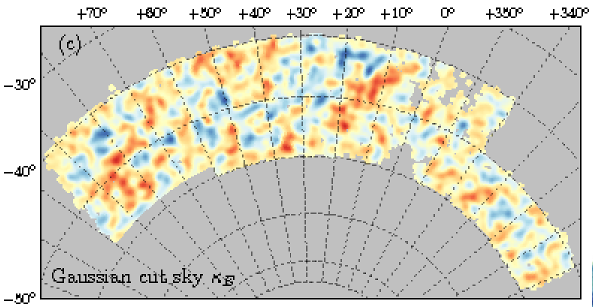
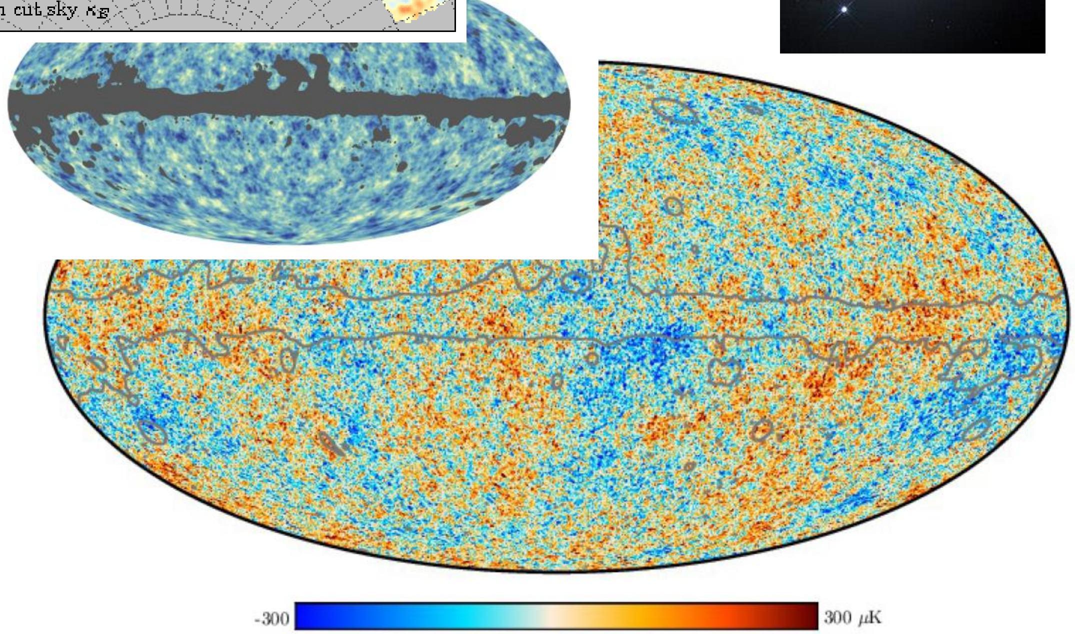
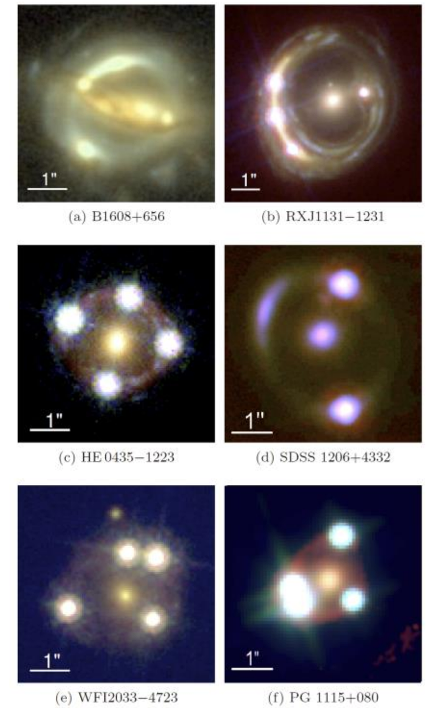
Cosmic Concordance and Tensions







UNIVERSITY OF SUSSEX

Antony Lewis

http://cosmologist.info/

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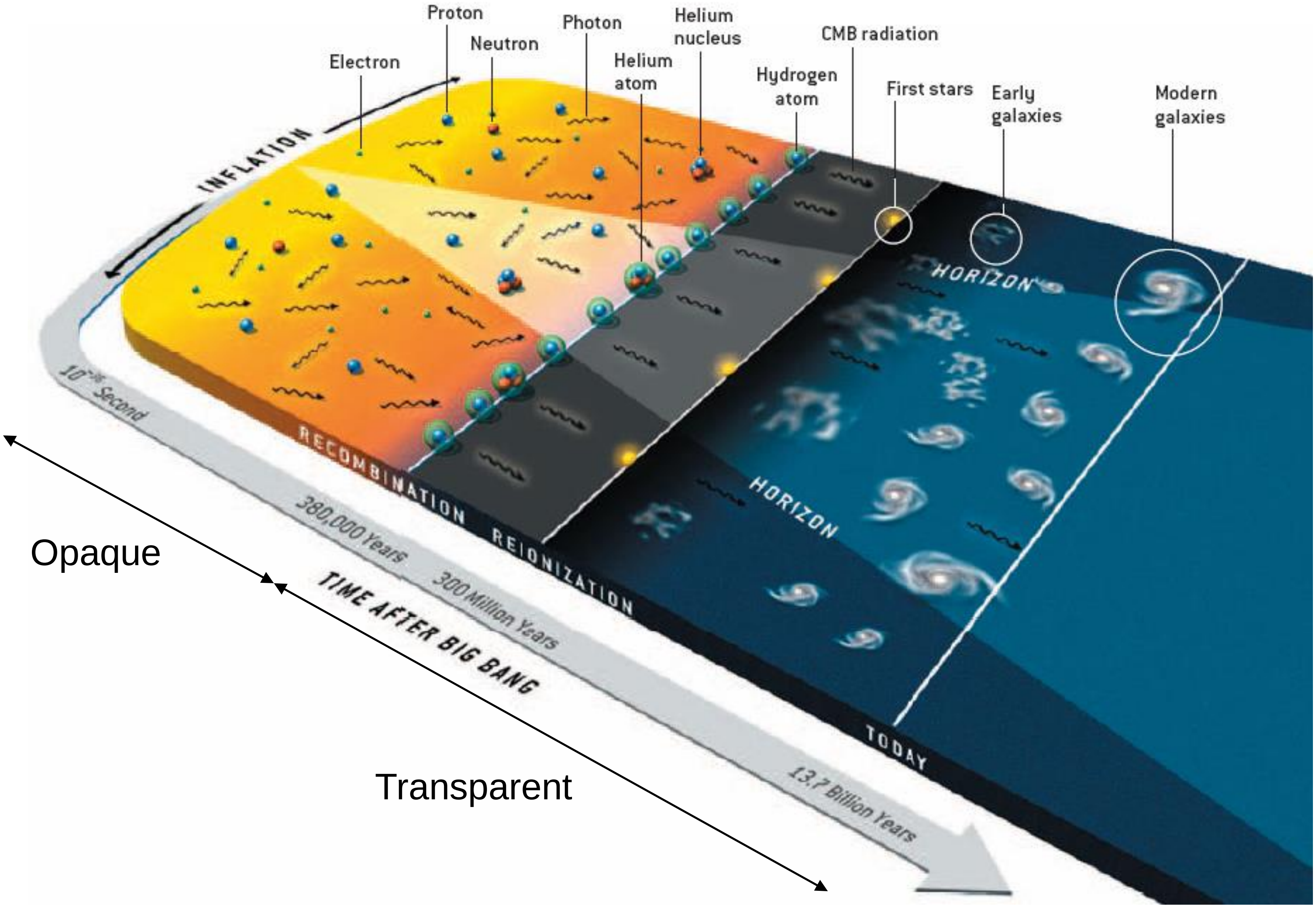
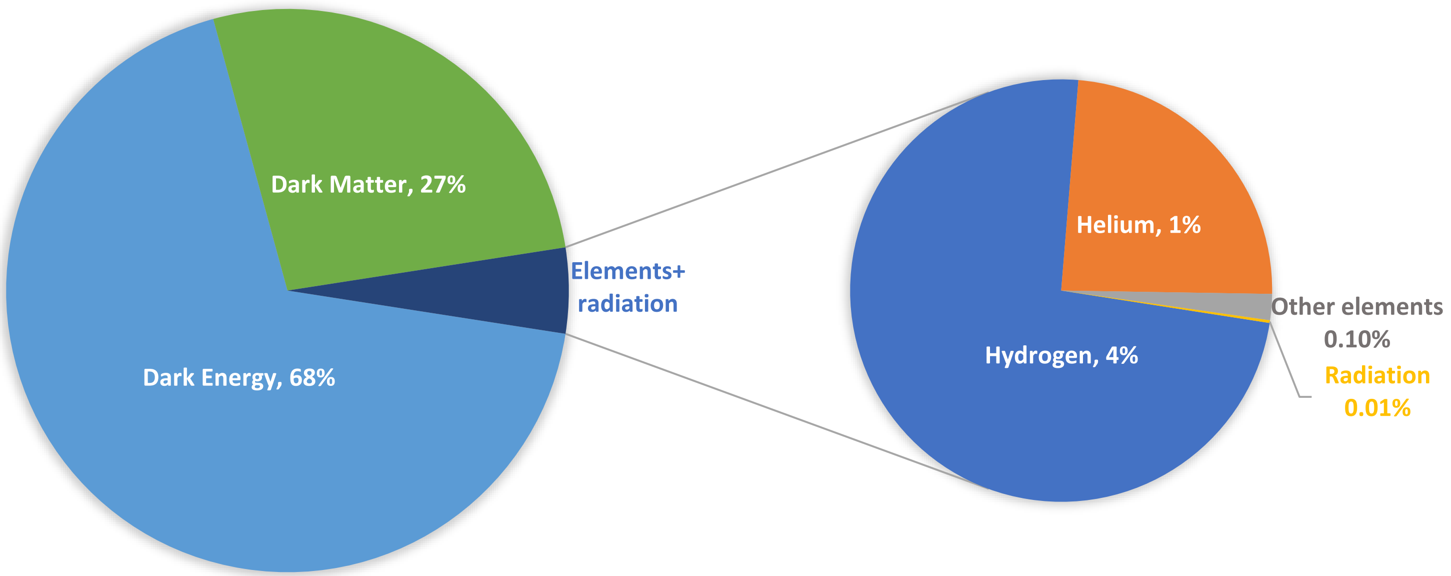
Evolution in the standard cosmology



Hu & White, Sci. Am., 290 44 (2004)

Contents of the Universe today



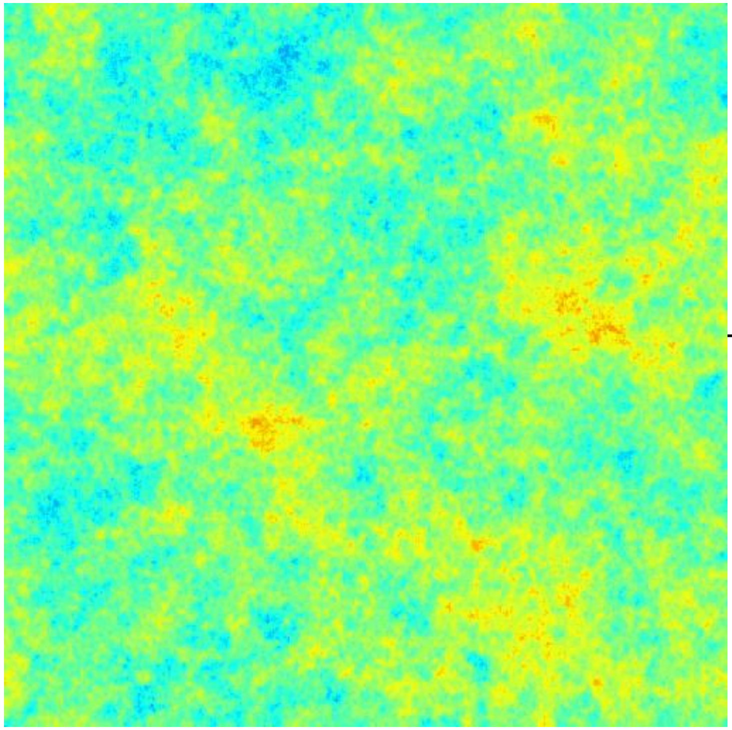
Define and test perturbatively-FRW ΛCDM model:

- 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, 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 $H_0 = 100h\,\mathrm{km\,s^{-1}Mpc^{-1}}$ *(or* $\Omega_\Lambda, \Omega_m, \theta_*, \ldots$*)*

