The Hubble Hunter’s Guide

Cosmic Acceleration 2020 – Kavli IPMU - Japan

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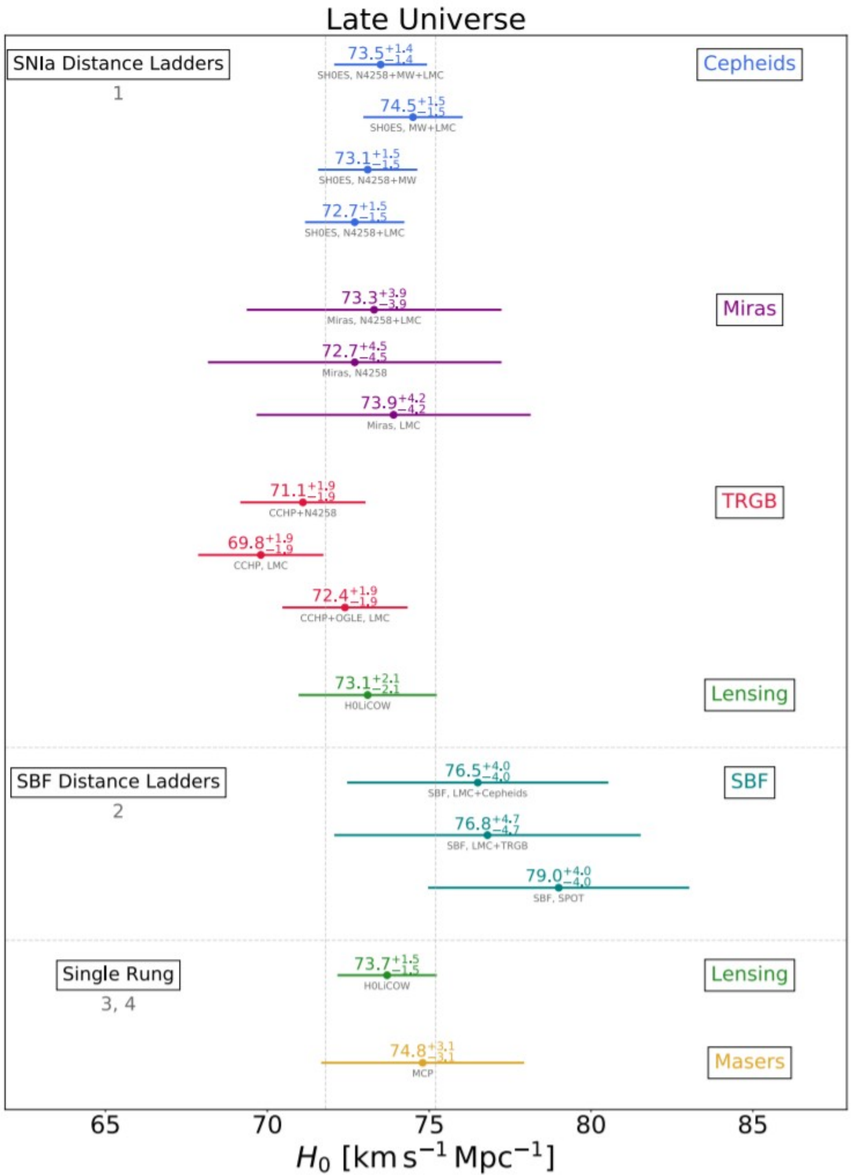
Outline

- How to constrain H_0 from CMB observations
- What Planck told us about H_0
- **A guide for observers and theorists:** How do we resolve the tension cosmologically?

Riess 2019



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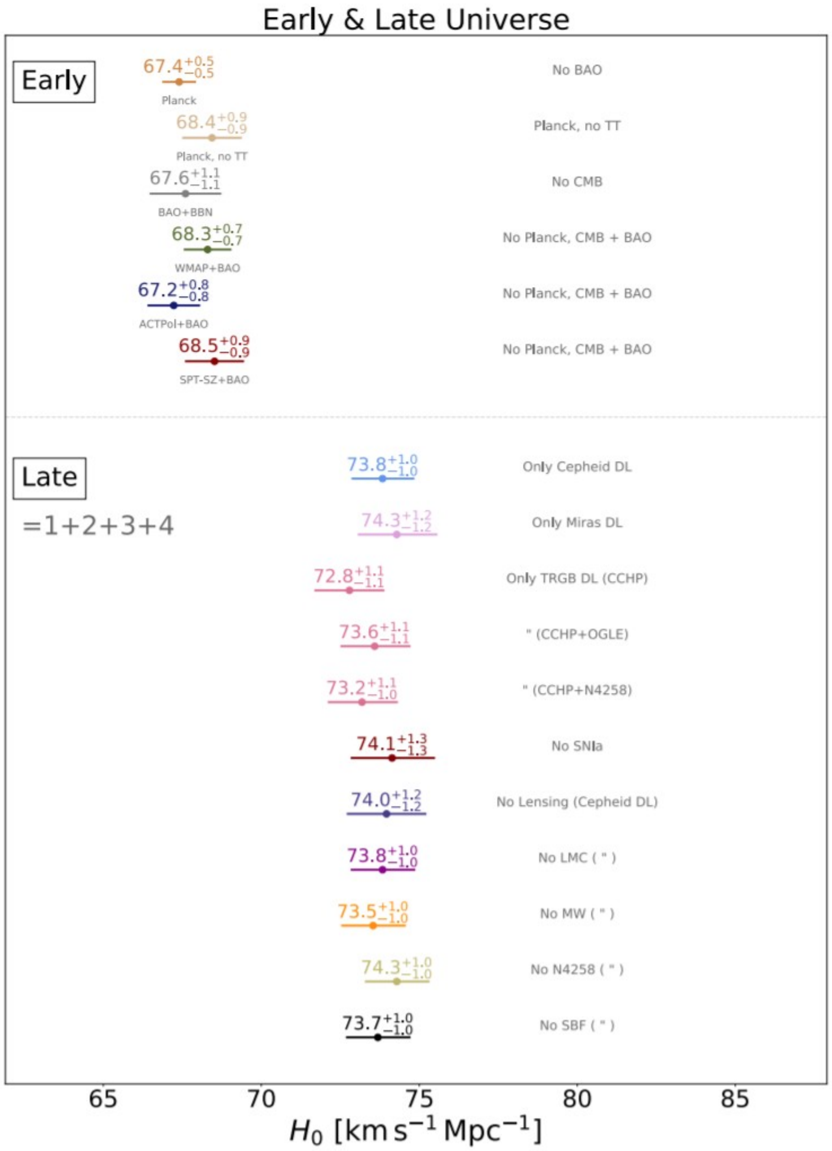
Riess 2019



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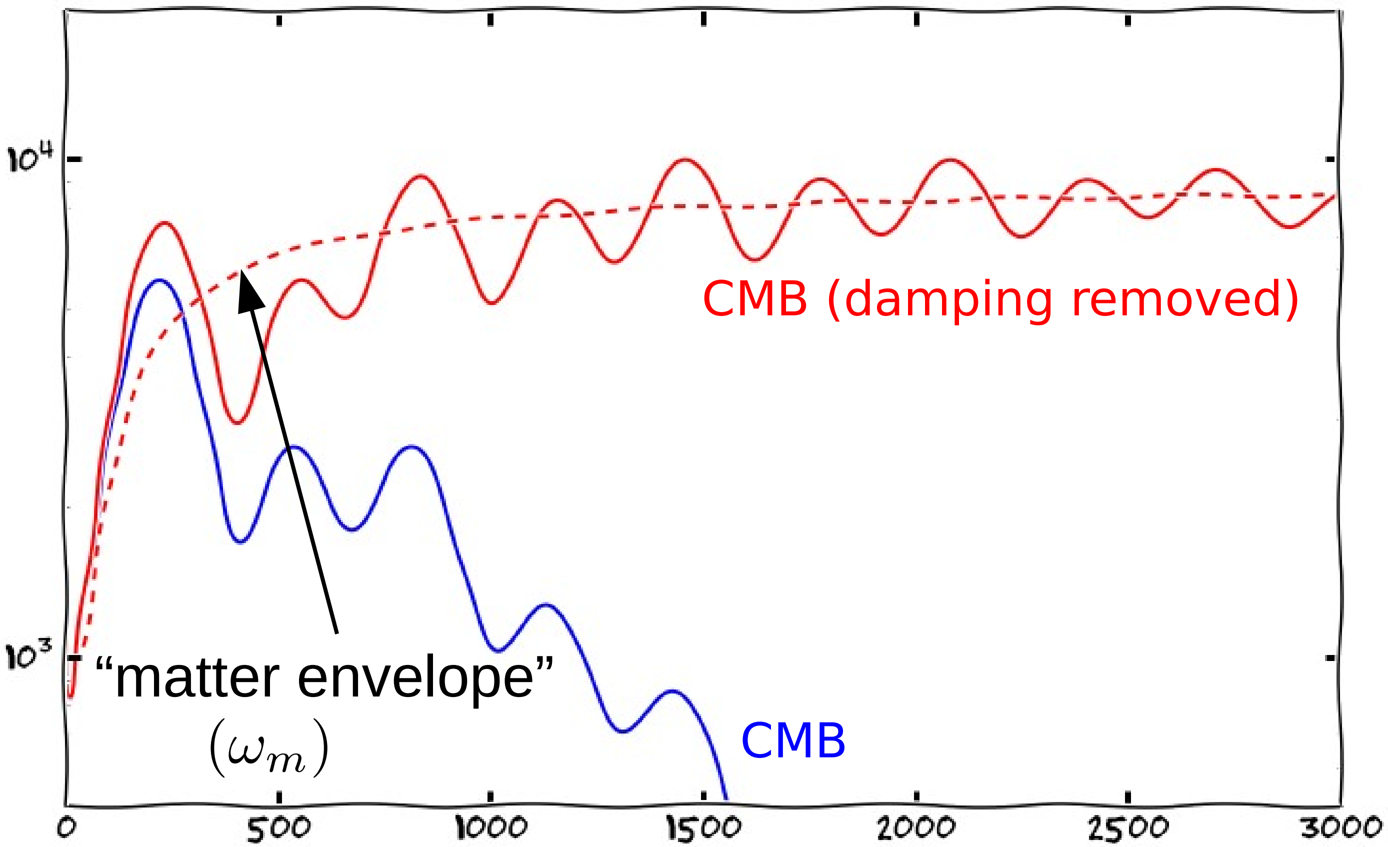
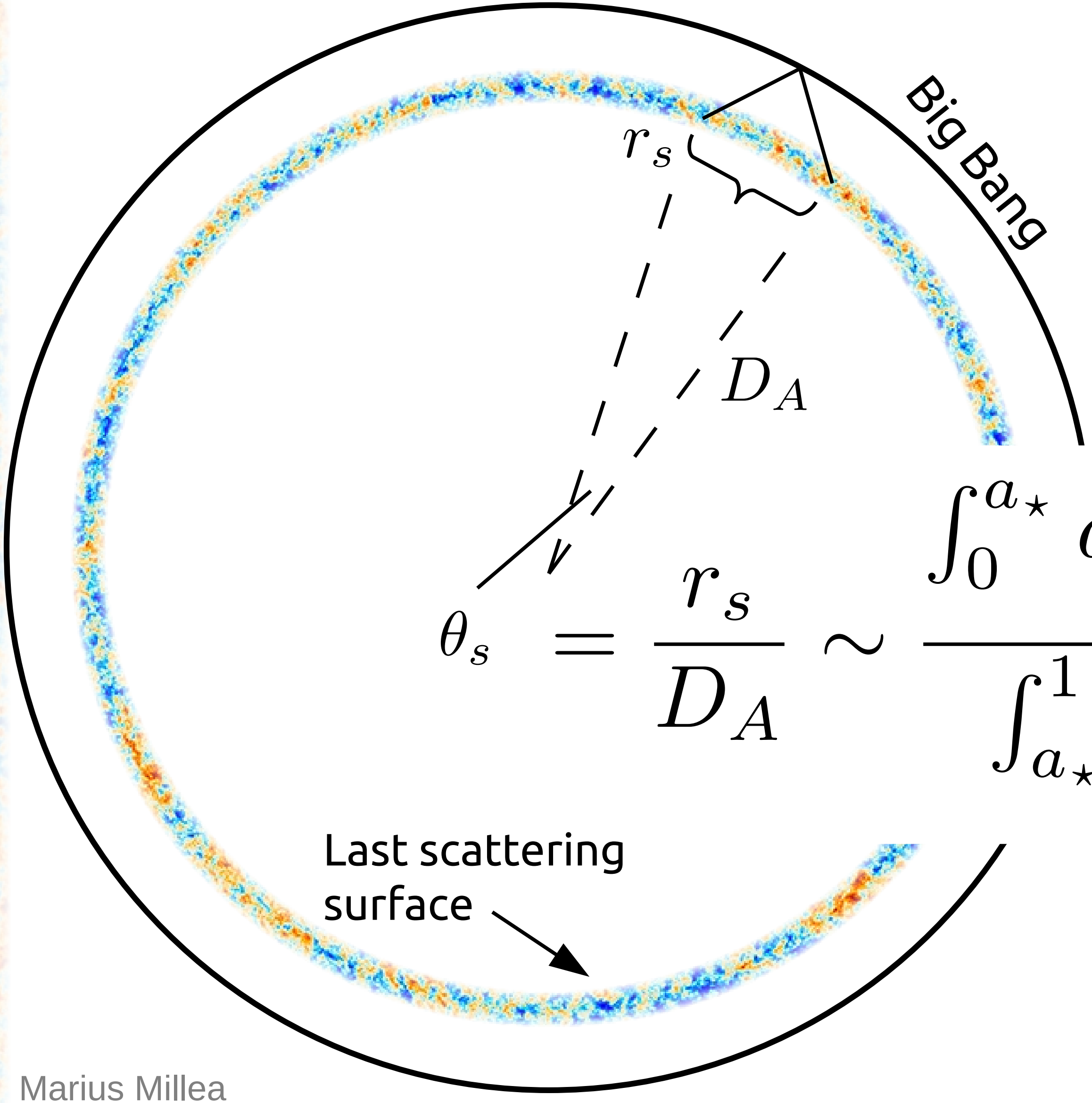
How to constrain H_0 from the CMB assuming ΛCDM?

Friedmann equation: $$H_0^2 \sim \omega_m + \omega_\Lambda$$

$$\omega_x = \Omega_x h^2 = \frac{\rho_x}{1.88 \cdot 10^{-26}\,\mathrm{kg/m^3}}$$

