DESI 2025:
The history of cosmic expansion as revealed by the Dark Energy Spectroscopic Instrument

Martin White
UC Berkeley/LBNL
for the DESI collaboration

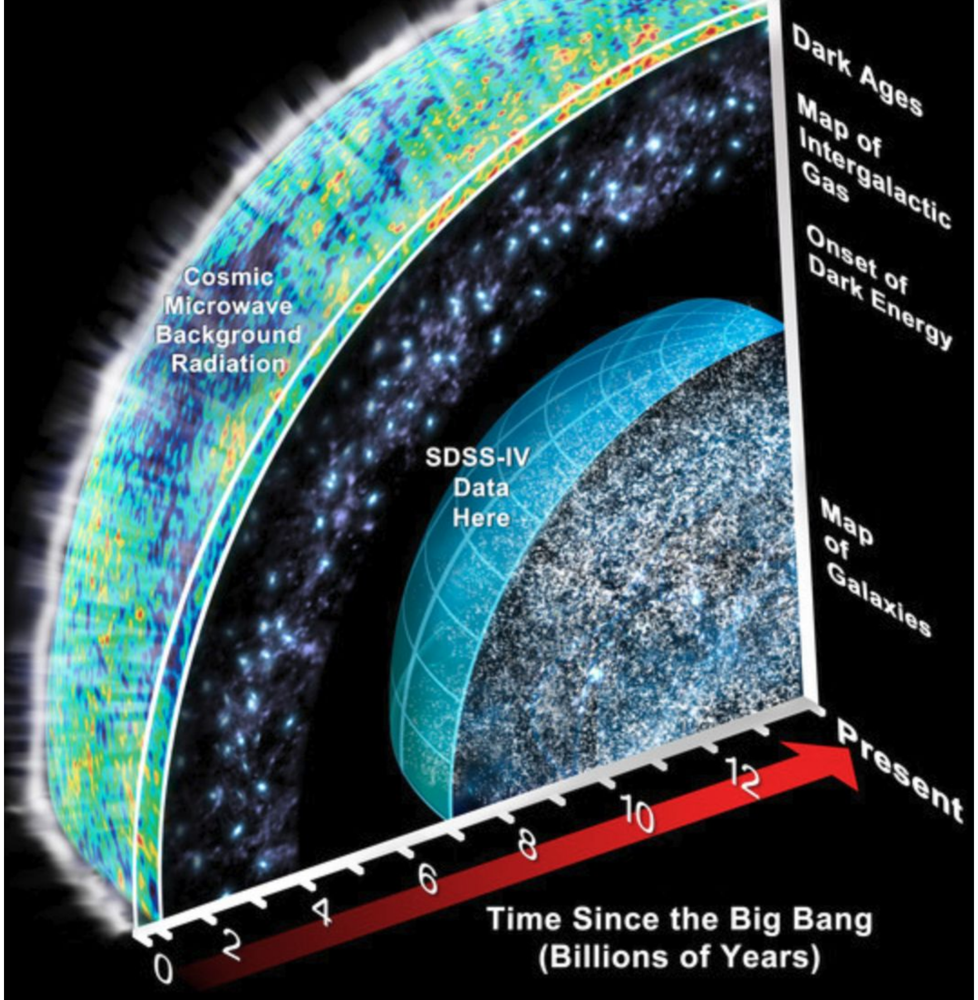
Outline

- What is the large-scale structure in the Universe.
  - And why bother to study it?
- What is the Dark Energy Spectroscopic Instrument (DESI)?
- DESI progress and the Y3/DR2 dataset.
- Key results – distance scale (expansion history).
- Implications for DE and ν mass.
- What's next?
- Conclusions.

Large-scale structure

- When we view the Universe today we see structure on scales from the cosmological horizon to planetary systems.
- This structure is puzzling for a number of reasons:
  - Patches of the CMB sky separated by several degrees should have been out of causal contact.
  - A typical galaxy moves <10Mpc over the age of the Universe.
- Large-scale structure is related to processes in the early Universe!

Credit: eBOSS



The story we tell

- A period of very rapid expansion (“inflation”) in the very early Universe turned quantum fluctuations into classical perturbations in the density of all species. (Not my focus today!)
- Fluctuations grow over time through gravitational instability to form all of the structure we see today.
    - 14Gyr of evolution shapes the fluctuations, probing a wide range of energy densities, temperatures, …
- Major constituents of “standard model” (ΛCDM) are:
    - Λ, the cosmological constant or “dark energy” (DE) – dominates the energy density today and is responsible for late-time accelerated expansion.
    - CDM, cold dark matter – dominates the matter density and gravitational potentials today.
    - Plus “trace amounts” of atoms, protons, electrons, neutrinos, etc.

The metric/expansion history

I will focus on the expansion history ...

- The amplitude of large-scale structure decreases as scale increases.
- The Universe is homogeneous and isotropic on largest scales, thus the background metric is of the FRW form – with LSS as fluctuations around this "background".
- Observations strongly restrict the curvature of spatial hypersurfaces, so there is really only 1 degree of freedom at lowest order: the scale factor, *a(t)*

$$ds^2 \simeq -dt^2 + a^2(t)\, dx^2$$

- Measuring *a(t)* has been a goal of observational cosmology since the beginning.

Distance-redshift relation

Measure *a(t)* using a relation between distances and redshifts ...

- We see objects along the past lightcone – light emitted from far away was emitted long ago. So “distance ↔ time”.
  - The “best” distance measures are geometric: e.g. find something whose size you know and measure the angle or redshift interval it subtends.
- The wavelength of light stretches as the scale factor, *a(t),* increases.
- Spectral features are redshifted (stretched).
- By taking the spectrum of an object we can determine the amount of redshifting and hence a(t) when the light was emitted.

$$1 + z \equiv \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} = \frac{1}{a(t_{\rm emit})}$$

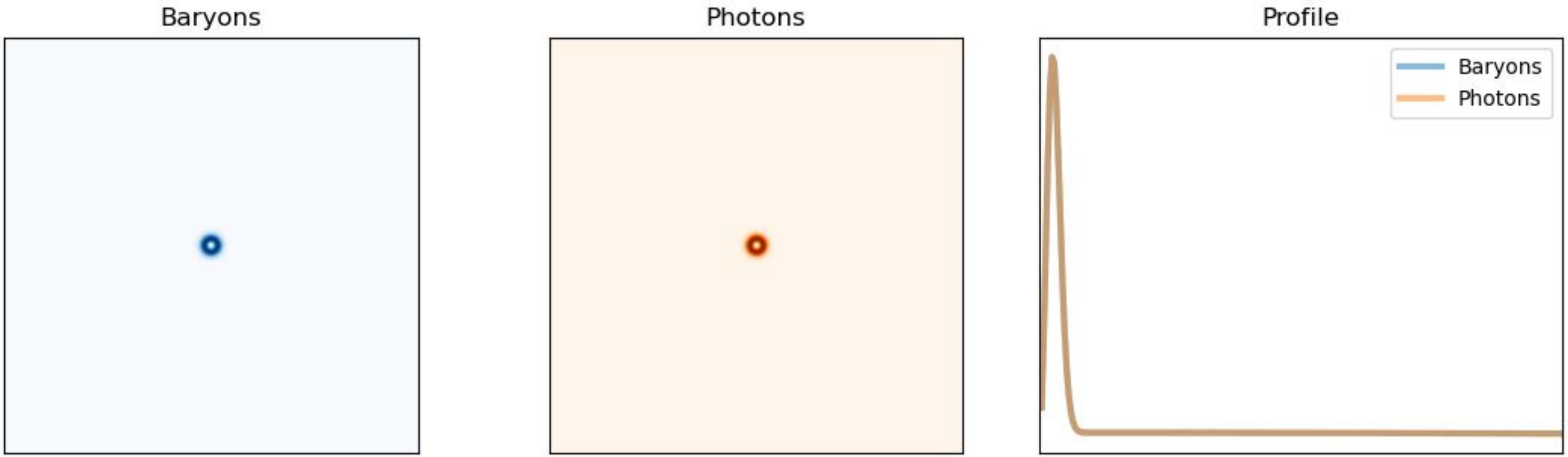
Where could we find a “standard ruler” whose length we know, and which won’t change over 14Gyr of cosmic evolution?

A brief history of the Universe

- The early Universe was hot, dense and ionized.
- Photons scatter rapidly from the free electrons, and thus have a small mean free path. Electrons coupled to protons by Coulomb forces.
- Photons and “baryons” (i.e. p+e) form a tightly coupled fluid, sharing density and momentum.
- Perturbations in the density (equivalently: gravitational field) propagate as sound waves in this primordial fluid – acoustic oscillations.

The acoustic wave
(Green's function picture)

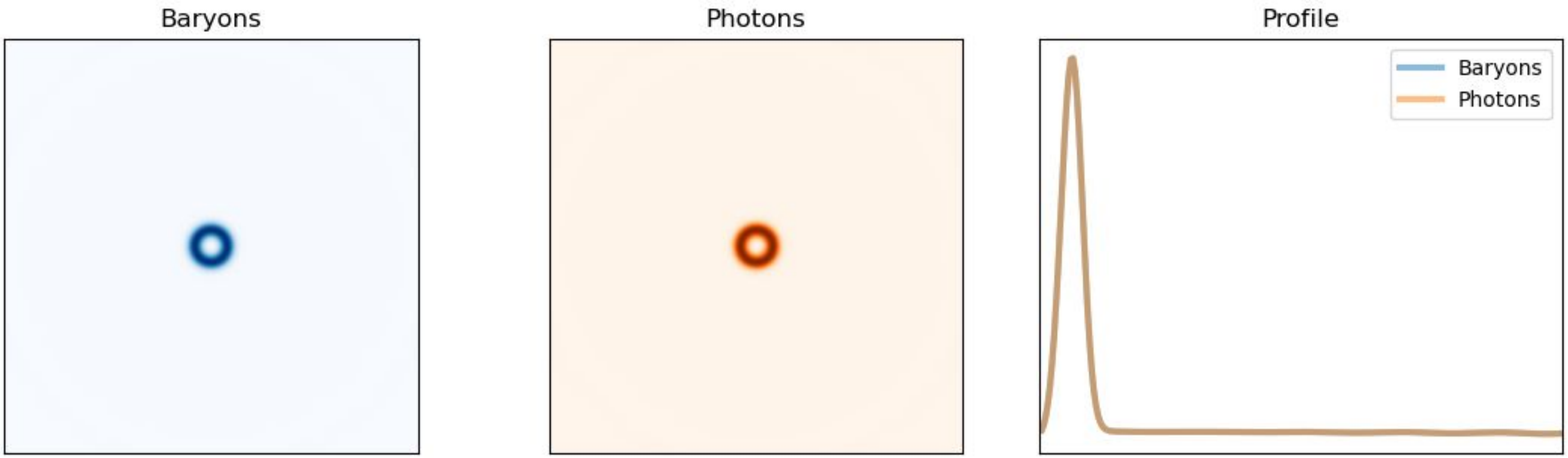
Start with a single perturbation. The plasma is uniform except for a δ-fn at the origin.
High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Eisenstein, Seo & White (2006)

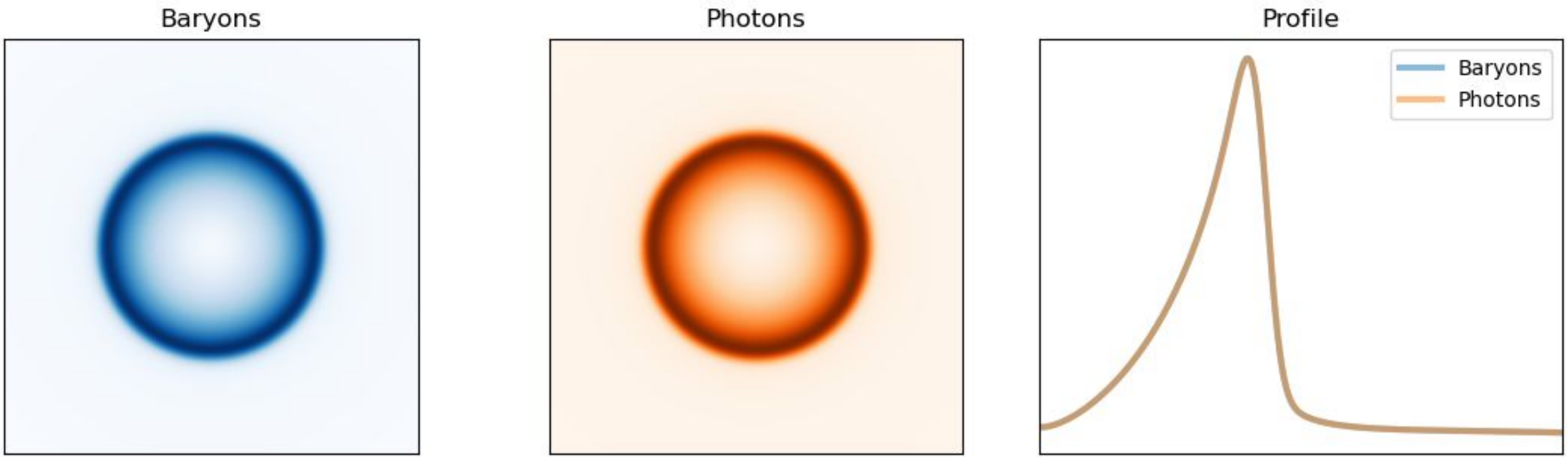
The acoustic wave

Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light.



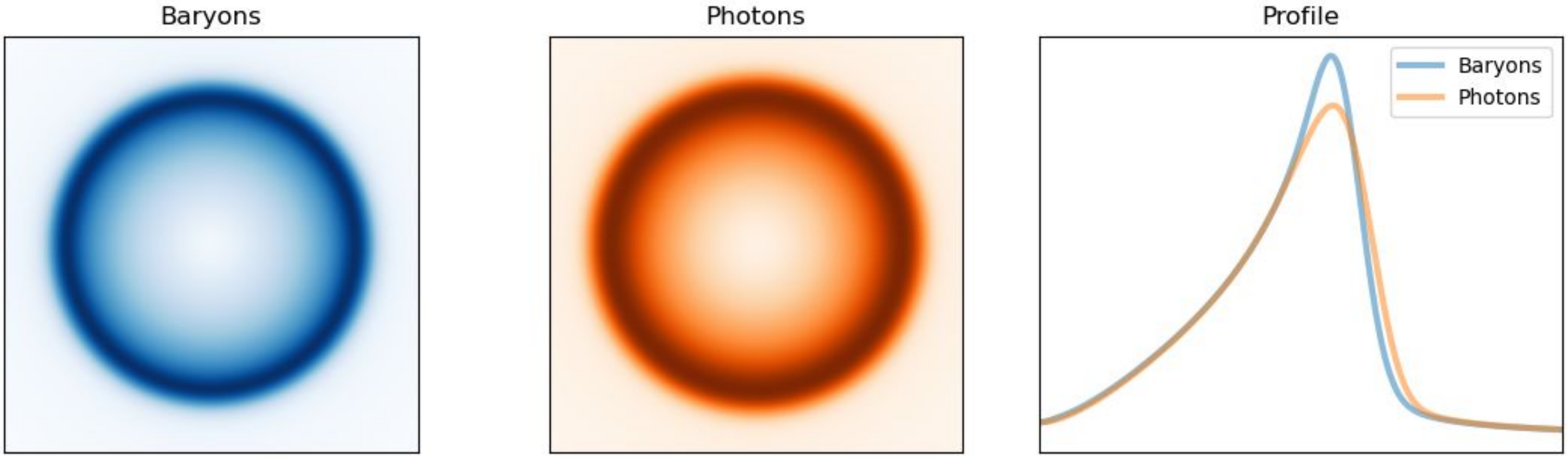
The acoustic wave

This expansion continues for 10^5 years



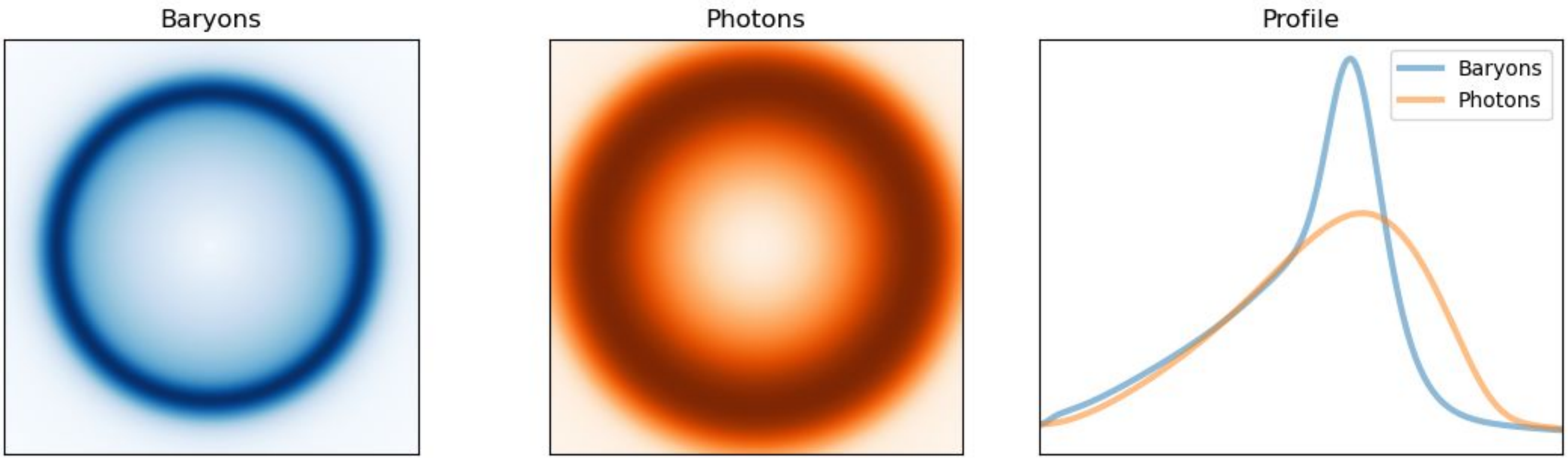
The acoustic wave

After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen. This decouples the photons from the baryons. Knowing atomic physics, we know at what T this happens.

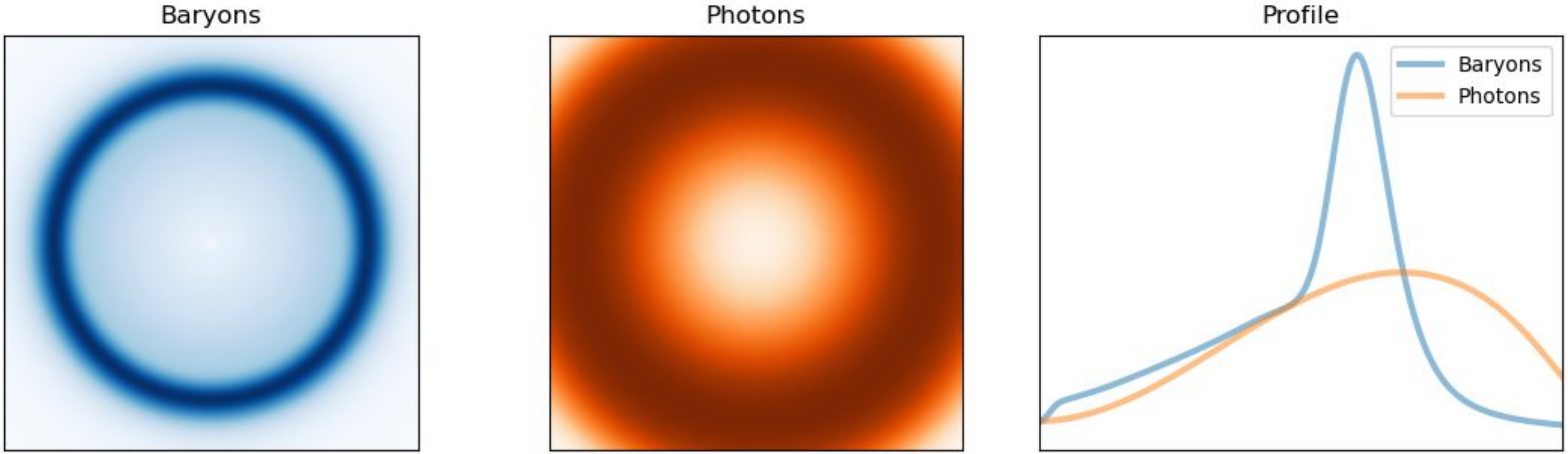


The acoustic wave

The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.



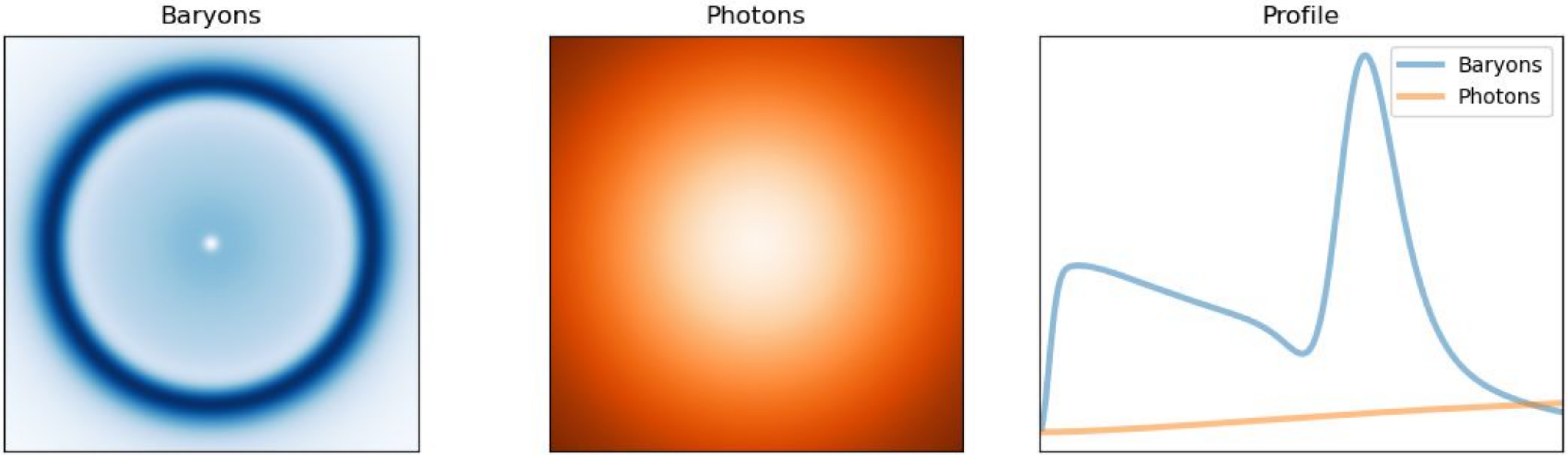
The acoustic wave



The acoustic wave

The photons have become almost completely uniform, but the baryons remain overdense in a shell 150Mpc in radius.

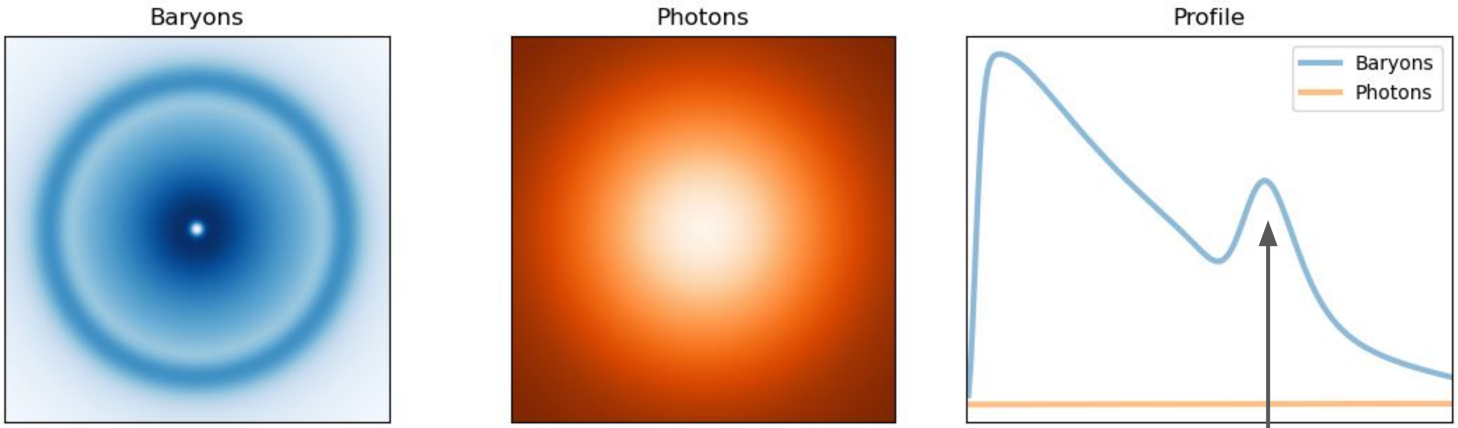
In addition, the large gravitational potential well which we started with starts to draw material back into it.



The acoustic wave

The perturbations grow by ~10^3 & the baryons and DM reach equilibrium densities.

The final configuration is our original peak at the center (which we put in by hand) and an "echo" in a shell roughly 150Mpc in radius.

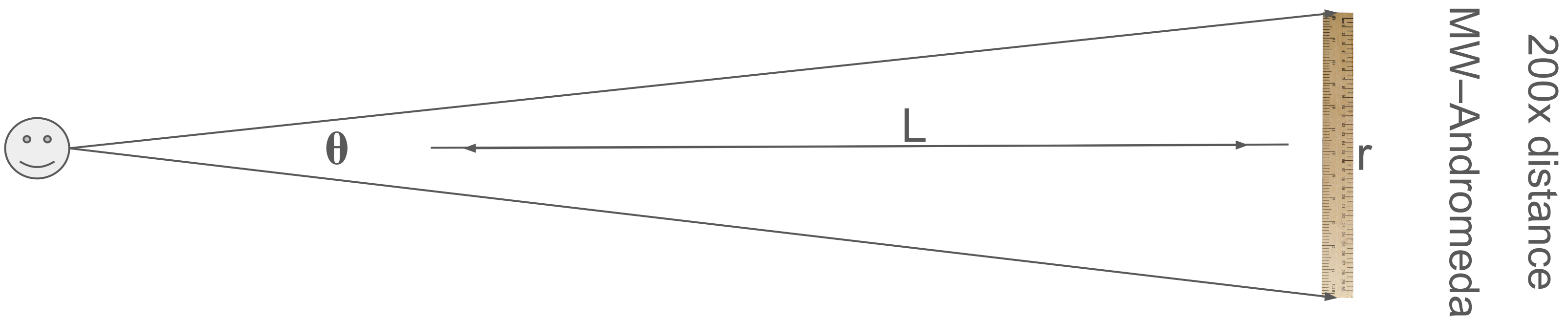


Standard ruler

This “Baryon Acoustic Oscillation (BAO) feature” can serve as a standard ruler, calibrated in “physical units” by our knowledge of the speed of sound of a relativistic fluid and temperature at which hydrogen ionization occurs:

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)}\, dz \quad \text{with} \quad c_s = \frac{c}{\sqrt{3}} \left(1 + \frac{3\rho_B}{4\rho_\gamma}\right)^{-1/2}$$

$$r_d \approx 150\,\mathrm{Mpc} \simeq 4.6 \times 10^{24}\,\mathrm{m}$$



Standard ruler

- Of course we have a spectrum of initial fluctuations, not a single perturbation.
- But each “initial impulse” leads to an “echo” in the matter (potentials) in a shell of radius ~150Mpc.
- We search for this feature statistically as an <u>excess of galaxy pairs</u> at ~150Mpc separations.
- Sitting on a galaxy, the probability of finding a second galaxy a distance r away is:

$$dP = \bar{n}\left[1 + \xi(r)\right] dV$$

Looking for a peak in this!

