Elucidating CDM: Impact of Baryon Acoustic Oscillation Measurements on the Hubble Constant Discrepancy

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Tensions in the LCDM paradigm

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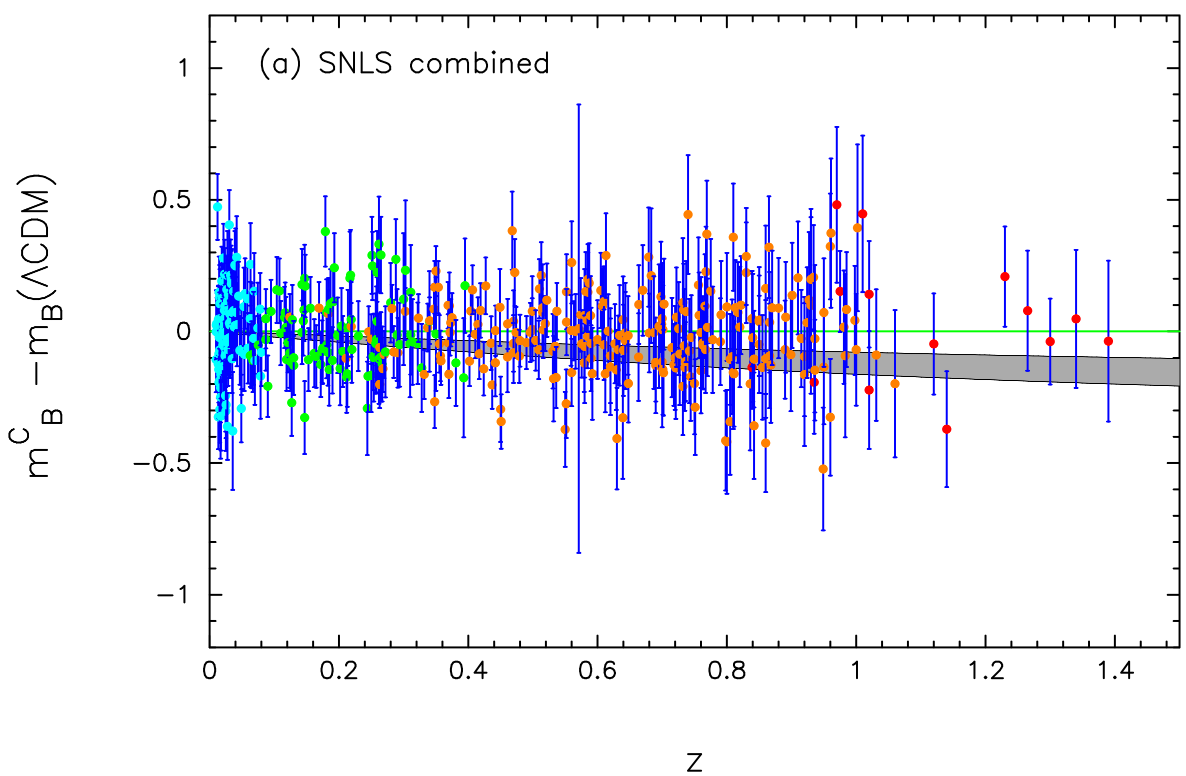
(updated post-Riess *et al.* 2018b 1804.10655, H_0=73.52±1.62)

Low-redshift tensions with *Planck* 2013

Planck XVI 2013 results in 2-2.5σ tension with various low-redshift measurements…



Tensions with some high-redshift SNe compilations: ***resolved with improved / unified SNe calibration*** (Betoule *et al.* 2014)

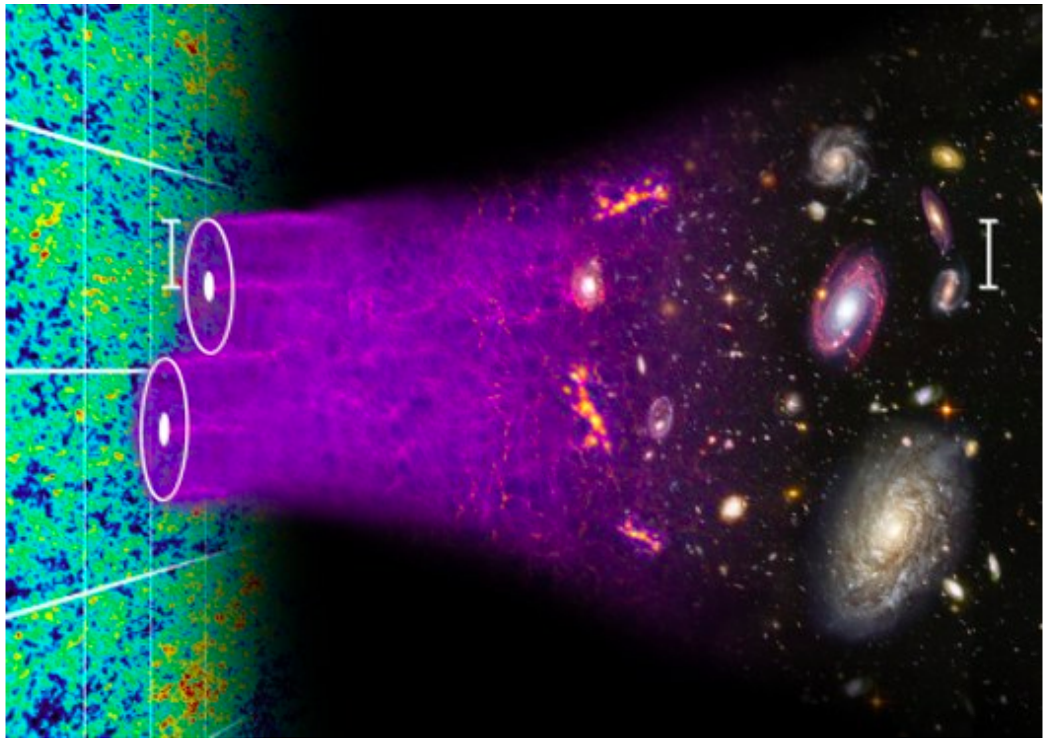
Tensions with some galaxy weak lensing surveys: ***not fully resolved;*** a lot of scrutiny, more work on lensing systematics

Tensions with some cluster constraints: ***not fully resolved;*** mass calibration!

