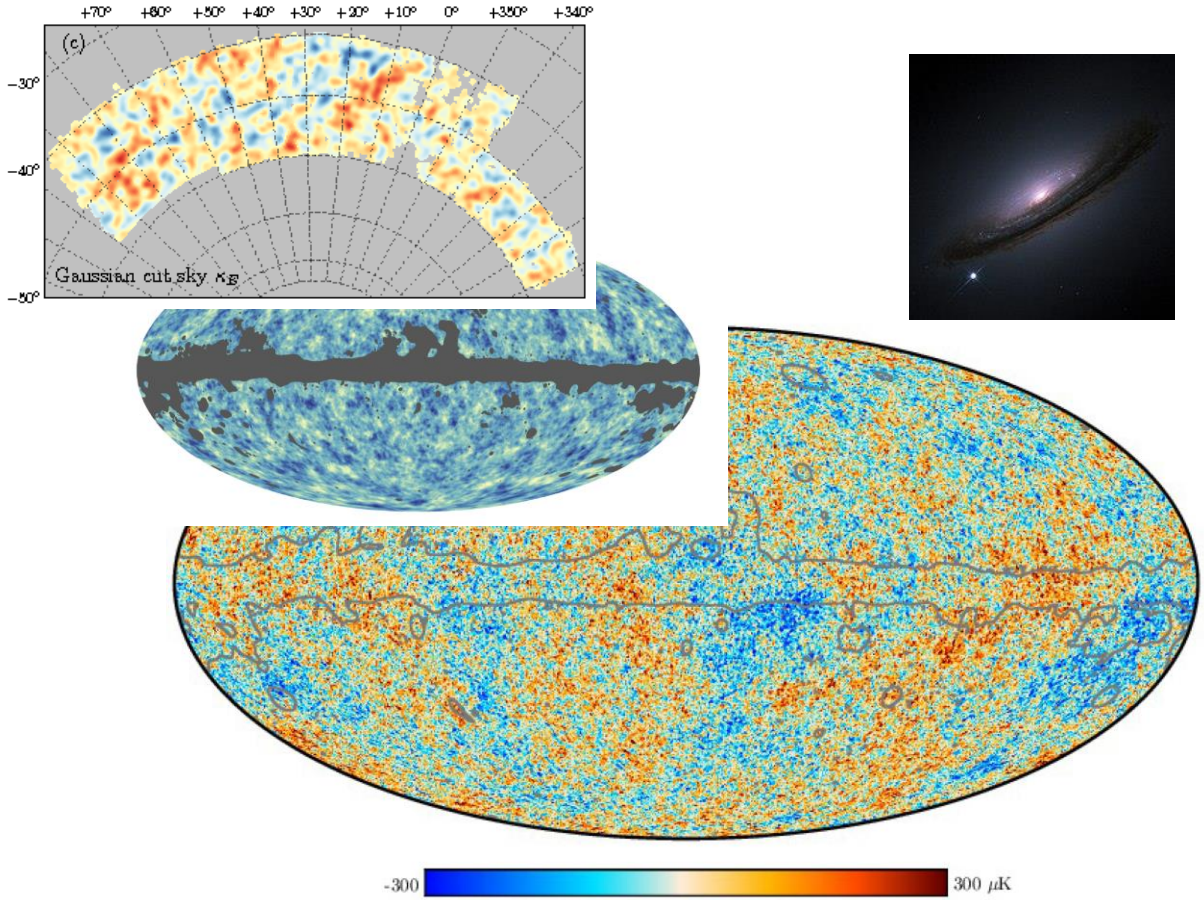
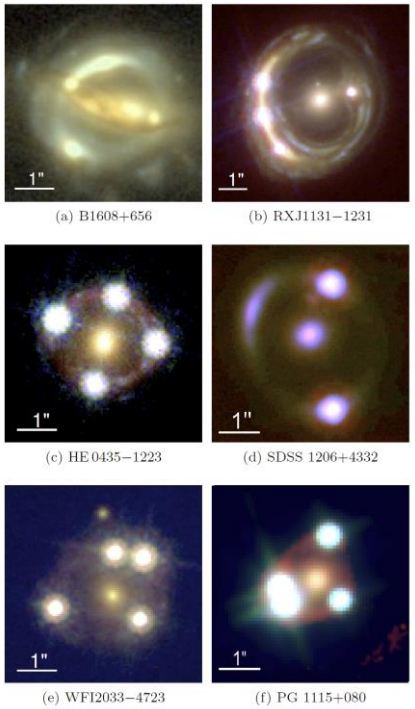
Cosmic concordance, tensions and lensing





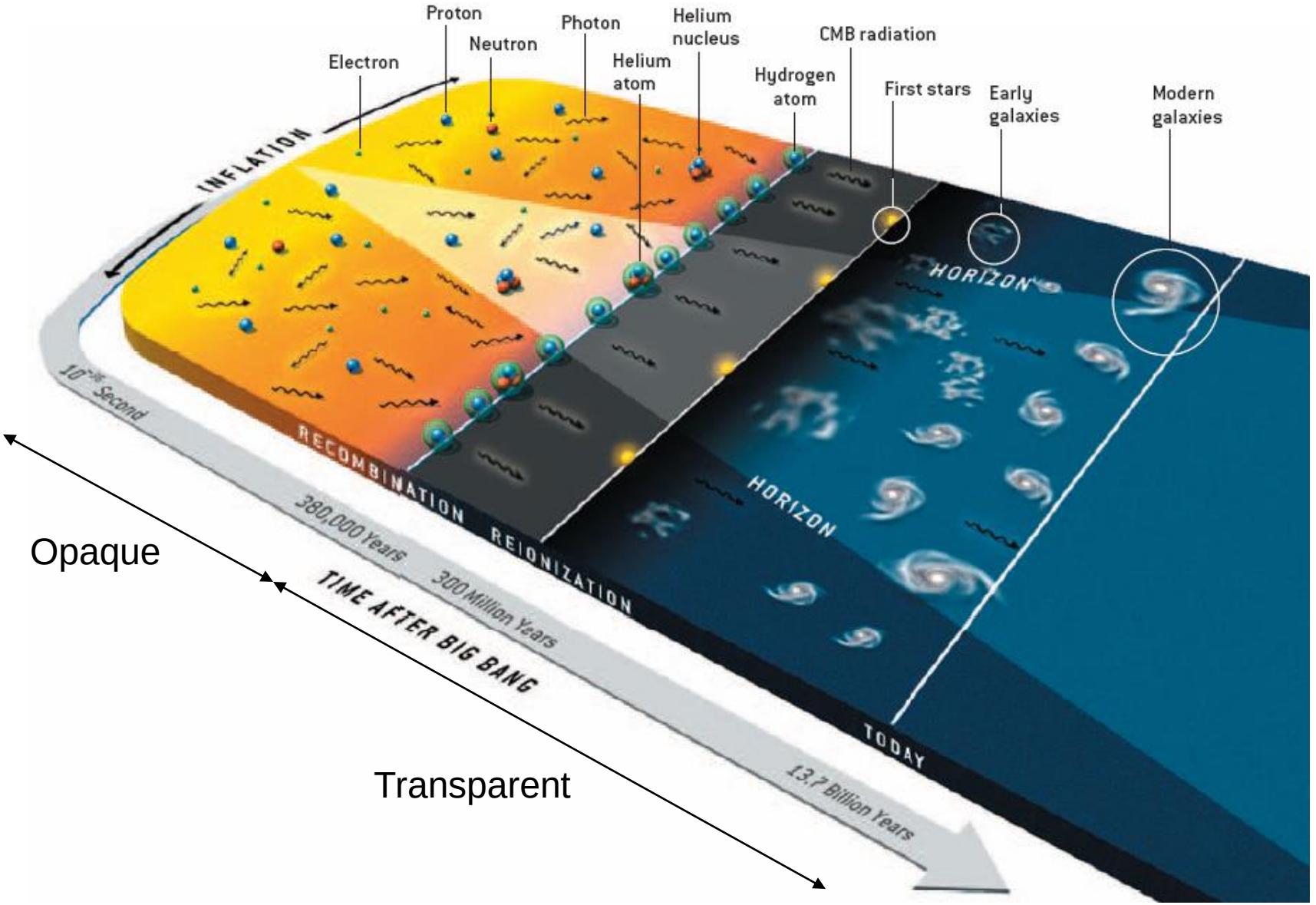
Antony Lewis
http://cosmologist.info/

UNIVERSITY OF SUSSEX

European Research Council
Established by the European Commission

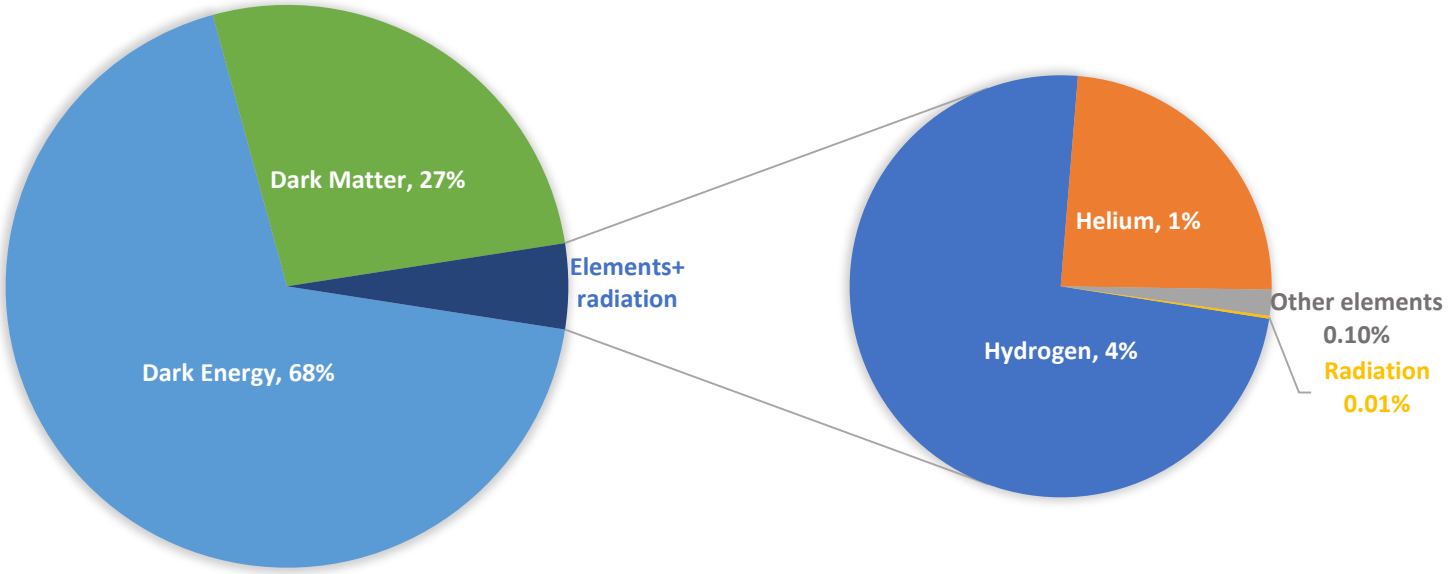
Science & Technology Facilities Council

Evolution in the standard cosmology



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

Contents of the Universe today



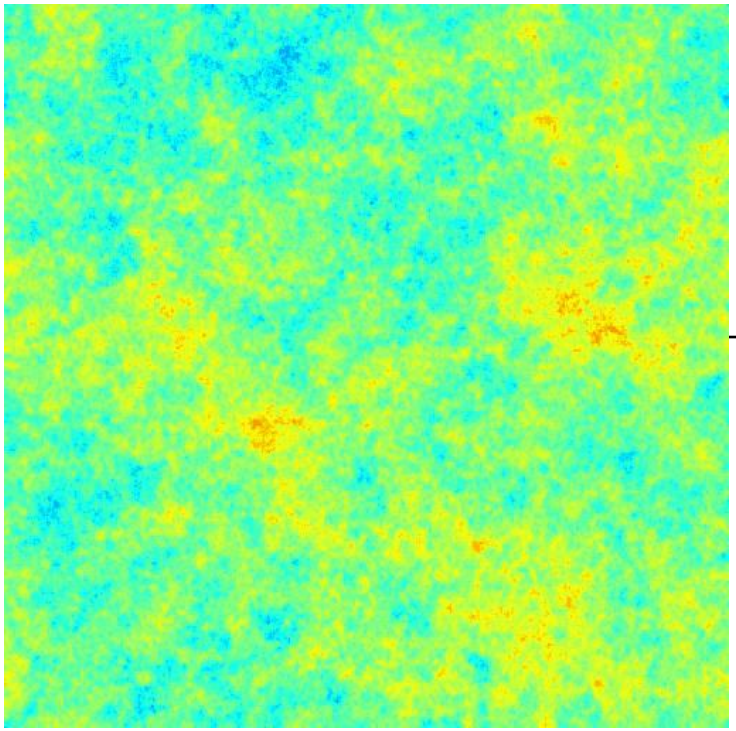
Define and test perturbatively-FRW ΛCDM model:

- 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* $\Omega_\Lambda, \Omega_m, \theta_*, \ldots$*)*