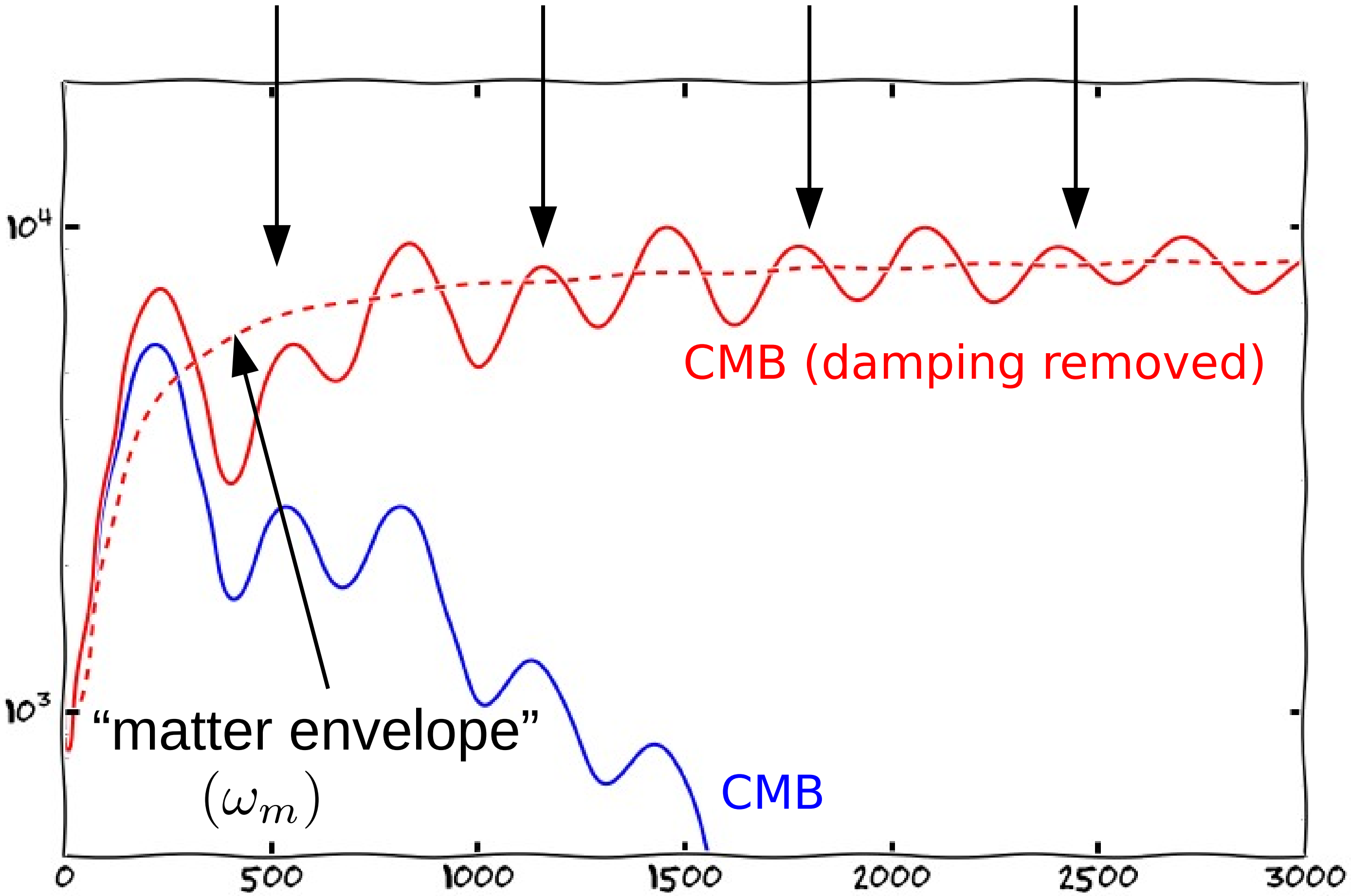


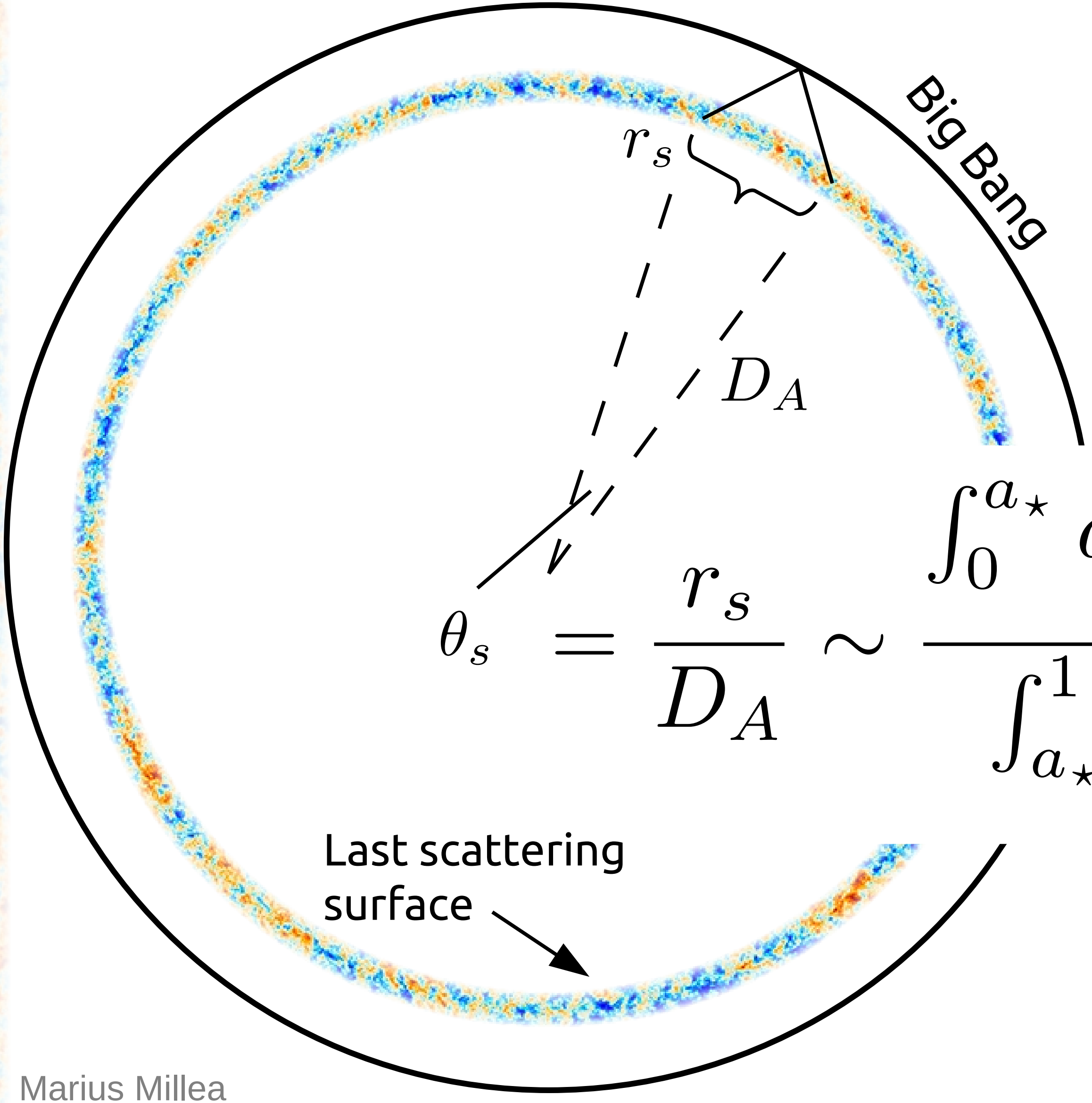
CMB (damping removed)
CMB
“matter envelope”
(ω_m)
10^4
10^3
0
500
1000
1500
2000
2500
3000



$$\theta_s = \frac{r_s}{D_A} \sim \frac{\int_0^{a_\star} da \frac{c_s(a;\omega_b)}{\sqrt{\omega_m a^{-3} + \omega_r a^{-4}}}}{\int_{a_\star}^{1} da \frac{1}{\sqrt{\omega_m a^{-3} + \omega_\Lambda}}}$$

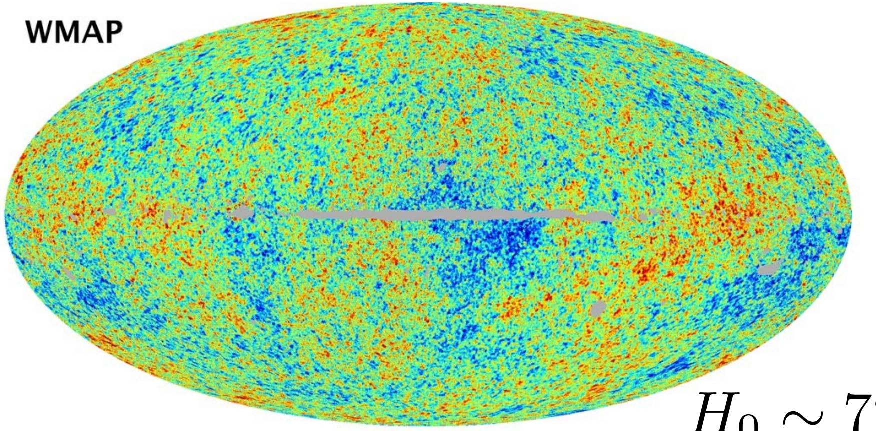
Even / odd peak height modulation (ω_b)



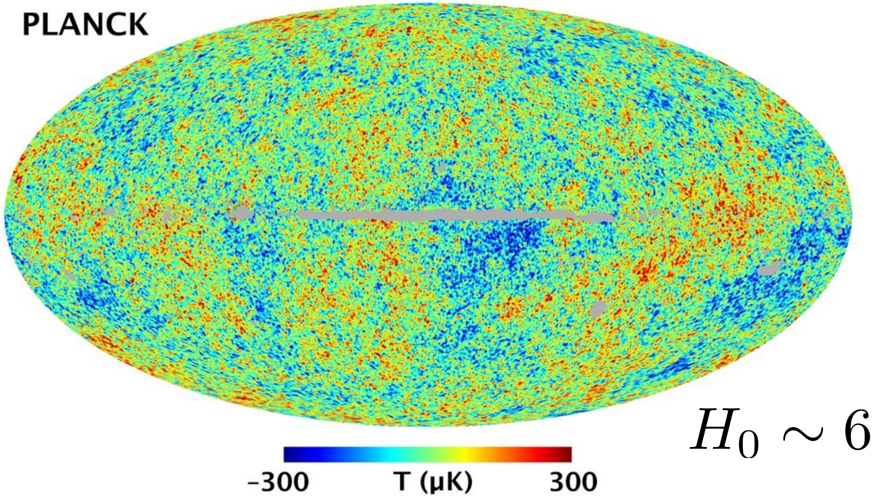


$$\theta_s = \frac{r_s}{D_A} \sim \frac{\int_0^{a_\star} da \, \frac{c_s(a;\omega_b)}{\sqrt{\omega_m a^{-3} + \omega_r a^{-4}}}}{\int_{a_\star}^{1} da \, \frac{1}{\sqrt{\omega_m a^{-3} + \omega_\Lambda}}}$$

Circa 2014, ΛCDM was looking great...

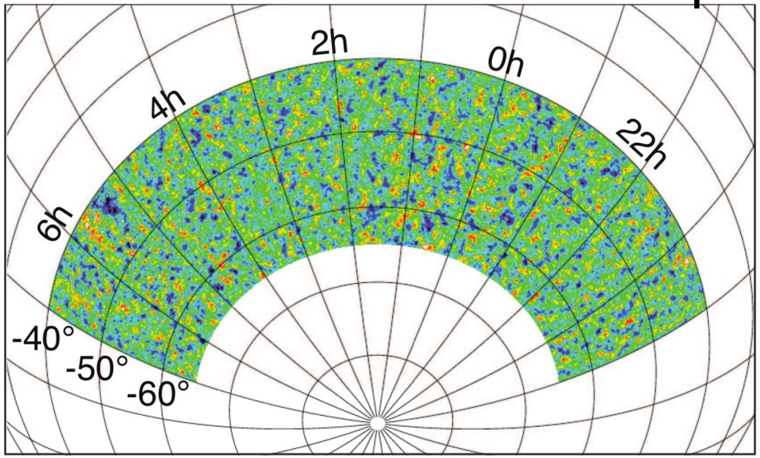


$H_0 \sim 72$

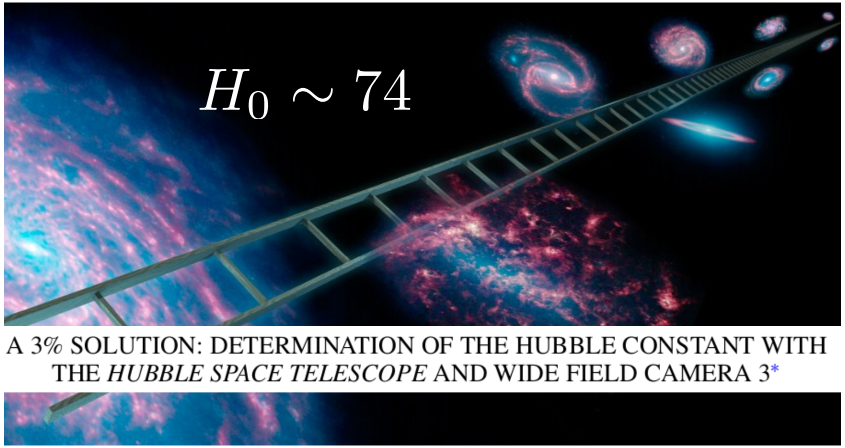


$H_0 \sim 67$

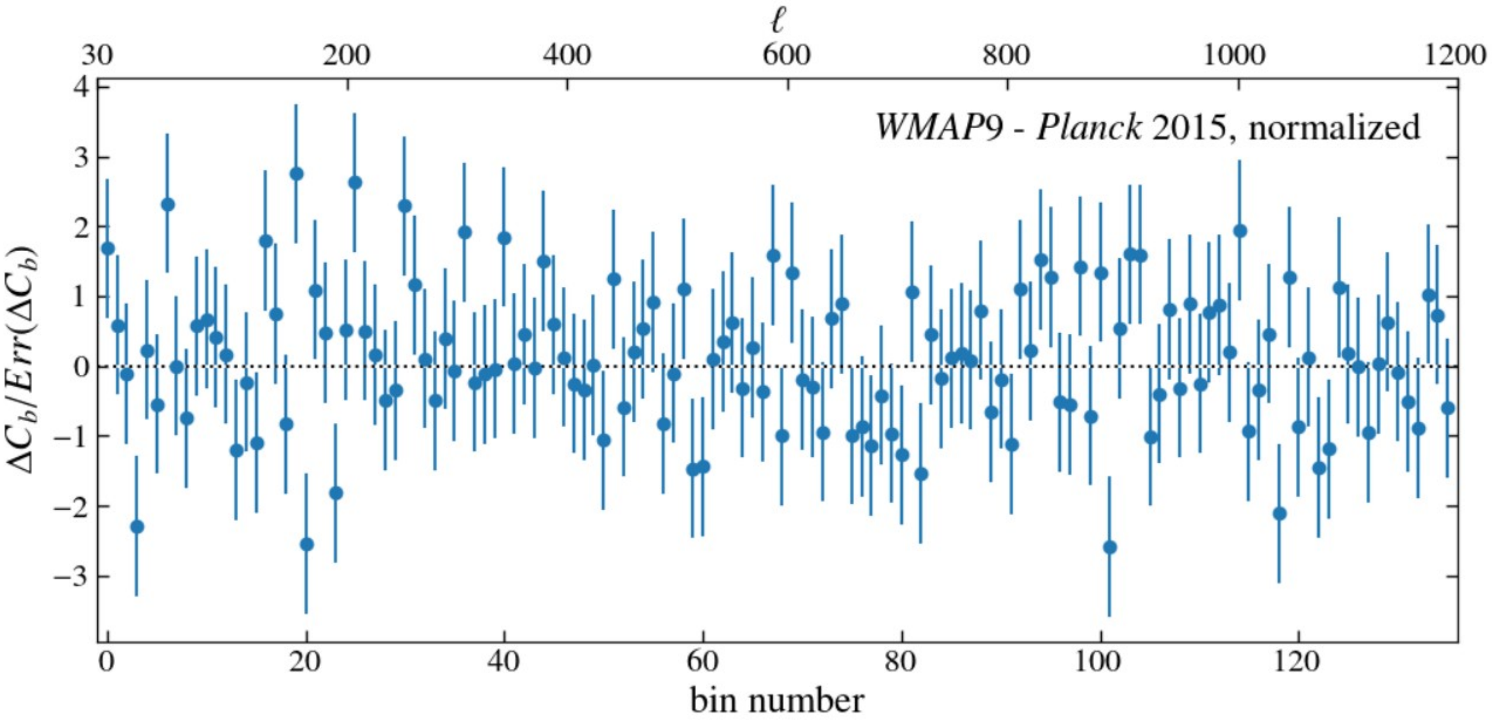
+South Pole Telescope



$H_0 \sim 74$



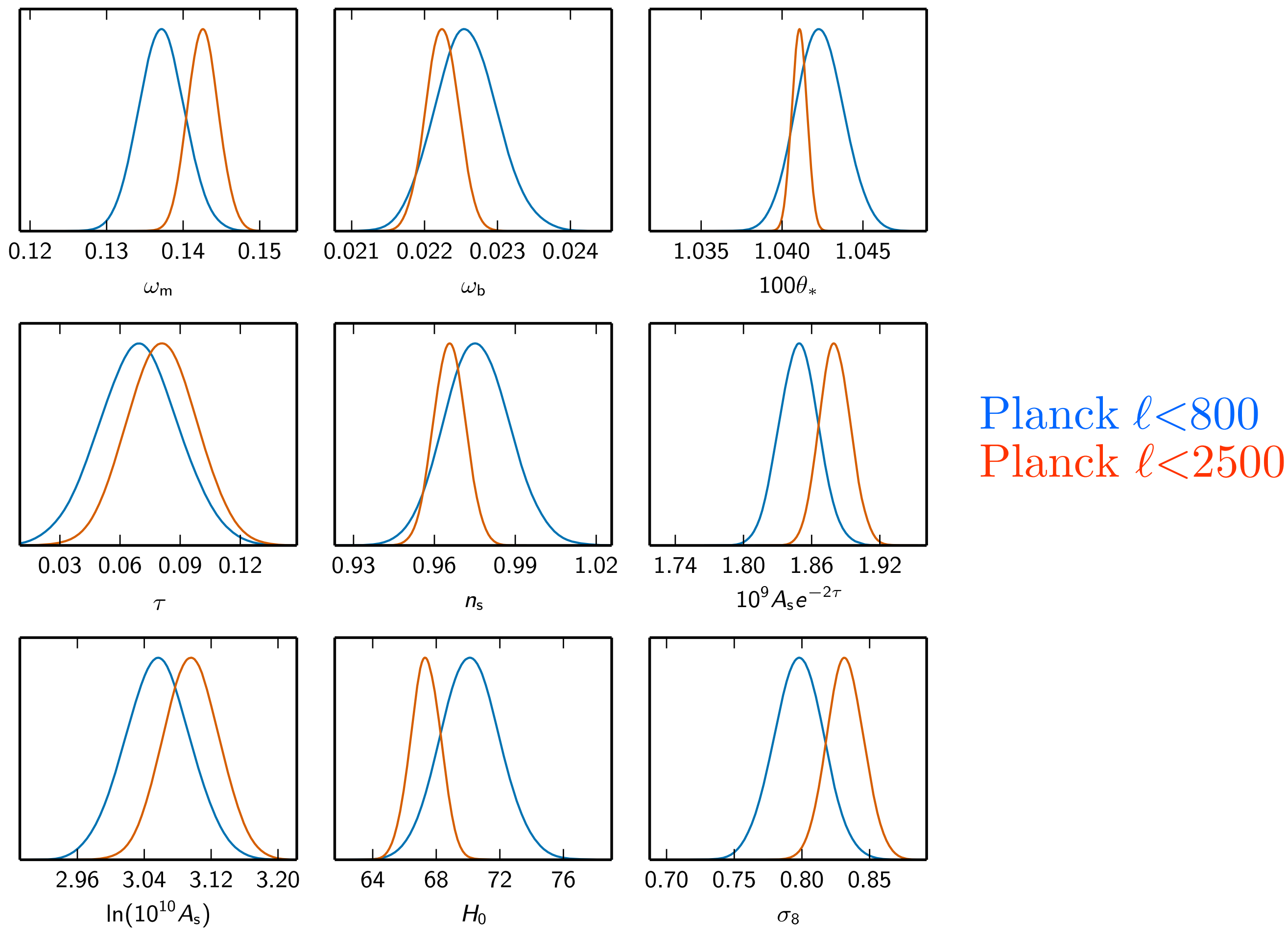
Great agreement between WMAP and Planck
on the scales which WMAP measured well.



