H_0 tension: cracks in standard cosmology?

Deanna C. Hooper

VUB Theory Seminar

30th June 2020

PHYS TH

ULB UNIVERSITÉ LIBRE DE BRUXELLES

fnrs FREEDOM TO RESEARCH

Overview

- Measuring H_0
  - Standard candles
  - Standard rulers
- Origin of discrepancy
  - Systematics?
  - New physics?
- Modifying ΛCDM
  - Types of solutions
  - Example case: $N_{\rm eff}$
  - What will a solution look like?
- Outlook (is there any hope?)

A growing tension

- A question that has plagued cosmologist for decades:

How fast is the universe expanding?

- There are two main ways to answer this: local measurements (supernovae), and early-universe measurements (CMB)
- In a consistent cosmological model, we would expect to find the same answer…
- … but early-time and late-time measurements do not agree

How bad is it?

A growing tension

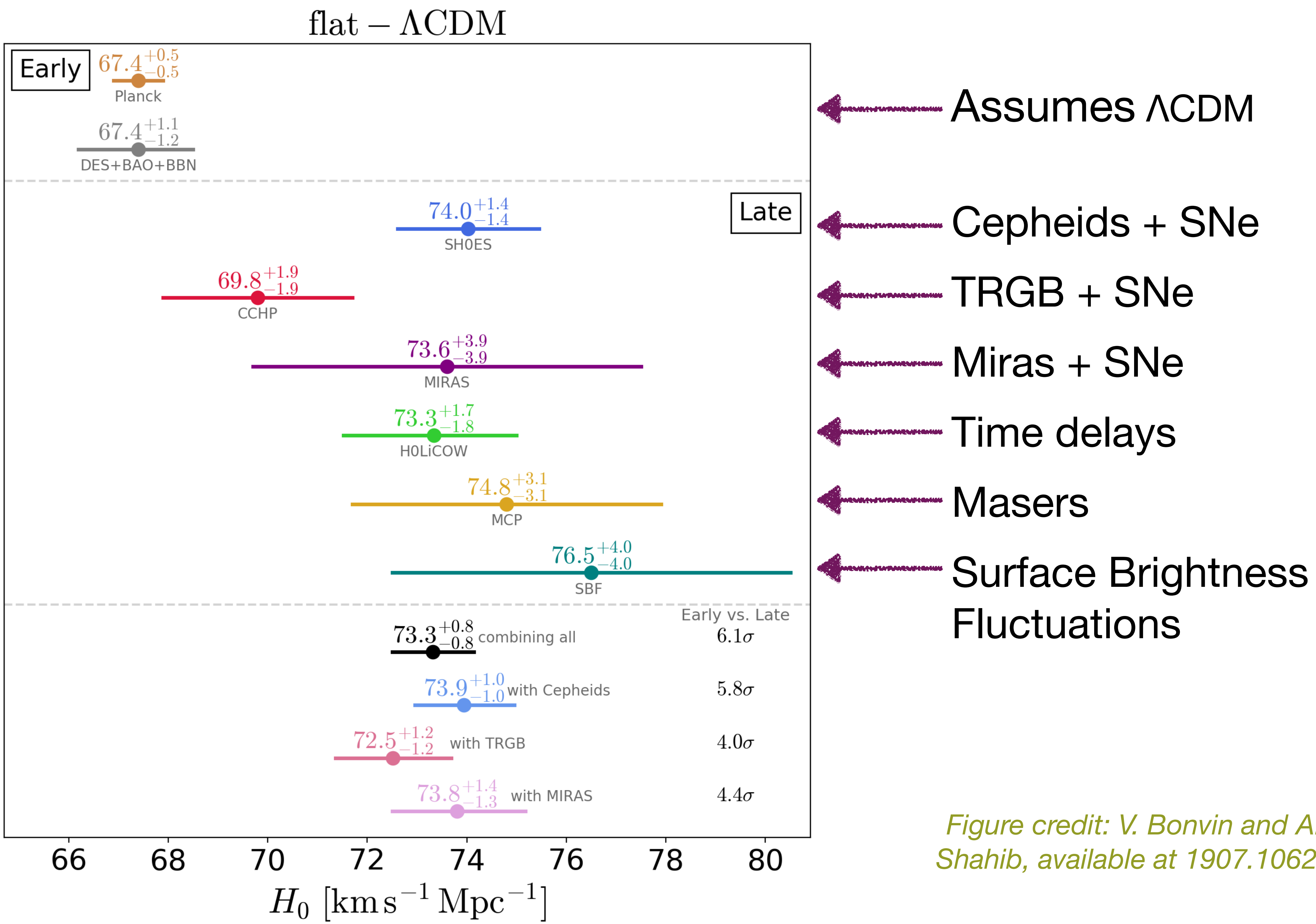
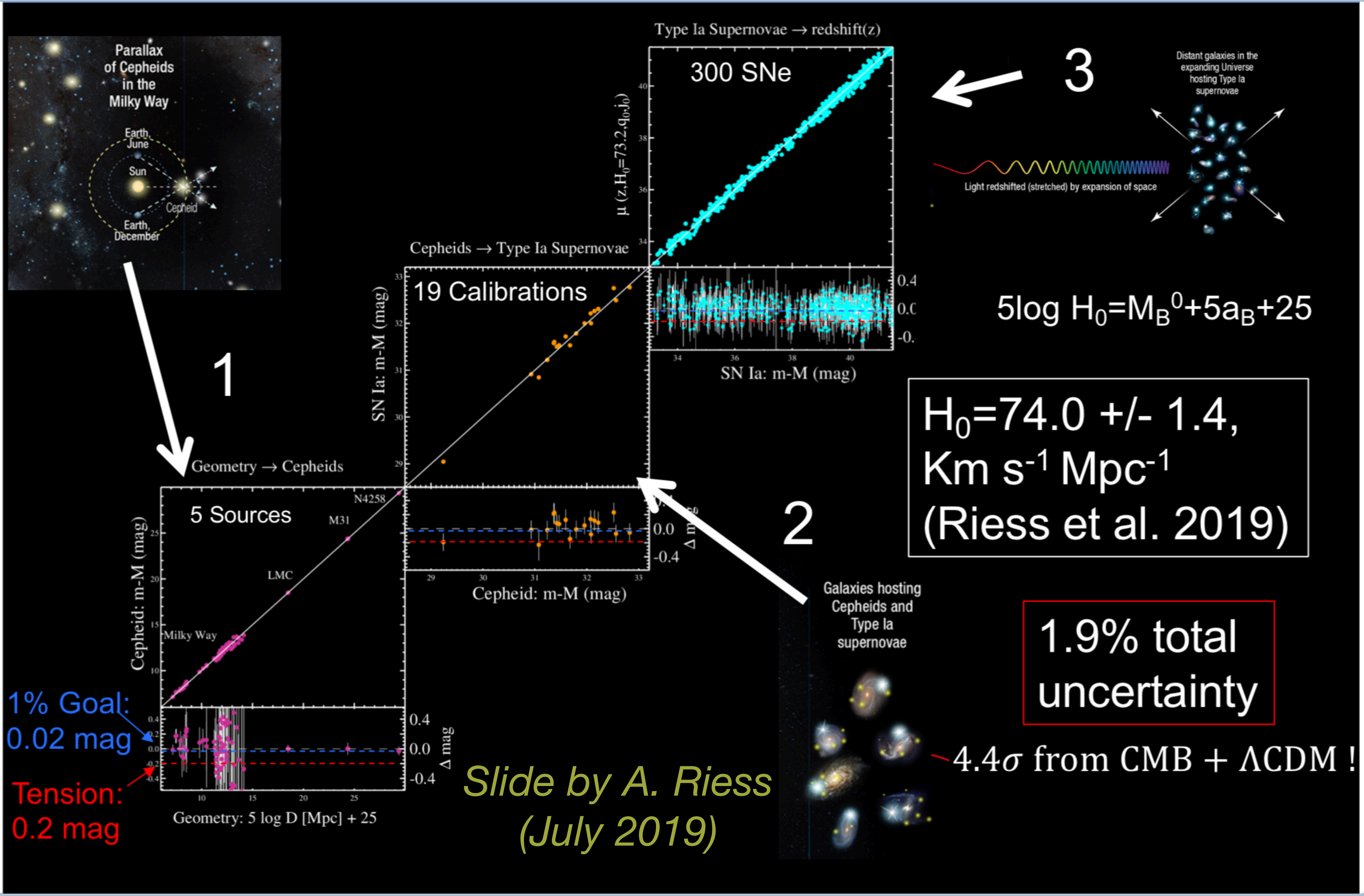


Figure credit: V. Bonvin and A. Shahib, available at 1907.10625

H_0 from supernovae



H_0 from supernovae

Forward distance ladder: Geometry — Cepheids — Supernovae

1. Measure geometric distances to calibrate Cepheids

   Construct Period - Luminosity - Distance relation

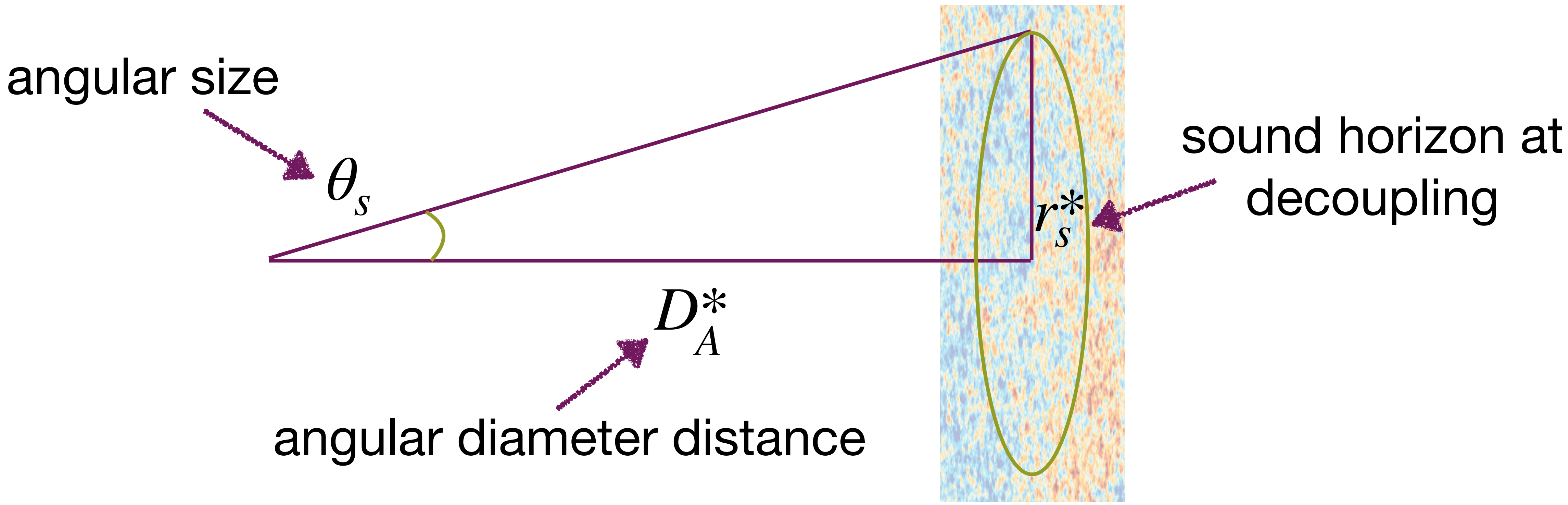
2. Observe Cepheids in galaxies that also host supernovae

   Use previous relation to get SN luminosity - distance ruler

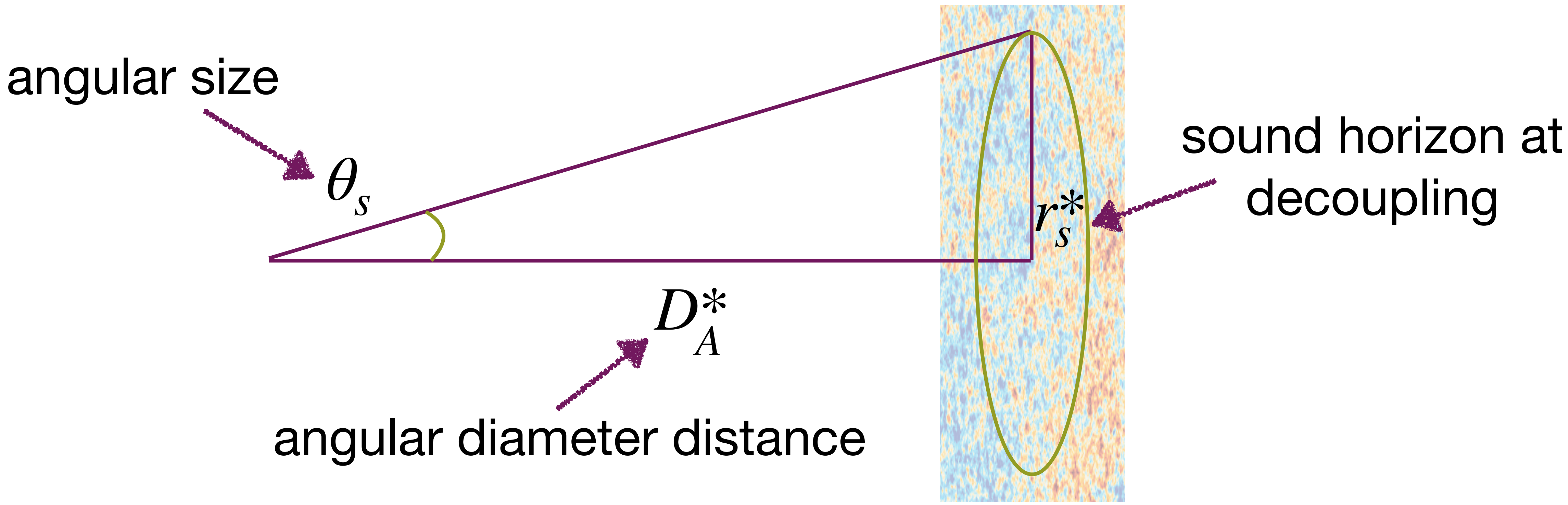
3. Observe more distant supernova in the Hubble flow

   Use calibrated ruler to get distance, construct Hubble diagram

H_0 from CMB

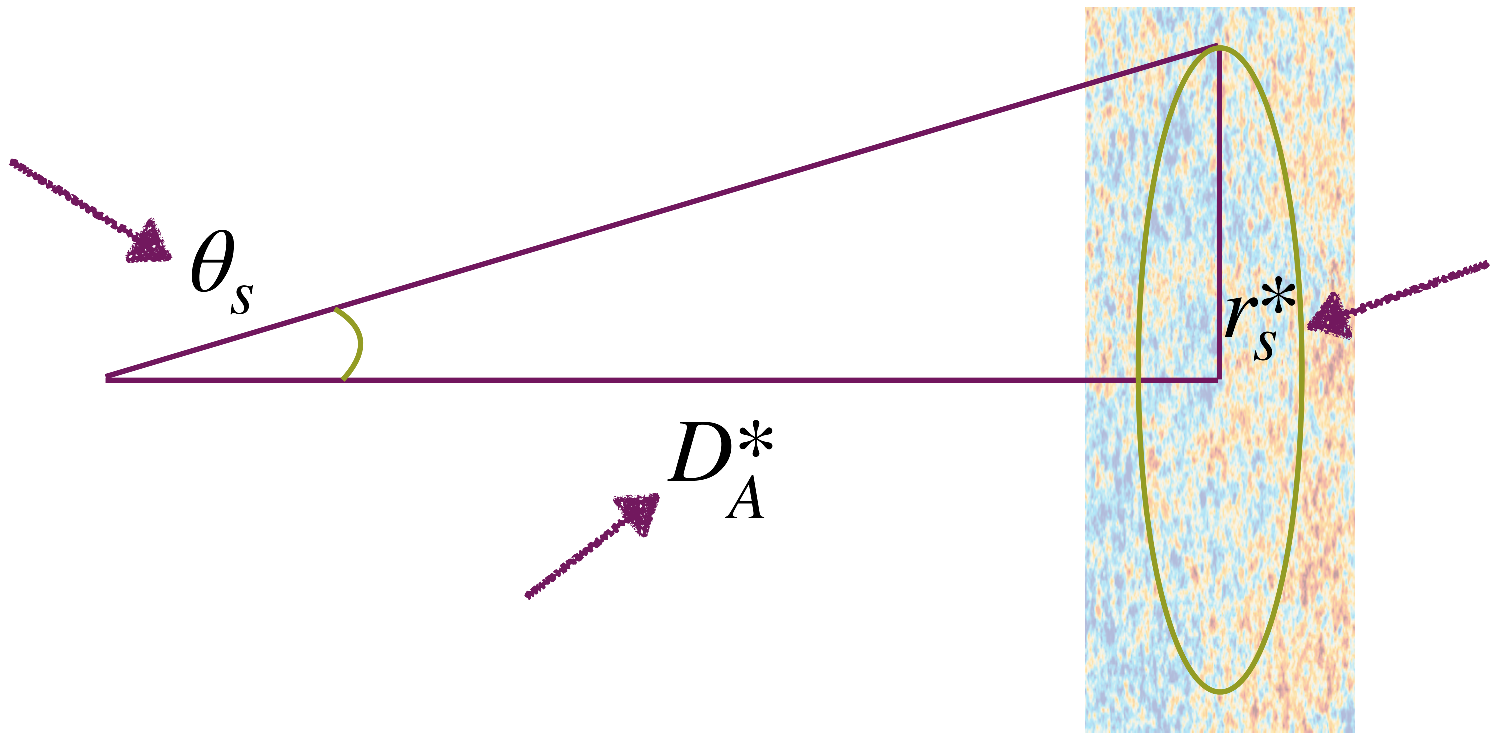

angular size
θ_s
sound horizon at decoupling
r_s^*
D_A^*
angular diameter distance