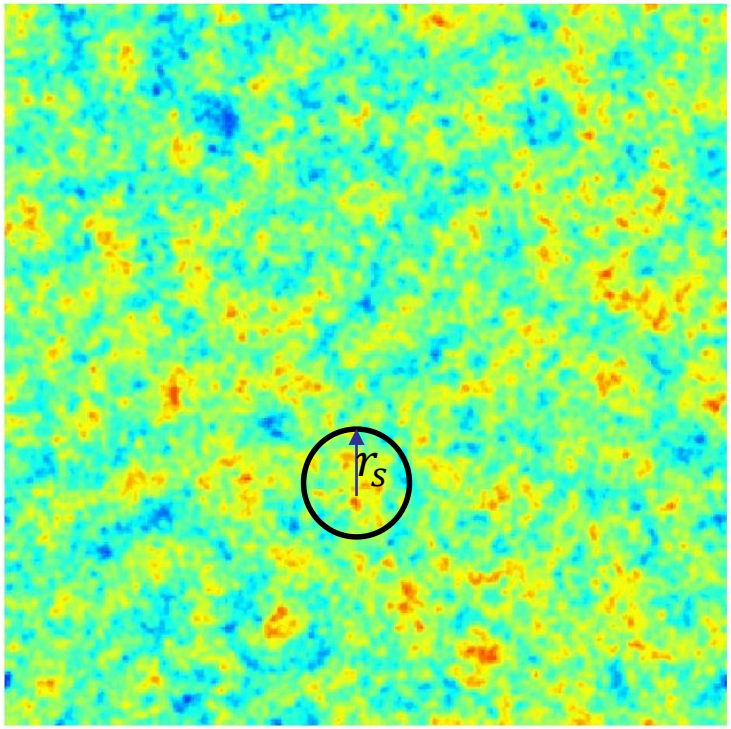
Perturbation evolution

Perturbations: start of hot big bang

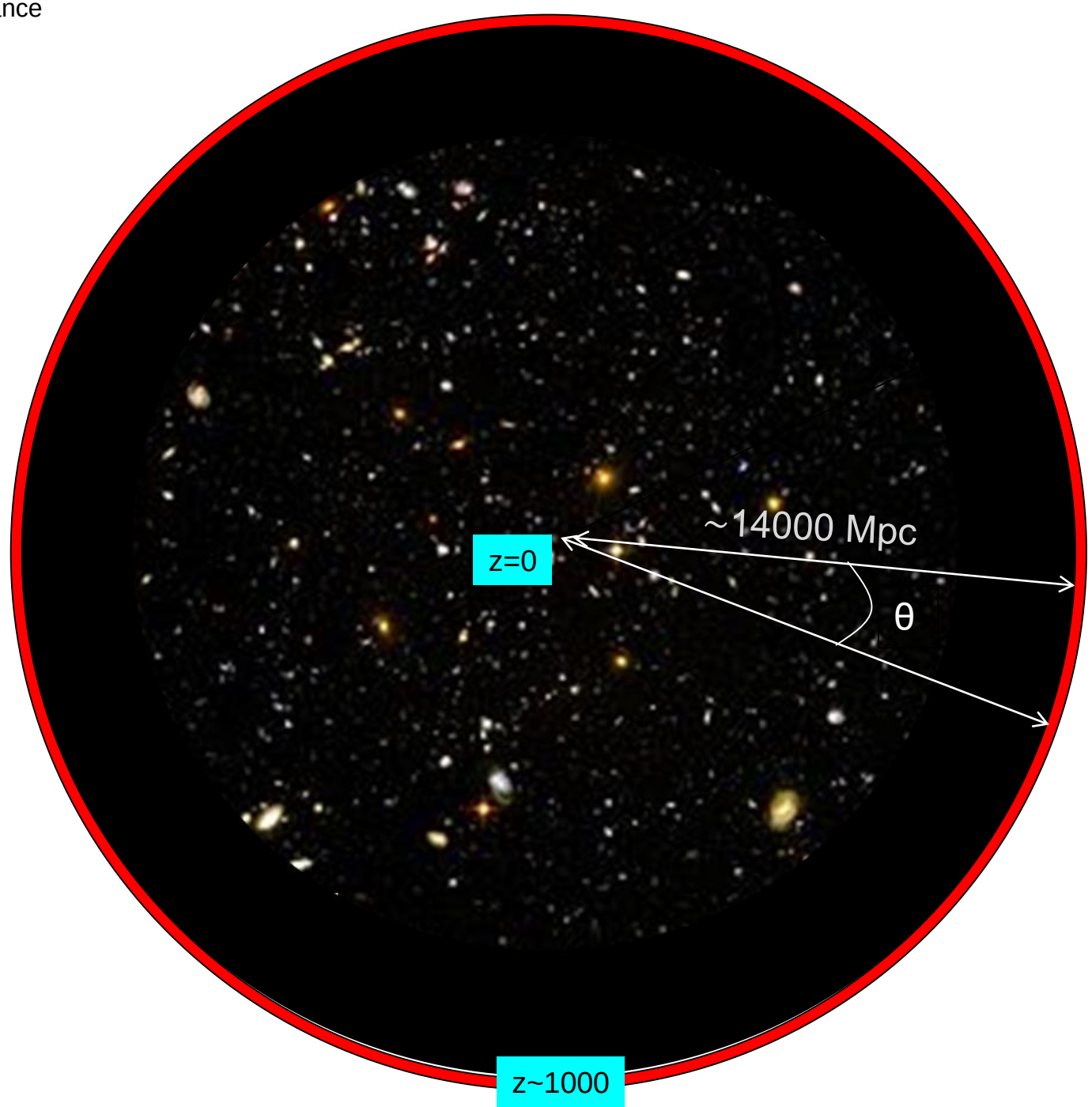


gravity+
pressure+
diffusion

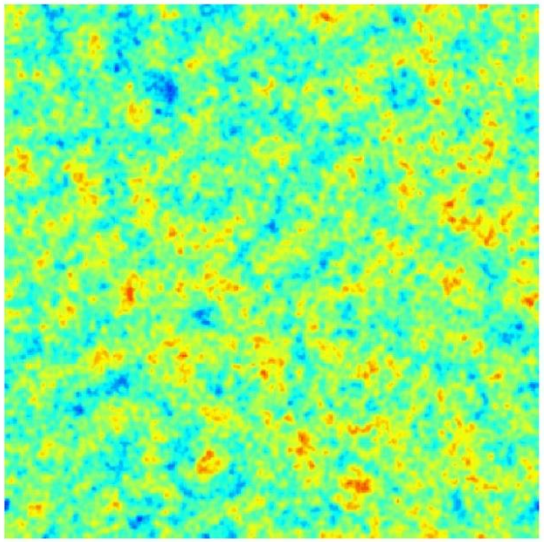
Perturbations: Last scattering surface



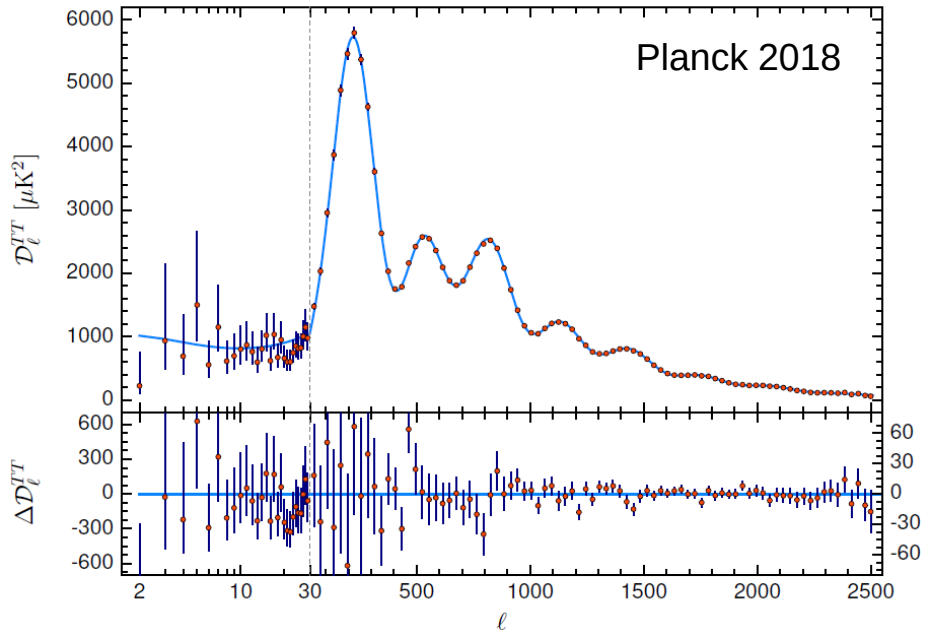
In comoving distance



Observed CMB power spectrum



arXiv:1807.06209



Observations

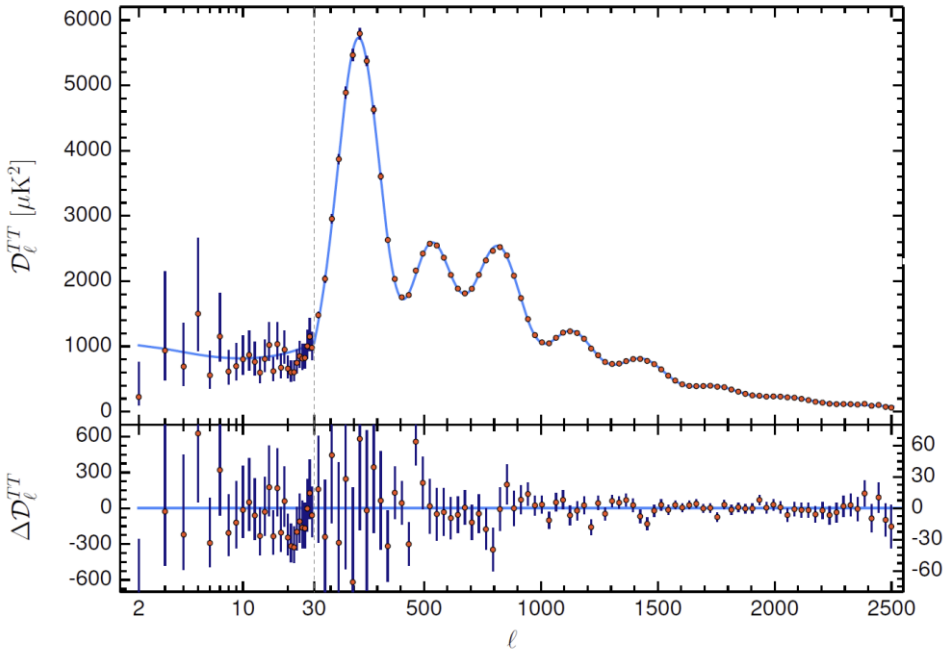
(10^{-5} perturbations)

Assume model, constrain parameters
- test constancy with other probes

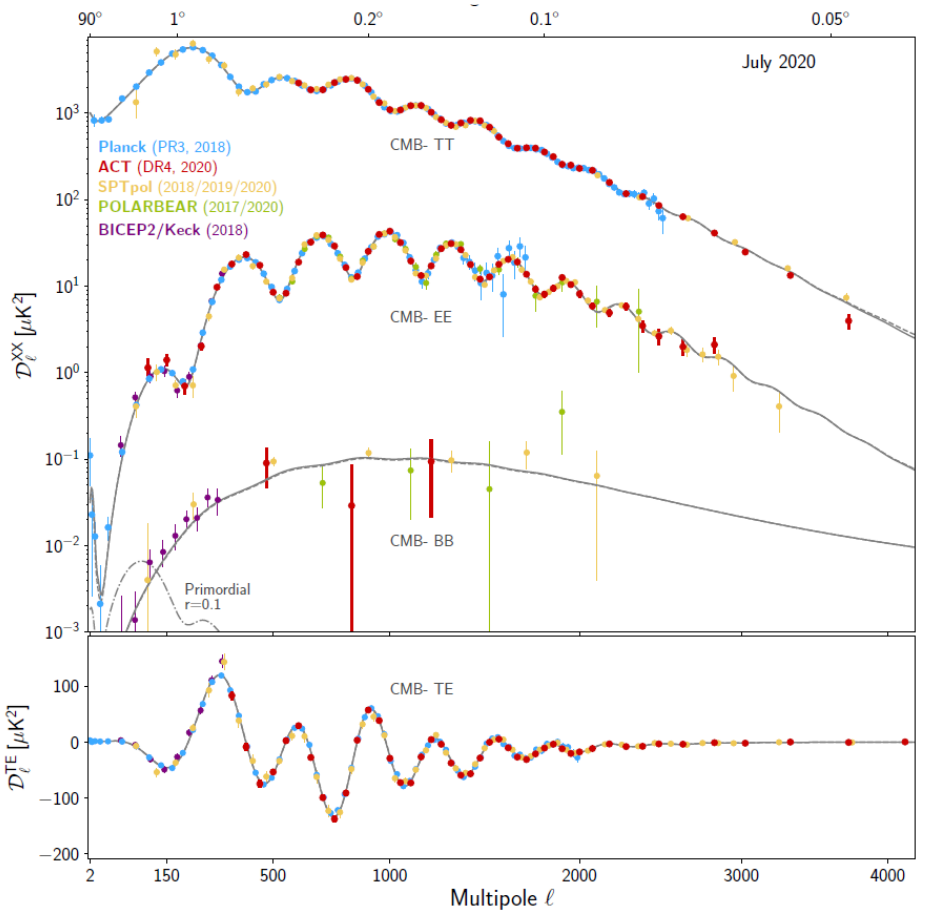
Linear perturbation theory very accurate: given a model, can calculate to high precision

Cosmic Microwave Background power spectrum fits to ΛCDM

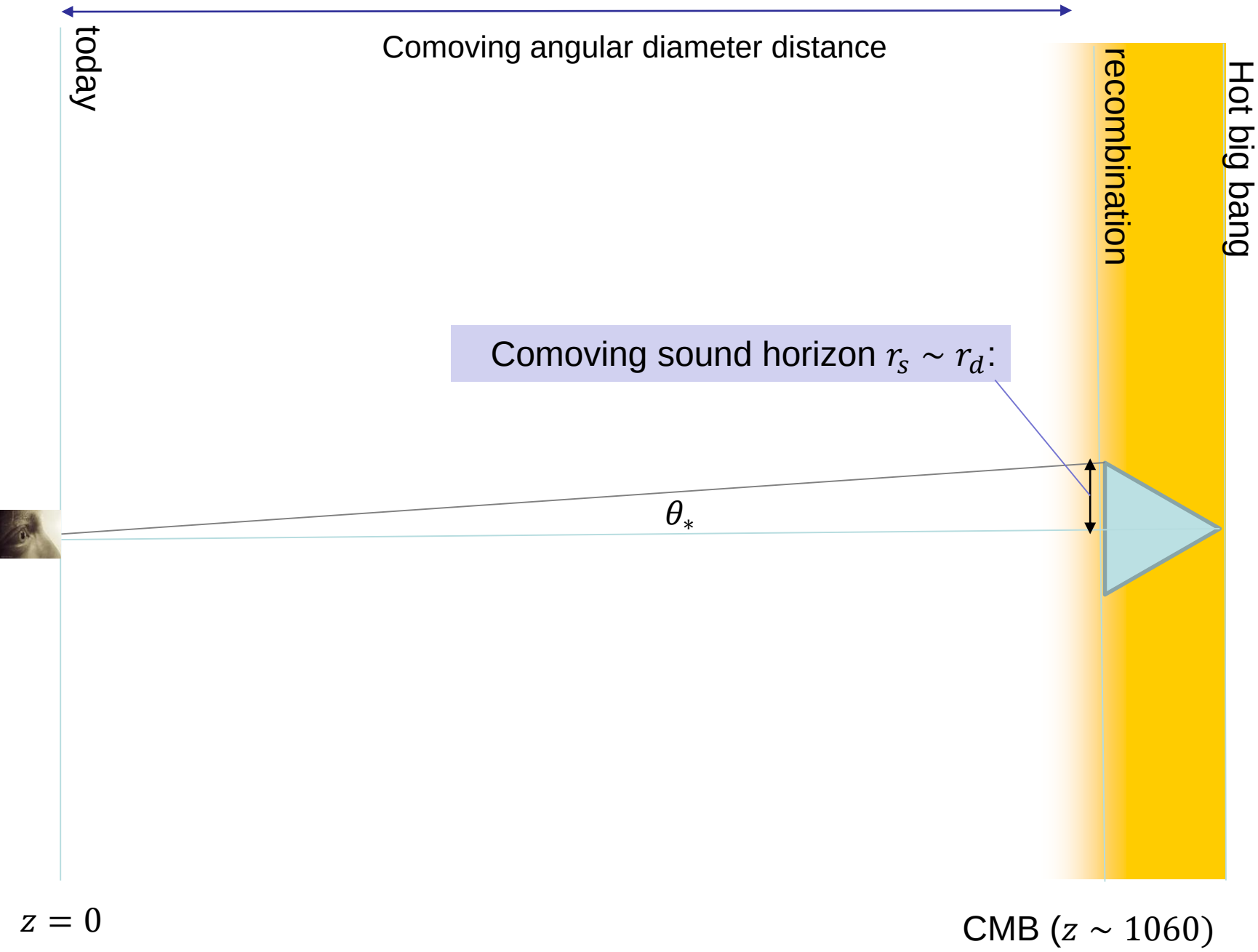
Planck 2018 (arXiv: 1806.06209)

