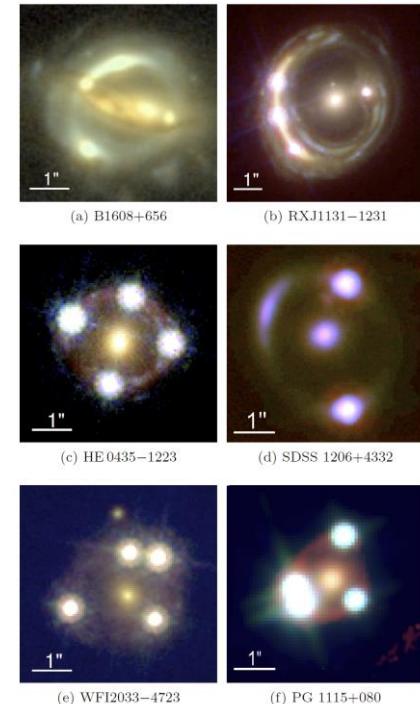
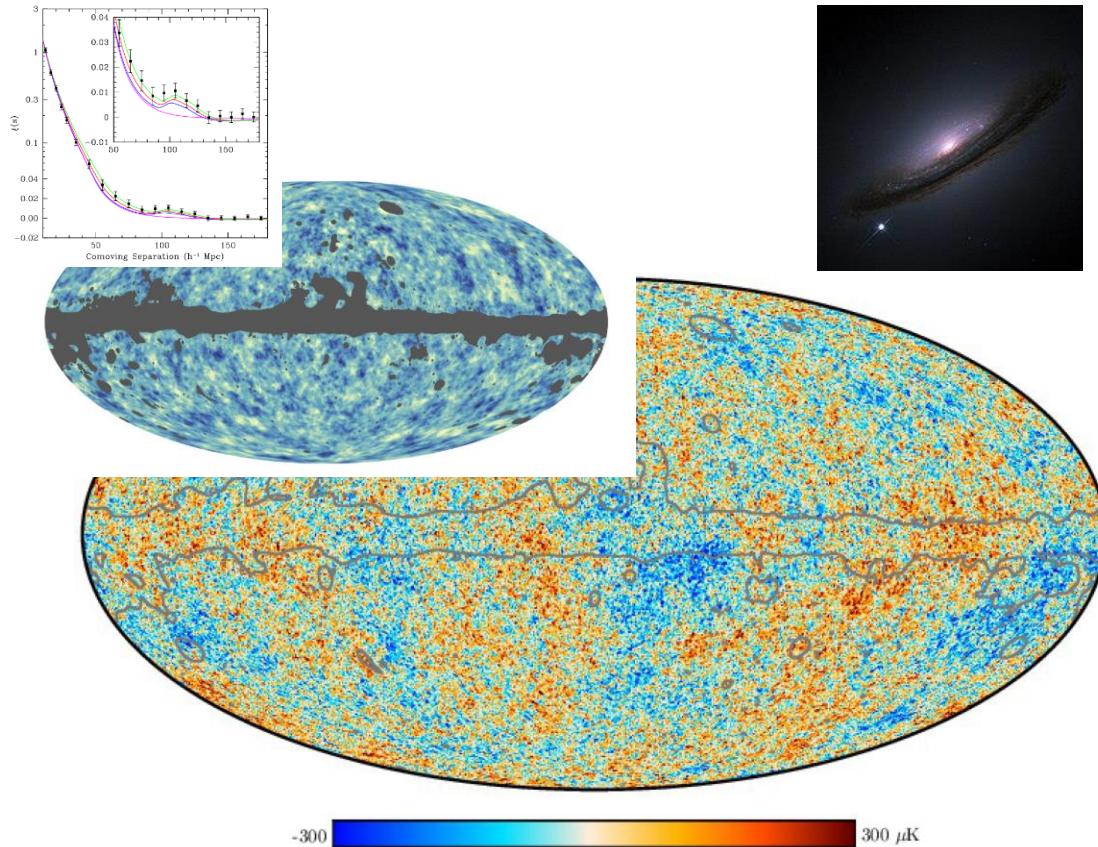
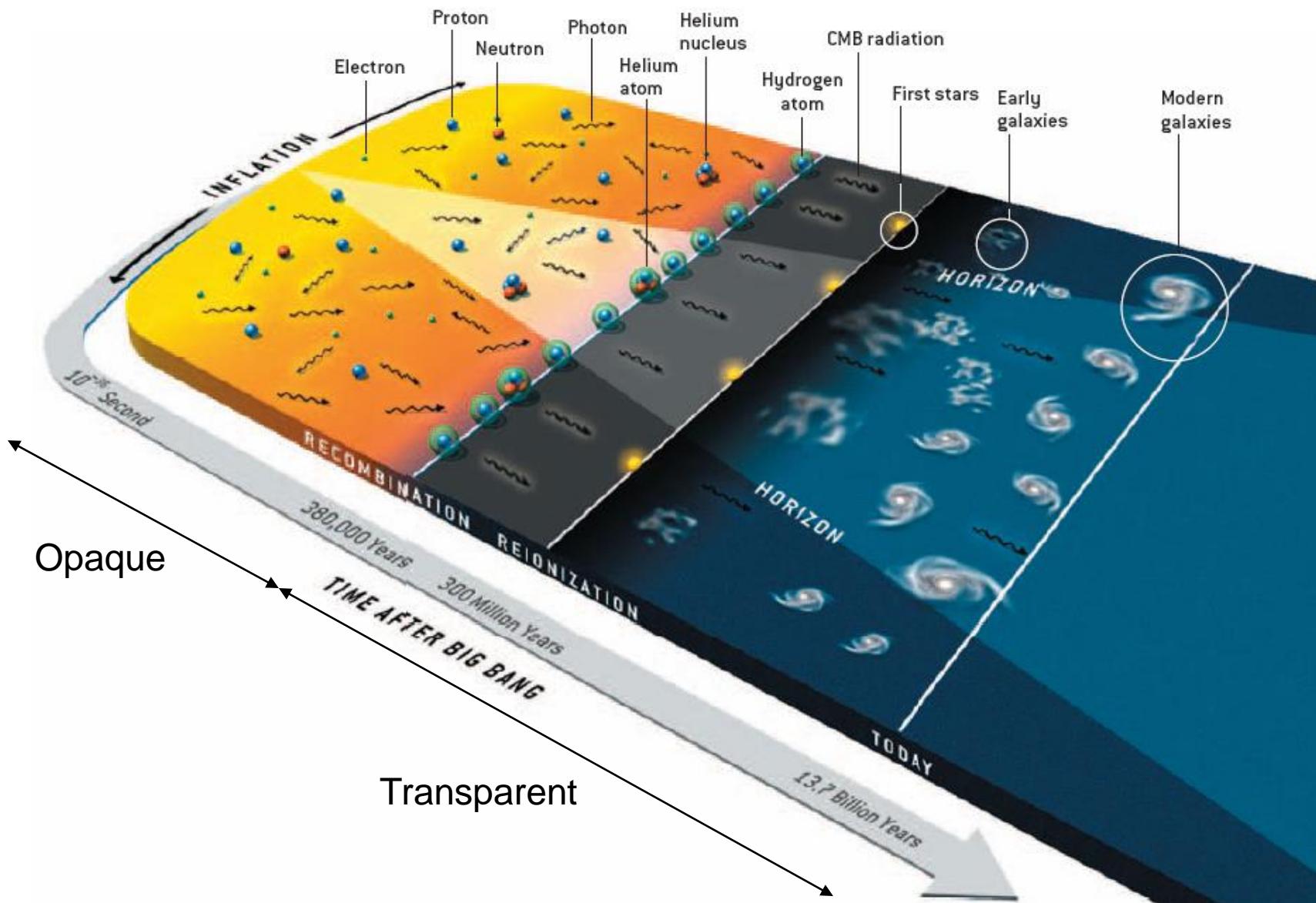


Cosmological Hubble Tension



Evolution in the standard cosmology



Hubble Constant

$$\text{Hubble's Law: } v = H_0 D$$

Recession velocity = (Hubble's Constant) \times (Proper Radial Distance)

Hubble 1929

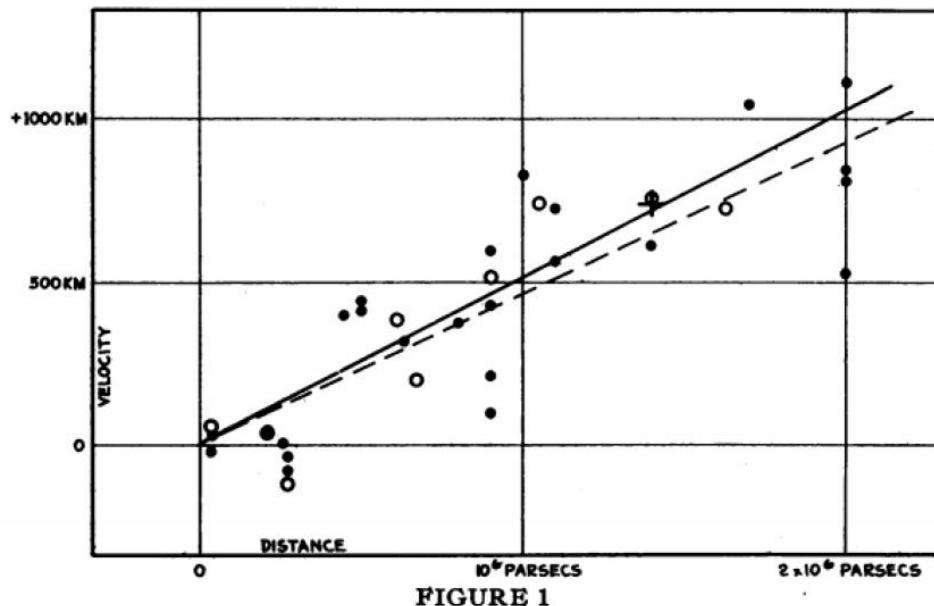


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Well outside the Milky Way

Theory perspective (today $t = t_0$):

Universe expanding $\propto a(t)$ [$a(t_0) = 1$ today]

$$D = a(t)D_0$$

$$\Rightarrow v \equiv \frac{d D}{dt} = \frac{d a}{dt} D_0 = \frac{1}{a} \frac{d a}{dt} D = HD$$

