Concordance Cosmology?

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H_0 Workshop
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H_0 with DES+BAO+BBN

Sounds horizon: $r_s \sim c_s \tau$

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Sounds speed.
Depends on $\Omega_{\mathrm{b}} h^2$

Time to last scattering.
In LCDM, depends on $T_{\mathrm{cmb}}, \Omega_{\mathrm{m}}, h$.

H_0 with DES+BAO+BBN

Sounds horizon: $r_s \sim c_s \tau$

Observables:

- Angular separation: $\theta = r_s / D_A$
- Redshift separation: $cH^{-1}\Delta z = r_s$

Both D_A and $H(z)$ depend on h, Ω_{m}.

H_0 with DES+BAO+BBN

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In a flat LCDM Universe,

BAO observables depend only on: $h,\ \Omega_{\mathrm{m}},\ \Omega_{\mathrm{b}}$.

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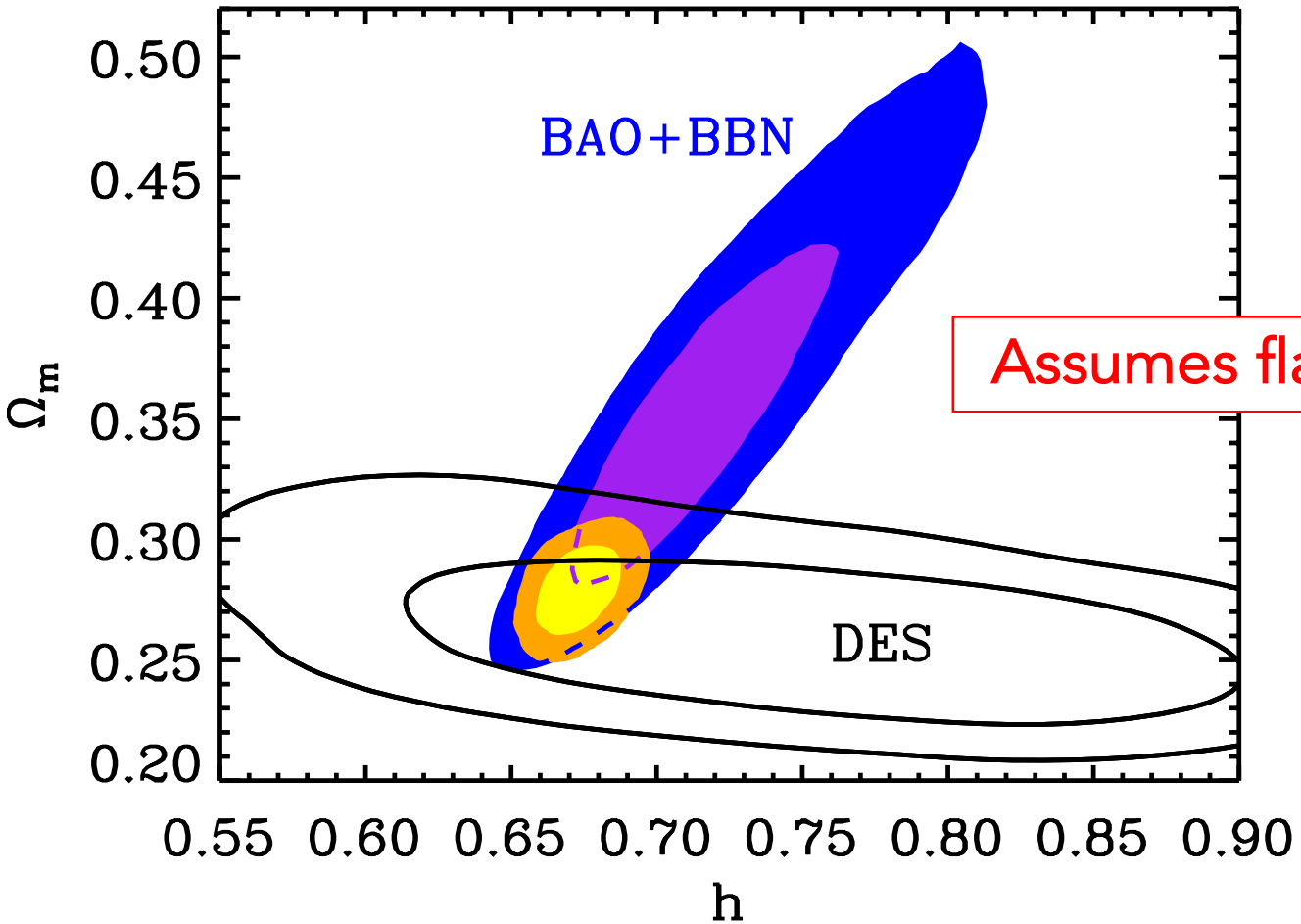
DES BBN

