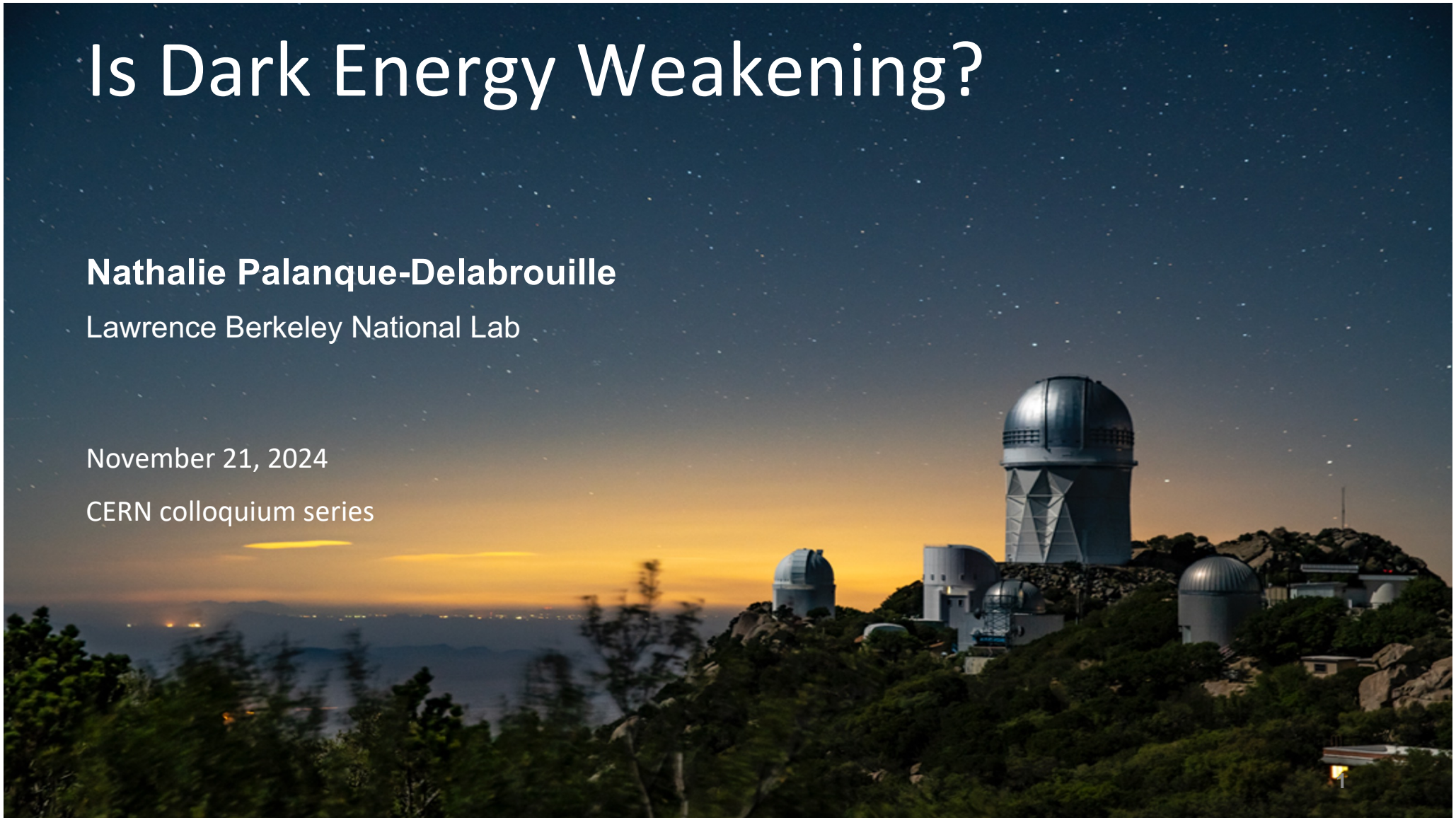
Is Dark Energy Weakening?



Nathalie Palanque-Delabrouille

Lawrence Berkeley National Lab

November 21, 2024

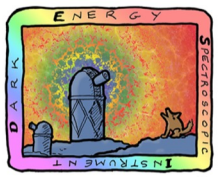
CERN colloquium series

Is Dark Energy Weakening?

Probes of the expanding universe

The Dark Energy Spectroscopic Instrument (DESI)

DESI First-year BAO results



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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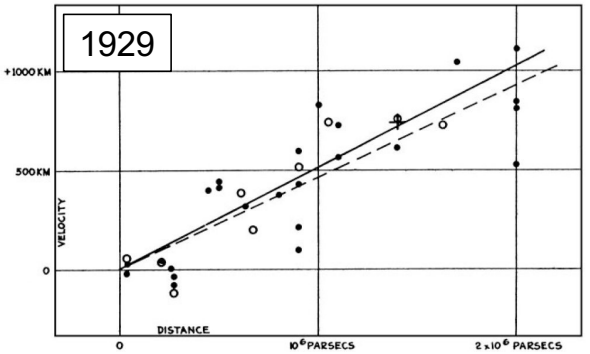
Expanding Universe

Receding galaxies (Hubble & Lemaître, 1929)

Receding velocity increases with distance

→ Expanding universe

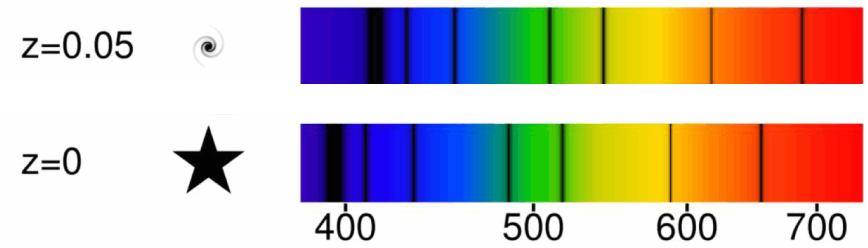
v = H . D



Spectrum

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

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



Photometry

Source of known luminosity

Cepheids: period – luminosity

Type Ia supernovae: Max luminosity known

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

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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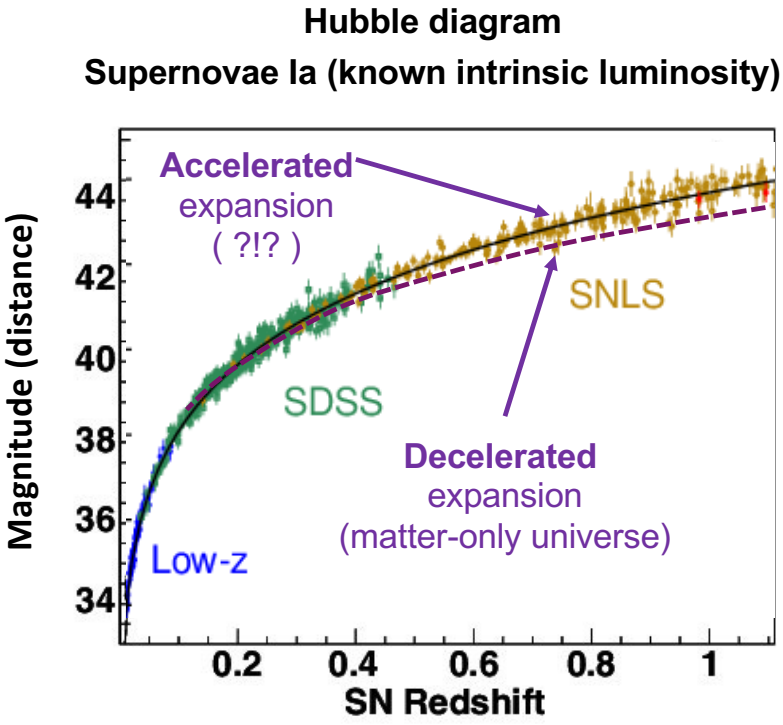
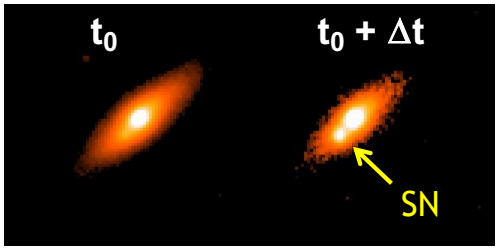
Expanding Universe

2011 Nobel Prize

Perlmutter et al., 1998

Riess et al., 1998





Supernovae Ia
(known intrinsic luminosity)

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

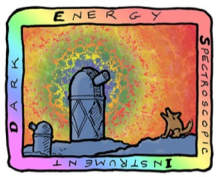
↓

Accelerated expansion

Inconsistent with matter-only universe

↓

DARK ENERGY!



DARK ENERGY SPECTROSCOPIC INSTRUMENT

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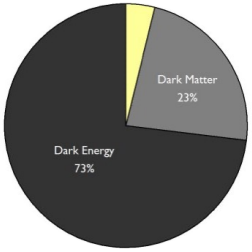
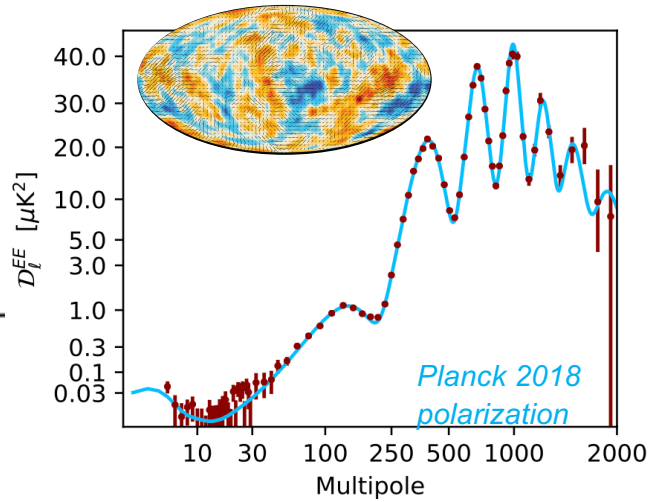
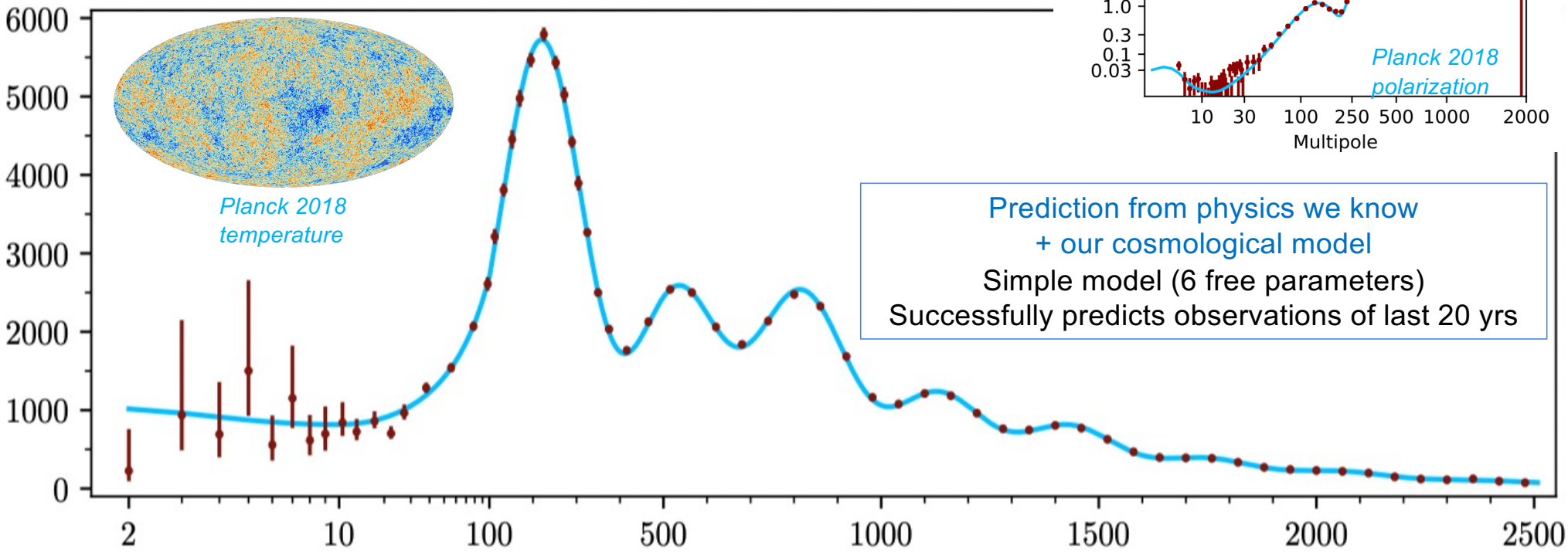
ΛCDM model