Tension with local distance ladder: ***much worse (2.5σ has become 3.8σ)!***

None of these effects disappeared as statistical fluctuations

What is the BAO scale?



- Standard ruler length set at recombination ('sound horizon')
- Expands with the universe
- **~150 Mpc comoving** large enough scale to be (nearly) unchanged by nonlinear growth

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

sound horizon

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

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

BAO observables

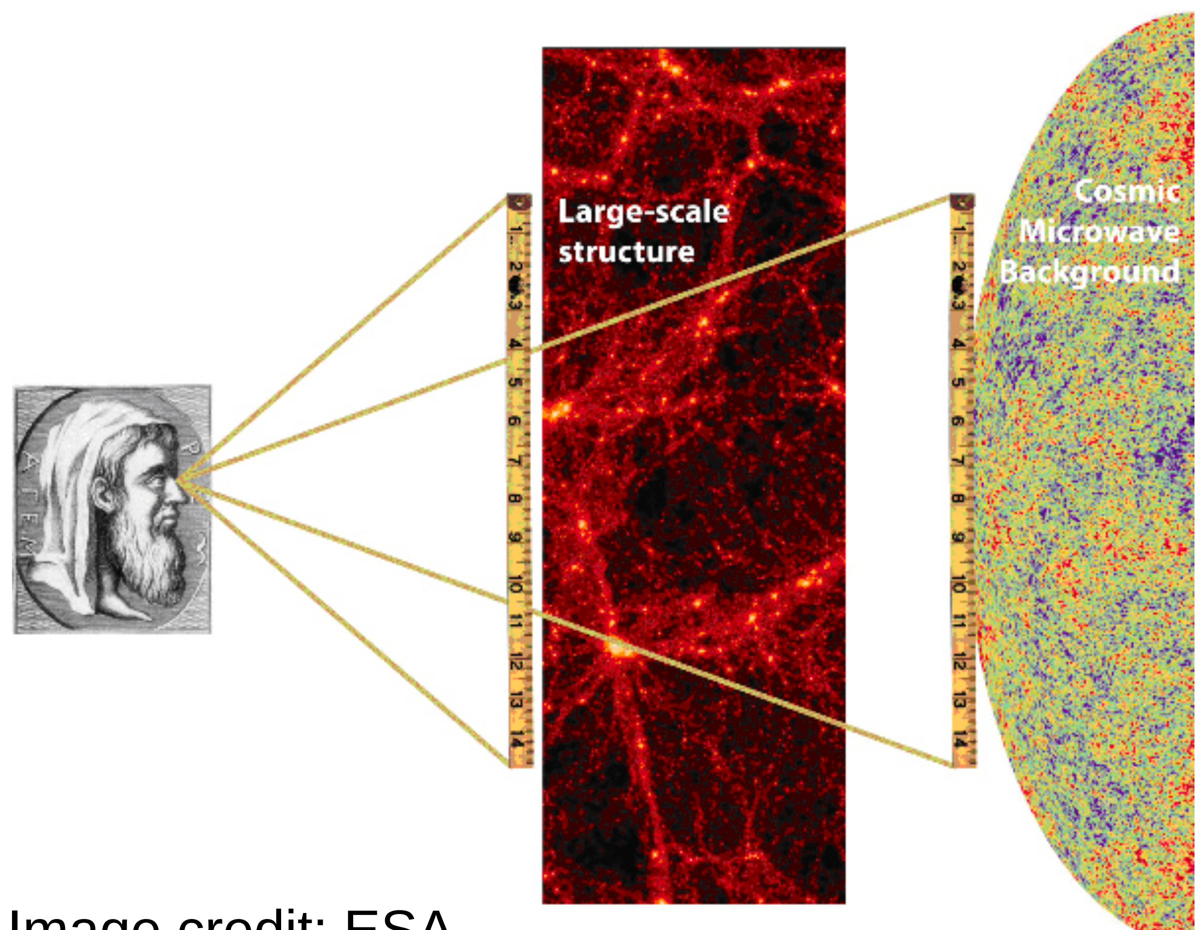


Image credit: ESA

What is the BAO scale?

- Early-universe expansion rate (***matter vs radiation***)
- ***Baryon-photon ratio***
- Number of effective ***neutrino species***

$$\Delta\theta = r_{\rm s}/(1+z)D_{\rm A}$$

Late-time expansion (***matter vs dark energy***)

BAO measurements alone cannot distinguish between change in absolute sound horizon r_s and change in H_0

Addison *et al.* (2018): BAO data sets

Data Set	LSS Tracer	$z_{\rm eff}$	Measurement[a]	Constraint[a]	References
6dFGS	galaxies	0.106	$r_d/D_V(z_{\rm eff})$	0.336 ± 0.015	Beutler et al. (2011)
SDSS MGS	galaxies	0.15	$D_V(z_{\rm eff})r_{d,\rm fid.}/r_d$ [Mpc]	664 ± 25	Ross et al. (2015)
BOSS DR12	galaxies	0.38	$D_M(z_{\rm eff})r_{d,\rm fid.}/r_d$ [Mpc]	1512 ± 25	Alam et al. (2017)
			$H(z_{\rm eff})r_d/r_{d,\rm fid.}$ [km s^{-1} Mpc^{-1}]	81.2 ± 2.4	
		0.51	$D_M(z_{\rm eff})r_{d,\rm fid.}/r_d$ [Mpc]	1975 ± 30	
			$H(z_{\rm eff})r_d/r_{d,\rm fid.}$ [km s^{-1} Mpc^{-1}]	90.9 ± 2.3	
		0.61	$D_M(z_{\rm eff})r_{d,\rm fid.}/r_d$ [Mpc]	2307 ± 37	
			$H(z_{\rm eff})r_d/r_{d,\rm fid.}$ [km s^{-1} Mpc^{-1}]	99.0 ± 2.5	
BOSS DR11 Lyα	Lyα absorbers[b]	2.34	$D_A(z_{\rm eff})/r_d$	11.28 ± 0.65	Delubac et al. (2015)
			$c/[H(z_{\rm eff})r_d]$	9.18 ± 0.28	
BOSS DR11 QSO $\times$ Lyα	QSO, Lyα[b]	2.36	$D_A(z_{\rm eff})/r_d$	10.8 ± 0.4	Font-Ribera et al. (2014)
			$c/[H(z_{\rm eff})r_d]$	9.0 ± 0.3	

