Cosmic Microwave Background, Baryon Acoustic Oscillations and Tensions

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Tensions between the Early and the Late Universe
KITP, UC Santa Barbara
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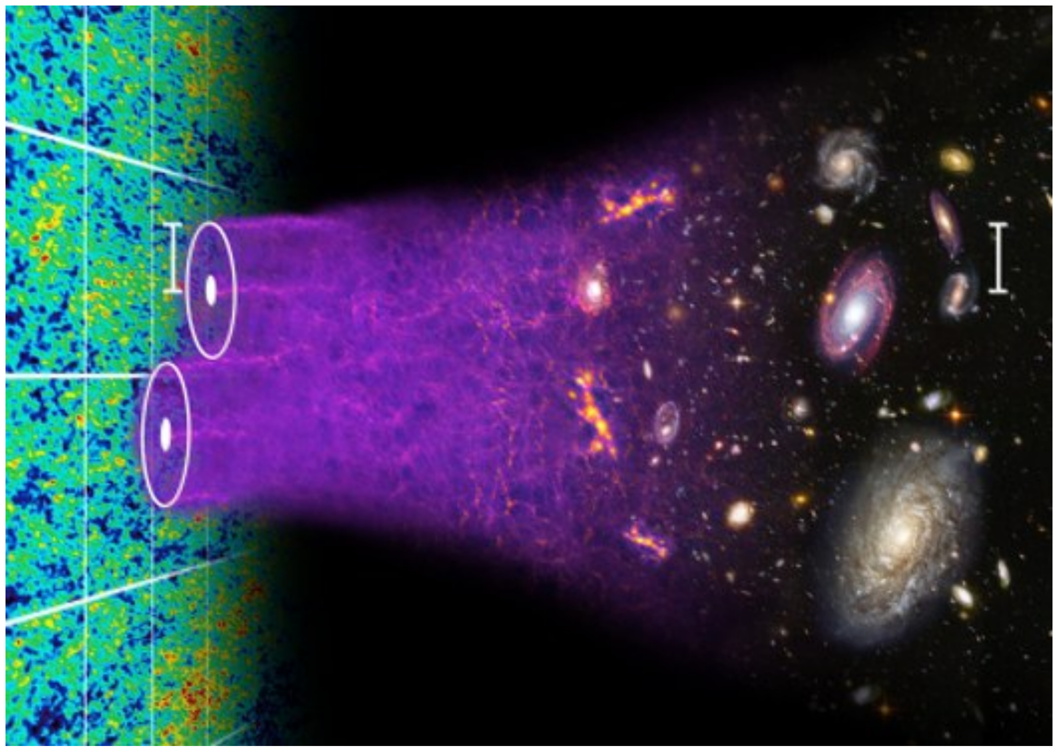
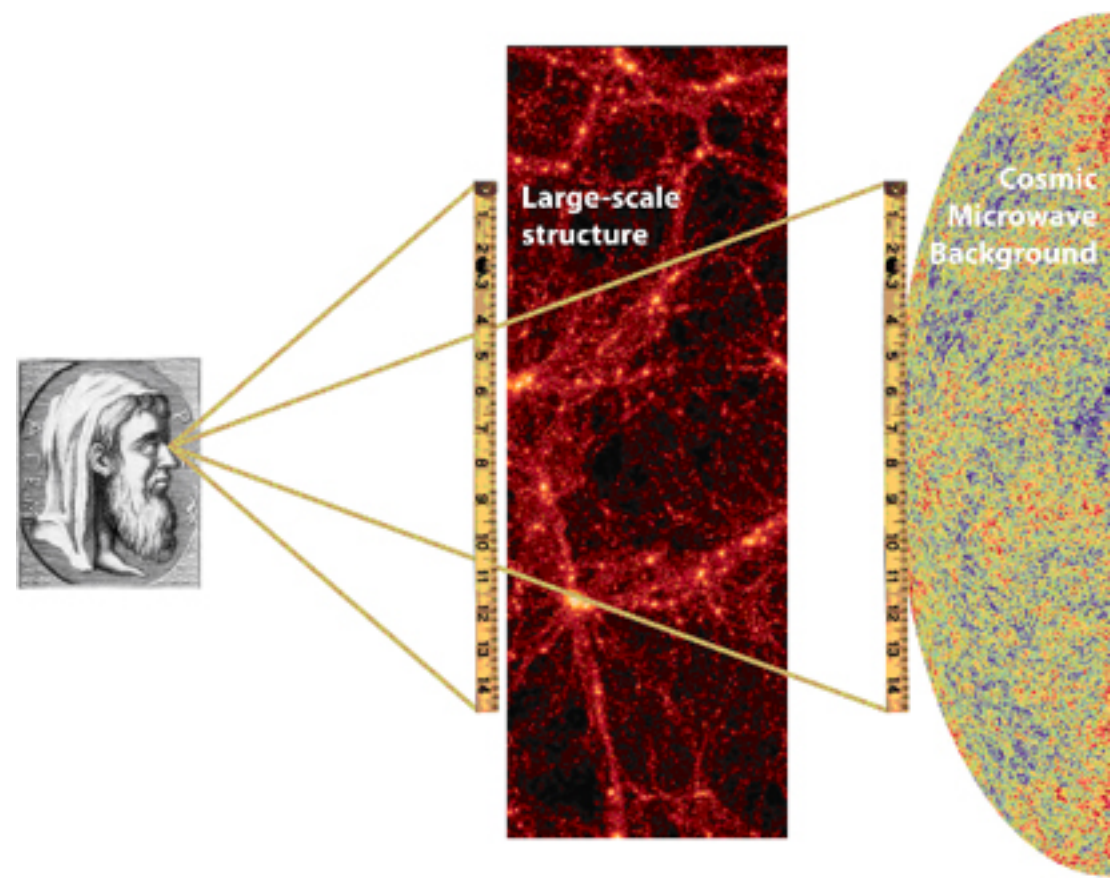
What is the BAO scale?



- Standard ruler length set at the end of the drag epoch
- Expands with the universe
- ~150 Mpc (in ΛCDM): large enough to be ~unchanged by nonlinear growth



Sound horizon at drag epoch:

$$r_d = r_{\rm drag} = r_s(z_{\rm drag}) = \int_{z_{\rm drag}}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Image credit SDSS; C. Blake & S. Moorfield, ESA

‘Early universe’ physics in ΛCDM

	Inflation, baryogenesis
~10^{-4} s	**proton/antiproton annihilation**
couple mins	**e^-/e^+ annihilation, Big Bang Nucleosynthesis (BBN)**
~1 month	**CMB blackbody frequency spectrum fixed**
~56k years	**Matter-radiation equality**
~380k years	**Last scattering, CMB emitted**

Useful to divide cosmological data depending on whether they are sensitive to pre-recombination physics

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BAO:

Sound speed: $\Omega_\gamma h^2$, $\Omega_b h^2$

$$r_d = r_{\rm drag} = r_s(z_{\rm drag}) = \int_{z_{\rm drag}}^{\infty} \frac{c_s(z)}{H(z)} dz$$

Expansion rate: Ω_r (photons & neutrinos), Ω_m

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CMB: **…sensitive to same physics as BAO but a lot of other stuff too!**

Damping tail sensitive to $H(z)$ during recombination, also He fraction through free e^- density

Extra baryon dependence: acoustic peak structure, small-scale suppression of power

Growth of potentials (Sachs-Wolfe, ISW)

Primordial power spectrum, A_s & n_s

Last scattering vs drag epoch

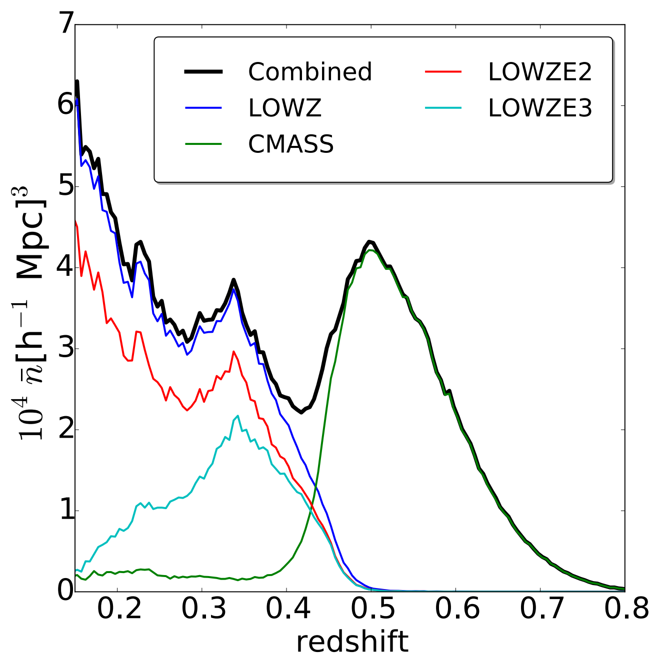
- z_*: redshift at **last scattering**; redshift at which CMB photon optical depth equals unity

- z_d or z_drag: redshift corresponding to end of **baryon drag epoch;** baryons released from Compton drag of photons

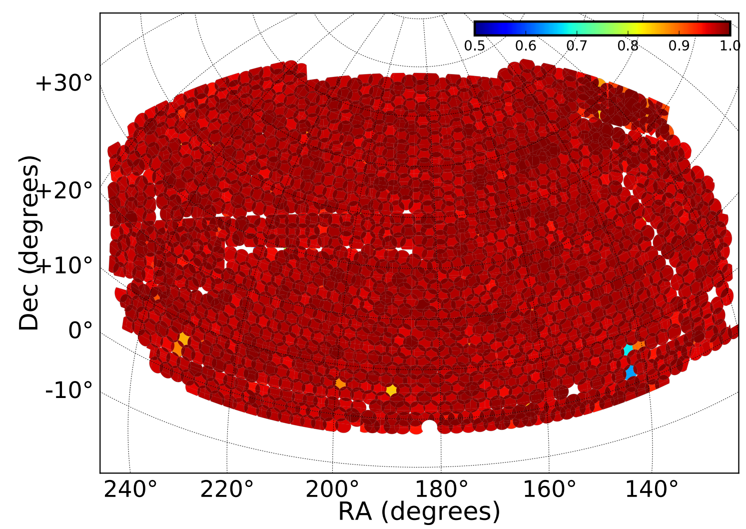
- *Planck* 2018 TT+TE+EE+lowE+lensing in ΛCDM:
  z_*=1089.92 ± 0.25; z_drag=1059.94 ± 0.30
  r_*=144.43 ± 0.26 Mpc; r_drag=147.09 ± 0.26 Mpc

