DESI 2024: The history of cosmic expansion as revealed by the Dark Energy Spectroscopic Instrument

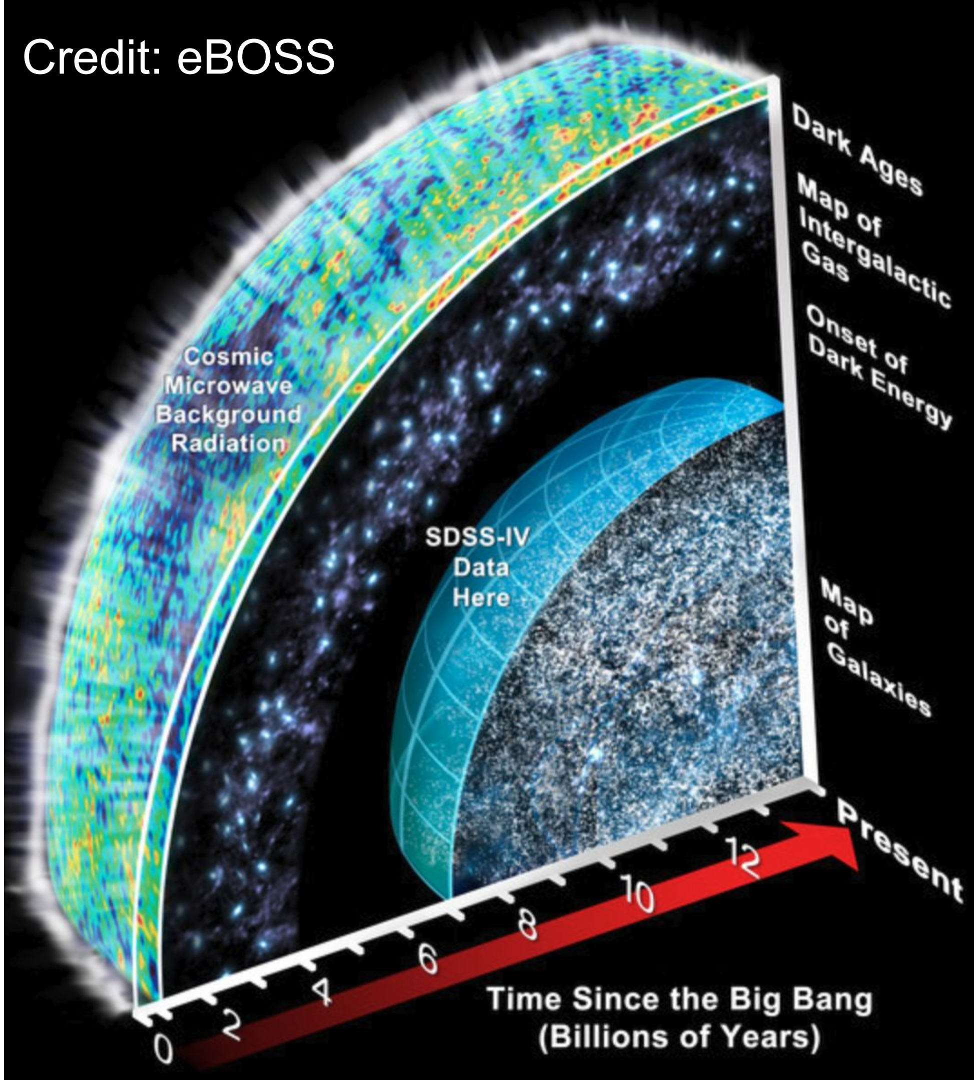
Martin White
UC Berkeley/LBNL
for the DESI collaboration

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 Y1 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!



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.
- 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.
- 14Gyr of evolution shapes the fluctuations, probing a wide range of energy densities, temperatures, …

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 (DESI)

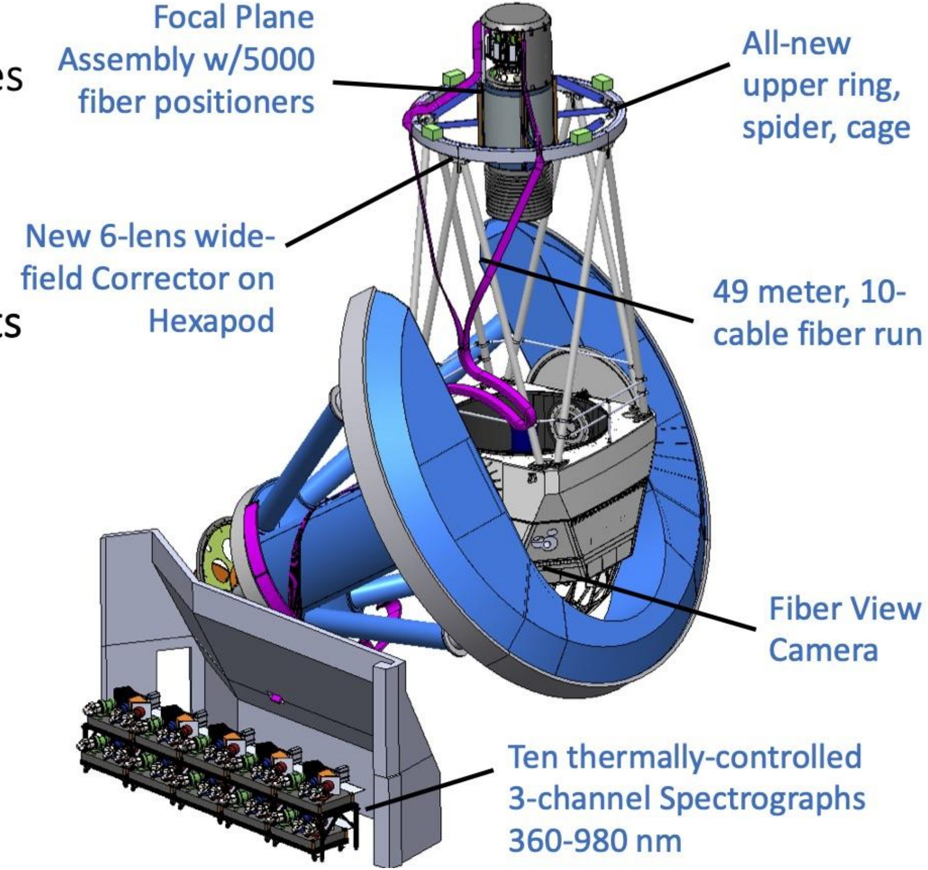
DESI is a spectroscopic survey whose goal is to study the large-scale structure in the Universe to constrain the evolution of the cosmos and fundamental physics …

DESI will measure 40M galaxy redshifts over ⅓ of the sky, looking back over 11Gyr using 5 different classes of targets.

This talk is based on the “Y1” data release covering data taken from May 14, 2021 through June 14, 2022. This is already the largest such dataset ever taken …

DESI by the Numbers

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



The metric/expansion history

Today I will focus on the expansion history ...

- The fact that the Universe is homogeneous and isotropic on large scales implies that 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 0th order: the scale factor, a(t)

$$ds^2 = -\left[1 - 2\Psi\right] dt^2 + a^2(t) \left[1 + 2\Phi\right] d\vec{x}^2$$

- Measuring a(t) has been a goal of observational cosmology since the beginning – best way of measuring it is through distance vs. z=1/a-1.
- The "best" distance measures are geometric: e.g. find something whose size you know and measure the angle or redshift interval it subtends.

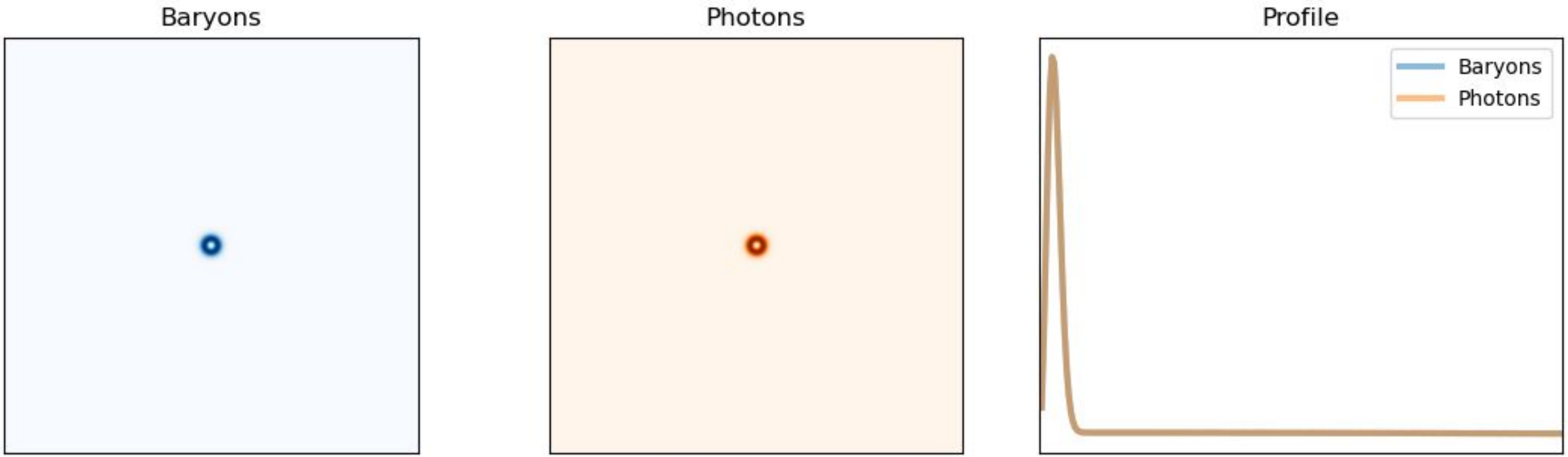
A brief history of the Universe

- 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)

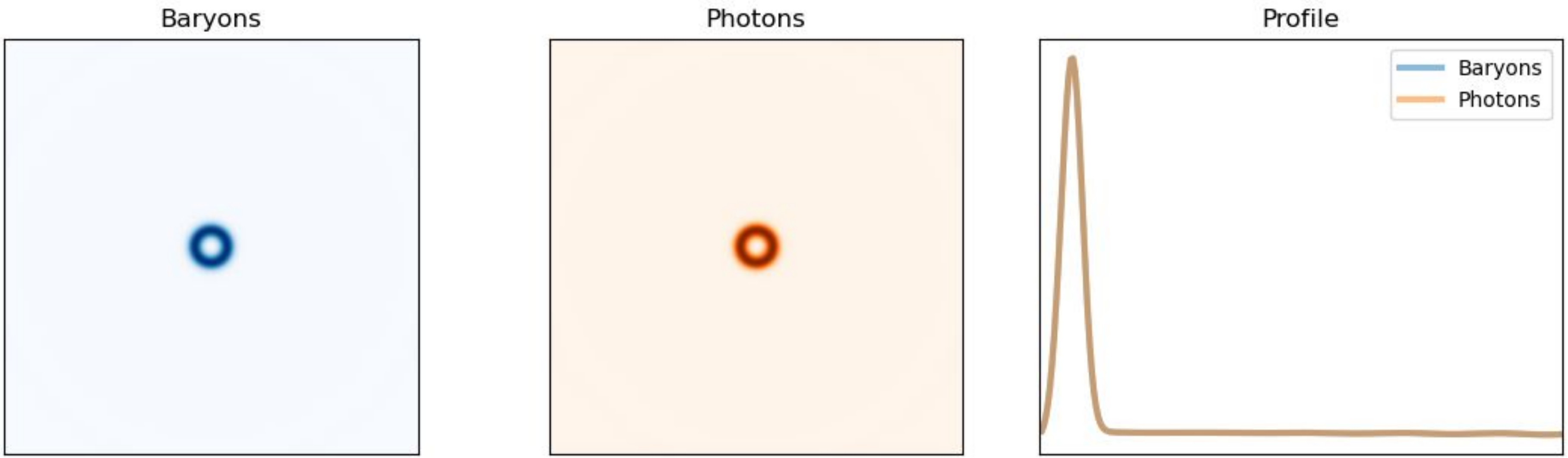
Start with a single perturbation. The plasma is uniform except for a δ-fn at the origin.
High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Eisenstein, Seo & White (2006)

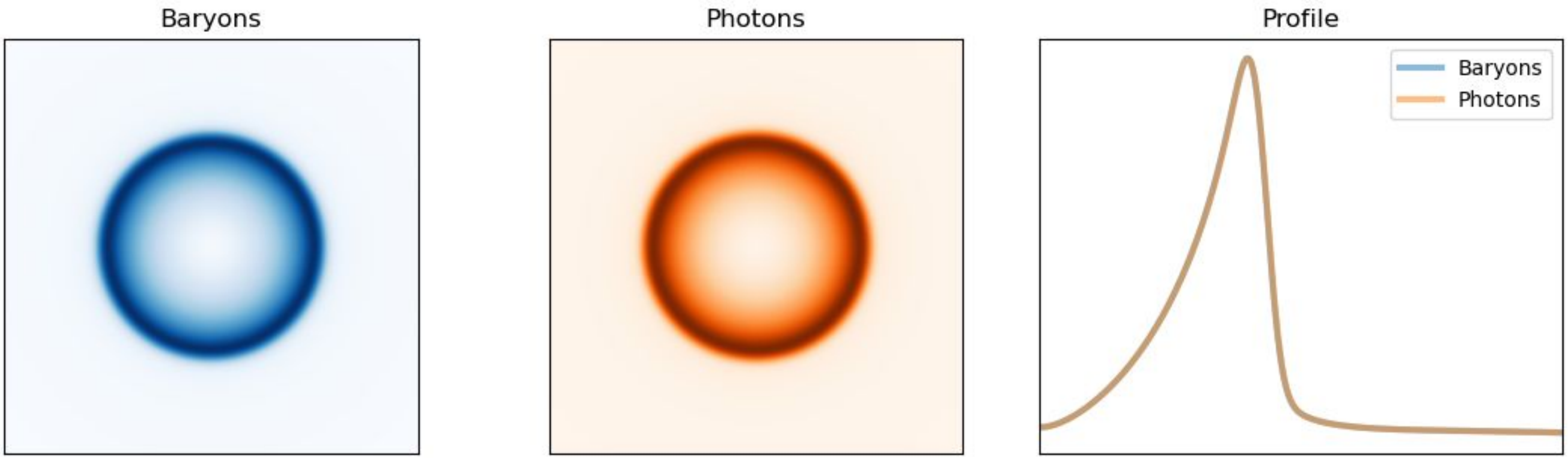
The acoustic wave

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



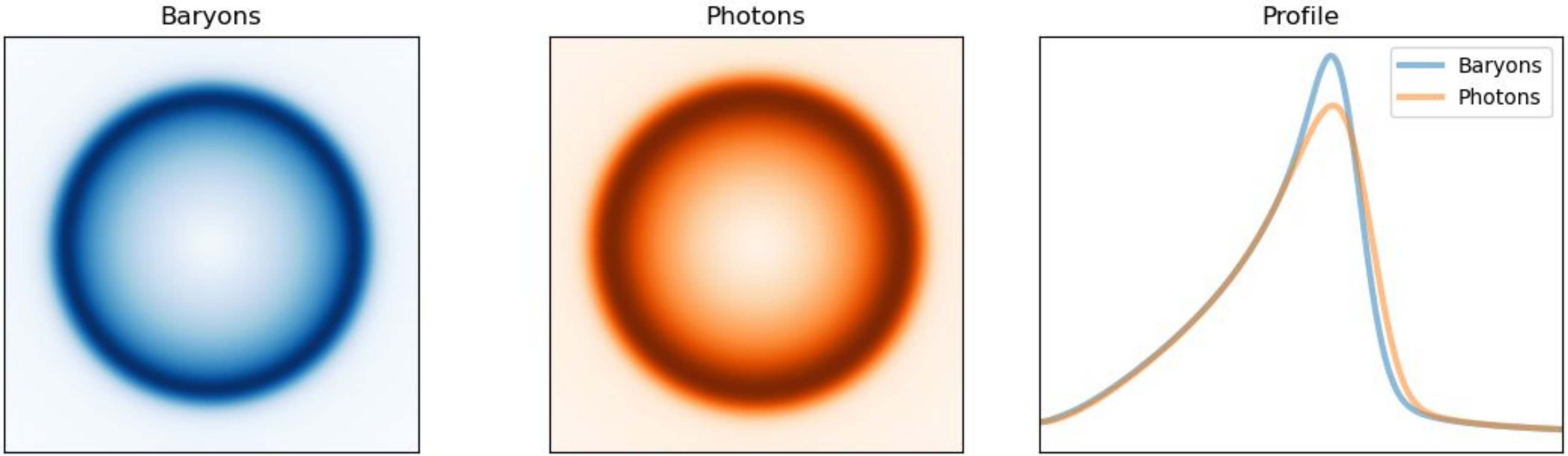
The acoustic wave

This expansion continues for 10^5 years



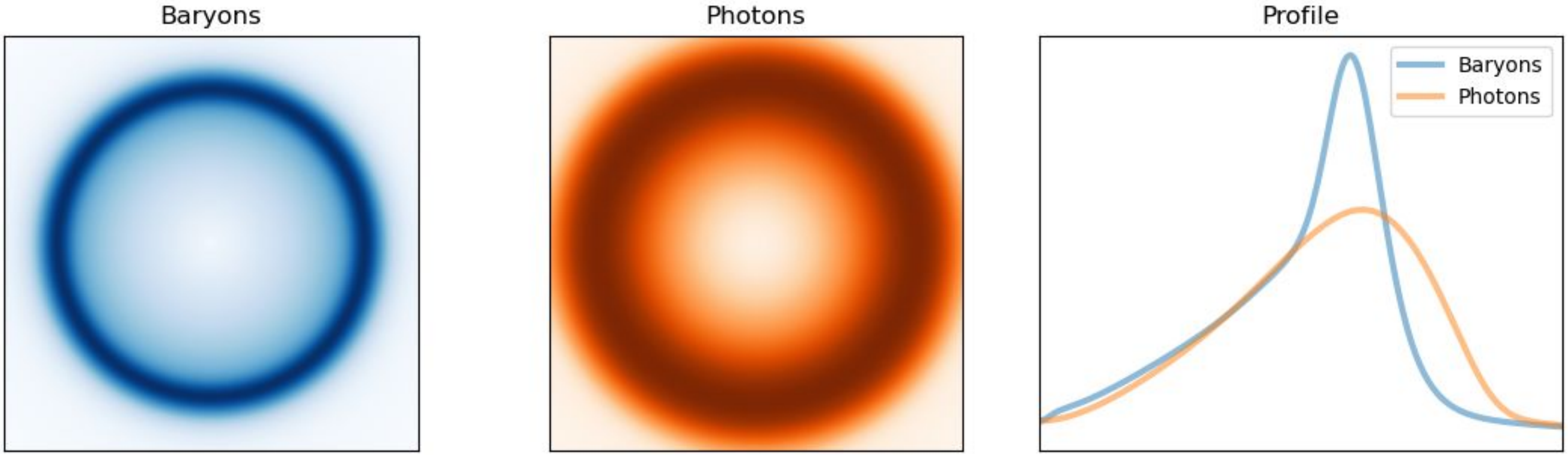
The acoustic wave

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.