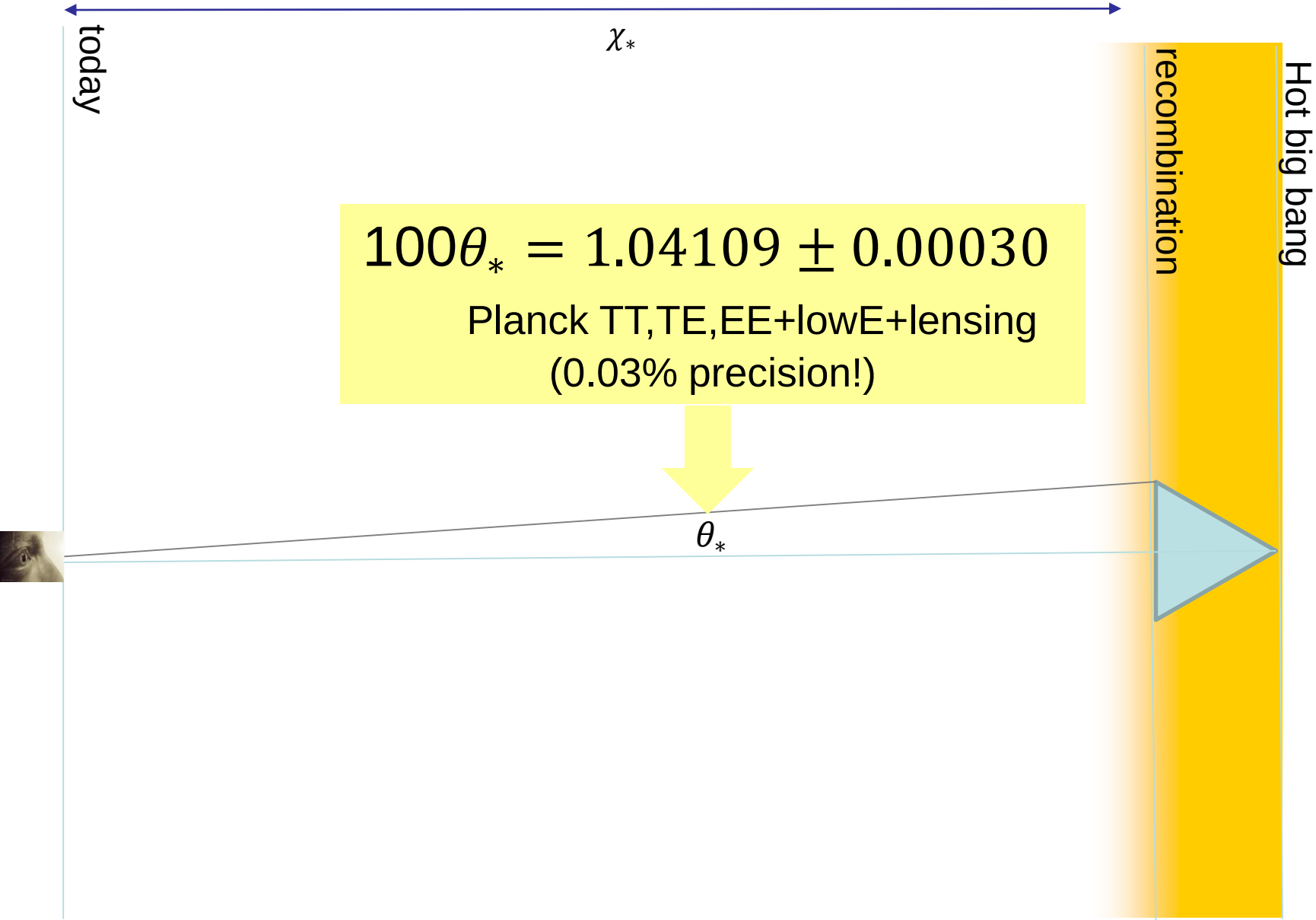


Choi et al. (2007.07289)



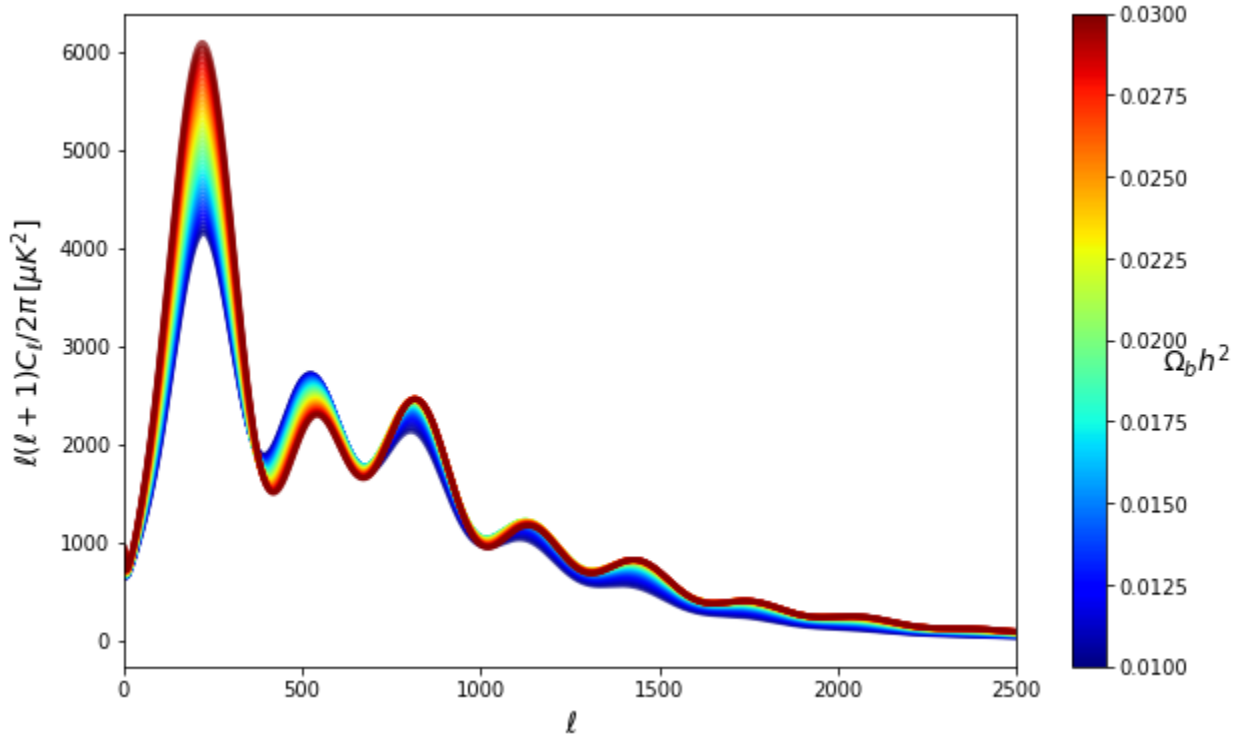
In Comoving Distance (not to scale!)




today
χ_*
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)



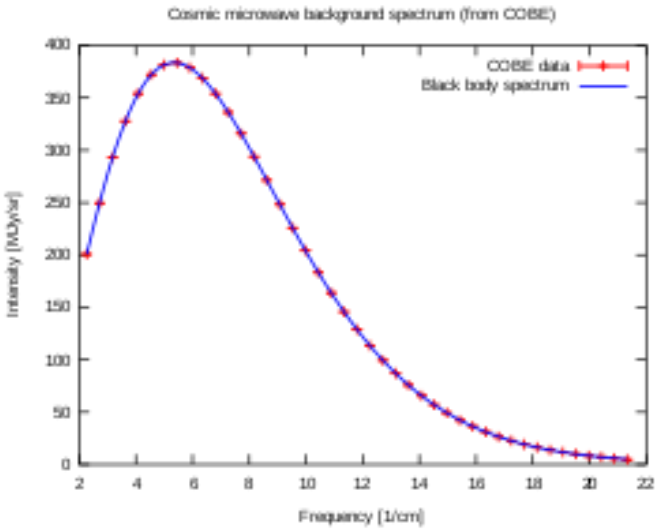
Odd/even height ratio distinctive and quite robust:

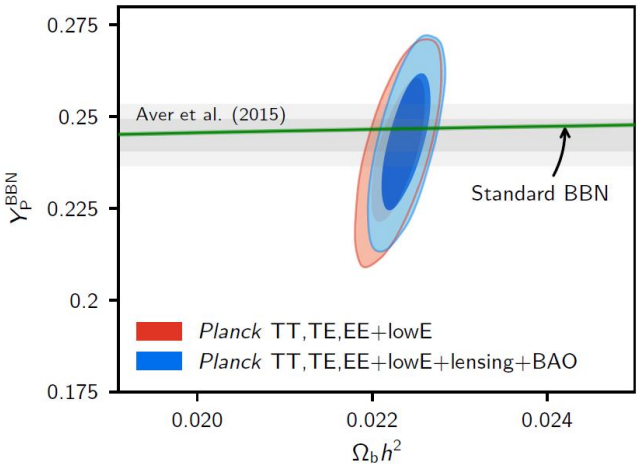
$$\Omega_b h^2 = 0.0224 \pm 0.0002$$

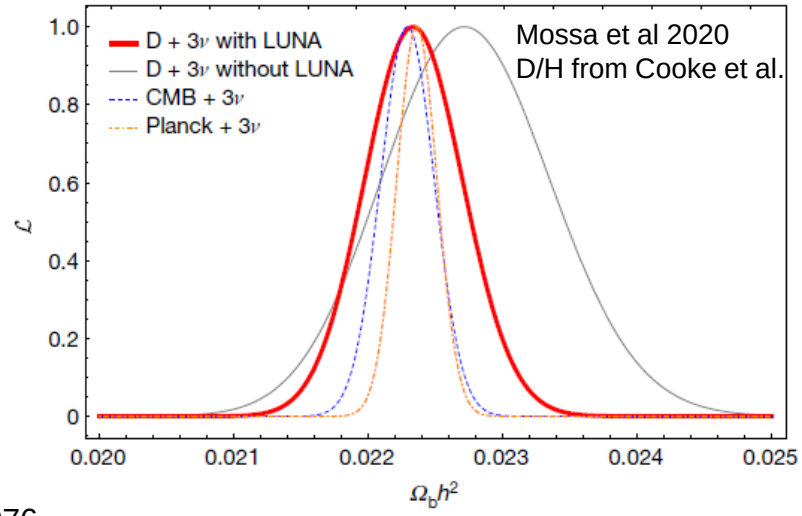
Consistency with standard Big-Bang Nucleosynthesis

arXiv: 1806.06209

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







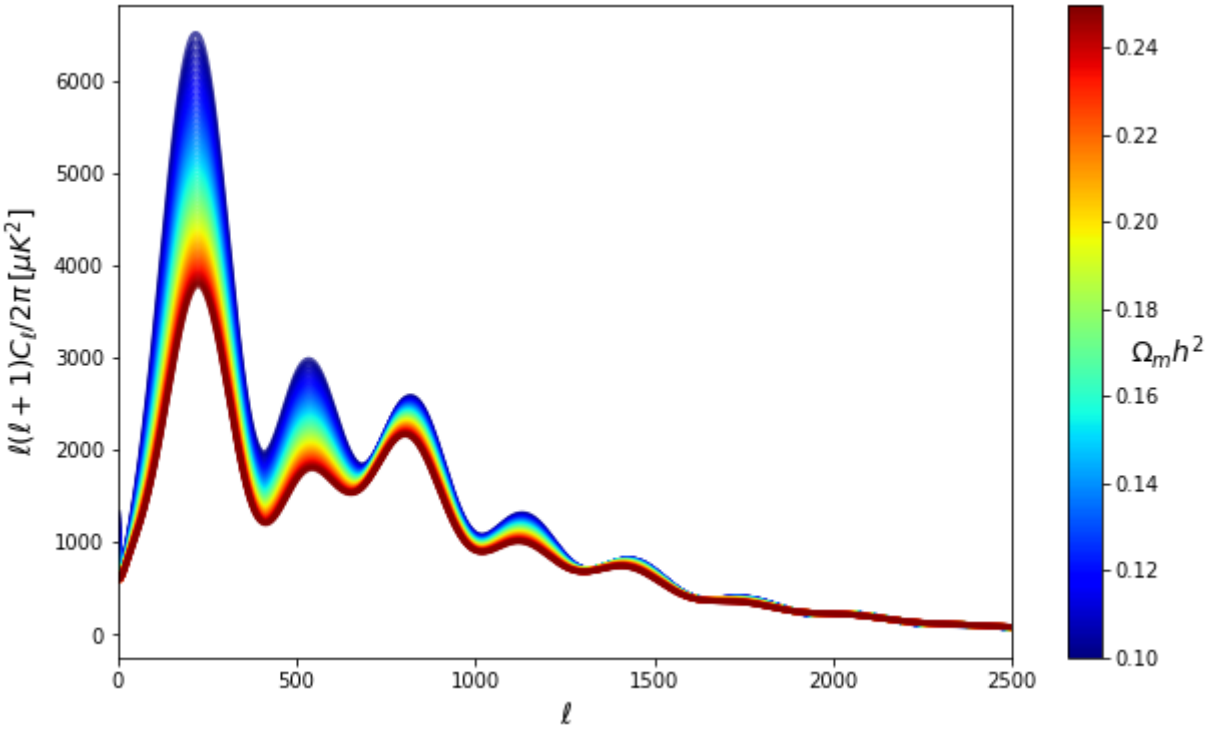
BUT: Lithium problem remains around 5σ

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

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

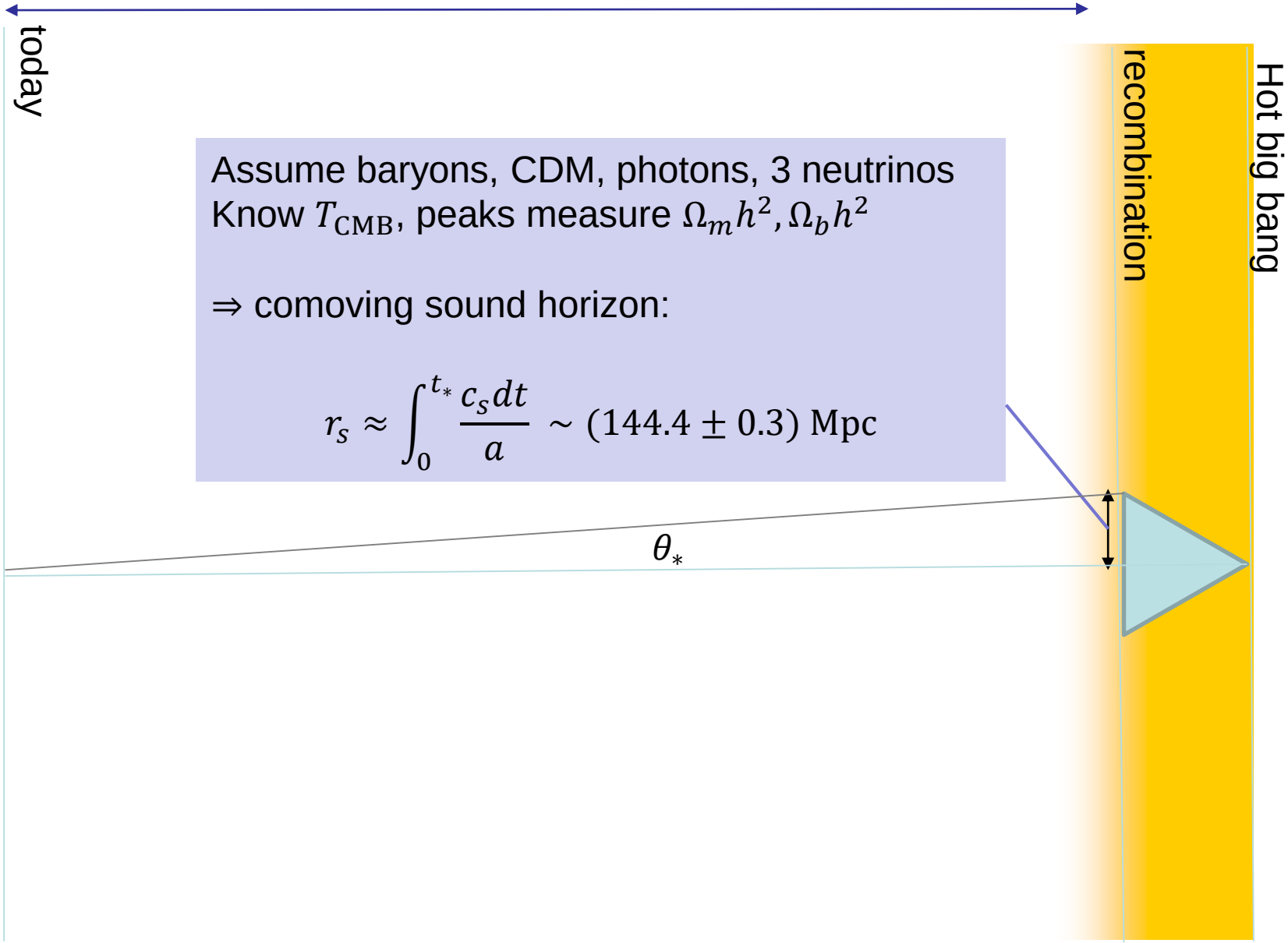
ΛCDM matter density at fixed θ_*, $\Omega_b h^2$

