Evidence for suppression of growth in the standard cosmological model

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Early DESI data; D. Schlegel/Berkeley Lab
Timeline of the universe

Figure credit: Noah Weaverdyck
Current data are in excellent consistency with LCDM model

from Huterer & Shafer (2017) review
Hubble Tension:

**SH$_0$ES** (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!
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 $H_0$

starting with

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

we get

$$m = 5 \log_{10}(H_0d_L) + \mathcal{M}, \quad \text{where} \quad \mathcal{M} \equiv M - 5 \log_{10}(H_0 \cdot 1\text{Mpc}) + 25$$

Because SNIa measure relative distances, to get at $H_0$ they need to be “anchored” by absolute distances from e.g. Cepheids.
**H₀ tension - theory**

- There are literally hundreds of models out there
- However, there is only ONE simple model.

**Sample/cosmic variance?**

⇒ Global H₀ is ~67, but H₀ in our local volume is ~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
$\sim 1.5$ million times on numerical (Nbody) LCDM simulations

Wu & Huterer (2017)

$$\sigma^{CV}(H_0) \simeq 0.3 \text{ km/s/Mpc} \simeq \frac{1}{20} (H_0^{SHOES} - H_0^{CMB})$$
There is also the $S_8$ tension, but it is not as significant

$$S_8 \equiv \sigma_8 \left( \frac{\Omega_m}{0.3} \right)^{0.5}; \quad \sigma_8^2 = \int \Delta^2(k, R = 8h\text{Mpc}^{-1})W^2(kR)d\ln k$$

“DES-Y3 + KiDS 1000: Consistent Cosmology Combining Cosmic Shear Surveys”, arXiv:2305.117173

(HSC also gets a similar constraint)

However, the S8 tension is also seen in other LSS data (“lensing is low” etc)
Major current or upcoming DE experiments:

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

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

- **Space:**
  - Euclid (just launched July 2023!)
  - Nancy Roman Telescope
Dark Energy Spectroscopic Instrument (DESI)

- on 4m Mayall telescope at Kitt Peak (AZ)
- international collaboration ~1000 scientists
- 5000 spectra at once
- operating very 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
What if gravity deviates from GR?

For example:

\[ H^2 - F(H) = \frac{8\pi G}{3} \rho, \quad \text{or} \quad H^2 = \frac{8\pi G}{3} \left( \rho + \frac{3F(H)}{8\pi G} \right) \]

Modified gravity

Dark energy

Notice: there is no way to distinguish these two possibilities just by measuring expansion rate H(z)!

Growth of structure comes to the rescue: in standard GR, H(z) determines distances and growth of structure

\[ \ddot{\delta} + 2H \dot{\delta} - 4\pi \rho_M \delta = 0 \]

⇒ compare geometry [D(z), Vol(z)] and growth [Pk(z)]
Comparing geometry and growth ("geometry-growth split")

One approach: Double the standard DE parameter space

Instead of $\Omega_M$ and $w$, have:

$$\Omega_{M_{\text{geom}}}, w_{\text{geom}} \Omega_{M_{\text{grow}}}, w_{\text{grow}}$$

[In addition to other, usual parameters]

<table>
<thead>
<tr>
<th>Cosmological Probe</th>
<th>Geometry</th>
<th>Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pantheon</td>
<td>$H_0D_L(z)$</td>
<td>—</td>
</tr>
<tr>
<td>eBOSS DR16</td>
<td>{(D_M(z); D_H(z))}</td>
<td>$r_d(z_d)$</td>
</tr>
<tr>
<td>Planck2018</td>
<td>(j_{\ell}[k\chi(z)])</td>
<td>(S_T(k,z))</td>
</tr>
<tr>
<td>KiDS-1000</td>
<td>(\frac{d\chi(z)}{d(z)}g_i(z)g_j(z))</td>
<td>$\Omega_m^2P_\delta \left(\frac{\xi}{\chi}, z\right)$</td>
</tr>
<tr>
<td>eBOSS DR16</td>
<td>—</td>
<td>$f(z)\sigma_8(z)$</td>
</tr>
</tbody>
</table>