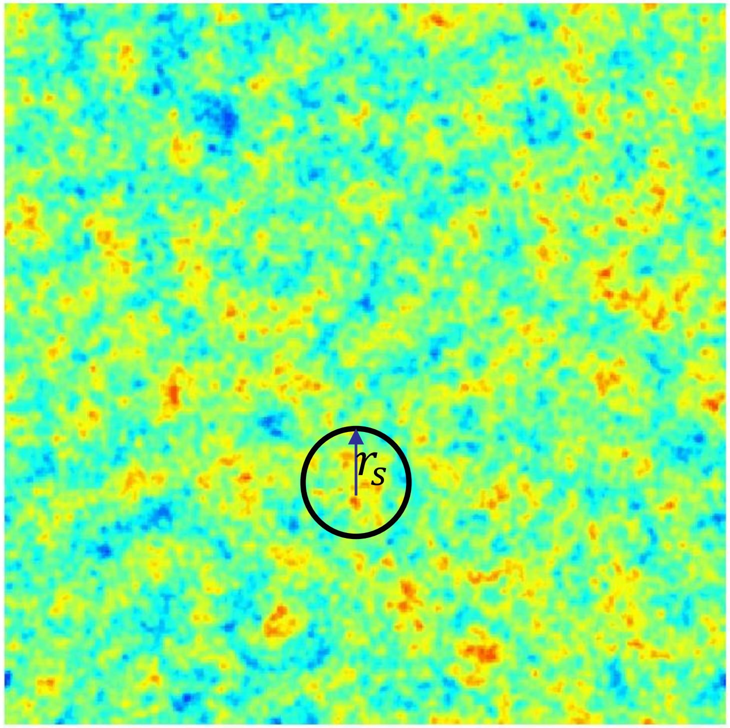
Perturbation evolution

Perturbations: start of hot big bang

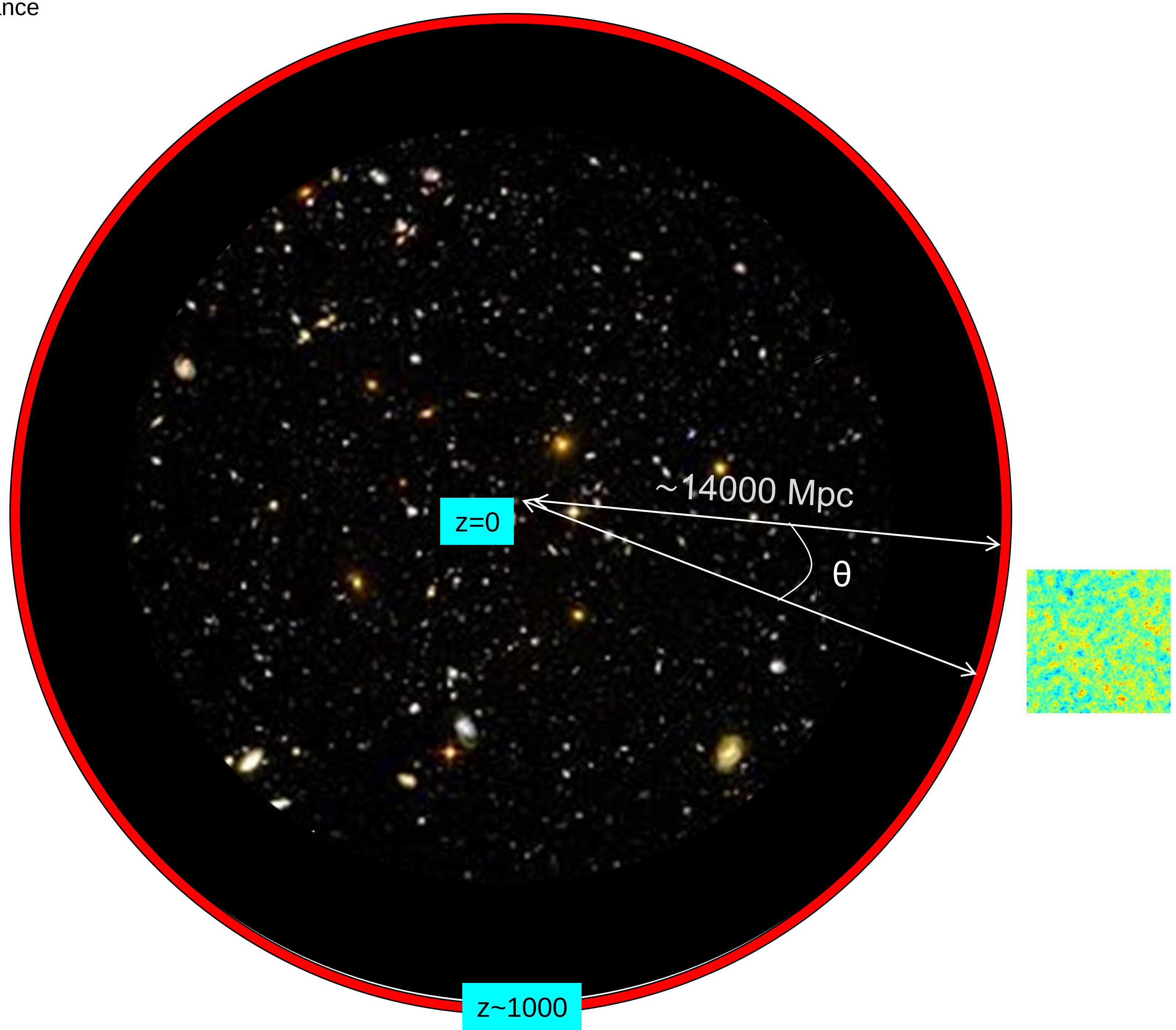


gravity+
pressure+
diffusion

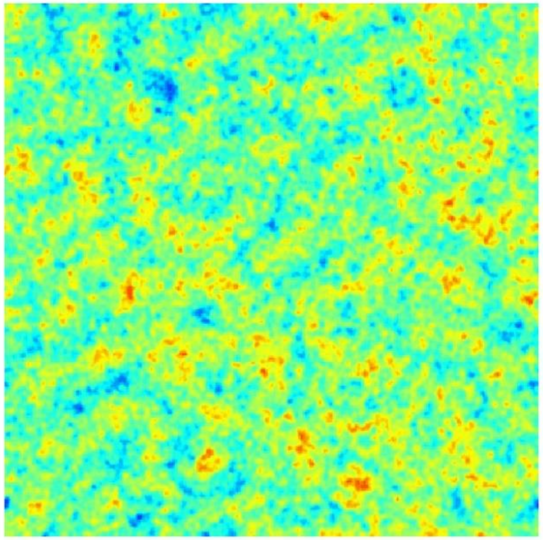
Perturbations: Last scattering surface



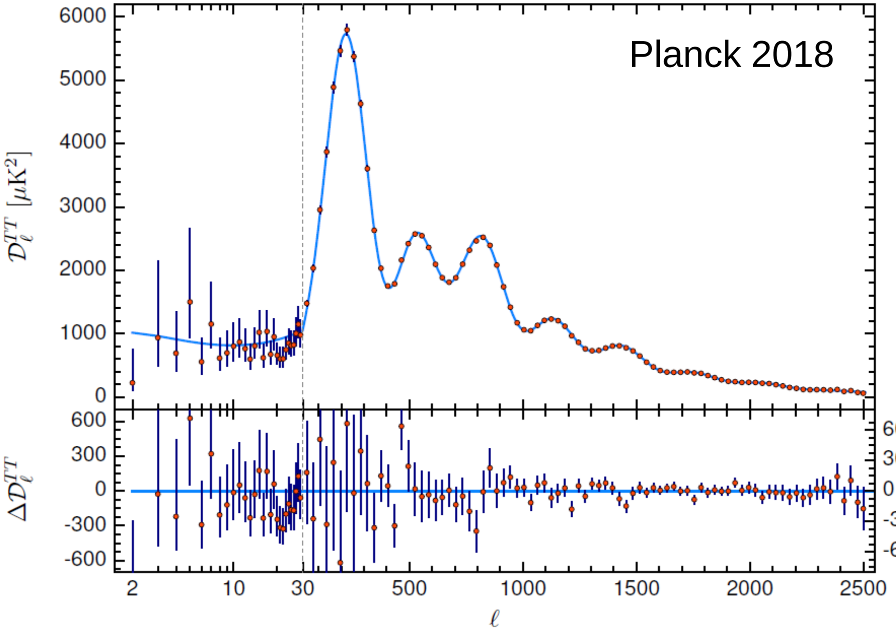
In comoving distance



Observed CMB power spectrum



arXiv:1807.06209



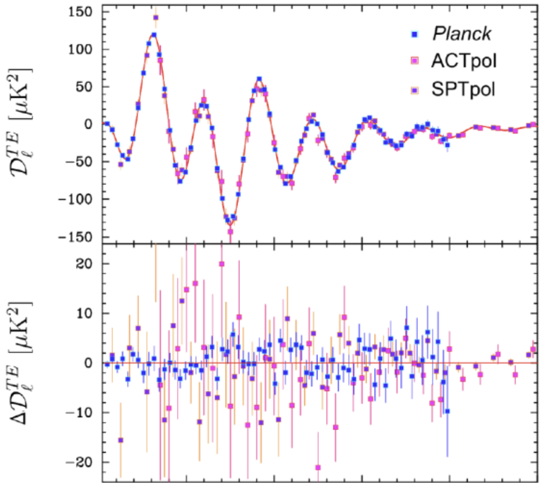
Observations

$(10^{-5}$ **perturbations)**

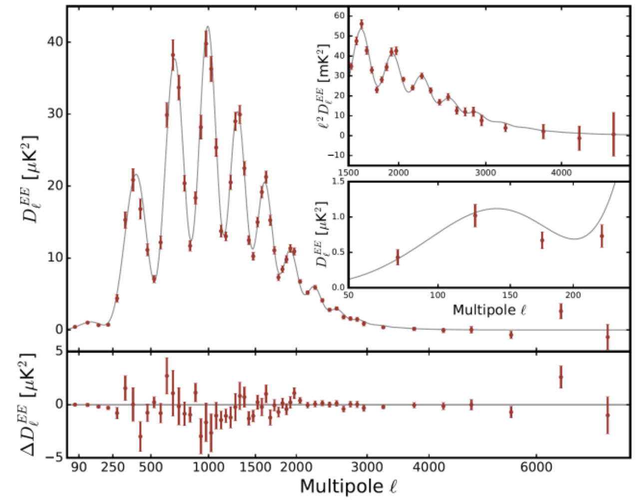
Assume model, constrain parameters
- test constancy with other probes

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

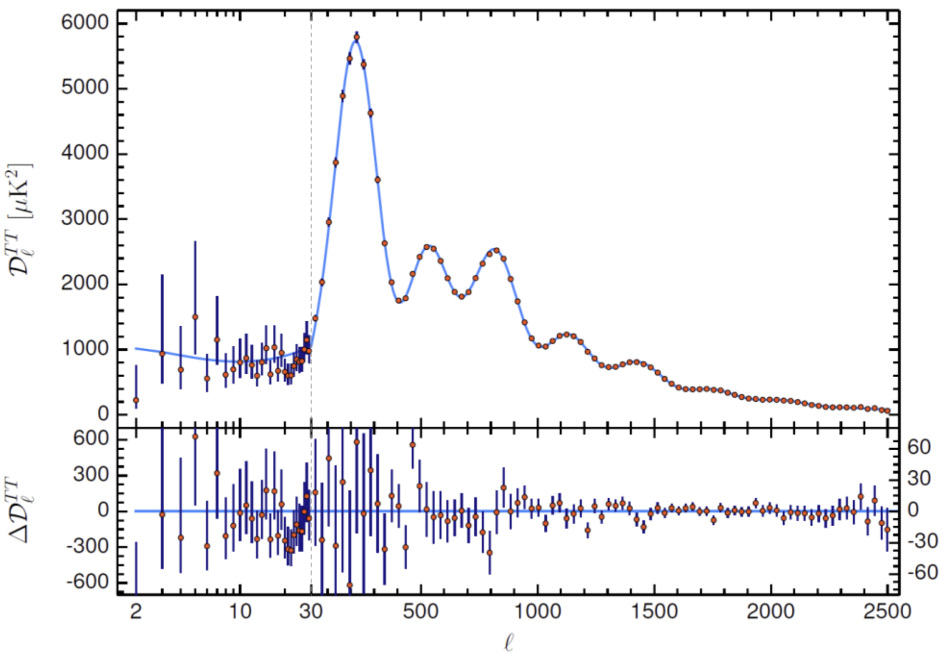
Cosmic Microwave Background power spectrum fits to ΛCDM



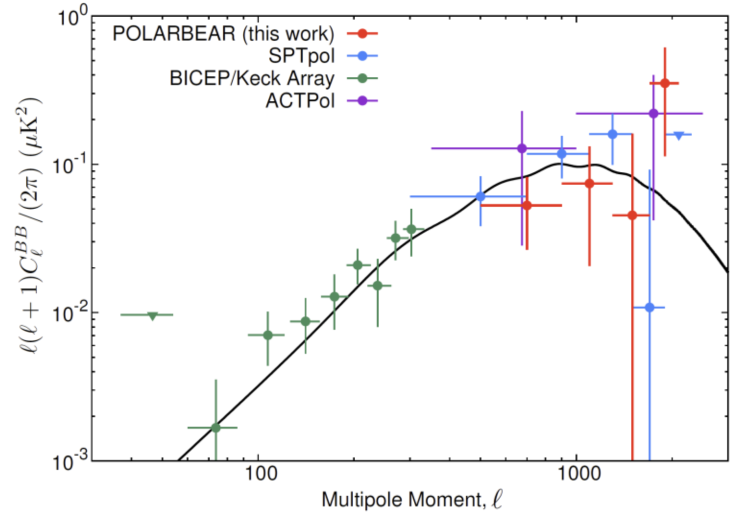
SPTpol: arXiv:1707.09353



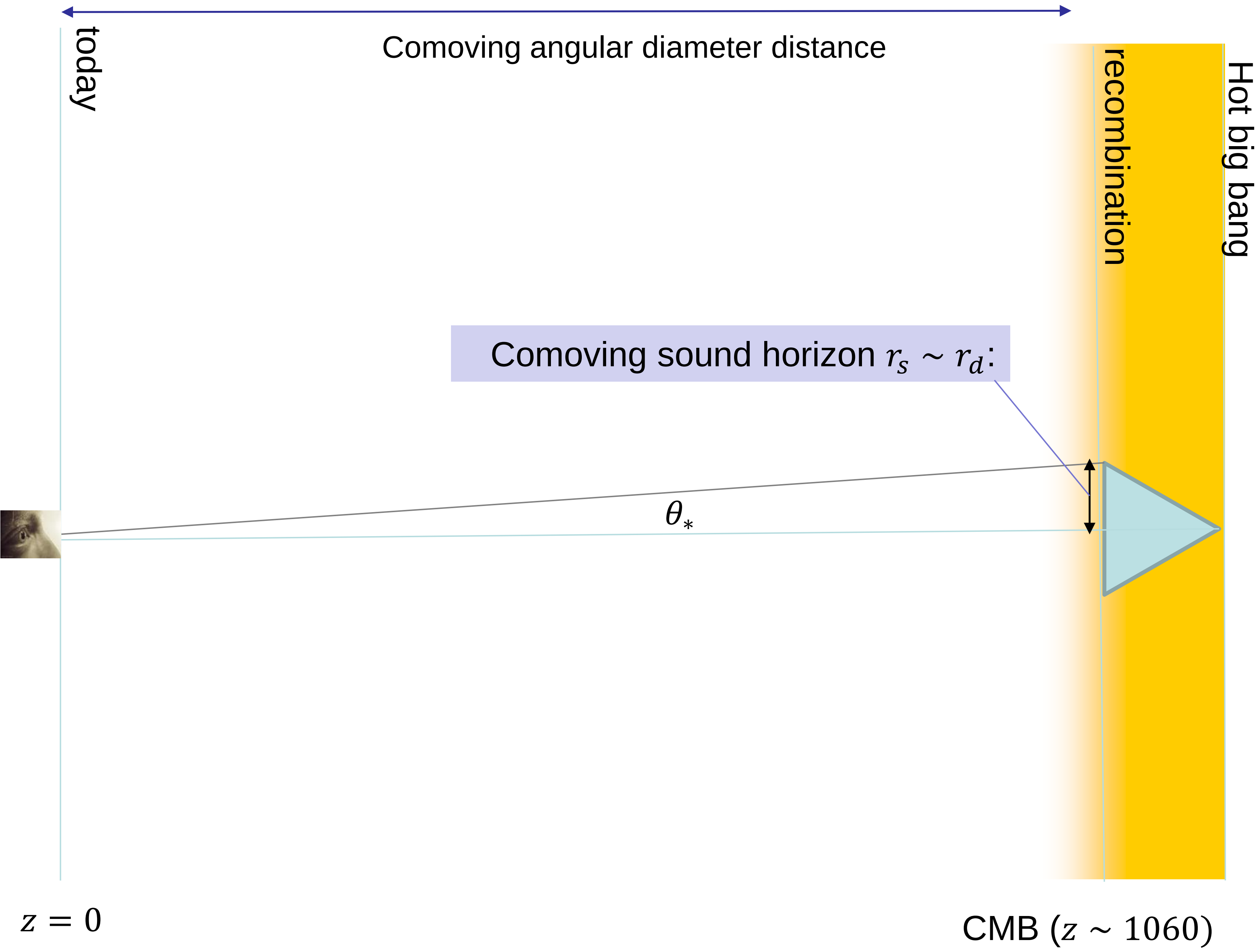
Planck 2018 (arXiv: 1806.06209)

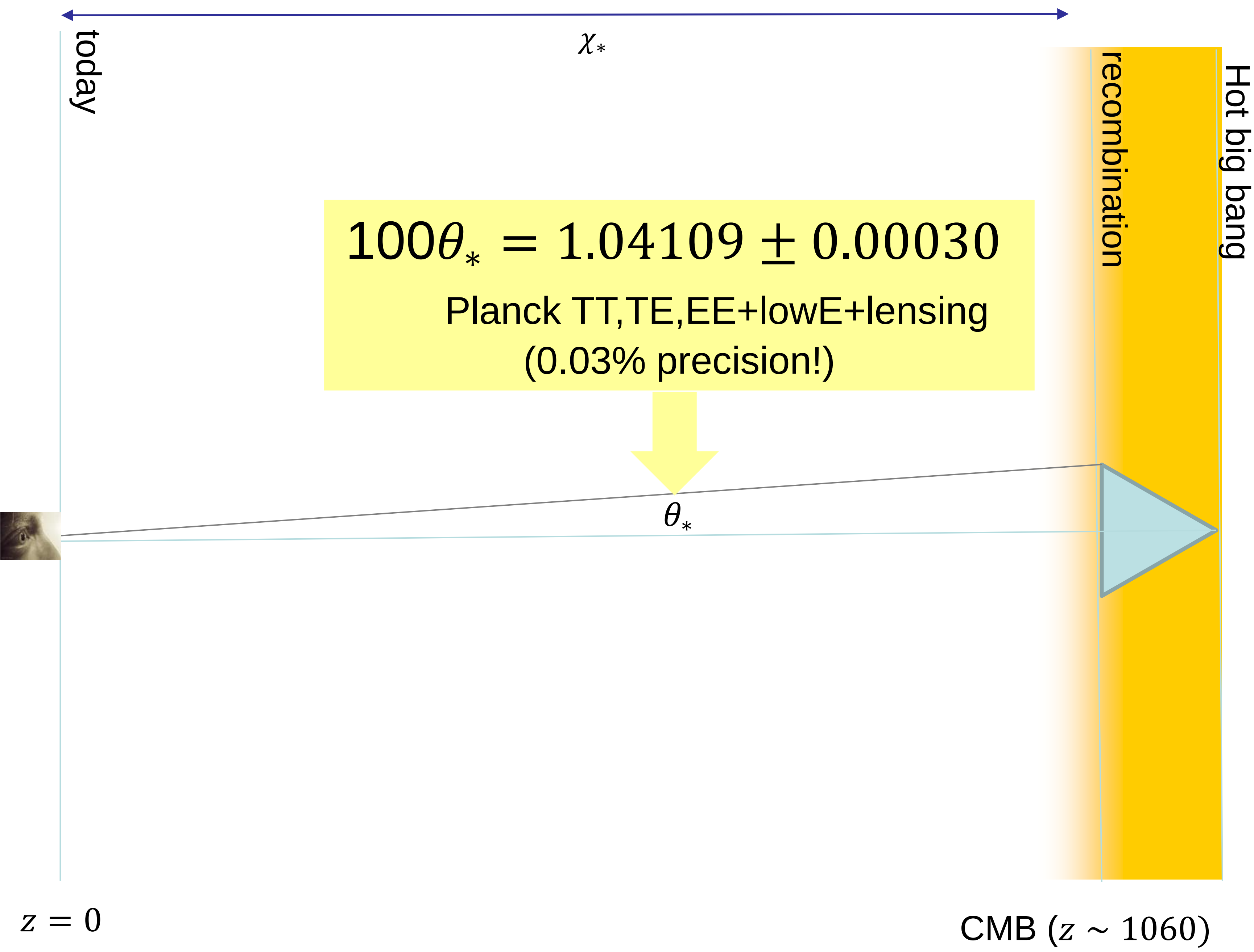


arXiv:1705.0290



In Comoving Distance (not to scale!)