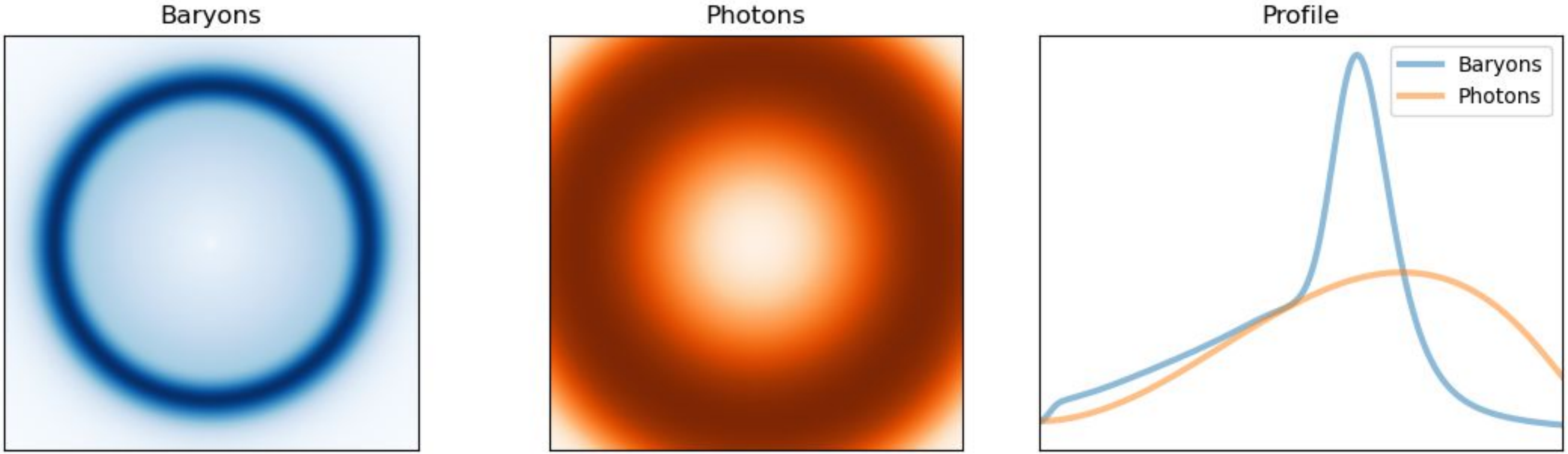


The acoustic wave

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

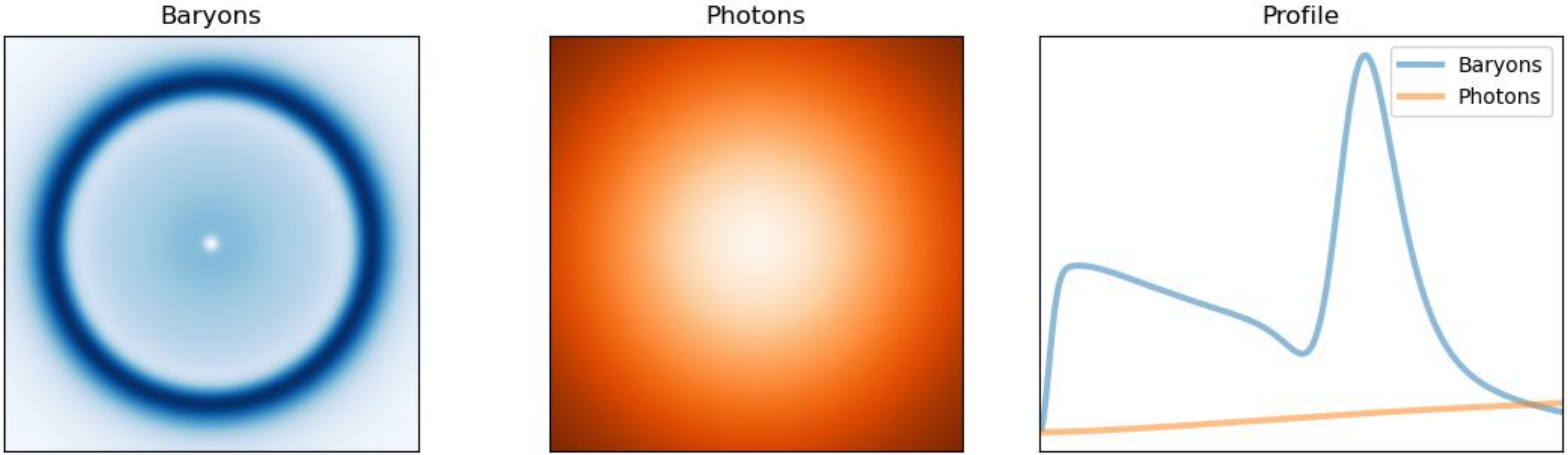


The acoustic wave



The acoustic wave

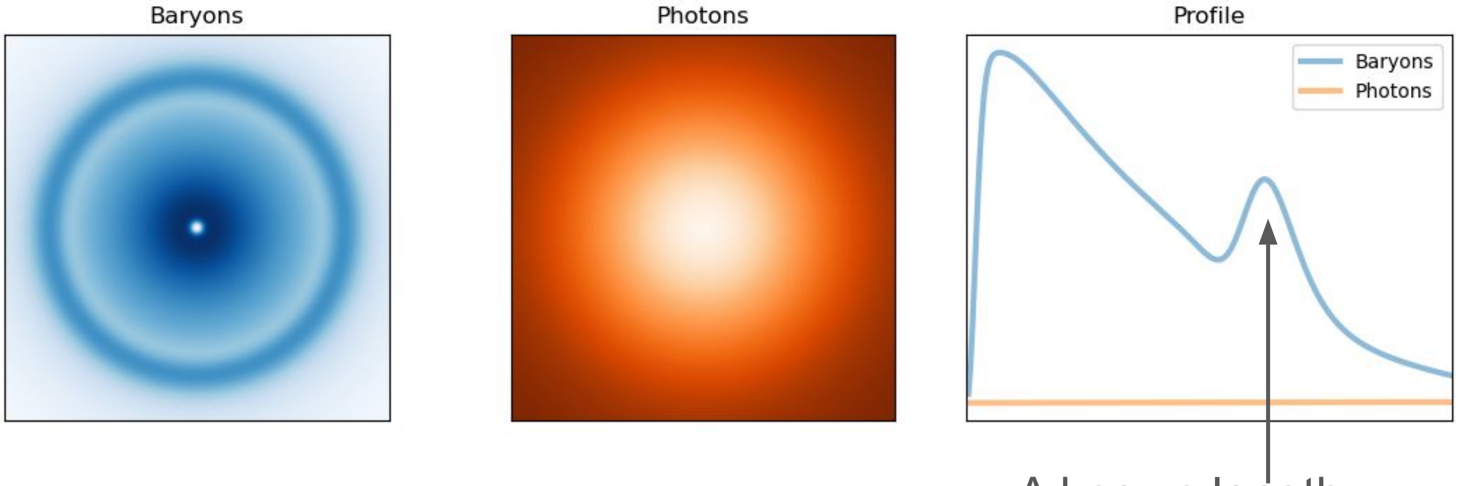
The photons have become almost completely uniform, but the baryons remain overdense in a shell 100Mpc in radius.
In addition, the large gravitational potential well which we started with starts to draw material back into it.



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 100Mpc in radius.



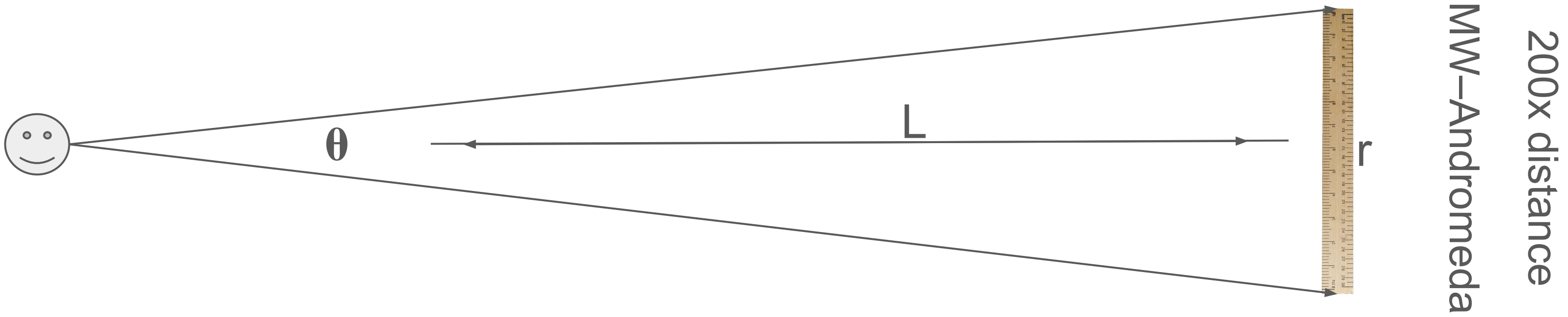
A known length scale: our “ruler”.

Standard ruler

This “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 excess of galaxy pairs 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

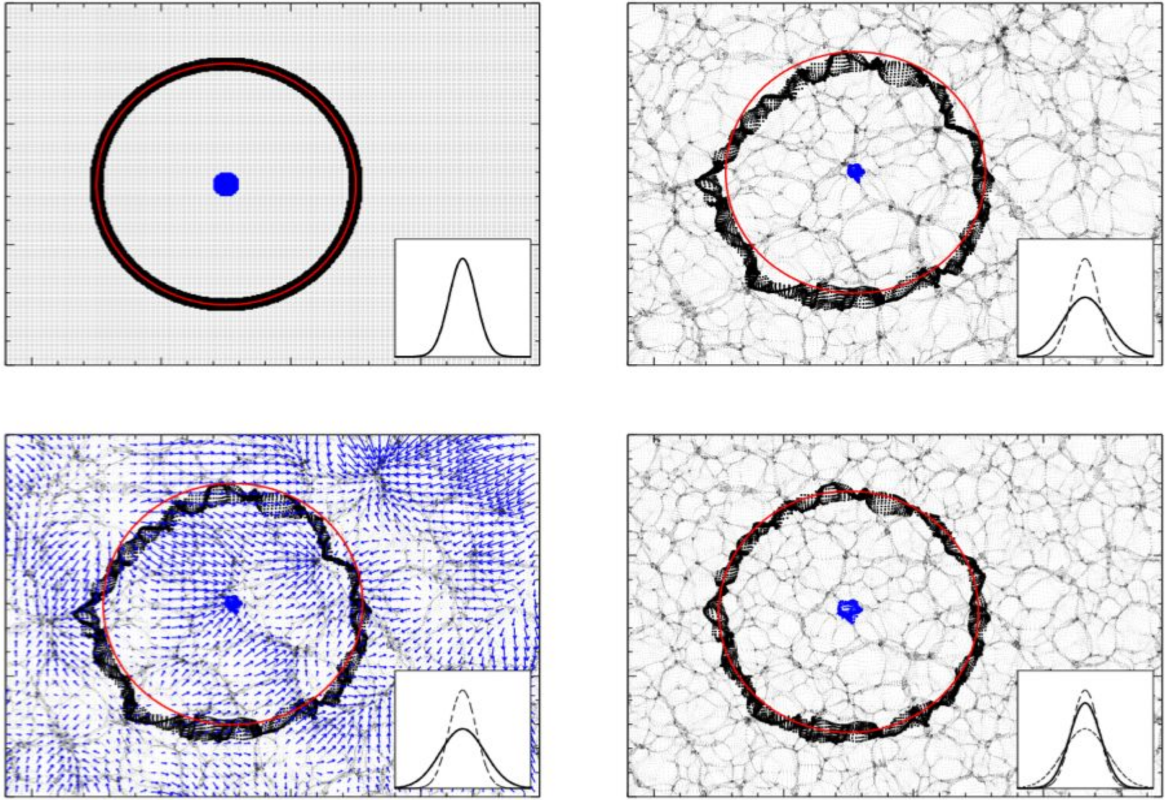
- All I’ve really done so far is show you that a feature exists in the matter correlation function (or power spectrum) in linear theory.
- To make contact with observations need to address:
  - **Non-linear evolution.**
  - The fact that we observe galaxies or the IGM, not matter (bias).
  - The fact 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.

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.

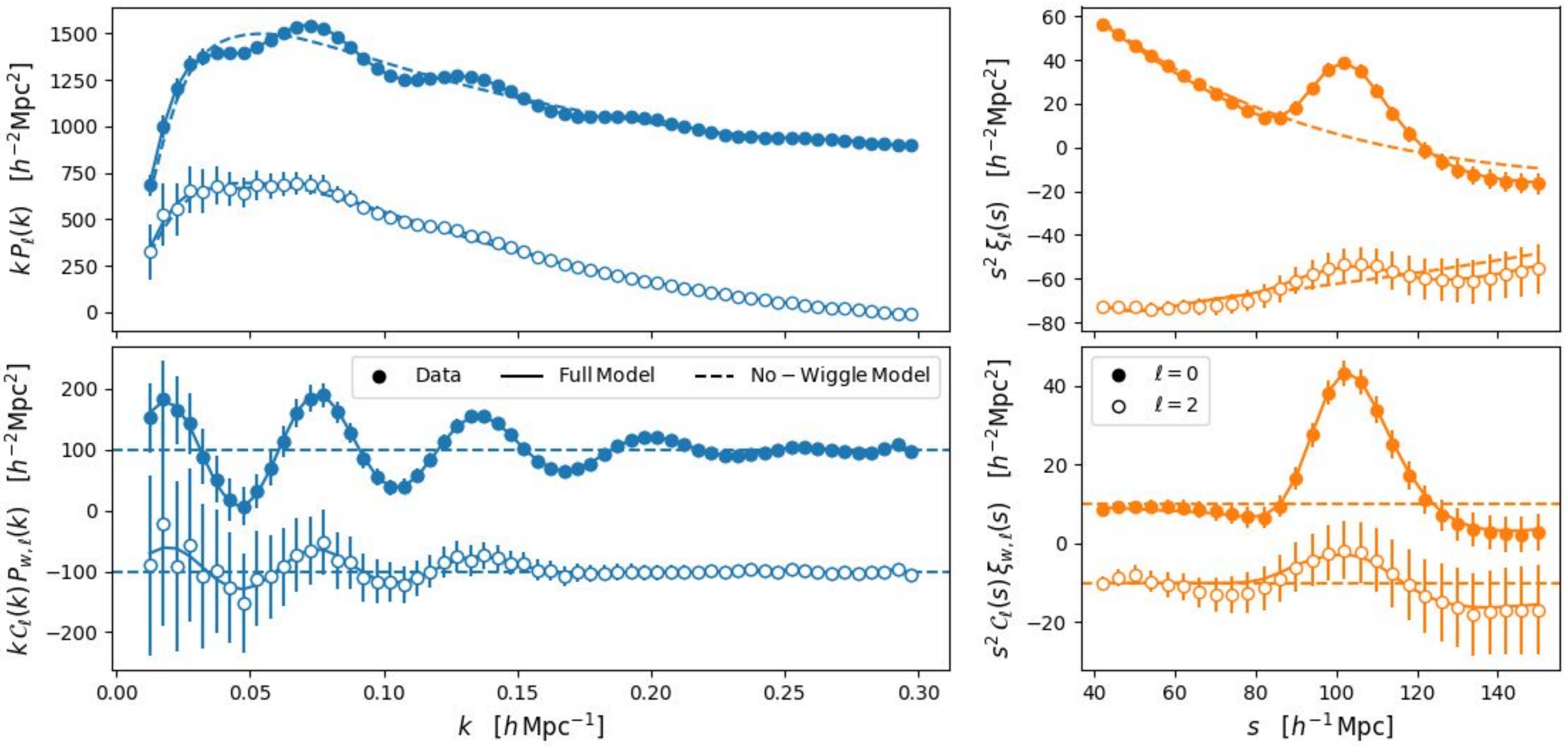


Padmanabhan et al. (2012)

Modeling

- 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!
    - 1st time unified framework for all discrete tracers.
    - 1st 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.
    - Flat priors on b & β parameters, rather than Gaussian.
    - …

Model test: theory vs simulation

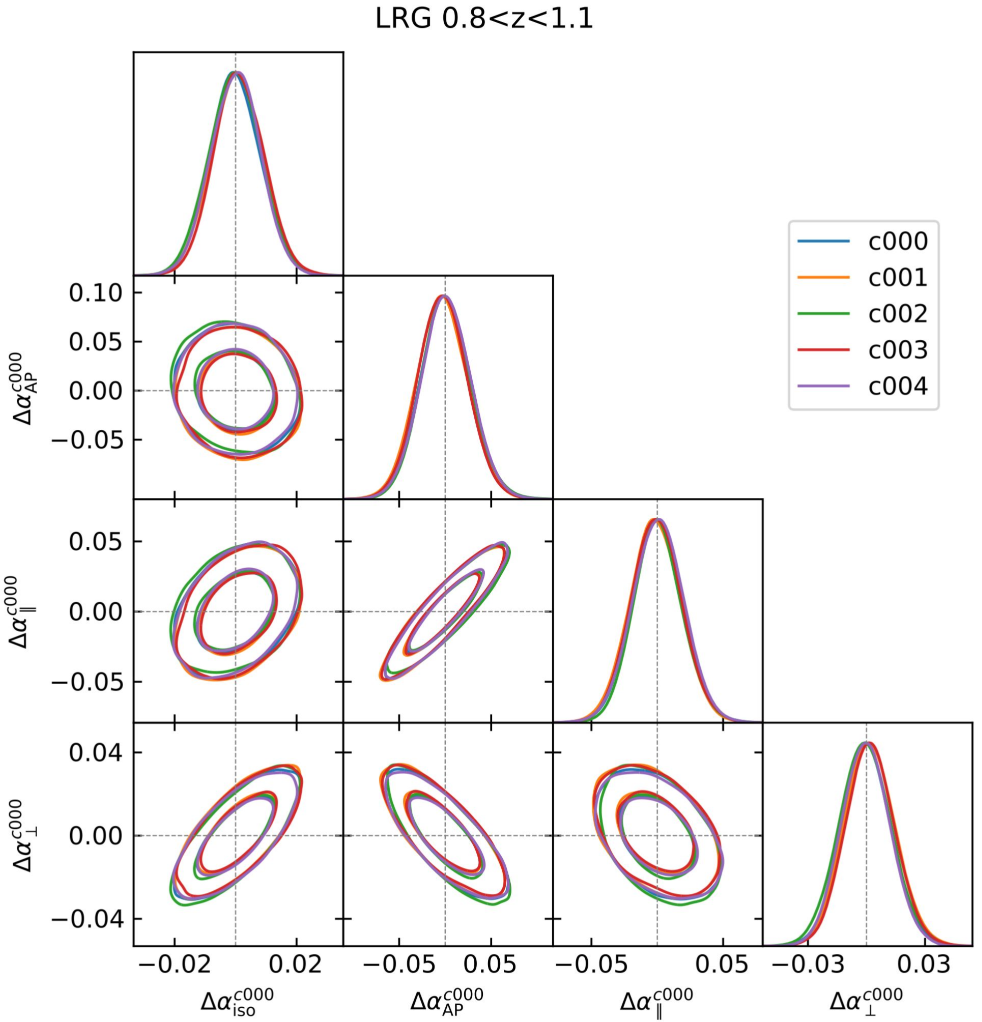


Systematic tests

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.