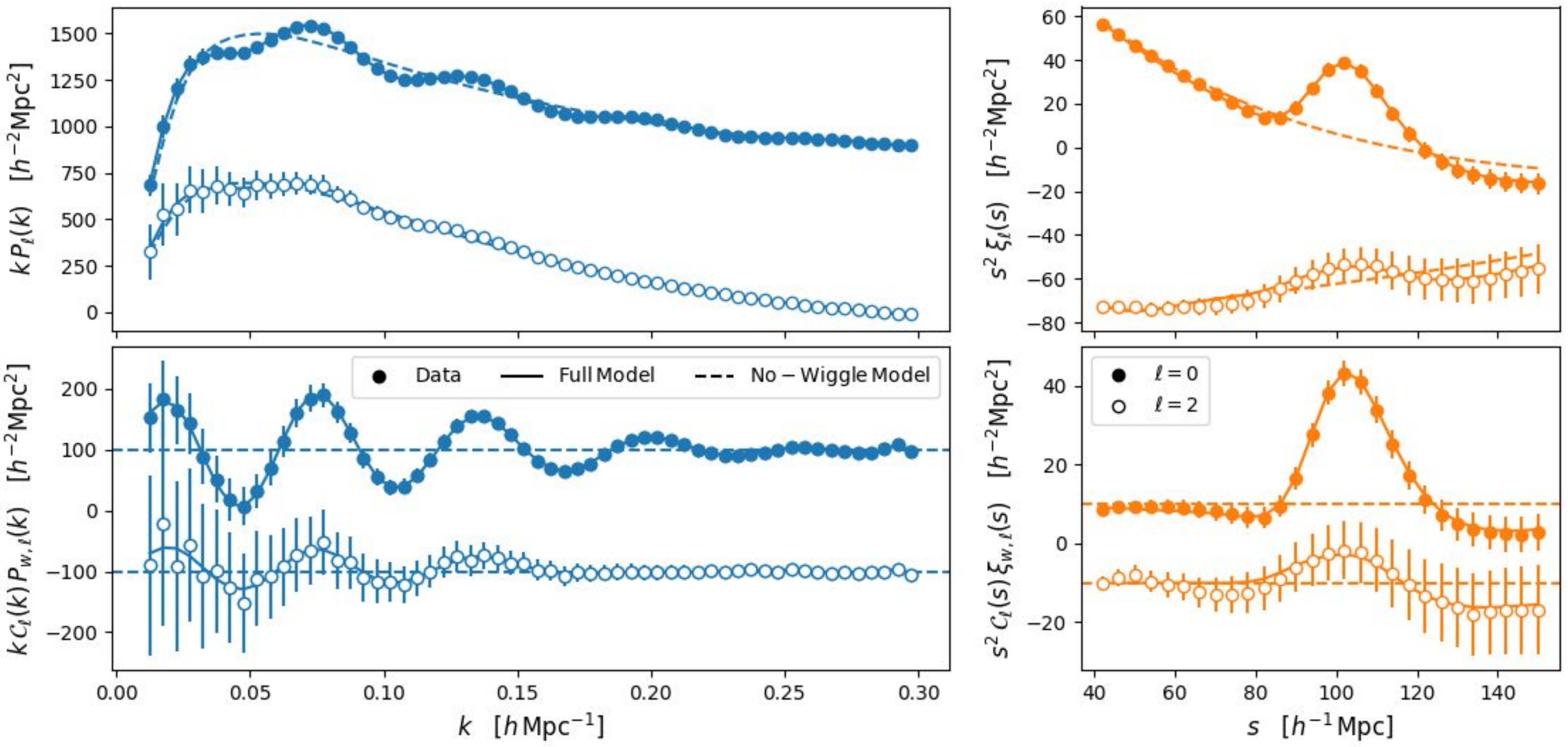
Those pesky details

- All I’ve really done so far is show you that a feature exists in the matter correlation function (or power spectrum) in linear theory.
- To make contact with observations need to address:
    - Non-linear evolution.
    - The fact that we observe galaxies or the IGM, not matter (bias).
    - The fact that redshifts are a combination of Hubble recession velocity and peculiar velocities (which are sourced by gravity, which is basically density, which is our signal).
    - Observational systematics, gaps in the data, etc., etc., etc.

Modeling

- To counteract non-linear evolution we apply density field “reconstruction” (using a new scheme).
- To handle bias and redshift-space distortions (peculiar velocities) we build an effective field theory model.
- The model used by DESI is a full 1-loop treatment with self-consistent IR resummation and a symmetries-constrained operator expansion …
    - New reconstruction method, algorithms and codes – **open source toolchain**!
    - Unified framework for all discrete tracers.
    - Use of combined tracers to measure BAO.
    - New template for defining “wiggle-no-wiggle” split.
    - Dilate only BAO wiggles, not broadband.
    - BAO damping parameters now varied, with tight priors, and made more accurate and theoretically self-consistent.
    - Apply FoG damping only to broadband, eliminating interaction with BAO and making interpretation of BAO damping parameters cleaner.
    - Spline-based broadband model rather than polynomials in 1/r or k.
    - …

Model test: theory vs simulation

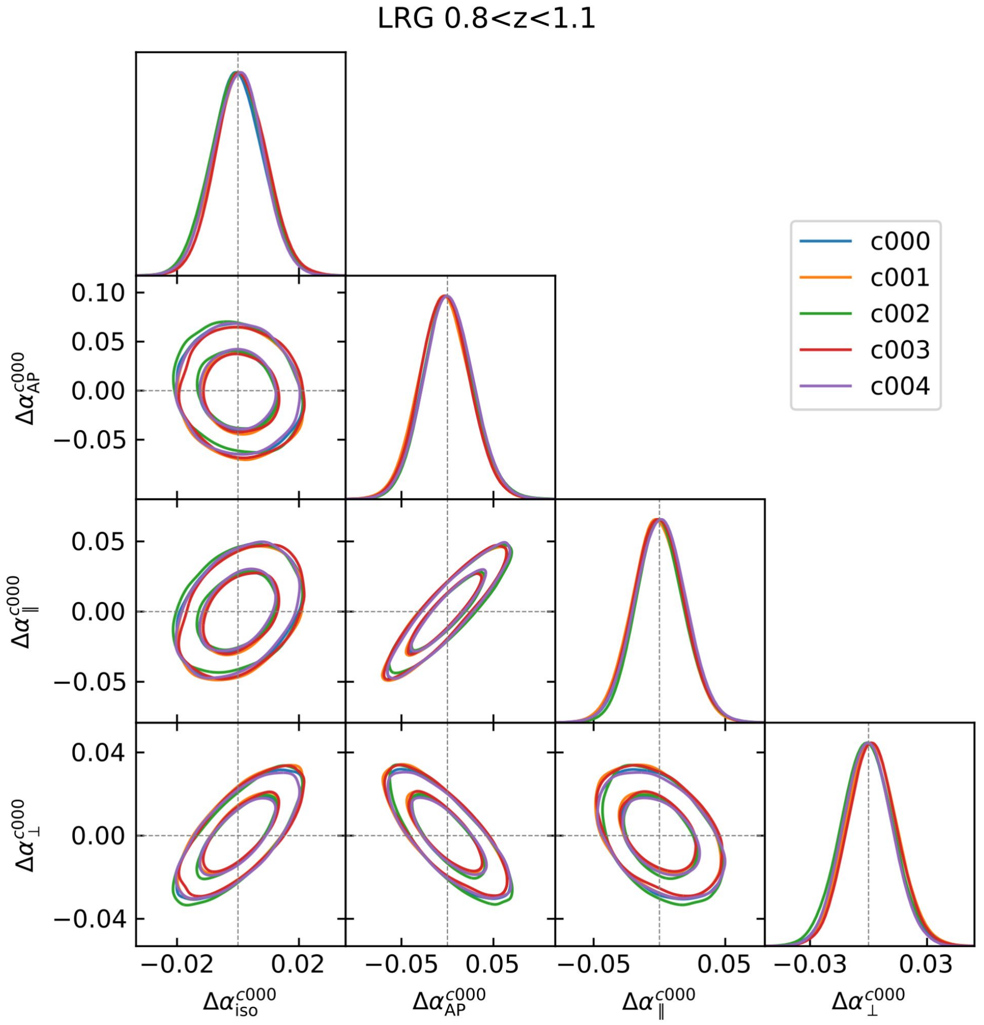


Systematic tests

One of a very large number of systematics checks (that are pretty boring to show!).

Here we show we can recover the input cosmology for five different choices (std, lower matter density, thawing DE, extra radiation, lower clustering) of the fiducial cosmology used to convert angles and redshifts to distance (for one of our redshift slices and galaxy samples).

All consistent.



The Dark Energy Spectroscopic Instrument (DESI) Y3 BAO results (DR2)

Dark Energy Spectroscopic Instrument (DESI)

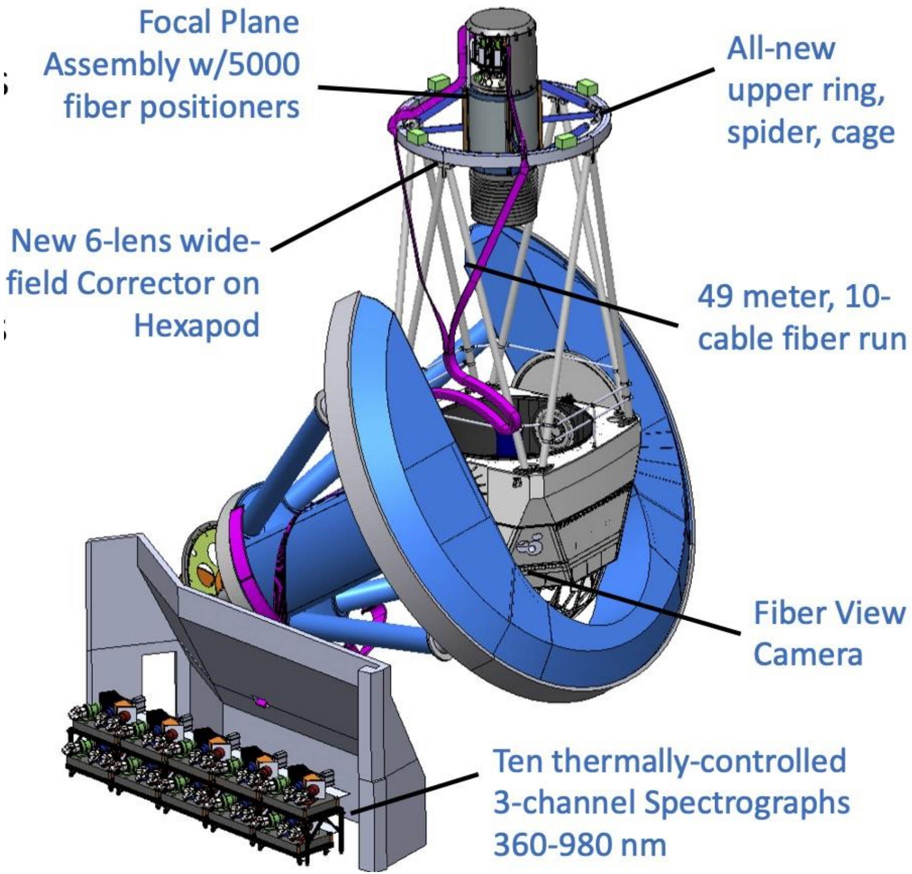
DESI's goal is to study the large-scale structure in the Universe to constrain the evolution of the cosmos and fundamental physics …

DESI will measure the spectra, and hence redshifts, of 50M galaxies over ⅓ of the sky, looking back over 11Gyr using 5 different classes of targets. It also measures fluctuations in the density of the intergalactic medium using absorption lines in the spectra of QSOs.

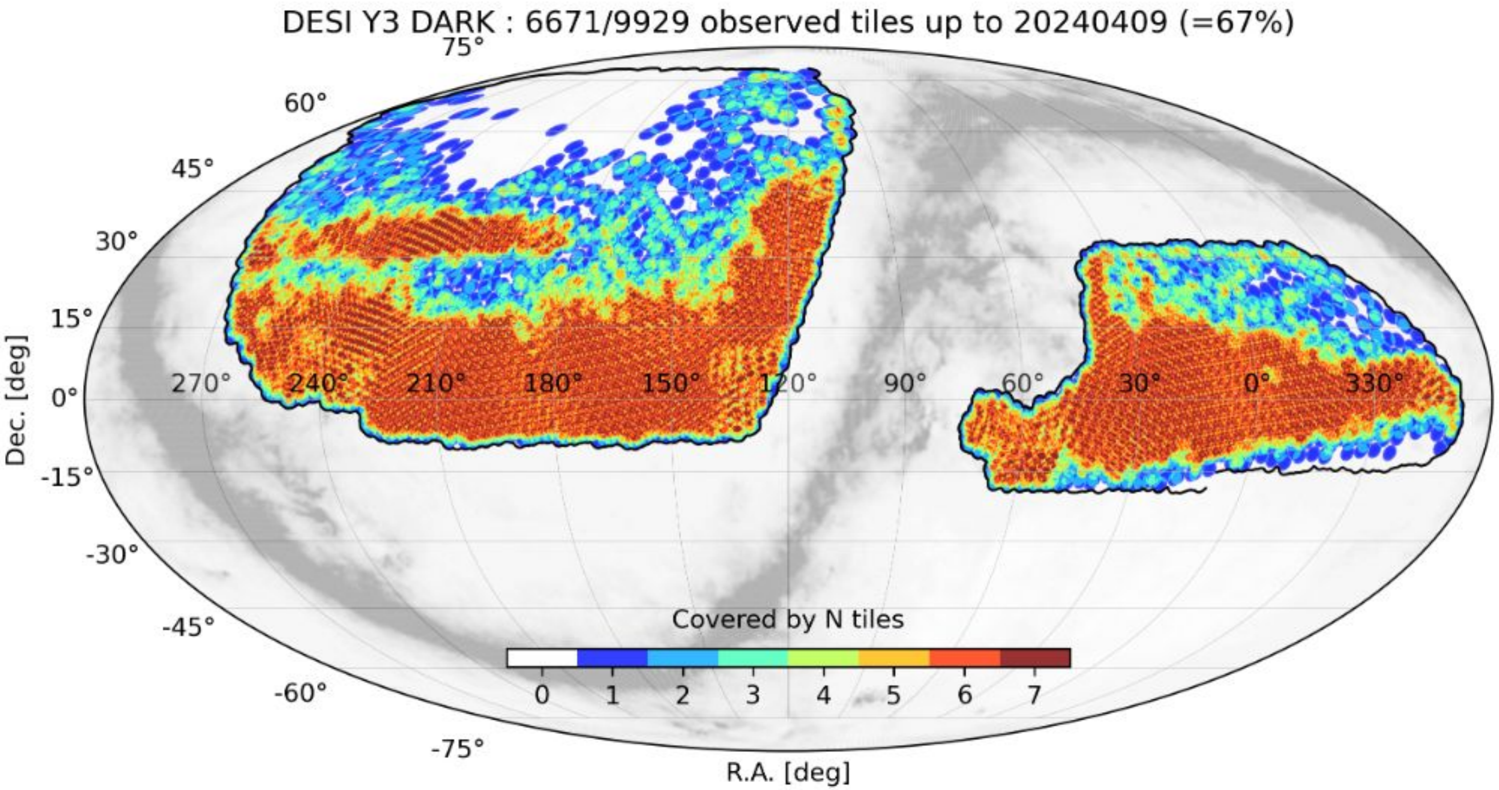
This talk is based on the 2nd data release covering data taken from May 14, 2021 through April 9, 2024 which employs 14M galaxies and 1M QSOs. This is already by far the largest such dataset ever taken …

DESI instrument

- DESI is a fiber-fed multi-object spectrograph with an 8 sq.deg. FOV.
- It uses 5000 robots to position optical fibers onto the location of objects in the focal plane.
- The fibers are fed to ten, 3-channel spectrographs.
- DESI can measure 10^5 galaxy redshifts in a night!



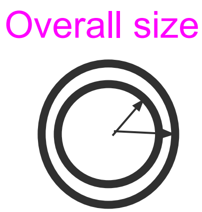
The DESI DR2 sample

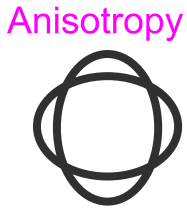


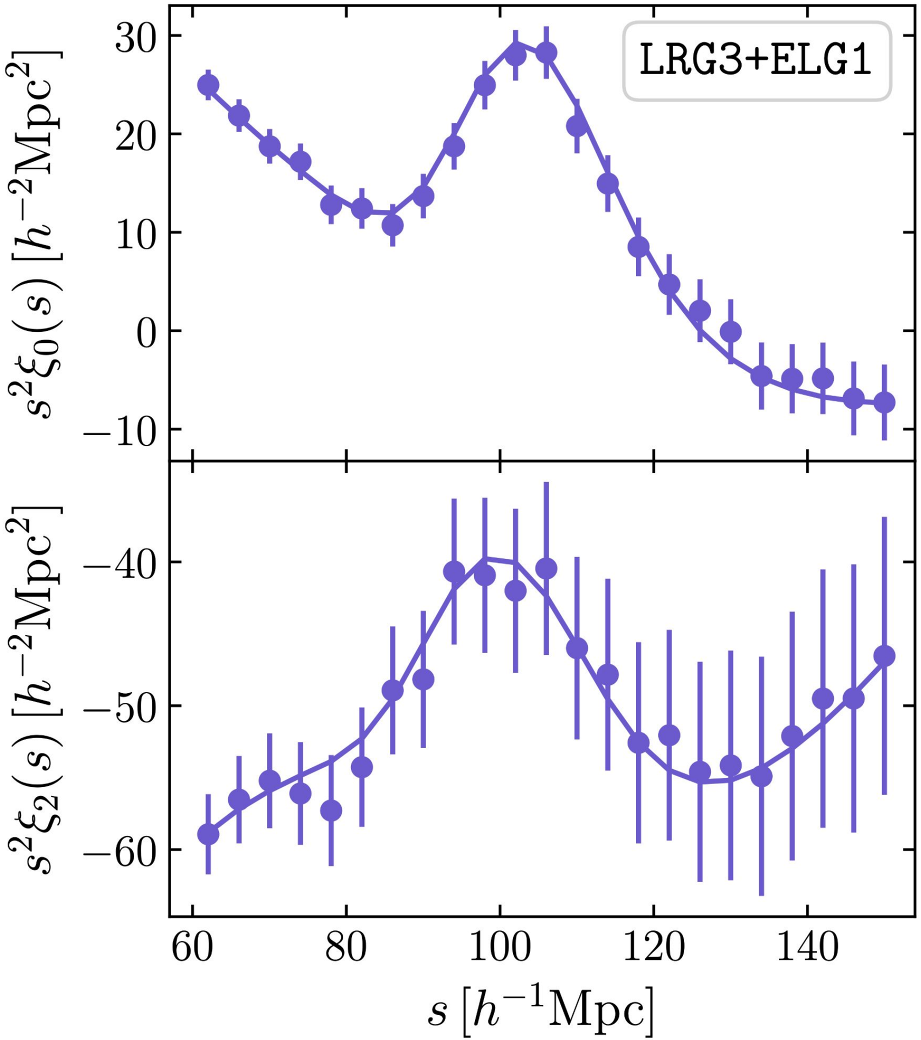
Measured clustering

With DR2 we have excellent measures of the excess clustering at the BAO scale across a wide range of redshifts!

The solid lines show the best-fit model, and the fit is excellent (beware, the error bars are quite correlated).



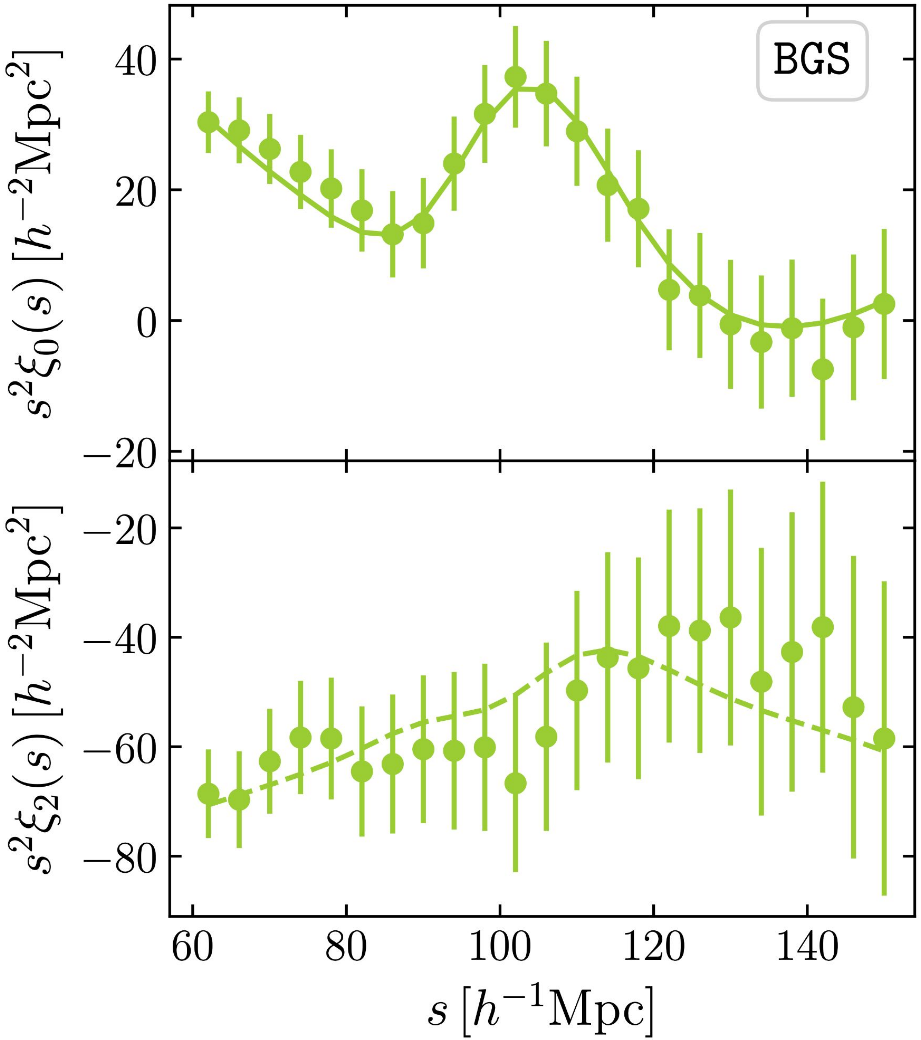




Lowest redshift

Here is our lowest redshift (closest) sample, just to show the first figure was not a fluke!

The data are noticeably noisier, but the fit remains good (again, beware correlated error bars!)



Each distance gives a constraint on 2 parameters

- Within the standard model (ΛCDM):
  - Redshift-dependence of isotropic measurement (DV/rd) and the anisotropic measurement (DM/DH) are both determined by matter density (Ωm).
  - Redshift-independent (i.e. constant) normalisation term for DV/rd set by "length" of the ruler: H0.rd
- Measuring the distance to a specific redshift carves out a "strip" in the Ωm-H0.rd plane.
- The ΛCDM model is consistent with the data if all of these strips overlap …

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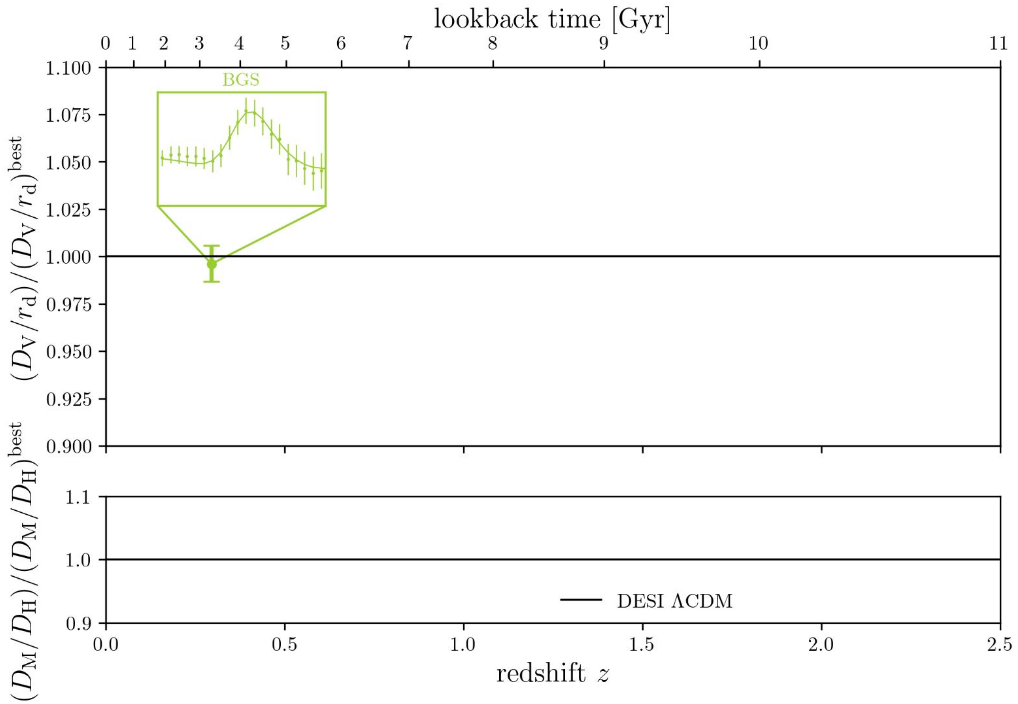
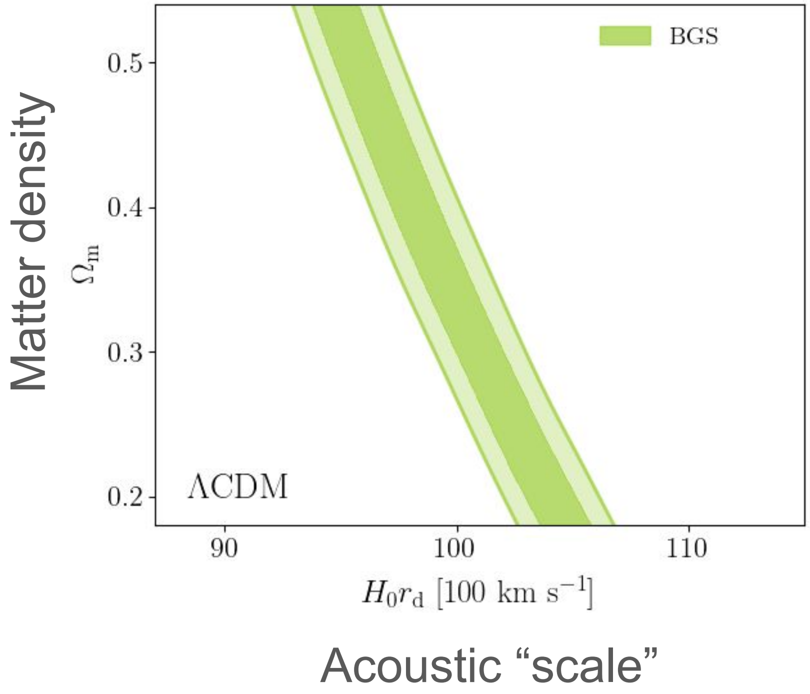
DESI BAO measurements