Define Hubble Parameter $H(t) \equiv \frac{1}{a} \frac{d a}{dt}$

$$H_0 \equiv H(t_0)$$

Homogeneous + Isotropic Universe (on large scales) + General Relativity

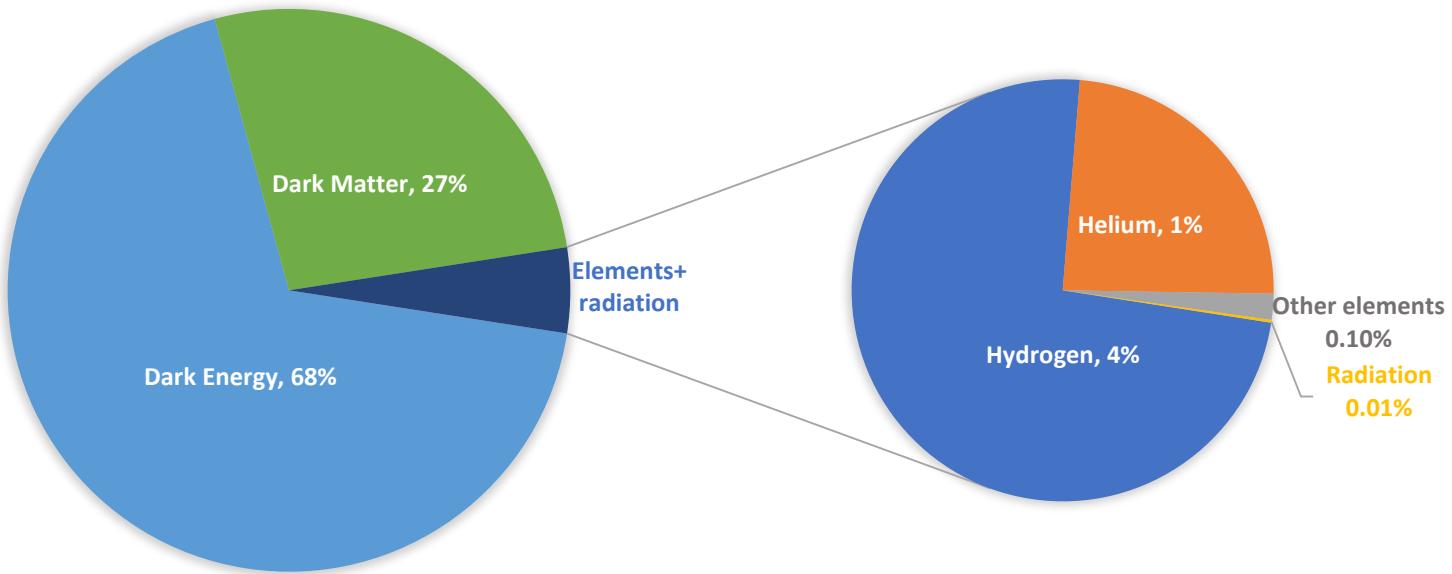
FRW solution

$$H^2 = \frac{8\pi G}{3} \rho - \frac{K}{a^2}$$

Total energy density

Curvature constant, $\frac{|K|}{H^2} \ll 1$ empirically

Contents of the Universe today



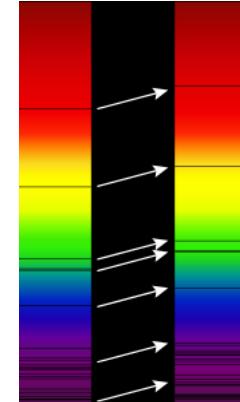
Define and test perturbatively-FRW Λ CDM model:

- Photons (CMB temperature today ~ 2.7255 K)
- 3 active neutrinos, assuming minimal mass hierarchy with $\sum m_\nu = 0.06$ eV
- Standard model baryons (taken to include electrons etc), density $\Omega_b h^2$
- Cold (pressureless) non-interacting and stable matter (CDM), density $\Omega_c h^2$
- Cosmological constant Λ , giving a flat universe with $\Omega_K = 0$
- Reionization parameterized by a single effective optical depth τ
- Gaussian adiabatic primordial curvature perturbations with power spectrum $P_R = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$
Remaining free parameter is $H_0 = 100h \text{ km s}^{-1}\text{Mpc}^{-1}$ (or $\Omega_\Lambda, \Omega_m, \theta_, \dots$)*

Observational perspective:

Can only measure redshift: $z \equiv \frac{\lambda_{\text{obs}}}{\lambda_{\text{lab}}} - 1$

Define recession velocity: $v = c z$



Nearby ($z \ll 1$): $H_0 = \frac{cz}{D}$

BUT: D is not observable. Only see photons and angles on the sky today.

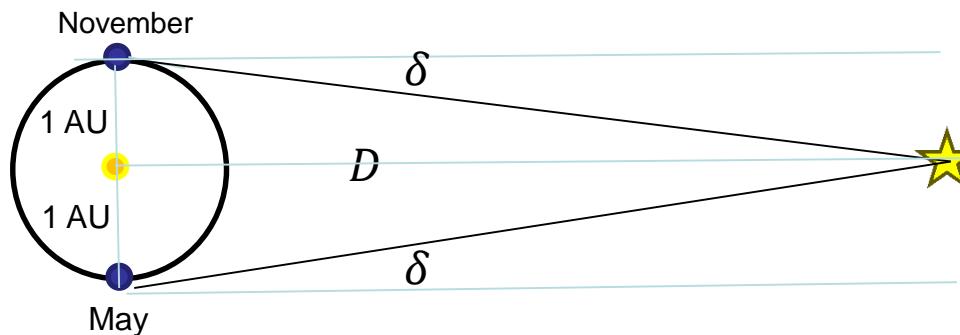
Redshifts are “easy”:



$$H_0 \propto 1/D$$

How to measure distance?

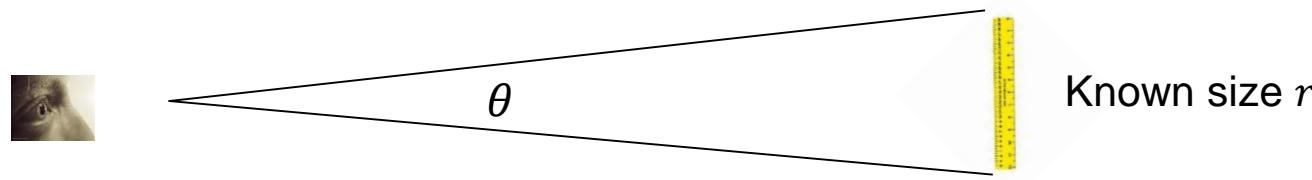
Parallax



$$D = 1 \text{ AU}/\delta$$

Large D impossible

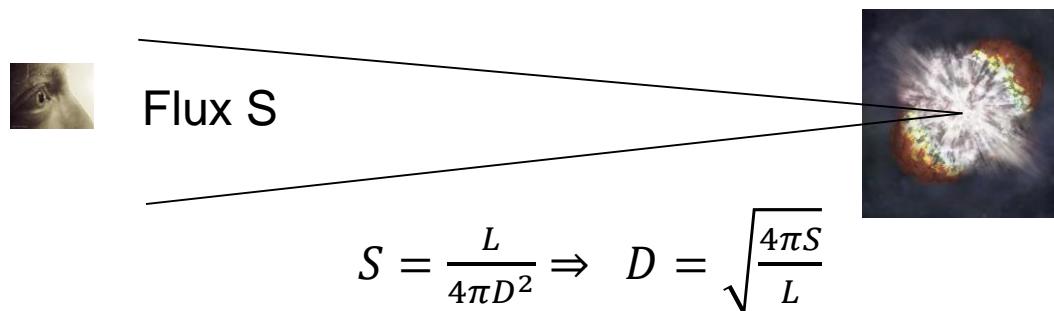
Standard Rulers



$$D = r/\theta$$

Large D: $D \rightarrow d_A/d_M$

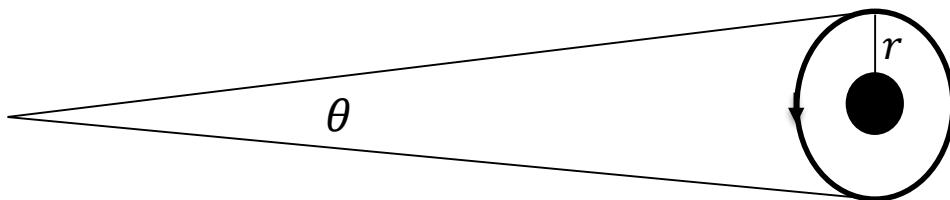
Standard Candles



$$S = \frac{L}{4\pi D^2} \Rightarrow D = \sqrt{\frac{4\pi S}{L}}$$

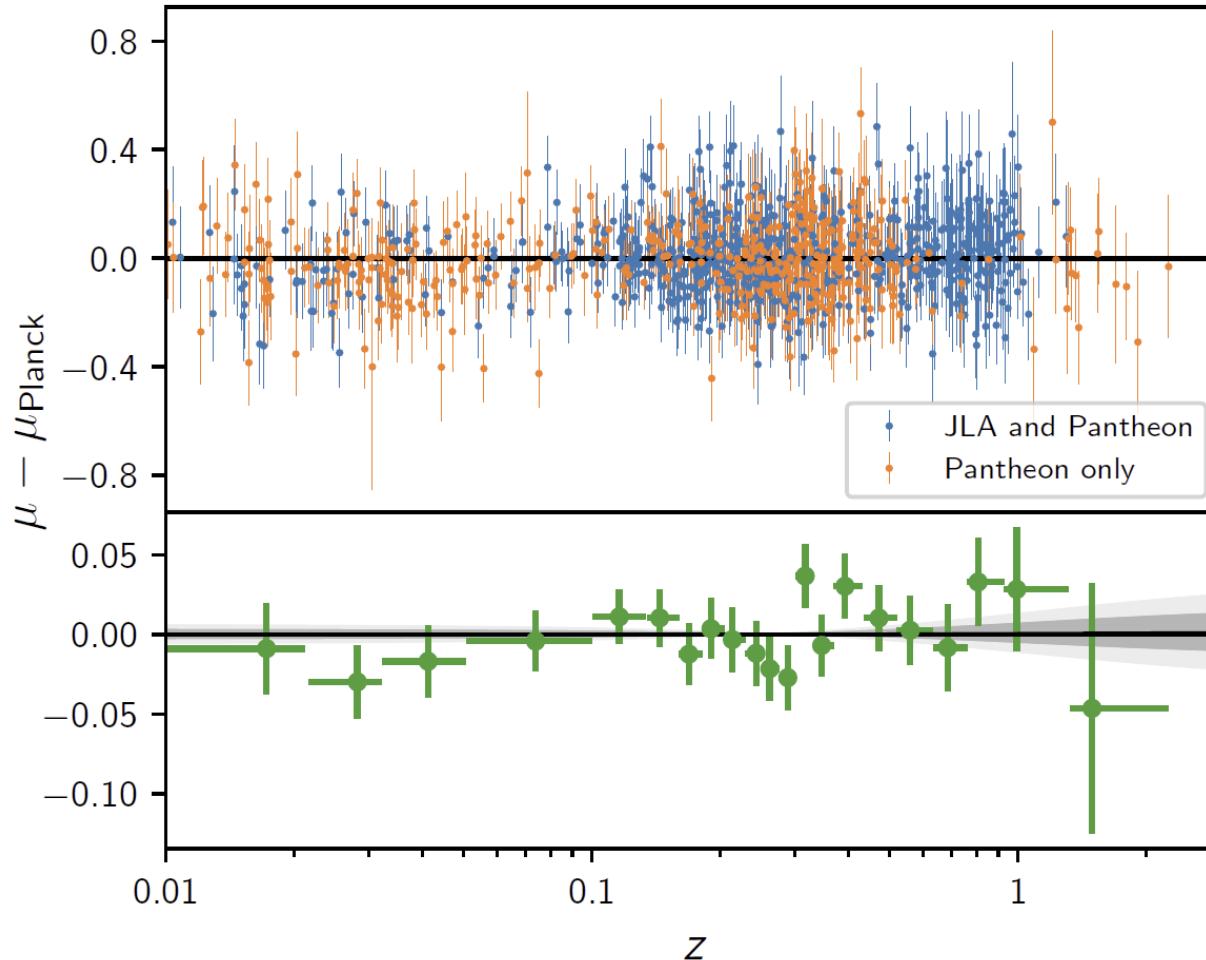
Large D: $D \rightarrow d_L$

E.g. Orbital standard ruler (megamaser)



