Cosmological Constraints From The SPTpol CMB Lensing Power Spectrum

FEDERICO BIANCHINI

W/ KIMMY WU & THE SPT COLLABORATION

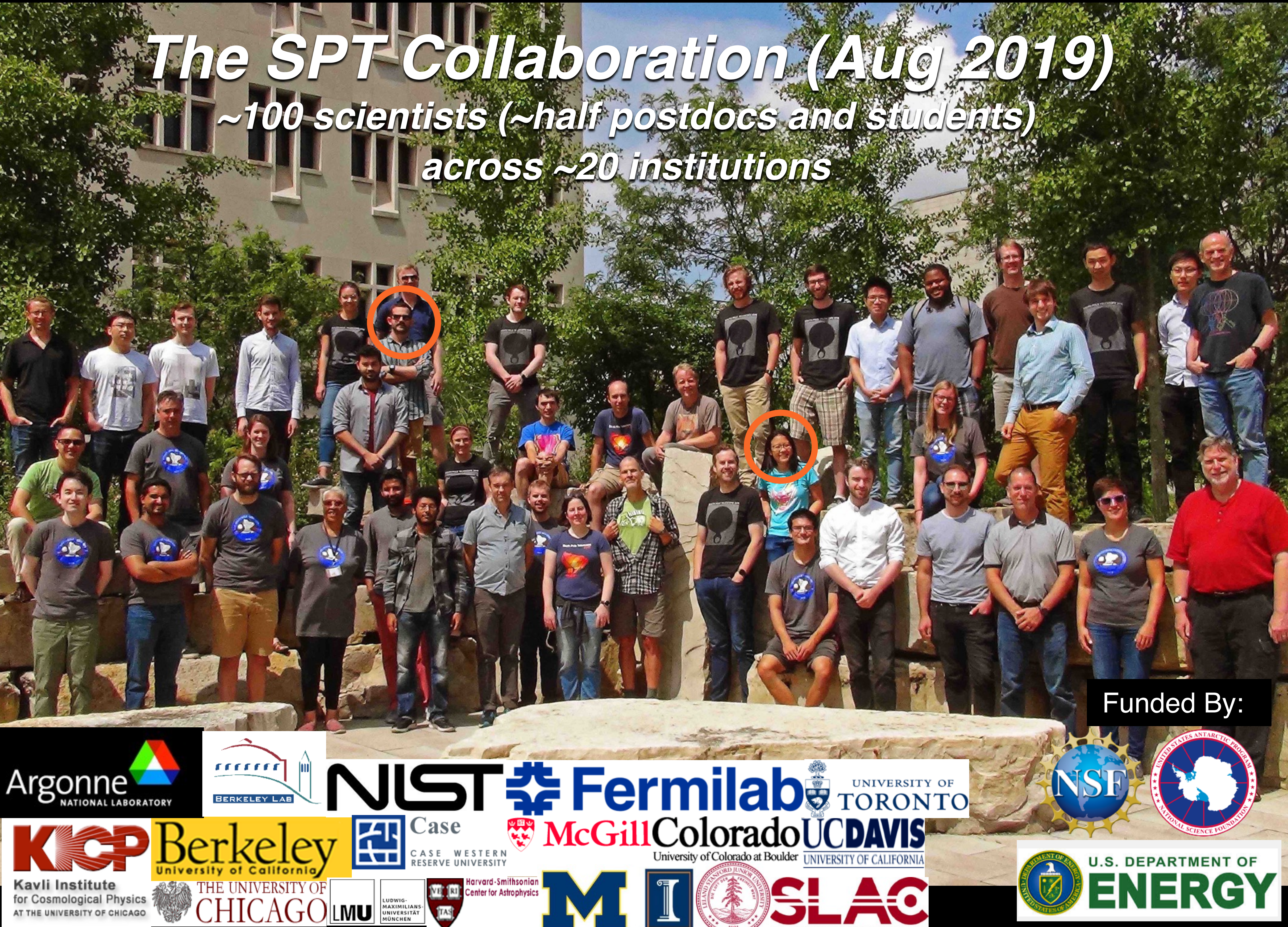
THE UNIVERSITY OF MELBOURNE

Based on
astro-ph:1905.05777
astro-ph:1910.07157

The SPT Collaboration (Aug 2019)

~100 scientists (~half postdocs and students)

across ~20 institutions



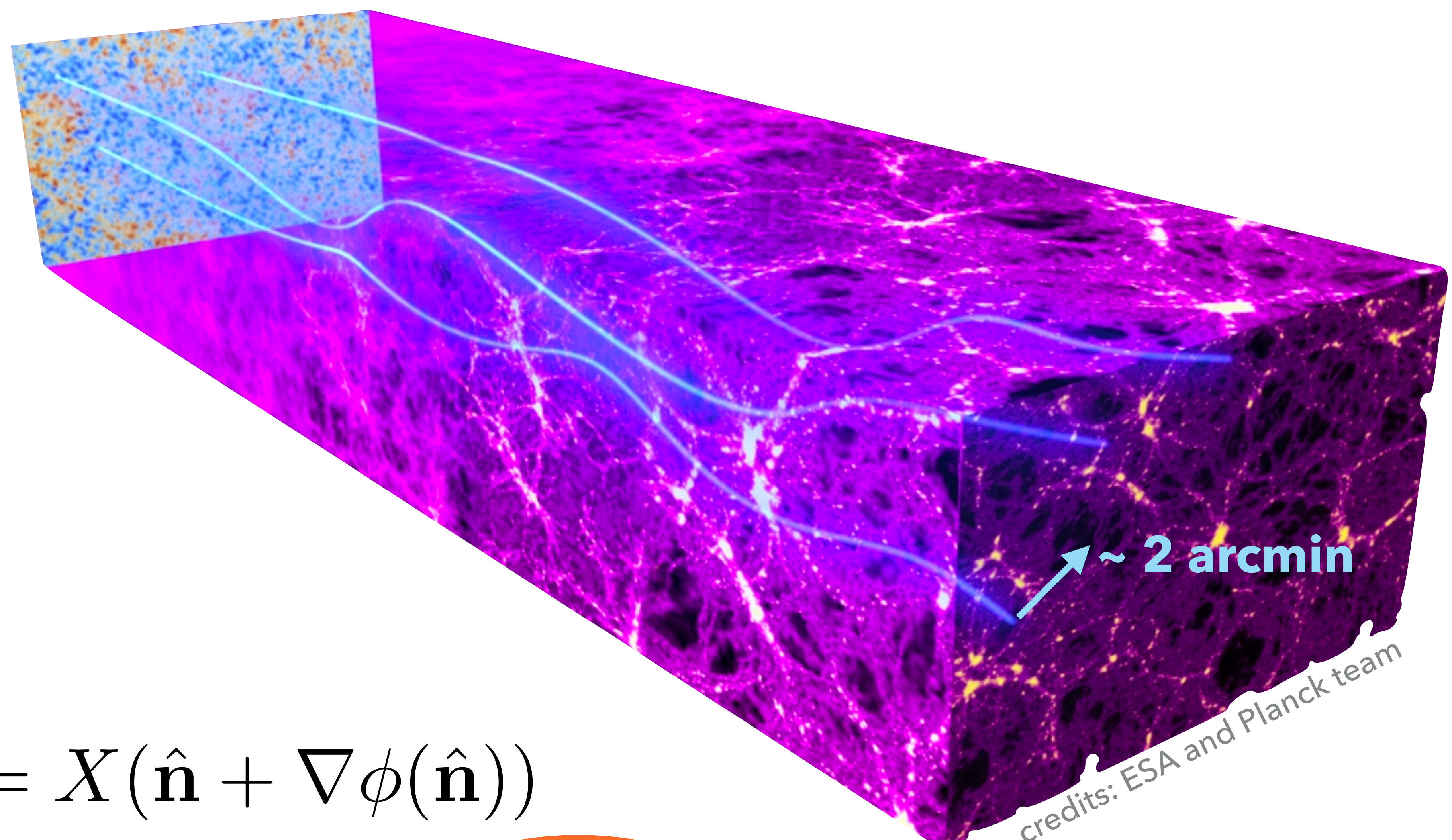
Outline

- CMB lensing primer
- SPTpol: data & instrument
- SPTpol lensing: measurement & interpretation
- Looking ahead: SPT-3G

CMB lensing in a nutshell

THE UNIVERSITY OF MELBOURNE

CMB photons are weakly gravitationally deflected by the intervening matter distribution during their cosmic journey

