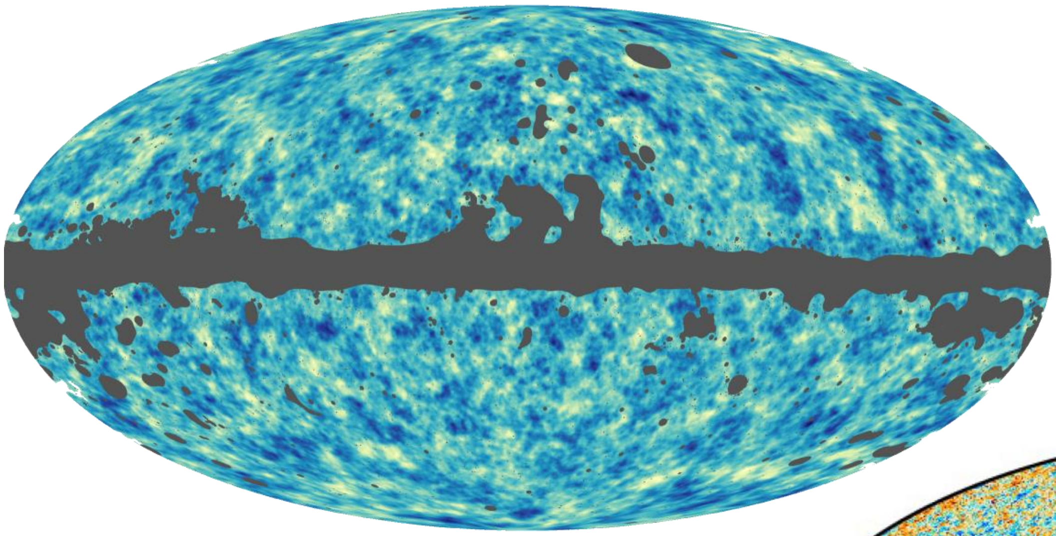
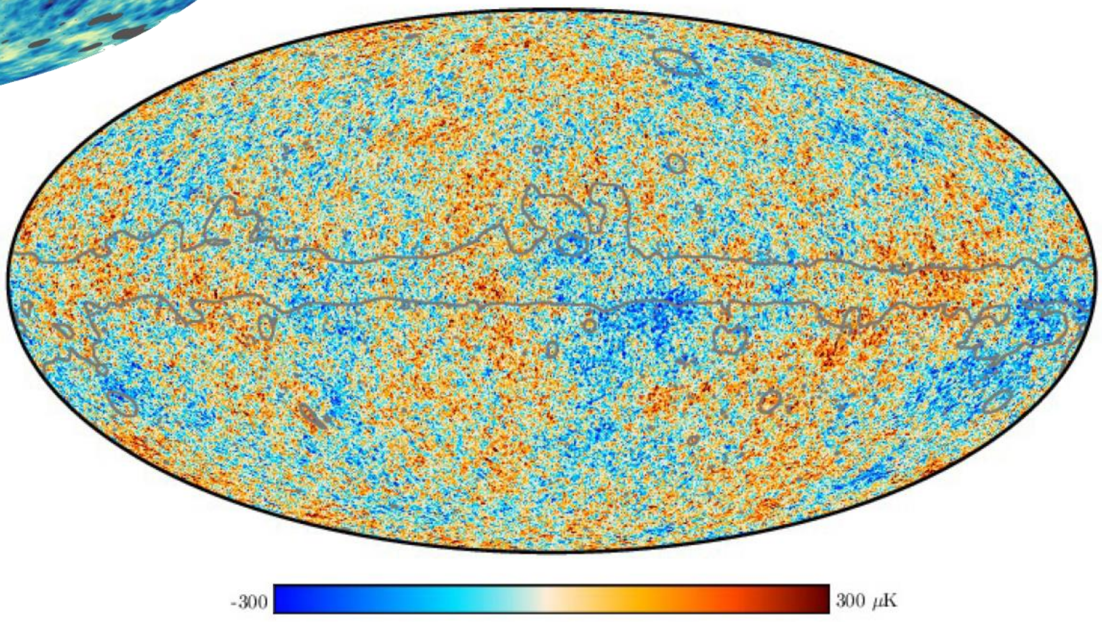
Growth of Structure from CMB

https://growthofstructure.sites.ucsc.edu/



Antony Lewis

cosmologist.info



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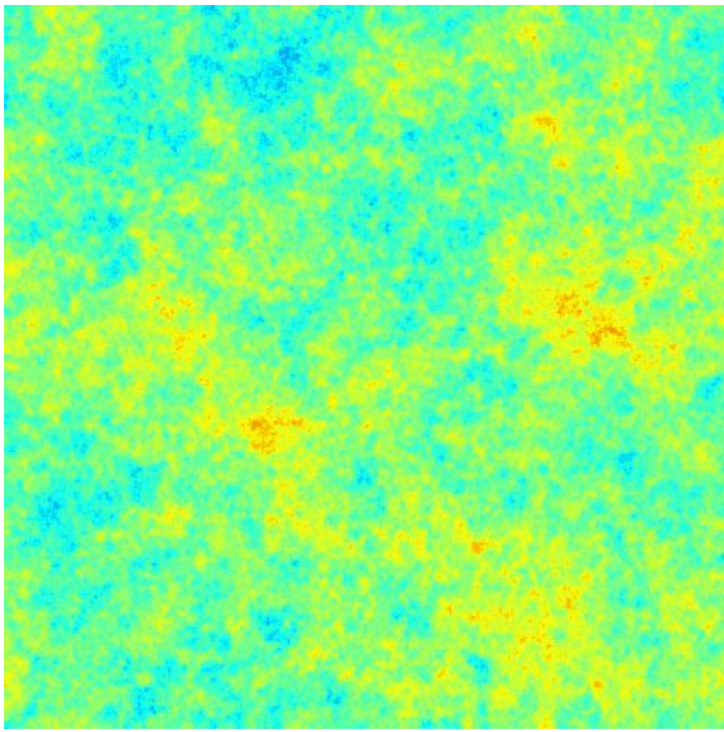
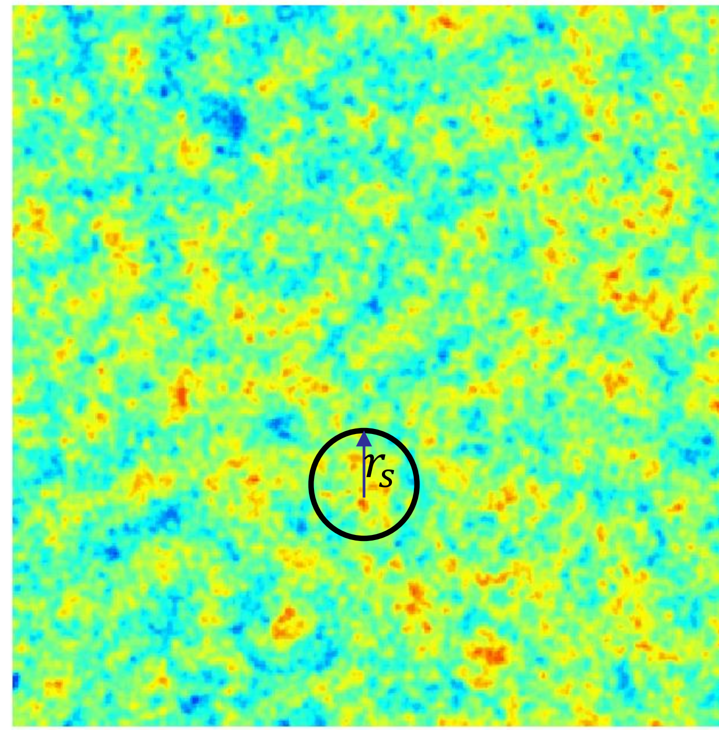
Perturbation evolution