Prediction from physics we know
+ our cosmological model

Simple model (6 free parameters)

Successfully predicts observations of last 20 yrs

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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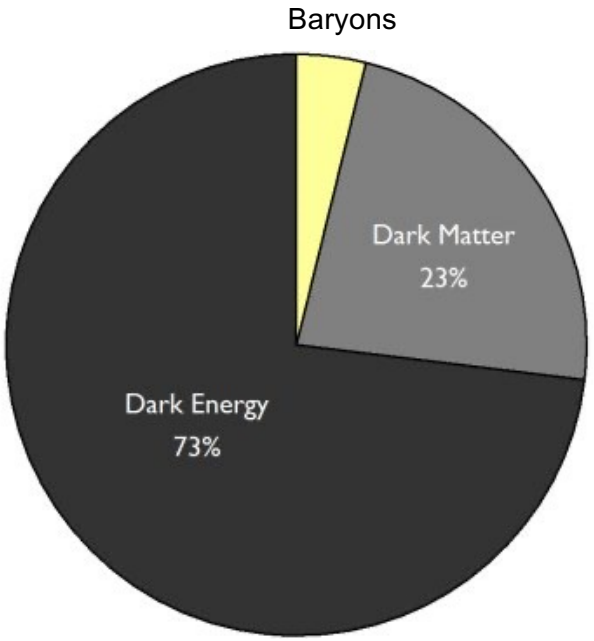
ΛCDM model

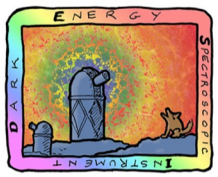


Cosmology model based upon

Two components of unknown nature

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

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



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Dark Energy

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

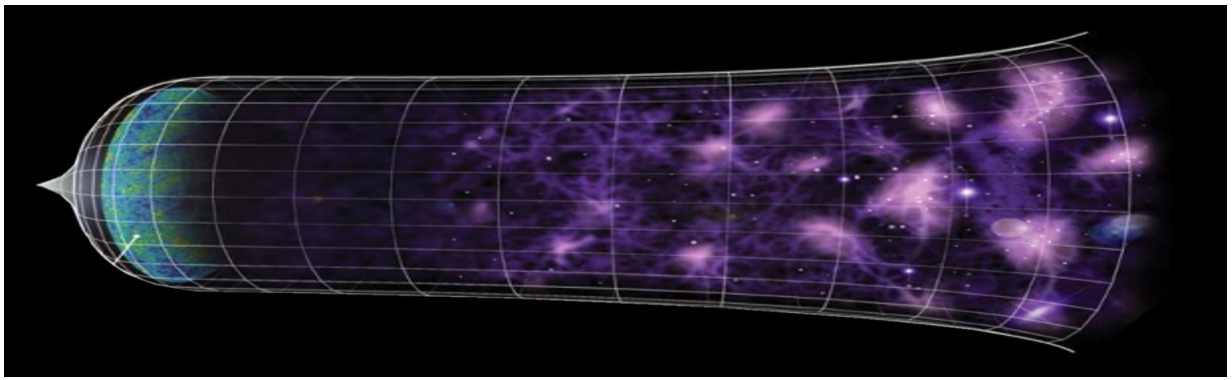
Geometry?
Cosmological constant Λ

Additional fluid (energy content)?

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

Accelerated expansion

Modified gravity?



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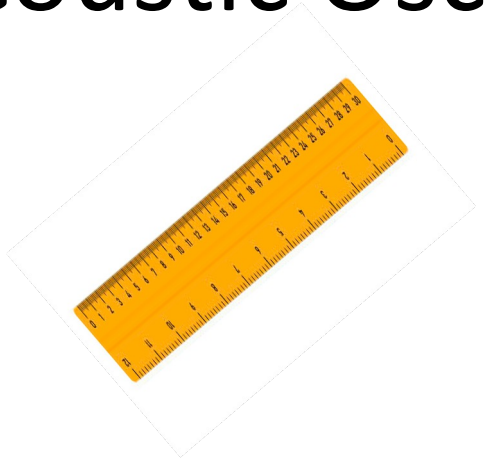
Baryon Acoustic Oscillations



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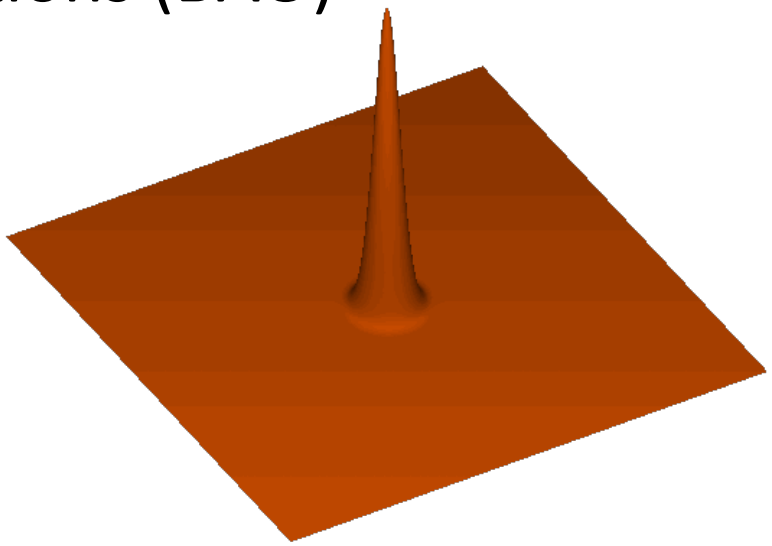
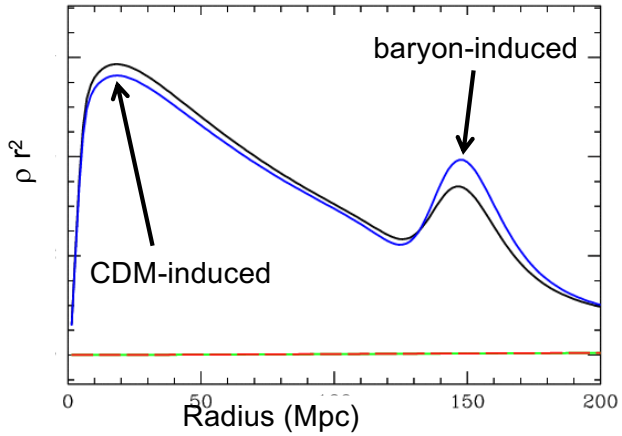
Baryon Acoustic Oscillations (BAO)

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

At recombination (z~1100): p + e- → H

- Plasma evolves from optically thick to optically thin
- Baryons decouple from photons
- Waves freeze



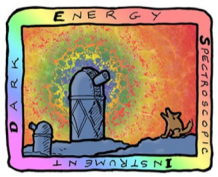


Residual spherical shell ⟶ Peak in clustering of matter

Size of feature = distance sound wave traveled

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

r_s ~ 150 Mpc (today)



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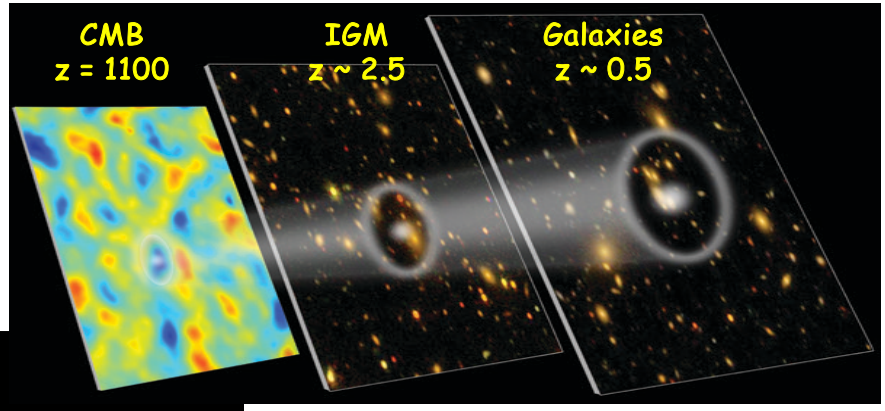
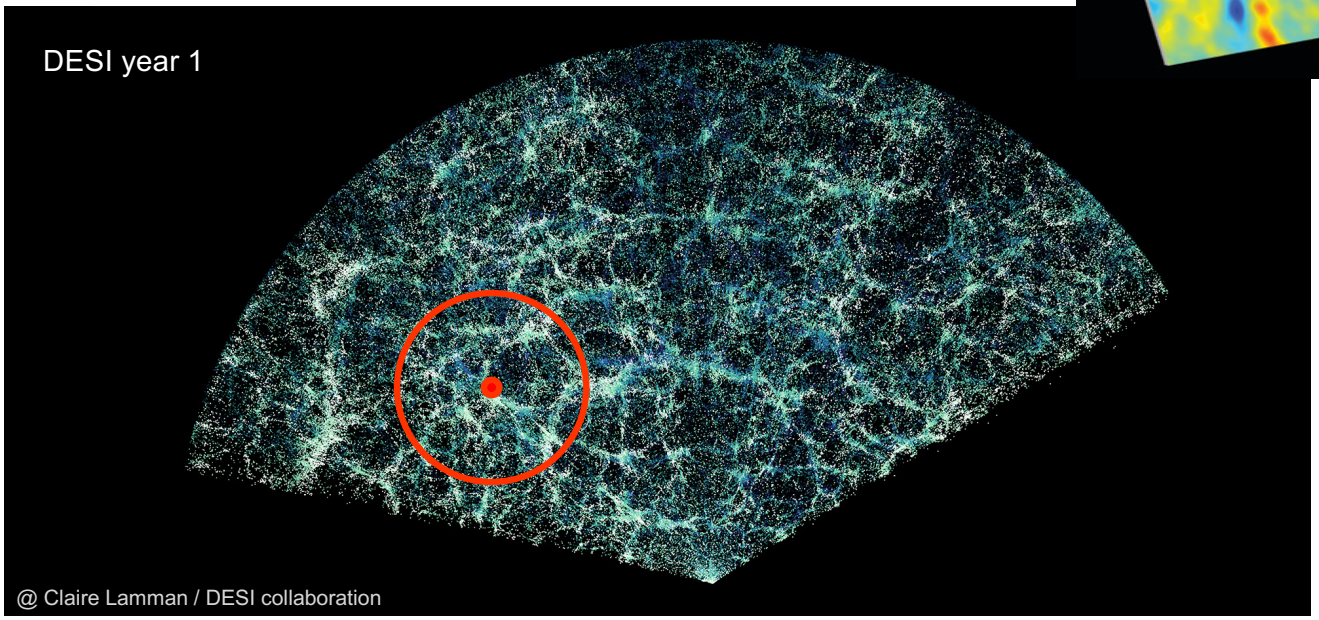
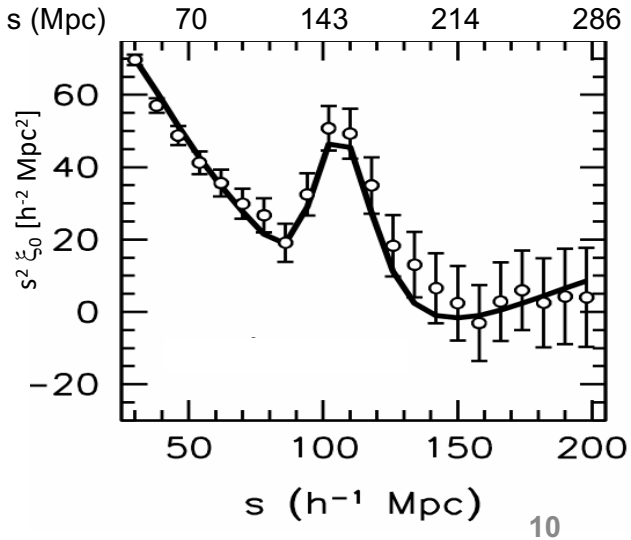
Baryon Acoustic Oscillations (BAO)