Flat ΛCDM results



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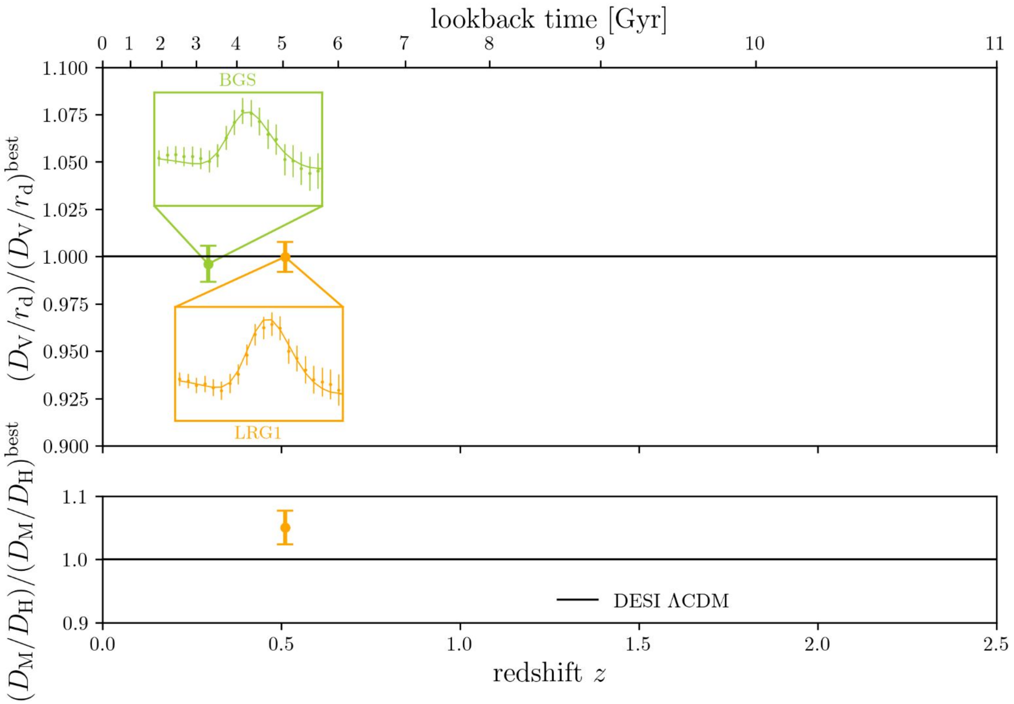

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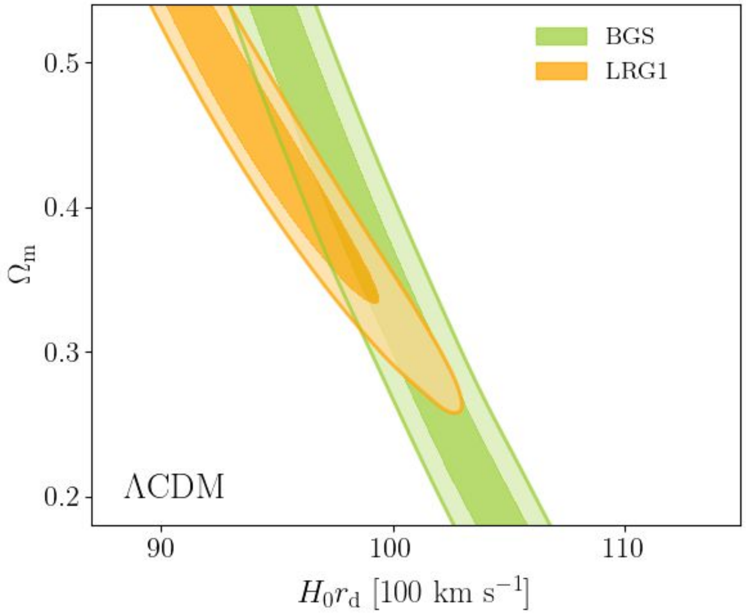

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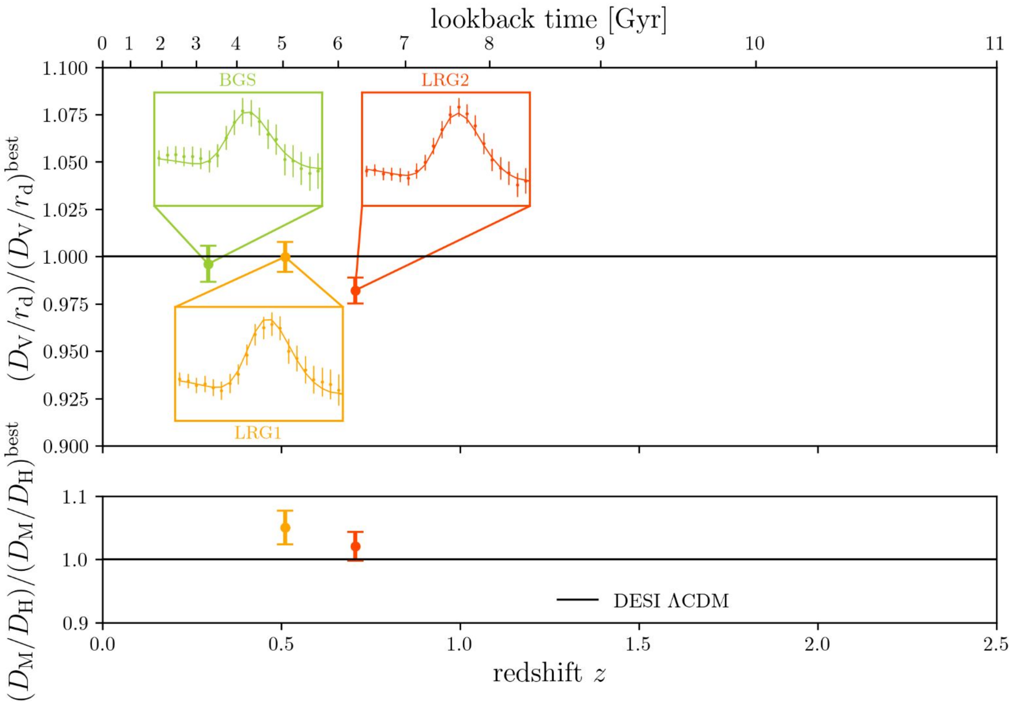
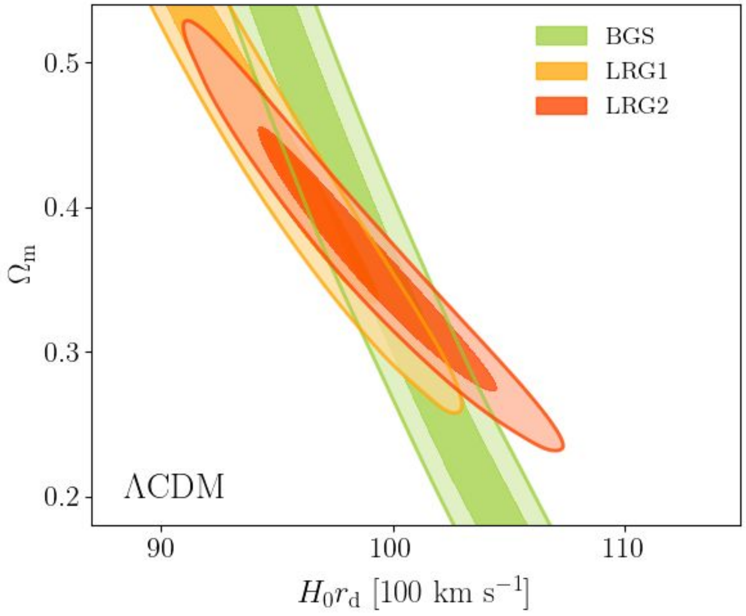
DESI BAO measurements



Flat ΛCDM results



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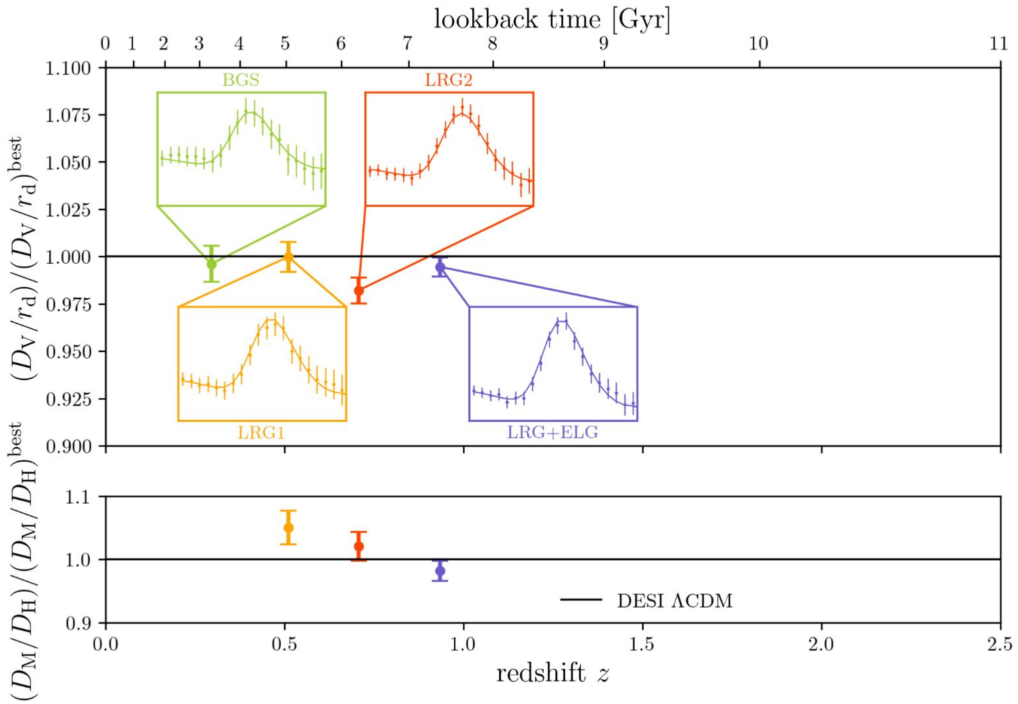
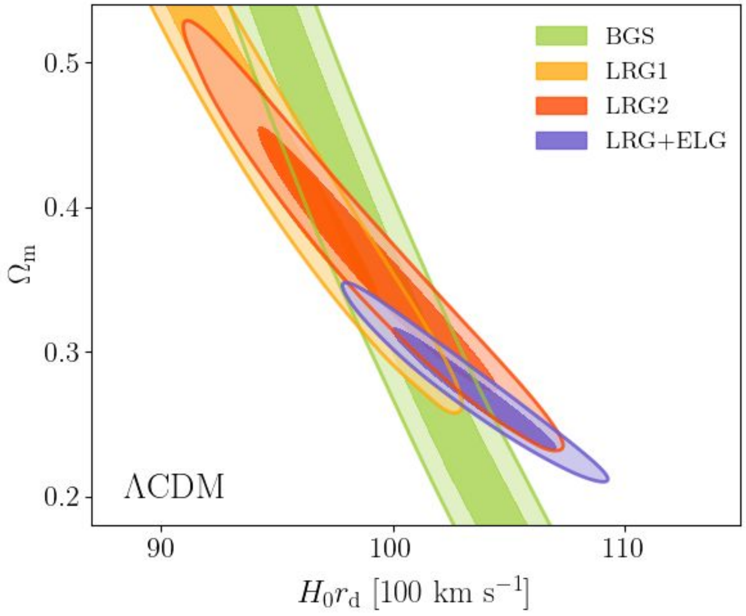
DESI BAO measurements



Flat ΛCDM results



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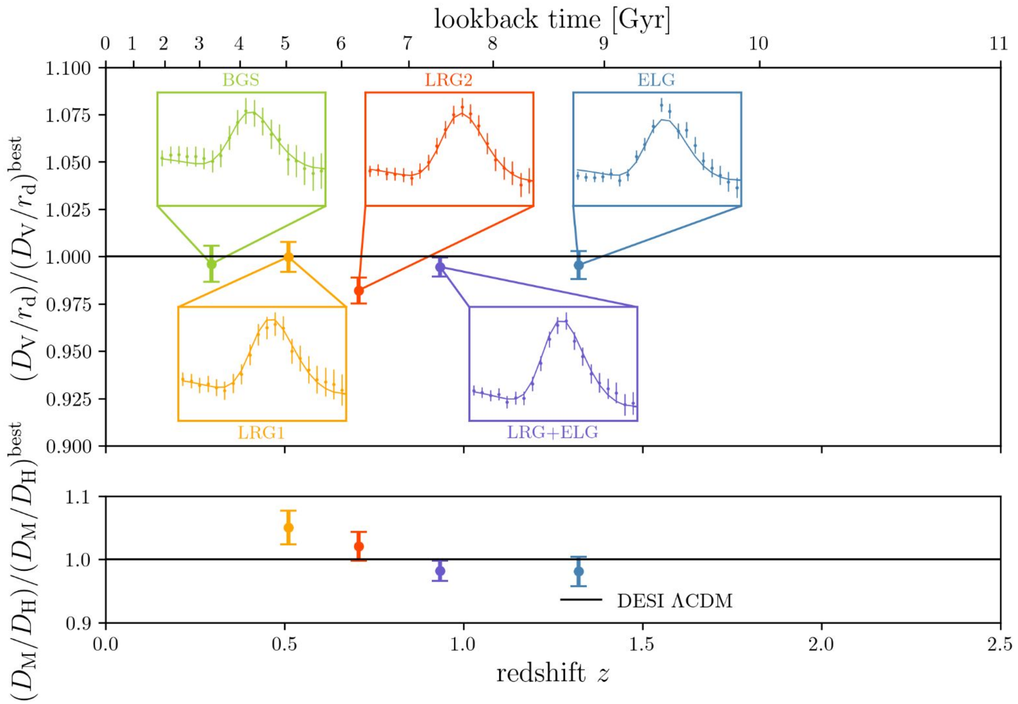
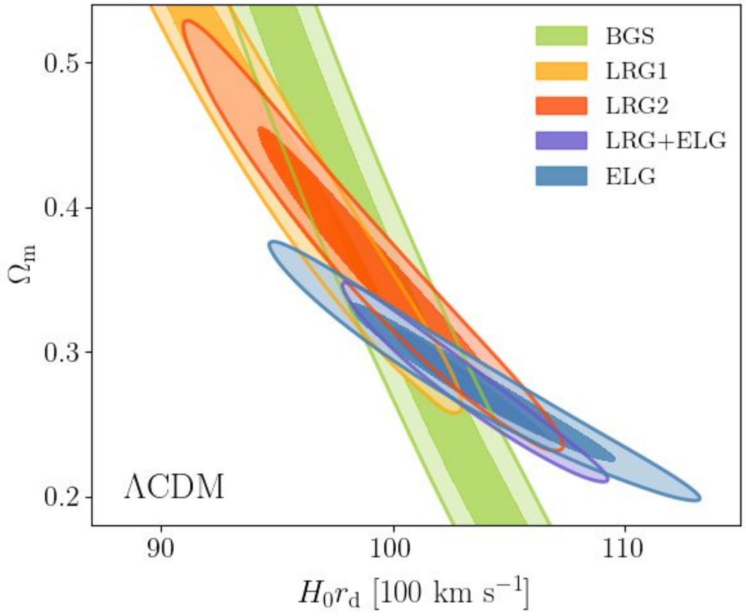
DESI BAO measurements



Flat ΛCDM results



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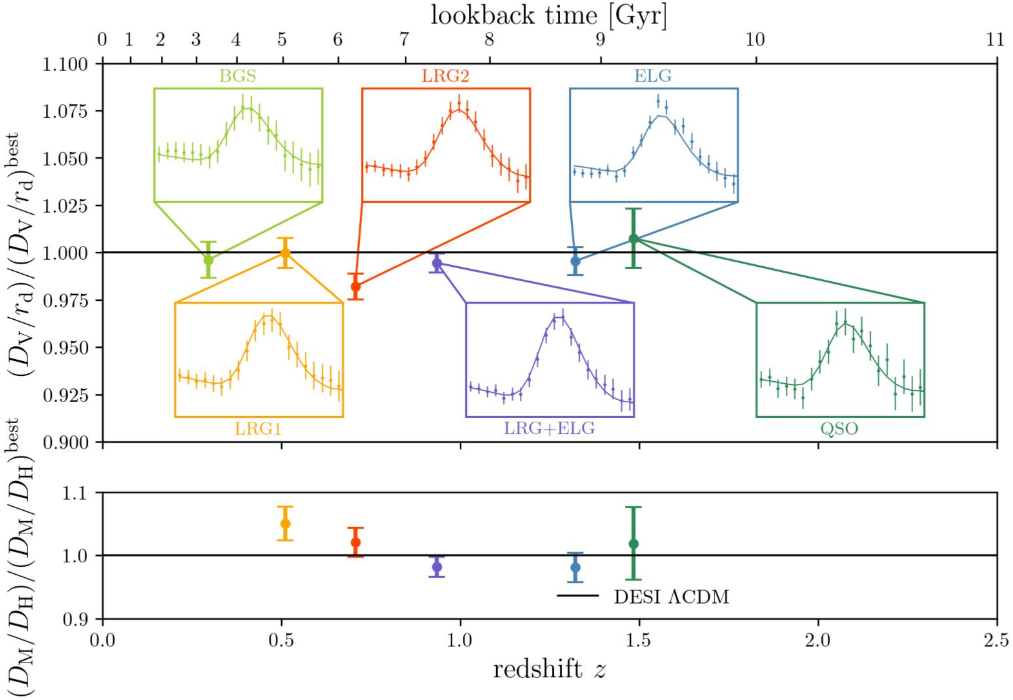
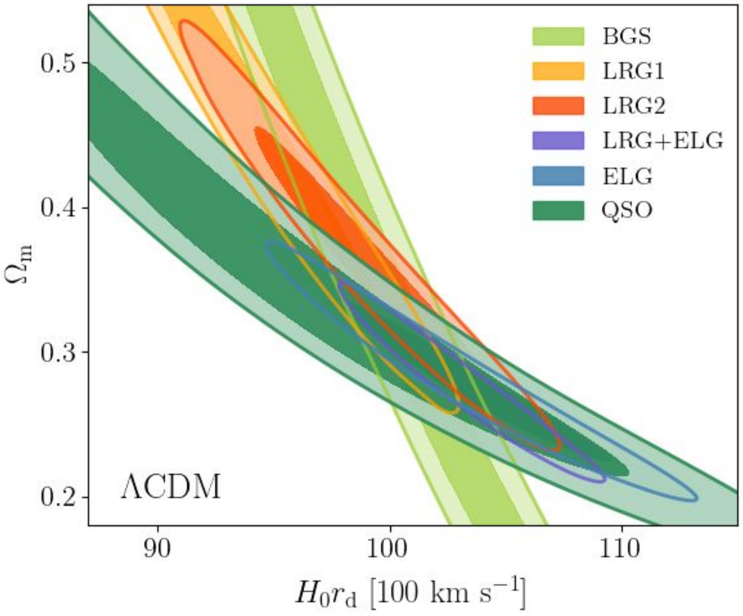
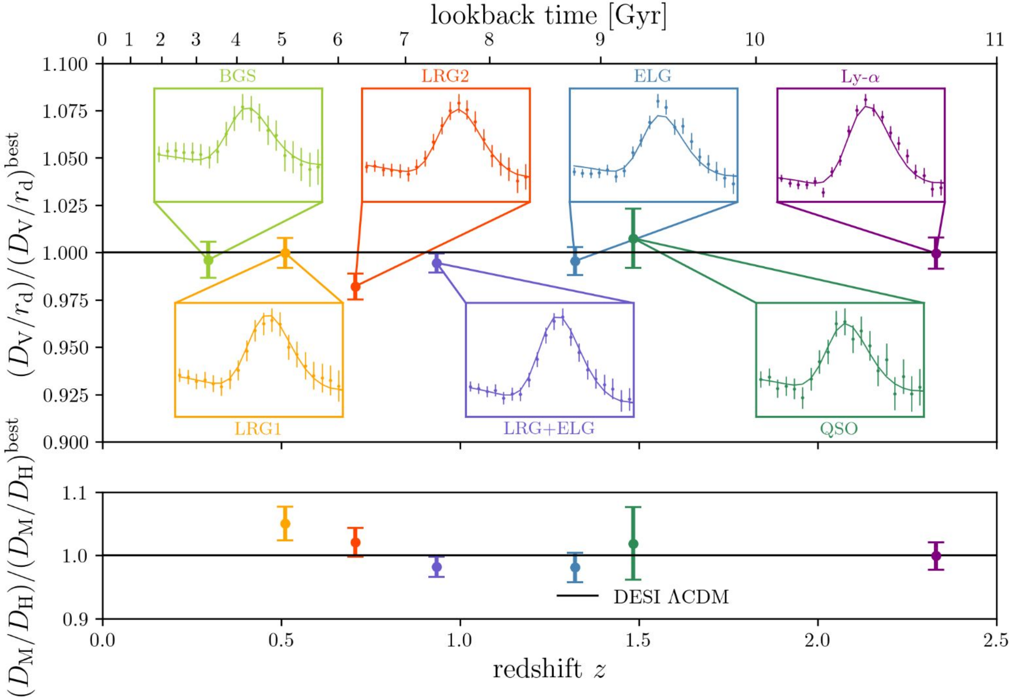
DESI BAO measurements



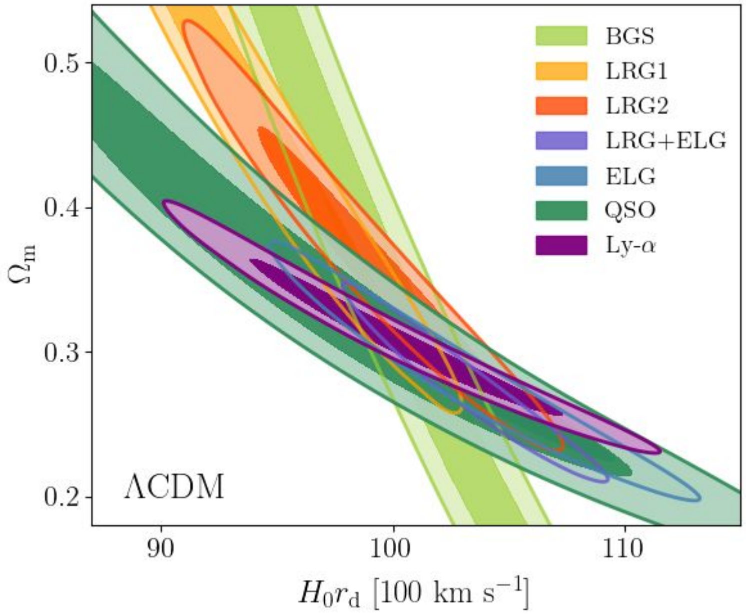
Flat ΛCDM results



DESI BAO measurements



Flat ΛCDM results



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DESI BAO measurements

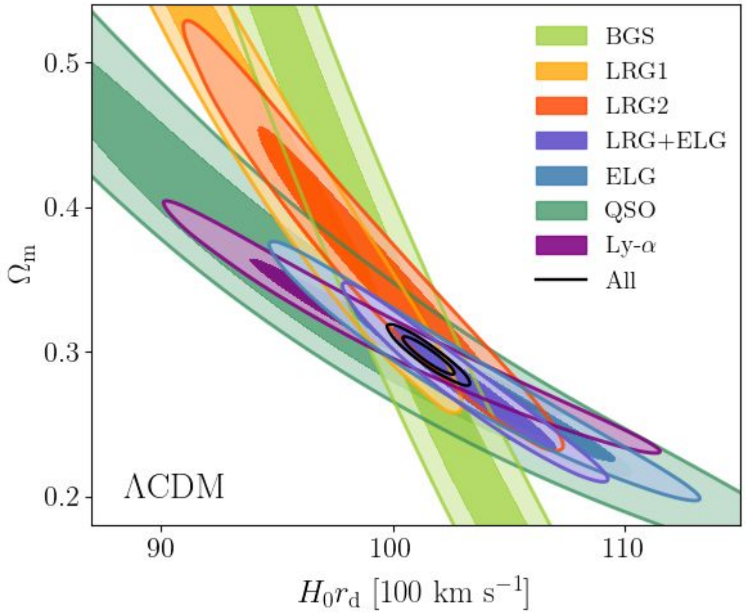
Consistent with each other, and complementary

$\Omega_m = 0.2975 \pm 0.0086$ **(2.9%)**

$H_0 r_d = (101.54 \pm 0.73)$ [100 km/s] **(0.7%)**

DESI

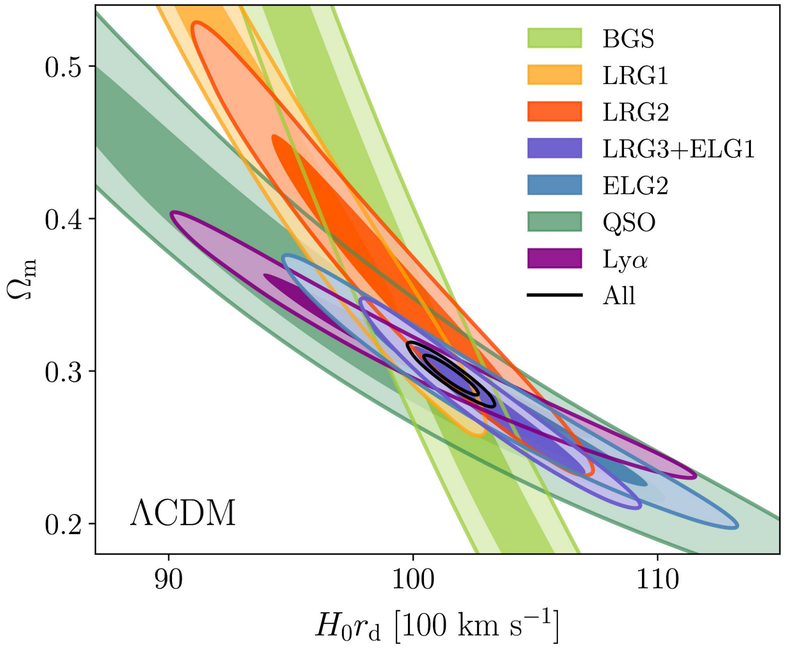
Flat ΛCDM results

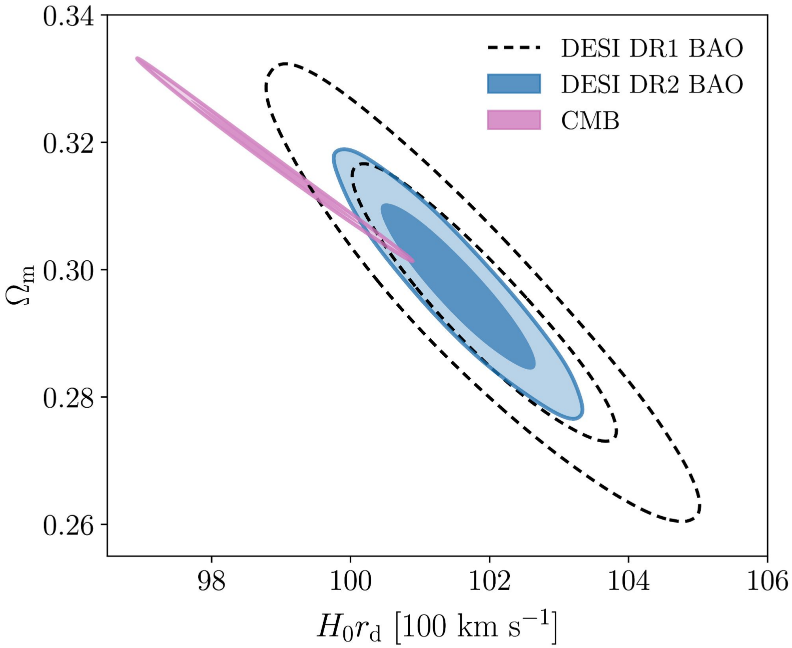


“Acoustic tension” within ΛCDM

All samples and redshifts consistent with same two values!