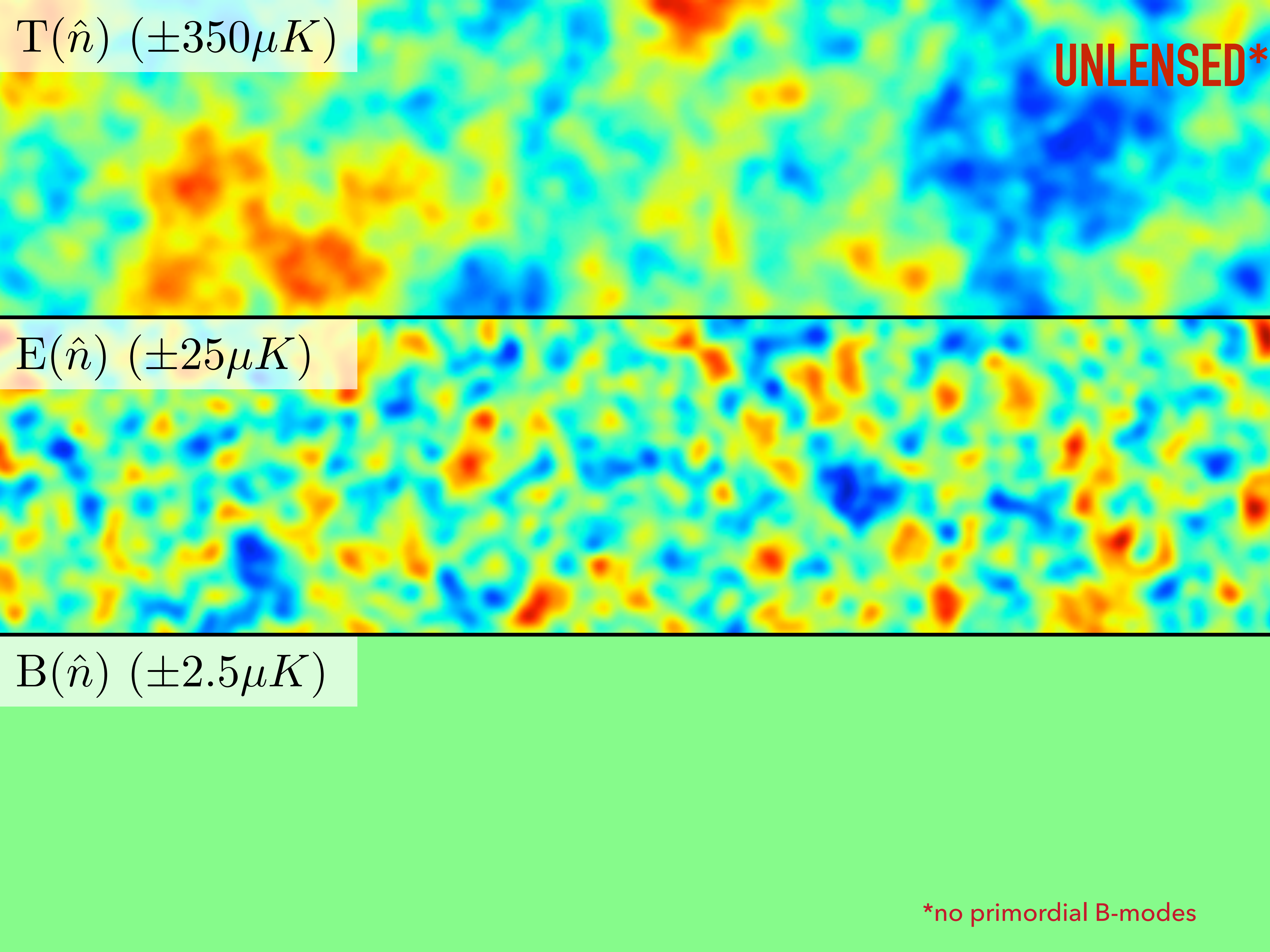


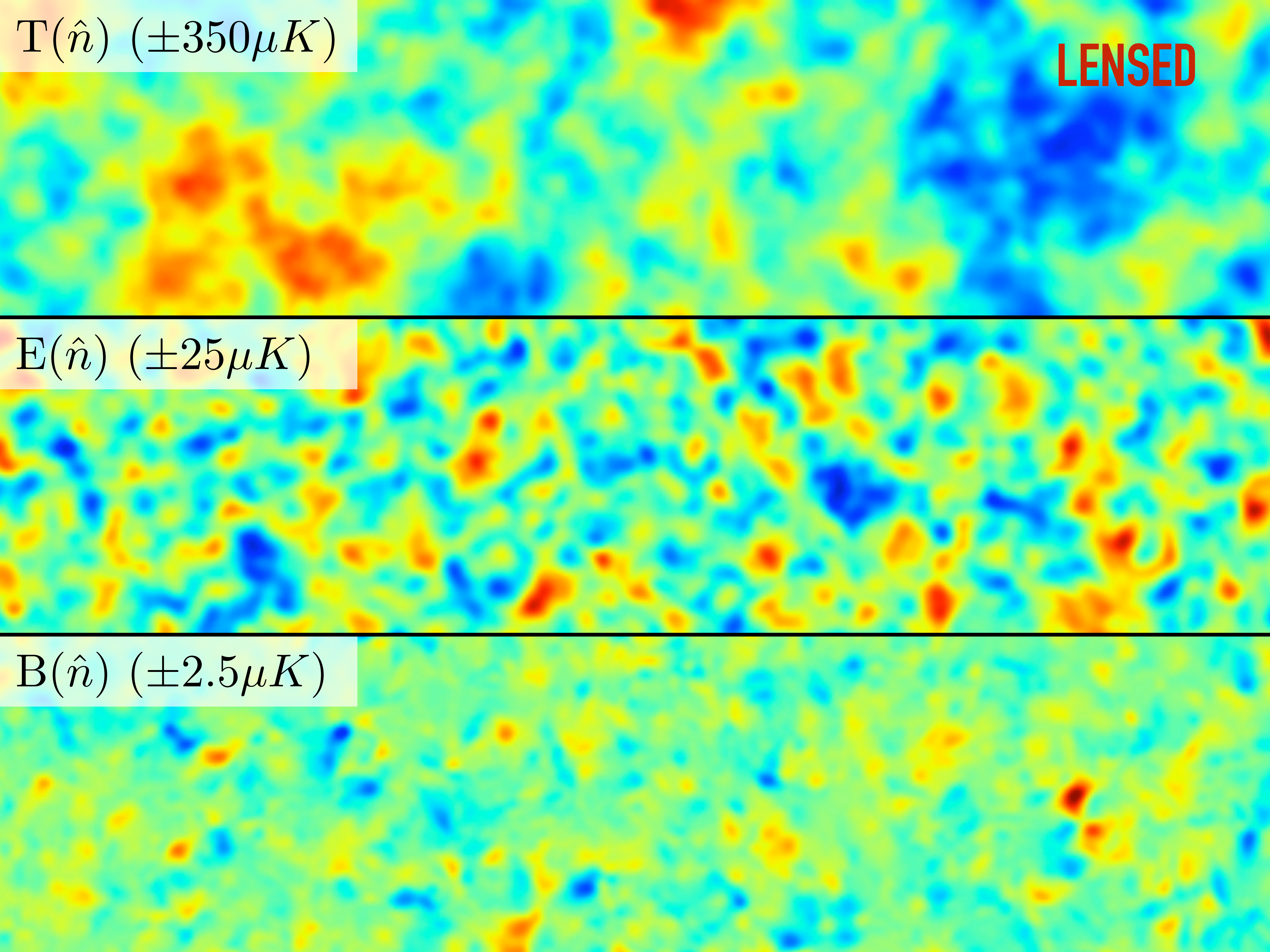
$$\tilde{X}(\hat{\mathbf{n}}) = X(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$

$$\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_*} \mathrm{d}\chi \, \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{\mathbf{n}}; \eta_0 - \chi)$$

Geometry

Growth of structures


T(n̂) (±350μK)
UNLENSED*
E(n̂) (±25μK)
B(n̂) (±2.5μK)
*no primordial B-modes


T($\hat{n}$) ($\pm 350\mu K$)
LENSED
E($\hat{n}$) ($\pm 25\mu K$)
B($\hat{n}$) ($\pm 2.5\mu K$)

CMB lensing reconstruction

THE UNIVERSITY OF MELBOURNE

Lensing introduces **statistical anisotropy**, i.e. correlates previously uncorrelated multipoles

$$\langle X(\mathbf{l})Y^*(\mathbf{l}-\mathbf{L})\rangle = 0 \quad \xrightarrow{\text{w/ lensing}} \quad \langle X(\mathbf{l})Y^*(\mathbf{l}-\mathbf{L})\rangle \propto \phi(\mathbf{L})$$

METHOD

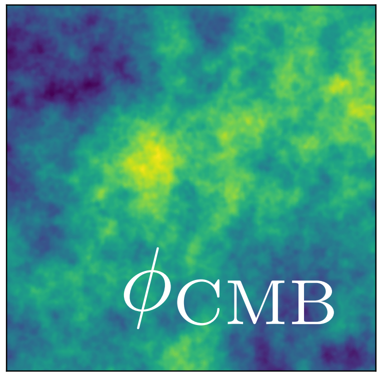
We can extract lensing by looking at the off-diagonal correlations between X and Y

$$\bar{\phi}^{XY}_{\mathbf{L}} = \frac{1}{\mathcal{R}^{XY}_{\mathbf{L}}} \int d^2\boldsymbol{\ell}\, W^{XY}_{\boldsymbol{\ell},\boldsymbol{\ell}-\mathbf{L}} \bar{X}_{\boldsymbol{\ell}} \bar{Y}^*_{\boldsymbol{\ell}-\boldsymbol{L}}$$

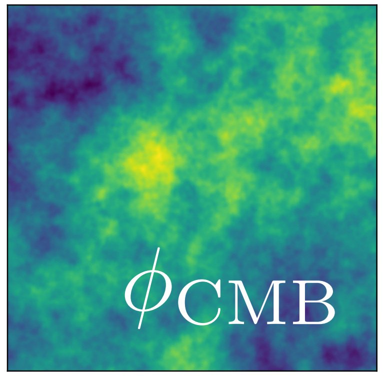
Hu&Okamoto02
Seljak&Zaldarriaga97

Lensing Potential | Normalization | Optimally-chosen weight function | Filtered (data) maps X,Y ϵ [T,E,B]