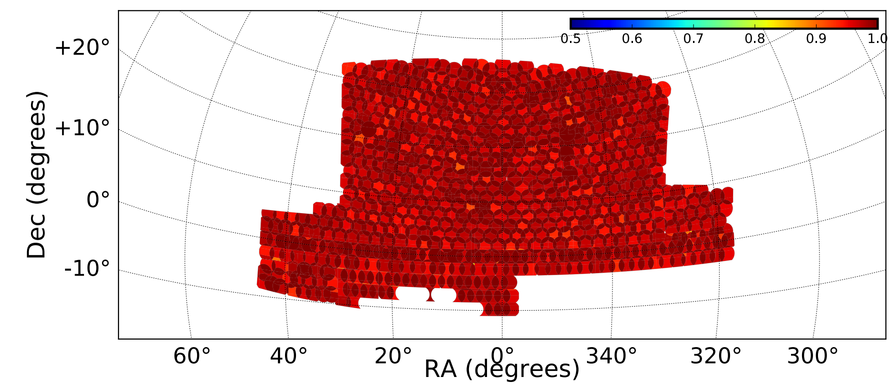
- O(10^9) photons per baryon: photons stop caring about baryons before baryons stop caring about photons

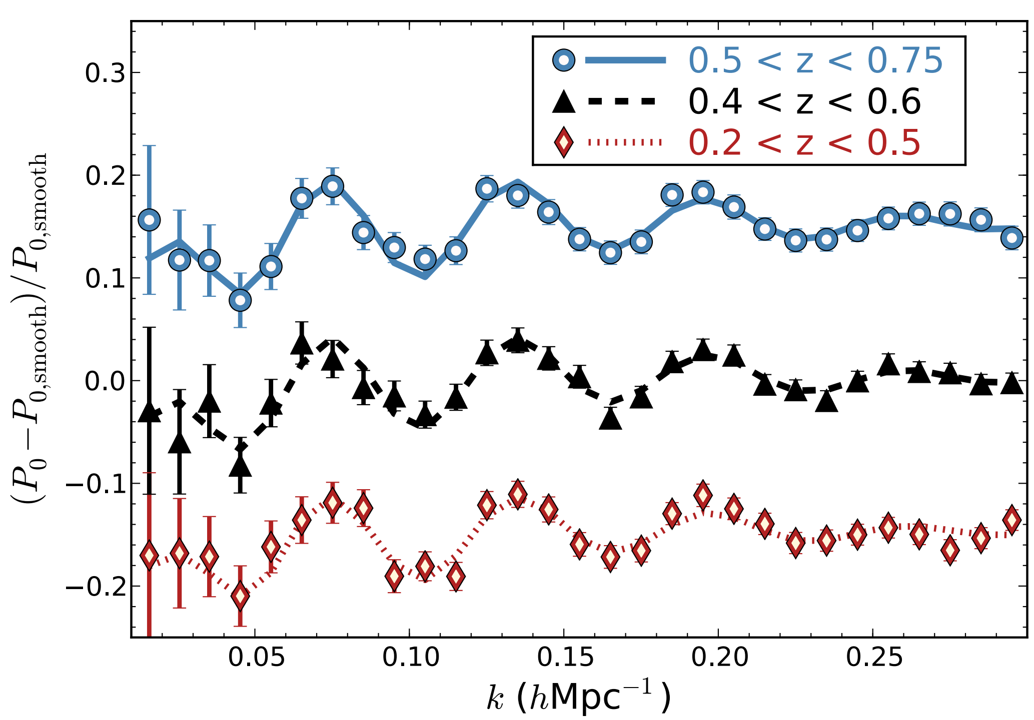
BAO from BOSS (Baryon Oscillation Spectroscopic Survey)

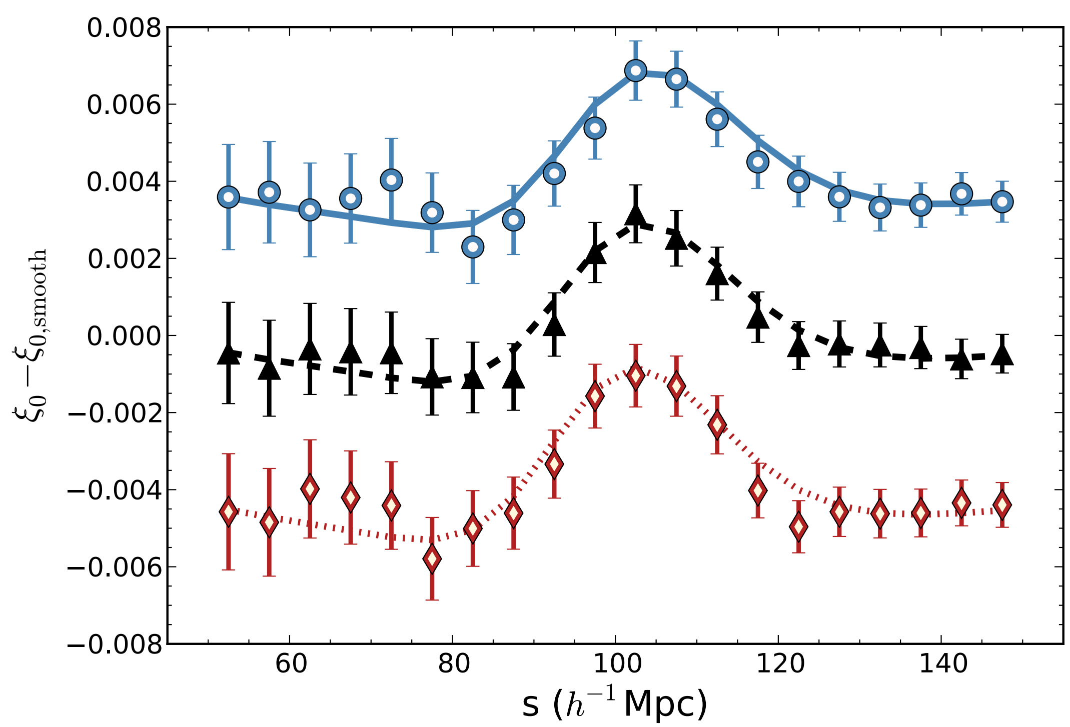


1.2M massive galaxies (LRGs), 9.3k sq deg









Alam *et al.* (2017), MNRAS 470, 3; 1607.03155

BAO Observables

Fit for dimensionless dilation parameters corresponding to deviation away from some ***fiducial model***:

$$\alpha_\perp = \frac{D_M(z) r_{d,\mathrm{fid}}}{D_M^{\mathrm{fid}}(z) r_d} \qquad \alpha_\parallel = \frac{H^{\mathrm{fid}}(z) r_{d,\mathrm{fid}}}{H(z) r_d}$$

Correspond to separations of tracers in plane of sky (separation in ***angle***)

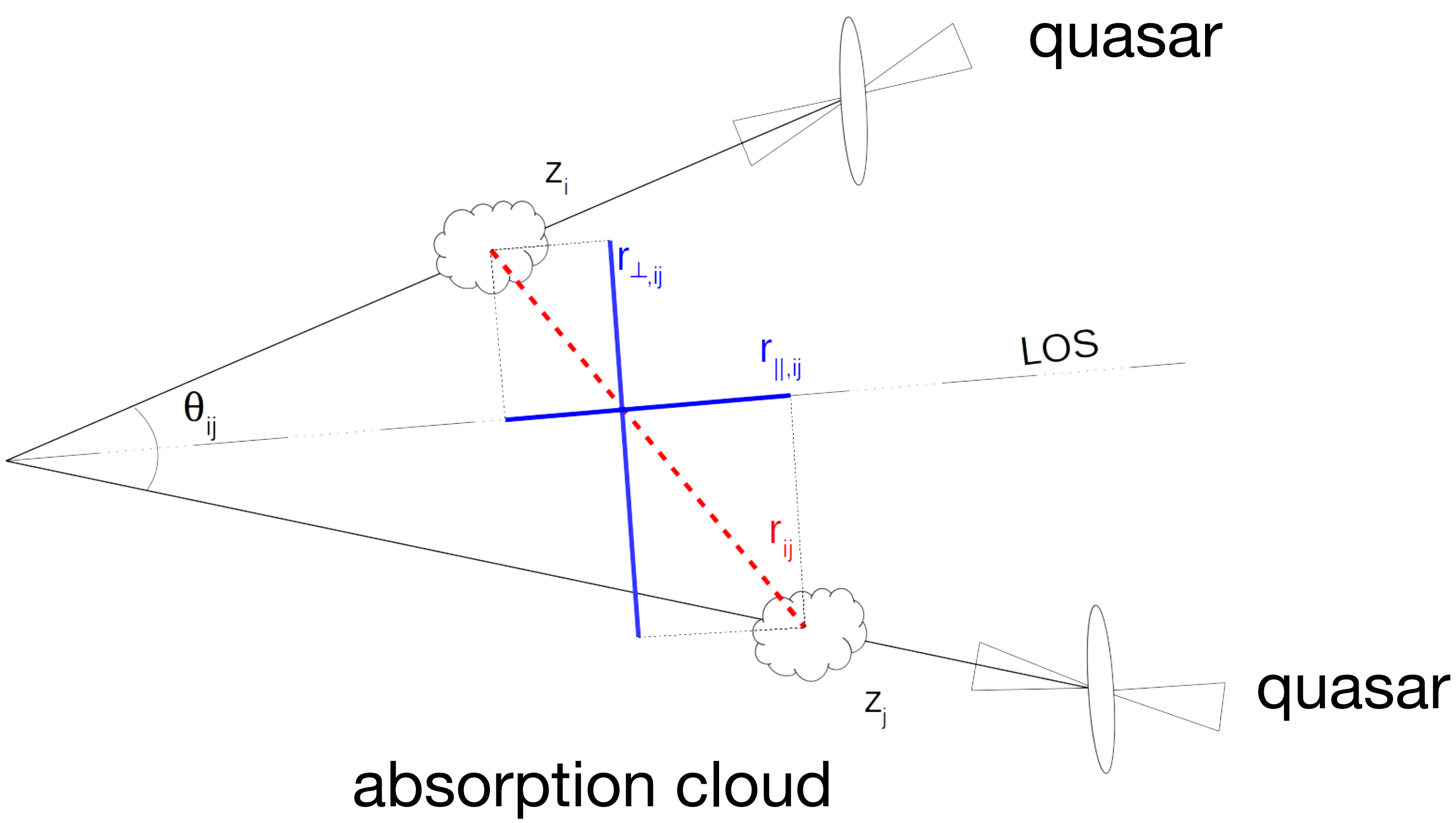
$$\Delta\theta = r_d / D_M(z) = r_d / (1+z) D_A(z)$$