(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:

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


today
recombination
Hot big bang
Assume baryons, CDM, photons, 3 neutrinos
Know $T_{\rm CMB}$, peaks measure $\Omega_m h^2, \Omega_b h^2$
⇒ comoving sound horizon:
$r_s \approx \int_0^{t_*} \frac{c_s dt}{a} \sim (144.4 \pm 0.3)$ Mpc
θ_*
$z = 0$
CMB ($z \sim 1060$)

CMB

Assuming flat ΛCDM cosmology

today

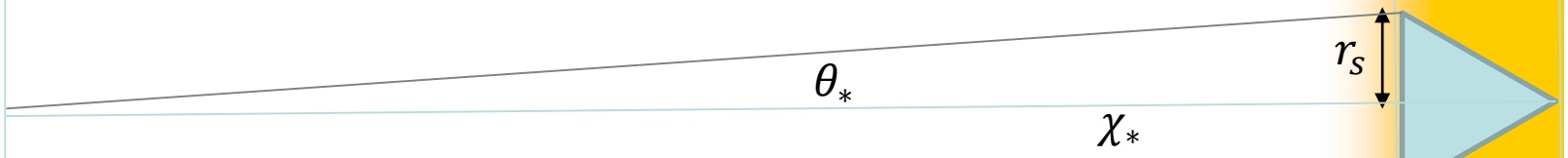
recombination

Hot big bang

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

$$\chi_* = \int \left(\frac{cdt}{a}\right) = \int \left(\frac{da}{a^2 H}\right) \approx \int \frac{da}{\sqrt{a\Omega_m H_0^2 + a^4 \Omega_\Lambda H_0^2}}$$

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



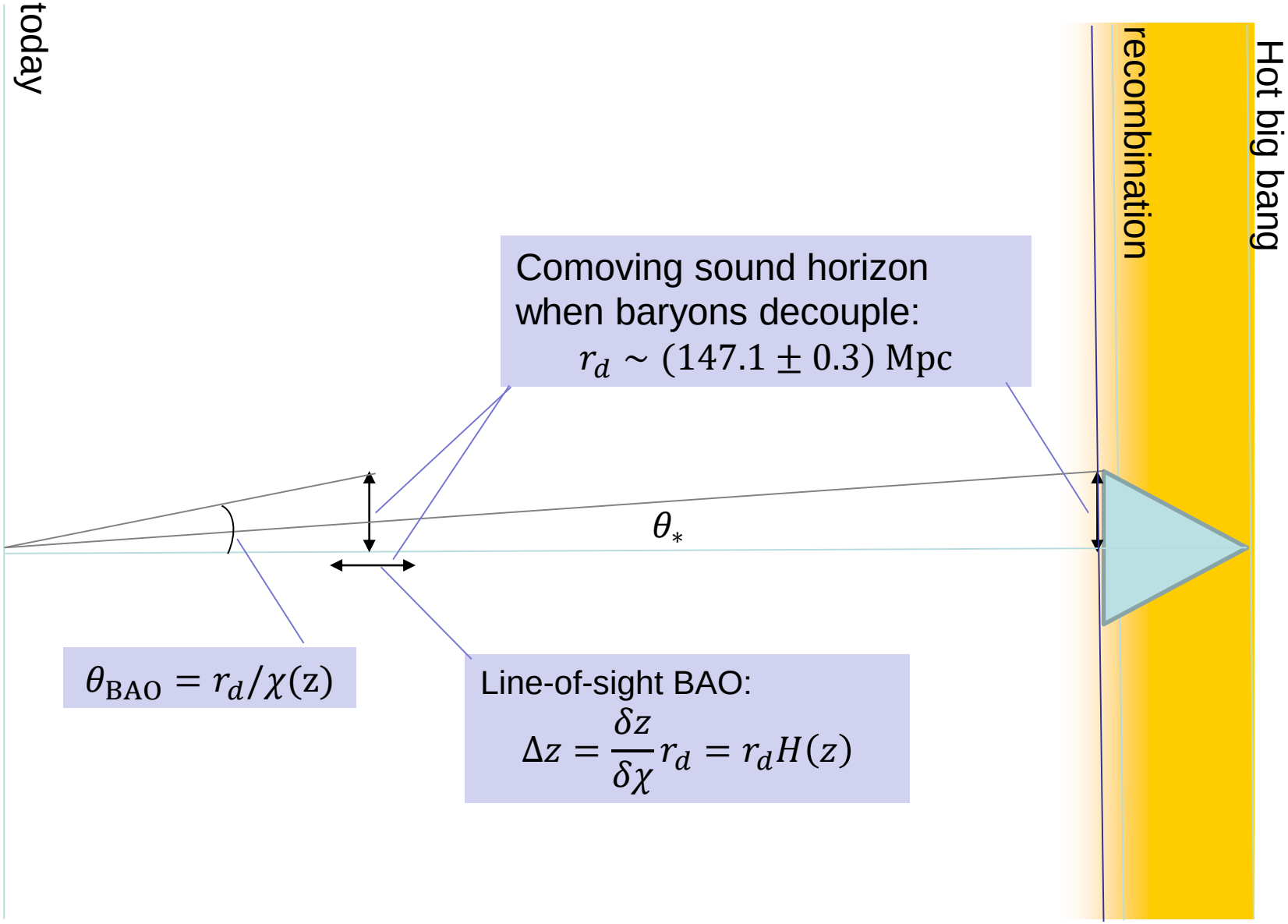
$\Rightarrow H_0 = (67.3 \pm 0.6)$ km s^{-1}Mpc^{-1}

(Planck, confirmed by ACT)

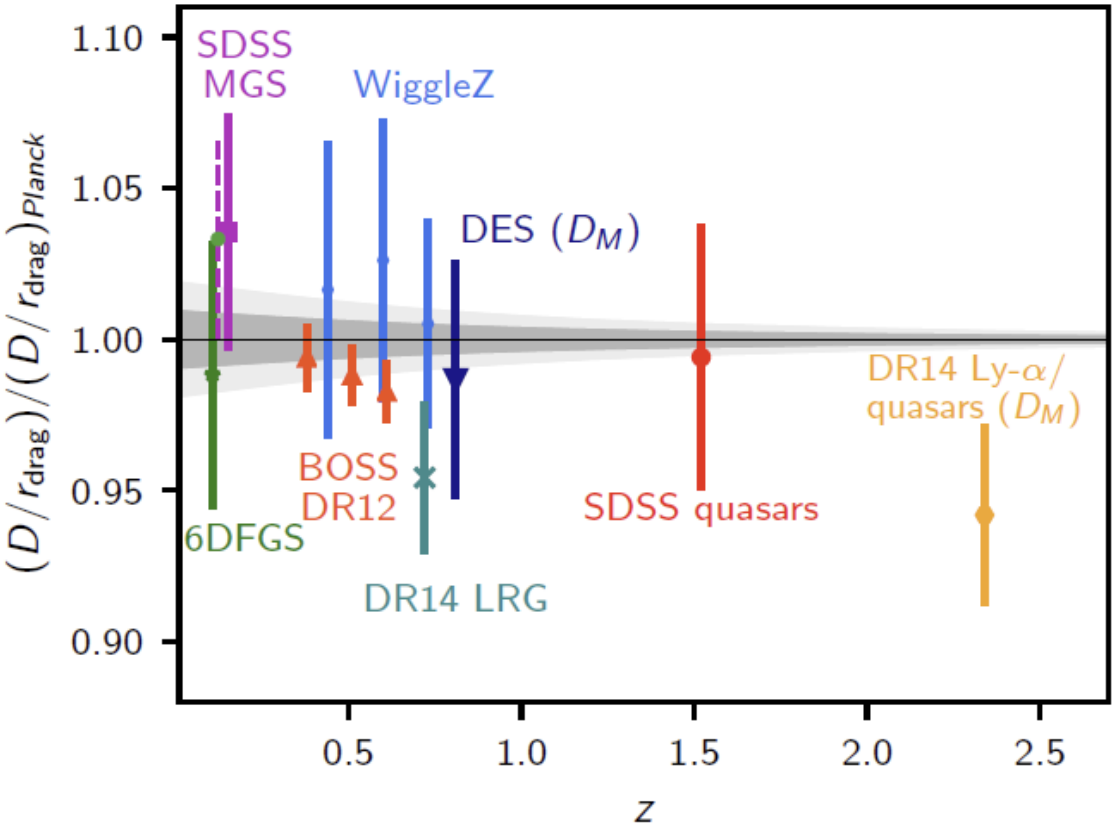
$z = 0$

CMB ($z \sim 1060$)

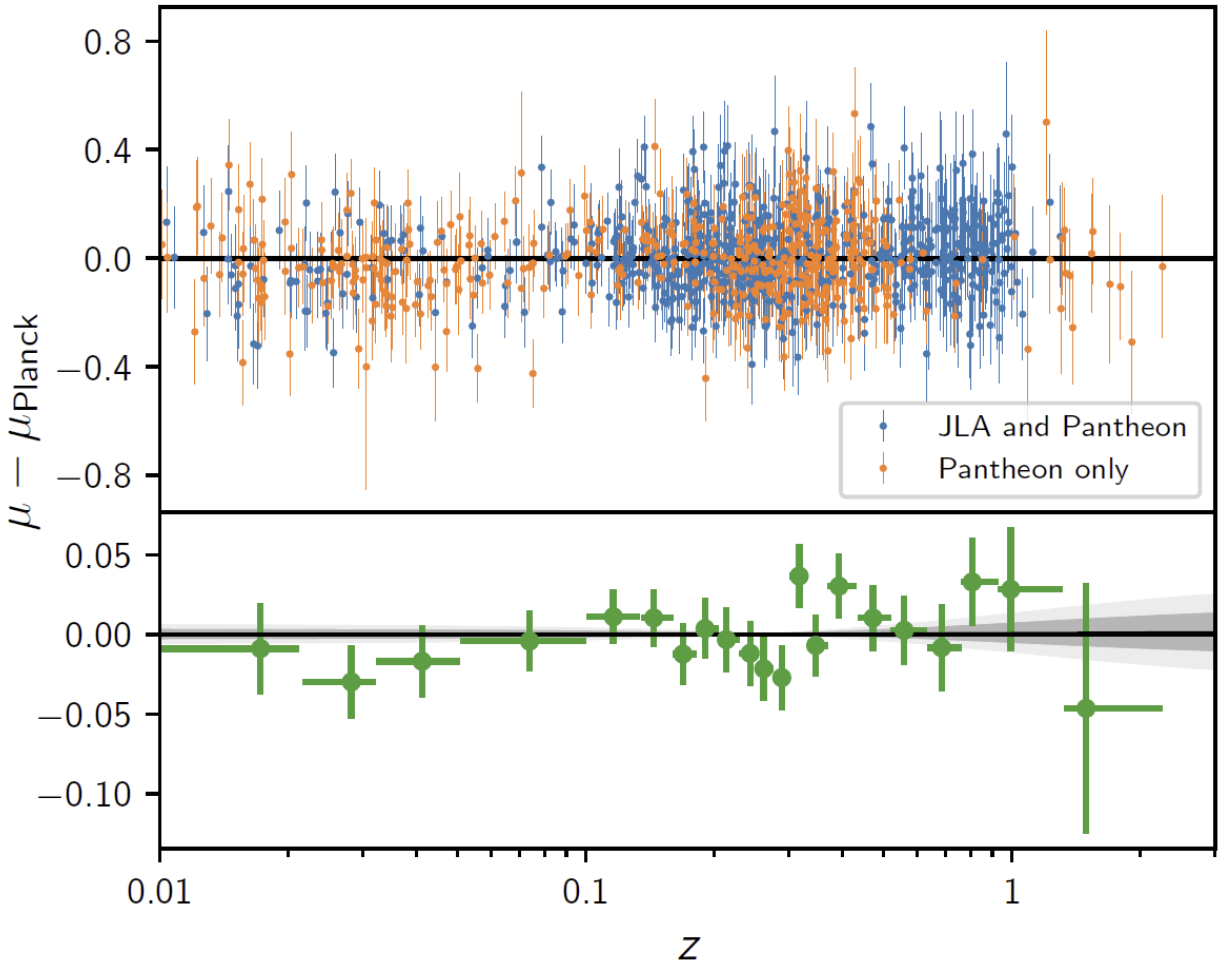
CMB and BAO consistency in ΛCDM



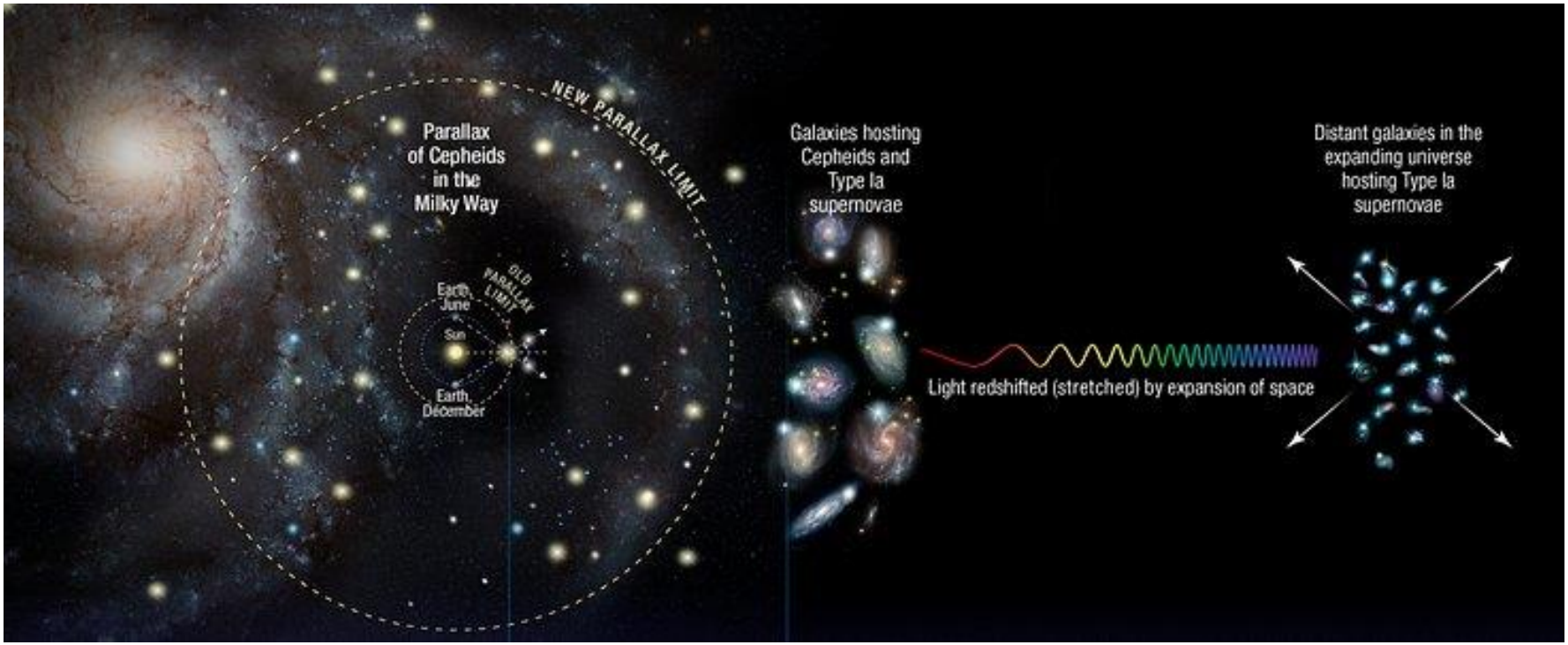
Baryon Acoustic Oscillation (BAO) concordance