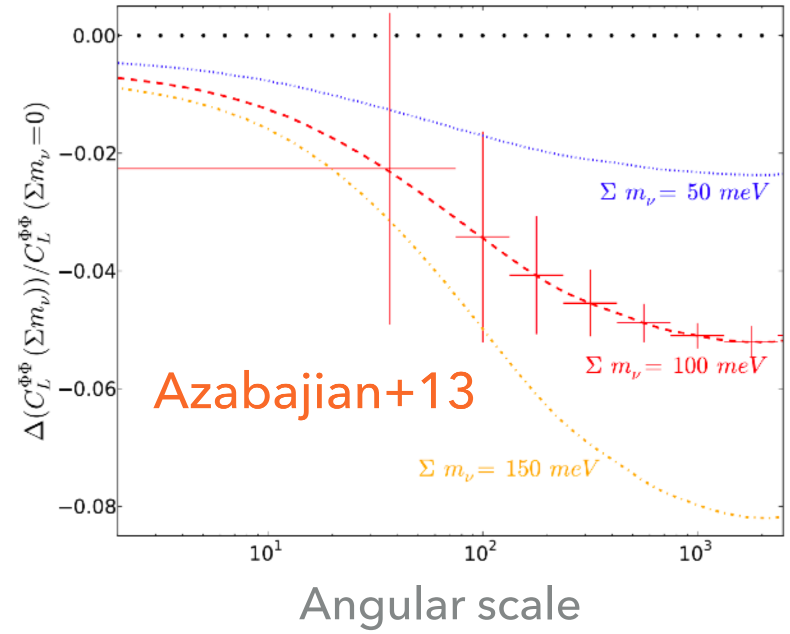
(a Few) Applications of CMB lensing

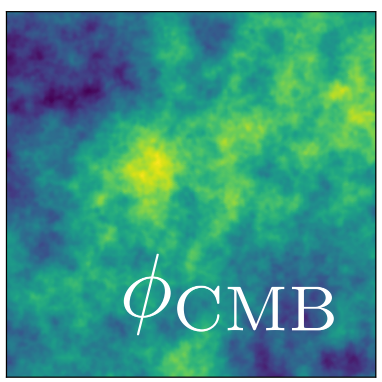


x



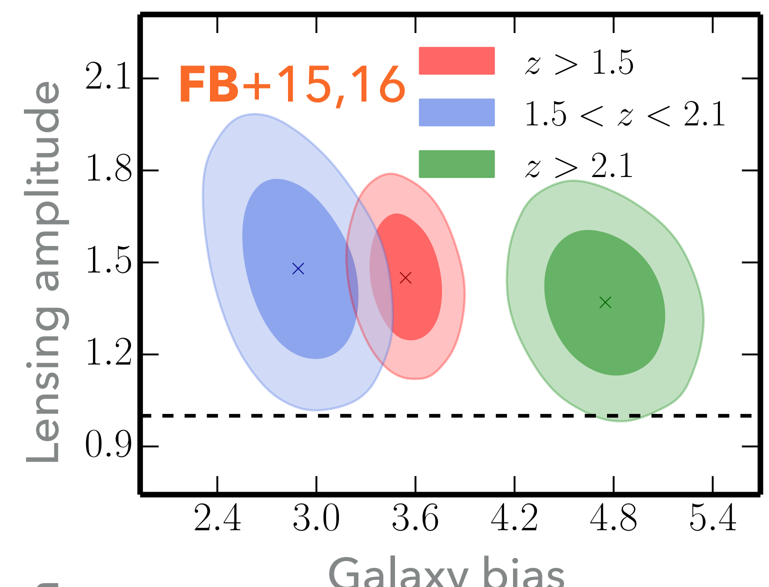
- **Neutrino masses**
- Dark energy
- Curvature

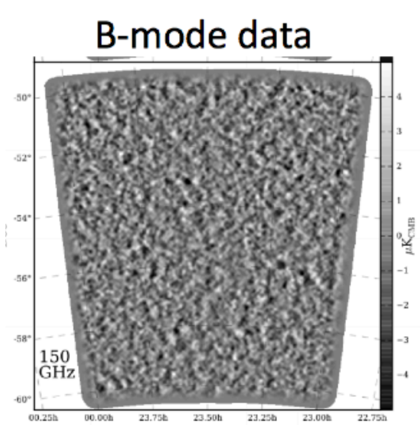


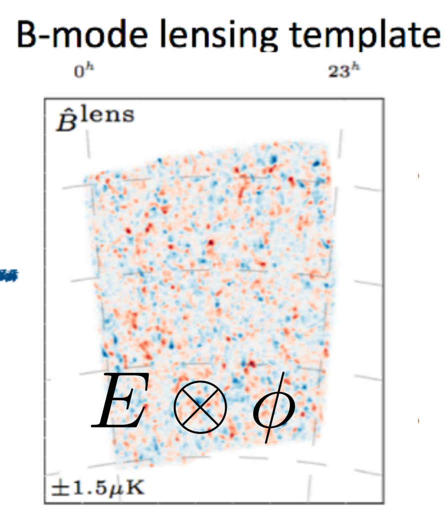


x

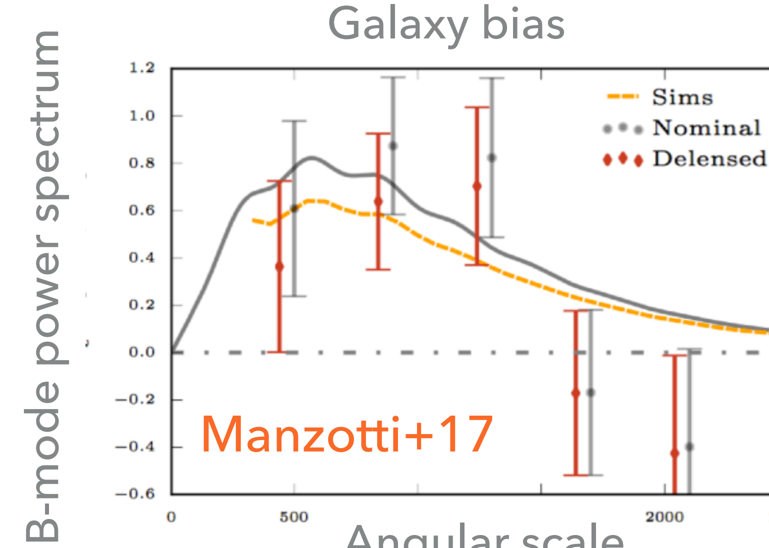
- **Tracers bias**
- Shear bias calibration
- Photo-z uncertainties







- Delens B-modes
- **Inflationary gravitational waves**
- Scale energy of inflation

