Tensions in ΛCDM

Interplay between Particle and Astroparticle physics
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Addison *et al.* (2016), ApJ, 818, 132, **arXiv/1511.00055**
Addison *et al.* (2018), ApJ, 853, 119, **arXiv/1707.06547**
Huang, Addison, *et al.* (2018), ApJ submitted, **arXiv/1804.05428**

Overview

- Status of Hubble constant tension in 2018

- Challenges for new physics explanations

- Tensions in growth of structure (e.g., weak lensing)

Hubble constant tension in 2018

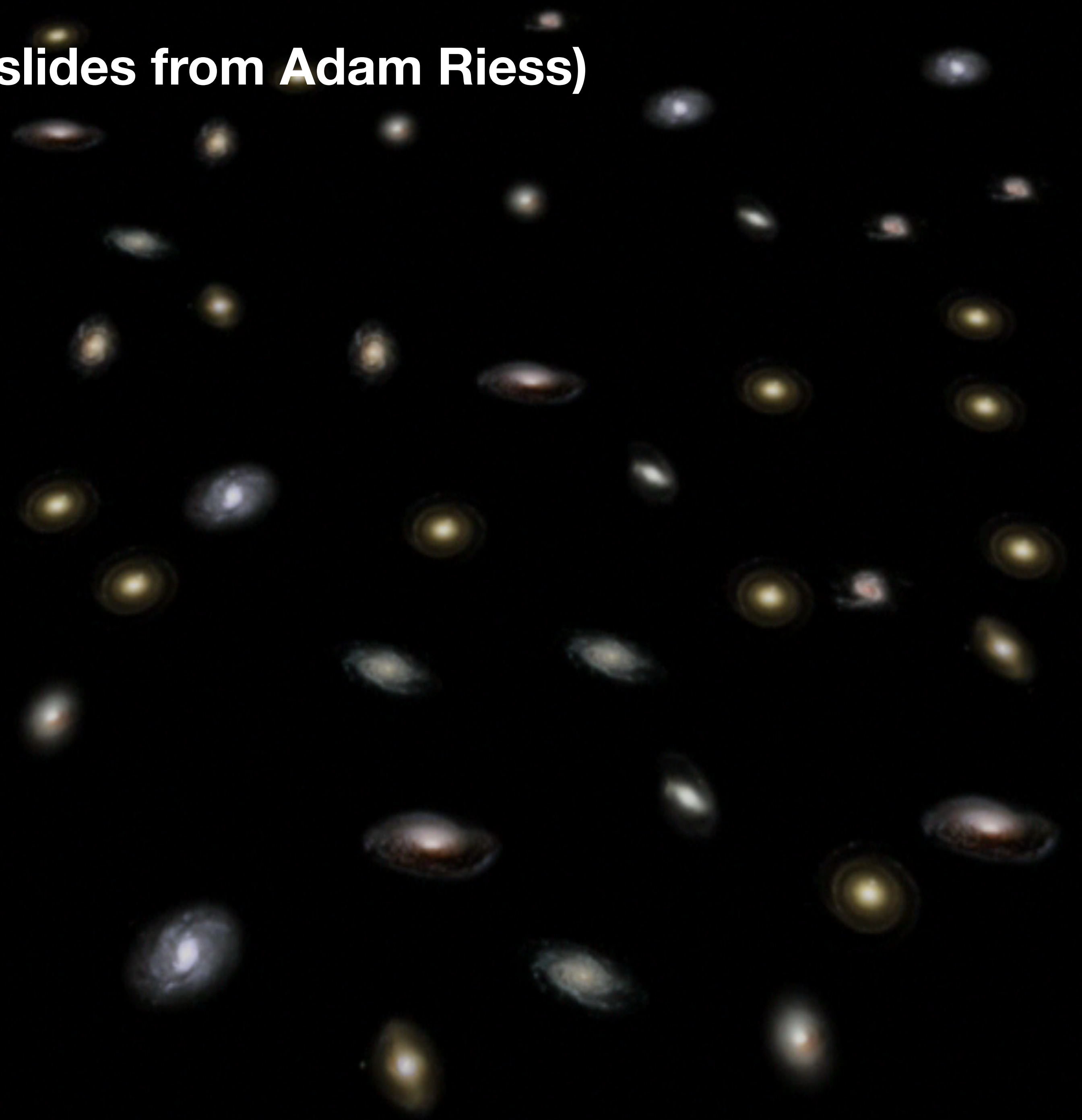
- **April 2018:** GAIA data release 2. New parallax measurements to Milky Way Cepheid variable stars. New distance ladder constraint **73.53 ± 1.62 km s^{-1} Mpc^{-1}**

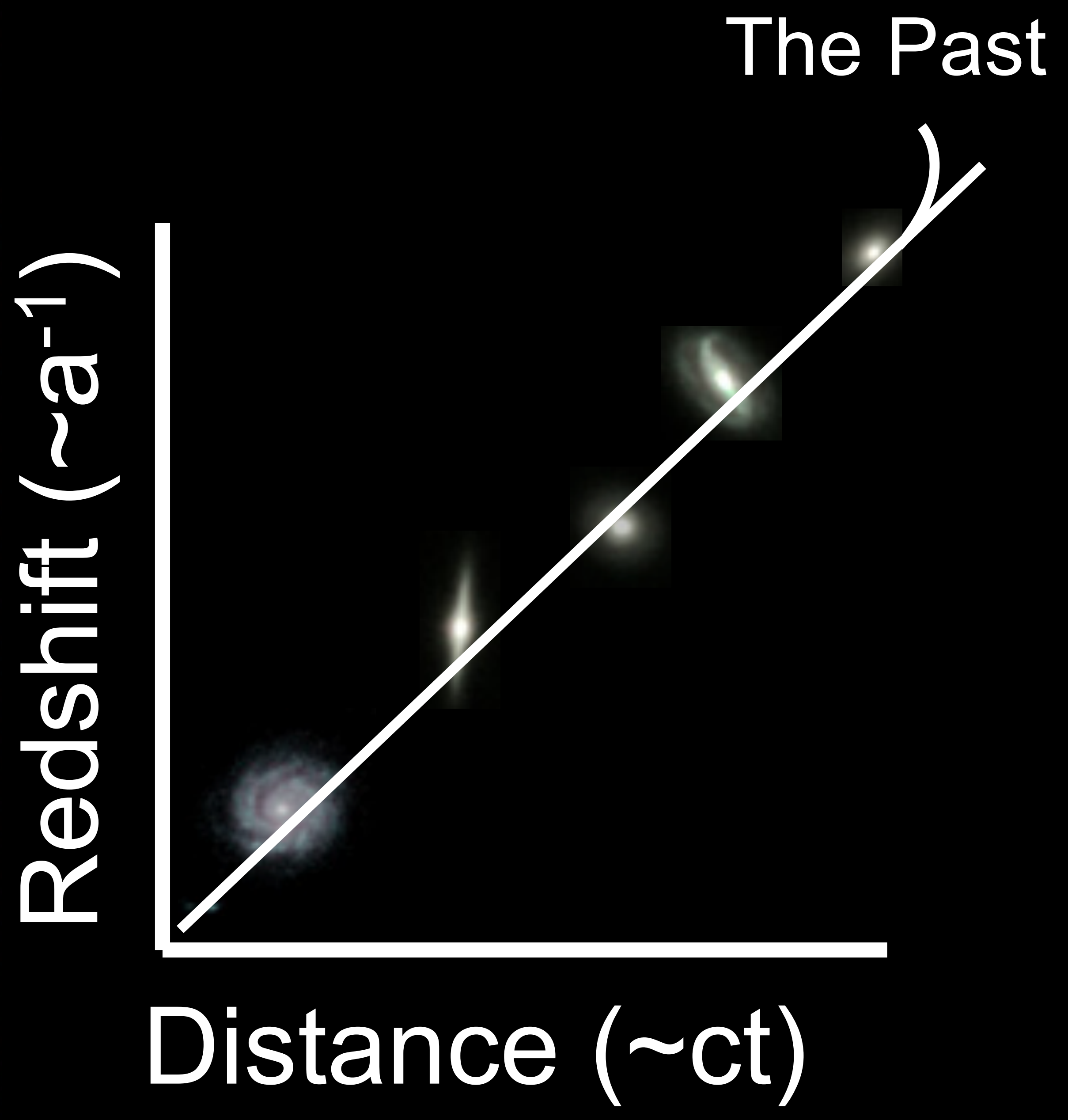
- **July 2018:** *Planck* 2018 (final*) data release. Improved CMB polarization measurements tighten ΛCDM H_0 constraint to **67.36 ± 0.54 km s^{-1} Mpc^{-1}**

- **3.6σ** tension, rising to over 4σ using preliminary improvements to GAIA parallax offset correction (see Riess *et al.* 2018 arXiv/1804.10655 for more details)

Direct Measurement of the Present Expansion Rate, H_0

(slides from Adam Riess)





In the expanding Universe, a(t), the expansion rate is:
Want a(t), measure proxies → Hubble diagram, D(z)
Need <u>absolute distances</u>, use a "distance ladder"

$$\boxed{H_0 = \left.\frac{\dot{a}}{a}\right|_{t=t_0}}$$

A Coordinated Program to Measure H_0 to percent precision

The SH_0ES Project (2005)

(Supernovae, H_0 for the dark energy Equation of State)

A. Riess, L. Macri, S. Casertano, D. Scolnic, A. Filippenko, W. Yuan, S. Hoffman, et al

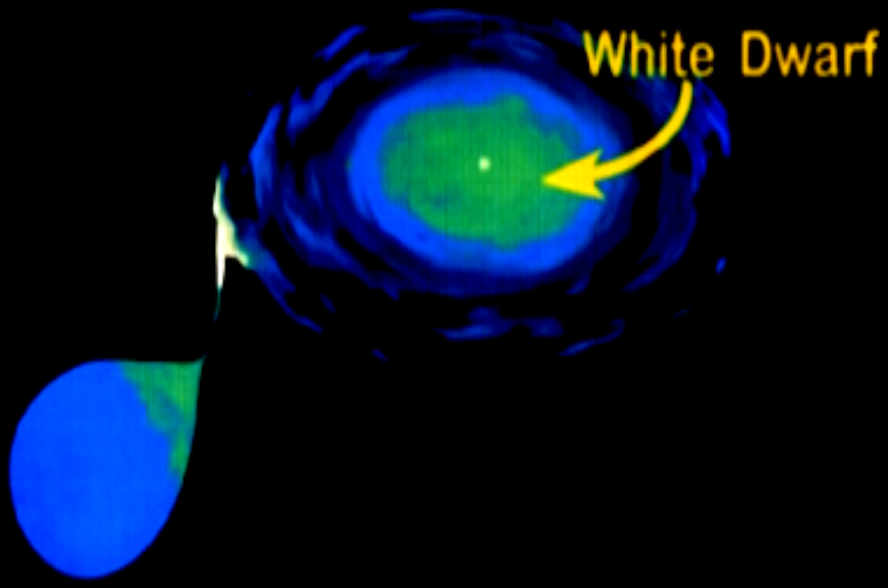
Measure H_0 to percent precision purely empirically by:

- A clean, simple ladder: Geometry → Cepheids → SNe Ia
- Reducing systematic error with better data, better collection
- Thorough propagation of statistical and systematic errors