H_0 from CMB



$$\theta_s = \frac{r_s^*}{D_A^*}$$

H_0 from CMB

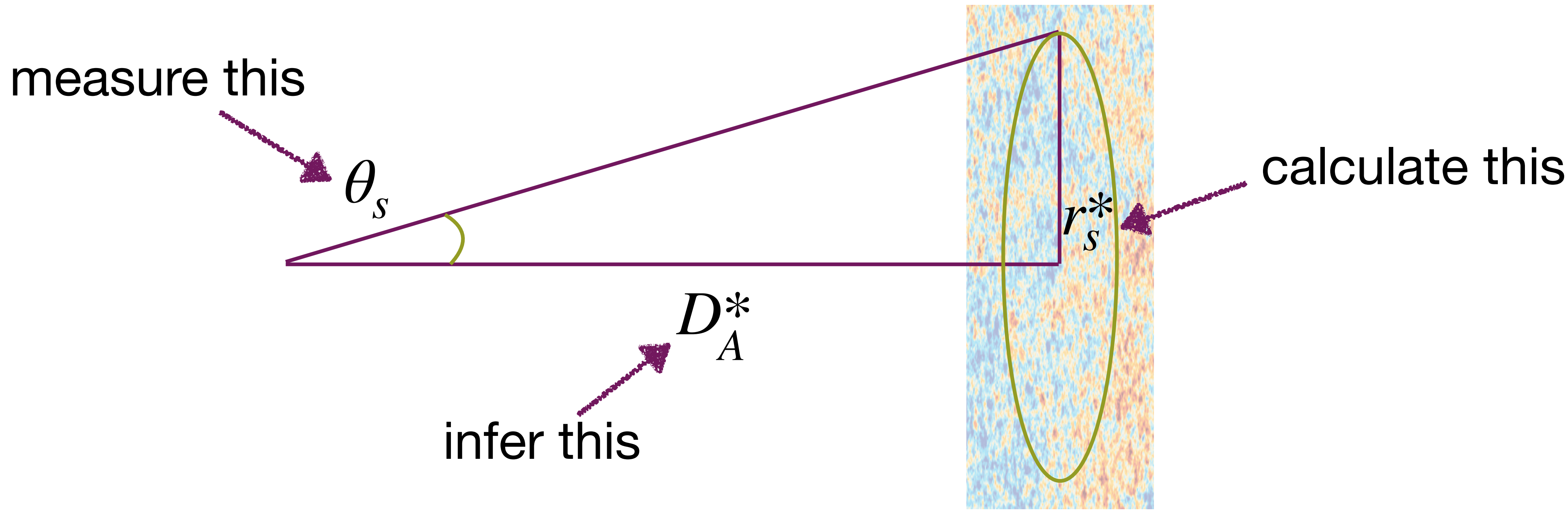


sound horizon at decoupling

angular size → $$\theta_s = \frac{r_s^*}{D_A^*}$$

angular diameter distance

H_0 from CMB



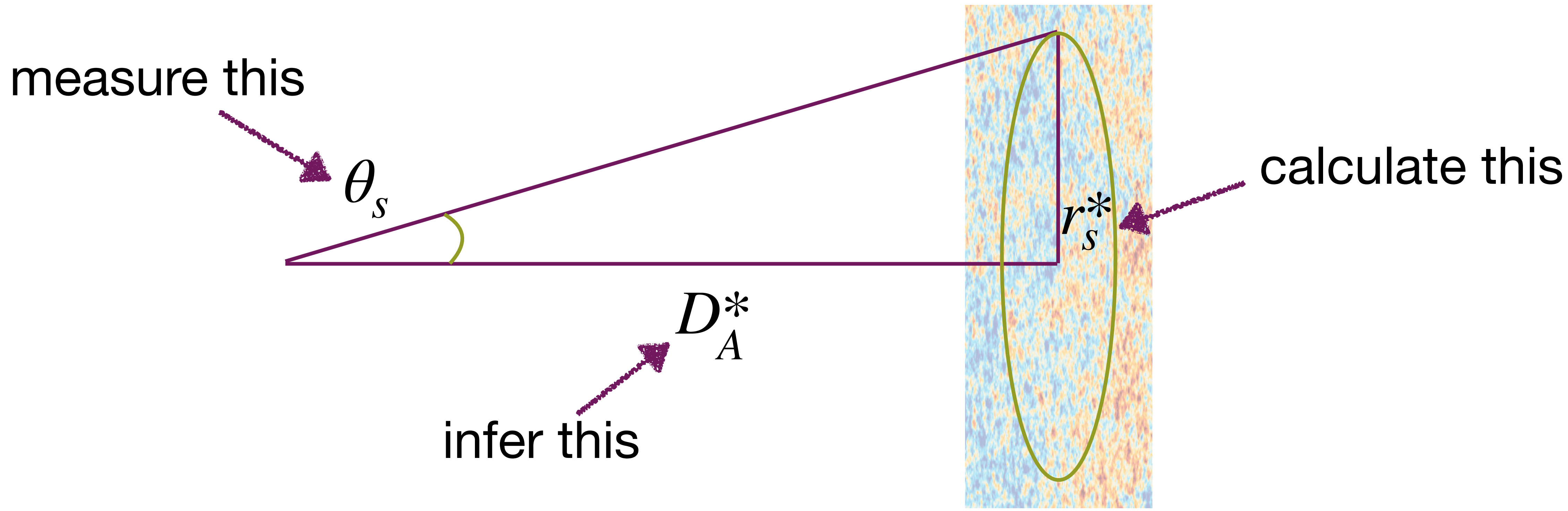
sound horizon at decoupling

angular size

$$\theta_s = \frac{r_s^*}{D_A^*}$$

angular diameter distance

H_0 from CMB



sound horizon at decoupling

angular size $\longrightarrow$ $\theta_s = \dfrac{r_s^*}{D_A^*} \propto \dfrac{\textbf{pre-recombination physics}}{\textbf{post-recombination physics}}$

angular diameter distance

H_0 from CMB

$$\theta_s = \frac{r_s^*}{D_A^*} \propto \frac{\textbf{pre-recombination physics}}{\textbf{post-recombination physics}}$$

H_0 from CMB

$$\theta_s = \frac{r_s^*}{D_A^*} \propto \frac{\textbf{pre-recombination physics}}{\textbf{post-recombination physics}}$$

$$r_s^* = \int_{z_*}^{\infty} dz \frac{c_s^*}{H(z)}$$

H_0 from CMB

$$\theta_s = \frac{r_s^*}{D_A^*} \propto \frac{\textbf{pre-recombination physics}}{\textbf{post-recombination physics}}$$

$$c_s^* = \frac{1}{\sqrt{3\left(1 + \frac{3\rho_b}{4\rho_\gamma}\right)}}$$

baryon - photon sound speed

$$r_s^* = \int_{z_*}^{\infty} dz \frac{c_s^*}{H(z)}$$

H_0 from CMB

$$\theta_s = \frac{r_s^*}{D_A^*} \propto \frac{\textbf{pre-recombination physics}}{\textbf{post-recombination physics}}$$

$$r_s^* = \int_{z_*}^{\infty} dz \frac{c_s^*}{H(z)}$$

$$c_s^* = \frac{1}{\sqrt{3\left(1 + \frac{3\rho_b}{4\rho_\gamma}\right)}}$$

baryon - photon
sound speed

$$H^2(z) = \frac{8\pi G}{3}\left(\rho_\gamma + \rho_\nu + \rho_{\mathrm{M}}\right)$$

using ΛCDM
in early universe

H_0 from CMB

$$\theta_s = \frac{r_s^*}{D_A^*} \propto \frac{\textbf{pre-recombination physics}}{\textbf{post-recombination physics}}$$

$$c_s^* = \frac{1}{\sqrt{3\left(1 + \frac{3\rho_b}{4\rho_\gamma}\right)}}$$

baryon - photon sound speed

$$r_s^* = \int_{z_*}^{\infty} dz \frac{c_s^*}{H(z)}$$

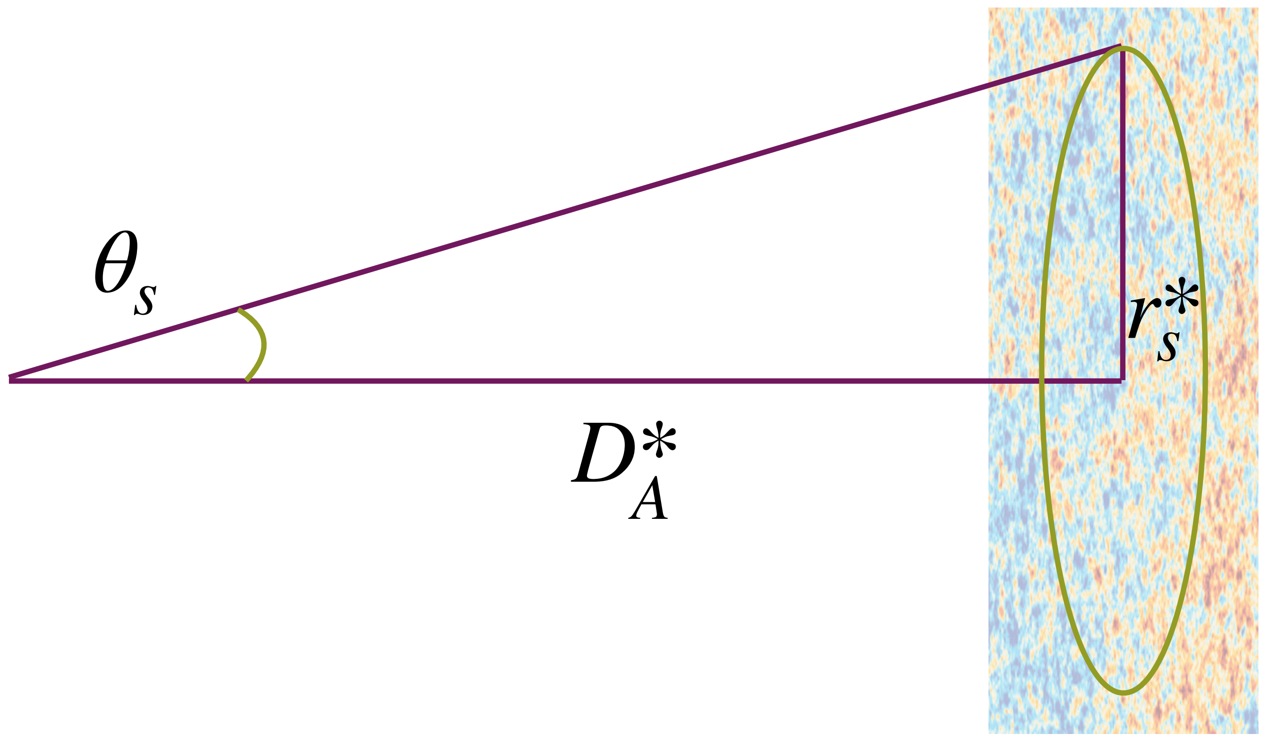
$$H^2(z) = \frac{8\pi G}{3}\left(\rho_\gamma + \rho_\nu + \rho_\mathrm{M}\right)$$

using ΛCDM in early universe

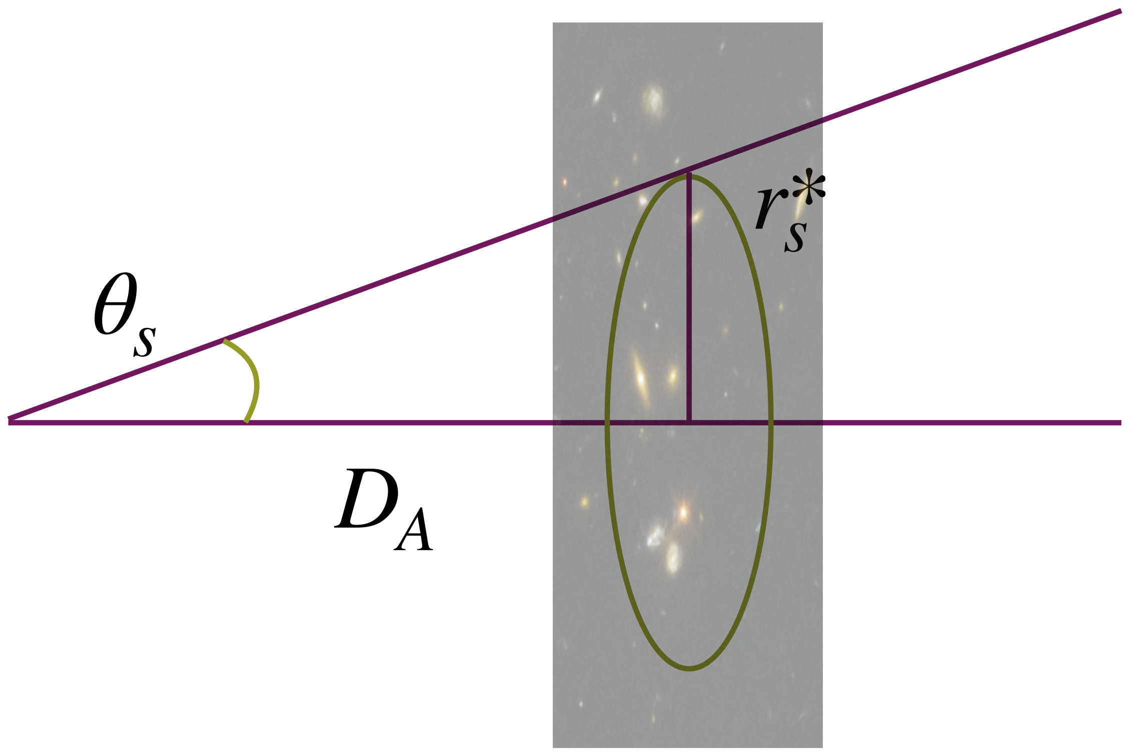
$$D_A^* = \int_0^{z_*} \frac{dz}{H_0\sqrt{\Omega_\mathrm{M}(1+z)^3 + \Omega_\Lambda(z)}}$$