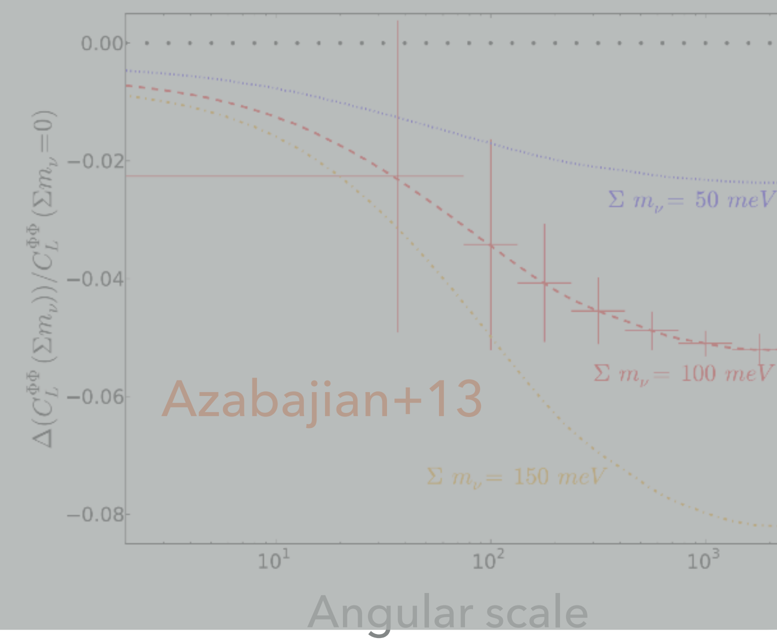


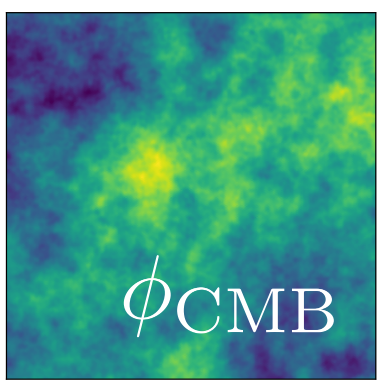
(a Few) Applications of CMB lensing

X

- Neutrino masses
- Dark energy
- Curvature

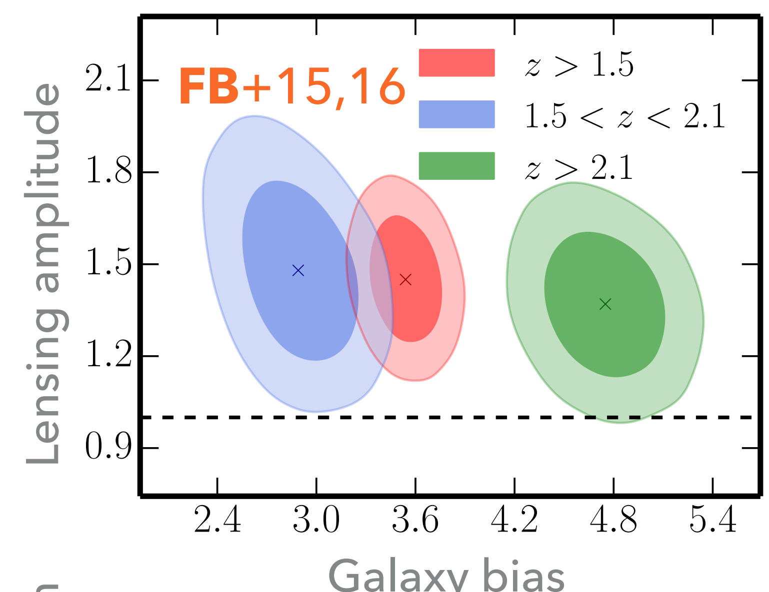
This talk

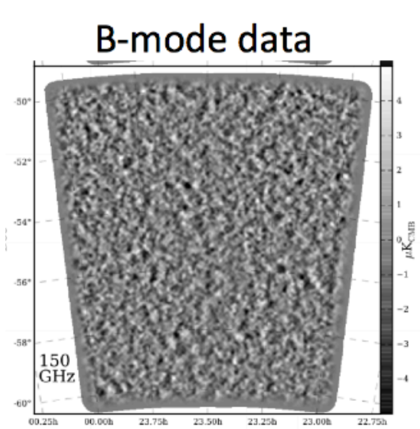


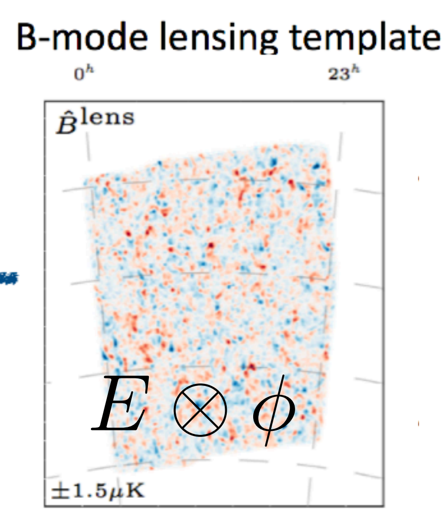


X

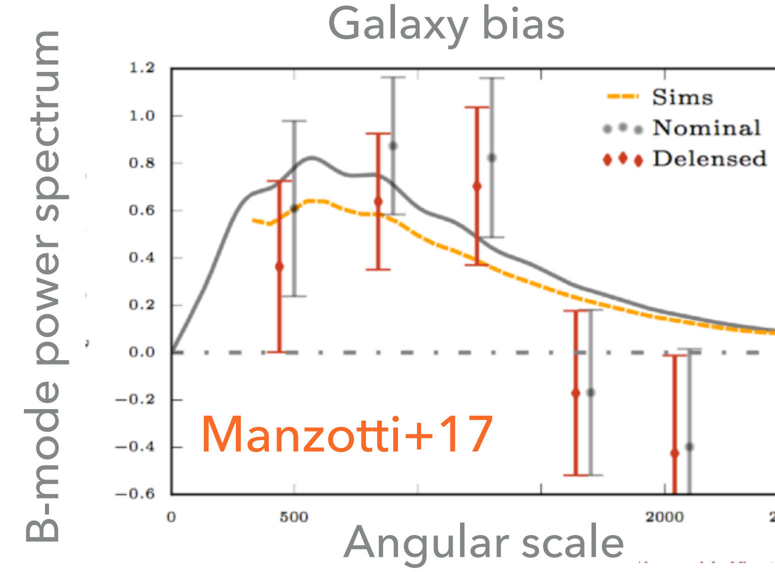
- **Tracers bias**
- Shear bias calibration
- Photo-z uncertainties







- Delens B-modes
- **Inflationary gravitational waves**
- Scale energy of inflation

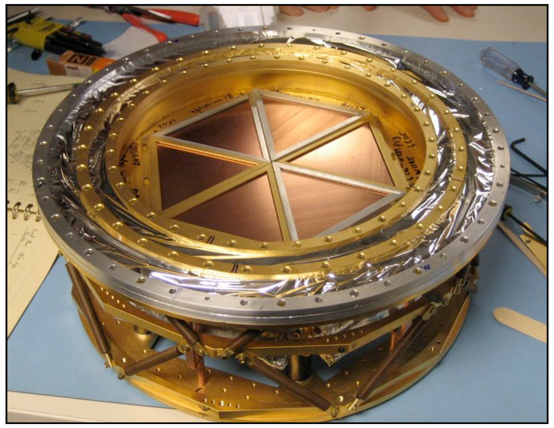


The South Pole Telescope (SPT)

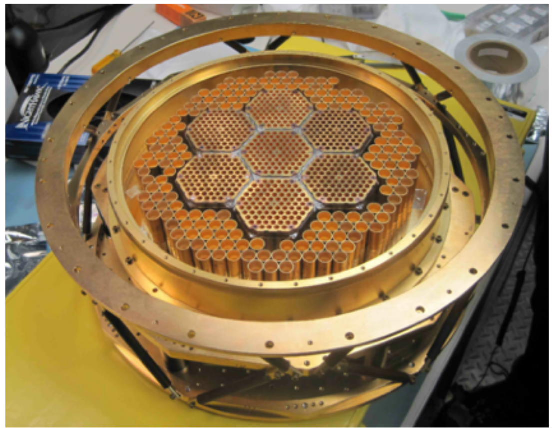
THE UNIVERSITY OF MELBOURNE

10-meter telescope
arcmin resolution

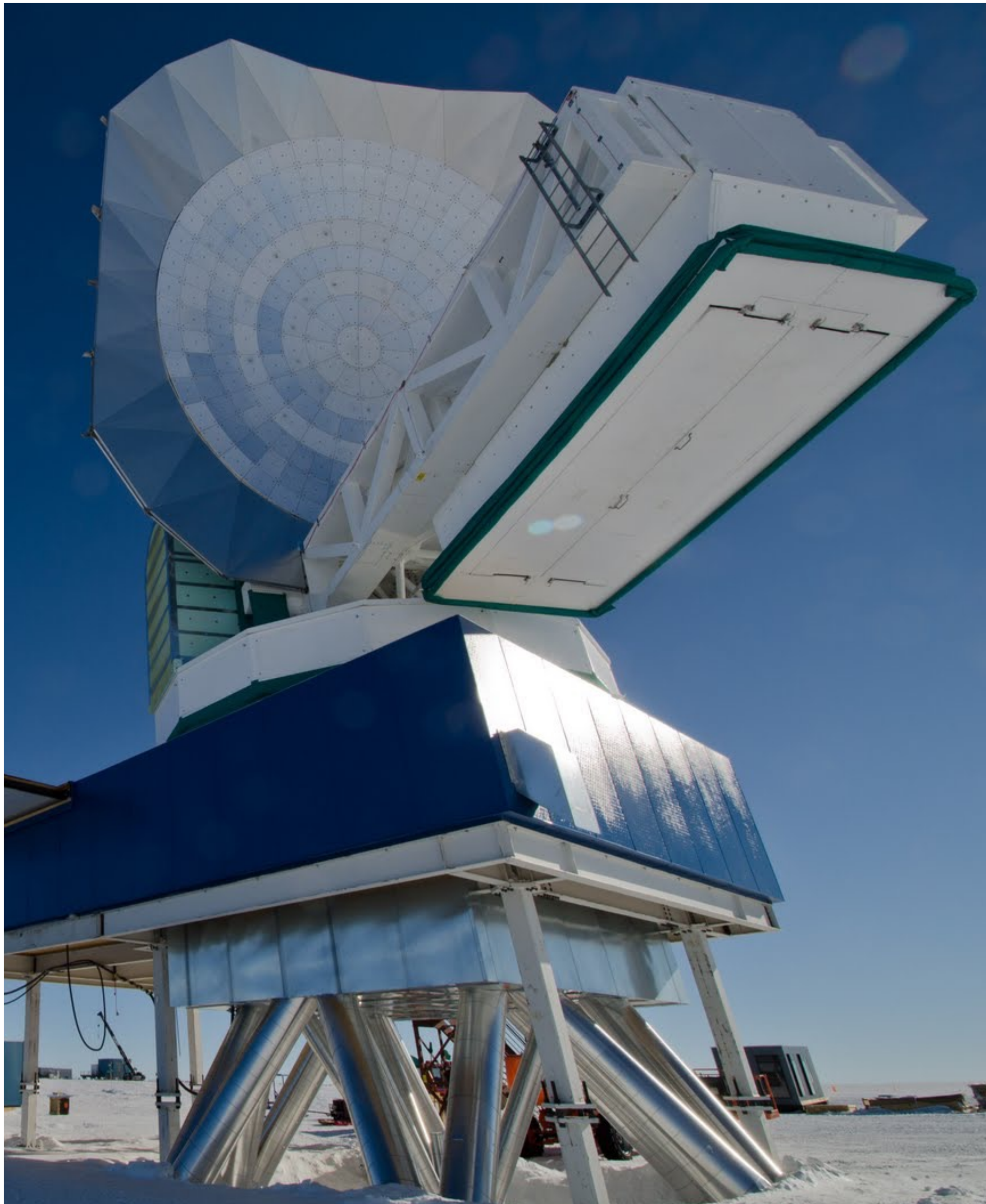
2007: SPT-SZ
960 detectors
95,150,220 GHz