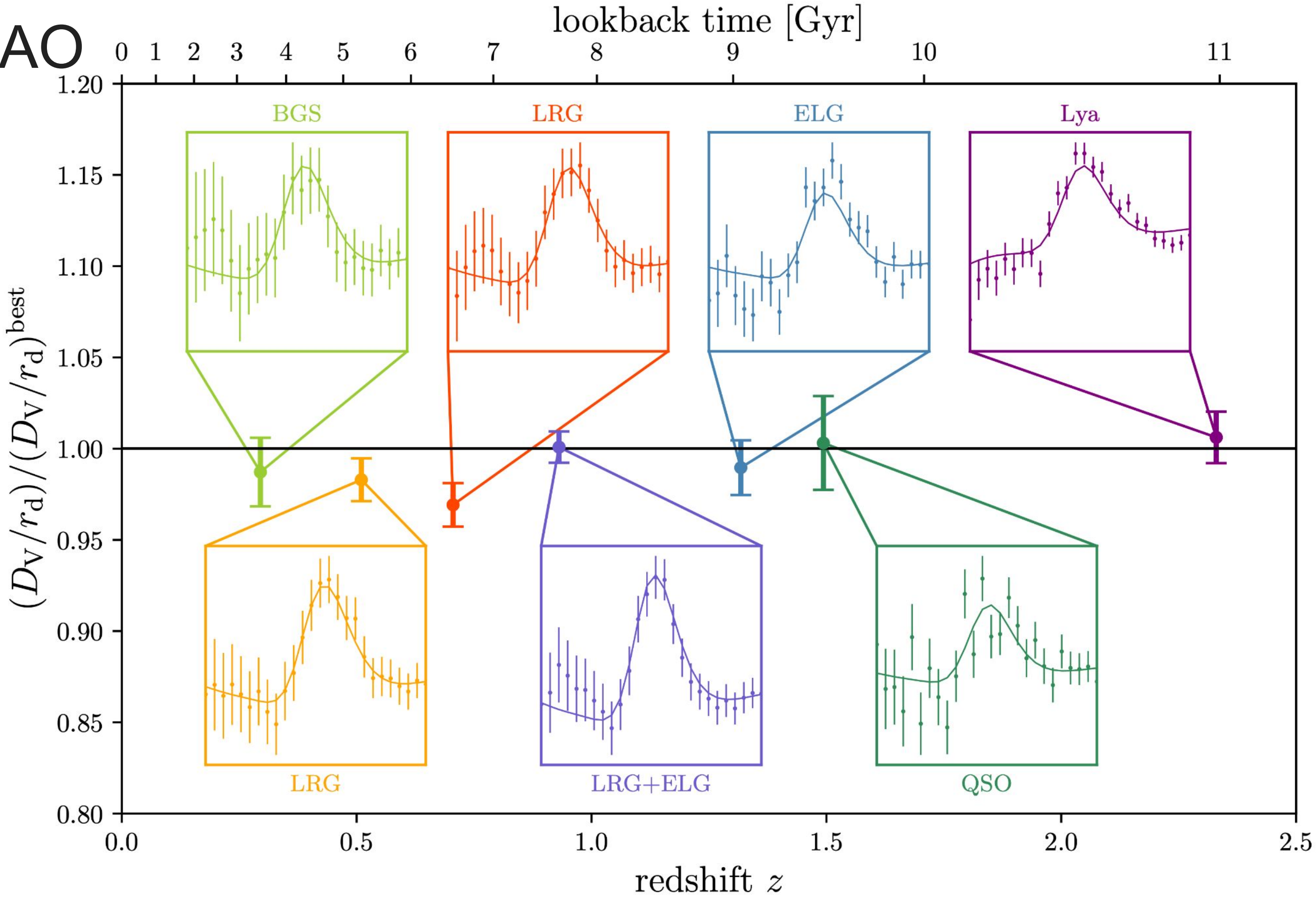


DESI Y1 BAO results

DESI 2024 BAO

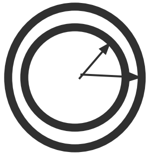
Constraints on distance scale and expansion history back to 11Gyr ago (Universe is 13.8Gyr old).

Our Y1 results are already better than 10yrs of SDSS!

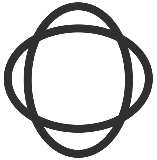


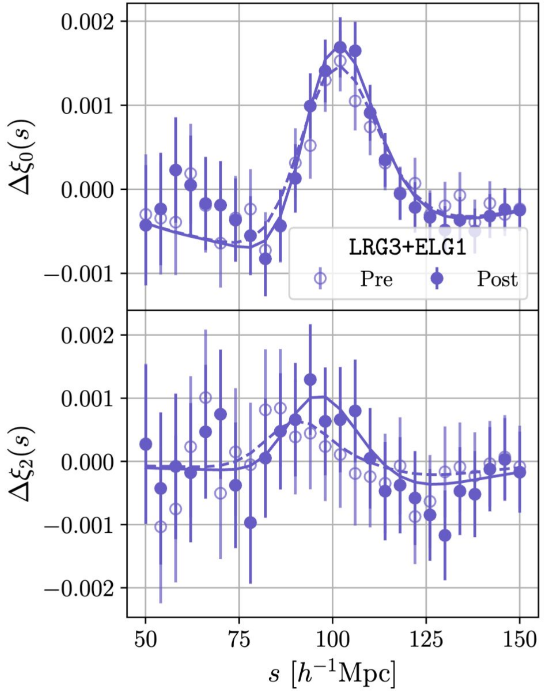
Zoom in on individual samples

Overall size of the BAO

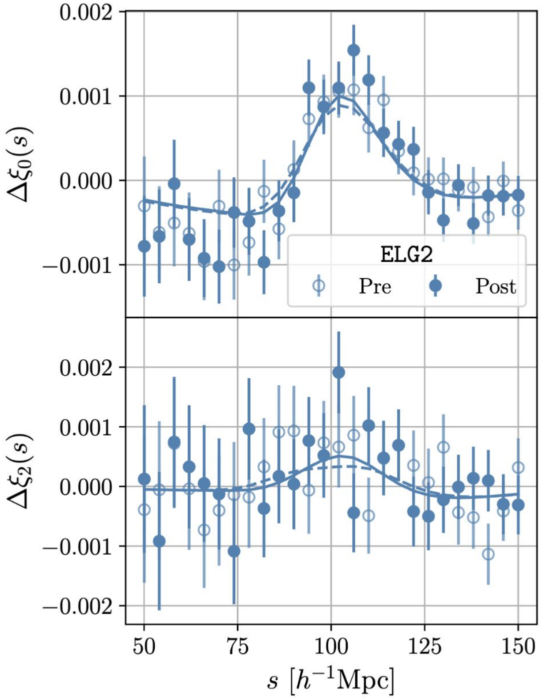


Anisotropy of the BAO





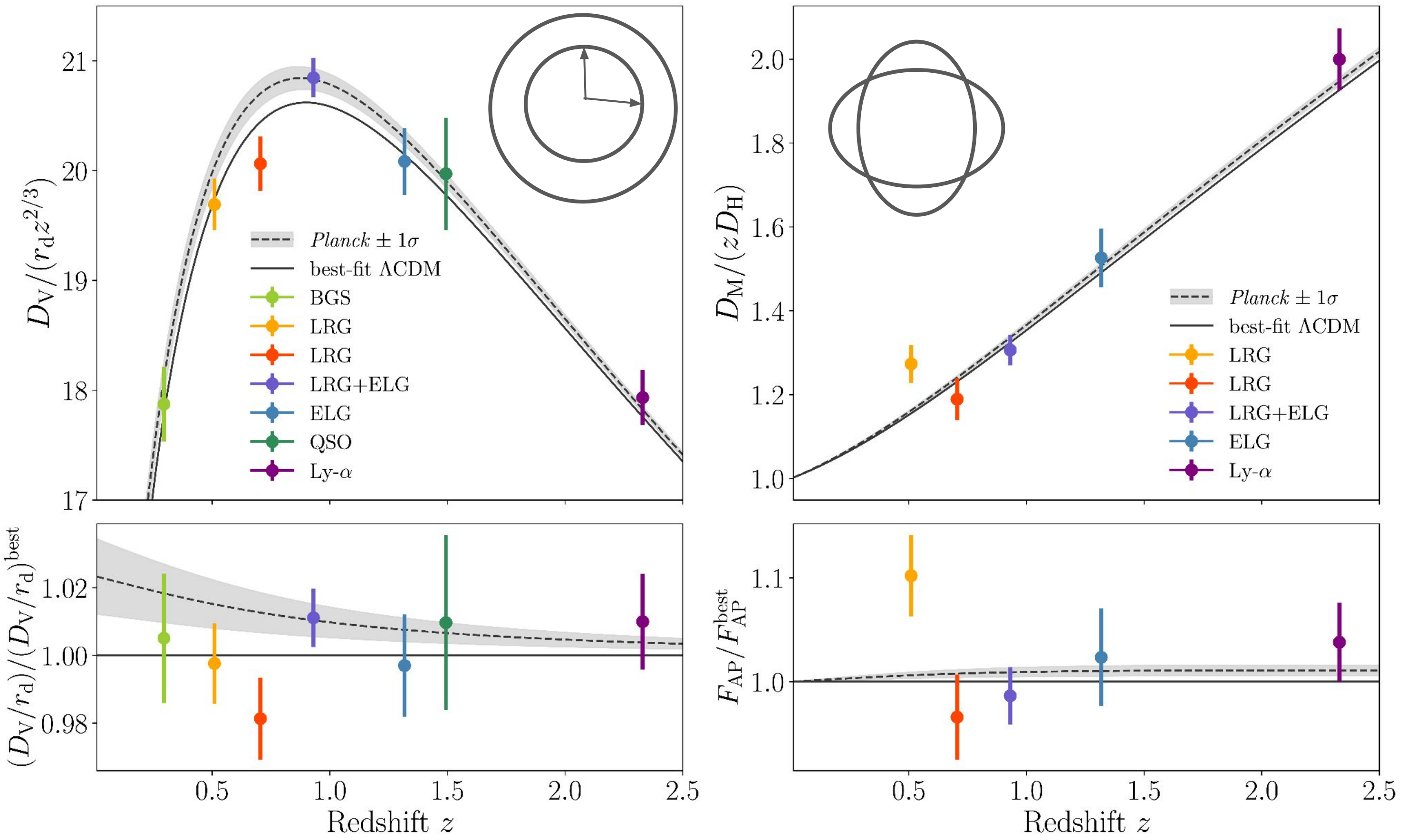
Combined tracer
at zeff = 0.93
Distance measured at 0.8%



Emission Line Galaxies
at zeff = 1.32
Distance measured at 1.5%.

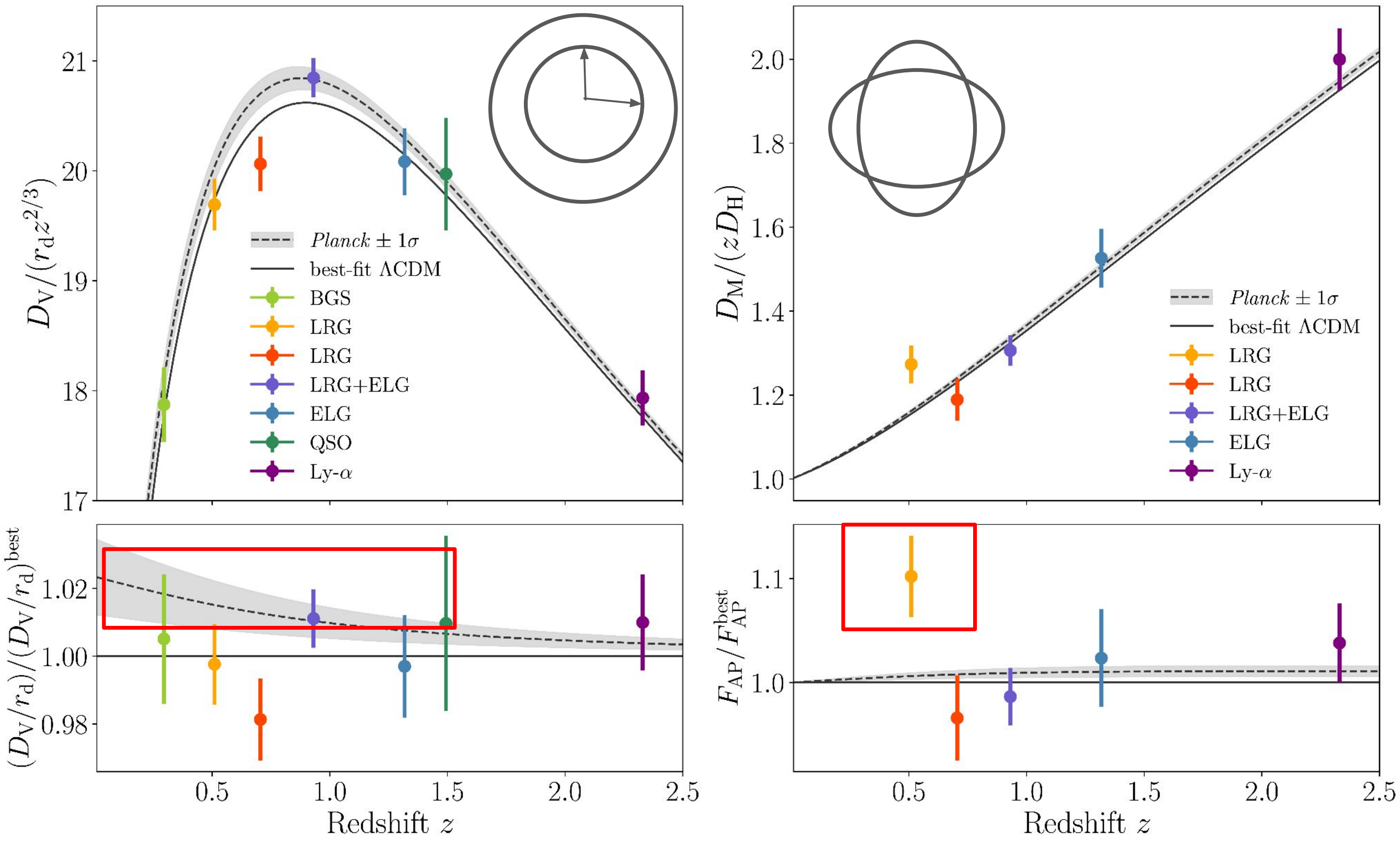
Summary

Best fit ΛCDM model has χ^2=12.66 for 10 d.o.f.



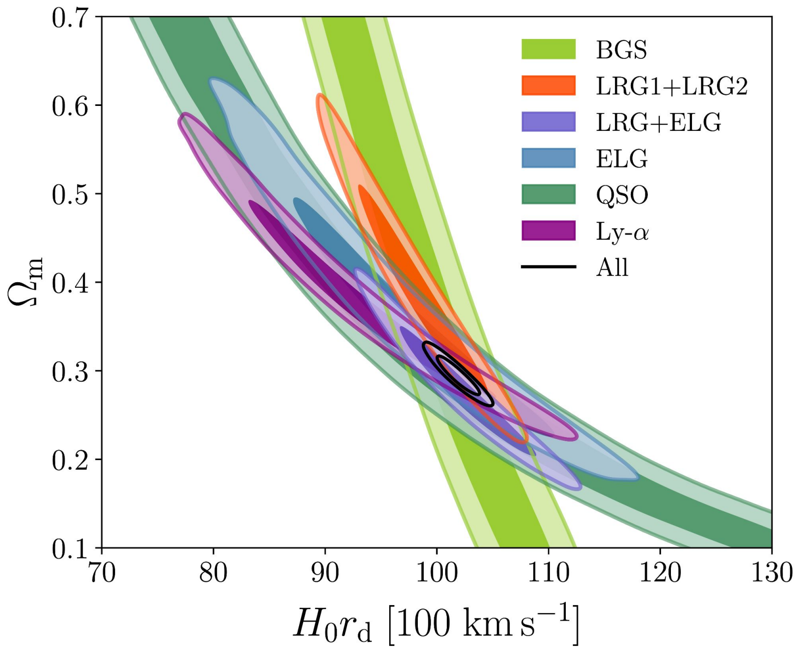
Summary

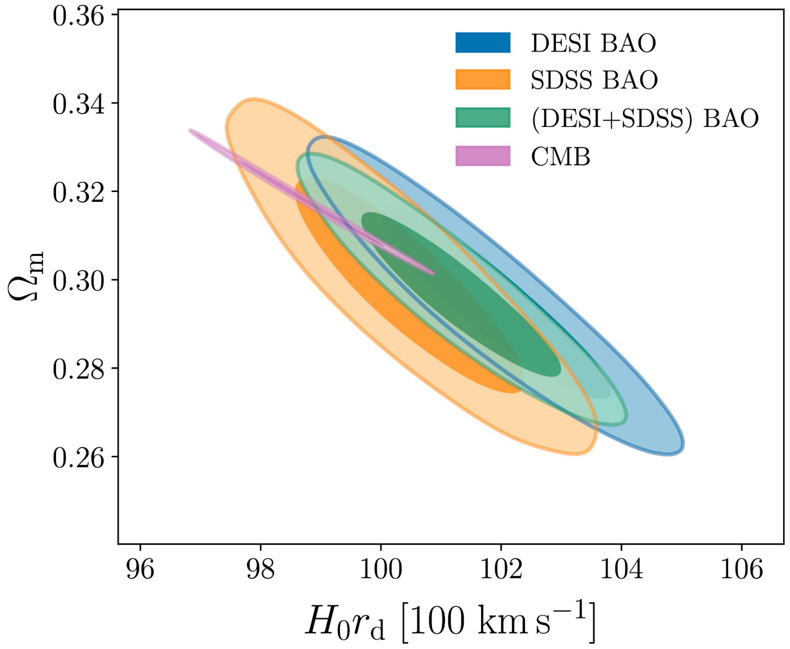
Best fit ΛCDM model has χ^2=12.66 for 10 d.o.f.



Within ΛCDM: two basic parameters

DM/DH and the shape of DV/rd determined by Ωm.
Redshift-independent constant normalisation term for DV/rd set by H0.rd
All samples and redshifts consistent with same two values!