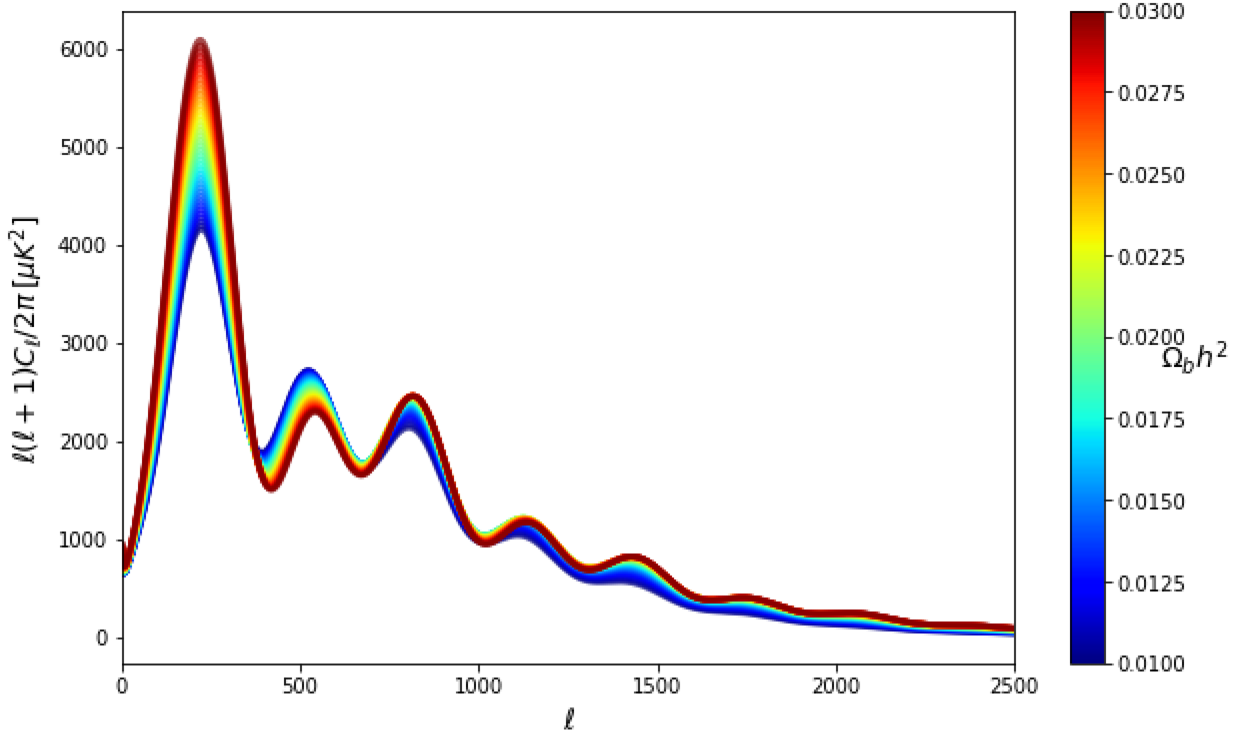




χ_*
today
recombination
Hot big bang
$100\theta_* = 1.04109 \pm 0.00030$
Planck TT,TE,EE+lowE+lensing
(0.03% precision!)
θ_*
$z = 0$
CMB ($z \sim 1060$)

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

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

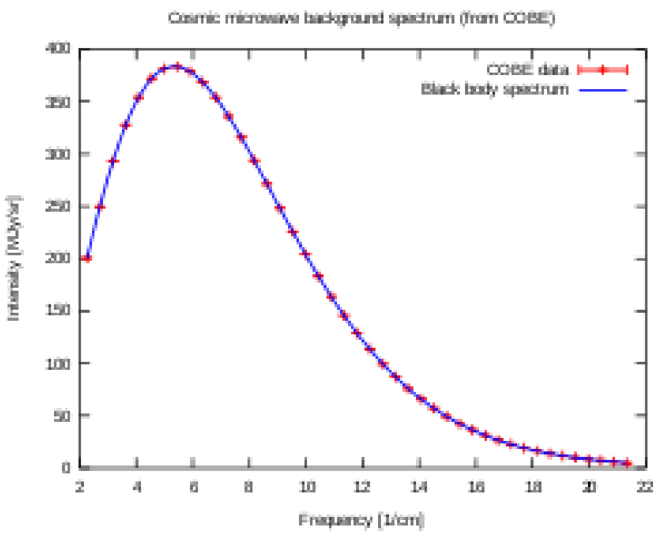


Odd/even height ratio distinctive and quite robust:

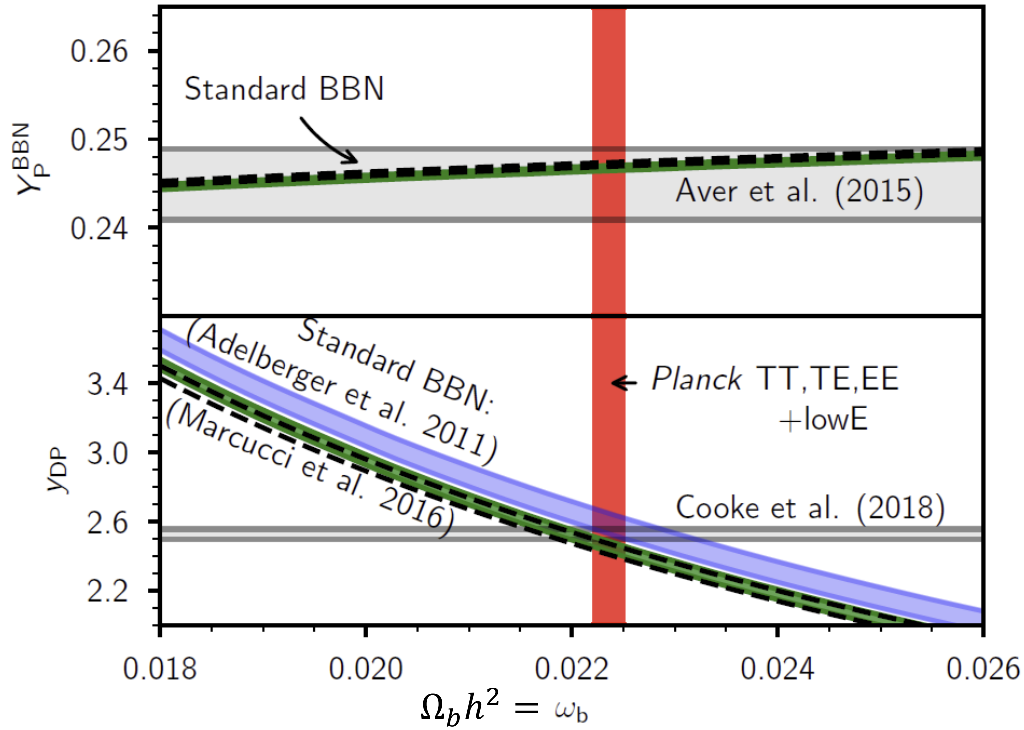
$\Omega_b h^2 = 0.0224 \pm 0.0002$

Consistency with standard Big-Bang Nucleosynthesis

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



(arXiv: 1806.06209)



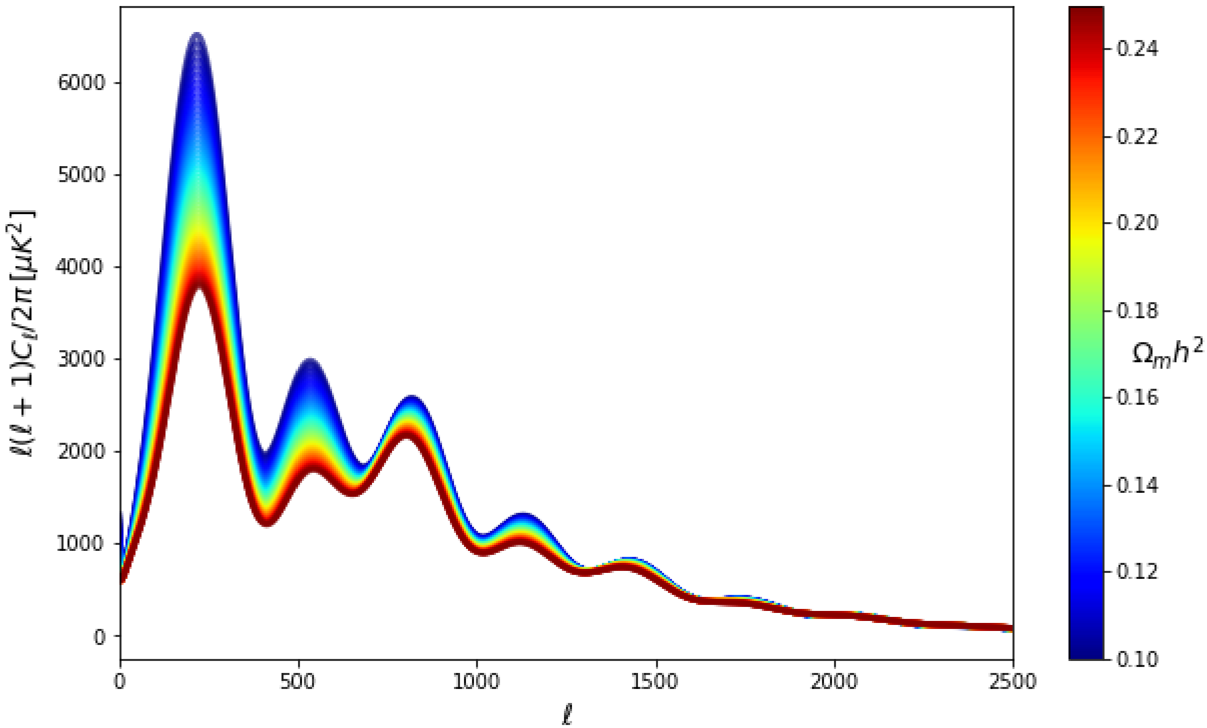
BUT: Lithium problem remains around 5σ

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

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

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

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



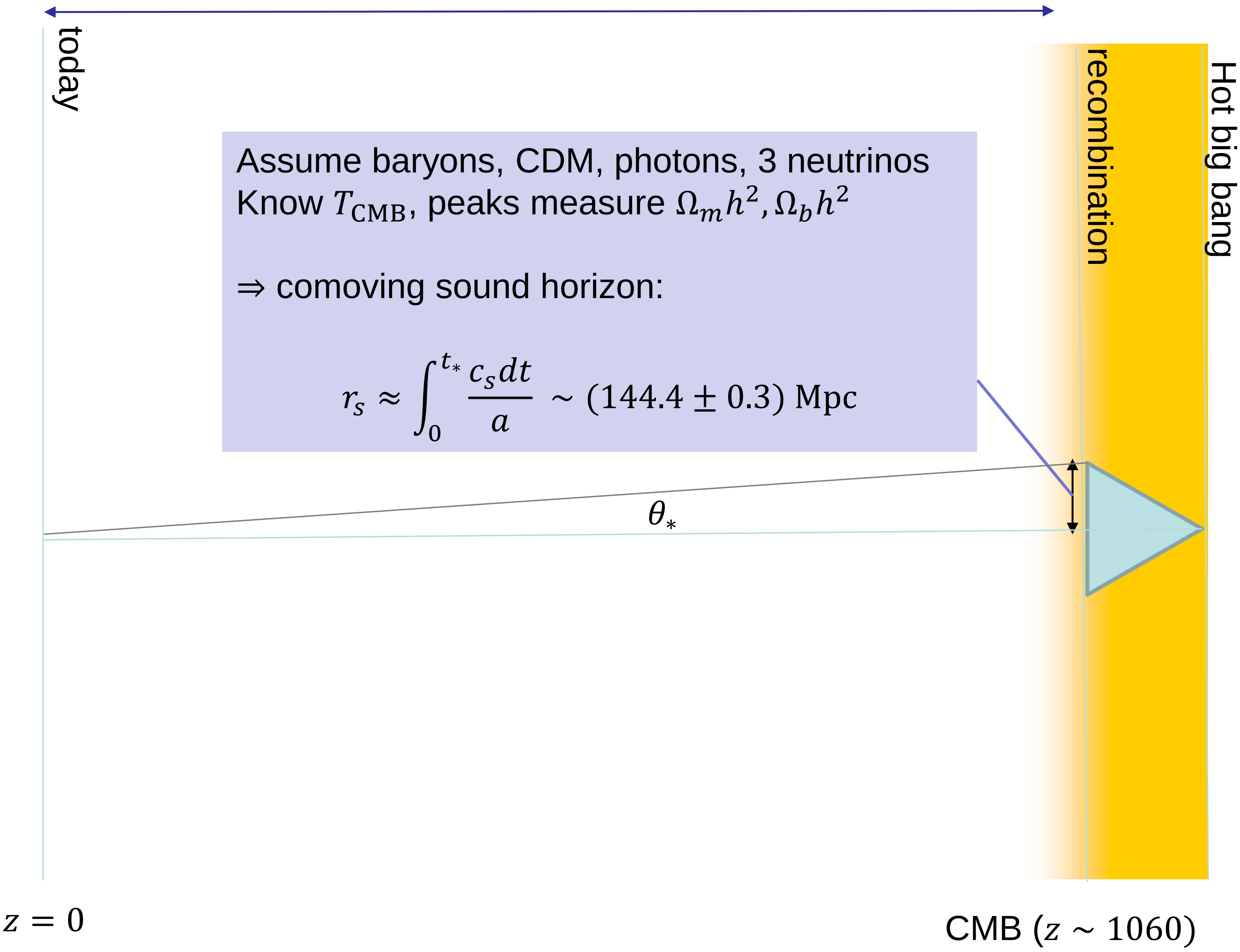
Can be partly compensated by changing initial power A_s, n_s and foregrounds.
But detailed shape is still quite distinctive and robust:

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

Assume baryons, CDM, photons, 3 neutrinos
Know $T_{\rm CMB}$, peaks measure $\Omega_m h^2, \Omega_b h^2$

⇒ comoving sound horizon:

$$r_s \approx \int_0^{t_*} \frac{c_s dt}{a} \sim (144.4 \pm 0.3)\ \mathrm{Mpc}$$



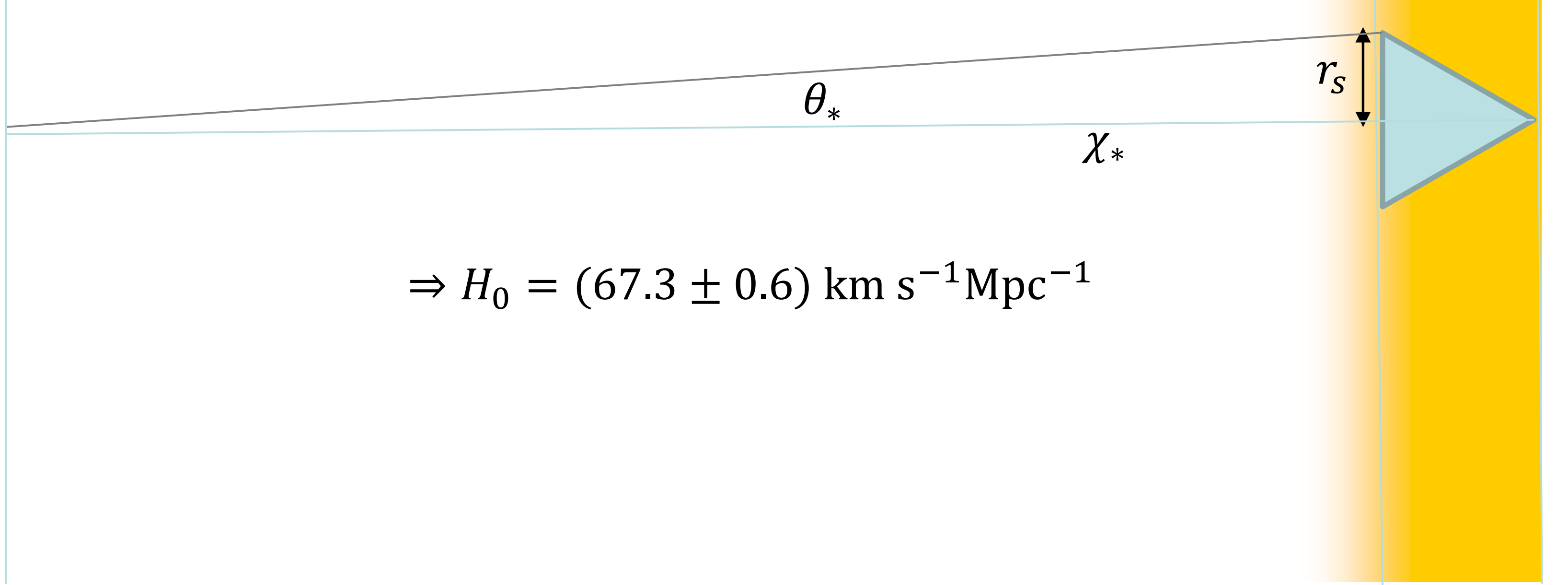
CMB

Assuming flat ΛCDM cosmology

$r_s, \theta_* \Rightarrow$ Comoving radial distance $\chi_* \sim (13.87 \pm 0.03)\ \mathrm{Gpc}$

$$\chi_* = \int \left(\frac{c\,dt}{a}\right) = \int \left(\frac{da}{a^2 H}\right) \approx \int \frac{da}{\sqrt{a\Omega_\mathrm{m} H_0^2 + a^4 \Omega_\Lambda H_0^2}}$$

$\Omega_\Lambda H_0^2 = H_0^2 - \Omega_m H_0^2$ and know $\Omega_m h^2 \Rightarrow H_0$