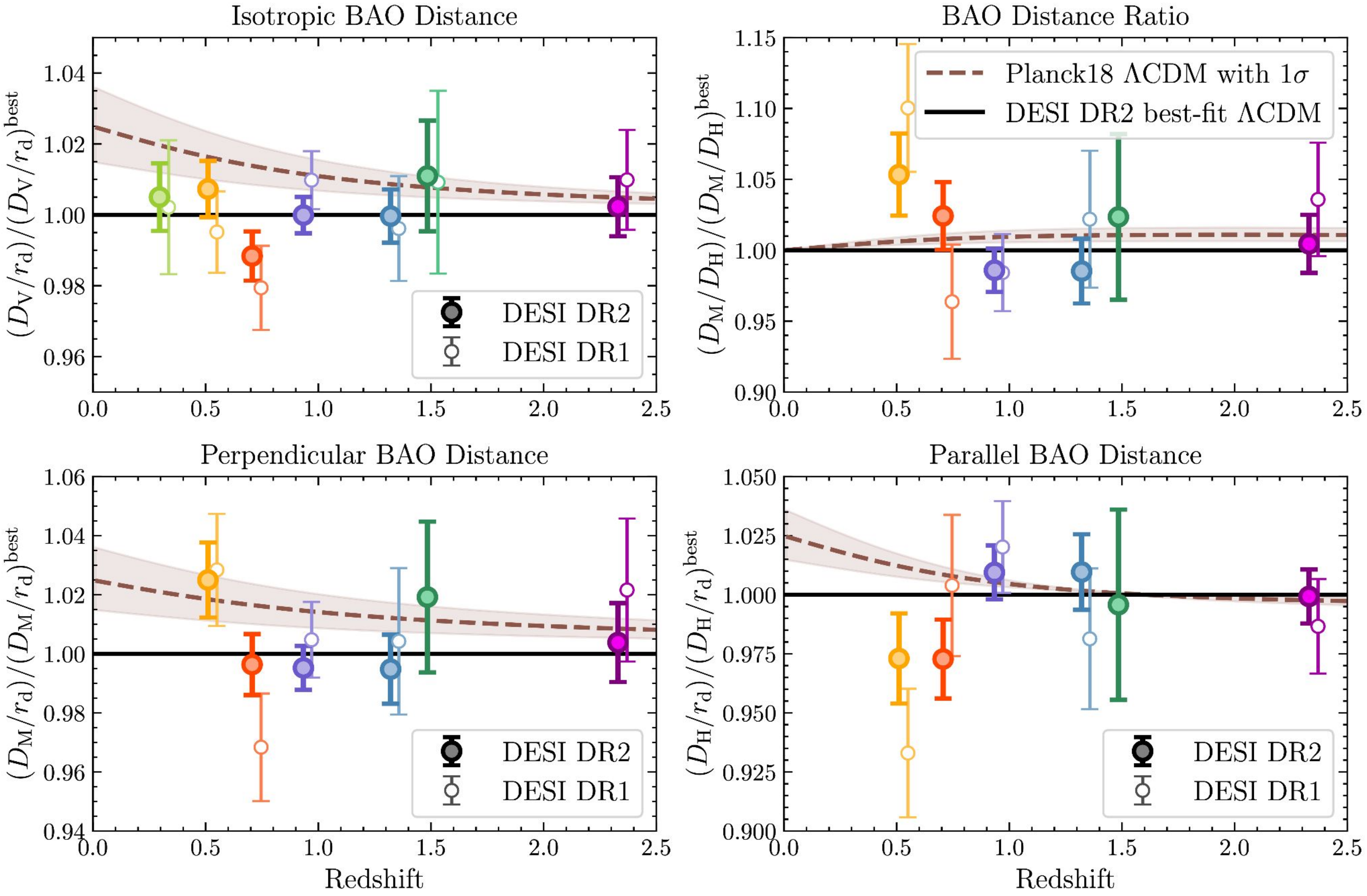
However those values are 2.3**σ** inconsistent with the CMB-preferred values …





Distance ladder from DR2

Good agreement with ΛCDM, but not the same model the CMB likes…



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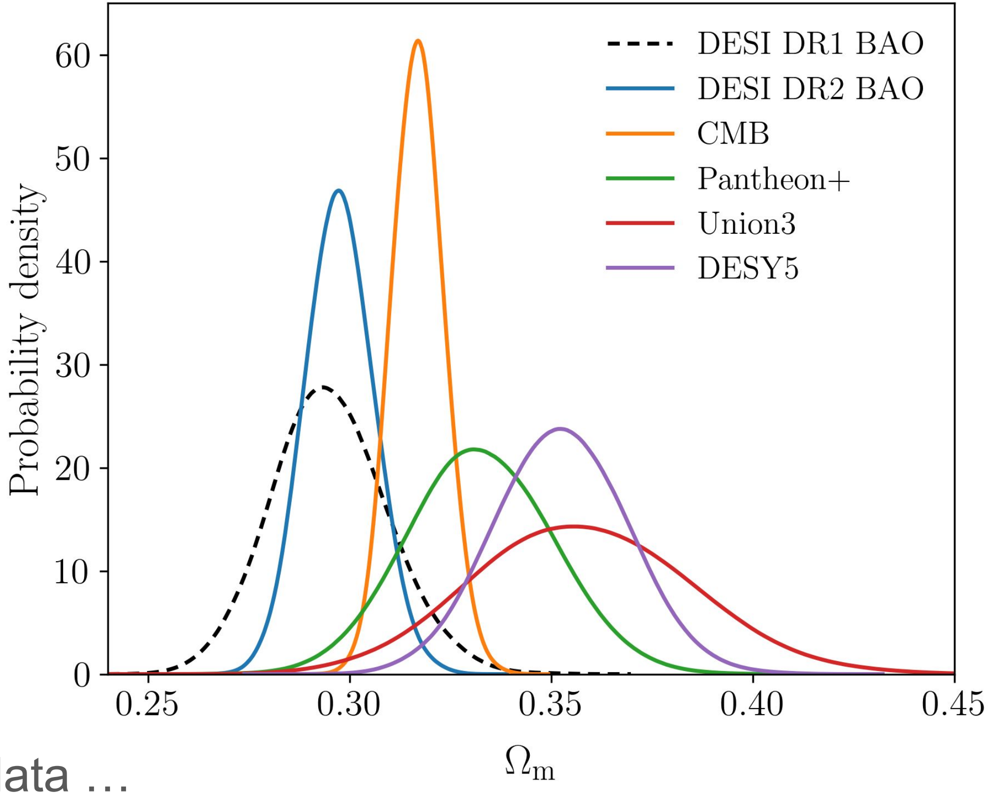
Other datasets also show "tensions"

- **DESI DR2** consistent with DESI DR1
- **DESI DR2** is lower than the CMB
- **DESI DR2** is lower than Supernovae:
  - 1.7σ lower than Pantheon+
  - 2.1σ lower than Union3
  - 2.9σ lower than DESY5



Standard model can't explain all of our data …

Modest tension …

We see similar tensions, pointing to the same kinds of solutions, when combining with other datasets.

Logically, we have 4 options …

- A “rare” statistical fluctuation.
- Some of the data/interpretations are wrong.
- Unexpected evolution in expansion [$H(z)=d\,ln(a)/dt$] at low z.
- Unexpected evolution in expansion [$H(z)=d\,ln(a)/dt$] at high z.

While the first two options are certainly possible, let’s focus on the last two …

Evolving DE/evolving EoS at low-z

If DE is not Λ, then it is not unreasonable to expect the equation of state (EoS: $w=p/\varrho$) will evolve with time/expansion. 1st law thermo. then gives evoln…

Absent strong theoretical guidance, choose a phenomenological form:

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

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

If w(z)>-1 then DE density drops with time.

If w(z)<-1 then DE density grows with time.

Λ is the point (w0,wa)=(-1,0)

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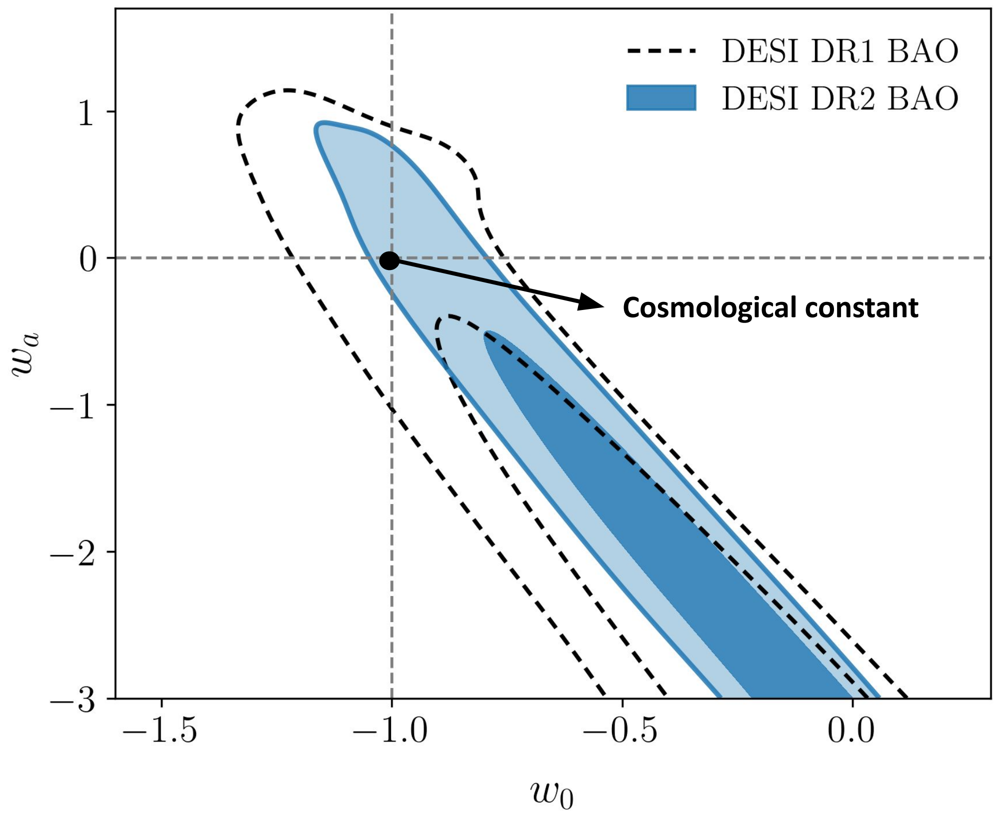
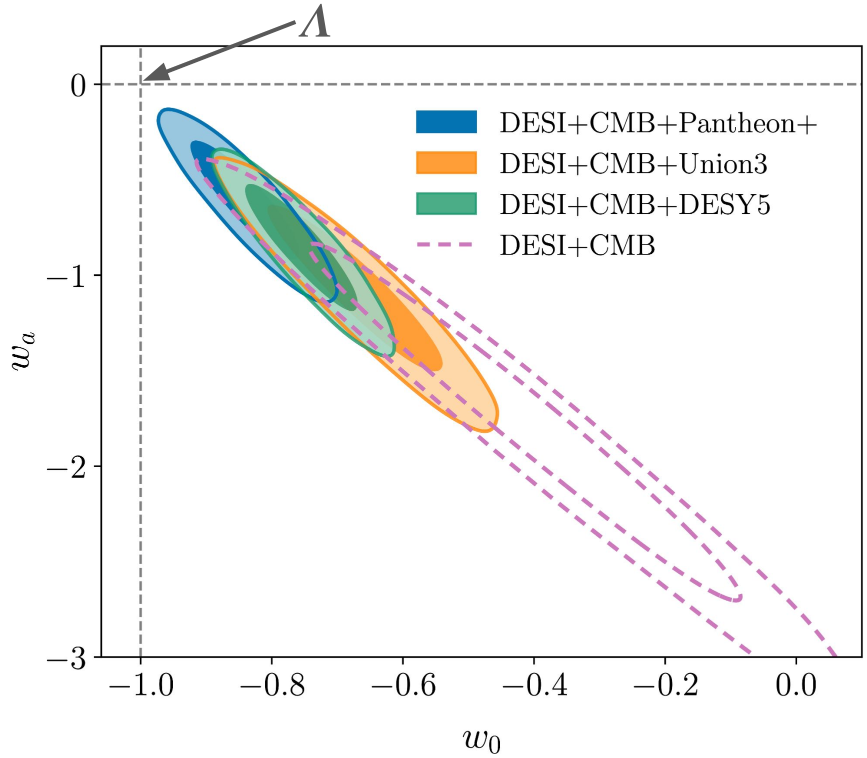
If we allow the EoS of the DE to vary, DESI alone provides weak constraints – with a mild preference for the “lower right quadrant”.

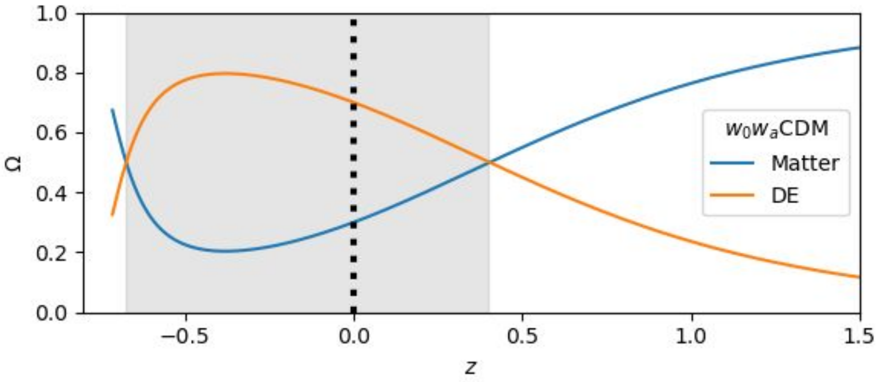
When we combine with other data things get interesting …



w0waCDM

If we allow the EoS of the DE to vary, DESI alone provides weak constraints. When we combine with other data things get interesting …





w0waCDM is preferred over ΛCDM at 2.8**σ**, 3.8**σ** and 4.2**σ** for combinations with the Pantheon+, Union3 and DESY5 SNe samples (respectively) and 3.1**σ** for DESI+CMB (no SNe).

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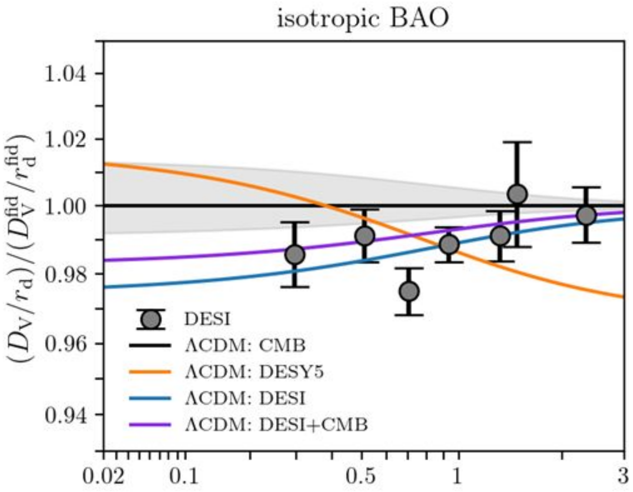
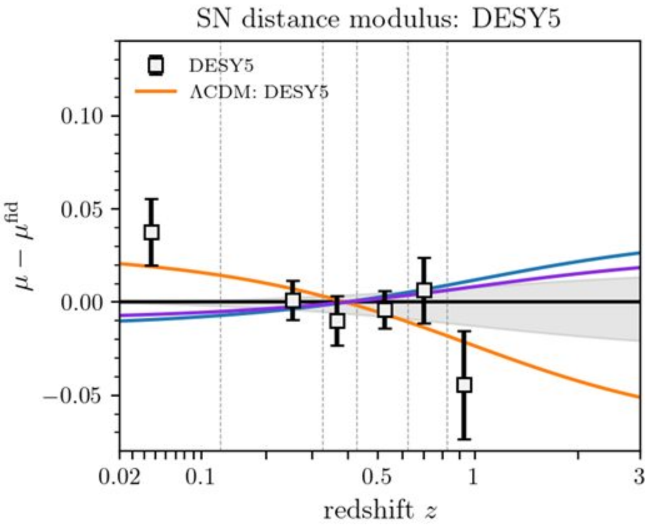
Isotropic BAO distance measurement



- There is a **ΛCDM** model that fits DESI BAO well
- DESI points at $z < 1$ prefer distances 1-2% lower than the CMB prediction

Supernovae distance modulus



- There is a **ΛCDM** model that fits SNe well
- Tension with DESI and CMB due to the contrast between $z < 0.1$ and $z > 0.1$ SNe

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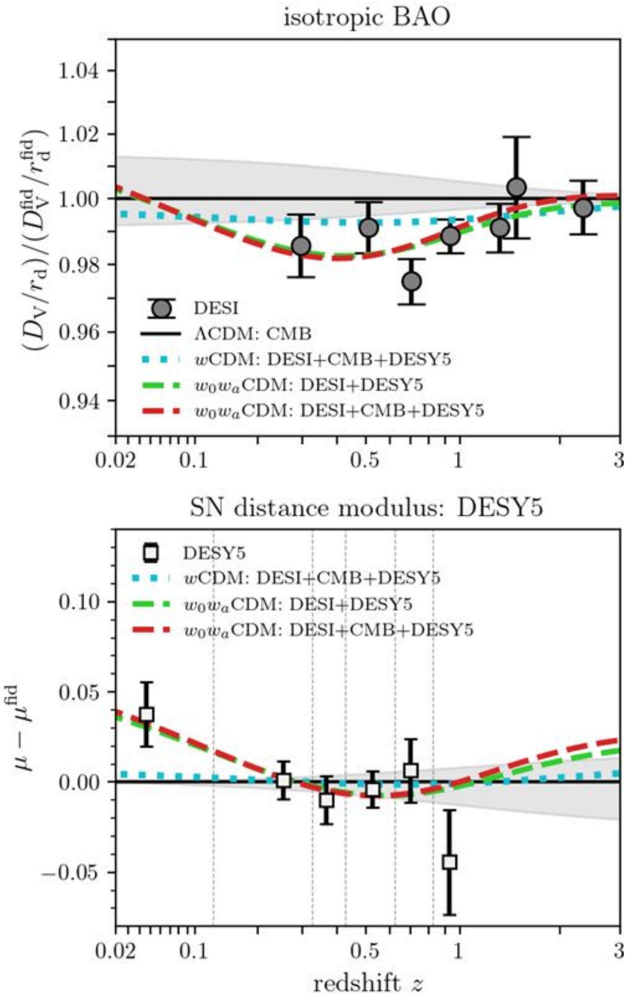
Isotropic BAO distance measurement

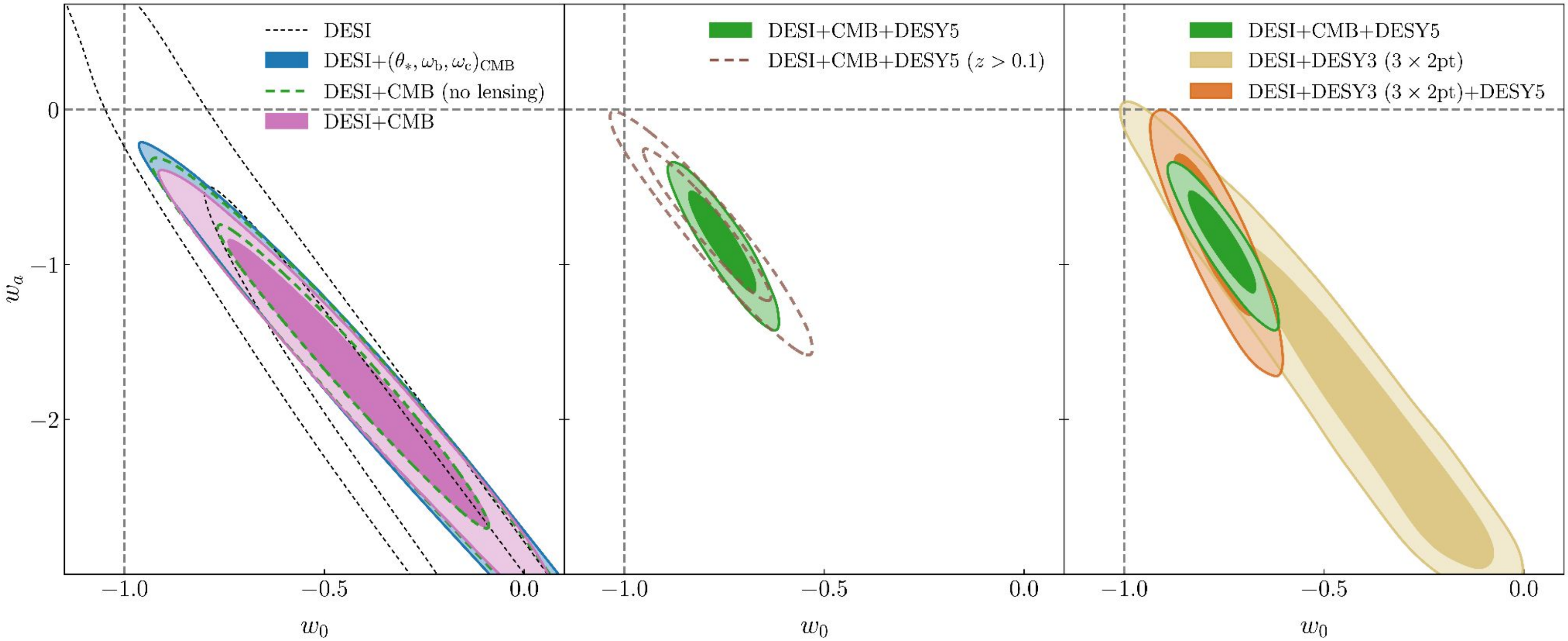
Supernovae distance modulus



$\Longrightarrow$ w0wa parameterization is the simplest that has sufficient flexibility to simultaneously achieve a good fit to all 3 datasets.

w0waCDM

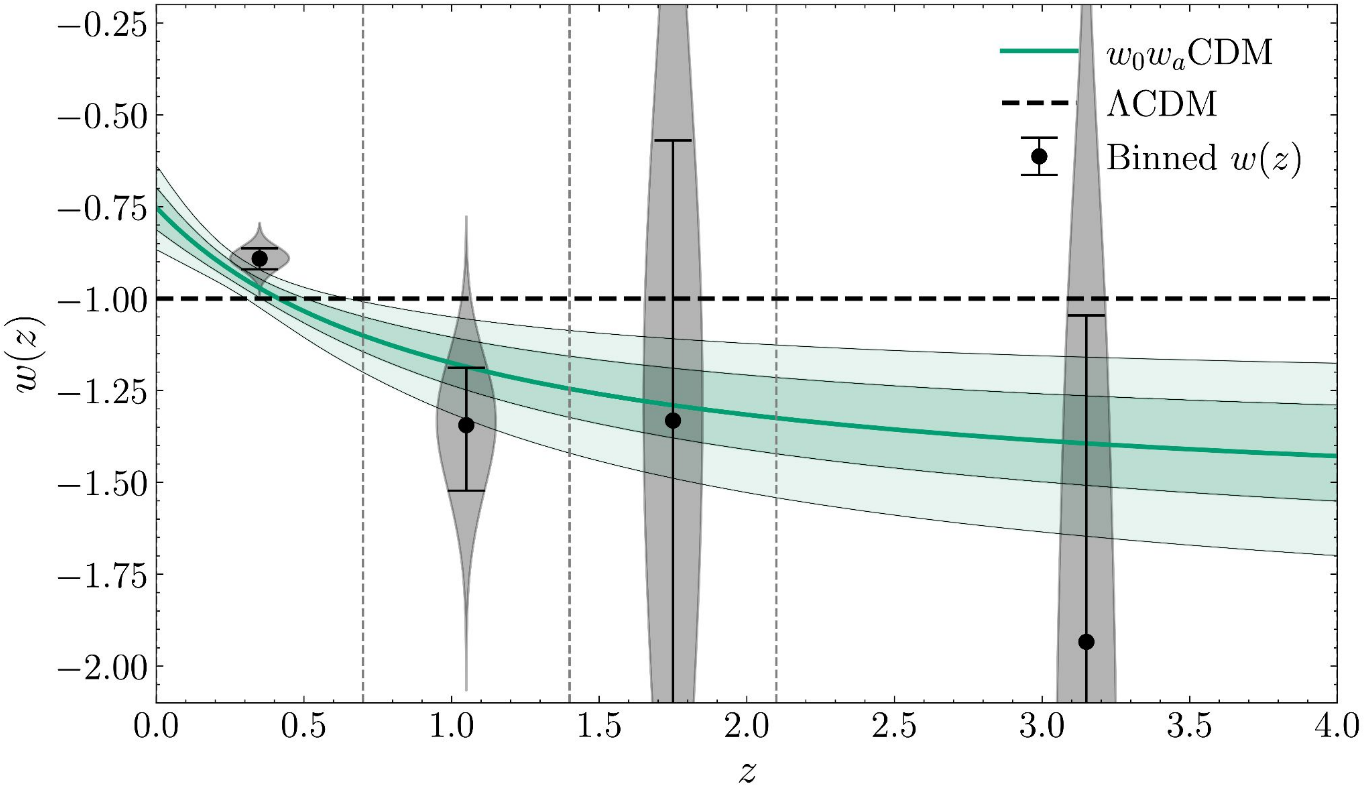
We need more than just DESI to see the tension, but we can swap what “else” we use …



Binned EoS

The assumption of a linear evolution of the EoS is quite strong.

However the tendency persists even when we try a “binned” EoS.

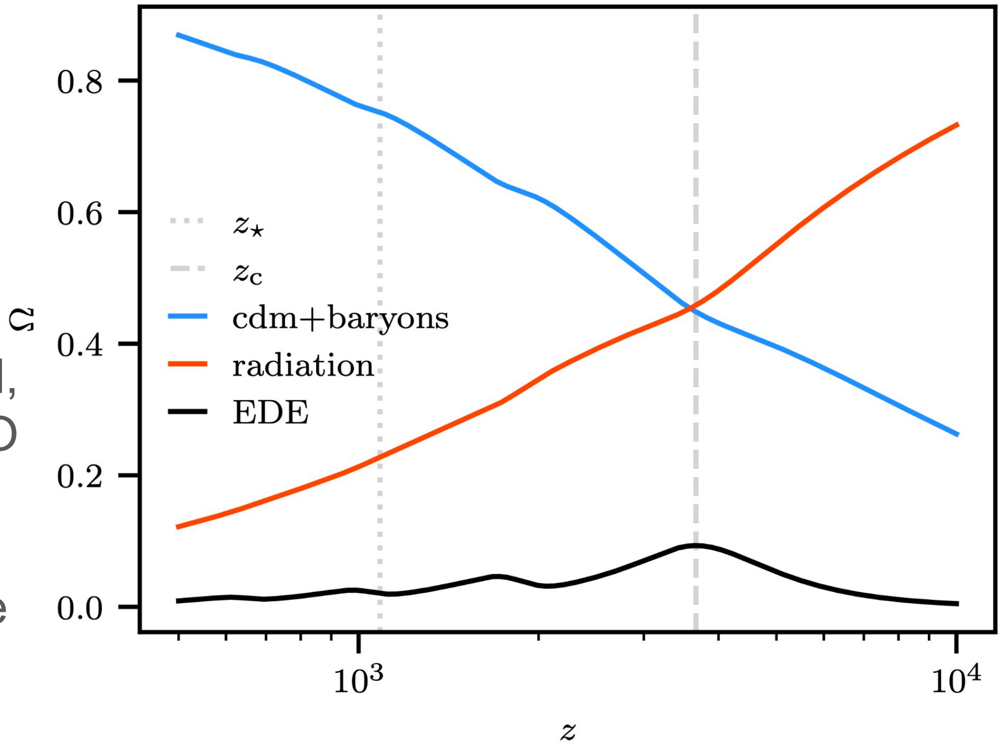


Early dark energy (EDE; high z)

This is an "old" idea that was first introduced to explain the "Hubble tension" (later!).