Perturbations: start of hot big bang



gravity+
pressure+
diffusion

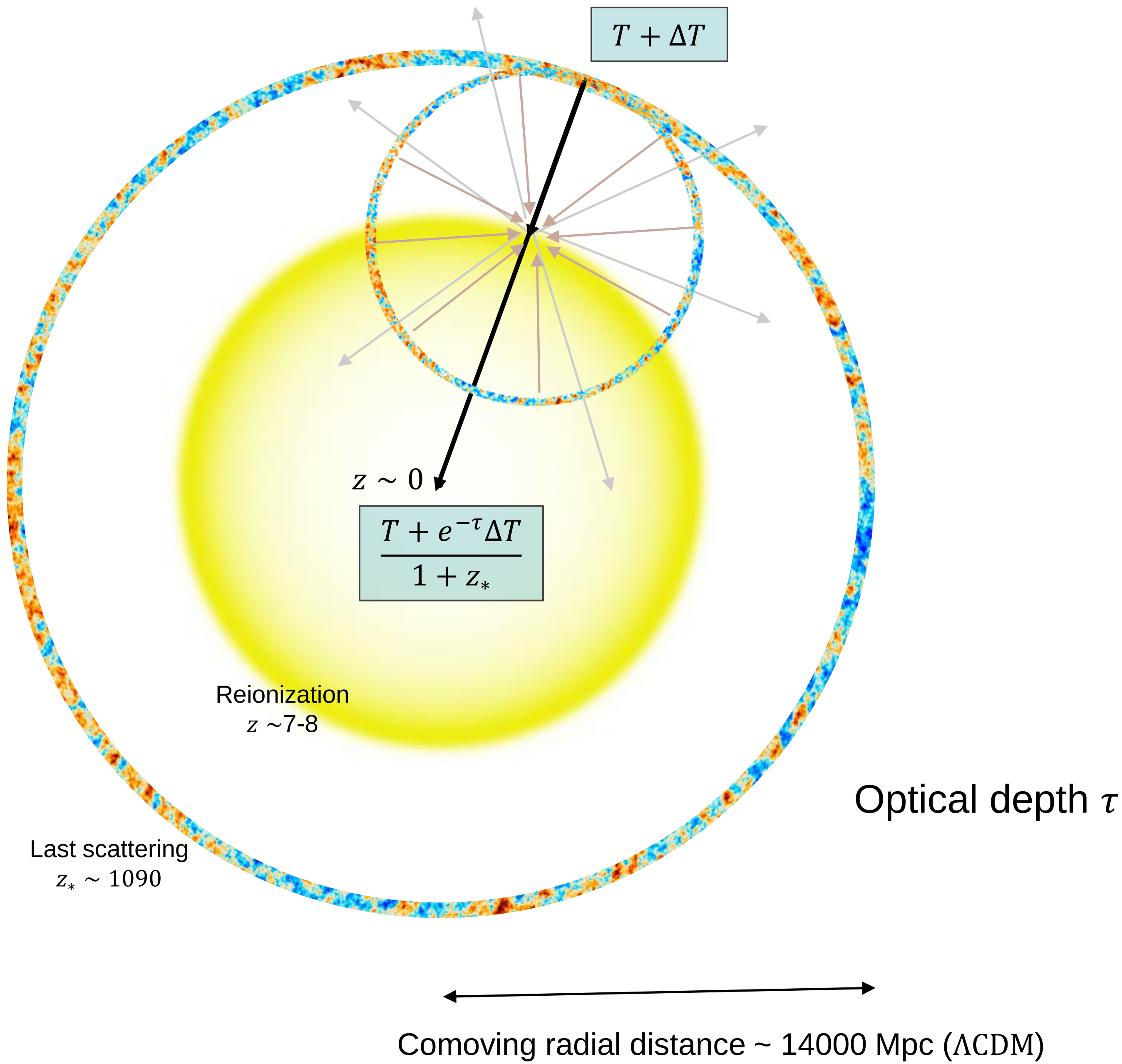
Perturbations: Last scattering surface (z_*)



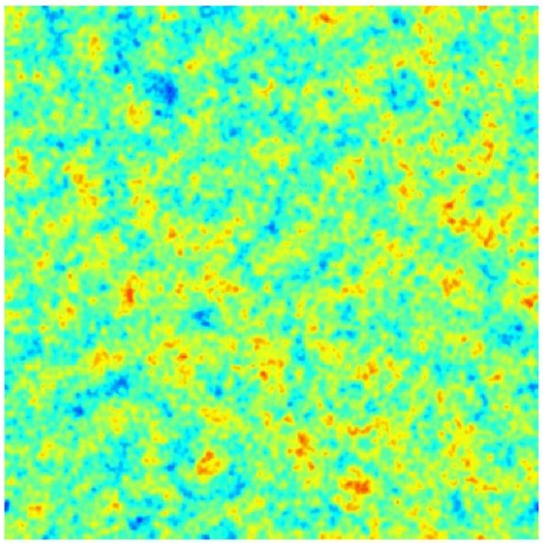
$$P_\zeta(k) \sim A_s \left(\frac{k}{k_s}\right)^{n_s-1}$$

$$P_{\Delta T}(k) \sim [T(k,z_*)]^2 \; A_s \left(\frac{k}{k_s}\right)^{n_s-1}$$

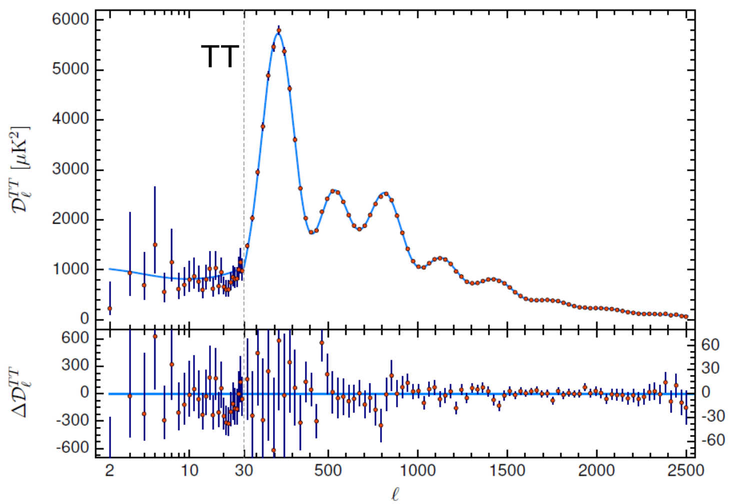
Lowest order for small-scale perturbations: photons travel on straight lines + Thomson scattering

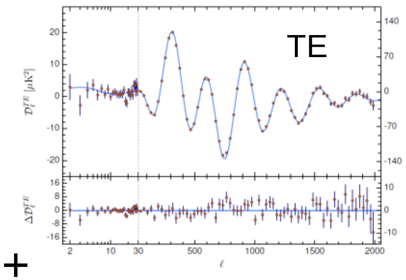


Observed CMB power spectrum

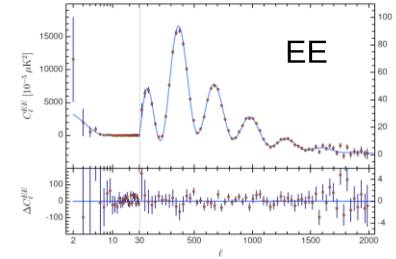


Planck 2018 arXiv:1807.06209





+



Observations

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

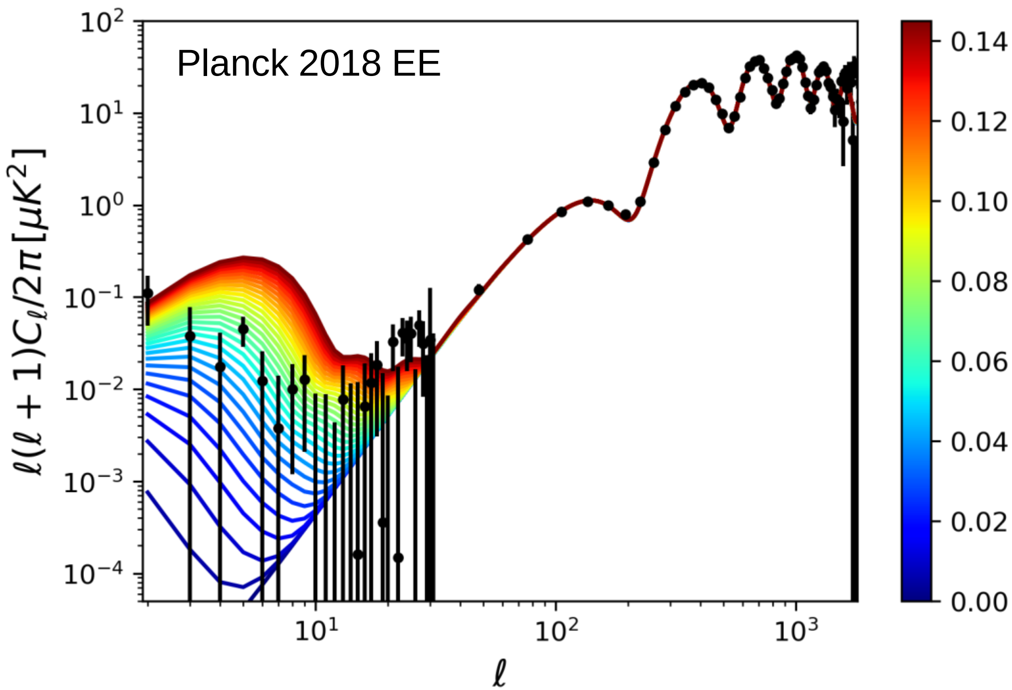
Assume model, constrain parameters

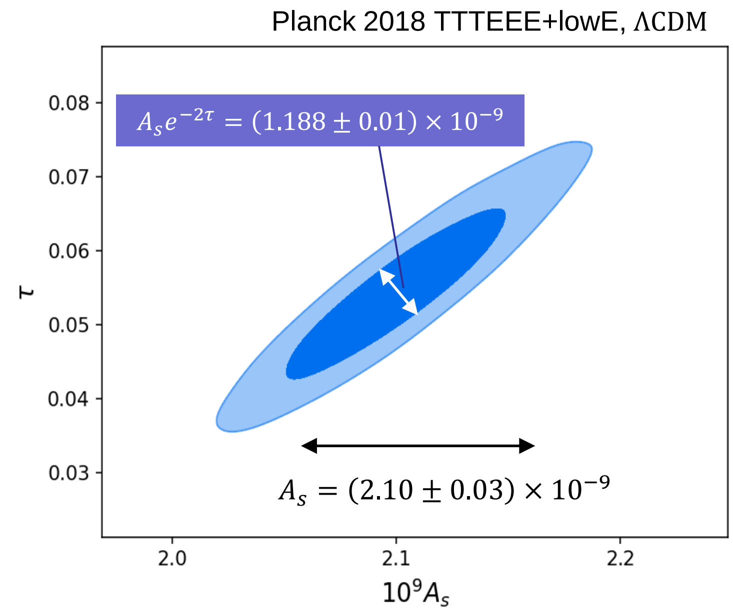
small scales: $D_l \propto e^{-2\tau} A_s$

