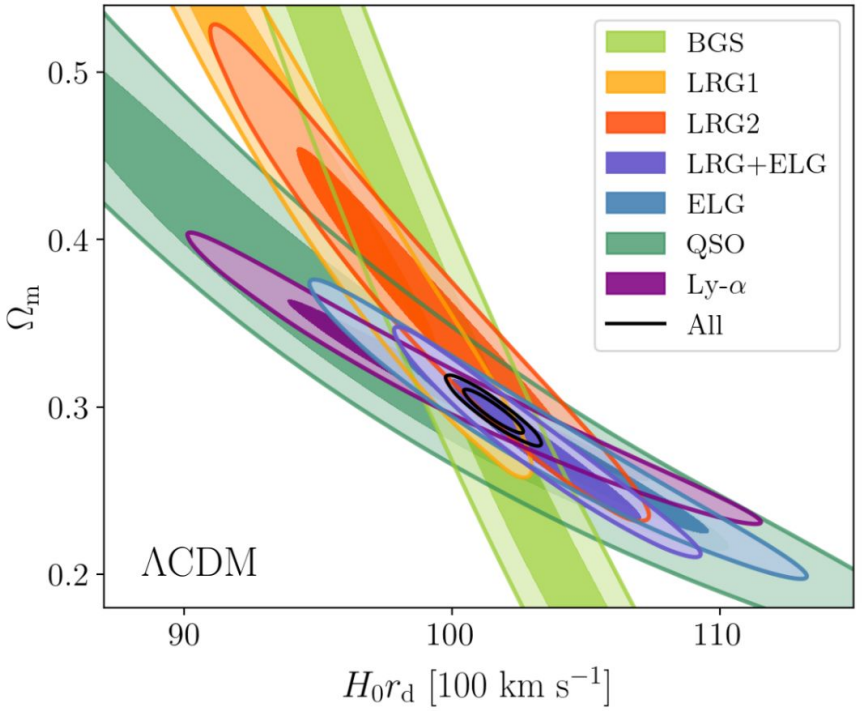
Constraints under ΛCDM

- 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.



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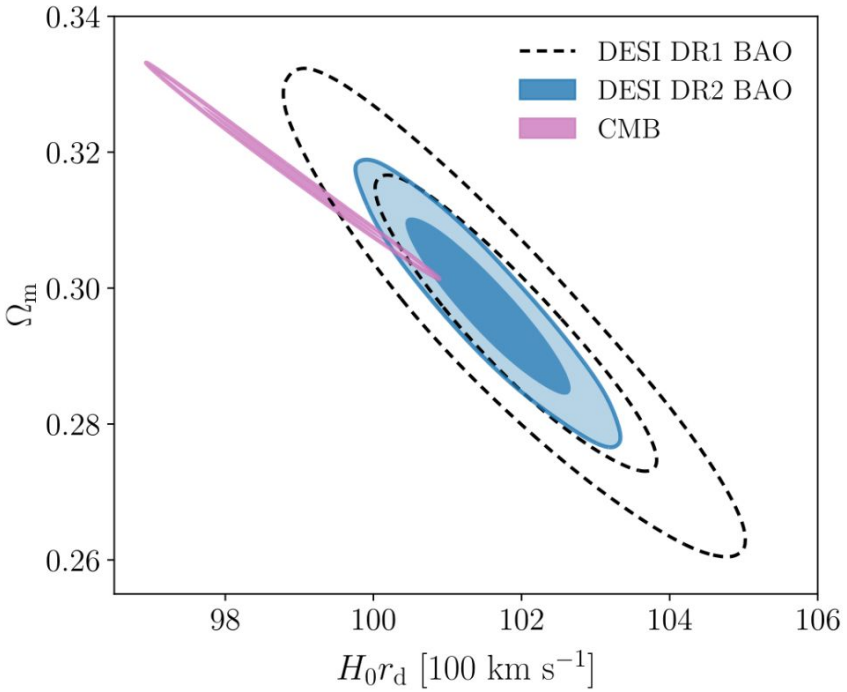
Constraints under ΛCDM