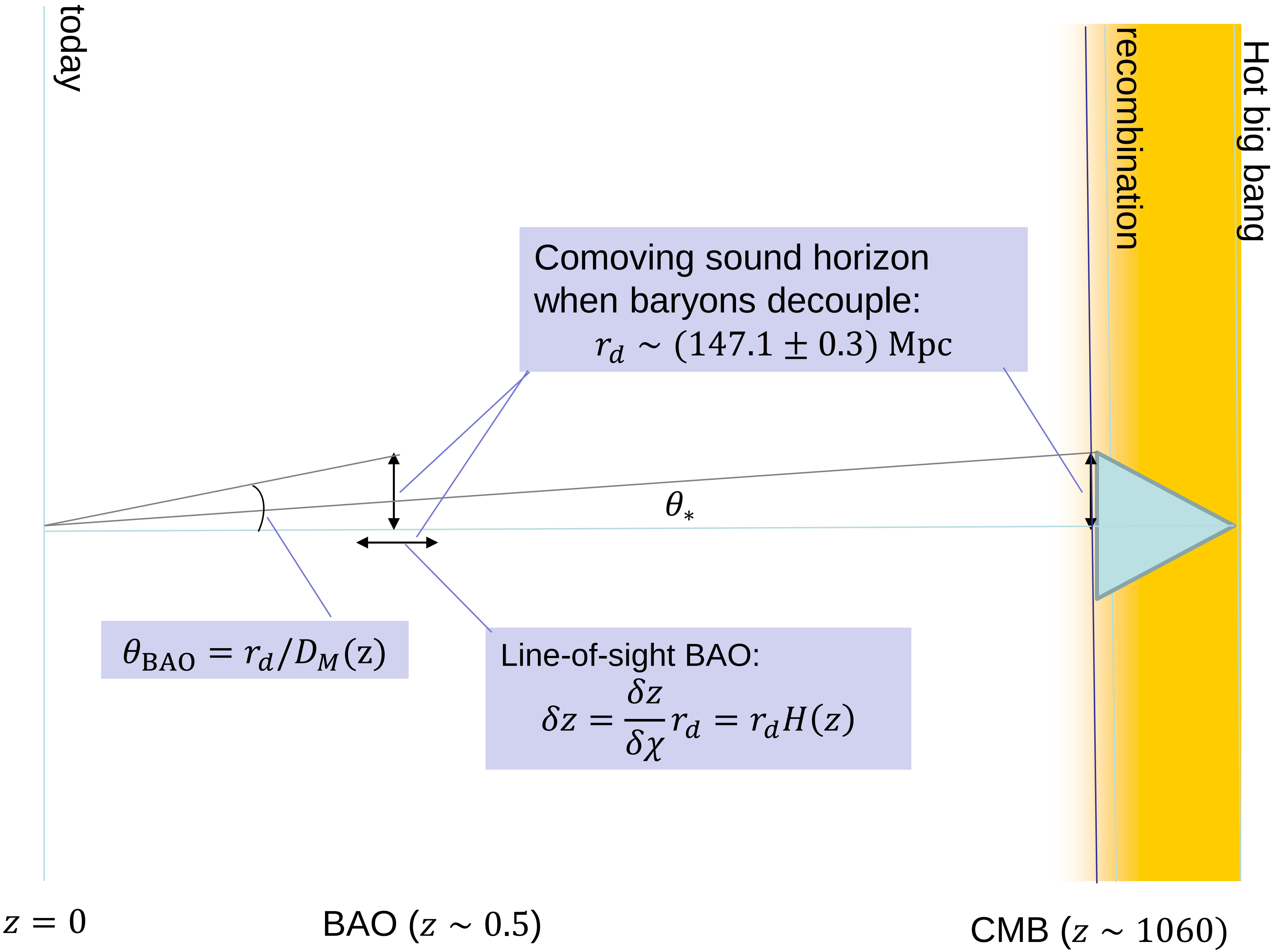


$$\Rightarrow H_0 = (67.3 \pm 0.6)\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

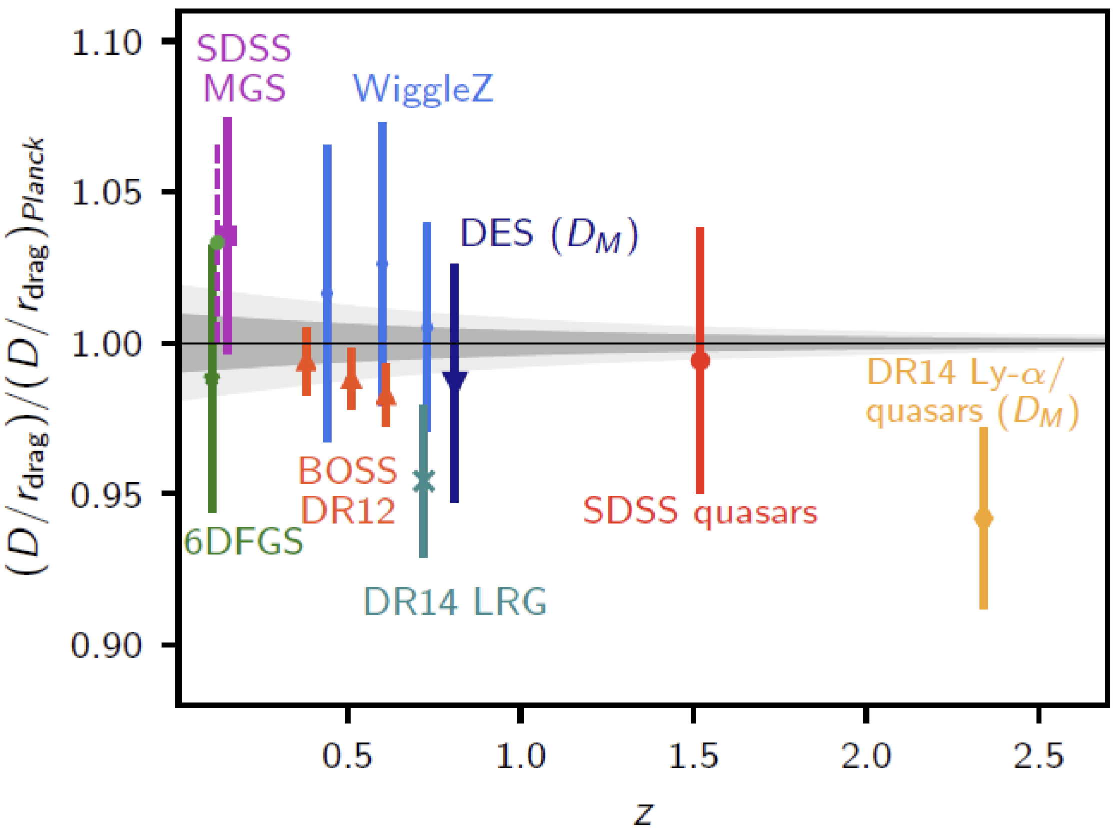
$z = 0$

CMB ($z \sim 1060$)

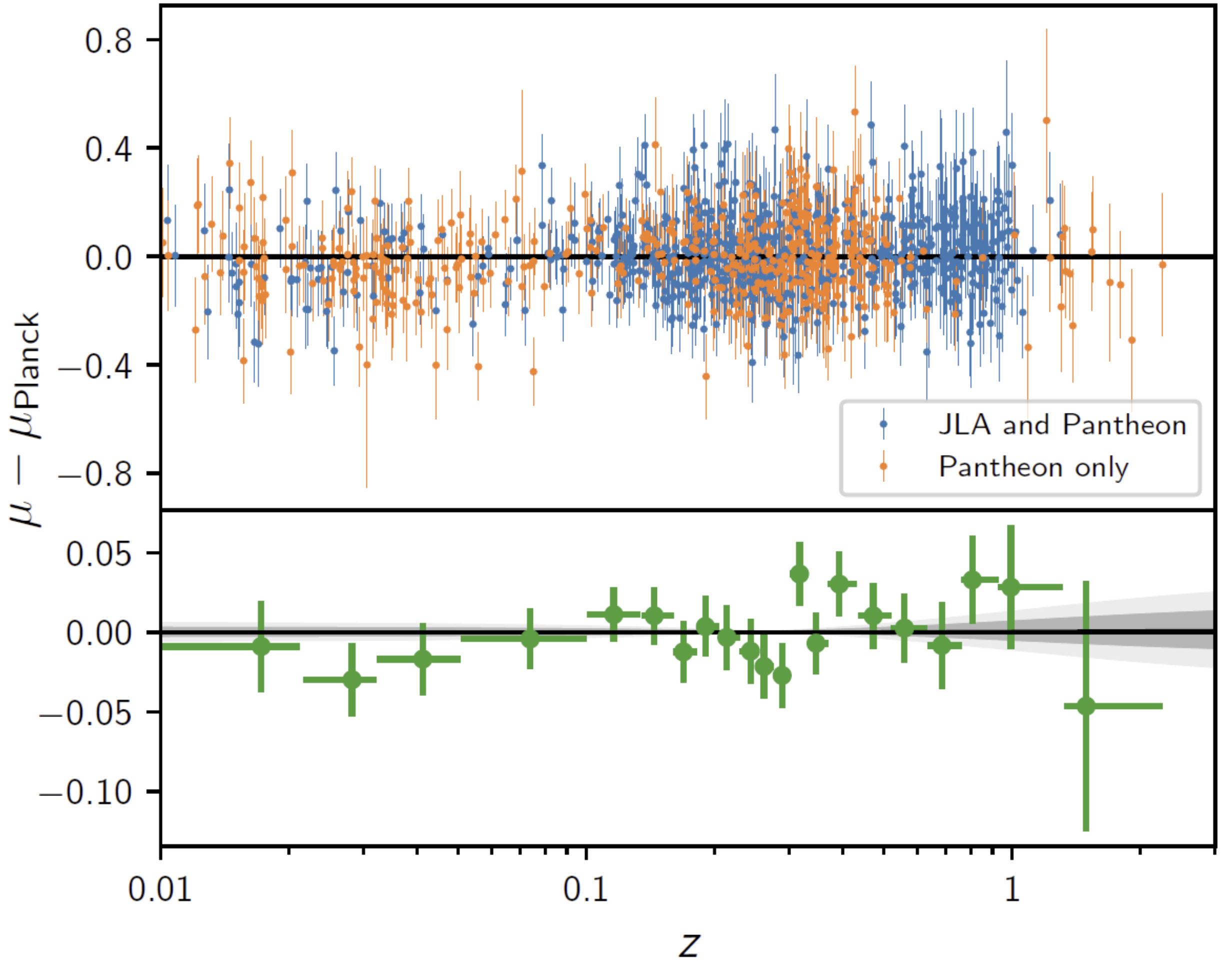
CMB and BAO consistency in ΛCDM



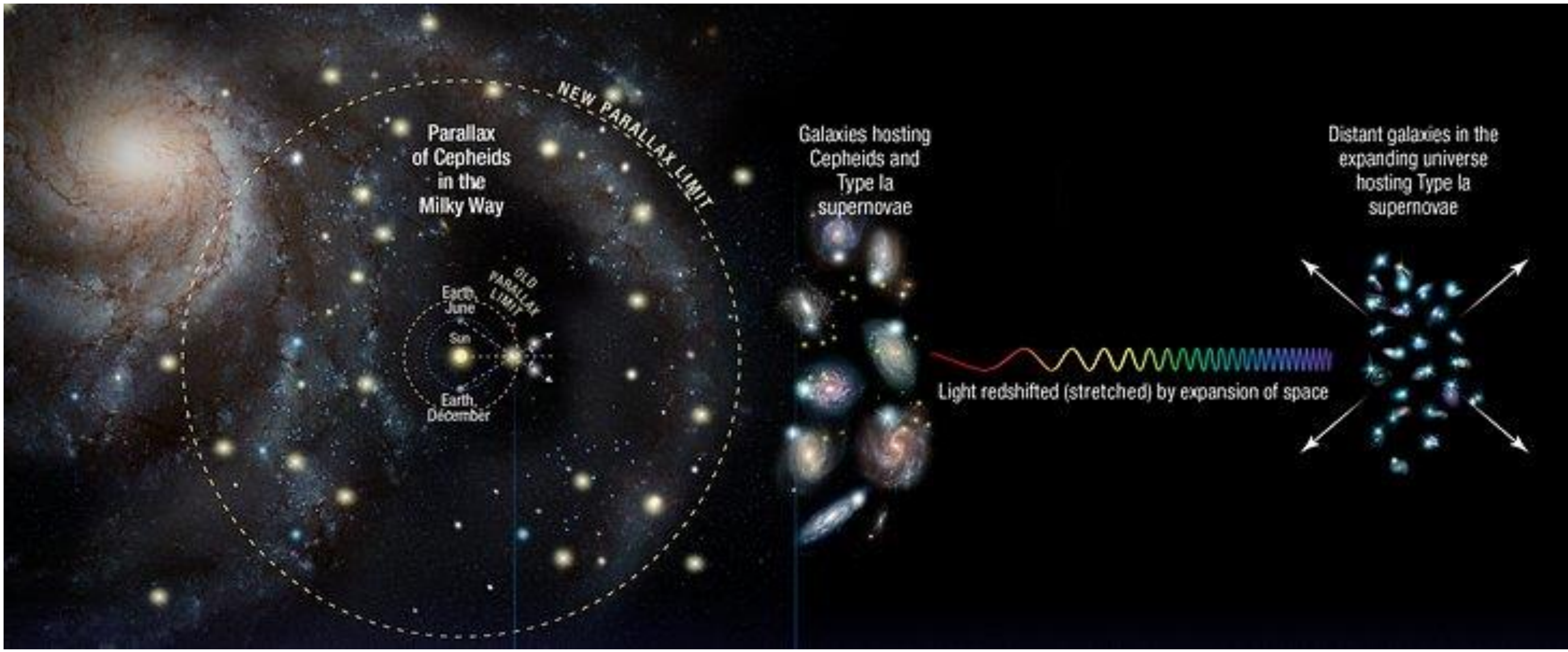
Baryon Acoustic Oscillation (BAO) concordance



Supernovae constrain redshift evolution (as standardizable candles, measure d_L)



H_0 from local distance ladder



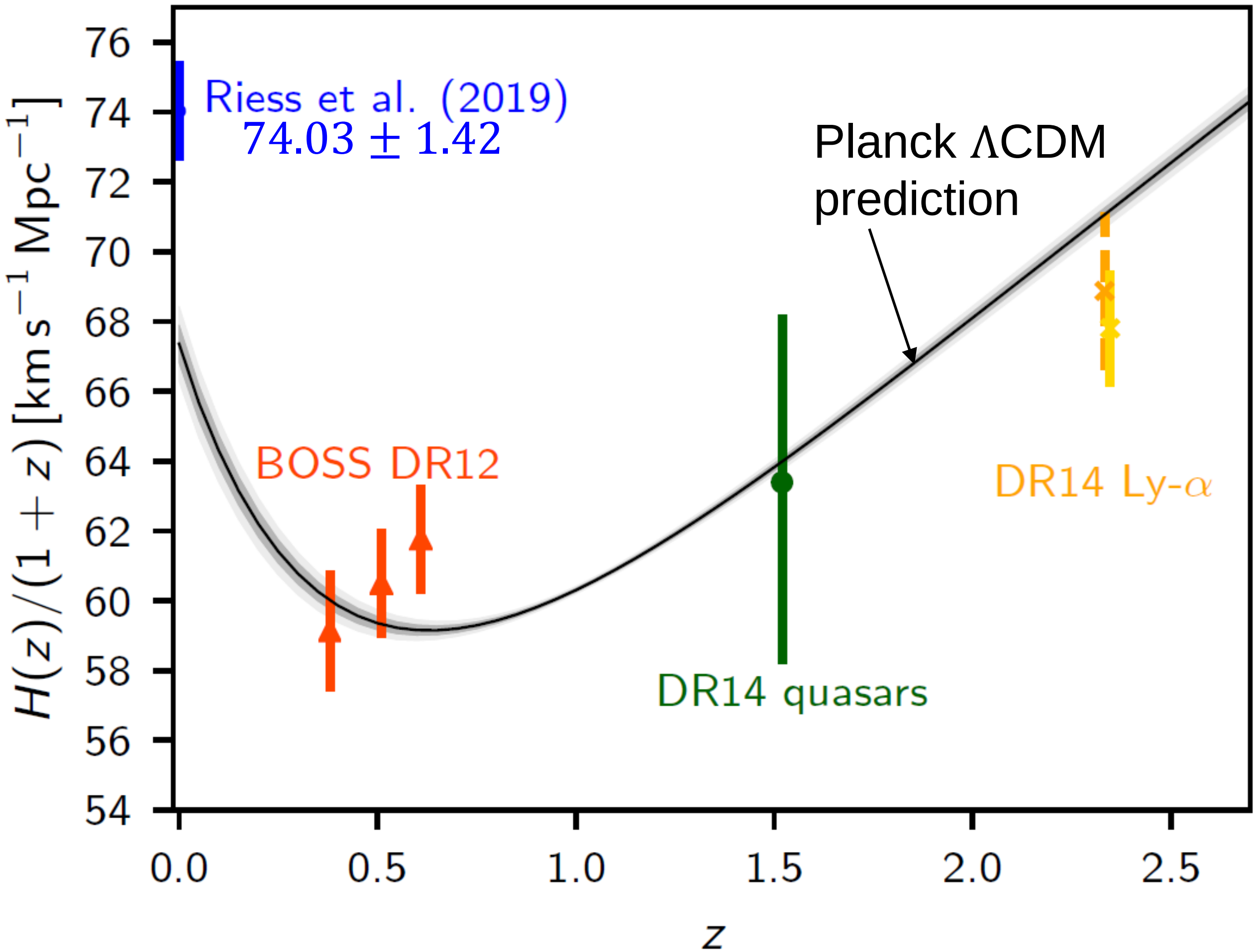
https://www.spacetelescope.org/news/heic1611/