Introduce a new degree of freedom with an "axion like" potential into the Universe before the CMB decoupled, to change the calibration of the "BAO standard ruler".

Need to arrange it to peak at just the right time, then decay away very rapidly … (plus Λ at late times!).

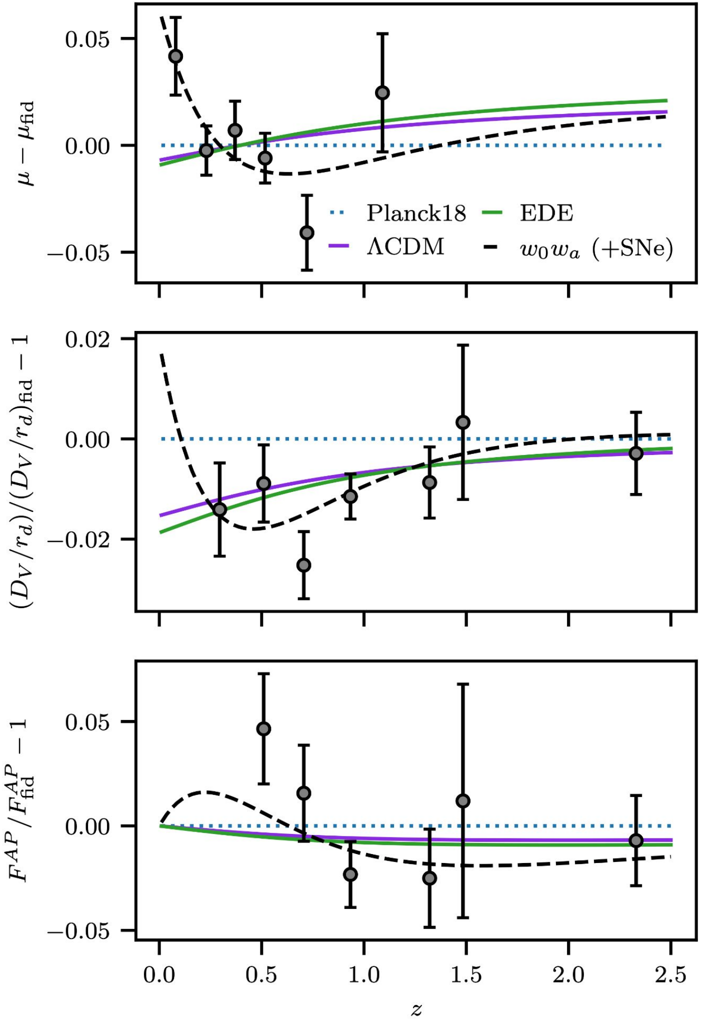


Early dark energy

A model invoking a rolling scalar field in the early Universe brings the “acoustic data sets” (CMB and BAO) into agreement.

It’s not quite as good a fit to the DESI data as w0wa, but is significantly better than ΛCDM.

It doesn’t match the late-time expansion history quite as well as the w0wa model does, and provides a worse fit to the “uncalibrated” SNe [but a better fit to the “calibrated” SNe].

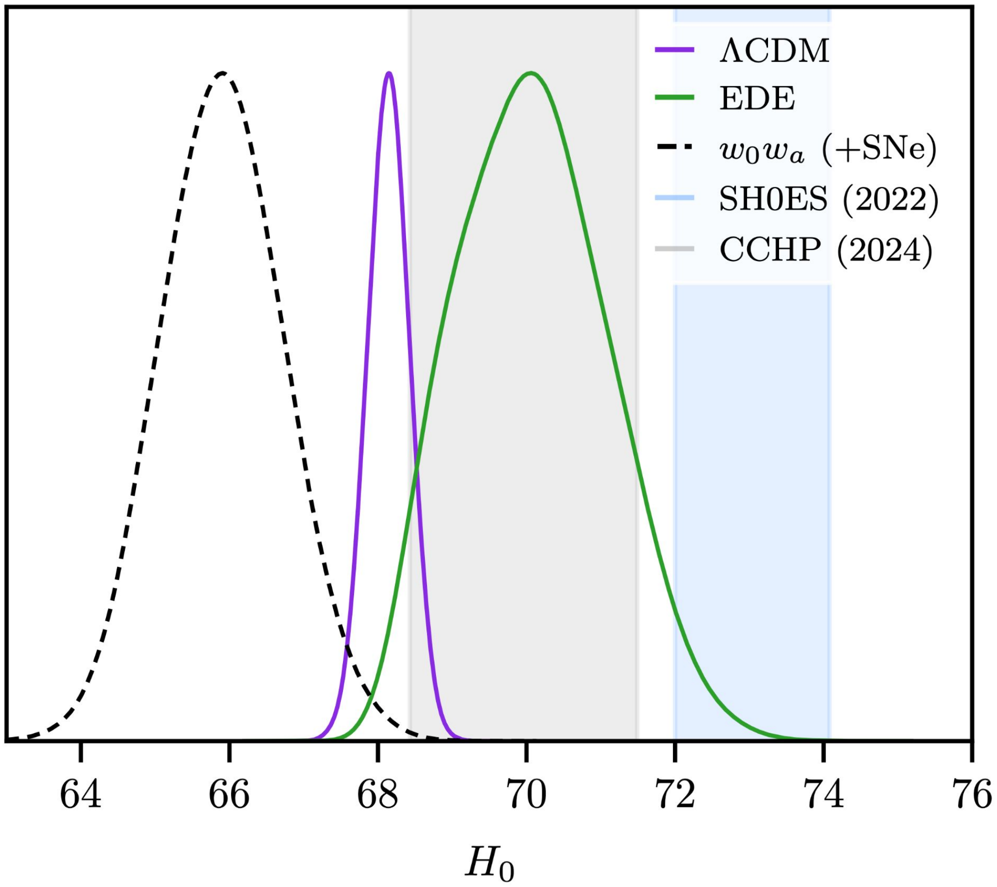


EDE reduces the "Hubble tension"

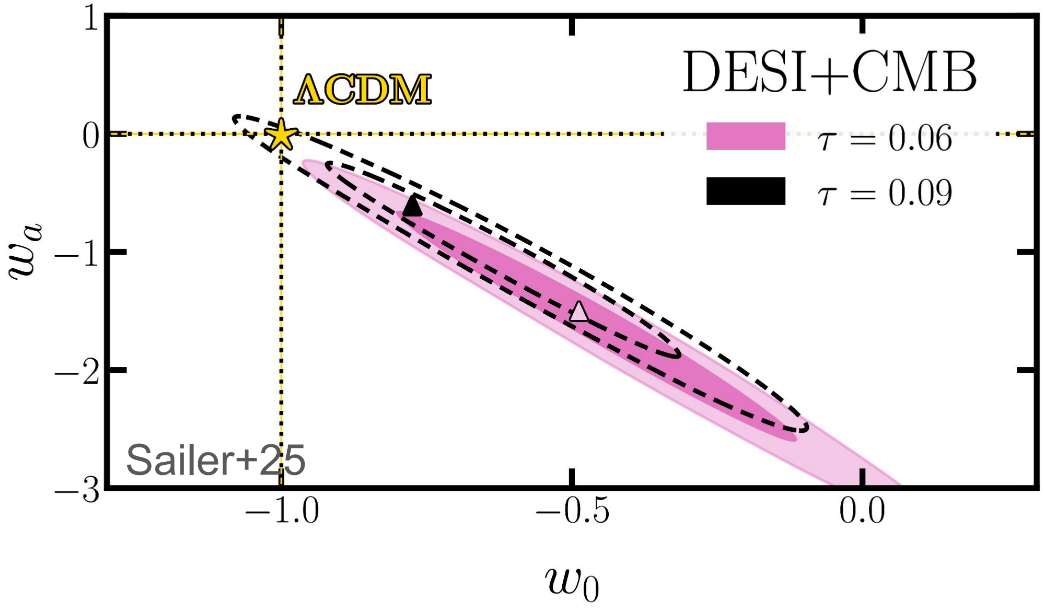
We can measure the expansion rate today (H0) using an "inverse distance ladder". Doesn't match local estimates!

The original motivation of the EDE model was to reduce this tension – not too surprisingly, it does this.

While it it doesn't match the uncalibrated SNe as well it can provide a better fit (2**σ**) to the CMB+BAO data and H0 …



Other options …



Of course, these options aren't exhaustive!

We could also have a small amount of positive spatial curvature (2x10^{-3}!) and reconcile CMB+BAO (but not "uncalibrated" SNe or H0).

We could have misestimated $\boldsymbol{\tau}$, and reduce the CMB+BAO tension …

etc.

Implications for neutrino mass

- Cosmology provides strong evidence for the existence of a neutrino background that behaves as we expect at the time of the CMB.
- Neutrinos are the only known particles to behave as radiation in the “early” Universe and as dark matter at late times – thus they leave an imprint on cosmological observables that is sensitive to their total number and mass.
  - At the “background level” νs change the expansion history ($H \sim \sum \rho$).
  - At the “perturbation level” neutrino free streaming suppresses power.

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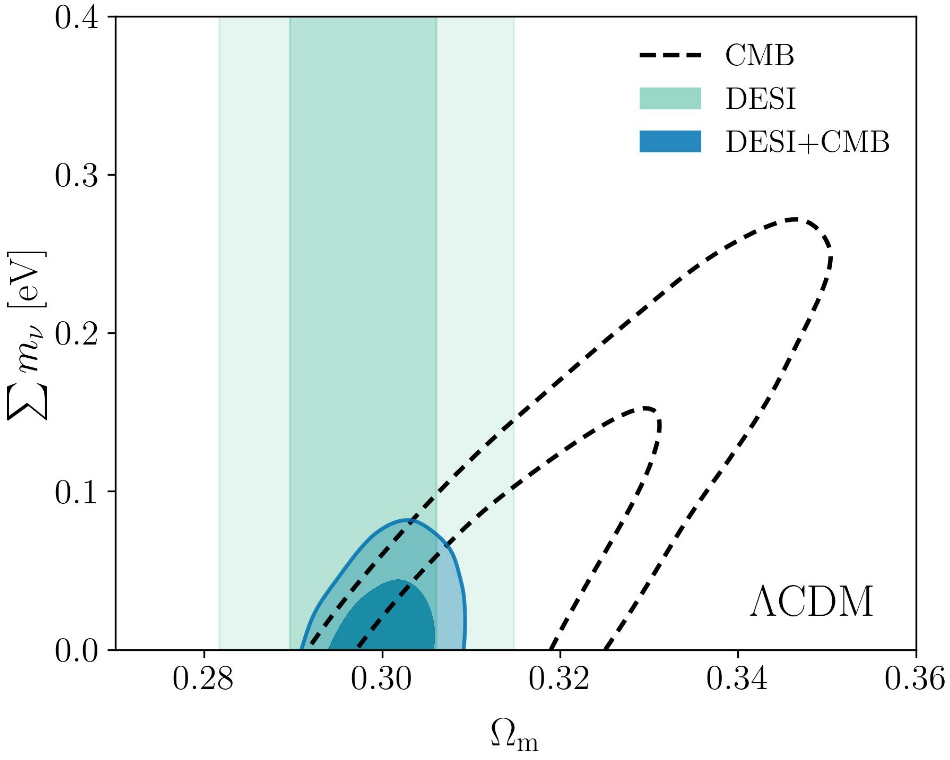

- Massive neutrinos change the expansion rate and thus the distance to the CMB (when $k_B T$~eV).
- However this is degenerate with the effects of other parameters (e.g. **Ω**m).
- DESI BAO help to break this degeneracy – but depends upon the assumed model!

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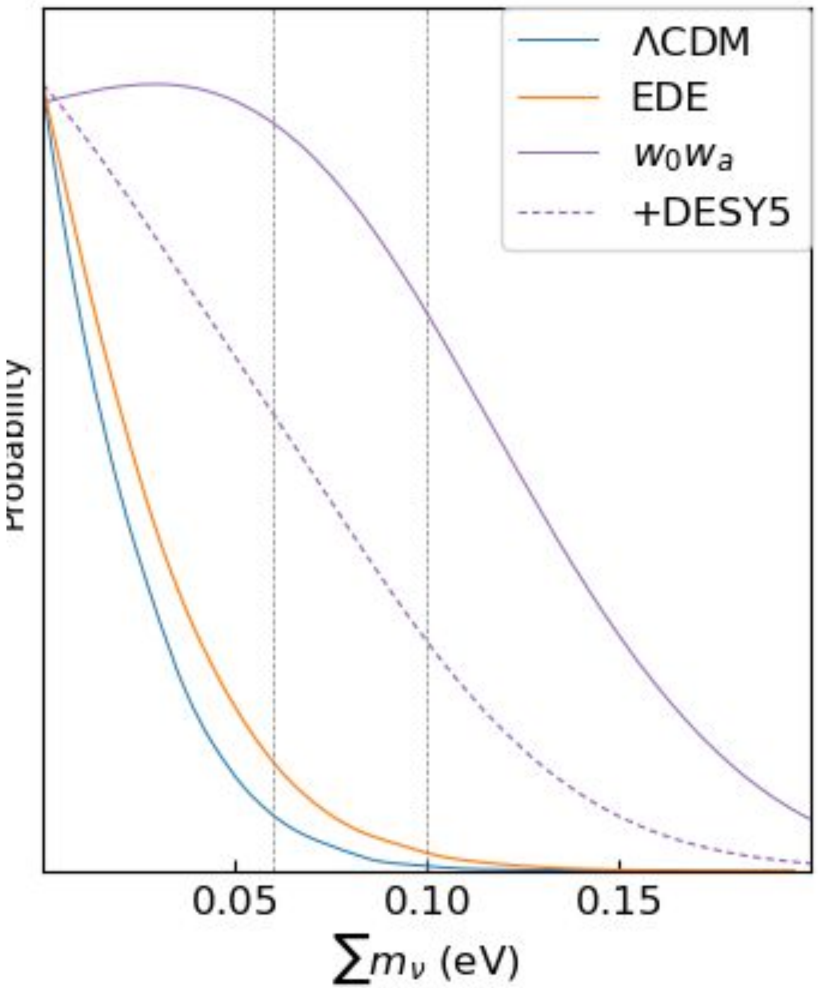
- Assuming **a ΛCDM background**:

$$\sum m_\nu < 0.0642 \text{ eV (95\% CI)}$$

- Close to the lower limit allowed by terrestrial experiments ($\sum m_\nu >$ 0.059 eV)

- Constraint significantly relaxed for **a w_0w_aCDM model**:

$$\sum m_\nu < 0.163 \text{ eV (95\% CI)}$$



Golden age of (cosmological) surveys

These results rely on combining experiments … which we are still learning to do. Moving forward we anticipate that much of the best science will come from these endeavours so we need to learn how to do this well …

- **DESI is nearly finished its 1st survey**
- PFS has started.
- Euclid is observing at L2.
- South Pole Observatory running.
- Simons Observatory is running (Adv SO is approved).
- SPHEREx is in orbit.
- LSST will be coming online very soon.
- Roman will launch later this decade.
- CMB-S4 will follow in the next decade.
- … and others waiting in the wings ...

Each is powerful in its own right, together they will be amazing …

What’s next for DESI?

- The results I showed depended only on a single feature in the clustering (the “BAO peak”).
- A “full shape” analysis, probing the gravitational potentials and growth of large-scale structure will follow next year. Expect tightest constraints from large-scale structure to date!
- Combination of DESI spectroscopic data with other surveys (e.g. Planck, ACT, … DES, …) on a similar timescale.
- Inclusion of higher-order correlators, beyond the 2-point function.

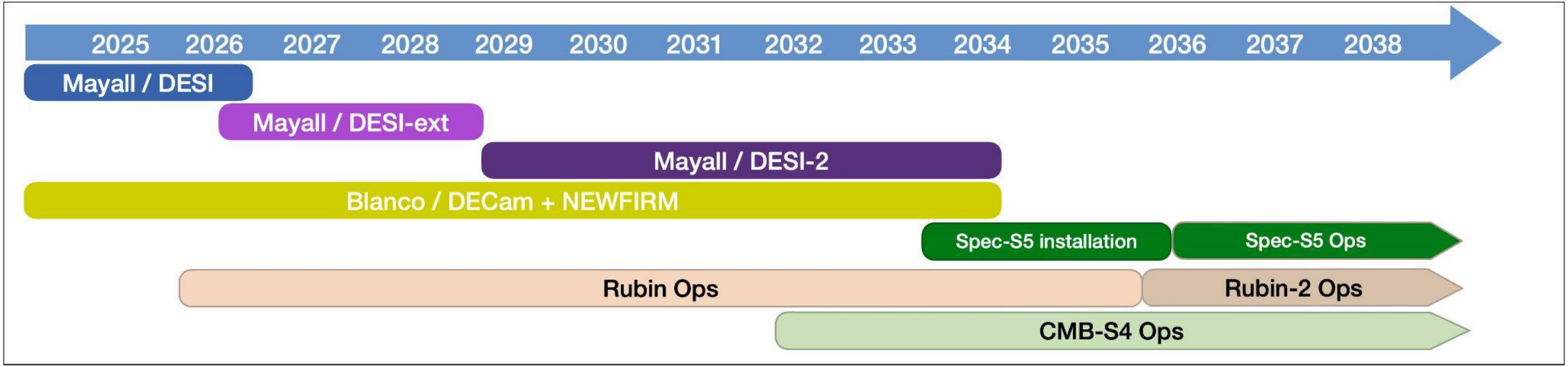
We expect these to be a significant advance over our Y1 results in both methodology and volume of data!

Beyond the main DESI samples

- Many pilot surveys completed over last several years.
  - Explore the capabilities of the DESI spectrograph
- More than 200K spectra collected in Rubin Deep Drilling Fields
  - $z>2$ galaxies for primordial physics
  - $z<1$ galaxies for galaxy-galaxy lensing science
  - Faint galaxies for photo-z training
  - Host galaxies for SNe cosmology
  - Dwarf galaxies for dark matter
  - etc, etc, etc, …

Spectroscopic roadmap

- Dark Energy Spectroscopic Instrument (DESI; primarily z<1.5)
  - Ahead of schedule, and nearly finished its 6yr program.
  - Planning “extended” observations to increase footprint and # objects.
- DESI+ (continued observational program, “pathfinder” for “Stage 5”)
  - As powerful as DESI, but at z>2 with unique access to primordial physics.
  - Synergies with other cosmology experiments.
- Spec-S5 (new, dedicated facility >10x more powerful than DESI)
  - Dramatic improvements in multiple science directions at once.



Conclusions

- DESI is performing well — survey is ahead of schedule!
- We have the world's best BAO measurement(s).
- Tight bounds on systematic errors (all well below statistical precision).
- Composite precision on distance scale better than 0.3%.
- Shift to lower matter density and faster expansion rate than CMB (in ΛCDM).
- DESI alone is consistent with ΛCDM, but when combined with CMB+SN data start to see "hints" of tensions ("thawing DE", "phantom DE" or "early DE").
- No detection of neutrino mass yet – upper limits depend upon "tensions" and model choices.
- Much more science to come!

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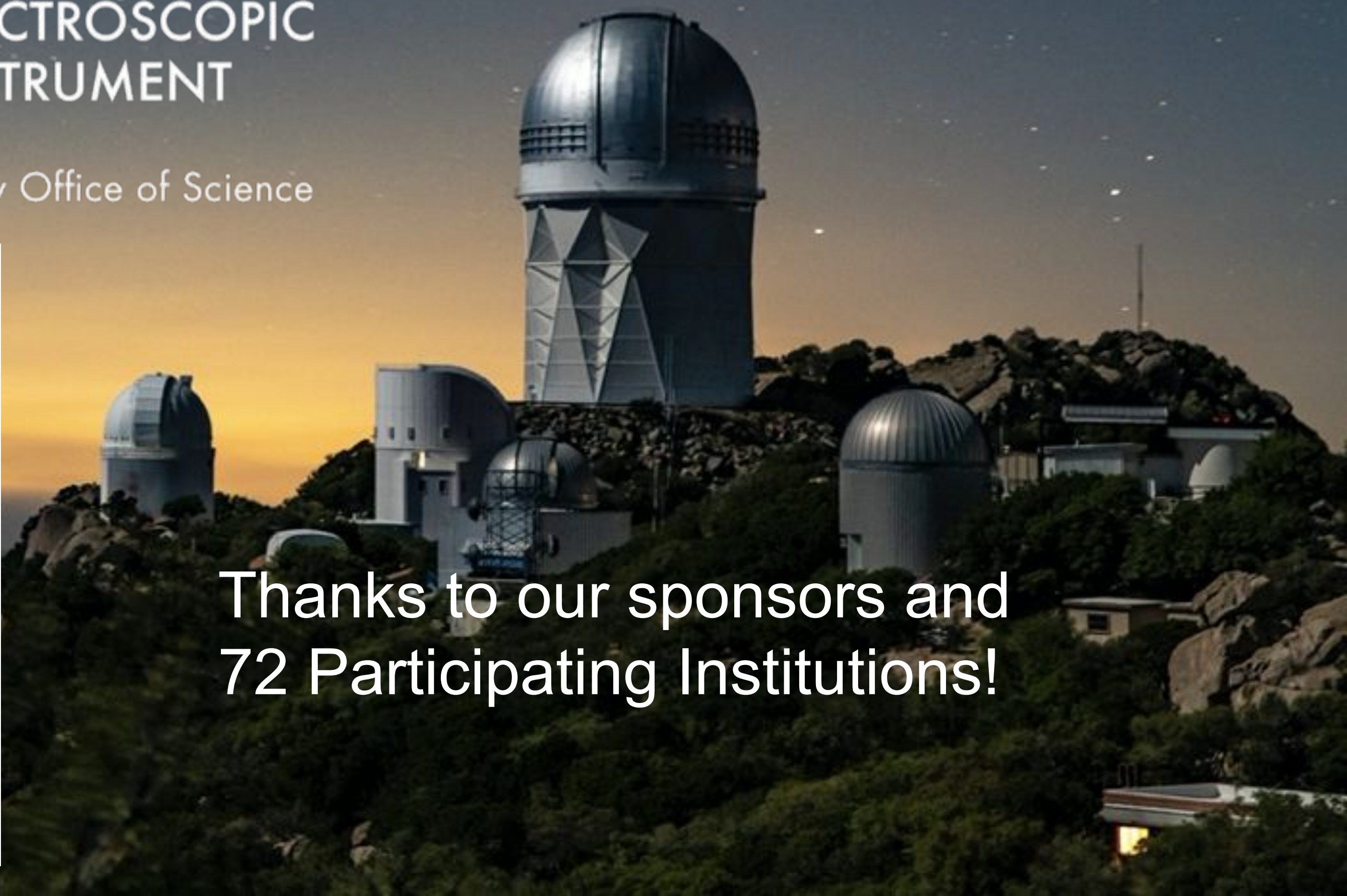