E.g. Supernova standard(izable) candles

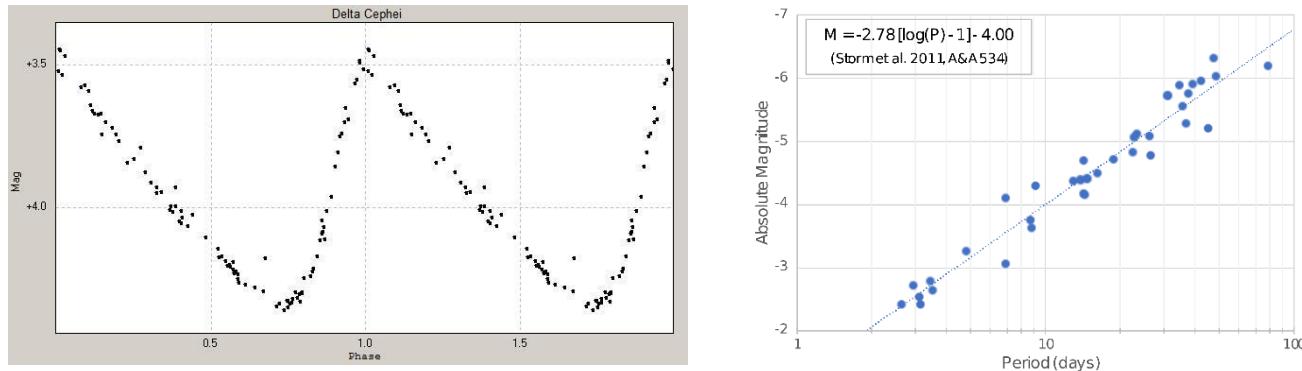
measure $d_L^2 L_{\text{SN}}$ - but intrinsic luminosity L_{SN} unknown
⇒ constrain *relative* redshift evolution very well, $d_L(z) \propto \text{const}$



Unknown L_{SN} ⇒ no direct constraint on H_0
(can measure Ω_m, Ω_K)

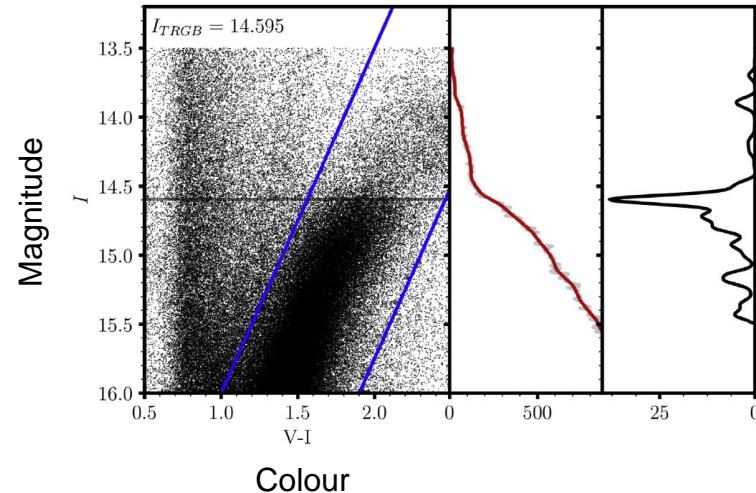
E.g. Other standardizable candles

Cepheid variable stars – using period/luminosity relation (Leavitt law)



Tip of the Red Giant branch (TRGB)

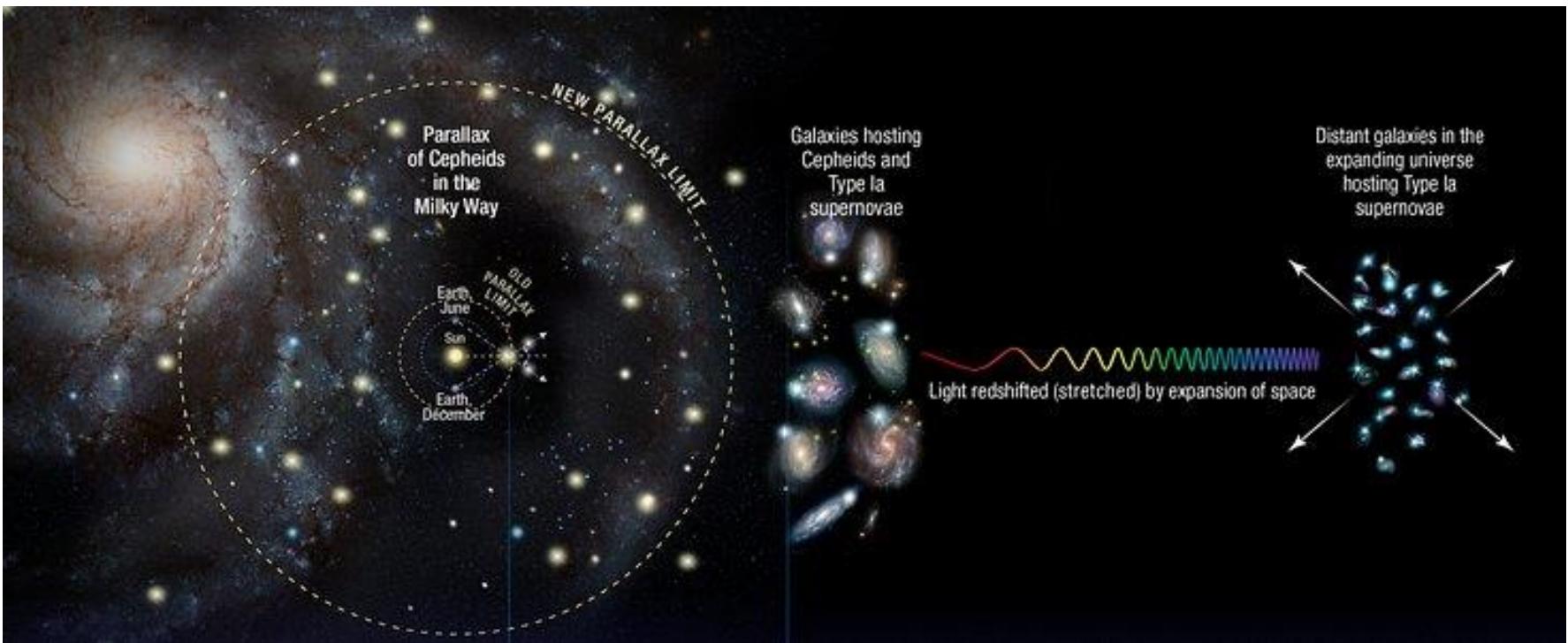
Freedman et al. arXiv:1907.05922



Also need calibrating, no *direct* H_0 measurement

+ others...

H_0 from local distance ladder



<https://www.spacetelescope.org/news/heic1611/>

Parallax+cepheids+SN (+ megamaser)

$$H_0 = (73.2 \pm 1.3) \text{ km s}^{-1}\text{Mpc}^{-1}$$

Riess et al. arXiv: 2012.08534

Other forward distance ladders

Tip of the red giant branch

$$H_0 = 69.8 \pm 1.9 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Freedman et al. arXiv:1907.05922, 2002.01550

$$H_0 = 72.4 \pm 2.0 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Yuan et al. arXiv: 1908.00993

$$H_0 = 71.5 \pm 1.8 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Anand et al. arXiv: 2108.00007

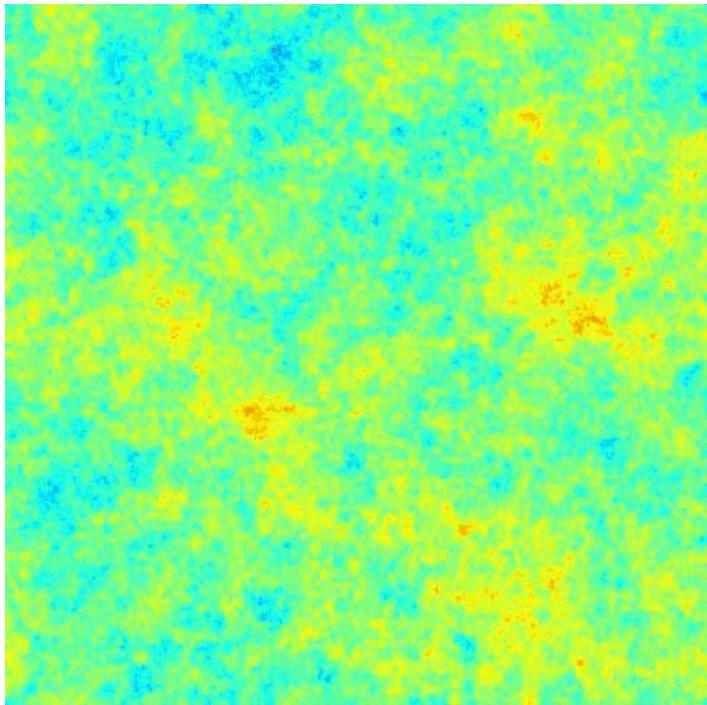
- + other several results using other local calibrators,
all giving broadly consistent results
- Nearly independent of the cosmological model

Cosmology

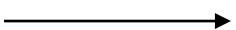
“Inverse distance ladder”