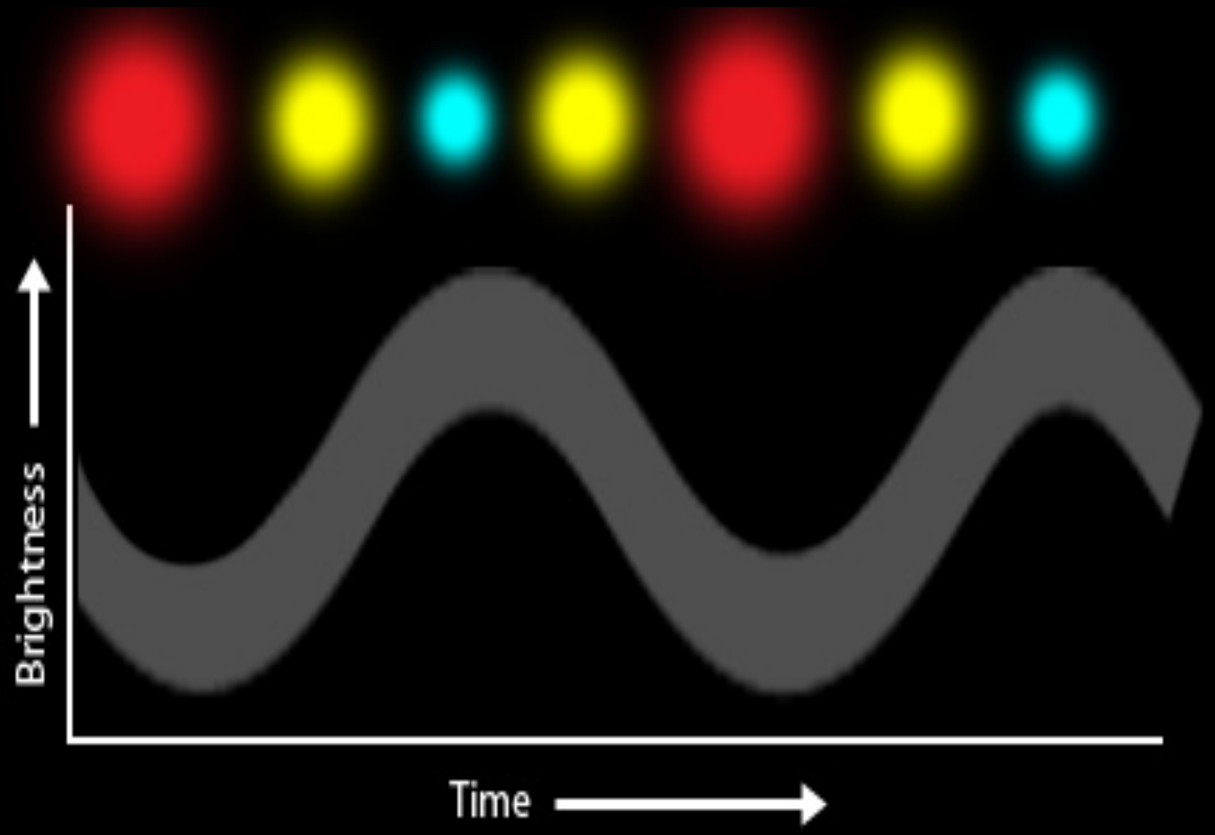
SN Ia and Cepheids: Best Proven Standardized Candles for far, *relative* distances

Type Ia Supernovae, Exploding Stars, $10^9\ L_\odot$
Among Brightest Supernovae
Intrinsic Precision ~ 5% in distance

Cepheids, Pulsating Stars, $10^5\ L_\odot$
Period-luminosity relation, bright
Intrinsic Precision~ 4% in distance

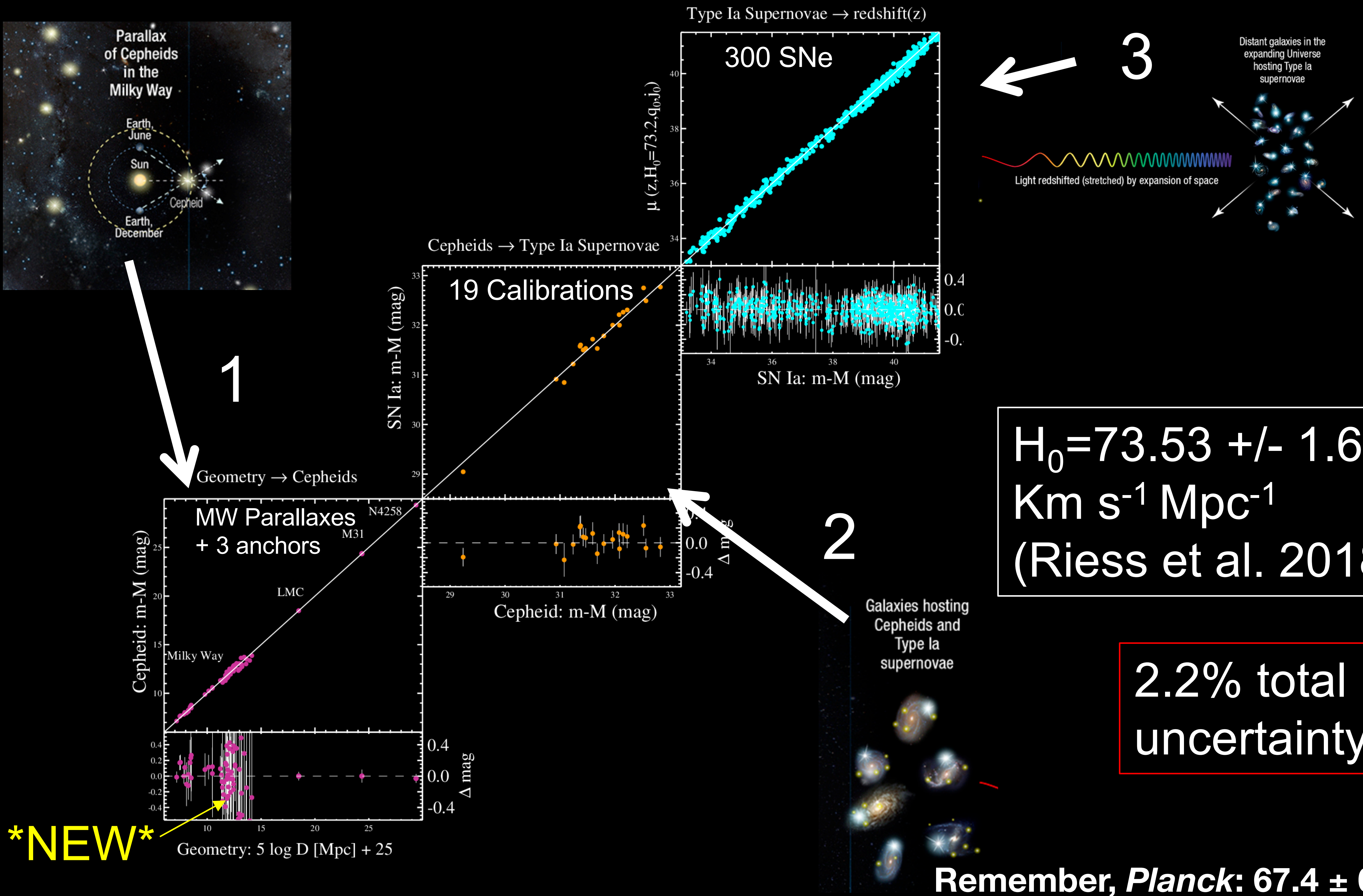


An explosion resulting from the thermonuclear detonation of a White Dwarf Star.



Cepheids are common in hosts of SNe Ia

The Hubble Constant in 3 Steps: Present Data



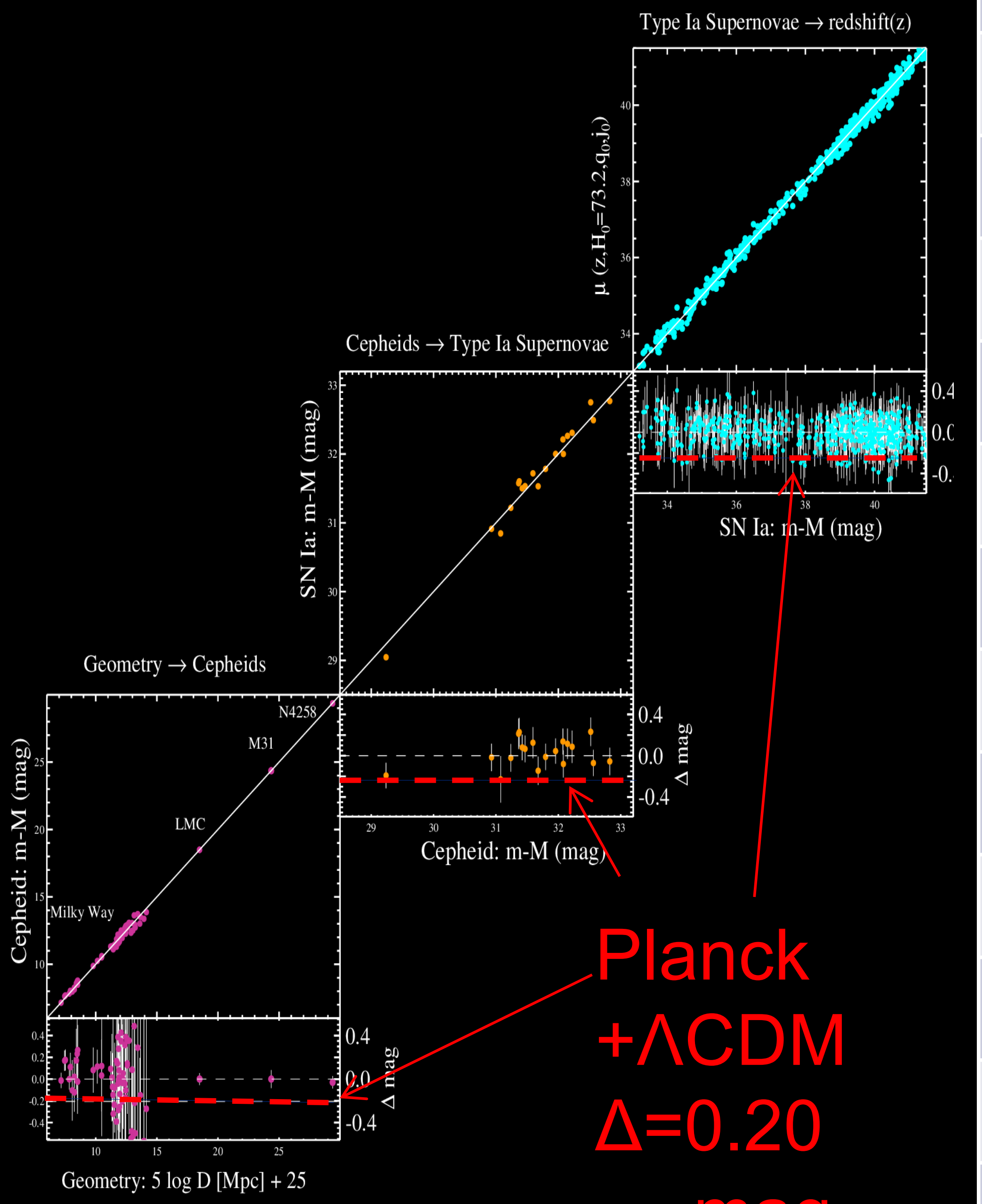
H_0=73.53 +/- 1.62,
Km s^{-1} Mpc^{-1}
(Riess et al. 2018)

2.2% total uncertainty

Remember, *Planck*: 67.4 ± 0.5!