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

Planck optical depth constraint

Large-scale E polarization (+foregrounds, systematics…)





Planck 2018

$\tau = 0.054 \pm 0.007$

Pagano et al, arXiv:1908.09856
('SRoll2' Planck HFI reanalysis) $\tau = 0.057 \pm 0.006$

Planck 2020, arXiv:2007.04997
('NPIPE' Planck HFI reanalysis) $\tau = 0.051 \pm 0.006$

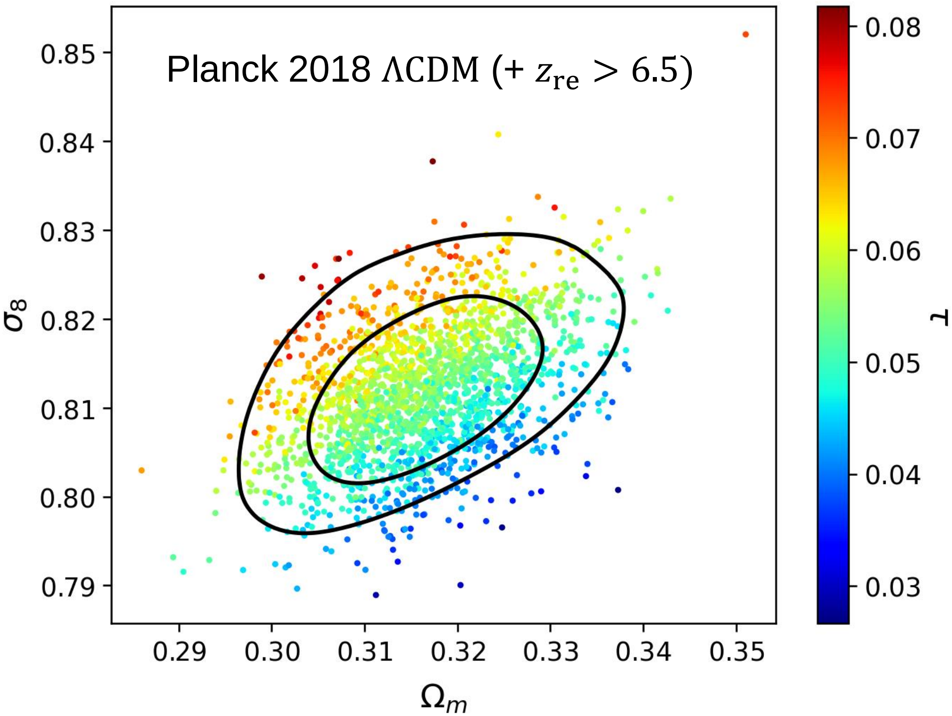
Belsunce et al., arXiv:2103.14378
(\`\`SRoll2'' reanalysis) $\tau = 0.058 \pm 0.0055$

Late-time amplitude constraints

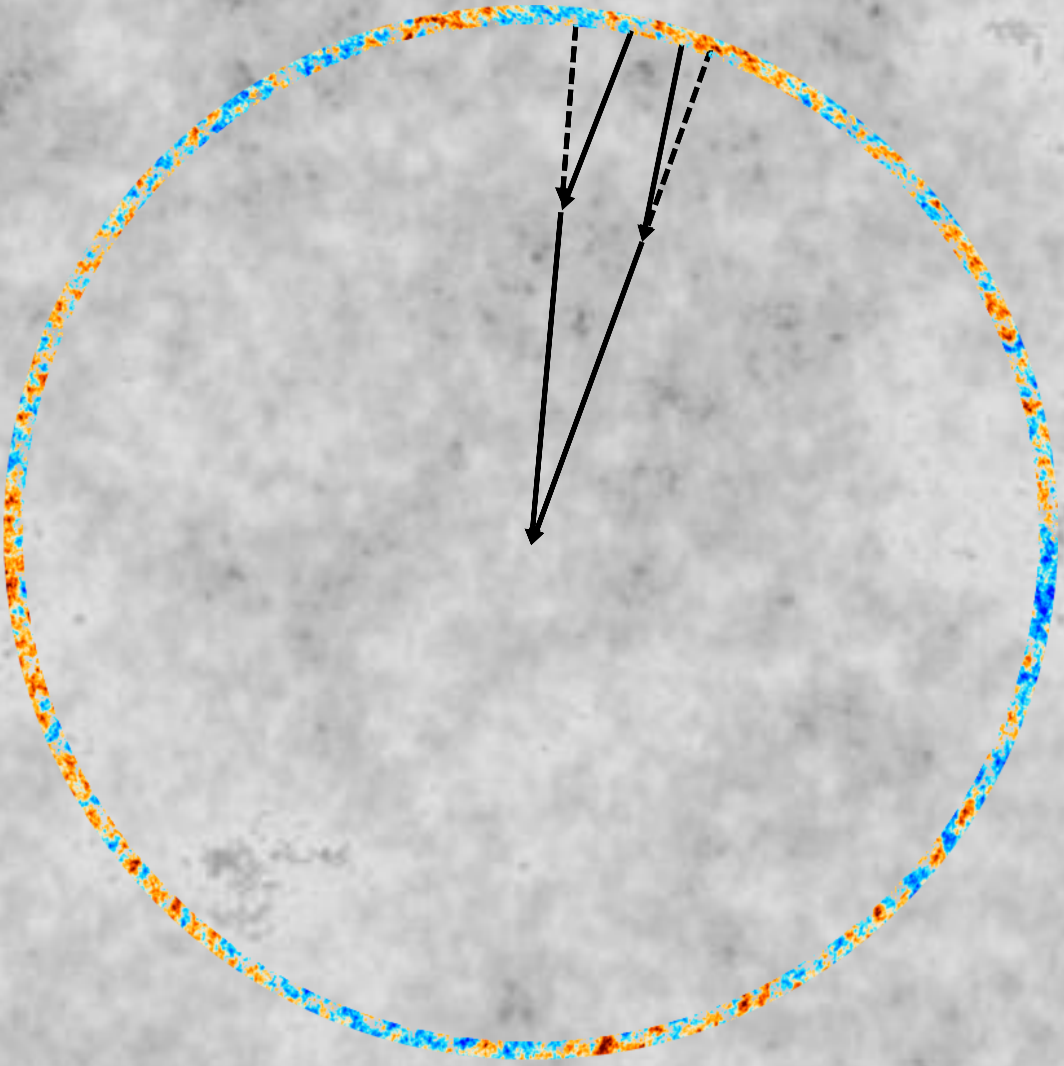
- Primary (lowest-order) CMB amplitude **only at $z \sim 1090$**
  (+ weak ISW constraint from very large scales)
  $\Rightarrow$ no direct constraint on growth

- Assuming $\Lambda\mathrm{CDM}$ (or other model), can *predict* low-redshift matter evolution.

σ_8 $\equiv$ RMS $z = 0$ non-relativistic matter density fluctuation in 8 $h^{-1}\mathrm{Mpc}$ spheres if the perturbations were linear



CMB Lensing: 1^{st} order light propagation



Spatially varying gravitational potentials: high-z kernel, mostly linear

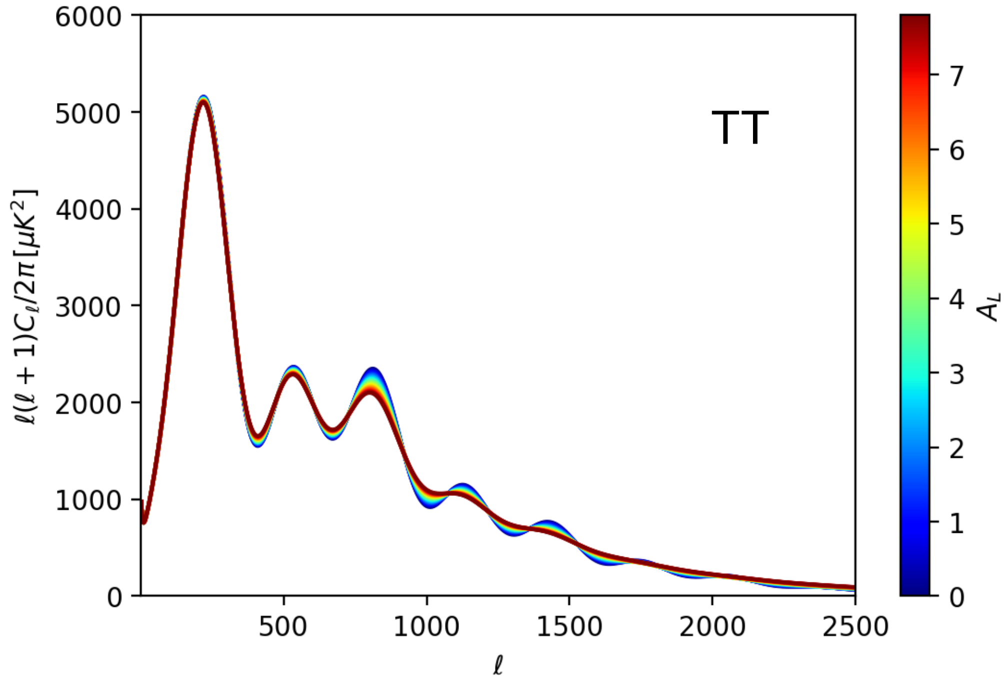
(perturbations here not to scale)