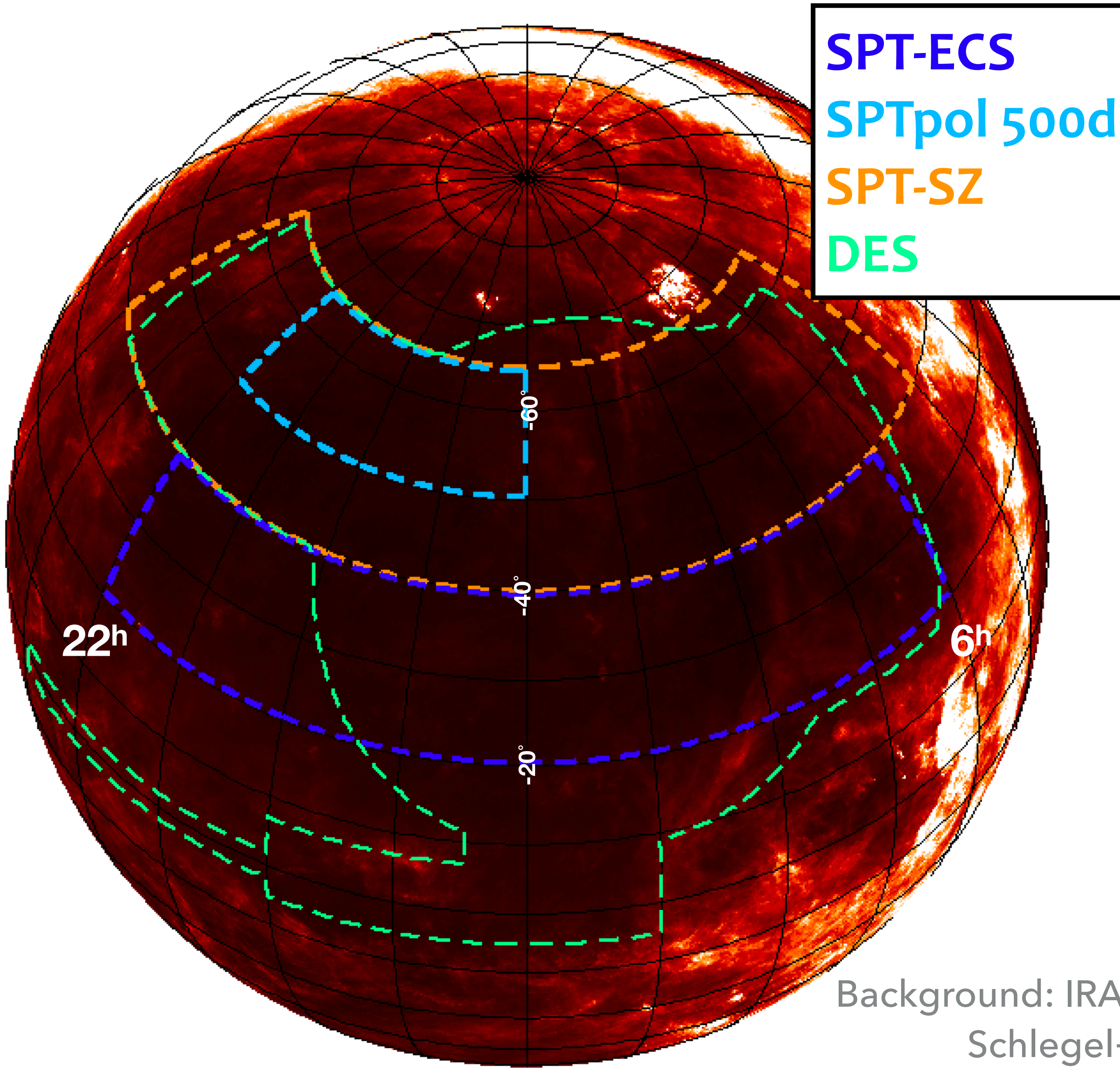
2012: SPTpol
1600 detectors
95,150 GHz
+polarization



2017: SPT-3G
~16,200 detectors
95,150, 220 GHz
+polarization



SPTpol survey

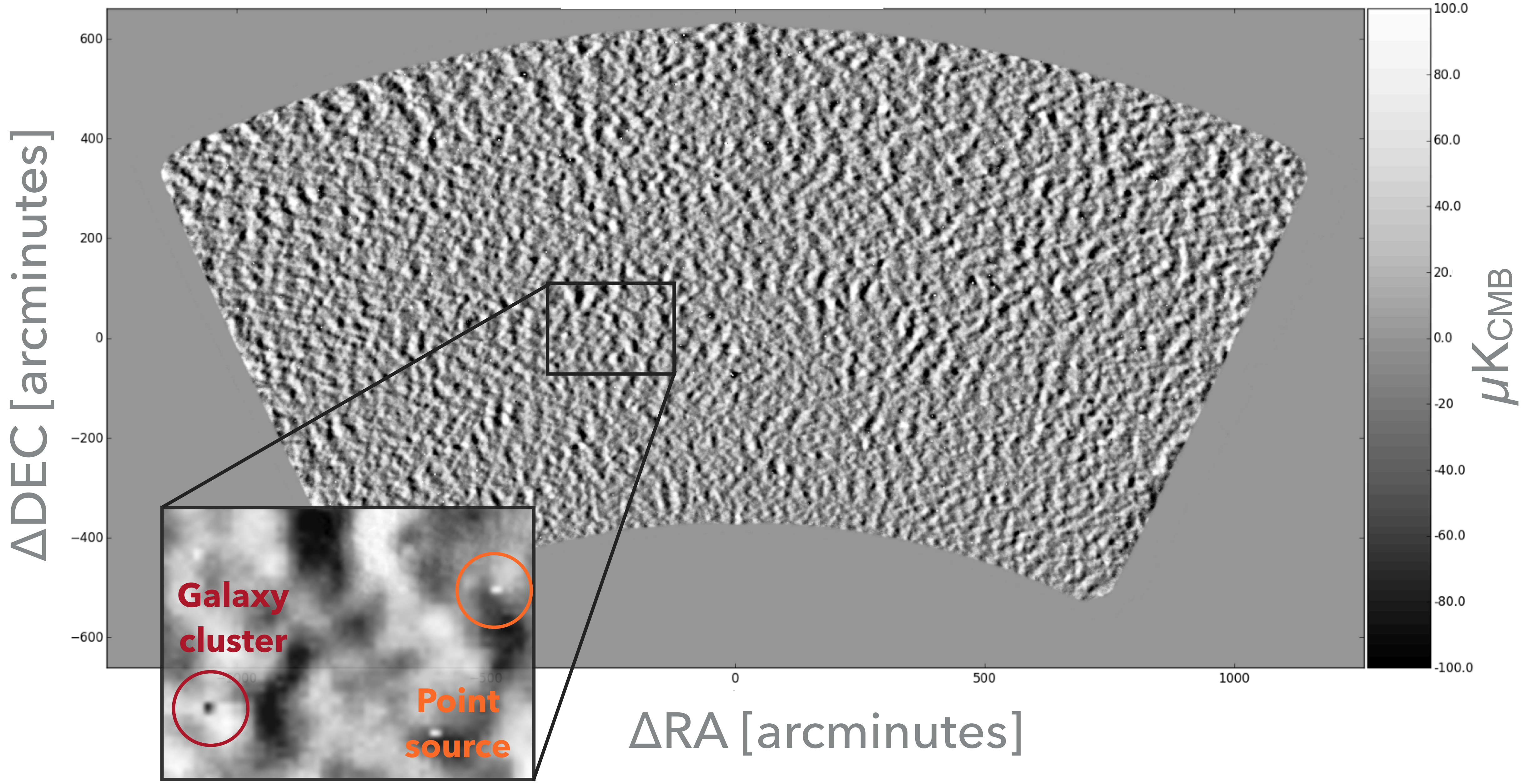


Background: IRAS dust map
Schlegel+98

Survey	Obs. Years	Area (deg²)	95 GHz (uK-')	150 (uK-')	220 (uK-')
SPT-SZ	2007-11	2500	40	17	80
SPTpol-Main	**2012-16**	**500**	**12**	**5**	**-**
SPTpol-Deep	2012-16	100	10	3.5	-

SPTpol maps

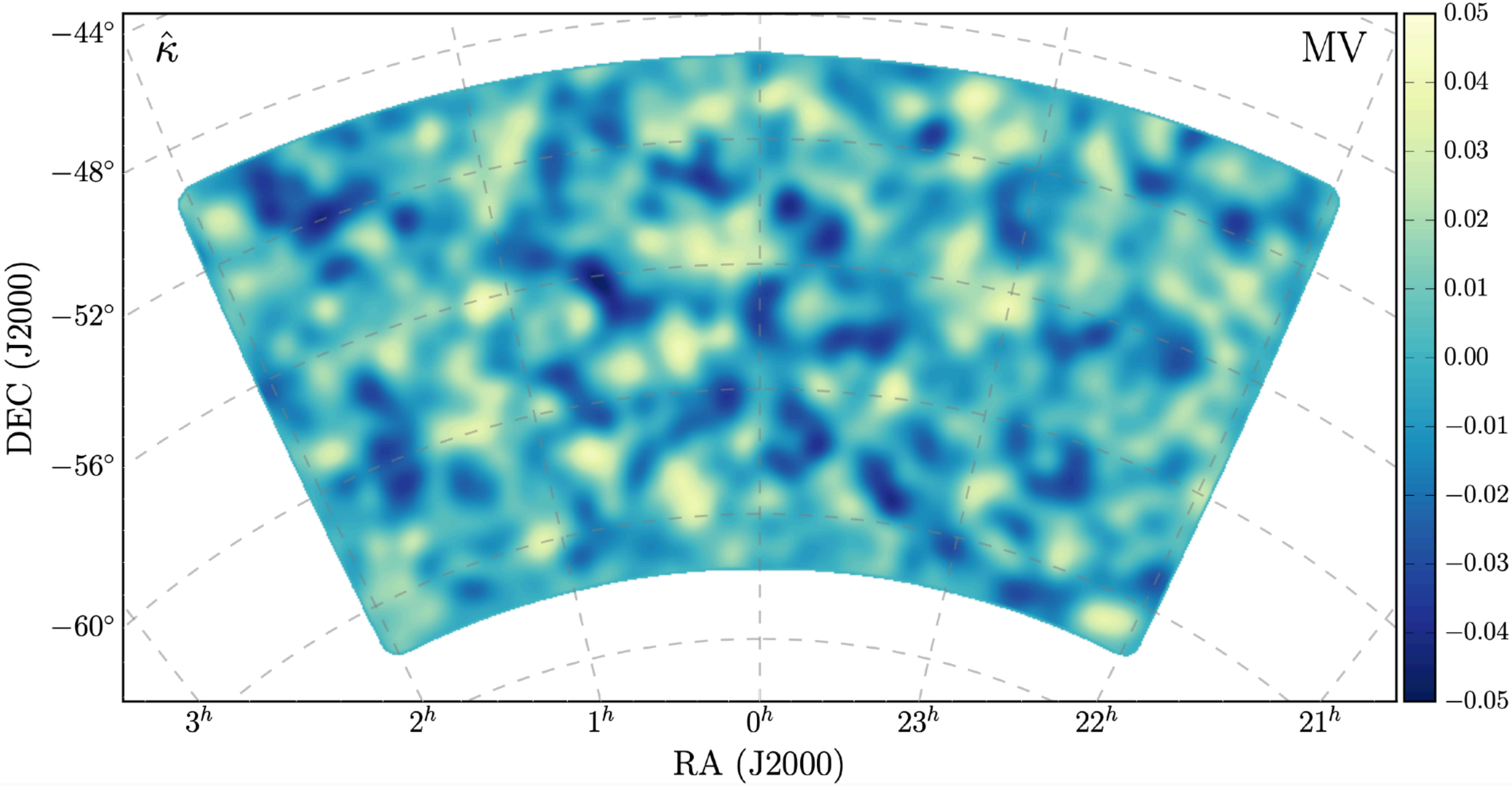
(high-pass filtered) **temperature** map at **150 GHz** for all data from 2013 to July 2015