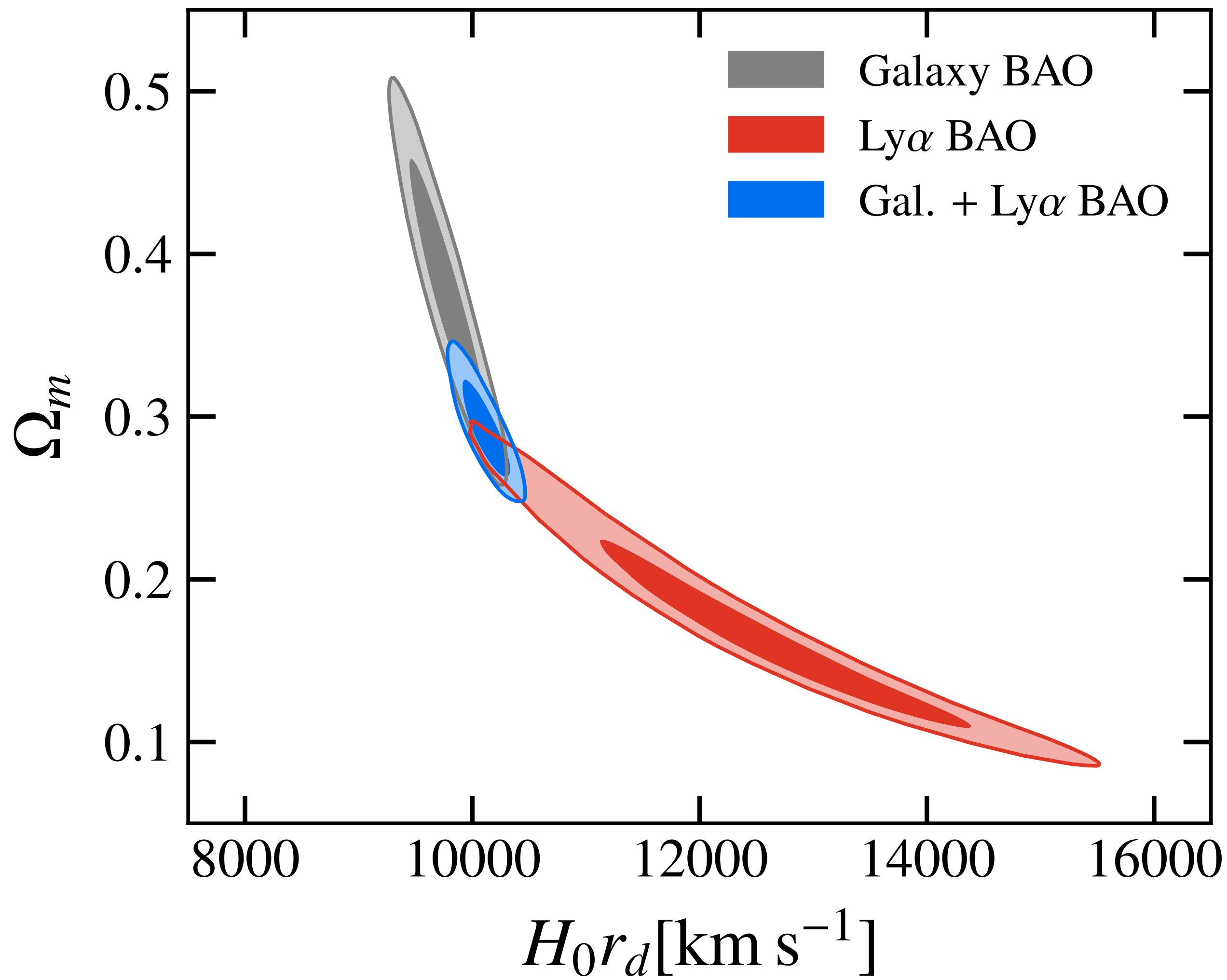
Caveats!