Parallax+cepheids+SN

$$H_0 = 74.03 \pm 1.42 \text{ km } s^{-1}\text{Mpc}^{-1}$$

Riess et al. arXiv: 1903.07603

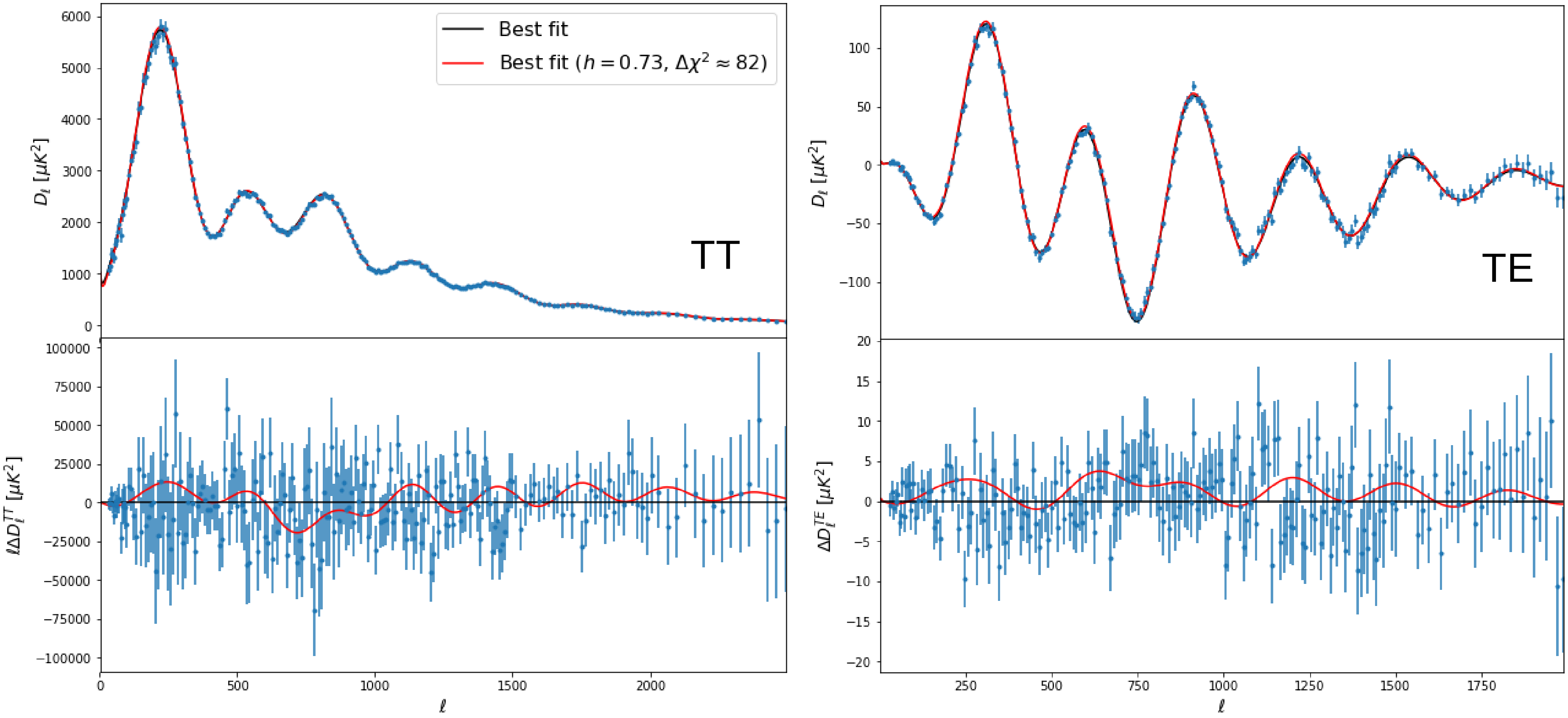
The Hubble discrepancy assuming ΛCDM and Planck sound horizon r_d



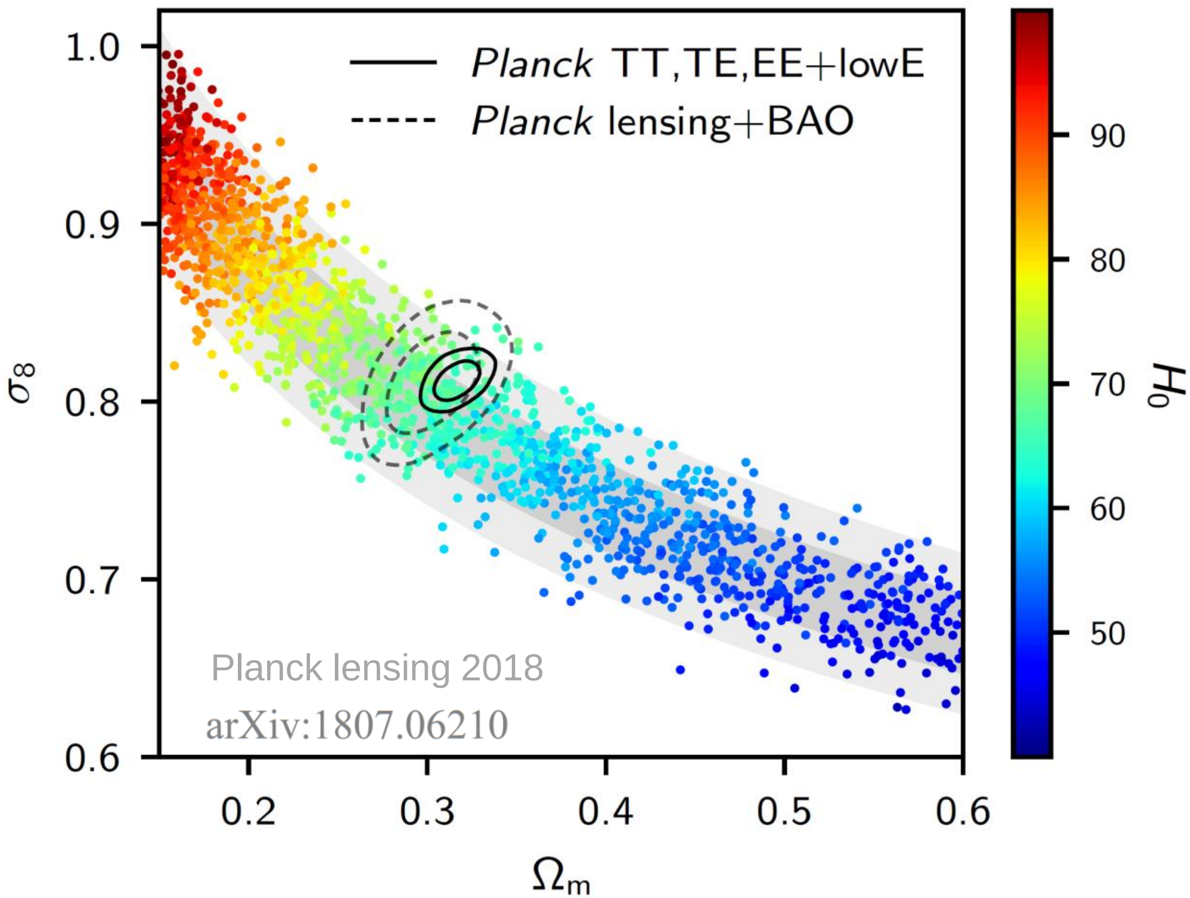
A $4.4\sigma \sim 10\%$ discrepancy between local and CMB-inferred ΛCDM H_0?

Model fits

LCDM best-fits: $H_0 = 67.3$ ($n_s = 0.966$, $\Omega_m = 0.32, \Omega_m h^2 = 0.143$)
vs. best fit for $H_0 = 73.0$ ($n_s = 0.995$, $\Omega_m = 0.25, \Omega_m h^2 = 0.132$)



Planck CMB lensing



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

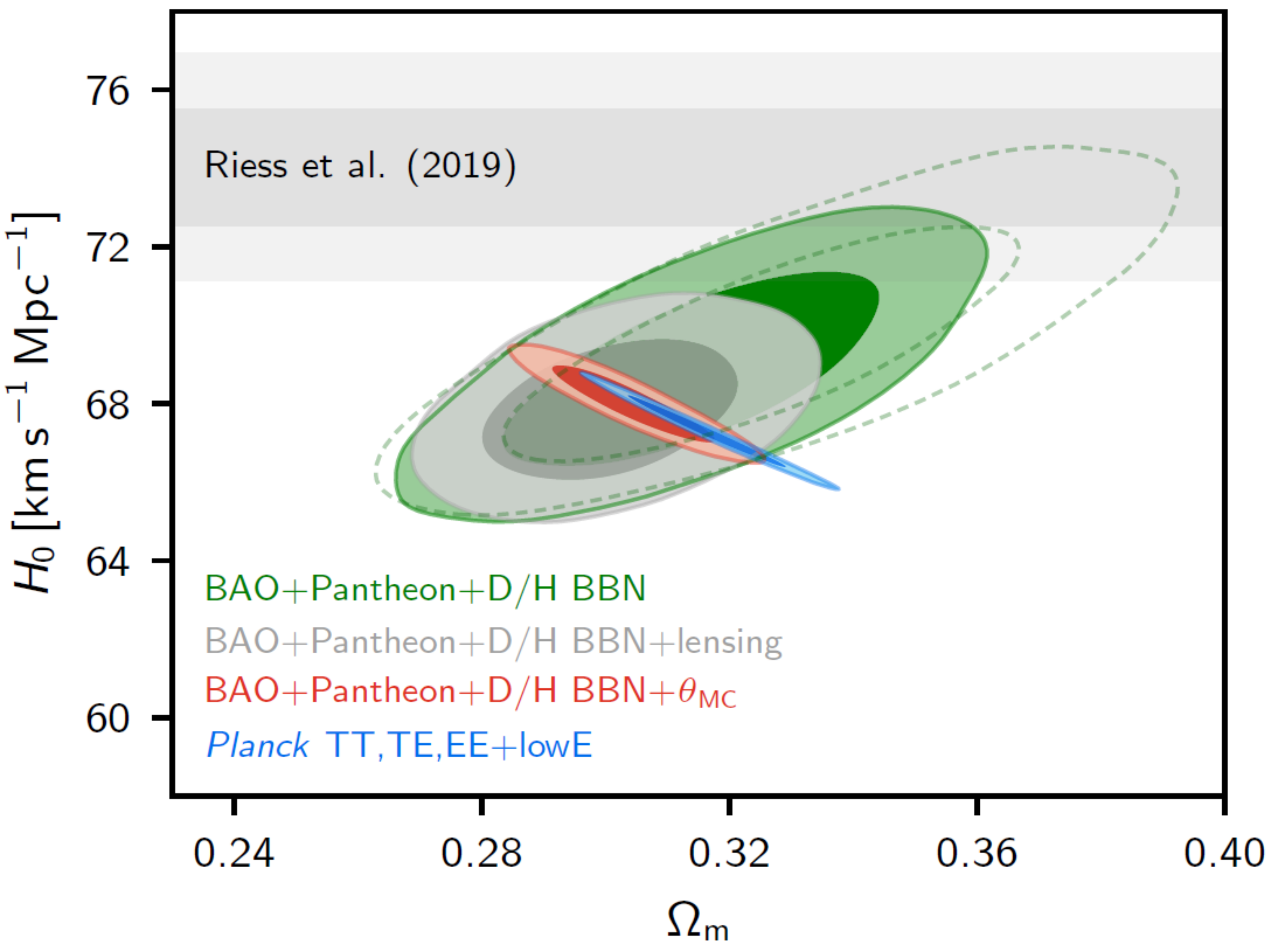
$$\left.\begin{aligned} H_0 &= 67.9^{+1.2}_{-1.3}\ \mathrm{km\ s^{-1} Mpc^{-1}}, \\ \sigma_8 &= 0.811 \pm 0.019, \\ \Omega_m &= 0.303^{+0.016}_{-0.018}, \end{aligned}\right\} \quad 68\,\%,\ \text{lensing+BAO}$$

Also adding robust CMB θ_* constraint:

$H_0 = 68.0 \pm 0.7$ (68 %, lensing+BAO+θ_*)

("Lensing-only" priors: $\Omega_b h^2 = 0.0222 \pm 0.0005, n_s = 0.96 \pm 0.02, 0.4 < h < 1$)

Independent ΛCDM inverse distance ladder is also consistent with Planck



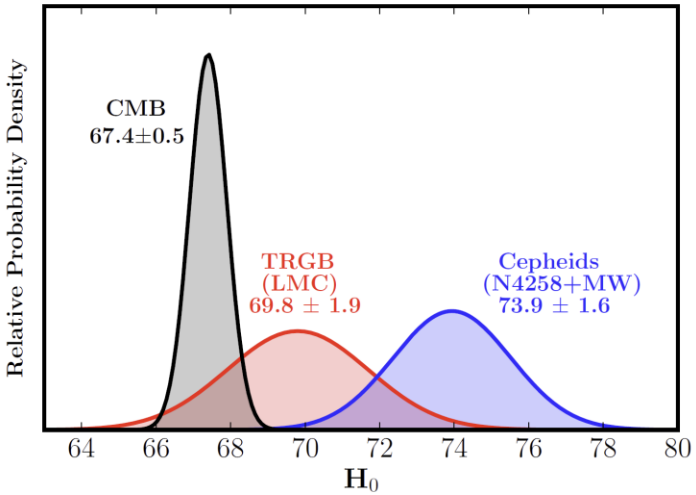
Some other Hubble parameter measurements

Forward distance ladder

Tip of the red giant branch

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

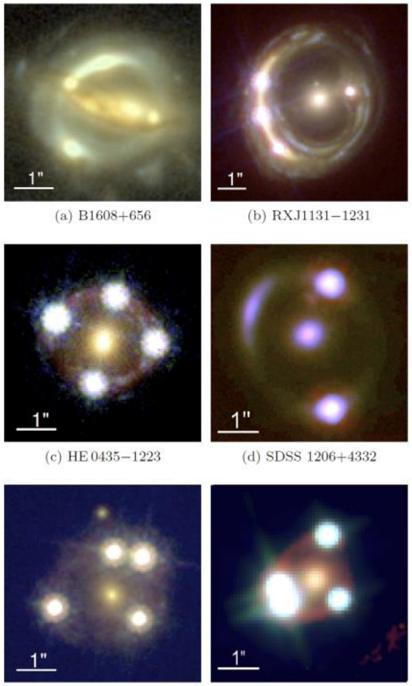
Freedman et al. arXiv:1907.05922



Recalibration analysis Yuan et al. arXiv:1908.00993

$$H_0 = 72.4 \pm 2 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Strong Lensing



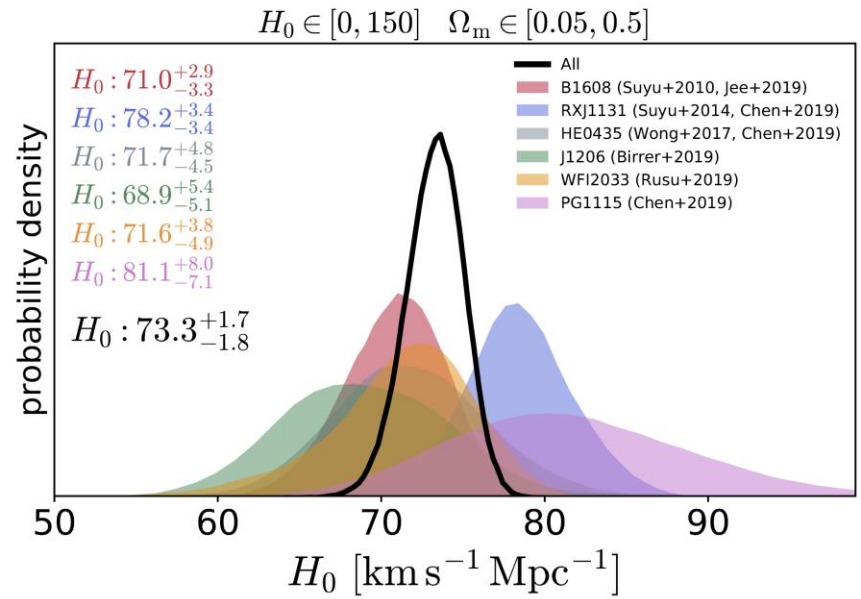
(a) B1608+656 (b) RXJ1131−1231

(c) HE 0435−1223 (d) SDSS 1206+4332

(e) WFI2033−4723 (f) PG 1115+080

Lens modelling etc..

$$D_{\Delta t} \equiv (1+z_{\rm d})\frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}}$$



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

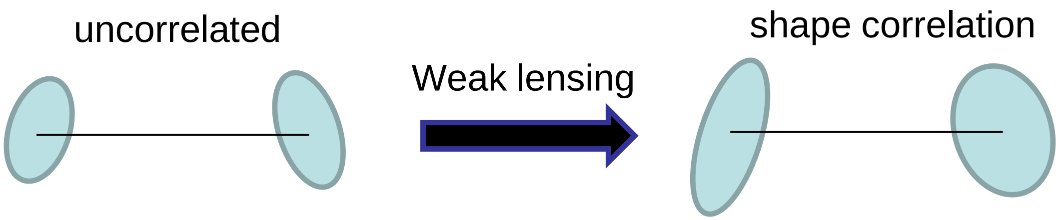
Wong et al. arXiv:1907.04869

(some cosmology dependence)

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

$\Rightarrow$ tension with CMB independent of very local environment

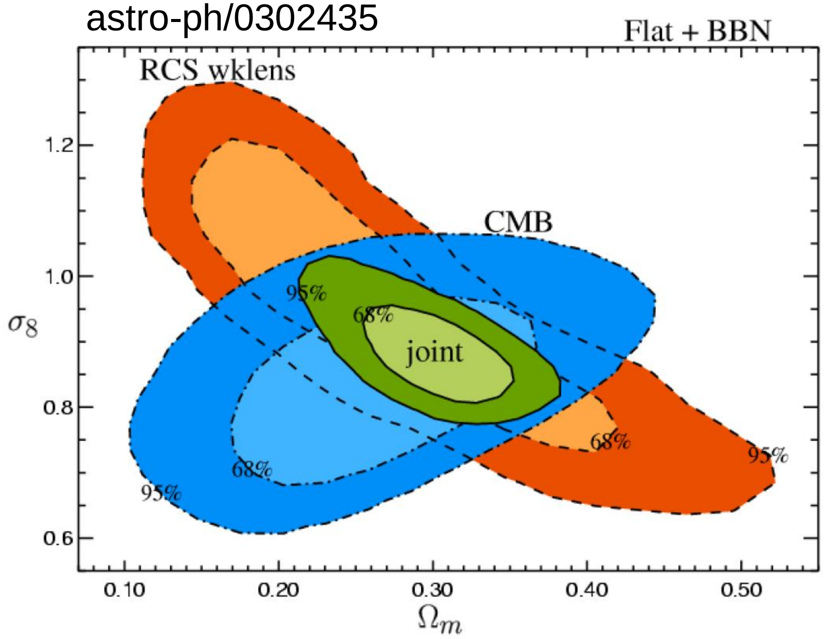
Galaxy weak gravitational lensing – cosmic shear