- 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

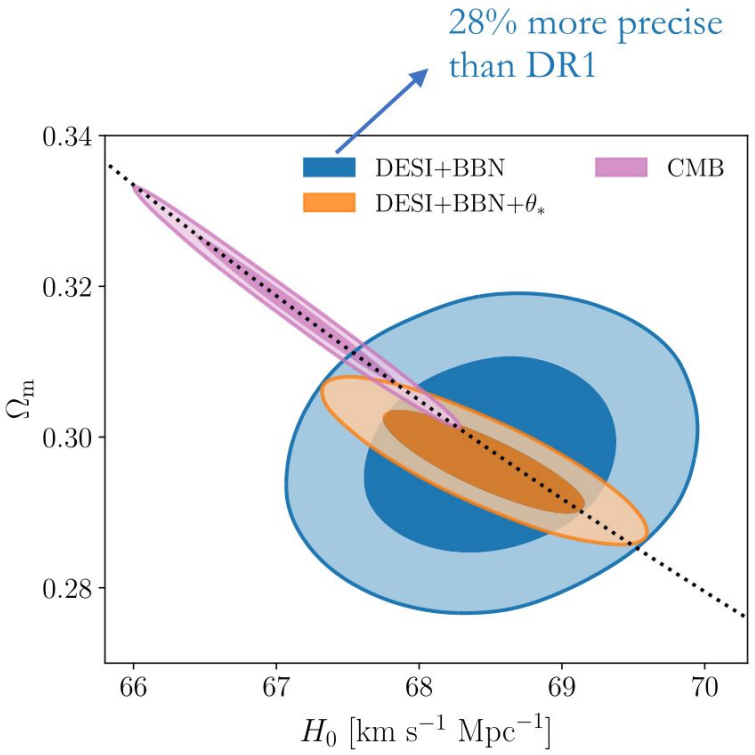
Constraints under ΛCDM

- 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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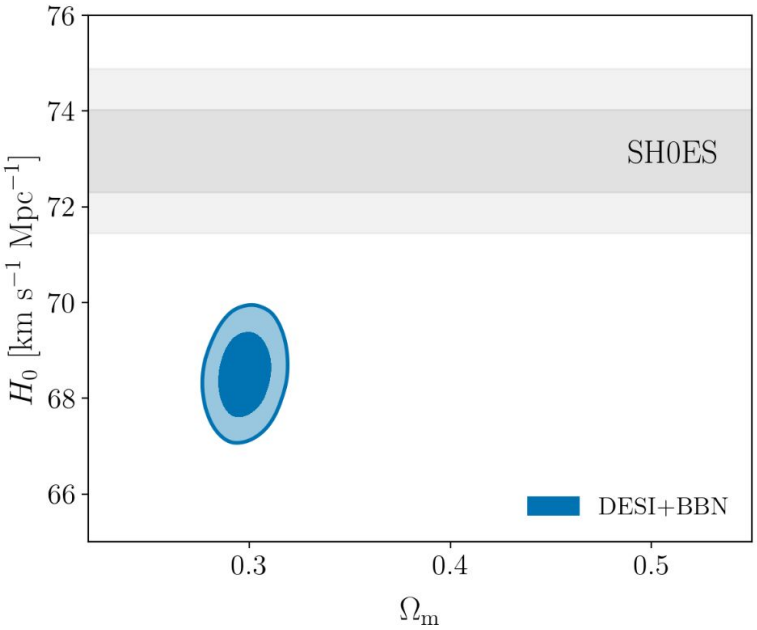
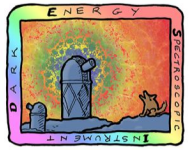
The Hubble tension

Hubble tension: significant discrepancy between the value of the **Hubble constant** measured from the **early universe** and the **local universe**.