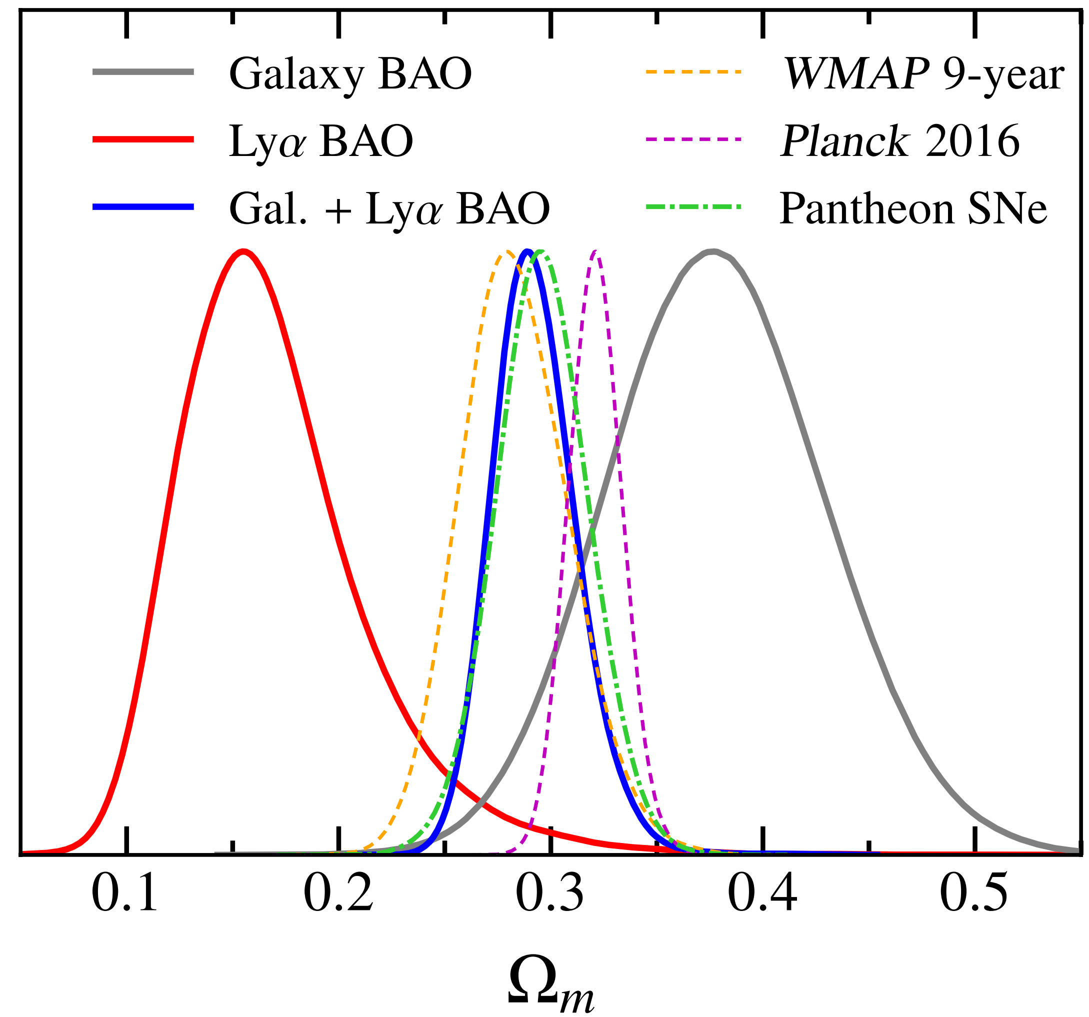
Assume Gaussian likelihood for some measurements: known to be inaccurate far from peak of likelihood for some of the less-precise measurements

Use BAO scale constraints like data points: not fit to 2-point measurements

Error bars from sims: assume fiducial cosmological model and values of params for covariance; validity beyond LCDM? (e.g. $N_{\rm eff}$)

Comparing galaxy and Lyα BAO



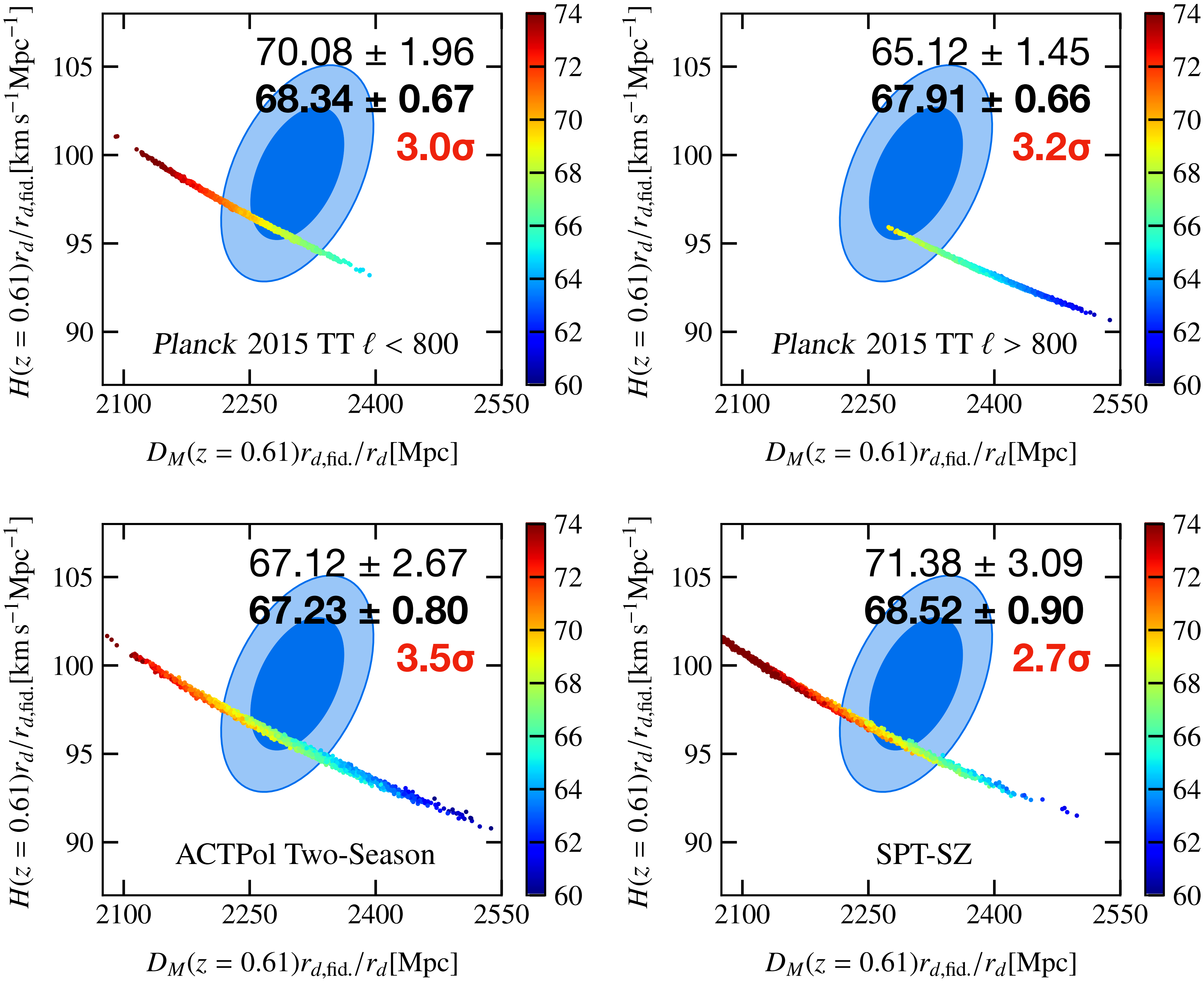


For flat LCDM ***ALL*** BAO constrain Ω_m and $H_0 r_d$ (Addison *et al.* 2013)