using ΛCDM in late universe, we can calculate H_0

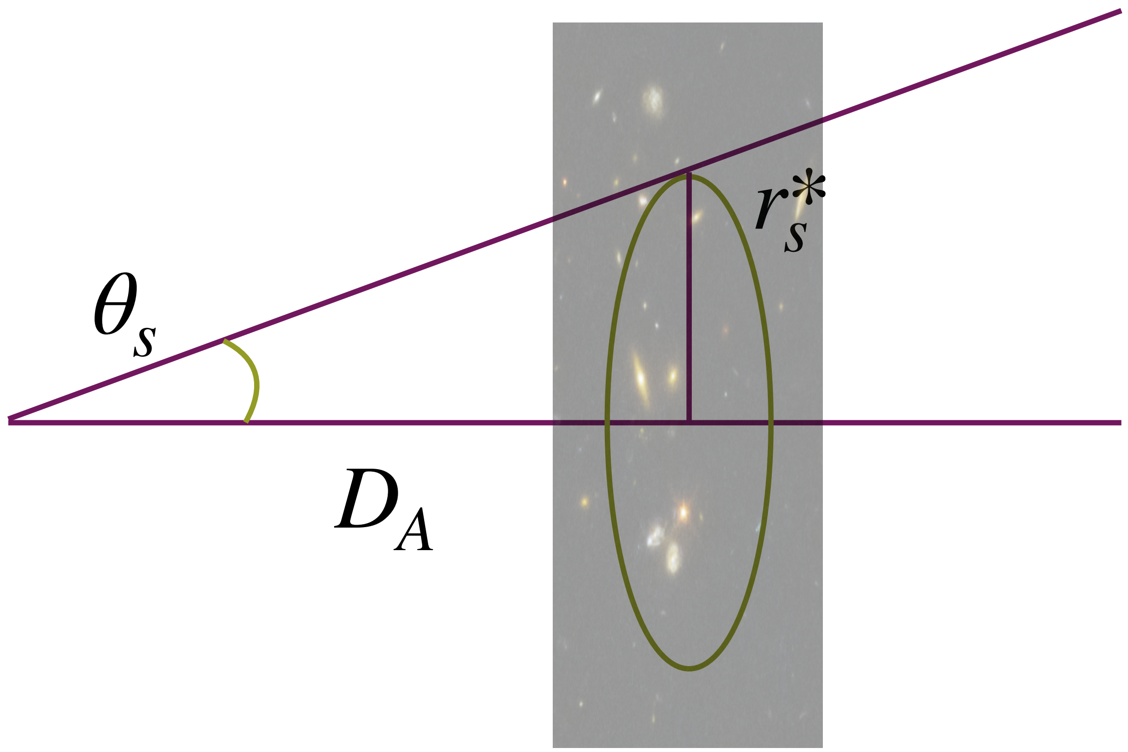
H_0 from BAO



H_0 from BAO



H_0 from BAO

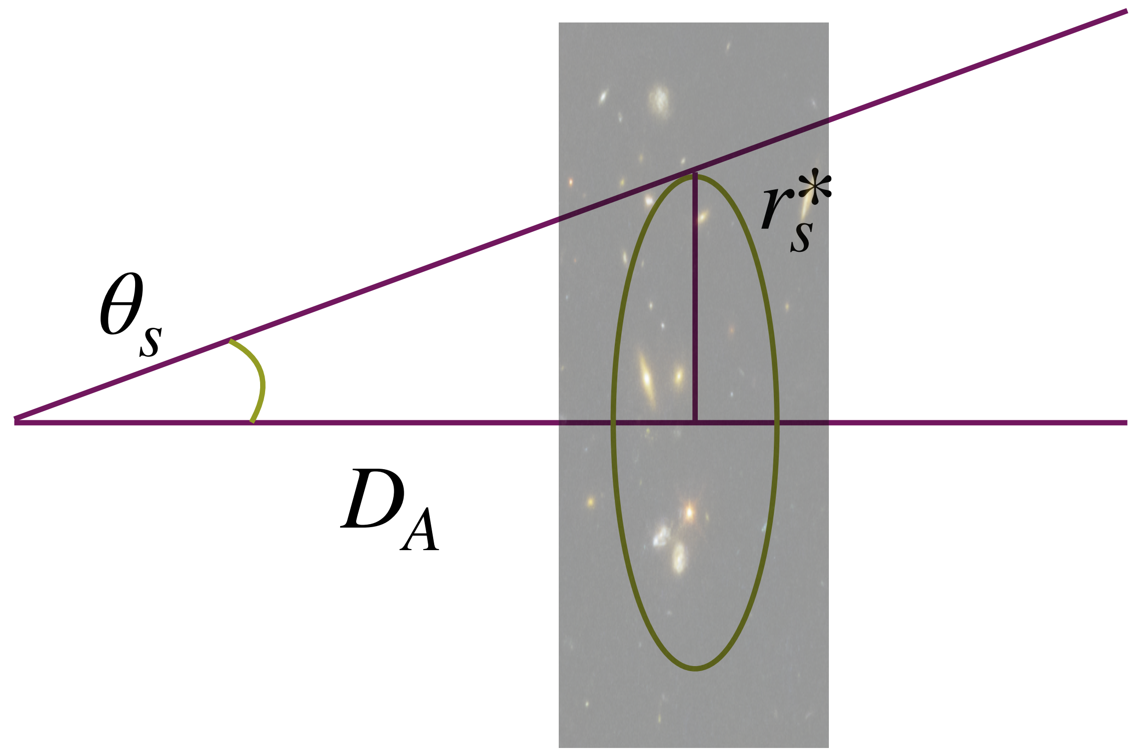


BAO measures two processed versions of the sound horizon:

Line of sight: $H(z)r_s$

Transverse: $r_s/D_A(z)$

H_0 from BAO



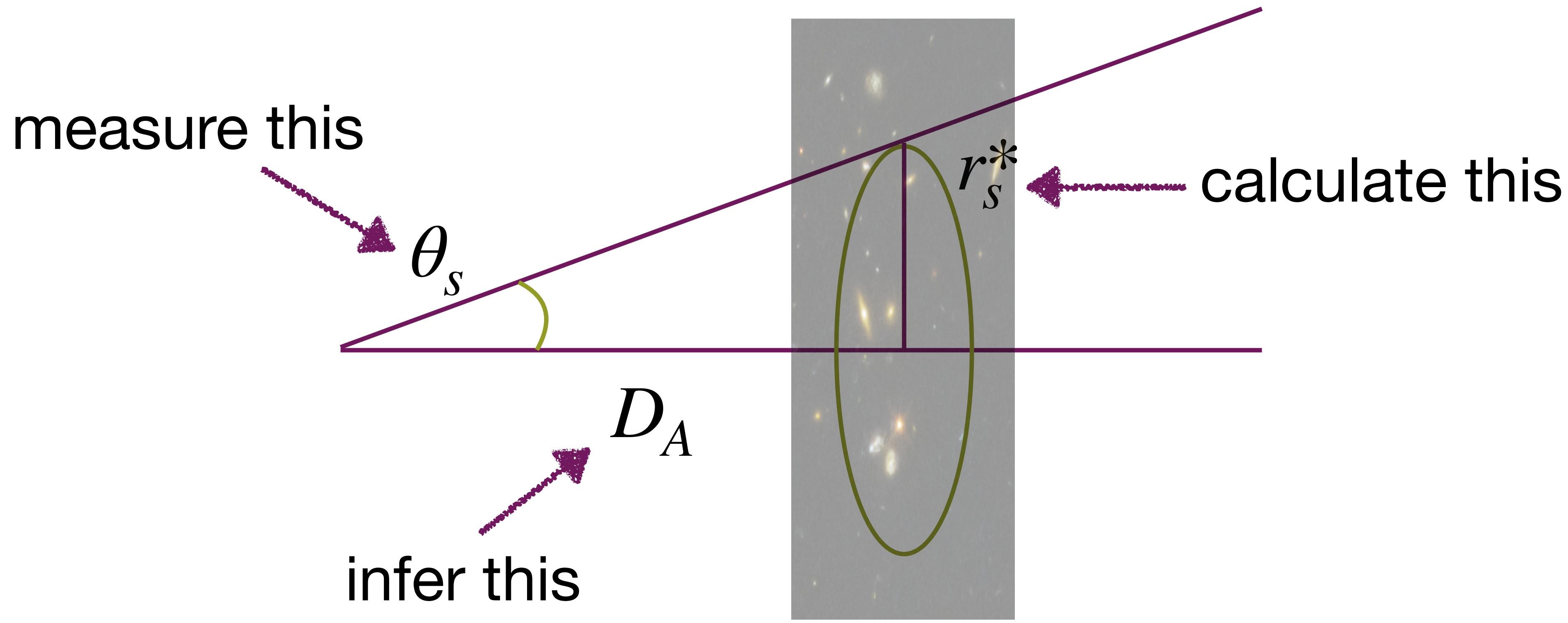
BAO measures two processed versions of the sound horizon:

Line of sight: $H(z)r_s$

Transverse: $r_s/D_A(z)$

We always need an anchor:

H_0 from BAO



BAO measures two processed versions of the sound horizon:

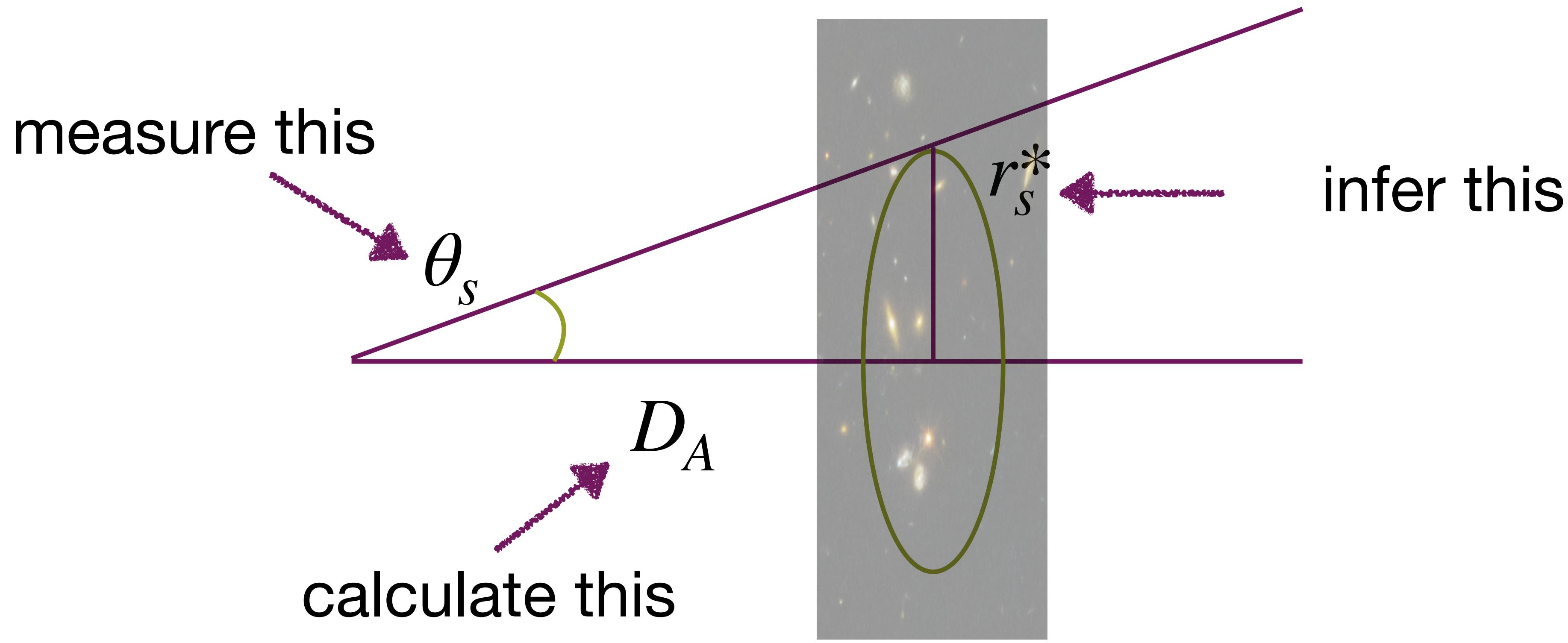
Line of sight: $H(z)r_s$

Transverse: $r_s/D_A(z)$

We always need an anchor:

- CMB

H_0 from BAO



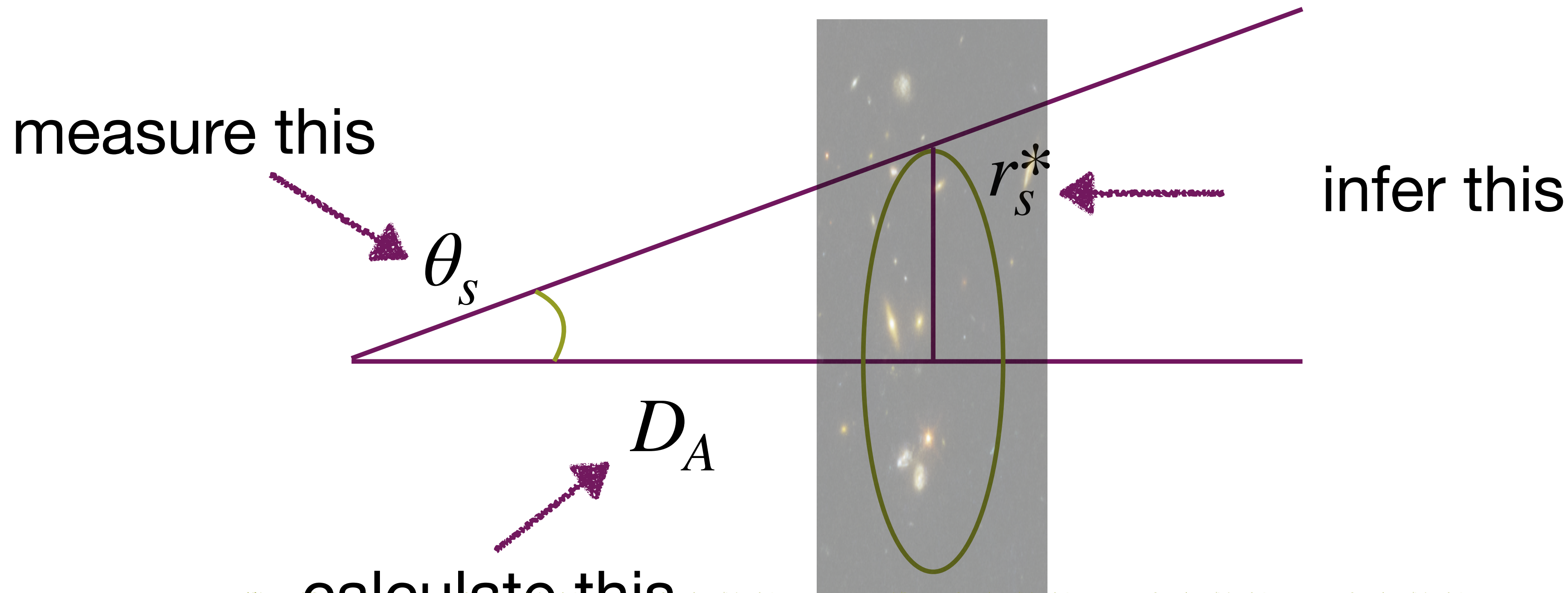
BAO measures two processed versions of the sound horizon:

Line of sight: $H(z) r_s$

Transverse: $r_s / D_A(z)$

We always need an anchor:

- CMB
- Supernovae



The Hubble tension can be formulated as a sound horizon tension

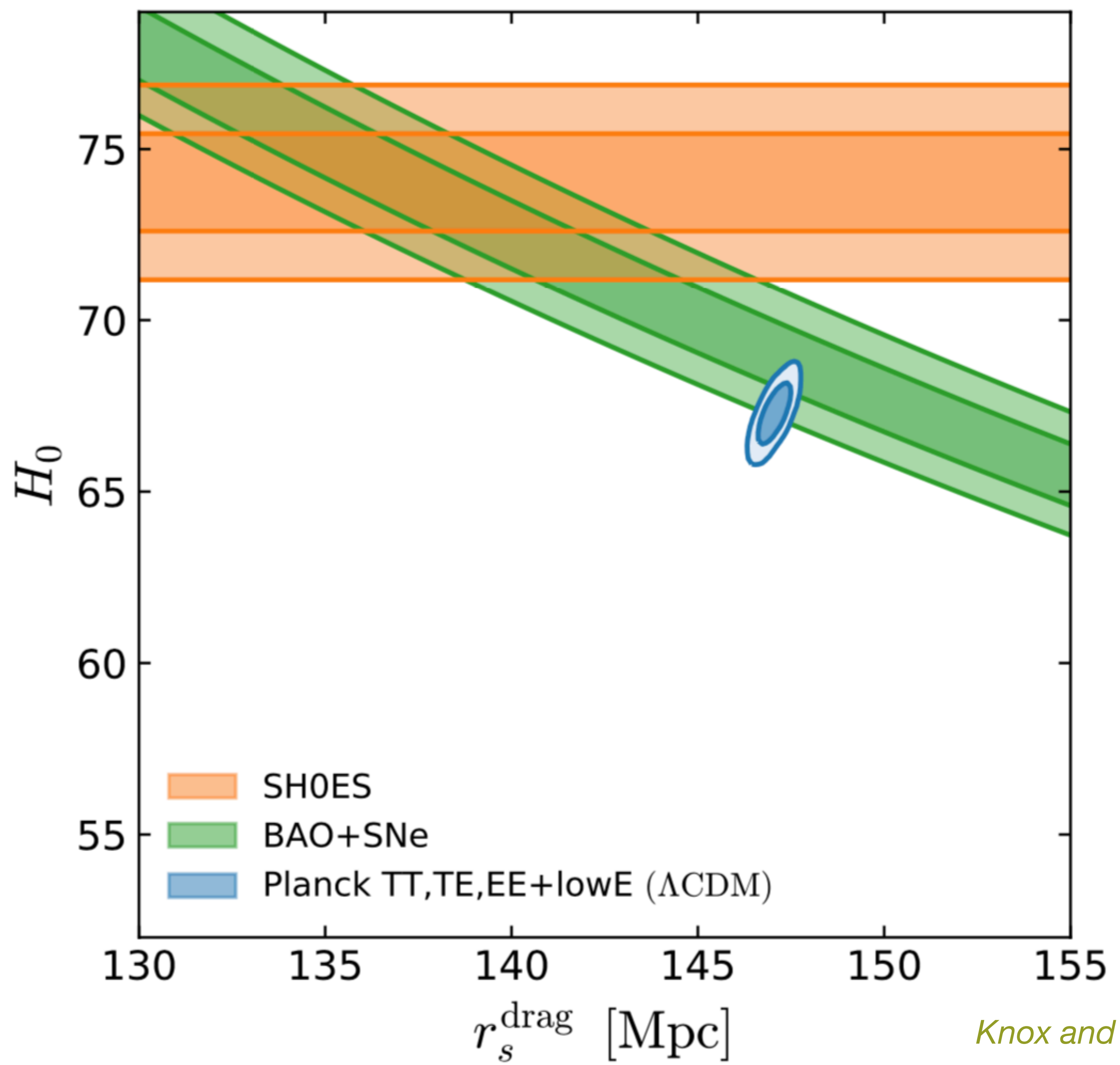
BAO mea d an
versions of the sound horizon: anchor:

Line of sight: $H(z) r_s$

Transverse: $r_s / D_A(z)$

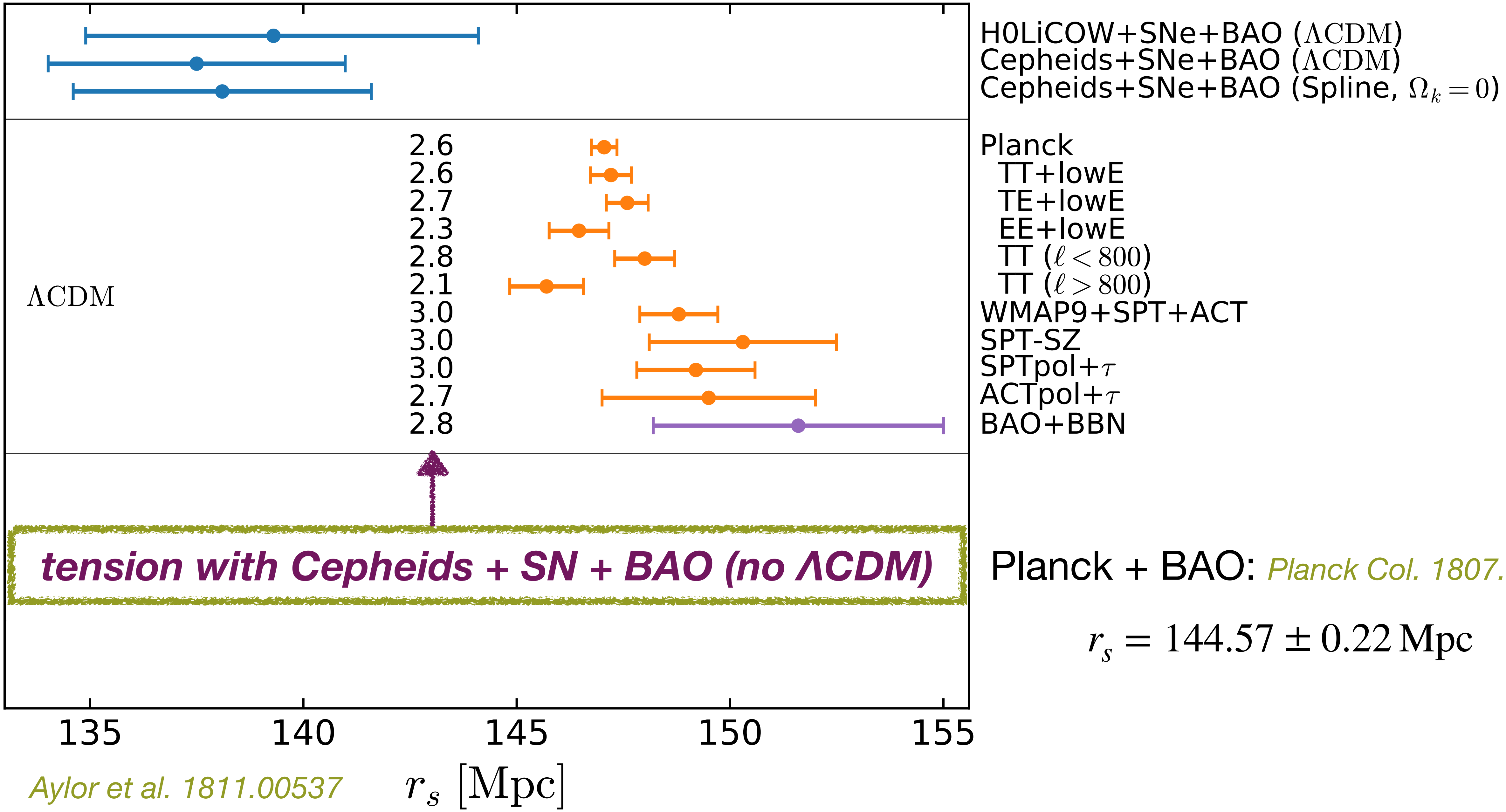
- CMB
- Supernovae

The sound horizon tension



Knox and Millea 1908.03663

The sound horizon tension



Aylor et al. 1811.00537

Planck + BAO: Planck Col. 1807.06209

$$r_s = 144.57 \pm 0.22\,\mathrm{Mpc}$$

BAO data will be crucial to test different solutions

What could be the origin?

- Systematics in supernovae
- Systematics in Planck
- New physics

What could be the origin?

- Systematics in supernovae
- Systematics in Planck
- New physics
- Statistical fluke

What could be the origin?

- Systematics in supernovae
- Systematics in Planck
- New physics

- ~~Statistical fluke~~

What could be the origin?

COSMO'19 POLL:

- Systematics in supernovae — ~85%
- Systematics in Planck — ~1%
- New physics — ~10%

~4% not sure

- ~~Statistical fluke~~

Problems with supernovae?

Problem with geometry?

	Independent Geometric Source	σ	H_0
	NGC 4258 H_20 Masers: Humphreys et al 2013, Riess et al 2016 Reid et al. (2019) in prep	~~2.6%~~ 1.5%	~~72.3~~ ~72.0
NEWER	LMC 20 Late Detached Eclipsing Binaries: Pietzrynski et al. 2019 +70 HST LMC Cepheids Riess et al (2019)	1.3%	74.2
	Milky Way 10 HST FGS Short P Parallaxes: Benedict et al. 2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
NEW	Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess et al. 2018	3.3%	75.7
NEW	Milky Way 50 Gaia+HST, Long P Parallaxes: Riess et al. 2018	3.3%	73.7

Table credit: A. Riess

Problems with supernovae?

Systematics in Cepheids or supernovae?

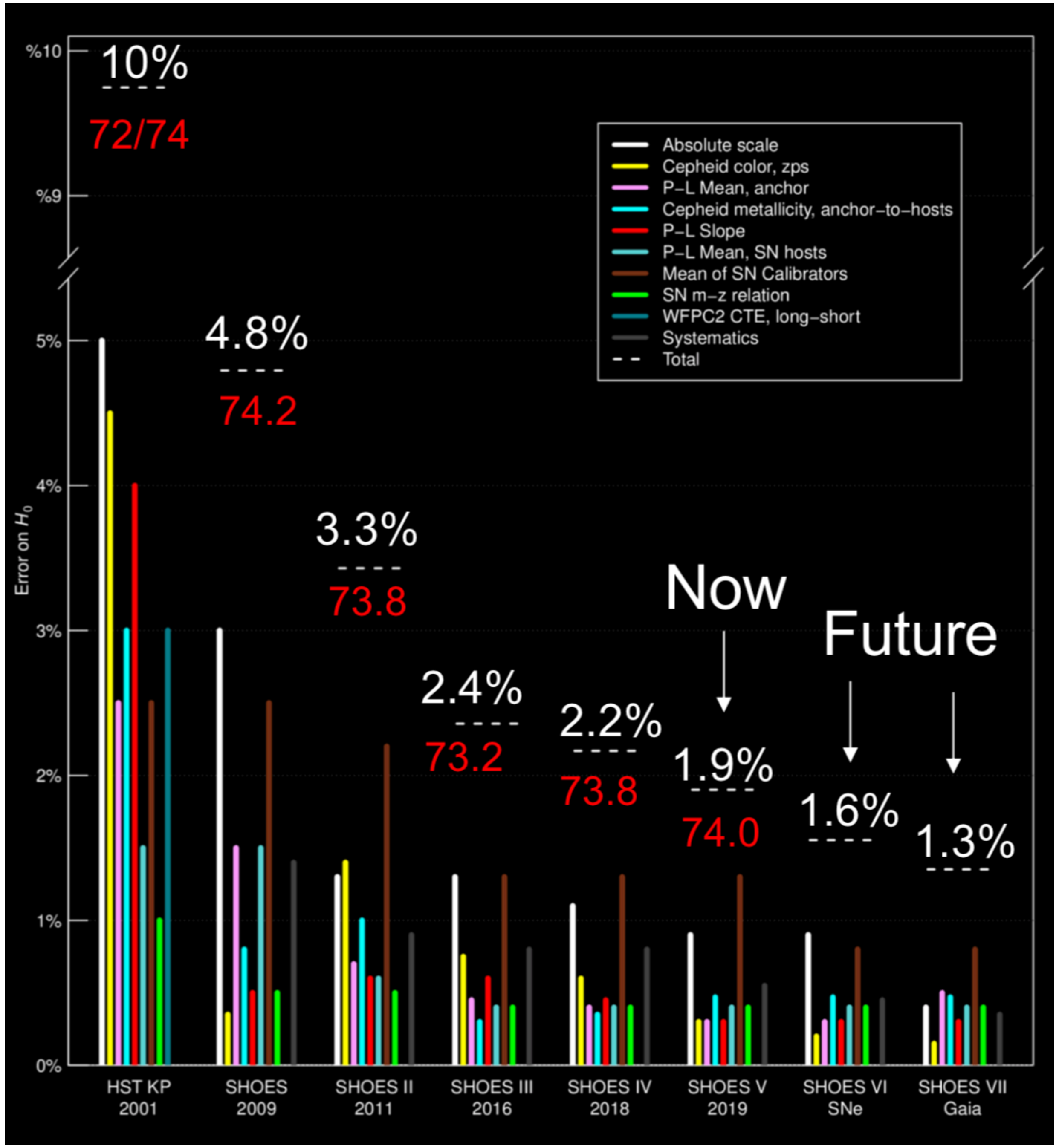
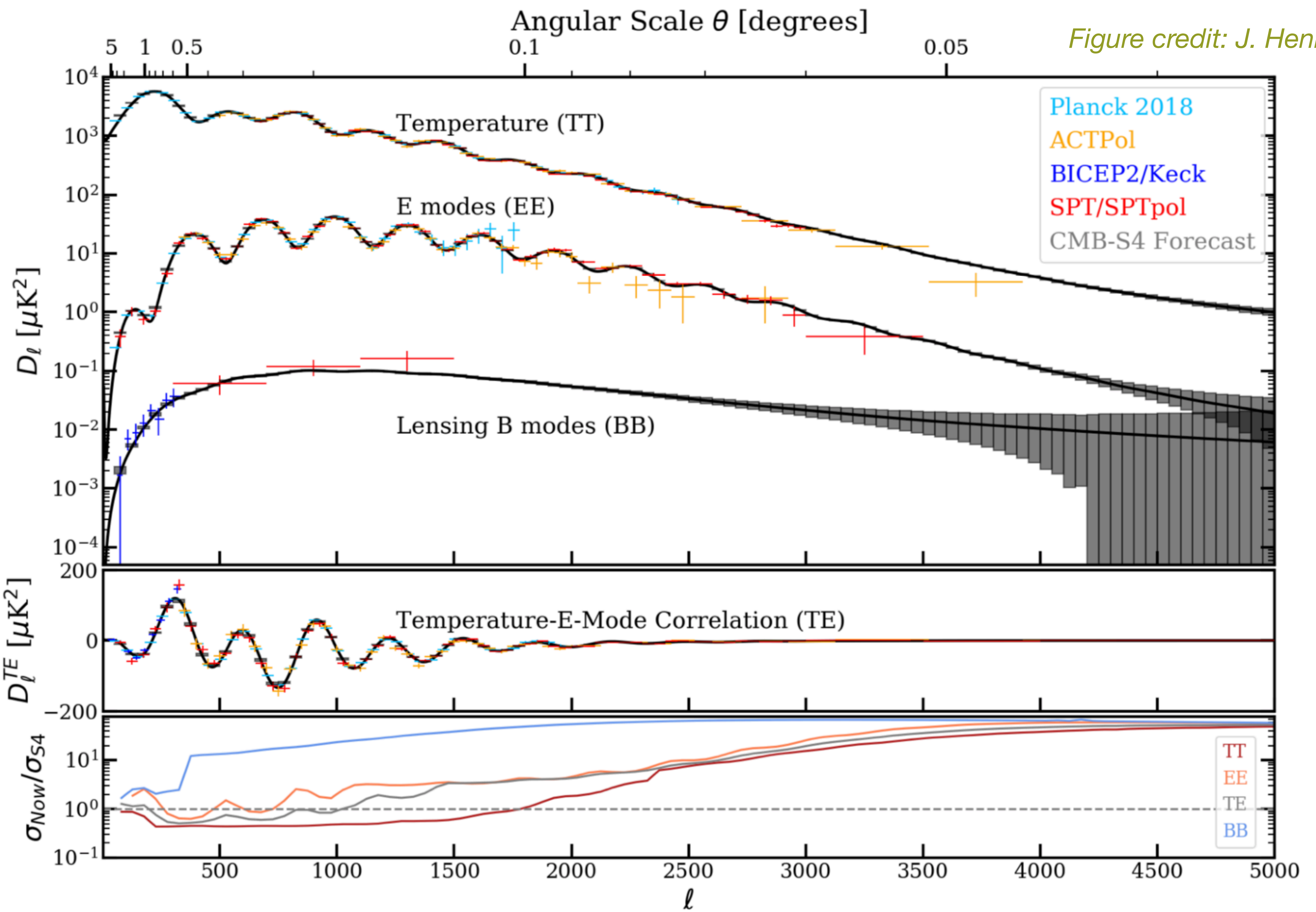


Figure credit: A. Riess

- Reanalysis by independent groups find same result
- Changing assumptions on Cepheids barely effect H_0 *(Follin and Knox 1707.01175)*
- Reduction of supernovae not independently cross-checked
- It is not only supernovae: quasar time delays, megamasers, and surface brightness fluctuations all find similar H_0 values

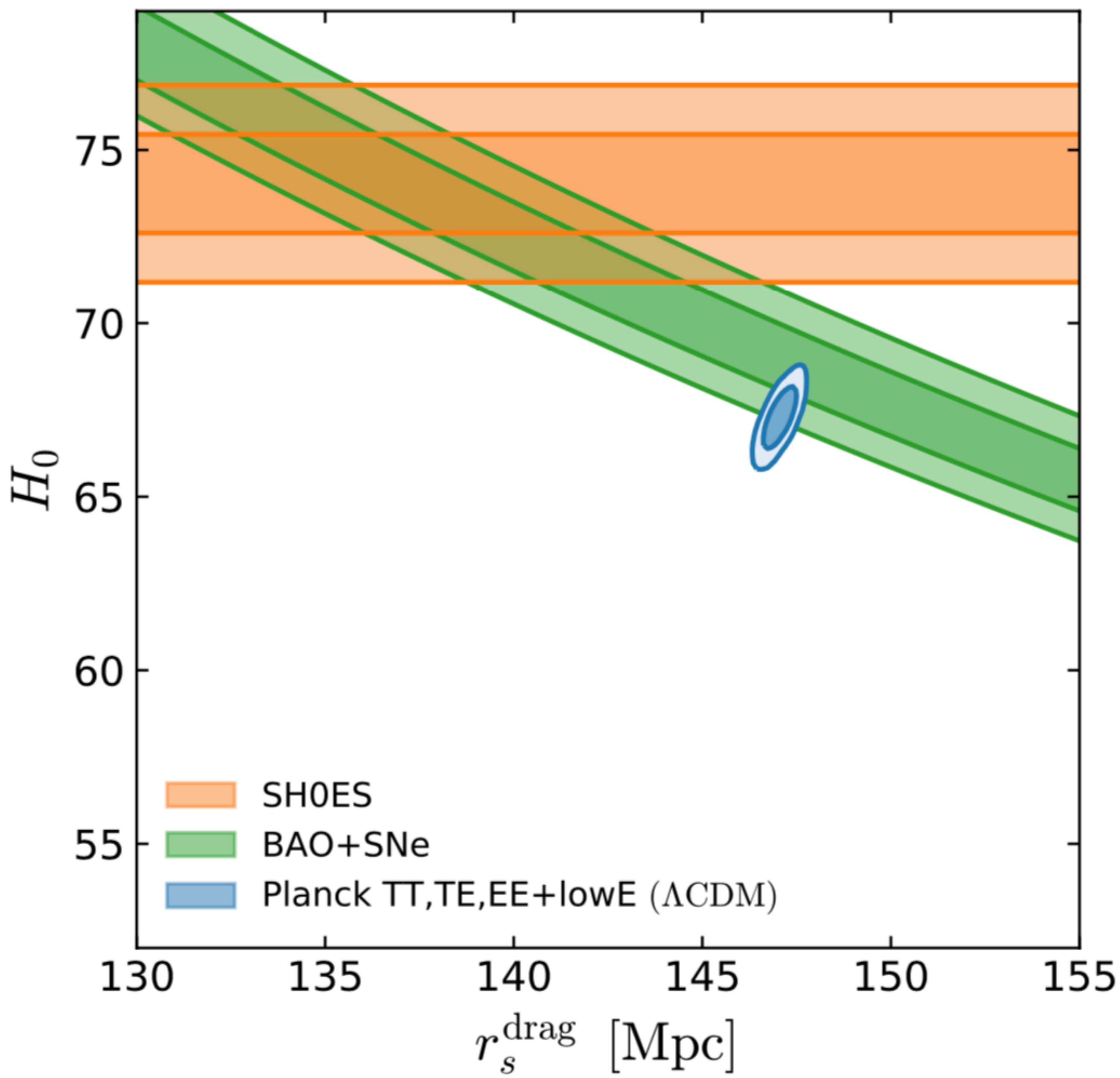
Problems in the CMB?