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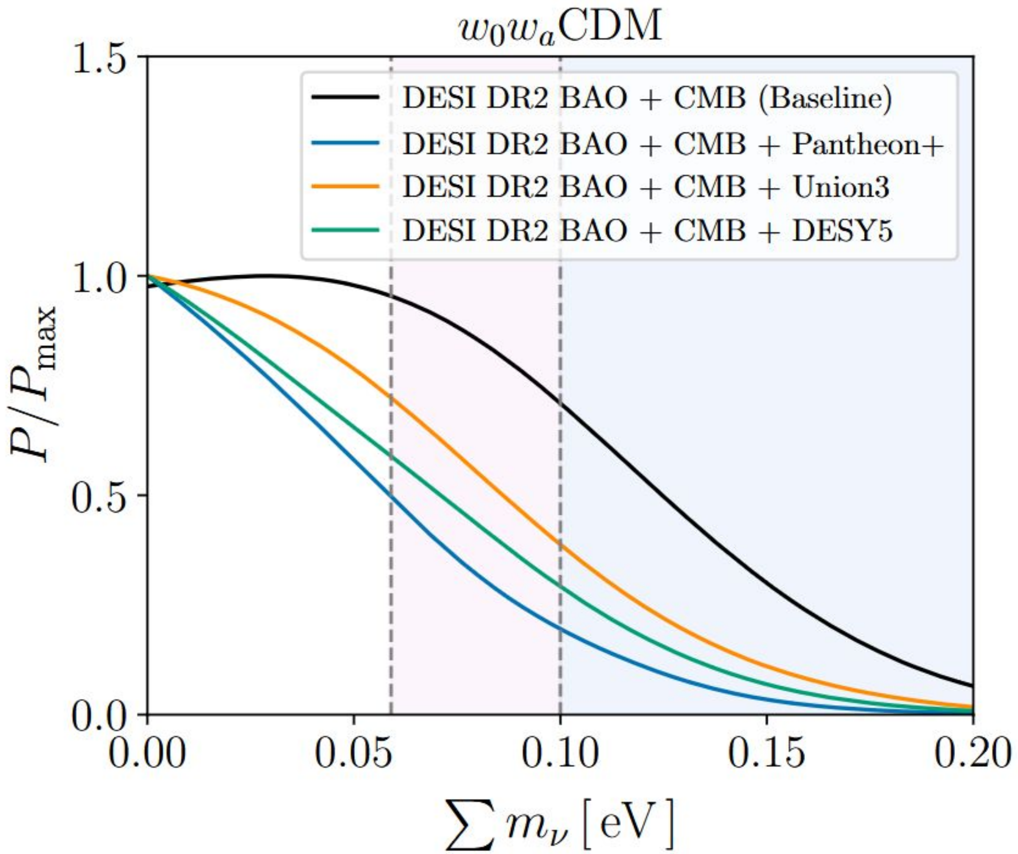
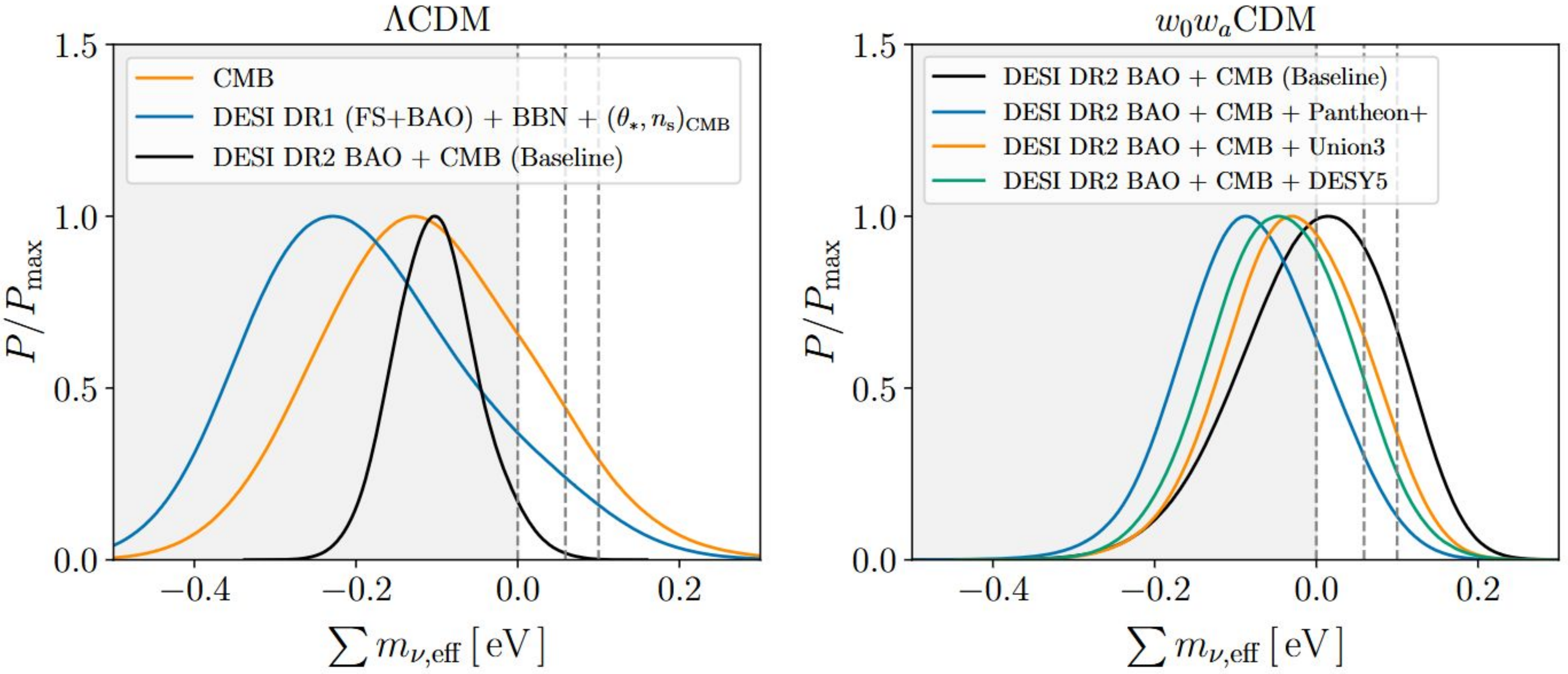
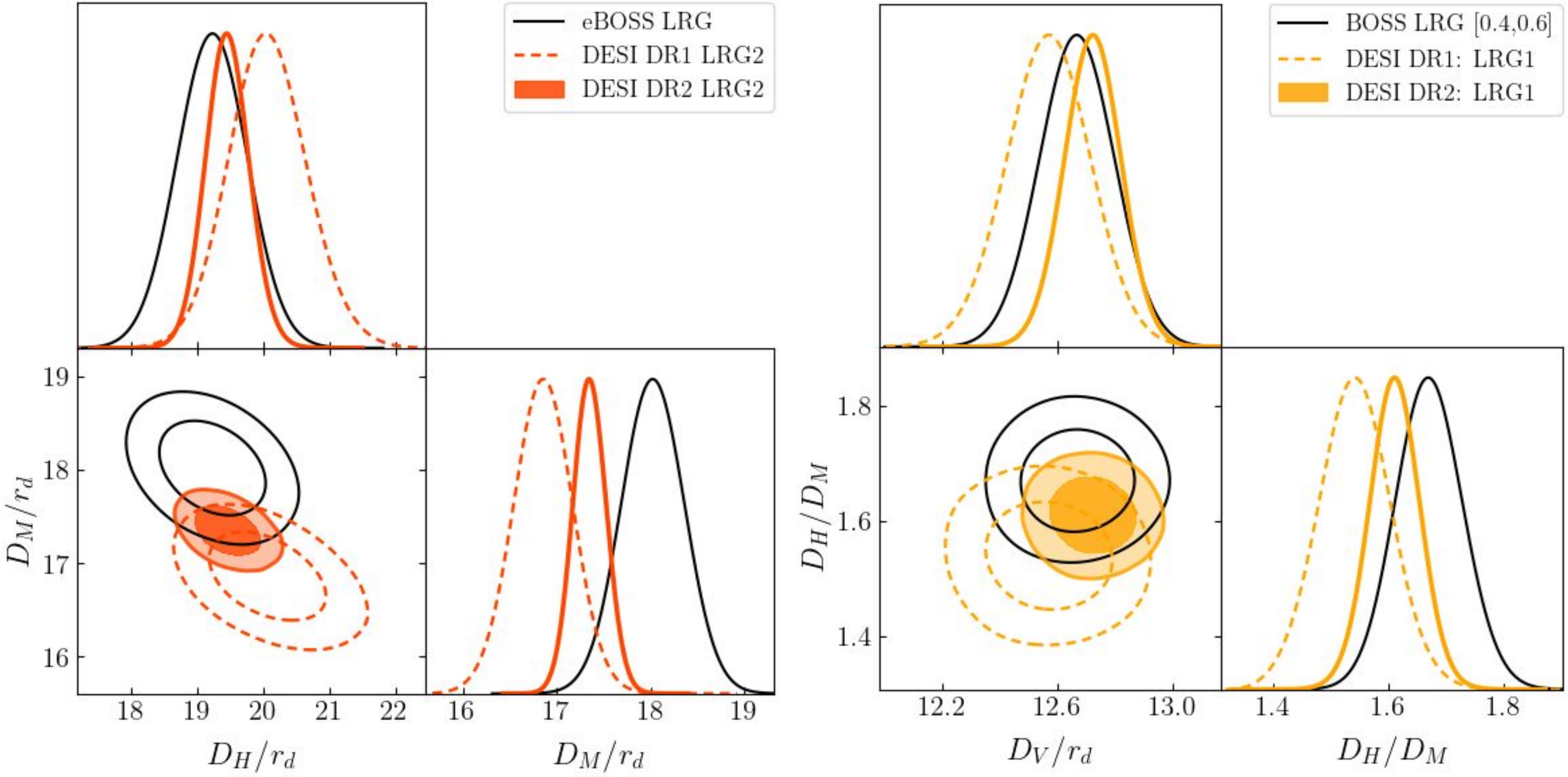
The End

Neutrino constraints with SNe




ΛCDM
CMB
DESI DR1 (FS+BAO) + BBN + $(\theta_*, n_s)_{CMB}$
DESI DR2 BAO + CMB (Baseline)
P/P_{max}
1.5
1.0
0.5
0.0
−0.4
−0.2
0.0
0.2
$\sum m_{\nu,\mathrm{eff}}\,[\mathrm{eV}]$
w_0w_aCDM
DESI DR2 BAO + CMB (Baseline)
DESI DR2 BAO + CMB + Pantheon+
DESI DR2 BAO + CMB + Union3
DESI DR2 BAO + CMB + DESY5
P/P_{max}
$\sum m_{\nu,\mathrm{eff}}\,[\mathrm{eV}]$

Agreement with SDSS



Combining all DESI + CMB + SN

$w_0 = -0.838 \pm 0.055 \qquad w_a = -0.62^{+0.22}_{-0.19}$

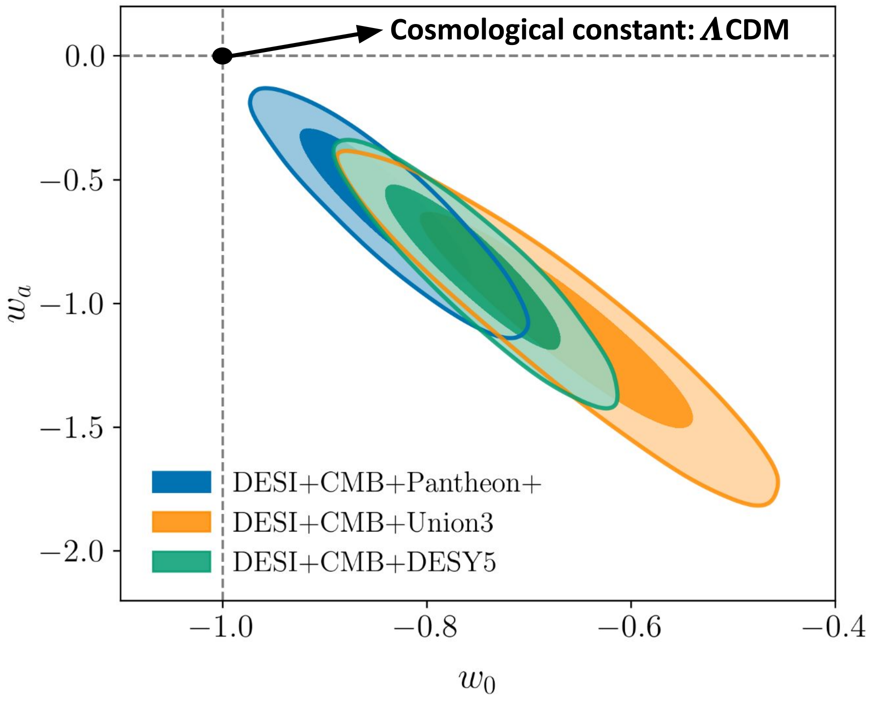
DESI + CMB + Pantheon+ $\Longrightarrow$ 2.8σ

$w_0 = -0.667 \pm 0.088 \qquad w_a = -1.09^{+0.31}_{-0.27}$

DESI + CMB + Union3 $\Longrightarrow$ 3.8σ

$w_0 = -0.752 \pm 0.057 \qquad w_a = -0.86^{+0.23}_{-0.20}$

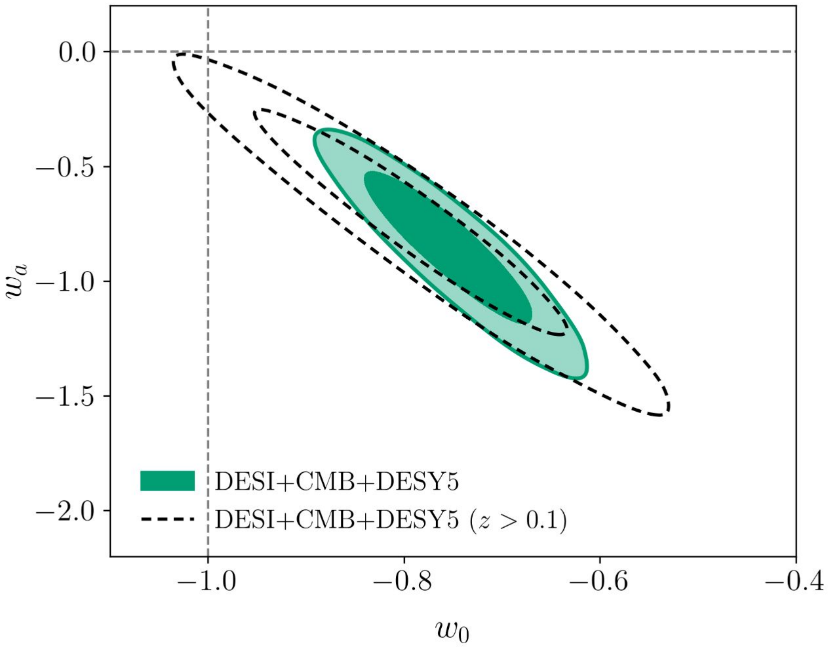
DESI + CMB + DESY5 $\Longrightarrow$ 4.2σ



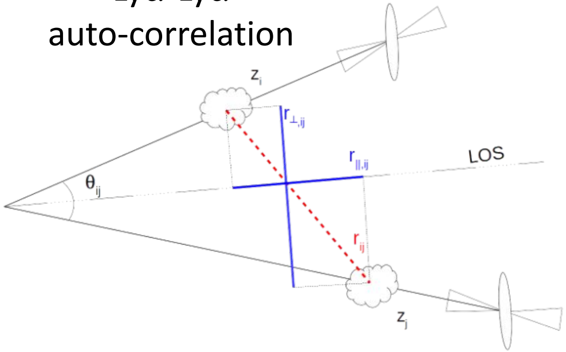
- Constraining power of SNe primarily from comparison of $z < 0.1$ and $z > 0.1$ SNe

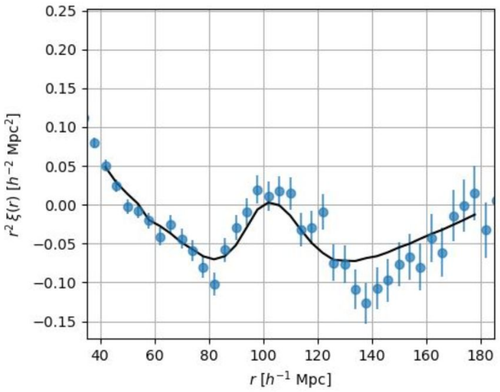
- No SNe compilation has uniformly observed objects from both regimes

- Removing the $z < 0.1$ SNe weakens the preference for evolving dark energy

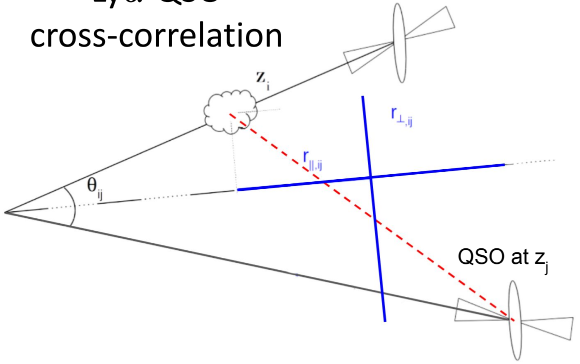


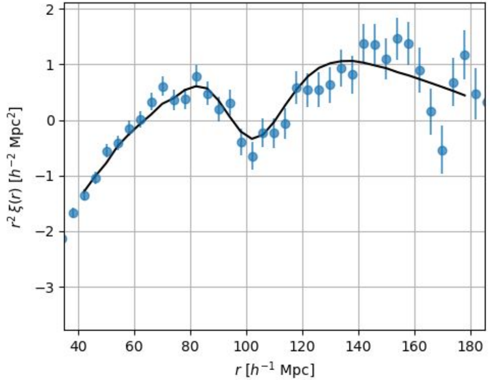
Lyα-Lyα auto-correlation





Lyα-QSO cross-correlation





The DESI DR2 sample

- Over 14 million galaxies and quasars in the sample used in this analysis
- Compared to DR1, this represents a factor of ~2.4 improvement in data volume

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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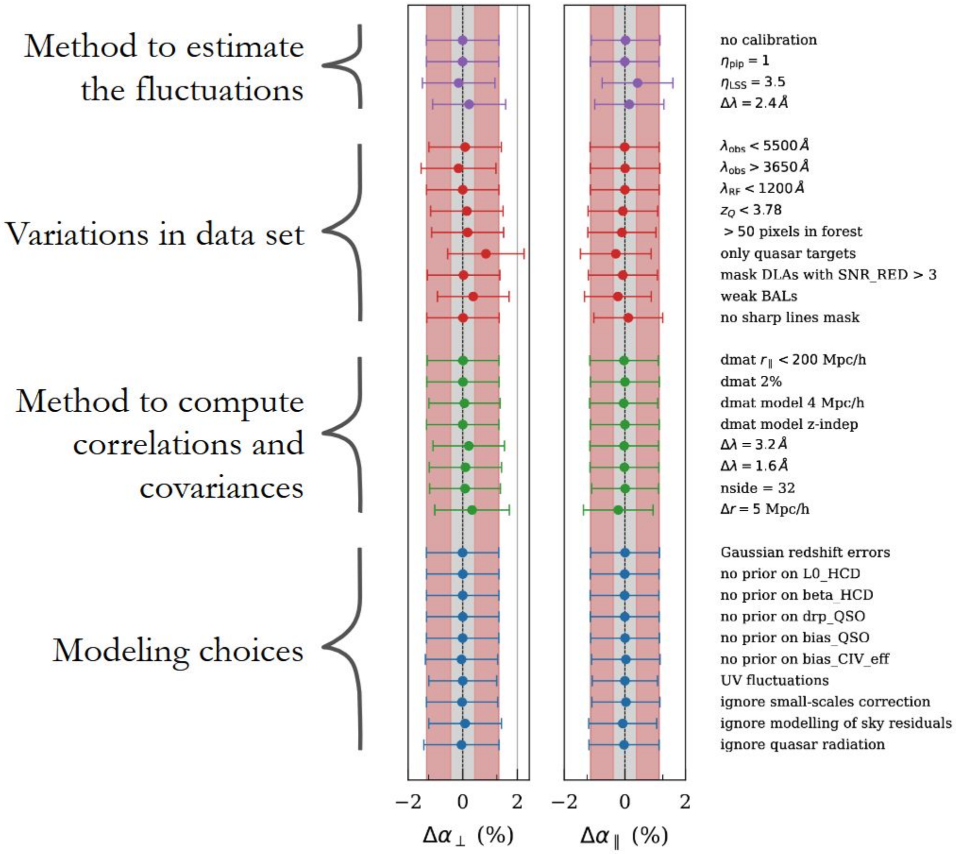
DR2 Lyα BAO robustness tests

DESI DR2 Results I: Baryon Acoustic Oscillations from the Lyman Alpha Forest

Supporting paper: Validation of the DESI DR2 Lyα BAO analysis using synthetic datasets (Casas++ 2025)

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



Galaxy clustering

Tracer	Parameter	Theory (%)	HOD (%)	Fiducial (%)	Total (%)
BGS	$\alpha_{\rm iso}$	0.1	No detection	0.1	0.141
LRG1	$\alpha_{\rm iso}$	0.1	No detection	0.1	0.141
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329
LRG2	$\alpha_{\rm iso}$	0.1	No detection	0.1	0.141
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329
LRG3	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329
LRG3+ELG1	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329
ELG1	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	No detection	0.1	0.224
ELG2	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	No detection	0.1	0.224
QSO	$\alpha_{\rm iso}$	0.1	0.17	0.1	0.221
	$\alpha_{\rm AP}$	0.2	0.19	0.18	0.329

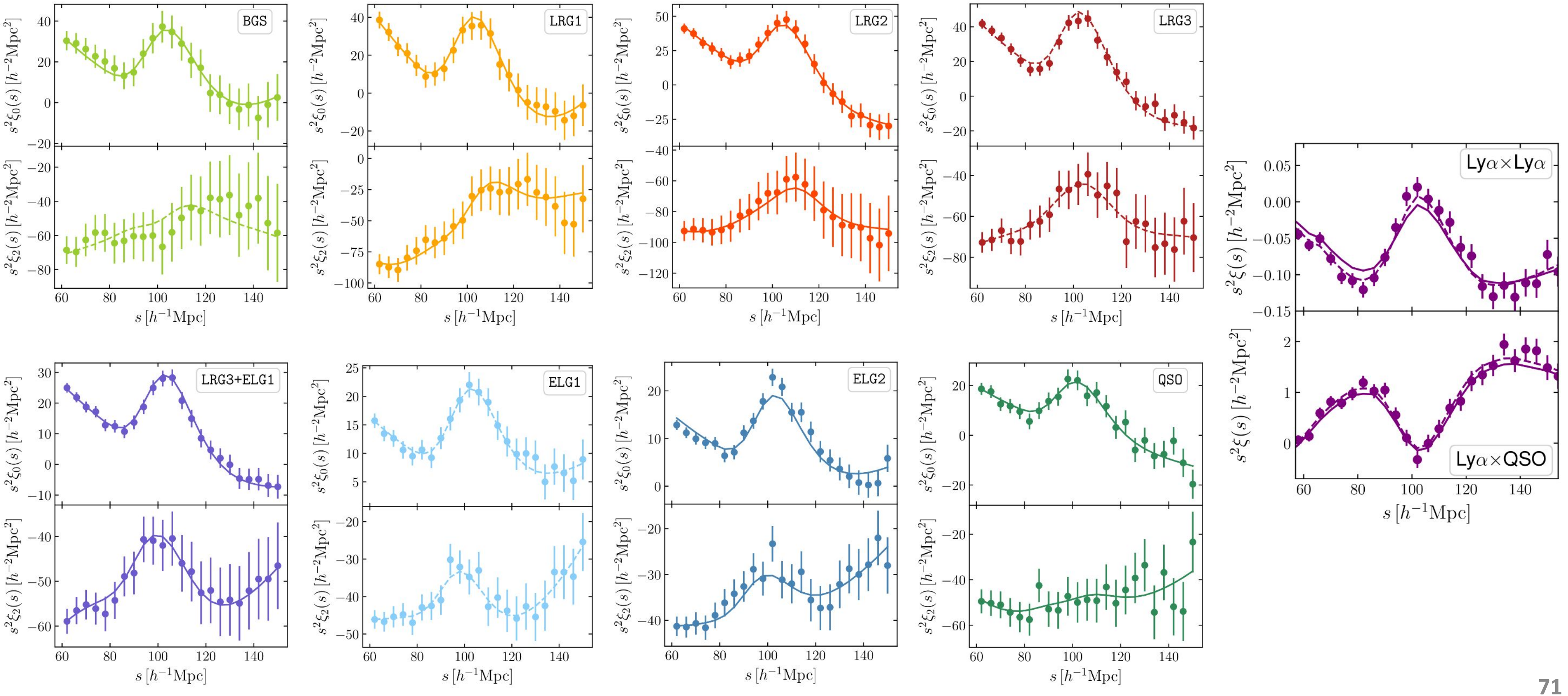
Lyα forest

$\Delta\alpha_{\parallel} = 0.3\%$

$\Delta\alpha_{\perp} = 0.3\%$

(due to non-linear evolution of the BAO peak)

DESI DR2 clustering measurements



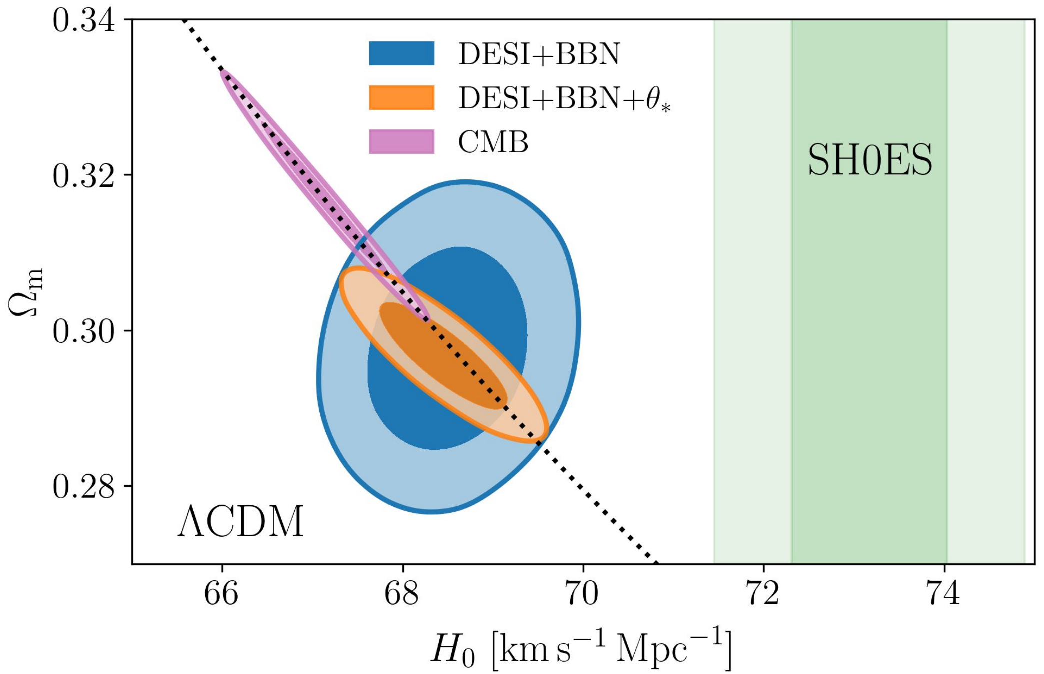
$H_0 = (68.51 \pm 0.58)$ km/s/Mpc

DESI + BBN

$H_0 = (68.45 \pm 0.47)$ km/s/Mpc

DESI + θ_* + BBN

- In 4.5σ tension with SH0ES
- θ_* - CMB angular acoustic scale
- Close to CMB, but still higher
- CMB degeneracy direction points to our result (dotted line)



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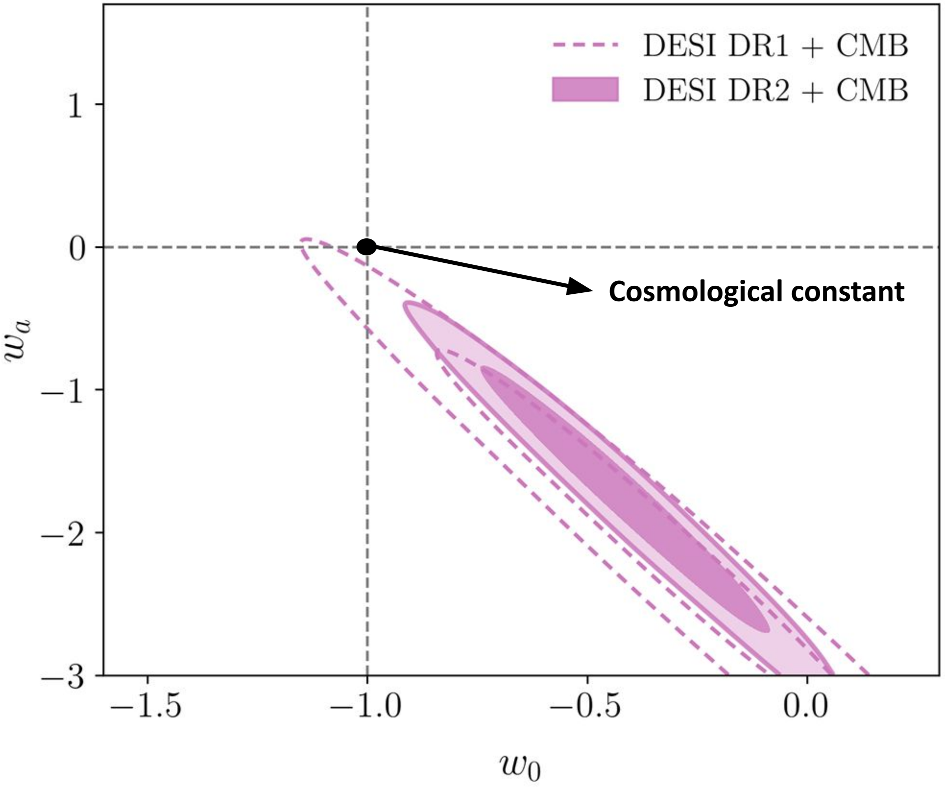
- DESI DR1 + CMB: 2.6σ from ΛCDM

- **3.1σ** preference for evolving dark energy with DESI DR2 + CMB

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



CMB alternatives where we marginalize over information dependent on late-time models

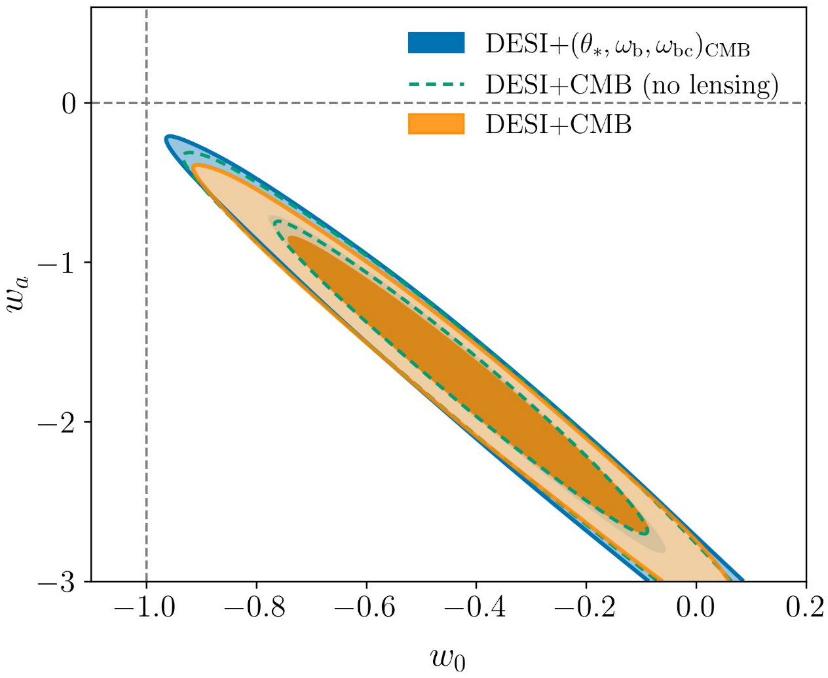
- Using early-Universe priors on $(\theta_*, \omega_b, \omega_{bc})$ derived from the CMB:

  DESI + $(\theta_*, \omega_b, \omega_{bc})_{CMB} \Longrightarrow$ 2.4σ

- Using CMB without lensing:

  DESI + CMB (no lensing) $\Longrightarrow$ 2.7σ

Preference for dynamic dark energy weakens (from 3.1σ), but posteriors remain very similar



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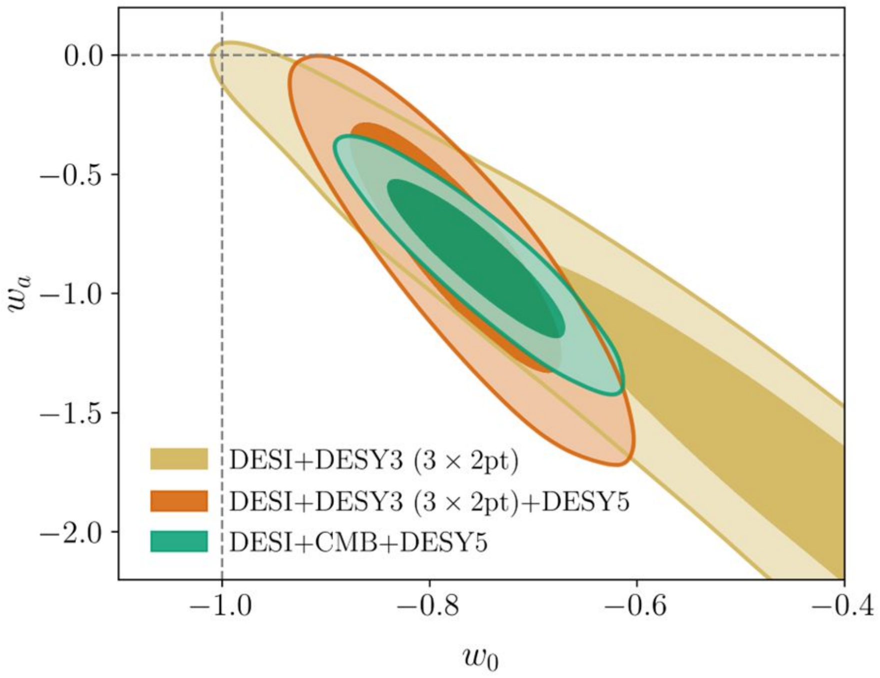
- Replacing the CMB with DESY3 3 × 2pt (weak lensing + galaxy clustering)

- Constraint coming entirely from low-redshift probes

- Still see preference for the same region:

DESI + DESY3 (3 × 2pt) ⟹ 2.2σ

DESI + DESY3 (3 × 2pt) + DESY5 ⟹ 3.3σ



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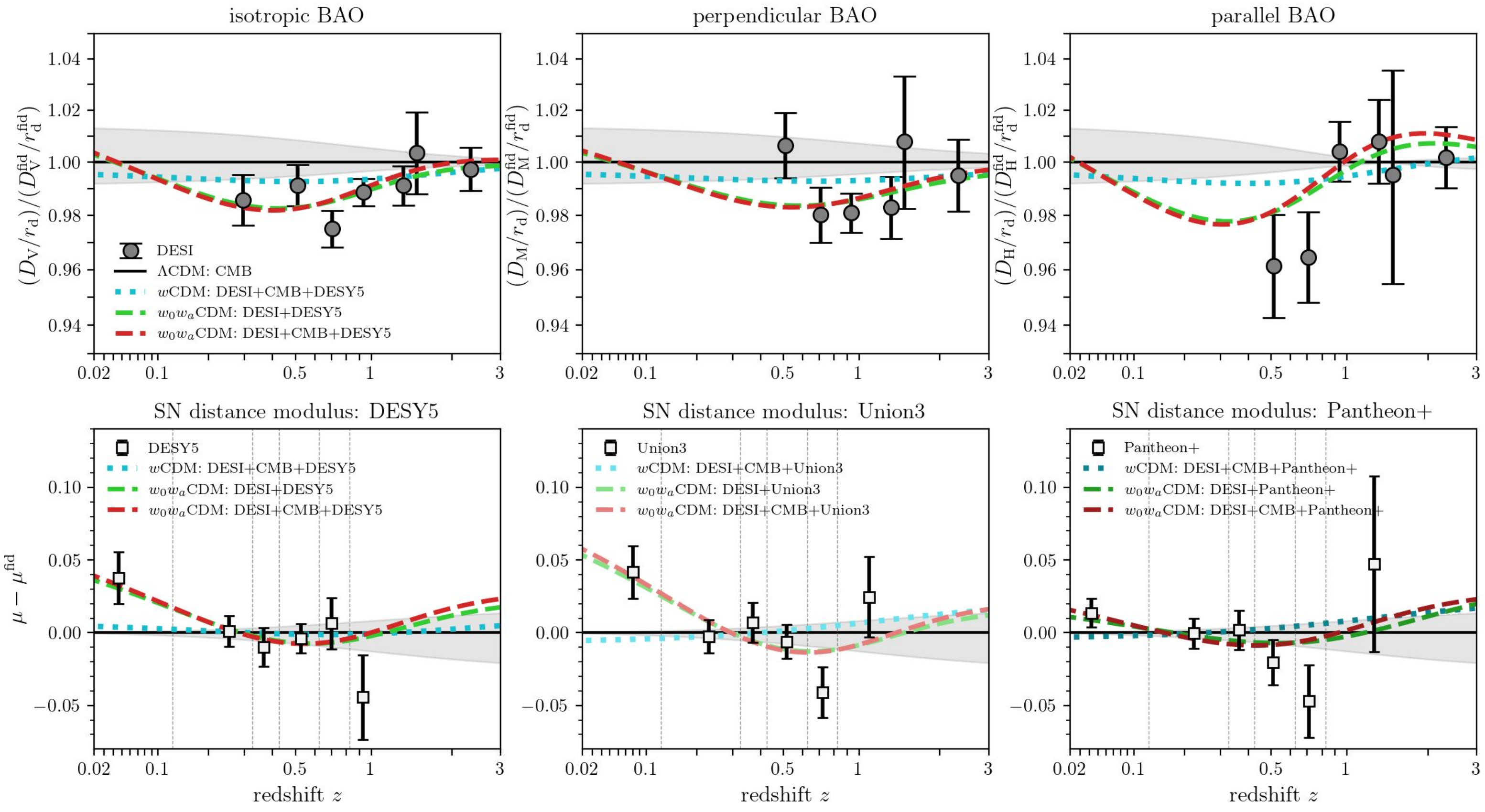
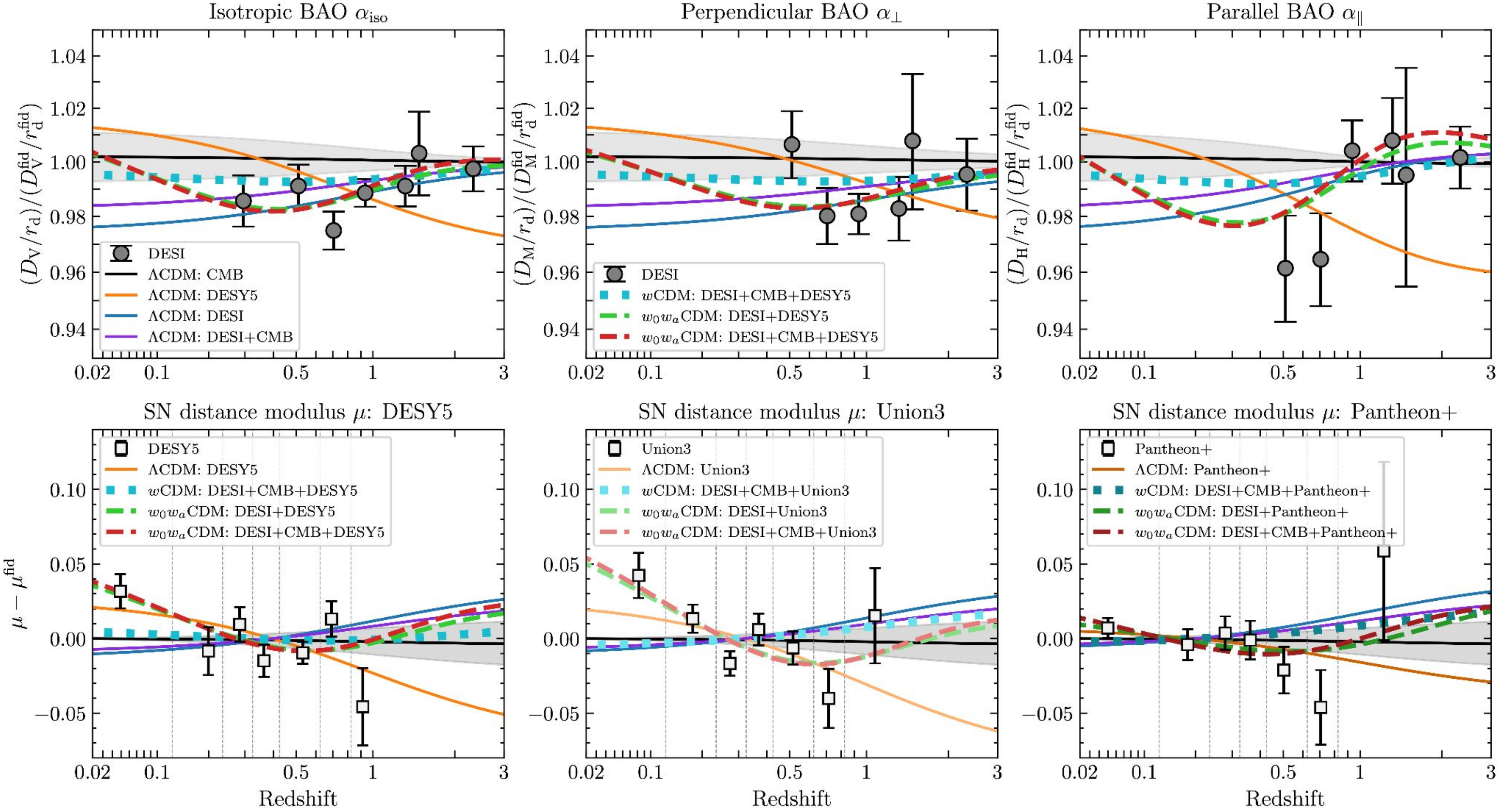
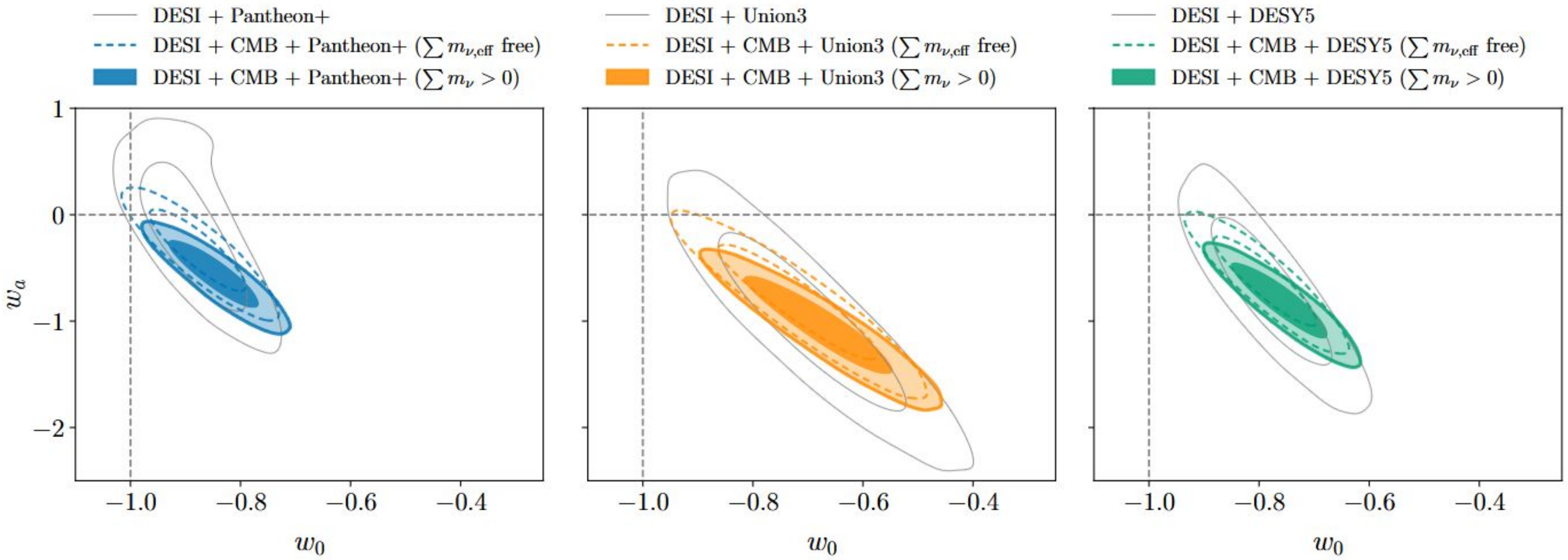


w0waCDM



Isotropic BAO $\alpha_{\rm iso}$
Perpendicular BAO $\alpha_\perp$
Parallel BAO $\alpha_\parallel$
$(D_{\rm V}/r_{\rm d})/(D_{\rm V}^{\rm fid}/r_{\rm d}^{\rm fid})$
$(D_{\rm M}/r_{\rm d})/(D_{\rm M}^{\rm fid}/r_{\rm d}^{\rm fid})$
$(D_{\rm H}/r_{\rm d})/(D_{\rm H}^{\rm fid}/r_{\rm d}^{\rm fid})$
DESI
ΛCDM: CMB
ΛCDM: DESY5
ΛCDM: DESI
ΛCDM: DESI+CMB
wCDM: DESI+CMB+DESY5
w_0w_aCDM: DESI+DESY5
w_0w_aCDM: DESI+CMB+DESY5
SN distance modulus μ: DESY5
SN distance modulus μ: Union3
SN distance modulus μ: Pantheon+
$\mu - \mu^{\rm fid}$
DESY5
Union3
ΛCDM: Union3
wCDM: DESI+CMB+Union3
w_0w_aCDM: DESI+Union3
w_0w_aCDM: DESI+CMB+Union3
Pantheon+
ΛCDM: Pantheon+
wCDM: DESI+CMB+Pantheon+
w_0w_aCDM: DESI+Pantheon+
w_0w_aCDM: DESI+CMB+Pantheon+
Redshift

$w_0 w_a$CDM with free neutrino mass



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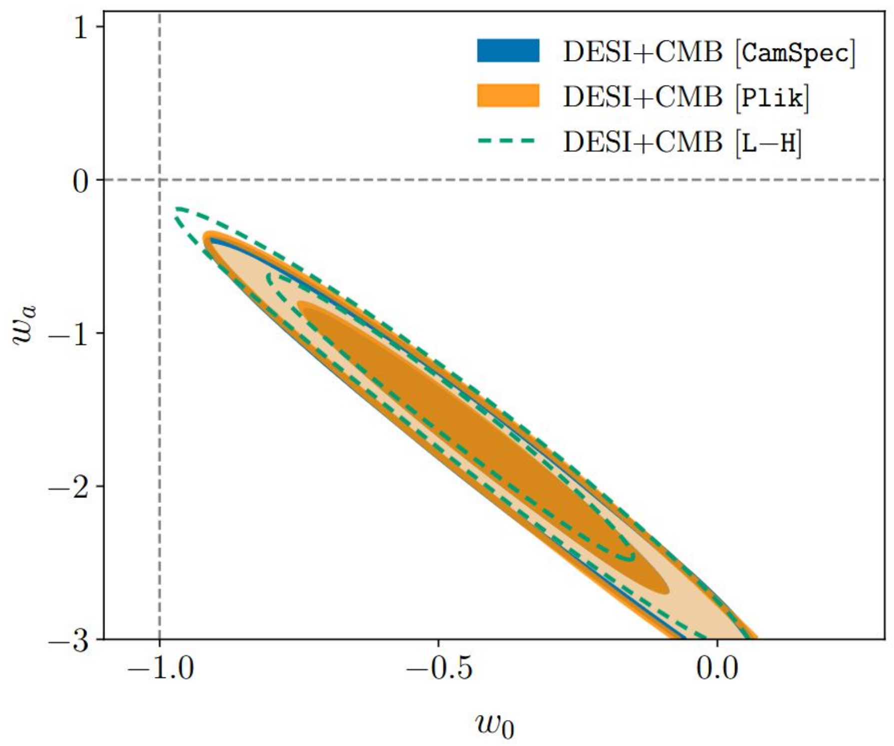
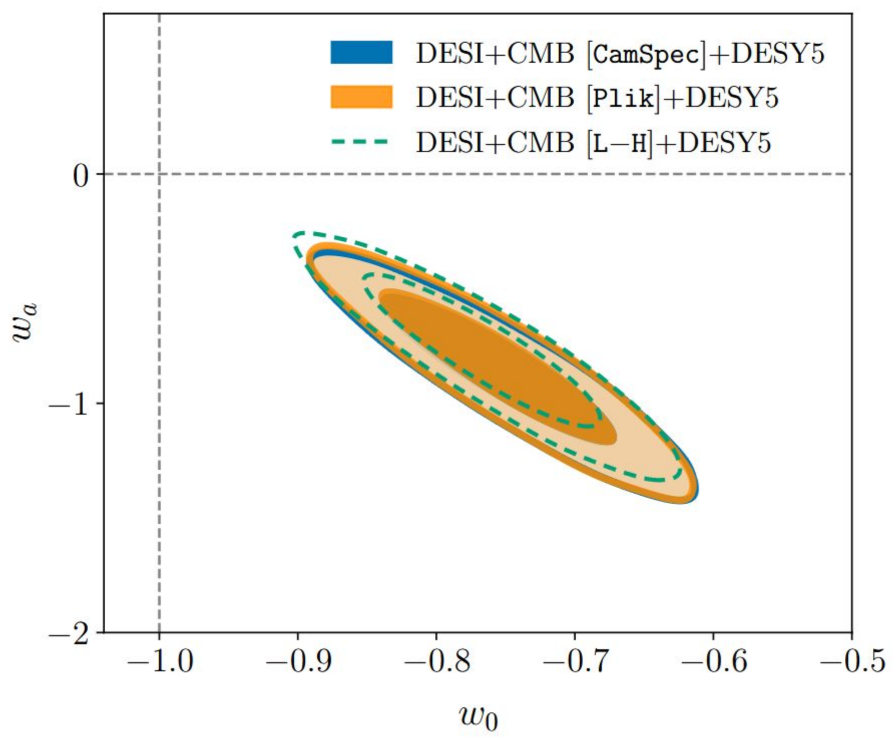
Impact of CMB likelihood





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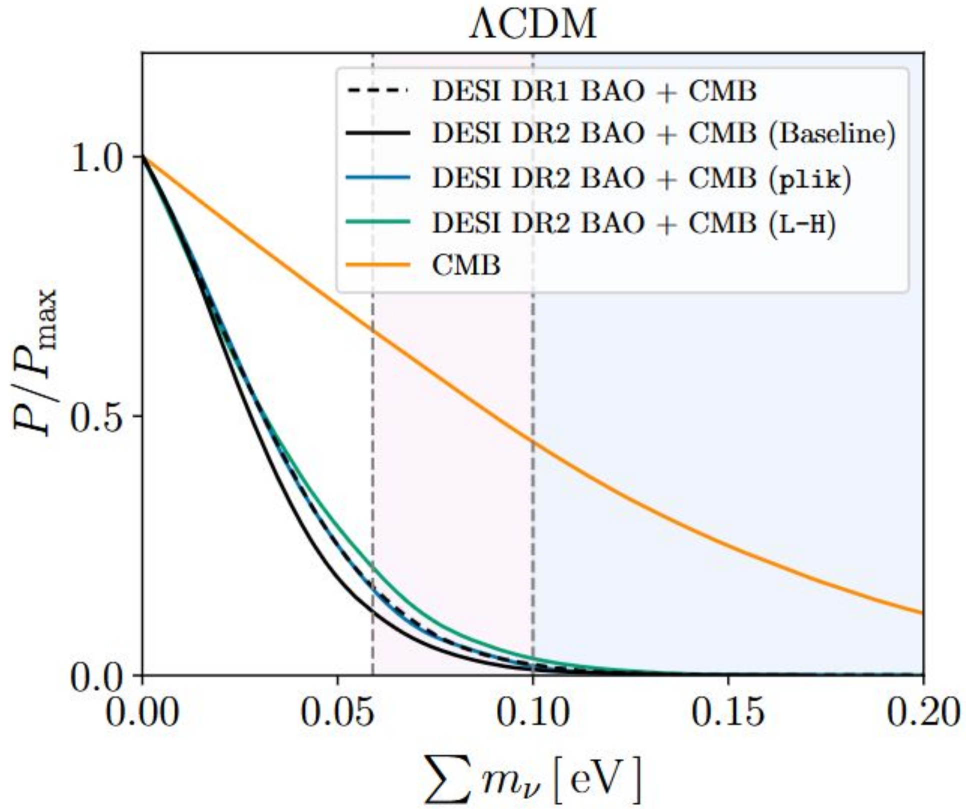
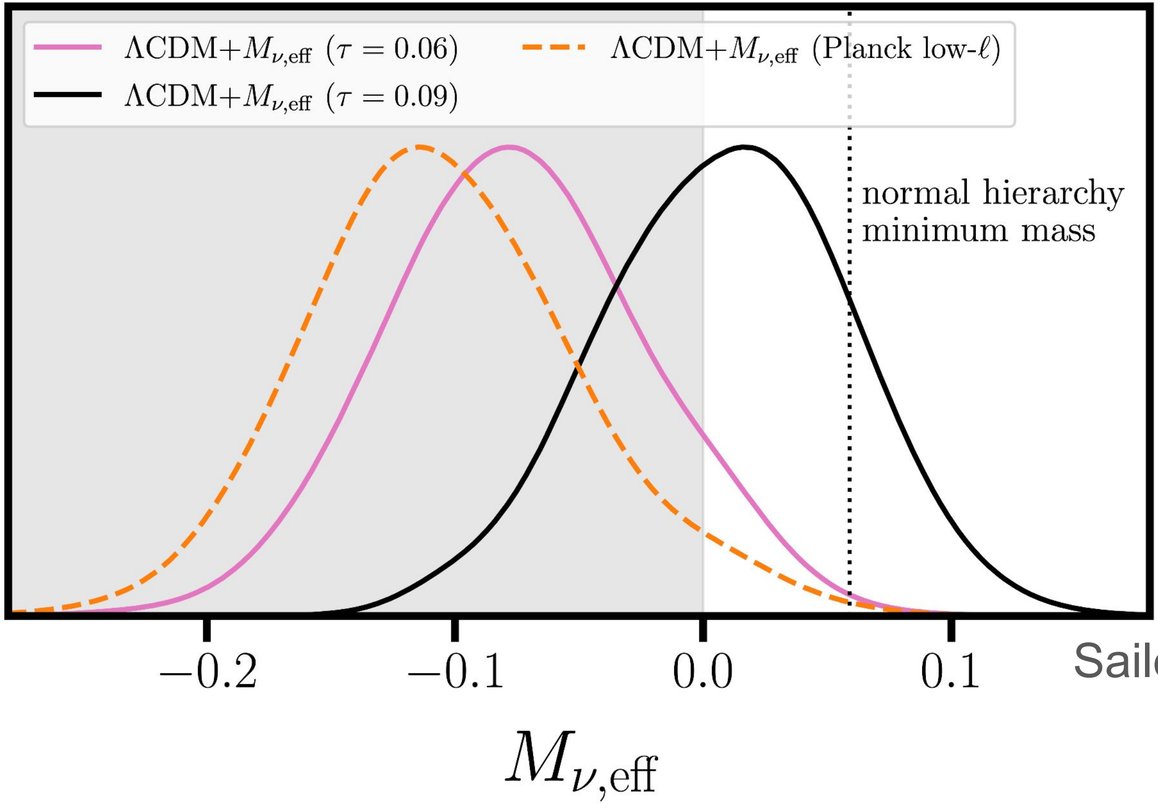
Impact of CMB likelihood



