The H0 game: E2E test

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ICREA & ICCUB
Is there a problem?

First, be quantitative

Cosmological-model dependent

JL Bernal thesis defense
Is there a problem?

First, be quantitative

Between 4 and 6 sigmas*

Summary of July 2019 KITP conference
courtesy of Vivien Bonvin
https://github.com/vbonvin/

Nature Astronomy 2019
Working hypothesis: early vs late

WHY?

But there is not much wiggle room in the middle!

Bernal et al 2016, Aylor et al 2017
Where is the problem?

Is it in any specific data set? (keeping the standard LCDM context)

Early. For a while some people put the blame on Planck....

BUT $H_0$(Early) does not budge if you take Planck (or CMB data) out.
Completely (even for Neff-extended models Shonenberg et al 2019)

Before who dropped Planck used instead WMAP+ACT/SPT.

NOT in CMB data
Aside: if not Lya BAO, use SNe

Shonenberg et al 2019

Neff free
Aver et al. (Yp)

Cooke et al.
Where is the problem?

Is it in any specific data set?

All low z determinations (except 1) hoover above 70.
Let’s invoke BACCUS

Bernal & Peacock 2018

BACCUS allows an unknown shift (systematic error) in each measurement e.g.,:

$$P/P_{\text{max}}$$

$$N = 4$$
Let’s invoke BACCUS

Bernal & Peacock 2018

BACCUS allows an unknown shift (systematic error) in each (low z) measurement:

2.6(2.8) or 99.1%(99.5%) CL away from a \( H_0 \) value of 68 (67.4) km/s/Mpc
A word on the meaning of these percentages
Both $5 \sigma$ discovery level and BACCUS were motivated by
Doing both would be ONE TOO MANY
Where is the problem?

If not in the data then in the model...?
Where is the problem?

If not in the data then in the model...?

Early-time measurements assume standard LCDM. Effectively this yields \( r_d \) (the length of the standard ruler)

\[
    r_s(z_D) = \int_0^{\tau_D} c_s(\tau) d\tau
\]

\( z \sim 0 \) measurements do not do assumptions about cosmology

Shall we look pre or after recombination?

See L. Knox talk and Knox Millea 2019
Post recombination?

I leave to ADAM to discuss what can be changed in SN, Cepheids, etc. Including screening and MG (creative attempt in H. Desmond talk) etc.

My take: it’s complicated as it would have to affect several different things at once, including time-delay distances

Increase the freedom of H(z); Bernal, Raveri, Joudaki, Keeley...
The price is high: many extra degrees of freedom (epicycles?)

It is also very hard to change rs by 7% one has to tinker with wb (hard), wm (by ~20%) Without changing matter radiation equality scale in the CMB...

It is also hard to just mess around with the standard ruler as seen in BAO
My slides from 2017

The anchoring is uncomfortable

Up up... no down a little...

But not quite at this stage yet...

Maybe now we are at this stage...
Some solutions avoid Shonenberg et al 2019 constraint

Change sound speed
Change the initial conditions
Extra components
Extra interactions among (early) components
Change $H(z)$
pre-recombination solutions

Modify the model right where we most like it

Decrease the sound horizon, by 7%
without wreaking havoc on damping tail... and everything else

Reminds me of fine tuning

Knox & Millea 2019
pre-recombination solutions

Modify the model right where we most like it

Decrease the sound horizon, by 7%
without wreaking havoc on damping tail... and everything else

Early dark energy... affects the damplig tail (can look for signatures)

Change initial conditions

Extra components/ Extra interactions/ Energy injection (localized!)

High T recombination

Change $H(z) \rightarrow$ change of inferred $\omega_m$ with scale

Cyr-Racine, Knox talks

These are not all equivalent!
Beyond $H_0$

This is not just a $H_0$ problem.

It is a $\Omega_m$ problem too

And.. What’s the age of the Universe anyway?

Bernal et al in prep.
How old is the Universe?

Jimenez et al 2019

very-low-metallicity stars
HD140283 (Bond et al 2013)
J18082002-5104378 A (Schlaufman et al 2018)

O’Malley et al ‘18 22 GC
How old is the Universe anyway?

Early: high $t_0$
Late: low $t_0$

$H_0$ [km/s/Mpc]

$\tau_U$ [Gyrs]

?
Theoretical solutions

Should improve (or not worsen) other tensions

We should quantify improvement vs predictability (degrees of freedom)

Parallelism with \( \Lambda \ldots \)

Model-dependent vs model independent approaches

At what point are we adding epicycles?