Figure credit: J. Henning



Problems in the CMB?

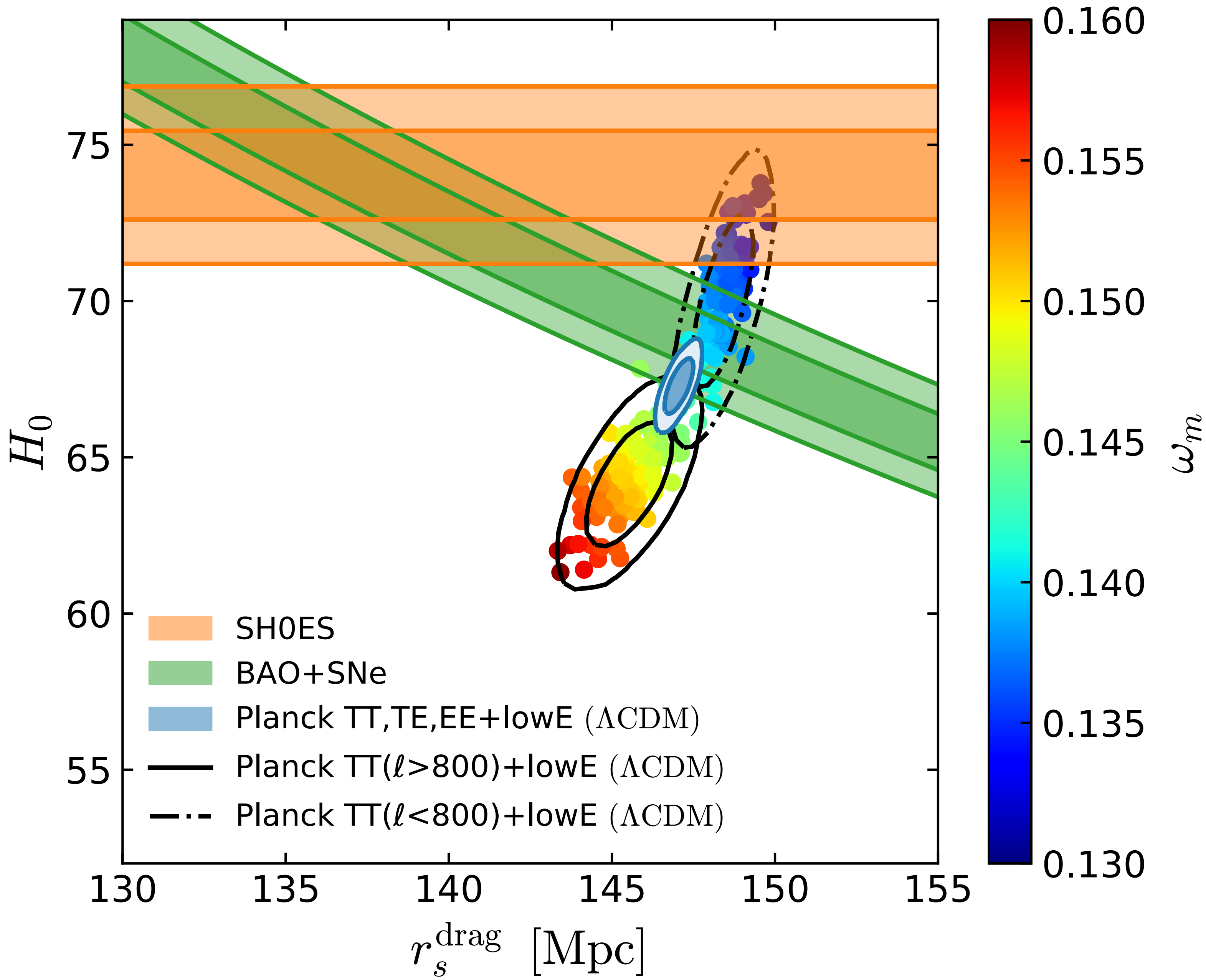
Knox and Millea 1908.03663



- CMB remarkably consistent across different modes and experiments
- This consistency has been tested down to the Planck level of precision

Problems in the CMB?

Knox and Millea 1908.03663



- CMB remarkably consistent across different modes and experiments
- This consistency has been tested down to the Planck level of precision
- Small anomaly between low-ℓ and high-ℓ TT data - is this significant?

Problems with ΛCDM?

"Once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth." - Sherlock Holmes

$$\theta_s = \frac{r_s^*}{D_A^*} \propto \frac{\textbf{pre-recombination physics}}{\textbf{post-recombination physics}}$$

- **Early universe solutions:** for a fixed θ_s, decrease r_s^* to decrease D_A^* and increase H_0 (change recombination or pre-recombination physics, without messing up the CMB)

- **Late universe solutions:** for a fixed r_s^* and D_A^*, change $D_A(z < z^*)$ to allow for higher H_0 (decrease energy density between $0 < z < z^*$)

Classes of solutions

Pre-recombination

- Sound speed reduction
- High-temperature recombination
- Photon cooling/conversion
- Increasing H(z) with additional components:

  A. Light Relics, $N_{\rm eff}$

  B. Early Dark Energy

  C. Designer H(z)

Classes of solutions

Pre-recombination

- Sound speed reduction
- High-temperature recombination
- Photon cooling/conversion
- Increasing H(z) with additional components:
    A. Light Relics, N_{eff}
    B. Early Dark Energy
    C. Designer H(z)

Post-recombination

- H(z) wiggles
- Post-recombination decrease in energy density
- Late-time photon interactions
- New physics impacting some Cepheids
- New physics impacting some supernovae

See Hubble Hunter's Guide for more details
Knox and Millea 1908.03663

Classes of solutions

Pre-recombination

- Sound speed reduction
- High-temperature recombination
- Photon cooling/conversion
- Increasing H(z) with additional components:

  A. Light Relics, N_{eff}

  B. Early Dark Energy

  C. Designer H(z)

Post-recombination

- H(z) wiggles
- Post-recombination decrease in energy density
- Late-time photon interactions
- New physics impacting some Cepheids
- New physics impacting some supernovae

See Hubble Hunter's Guide for more details
Knox and Millea 1908.03663

Can $N_{\rm eff}$ solve the tension?

- Extra relativistic species in the early universe are predicted by many extensions to the Standard Model (N-Naturalness, Twin Higgs, etc)

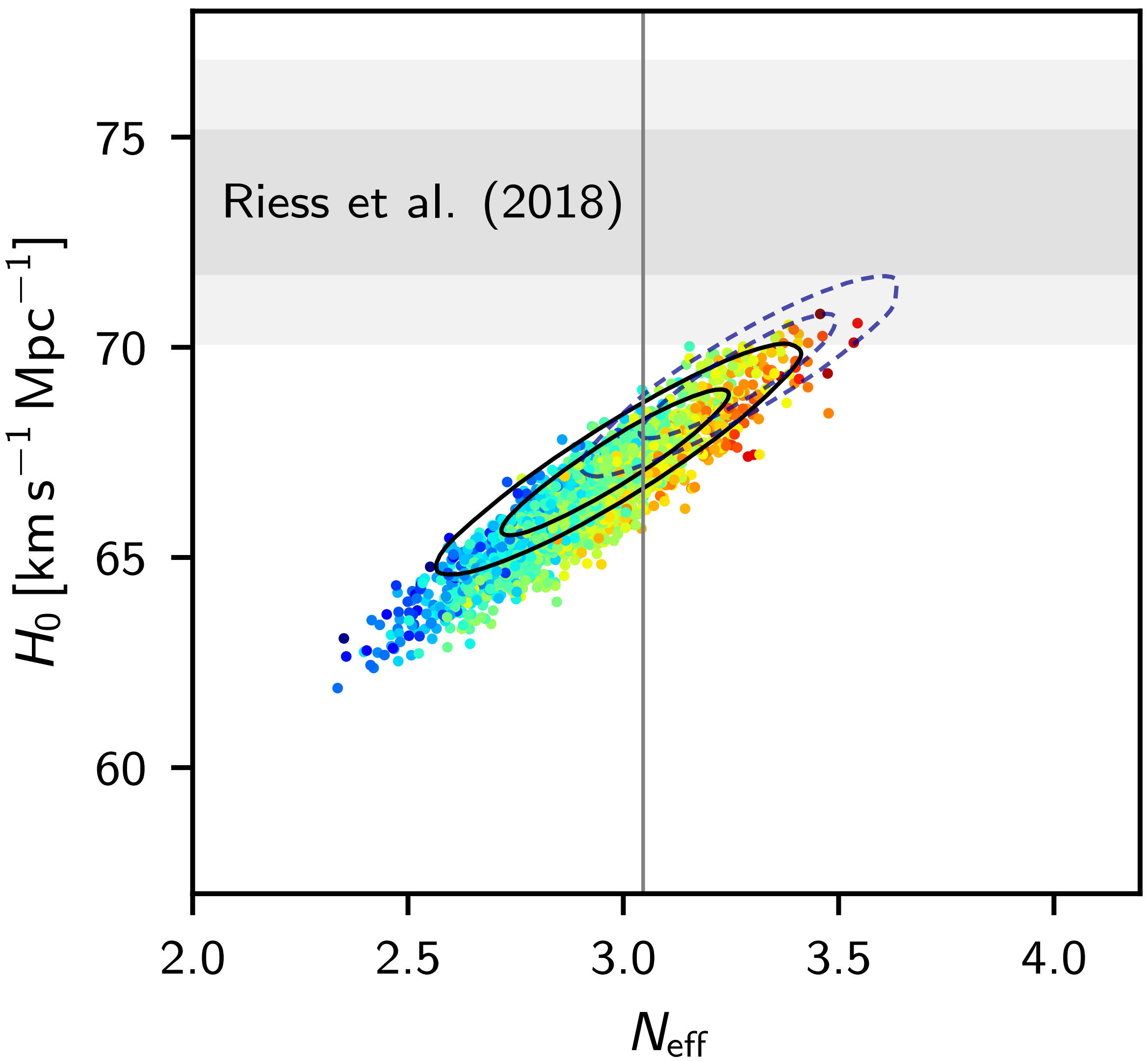
- Increase $N_{\rm eff}$ → increase $\rho_{\rm R}$ → decrease r_s^* → increase H_0

$$\rho_{\rm R} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right) \longrightarrow H^2(z) = \frac{8\pi G}{3}\left(\rho_{\rm R} + \rho_{\rm M}\right) \longrightarrow r_s^* = \int_{z_*}^{\infty} dz \frac{c_s^*}{H(z)}$$

- To fully solve the tension we need $N_{\rm eff} \sim 3.5 - 4.0$
(Bernal et al. 1607.05617)

Can N_{eff} solve the tension?

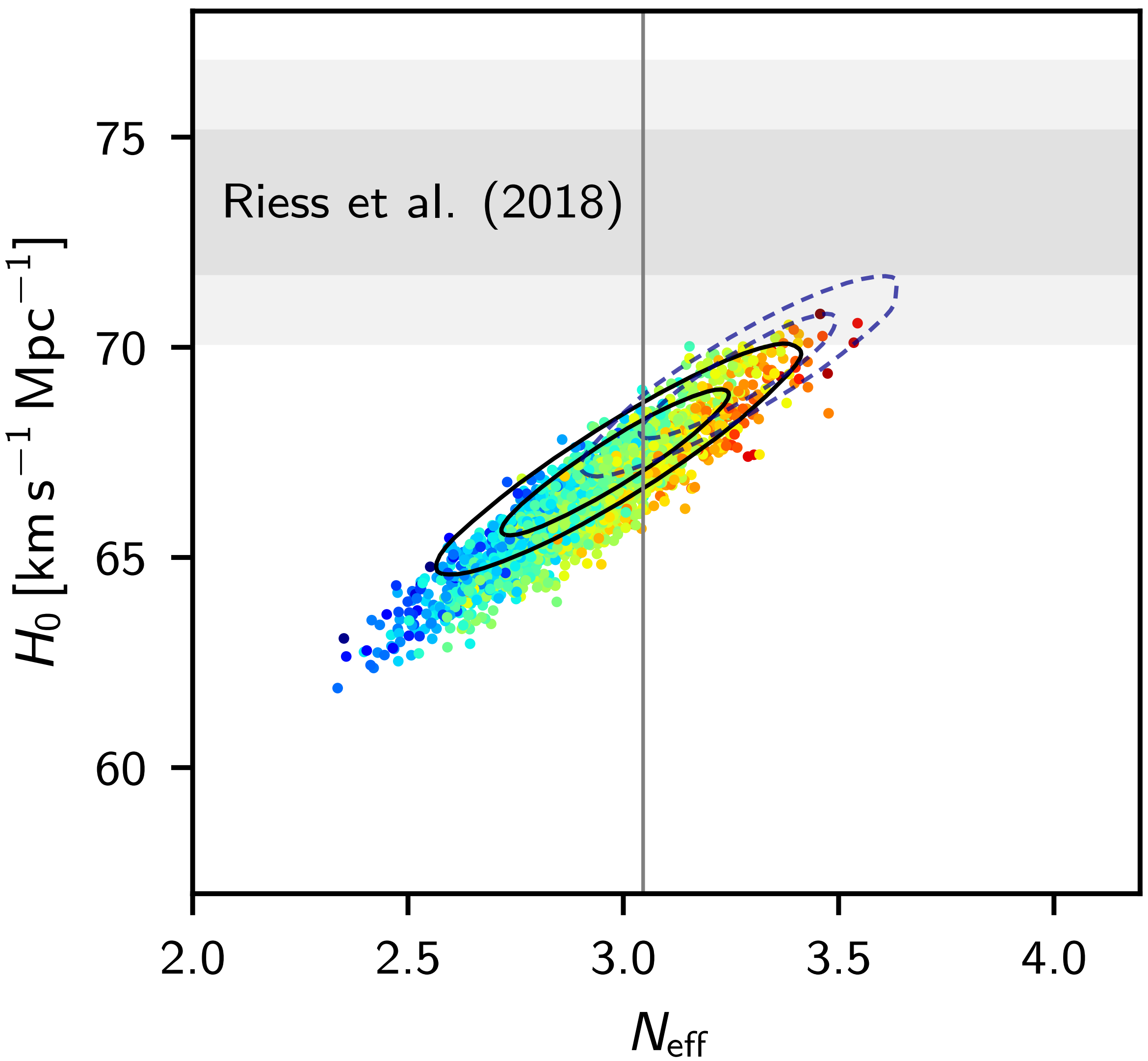
High-ℓ CMB temperature does not allow such high values of N_{eff}



Aghanim et al. 1807.06209

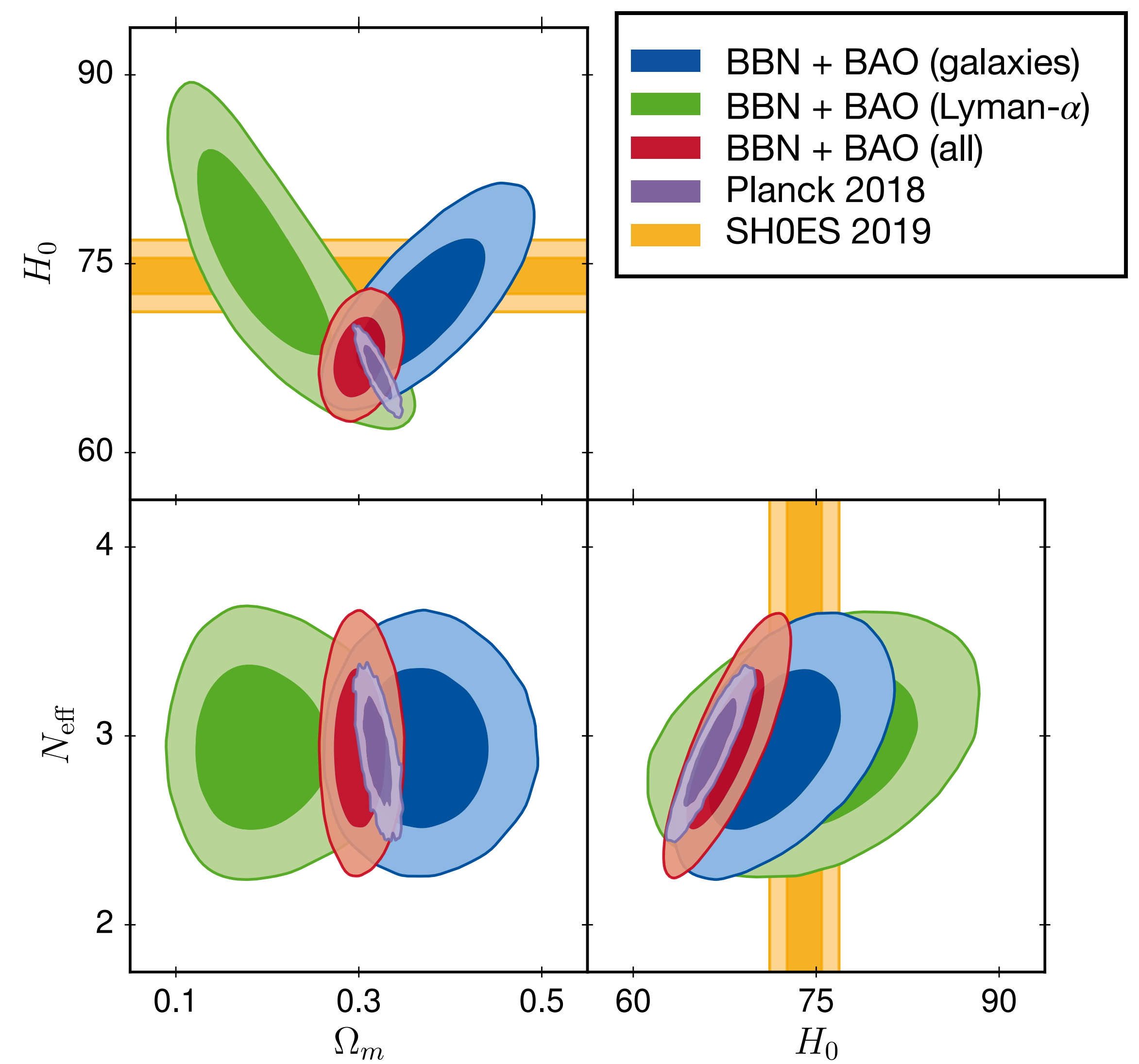
Can N_{eff} solve the tension?