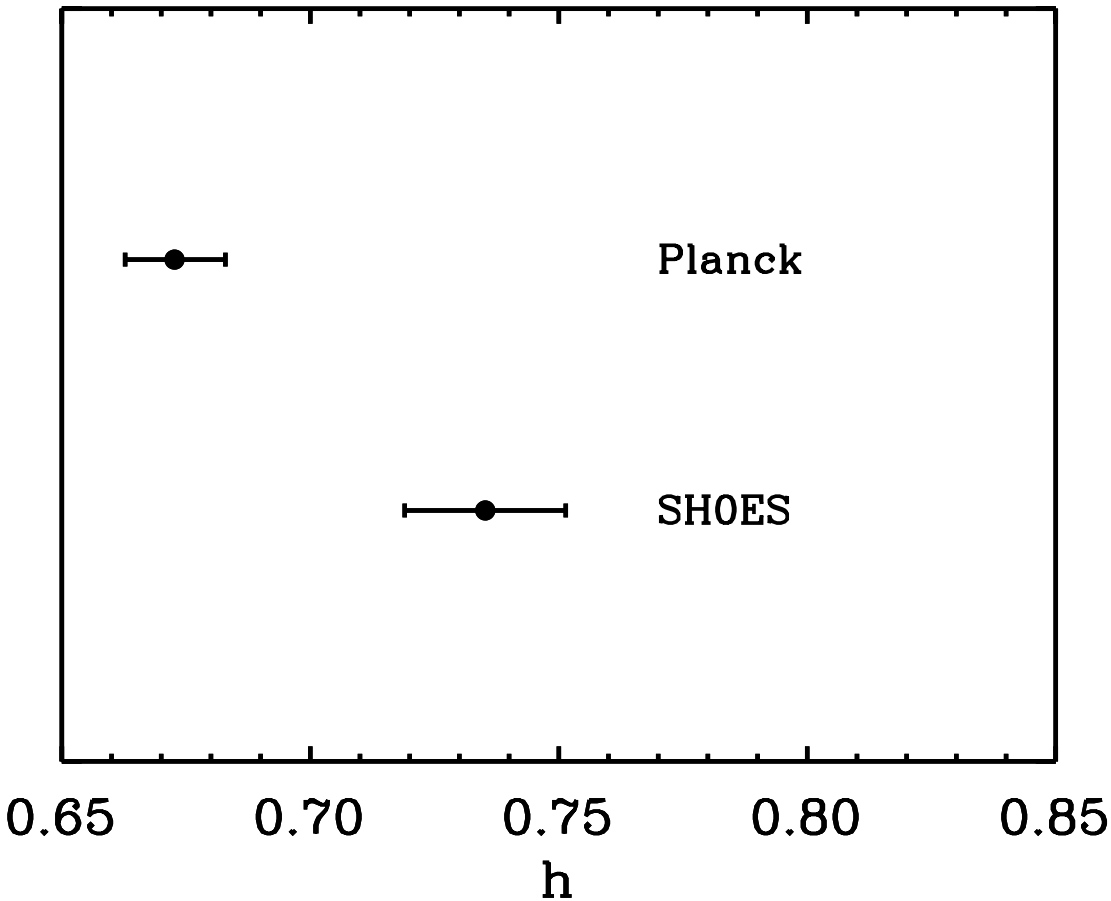
$$H_0 = 67.4^{+1.1}_{-1.2} \text{ km/s/Mpc}$$