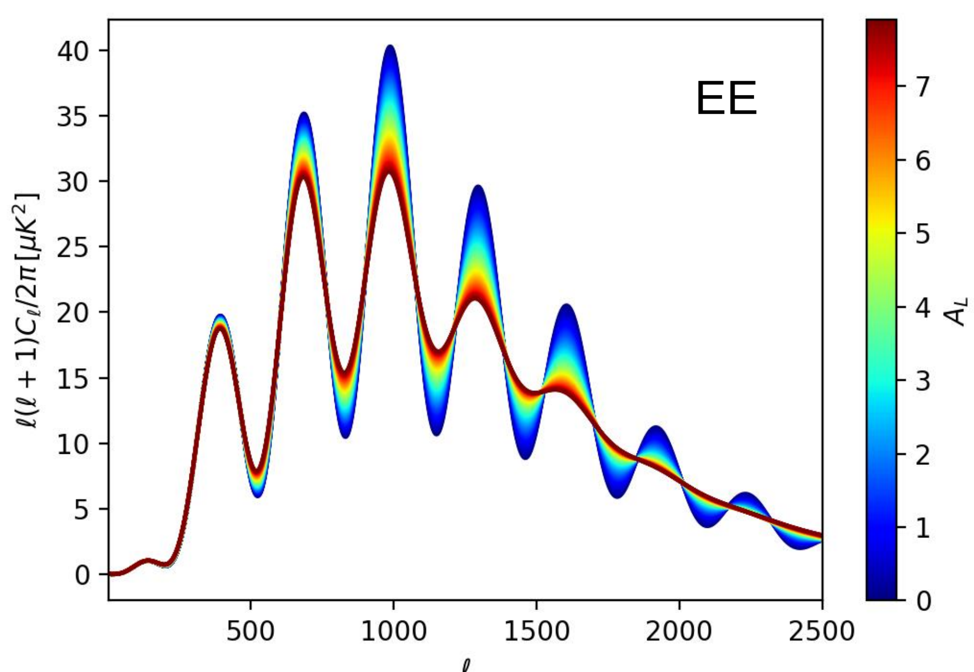
Lensing power smoothing

Effect of different lensing amplitudes A_L

$A_L = 1$
is physical $\Lambda\mathrm{CDM}$ prediction

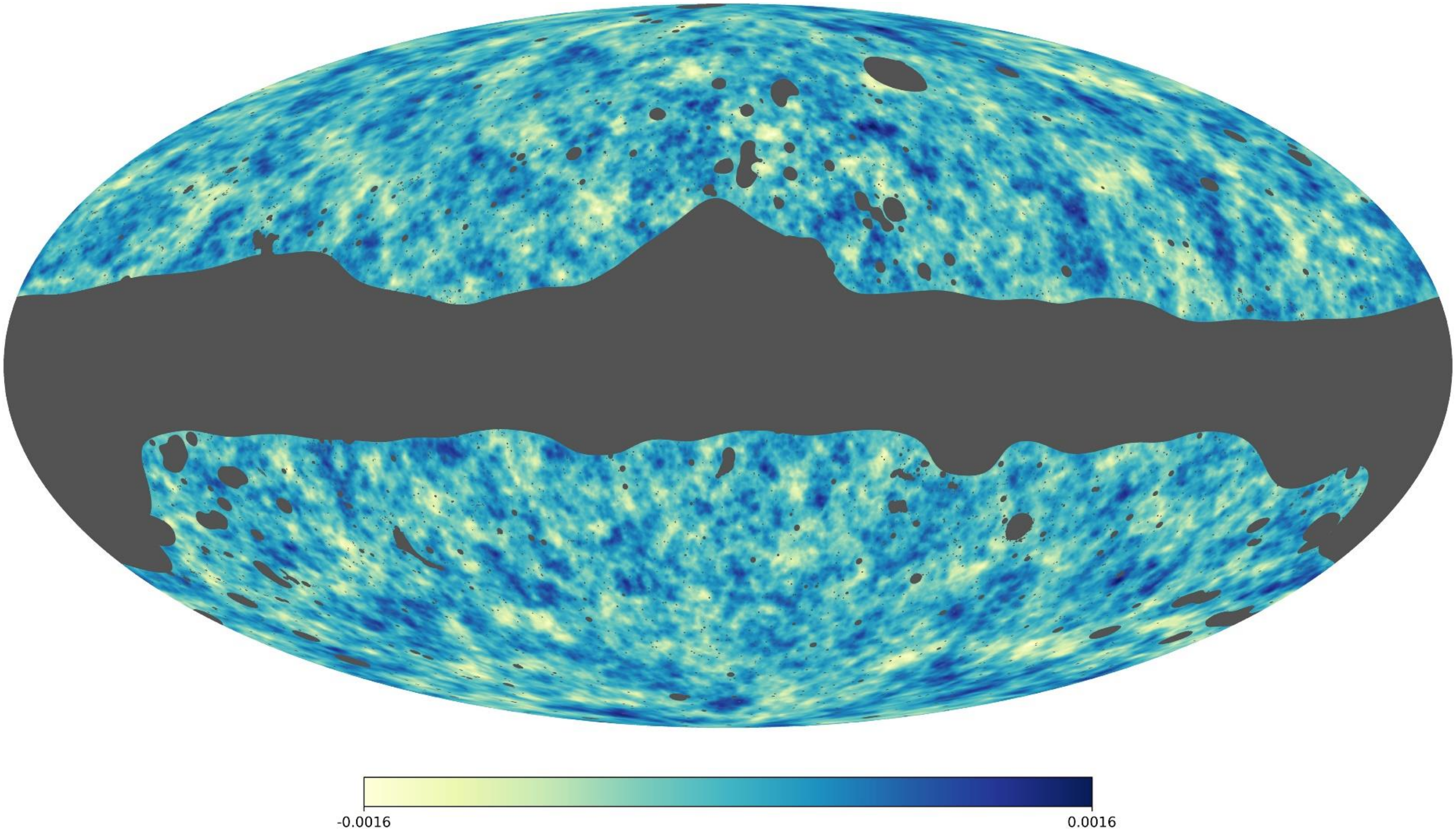
Smoothing alone only gives fairly weak constraint on late-time growth.