Zhang, Hui, & Stebbins (2005)
Wang et al (2007)
Zhao, Knox & Tyson (2009)
Ruiz & Huterer (2015)
Bernal et al (2016)
Muir et al (2020) → DES
Ruiz-Zapatero et al (2021) → KIDS
Andrade et al (2021)
Comparing geometry and growth

Advantages:
- physically well motivated (modified gravity)
- failure of geom=grow in measurements implies something is off regardless of implementation

Ruiz & Huterer (2015)
A simpler alternative to full geometry-growth split:

**growth index $\gamma$**

(Peebles ~1980, Linder 2005)

$$f(a) \equiv \frac{d \ln D}{d \ln a} \simeq \Omega_m(a)^\gamma$$

then the linear growth is

$$D(a) = \exp \int_1^a d \ln a' \Omega_m^{\gamma}(a')$$

fits DE models in GR, to very high accuracy (0.1%)

$$\gamma \simeq 0.55$$

(really $\gamma \simeq 0.55[1 + 0.02w(z = 1)]$)

Growth index also fits MG models (e.g. $\gamma \approx 0.67$ in DGP), though see Wen, Nguyen & Huterer, JCAP 2023

• Pros: $\gamma$ is easy to implement

• Cons: not “physical” (but neither is $S_8$)

• Pros: very robust - if $\gamma \neq 0.55$ then *something* is wrong
Evidence for suppression of growth in the standard cosmological model

Nguyen, Huterer & Wen, PRL 131, 111001 (2023);
PRL Editor’s Suggestion

1. Implemented, validated growth index to theory pipeline. CMB affected by $\gamma$ only via lensing.
2. Applied to analysis of CMB+fs8+DESY1+BAO data
Basic result:

- $3.7\sigma$ tension
- $4.2\sigma$ tension

GR value

Nguyen, Huterer & Wen (2023)
<table>
<thead>
<tr>
<th>Data</th>
<th>$\gamma$</th>
<th>$S_8$</th>
<th>$H_0$ [kms$^{-1}$Mpc$^{-1}$]</th>
<th>$\log_{10} B F_{10}$</th>
<th>$\Delta \chi^2 \equiv \chi^2_{\gamma} - \chi^2_{\gamma=0.55}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL18</td>
<td>0.668$^{+0.068}_{-0.067}$</td>
<td>0.807$^{+0.019}_{-0.019}$</td>
<td>68.1$^{+0.7}_{-0.7}$</td>
<td>0.4</td>
<td>-2.8</td>
</tr>
<tr>
<td>PL18+$f\sigma_8$</td>
<td>0.639$^{+0.024}_{-0.026}$</td>
<td>0.814$^{+0.011}_{-0.011}$</td>
<td>67.9$^{+0.5}_{-0.5}$</td>
<td>1.7</td>
<td>-13.6</td>
</tr>
<tr>
<td>PL18+$f\sigma_8$+DESY1+BAO</td>
<td>0.633$^{+0.025}_{-0.024}$</td>
<td>0.802$^{+0.008}_{-0.008}$</td>
<td>68.4$^{+0.4}_{-0.4}$</td>
<td>1.2</td>
<td>-13.2</td>
</tr>
<tr>
<td>PL18+$f\sigma_8$+DESY1+BAO (flat $\Lambda$CDM+GR)</td>
<td>0.55</td>
<td>0.803$^{+0.008}_{-0.008}$</td>
<td>68.5$^{+0.4}_{-0.4}$</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

Nguyen, Huterer & Wen (2023)
More details

$\gamma$

Probability density

- $f\sigma_8 + \text{PL18} + \text{DESY1+BAO}$
- $f\sigma_8 + \text{PL18}$
- $f\sigma_8 + \text{DESY1+BAO}$
- $\text{PL18+DESY1+BAO}$

Nguyen, Huterer & Wen (2023)
Signature of suppressed growth in CMB

PL18 temp.+pol.