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







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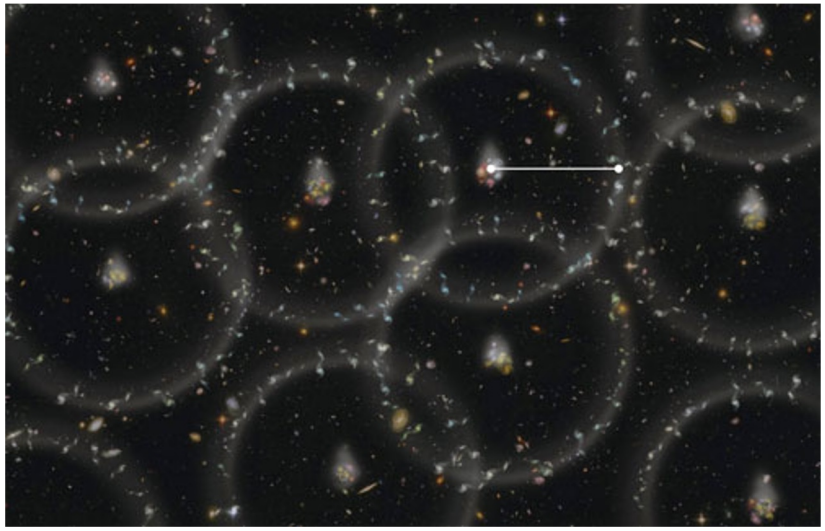
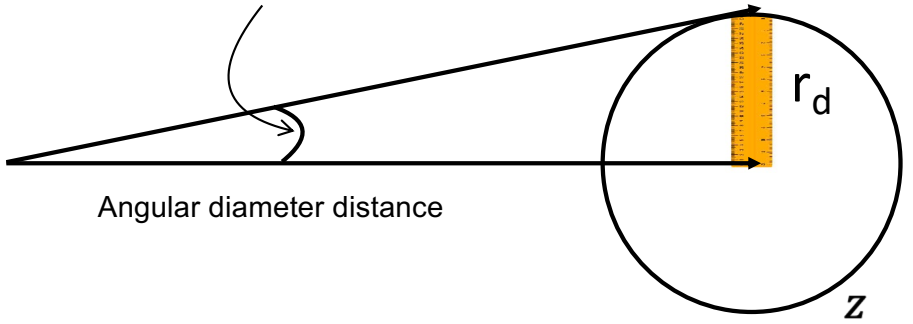
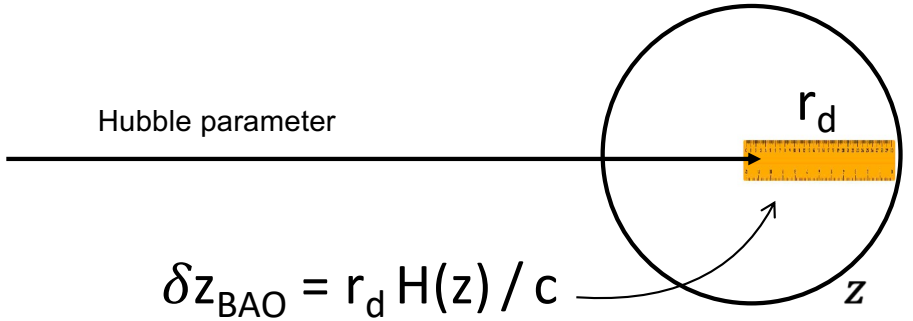
The BAO standard ruler

Artist's view of BAO



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





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

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

Is Dark Energy Weakening?

Probes of the expanding universe

The Dark Energy Spectroscopic Instrument – DESI

DESI First-year BAO results

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Stage-IV Dark Energy Experiment

- Factor 10 on σ_{w0} . σ_{wa} compared to Stage-II (SNIa) experiments using expansion history (BAO) and growth of structures (RSD)

- Maximize volume **V = A x Δz**
  - Maximize area: 14,000 deg^2
  - Maximize redshift coverage 0.1 < z < 4.2

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

- Maximize tracer number density **n**
  - **n**P ~ 1 (beyond which more valuable to increase volume)

clustering power dominates over galaxy shot noise

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DESI targets

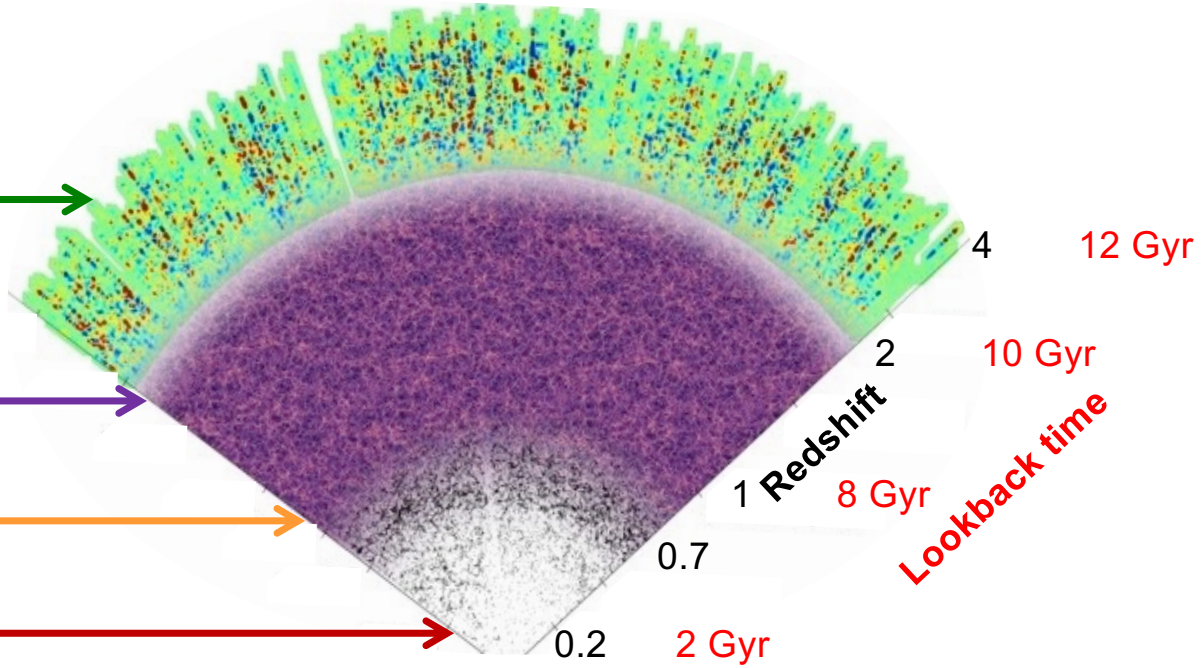
40 million
galaxies and quasars
covering 0 < z < 4

3 million QSOs
1.0 < z < 4.0

16 million ELGs
0.6 < z < 1.6

8 million LRGs
0.4 < z < 1.0

13 million Bright galaxies
0.0 < z < 0.4



+10 million Milky Way stars

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DESI instrument

Mayall telescope
at Kitt Peak Observatory (AZ)

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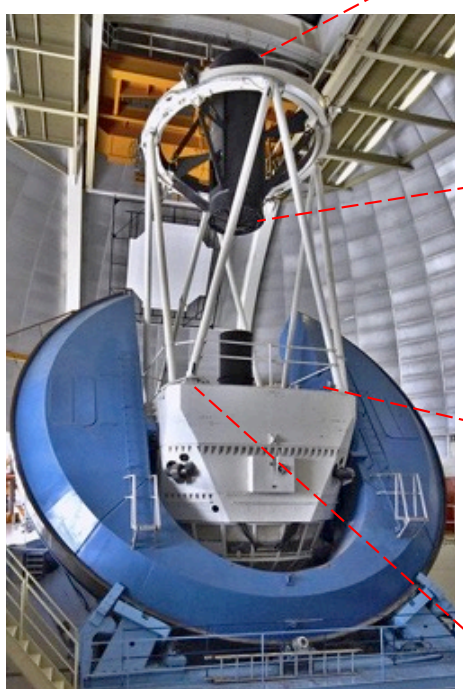
DESI instrument

New corrector
8 deg^2 FOV
(survey speed)



4m primary mirror
(collecting area)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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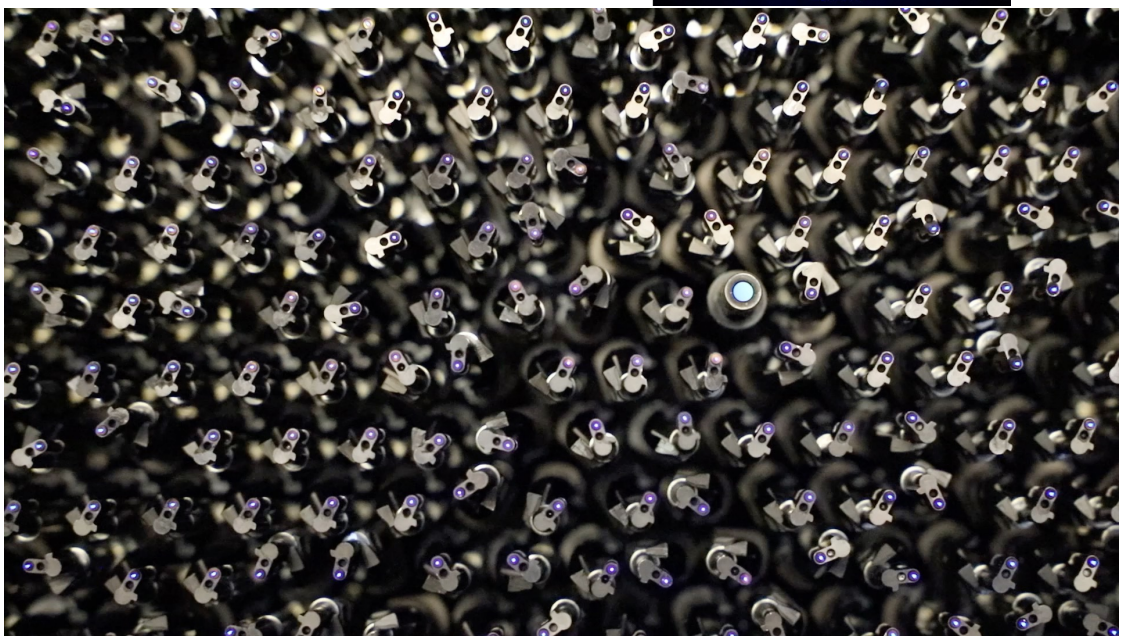
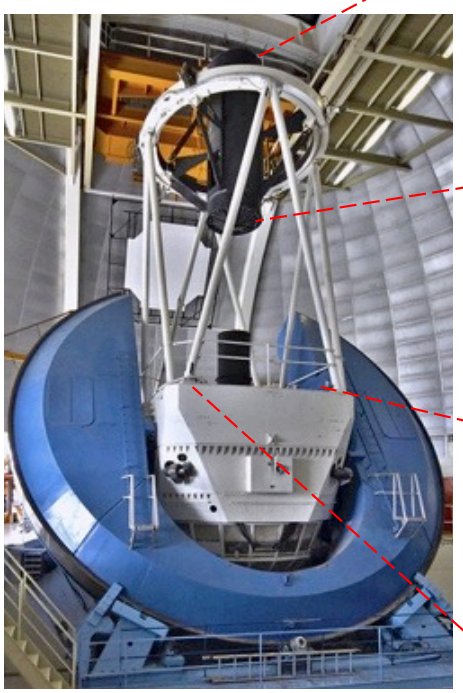
DESI instrument