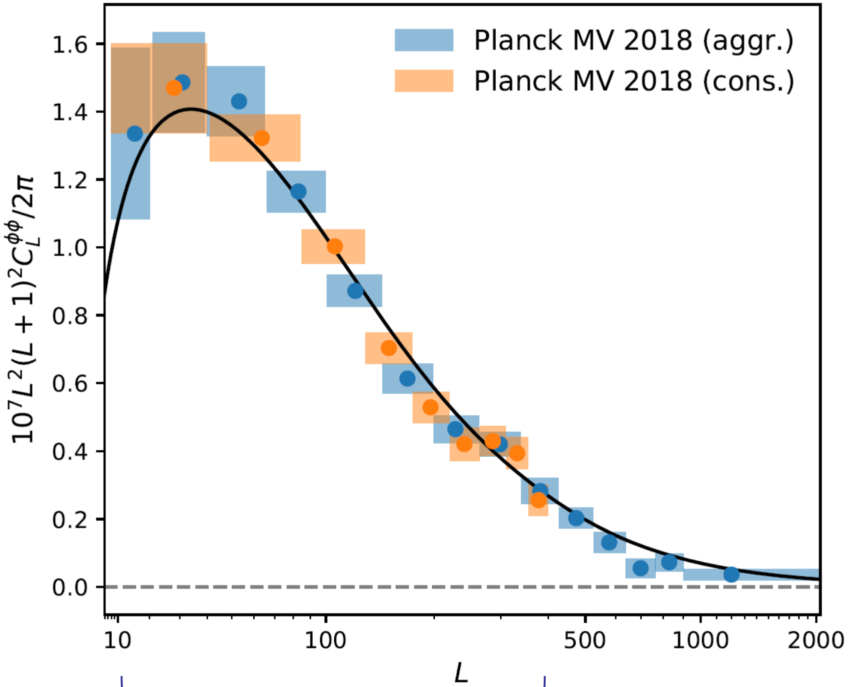


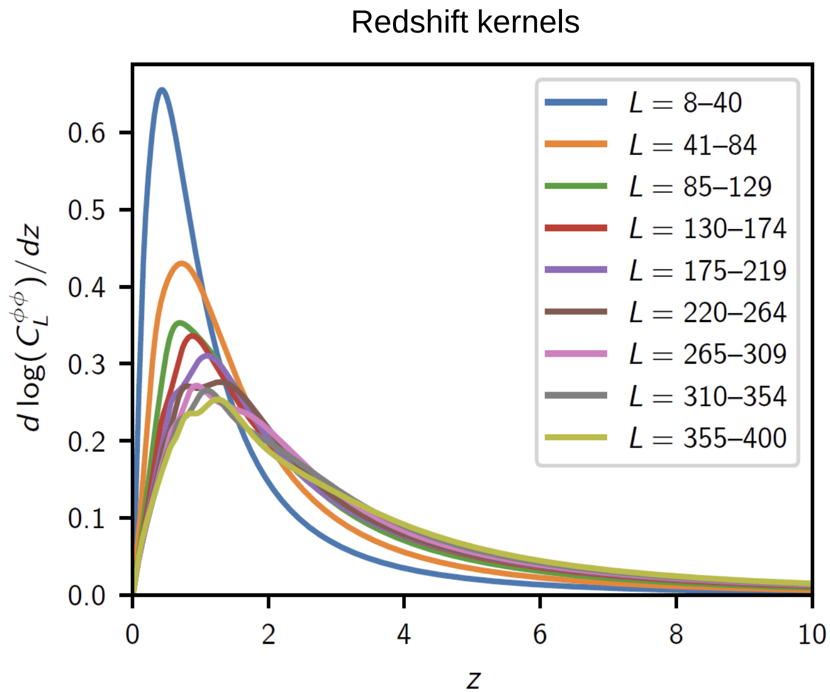
Map of the gradient-mode lensing

Planck Lensing 2018 arXiv:1807.06210



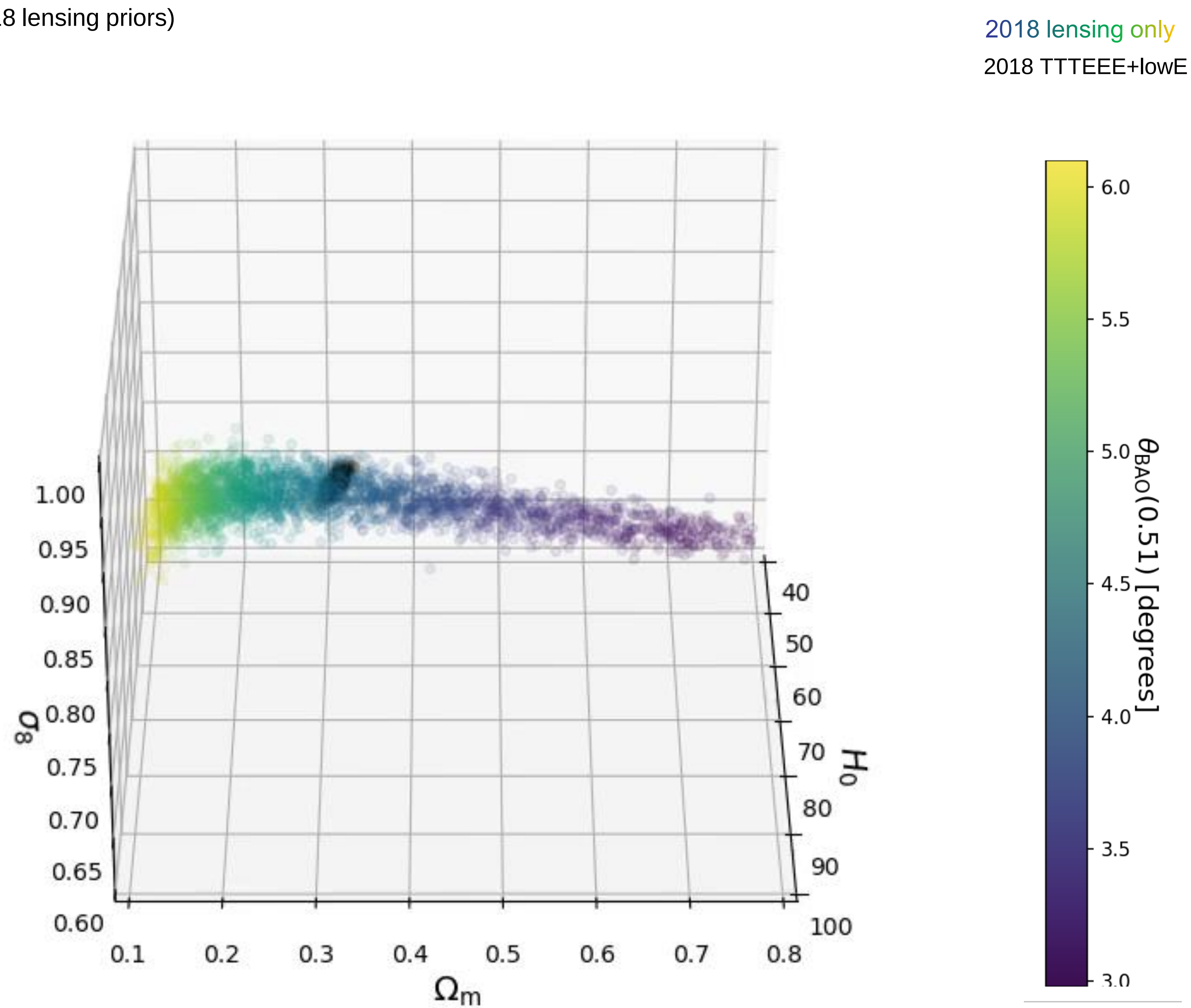
Planck 2018 CMB lensing potential power spectrum
(MV includes temperature and polarization)





$8 \leq L \leq 400$:
"Conservative" lensing likelihood

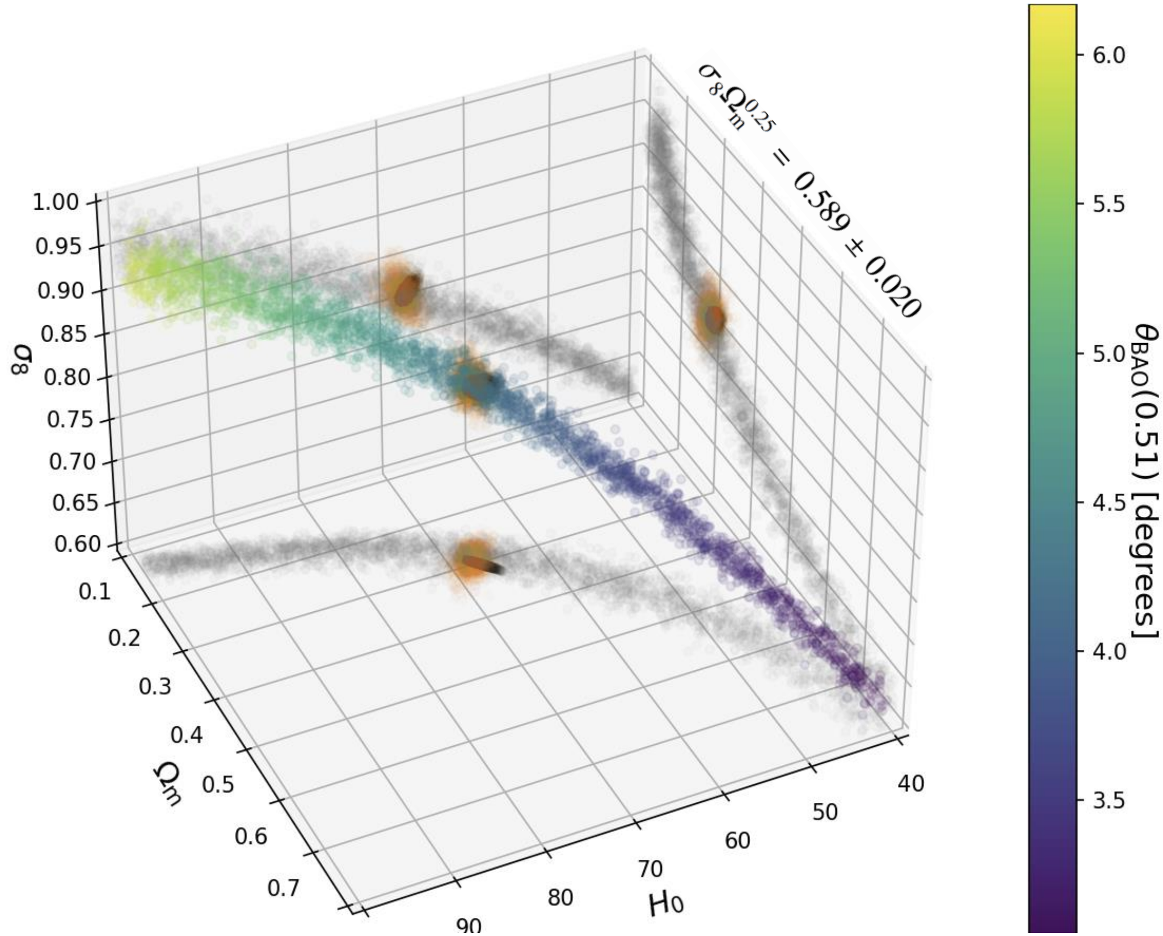
ΛCDM (Planck 2018 lensing priors)