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



H_0 from local distance ladder



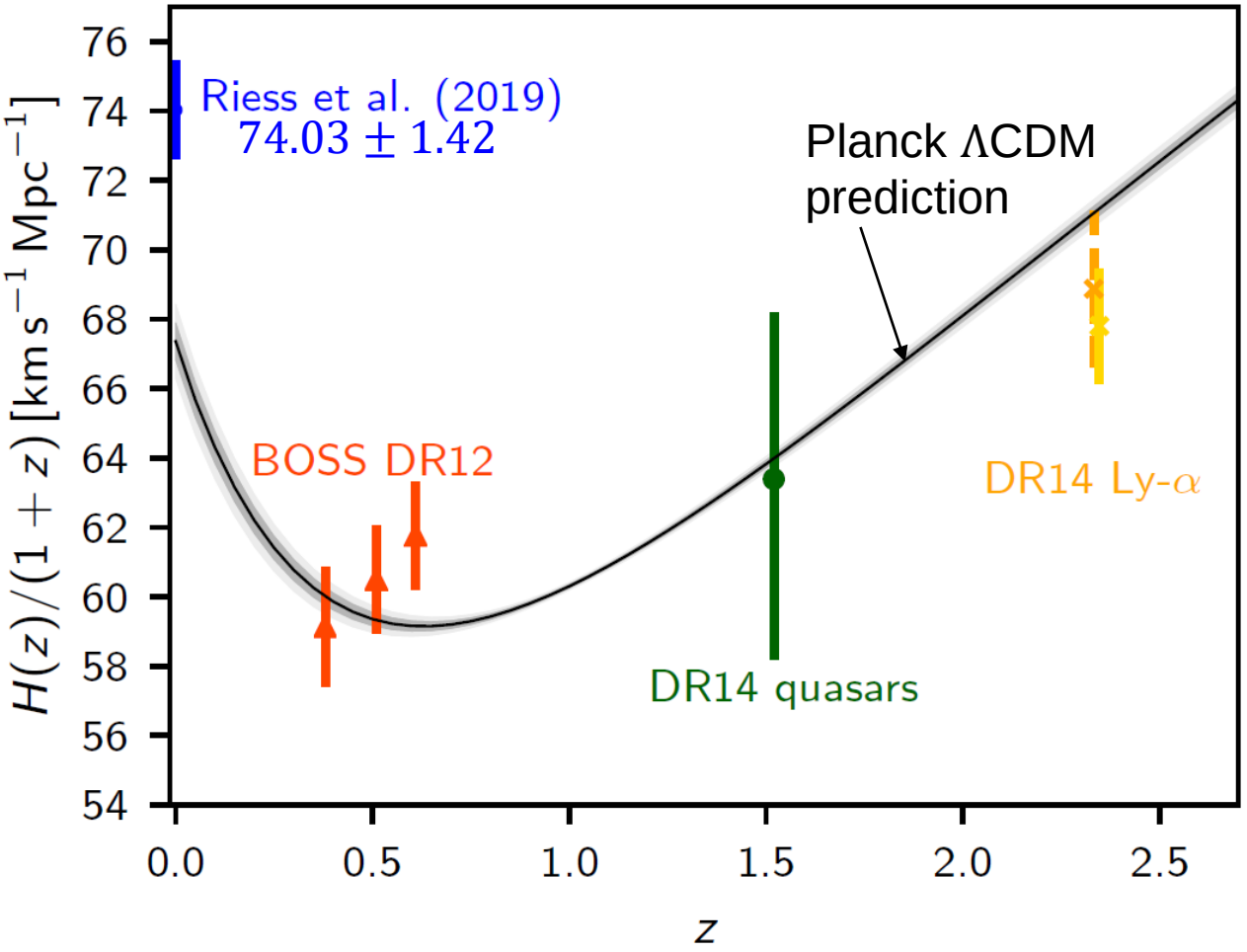
https://www.spacetelescope.org/news/heic1611/

Parallax+cepheids+SN

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

Riess et al. arXiv: 1903.07603

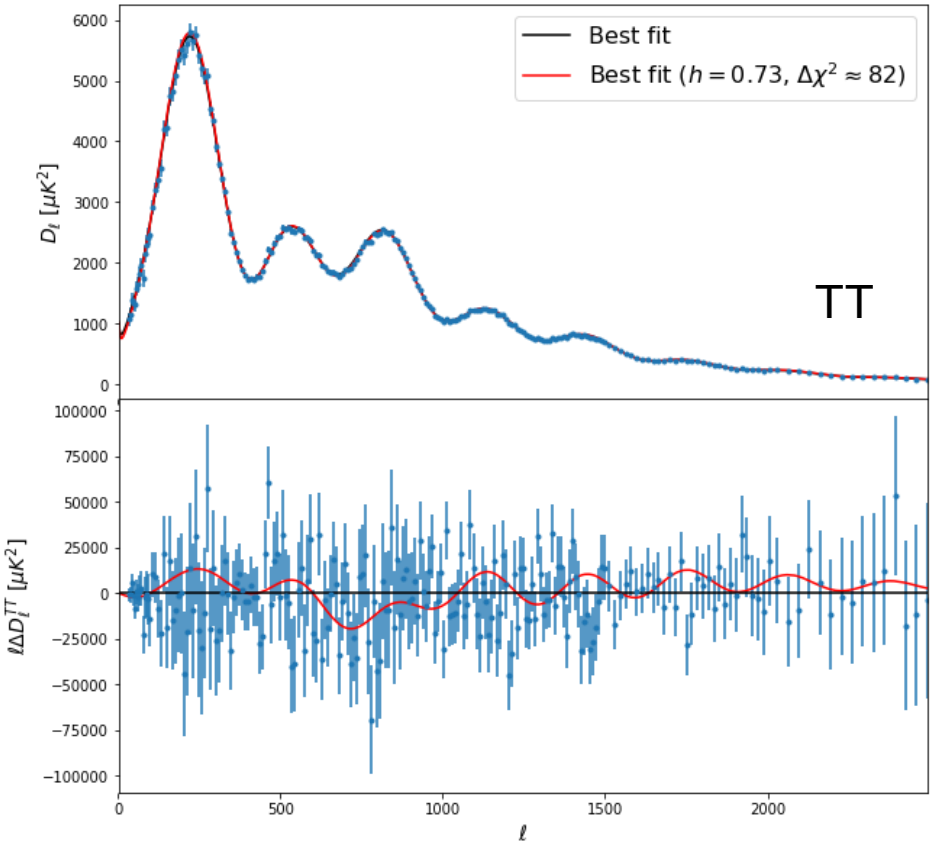
The Hubble discrepancy assuming ΛCDM and Planck sound horizon r_d

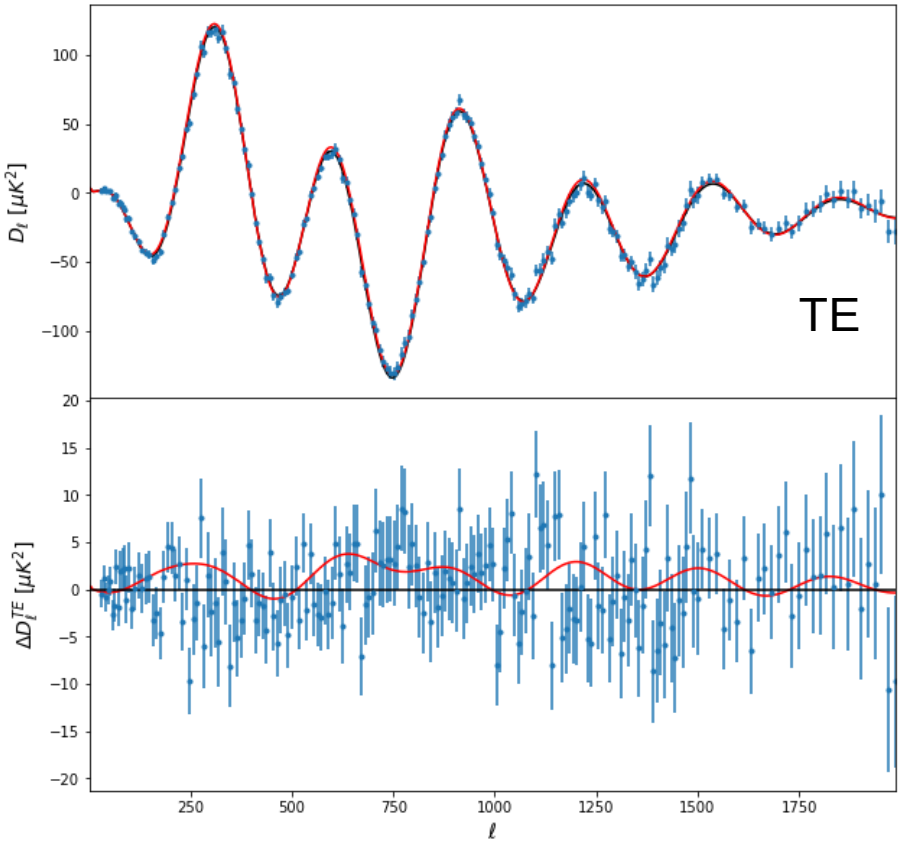


A $4.4\sigma \sim 10\%$ discrepancy between local and CMB-inferred ΛCDM H_0?

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 $H_0 = 73.0$ ($n_s = 0.995,\ \Omega_m = 0.25, \Omega_m h^2 = 0.132$)





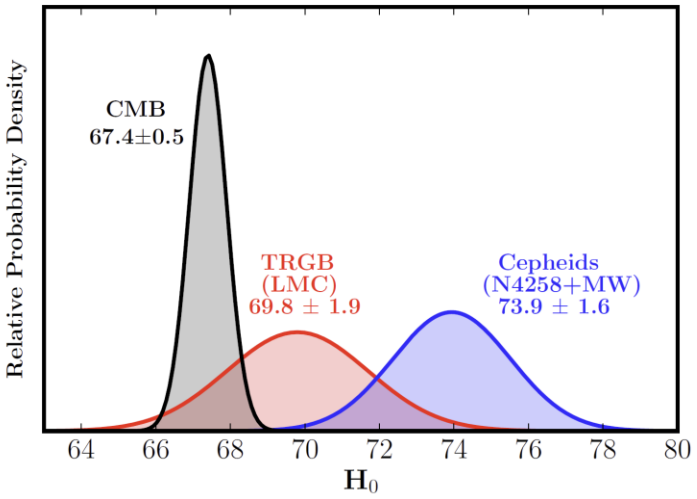
Other local Hubble parameter measurements

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, 2002.01550



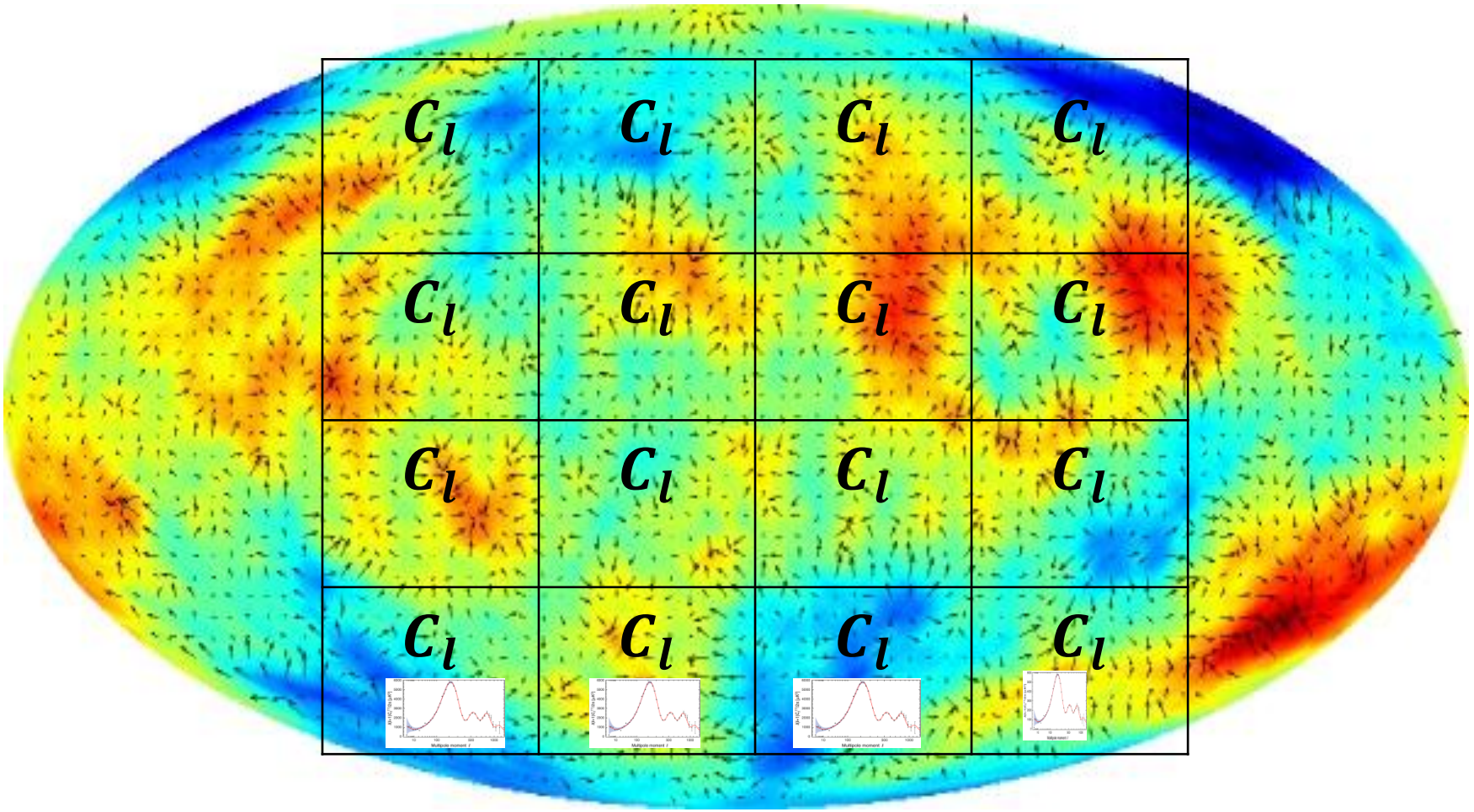
+ other several results using other local calibrators, all giving high H_0