Combined fit produces matter density in agreement with CMB, SNe

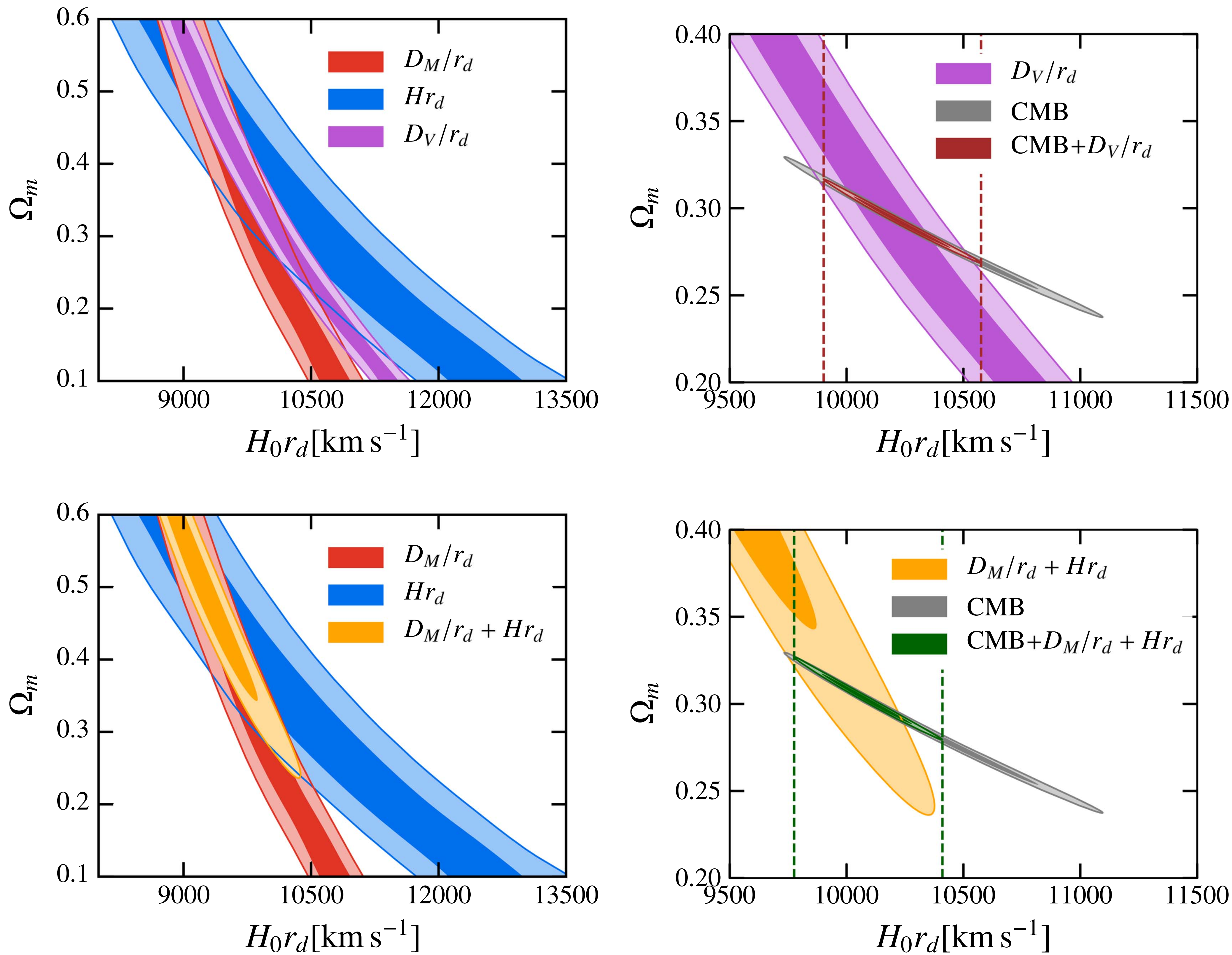
But ~2.4σ tension between galaxy and Lyα measurements

Synergy between BAO and CMB



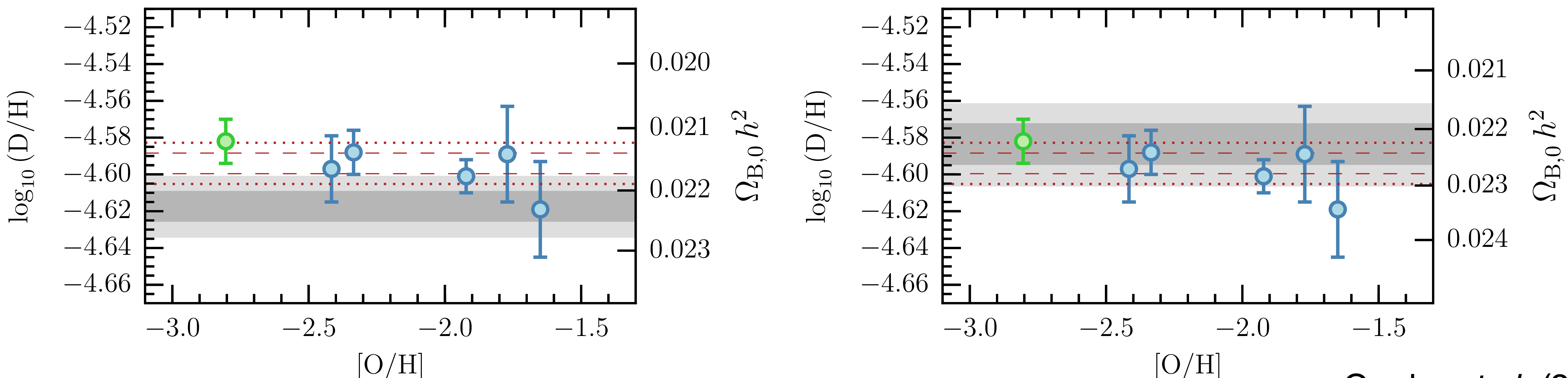
$\tau = 0.07 \pm 0.02$

Synergy between BAO and CMB



Angle-averaged D_V is compression of information - diminishes downward pull on H_0 in CMB+BAO