Systematics R16: 23 Analysis Variants

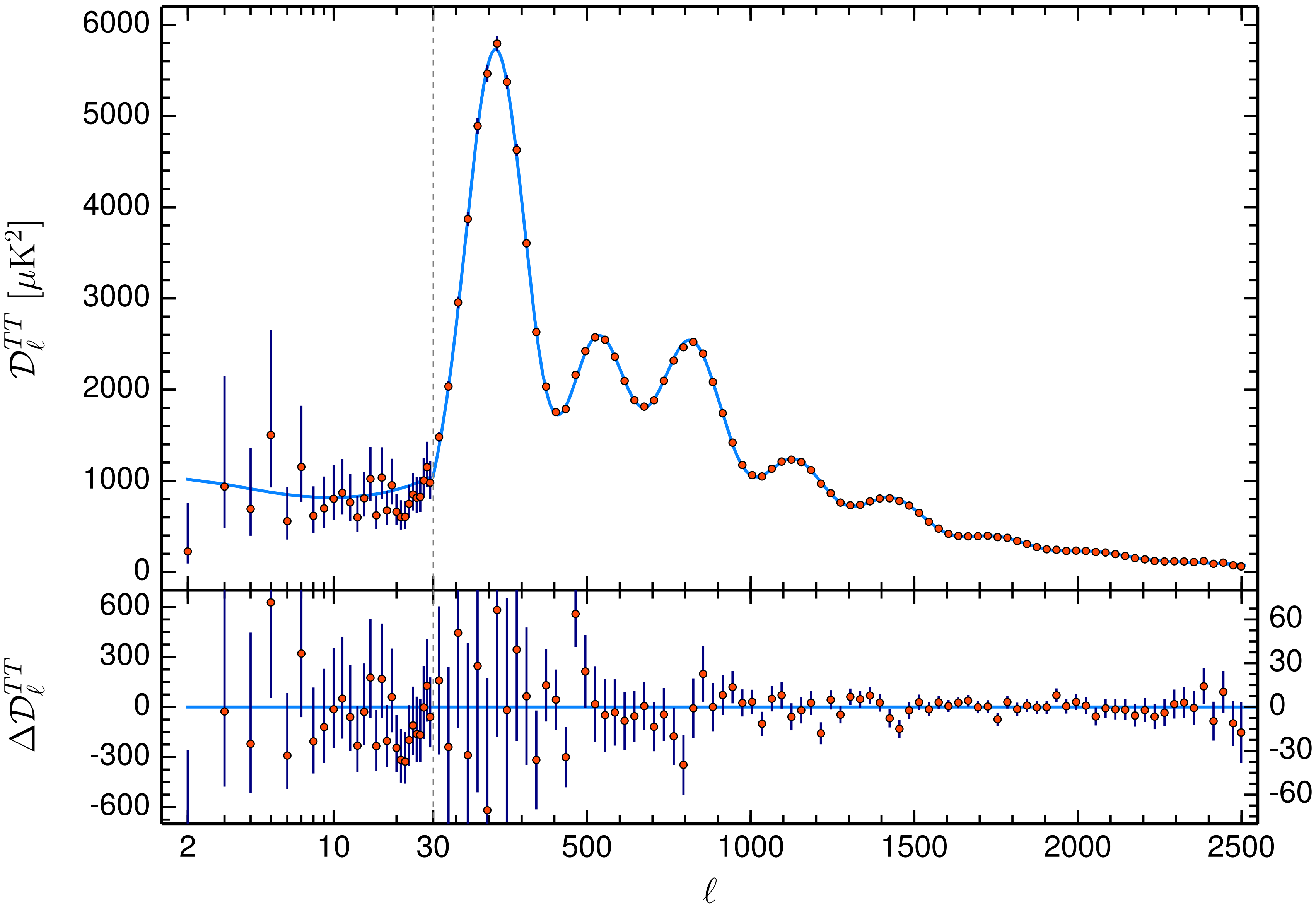
Best Fit



Planck +ΛCDM Δ=0.20 mag

Analysis VariantB	**H_0**
Best Fit (R16, w/ HST,Gaia π, R18=73.53)	73.24
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.15
Reddening Law: Bulge-like (N15)	73.39
No Cepheid Outlier Rejection (normally 2%)	73.49
No Correction for Extinction	74.79
No Truncation for Incomplete Period Range	74.39
Metallicity Gradient: None (normally fit)	73.30
Period-Luminosity: Single Slope	73.26
Period-Luminosity: Restrict to P>10 days	71.64
Period-Luminosity: Restrict to P<60 days	73.06
Supernovae z>0.01 (normally z>0.023)	73.38
Supernova Fitter: MLCS (normally SALT)	74.39
Supernova Hosts: Spiral (usually all types)	73.37
Supernova Hosts: Locally Star Forming	73.54
Cepheid Measurements: Optical Only	71.74

Planck 2018 results (July)



$\Omega_c h^2$ **= 0.1200 ± 0.012**

$\Omega_b h^2$ **= 0.02237 ± 0.00015**

$10^9 A_s$ **= 2.100 ± 0.030**

n_s **= 0.9649 ± 0.0042**

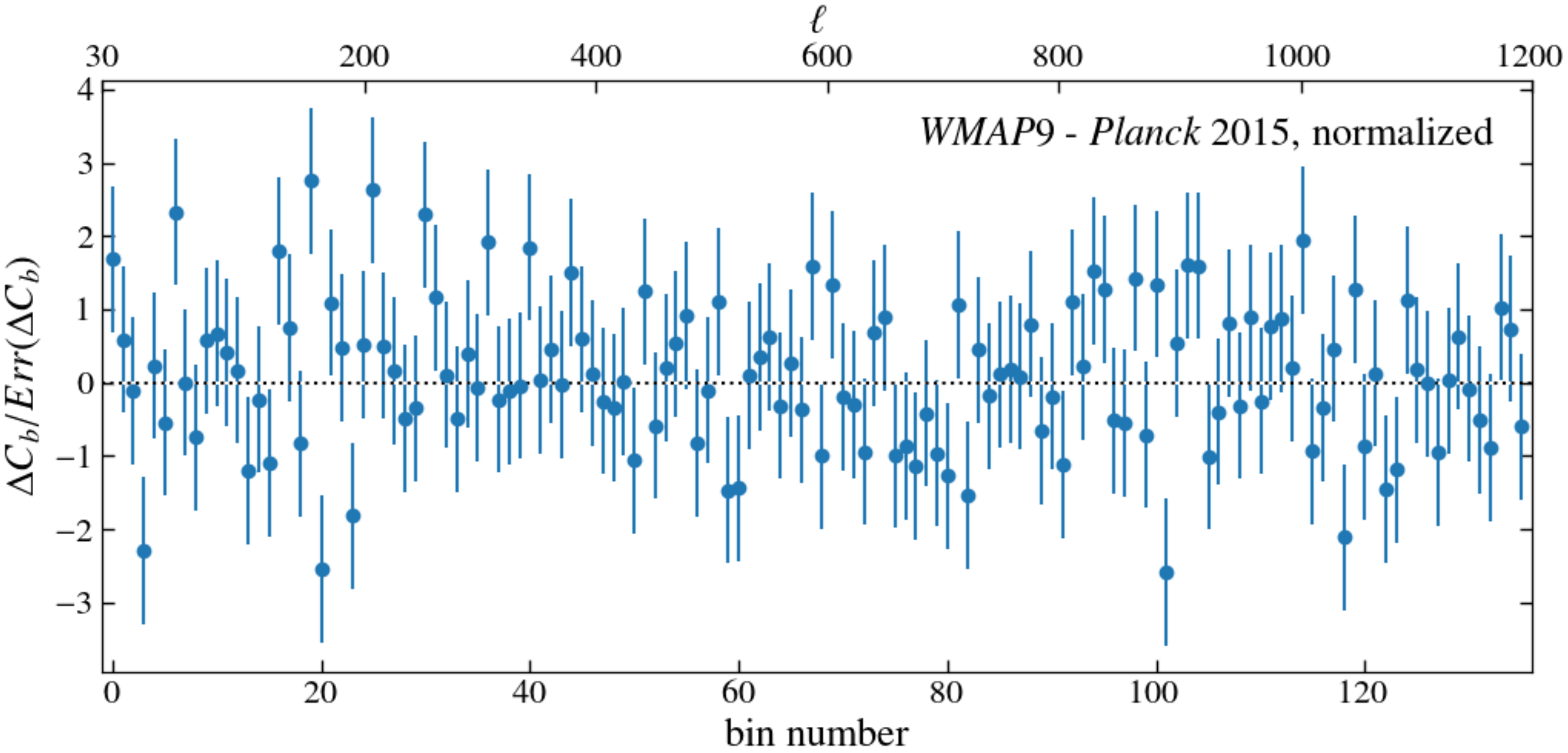
τ **= 0.0544 ± 0.0073**

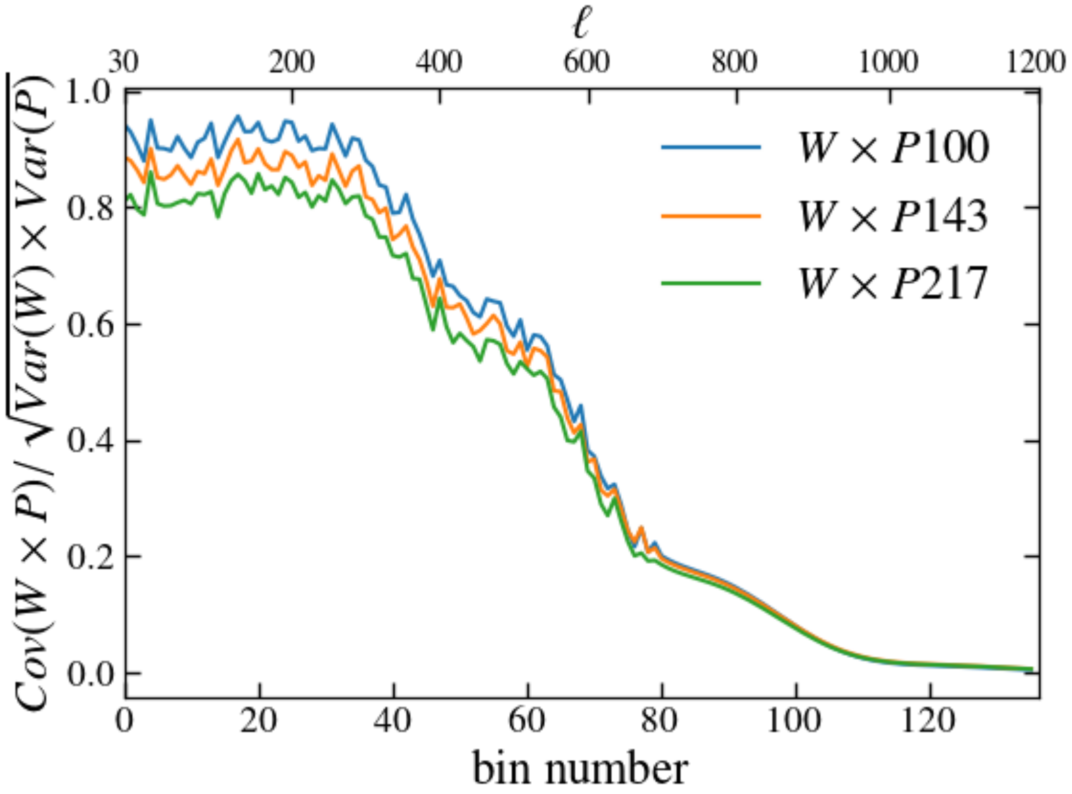
H_0 **= 67.36 ± 0.54 km s^{-1} Mpc^{-1}**

Allowed param volume space shrunk by factor of **several x10^5** since pre-*WMAP*

Message from CMB: ΛCDM has not broken!