High-ℓ CMB temperature does not allow such high values of N_{eff}



Aghanim et al. 1807.06209

BAO+BBN data disfavour N_{eff} as a solution (still 2.6σ tension) already at the background level



*Schöneberg, Lesgourgues, **DCH** 1907.11594*

A catalogue of solutions

- DM-DR interactions (NADM) *Buen-Abad et al. 1708.09406, Archidiacono et al. (**DCH**) 1907.01496*
- Early Dark Energy *Agrawal et al. 1904.01016, Poulin et al. 1811.04083*
- Extra radiation, $N_{\rm eff}$ *Bernal et al. 1607.05617, Agrawal et al. 1904.01016*
- Neutrino interactions *Kreisch et al. 1902.00534, Blinov 1905.02727*
- Decaying DM *Pandey et al. 1902.10636, Vattis et al. 1903.06220*
- Interacting DM-DE *Wang et al. 1603.08299, DiValentino et al. 1908.04281, Lucca and **DCH** 2002.06127*
- ++ countless other models *Bernal et al. 1607.05617, Knox and Millea 1908.03663*

A catalogue of solutions

non-exhaustive

- DM-DR interactions (NADM) *Buen-Abad et al. 1708.09406, Archidiacono et al. (**DCH**) 1907.01496*

- Early Dark Energy *Agrawal et al. 1904.01016, Poulin et al. 1811.04083*

- Extra radiation, $N_{\rm eff}$ *Bernal et al. 1607.05617, Agrawal et al. 1904.01016*

- Neutrino interactions *Kreisch et al. 1902.00534, Blinov 1905.02727*

- Decaying DM *Pandey et al. 1902.10636, Vattis et al. 1903.06220*

- Interacting DM-DE *Wang et al. 1603.08299, DiValentino et al. 1908.04281, Lucca and **DCH** 2002.06127*

- ++ countless other models *Bernal et al. 1607.05617, Knox and Millea 1908.03663*

A catalogue of ~~solutions~~ problems

- DM-DR interactions (NADM) — can only mitigate the problem, possible prior dependence
- Early Dark Energy — model building is hard, fine tuning, coincidence problem
- Extra radiation, $N_{\rm eff}$ — can only mitigate, disfavoured by BAO+BBN
- Neutrino interactions — model building is hard, requires very strong interaction
- Decaying DM — BAO + SN point to an early universe solution, can only mitigate problem
- Interacting DM-DE — BAO + SN point to an early-universe solution, can only mitigate problem

Current status

- All proposed solutions have drawbacks

- We have yet to identify a complete solution that fits all cosmological data and is physically well-motivated

- Model building is challenging: highly precise CMB measurements are well-fit by ΛCDM, but BAO+SN push us to an early-universe solution

- But we have some hints as to what a solution will look like

How to build a solution

- Solutions should be thought of in terms of the $r_s^* - H_0$ plane
- Most likely solution will imply a reduction of conformal time to recombination, lowering r_s^*
- Promising avenue: increasing $H(z)$ with additional components (perhaps just prior to recombination)
- New models must be compatible with CMB, BAO, and SN data
- Any solution should not make other tensions worse
- Will a solution be related to the $\ell < 800$ vs $\ell > 800$ discrepancy?

The H_0 tension

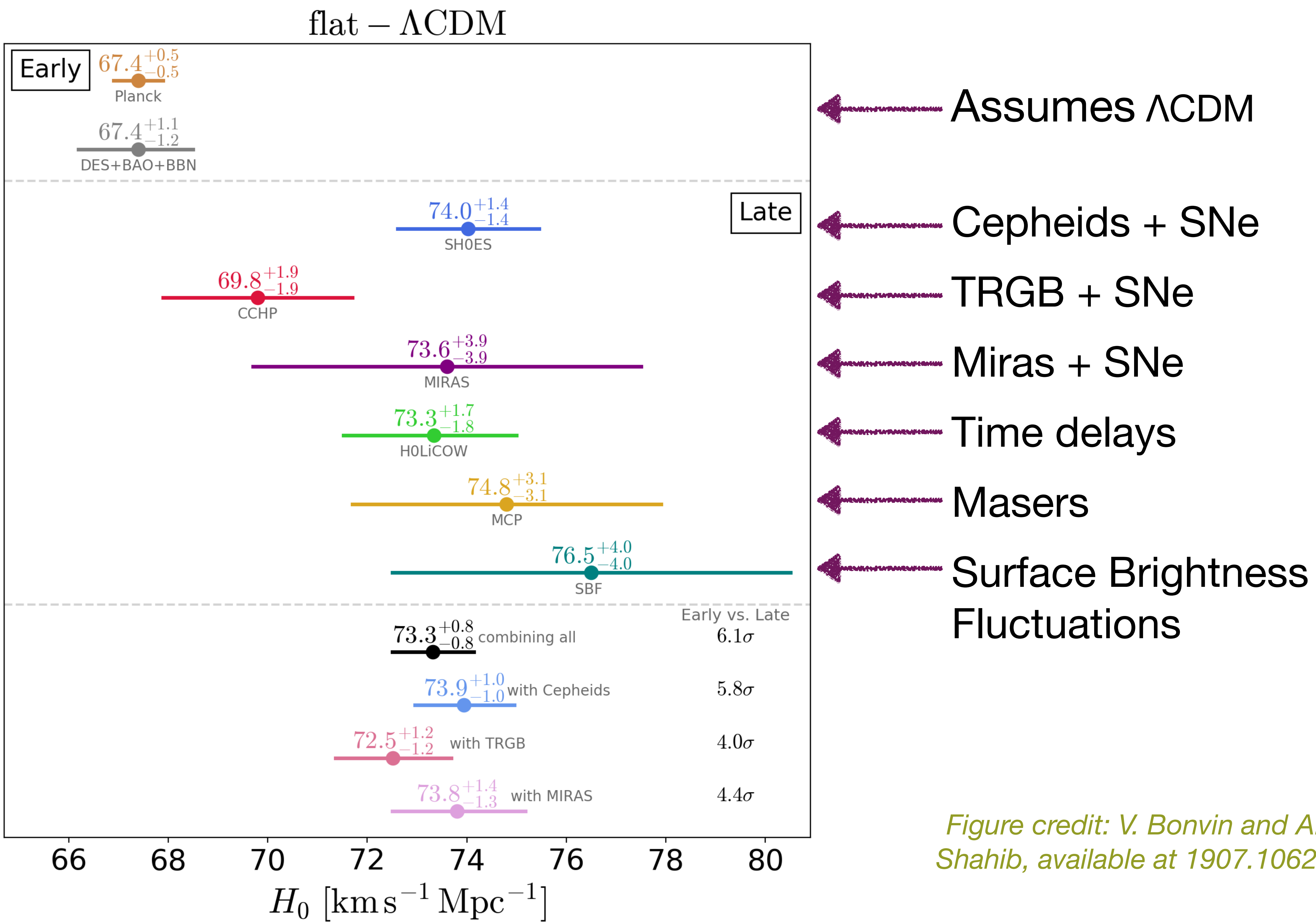


Figure credit: V. Bonvin and A. Shahib, available at 1907.10625

The H_0 tension

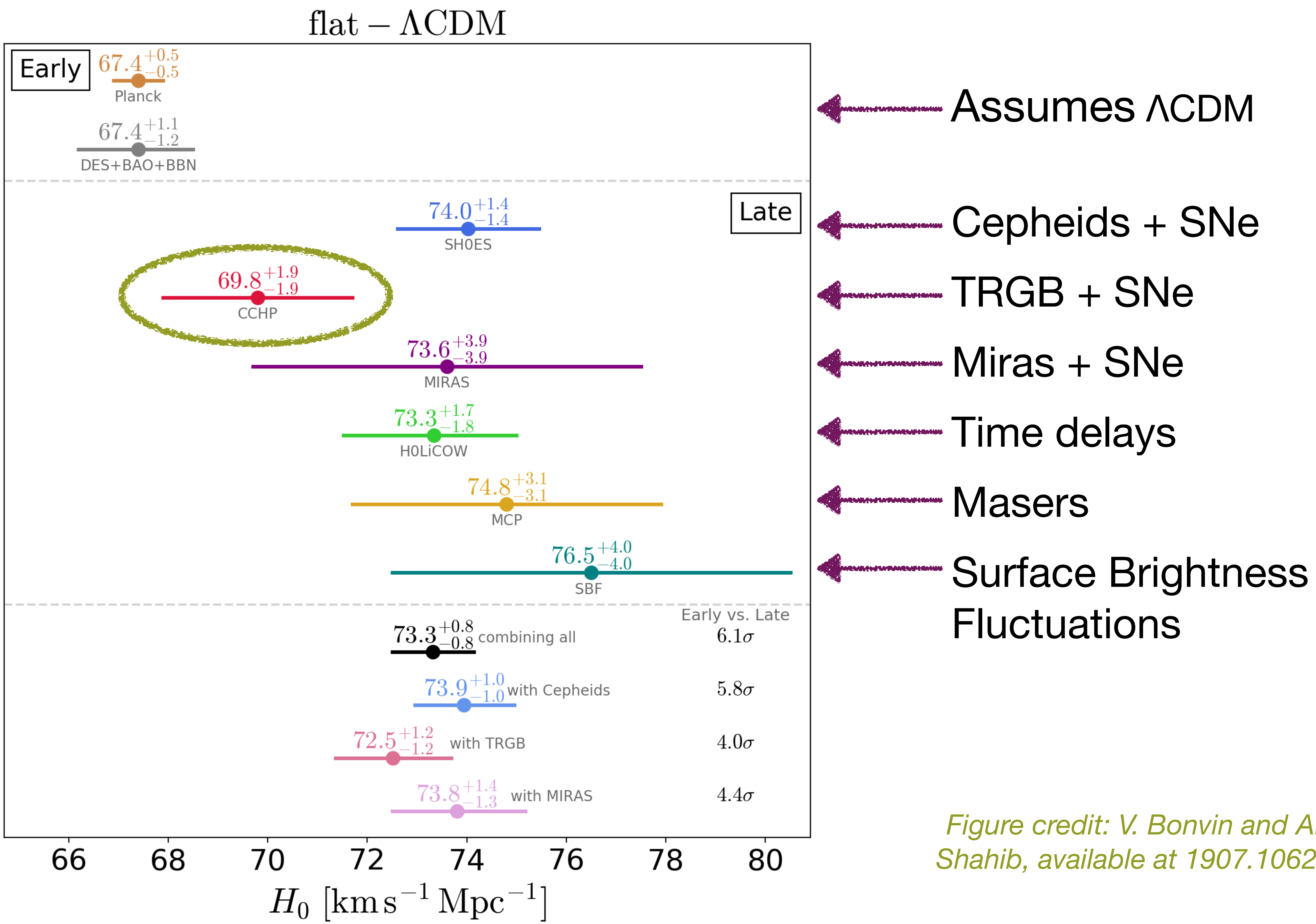


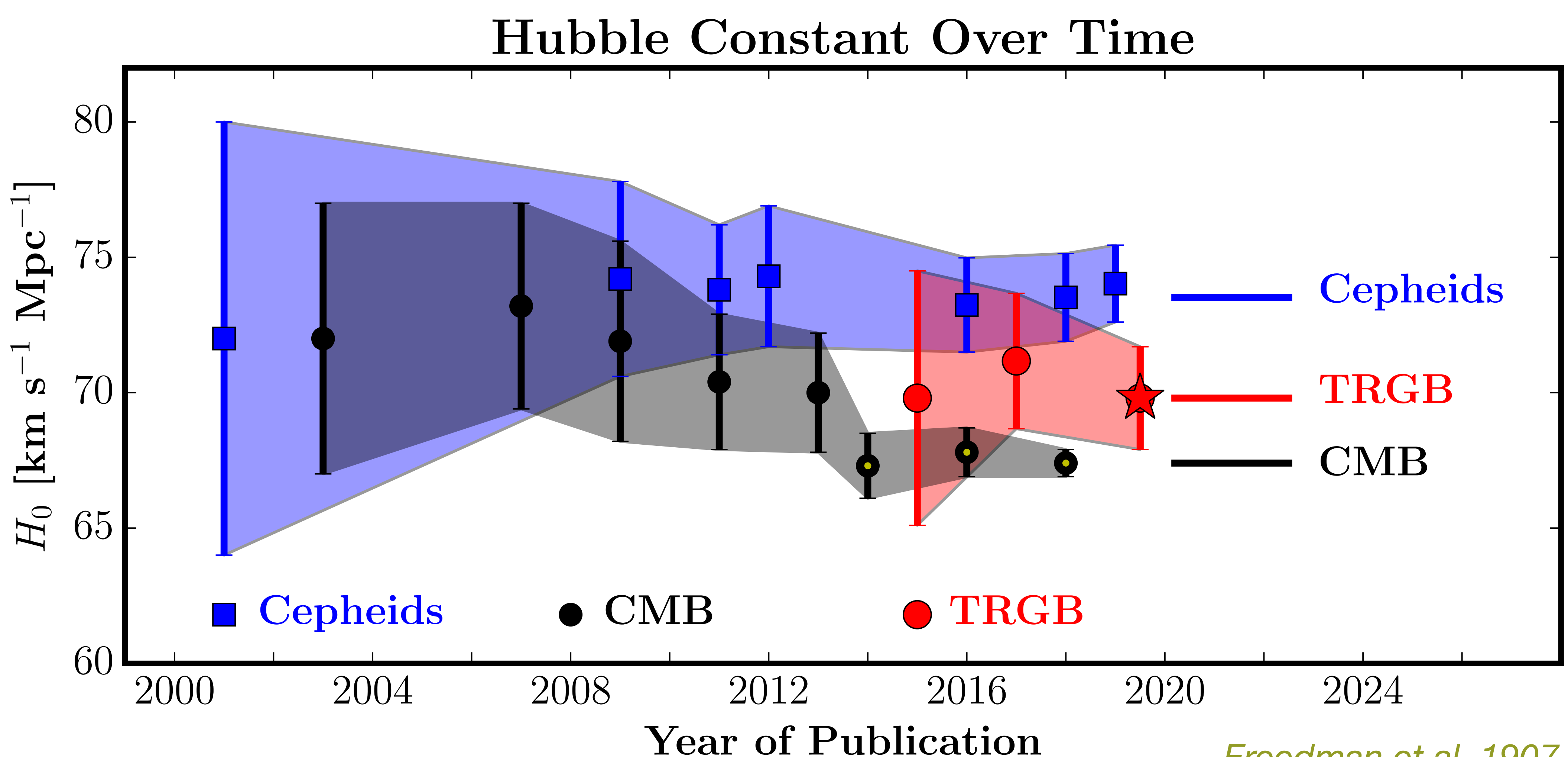
Figure credit: V. Bonvin and A. Shahib, available at 1907.10625

Will more data help?