Focal plane:
5000 fiber positioners
(high multiplexing)





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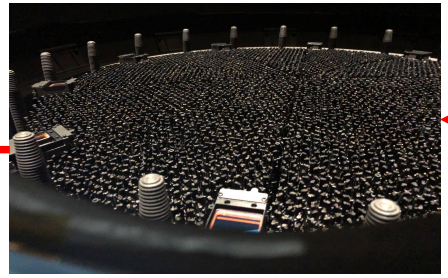
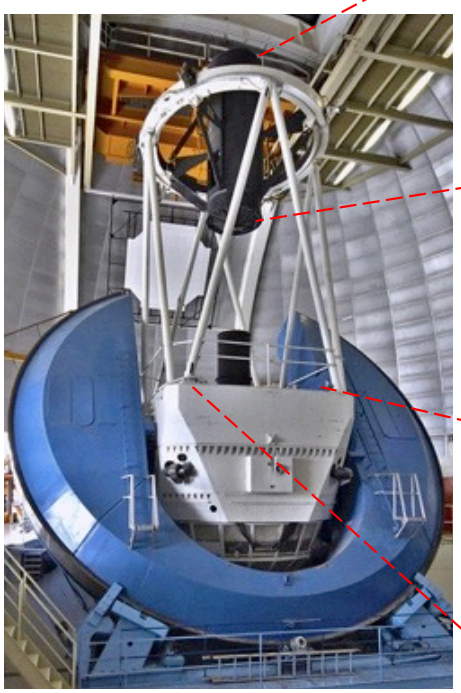
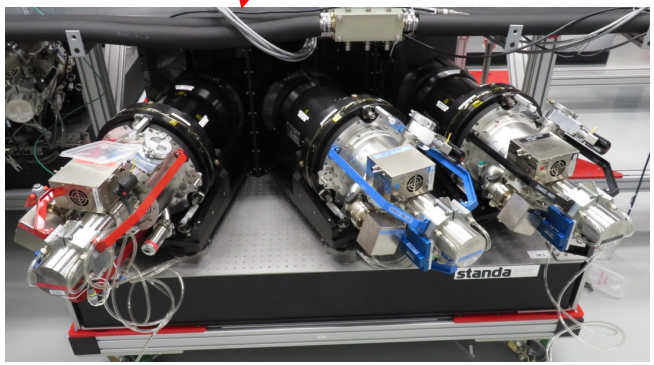
DESI instrument



40m-long optical fibers



10 3-band spectrographs
(high multiplexing)



Is Dark Energy Weakening?

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DESI First-year BAO results

BAO analysis

Cosmological interpretation

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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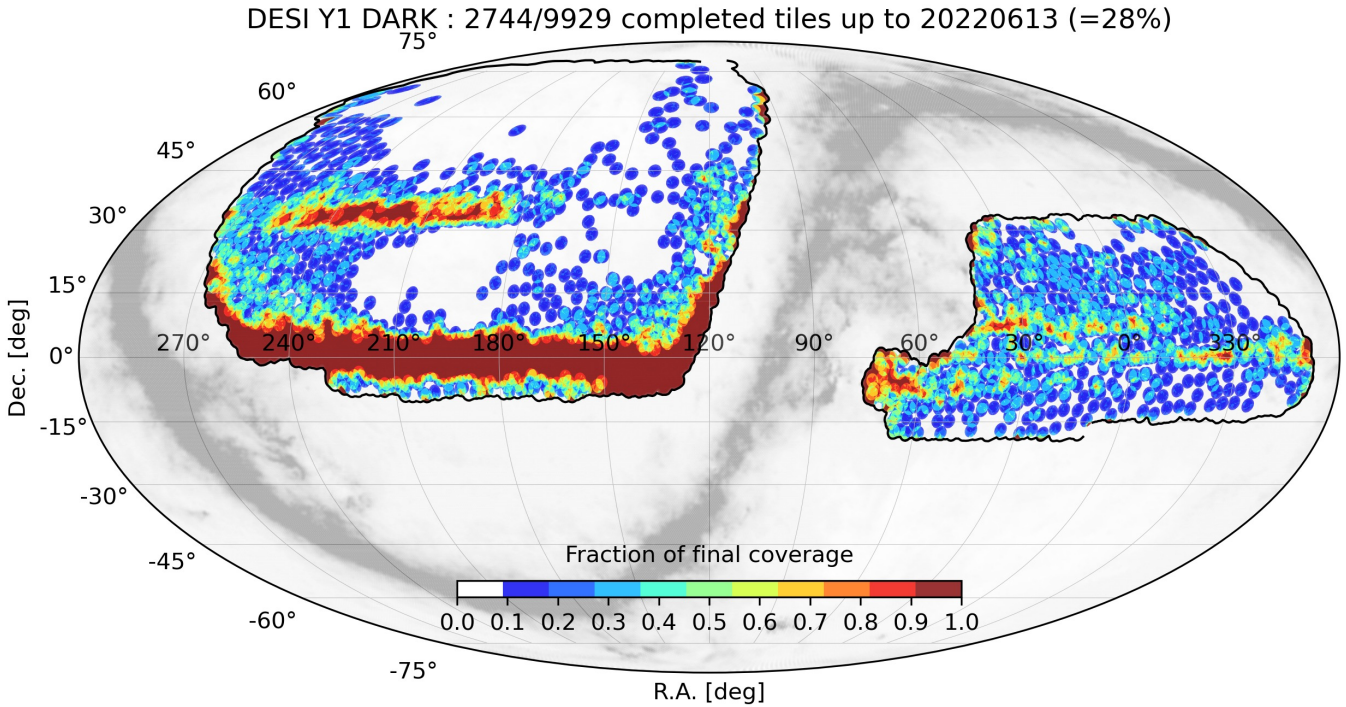
DESI Data Release 1 footprint



Year-1 sample – 2 to 3x larger than SDSS (20 years)
5.7 million galaxies and quasars
420,000 Lyman-a forests

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

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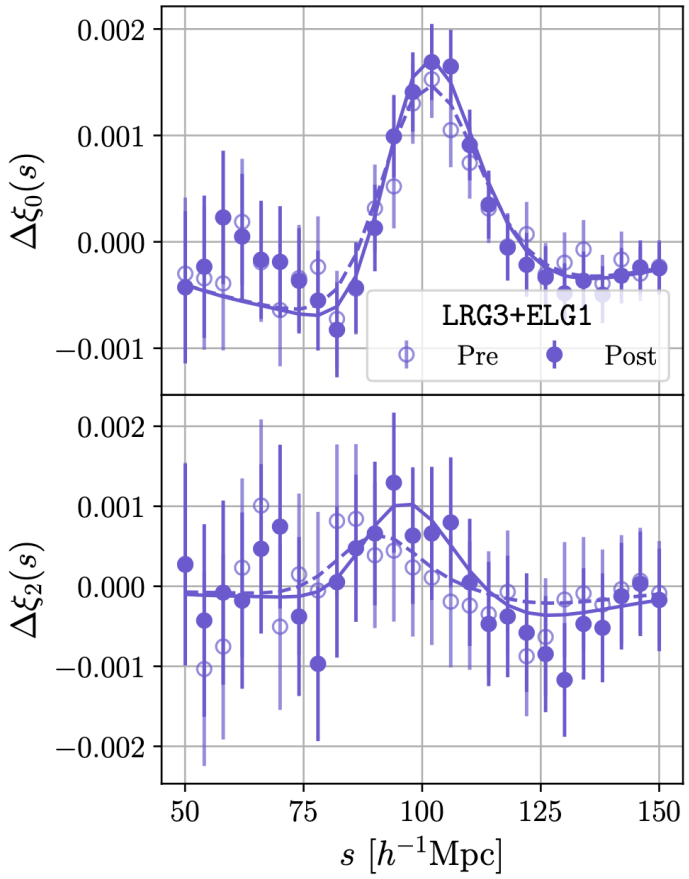
BAO detection

LRG + ELG (0.8<z<1.1)

9σ detection of BAO
at z_{eff} = 0.93



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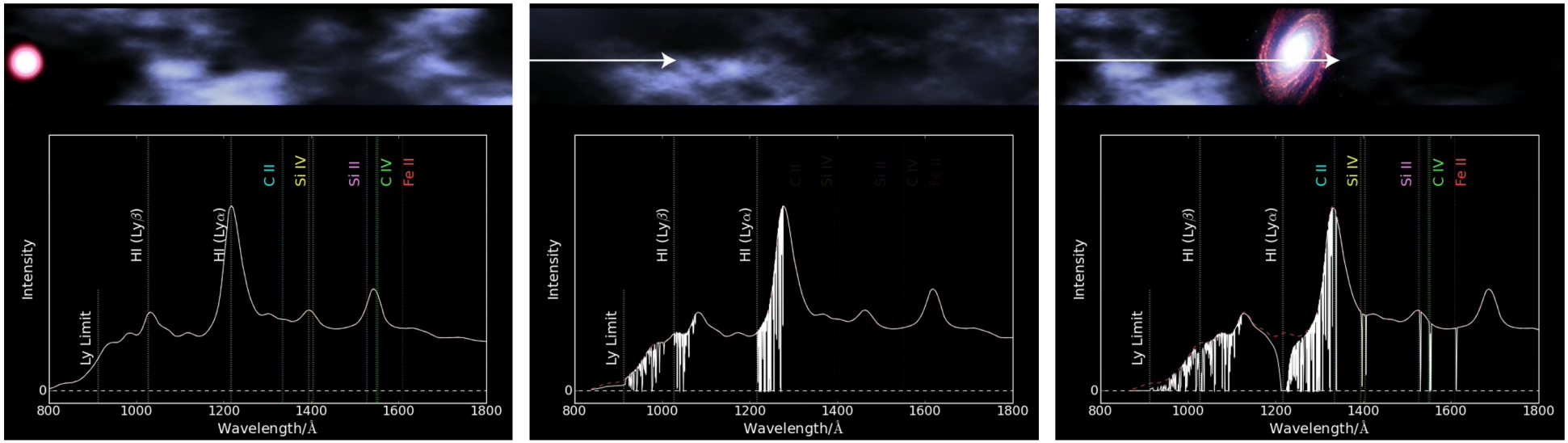
The Lyman-α Forest at z>2.1