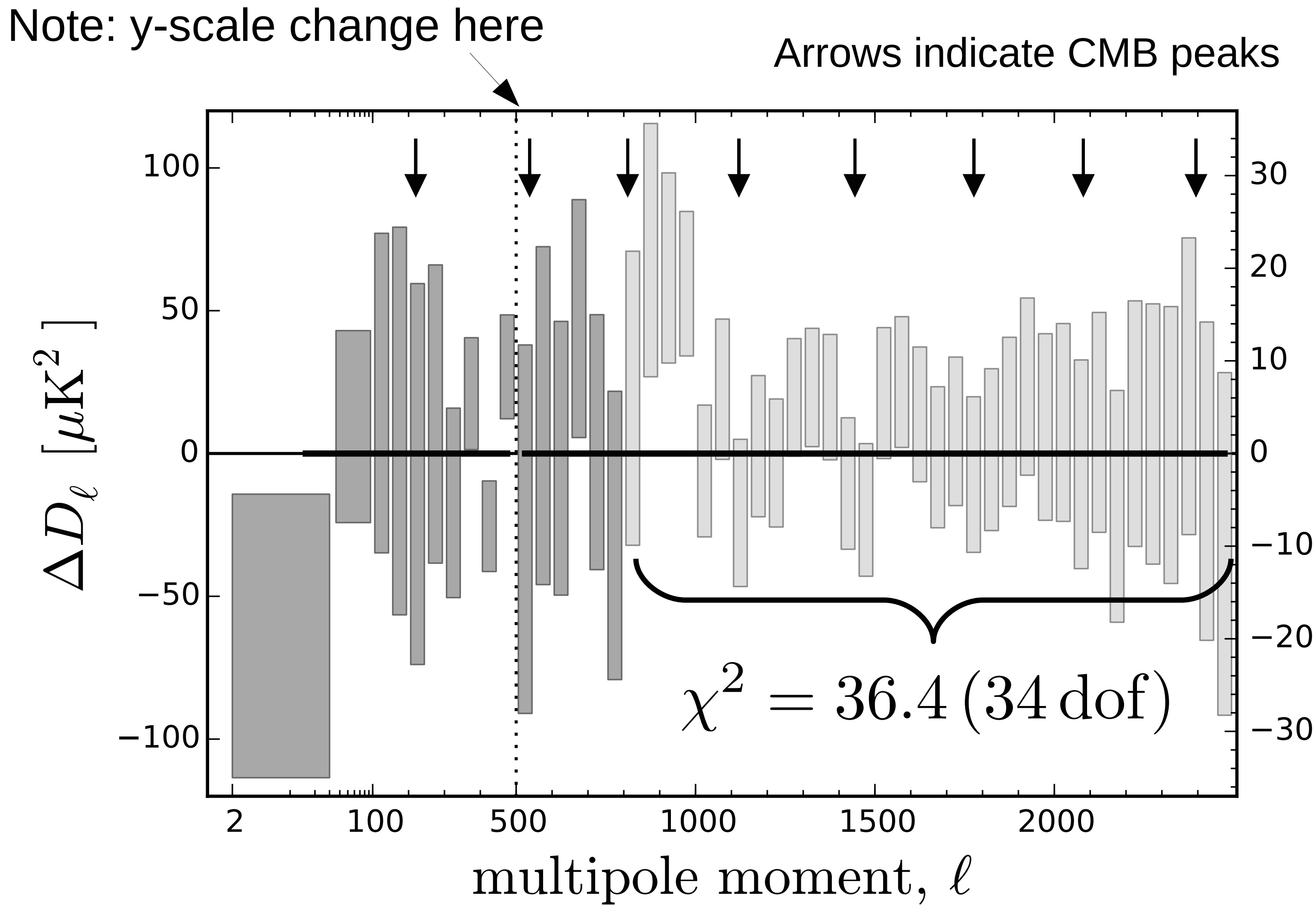
Huang, Addison, Weiland & Bennett (2018)

“Primary” 6
ΛCDM parameters

“Derived”

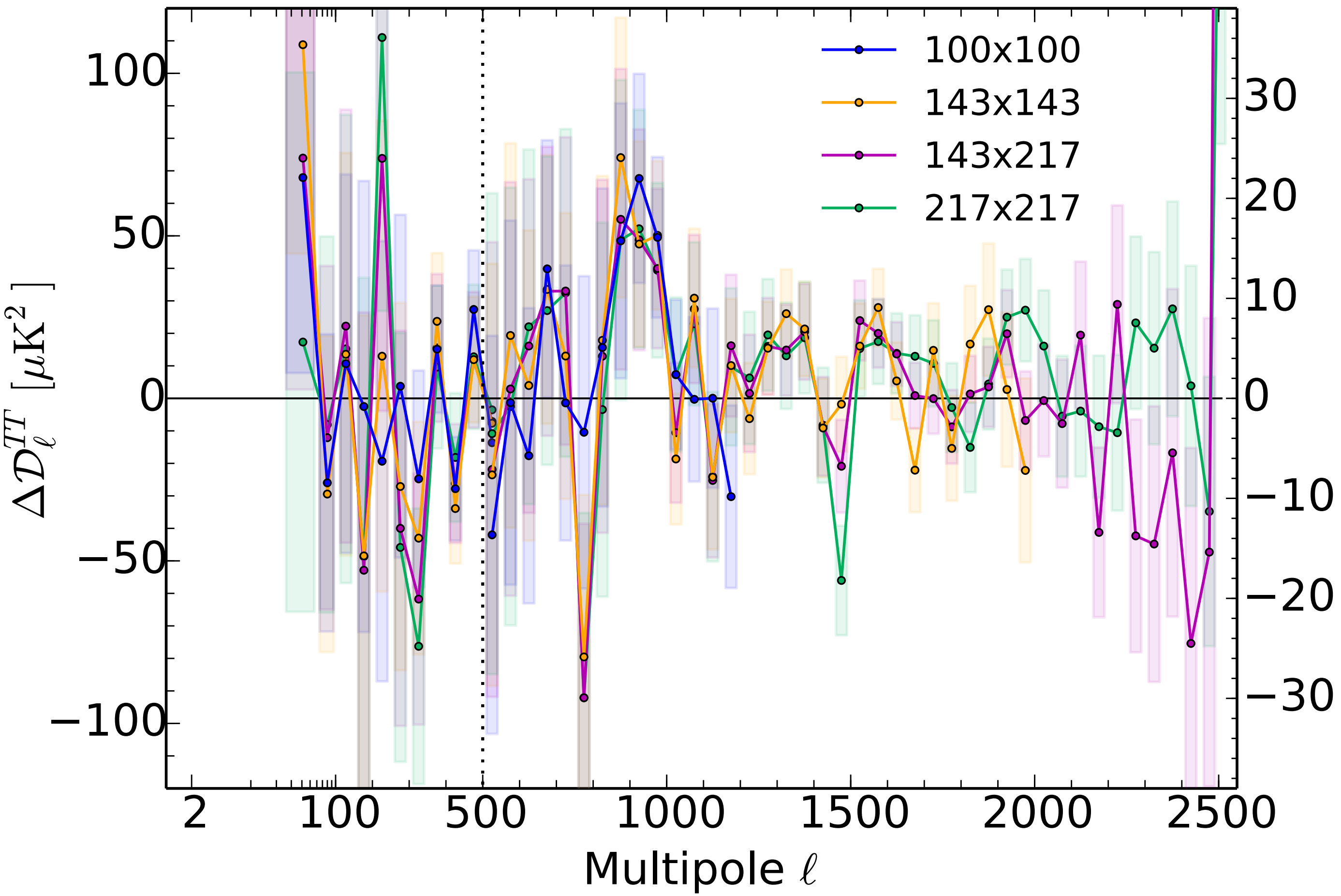


$$H_0 = 70.0 \pm 1.9 \quad \rightarrow \quad H_0 = 67.3 \pm 1.0$$



Note: y-scale change here
Arrows indicate CMB peaks
$\Delta D_\ell\ [\mu\mathrm{K}^2]$
100
50
0
−50
−100
30
20
10
0
−10
−20
−30
$\chi^2 = 36.4\,(34\,\mathrm{dof})$
2
100
500
1000
1500
2000
multipole moment, ℓ

These features present in all Planck frequencies.



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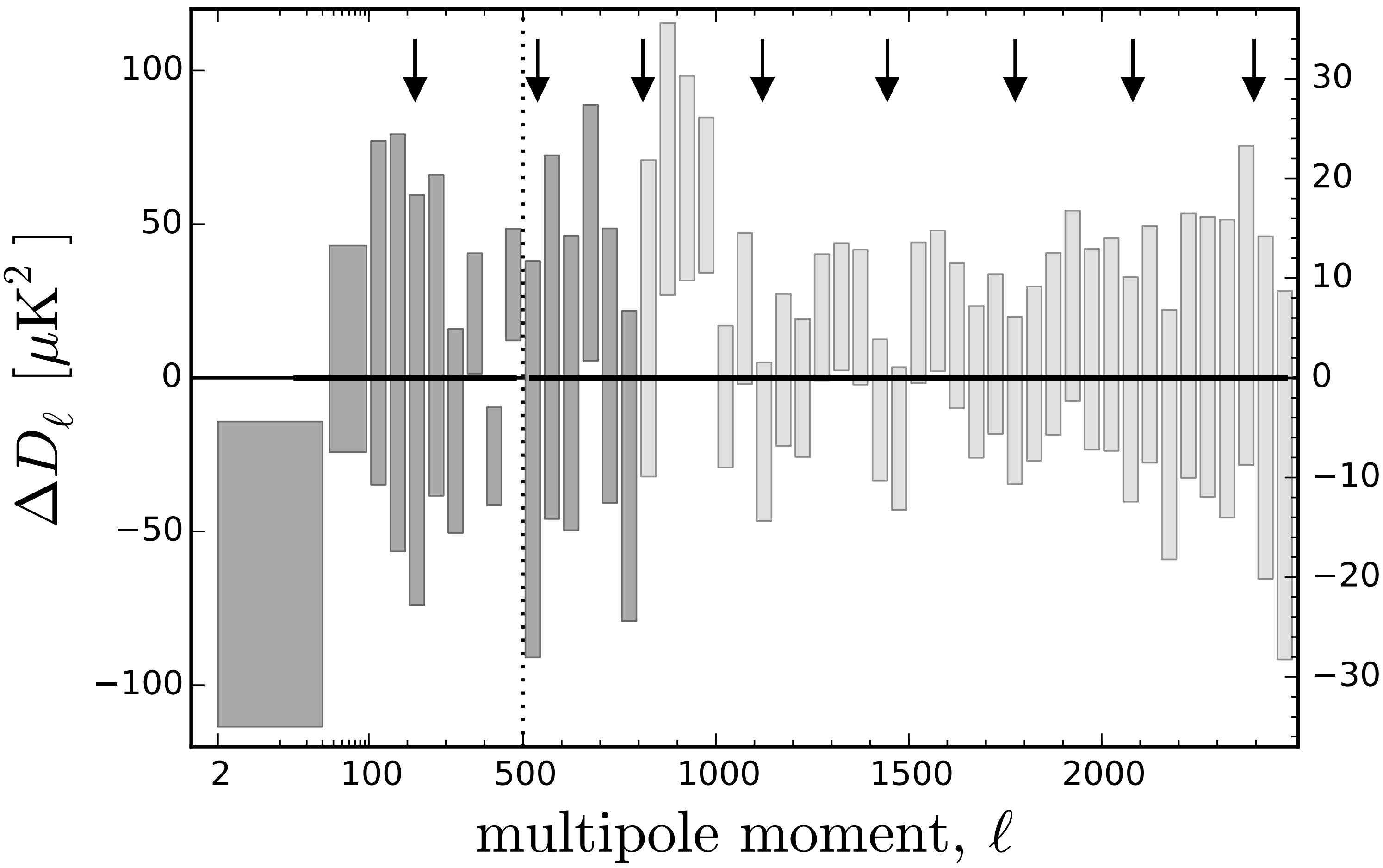
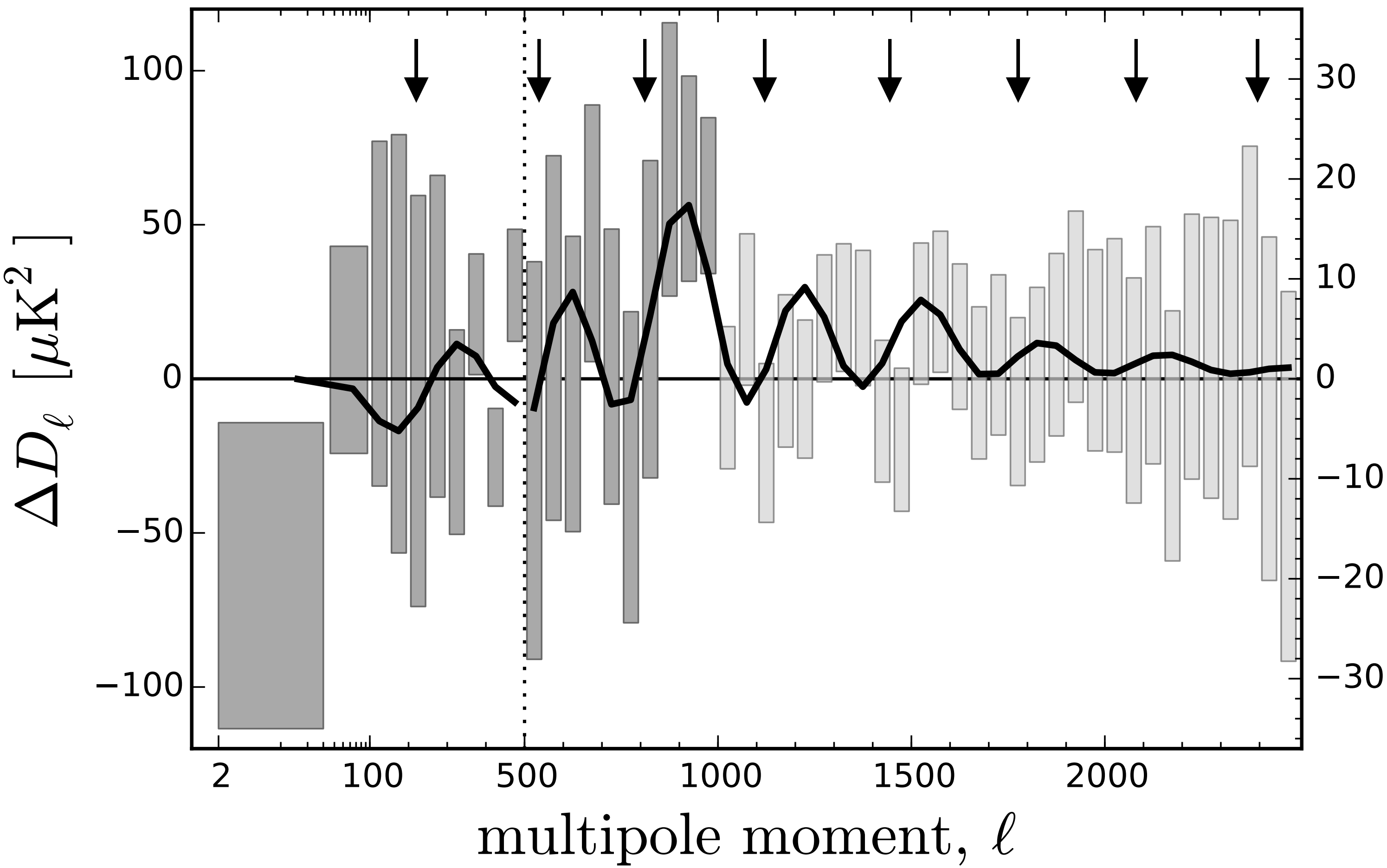
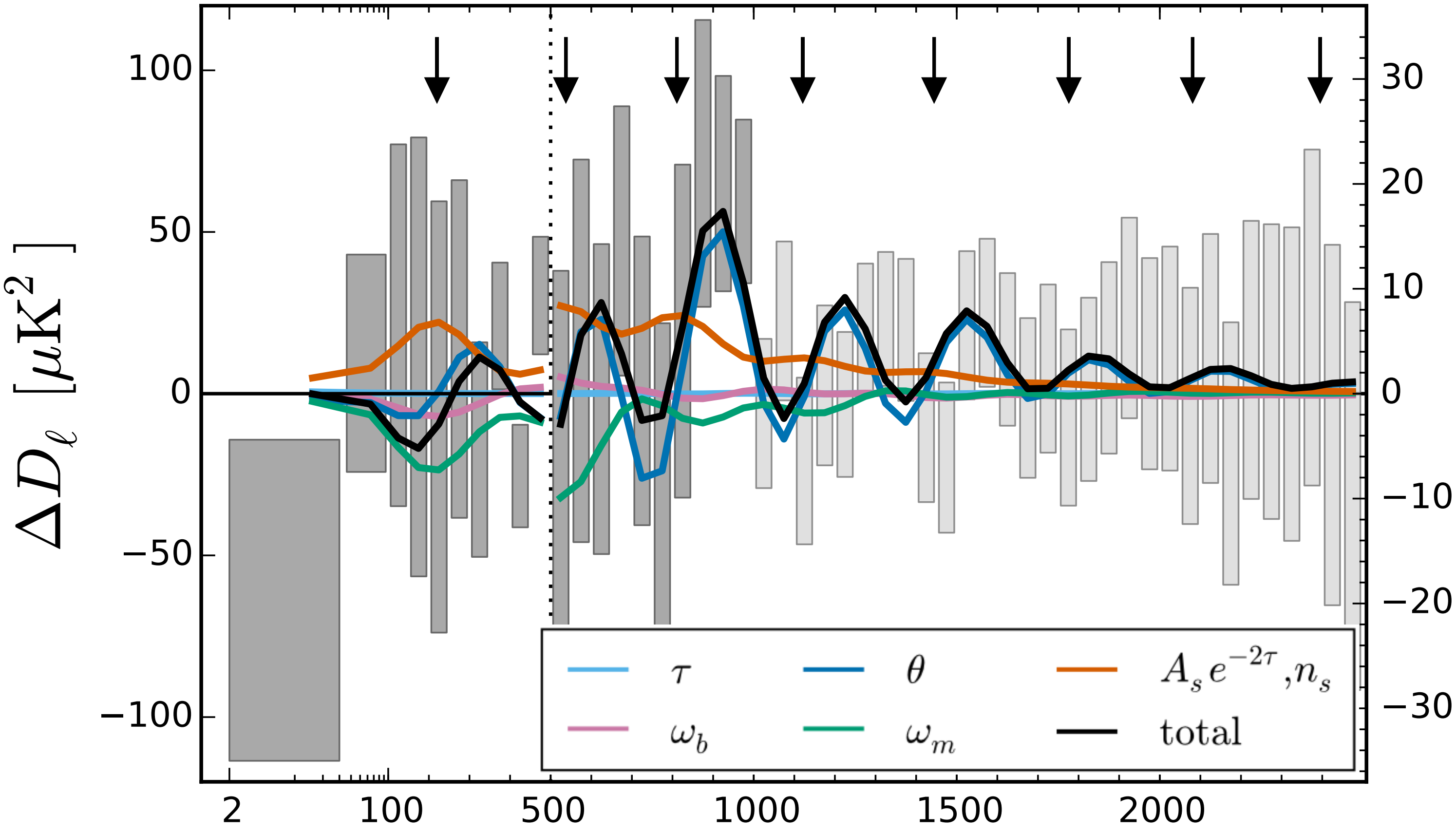