Consistency between *WMAP* and *Planck* 2015



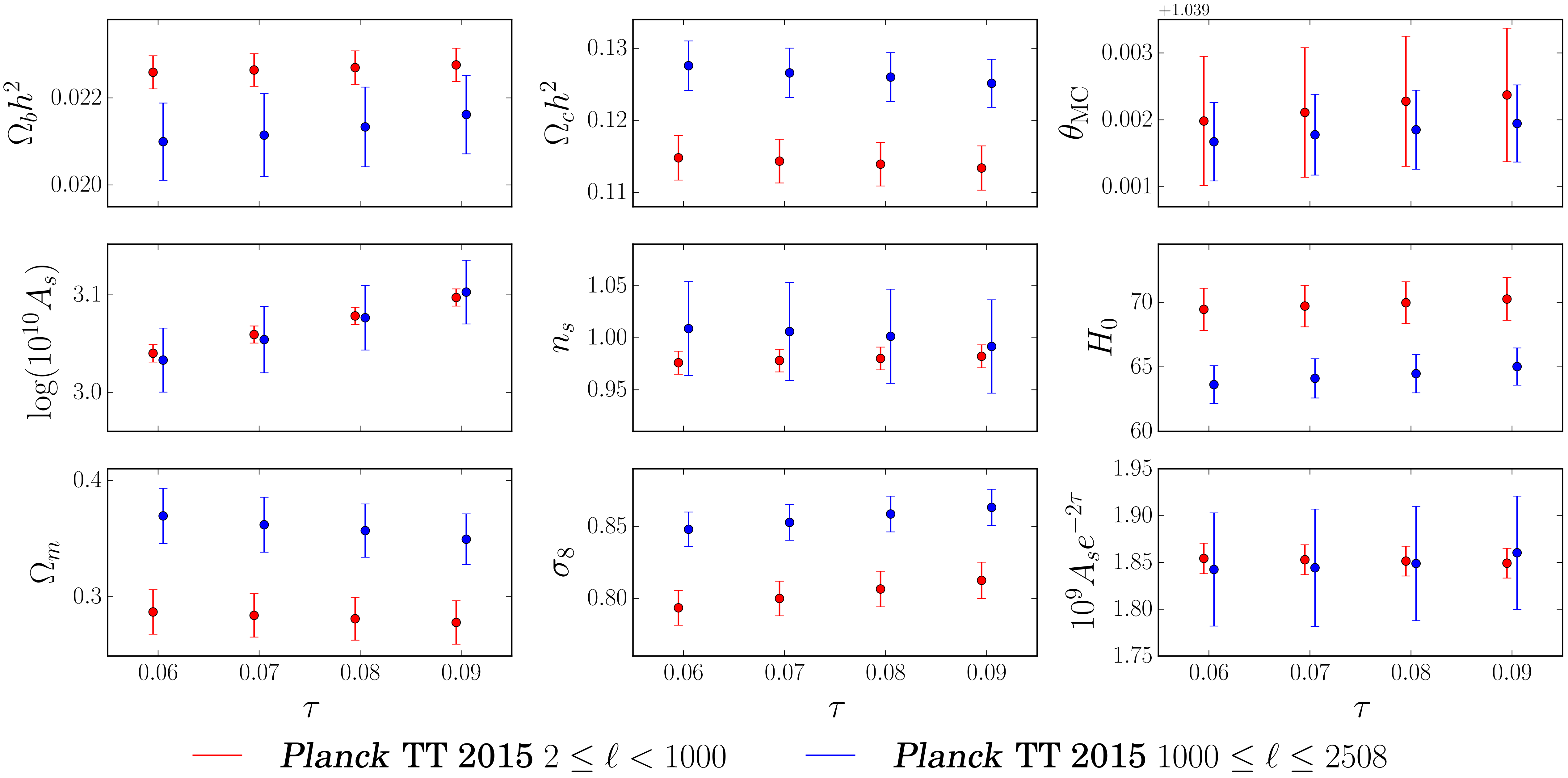


WMAP **& *Planck* 2015 TT spectra consistent over common multipole range (within 1σ),**

What about additional information at higher multipoles that *WMAP* did not measure?

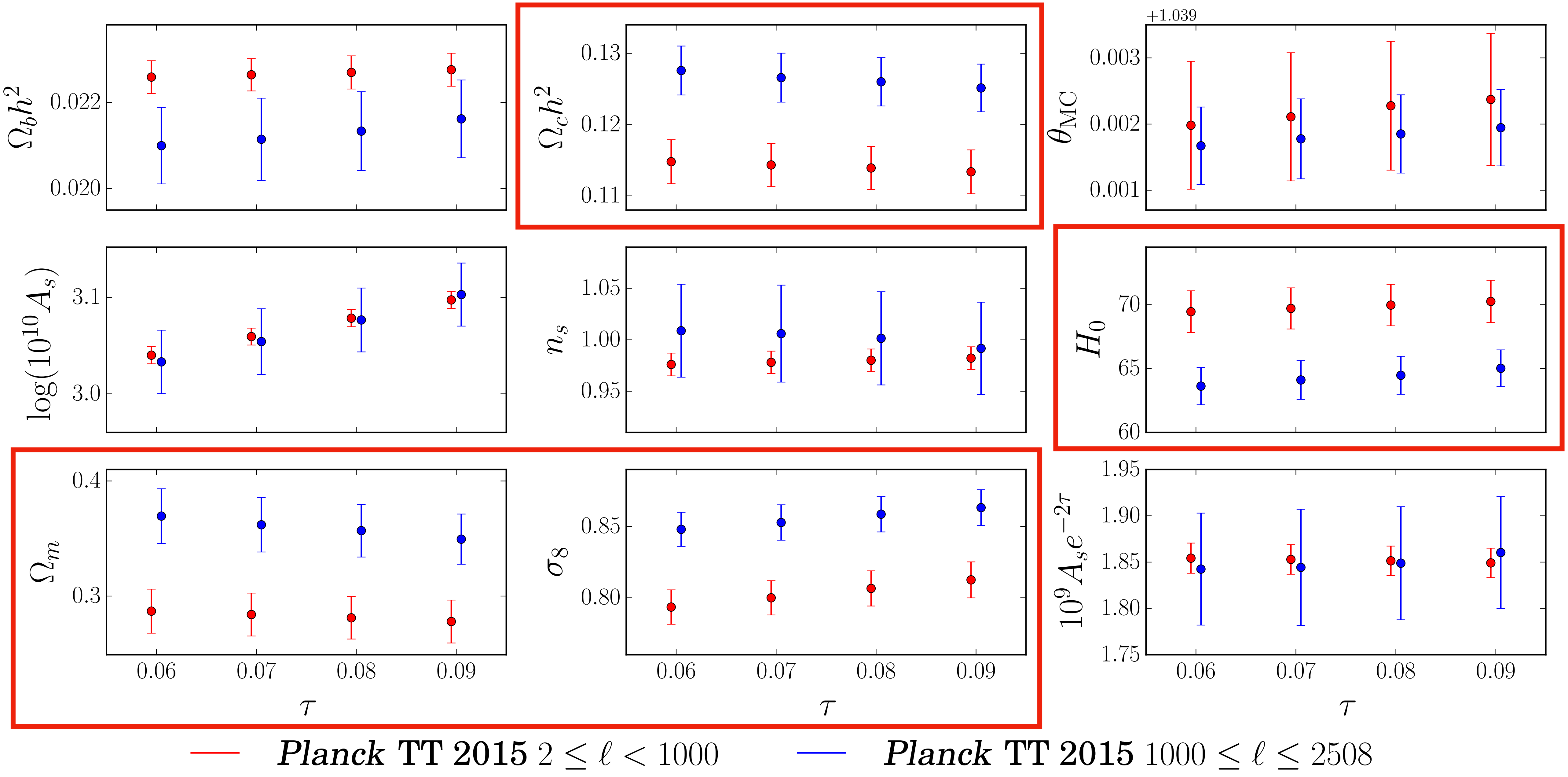
Huang, Addison, *et al.* (ApJ submitted)

Planck high-ℓ vs low-ℓ ΛCDM parameters



Addison *et al.* (2016)

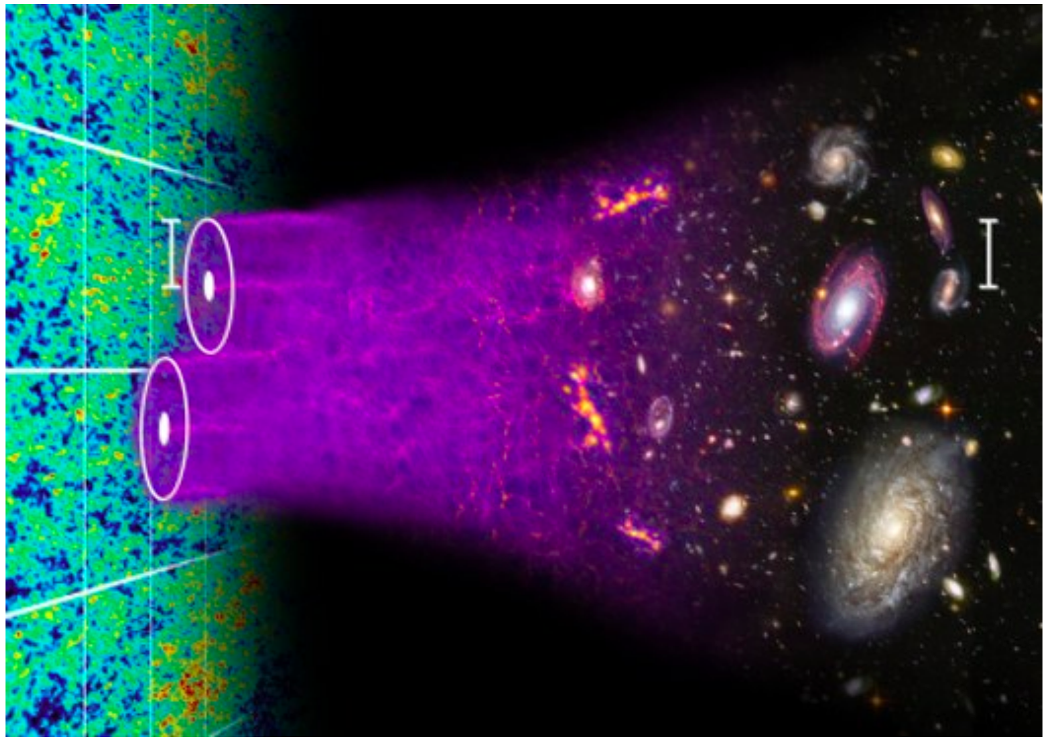
Planck high-ℓ vs low-ℓ ΛCDM parameters



~2.5σ internal tension in parameters relevant for low-redshift comparisons

Addison *et al.* (2016)

Information from Baryon Acoustic Oscillations (BAO)