credit: Andrew Pontzen

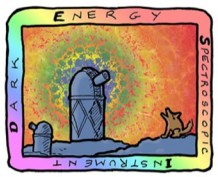


Background quasar → Intervening gas → Earth

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

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

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



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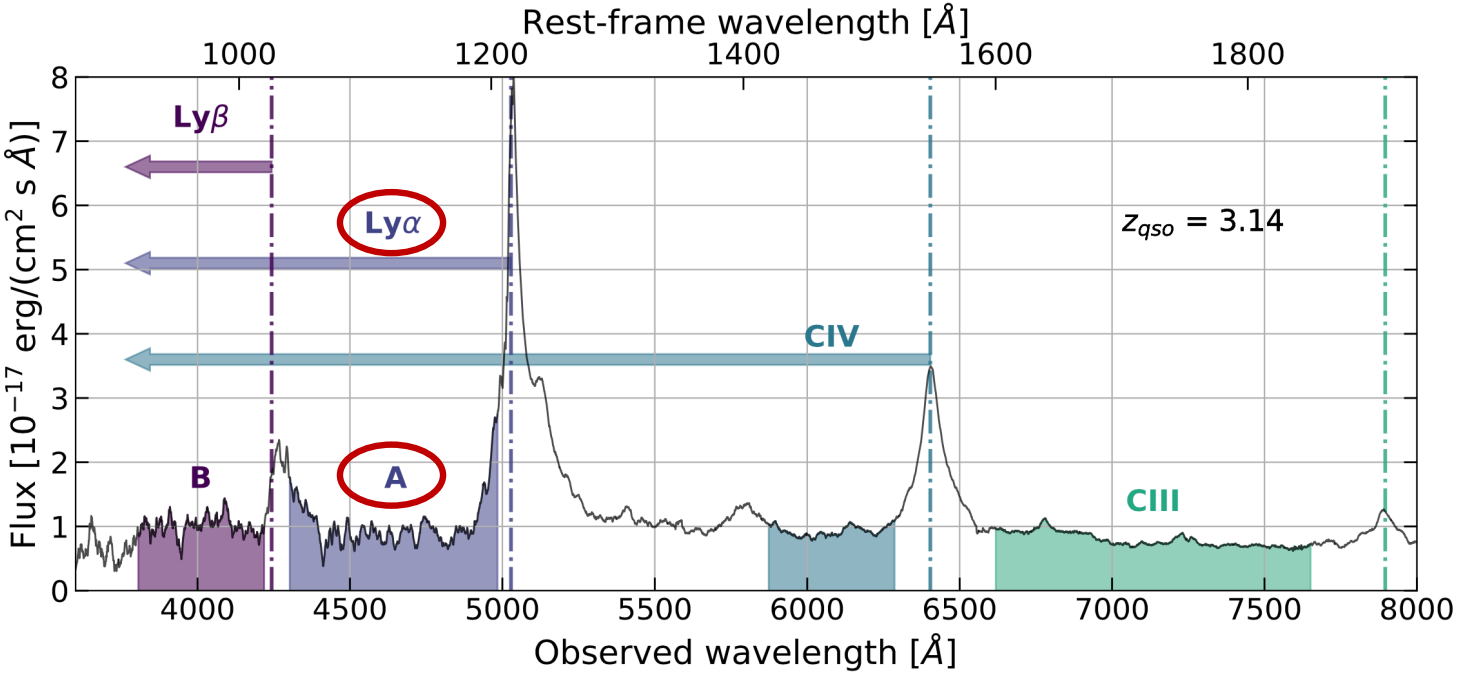
The Lyman-alpha forest

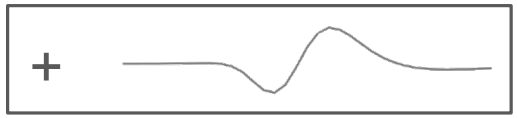
DESI quasar at z=3.14



DESI 2024 BAO

Blind analysis

- Catalog-level – Galaxies & quasars
- Cosmology-level – Lyman-alpha forest



Goals

Determine analysis parameters
& validate choices based on
- Simulated data (*mocks*)
- Data splits (*blinded data*)

Systematic uncertainty

leads to <5% increase of σ_{tot} over σ_{stat}

→ **Statistics-limited results!**

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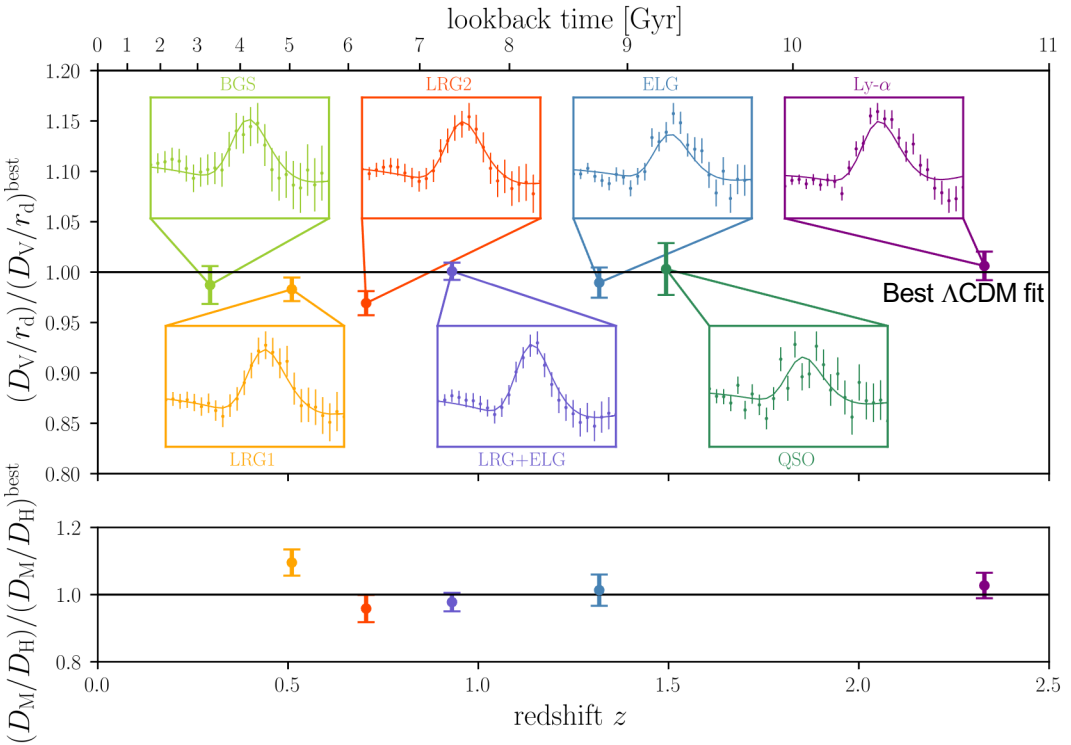
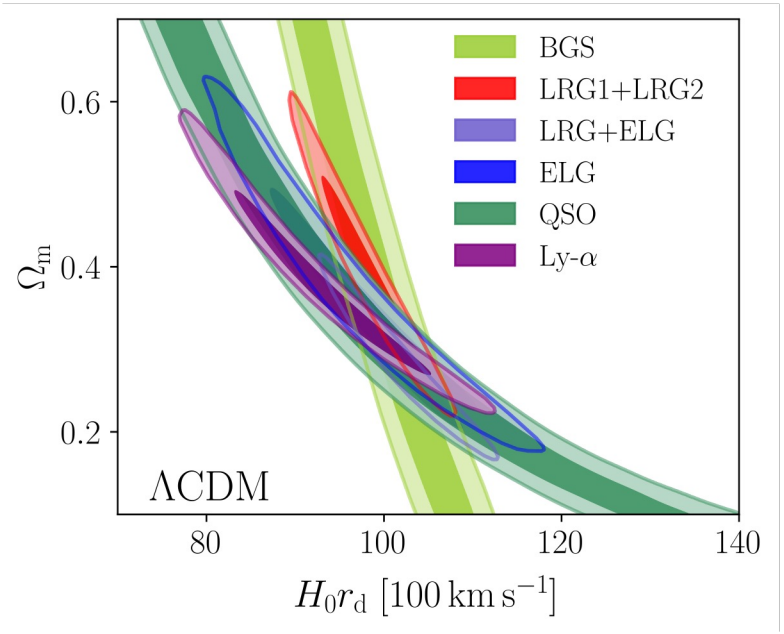
DESI year-1 BAO

BAO data: $\Delta\theta$ and Δz ⟶ D_M / r_d and D_H / r_d

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



Ω_M and $H_0 r_d$



DESI 2024 VI (2404.03002)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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DESI year-1 BAO

BAO data: $\Delta\theta$ and Δz ⟶ D_M / r_d and D_H / r_d

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

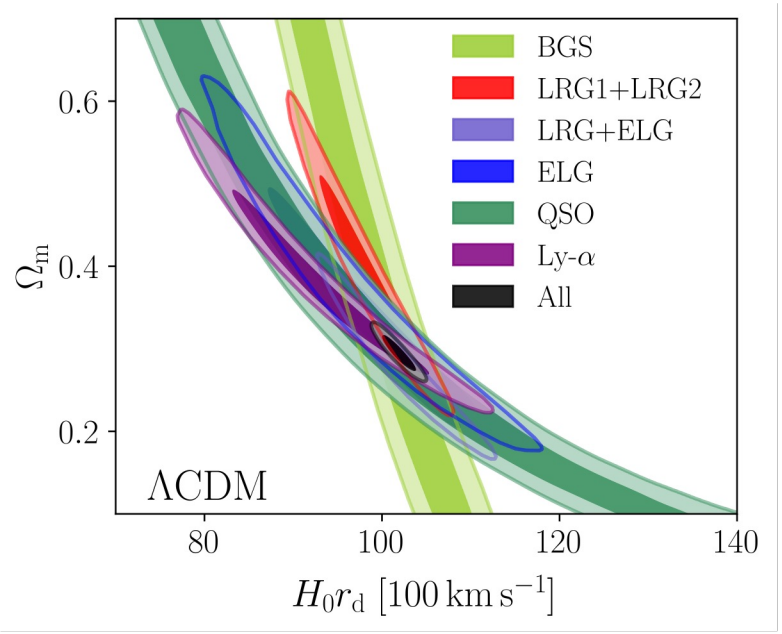
⟶ Ω_M and $H_0 r_d$

Consistent with each other,
and complementary

$$\Omega_m = 0.295 \pm 0.015 \quad (\mathbf{5.1\%})$$
$$H_0 r_d = (101.8 \pm 1.3)\,[100\,\mathrm{km\,s^{-1}}] \quad (\mathbf{1.3\%})$$

DESI

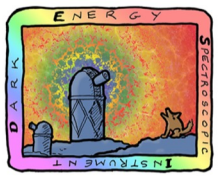
χ^2 = 12.66 for 12 data points and 2 parameters



Aggregated precision on BAO distance scale: 0.49%

(vs. 0.60% for final SDSS)

DESI 2024 VI (2404.03002)



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H_0

DARK ENERGY SPECTROSCOPIC INSTRUMENT | H_0

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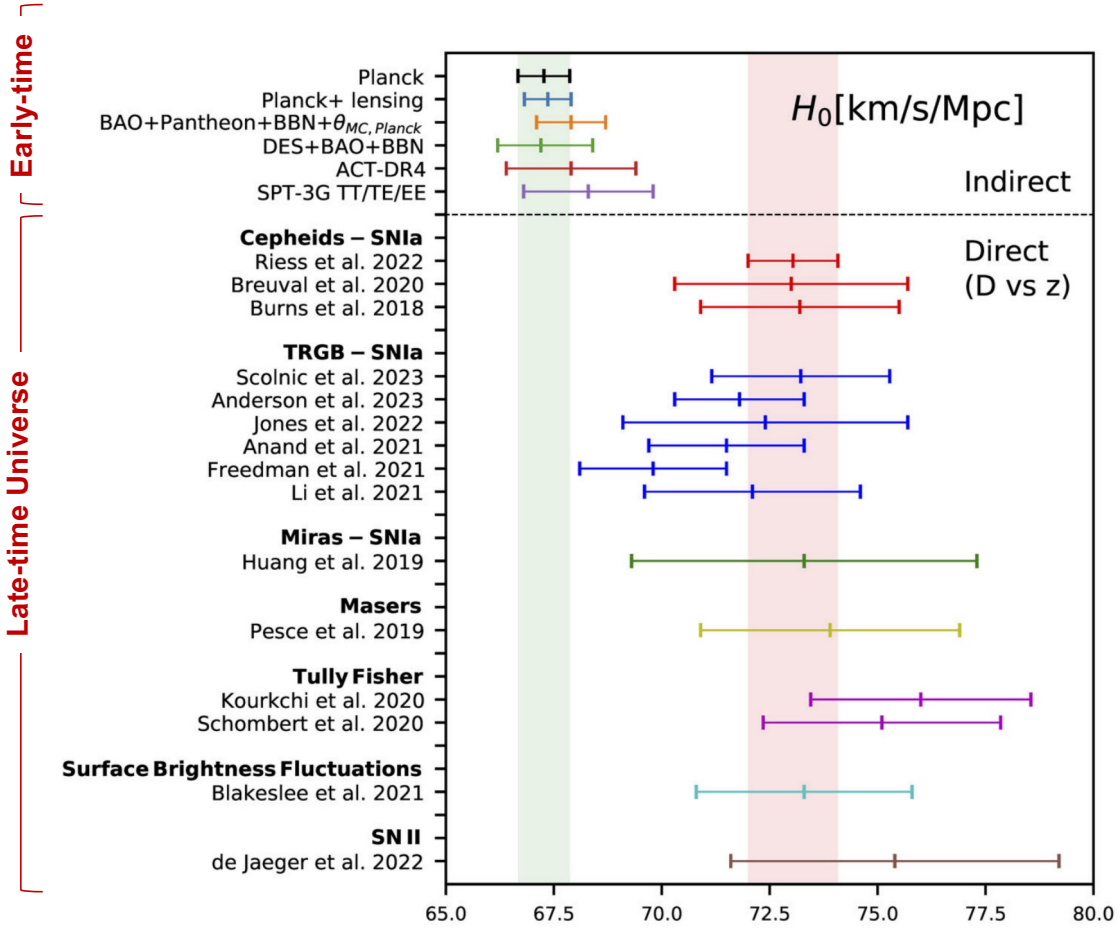
Extrapolation to z=0 of fit to early-universe data