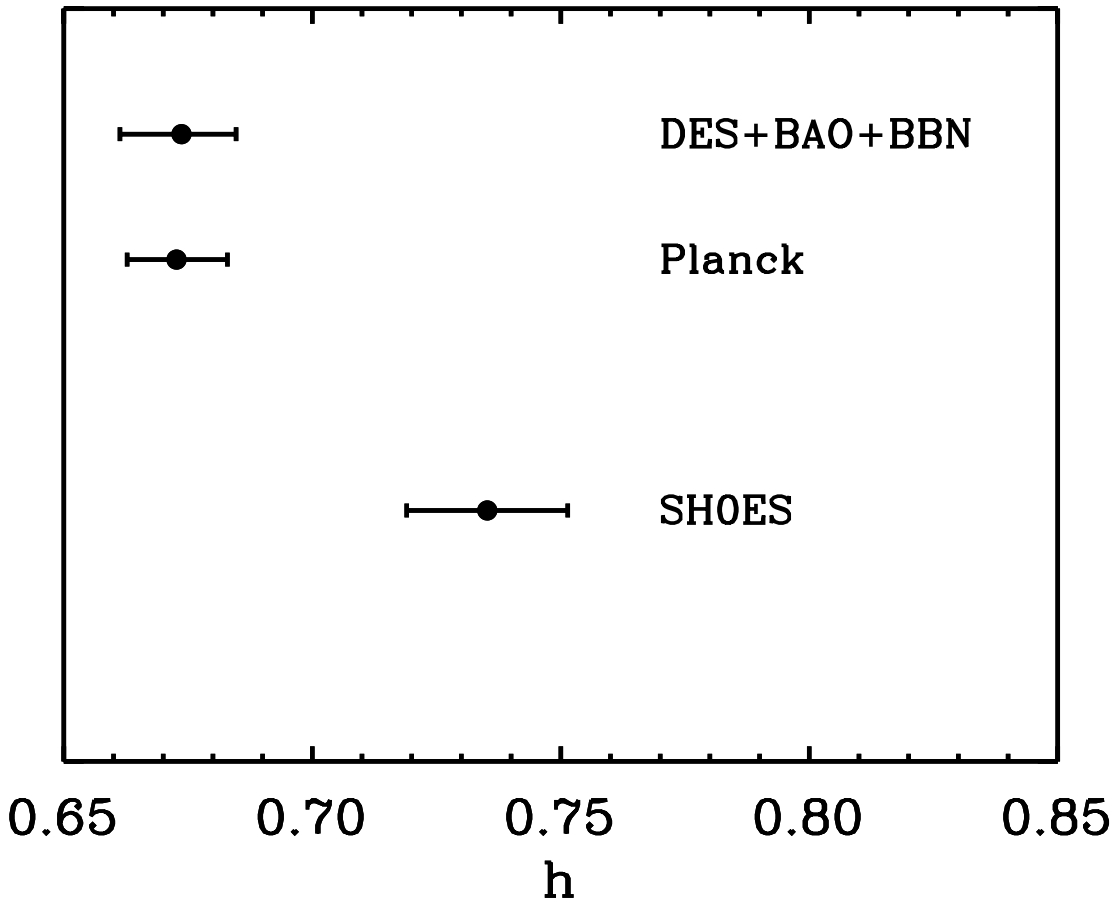
Assumes flat LCDM

Dark Energy Survey Year 1 Results: 1711.00403

H_0 Measurements



H_0 Measurements



Conclusions

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Should we just give up on flat LCDM?

Speculation

- If we add Pantheon, relative distances are fixed irrespective of curvature/DE.
- Breaking BAO+BBN+Ω_{m} measurements is by breaking r_s. *Need to mess w/ the early Universe!*
- Very tough to do. Simplest route is N_{eff}, but runs into high-l CMB tail.

Other possible routes?

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Question

- Could distance-ladder have some systematics?

In an act of desperation, let's indulge in a posteriori statistics.

Distance Ladder Measurements

Table 6
Best Estimates of H_0 Including Systematics

Anchor(s)	Value ($\mathrm{km\ s^{-1}\ Mpc^{-1}}$)
One Anchor	
NGC 4258: Masers	72.25 ± 2.51
MW: 15 Cepheid Parallaxes	76.18 ± 2.37
LMC: 8 Late-type DEBs	72.04 ± 2.67
M31: 2 Early-type DEBs	74.50 ± 3.27
Two Anchors	
NGC 4258 + MW	74.04 ± 1.93
NGC 4258 + LMC	71.62 ± 1.78
Three Anchors (**Preferred**)	
NGC 4258 + MW + LMC	$\mathbf{73.24 \pm 1.74}$

Riess et al. 2016

Distance Ladder Measurements

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NGC 4258 + LMC	71.62 ± 1.78
NGC 4258 + MW + LMC	$\mathbf{73.24 \pm 1.74}$

These error bars **must** be correlated

MW: 15 Cepheid Parallaxes	76.18 ± 2.37
NGC 4258 + LMC	71.62 ± 1.78
NGC 4258 + MW + LMC	**73.24 ± 1.74**

- Analyses share all the same SN, Cepheids, and calibration galaxies.