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

Main results
II. Dark energy beyond ΛCDM



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Parameters to keep in mind

- Present value (w_0) and time evolution (w_a) of the DE equation of state:

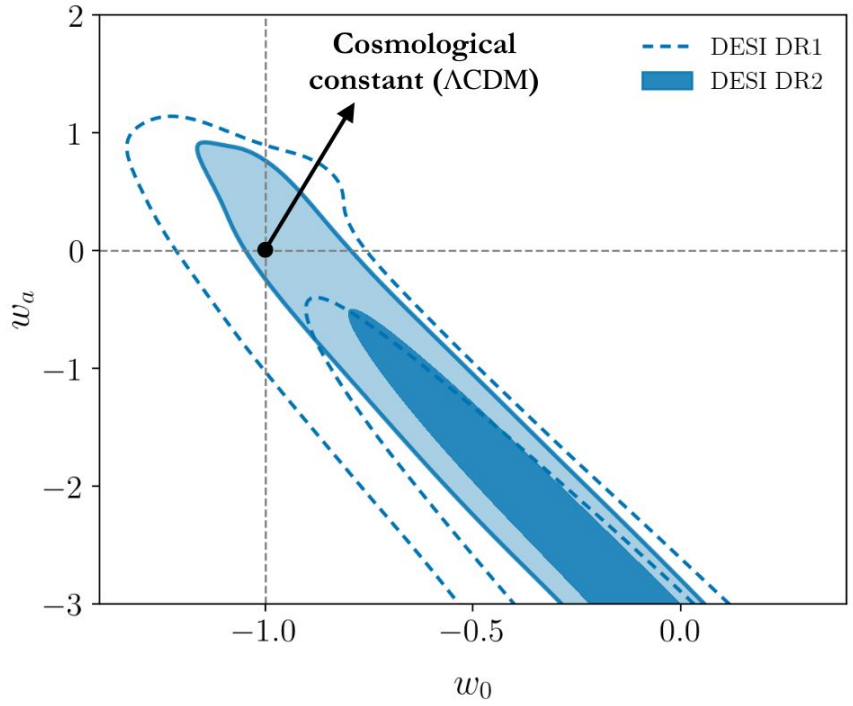
$$w(a) = w_0 + w_a(1 - a)$$

Dynamical dark energy

$$p = w\rho$$

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

- 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.