Distance-ladder calibration approach



Riess & Breuval 2023

DARK ENERGY SPECTROSCOPIC INSTRUMENT | H_0

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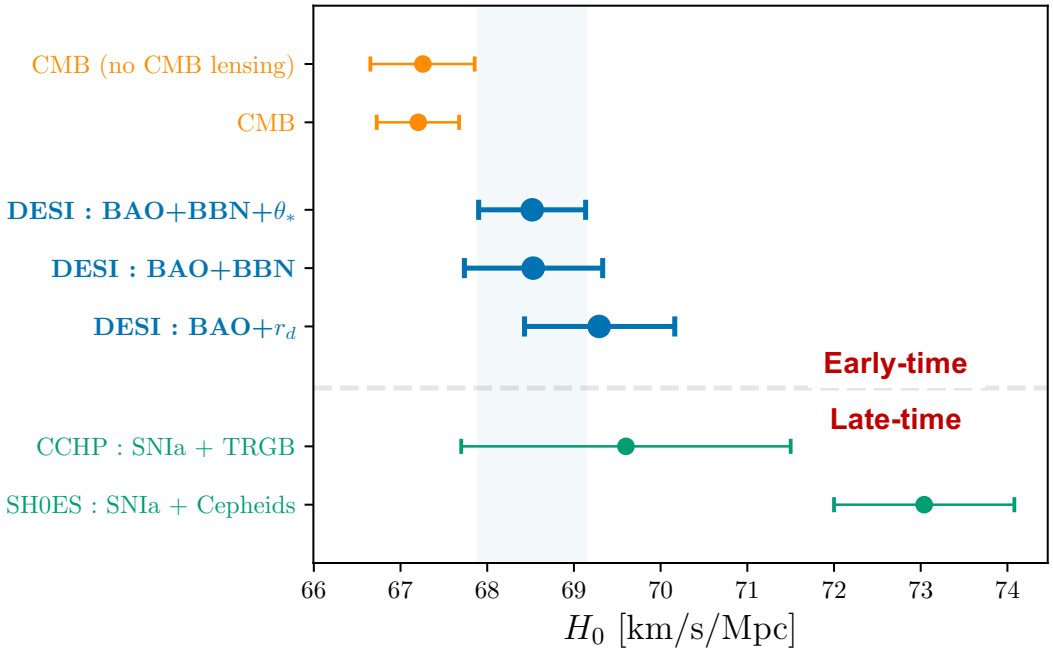
BAO data: $\Delta\theta$ and Δz ⟶ D_M / r_d and D_H / r_d ➡ Ω_M and $H_0 r_d$

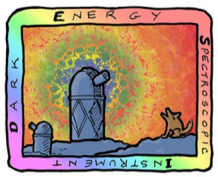
Need r_d from other probe

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

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

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





DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Dark Energy

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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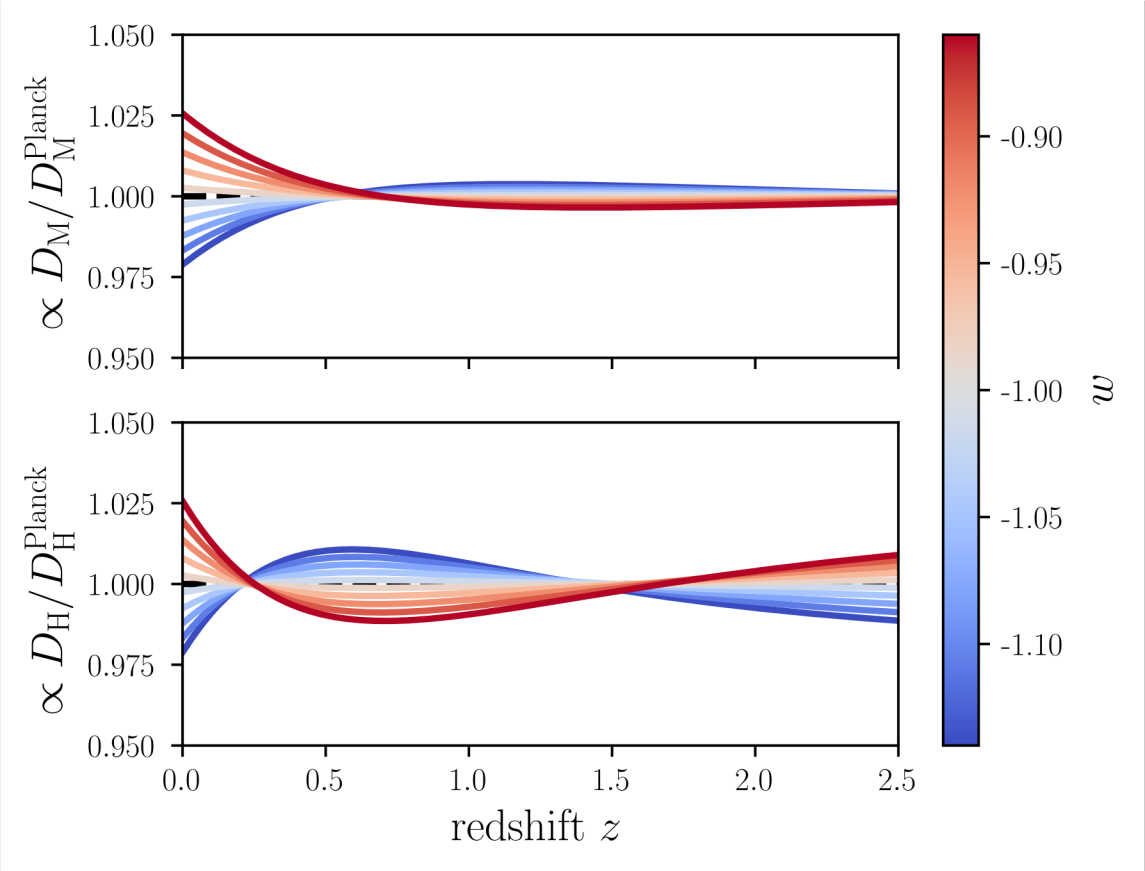
Dark Energy – Equation of State w=P/ρ

Constant EoS (w constant)

Cosmological constant Λ

⟹ w = -1

(converse not true)



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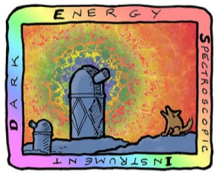

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Dark Energy – Equation of State w=P/ρ

DESI only:

$\Omega_m = 0.293 \pm 0.015$ (**5.1%**)
$w = -0.99 \pm 0.15$ (**15.2%**)

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

$\Omega_m = 0.3095 \pm 0.0065$ (**2.1%**)
$w = -0.997 \pm 0.025$ (**2.5%**)

Assuming a constant EoS,

DESI BAO compatible with ΛCDM
(Dark Energy = cosmological constant)

but …

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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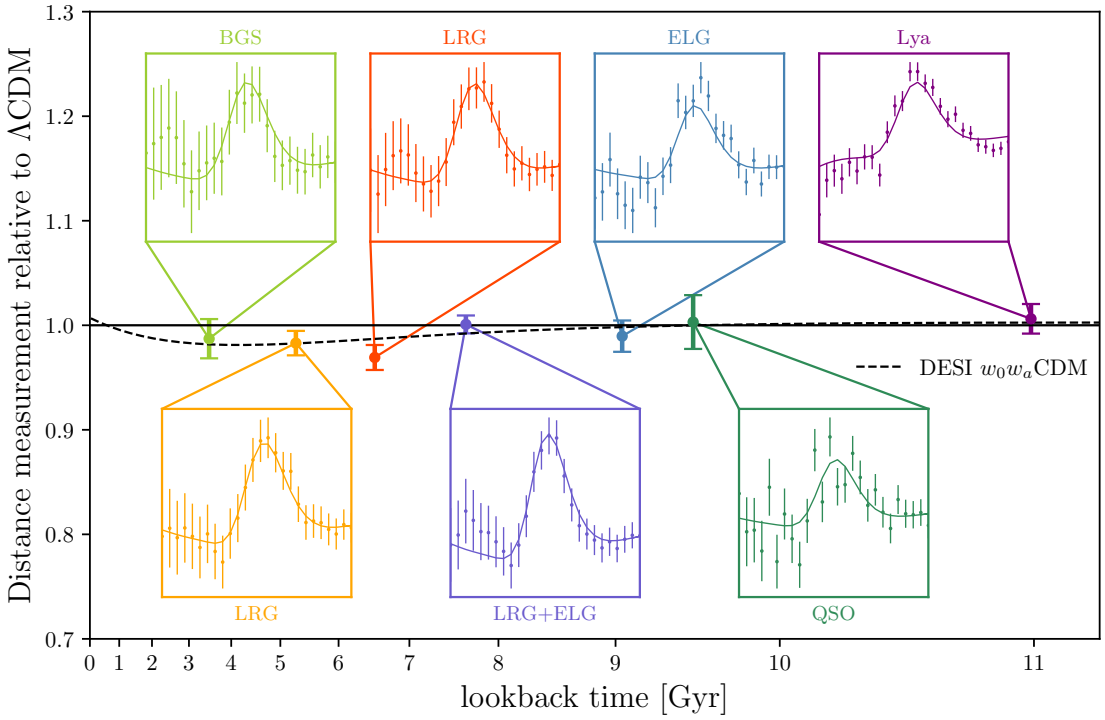
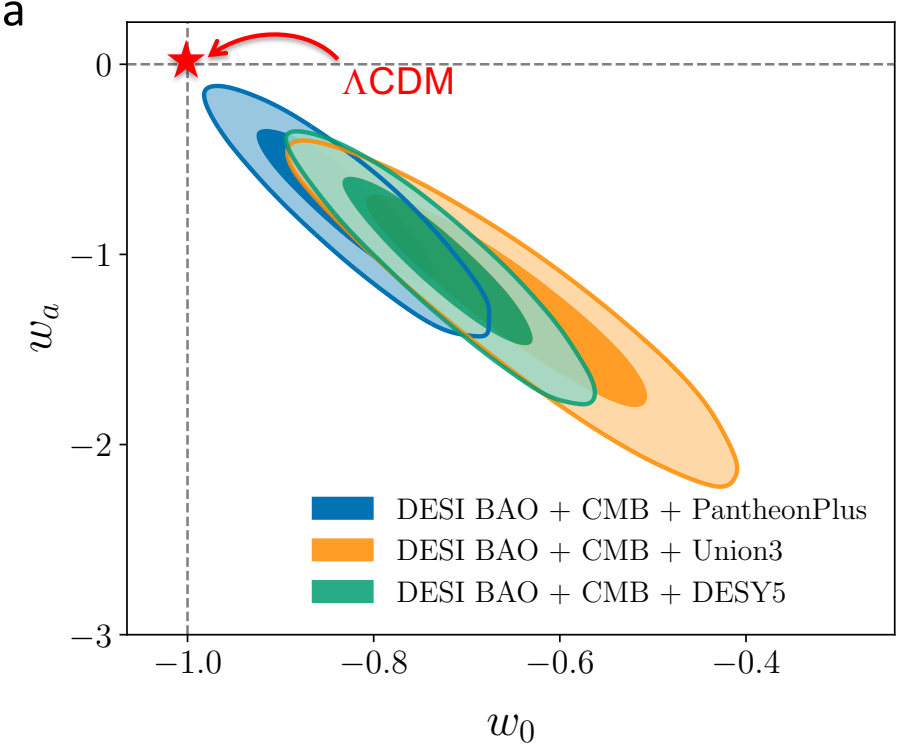
Dark Energy – w_0 w_a