500d CMB lensing map

High S/N map of the projected **mass distribution** out to the surface of last scattering

$$\kappa = -\frac{1}{2}\nabla^2\phi$$

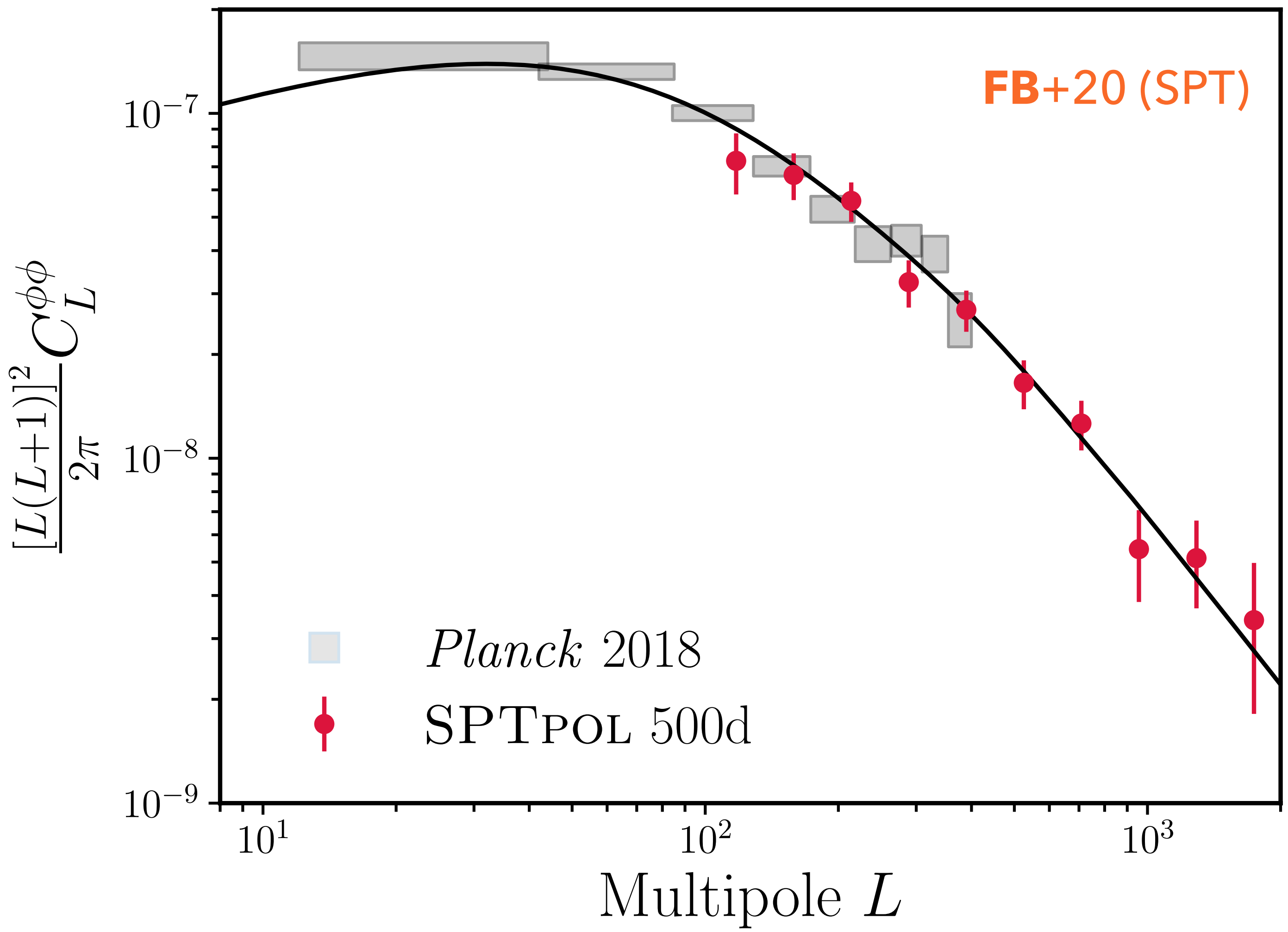


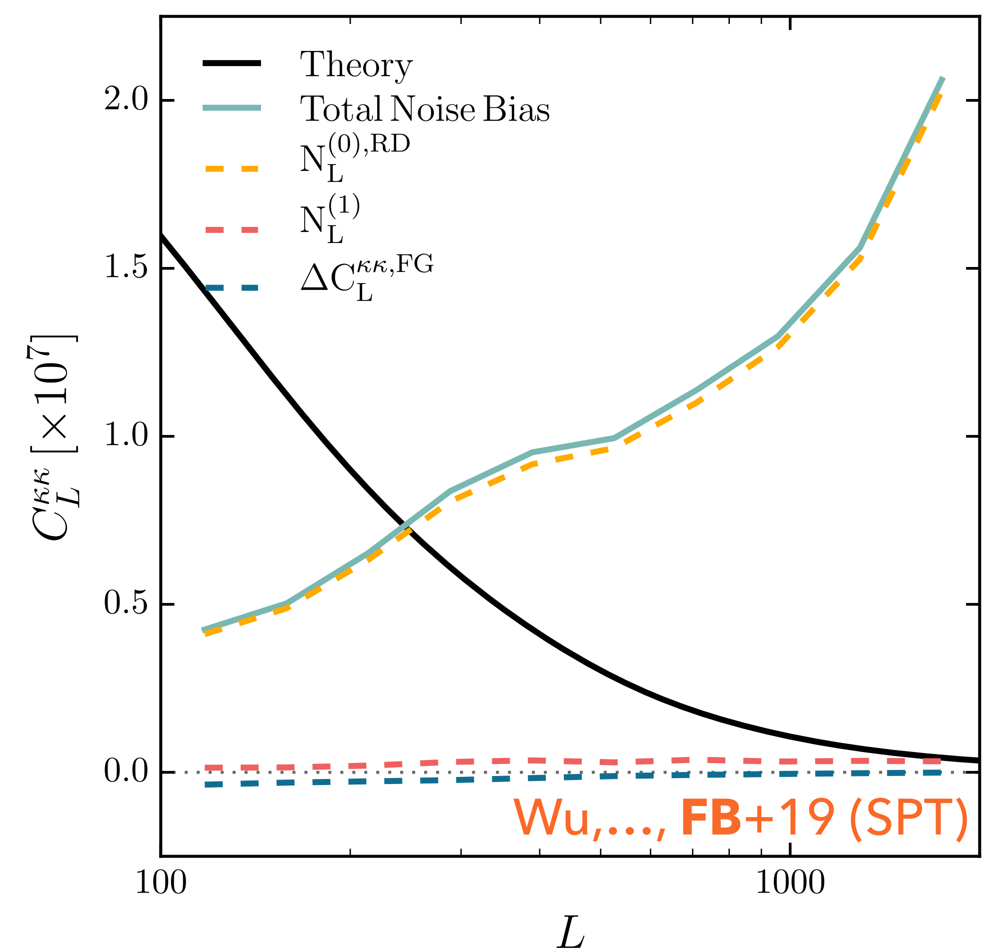
Wu,..., **FB**+19 (SPT)