Potentially clean probe of total matter perturbations and geometry

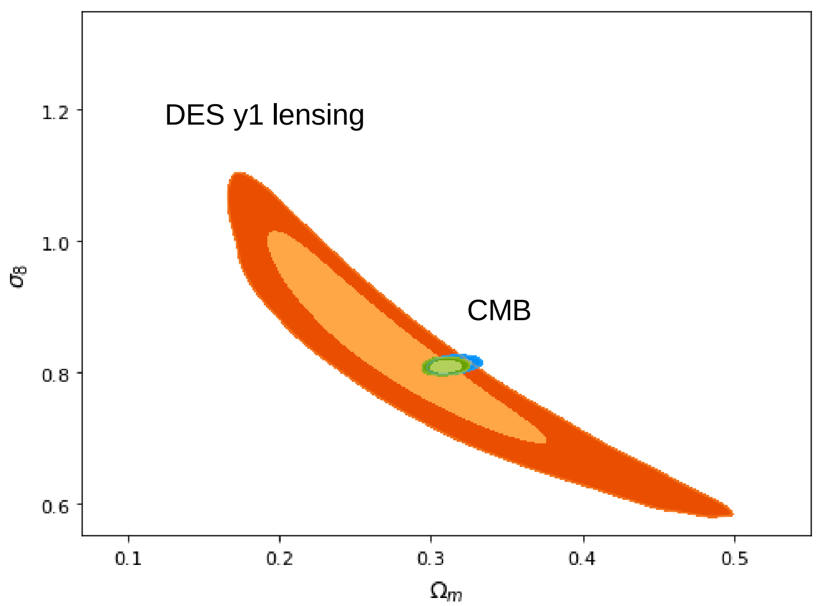
***But**, non-linearities, redshift uncertainties, intrinsic alignment, shape biases…*

astro-ph/0302435



2003

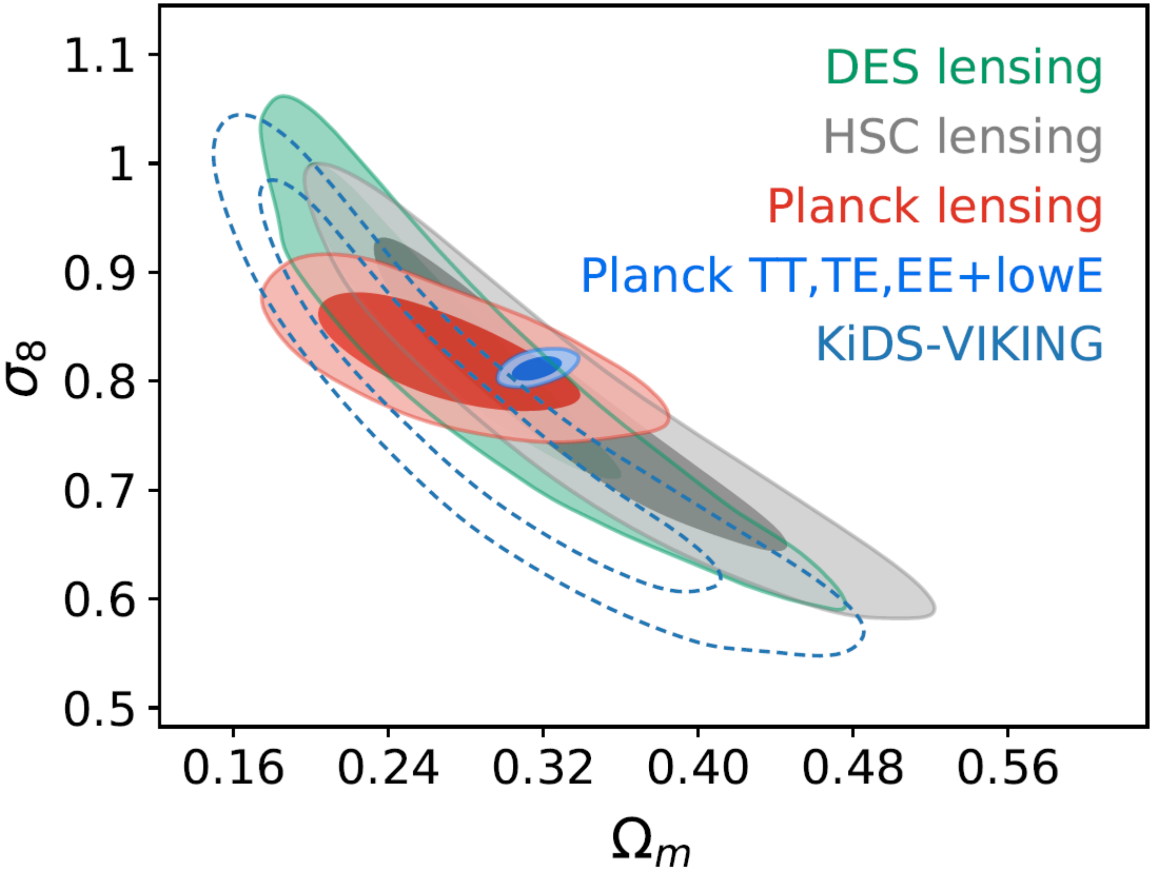
arXiv:1708.01530



2018

(+ similar errors from KiDs, HSC)

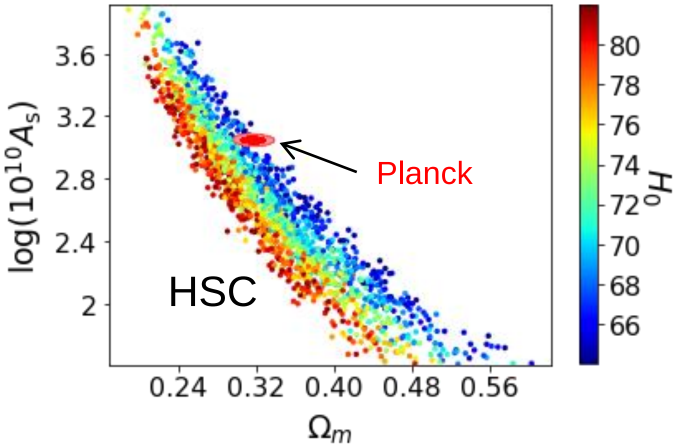
Current weak lensing constrints



Troxel et al. 1708.01538

Hamana et al. 1906.06041

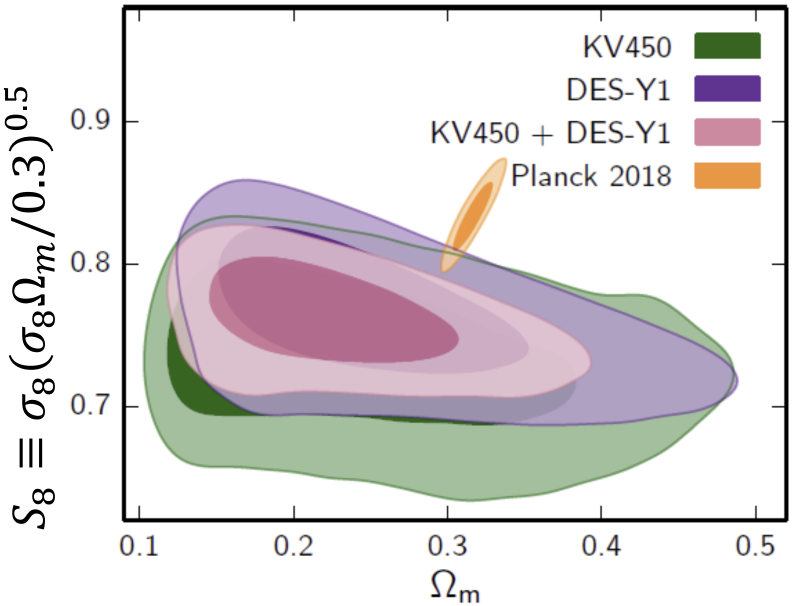
Hildebrandt et al. 1812.06076



(Nearly-consistent priors $1.609 < \log\left(10^{10}A_s\right) < 3.912$; $0.64 < h < 0.82$)

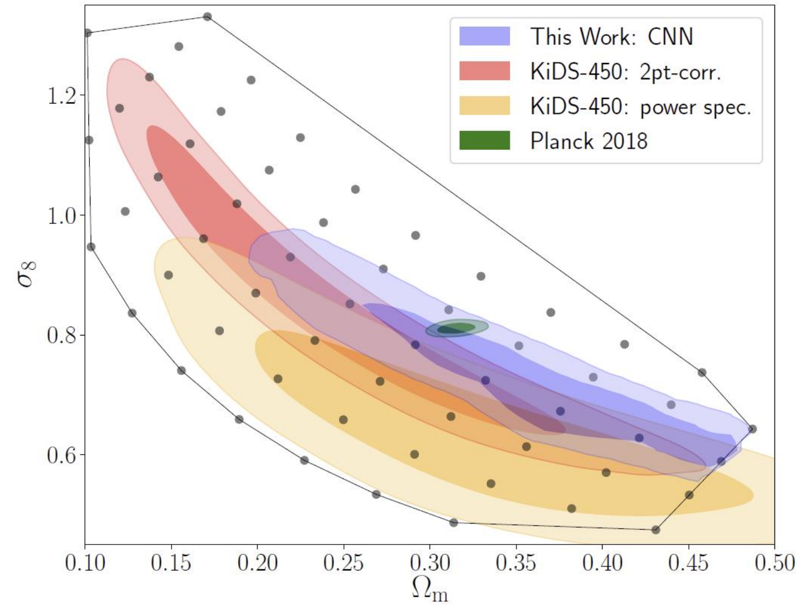
shifts with data cuts and analysis choices, constraints moving around …

Joudaki et al 1906.09262



DES+KiDs 2.5σ tension with Planck
(without Planck lensing)

Fluri et al. arXiv:1906.03156



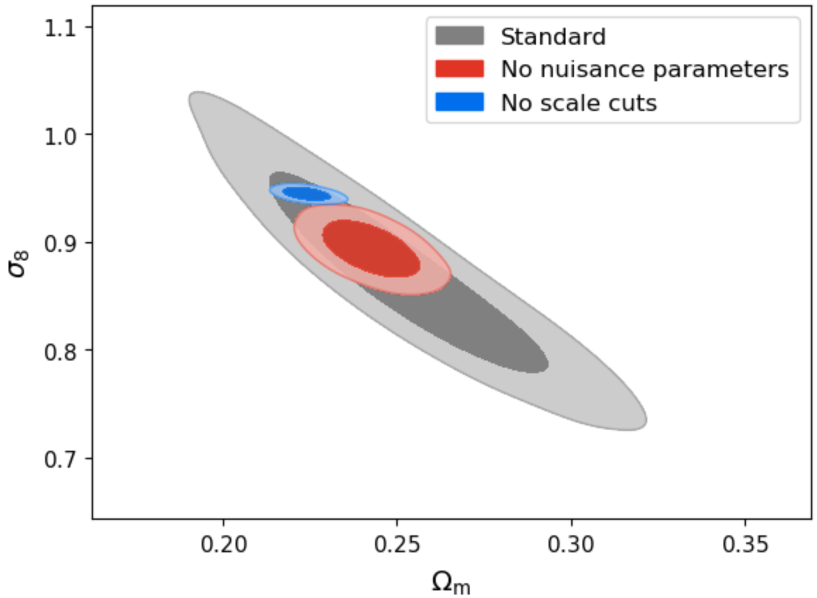
Results use different scale cuts

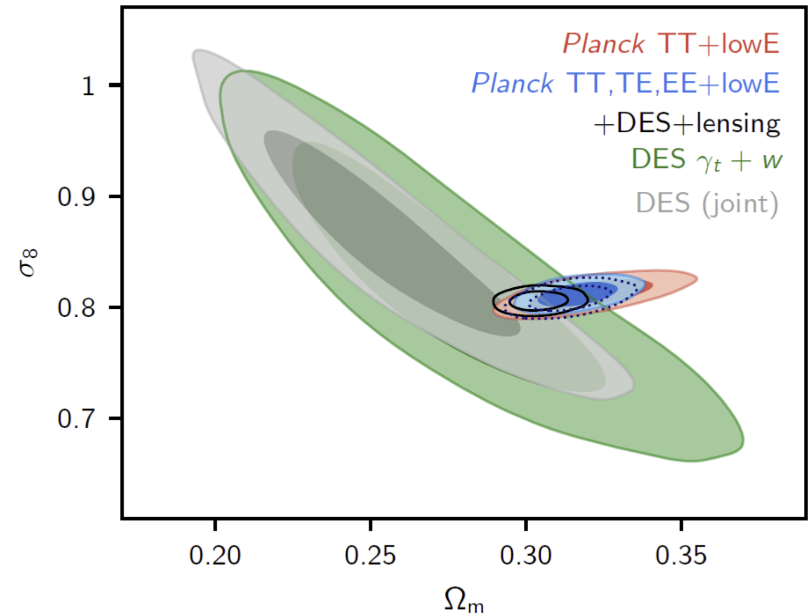
CNN includes beyond-power spectrum information
- no tension

Galaxy lensing + galaxy counts

also depends on galaxy bias parameters

e.g. DES Y1

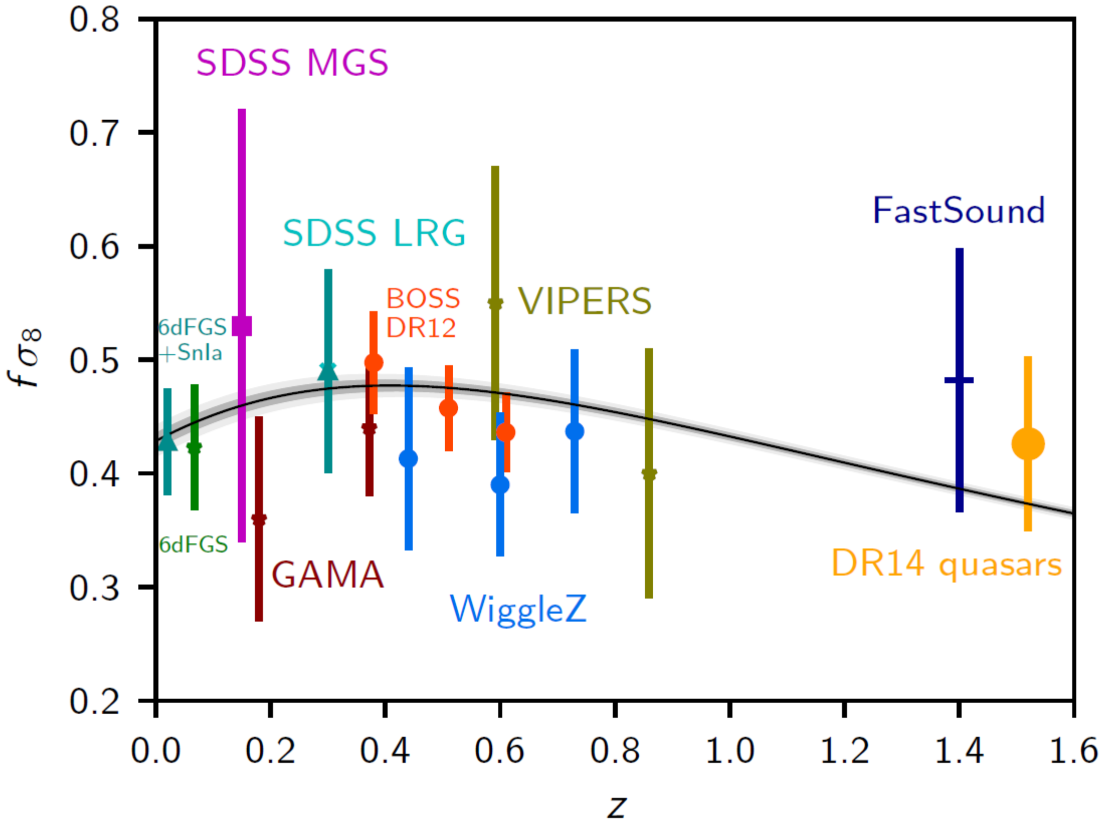




Marginally consistent/small tension with Planck

Some others more significant, but all require complex modelling

Redshift Distortions



Currently no compelling evidence for deviations from Planck ΛCDM in LSS observations.