Perturbation evolution

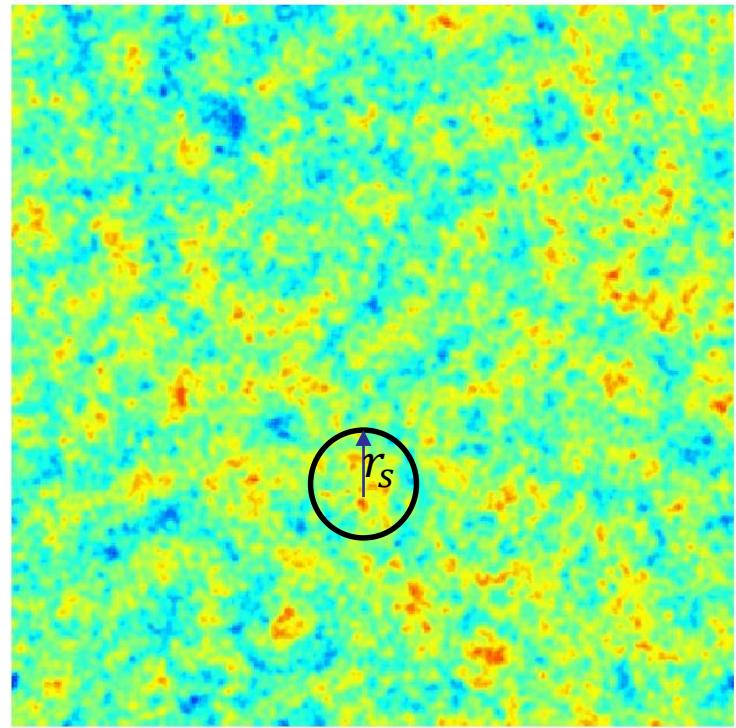
Perturbations: start of hot big bang



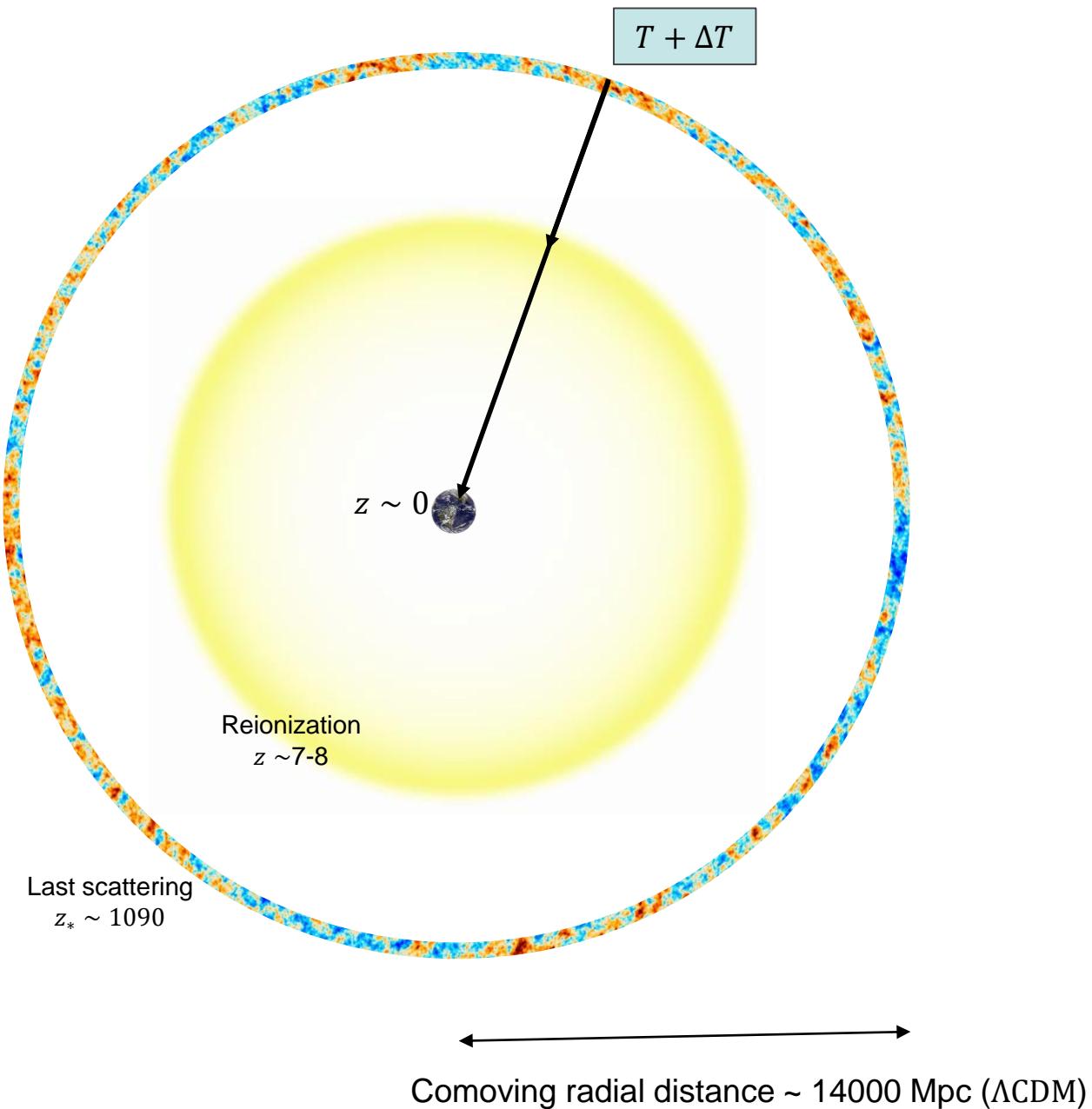
gravity+
pressure+
diffusion



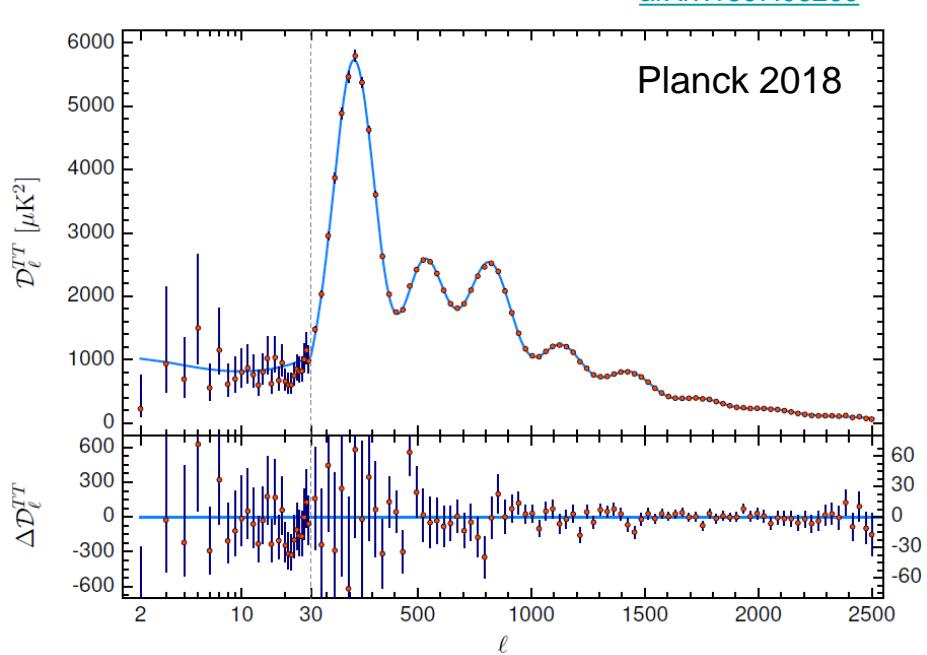
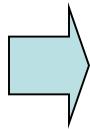
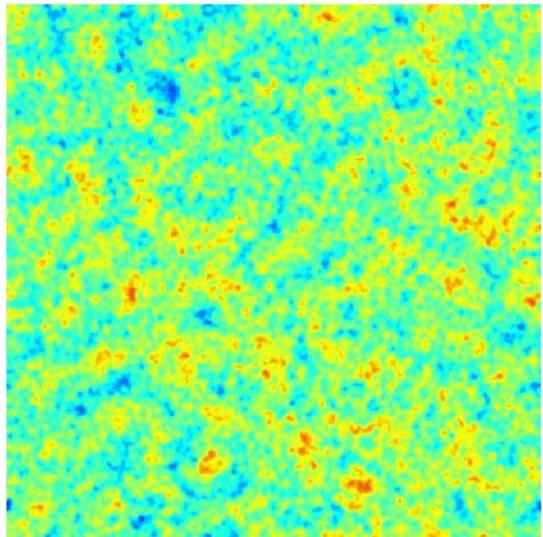
Perturbations: Last scattering surface



In comoving distance



Observed CMB power spectrum

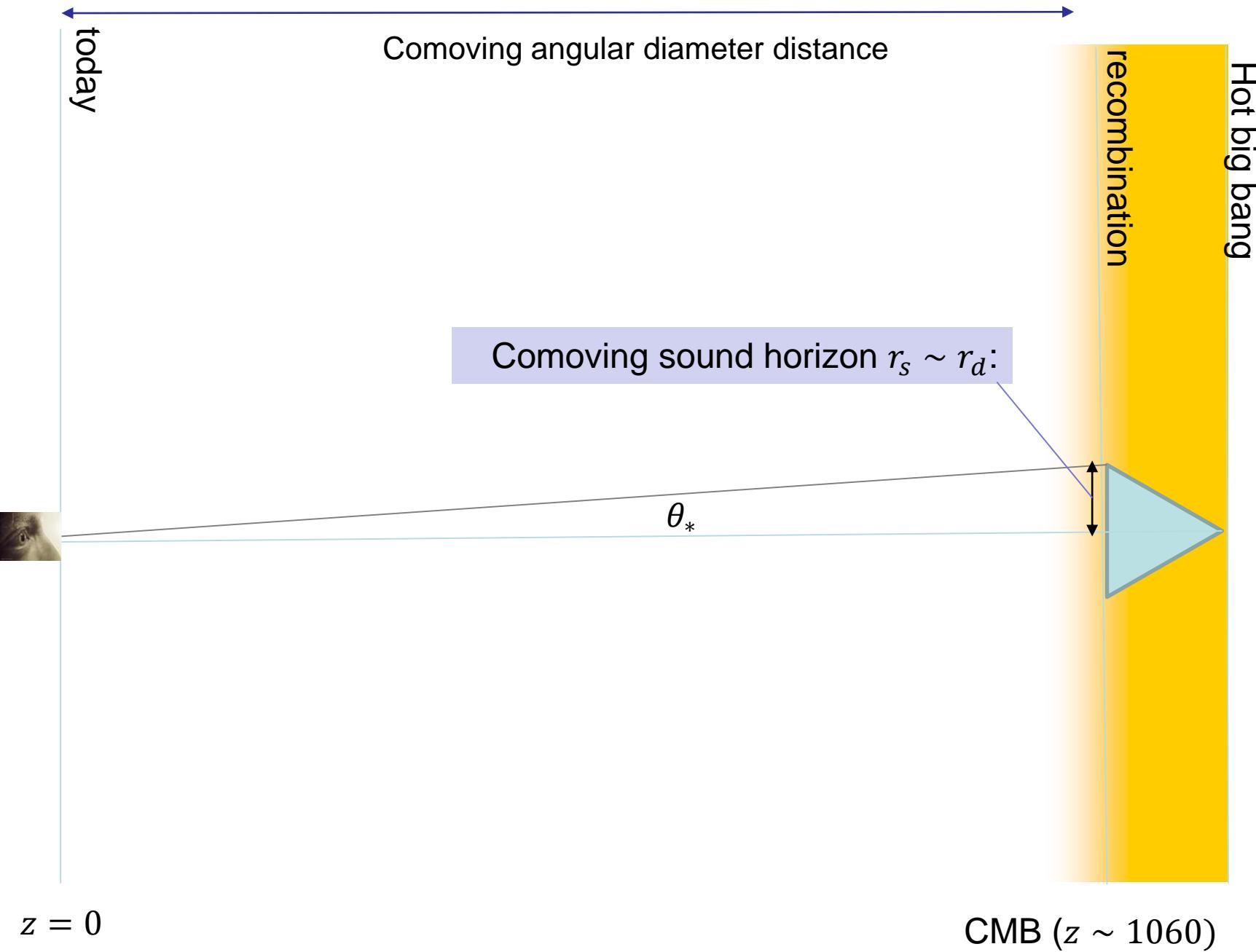


Observations
(10^{-5} perturbations)



**Assume model, constrain parameters
- test constancy with other probes**

Linear perturbation theory very accurate: given a model, can calculate to high precision





today

D_M

$$100\theta_* = 1.04109 \pm 0.00030$$

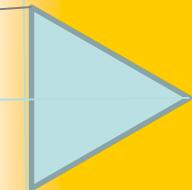
Planck TT,TE,EE+lowE+lensing
(0.03% precision!)

θ_*



recombination

Hot big bang

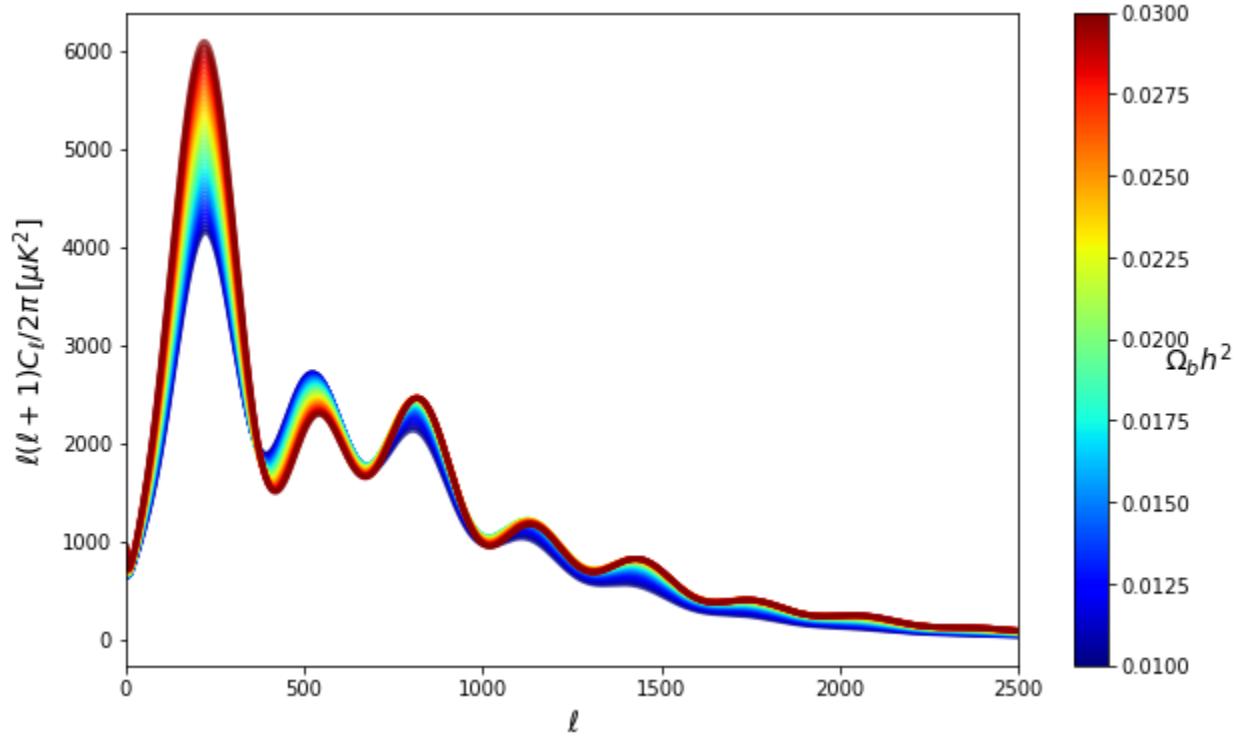


$z = 0$

CMB ($z \sim 1060$)