500d CMB lensing power spectrum

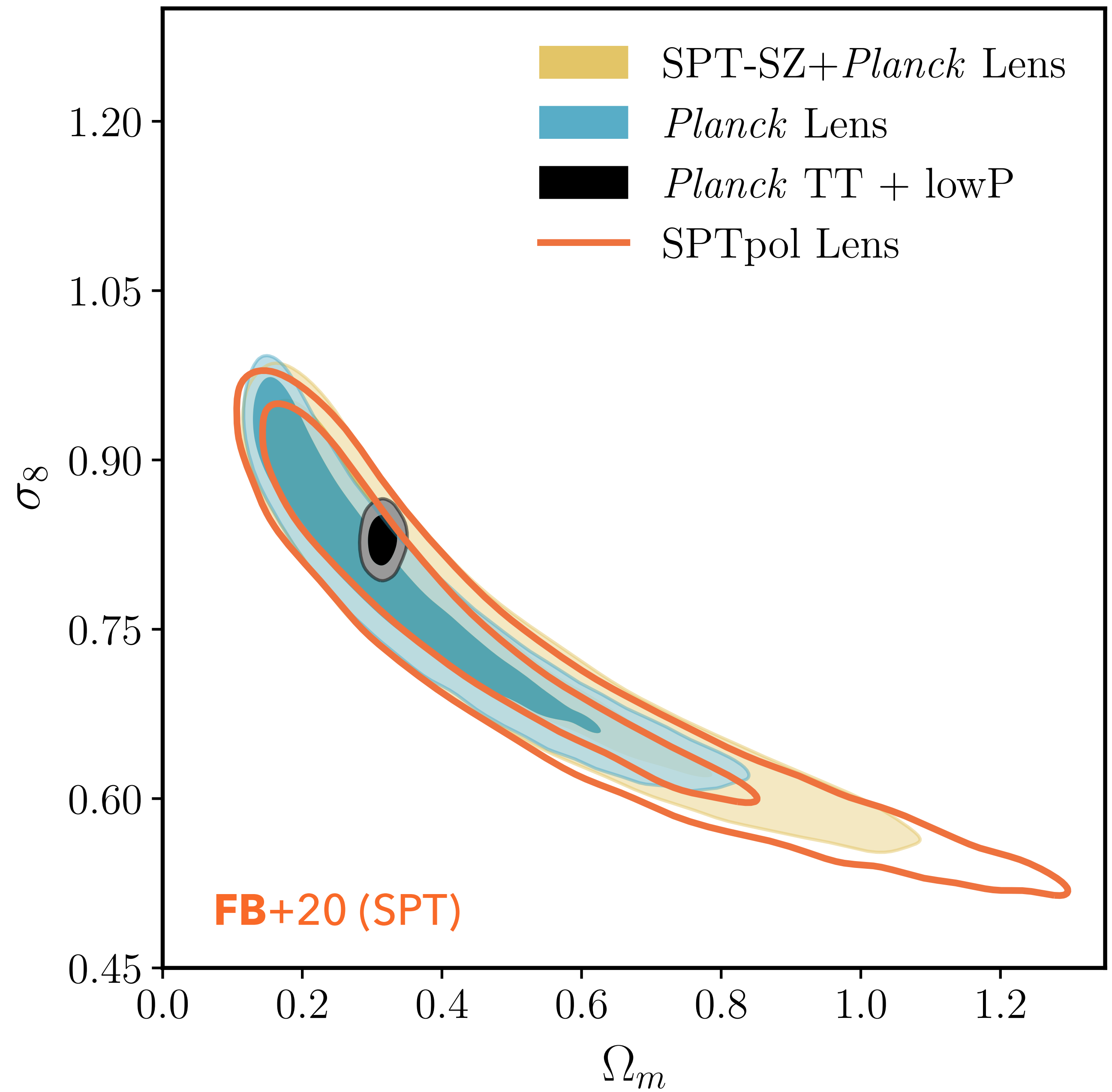
- **No lensing hypothesis ruled out at 40σ**
- **S/N > 1** (sample variance limited) for modes **L $\lesssim$ 250**

$$A_{\rm MV} = 0.94 \pm 0.06(stat) \pm 0.025(sys)$$
$$A_{\rm POL} = 0.91 \pm 0.09(stat) \pm 0.04(sys)$$
$$A_{\rm TT} = 0.83 \pm 0.10(stat) \pm 0.01(sys)$$





500d CMB lensing constraints*
ΛCDM: Ω_M vs σ_8

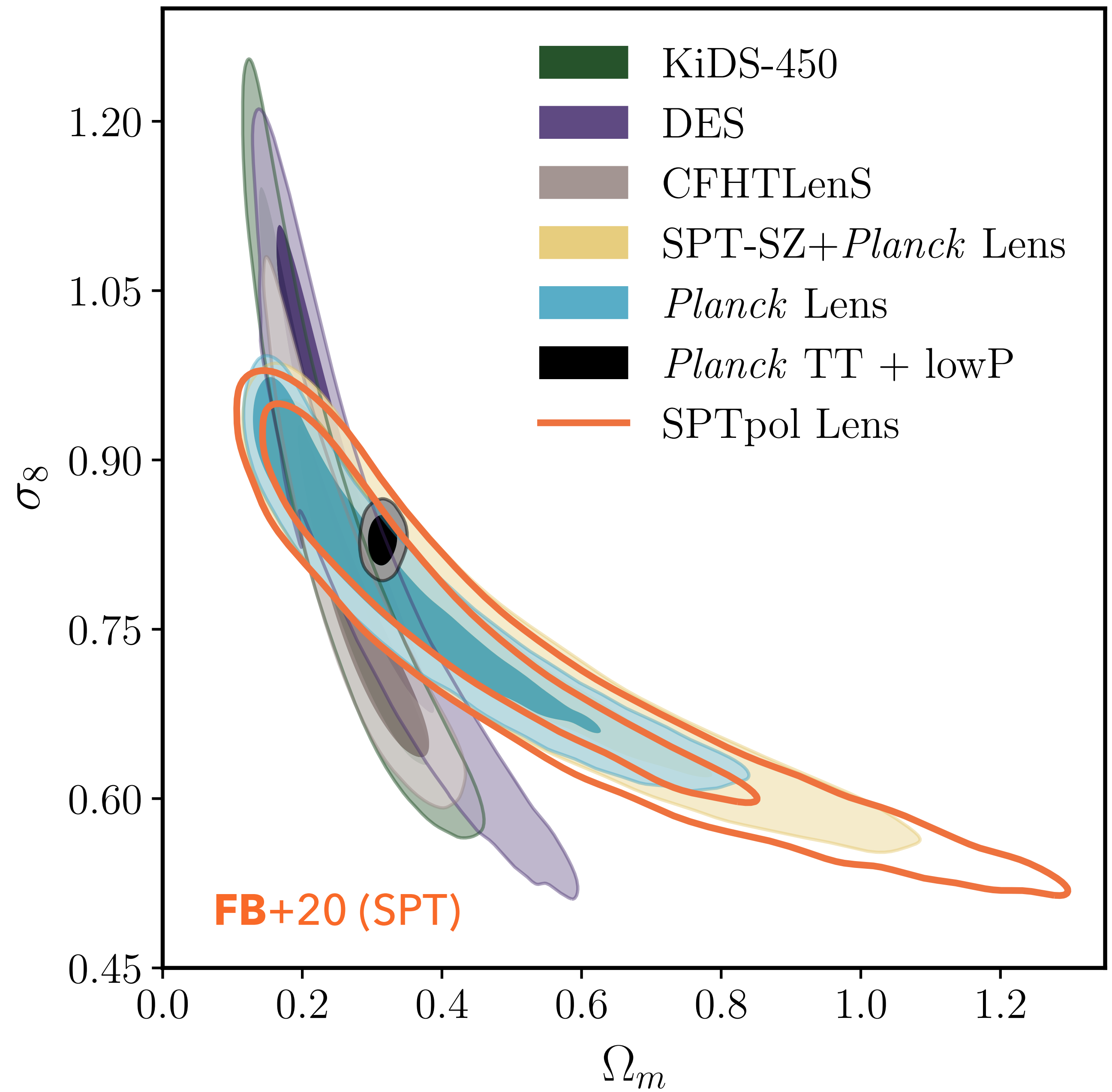


$$\sigma_8\Omega_m^{0.25} = 0.593 \pm 0.025 \quad \text{SPTpol CMB lensing only (4\%)}$$

$$\sigma_8\Omega_m^{0.25} = 0.590 \pm 0.020 \quad \textit{Planck} \text{ CMB lensing only (3\%)}$$

*"Lensing-only" priors: $\Omega_b h^2 = 0.0222 \pm 0.0005, n_s = 0.96 \pm 0.02, 0.4 < h < 1$ **+ *fix tau***

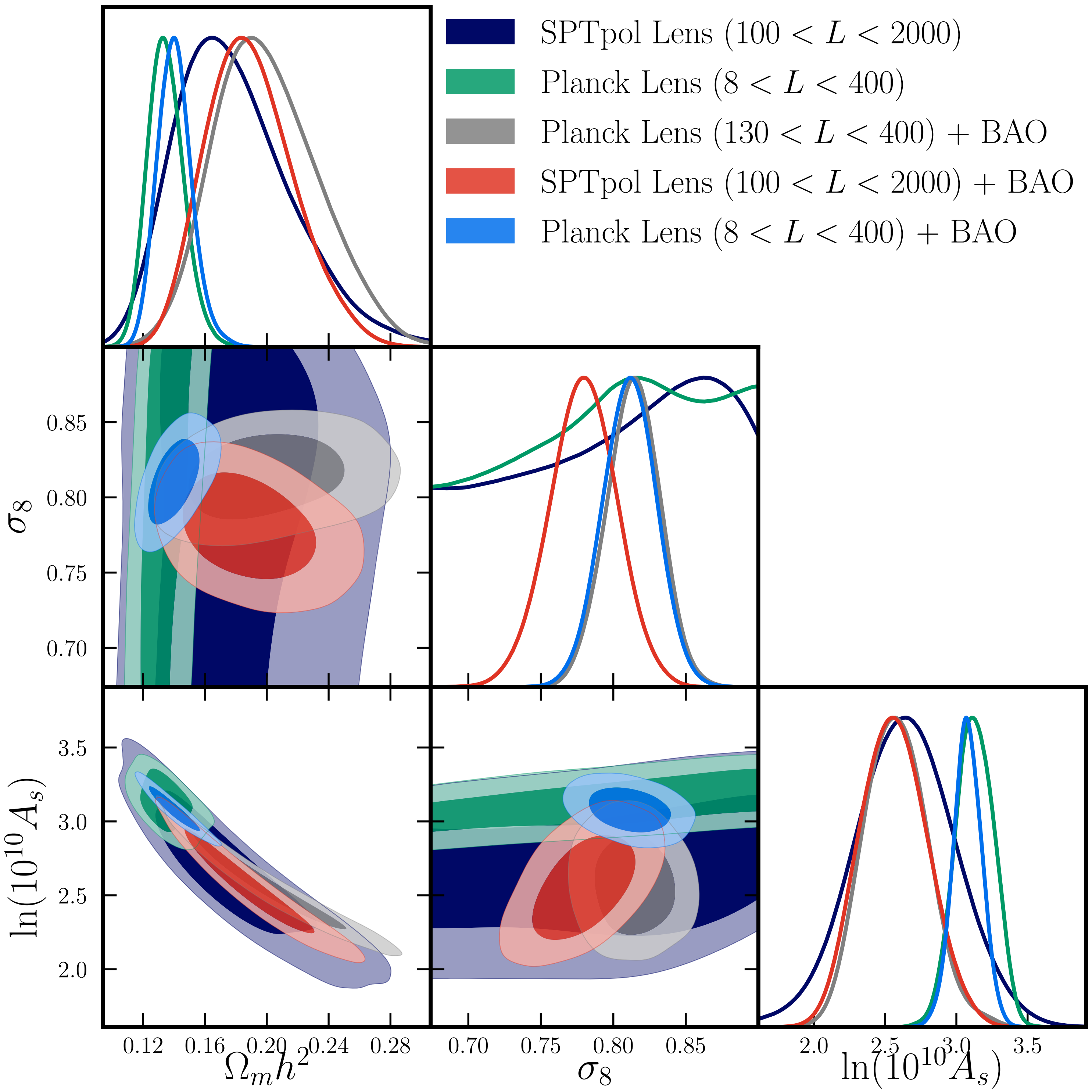
500d CMB lensing constraints
ΛCDM: Ω_M vs σ_8