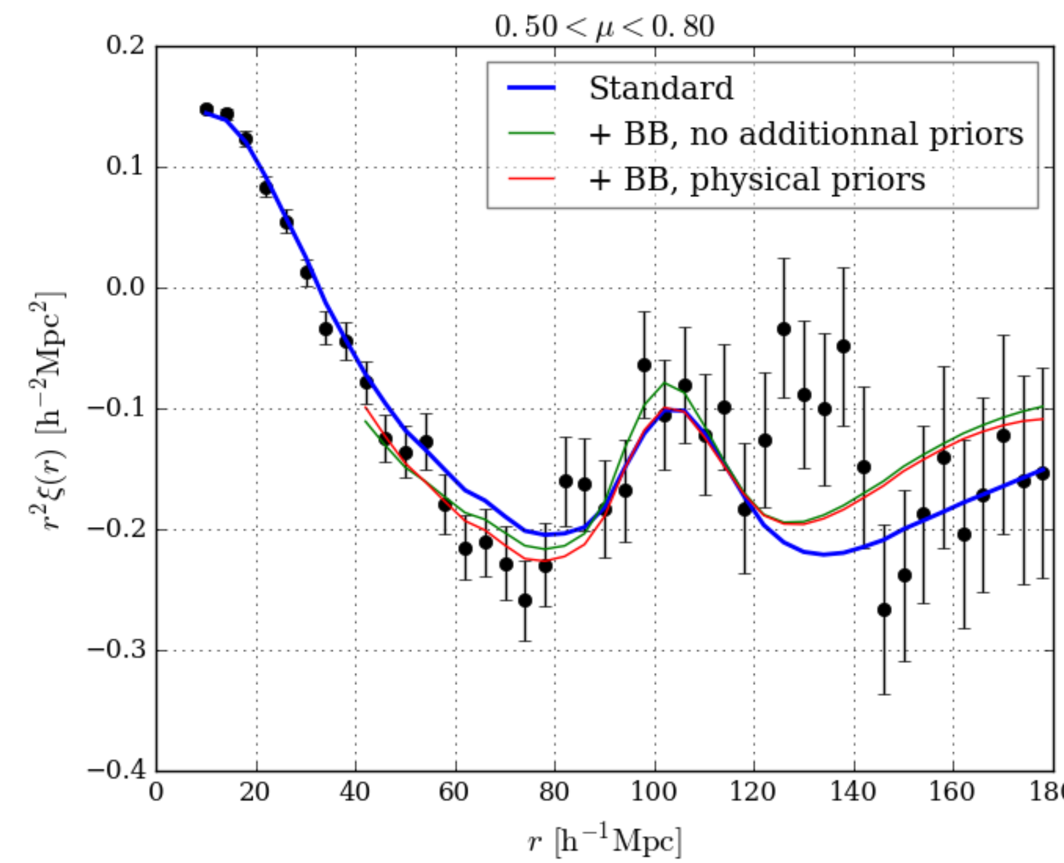
… and along line of sight (separation in ***redshift***)

$$\Delta z = H(z) r_d / c$$

D_M(z) and H(z) at redshift of galaxies etc. mean BAO measurements also sensitive to late-time physics (e.g., dark energy)