Neutrinos and the optical depth



Sailer+25

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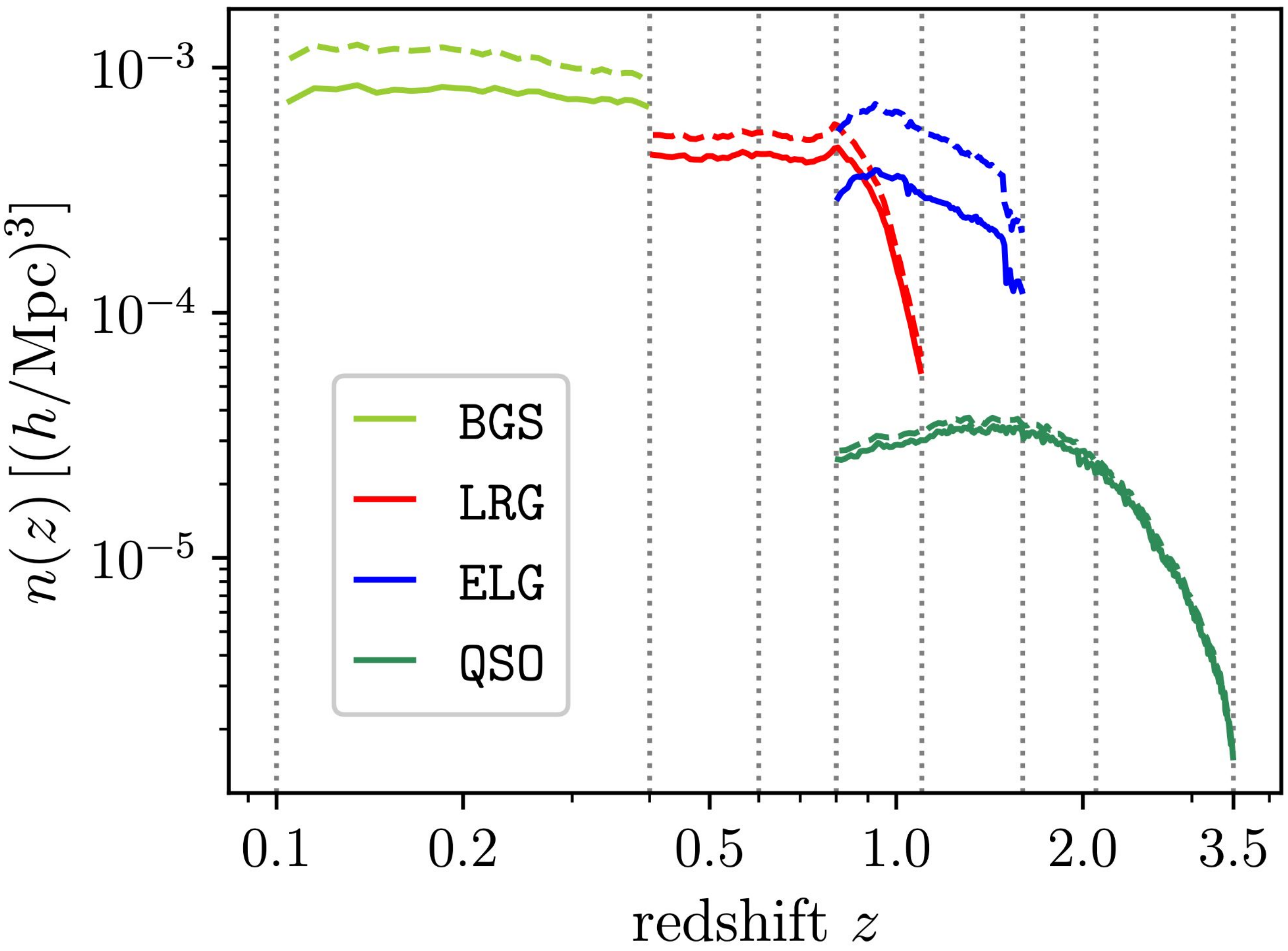
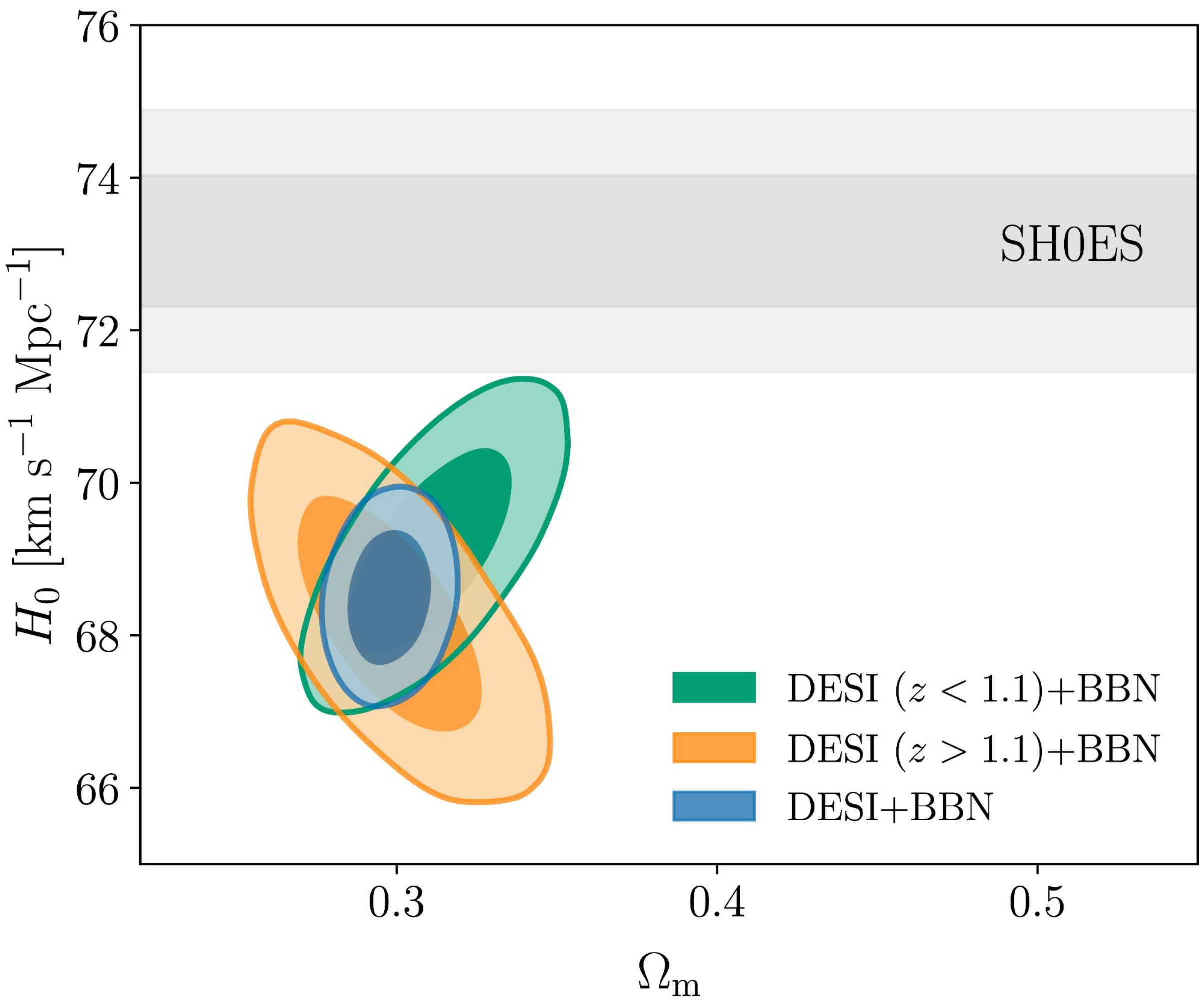
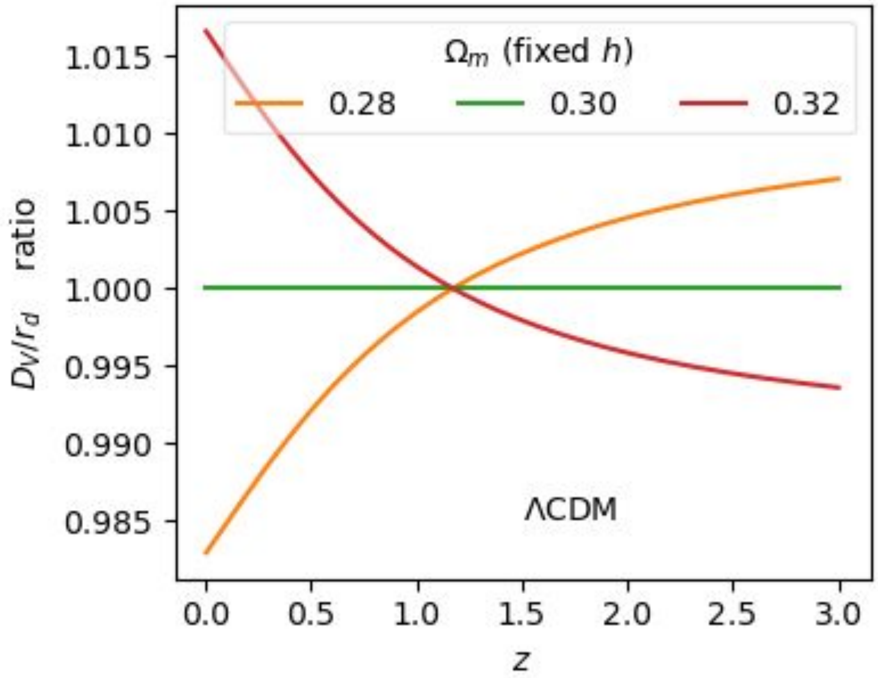
Number density

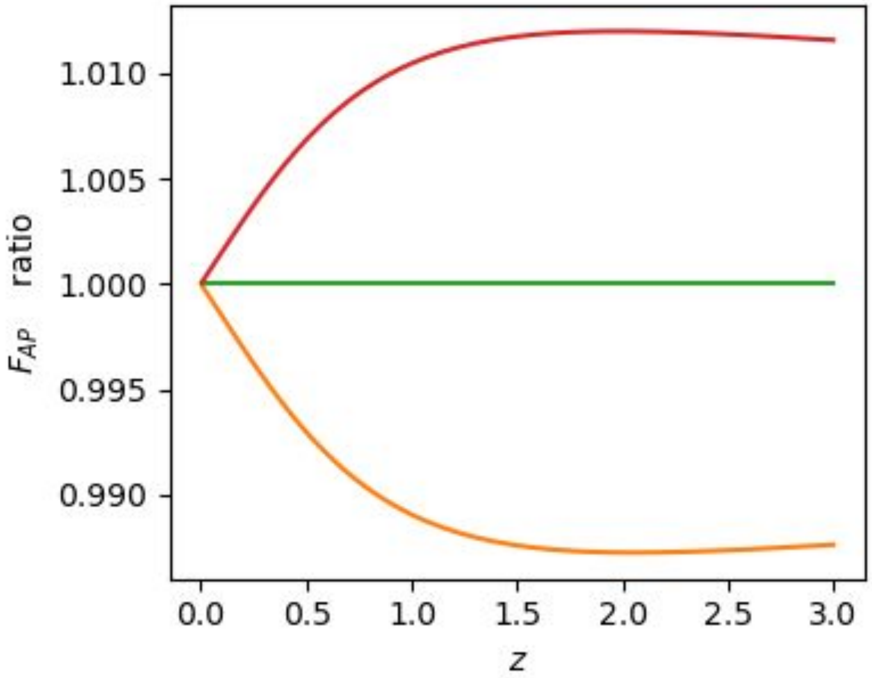


Tension with SH0ES

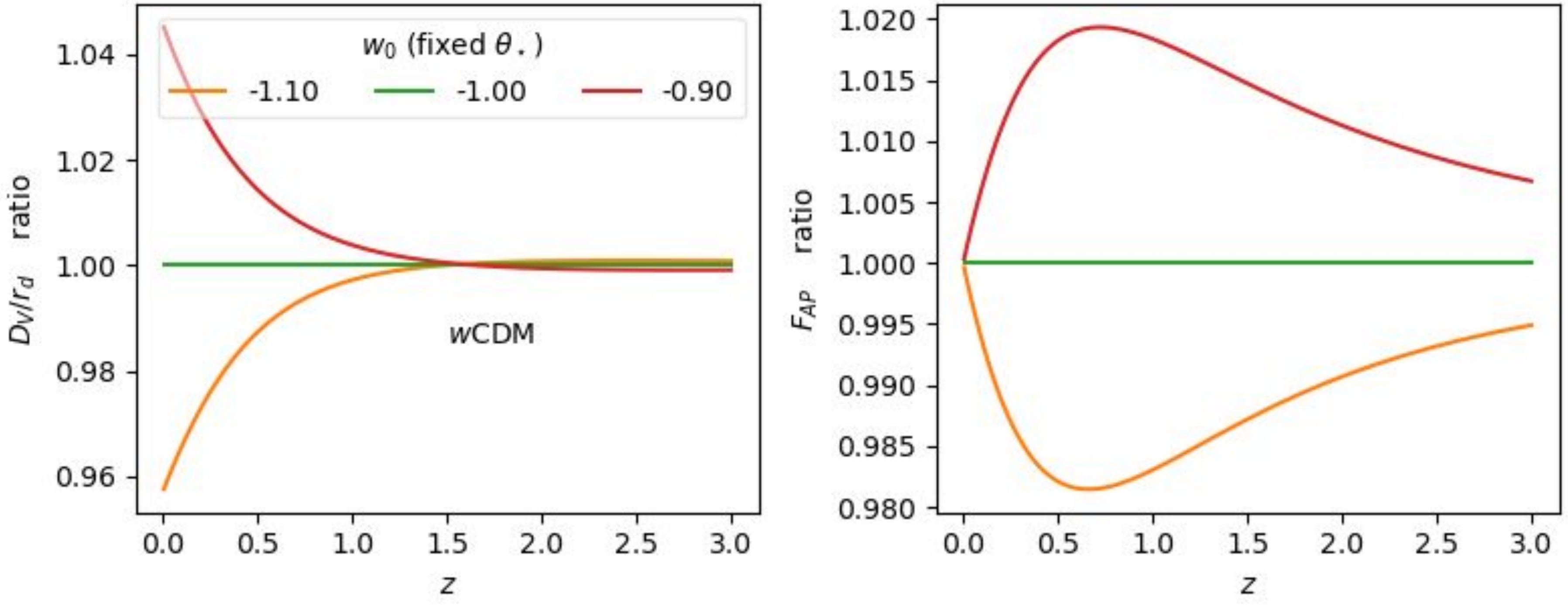


BAO observables

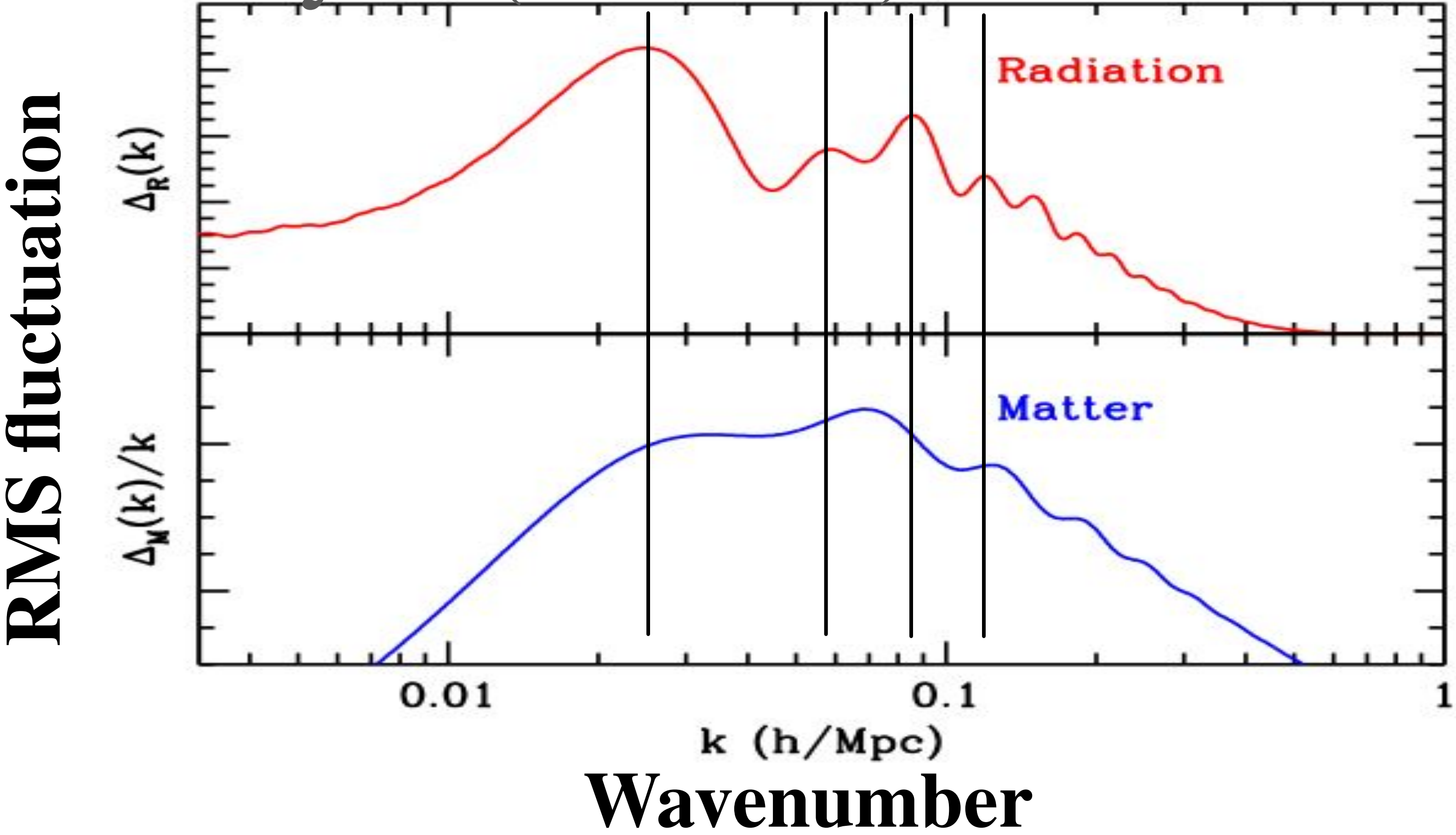




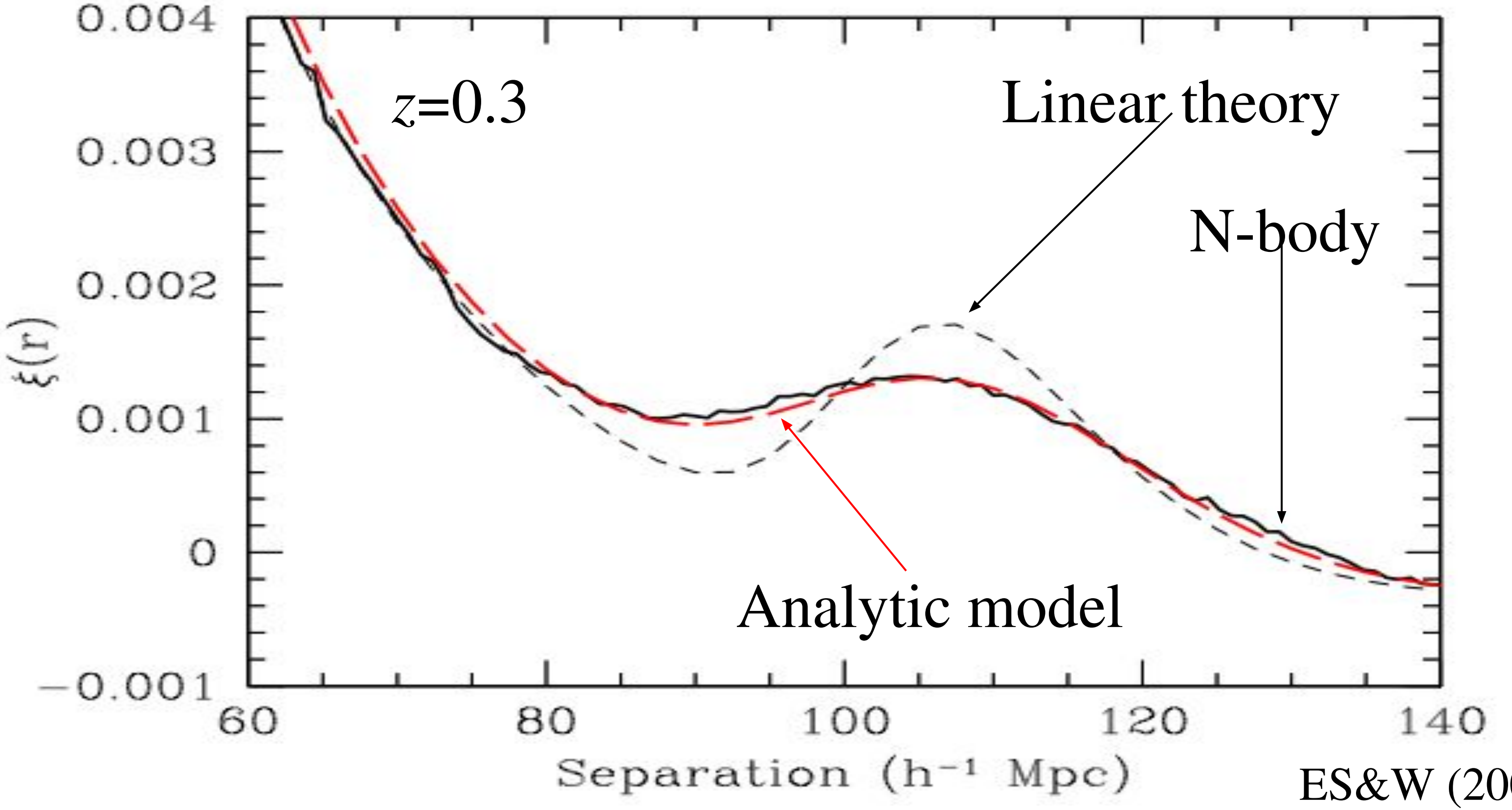
BAO observables



Baryon (acoustic) oscillations



Non-linearities smear the peak



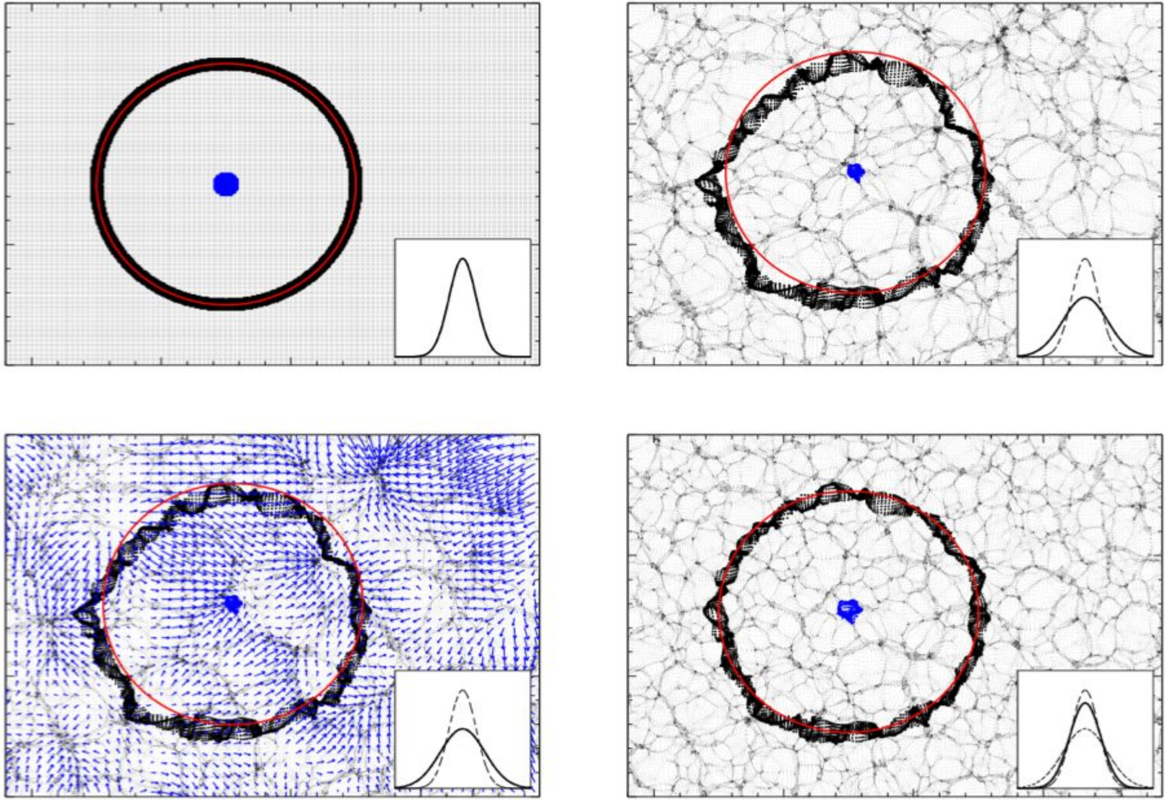
ES&W (2006)

Reconstruction

The broadening of the peak comes from large scale tidal forces acting on the galaxies.

Fortunately we measure the material responsible for these tidal forces in the survey itself, so we can “undo” the peak broadening to some extent.

Really just a clever use of the continuity equation.



Padmanabhan et al. (2012)

Under the hood

I will be showing mostly pictures, lines on plots or data but as physicists you probably want to know what's going on "under the hood":

- Cosmology deals with relativistic gauge field theories (like many of you!).
- Equations of motion are non-linear. Handle this using PT.
- PT developed starting in the 1960s, reached its classical form in the early 1990s (with important developments to this day).
- Standard techniques familiar from QM, condensed matter, particle physics, …
    - Effective field theory framework, Greens functions, diagrams, "tree level", "1 loop", normal ordering, regularization, renormalization, running, counter terms, IR resummation, …

Sort-of like QFT

- Collect density, velocity, etc. into a vector: φ^a
- Rewrite EOM as "propagation" and "interaction".
- Rather than a Feynman path integral for operator expectation values have ensemble averages over "initial" fields:

$$\langle \varphi^a \cdots \varphi^b \rangle = \int \mathcal{D}\phi_{\rm ic} \; \varphi^a[\phi_{\rm ic}] \cdots \varphi^b[\phi_{\rm ic}] \exp \underbrace{\left[-\frac{1}{2} \phi^i_{\rm ic} \{P^{-1}_{ij}\} \phi^j_{\rm ic} \right]}_{S_0[\phi_{\rm ic}]}$$

- That can be obtained by functional derivatives of (log of)

$$Z[J] = \int \mathcal{D}\phi_{\rm ic} \;\; \exp \left\{ S_0[\phi_{\rm ic}] + J_i \varphi^i[\phi_{\rm ic}] \right\}$$

- And the integral broken up into "IR" and "UV" pieces, etc., etc., etc.

The story we tell

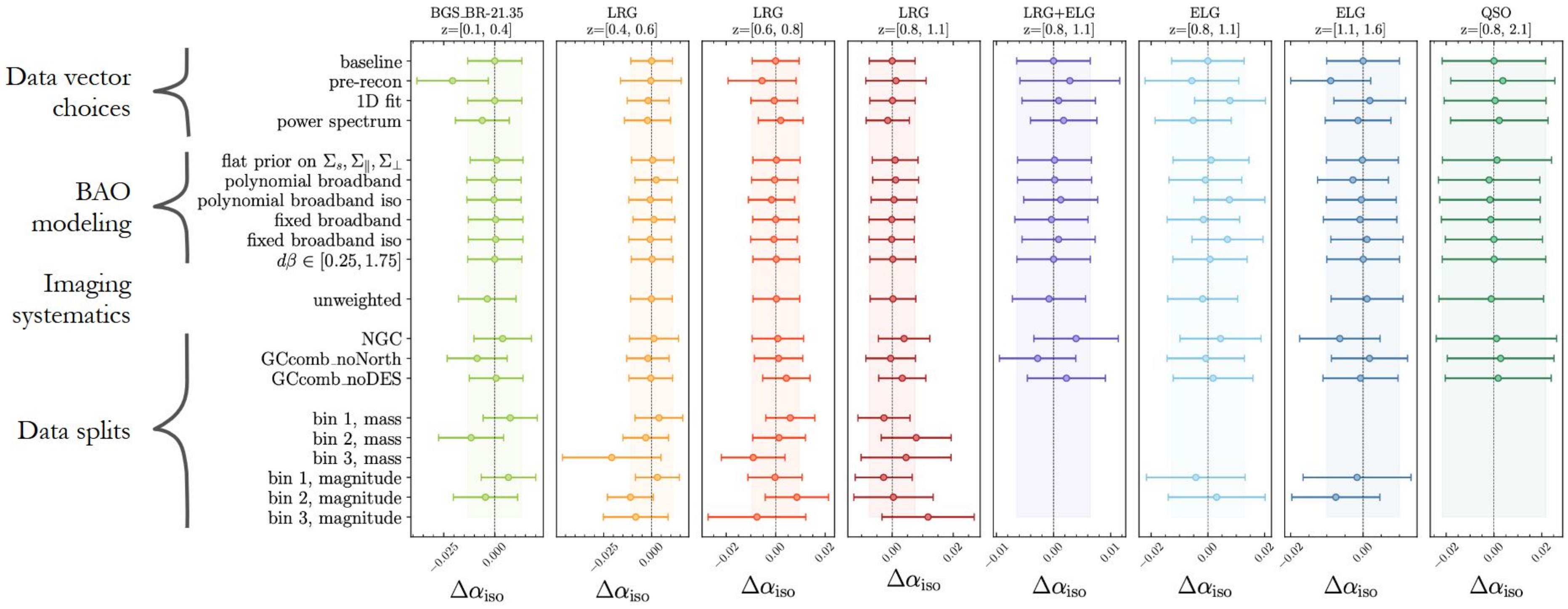
- Growth is a competition between gravity and expansion
  - Depends upon the laws of gravity (general relativity)
  - Depends upon the expansion of the Universe (metric)
  - Depends upon the constituents and their properties

“LSS program”
Probe the metric, particle content and both epochs of accelerated expansion – with high precision!

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

DR2 Galaxy BAO robustness tests



Differences in the isotropic BAO dilation

Supporting paper: Validation of DESI DR2 BAO from Galaxies and Quasars (Andrade++ 2025)

Hubble constant

We can measure the expansion rate (H0) using an "inverse distance ladder".

Result remains robustly* discrepant with result from the SH0ES team.

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