If no correlation: $H_0 = 73.21 \pm 1.42$

Recovered error bar implies $r \approx 0.5$.

Are All Distance Anchors Internally Self-Consistent?

MW: 15 Cepheid Parallaxes	76.18 ± 2.37
NGC 4258 + LMC	71.62 ± 1.78
NGC 4258 + MW + LMC	$\mathbf{73.24 \pm 1.74}$

- Given joint distribution $P(H_{\mathrm{LMC+maser}}, H_{\mathrm{MW}})$, we can compute $P(H_{\mathrm{LMC+maser}} - H_{\mathrm{MW}})$

$\Delta H = 4.28 \pm 1.96\ \mathrm{km/s}$ :: 2.2σ tension.

- Clearly not definitive, but does merit a closer look.

Rozo and Saidian, in prep.

Conclusions

- Current tension can't just be "there's some weird systematic in *Planck*."
- Reconciling BAO+ w/ distance-ladder requires changing the early Universe.
- It is possible the current distance anchors are not all internally self-consistent.

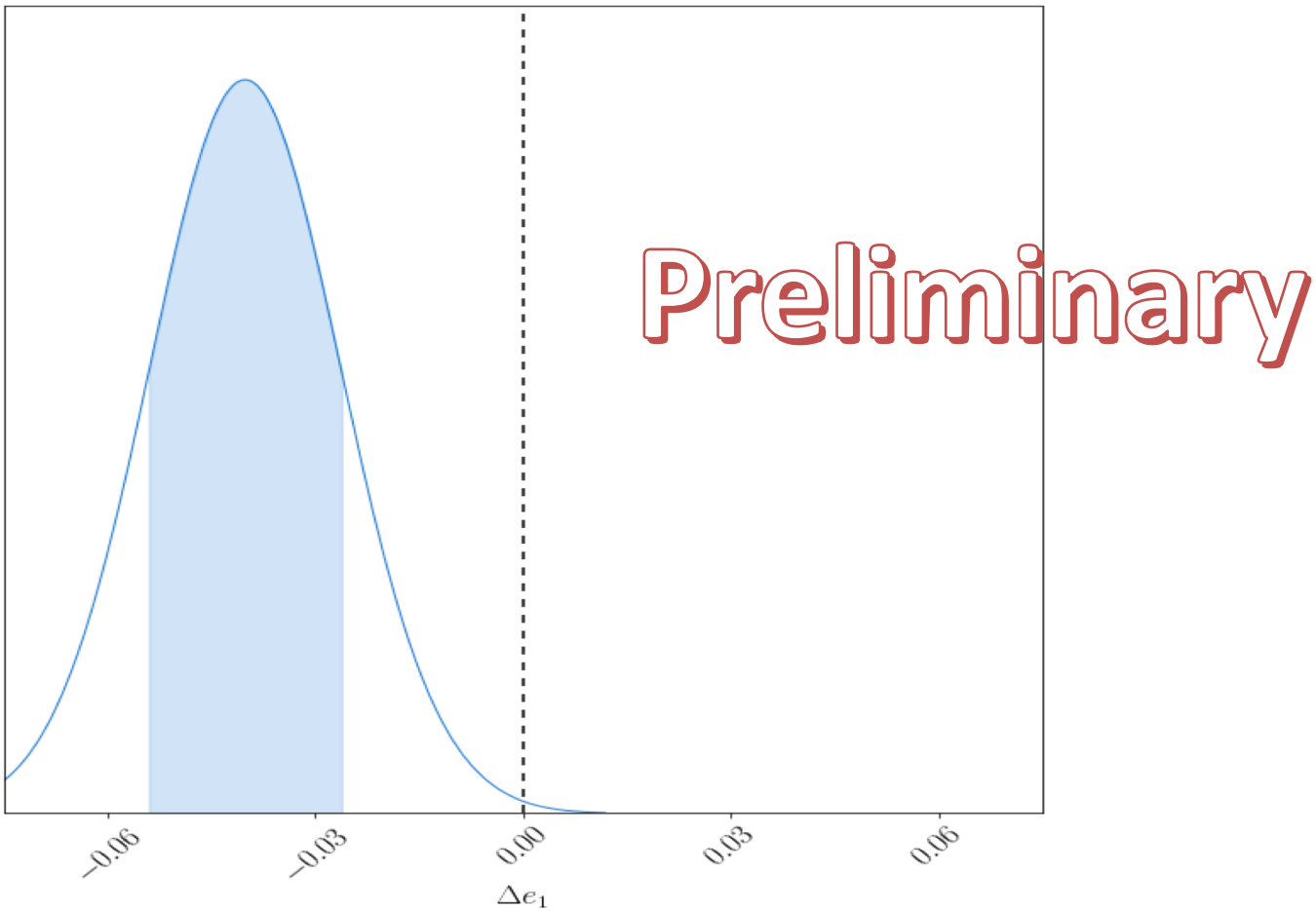
Main obstacle: if real, I have no idea what could lead to that tension.