BAO in the Lyman-α Forest of (e)BOSS quasar spectra at 2.0< z<3.5

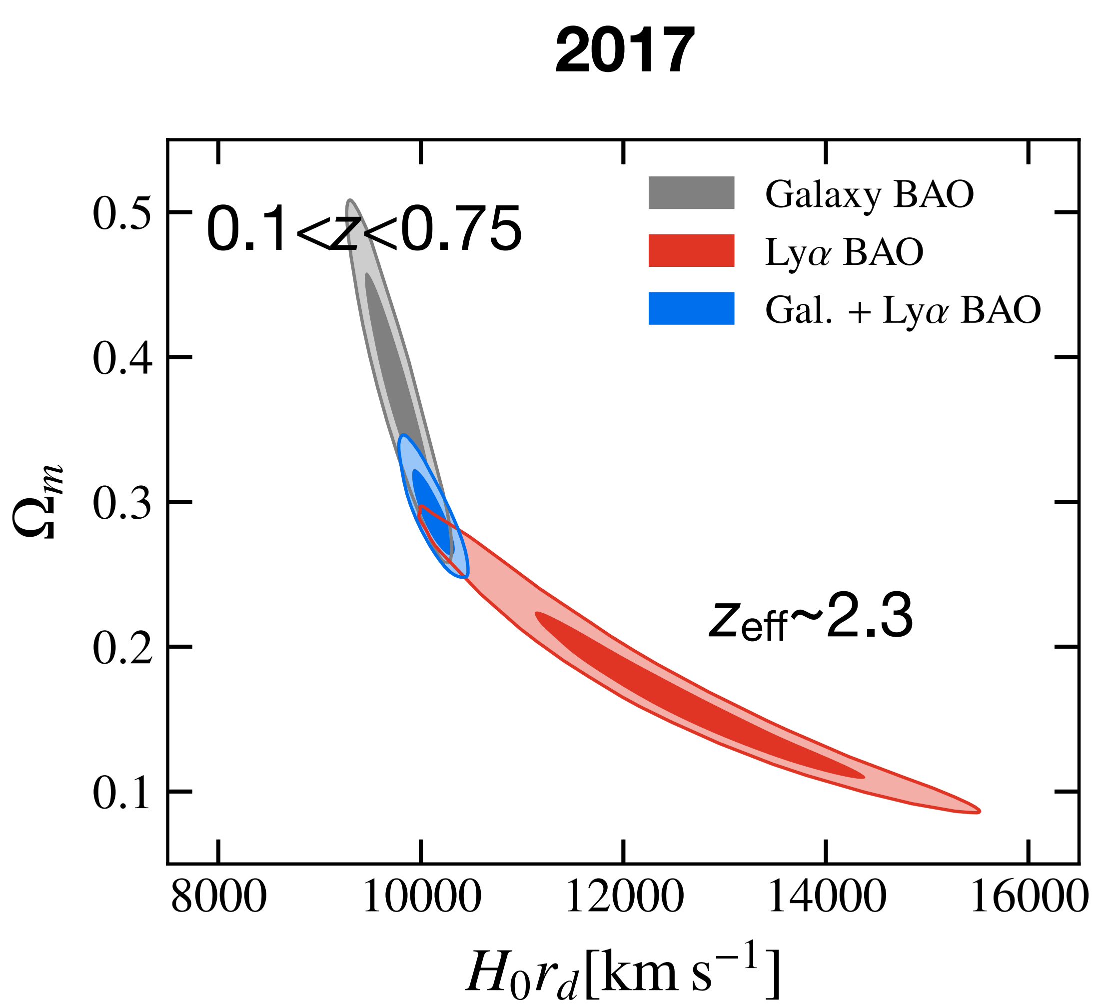


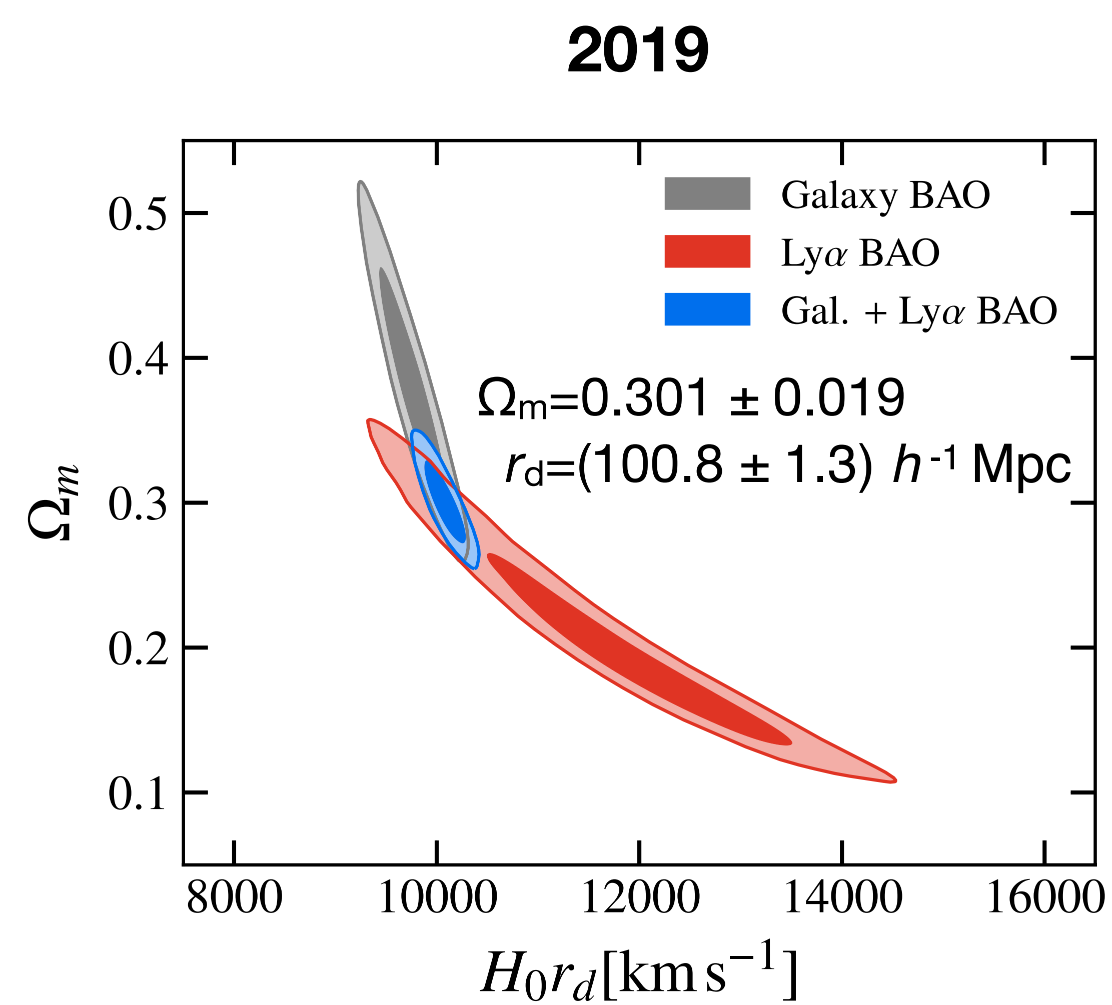


- 3-5% precision (compared to ~1% for BOSS LRGs)
- Probe decelerating, matter dominated universe

DR14: de Sainte Agathe *et al.* (2019), 1904.03400; Blomqvist *et al.* (2019), 1904.03430

'Uncalibrated' BAO-only constraints

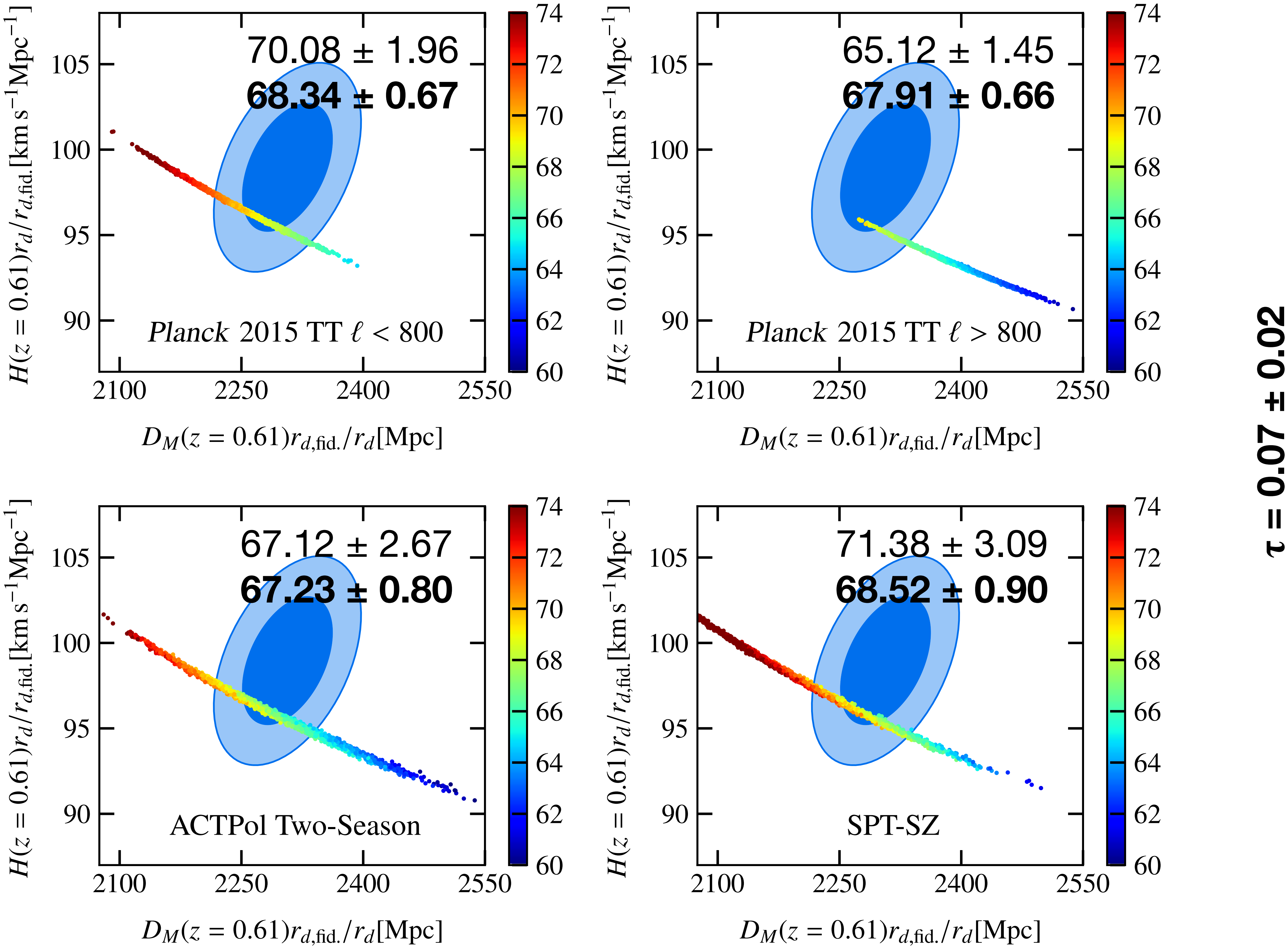




- Assume flat ΛCDM: BAO at different redshifts constrain relative expansion (Ω_m)
- H_0 and r_d are degenerate without external information
- 2.4σ tension between galaxy, Lyα in 2017, reduced to 1.7σ in 2019 (DR14 Lyα)

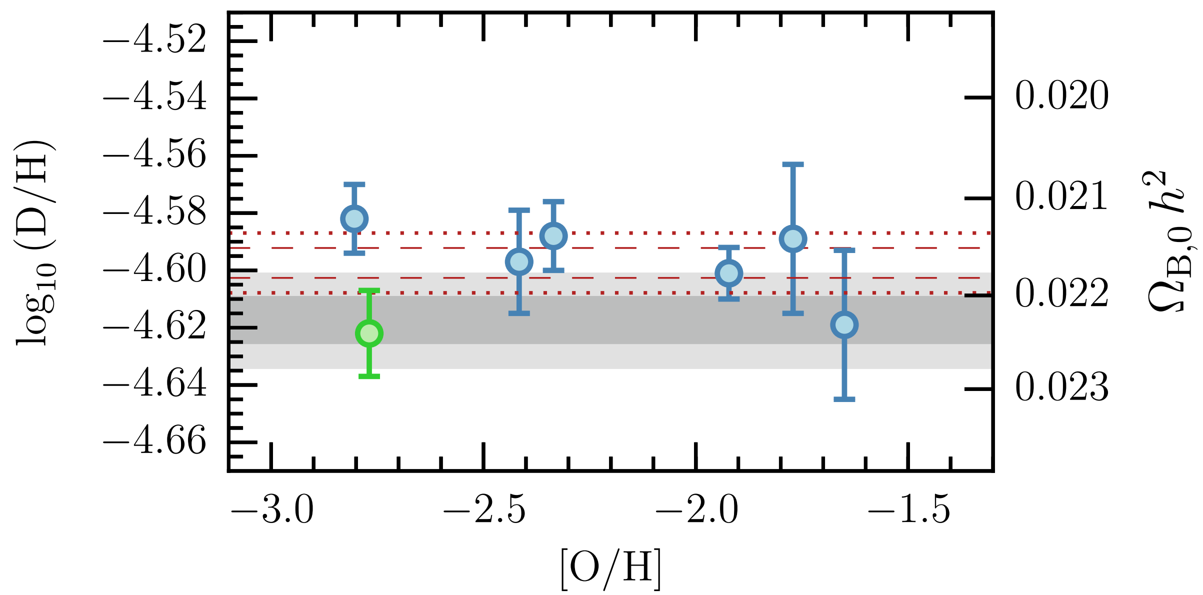
Addison *et al.* (2018), ApJ 853, 119; 1707.06547

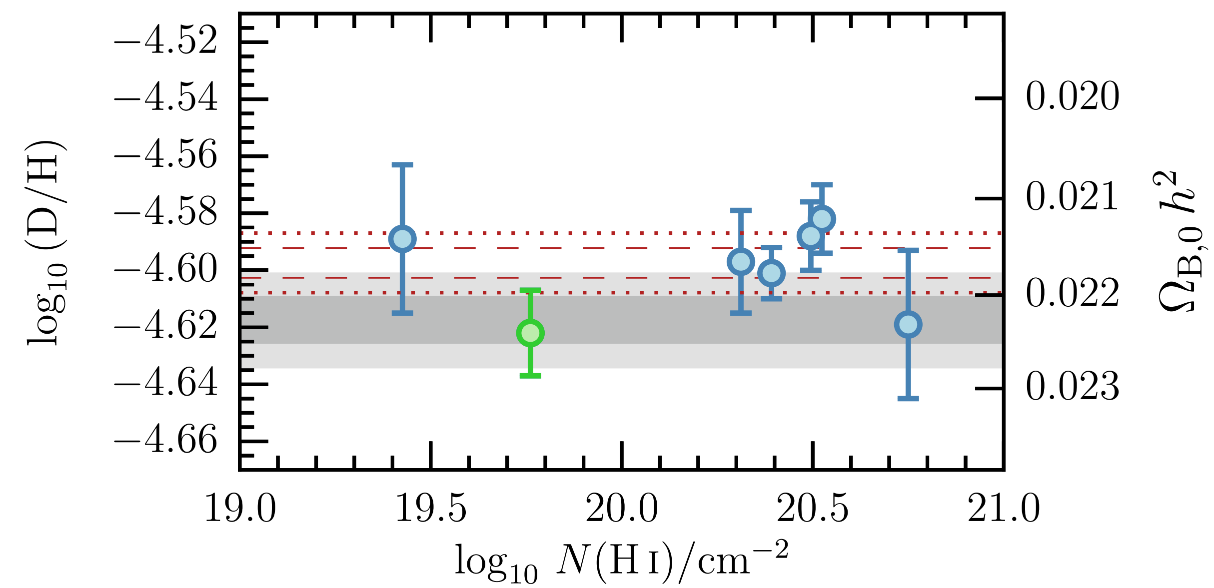
CMB & BAO synergy



Addison *et al.* (2018)