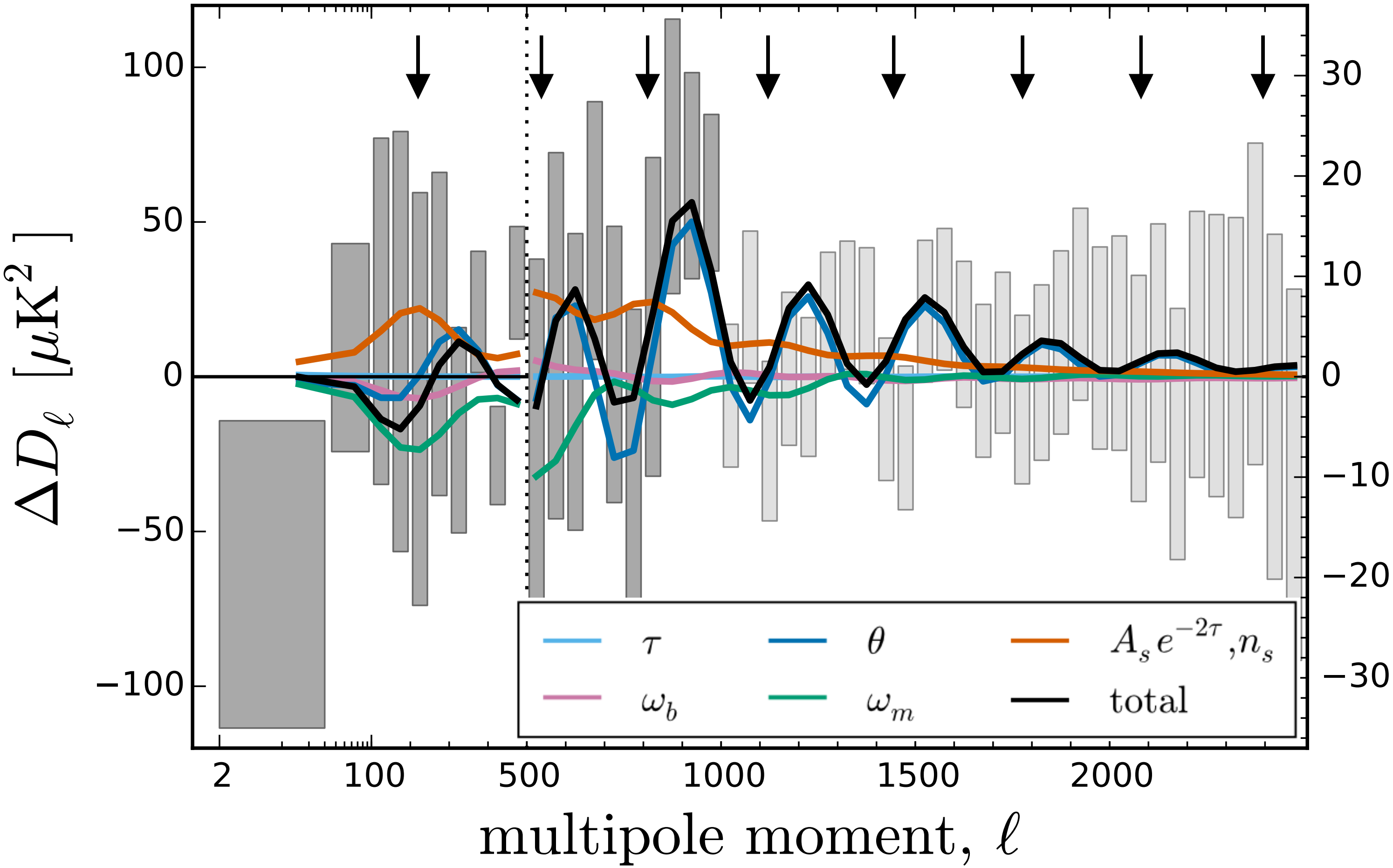
ΔD_ℓ [μK^2]
multipole moment, ℓ
100
50
0
−50
−100
30
20
10
0
−10
−20
−30
2
100
500
1000
1500
2000

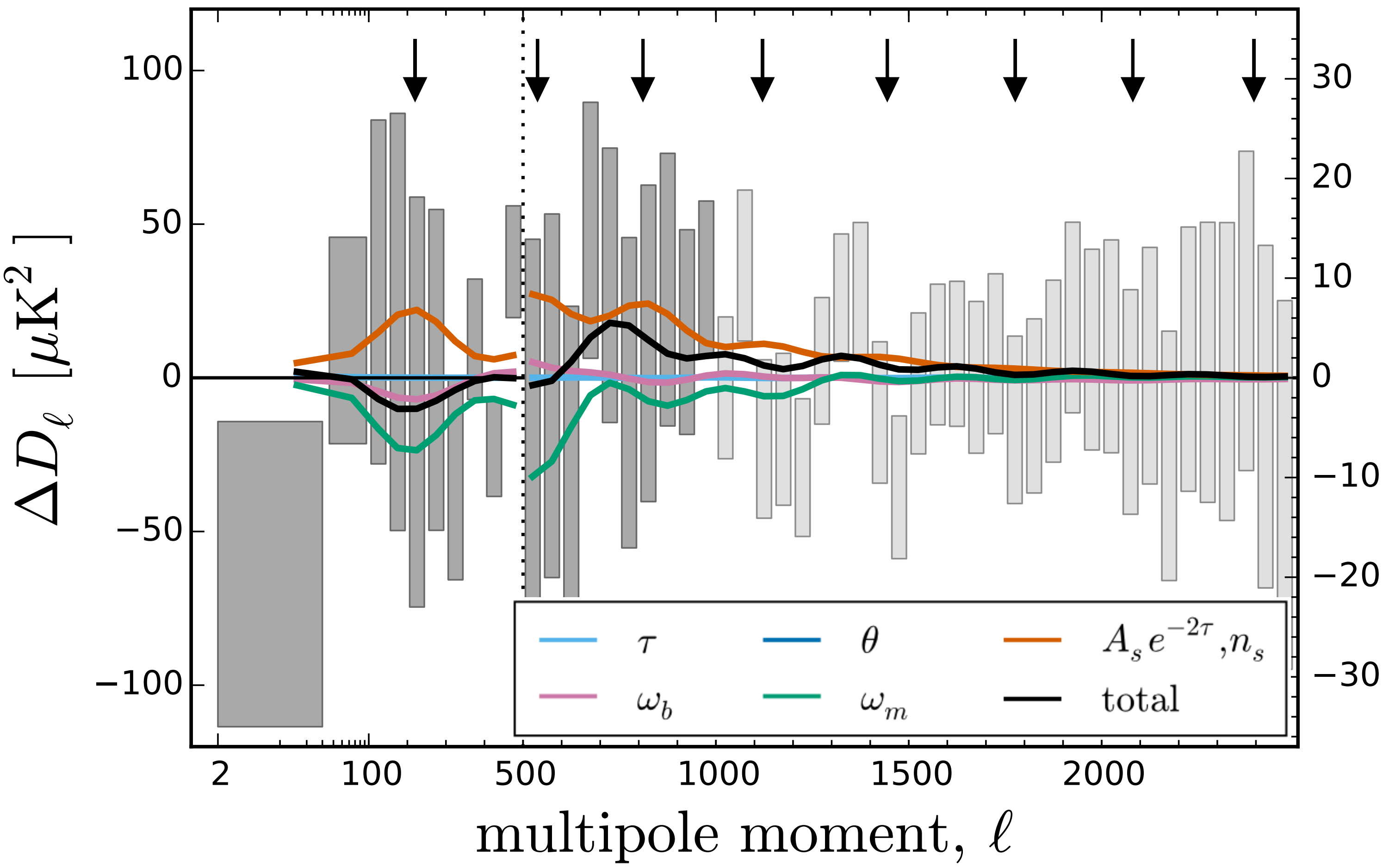


$\Delta D_\ell\ [\mu\mathrm{K}^2]$
100
50
0
−50
−100
30
20
10
0
−10
−20
−30
2
100
500
1000
1500
2000
multipole moment, ℓ

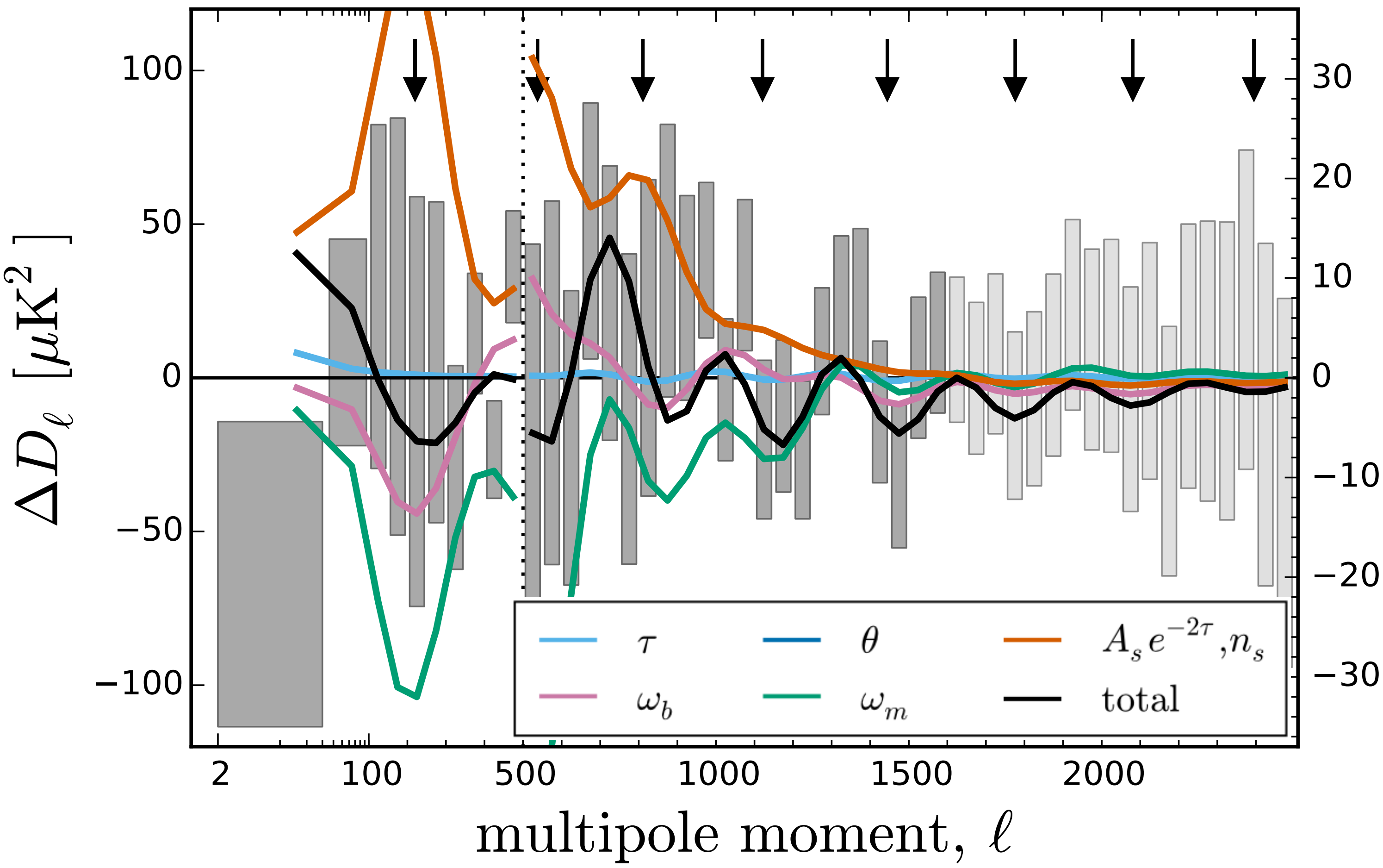


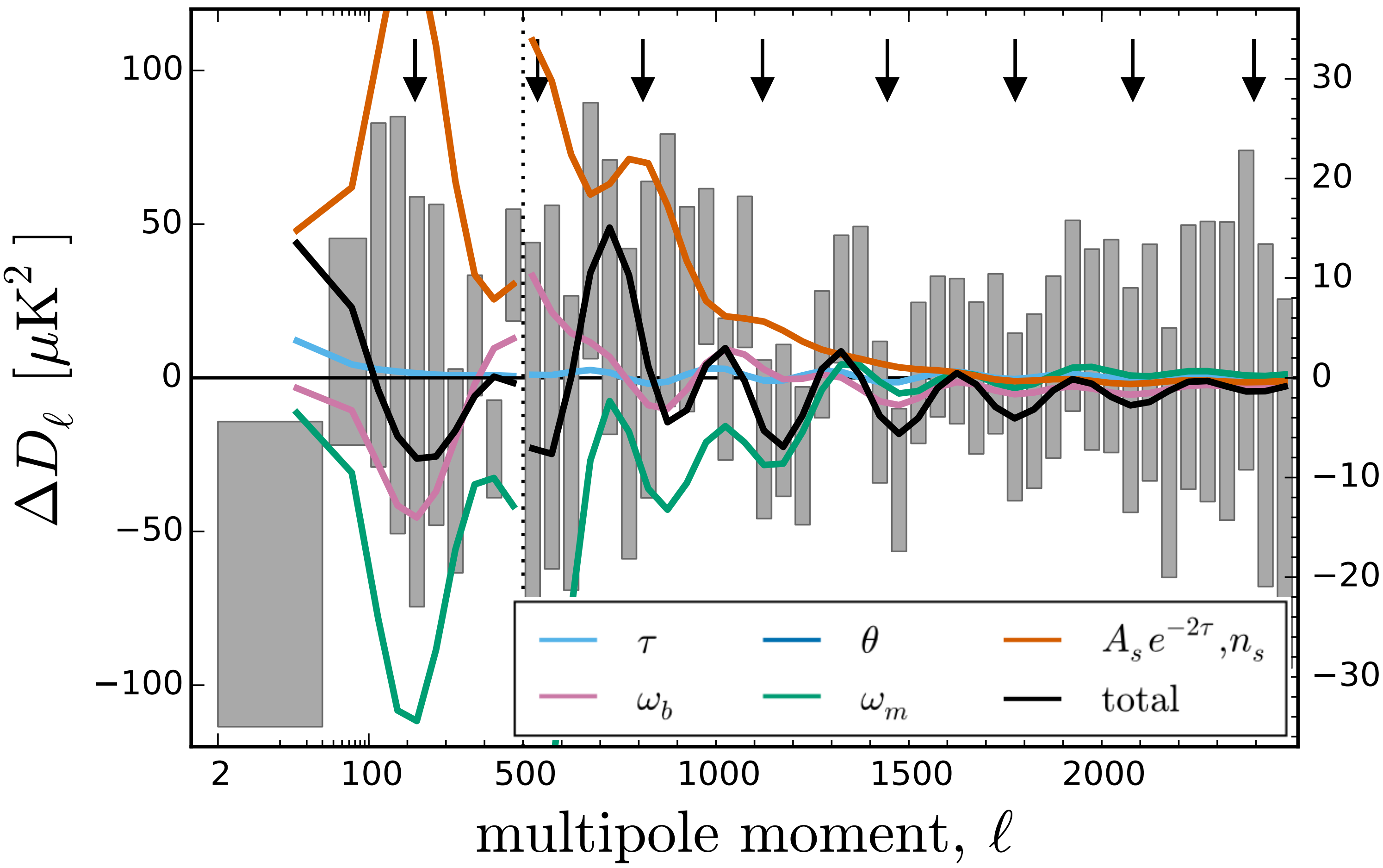
$$C_\ell = C_\ell^{\rm fid} + \frac{dC_\ell}{dp_1}\Delta p_1 + \frac{dC_\ell}{dp_2}\Delta p_2 + \ldots$$