Λ CDM baryon density at fixed θ_* , $\Omega_m h^2$

(baryons deepen overdensity compressions: enhance odd peaks of spectrum)



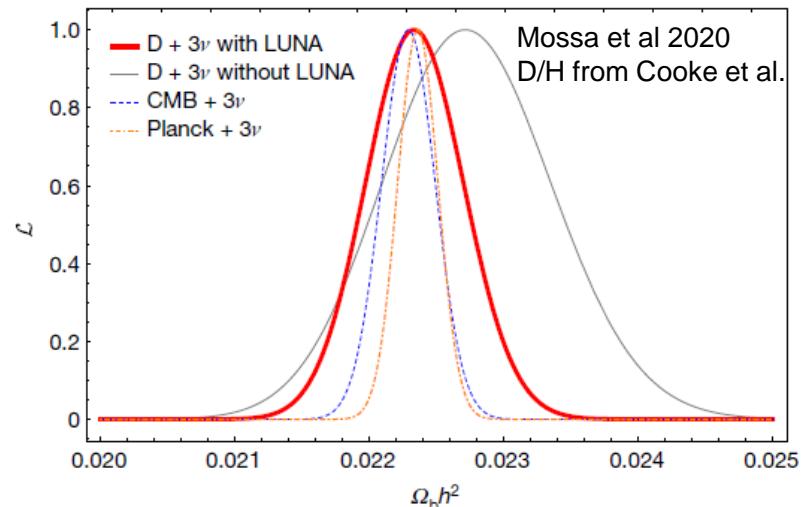
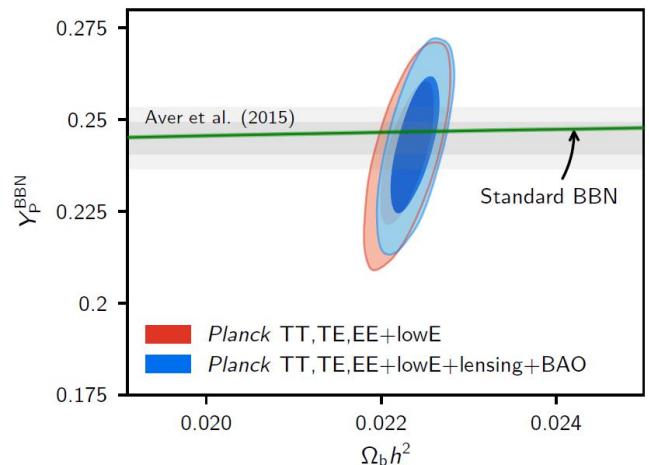
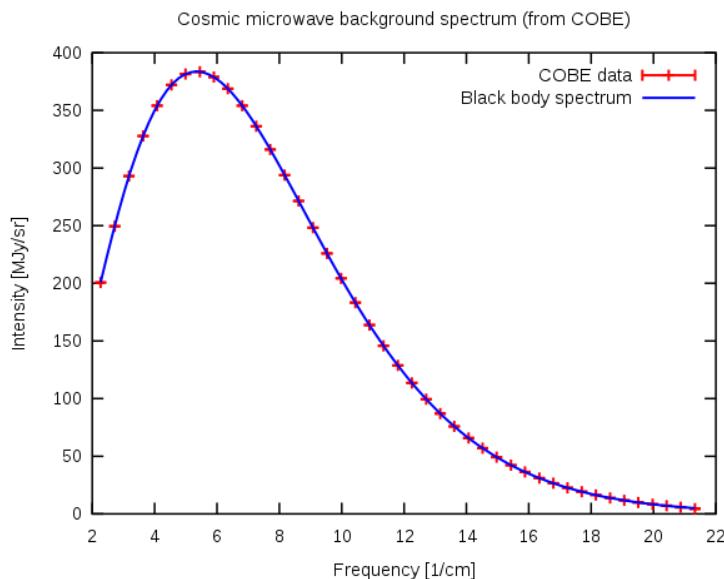
Odd/even height ratio distinctive and quite robust:

$$\Omega_b h^2 = 0.0224 \pm 0.0002$$

Consistency with standard Big-Bang Nucleosynthesis

arXiv: 1806.06209

COBE measured $T_{\text{CMB}} \sim 2.7255 \text{ K}$



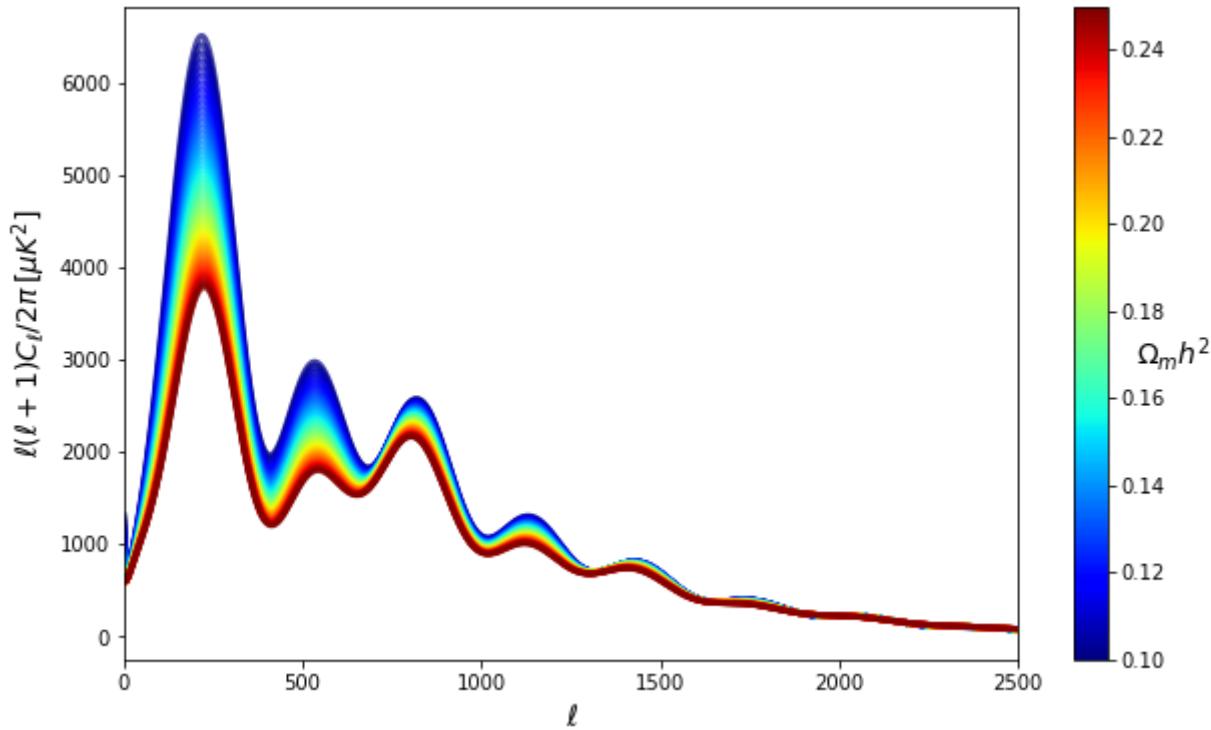
BUT: Lithium problem remains around 5σ

Measured: ${}^7\text{Li}/\text{H} = (1.58 \pm 0.35) \times 10^{-10}$ arXiv: 1505.01076

Prediction: ${}^7\text{Li}/\text{H} = 4.5 \times 10^{-10}$

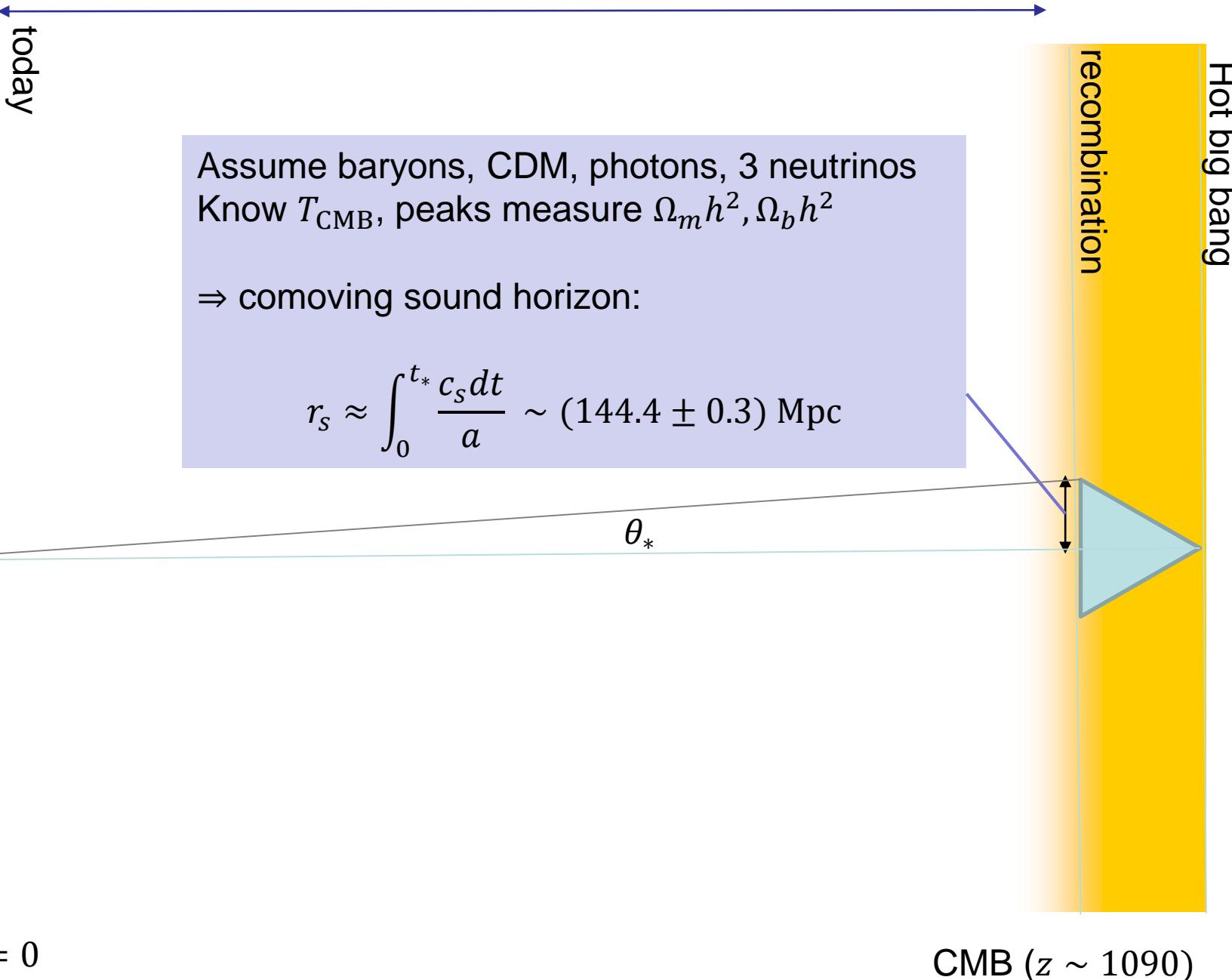
Λ CDM matter density at fixed θ_* , $\Omega_b h^2$