Breaking the BAO H_0-r_d degeneracy with baryon density constraint



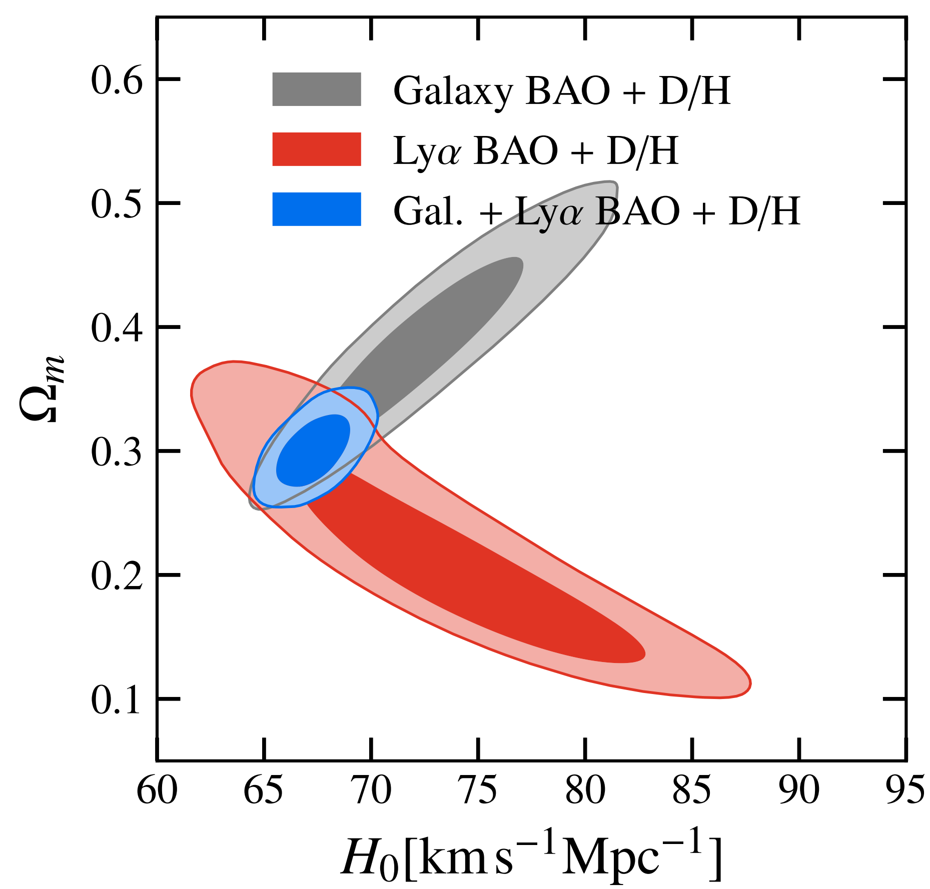


- Need external constraint on baryon density to get H_0 from BAO
- Want something independent from the CMB anisotropy
- ***Primordial deuterium abundance*** sensitive to baryon-to-photon ratio (assuming standard Big Bang nucleosynthesis - BBN - physics)
- Estimated using extremely metal-poor damped Lyα systems to ~1% precision

Cooke *et al.* (2018), ApJ 855, 102; 1710.11129

H_0 from BAO+D/H

2019



Combining galaxy and Lyα BAO with D/H:

$\boldsymbol{H_0 = 67.32 \pm 1.17}$ **km s^{-1} Mpc^{-1}**

3.6σ lower than the distance ladder…

… and ***independent*** of CMB anisotropy measurements

$d(p,\gamma)^3$He reaction rate uncertainty important: empirical rate -> **68.19 ± 1.21 km s^{-1} Mpc^{-1}**

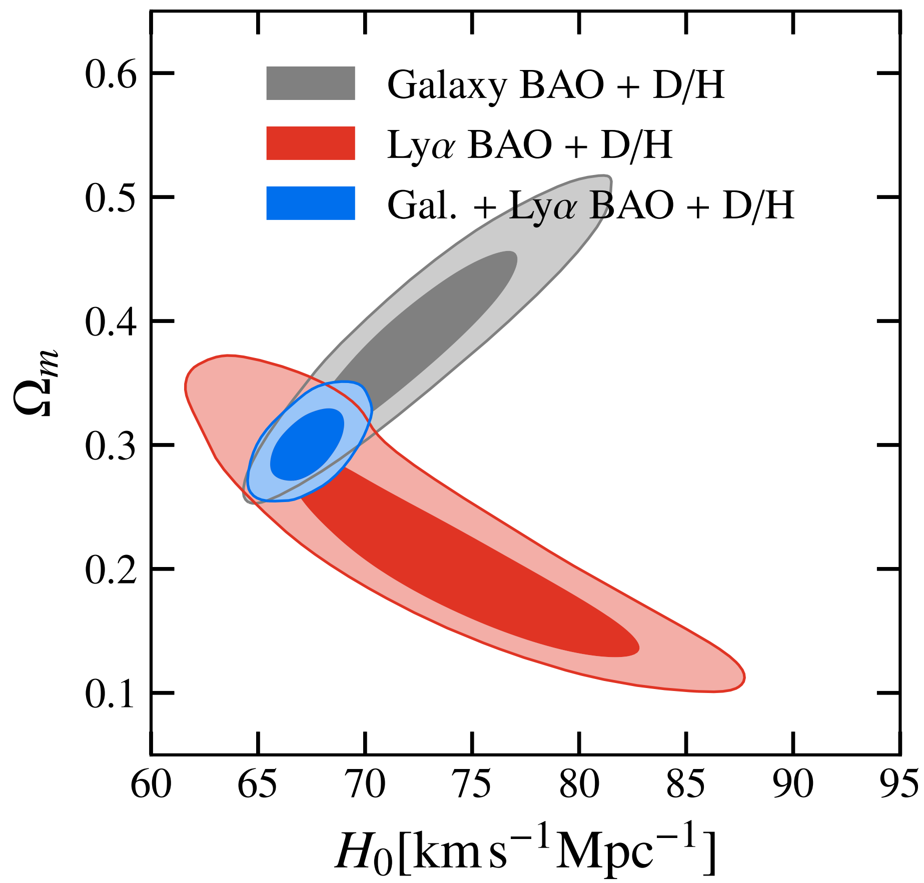
(3.1σ)

Big improvement compared to first BAO+D/H constraint **68.9 ± 3.0 km s^{-1} Mpc^{-1}** (Addison, Hinshaw & Halpern 2013, MNRAS 436, 1674; 1304.6984)

[see also e.g., Aubourg *et al.* 2015, PhRvD 92, 12, 123516; 1411.1074 and Cuceu *et al.* 2019, 1906.11628]

Galaxy, Lyα BAO not in perfect agreement…

2019



But can switch Lyα for other data and get similar result:

DES (2018, MNRAS 480, 3; 1711.00403)
67.4 ± 1.2 km s^{-1} Mpc^{-1}

Planck CMB lensing (+n_s prior, 2018; 1807.06210)
67.9 ± 1.3 km s^{-1} Mpc^{-1}

Gamma-ray attenuation (2019; 1903.12097)
67.5 ± 1.5 km s^{-1} Mpc^{-1}

Upcoming BAO from:

- **eBOSS quasars** (z_{eff}~1.5, e.g., Ata *et al.* 2018, MNRAS 473, 4773, 1705.06373)
- **eBOSS LRGs** (z_{eff}~0.72, Bautista *et al.* 2018, ApJ 863, 110, 1712.08064)
- **DESI** (bright z<0.4 galaxies, z<1 LRGs, z<1.6 ELGs, QSOs, Lyα)
- **Euclid** (planned June 2022 launch, primary target Hα ELGs at 0.9<z<1.8)

BAO + D/H

- D/H + CMB mean temperature (*COBE*/FIRAS) +BBN physics provides $\Omega_b h^2$
- Calculate r_d as function of Ω_m, $\Omega_b h^2$, and H_0 assuming ΛCDM
- Independent of CMB *anisotropy*
- r_d integral depends on early universe physics