There's More to Life than h

Let's look briefly at *Planck* and DES.

- DES effective constrains only *one* parameter: $\sigma_8 \Omega_{\rm m}^{0.76}$.
- We should only look at the tension in this parameter! (see Marco's talk tomorrow).
- Compute $\sigma_8 \Omega_{\rm m}^{0.76}$ from both DES and P18 chains, take the difference. Is it consistent with zero?

DES and *Planck* are in 2.9σ Tension



Park and Rozo, in prep.

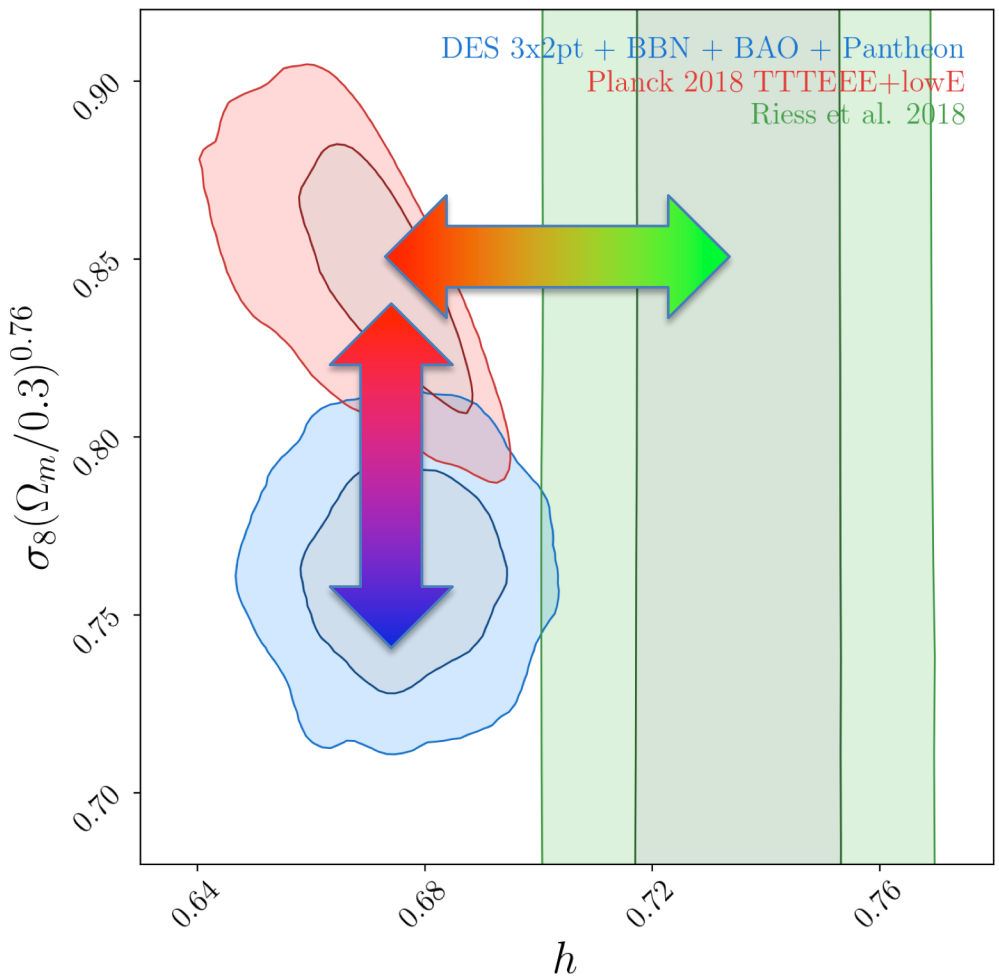
Speculation

- Unlike BAO+, the *Planck* tension w/ DES could be ameliorated by breaking late-Universe physics.