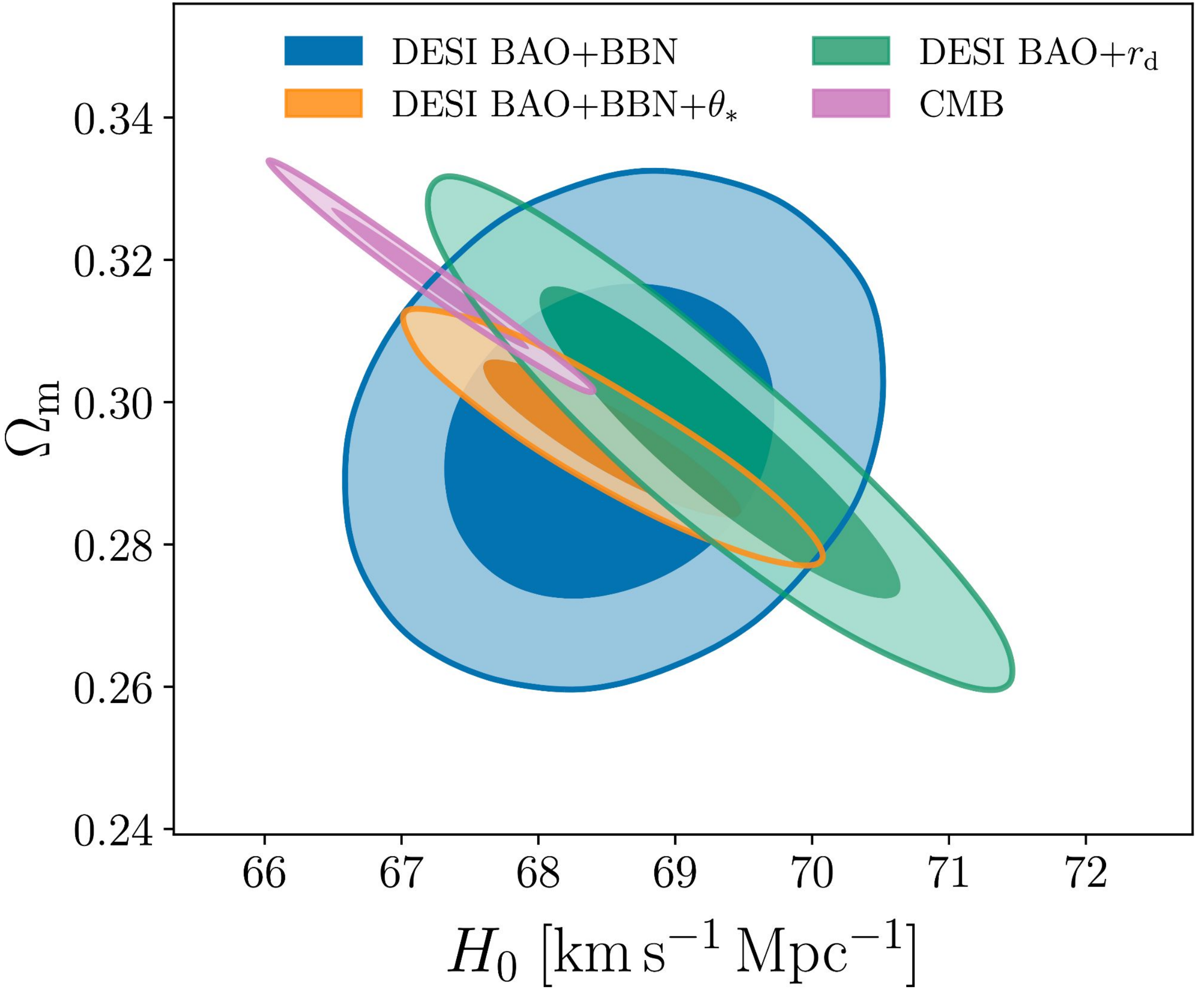


Ωm-H0

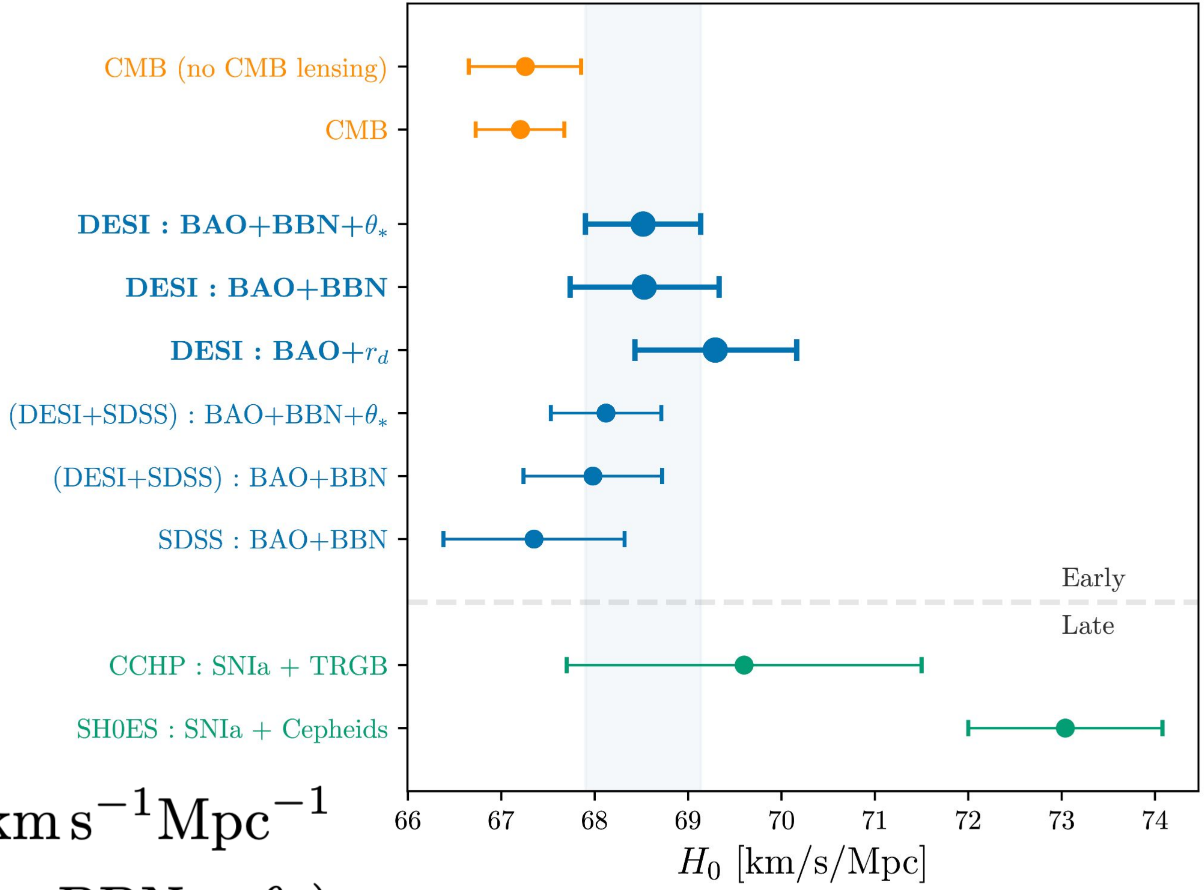
Including information from BBN or CMB allows us to convert to the dimensionful expansion rate: H0.

The devil is in the details, but we tend to have lower **Ω**m and higher H0 than primary CMB anisotropies.

Shift is of low statistical significance (2**σ**).



Hubble constant



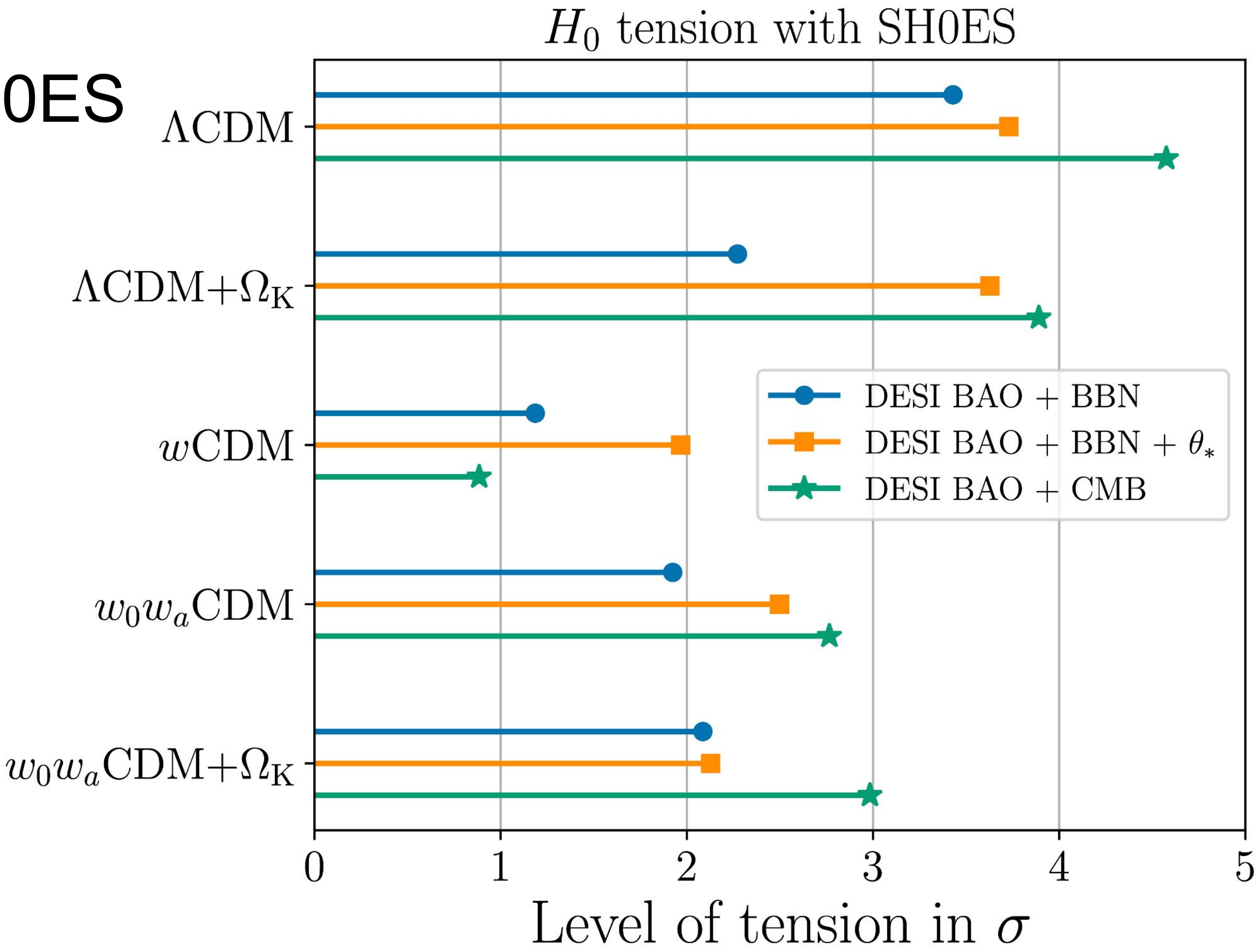
$$H_0 = (68.52 \pm 0.62)\ \mathrm{km\,s^{-1}Mpc^{-1}}$$
$$(\mathrm{DESI} + \mathrm{BBN} + \theta_\star)$$

Tension with SH0ES

Our result for H0 is lower than inferred by the SH0ES team from Type Ia SNe.

Continues “long running” tension in the field.

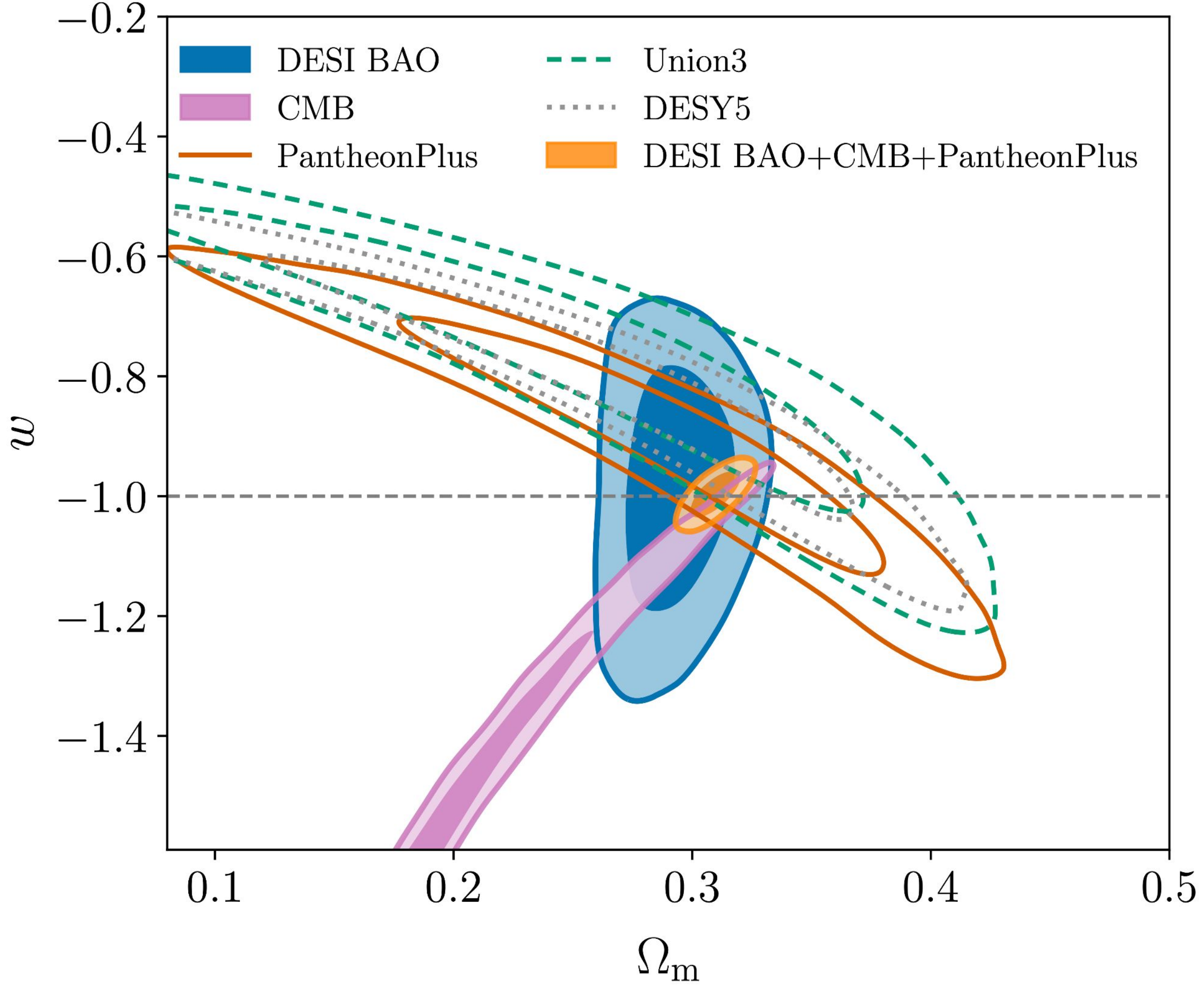
Significance is somewhat model and prior dependent, but “high”.



wCDM

One way of testing for agreement with ΛCDM is to allow the equation of state (EoS=p/ϱ) of the DE to deviate from that of Λ, i.e. w=-1.

DESI alone is compatible with ΛCDM.



Evolving DE/evolving EoS

If DE is evolving in time, then it is not unreasonable to expect the equation of state (EoS) will also evolve.

Absent strong theoretical guidance, choose a phenomenological form:

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

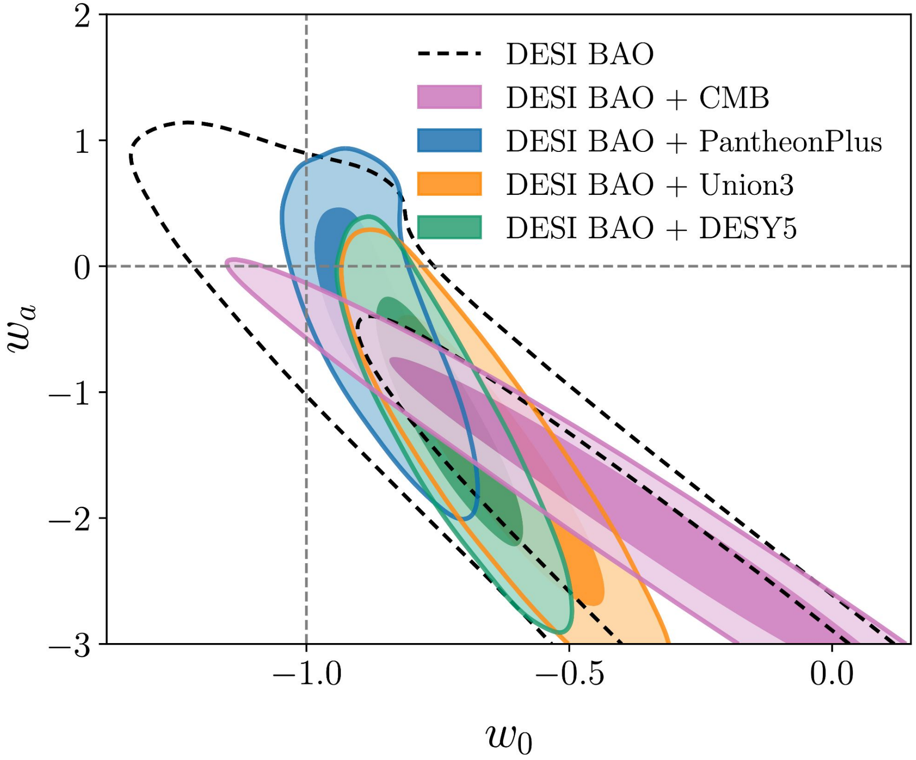
$$w(z) = w_0 + w_a \frac{z}{1 + z}$$

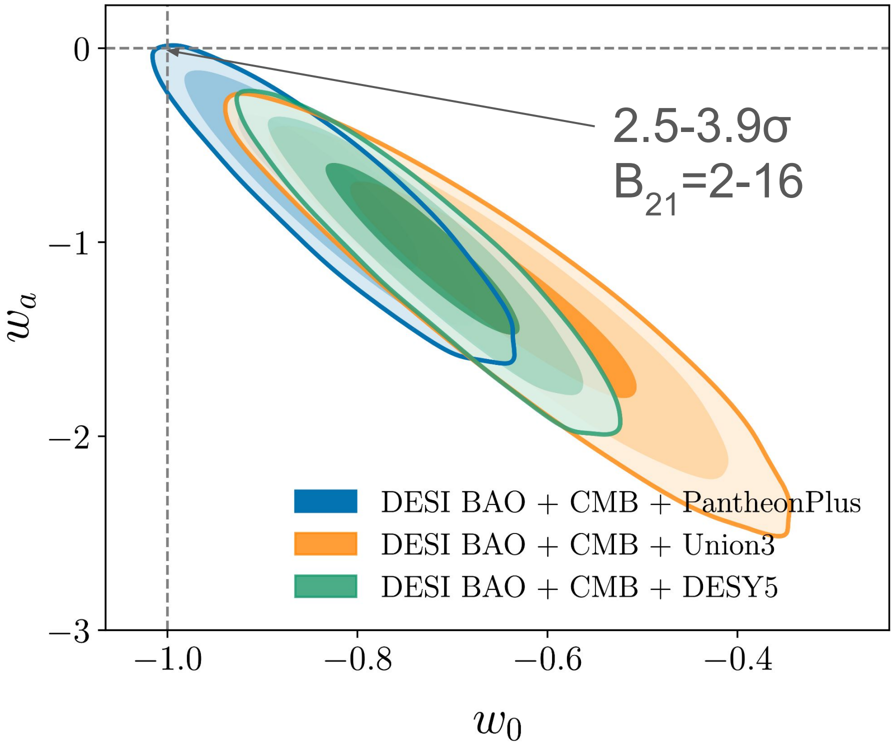
If w(z)>-1 then DE density drops with time.