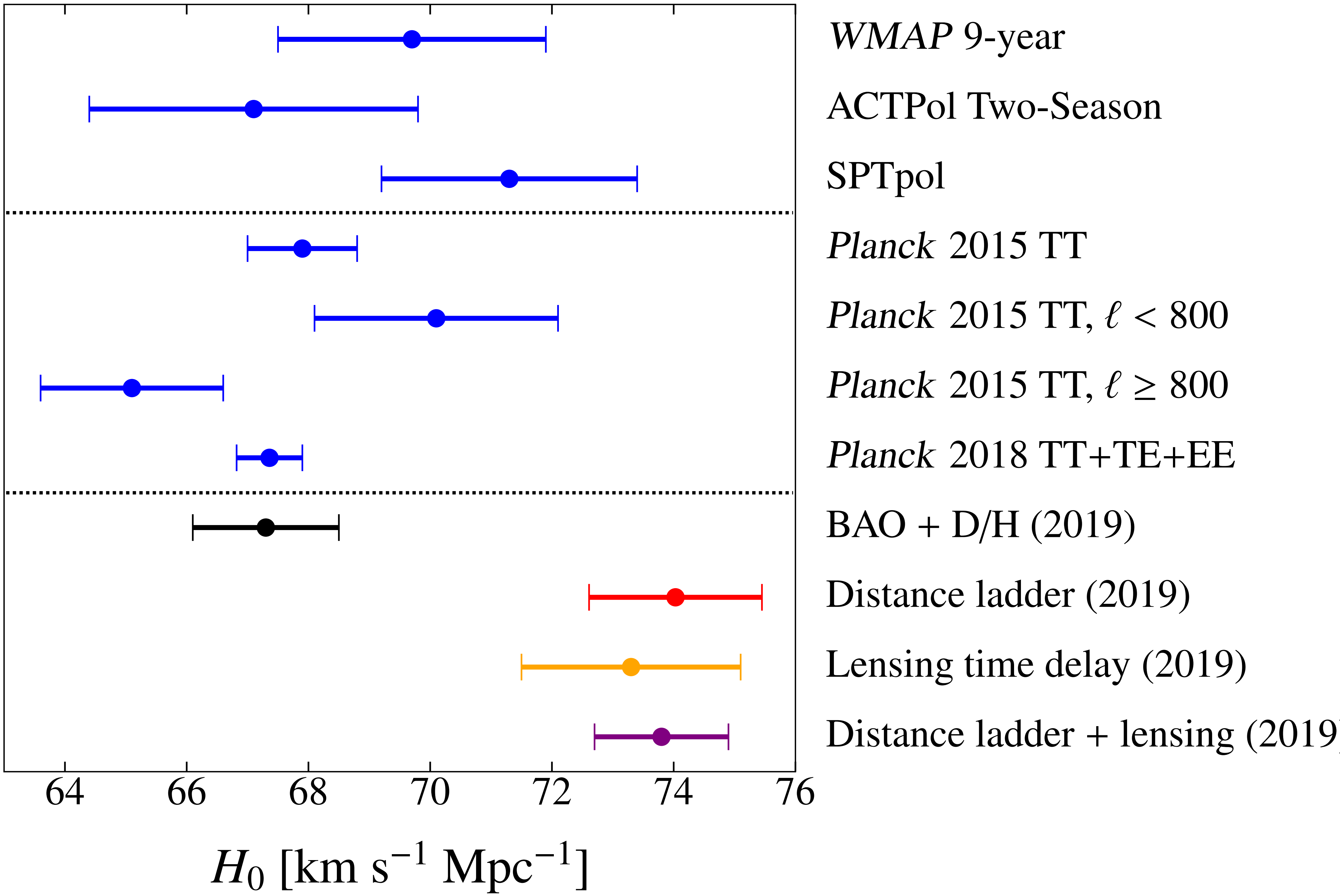
Addison, Hinshaw & Halpern (2013)

Inverse distance ladder

- Use r_d constraint from e.g. *WMAP* or *Planck*
- Constrain H_0 using BAO, optionally other low-redshift data (e.g. SNe)
- Test late-time expansion e.g. modifying dark energy
- r_d from CMB depends on early universe physics

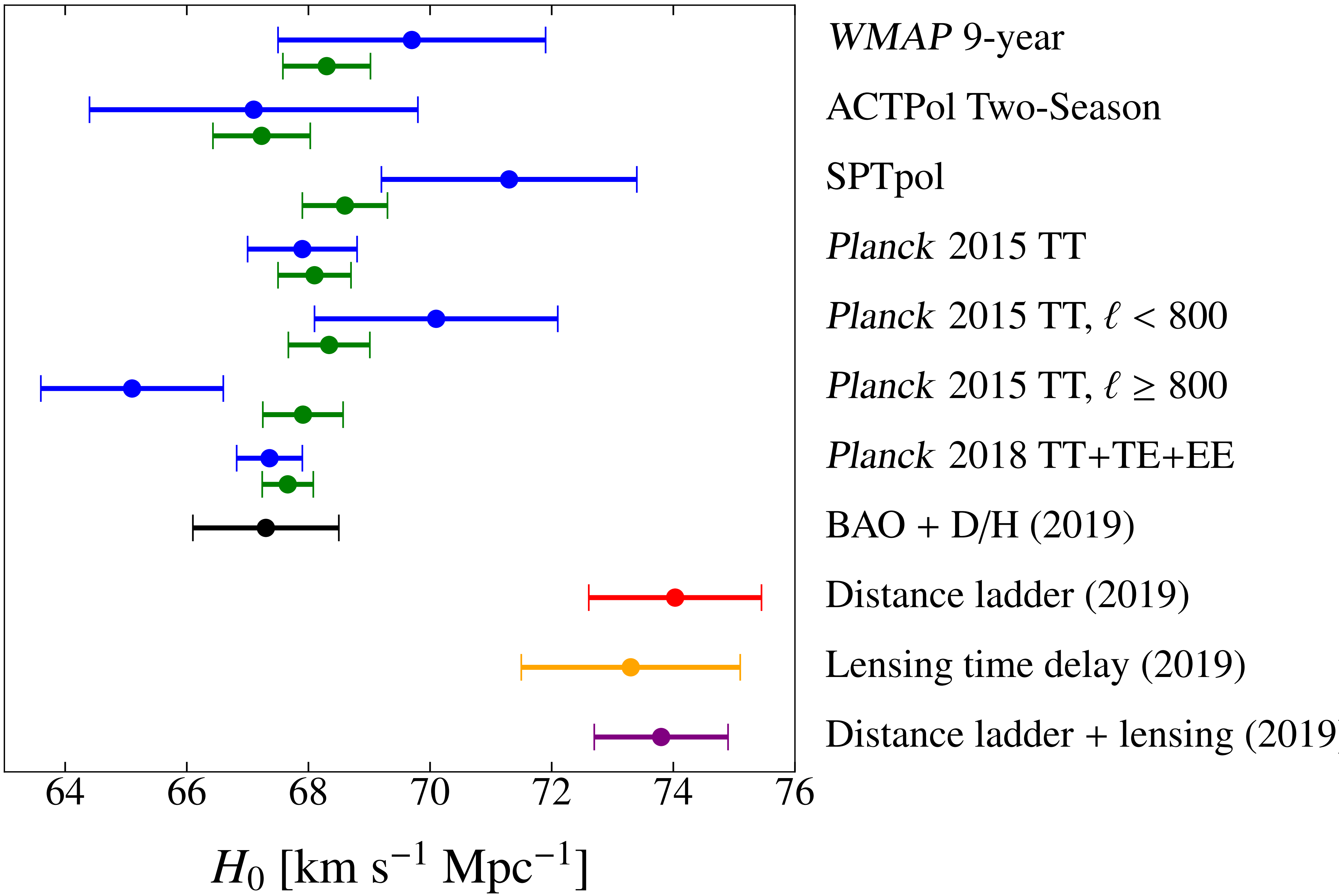
Aubourg *et al.* (2015)

H_0 comparison



(w/τ prior of 0.07 ± 0.02 for TT/suborbital)

H_0 comparison (CMB + BAO)



(w/τ prior of 0.07 ± 0.02 for TT/suborbital)

H_0 tension is not (just) a *Planck* tension!

- Combining *WMAP* data with BAO gives 68.30 ± 0.72 km s^{-1} Mpc^{-1} (**3.6σ** lower than Riess *et al.* 2019, **4.2σ** lower than SH0ES+H0LiCOW 2019; Wong *et al.* 2019)

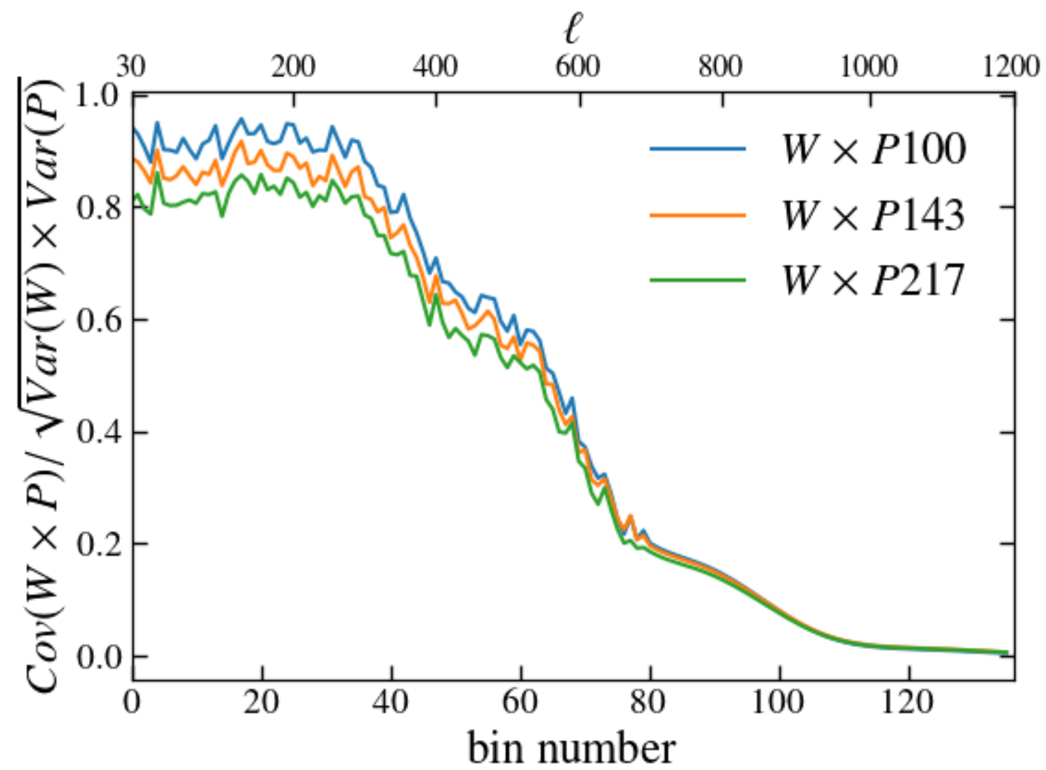
- BAO + D/H gives 67.3 ± 1.2 km s^{-1} Mpc^{-1} (**3.6σ / 4.0σ**), independent of *Planck* or any CMB anisotropy data

- We would be in the same situation even if we had never seen *Planck* data!