100
50
0
−50
−100
30
20
10
0
−10
−20
−30
ΔD_ℓ [μK^2]
2
100
500
1000
1500
2000
multipole moment, ℓ
τ
θ
$A_s e^{-2\tau}, n_s$
ω_b
ω_m
total



$\Delta D_\ell\ [\mu K^2]$
multipole moment, ℓ
100
50
0
−50
−100
30
20
10
0
−10
−20
−30
2
100
500
1000
1500
2000
τ
θ
$A_s e^{-2\tau}, n_s$
ω_b
ω_m
total

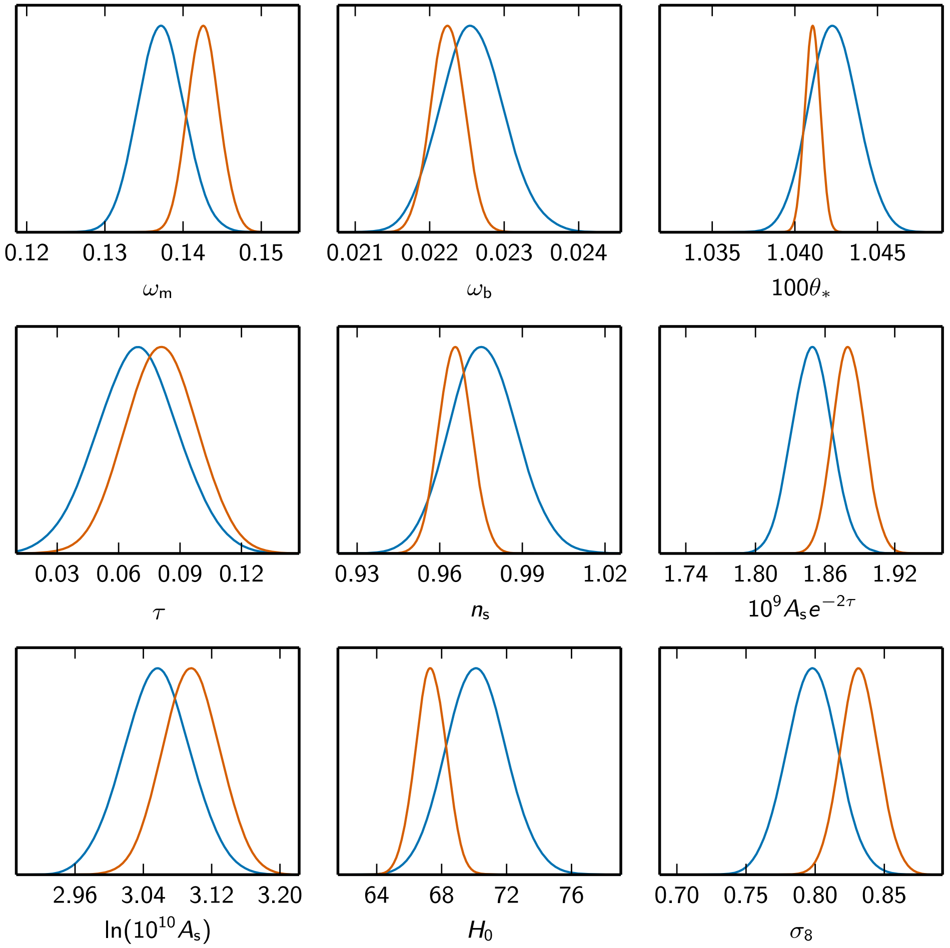

ΔD_ℓ [μK^2]
100
50
0
−50
−100
30
20
10
0
−10
−20
−30
2
100
500
1000
1500
2000
multipole moment, ℓ
τ
θ
$A_s e^{-2\tau}, n_s$
ω_b
ω_m
total



ΔD_ℓ $[\mu\mathrm{K}^2]$
100
50
0
−50
−100
30
20
10
0
−10
−20
−30
2
100
500
1000
1500
2000
multipole moment, ℓ
τ
θ
$A_s e^{-2\tau}, n_s$
ω_b
ω_m
total

“Primary” 6
ΛCDM parameters

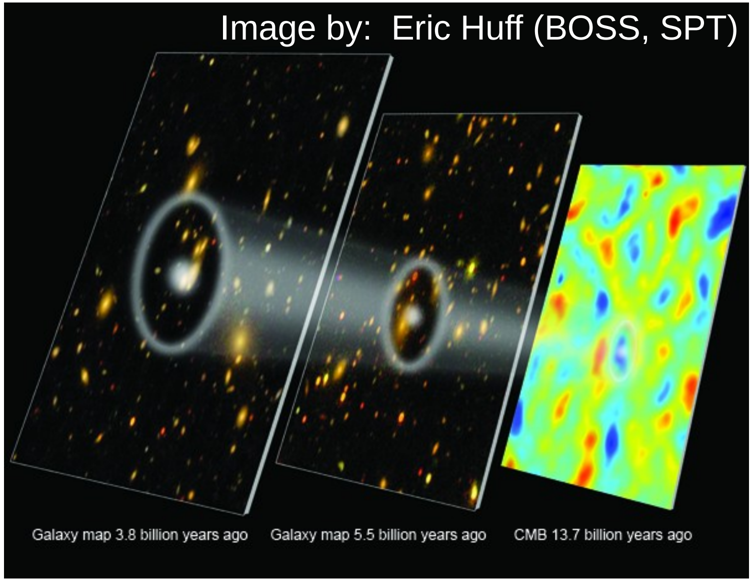
“Derived”



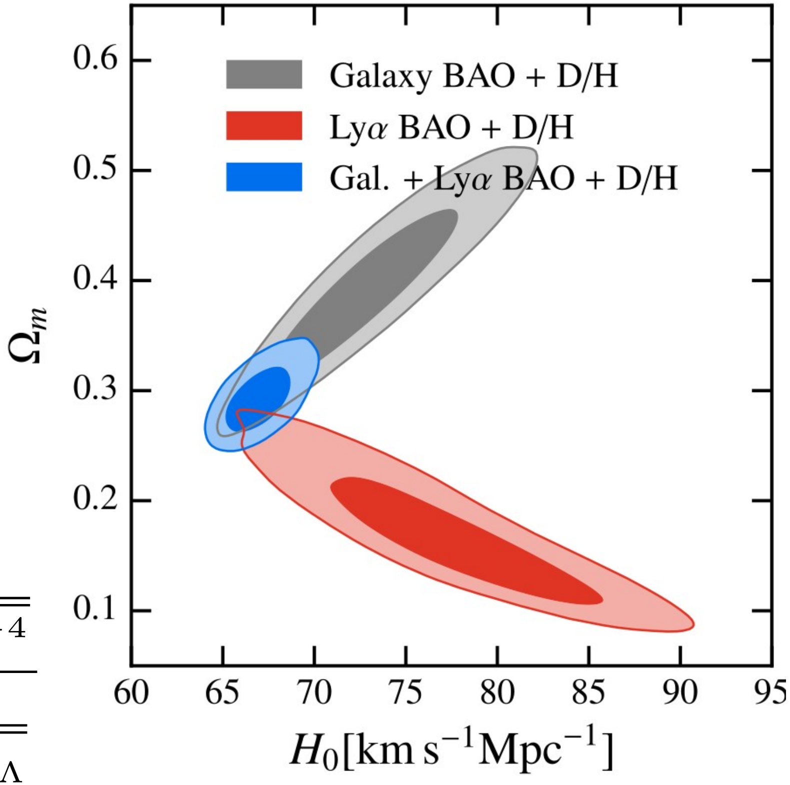
Planck ℓ<800
Planck ℓ<2500

$$H_0 = 70.0 \pm 1.9 \quad \rightarrow \quad H_0 = 67.3 \pm 1.0$$

Its not just the CMB which prefers a low value of H_0



Addison et al. 2017

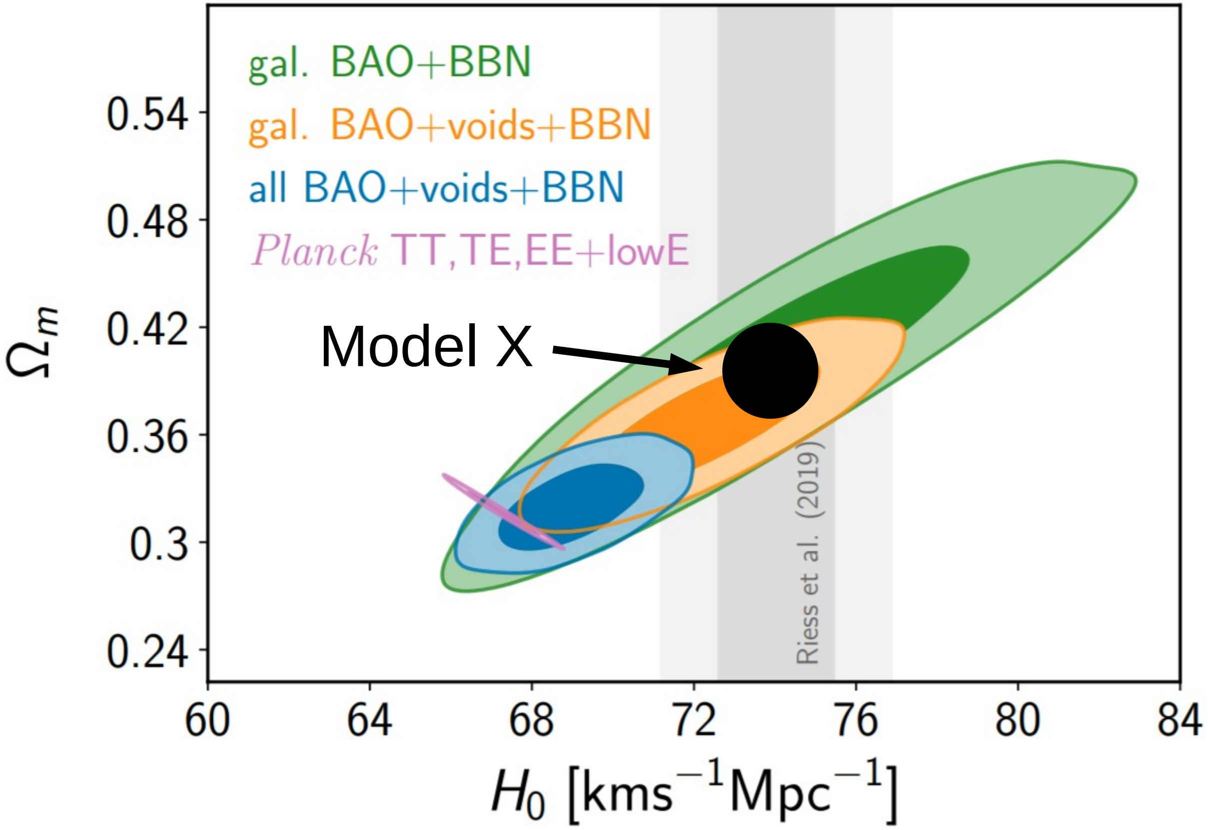


$$\theta_{\rm BAO} = \frac{r_{\rm s}}{D_{\rm A}(a_{\rm BAO})} \sim \frac{\int_{a^\star}^{1} da \frac{c_{\rm s}(a;\omega_{\rm b})}{\sqrt{\omega_{\rm m} a^{-3} + \omega_{\rm r} a^{-4}}}}{\int_{a_{\rm BAO}}^{1} da \frac{1}{\sqrt{\omega_{\rm m} a^{-3} + \omega_\Lambda}}}$$

BAO at many redshifts and line-of-sight vs. perpendicular breaks degeneracies and constrains the matter density, and therefore H_0 (when combined with baryon density)

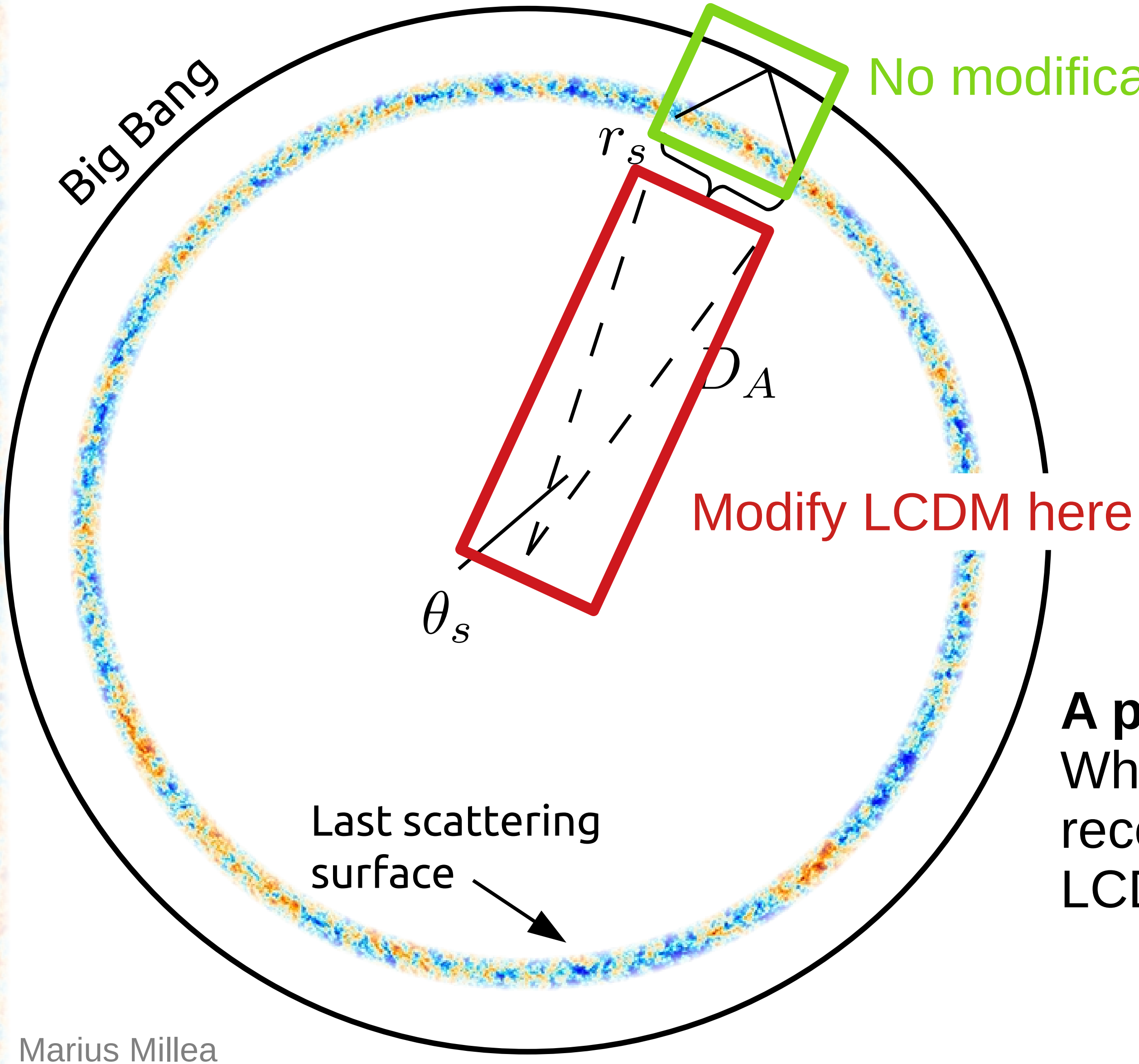
Cosmic voids x galaxies pull towards higher H_0

Goal: model X...
- Restores concordance
- Is compelling and beautiful
- Makes predictions...
- ...that are subsequently confirmed



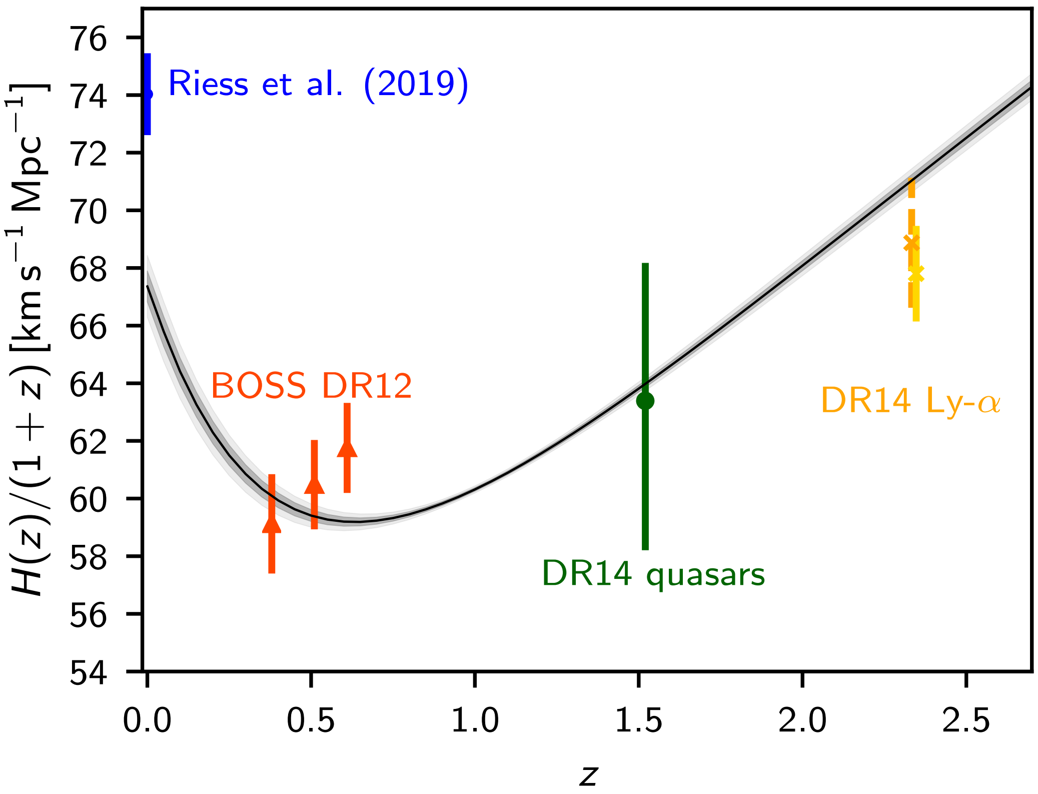
Nadathur et al. 2020

What can model X look like?

