Cosmological Constraints from the DESI Y1 Baryon Acoustic Oscillation Measurements

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A (small) part of DESI data; D. Schlegel/Berkeley Lab.
Timeline of the universe

- Inflation
- Reheating
- BBN
- Radiation Epoch
- CMB
- Matter Epoch
- Reionization
- Dark Energy Epoch

Redshift

Age

Figure credit: Noah Weaverdyck
Three key questions in cosmology

1. Inflation
2. Dark Matter
3. Dark Energy
type Ia supernova explodes…

…astronomers detect it and follow it up; they measure the light-curve…

…to use it as a standard candle (i.e. $L = \text{const}$)

$$f = \frac{L}{4\pi d_L^2}$$

…and make a correction for its width…
Supernova Hubble diagram
(binned; each error bar denotes ~20 SN)

$\Delta (m-M)$ vs Redshift $z$

- Always accelerates
- Accelerates now
- Decelerates in the past
- Always decelerates
- Flat
- Open
- Closed
Makeup of universe today

- **Baryonic Matter**
  - (stars 0.4%, gas 3.6%)

- **Dark Matter**
  - (suspected since 1930s, established since 1970s)

- **Dark Energy**
  - (suspected since 1980s, established since 1998)

Also:
- radiation (0.01%)
(Recent) constraints on dark energy

70% of energy density is in DE (~30% is in matter)

...and DE equation of state is

\[ w \equiv \frac{p_{\text{DE}}}{\rho_{\text{DE}}} \approx -1 \]
Dark Energy: Two Grand Mysteries
Fine-tuning problem I: “Why now?” (the coincidence problem)

Energy density

\[ \rho_{\text{mat}}(a) \propto a^{-3} \]
\[ \rho_{\text{rad}}(a) \propto a^{-4} \]
\[ \rho_{\text{DE}}(a) \propto a^{-3(1+w)} \approx a^0 \]

Past

Future

\[ \frac{\rho_{\text{DE}}}{\rho_{\text{M}}} \approx 2 : 1 \]

>100 orders of magnitude

Inflation
10^{-35} sec

BBN
1 min

Mat=Rad
50,000 yr

CMB
380,000 yr

Now
13.7 Gyr

Mat=Rad
50,000 yr
Fine Tuning Problem II: “Why so small?”
(cosmological constant problem)

Vacuum Energy: Quantum Field Theory predicts it to be cutoff scale

\[
\rho_{\text{VAC}} = \frac{1}{2} \sum_{\text{fields}} g_i \int_{0}^{\infty} \frac{d^3 k}{(2\pi)^3} \sqrt{k^2 + m^2} \sim \sum_{\text{fields}} \frac{g_i k_{\text{max}}^4}{16\pi^2}
\]

Measured: \( (10^{-3}\text{eV})^4 \)
SUSY scale: \( (1\text{TeV})^4 \)
Planck scale: \( (10^{19}\text{GeV})^4 \)

60-120 orders of magnitude smaller than expected!!
Lots of theoretical ideas, few compelling ones:

Very difficult to motivate DE naturally

E.g. ‘quintessence’
(evolving scalar field)

\[
\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0
\]

but would have to have a *teeny* mass:

\[m_\phi \approx H_0 \approx 10^{-33} \text{ eV}\]
Current status of dark energy is therefore:

1. Existence of dark energy has been established to a very high statistical significance (>100-sigma)

2. The measurements are quite precise (and getting better). They are currently consistent with the cosmological constant (i.e. $w = -1$)

3. Theory (i.e. a compelling theoretical explanation) is lagging far behind
Slope of this relation (velocity vs. distance) is the Hubble constant $H_0$. Hubble got 500 km/s/Mpc - off by a factor of seven! Modern value: $H_0 \approx 70$ km/sec/megaparsec
Hubble Tension:

**SHoES** (Riess et al 2022)

\[ H_0 = 73.04 \pm 1.04 \text{ (km/s/Mpc)} \]

**CMB**: (Planck 2018)

\[ H_0 = 67.36 \pm 0.54 \text{ (km/s/Mpc)} \]

Currently the premier challenge for the standard cosmological model, and the most exciting development in cosmology (imo).