- Implications for resolving tension: theory modification to high-multipole power spectrum can't be main effect

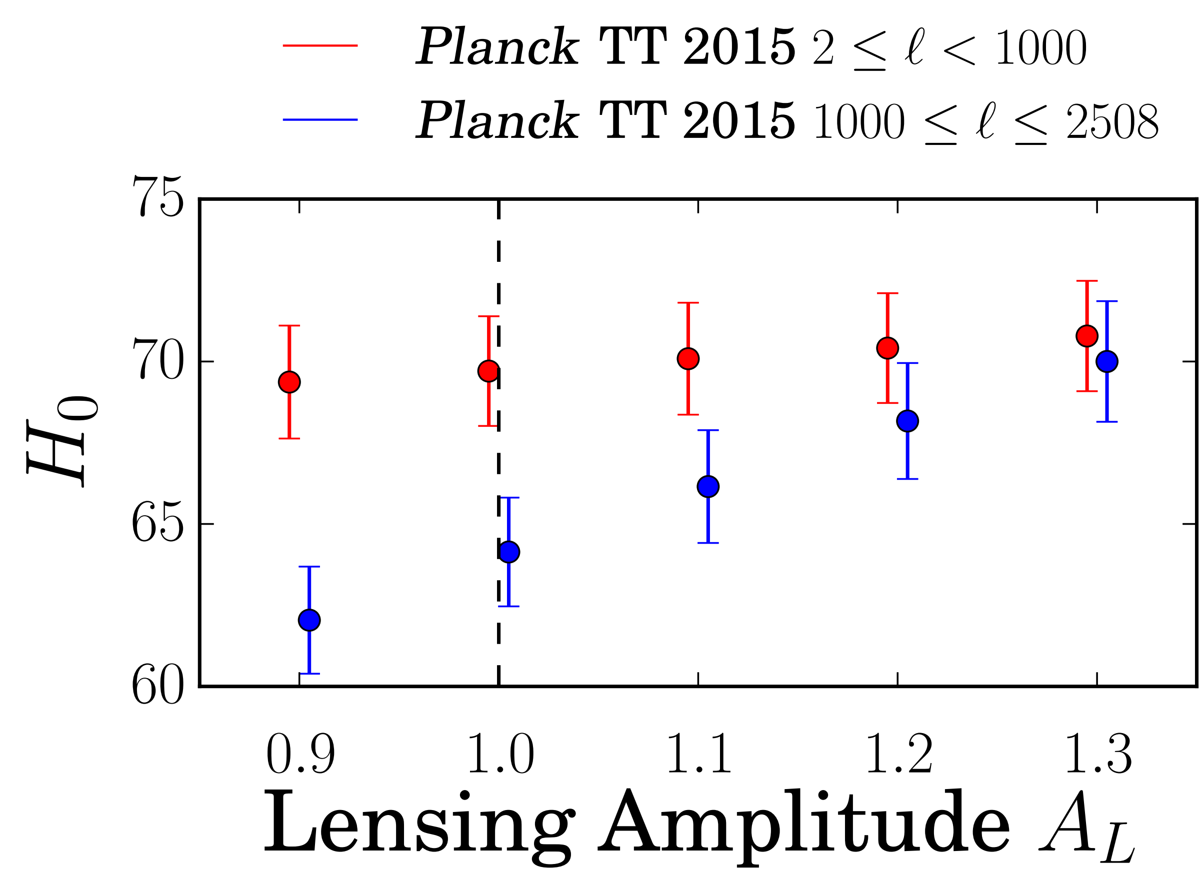
Internal *Planck* tension?

- *WMAP* & *Planck* TT spectra in good agreement over multipole range accessible to *WMAP*



- ~2.5σ tension in H_0 from different multipole ranges in *Planck*, connected to pref for A_L>1 in Planck TT

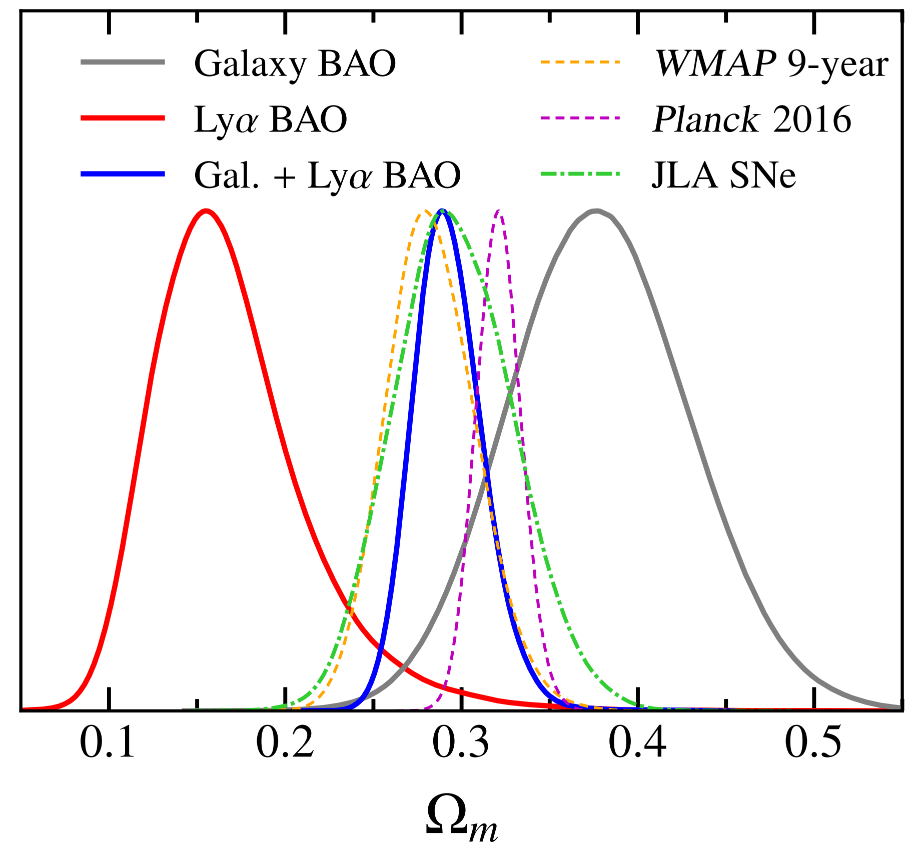
- But Hubble tension persists when adding BAO even if high multipoles discarded…



Addison *et al.* (2016), ApJ 818, 132, 1511.00055; Huang, Addison, *et al.* (2019), ApJ 869, 38; 1804.05428

Hypothesis: missing physics in early universe

- Let's take data at face value: H_0 really is (say) 73 km s^{-1} Mpc^{-1}
- Uncalibrated SNe and BAO agree well for late-time relative expansion, combined constraint Ω_m=0.300 ± 0.014

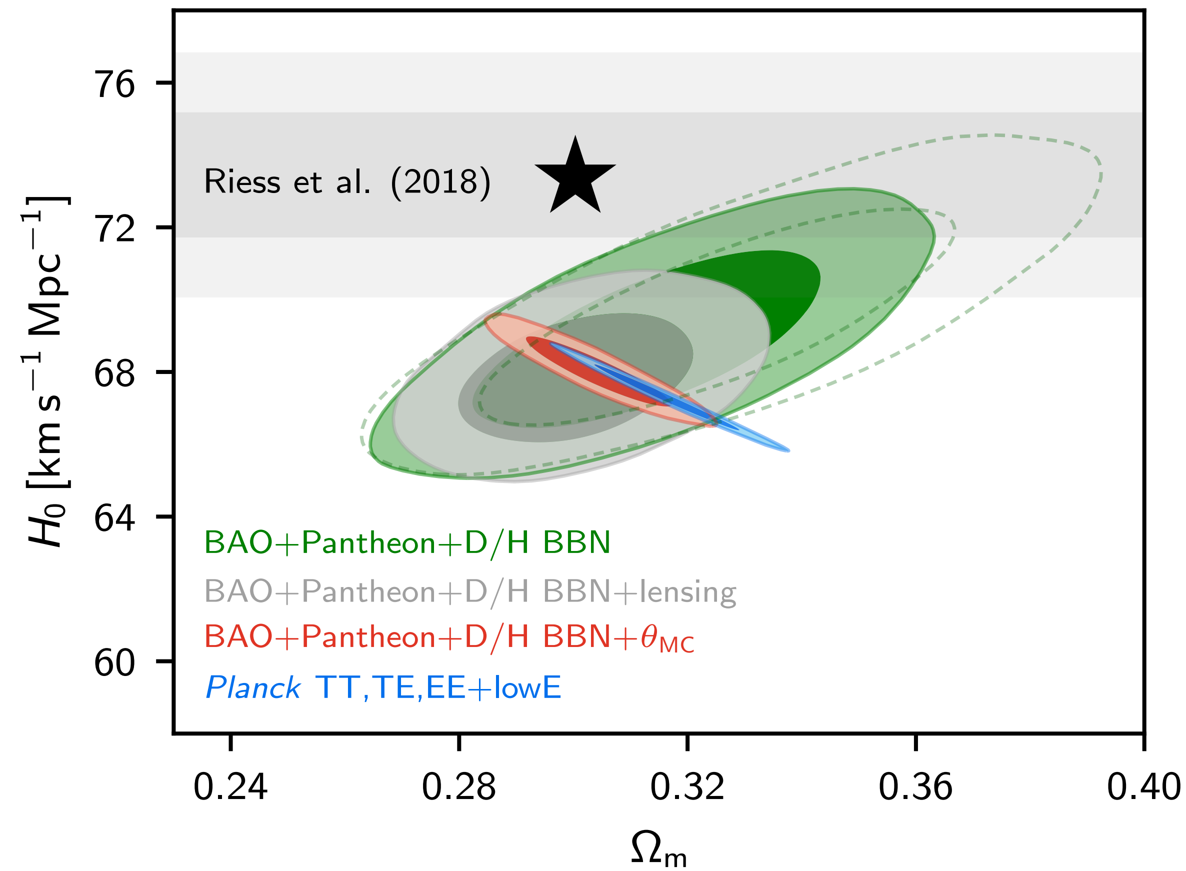


Addison *et al.* (2018)