Nguyen, Huterer & Wen (2023)
Resolves the $S_8$ tension, alleviates the $H_0$

- Planck’s $S_8$ is $\sim$lower than for fixed $\gamma$
- $f\sigma_8+$DESY1+BAO $S_8$ is $\sim$higher than for fixed $\gamma$
- (and the error bars are larger with $\gamma$ varied, so)
- $\Rightarrow$ S8 tension is resolved
- $H_0$ tension is somewhat alleviated

Nguyen, Huterer & Wen (2023)
The same effect (suppressed late-time growth) has been seen before in some geometry-growth-split analyses. Ruiz & Huterer (2015); also see Bernal, Verde & Cuesta (2015). Note: high $w_{\text{growth}}$ is equivalent to suppressed late-time growth.
So:
• A new intriguing piece of evidence that growth is suppressed, building upon previous work which found the same
• Will be very sharply tested with forthcoming data!
Conclusions

• Current status of DE: excellent consistency with ~70% dark energy ~30% matter flat universe

• Like particle physicists, we would really like to see some “bumps” in the data ⇒ $H_0$ tension, maybe $S_8$ tension

• ~4-sigma evidence that growth is suppressed (relative to LCDM expectation)

• This, along with other DE and DM science, will be sharply tested with forthcoming experiments
New textbook, out May 2023 (Cambridge University Press)
Emphasis: pedagogy, computation
Level: lower graduate
Extra slides
Probability density

$PR_3(\text{Plik})$

$PR_3(\text{CamSpec})$

$PR_4(\text{CamSpec})$

$PR_4(\text{Lo+HiLLiPop})$

Probability density

$f_{\sigma_8}(\text{all})+PL18$

$f_{\sigma_8}(\text{pecvel.})+PL18$

$f_{\sigma_8}(\text{RSD})+PL18$

Probability density

$f_{\sigma_8}(\text{Said})+PL18$

$f_{\sigma_8}(\text{Turner})+PL18$

$f_{\sigma_8}(\text{Beutler})+PL18$

$f_{\sigma_8}(\text{Huterer})+PL18$
More details

\[ f_{\sigma_8} + \text{PL18}, \quad \text{exclude Turner+}, \quad \text{exclude Said+}, \quad \text{DESY1+BAO+PL18}. \]

Nguyen, Huterer & Wen (2023)
<table>
<thead>
<tr>
<th>Data</th>
<th>low-(\ell) TT</th>
<th>low-(\ell) EE</th>
<th>high-(\ell) TTTEEE</th>
<th>lensing</th>
<th>(f\sigma_8)</th>
<th>DESY1</th>
<th>BAO</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL18 temp.+pol.</td>
<td>-1.1</td>
<td>-0.4</td>
<td>-7.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-8.5</td>
</tr>
<tr>
<td>PL18</td>
<td>-1.0</td>
<td>-0.1</td>
<td>-3.1</td>
<td>+1.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-2.8</td>
</tr>
<tr>
<td>PL18+(f\sigma_8)</td>
<td>+0.1</td>
<td>-0.3</td>
<td>-5.6</td>
<td>+0.5</td>
<td>-8.3</td>
<td>-</td>
<td>-</td>
<td>-13.6</td>
</tr>
<tr>
<td>PL18+DESY1+BAO</td>
<td>-0.6</td>
<td>-0.8</td>
<td>-3.7</td>
<td>+0.3</td>
<td>-0.7</td>
<td>+0.8</td>
<td>-</td>
<td>-4.7</td>
</tr>
<tr>
<td>(f\sigma_8)+DESY1+BAO</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-1.2</td>
<td>-2.9</td>
<td>-2.2</td>
<td>-6.3</td>
</tr>
<tr>
<td>PL18+(f\sigma_8)+DESY1+BAO</td>
<td>-0.2</td>
<td>-1.1</td>
<td>-5.3</td>
<td>-0.7</td>
<td>-6.8</td>
<td>+0.8</td>
<td>+0.1</td>
<td>-13.2</td>
</tr>
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