The tension recently crossed the 5-sigma threshold; this is an important step!
Ongoing or upcoming DE experiments:

- **Ground photometric:**
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES)
  - Hyper Supreme Cam (HSC)
  - LSST on Vera Rubin Telescope

- **Ground spectroscopic:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Prime Focus Spectrograph (PFS)
  - **Dark Energy Spectroscopic Instrument (DESI)**

- **Space:**
  - Euclid
  - Roman Space Telescope
Dark Energy Spectroscopic Instrument (DESI)

- on 4m Mayall telescope at Kitt Peak (AZ)
- international collaboration ~900 scientists, 72 institutions
- 5000 spectra at once (system built at Michigan - Tarlé group)
- operating extremely well: up to 100,000 spectra per night!
- world’s leading spectroscopic survey

DESI science:
1. dark energy
2. neutrino mass
3. primordial non-Gaussianity

this talk
For cosmologists, galaxies are test particles!
Mayall telescope at Kitt Peak, AZ

- Focal Plane Assembly w/5000 fiber positioners
- All-new upper ring, spider, cage
- New 6-lens wide-field Corrector on Hexapod
- 49 meter, 10-cable fiber run
- Fiber View Camera
- Ten thermally-controlled 3-channel Spectrographs 360-980 nm
Robotic fiber positioners

Designed and built at University of Michigan (Tarlé group)

“5,000 eyes on the sky”
DESI tracers

Five target classes

40 million redshifts in 5 years

3 million QSOs
Lya \( z > 2.1 \)
Tracers \( 0.9 < z < 2.1 \)

16 million ELGs
\( 0.6 < z < 1.6 \)

8 million LRGs
\( 0.4 < z < 1.0 \)

13.5 million Brightest galaxies
\( 0.0 < z < 0.4 \)

DESI (2021-2026)
Illustration of how a spectrum evolves in redshift/time

DESI tracers

Figure credit: Shadab Alam
Main/DARK: 2744/9929 completed tiles up to 20220611 (=28%, weighted=29%)

Stats for the 20220611 night:
Moon illumination: 0.94
1 DARK tiles completed
How Baryon Acoustic Oscillations observed by DESI constrain cosmological parameters

[This is the “most essential” application of DESI data]
Galaxy power spectrum

Matter power spectrum contains (almost!) all information at large scales in cosmology.
Baryon Acoustic Oscillations (BAO)

Multiple wiggles in Fourier space (power spectrum)

\[ P(k, z = 0) \propto k^{n_s} \]

\[ P(k) / P_{no \text{ wiggles}} \]

\[ k (h \text{ Mpc}^{-1}) \]

...or one wiggle in configuration space (2-point correlation function)

\[ r^2 \xi(r) = 120 \]

\[ \alpha = 1.016 \pm 0.017 \]

\[ \chi^2 = 30.53 / 39 \text{ dof} \]
How do the BAO wiggles come about?

At recombination (z~1000, t~300,000 yrs)

- Plasma becomes optically thin
- Baryons decouple from photons
- Sound wave stalls

\[ r_d = \frac{c}{\sqrt{3}} \int_0^{a_*} \frac{da}{a^2 H(a) \sqrt{1 + \frac{3\Omega_B}{4\Omega_\gamma} a}} \approx 150 \text{ Mpc} \]

A feature is imprinted the distance that the wave has traveled between the Big Bang and recombination

⇒ the sound horizon distance at recombination \( r_d \approx 150\text{ Mpc} \)
Baryon Acoustic Oscillations

- Therefore, there is excess probability for galaxies having a neighbor at distance $r_d$—excess probability for clustering
- This imprints a preferred scale in clustering - the “standard ruler"
- The angle to the standard ruler gives $D(z)/r_d$
- Actually measure *two* kinds of distances: transverse or parallel to the line-of-sight; can be expressed as

  Isotropic ("average") distance

  Ratio of transverse and line-of-sight distances
DESI Y1 cosmological analysis

- Fully **blinded** analysis ~7 million galaxies (with spectra!)
- Fully validated pipeline on how to extract the BAO signal
- **BAO results were unblinded in December 2023**
- We have been writing 2 key papers (I am analysis co-coordinator)
- BAO results announced at APS and in Moriond on April 4, 2024
- Full-shape analysis (the second key paper) still ongoing - quite a bit more complex than BAO. Results expected ~summer 2024. Expect constraints on cosmic growth; highly complementary to BAO.
postdoc Minh Nguyen (cosmo analysis)
postdoc Johannes Lange (DESI x lensing)
postdoc Uendert Andrade (blinding)
student Sikandar Hanif (fiber assignment)
student Otavio Alves (covariance)
student Tianke Zhuang (cosmo analysis)
student Jiaming Pan (cosmo analysis)

postdocs Humna Awan and Kuan Wang (Lyman-alpha)