Assume new physics takes *Planck* + BAO 'early universe' constraint from ΛCDM values to H_0=73, Ω_m=0.3

Hypothesis: missing physics in early universe

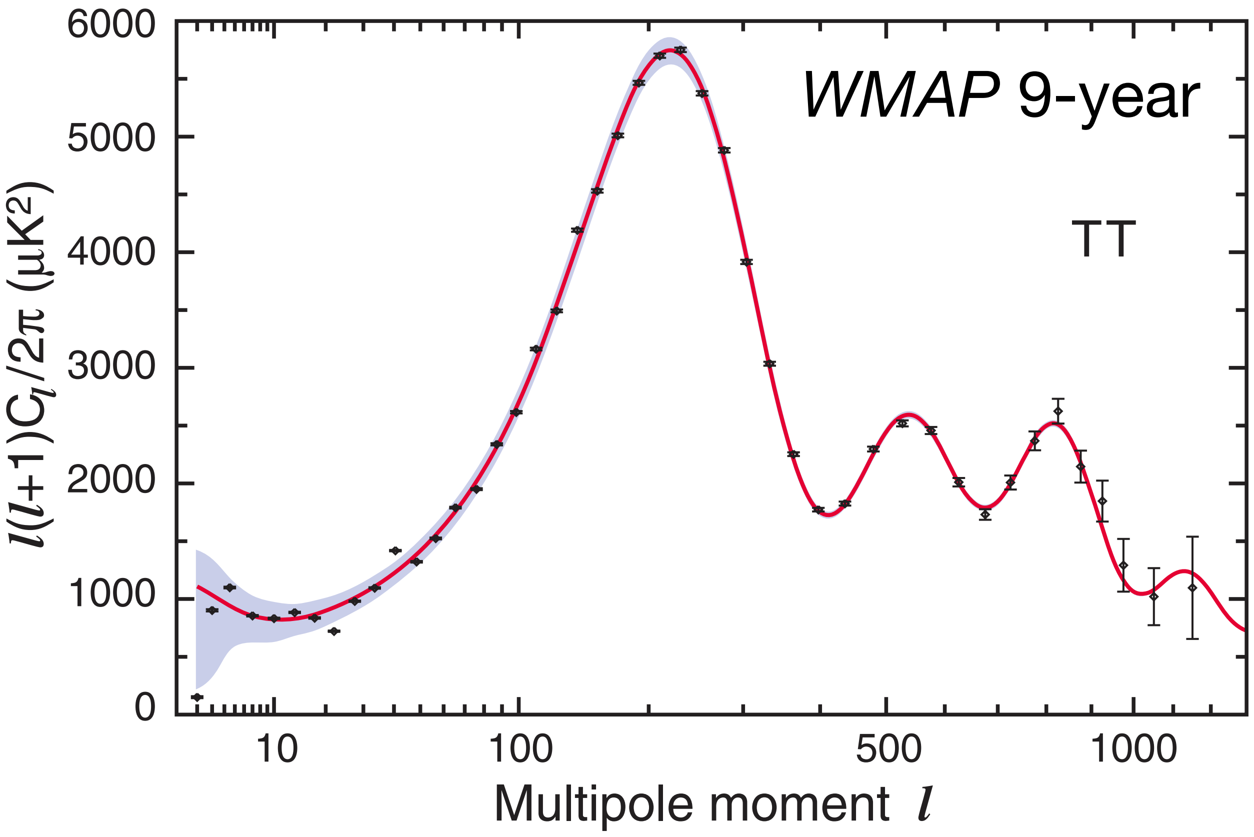
- Getting from H_0 of 67.66 ± 0.42 (*Planck* 2018 + BAO) to 73 km s^{-1} Mpc^{-1} is **13σ**
- In 2D it's even further (**65σ**) to get to (73, 0.3)



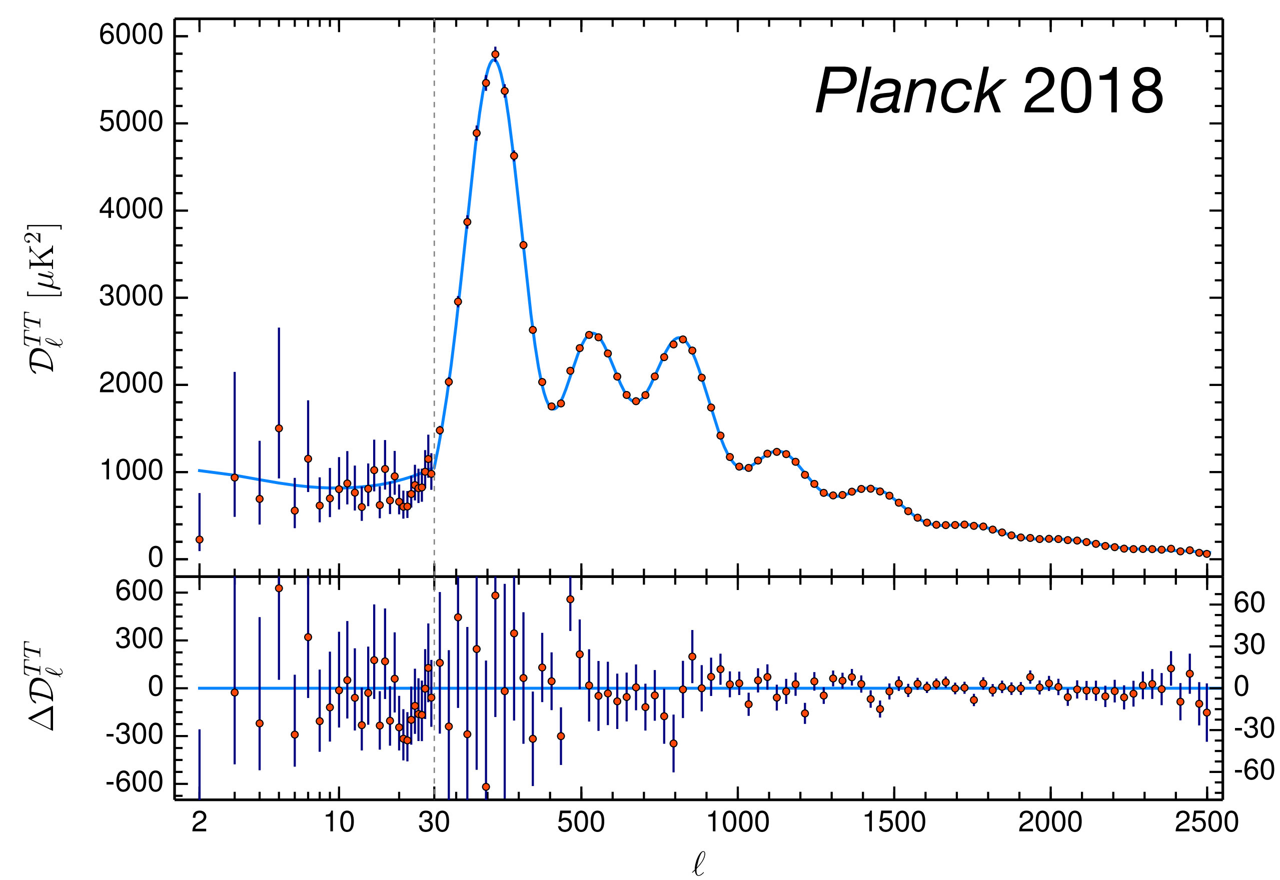
Planck VI 2018, 1807.06209

ΛCDM is very far from the true model for this scenario

But then why does ΛCDM fit so well?!



- *WMAP* shrunk allowed 6D ΛCDM parameter space by few x 10^4 (Bennett *et al.* 2013)
- *Planck* added another factor ~300
- Also CMB mean temperature (*COBE*/FIRAS), BBN, BAO…



- Consistent message from data ***actually sensitive to early universe***: ΛCDM good fit
- Deviations from ΛCDM in early universe likely to be 'small'

Requests for data analysts!

- More reproducibility! Allocate resources to write, test, document likelihood codes.

- Release more **low-level data products** where fewer choices and assumptions have been made (e.g., binned two-point clustering measurements rather than just final BAO scale…)

- Make it clear where ***cosmology dependence*** enters analysis! E.g., choice of fiducial models, input for simulations, estimating uncertainties / covariance, etc.

Requests for theorists!

- Make calculations reproducible! Preferably as public modifications to standard codes (e.g., CAMB, CLASS).

- Calculate forecasts for observables beyond current experiments: ***Where can we test / falsify your models? Where are deviations from ΛCDM most apparent?***

- E.g., **Large-scale structure:** how different is the matter power spectrum at $0<z<2$ (check with DESI, Euclid, WFIRST, etc.)?

- E.g., **Future CMB:** how will more precise TE, EE, lensing measurements help? (lots of room for improvement over *Planck* with Adv. ACTPol, SPT-3G, Simons Obs., CMB-S4)

Conclusions

- BAO scale measurements *alone* cannot constrain H_0, need external information to break degeneracy with sound horizon at drag epoch, r_d

- Hubble tension is not a *Planck* tension! ΛCDM H_0 from other CMB+BAO, or BAO+D/H, in 4σ+ tension w/SH0ES & H0LiCOW 2019

- Hard to resolve tension with late-time modification (see e.g., inverse distance ladder), requires contrived w(z), H(z) etc.

- But data sensitive to early universe (CMB, BBN, BAO) in good agreement with ΛCDM; no evidence for large deviation

So what is going on?