- Likewise, the *Planck*-DES tension can't be fixed with early Universe physics.

Key point…

These Tensions Are Not Related!



Preliminary

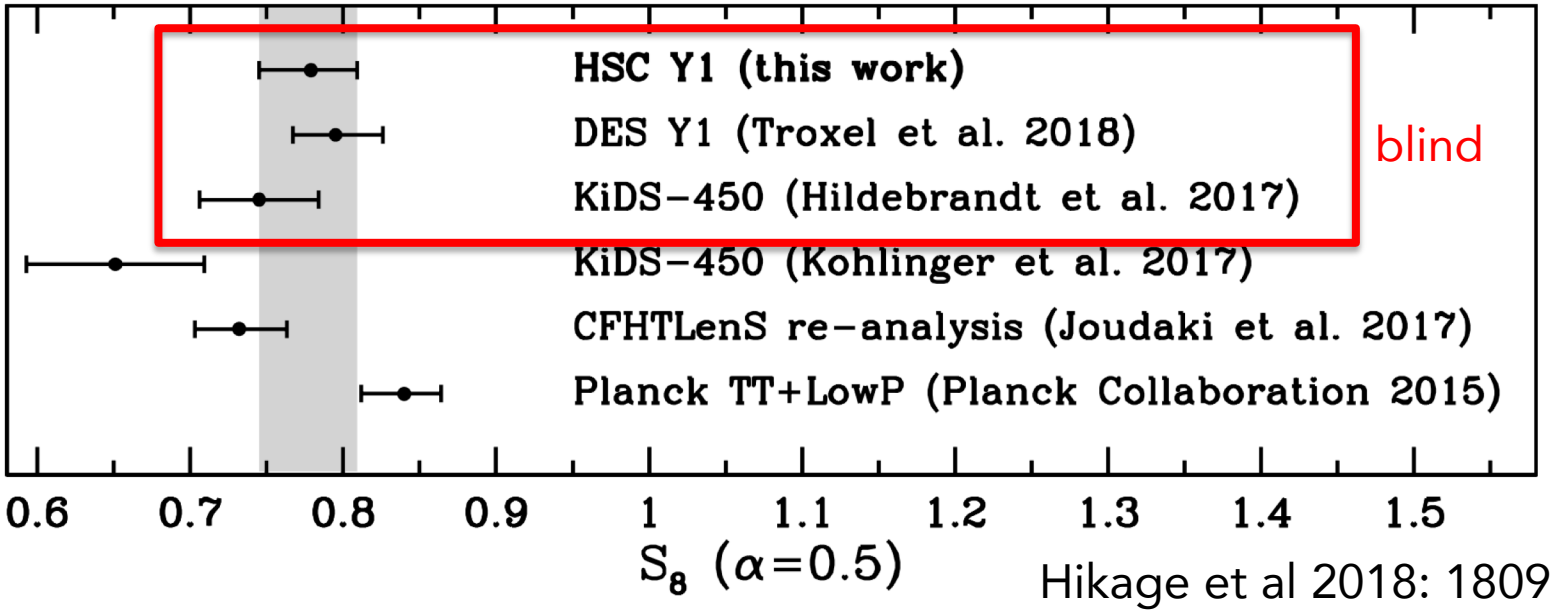
Park and Rozo, in prep.

Conclusions

- Current tension can't just be "there's some weird systematic in *Planck*."
- Reconciling BAO+ w/ distance-ladder requires changing the early Universe.
- It is possible the current distance anchors are not all internally self-consistent.
- *Planck* and DES are in 2.9σ tension.
- Fixing all tensions w/ physics will likely require ***<u>two</u>*** different modifications of the LCDM model.