Dynamical dark energy

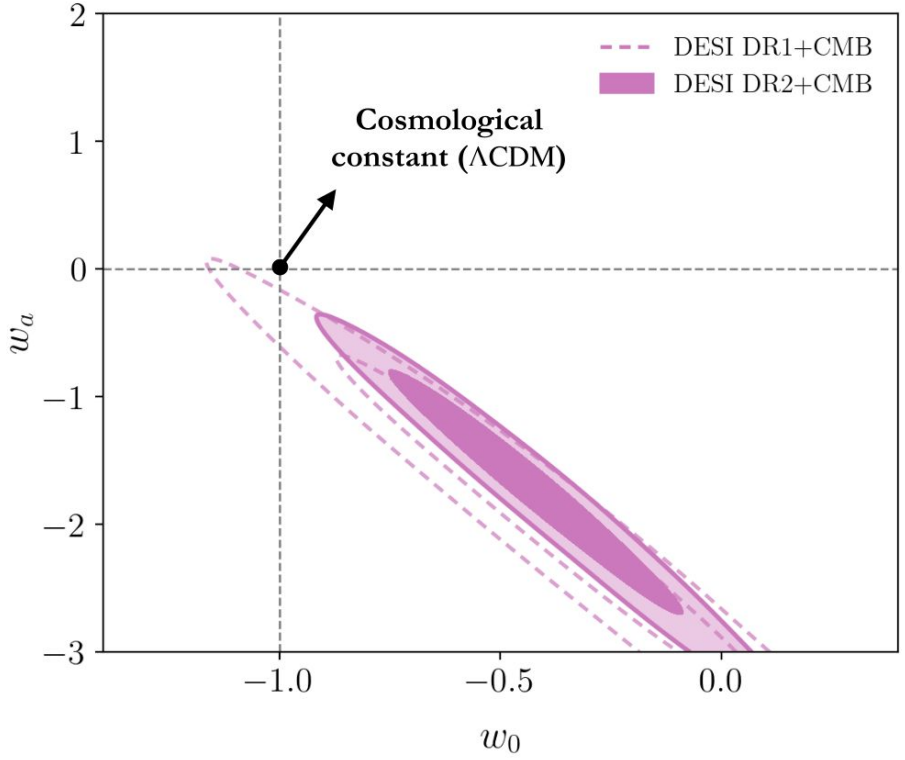
$$p = w\rho$$

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

- 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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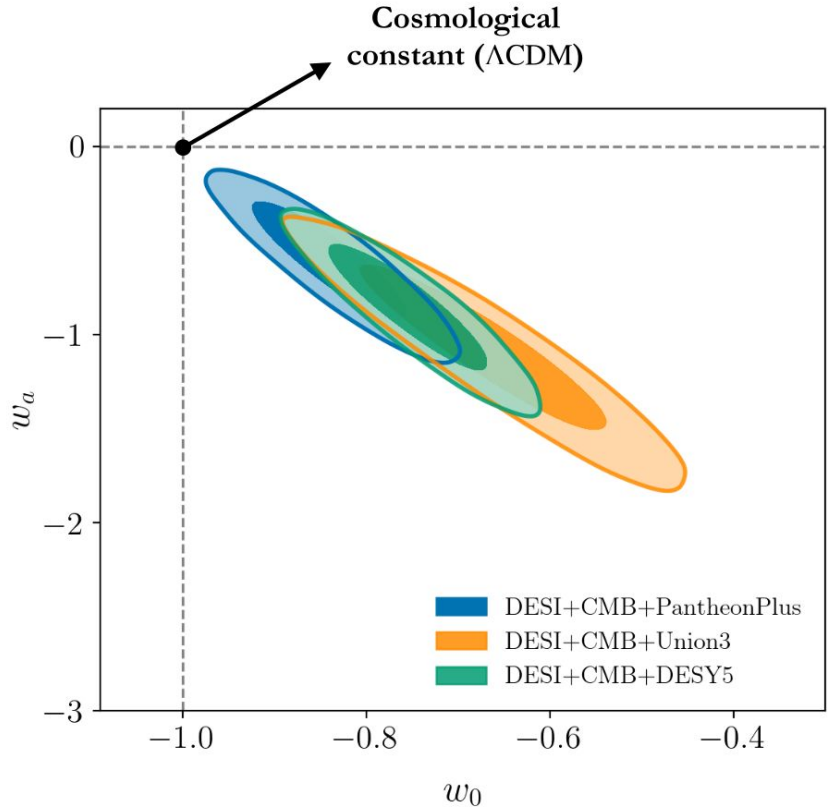
Dynamical dark energy

$$p = w\rho$$

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

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



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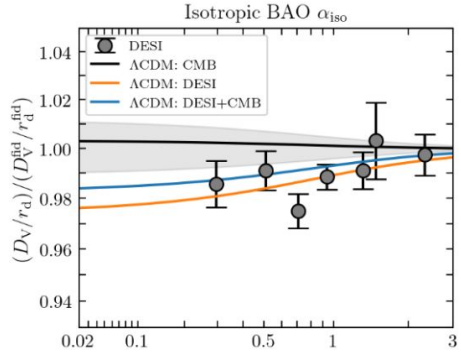
Dynamical dark energy

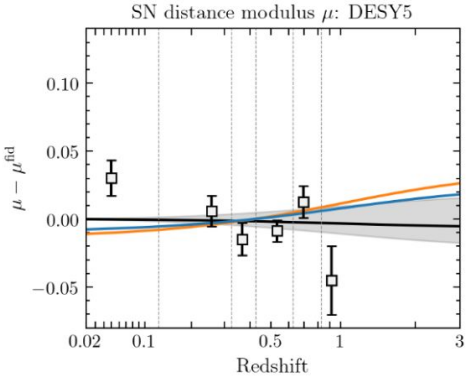
$$p = w\rho$$

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

Isotropic BAO distance measurement



Supernovae distance modulus

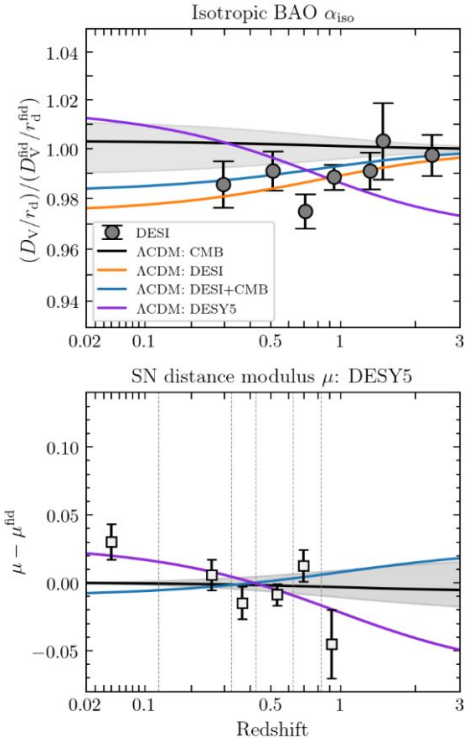


- There are ΛCDM models that each dataset prefer, but they are inconsistent in their Ω_m values.