(more matter *lowers* amplitude for modes that enter horizon in matter domination)



Can be partly compensated by changing initial power A_s , n_s and foregrounds.
But detailed shape is still quite distinctive and robust:

$$\Omega_m h^2 = 0.143 \pm 0.001$$



CMB

today

$$r_s, \theta_* \Rightarrow D_M \sim (13.87 \pm 0.03) \text{ Gpc}$$

recombination

Hot big bang

θ_*

D_M

r_s

Assuming flat Λ CDM cosmology

$$\Rightarrow H_0 = (67.3 \pm 0.6) \text{ km s}^{-1}\text{Mpc}^{-1}$$

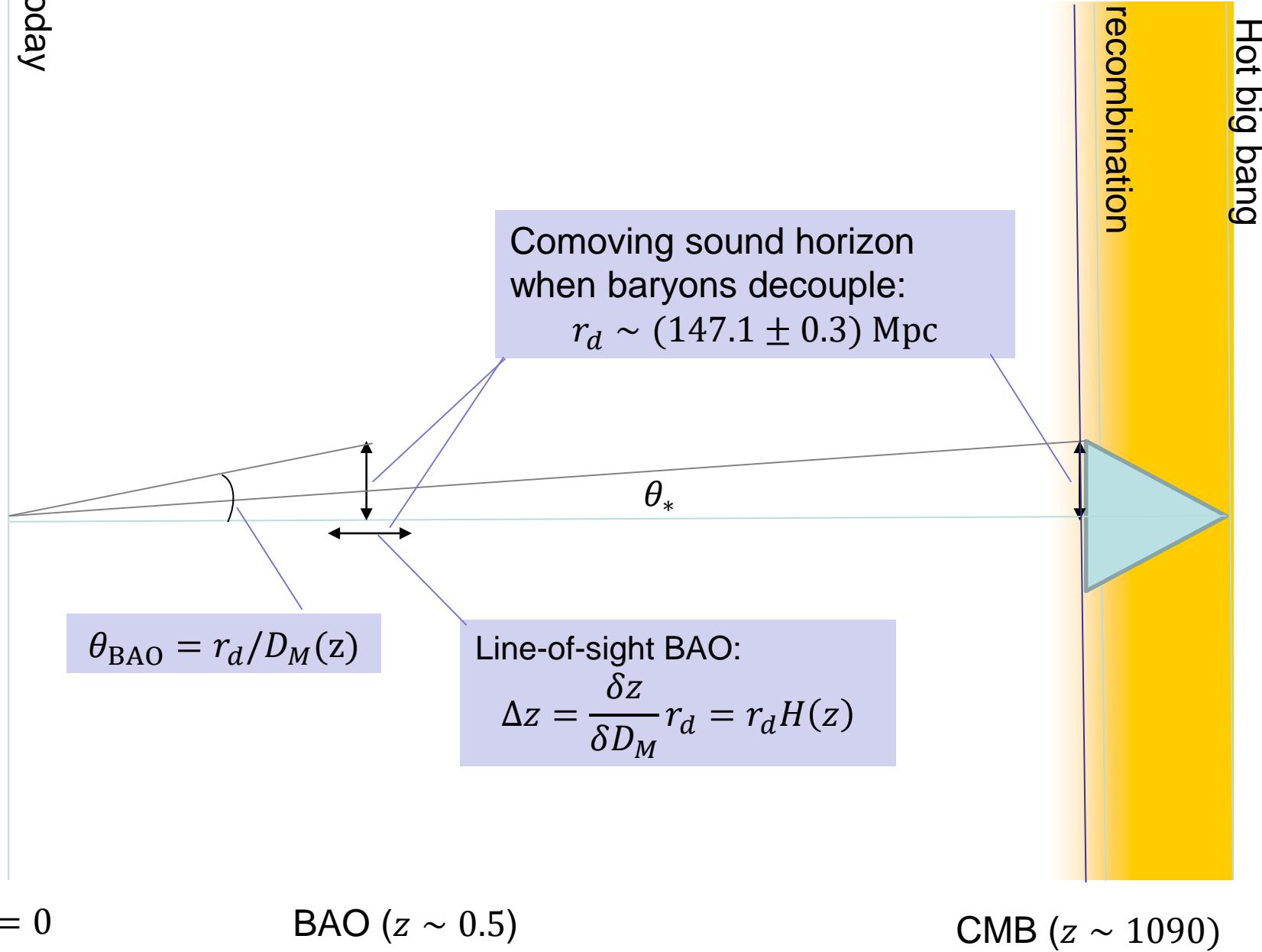
(Planck, confirmed by ACT)

$z = 0$

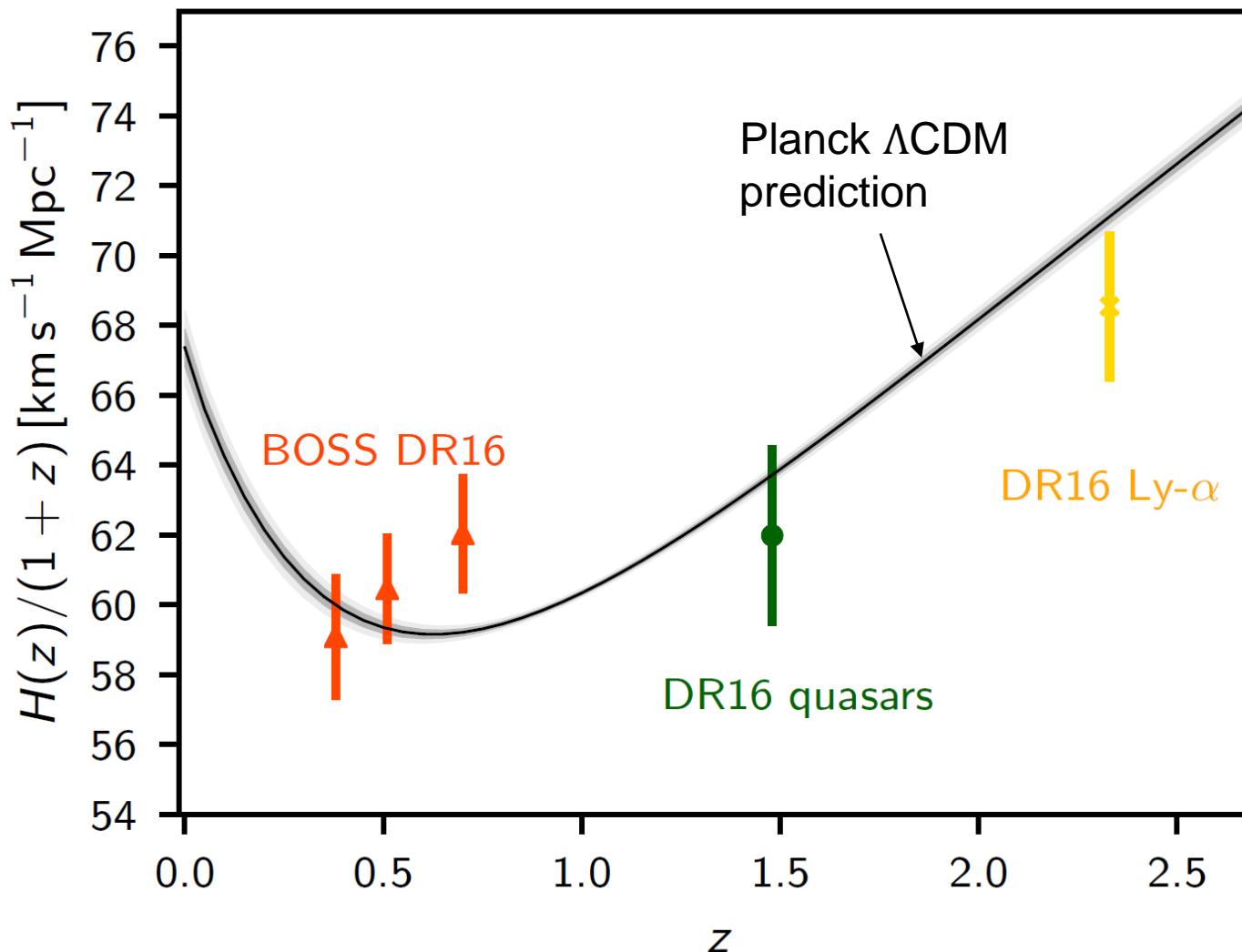
CMB ($z \sim 1090$)