Possible solutions to the H_0 tensions

Biases in data or underestimated error bars
- inverse distance ladder and CMB consistent ⇒ *both* CMB and BAO being wrong?
- Local H_0 and strong lensing independent; multiple local distance ladders
  but Feedman et al result lower and strong lensing errors relatively large

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

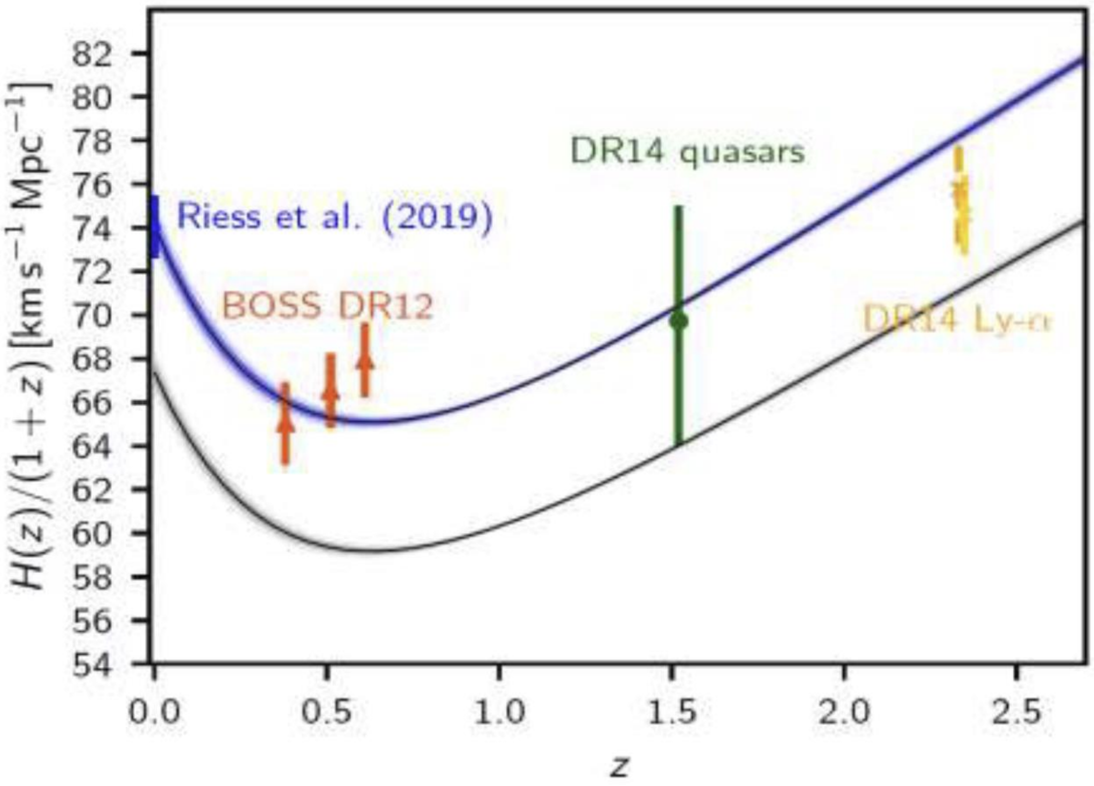
New physics at lower redshift/dark energy/modified gravity
- but $w > -1$ only makes H_0 from Planck *lower*
- have to fit BAO and $H(z)/H_0$ from supernovae (or find problem with supernovae)

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 ($N_{\mathrm{eff}} \neq 3.046$) not favoured by Planck spectra

More complicated (multi-parameter) extensions

- New species with interactions; new couplings between existing species, … (many refs…).

- Early dark energy (e.g. Poulin et al, Agrawal et al, Lin et al. etc..): must have $\frac{\rho_{DE}}{\rho} \sim 0.08$ near matter-radiation equality, then $\rho_{DE} \rightarrow \Lambda$.

- New ideas…!

Different models change the CMB spectra in distinctly different ways

e.g. via changes to matter-radiation equality, damping scale, peak phases

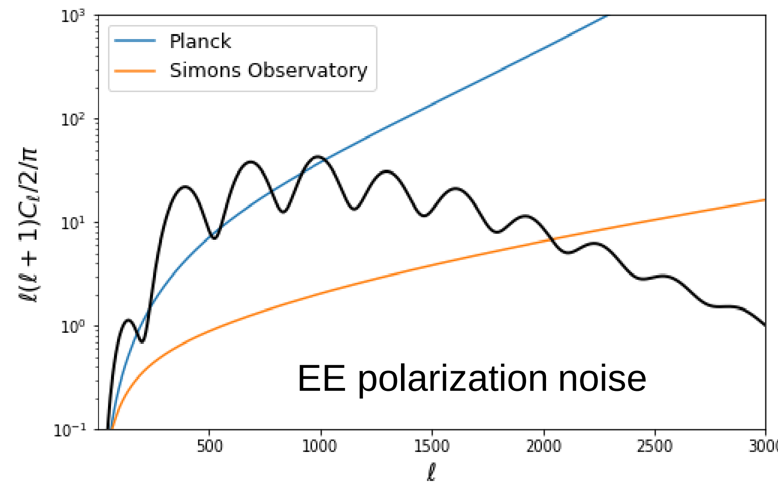
Difficult but not impossible to fit current data
e.g. trade changes from new physics with changes in $\Omega_c h^2, \Omega_b h^2, A_s, n_s$*, ...)*

⇒ If new physics is the solution, current $\Lambda\mathrm{CDM}$ measurements of parameters likely to be significantly wrong, e.g. significant implications for inflation n_s.

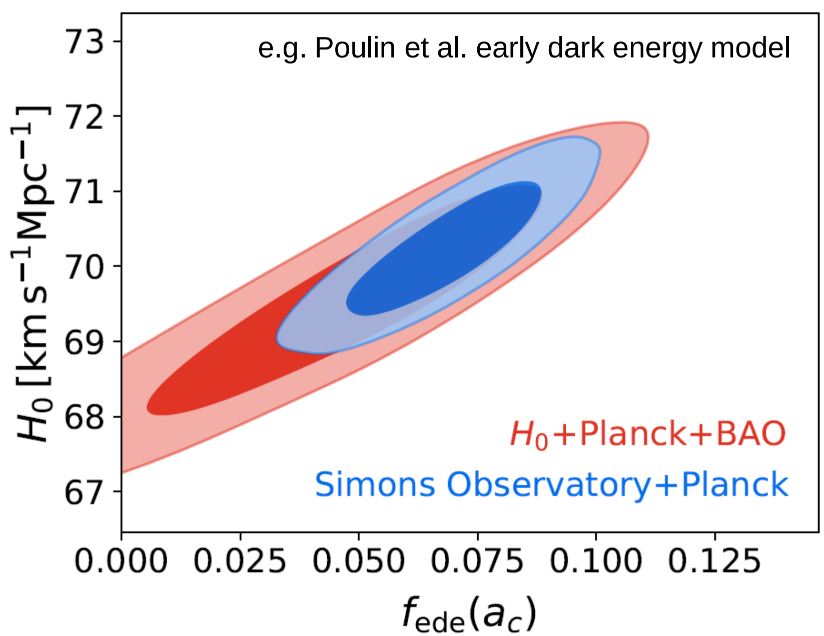
⇒ Almost impossible to *also* fit $\Lambda\mathrm{CDM}$ polarization to cosmic variance

<u>⇒ new "easily" detectable EE/TE signal that does not fit $\Lambda\mathrm{CDM}$</u>

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



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



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

Distinct physical models give different precision predictions

Cobaya: **Co**de for **Bay**esian **A**nalysis

Jesus Torrado, AL

Python parameter sampling framework: likelihoods -> parameter MC samples

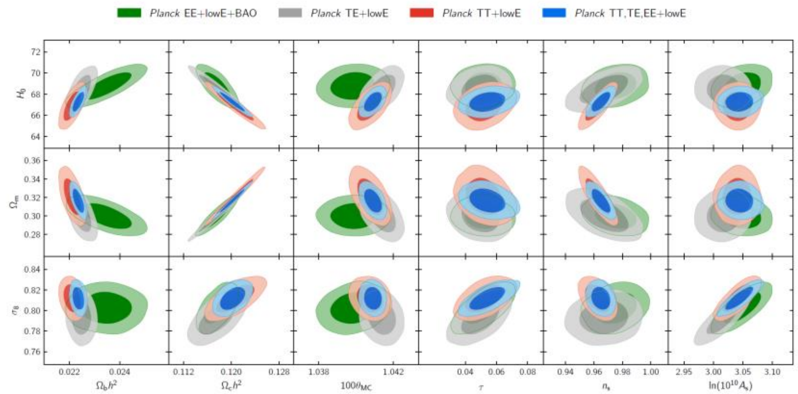
Optimizations to exploit different speeds of multiple dependent theory/likelihood modules each with multiple nuisance parameters

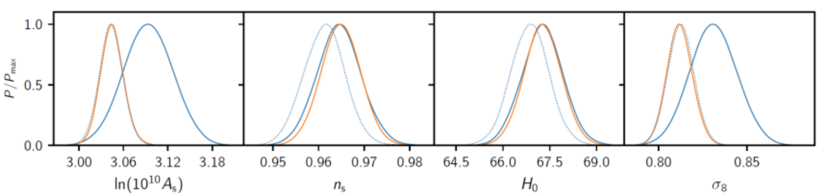
https://github.com/CobayaSampler/cobaya

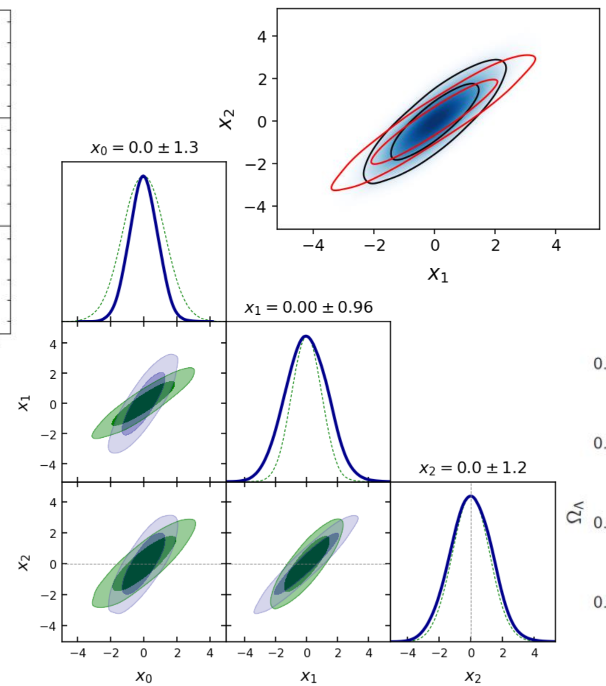
https://cobaya.readthedocs.io/

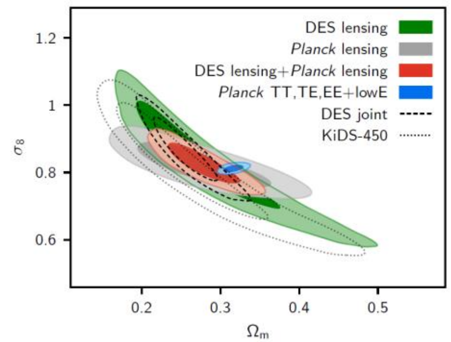
GetDist 1.0: Python Monte Carlo Sample Analyser

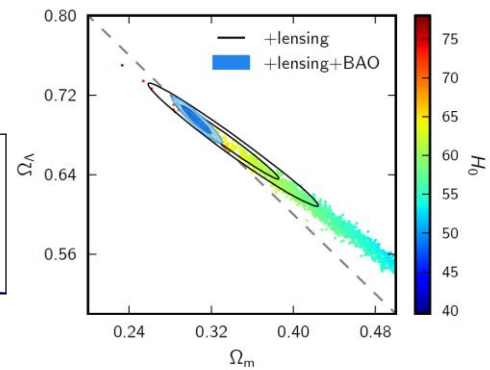
https://getdist.readthedocs.io (arXiv:1910.13970)











+ interactive GUI, KDE, PCA, convergence, latex, tables

Conclusions

ΛCDM 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

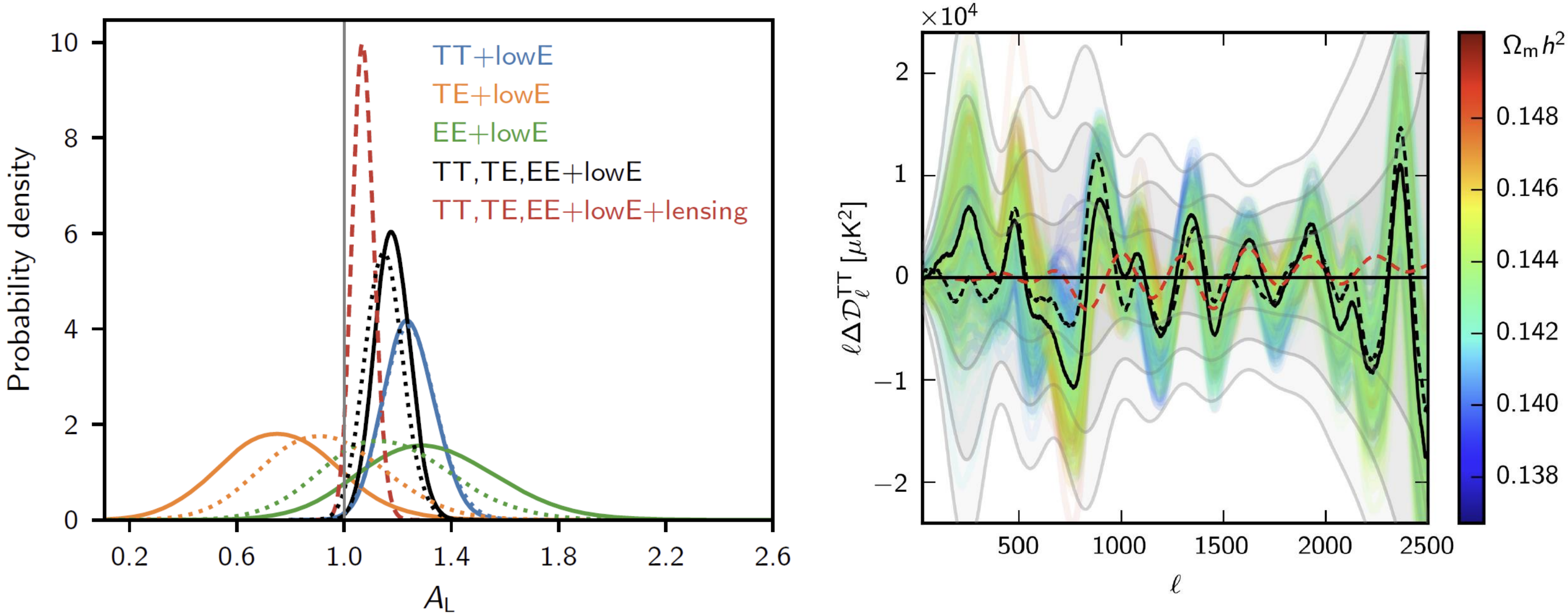
- New pre-recombination physics at 5-10 % level “easily” detectable soon with CMB polarization

    - can test *reason for* discrepancy ⇒ distinguish new physics

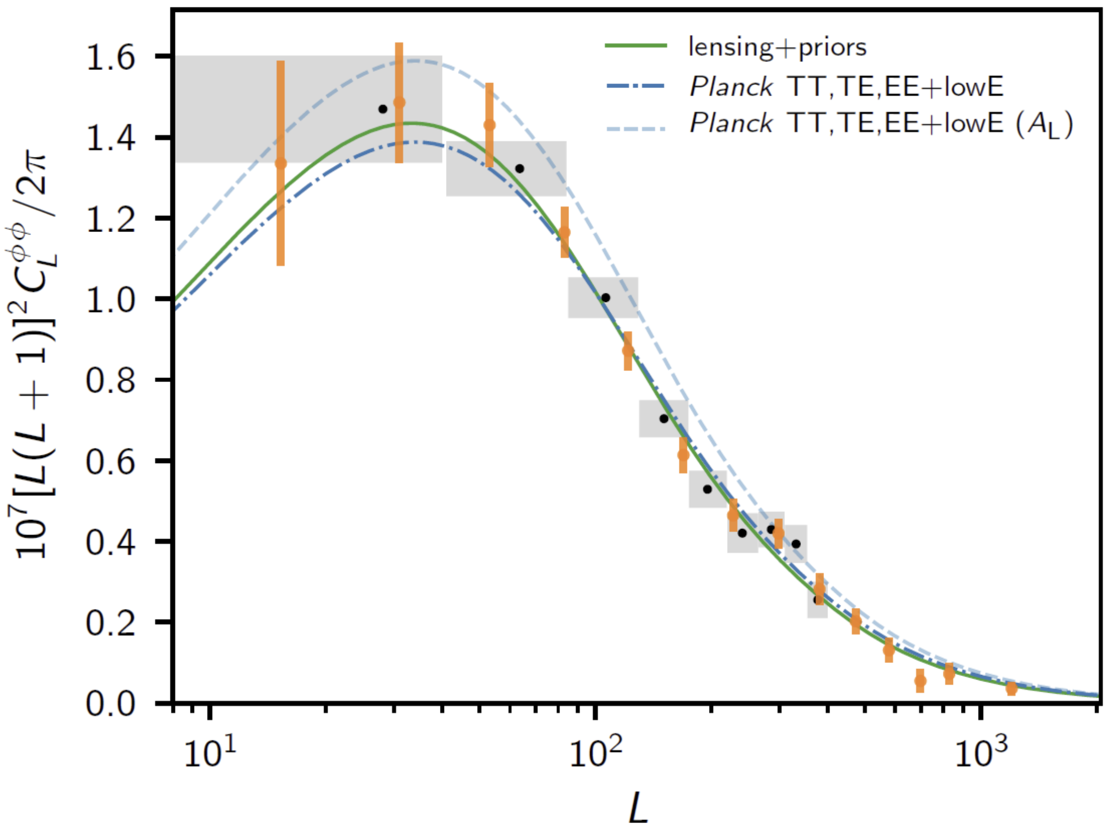
No models currently attempted are compelling or great fits.
- and why does it look in so many ways just like ΛCDM?