Dynamical dark energy

$$p = w\rho$$

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

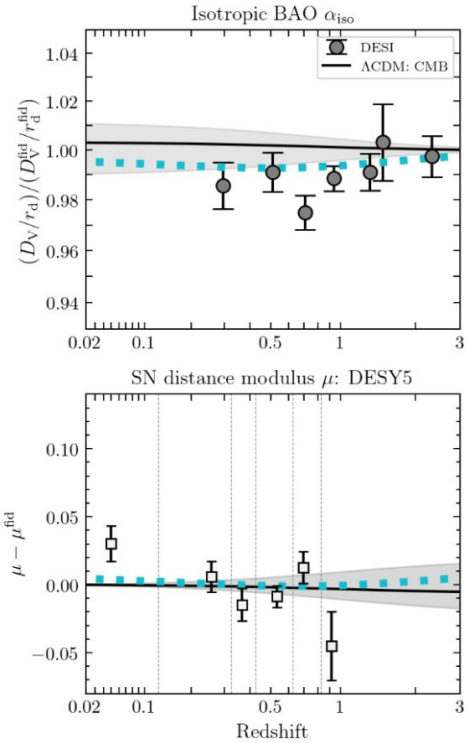


- There are ΛCDM models that each dataset prefer, but they are inconsistent in their $\Omega_{\rm m}$ values.
- ΛCDM does not provide a good fit to all data simultaneously.

Dynamical dark energy

$$p = w\rho$$

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

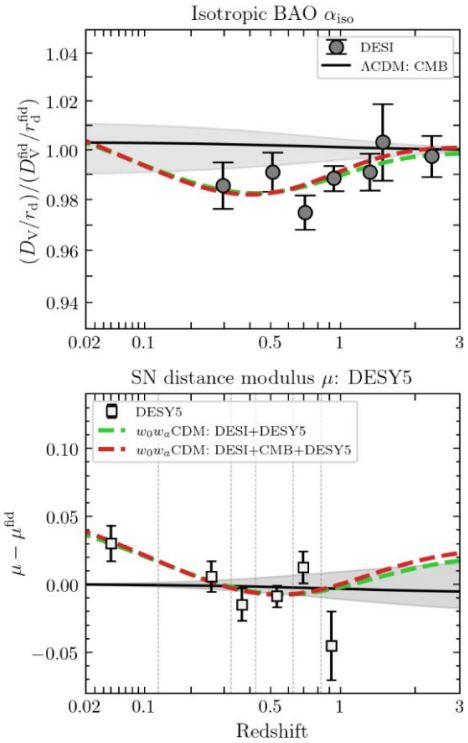


- wCDM model: constant equation of state $P/(\rho c^2)$, but not necessarily equal to -1.
- wCDM does not have enough freedom in the expansion history to fit BAO, CMB, and SNe simultaneously.

Dynamical dark energy

$$p = w\rho$$

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



- 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.