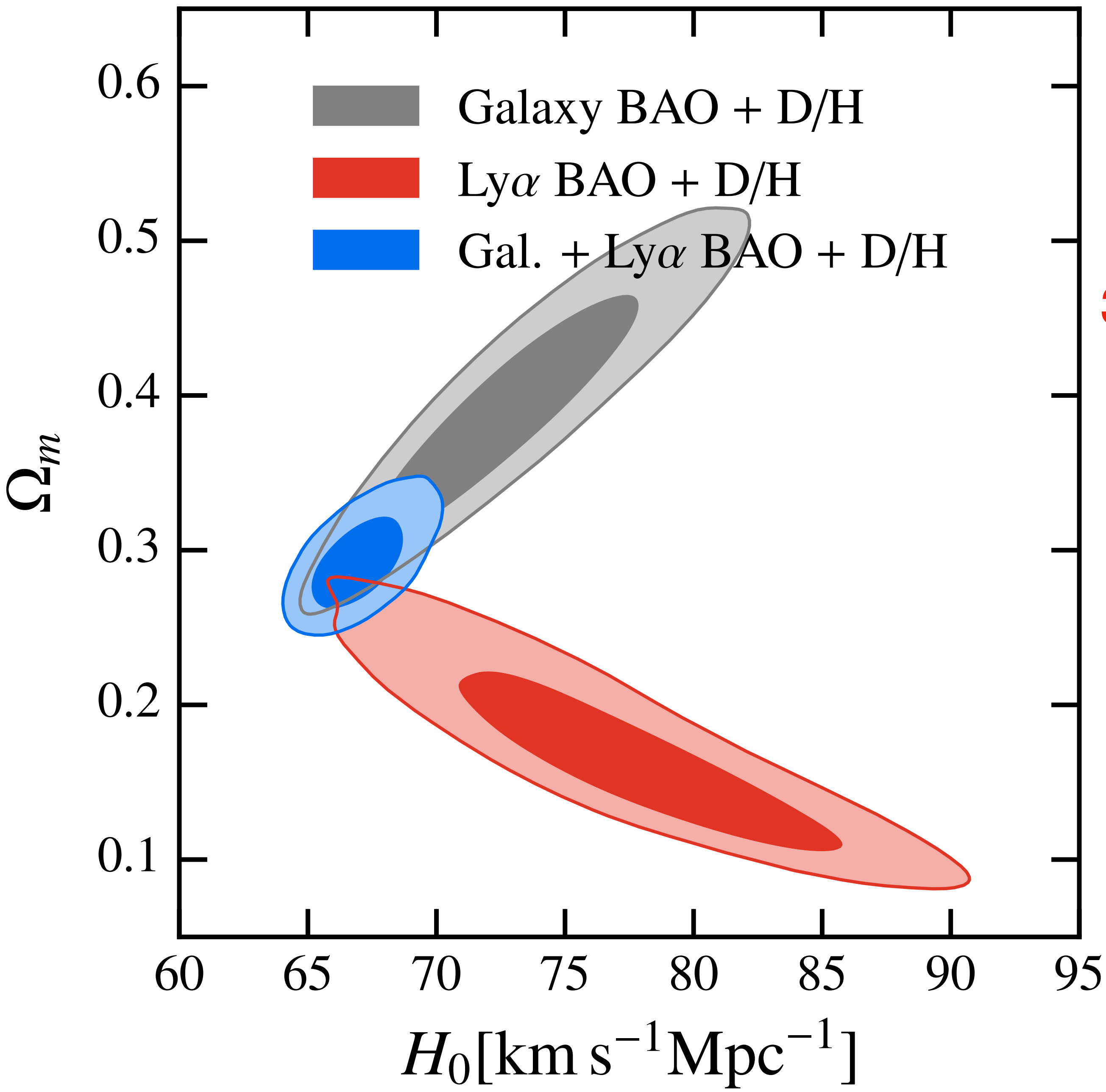
Breaking the BAO H_0-r_d degeneracy with baryon density constraint



Cooke *et al.* (2016)

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

BAO + baryon density from D/H



Combining galaxy and Lyα BAO with D/H:

$\boldsymbol{H_0}$ **= 66.98 ± 1.18 km s^{-1} Mpc^{-1}**

3.3σ

~~3.0σ~~ lower than the distance ladder…

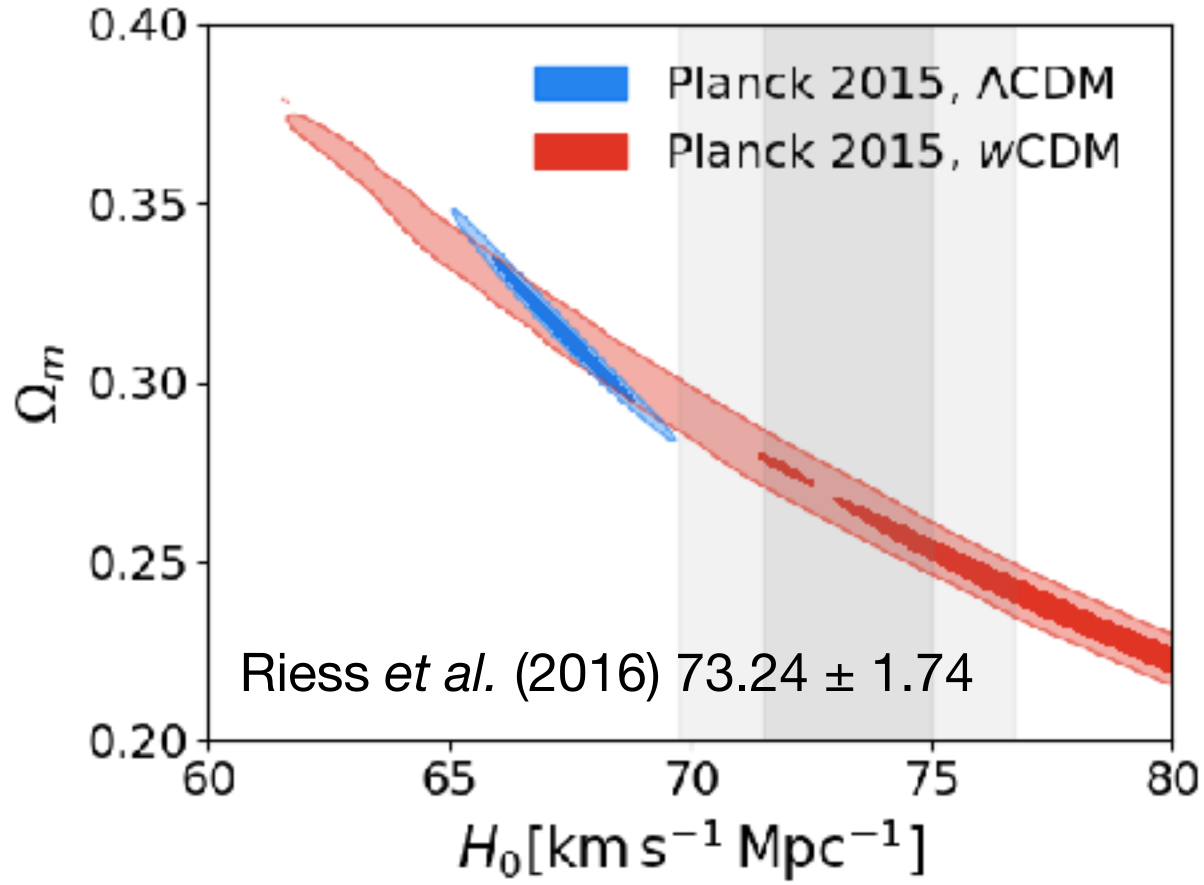
… and ***independent*** from CMB anisotropy measurements

d(*p*,γ)^{3}He reaction rate uncertainty important: empirical rate -> **67.81 ± 1.25 km s^{-1} Mpc^{-1}**

~~2.5σ~~ 2.8σ

Big improvement in precision (Addison *et al.* 2013: **68.9 ± 3.0 km s^{-1} Mpc^{-1}**)

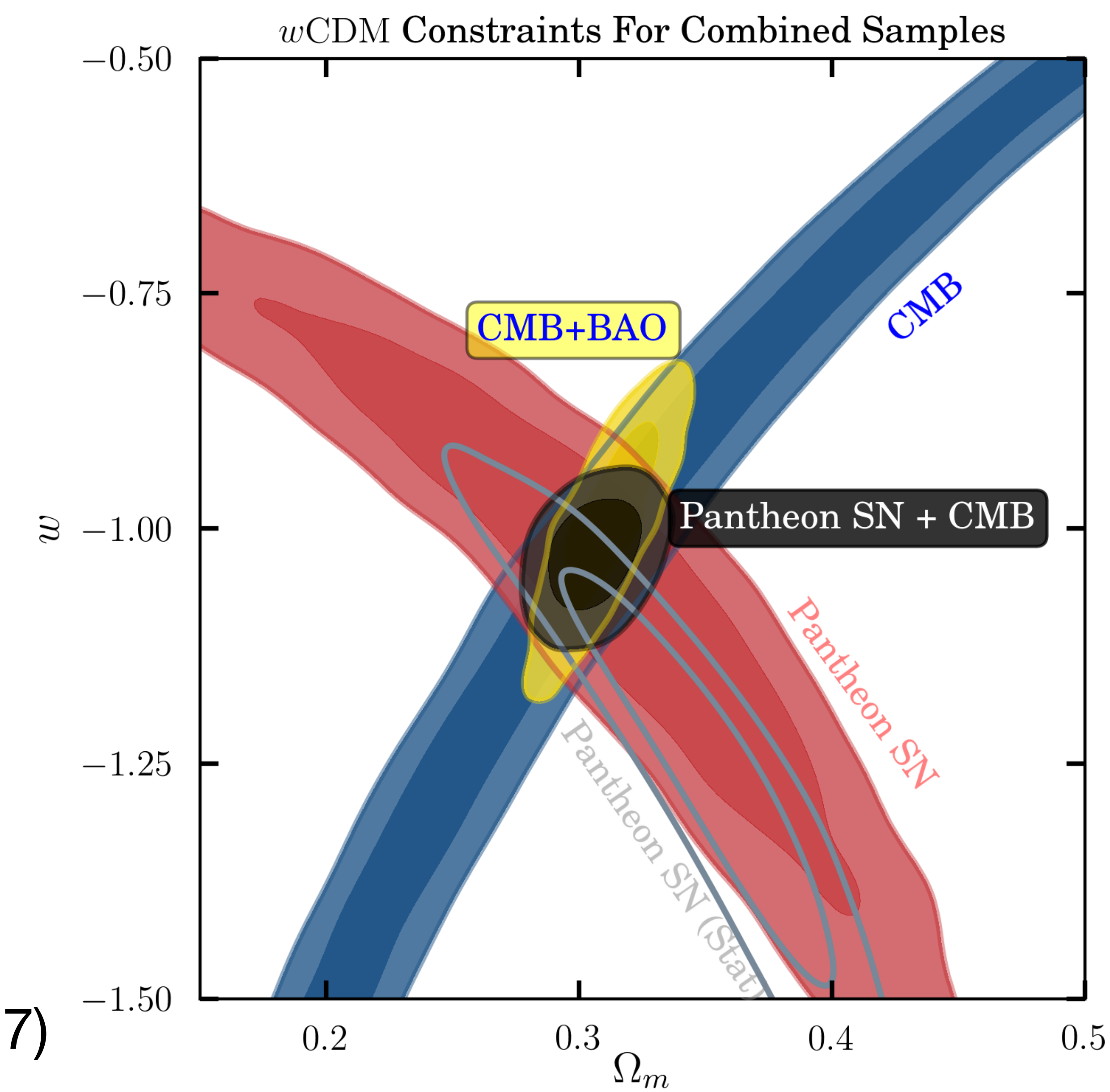
Galaxy, Lyα BAO individually prefer higher H_0…



Changing the CMB prediction for H_0?