Planck Lensing Reconstruction

Planck Lensing 2018 arXiv:1807.06210

Lead by Julien Carron at Sussex

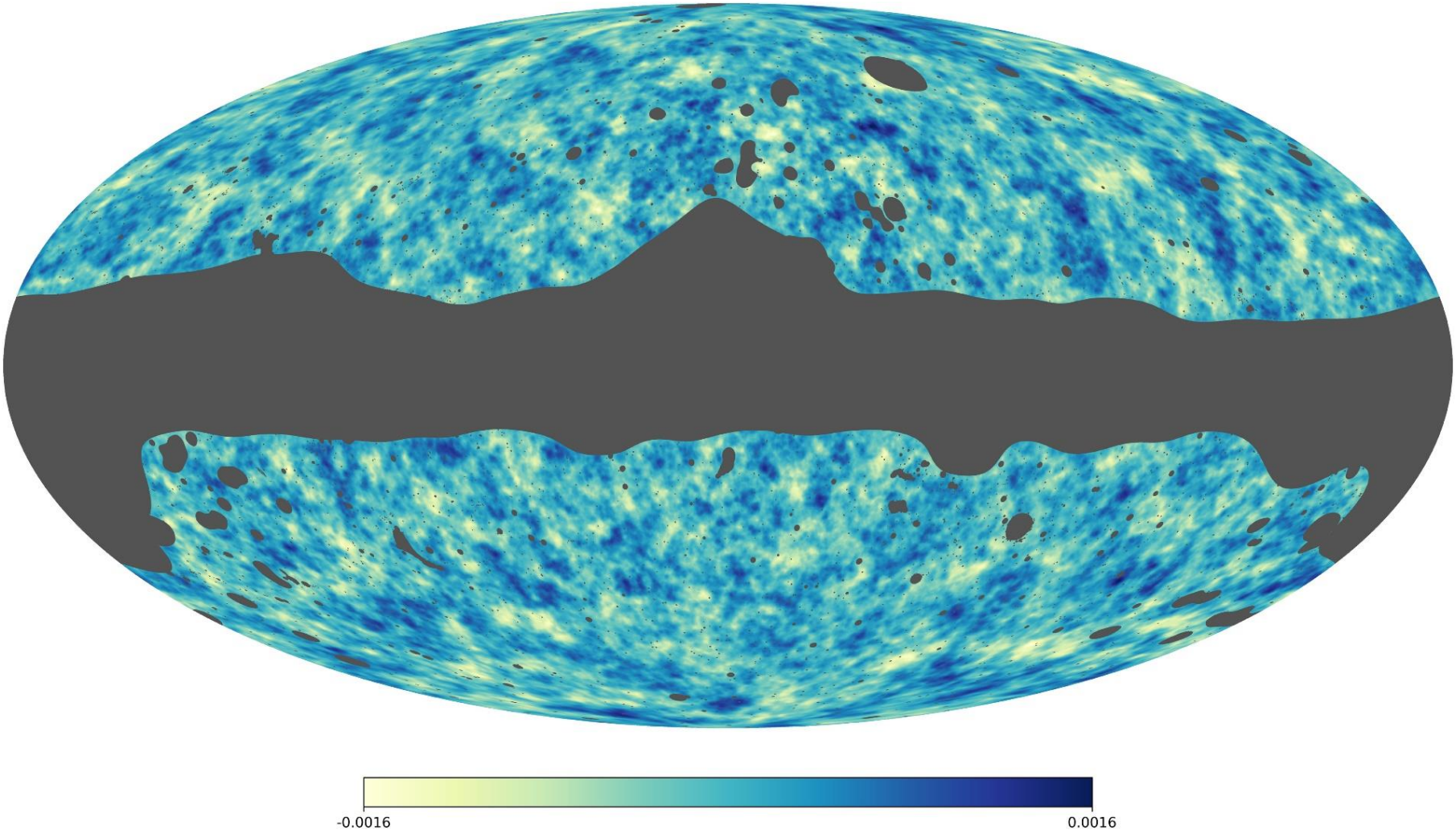
Lensing reconstruction (concept)

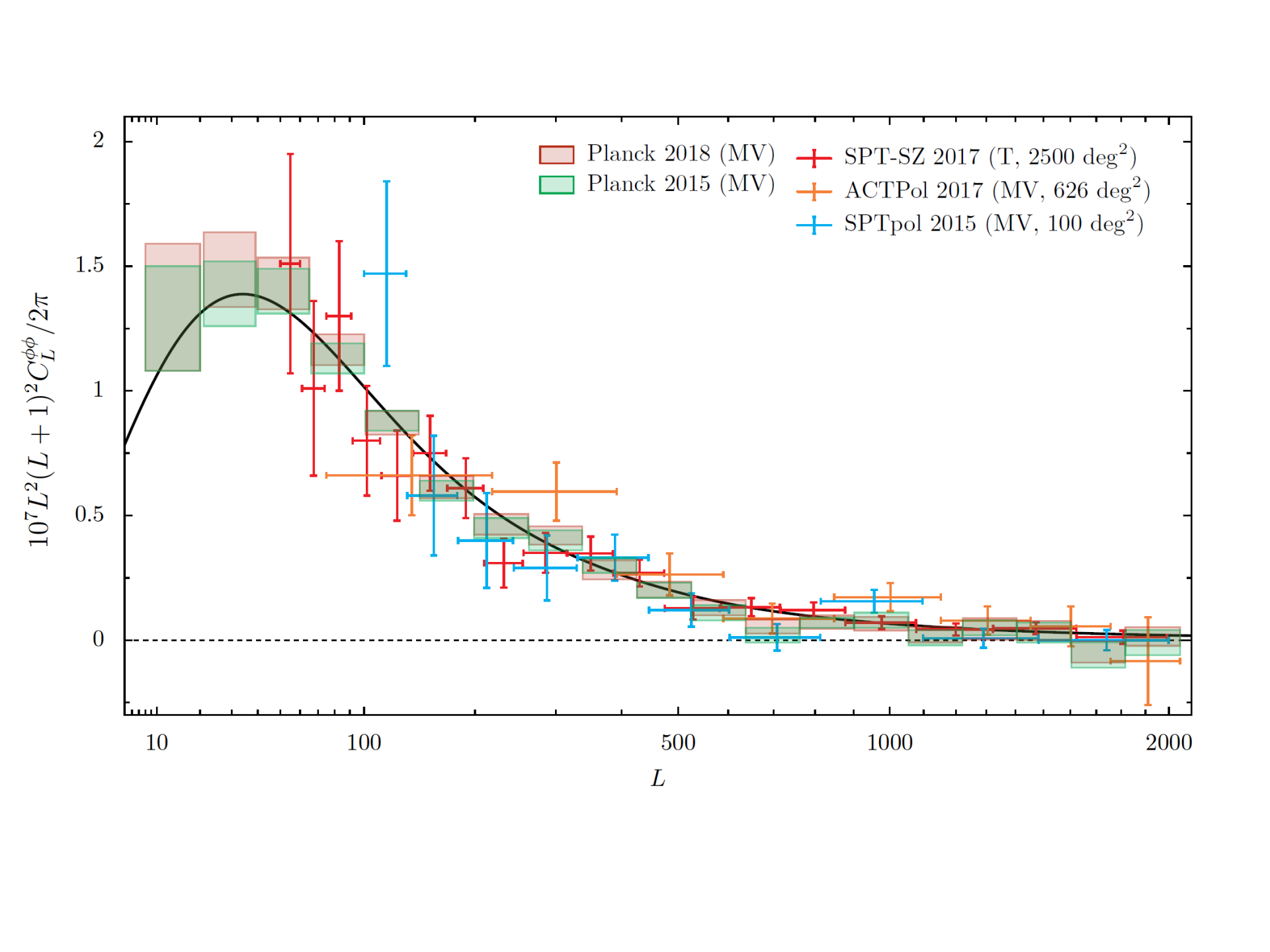


Measure spatial variations in magnification and shear

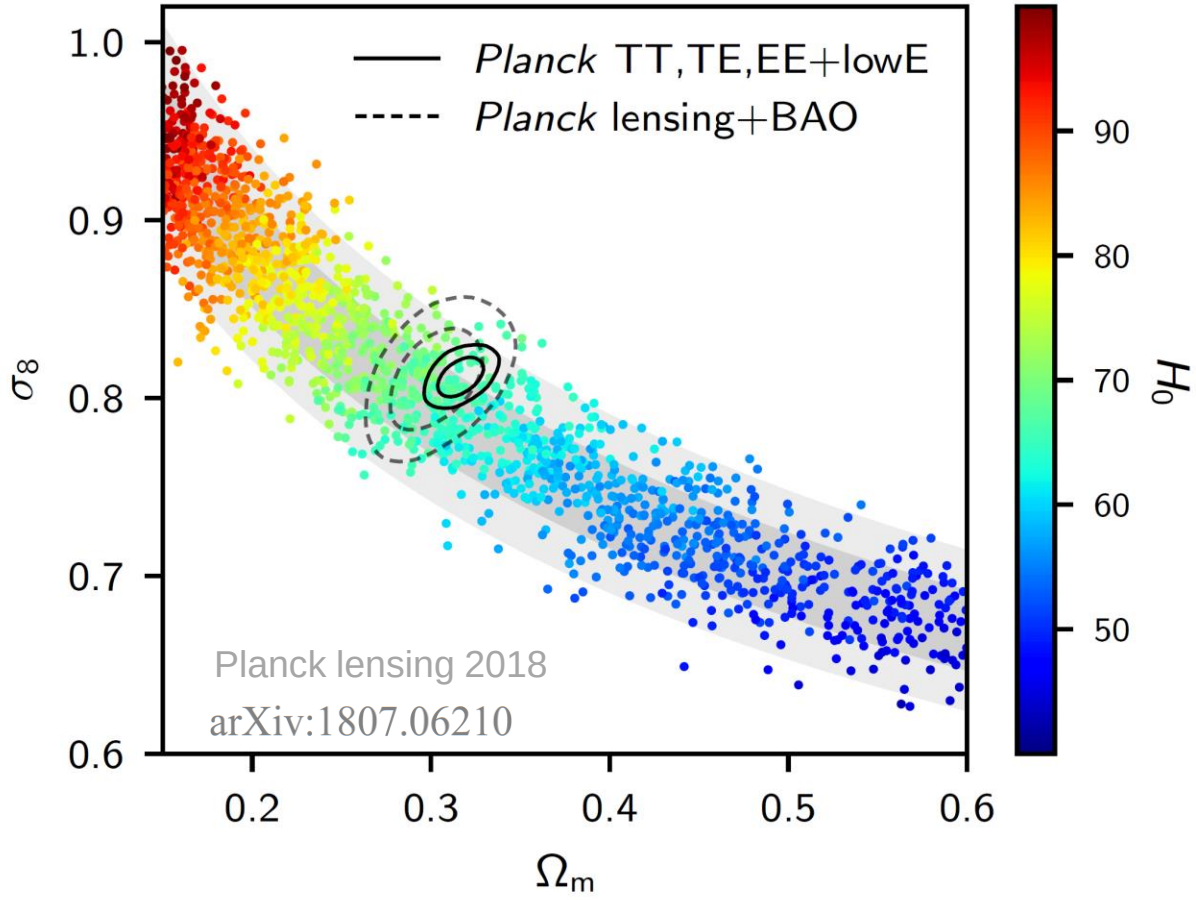
Use assumed unlensed spectrum, and unlensed statistical isotropy

Map of the gradient-mode lensing




Planck 2018 (MV)
Planck 2015 (MV)
SPT-SZ 2017 (T, 2500 deg^2)
ACTPol 2017 (MV, 626 deg^2)
SPTpol 2015 (MV, 100 deg^2)
$10^7 L^2(L+1)^2 C_L^{\phi\phi}/2\pi$
L
2
1.5
1
0.5
0
10
100
500
1000
2000

Planck CMB lensing parameters



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

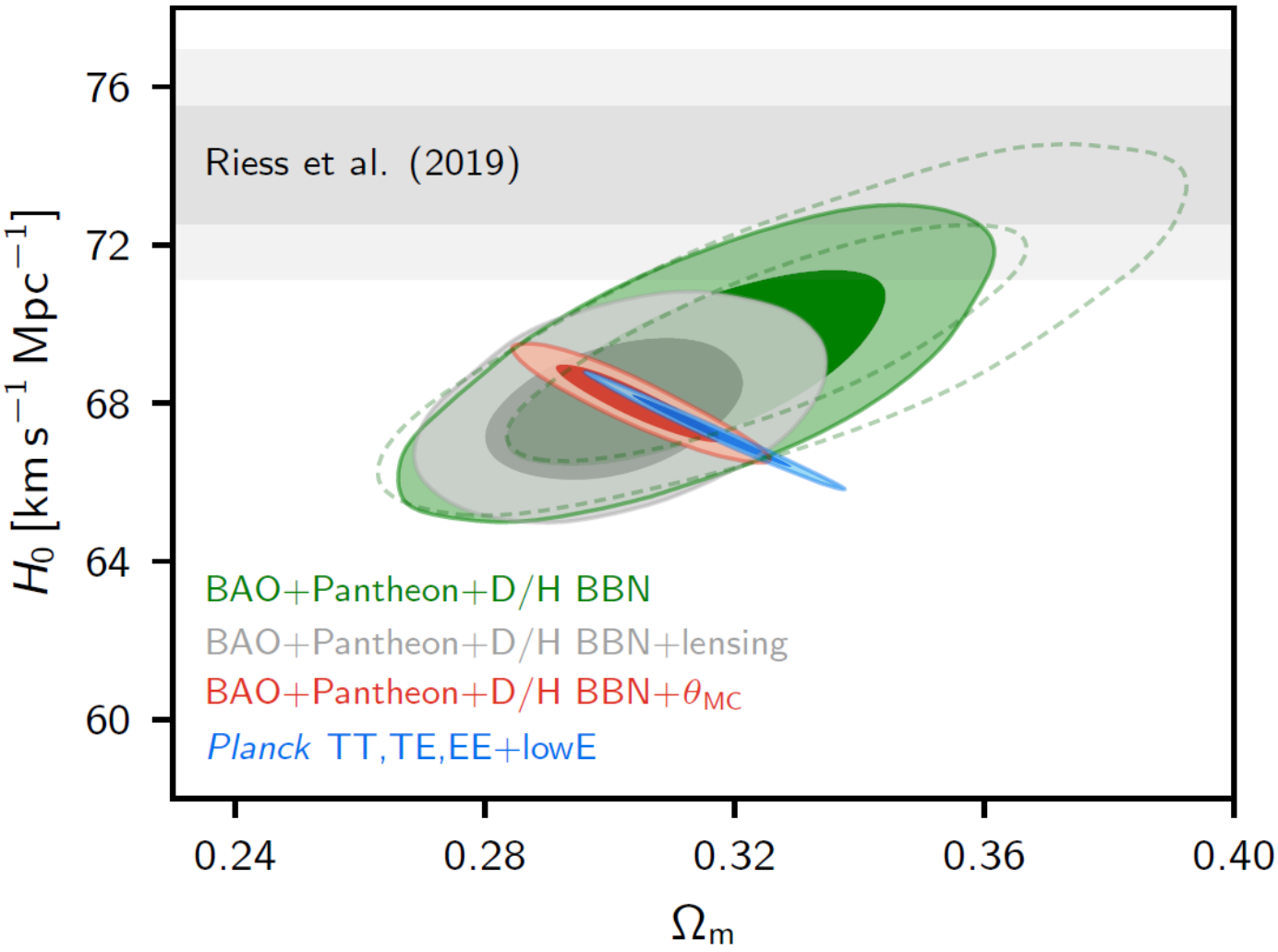
$$\left.\begin{aligned} H_0 &= 67.9^{+1.2}_{-1.3}\ \mathrm{km\ s^{-1}Mpc^{-1}}, \\ \sigma_8 &= 0.811 \pm 0.019, \\ \Omega_\mathrm{m} &= 0.303^{+0.016}_{-0.018}, \end{aligned}\right\} \ 68\,\%, \text{ lensing+BAO}$$