$$\theta_{\mathrm{BAO}}(0.51) \equiv r_s/D_{\mathrm{M}}(z=0.51)$$

Planck 2018 CMB lensing ΛCDM parameters

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

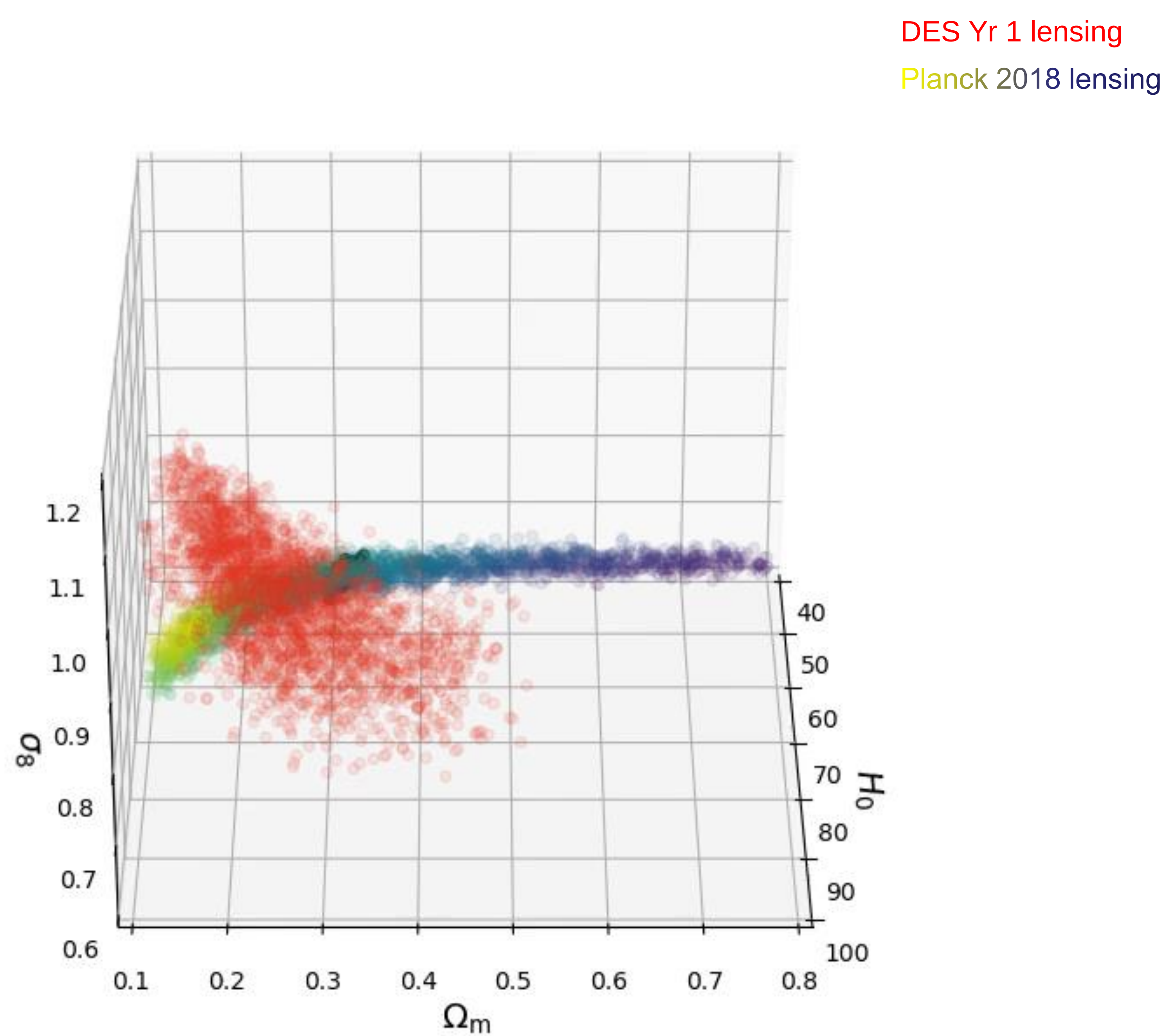


CMB lensing + BAO inverse distance ladder (with $\Omega_b h^2$ prior from abundance measurements)

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

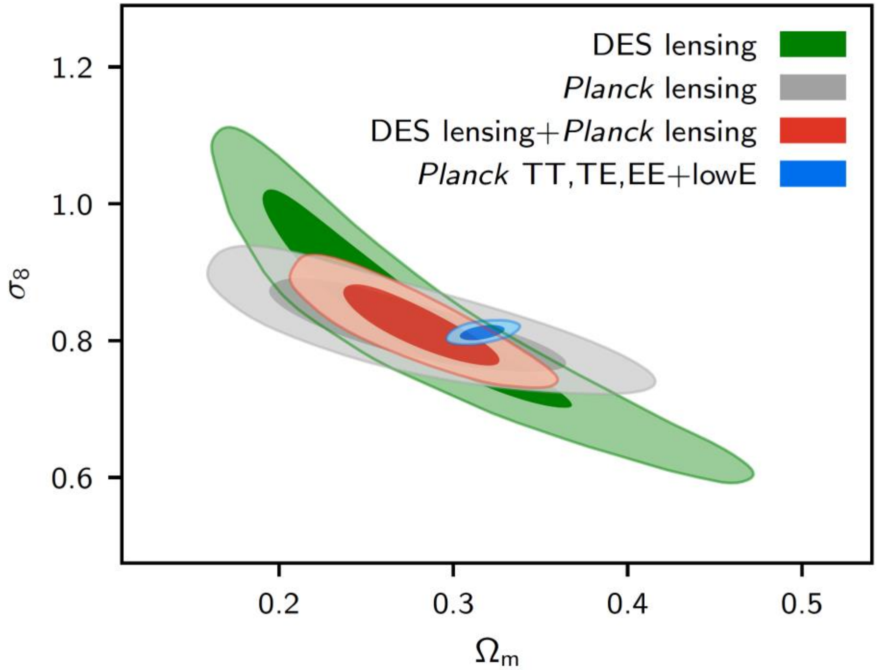
arXiv:1807.06210

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

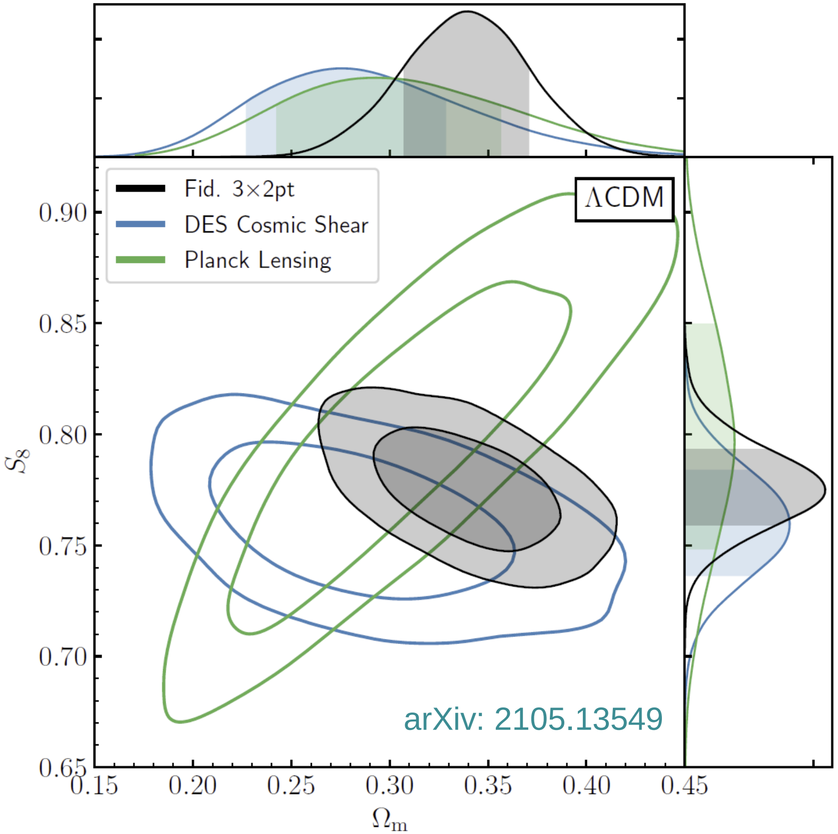

DES Yr 1 lensing
Planck 2018 lensing
1.2
1.1
1.0
0.9
0.8
0.7
0.6
σ_8
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Ω_m
40
50
60
70
80
90
100
H_0

Galaxy and CMB lensing complementary, tighter joint constraints

Planck 2018 lensing, DES Y1, ΛCDM (DES priors)