- 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

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

sound horizon

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

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

BAO observables

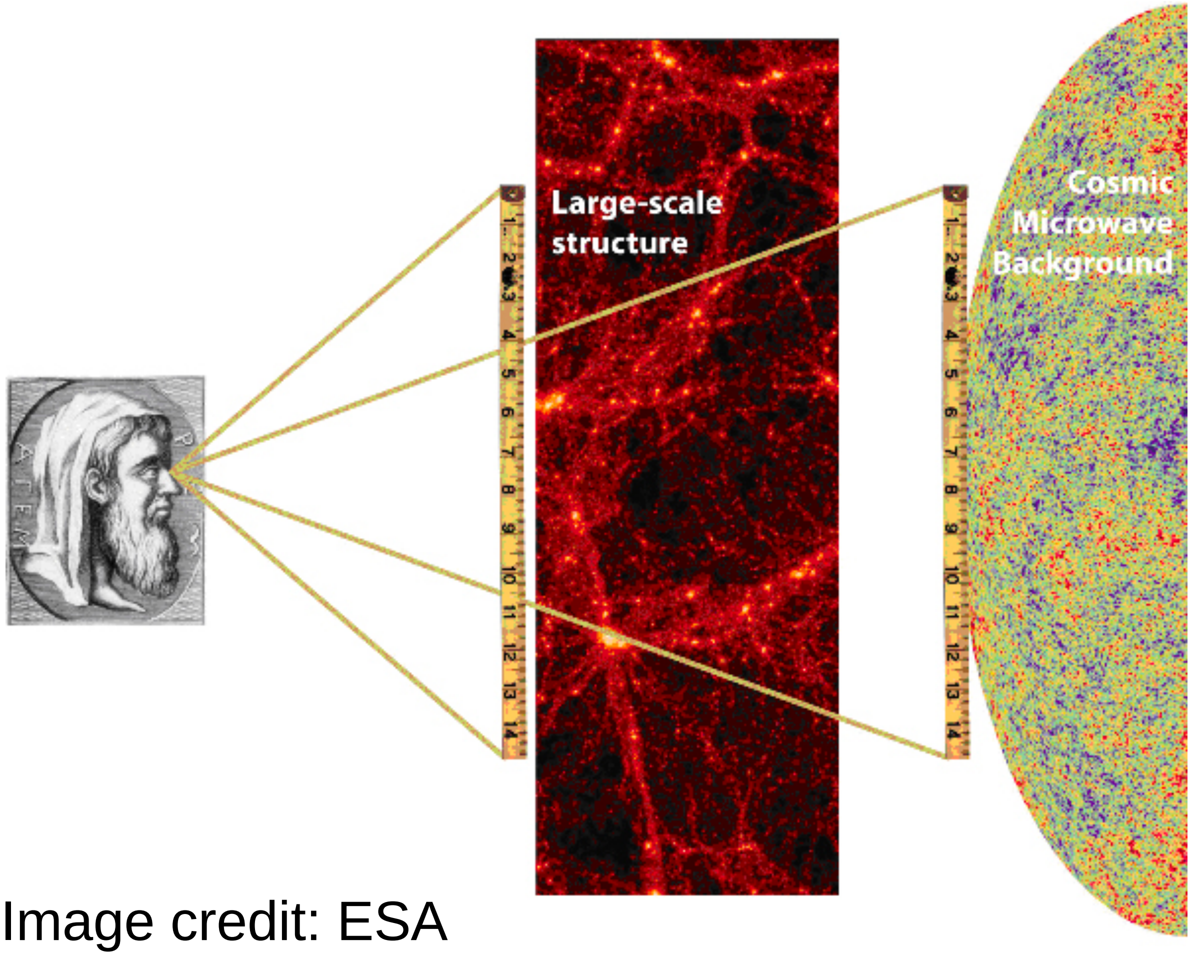
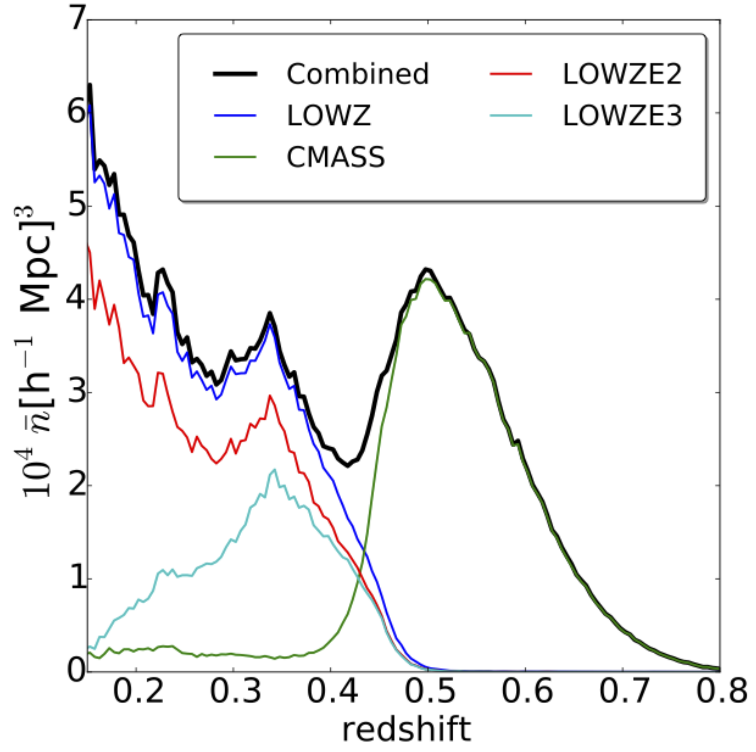
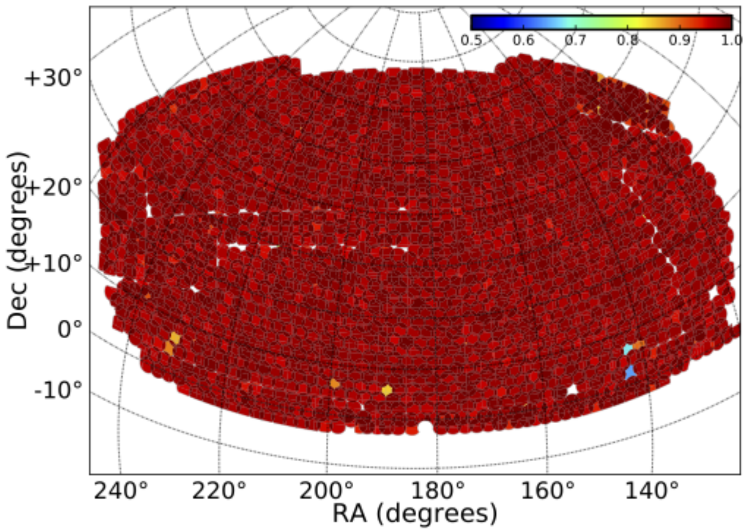


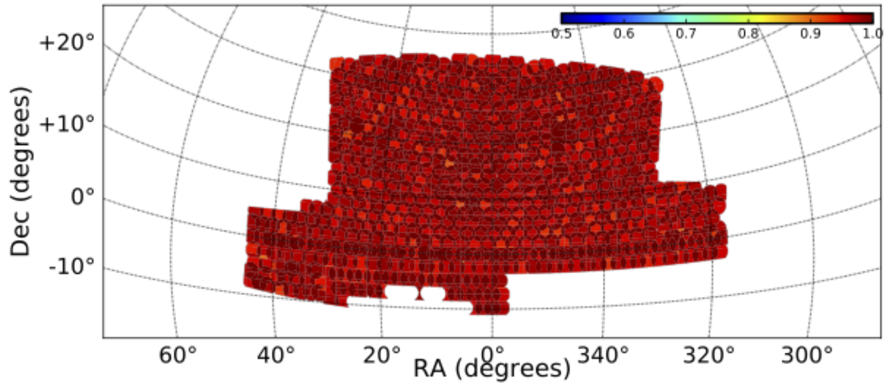
Image credit: ESA

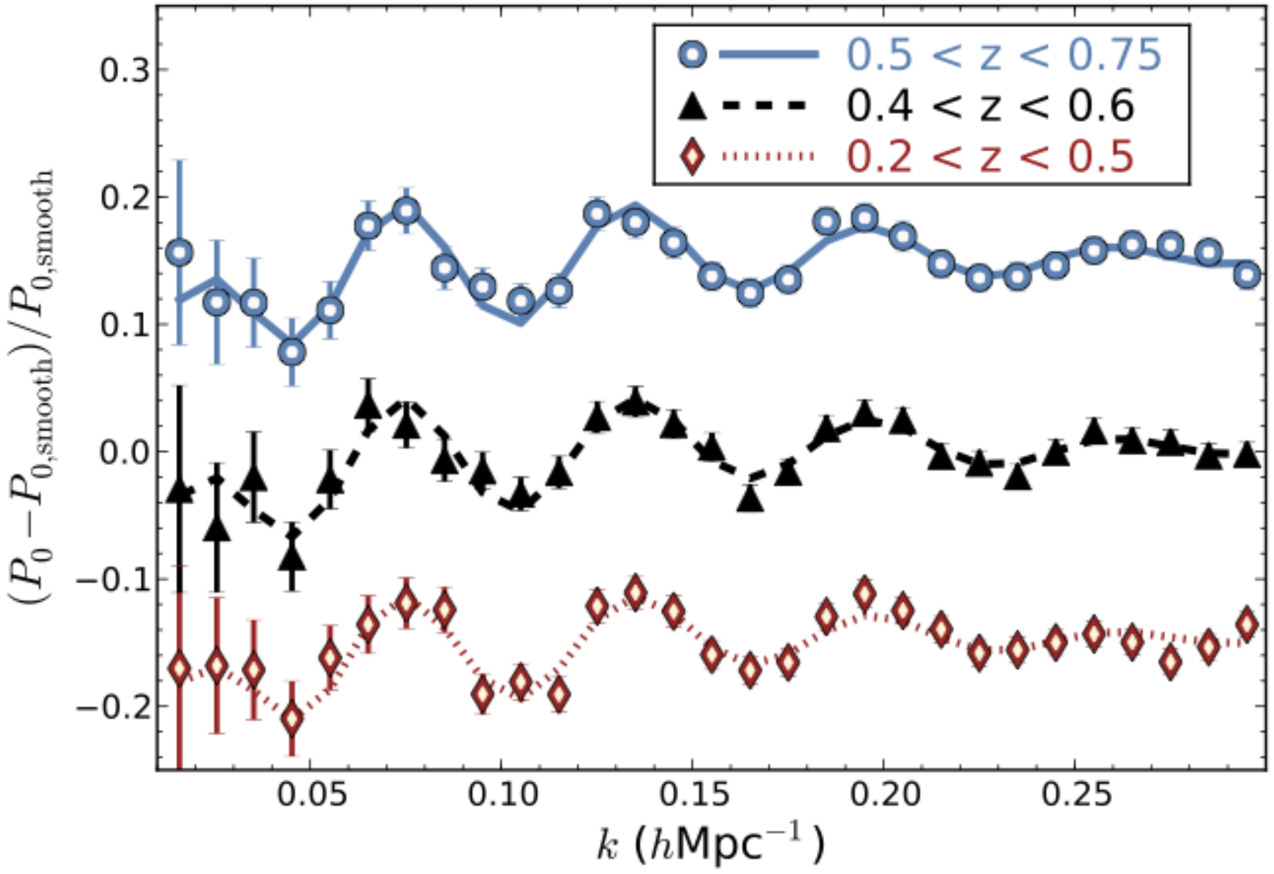
Baryon acoustic oscillations (BAO)

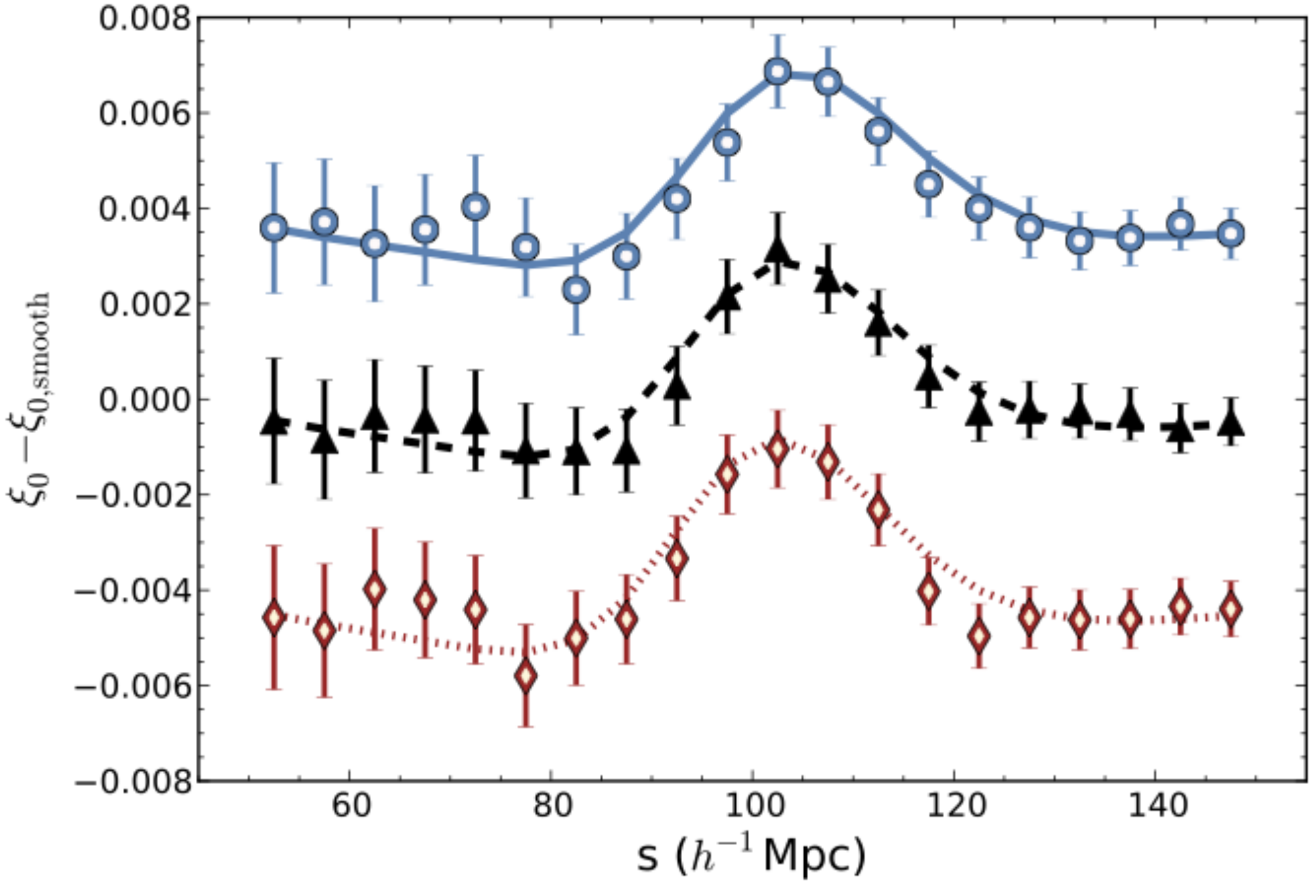


BOSS 2016, 1.2M massive galaxies, 9.3k sq deg (Alam *et al.*)









What is the BAO scale?