Some tensions in late-time σ_8 measurements, but complex and evolving

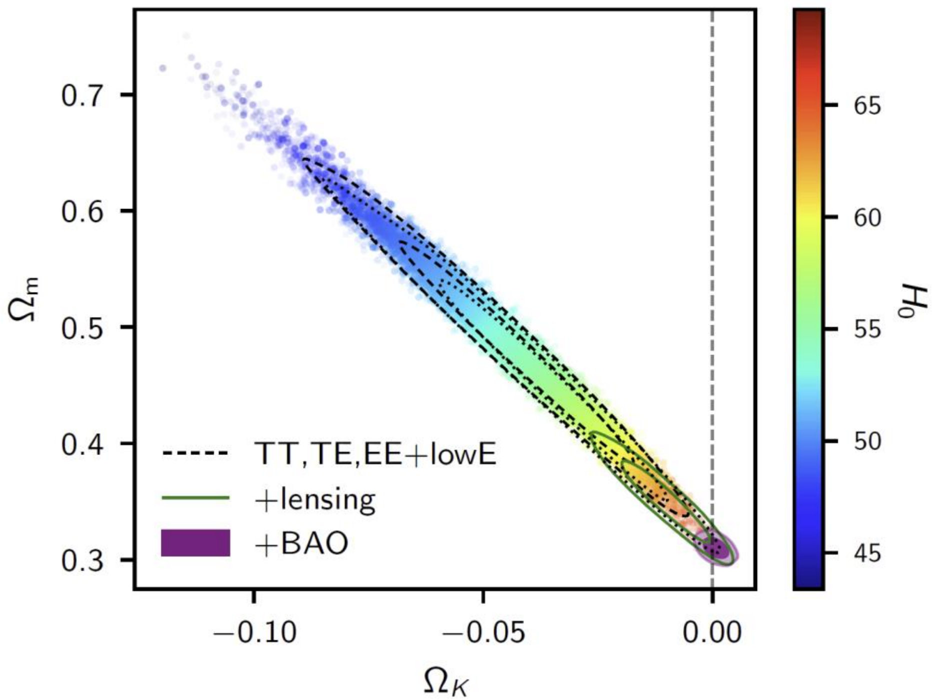
- More powerful LSS measurements soon could give clearer indication (*unless statistical power all soaked up by nuisance parameters in the complex modelling)*

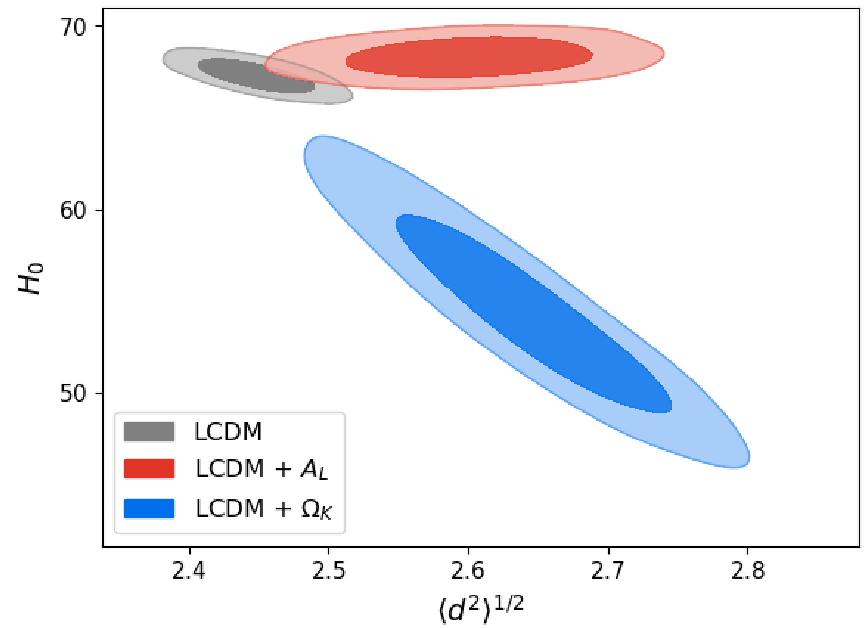


Probability density
10
8
6
4
2
0
0.2
0.6
1.0
1.4
1.8
2.2
2.6
A_L
TT+lowE
TE+lowE
EE+lowE
TT,TE,EE+lowE
TT,TE,EE+lowE+lensing
$\times 10^4$
$\ell \Delta \mathcal{D}_\ell^{TT}$ [μK^2]
2
1
0
−1
−2
500
1000
1500
2000
2500
ℓ
$\Omega_m h^2$
0.148
0.146
0.144
0.142
0.140
0.138



lensing+priors
Planck TT,TE,EE+lowE
Planck TT,TE,EE+lowE (A_L)
$10^7[L(L+1)]^2 C_L^{\phi\phi}/2\pi$
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^1
10^2
10^3
L





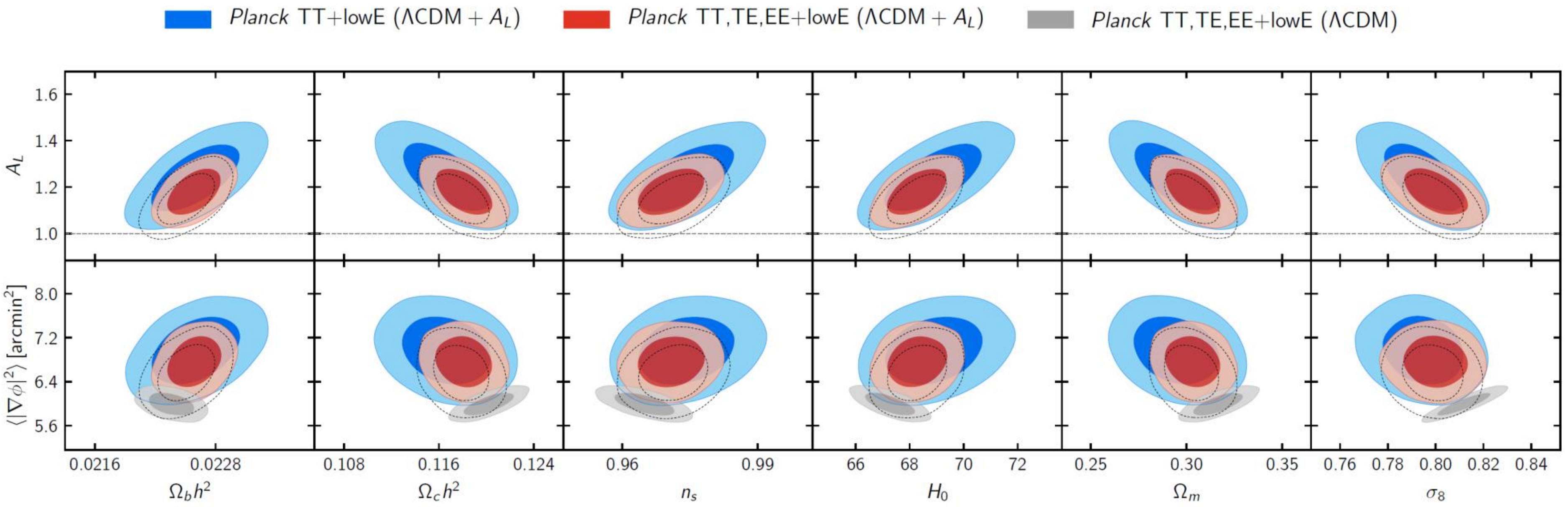
r.m.s. lensing deflection amplitude

$$\Omega_K = -0.044^{+0.018}_{-0.015} \quad (68\,\%, \textit{Planck}\ \text{TT,TE,EE+lowE}),$$

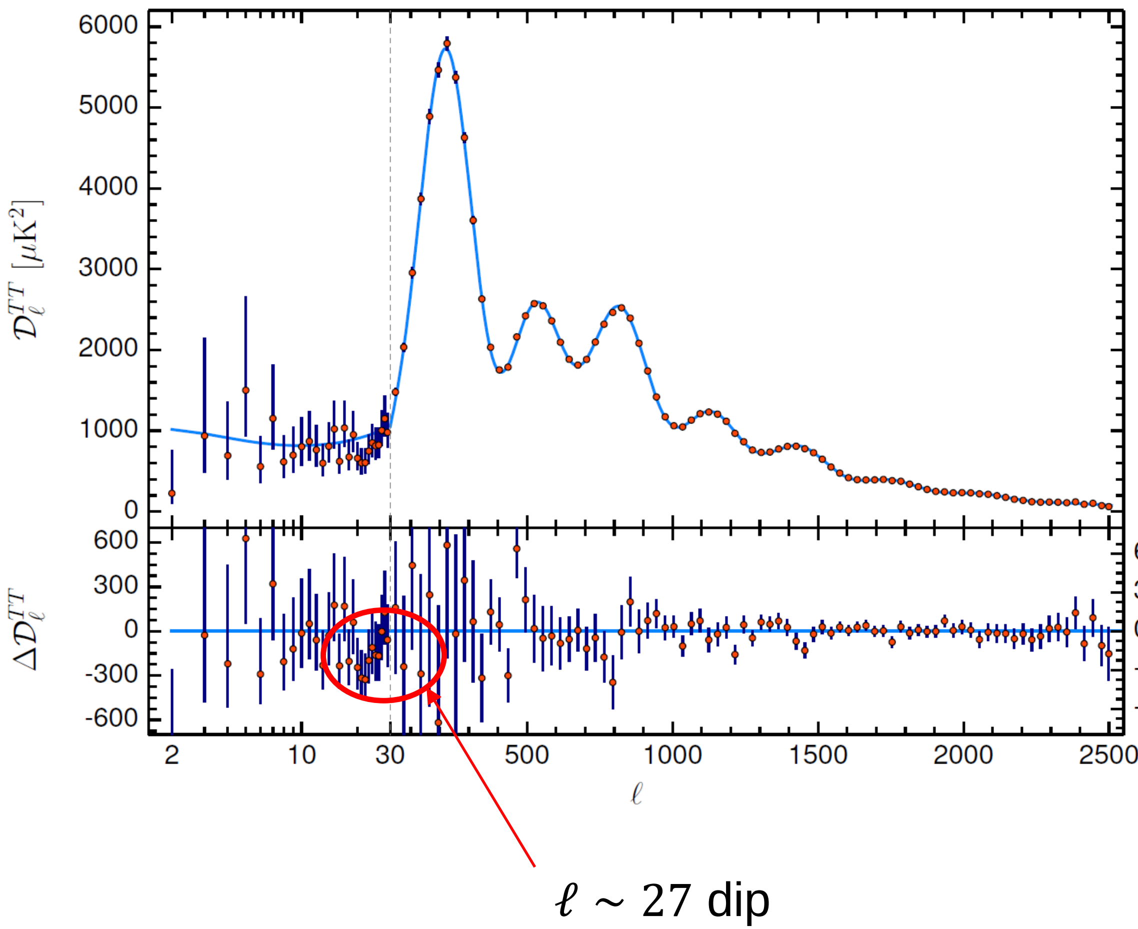
$$\Omega_K = 0.0007 \pm 0.0019 \quad \begin{array}{l}(68\,\%,\ \text{TT,TE,EE+lowE}\\ \text{+lensing+BAO}).\end{array}$$

$2 - 3\sigma$ preference for more "lensing" smoothing in TT spectrum

Introducing A_L parameter TT favours cosmological parameters which predict less lensing, but having $A_L > 1$ at $2 - 3\sigma$

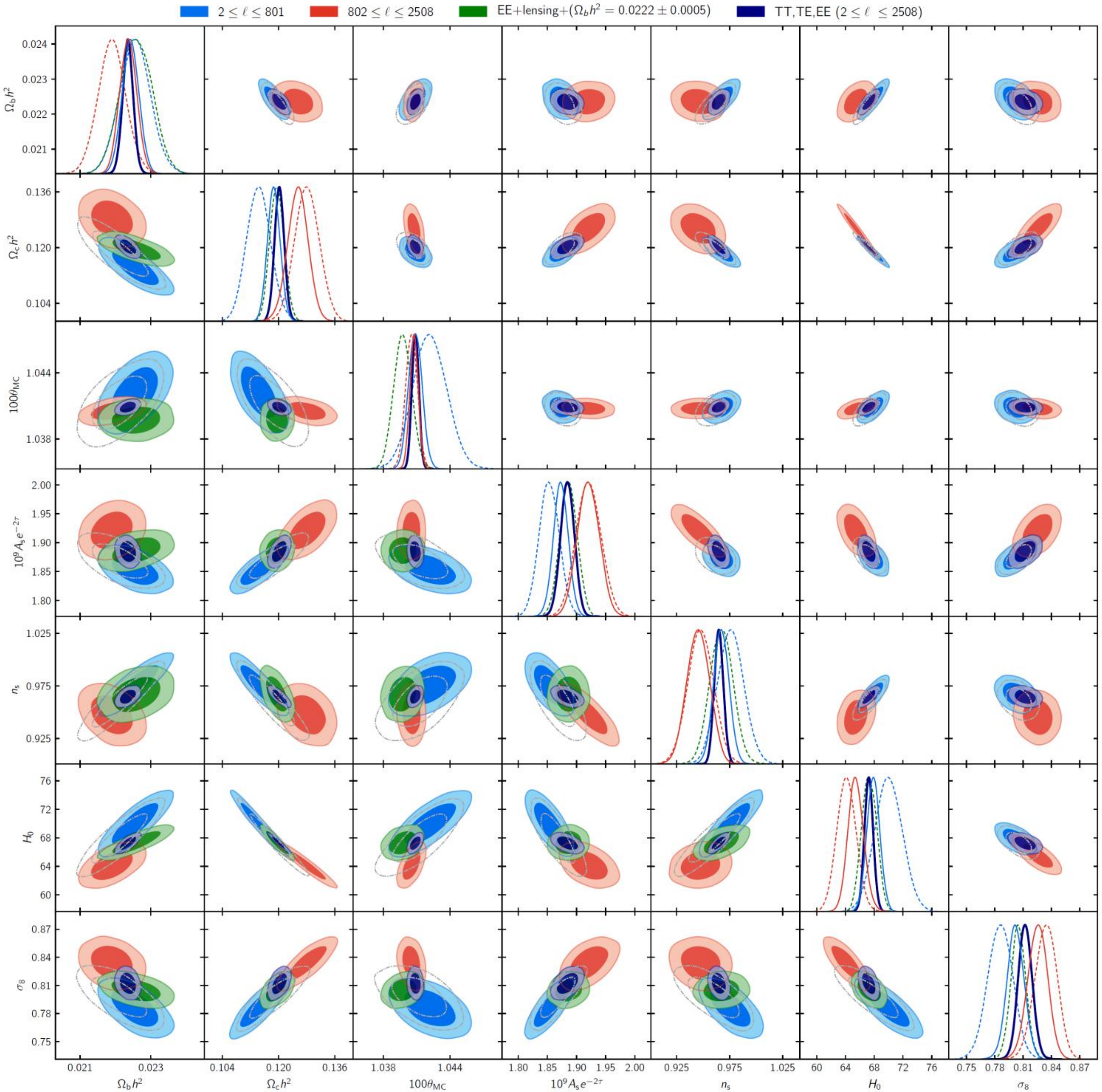


(it is probably *nothing* to do with actual lensing; lensing reconstruction gives $A_L \approx 1$)


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ
ℓ ~ 27 dip

$2-3\,\sigma$ "tension" between parameters from $\ell < 800$ and $\ell \geq 800$

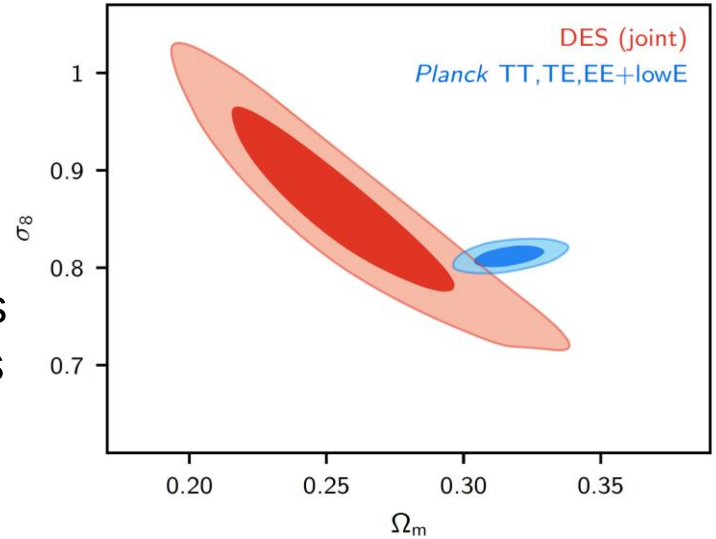
Looks consistent with fluctuation:
.. but *could* also be hint of new physics.



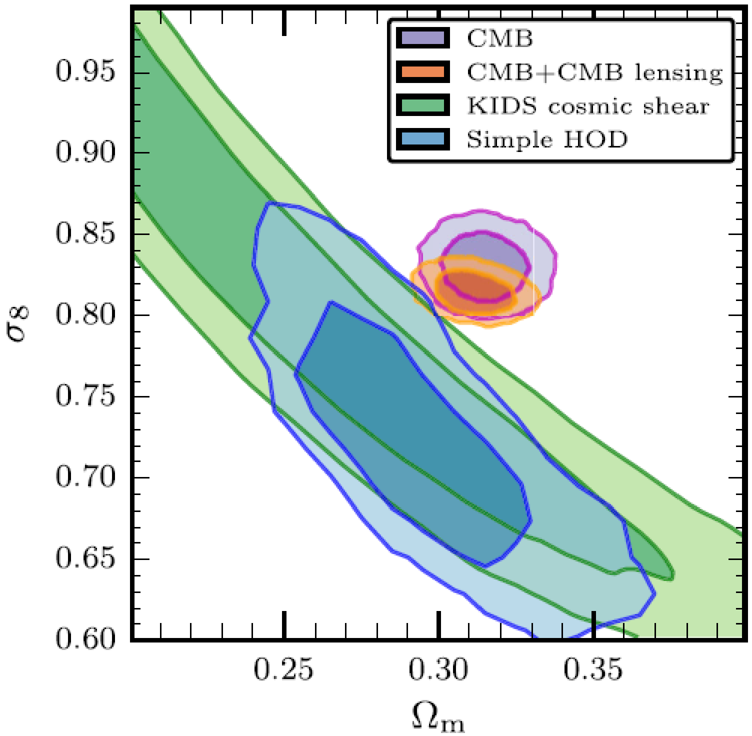
Are there hints of new physics elsewhere?

E.g. Galaxy clustering
Galaxy-galaxy lensing (galaxies x lensing)

BUT: not inconsistent or complex observations not modellable with simple understood physics



Lethaud et al. 1611.08606



BOSS (Lange et al. 1906.08680)