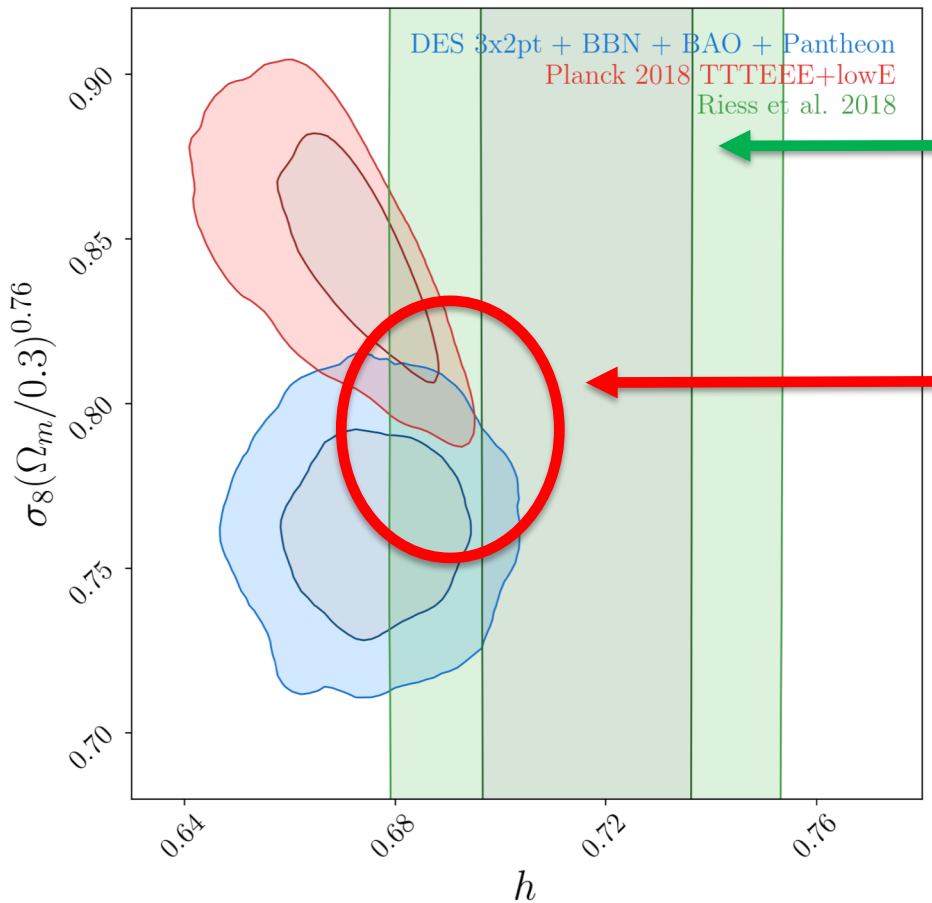
Can't We All Just Get Along?

- *Planck* and DES/KiDS/HSC need only move slightly to better agree.
    - *Planck* seems to have some room for finding some new details.
    - DES/KiDS/HSC- maybe less so?



Hikage et al 2018: 1809.09148

If I Were a Betting Man…



- Distance ladder with maser+LMC only.
- This region looks pretty good!