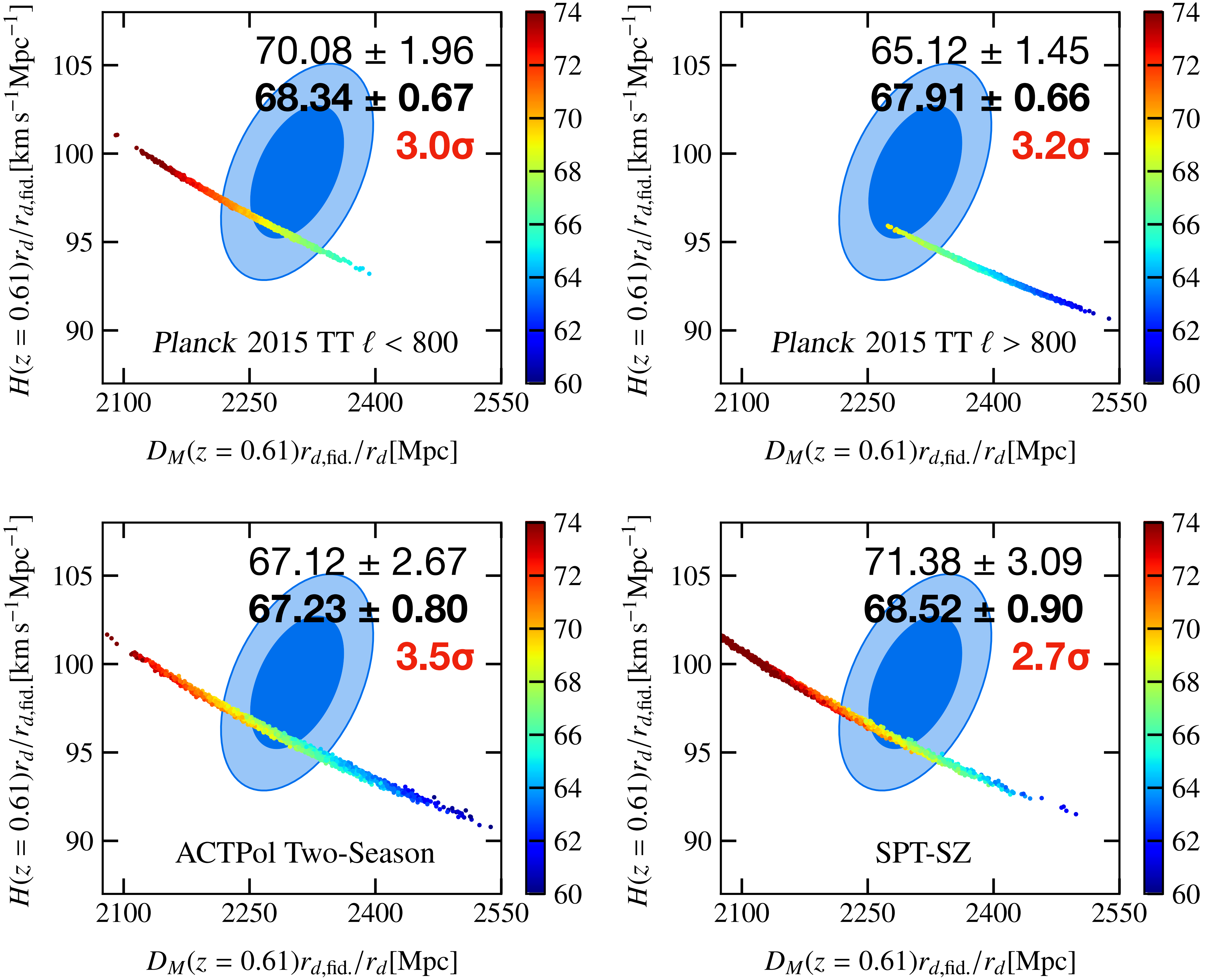
- Early-universe expansion rate (***matter vs radiation***)
- ***Baryon-photon ratio***
- Number of effective ***neutrino species***

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

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

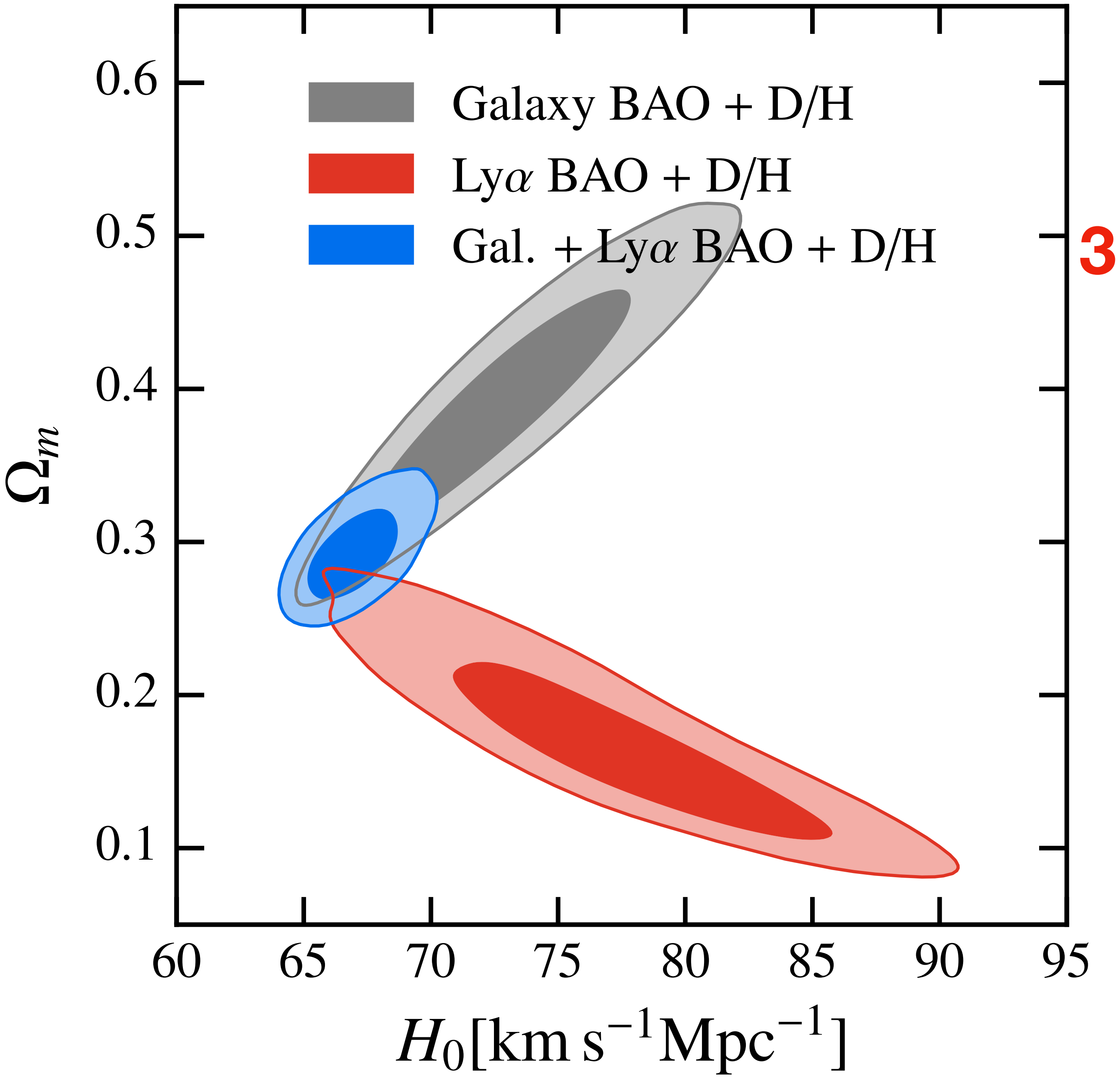
Synergy between BAO and CMB



τ = 0.07 ± 0.02

Addison *et al.* (2018)

BAO + baryon density from D/H



Combining galaxy and Lyα BAO with D/H:

3.3σ **H_0 = 66.98 ± 1.18 km s^{-1} Mpc^{-1}**

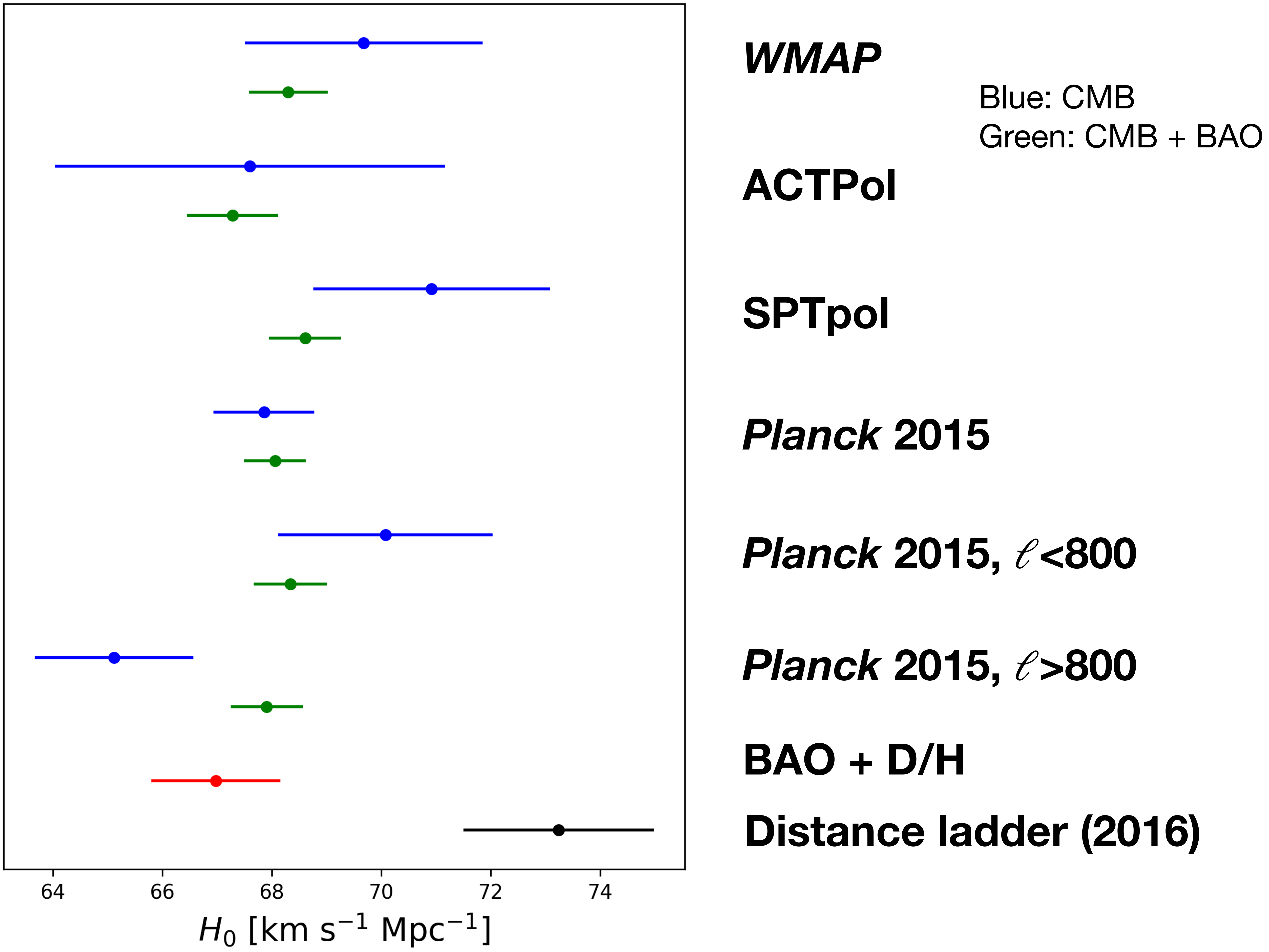
~~**3.0σ**~~ lower than the distance ladder…