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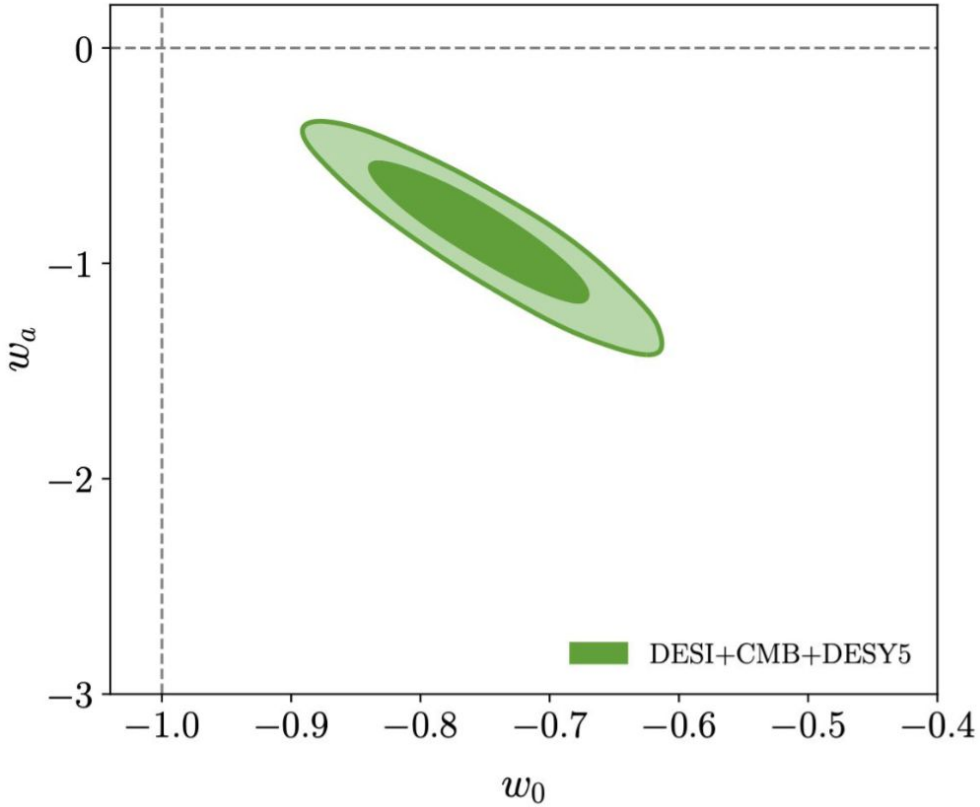
Implications for dark energy

$$p = w\rho$$
$$w(a) = w_0 + w_a(1-a)$$

- Our baseline result is in **4.2σ tension with ΛCDM**.
- Our results suggest a preference for

$$w_0 > -1, \quad w_a < 0$$



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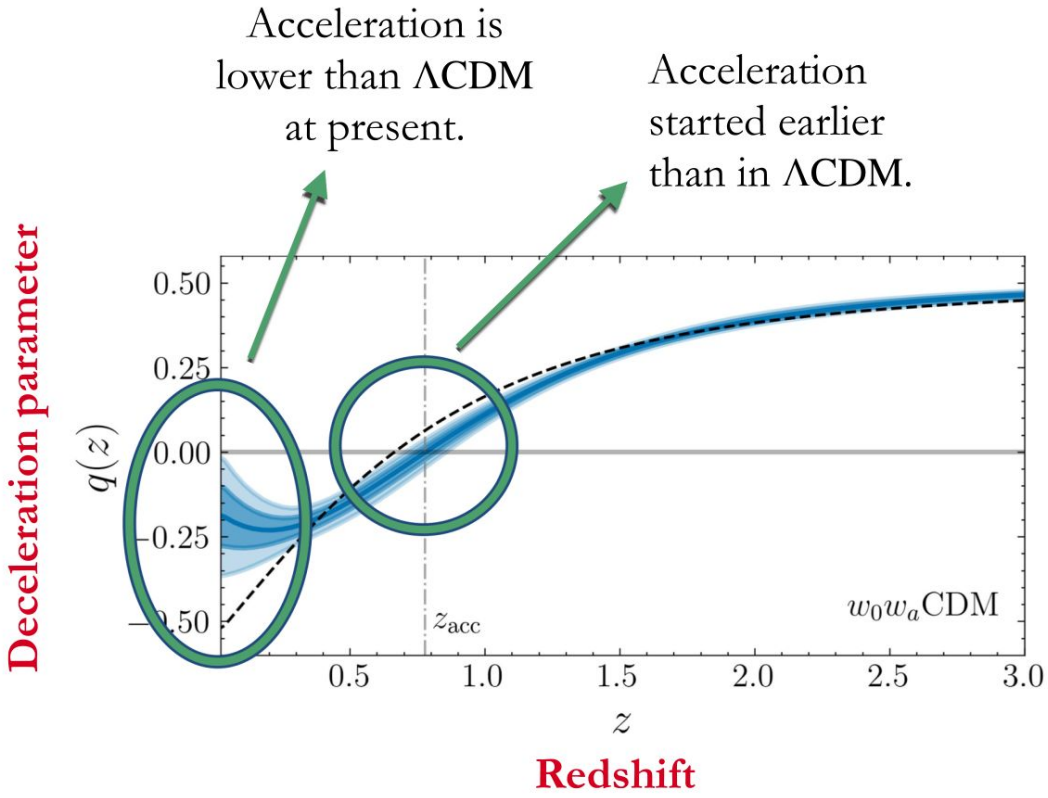
Implications: is the accelerated expansion getting weaker?