Changing low-redshift expansion history ***very*** effective at shifting CMB prediction for H_0…

But BAO and higher-z SNe do not allow big enough shifts to reconcile with distance ladder!



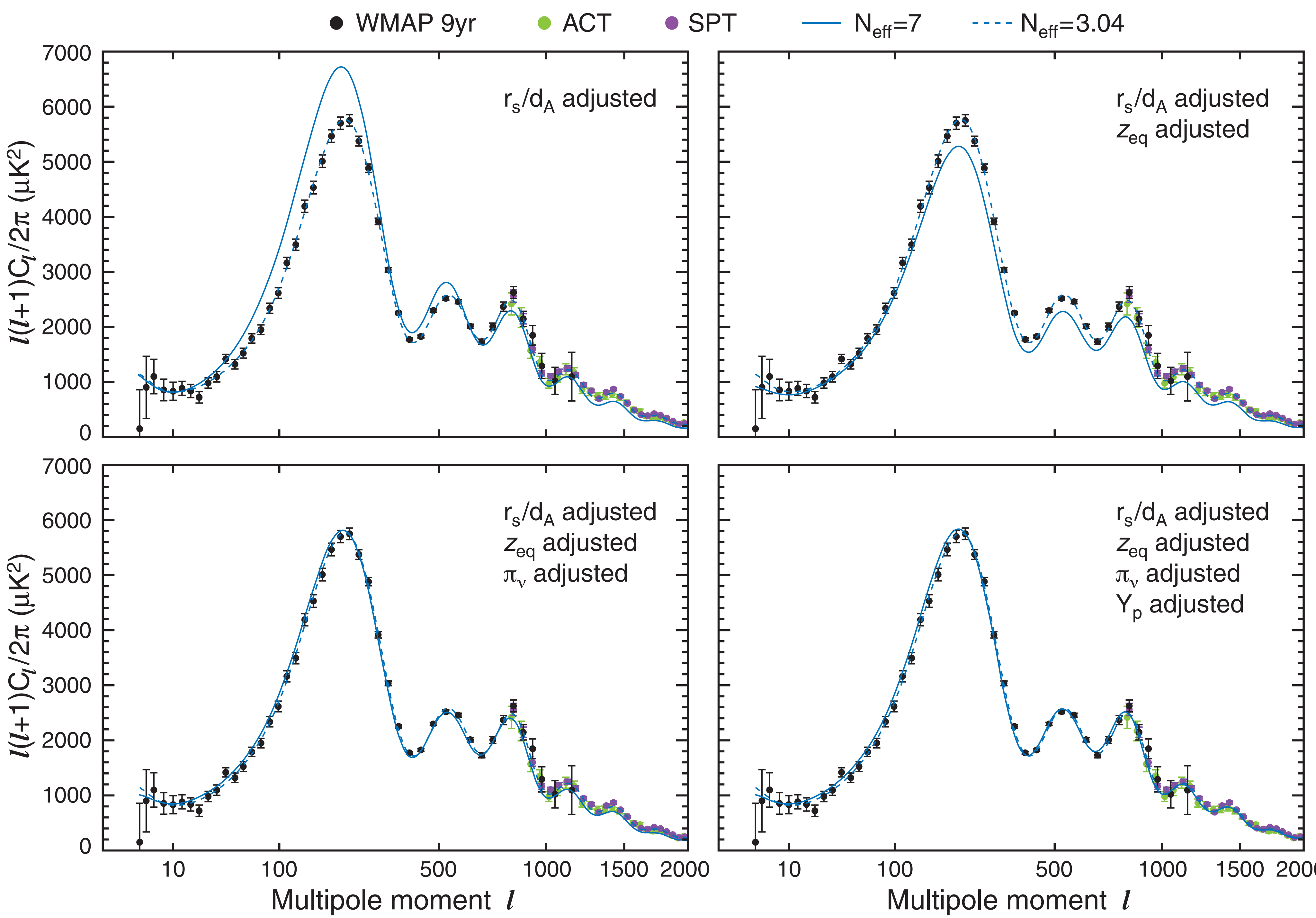
Planck, SNe, BAO
68.14 ± 0.85 (w)
68.18 ± 0.87 (w_0, w_a)

Scolnic *et al.* (2017)

Changing early universe physics?

- CMB, BAO, D/H & BBN data have some common dependence on early universe physics
- BUT dependence not the same! Not obvious in practice that a solution with H_0 compatible with distance ladder can be achieved.
- E.g. N_{eff}: affects BAO through sound horizon, affects BBN through early-universe expansion, affects CMB in several ways (not only acoustic scale through r_d)
- 67.5 ± 1.2 (Alam *et al.* 2017; *Planck*+BAO for LCDM+N_{eff})

N_{eff} impact on CMB



***N_{eff}* does NOT just affect *r_s* but also damping tail…** Hinshaw *et al.* (2013)

Conclusions

- Combining non-*Planck* CMB measurements with BAO produces H_0 values **2.7-3.5σ** lower than distance ladder
- BAO alone do not constrain H_0 (degeneracy with absolute sound horizon)
- Add information on baryon density (e.g. primordial deuterium abundance): tight H_0 constraint (**2.8-3.3σ** lower than distance ladder)
- But galaxy and Lyα BAO not in very good agreement with one another!
- Can't solely blame systematic in *Planck* data (although high-multipole *Planck* TT still drives tensions with other measurements)