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

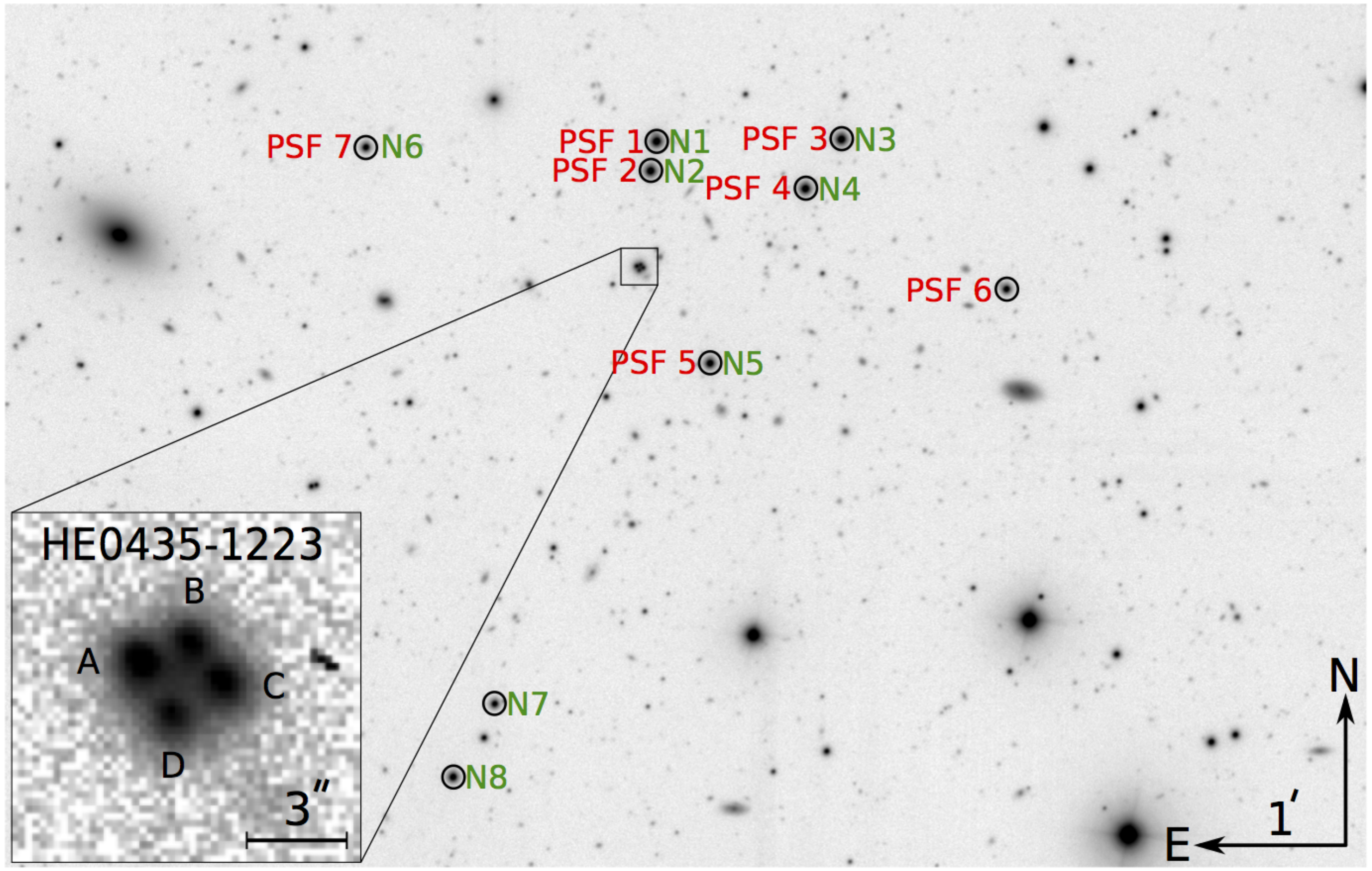
$d(p,\gamma)^3$He reaction rate uncertainty important: empirical rate -> **67.81 ± 1.25 km s^{-1} Mpc^{-1}**

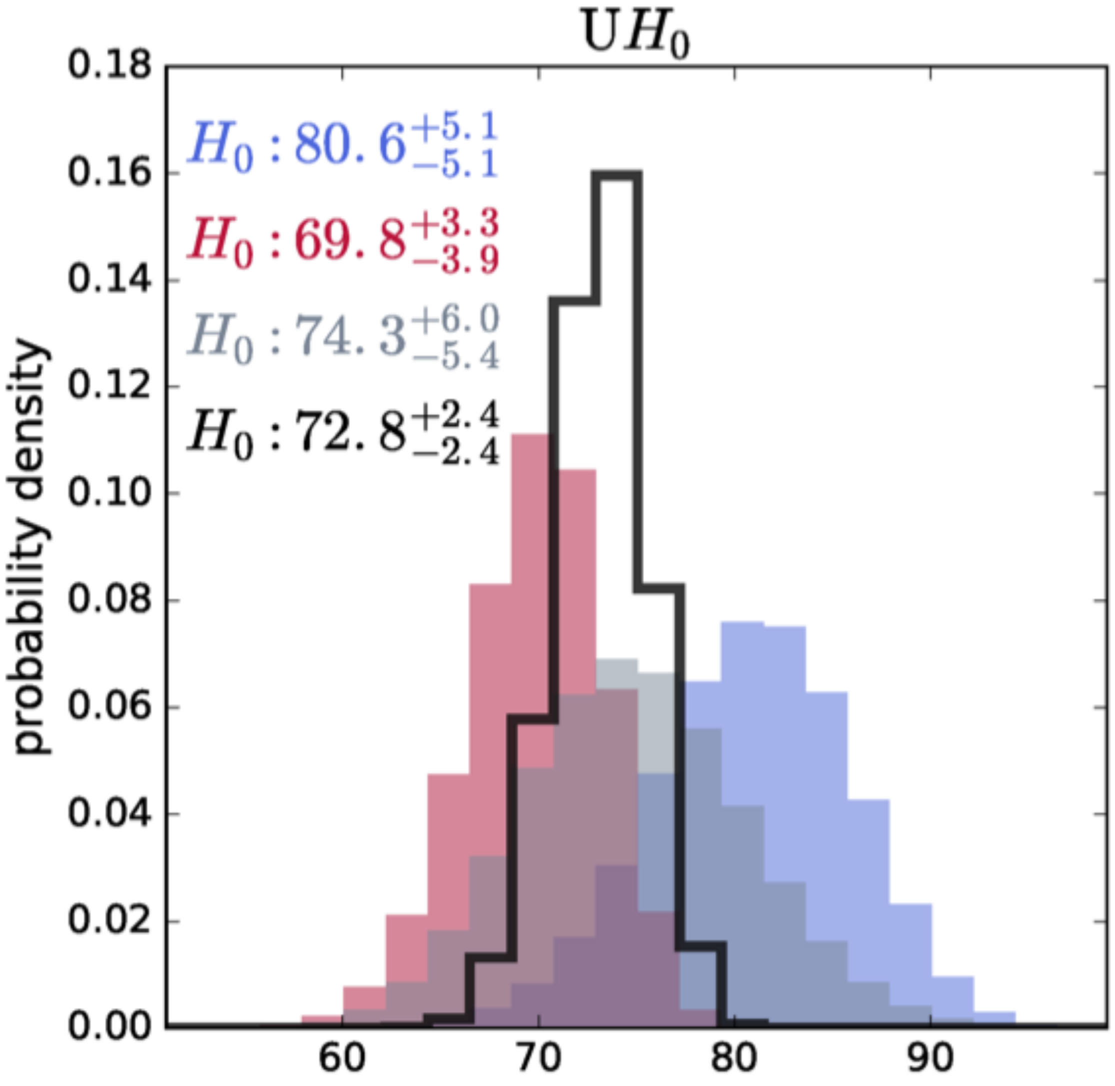
~~**2.5σ**~~ **2.8σ**

Galaxy, Lyα BAO individually prefer higher H_0… (but can replace Lyα with Dark Energy Survey galaxy weak lensing arXiv/1711.00403 and get essentially same answer)


WMAP
Blue: CMB
Green: CMB + BAO
ACTPol
SPTpol
Planck 2015
Planck 2015, ℓ<800
Planck 2015, ℓ>800
BAO + D/H
Distance ladder (2016)
64
66
68
70
72
74
H_0 [km s^{-1} Mpc^{-1}]

H0LiCoW time delay H_0 (1607.01790)



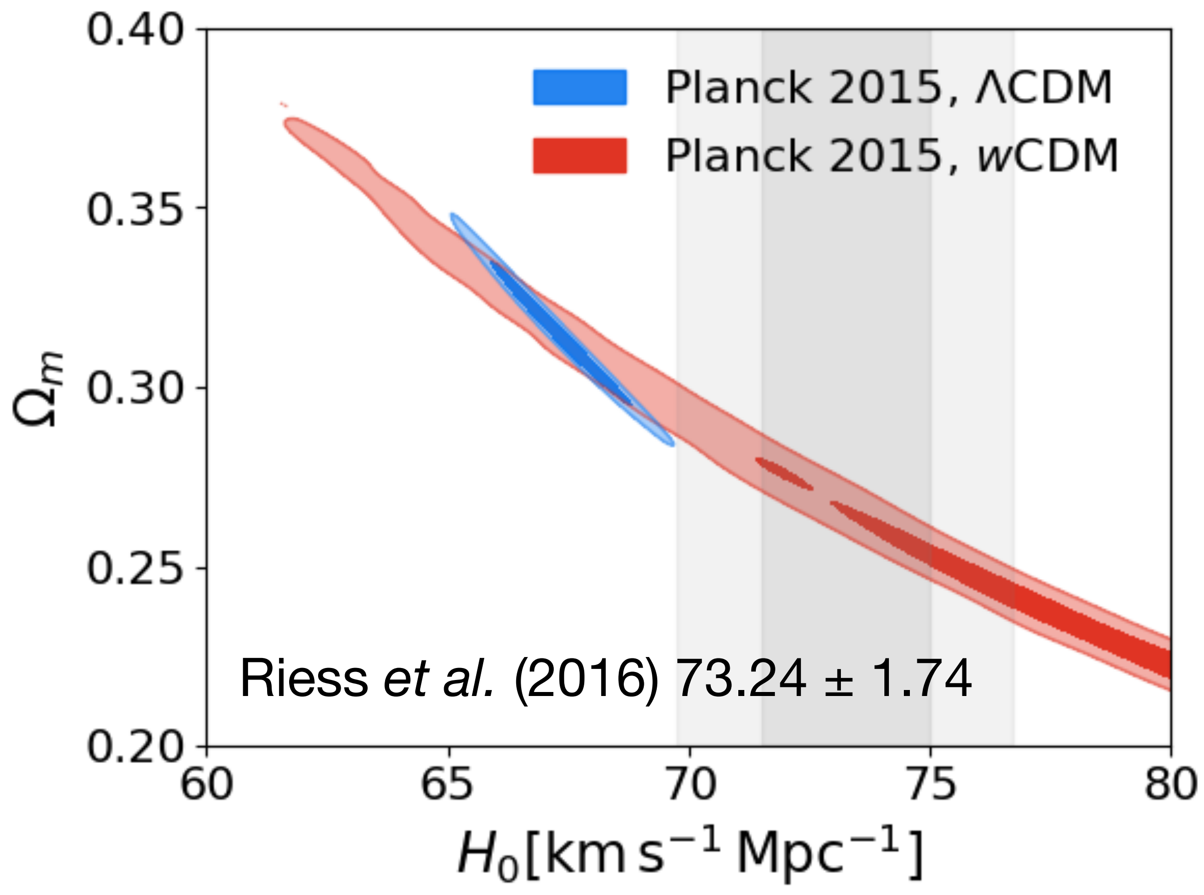


- Three lenses at z=0.30, 0.45, 0.63
- 2.5σ higher than Planck assuming ΛCDM
- Agree well with distance ladder