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

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 …





Cause of “tension”

It’s “definitely curious” that these 3 different probes like deviations from ΛCDM of the same form … “thawing DE”.

- For DESI alone, $\Delta\chi^2$=-3.7 for 2 extra d.o.f.
- Cause is mainly the “anisotropy” (DM/DH) measurement at z~0.5, which is “2σ high” compared to ΛCDM.
- Making w0>-1 gives w(z) more positive for z<0.5, then having wa<0 to drive w(z) down at higher redshift to better fit the other DESI points.
  - DE density first rises (with time) then declines towards the present – **another coincidence problem**?
- CMB (Planck+ACT) have $\Delta\chi^2$=-3.7 for 2 extra d.o.f.
- Combining DESI+Planck+ACT gives $\Delta\chi^2$=-9.5 (2.6σ), but constraints still prior dominated.
- When adding SN data we see “significant” tension with ΛCDM.

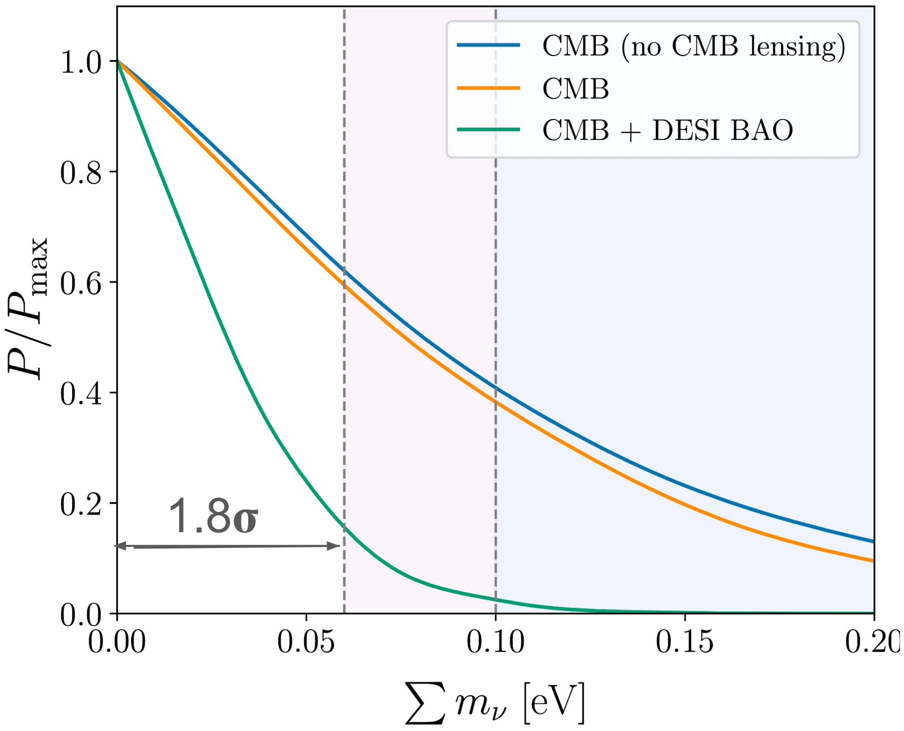
Implications for neutrino mass

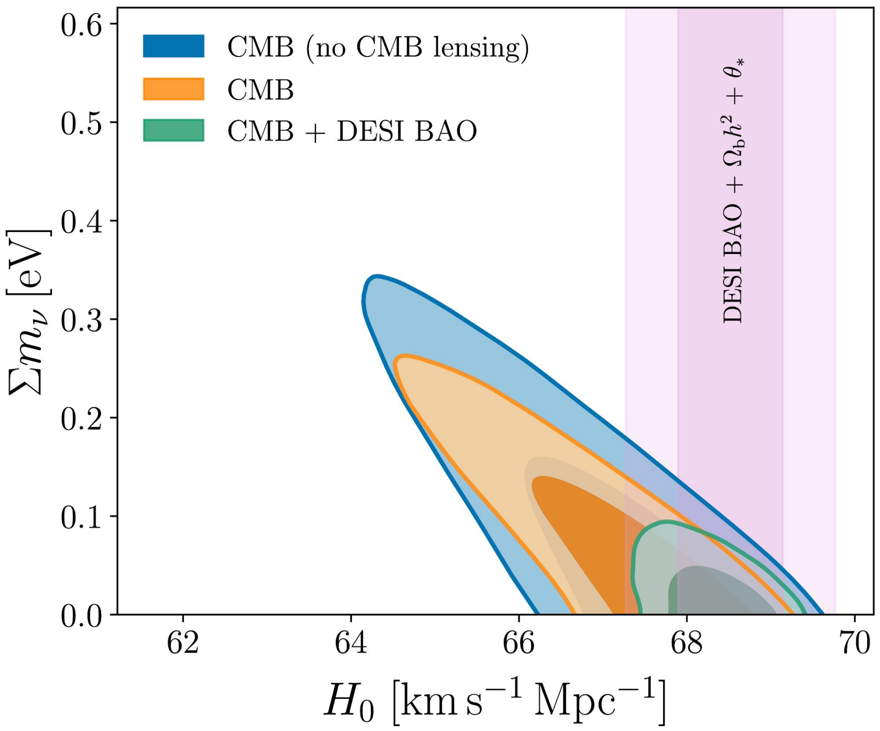
- Cosmology provides strong evidence for the existence of a neutrino background that behaves as we expect at the time of the CMB.
- Neutrinos are the only known particles to behave as radiation in the “early” Universe and as dark matter at late times – thus they leave an imprint on cosmological observables 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.

Implications for neutrino mass

- Comparing the amplitude of the power at z~1000 measured by the CMB and the lensing of CMB photons as they traverse large-scale structure we can measure the power suppression.
- However the inferred neutrino mass is degenerate with Ωm and H0.
- DESI BAO can break this “geometric degeneracy”!

Neutrino mass (sum)





Tighter constraints – but prior dependent!

We don't have a detection of neutrino mass, and the upper limits we get are prior dependent:

$$\sum m_\nu < 0.21 \text{ eV} \quad (95\%, \text{CMB})$$

$$\sum m_\nu < 0.072\,\text{eV} \quad (95\%, \text{DESI BAO} + \text{CMB})$$

$$\sum m_\nu < 0.113\,\text{eV} \quad (95\%, \text{DESI BAO} + \text{CMB} + \sum m_\nu > 0.059\,\text{eV})$$

But … we are starting to put "pressure" on inverted mass hierarchy (within the context of ΛCDM).

This will get more interesting when we add "growth of structure" information from DESI …

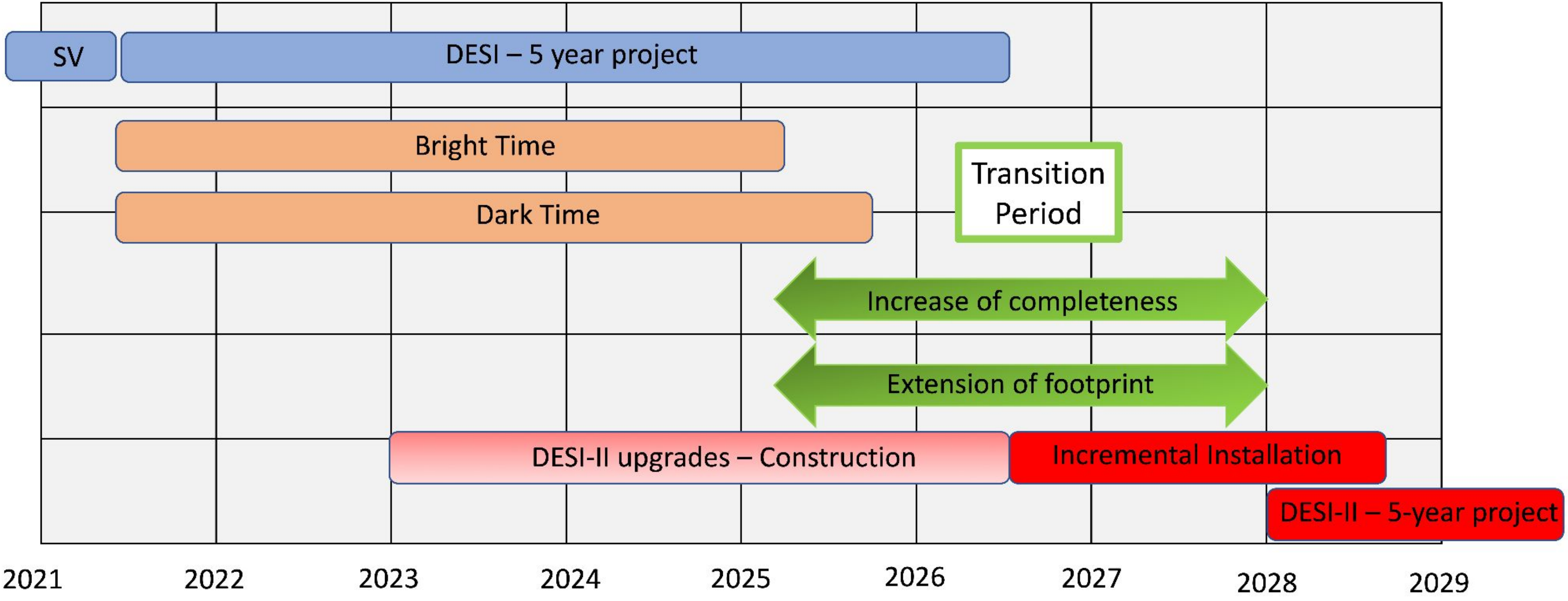
What’s next for Y1?

- Numerous “methodology” papers coming out soon.
- The “full shape” analysis, probing the gravitational potentials and growth of large-scale structure will follow in a few months. 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.
    - Paving the way for Y3 analyses.

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, …

The future


SV
DESI – 5 year project
Bright Time
Dark Time
Transition Period
Increase of completeness
Extension of footprint
DESI-II upgrades – Construction
Incremental Installation
DESI-II – 5-year project
2021
2022
2023
2024
2025
2026
2027
2028
2029

Spectroscopic roadmap

- Dark Energy Spectroscopic Instrument (DESI; primarily $z<1.5$)
  - Dark energy with BAO and RSD.
  - Ahead of schedule, and half way through its 6yr program.
- DESI-II (continued observational program, “pathfinder” for “Stage 5”)
  - As powerful as DESI, but at $z>2$ with unique access to primordial physics.
  - Early dark energy and the growth of structure in the matter dominated regime.
  - Strong constraints on existing tensions.
  - Professional training and real-world experience.
  - Synergies with other cosmology experiments.
- Spec-S5 (new, dedicated facility >10x more powerful than DESI)
  - Primordial physics (more constraining than CMB in important areas).
  - Increase the primordial figure of merit 10x over what DESI can achieve.
  - Requires a new facility.

Fundamental physics from future spectroscopic surveys
(LBNL, 6-8 May)

The goal of this conference is to gather high energy theorists and cosmologists to explore the observational signatures of physics beyond the standard model in Large-Scale Structure as can be measured with ongoing and future spectroscopic surveys. The 2023 P5 report identified the next generation of spectroscopic survey as a key tool to explore inflationary physics, late-time cosmic acceleration, light relics, neutrino masses, and dark matter.

….

https://indico.physics.lbl.gov/event/2769/

Conclusions

- DESI is performing well — survey is ahead of schedule!
- Using only 1yr of data we already have the world's best BAO measurement.
- Numerous methodological improvements, in addition to better data.
- Tight bounds on systematic errors (all well below statistical precision).
- Composite precision on distance scale of about 0.5%.
- Shift to lower matter density and faster expansion rate than CMB, but still in tension with SH0ES measurement.
- DESI alone is consistent with ΛCDM, but when combined with CMB+SN data start to see "hints" of tensions ("thawing DE").
- No detection of neutrino mass, but tighter upper limits – preference for NH.
- Much more science to come!

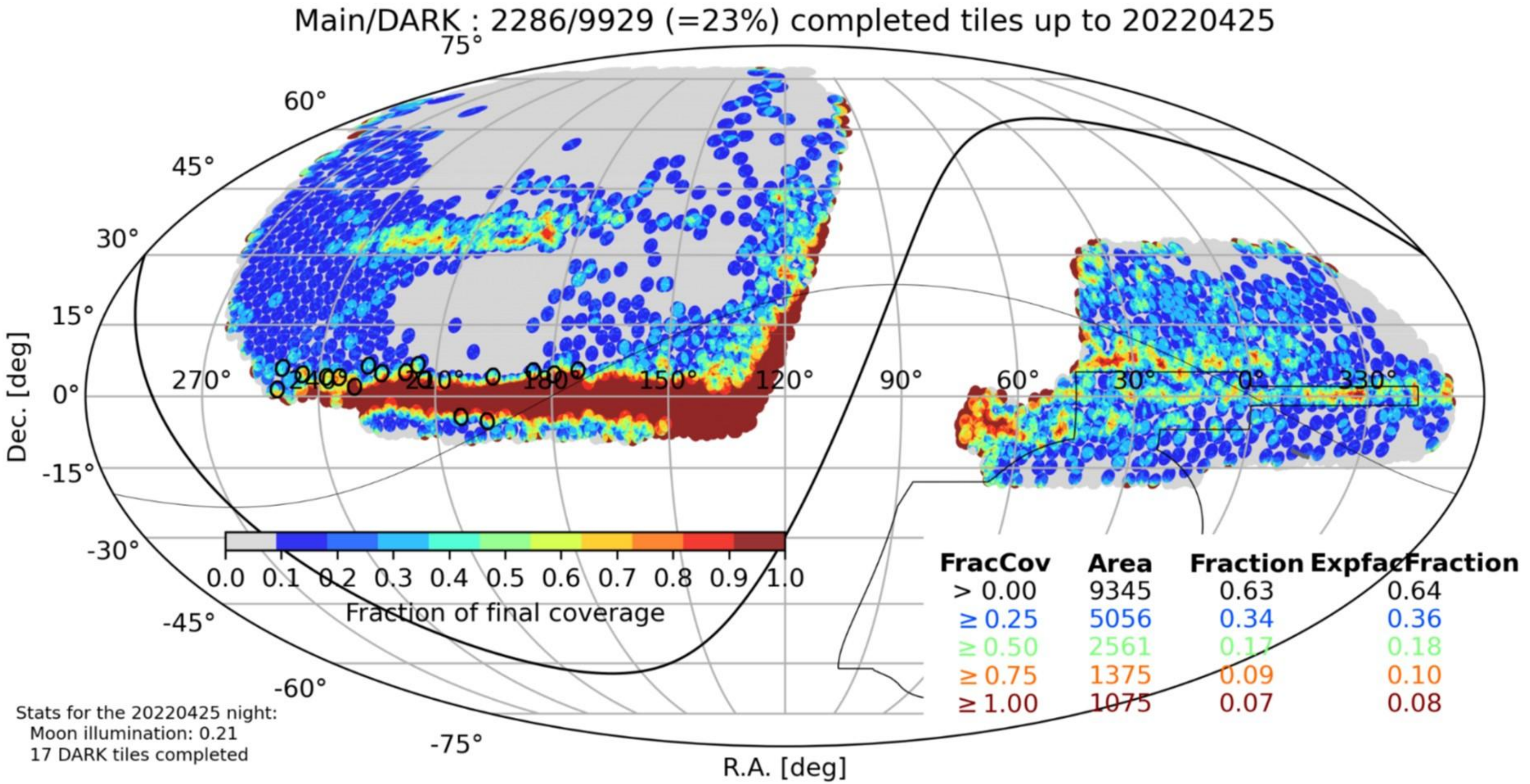

DARK ENERGY SPECTROSCOPIC INSTRUMENT
DARK ENERGY
SPECTROSCOPIC
INSTRUMENT
U.S. Department of Energy Office of Science
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA
NSF
NERSC
cea
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMIA Y COMPETITIVIDAD
CONACYT
HEISING-SIMONS FOUNDATION
GORDON AND BETTY MOORE FOUNDATION
Science & Technology Facilities Council
Thanks to our sponsors and
70 Participating Institutions!

The End

Golden age of (cosmological) surveys

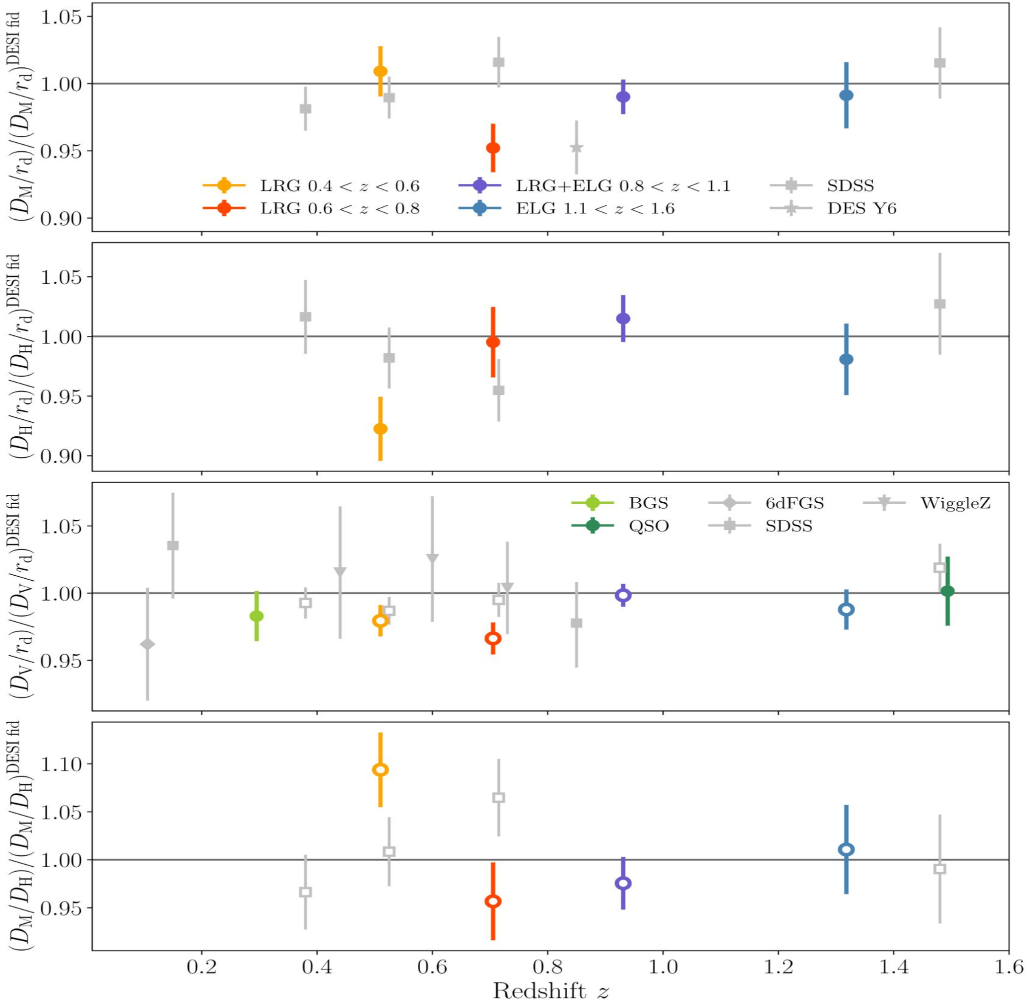
- **DESI is half-way through its (1st) survey**
- PFS is commissioning, WEAVE will begin soon.
- SPT and ACT have completed observations.
- Euclid is observing at L2.
- South Pole Observatory
- Simons Observatory is under construction (Adv SO is approved).
- LSST will be coming online in a few years.
- SPHEREx and Roman will launch later this decade.
- CMB-S4 and Spec-S5 will follow in the next decade.
- … and others.