Also adding robust CMB θ_* constraint:

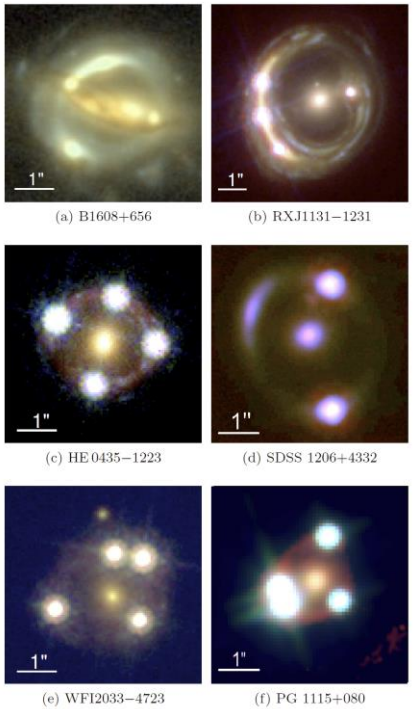
$H_0 = 68.0 \pm 0.7$ (68 %, lensing+BAO+θ_*)

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

Independent ΛCDM inverse distance ladder is also consistent with Planck

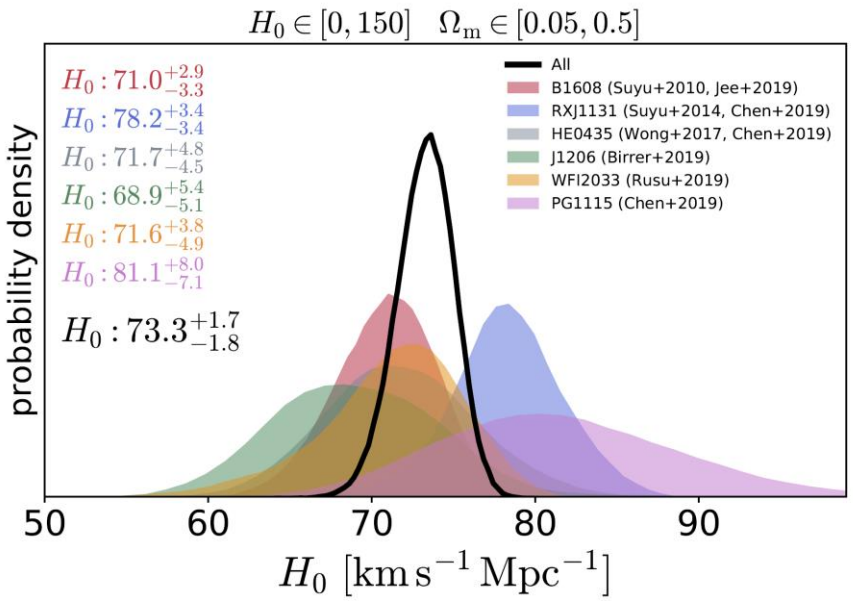


Strong Lensing



Lens modelling etc..

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



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

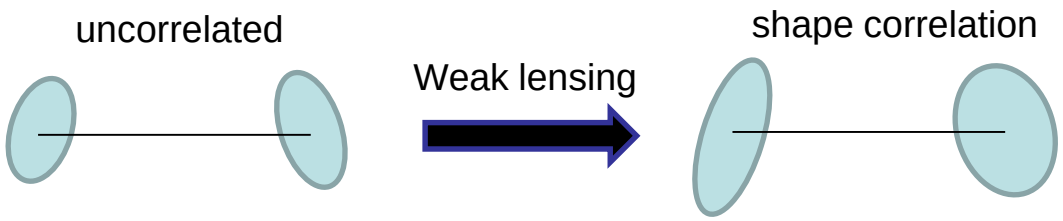
Wong et al. arXiv:1907.04869

(some cosmology dependence)

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

⇒ tension with CMB independent of very local environment

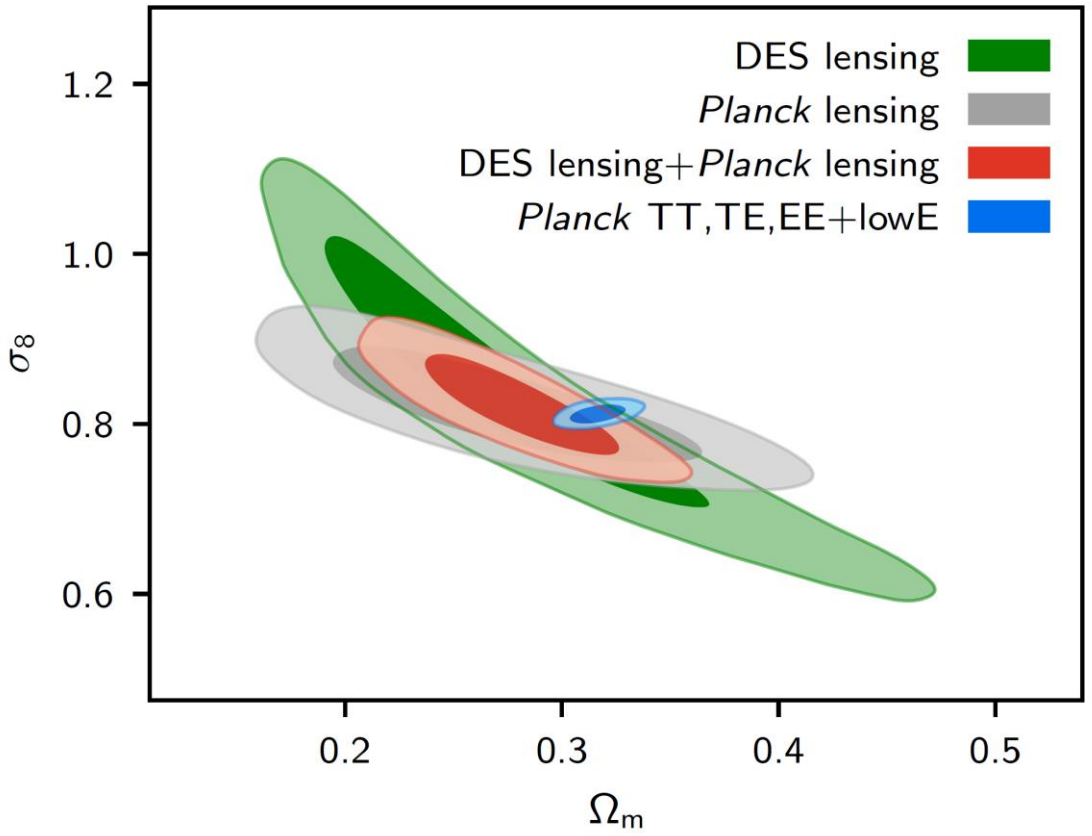
Galaxy weak gravitational lensing – cosmic shear



Potentially clean probe of total matter perturbations and geometry

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

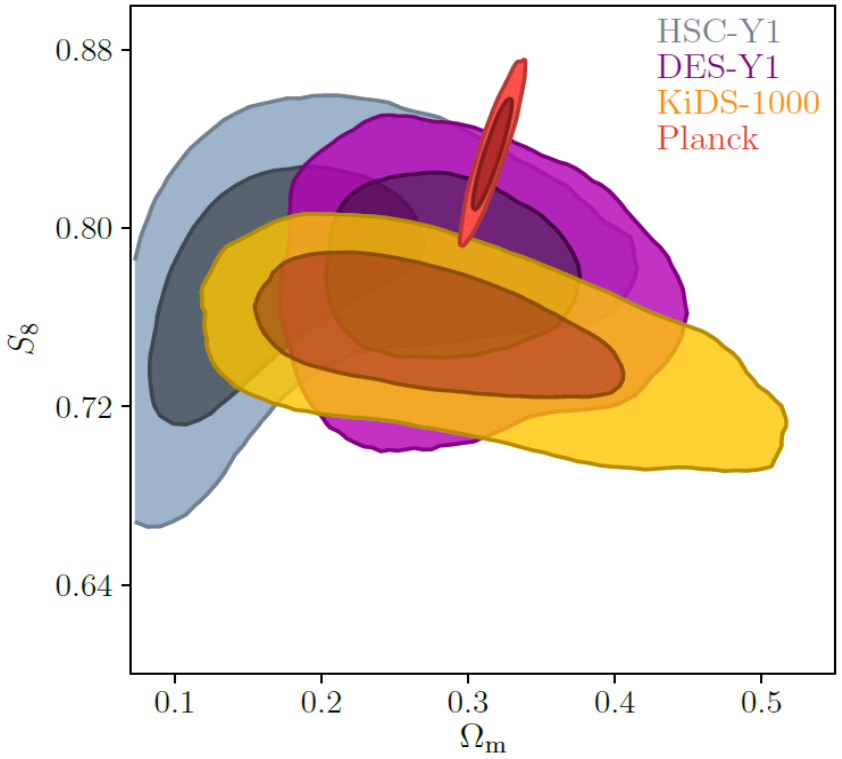
Galaxy and CMB lensing complementary, tighter joint constraints

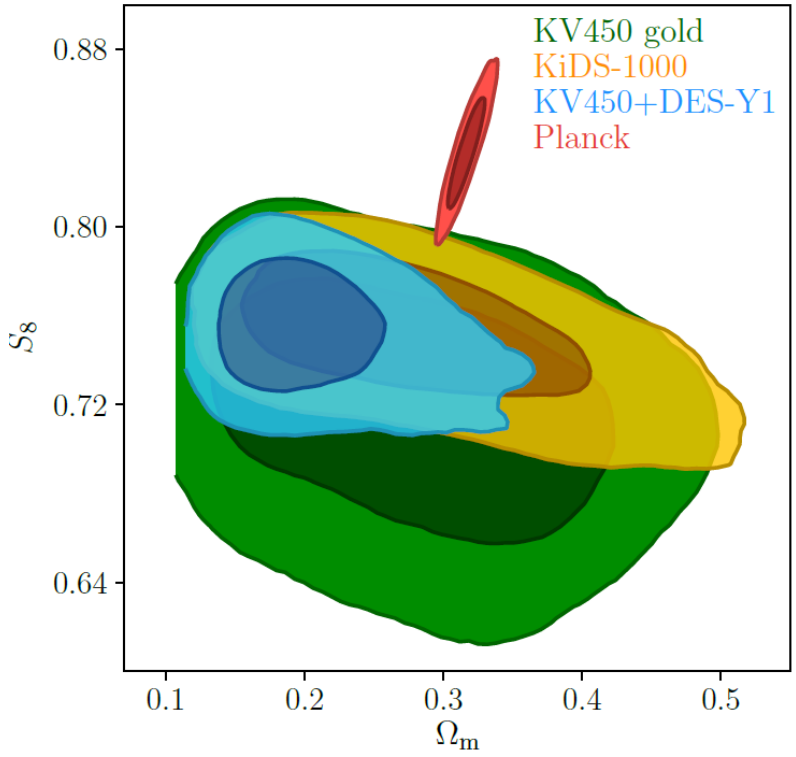


DES and Planck lensing very consistent

Other galaxy lensing results

Asgari et al. arXiv: 2007.15633

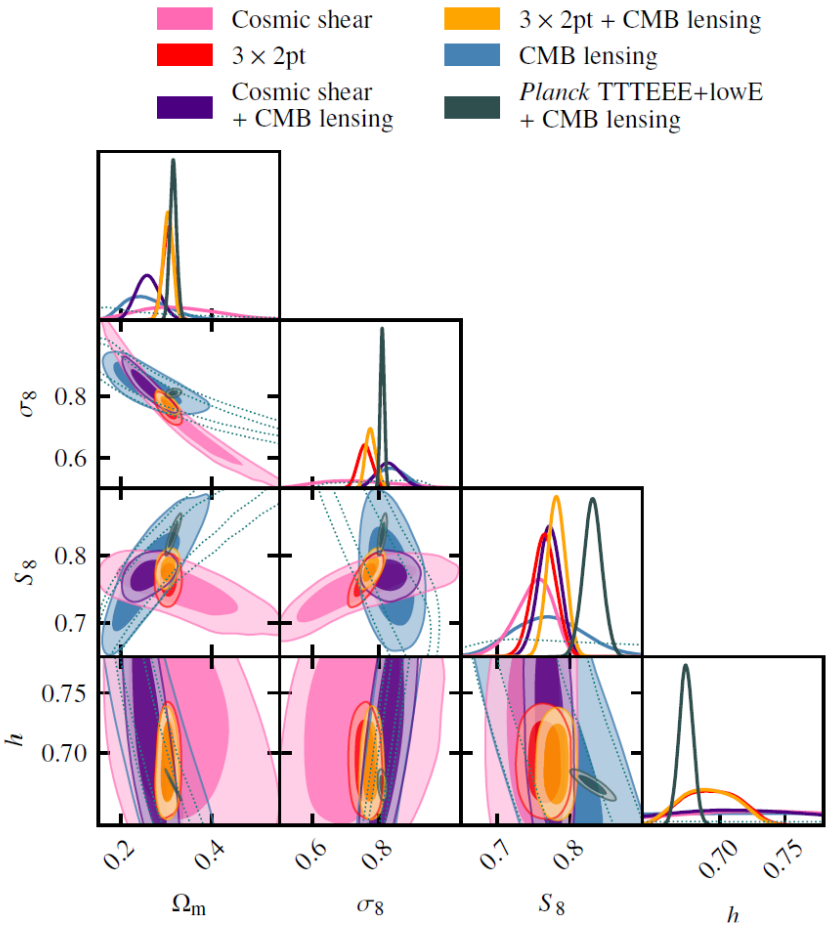




DES+KiDs significant tension with Planck on $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$