DESI Y1 analysis at UMich
DESI Y1
Cosmological Results
DESI Y1 measurements: compression to distances

$D_{\text{isotropic}} / r_d$

$D_{\text{transverse}} / D_{\text{line-of-sight}}$

Unblinded on December 12, 2023
Constraints from DESI Y1 BAO

Basic constraints in $\Lambda$CDM model

$$\Omega_m = 0.295 \pm 0.015 \quad (5.1\%)$$

$$r_d H_0 = (101.8 \pm 1.3) [100 \text{ km/s}] \quad (1.3\%)$$
$H_0 = (68.52 \pm 0.62) \text{ km/s/Mpc} \quad (\text{DESI} + \theta_* + \text{BBN})$

Consistent with CMB measurements
Sum of neutrino masses

From neutrino oscillation experiments

\[(\Delta m^2)_{\text{sol}} \simeq 8 \times 10^{-5} \text{ eV}^2\]
\[(\Delta m^2)_{\text{atm}} \simeq 3 \times 10^{-3} \text{ eV}^2\]

\[\text{\{ }\]
\[\sum m_i = 0.06 \text{ eV}^* \] (normal)
\[\sum m_i = 0.10 \text{ eV}^* \] (inverted)
\[[\text{\} }\]

*(assuming m_1=0)*
**Sum of neutrino masses**

Neutrinos are non-relativistic today

\[ \sum m_\nu \approx 0.1 \text{ eV} \gg T_0 \approx 10^{-4} \text{ eV} \]

so they contribute to (recent) expansion history just like matter

\[ \sum m_\nu < 0.072 \text{ eV} \text{ (at 95\%) } \]

CMB constraints, but its precision is limited by degeneracies

⇒ DESI helps here

[But significantly weakens in models beyond ΛCDM, e.g. \( \sum m_\nu < 0.195 \text{ eV} \text{ in w}_0\text{w}_a\text{CDM} \)]
Dark energy - constant $w$

Distances measured by BAO are very sensitive to dark energy.

**DESI alone:**

$\Omega_m = 0.293 \pm 0.015$

$w = -0.99^{+0.15}_{-0.13}$

**DESI + CMB + Panth:**

$\Omega_m = 0.3095 \pm 0.0065$

$w = -0.997 \pm 0.025$
Dark energy - \((w_0, w_a)\)

\[ w(a) = w_0 + w_a(1 - a) \]

**ACDM**
(standard model)

DESI shows preference for \(w_0 < -1, w_a < 0\)

\(a=0\): Big Bang
\(a=1\): today
Dark energy - \((w_0, w_a)\)

**DESI+CMB+Pantheon+**
\[
\begin{align*}
  w_0 &= -0.827 \pm 0.063 \\
  w_a &= -0.75_{-0.25}^{+0.29} \\
\end{align*}
\]
(2.5\(\sigma\) away from \(\Lambda\)CDM)

**DESI+CMB+Union3**
\[
\begin{align*}
  w_0 &= -0.64 \pm 0.11 \\
  w_a &= -1.27_{-0.34}^{+0.40} \\
\end{align*}
\]
(3.5\(\sigma\) away from \(\Lambda\)CDM)

**DESI+CMB+DES-SN5YR**
\[
\begin{align*}
  w_0 &= -0.727 \pm 0.067 \\
  w_a &= -1.05_{-0.27}^{+0.31} \\
\end{align*}
\]
(3.9\(\sigma\) away from \(\Lambda\)CDM)

**Therefore:** tantalizing hints of departure from LCDM
Dark energy: what the data prefer

best-fit $w_0w_a$ model
What’s next

• The results presented here were just the BAO; DESI Y1 full-shape analysis of galaxy clustering is forthcoming (~summer 2024)

• There will be a number of significant new analyses from DESI Y1:
  • correlation of DESI with photometric surveys (coordinated by UM postdoc ⇒ American Univ. professor Johannes Lange)
  • peculiar velocities (probe of gravity and dark energy)
  • higher-order correlation functions (3-pt, 4-pt...)
  • ..................................