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

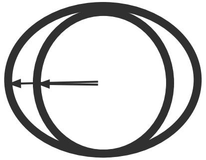


Main/DARK : 2286/9929 (=23%) completed tiles up to 20220425
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
Dec. [deg]
270°
240°
210°
180°
150°
120°
90°
60°
30°
0°
330°
R.A. [deg]
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Fraction of final coverage
FracCov Area Fraction ExpfacFraction
> 0.00 9345 0.63 0.64
≥ 0.25 5056 0.34 0.36
≥ 0.50 2561 0.17 0.18
≥ 0.75 1375 0.09 0.10
≥ 1.00 1075 0.07 0.08
Stats for the 20220425 night:
Moon illumination: 0.21
17 DARK tiles completed

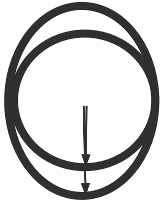
Comparison with earlier results



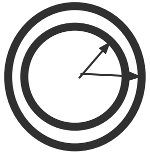
Transverse BAO



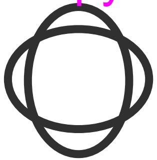
Line of sight BAO



Overall size of the BAO

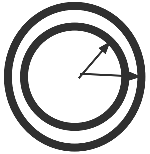


Anisotropy of the BAO

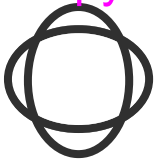


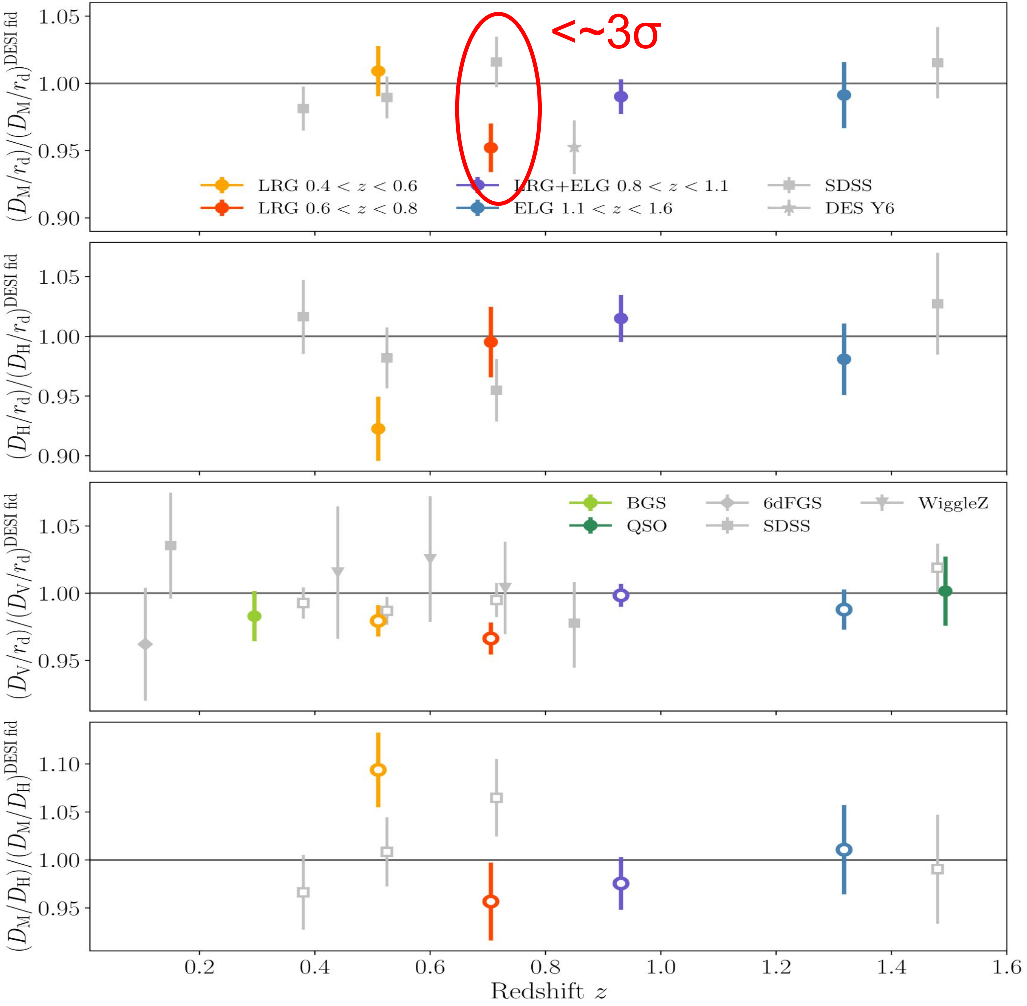
Comparison with earlier results

Overall size of the BAO

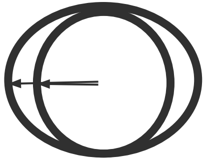


Anisotropy of the BAO

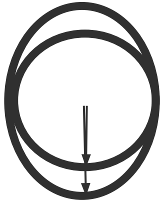




Transverse BAO

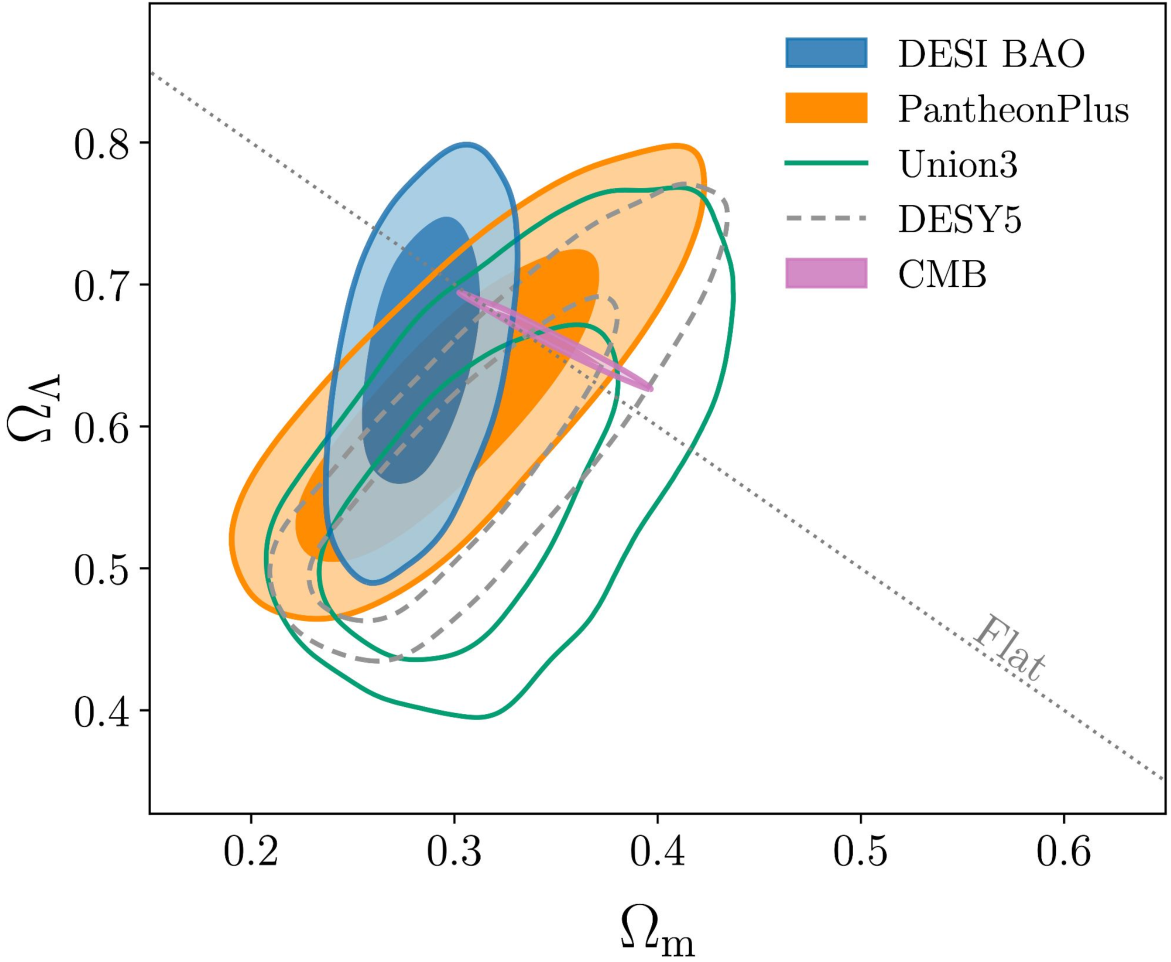


Line of sight BAO



Spatial flatness

$$\Omega_K = 0.0024 \pm 0.0016$$
$$\text{(DESI BAO + CMB)}$$

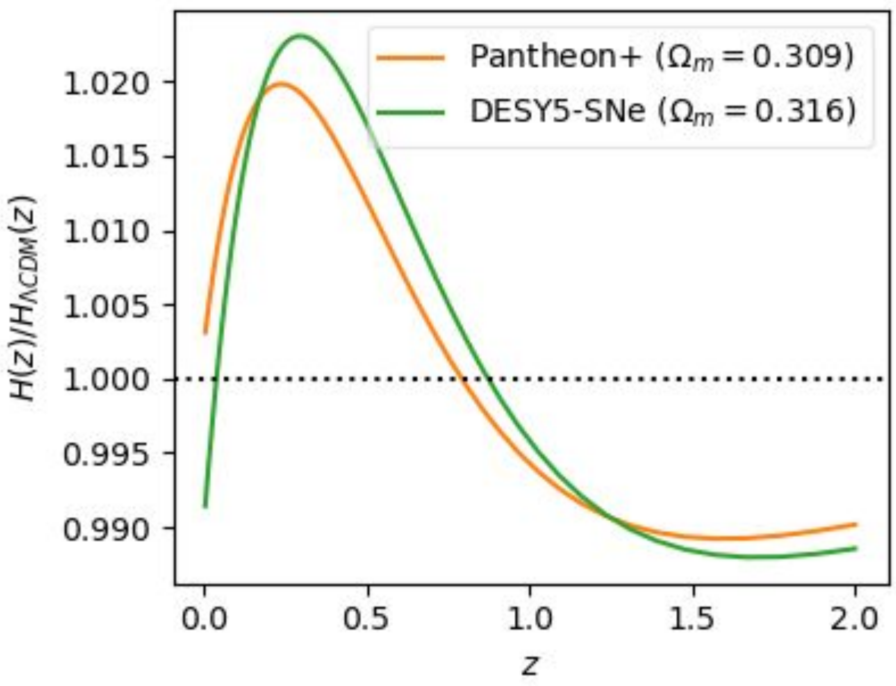


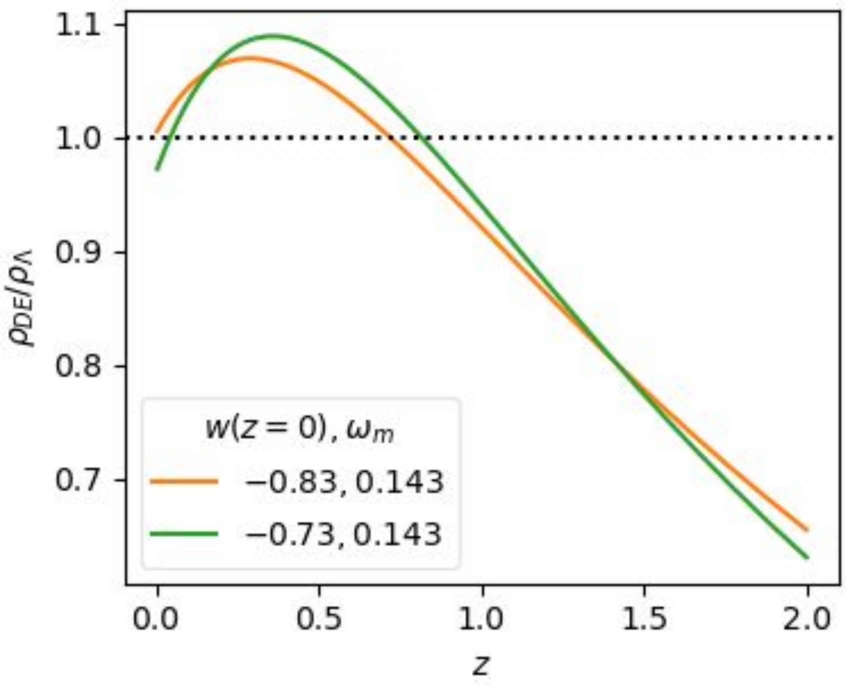
Comparison to SNe

$$\left.\begin{aligned} \Omega_m &= 0.295 \pm 0.015 \\ r_\mathrm{d}\, h &= (101.8 \pm 1.3)\mathrm{Mpc} \end{aligned}\right\} \quad \text{DESI BAO}$$

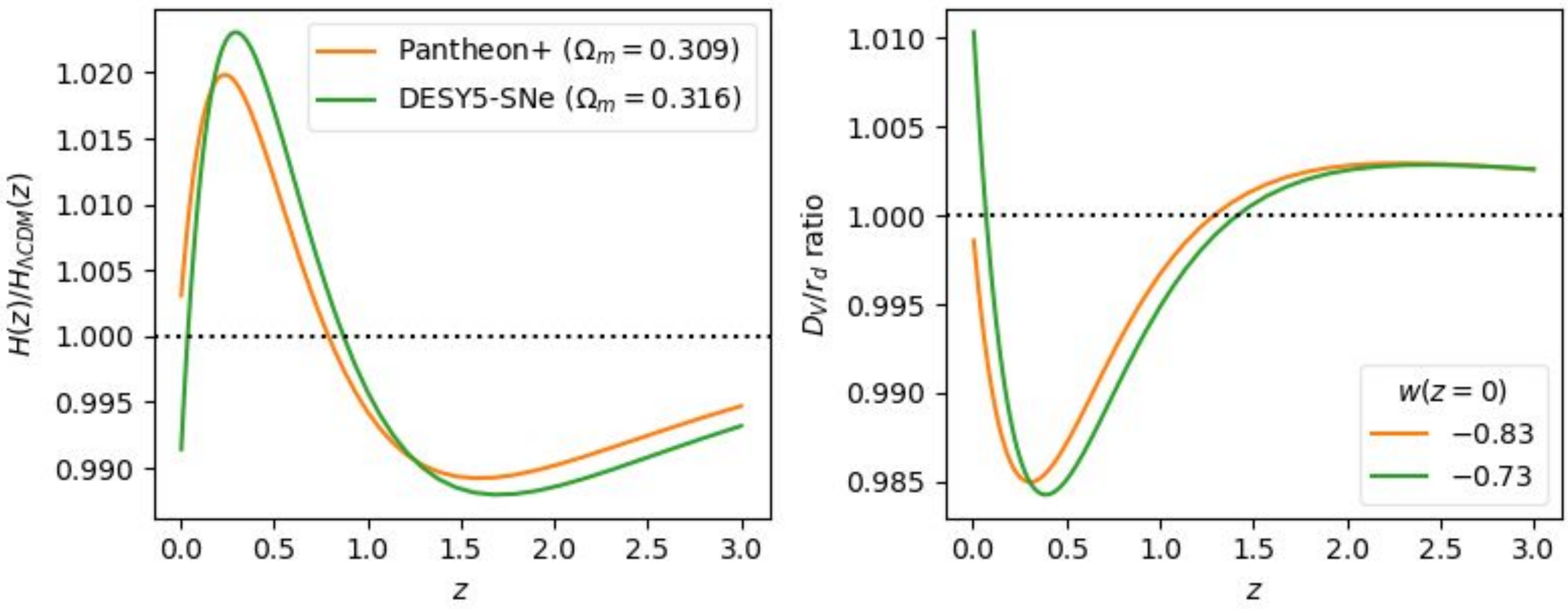
$$\begin{aligned} \Omega_\mathrm{m} &= 0.331 \pm 0.018 \quad (\mathrm{Pantheon+}; 1.7\sigma) \\ \Omega_\mathrm{m} &= 0.359 \pm 0.026 \quad (\mathrm{Union3}; 2.0\sigma) \\ \Omega_\mathrm{m} &= 0.353 \pm 0.017 \quad (\mathrm{DESY5}; 2.7\sigma) \end{aligned}$$