CMB and BAO consistency in Λ CDM

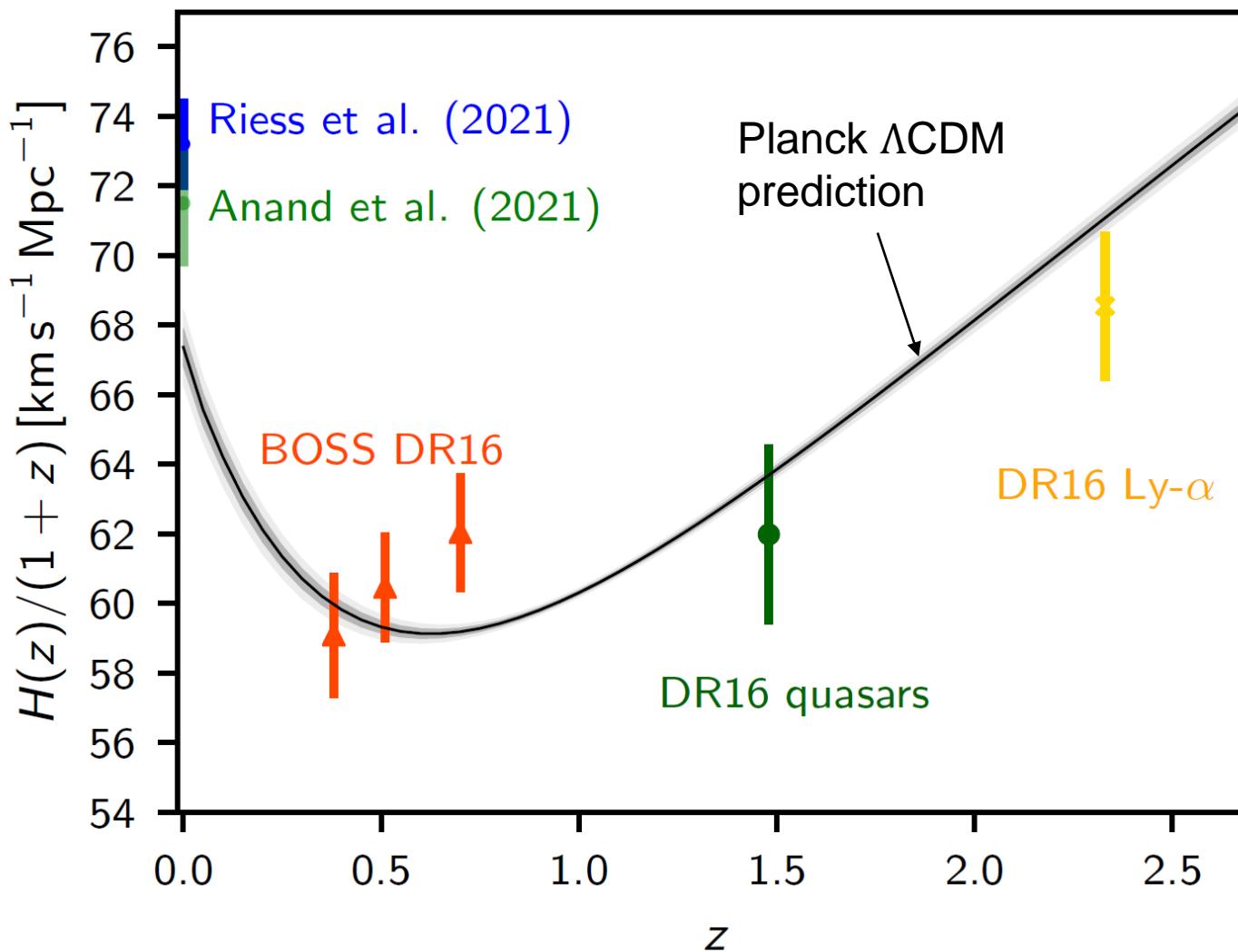
today



Assuming Λ CDM and Planck sound horizon r_d



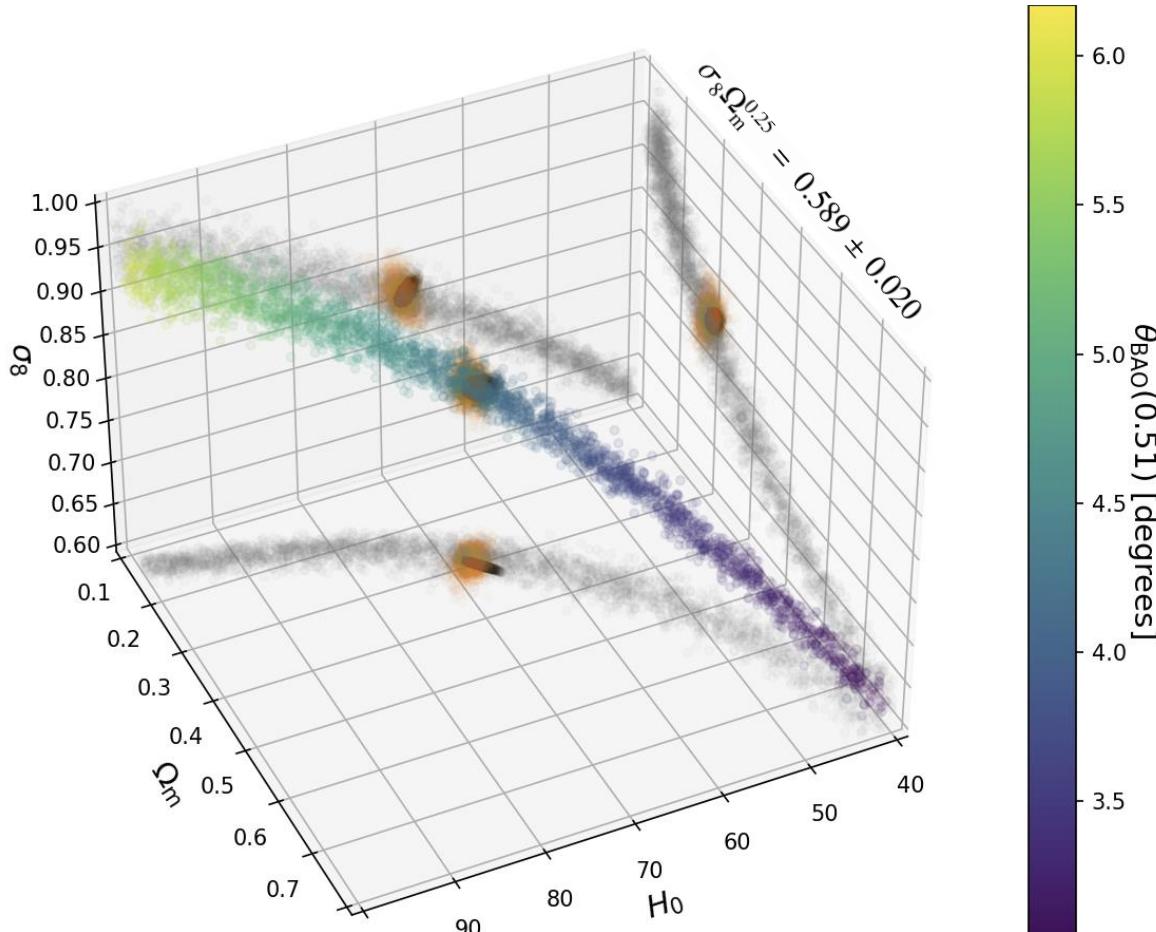
Assuming Λ CDM and Planck sound horizon r_d



Riess et al: $4.2\sigma \sim 10\%$ discrepancy between local and CMB-inferred Λ CDM H_0 ?

Planck 2018 CMB lensing Λ CDM parameters

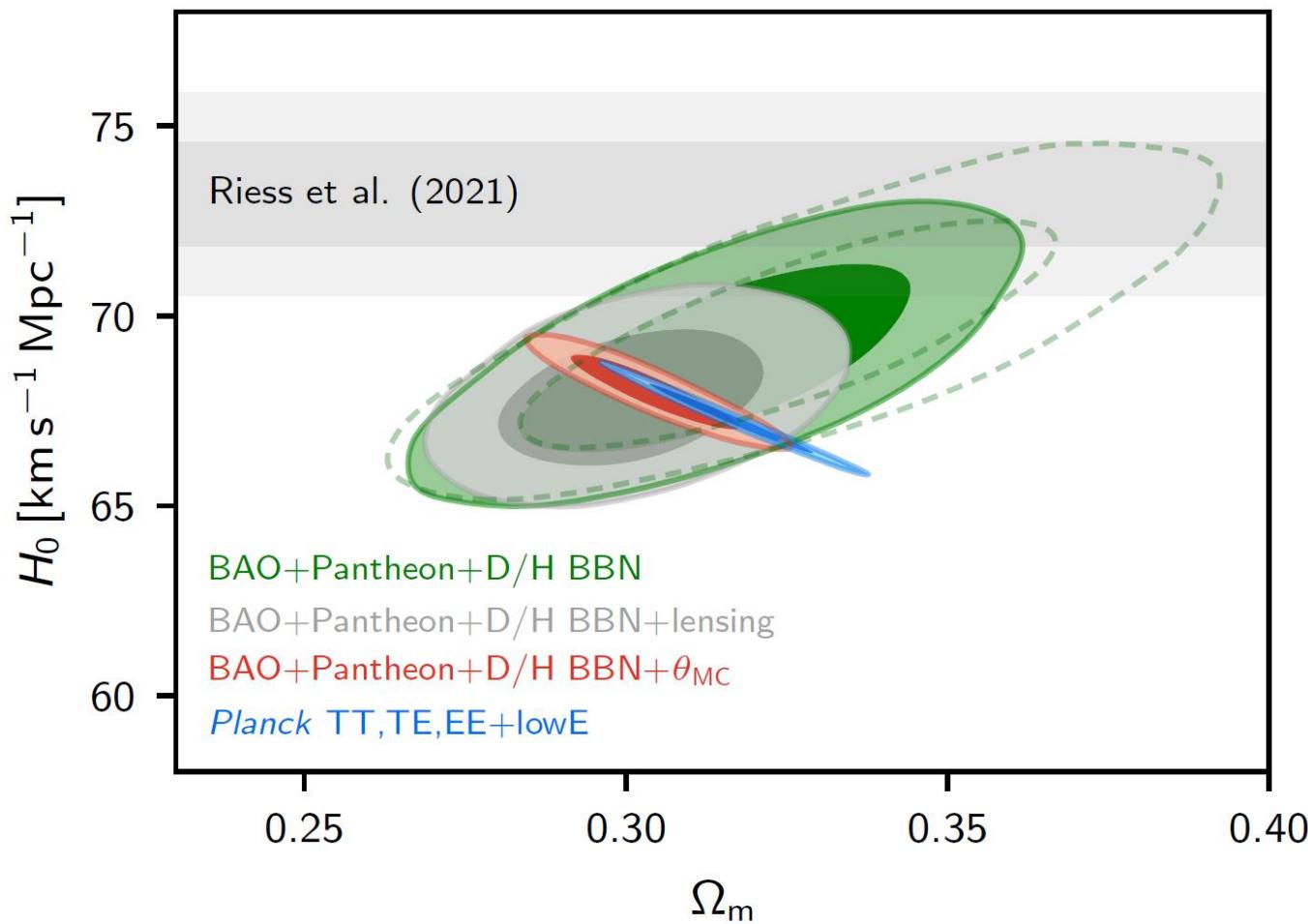
Planck lensing 2018
+ BOSS BAO (+ $\Omega_b h^2$ BBN)
Planck 2018 TTTEEE



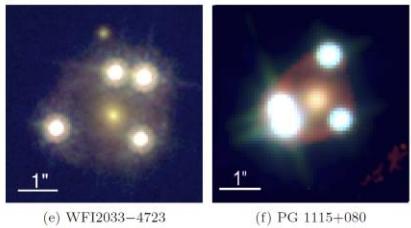
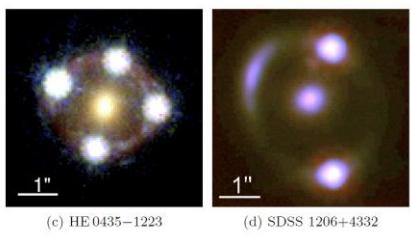
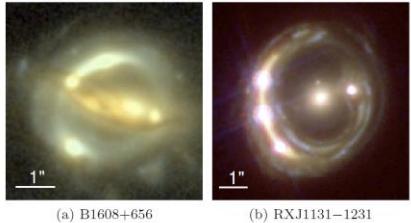
CMB lensing + BAO inverse distance ladder (with $\Omega_b h^2$ prior from abundance measurements)

$$\left. \begin{array}{l} H_0 = 67.9_{-1.3}^{+1.2} \text{ km s}^{-1} \text{Mpc}^{-1}, \\ \sigma_8 = 0.811 \pm 0.019, \\ \Omega_m = 0.303_{-0.018}^{+0.016}, \end{array} \right\} 68\%, \text{lensing+BAO}$$

Independent Λ CDM inverse distance ladder is also consistent with Planck

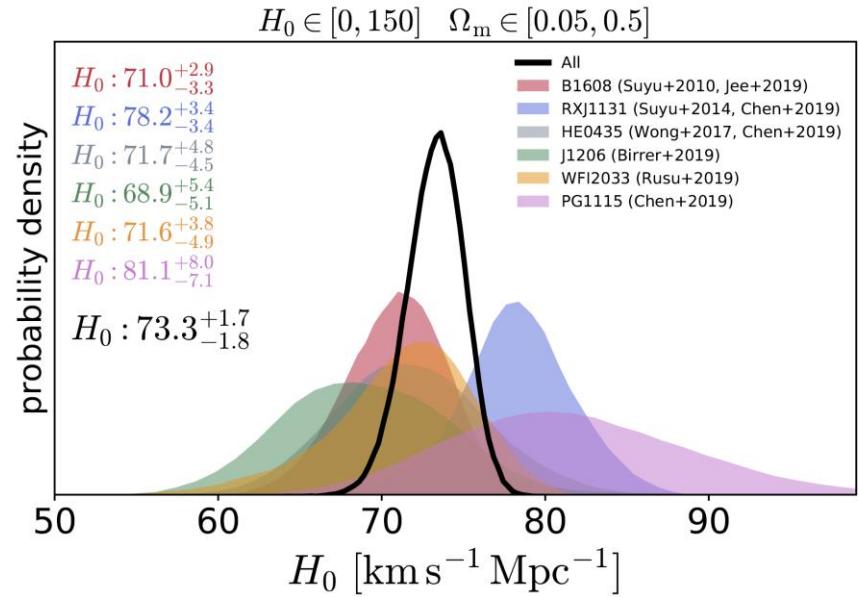


Strong Lensing



Lens modelling etc..