• 5 years of DESI will have information from ~40 million galaxies over 14,000+ square degrees

• DESI-2 (late 2020s) will significantly increase number of galaxies

• Stage-V spectroscopic survey (supported by P5 report; ~2035)
Conclusions

• Dark Energy is a premier mystery in physics/cosmology; physical reason for accelerating universe still an open question

• Impressive variety of new data; forthcoming: DES Y6, HSC, HtDex; DESI, LSST, Euclid, Roman.

• Like particle physicists, we would really like to see some “bumps” in the data (e.g. Hubble tension!).

• DESI Y1 BAO results highlights:
  • $H_0 = (68.52 \pm 0.62)$ km/s/Mpc
  • $\sum m_\nu < 0.072$ eV (DESI + CMB, at 95%)
  • dark energy: $2.5\sigma-3.9\sigma$ preference for model with $w(t)$ varying

• More soon:
  • DESI Y1 full-shape P(k) analysis
  • DESI Y3, Y5
Extra slides
Sum of neutrino masses

$P/P_{\text{max}}$ vs $\sum m_\nu$ [eV]

- CMB (no CMB lensing)
- CMB
- CMB + DESI BAO

$\sum m_\nu$ [eV]
Density field reconstruction

Refurbishes the ruler – *improves both precision and accuracy*
CMB measurement of $H_0$

$H_0$ is a “derived parameter” in the CMB - no special signature, but constrained very well.

Planck (2018) finds:

$$H_0 = (67.36 \pm 0.54) \text{ km/s/Mpc} \quad \text{[flat LCDM]}$$

$$H_0 = (63.6 \pm 2.2) \text{ km/s/Mpc} \quad \text{[curved LCDM]}$$
Distance-ladder measurements of $H_0$

Because SNIa measure relative distances, to get at $H_0$ they need to be “anchored” by absolute distances from e.g. Cepheids.

Starting with

$$m - M = 5 \log_{10} \left( \frac{d_L}{10\text{pc}} \right)$$

we get

$$m = 5 \log_{10}(H_0d_L) + \mathcal{M}, \quad \text{where} \quad \mathcal{M} \equiv M - 5 \log_{10}(H_0 \cdot 1\text{Mpc}) + 25$$
Therefore, the simplest “model” for Hubble tension - sample variance - is firmly ruled out.

This leaves many (~1000!) other models, most/all of which are fine-tuned.

Clashing Cosmic Numbers Challenge Our Best Theory of the Universe

By Liz Kruesi

January 19, 2024

That kind of fine-tuned model, where an additional type of dark energy surges for a moment and then fades out, is too complicated to explain what’s happening, said Dragan Huterer, a theoretical cosmologist at the University of Michigan. And other proposed solutions to the Hubble tension tend to match observations even more poorly. They’re “hopelessly tuned,” he said, like just-so stories that are too specific to be in step with the long-held idea that simpler theories tend to win out against complex ones.
There are literally hundreds of models out there
However, there is only ONE simple model.

Sample/cosmic variance?

⇒ Global $H_0$ is $\sim 67$, but $H_0$ in our local volume is $\sim 73$
(equivalent to: “we live in a void”)

However that model is completely ruled out.

Wu & Huterer (2017), Kenworthy, Scolnic & Riess (2019)

essentially because local measurements map out a pretty big local volume (so cosmic variance is small)

as explained on next slide...
We determined the **sample variance** of $H_0$ from the distance-ladder measurement by repeating the analysis ~$1.5$ million times on numerical (Nbody) LCDM simulations.

\[
\sigma_{CV}(H_0) \approx 0.3 \text{ km/s/Mpc} \approx \frac{1}{20} (H_0^{\text{SHOES}} - H_0^{\text{CMB}})
\]

Wu & Huterer (2017)
DES Y1 **Measurements:**
shear clustering, galaxy-galaxy lensing, gal clustering

cosmic shear Amon+ , Secco, Samuroff+
galaxy clustering
Rodriguez-Monroy+

galaxy-galaxy lensing
Prat+
(Bizarre) Consequences of DE

- Geometry is not destiny any more! Fate of the universe (accelerates forever vs. recollapses etc) depends on the future behavior of DE

- In the accelerating universe, galaxies are leaving our observable patch -> the sky will be empty in 100 billion years

- Under certain conditions we will have a Big Rip - galaxies, stars, planets, our houses, atoms, and then the fabric of space itself will rip apart!