Comparison of different MAP models

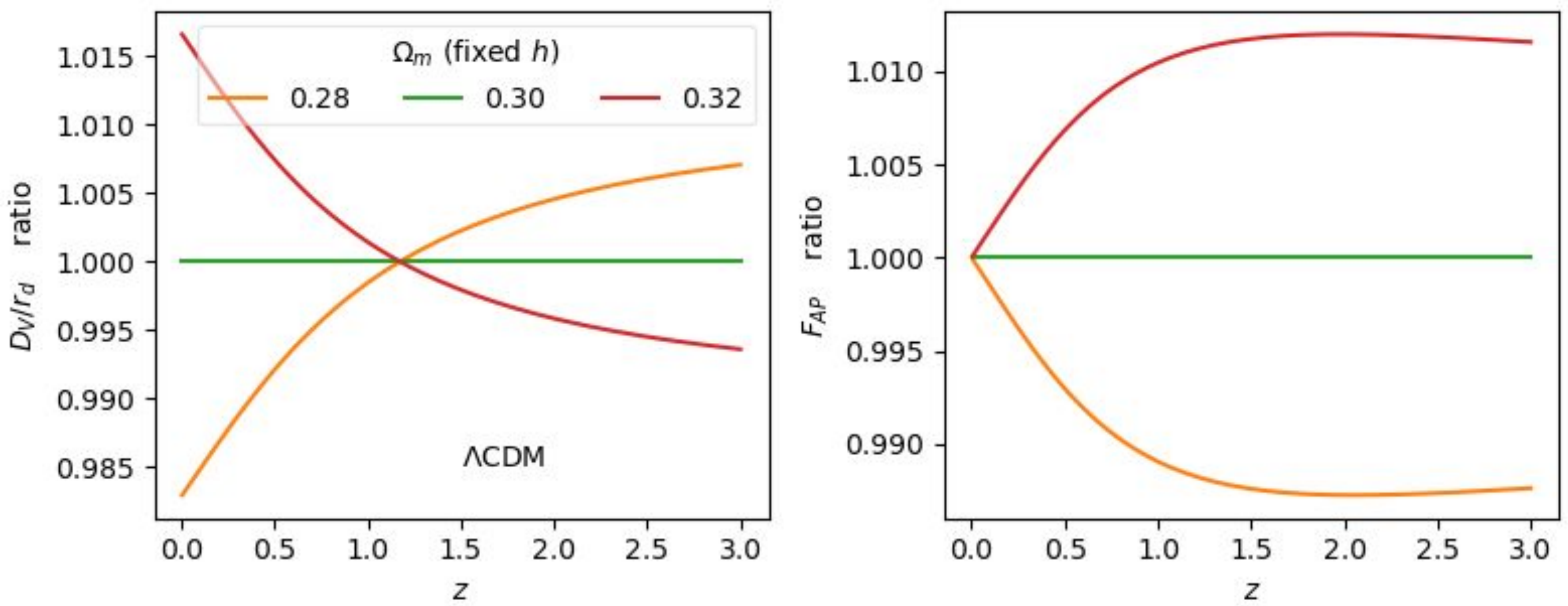




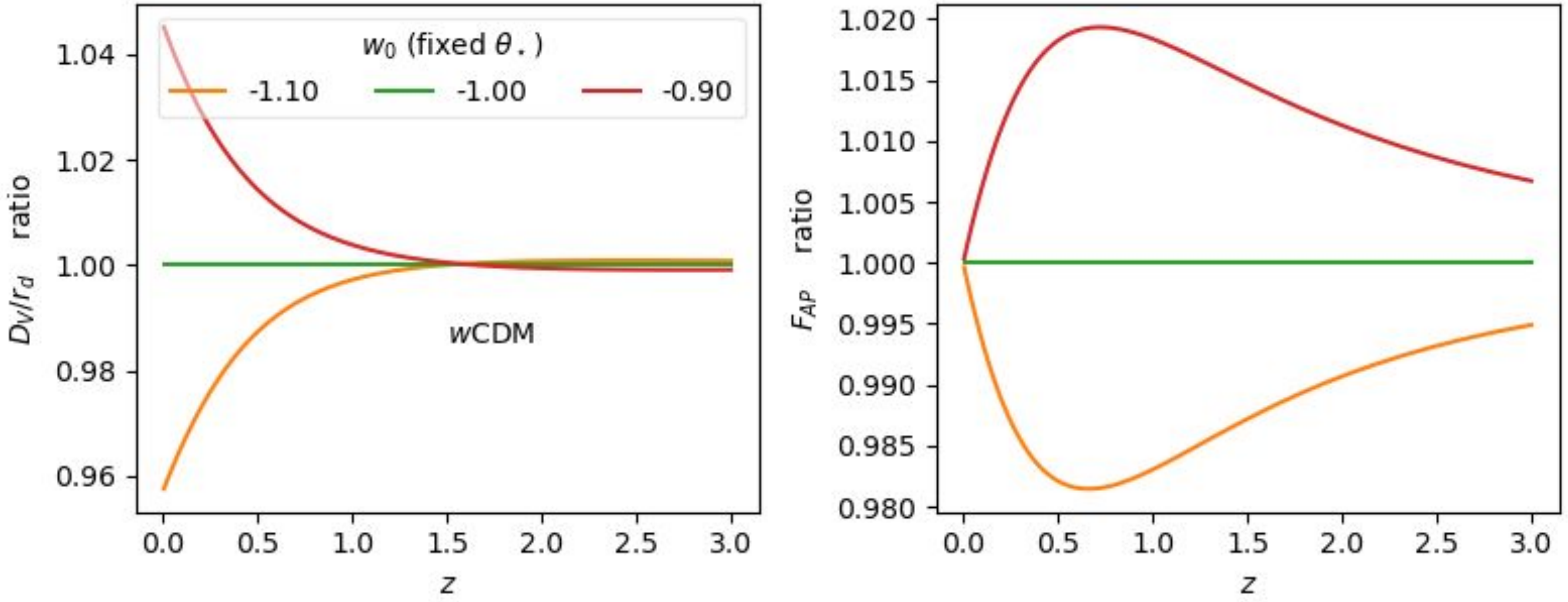
Comparison of different MAP models



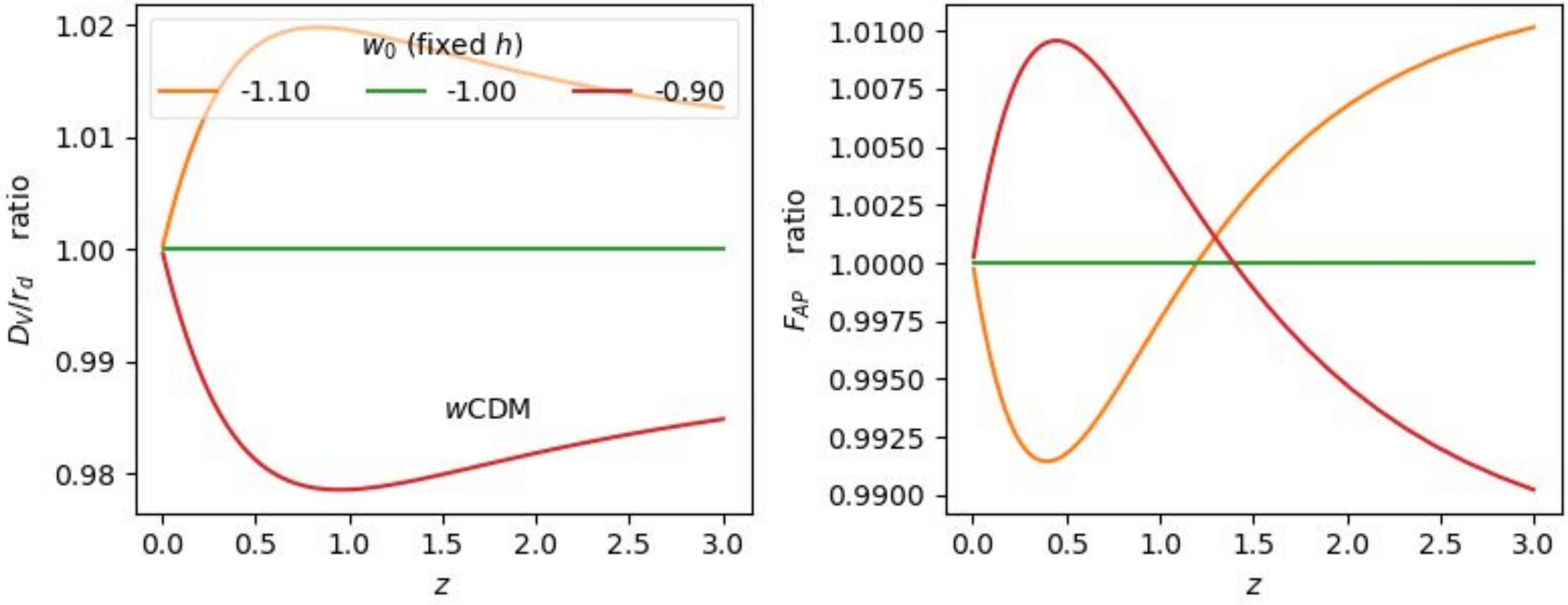
BAO observables



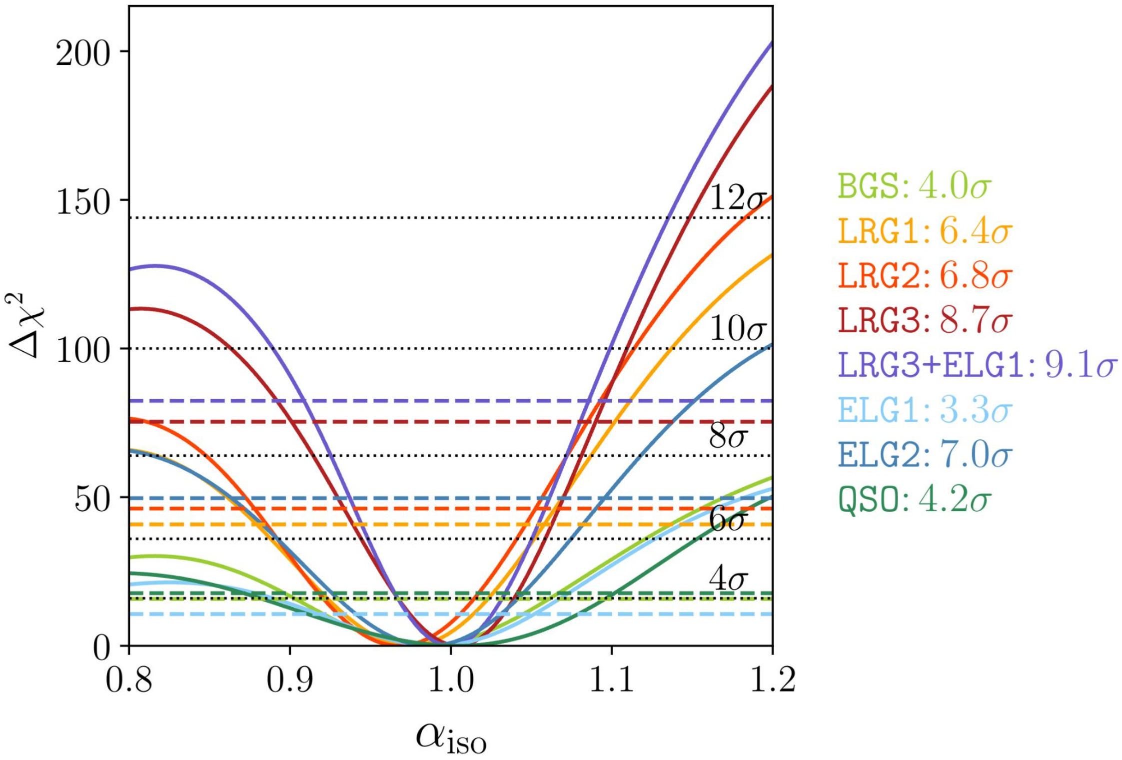
BAO observables



BAO observables



Unblinded galaxy BAO detection level



Aggregate distance precision (1yr):

0.52%

c.f. all SDSS galaxy BAOs (10yrs):

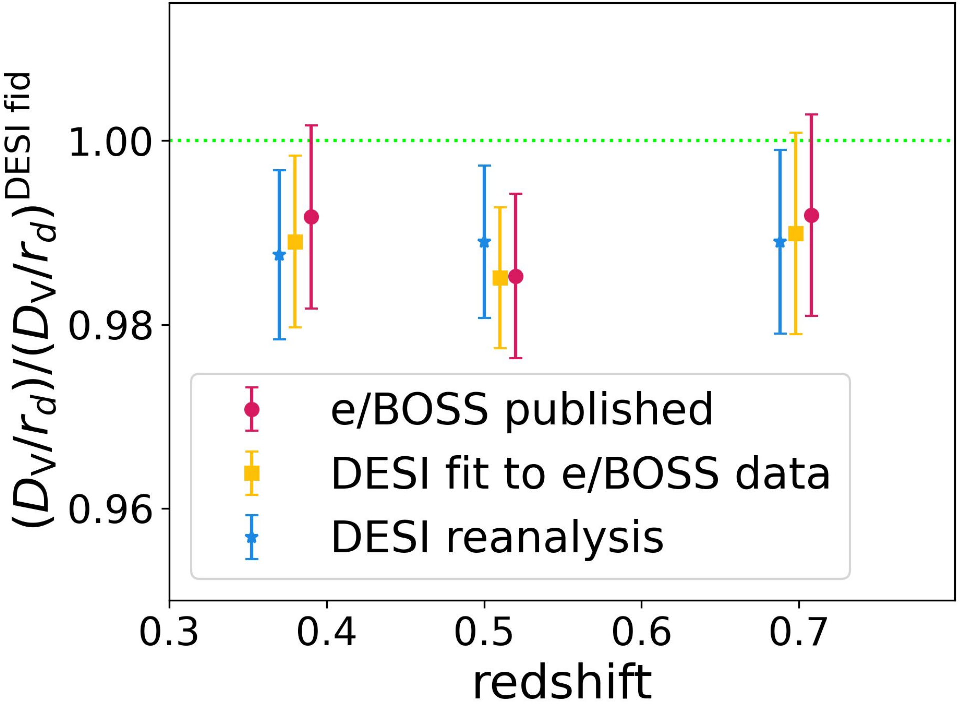
0.64%

Distance to last scattering: γAO

- Almost completely insensitive to late-time physics assumptions – though error bar can broaden in some models.
- Increase error to 0.00044.

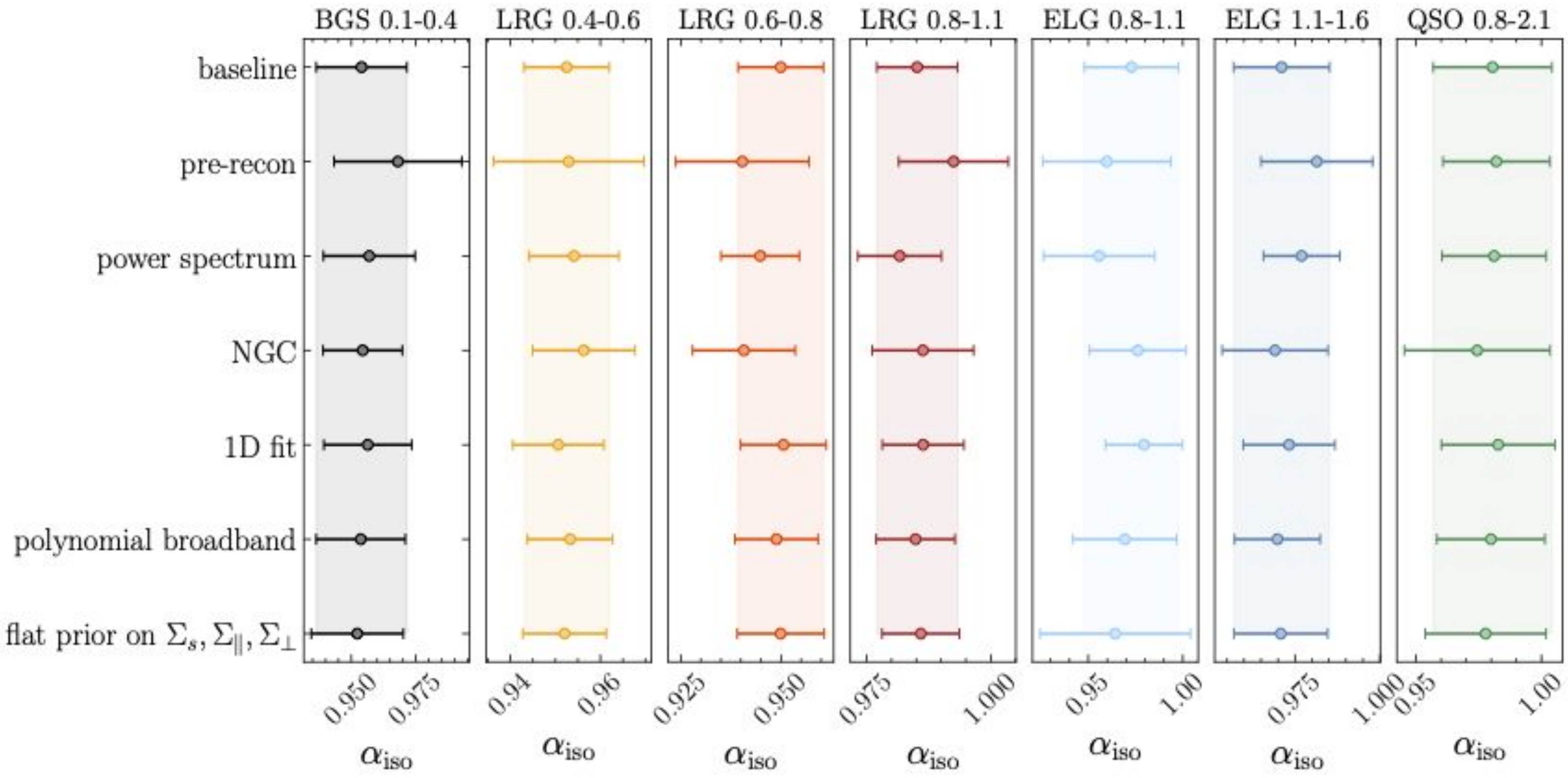
$$\theta_\star = (1.04109 \pm 0.00030) \times 10^{-2} \qquad (0.03\% \text{ uncertainty})$$

DESI reanalysis of SDSS



The reanalysis of SDSS is consistent with the published SDSS values.