$$p = w\rho$$

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



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Implications: phantom dark energy in the past?

$$p = w\rho$$

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

- Phantom dark energy:

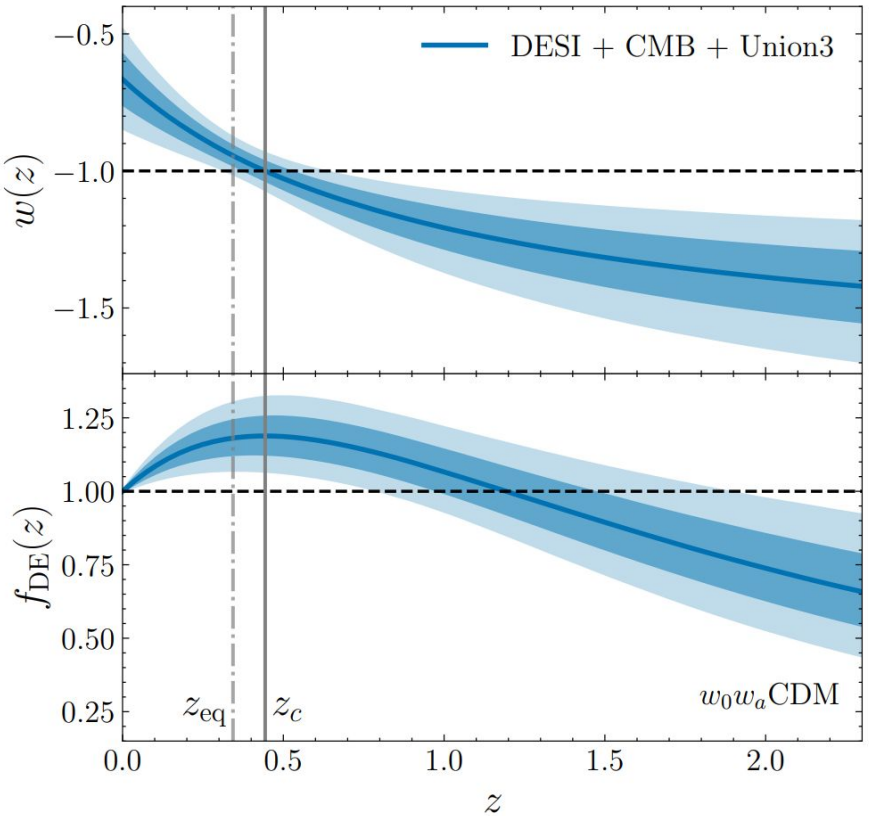
$$w(a) < -1$$

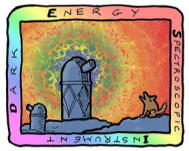
since

$$\dot{\rho} > 0$$

- The phantom crossing presents severe theoretical difficulties for single-scalar field models of DE.

$$f_{\rm DE}(z) = \frac{\rho_{\rm DE}(z)}{\rho_{\rm DE,0}} = \exp\left[3\int_0^z [1+w(z')]\frac{dz'}{1+z'}\right]$$