Planck 2018 lensing, DES Y3: ΛCDM+m_ν

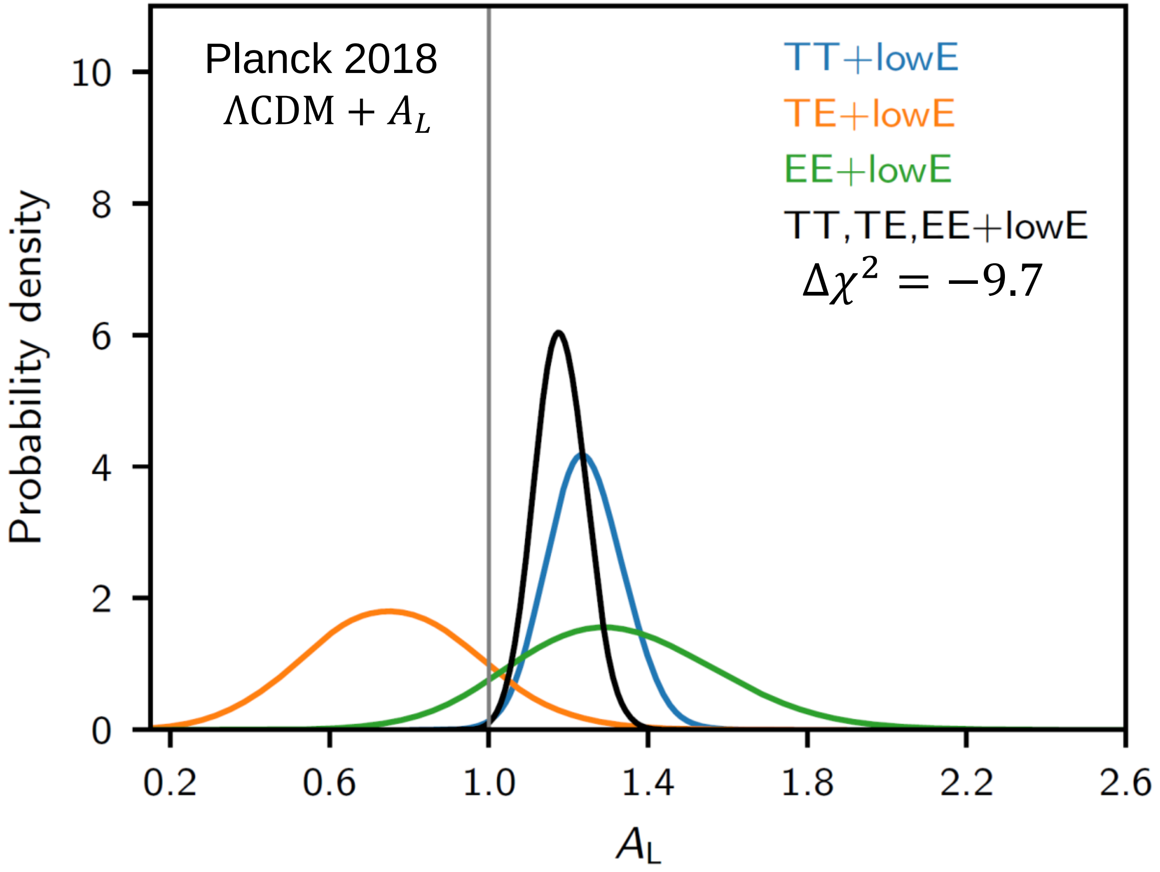


Similar with KiDs/HSC/etc, but may be less consistent

$$S8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

Consistency with lensing smoothing in power spectrum ?

$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$
$$A_L = 1.180 \pm 0.065 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowE}),$$



⇒ power spectrum-only constraints pull to models that predicts more lensing (Ω_K<0,..)
BUT: driven by TT, and more lensing not consistent with lensing reconstruction

NPIPE Planck reanalysis

arXiv: 2007.04997 (Planck, Reijo Keskitalo et al.)

- 8% more data from repointing manoeuvres

- Processing improvements

⇨ (slightly) lower noise and lower systematics

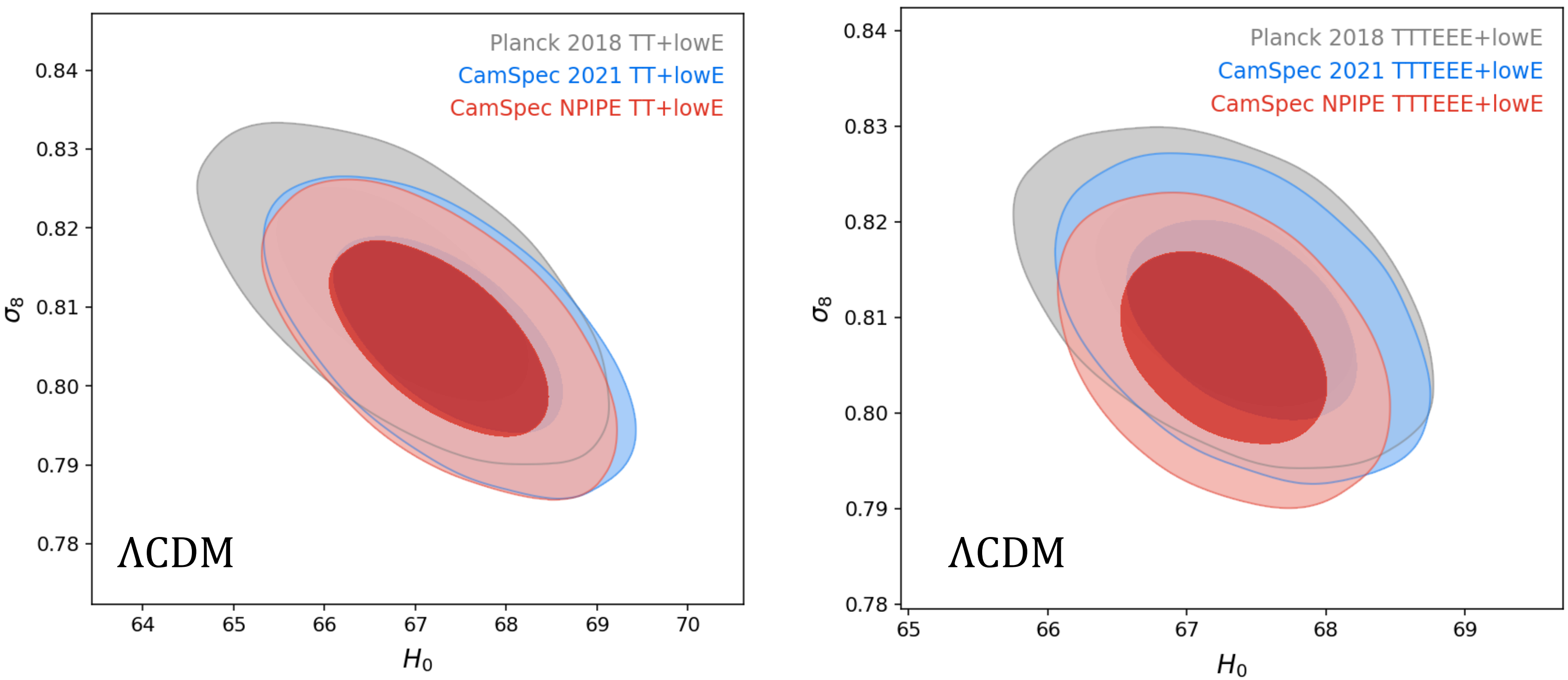
+ new sets of detector-split (A/B) maps for power cross-spectra rather than half-mission

Power spectrum

2018 vs CamSpec 2021 vs CamSpec NPIPE

Credit: Erik Rosenberg, Steven Gratton, George Efstathiou

Both using CamSpec 2021 likelihood with more sky following Efstathiou, Gratton: arXiv:1910.00483



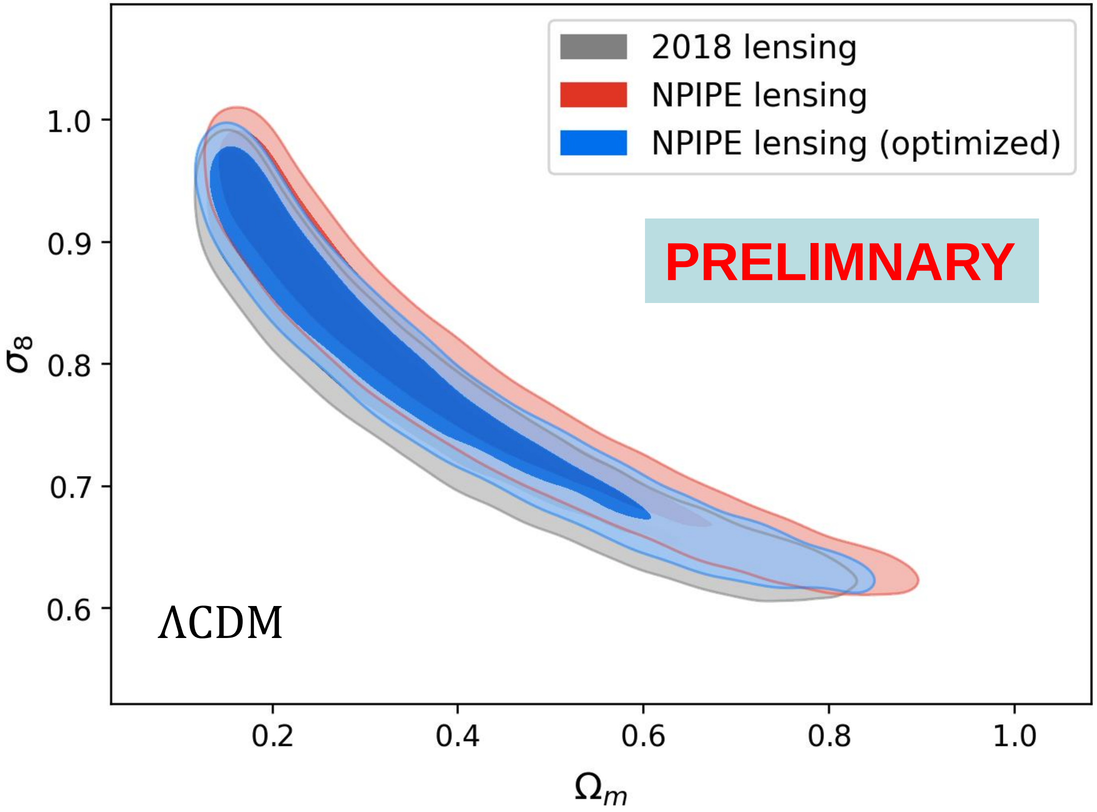
PRELIMNARY

CamSpec 2021 Python likelihood now available with Cobaya at https://cobaya.readthedocs.io/