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



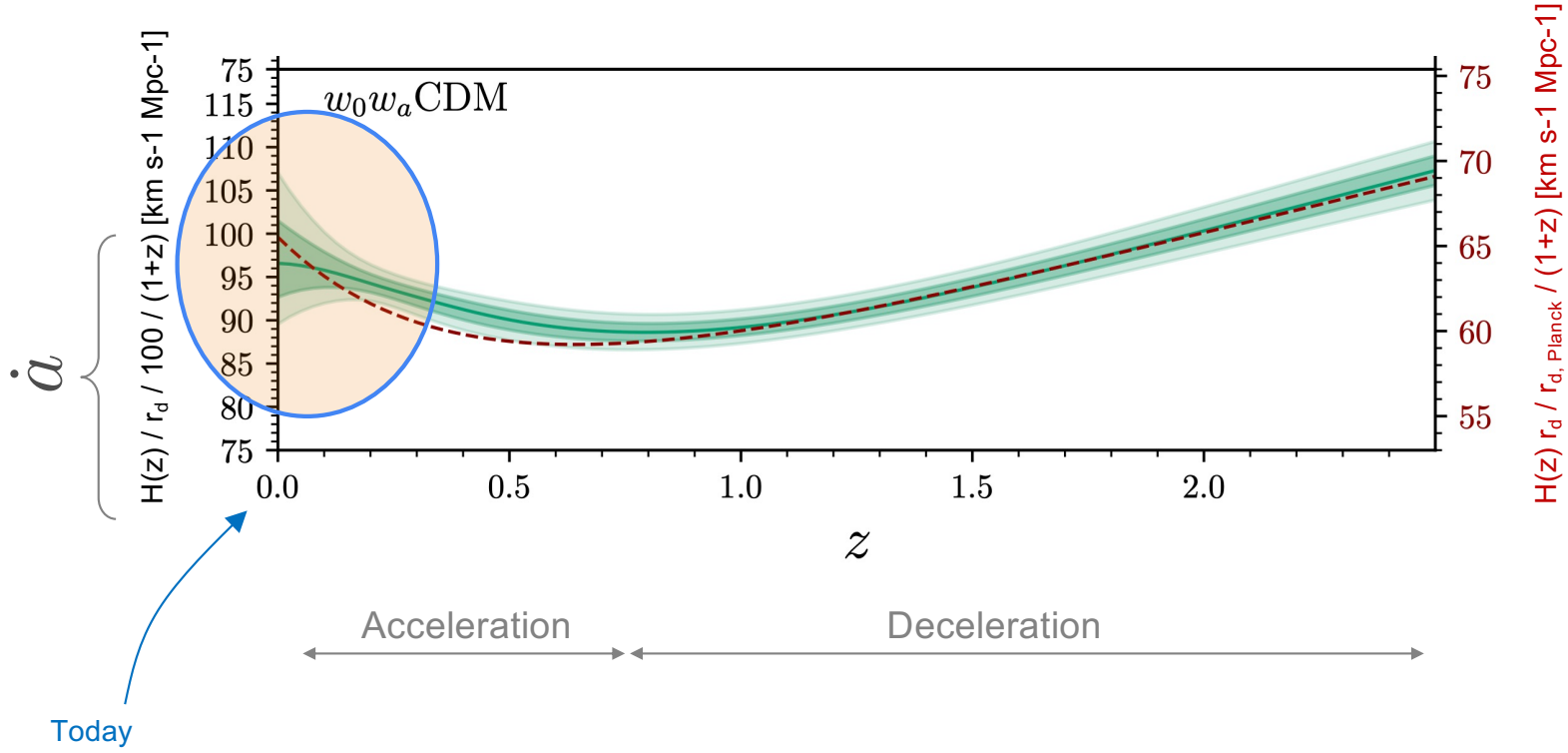
CMB = Planck (Temp. & Polar) & Planck + ACT DR6 lensing



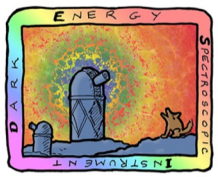
DESI + CMB + Pantheon+: 2.5σ
DESI + CMB + Union3: 3.5σ
DESI + CMB + DES-SN5Yr: 3.9σ

DESI 2024 VI (2404.03002)

Is dark energy weakening?



DESI 2024 VI (2404.03002)



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Brand new DESI Full shape results!

(= clustering on all scales)

DESI 2024 I: Year-1 Data release
DESI 2024 II: Year-1 catalogs *(arXiv:2411.12020)*
DESI 2024 III: BAO results from galaxies and quasars at z<2
DESI 2024 IV: BAO results from the Lyman-alpha forest at z>2
DESI 2024 V: Redshift-shape distortion (RSD) results from galaxy and quasars at z<2 *(arXiv:2411.12021)*
DESI 2024 VI: Cosmology implications of the BAO results from galaxies, quasars and Lyman-alpha forest
DESI 2024 VII: Cosmology implications of the RSD results from galaxies and quasars *(arXiv:2411.120202)*

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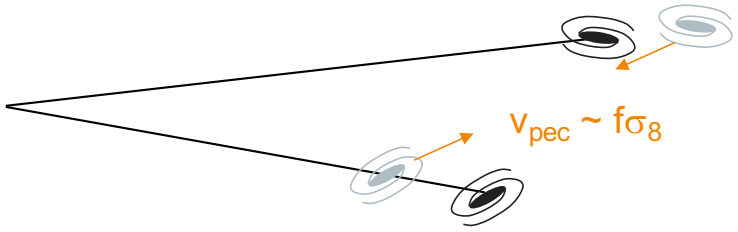
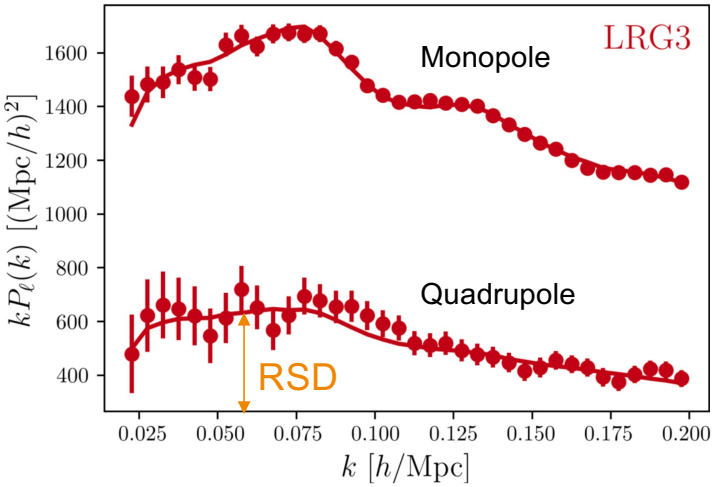
Redshift Space Distortions (RSD)



$z_{obs} = z_{cosmo} + z_{pec}$

Peculiar velocities ⟹ redshift-space distortion (RSD)



DESI 2024 II (2411.12020)

$$P(k,\mu) = \left[b + f\mu^2\right]^2 P_m(k)$$

Kaiser linear term

$$f(a,k) = \frac{\partial \ln \delta(a,k)}{\partial \ln a}$$

Logarithmic growth factor

$$f_{\rm GR} \simeq \Omega_m^{0.55}$$

$$\mu = \cos(\beta)$$

Angle of galaxy pair w.r.t. LOS

$$P_m(k,z) = \sigma_8(z) P_m(k, z=0)$$

BAO
→ Expansion

Full shape
→ Growth of structure (σ_8 / S_8)
→ Test of General Relativity (f)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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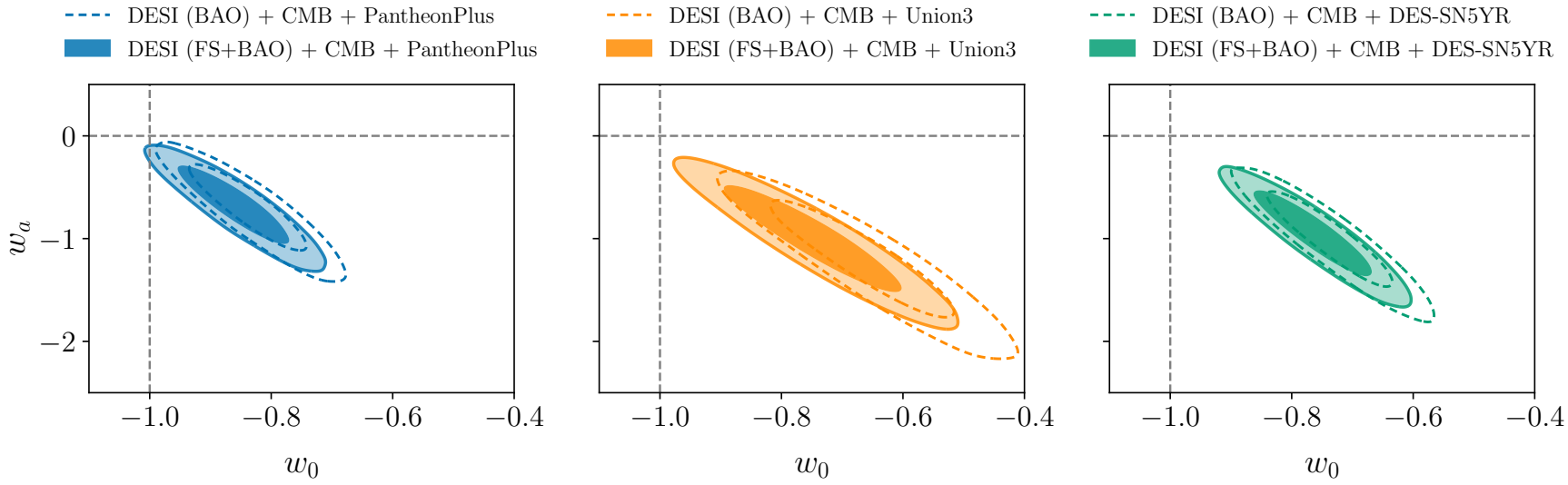
Structure growth updates on dark energy

Varying dark energy

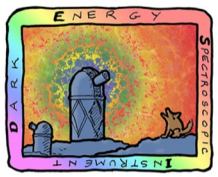
Constraints tightened by ~20%

Comparable shifts from ΛCDM as with BAO

DESI (BAO+FS) + CMB + Pantheon+: 2.5σ
DESI (BAO+FS) + CMB + Union3: 3.4σ
DESI (BAO+FS) + CMB + DES-SN5Yr: 3.8σ



DESI 2024 VII (2411.12022)



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Neutrino masses

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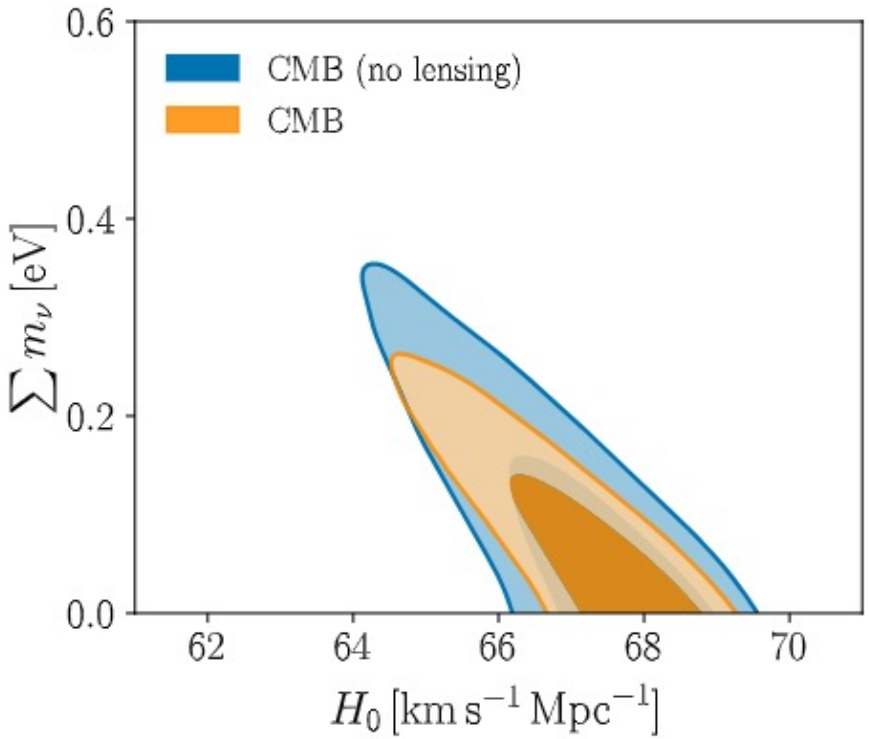
Neutrino masses