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Conclusions

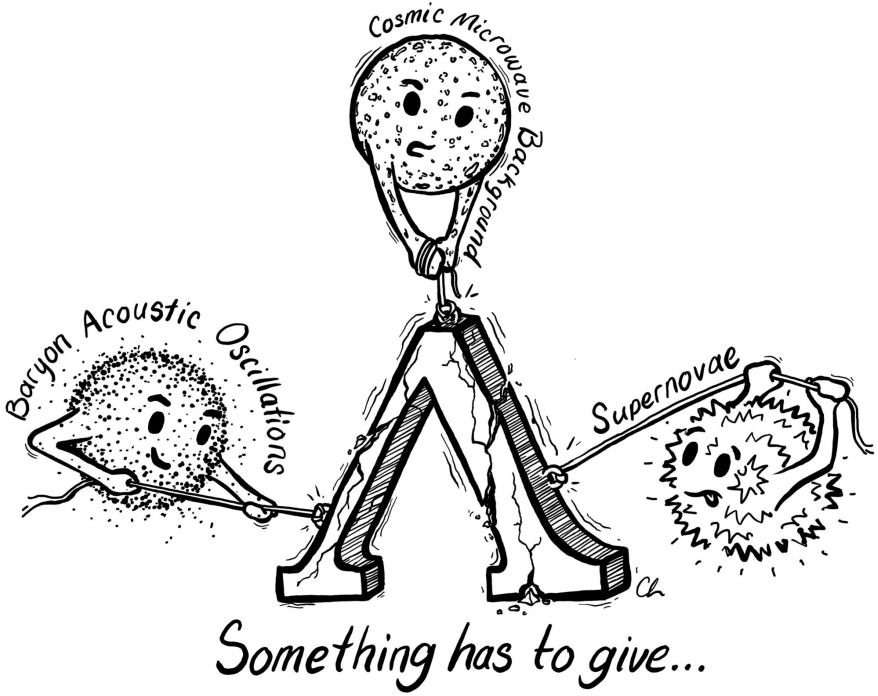
- Discrepant results within ΛCDM between
  - DESI and CMB in the Ω_m- H_0 plane.
  - DESI and SN in Ω_m.

- Growing incompatibility between different datasets when interpreted in the ΛCDM model.

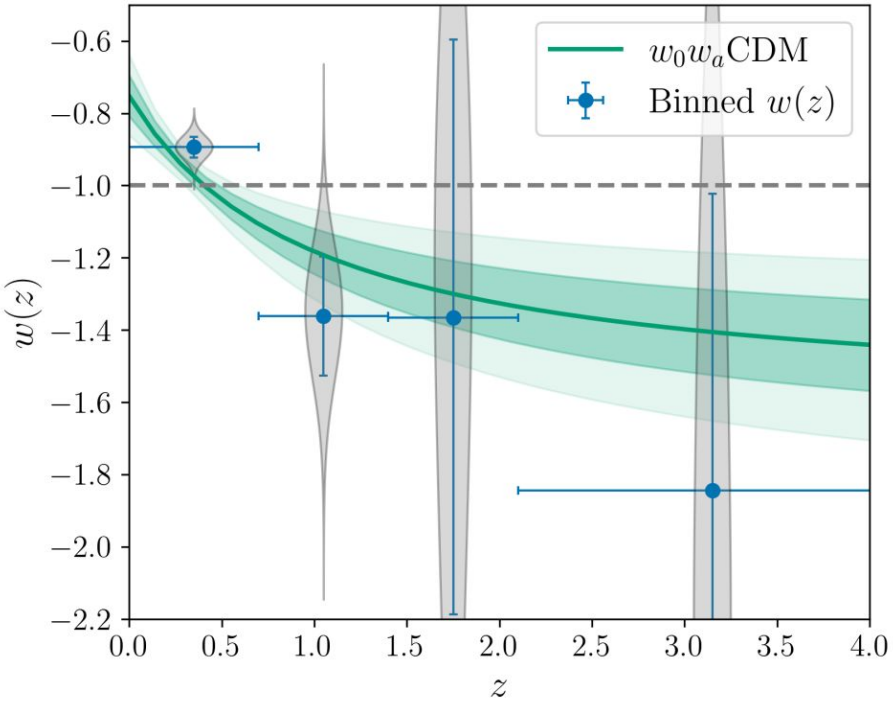
- Our observables are reconciled in w_0w_aCDM.

- Evidence for evolving dark energy using our DESI DR2 BAO data + type Ia SNe + CMB of up to **4.2σ**.

Thanks for your attention!



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.