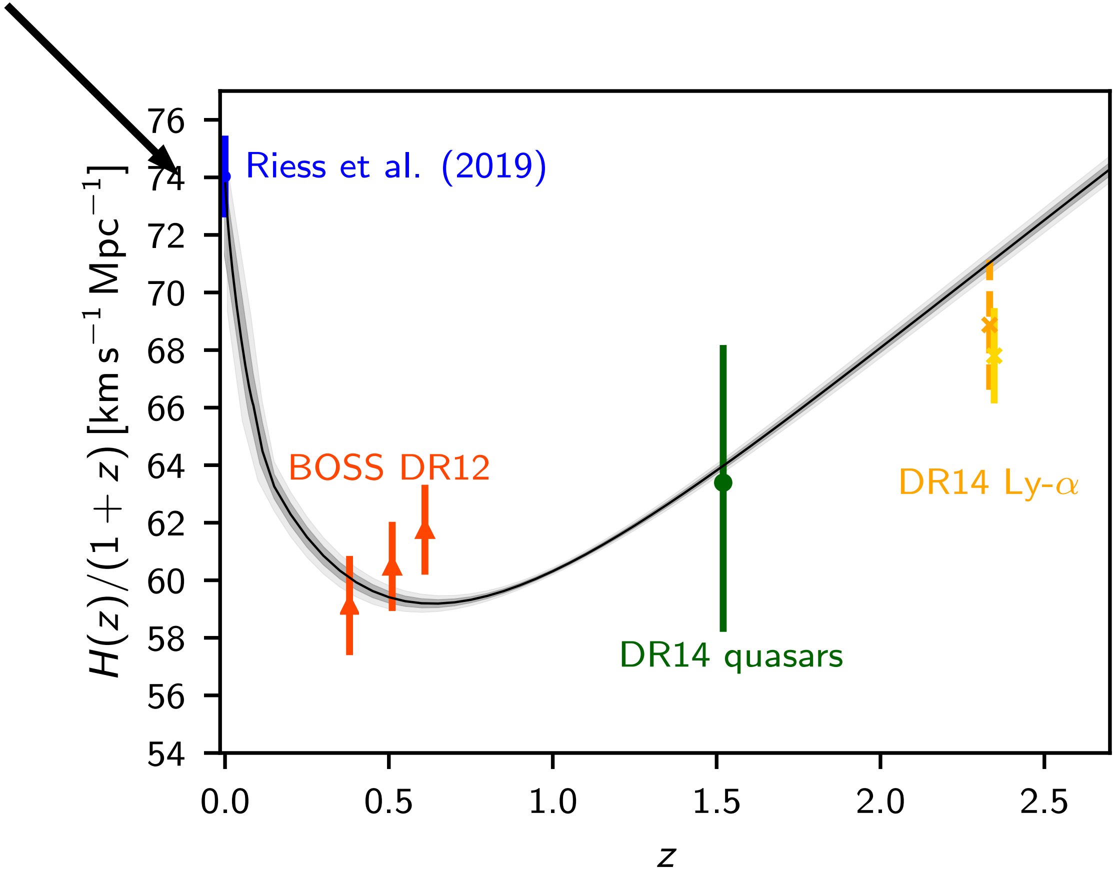


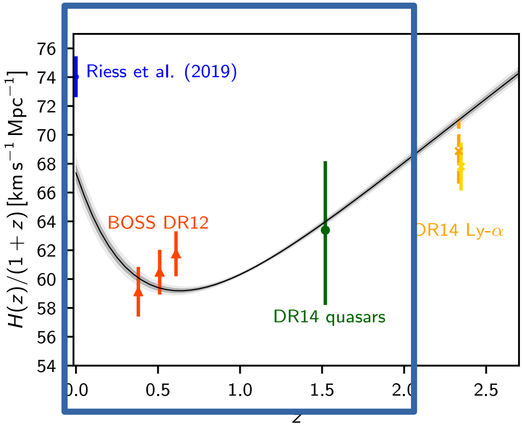
A proof by contradiction:
Why solutions with only post-recombination modification to LCDM are disfavored

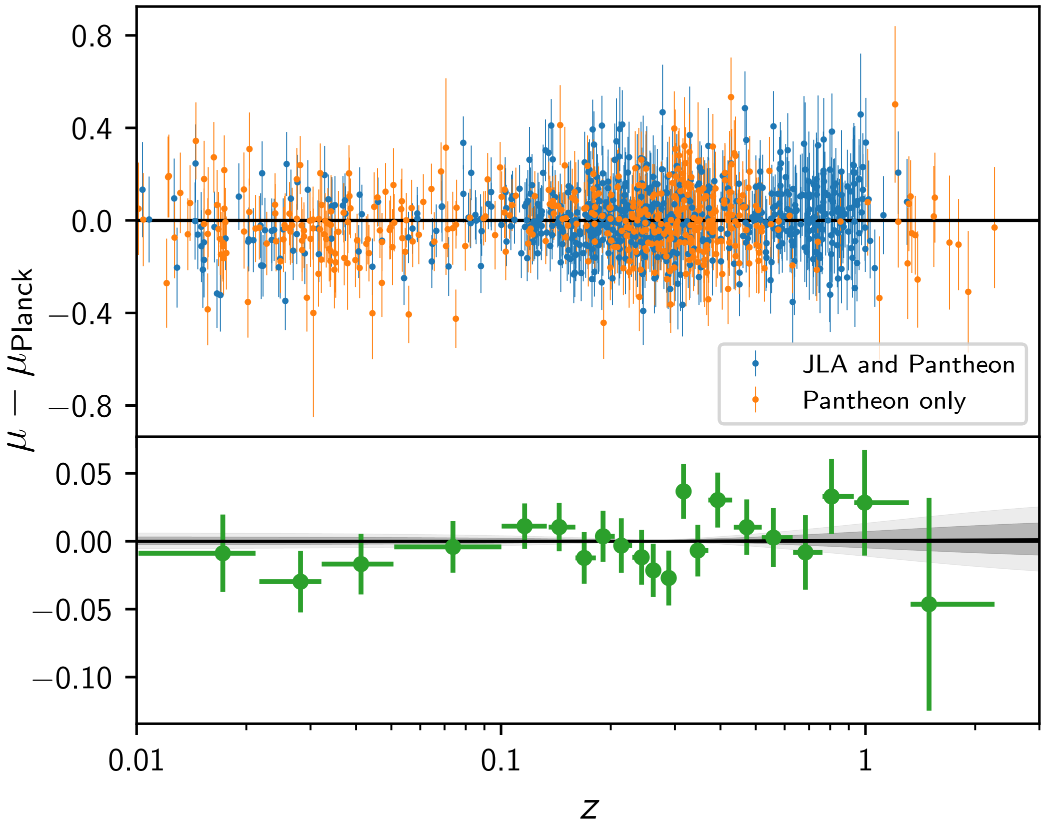
Planck Cosmological Parameters, 2018



Why doesn't this work?

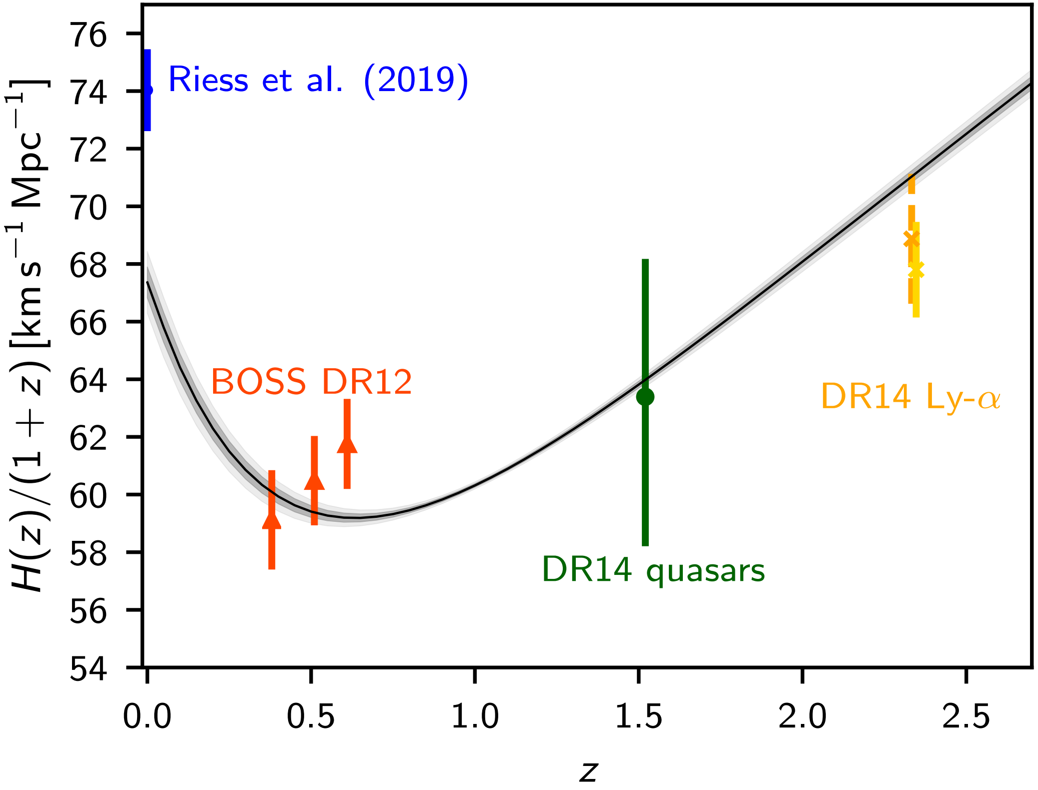




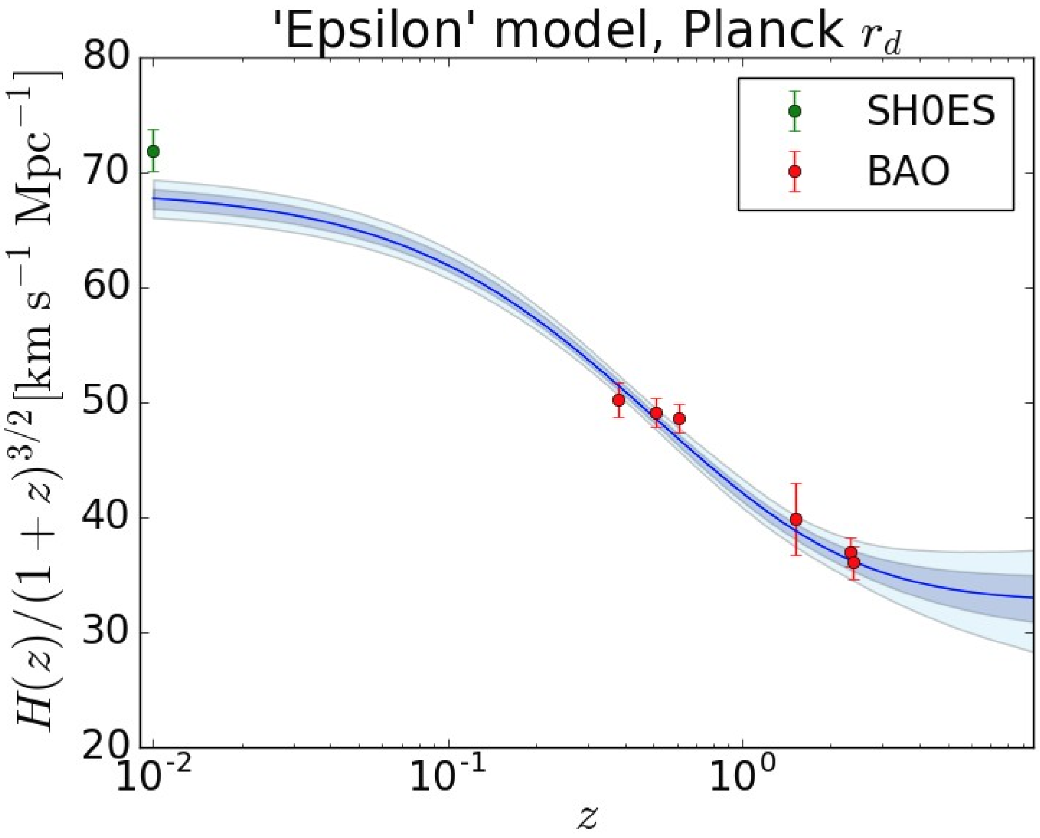


...because SNe don't allow a steep enough *slope*.

Planck Cosmological Parameters, 2018

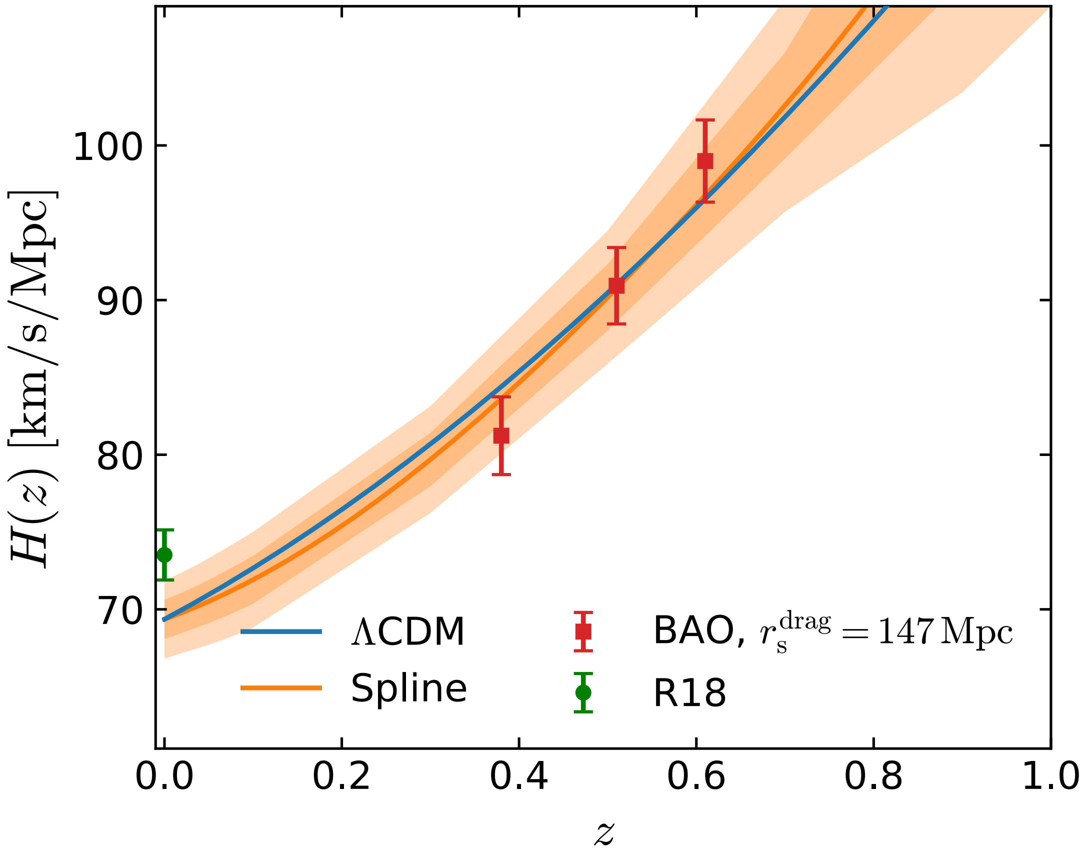


People have tried with fitting functions.