Internal CMB degeneracies limiting sensitivity to neutrino masses



DESI 2024 VI (2404.03002)

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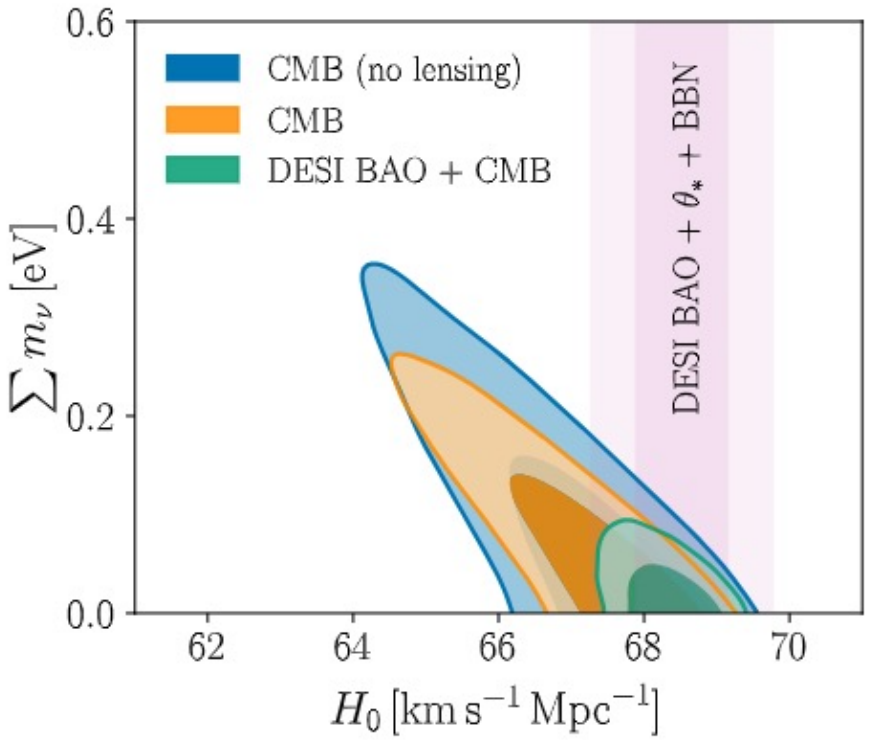
Neutrino masses

Internal CMB degeneracies limit sensitivity to neutrino masses

broken by BAO (through H_0)

DESI prefers high values of H_0, yielding

$\sum m_\nu < 0.082$ eV* (95%, DESI (BAO)+CMB)



DESI 2024 VI (2404.03002)

* DESI 2024 VII (2411.12022) update

DARK ENERGY SPECTROSCOPIC INSTRUMENT

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Structure growth updates on neutrino mass

Sum of neutrino masses

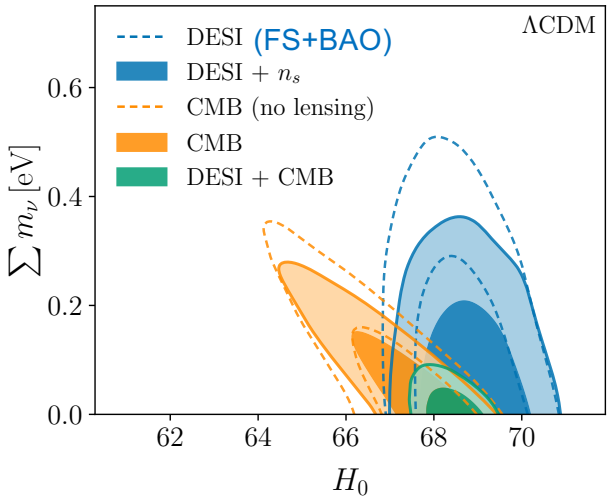
$\sum m_\nu < 0.082$ eV (95%, DESI (BAO)+CMB)

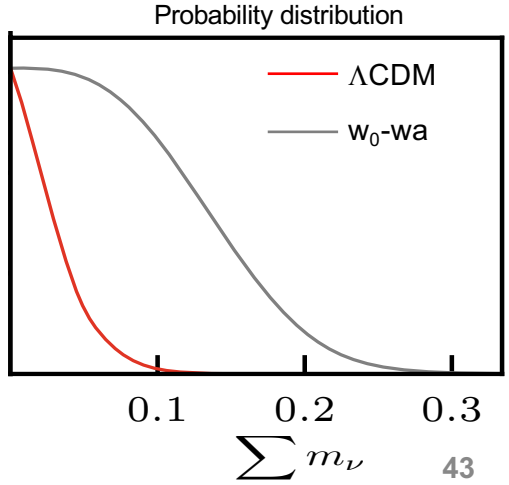
Additional constraining power (15% tighter)
Pull to slighter higher H_0

$\sum m_\nu < 0.071$ eV (95%, DESI (FS+BAO)+CMB)

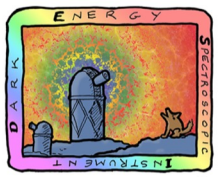
Relaxed in w_0w_aCDM to

$\sum m_\nu < 0.175$ to 0.201 eV (95%, DESI (FS+BAO)+CMB+SNIa)





DESI 2024 VII (2411.12022)



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Modified Gravity

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Modified Gravity

Metric (inhomogeneous Universe): $ds2 = a^2(\tau)[-(1+2\Phi)d\tau^2 + (1-2\Psi)\delta_{ij}dx^i dx^j]$

At late times,
Poisson equations governing trajectories of particles

$$\begin{cases} k^2\Psi &= -4\pi G a^2(1+\mu(a))\rho\delta \quad \text{(massive particles)} \\ k^2(\Psi+\Phi) &= -8\pi G a^2(1+\Sigma(a))\rho\delta \quad \text{(mass-less ie light)} \end{cases}$$

In General Relativity,

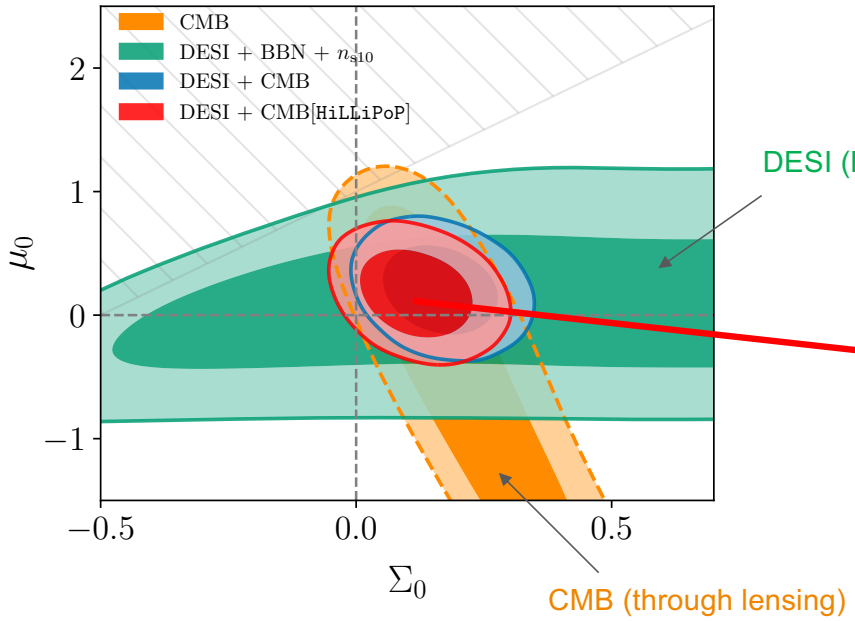
$\mu(a) = \Sigma(a) = 0$

Test GR with

$$\mu(a) = \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}\mu_0 \qquad \Sigma(a) = \frac{\Omega_\Lambda(a)}{\Omega_\Lambda}\Sigma_0$$

Clustering full shape → μ_0

Weak lensing & CMB → Σ_0



Compatible with General Relativity

DESI 2024 VII (2411.12022)

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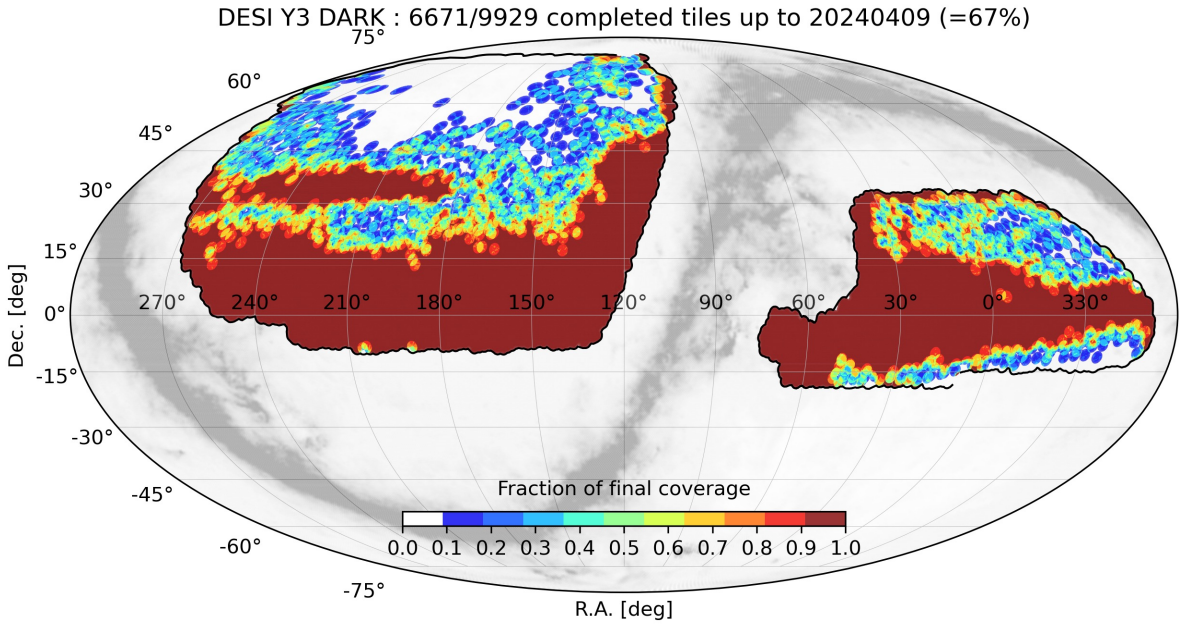
More to come!

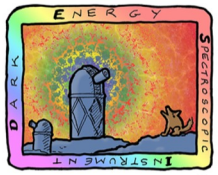
Year 3 sample already in hand!

31M galaxies & quasars
11M stars



Enhanced science goal

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



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Conclusions

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

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

Most precise BAO measurement to date

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

Result highlights

- H0 consistent with Planck, in tension with local value (SH0ES)
- Clustering compatible with General Relativity
- DESI consistent with ΛCDM but hint for varying dark energy, at 2.6σ (DESI+CMB) and 2.5σ to 3.8σ (DESI+CMB+SN)