Galaxy lensing + galaxy counts

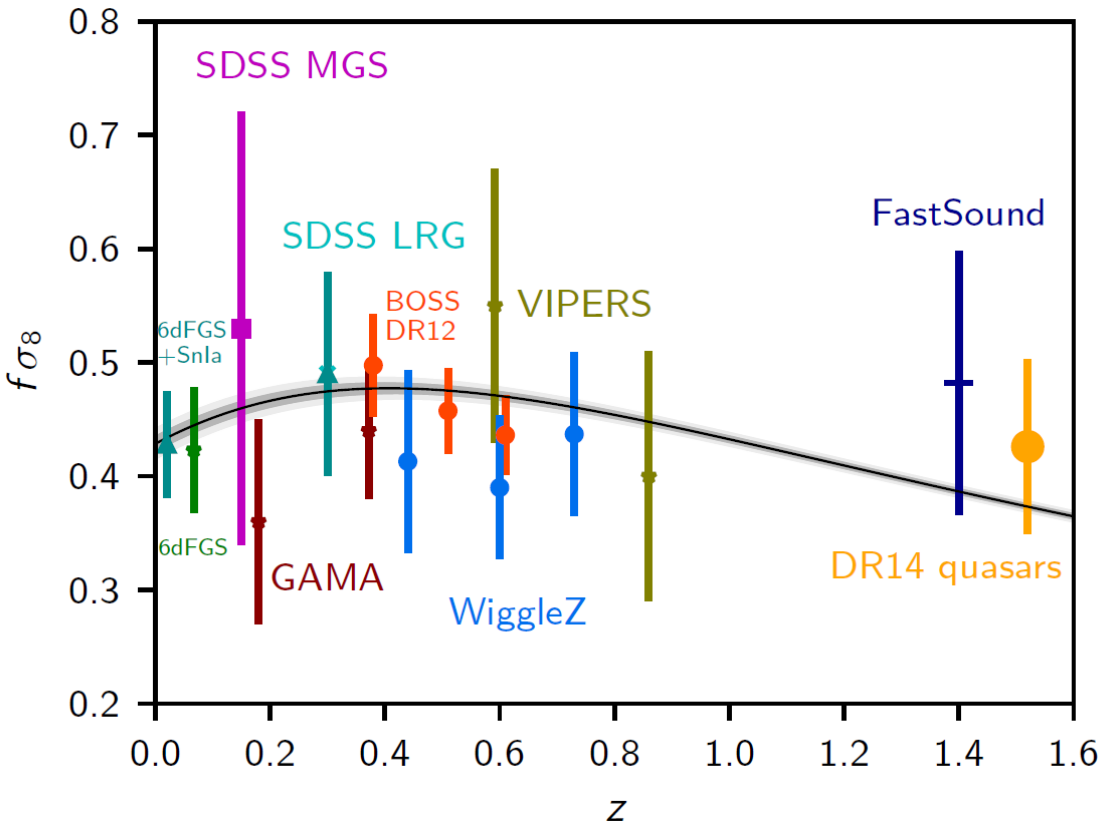
also depends on galaxy bias parameters



KiDS-1000
+BOSS: 3x2pt
arXiv:2010.16416

Marginally consistent/moderate tension with Planck

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 affect relevant inferred parameters (e.g. $\Omega_m h^2$)

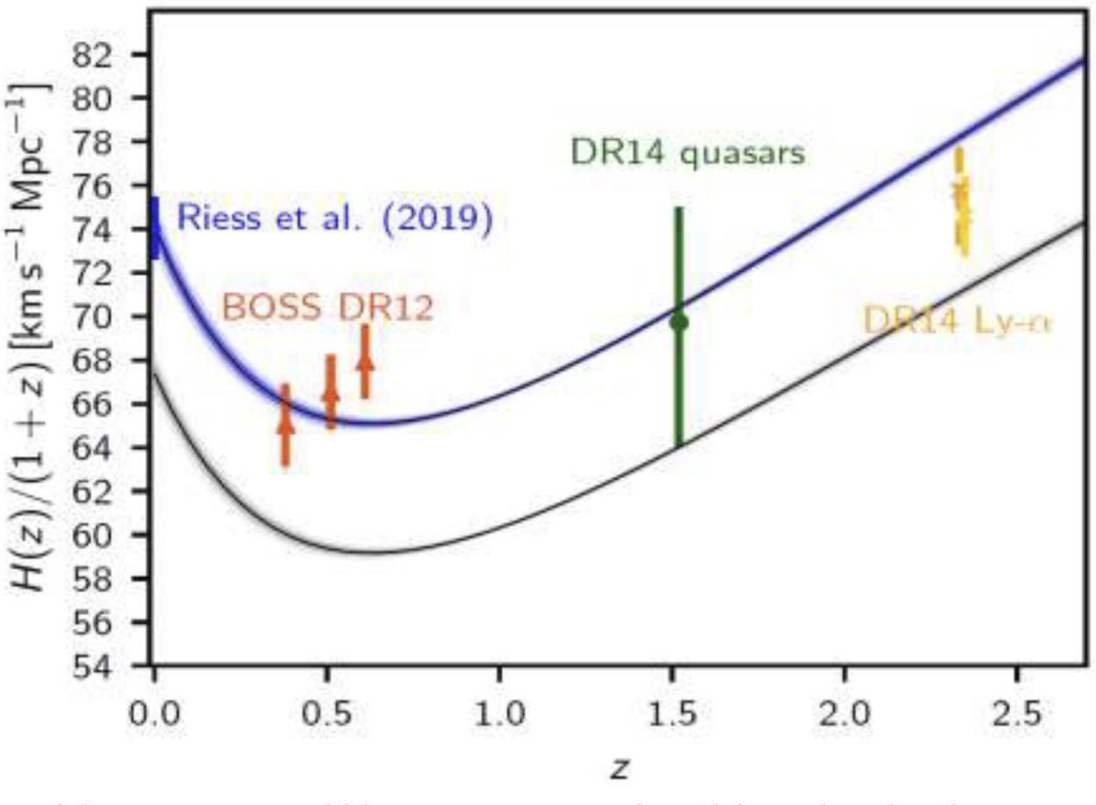
New physics at lower redshift/dark energy/modified gravity
- but $w > -1$ only makes H_0 from Planck *lower*
- have to fit BAO and $H(z)/H_0$ from supernovae (or find problem with supernovae)

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 $\mathrm{O}(10\%)$

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 (and disfavoured by BBN D/H)

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 $\Omega_c h^2, \Omega_b h^2, A_s, n_s, ...$*)*

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

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

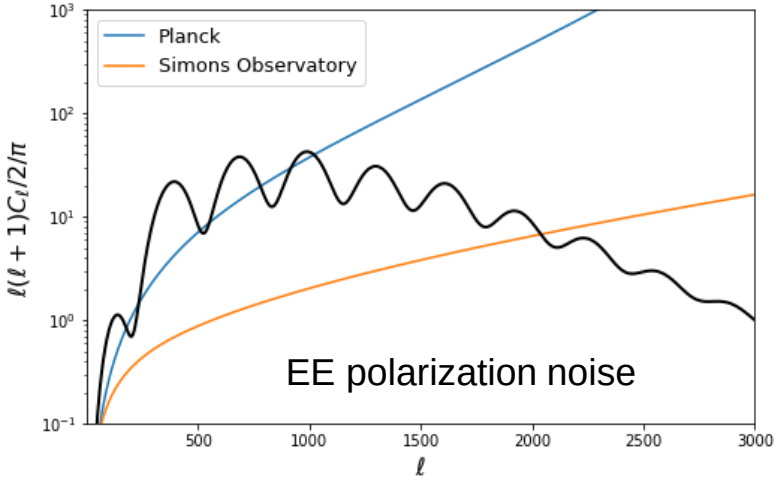
(note: if new physics is the solution, current $\Lambda\mathrm{CDM}$ measurements of parameters likely to be significantly wrong, e.g. significant implications for inflation n_s)

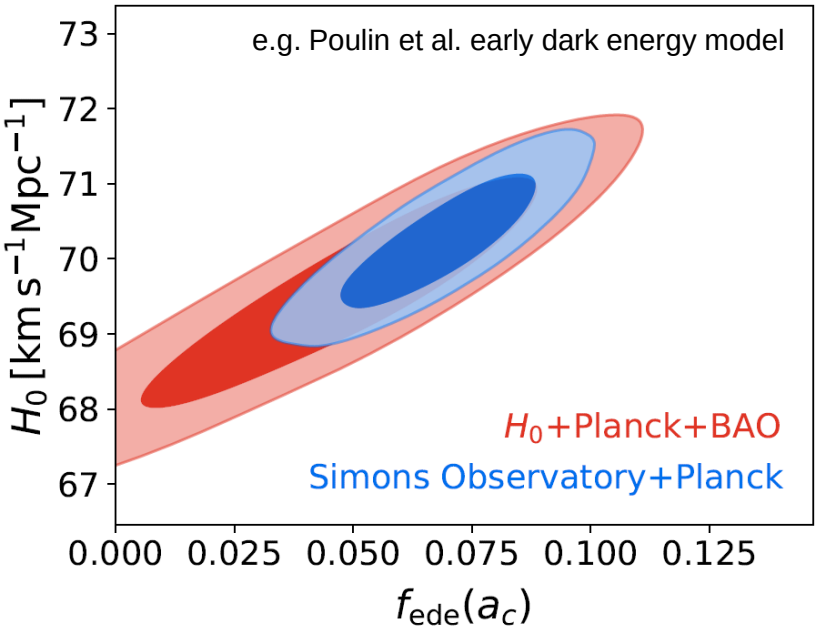
+ ActPol, SPTpol (now)
+ CMB-S4 (beyond)

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

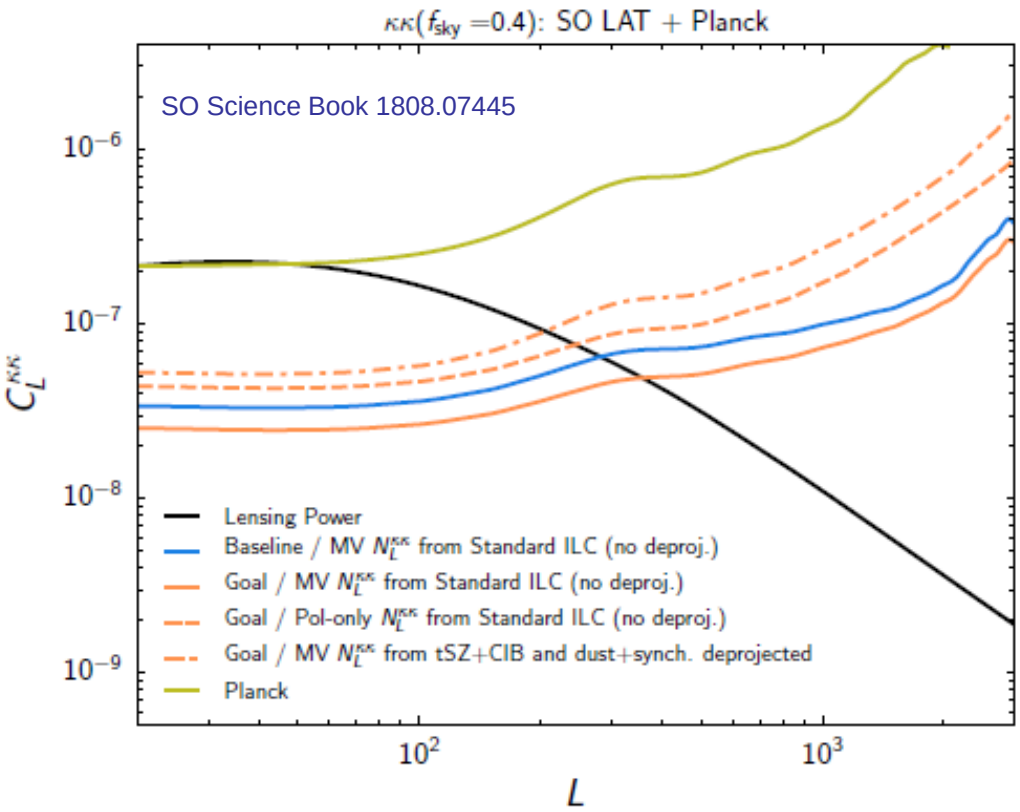
Distinct physical models give different precision predictions

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





Simons Observatory CMB Lensing forecast



CMB lensing constraints will dramatically improve
… and completely different systematics to galaxy lensing

+ new galaxy lensing from LSST, EUCLID, etc.

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?

CMB lensing and galaxy lensing complementary and very different systematics

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)*

Advertising supplement

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

Jesus Torrado, AL

arXiv:2005.05290

Python parameter sampling framework: likelihoods -> parameter MC samples

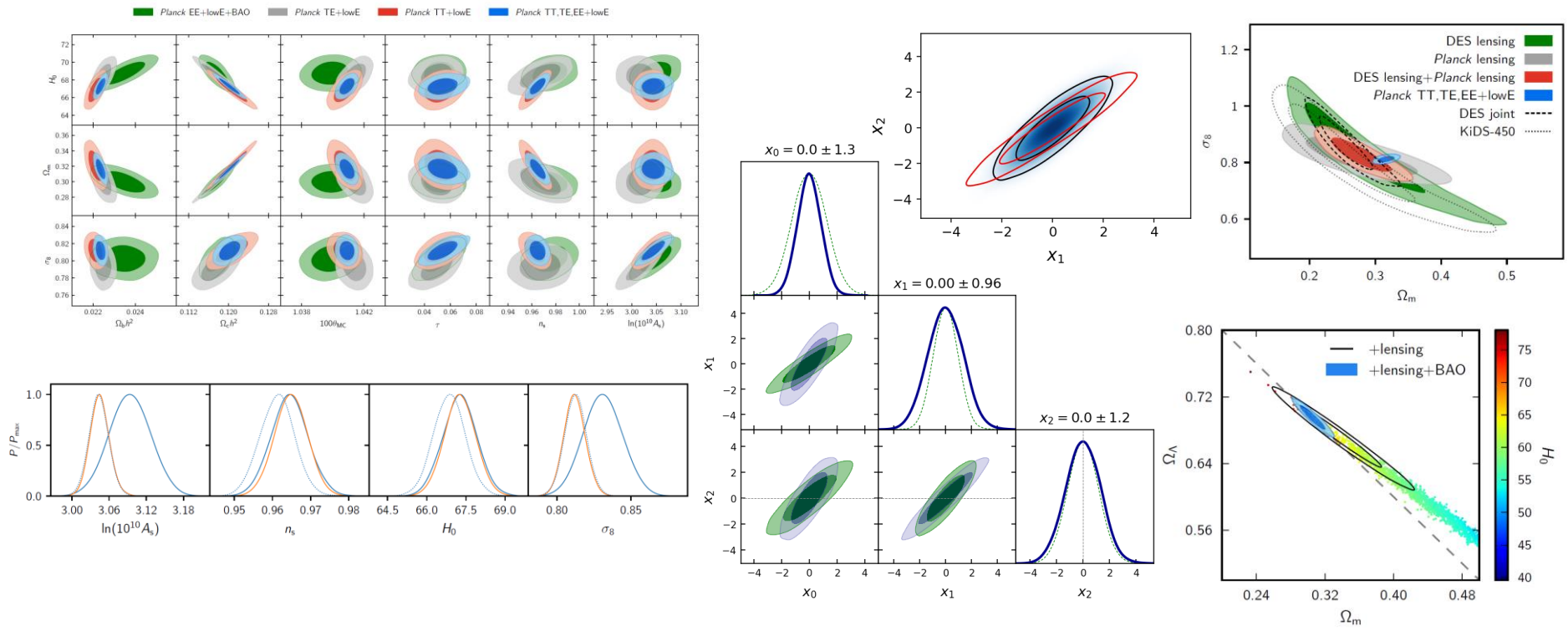
Optimizations to exploit different speeds of multiple dependent theory/likelihood modules each with multiple nuisance parameters

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