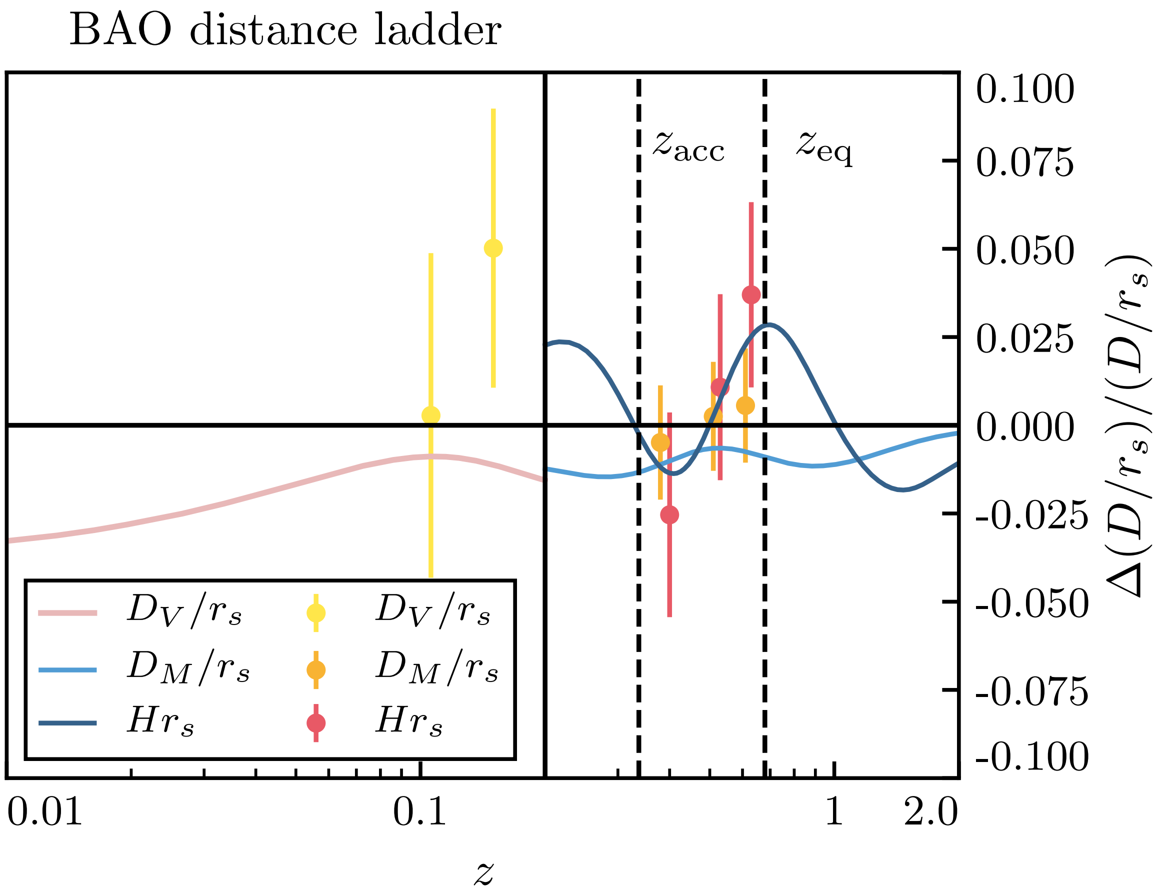
Aylor et al. 2018

...or spline fits.



Raveri 2019

The most complete attempt thus far, via modifying gravity.



Raveri 2019

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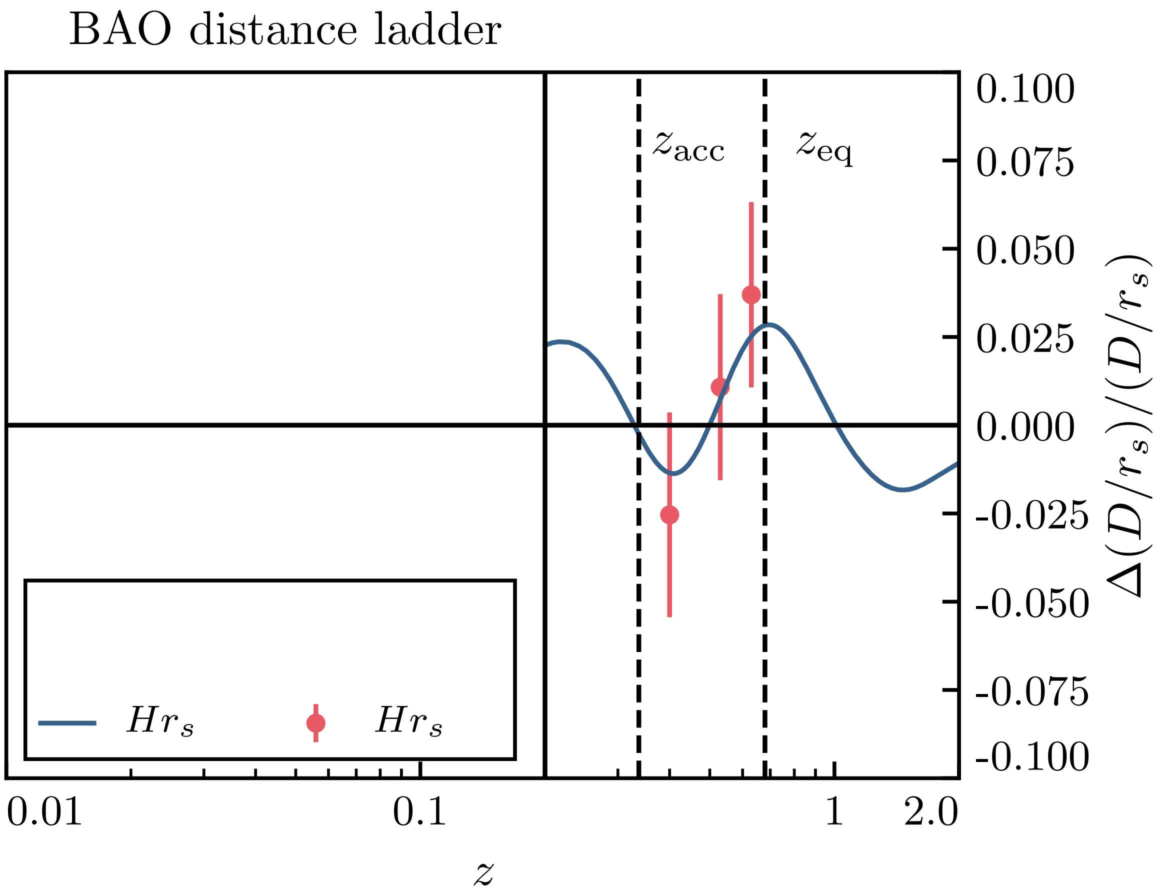
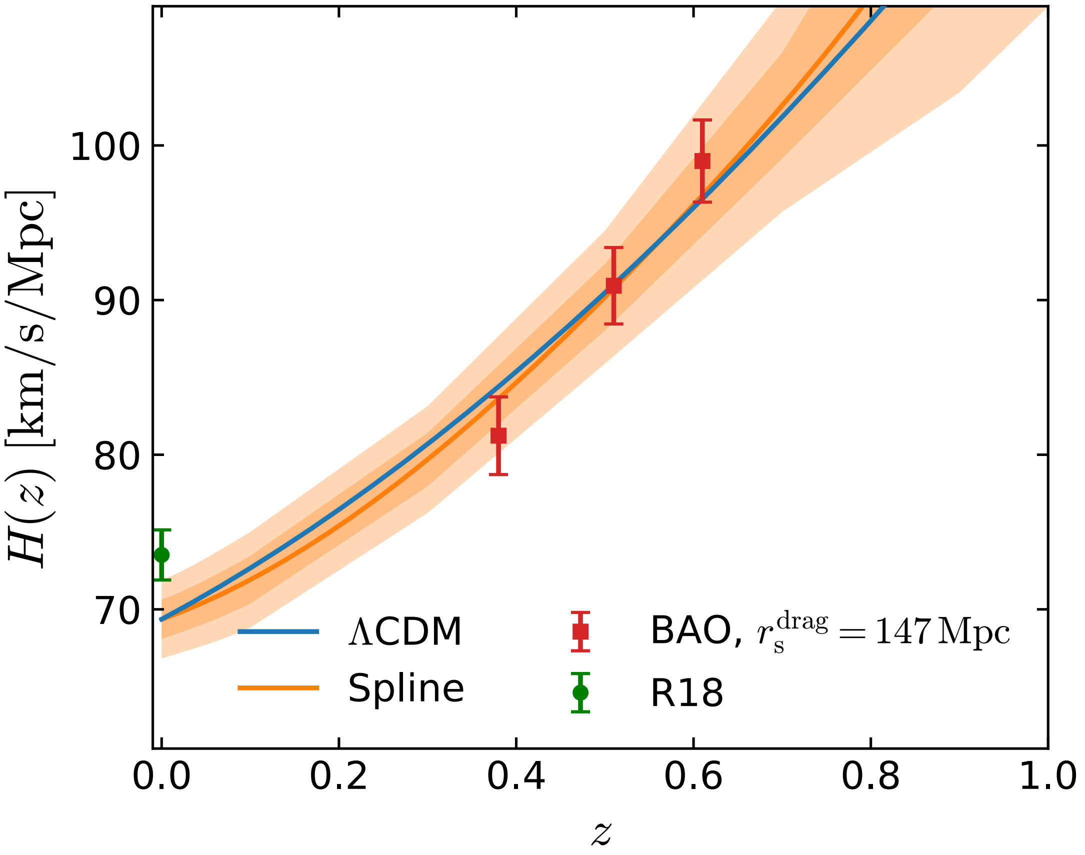


Aylor et al. 2018



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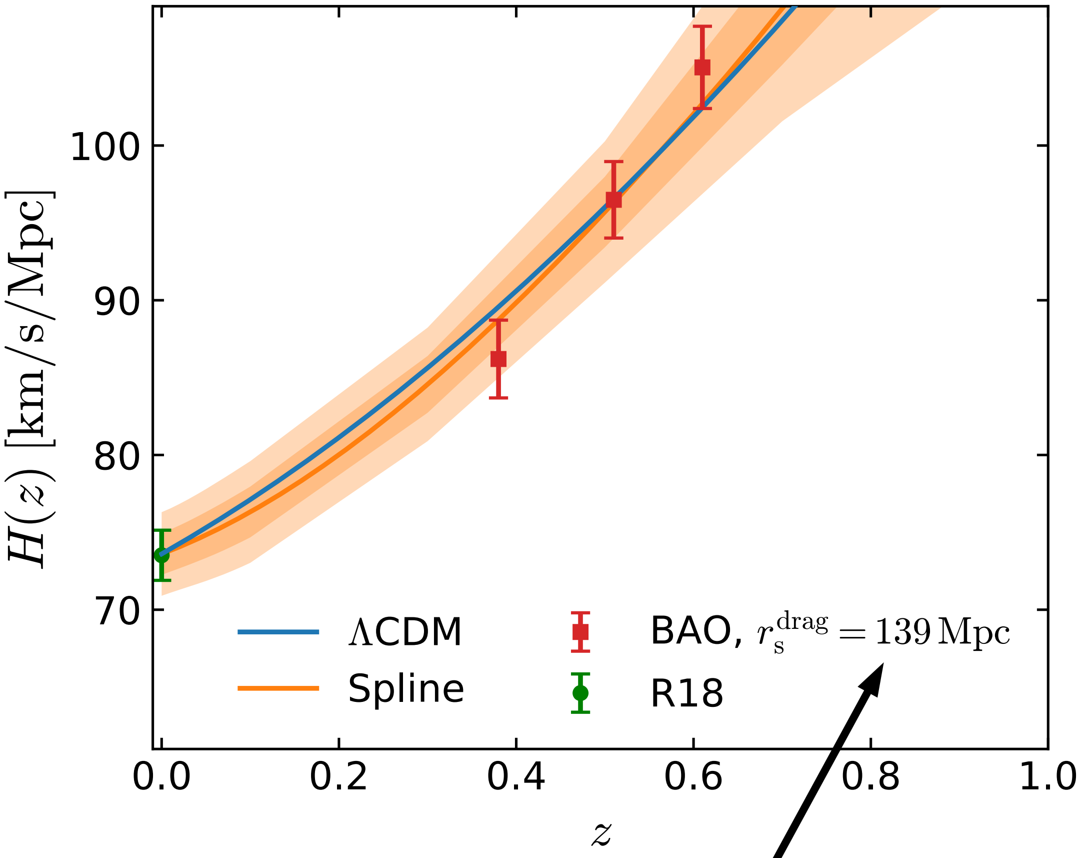
Aylor et al. 2018



7% reduction

$$r_s = \int_z^{z+\Delta z} dz\, \frac{1}{H(z)}$$

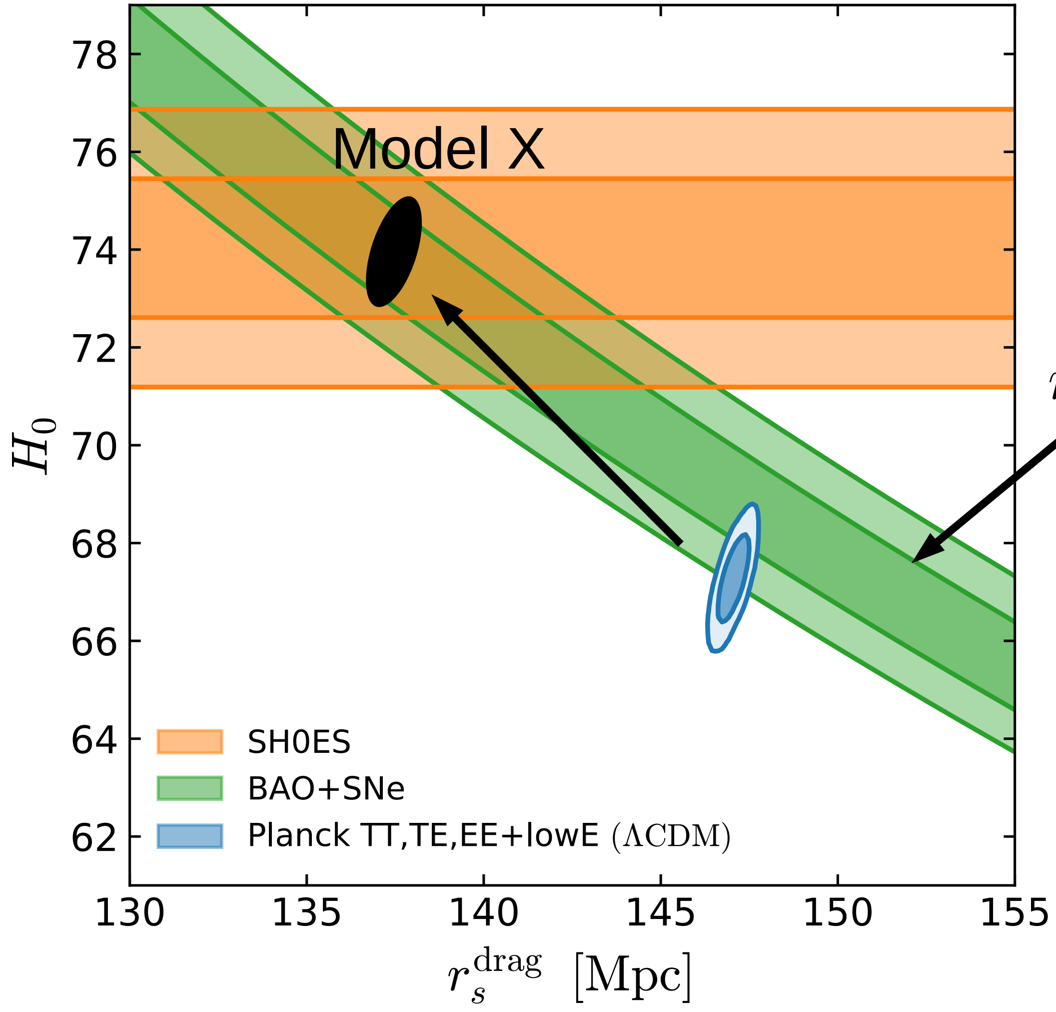
$$\approx \frac{1}{H(z)} \Delta z$$

$$\Delta z_{\rm BAO} = r_s\, H(z)$$

$$= r_s\, H_0$$

$$\times \left[H(z)/H_0 \right]$$

Knox and MM, 2019



$r_s H_0/c = 3.38 \pm 0.046$

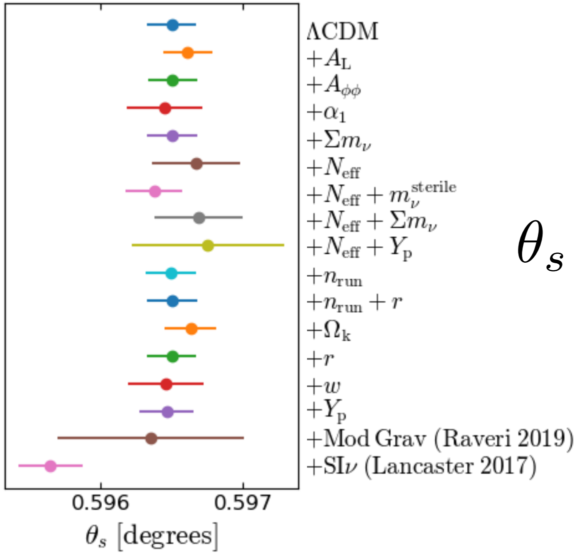
Need to reduce r_s by 7%

1908.03663

How do I reduce r_s by 7% in $\Lambda\mathrm{CDM}$?

$$r_s = \int_{z^\star}^{\infty} dz \frac{c_s(z)}{\sqrt{\omega_m(1+z)^3 + \omega_r(1+z)^4}}$$

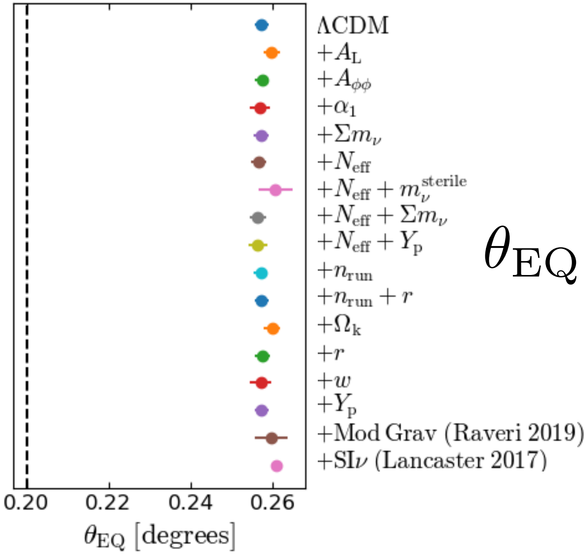
Increase ω_m by ~30%.