72.8 +/- 2.4

Newer results Birrer et al. 1809.01274

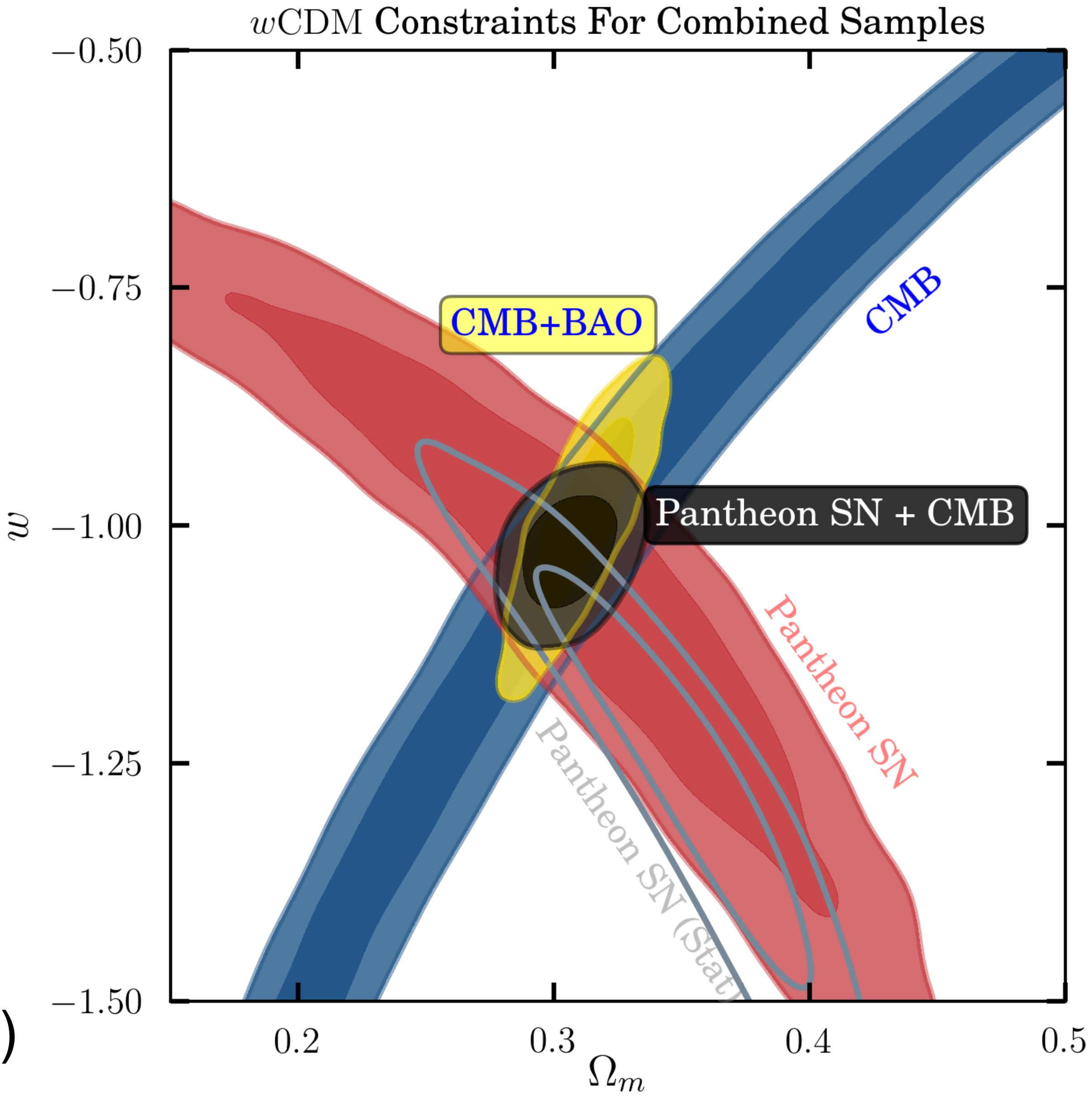
Changing the CMB prediction for H_0?



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

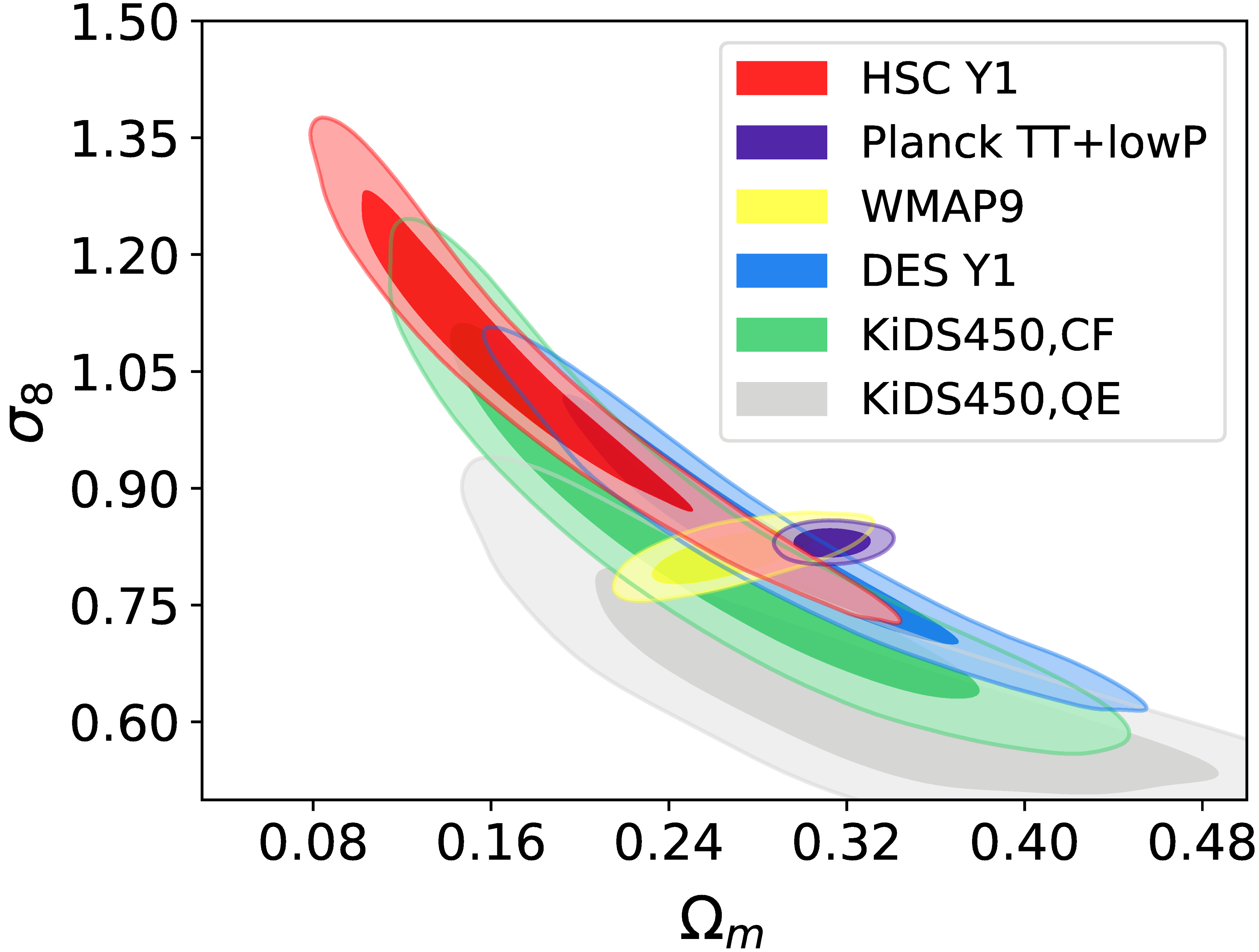
But BAO and higher-z SNe do not allow big enough shifts to reconcile with distance ladder!

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



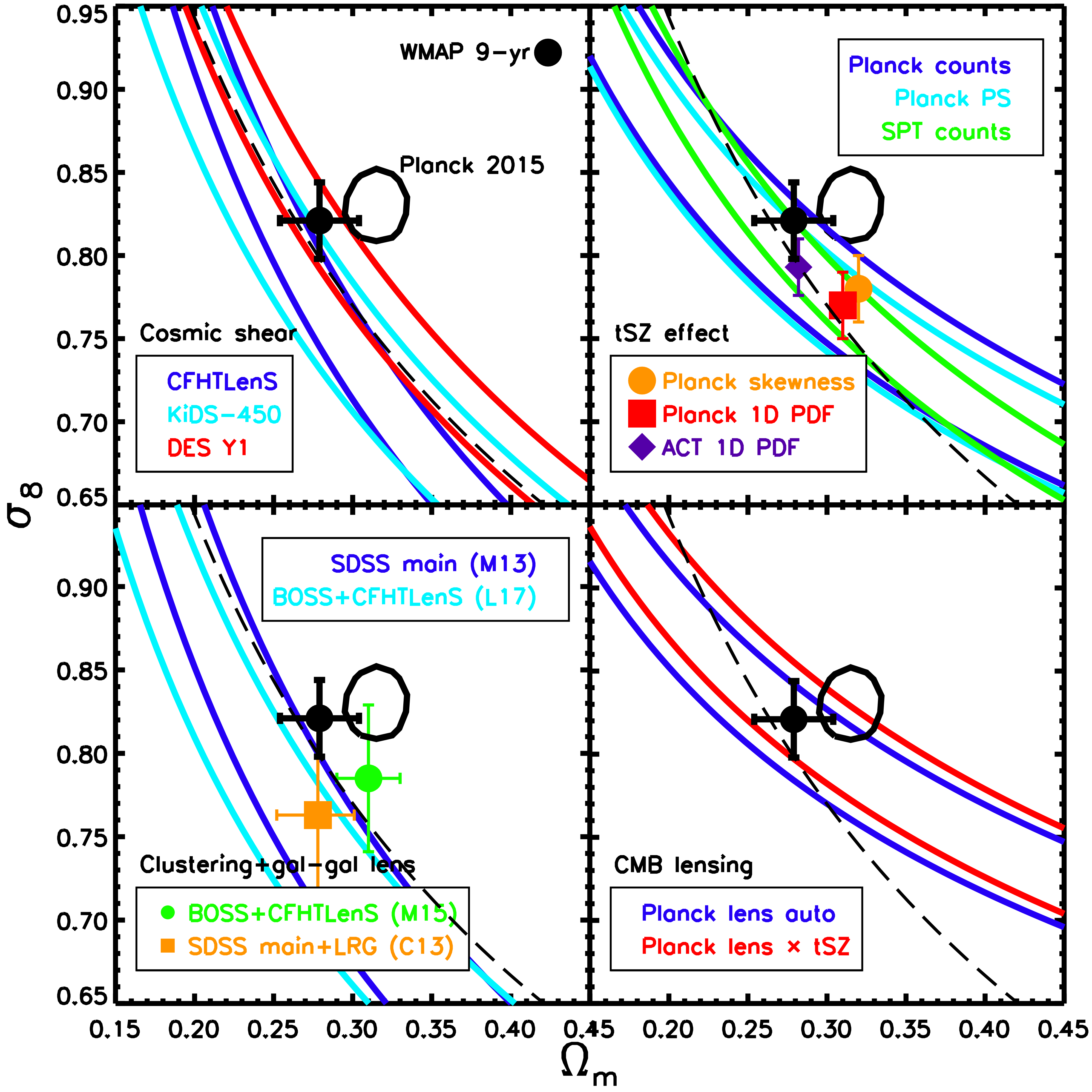
Scolnic *et al.* (2017)

Growth of structure tensions?



Hikage *et al.* (2018)

Subaru Hyper Suprime-Cam (HSC), Dark Energy Survey (DES), Kilo Degree Survey (KiDS) Stage-3 weak lensing surveys all find lower values of combinations of σ_8, Ω_m than *Planck*



Galaxy lensing
Clusters
Galaxy clustering
CMB lensing

… all low compared to *Planck* predictions

McCarthy *et al.* (2018)

The future…

- Billions of dollars going into future cosmology observations (e.g., Stage-3+4 CMB, DESI BAO, Euclid BAO+WL, LSST WL, WFIRST BAO+WL)

- ***Will understanding of systematic uncertainties improve to let us take advantage of the improvements in statistical precision?***

- Current tensions have motivated valuable work on systematics, how we assess statistical consistency, avoidance of biases (confirmation, etc.)

Conclusions

- Tension between *Planck* CMB results and distance ladder H_0 has persisted (currently around 3.6σ), despite improvements in both precision and robustness.

- There is some degree of internal tension in *Planck* power spectrum, but 2.7-3.5σ H_0 tension exists even without *Planck* (BAO plus other CMB data or BAO plus D/H).

- Challenging to improve agreement by modifying cosmological model without introducing some new tension (CMB, D/H, BAO, high-z SNe ~agree for ΛCDM)

- Various probes find lower structure amplitude (combination of σ_8, Ω_m) than *Planck*. Awaiting results of combined Stage-3 weak lensing analysis.