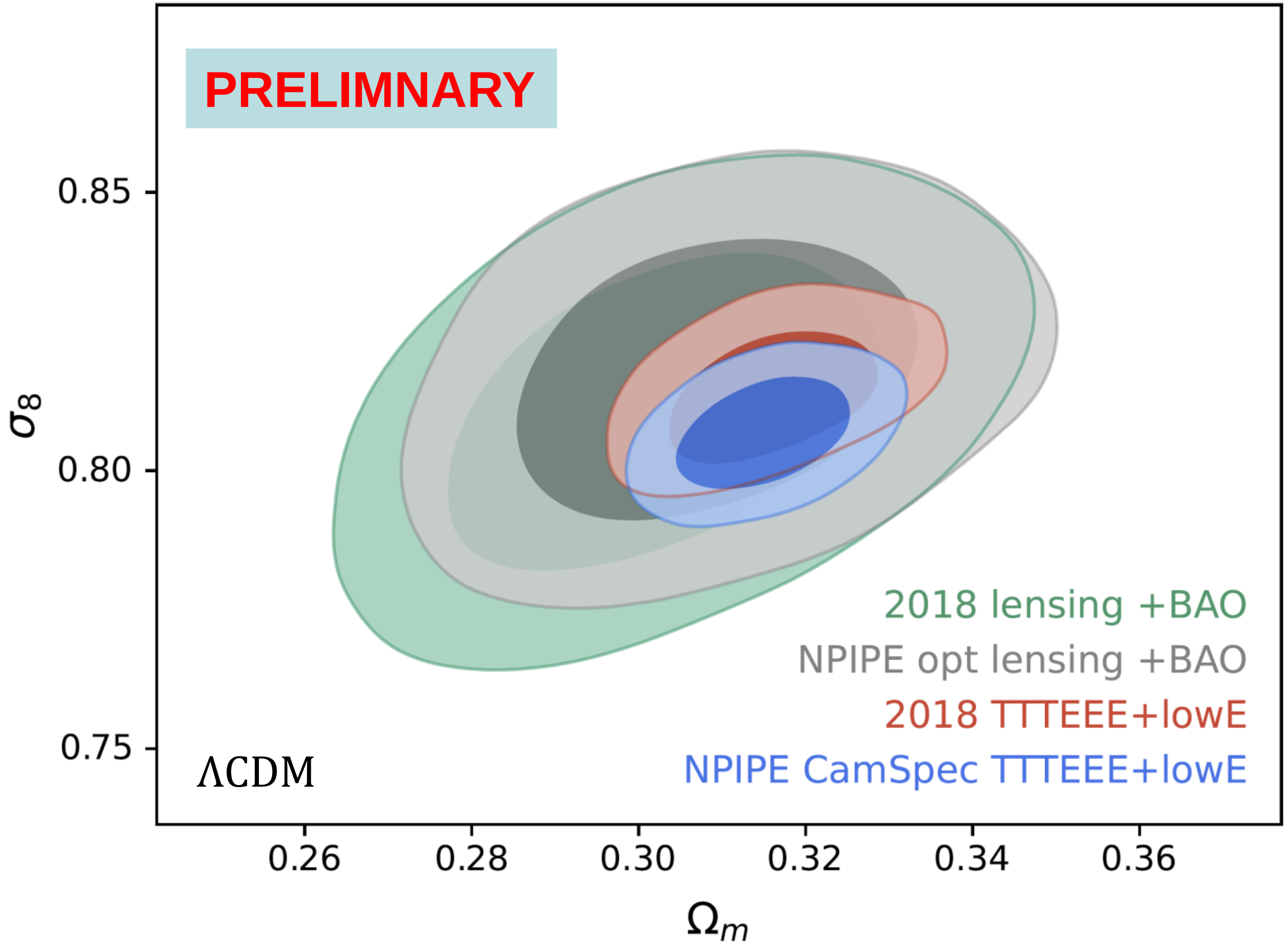
Lensing: 2018 vs NPIPE & NPIPE optimized

Julien Carron, Mark Mirmelstein, AL, SO et al

Optimized analysis: full optimal inhomogeneous T/E inverse filtering
+ κ-filtering (M Mirmelstein, JC, AL arXiv: 1909.02653)



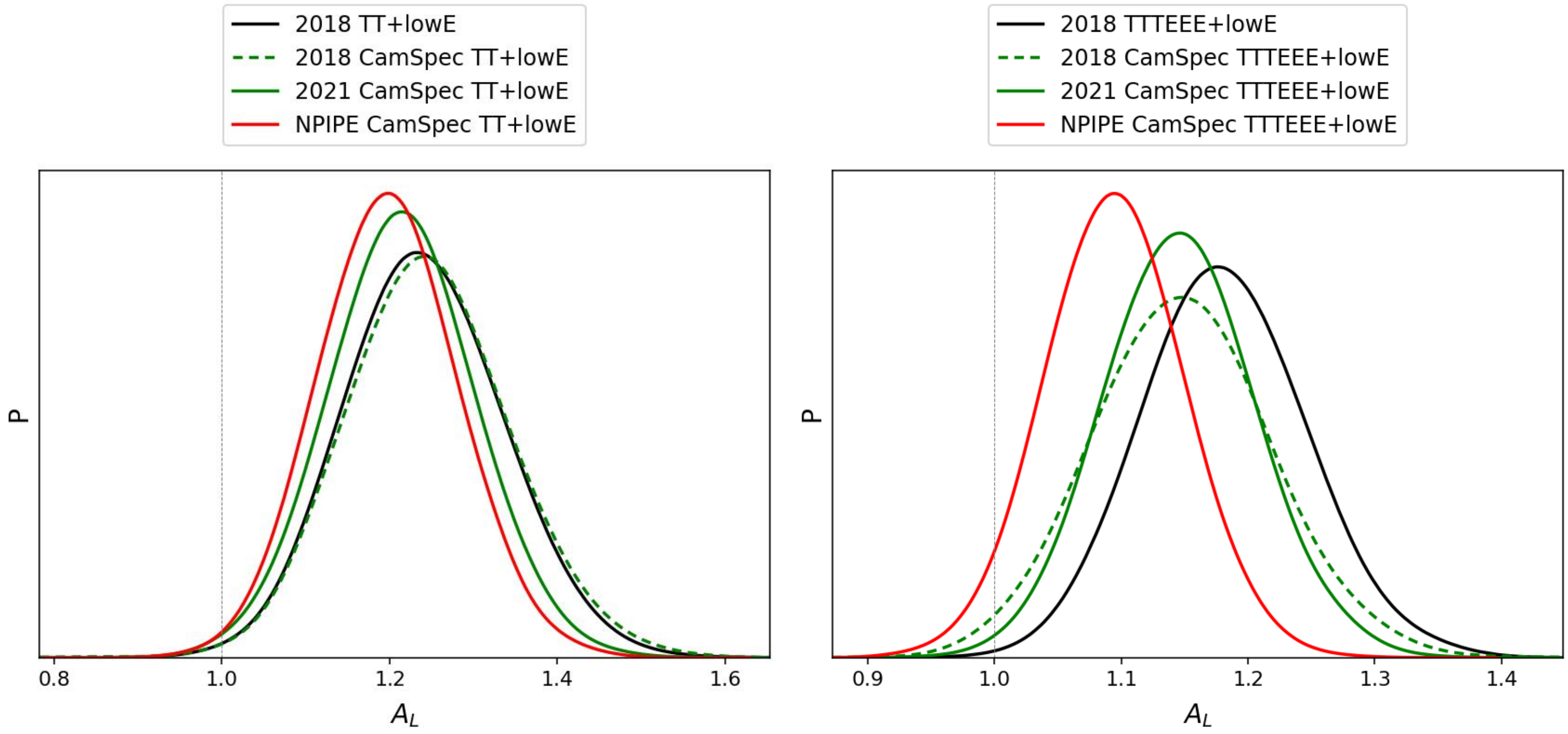
NPIPE ΛCDM constraint comparison



CamSpec credit: Erik Rosenberg, Steven Gratton, George Efstathiou

NPIPE lensing credit: Julien Carron, Mark Mirmelstein, AL, et al.

Note CamSpec result includes more sky than 2018 baseline; lensing using same mask



Credit: Erik Rosenberg, Steven Gratton, George Efstathiou

PRELIMNARY

Conclusions

- Planck gives high precision amplitude measurement at $z \sim 1090$, plus several other parameters
- $\Lambda\mathrm{CDM}$-inferred extrapolation to lower redshift consistent with CMB lensing, and lensing+BAO
- CMB lensing constraints complementary to galaxy lensing, very different (and fewer) systematics
- Some oddities (A_L>1?), but no evidence for internal σ_8 inconsistency. Analysis shifts likely consistent with original high A_L being largely a statistical fluctuation
- Analysis choices and reanalyses give shifts $< O(1\sigma)$ *and* σ *is small*