This decreases by 7%.

$$\theta_s = \frac{r_s}{D_A} \qquad r_s = \int_{z^\star}^{\infty} dz \frac{c_s(z)}{\sqrt{\omega_m (1+z)^3 + \omega_r (1+z)^4}}$$

Have to decrease this by 7% too.



This decreases by ~30%.

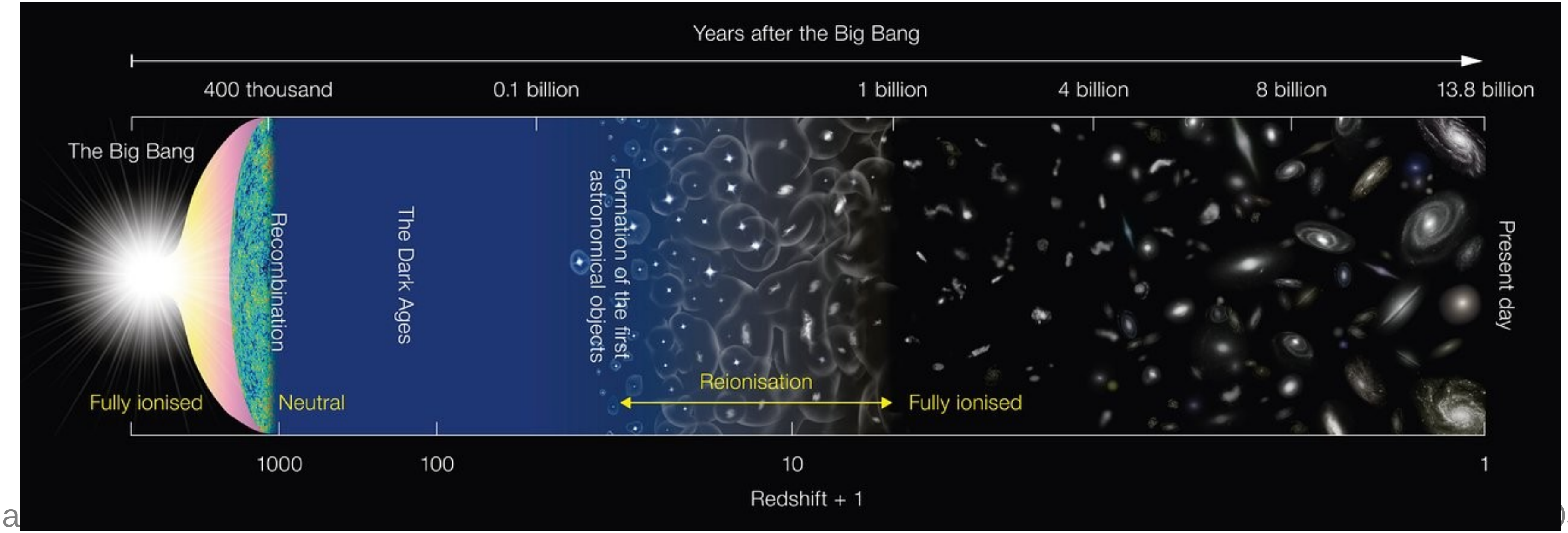
$$\theta_{EQ} = \frac{r_{EQ}}{D_A} \qquad r_{EQ} = \int_{z^{EQ}}^{\infty} dz \frac{c_s(z)}{\sqrt{\omega_m (1+z)^3 + \omega_r (1+z)^4}}$$

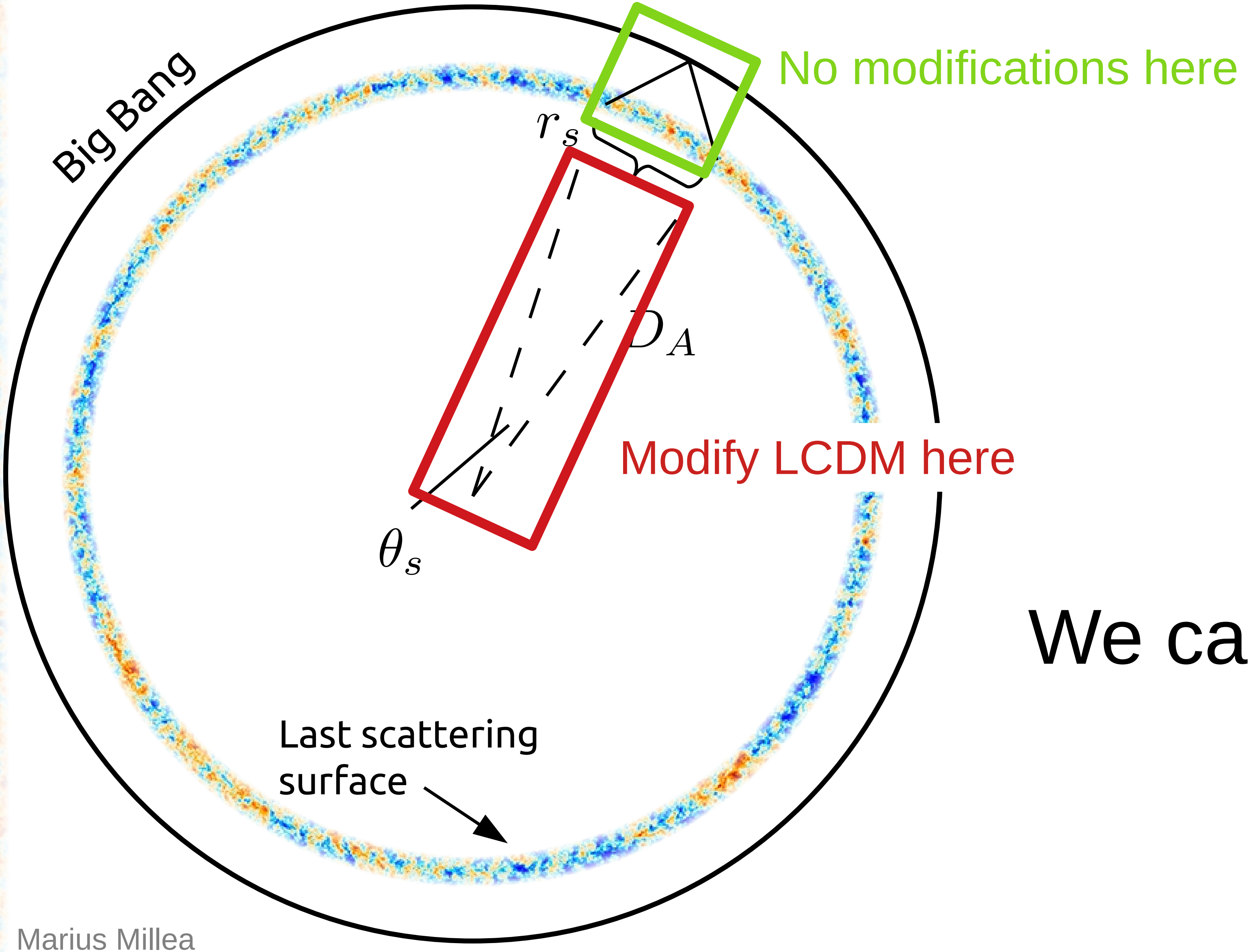
This decreases by 7%.

1908.03663

What might confuse the CMB determination of θ_s^{EQ} ?

- Early/late-time ISW?
  - ➔ We can use only TE/EE which don't have ISW
- Reionization?
  - ➔ Would need even lower optical depth
- Lensing?
  - ➔ Reconstruction is very consistent with $A_\phi = 1$





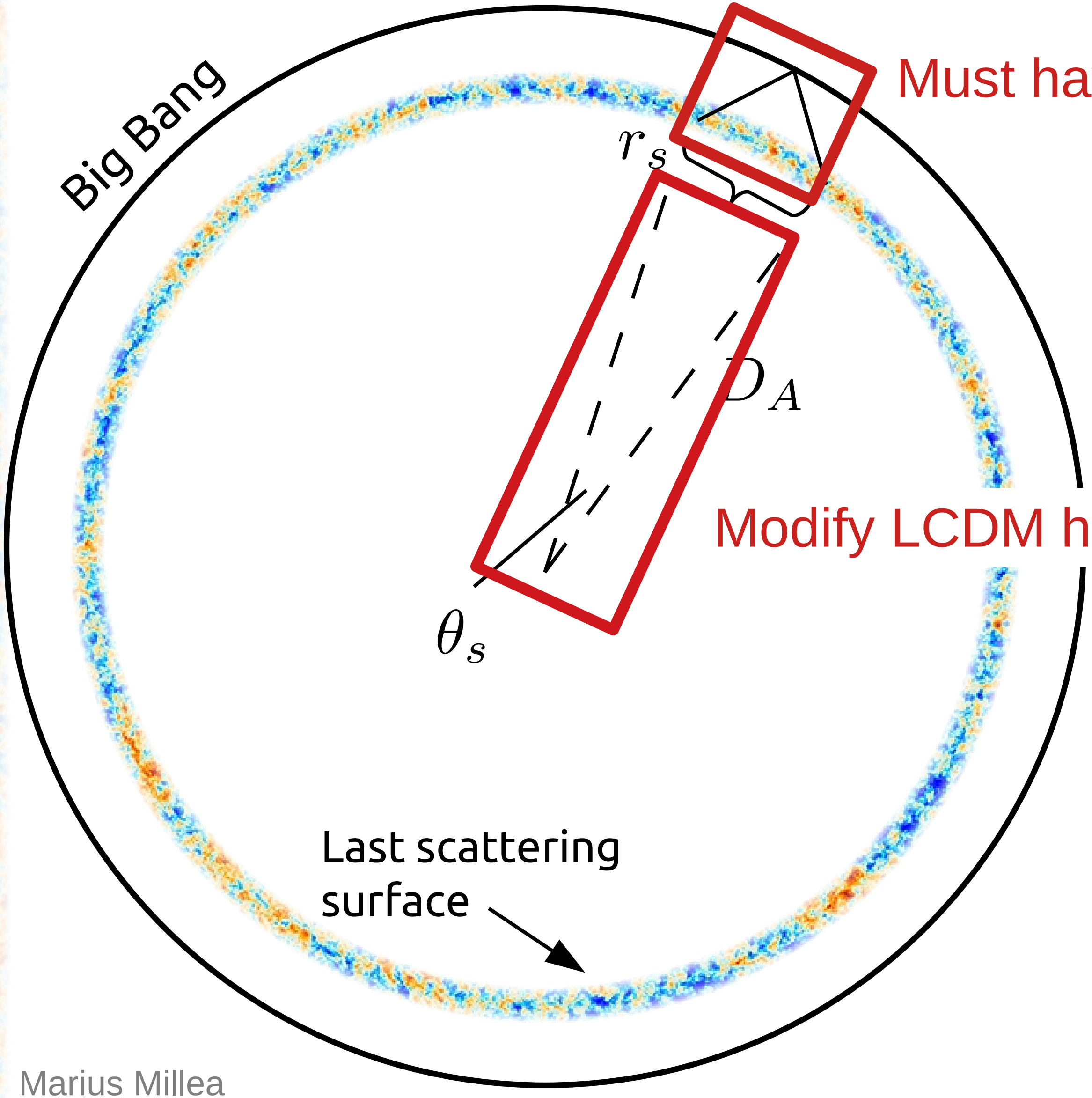
Big Bang
No modifications here
r_s
D_A
Modify LCDM here
θ_s
Last scattering
surface

We can't do it!

- The Hubble tension ↔ the r_s tension

- Model independent low-z probes say r_s is 139
  ⇒ we have to lower the CMB value

- If ΛCDM in the early universe, must increase ω_m, but there's no way confuse the CMB enough to allow that

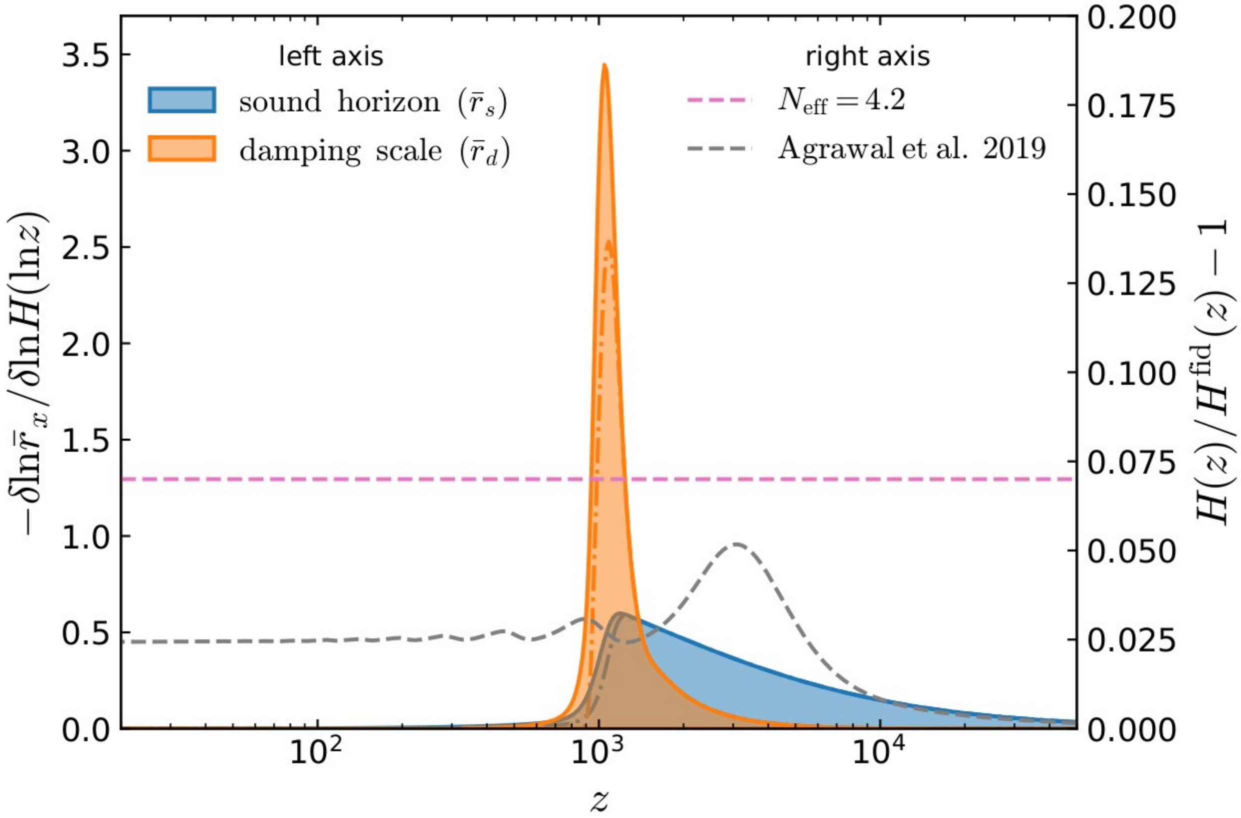


Must have some modifications here

Modify LCDM here

We can't do it!

Lowering r_s requires a careful adjustment of the expansion rate right near recombination:



E.g. self-interacting neutrinos, early dark energy, etc…
(Agrawal/Kreisch/Poulin/Smith et al... 2019, Lancaster et al. 2017,...)

Conclusion

- Models which resolve the tension should consider the CMB, BAO, SNe, local measurements, and look at both H_0 and r_s.
- The least disfavored solutions lower r_s by changing early universe physics
- More relevant data coming soon
  - eBOSS results
  - ACT CMB results, SPT-3G
  - Stage-4 CMB and galaxy surveys