$$D_{\Delta t} \equiv (1 + z_d) \frac{D_d D_s}{D_{ds}}$$



H0LiCOW: $H_0 = 73.3^{+1.7}_{-1.8} \text{ km s}^{-1} \text{Mpc}^{-1}$

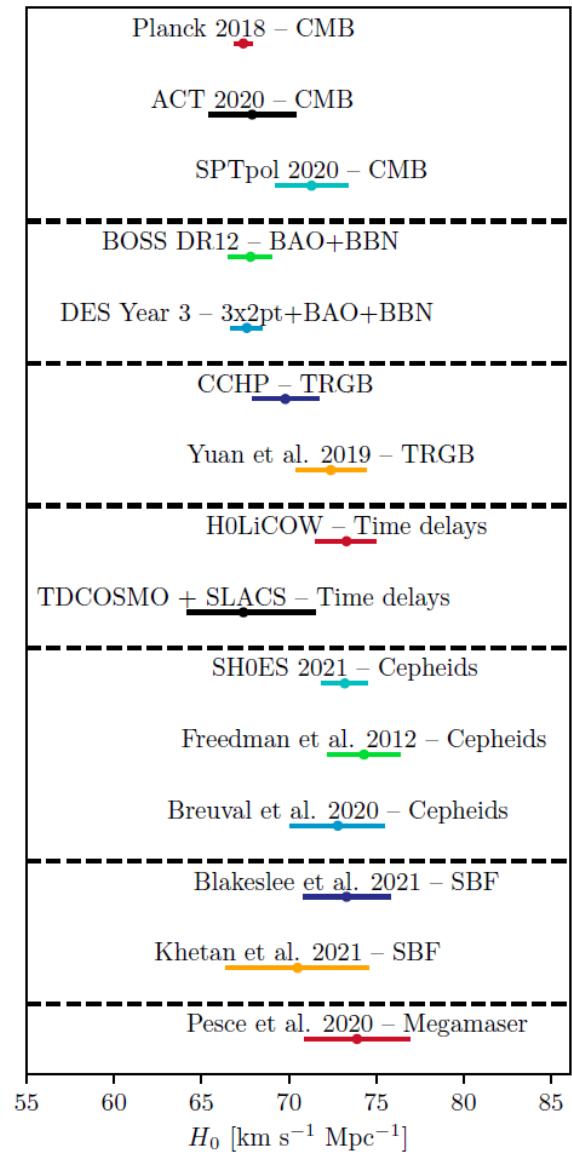
Wong et al. arXiv:1907.04869
(some cosmology dependence)

Independent of CMB and local distance ladder and mostly redshift $z > \sim 0.1$

⇒ tension with CMB independent of very local environment

TDCOSMO+SLACS: $H_0 = 67.4^{+4.1}_{-3.2} \text{ km s}^{-1} \text{Mpc}^{-1}$

Birrer et al. arXiv: 2007.02941



Possible solutions to the H_0 tensions

Biases in data or underestimated error bars

- inverse distance ladder: BAO and CMB consistent \Rightarrow both CMB and BAO being wrong?
- Local H_0 and strong lensing independent; multiple local distance ladders
but TRGB results lower and strong lensing modelling dependent

New physics prior to recombination:

- decrease sound horizon r_d : BAO and Planck H_0 both shift proportionately
- other changes that affect relevant inferred parameters (e.g. $\Omega_m h^2$)

New physics at lower redshift/dark energy/modified gravity

- have to fit BAO and $H(z)/H_0$ from supernovae (or find problem with supernovae)

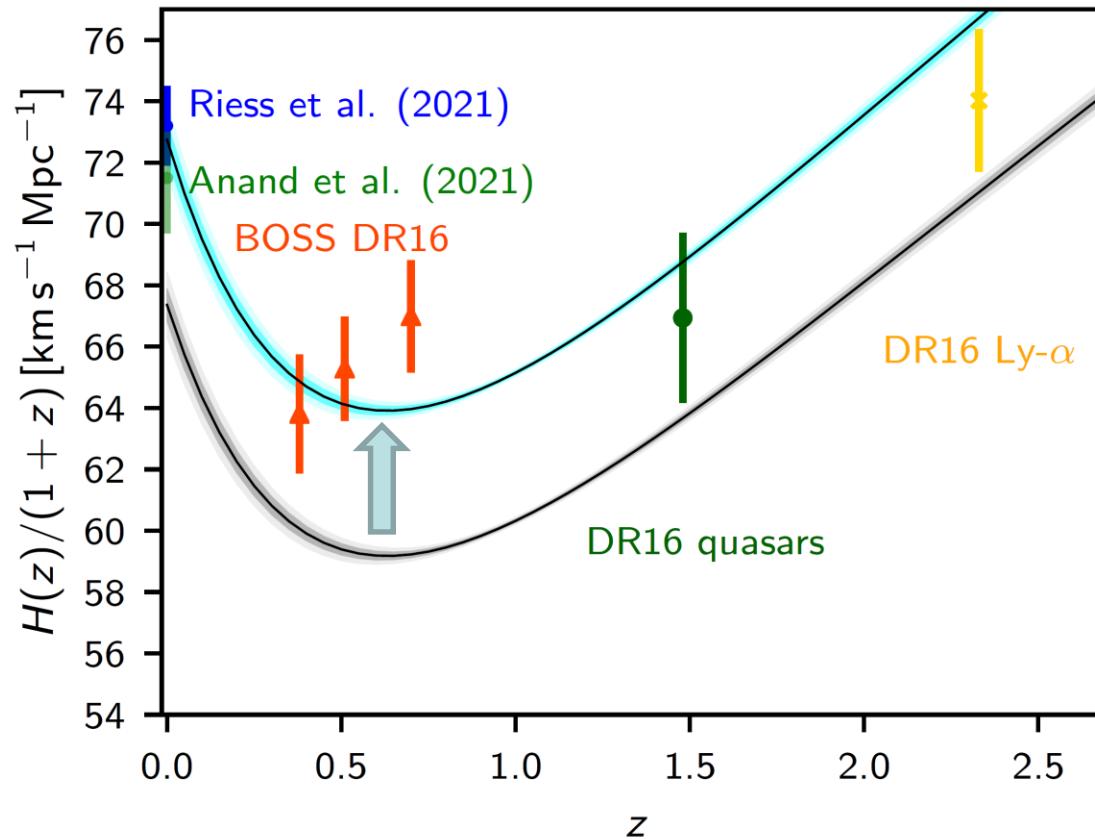
New physics/very unusual conditions in our local neighbourhood

- strong lensing results then in tension?

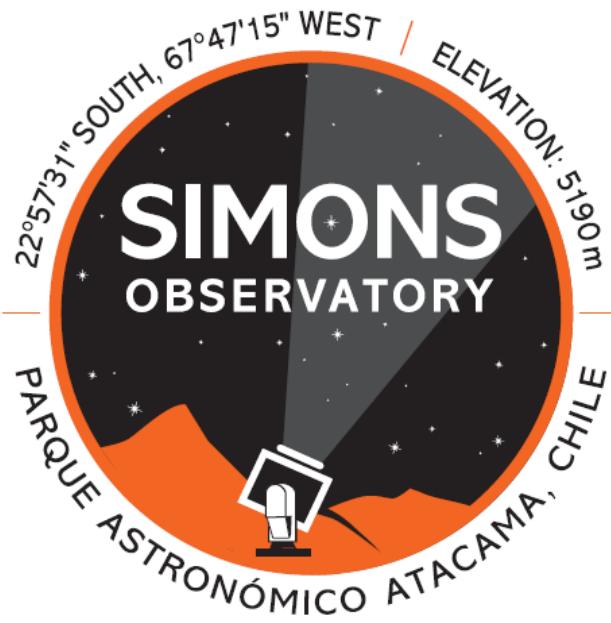
Some combination of the above

New early universe physics – decrease sound horizon r_d by $O(10\%)$

e.g. *increase expansion rate, decrease sound speed, shift recombination, ..*



But, simple models e.g. extra relativistic degrees of freedom ($N_{\text{eff}} \neq 3.046$) not favoured by Planck spectra (and disfavoured by BBN D/H)

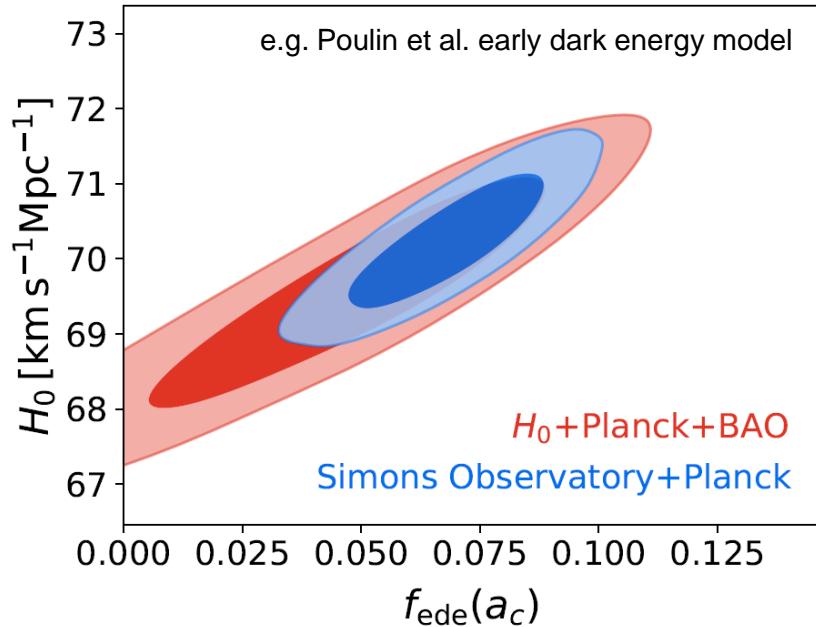
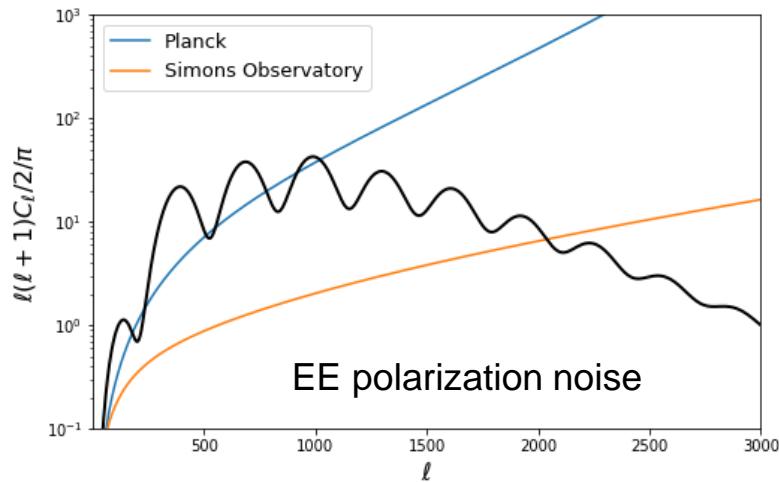


- + ActPol, SPTpol (now)
- + CMB-S4 (beyond)

If $H_0 > 71 \text{ km s}^{-1}\text{Mpc}^{-1}$,
new pre-recombination physics
likely detectable at $> 5\sigma$ soon

*Distinct physical models give
different precision predictions*

High resolution/sensitivity polarization:
precision small-scale EE, TE, TT power spectrum



Conclusions

Λ CDM concordance between CMB, BAO, SN, CMB lensing, BBN (except lithium)

... and *BAO and CMB are the cleanest and most robust probes*

H_0 tension 1-5+ σ

- Complex indirect measurements, but multiple independent or semi-independent probes
- New pre-recombination physics at 5-10 % level “easily” detectable soon with CMB polarization
 - can test *reason for discrepancy* \Rightarrow distinguish new physics

No models currently attempted are compelling or great fits.

- *and why does it look in so many ways just like Λ CDM ?*