Preliminary

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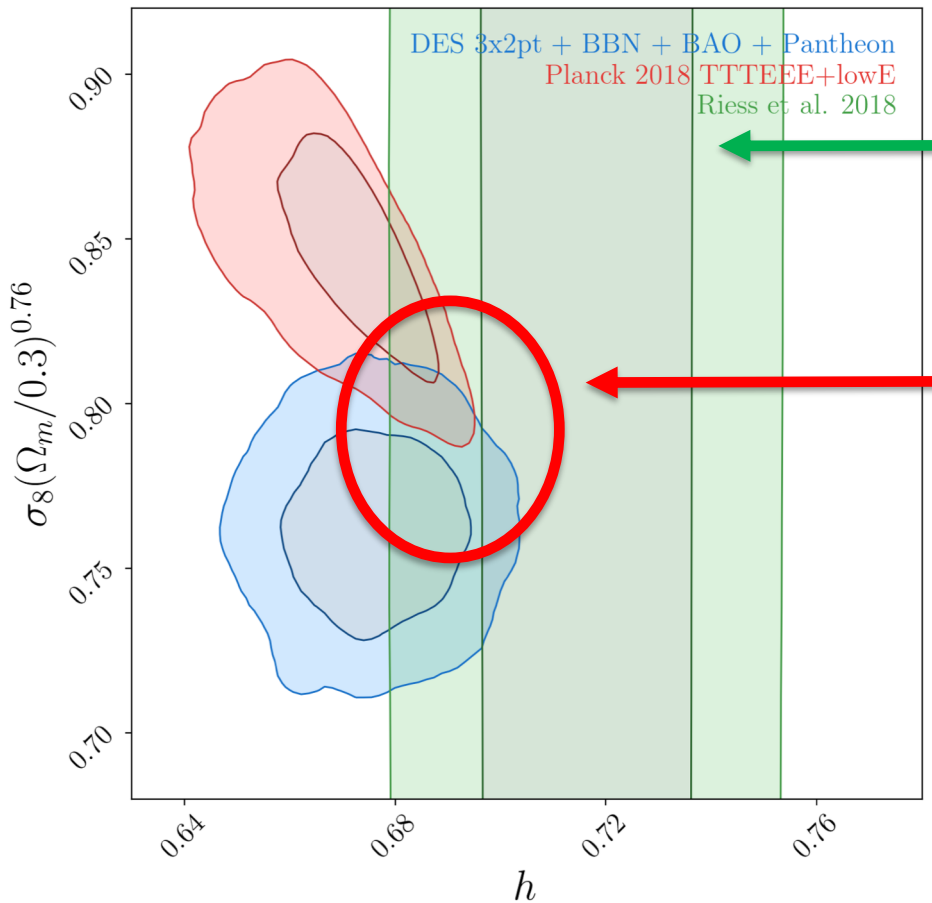
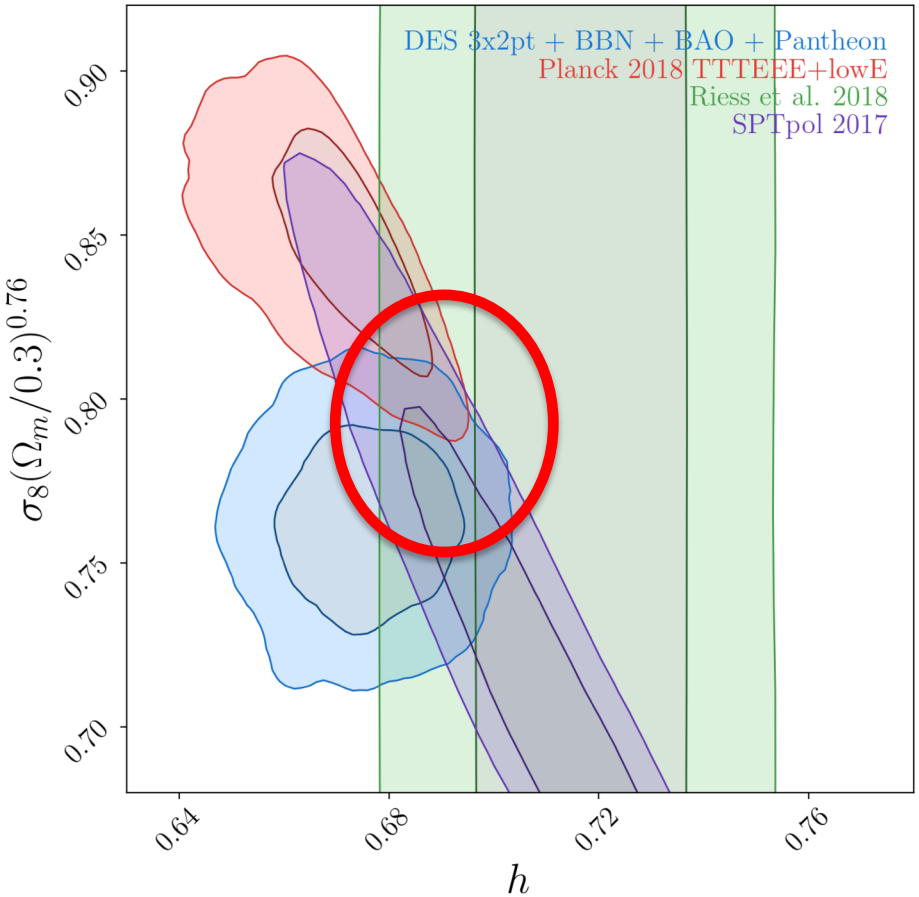


- Distance ladder with maser+LMC only.
- This region looks pretty good!
- Alternative is breaking LCDM in two different places!

Preliminary

Park and Rozo, in prep.

It Plays Nice With Others Too!



Preliminary

- Adding SPTpol
- H0LICOW is basically on top of maser+LMC

Park and Rozo, in prep.

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- Reconciling BAO+ w/ distance-ladder requires changing the early Universe.
- It is possible the current distance anchors are not all internally self-consistent.
- *Planck* and DES are in 2.9σ tension.
- Fixing all tensions w/ physics will likely require ***<u>two</u>*** different modifications of the LCDM model.
- <u>In aggregate</u>, there is still plenty of room for a consensus solution. This is probably the most conservative answer!