Summary of the unblinded data tests

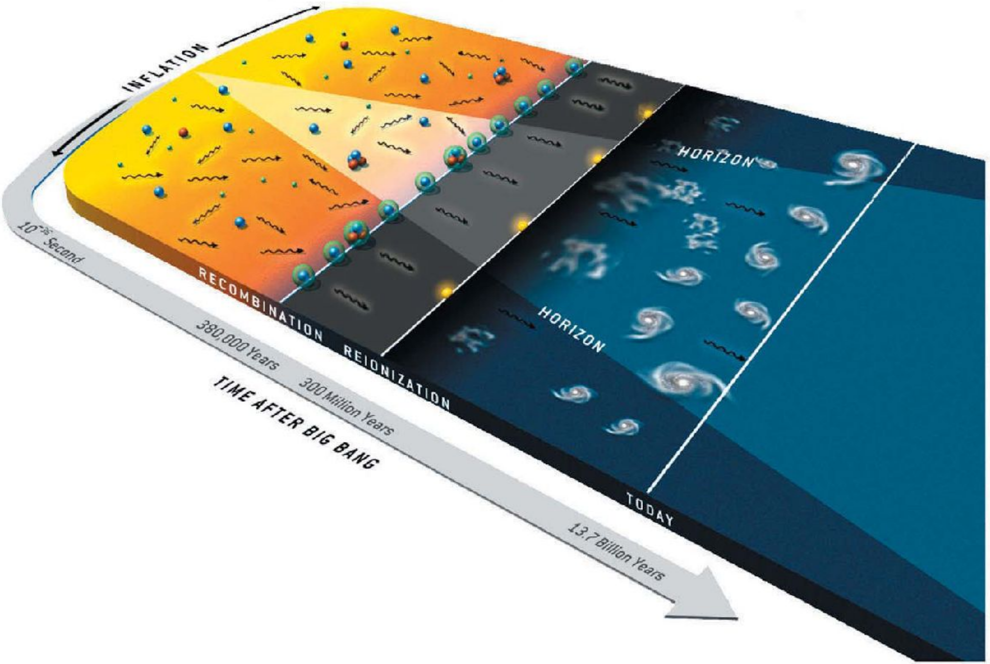


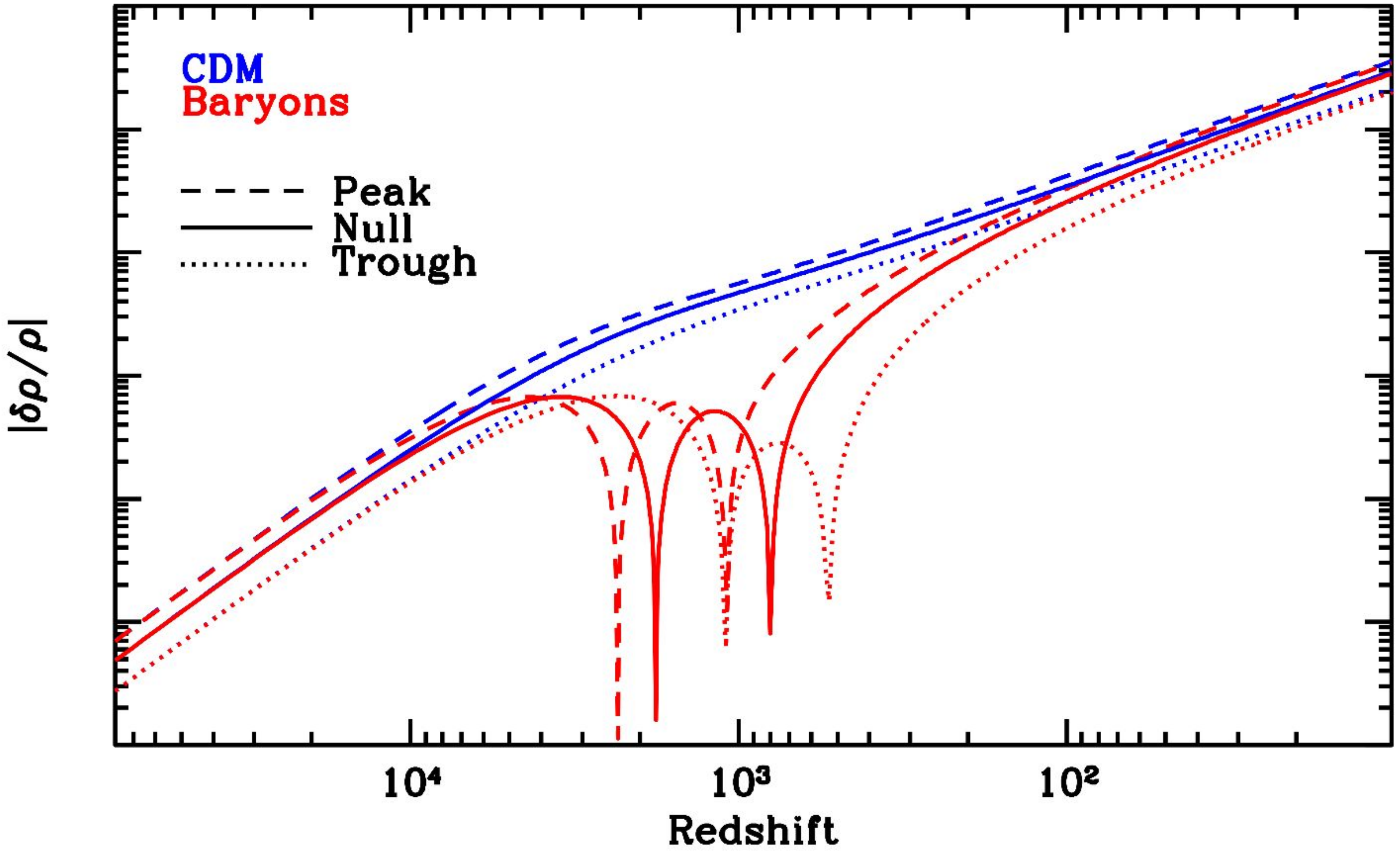
All consistent based on mock catalog tests.

Baryon acoustic oscillations (BAO)

In the early universe prior to recombination, the free electrons couple the baryons to the photons through Compton interactions, so these three species move together as a single fluid.

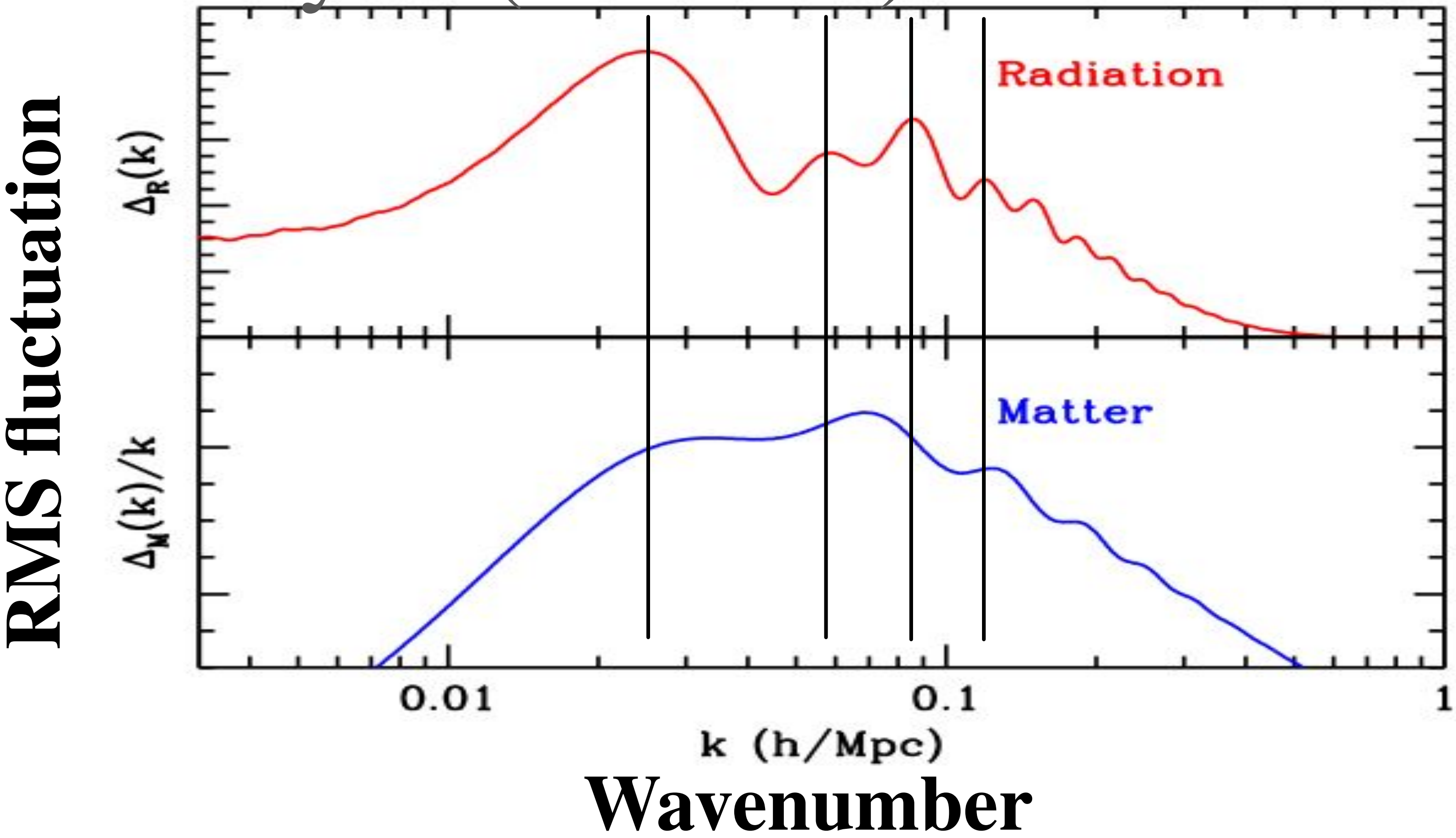
The primordial cosmological perturbations on small scales excite sound waves in this relativistic plasma, which results in the pressure-induced oscillations and acoustic peak.



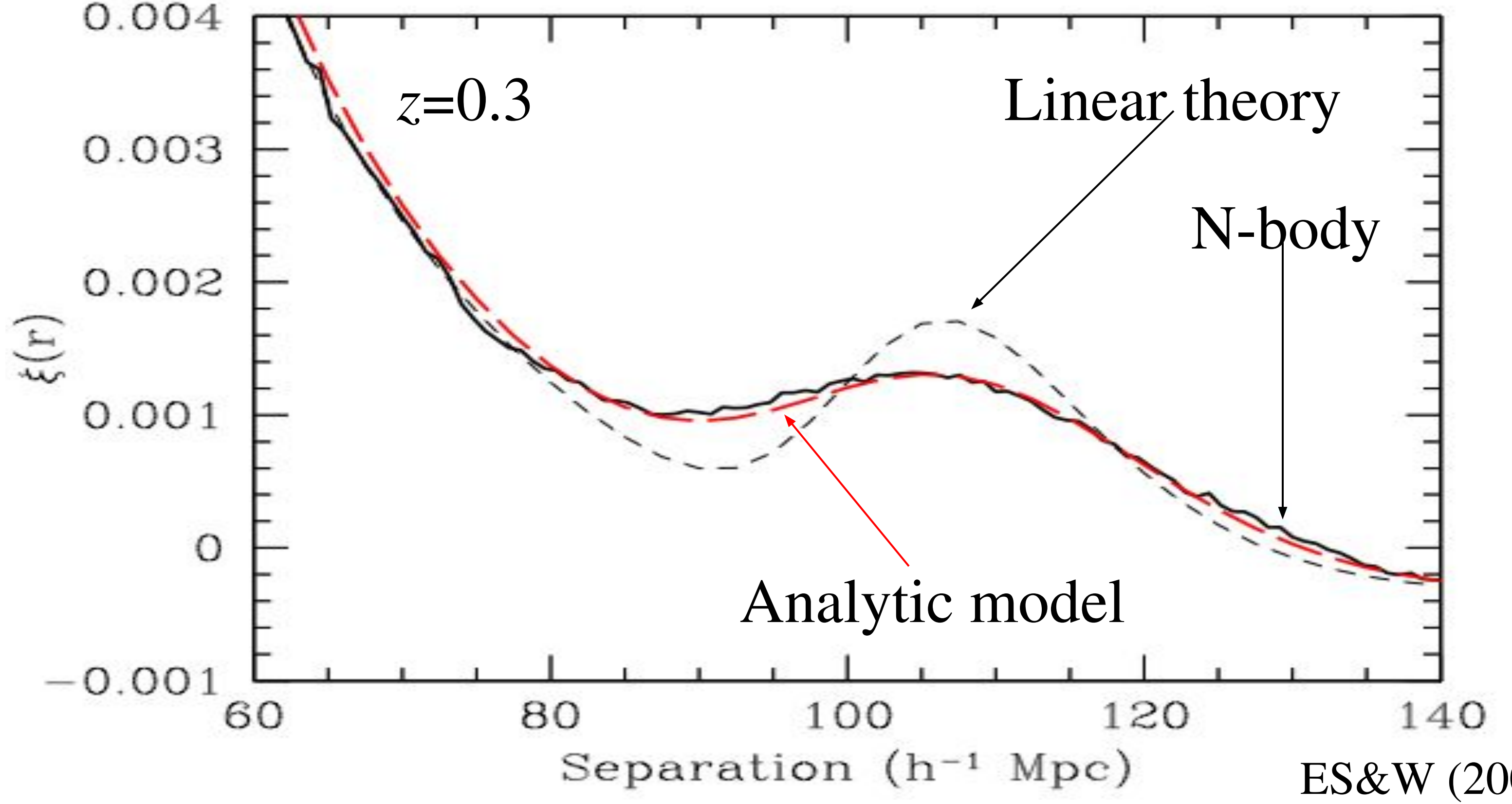


CDM
Baryons
Peak
Null
Trough
|δρ/ρ|
10^4
10^3
10^2
Redshift

Baryon (acoustic) oscillations



Non-linearities smear the peak



ES&W (2006)

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

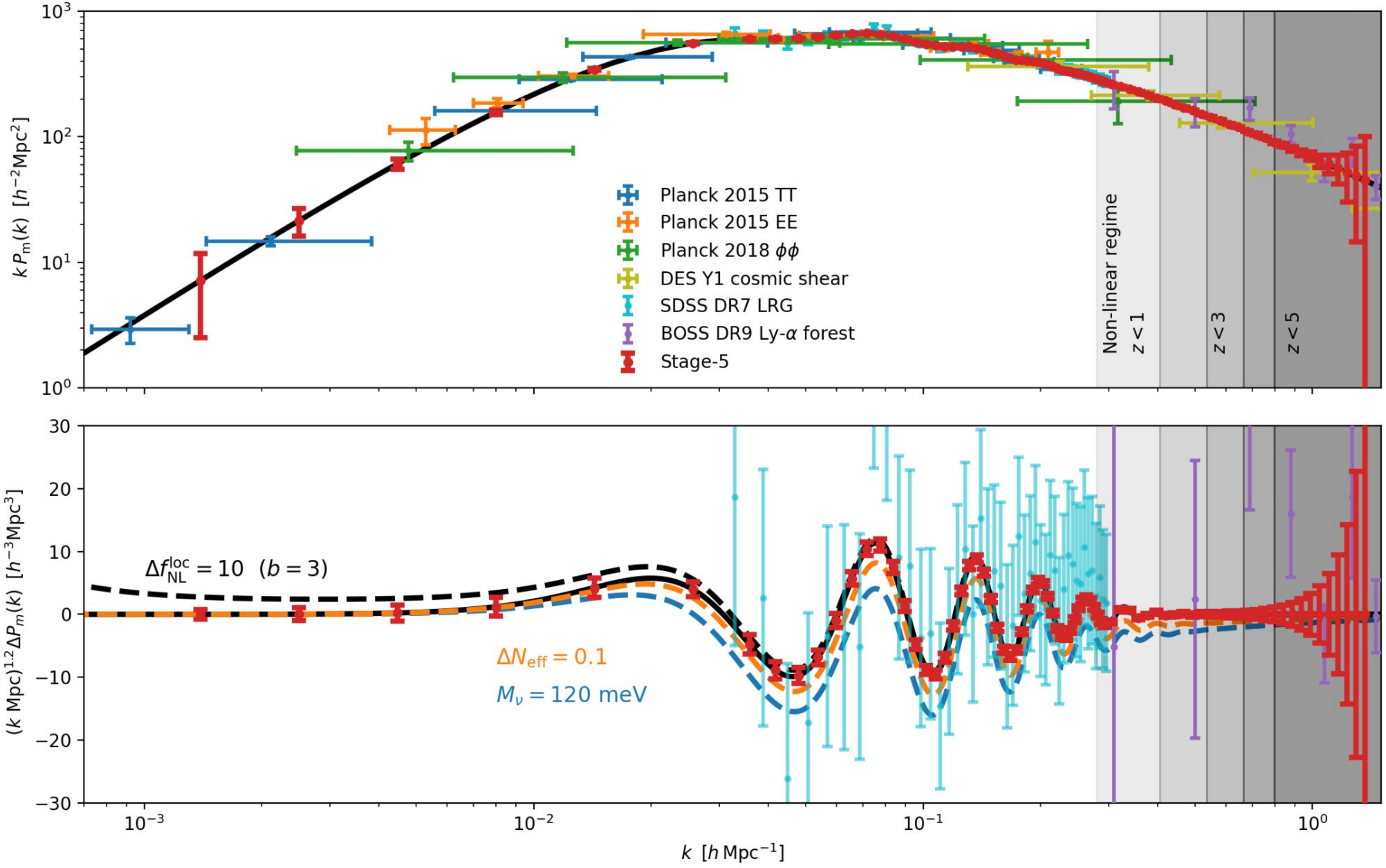
- Collect density, velocity, etc. into a vector: $\boldsymbol{\varphi}^{a}$
- Rewrite EOM as “propagation” and “interaction”.
- Rather than a Feynman path integral for operator expectation values have ensemble averages over “initial” fields:

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

- 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.


Planck 2015 TT
Planck 2015 EE
Planck 2018 $\phi\phi$
DES Y1 cosmic shear
SDSS DR7 LRG
BOSS DR9 Ly-α forest
Stage-5
Non-linear regime
$z < 1$
$z < 3$
$z < 5$
$k\,P_m(k)$ $[h^{-2}\mathrm{Mpc}^2]$
$(k\,\mathrm{Mpc})^{1.2}\Delta P_m(k)$ $[h^{-3}\mathrm{Mpc}^3]$
$\Delta f_{NL}^{loc} = 10$ $(b = 3)$
$\Delta N_{eff} = 0.1$
$M_\nu = 120$ meV
k $[h\,\mathrm{Mpc}^{-1}]$

See also:
Sailer et al. (arXiv:2106.09713)
Ferraro et al. (arXiv:2203.07506 ; Snowmass)

Hi-z science motivation

- Large number of linear modes - probes of primordial physics.
- Goal: obtain large number of linear modes well-correlated with the initial conditions by observing the high-redshift (z >~ 1.5) Universe.
- This is where the inference is the cleanest and the noise lowest.
  - Maximizes the discovery potential for BSM physics in a theory-agnostic manner.
  - Wide lever arms in both scale and time.
  - Well-controlled theory allows design and optimization of experiments.
- Can measure the power spectrum >10x better, including at very large scales → unprecedented access to imprints of primordial physics.

An order of magnitude increase in the number of linear modes is achievable within the next decade!

Large scale structure beyond z~1.5

- Currently constraints on LCDM parameters are dominated by measurements of the CMB anisotropies at the surface of last scattering (z~1100), with z<1 constraints from large-scale structure competitive for a handful of parameters.
- Continuous advances in detector technology and experimental techniques now enable us to map large-scale structure in the redshift window 1.5<z<6ish, using both relativistic (photons) and non-relativistic (galaxies) tracers.
- In this new regime, large-scale structure should overtake the CMB in several important areas!

Technically feasible with current technology for modest cost.

Gains from going to hi-z

- Degeneracy breaking in z
  - Degeneracy directions rotate as you push to high z, tightening constraints.
- Larger dynamic range in scale with “small” error bars.
  - Helps break degeneracies between different parameters.
  - Much tighter constraints on linear modes from increased volume.
- Less decorrelation with initial conditions.
  - Astrophysics and gravitational non-linearity erase information from the primordial Universe.
  - Typically require many parameters to describe the complexities of halo and galaxy formation on small scales, but a well-understood theory exists on large scales.
- New “frontier”, where current constraints are weak.
  - Some hints from “tensions” that this is a very interesting place to look.

Science goals

These observations would allow us to:

- Test inflation by constraining f_NL, running of spectral index, primordial features, "cosmological collider".
- Directly measure the Dark Energy density deep into matter domination epoch, testing large classes of dynamical DE models.
    - Compare Lyα and galaxy BAO constraints at z~2-3.
- Indirect measure of expansion up to z ~ 10^5 (e.g. search for EDE)
- Provide unprecedented constraints on modified gravity.
- Tests of parity violating physics.
- Constrain DM-baryon or DM-DR interactions, WDM, etc.
- Constrain light relics with σ comparable to CMB (independent of He abundance).
- Provide strong synergies with LSST, CMB-S4 and future experiments.