- Carnegie-Chicago Hubble Program: independent measurement
- 18 supernovae, only 9 in common with SH0ES
- Uses TRGB instead of Cepheids to calibrate

Will more data help?

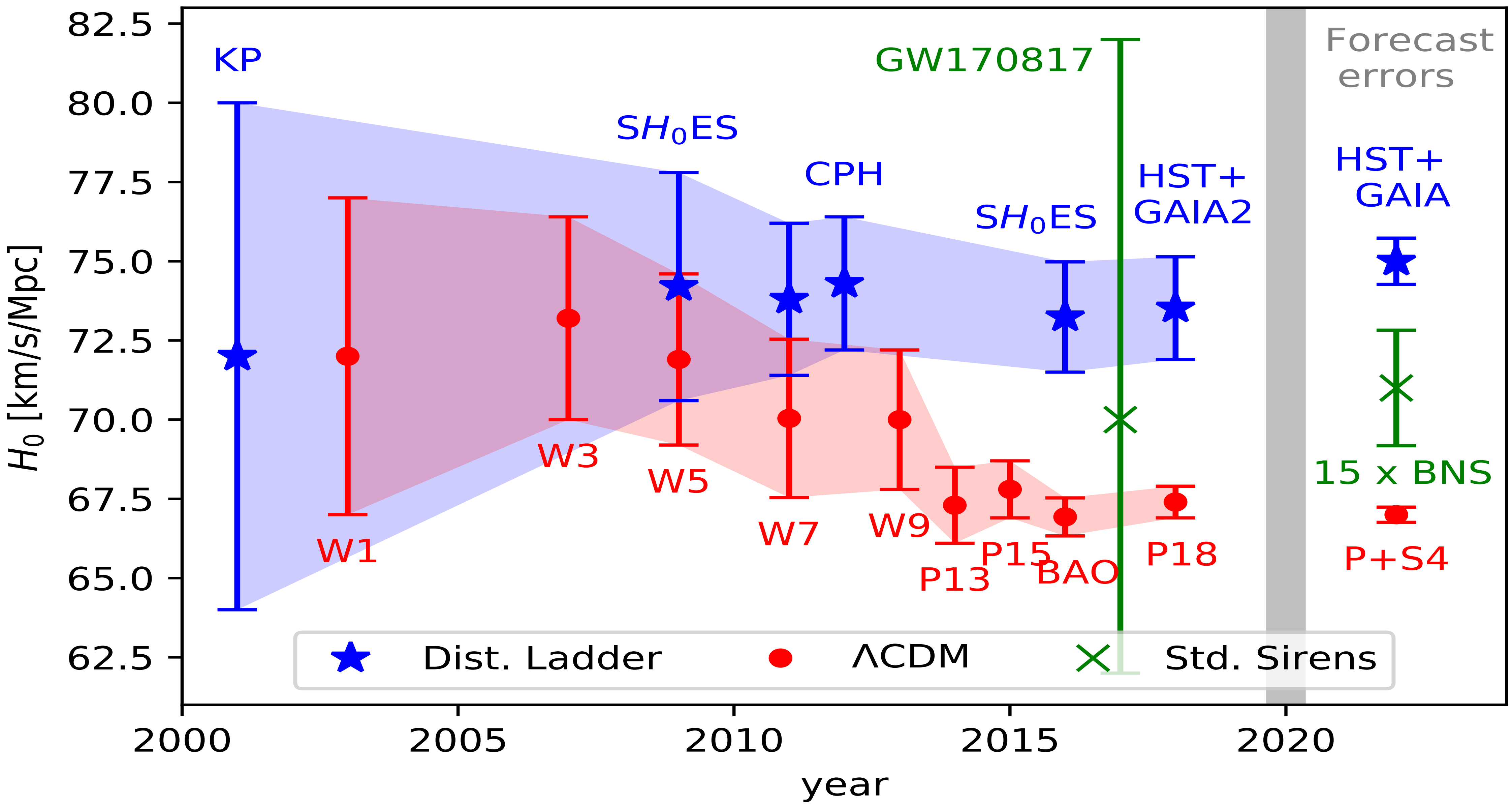
- Carnegie-Chicago Hubble Program: independent measurement
- 18 supernovae, only 9 in common with SH0ES
- Uses TRGB instead of Cepheids to calibrate



Freedman et al. 1907.05922

Will more data help?

Ezquiaga et al. 1807.09241



Gravitational waves will provide a completely independent measurement. Future cosmological missions will reach greater precision.

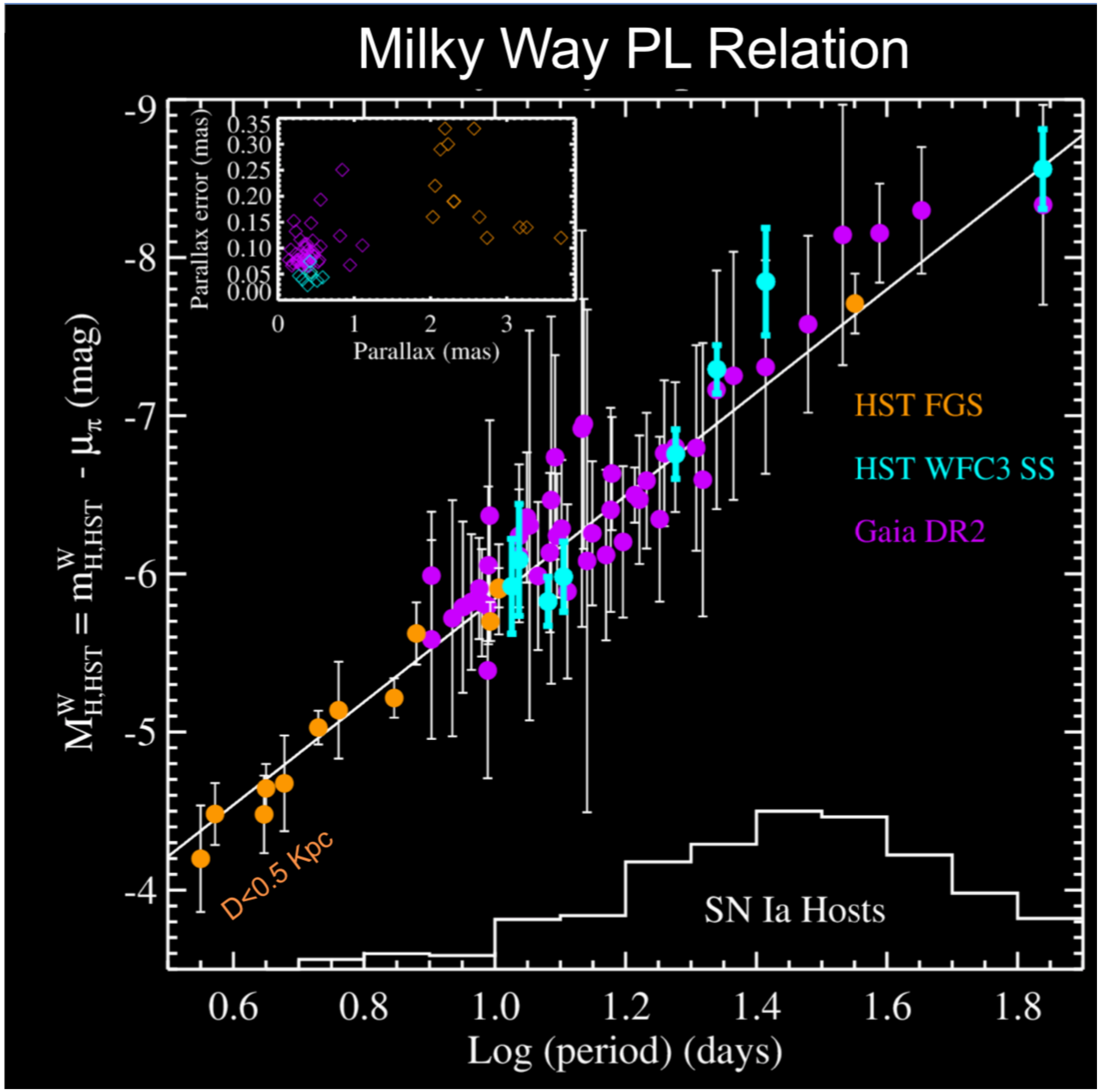
Summary

- Increasingly precise measurements are uncovering cracks in ΛCDM
- Tension between early and late time measurements now at 4.5σ
- No clear evidence for systematics in any measurement
- Multiple probes supporting different H_0 values
- We are yet to identify a well-motivated model compatible with all data
- Model building is challenging, but we have a lot of hints
- The next decade will make or brake our standard cosmological model

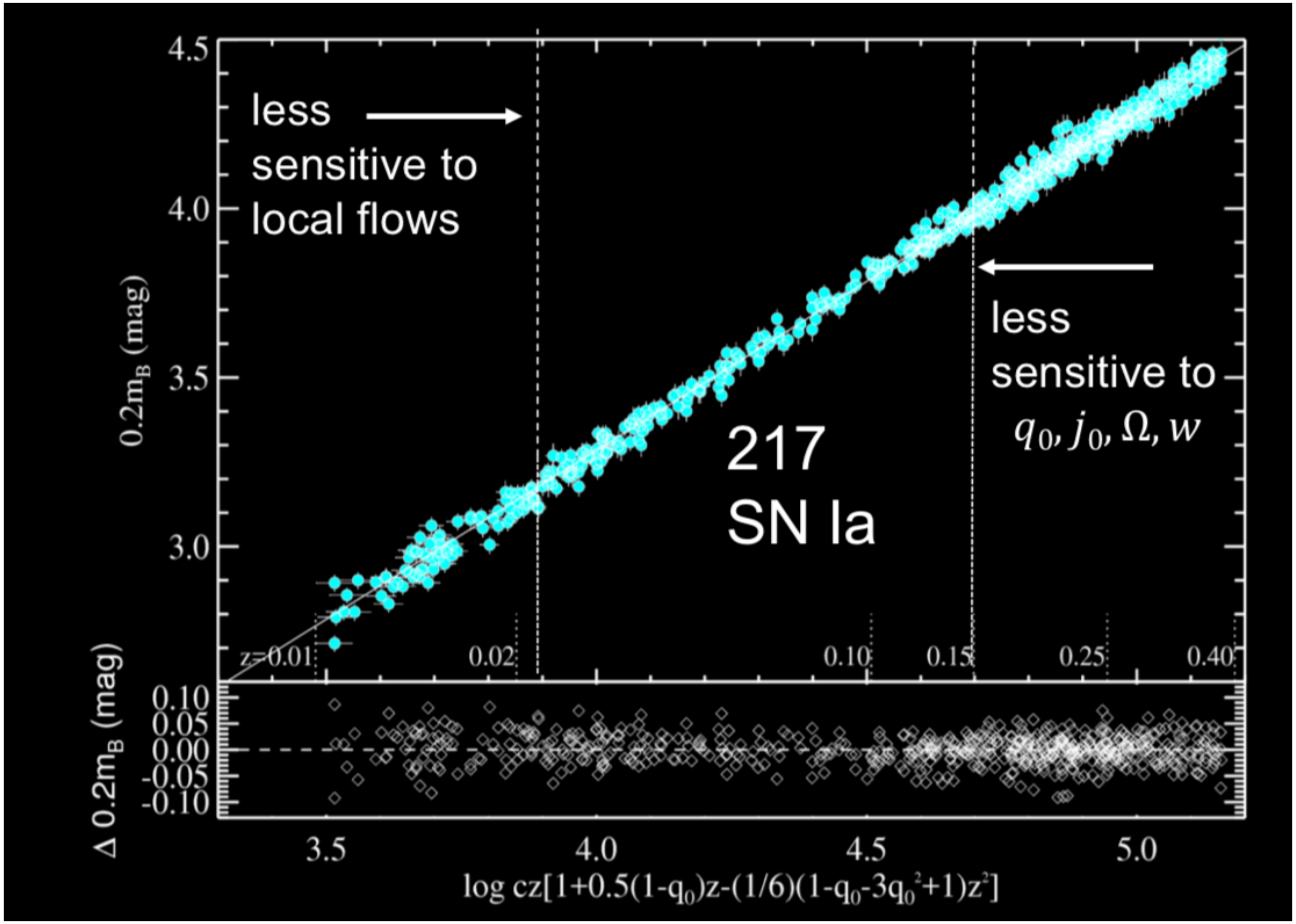
Thank you for your attention

Want to know more? Videos of all the talks at last week's five day ESO H_0 conference available here: http://www.eso.org/sci/meetings/2020/H0/program.html

Cepheid P-L relation



Hubble Flow



less sensitive to local flows
less sensitive to q_0, j_0, Ω, w
217 SN Ia
4.5
4.0
3.5
3.0
0.2m_B (mag)
z=0.01
0.02
0.10
0.15
0.25
0.40
0.10
0.05
0.00
-0.05
-0.10
Δ 0.2m_B (mag)
3.5
4.0
4.5
5.0
log cz[1+0.5(1-q_0)z-(1/6)(1-q_0-3q_0^2+1)z^2]

Systematics in supernovae

Analysis Variants	H_0
Best Fit (R16, w/ HST,Gaia , R18=73.53)	74.03
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.89
Reddening Law: Bulge-like (N15)	74.40
No Cepheid Outlier Rejection (normally 2%)	74.32
No Correction for Cepheid Extinction	75.72
No Truncation for Incomplete Period Range	75.08
Metallicity Gradient: None (normally fit)	74.51
Period-Luminosity: Single Slope	74.34
Period-Luminosity: Restrict to P>10 days	74.24
Period-Luminosity: Restrict to P<60 days	74.60
Supernovae z>0.01 (normally z>0.023)	74.16
Supernova Fitter: MLCS (normally SALT)	75.91

Independent Cepheid Tests

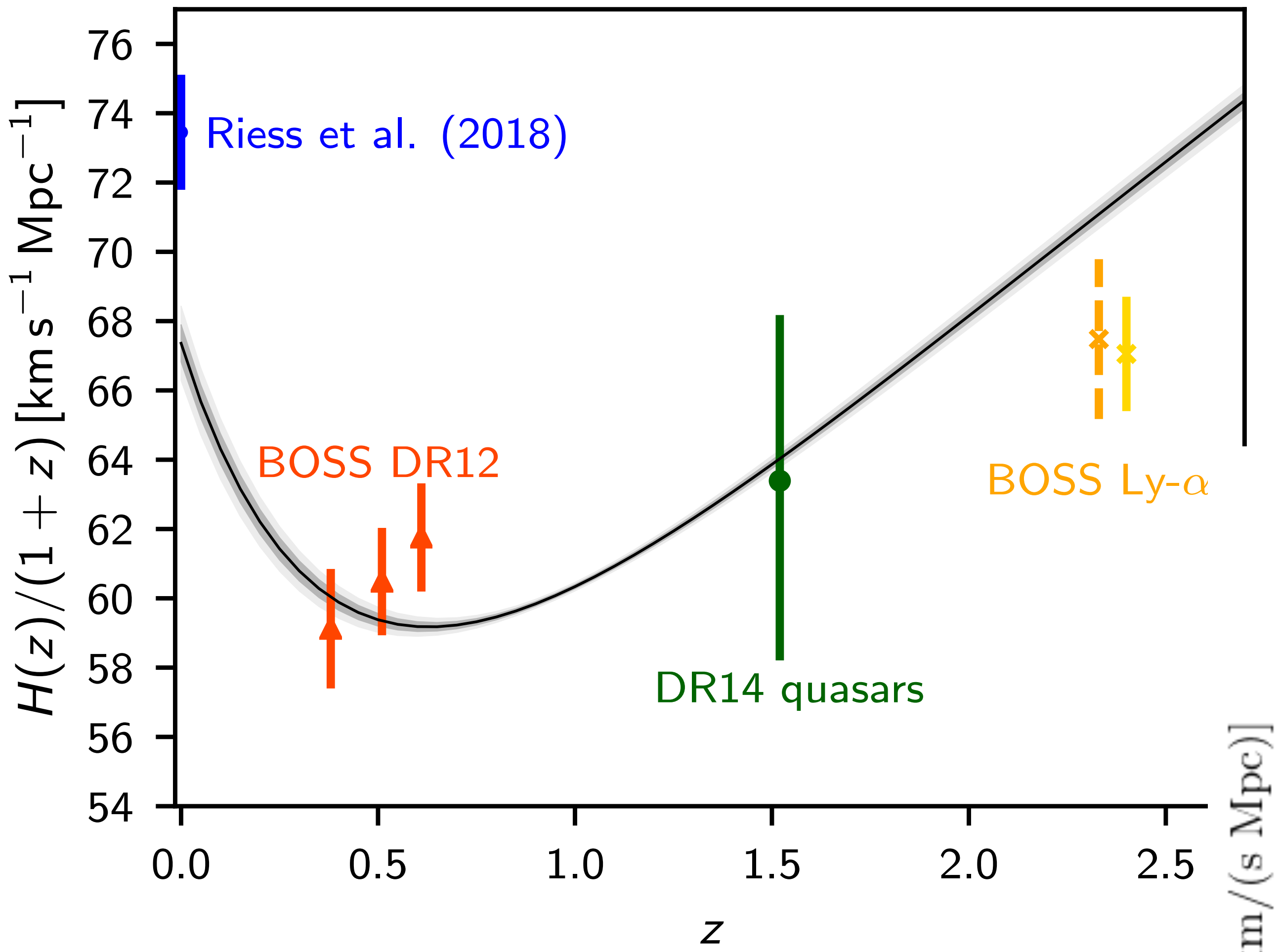
Summary of Follin and Knox 1707.01175

What they tried: loosened up assumptions about Cepheid modelling:

- let dust spectral dependence be uncertain
- let it vary from host galaxy to host galaxy
- introduced a large amount of freedom in Cepheid period-magnitude relation

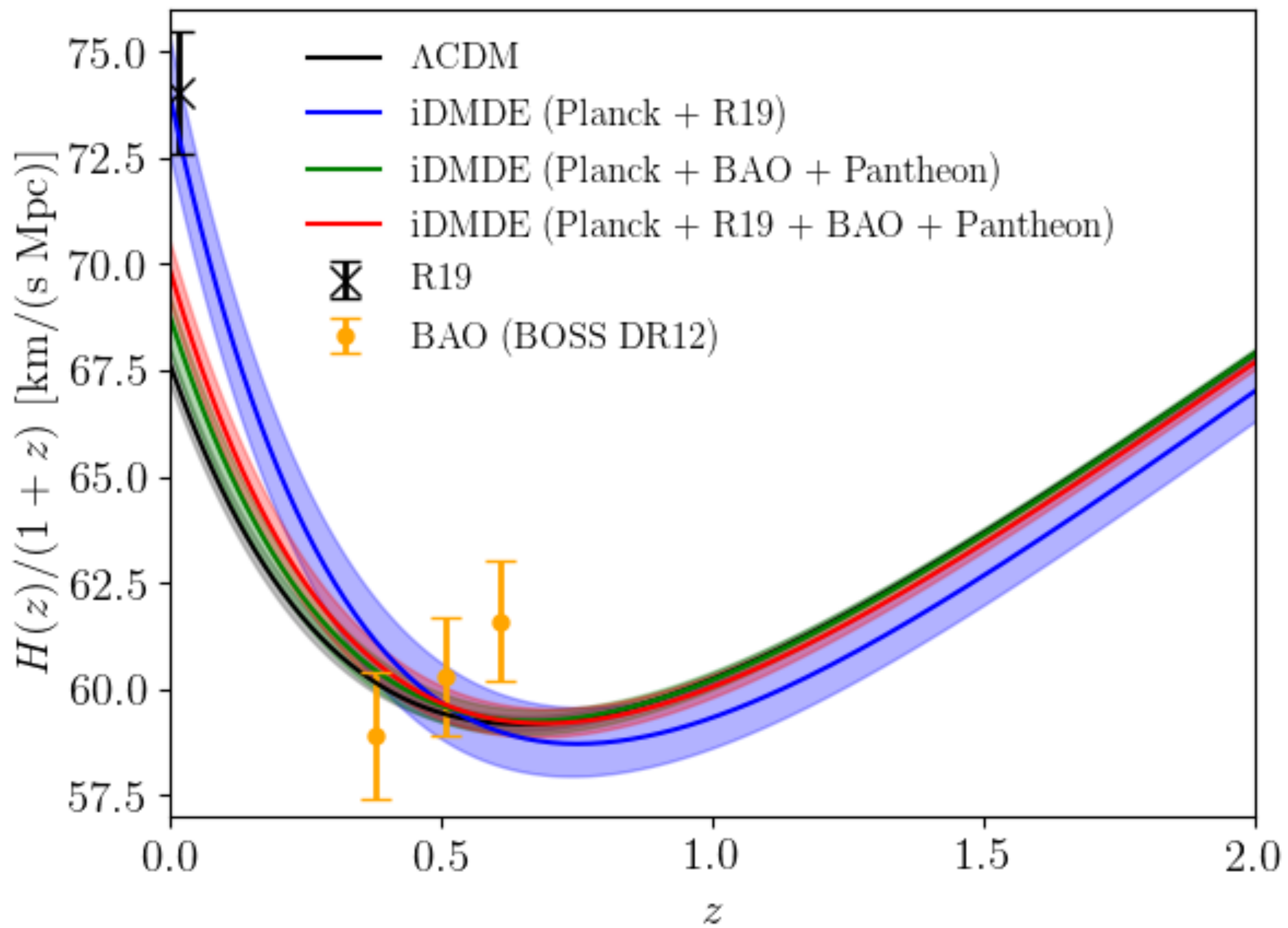
Conclusion: doing the above had very little impact on H_0 central value, and only slightly increased the uncertainty

H(z)

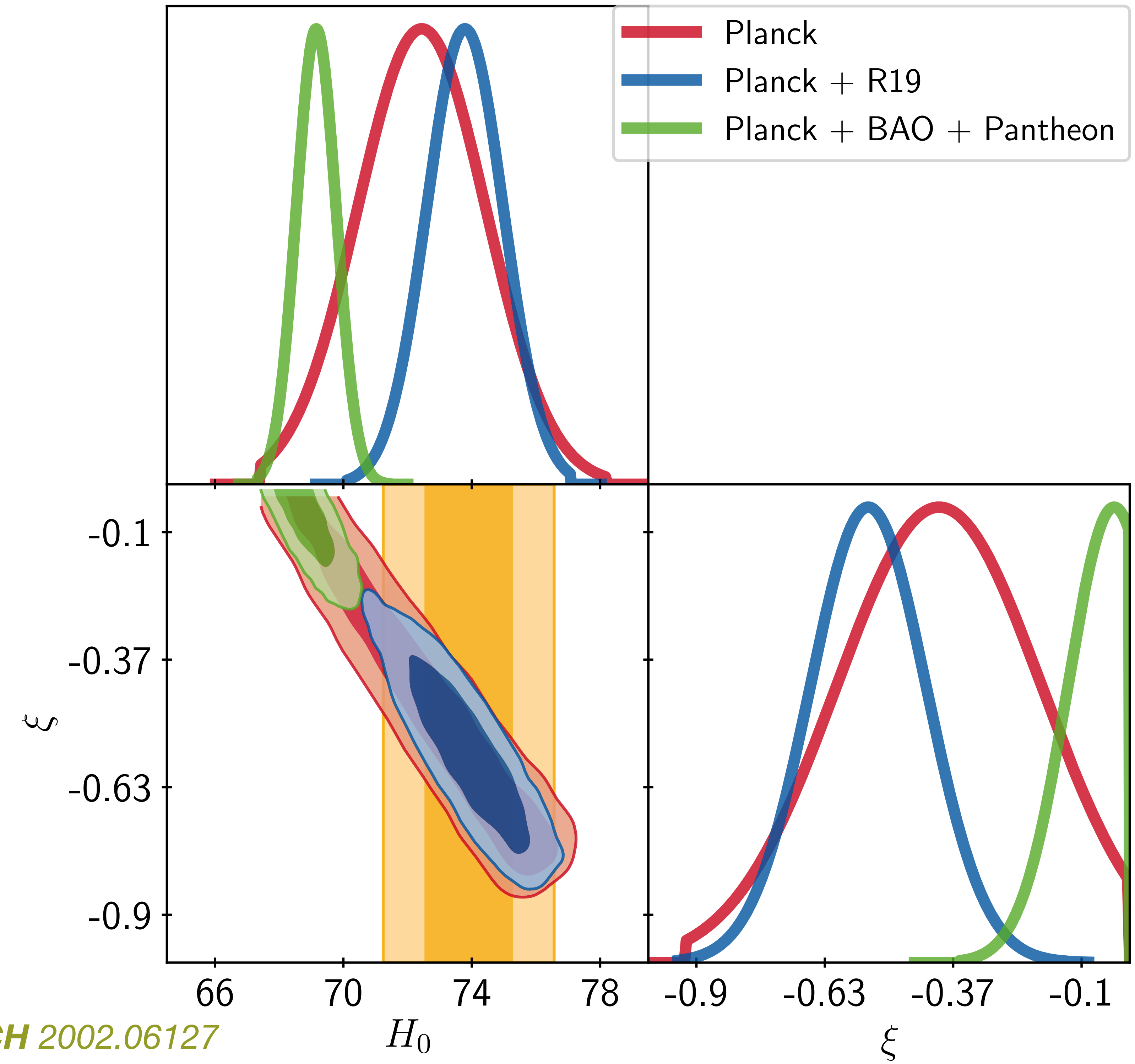


Aghanim et al. 1807.06209

*Lucca and **DCH** 2002.06127*

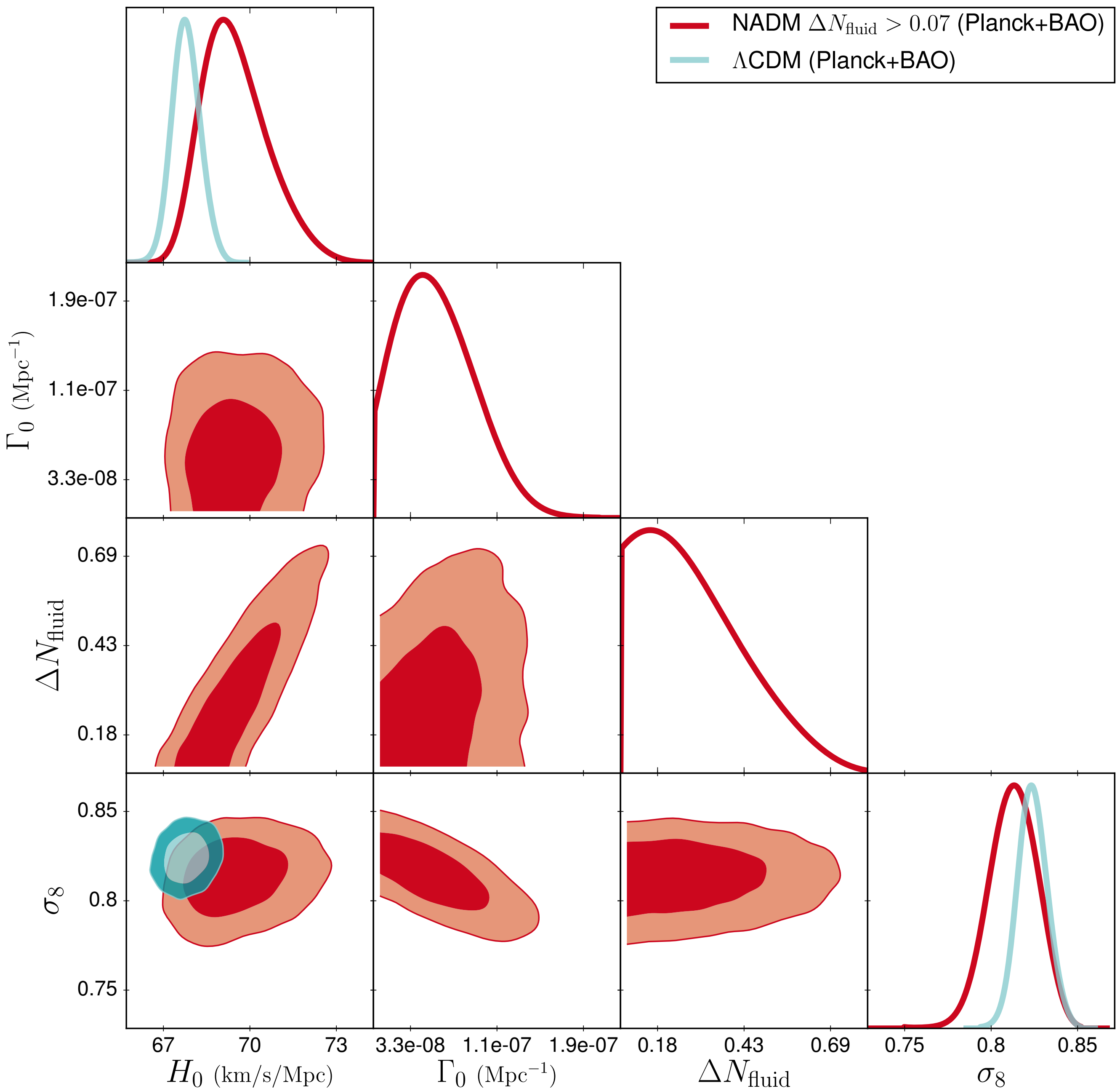


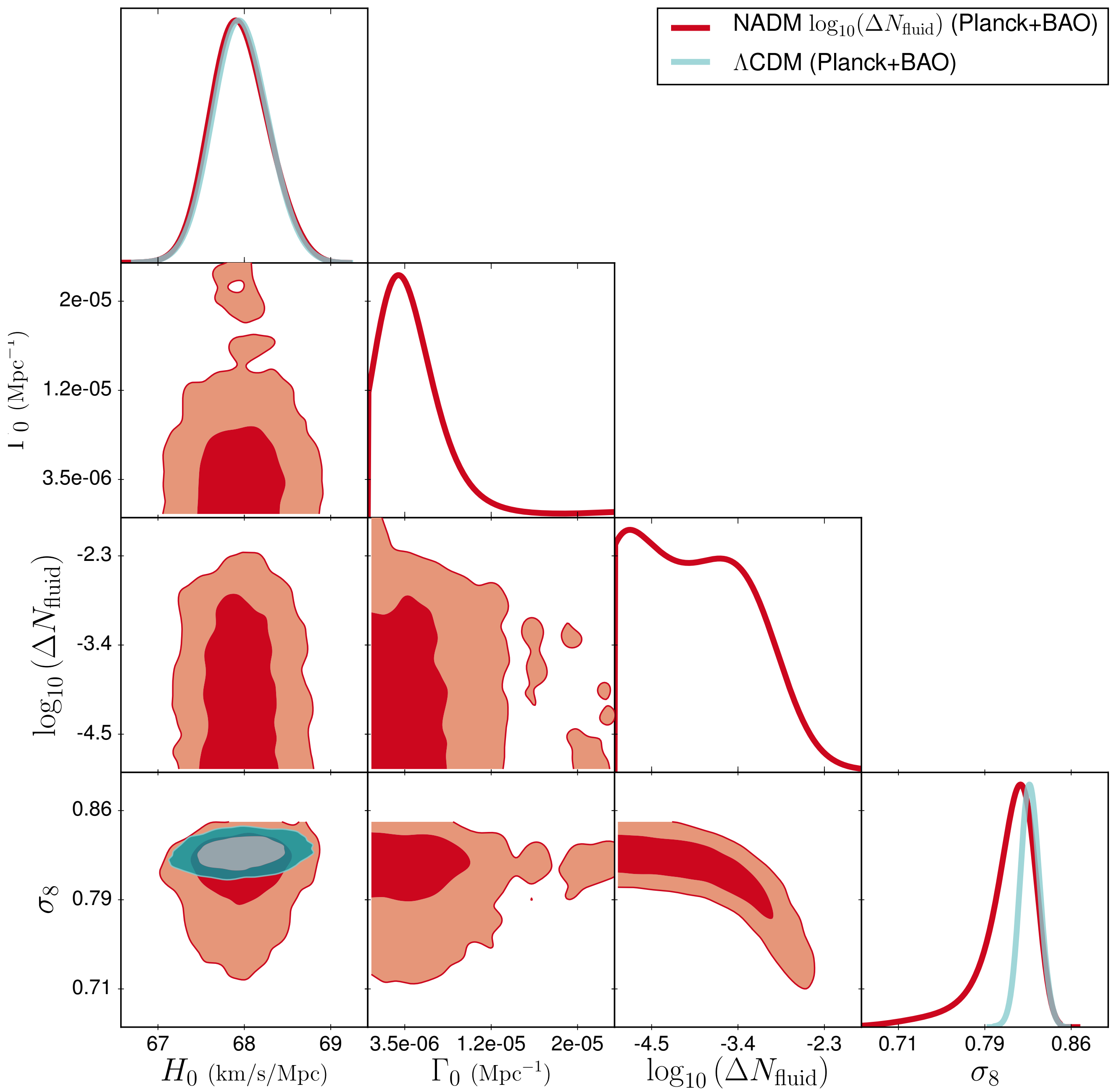
iDMDE



*Lucca and **DCH** 2002.06127*

NADM





*Archidiacono et al. (**DCH**) 1907.01496*