- Constraining power similar to galaxy lensing $S_8 = 0.86 \pm 0.11$ (SPTpol lensing)
- But degeneracy orientation different due to lower-z of source plane

Adding BAO information

Lensing is sensitive to $\sigma_8\Omega_m^{0.25}\left(\Omega_m h^2\right)^{-0.37}$, degeneracies can be broken by including BAO measurements



$H_0 = 72.0^{+2.1}_{-2.5}$ km s^{-1} Mpc^{-1}
$\sigma_8 = 0.779 \pm 0.023$
$\Omega_m = 0.368^{+0.032}_{-0.037}$
SPTPOL lensing + BAO

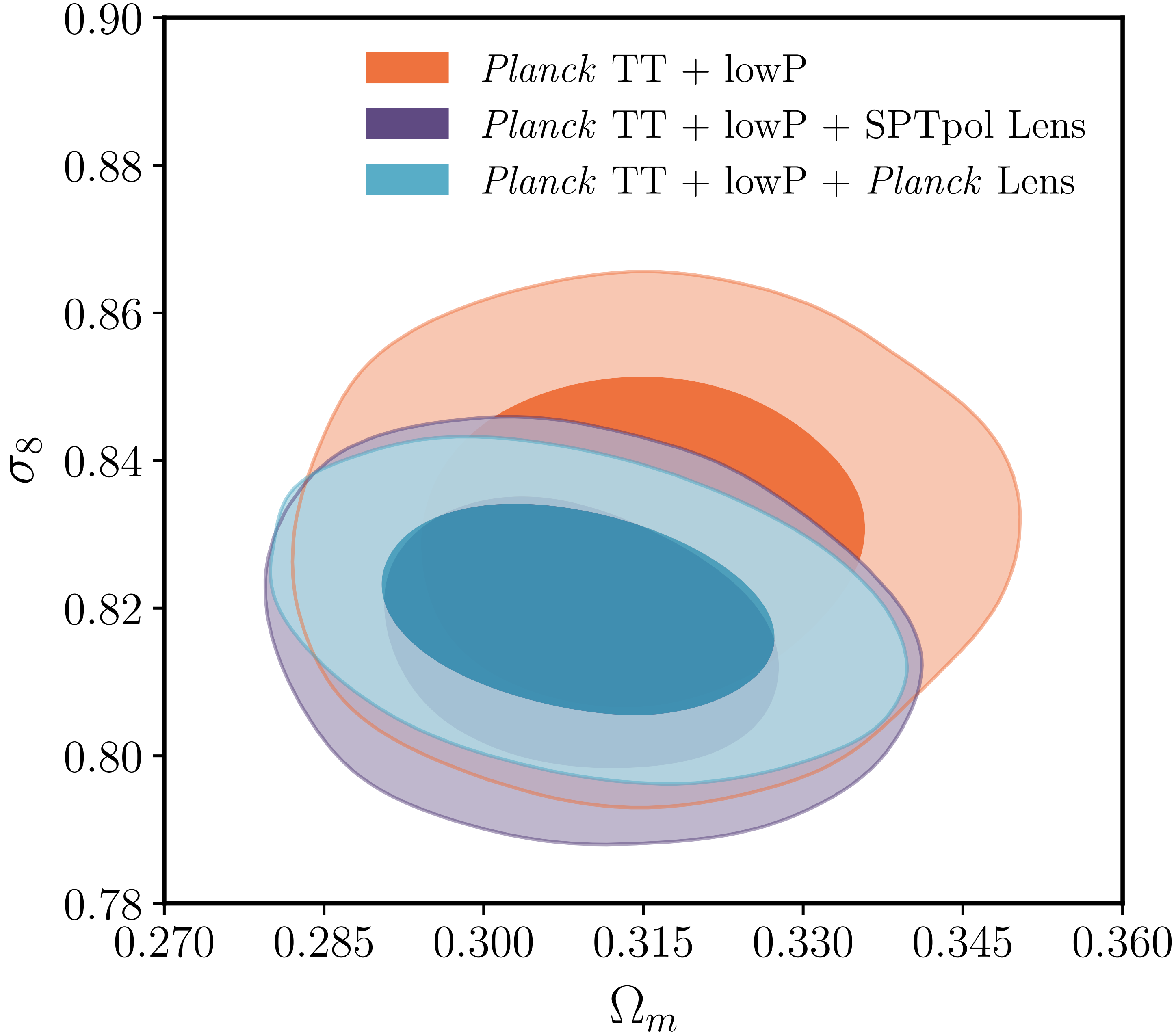
$H_0 = 67.9^{+1.1}_{-1.3}$ km s^{-1} Mpc^{-1}
$\sigma_8 = 0.811 \pm 0.019$
$\Omega_m = 0.303^{+0.016}_{-0.018}$
***Planck* lensing** + BAO

$H_0 = 72.6^{+2.3}_{-2.9}$ km s^{-1} Mpc^{-1}
$\sigma_8 = 0.814 \pm 0.019$
$\Omega_m = 0.379^{+0.036}_{-0.042}$
***Planck* lensing** $135 < L < 400$ + BAO

see also Wu+20 (arxiv:2004.10207)

Joint Constraints from Primary CMB and Lensing

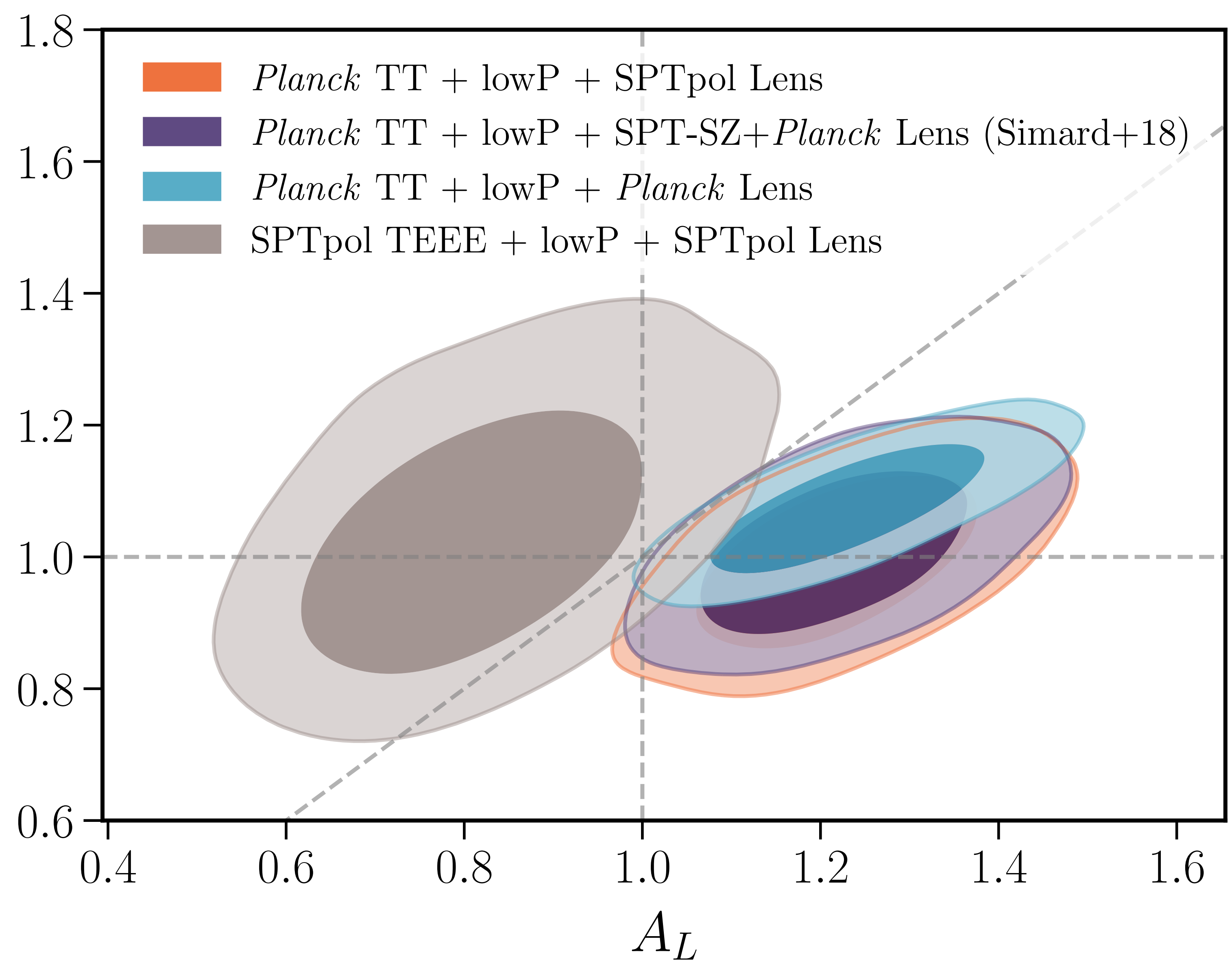
When primary CMB data are included, the lensing power spectrum shape is almost fixed, but the amplitude still has freedom, this helps breaking the $A_s e^{-2\tau}$ (and geometrical) degeneracy



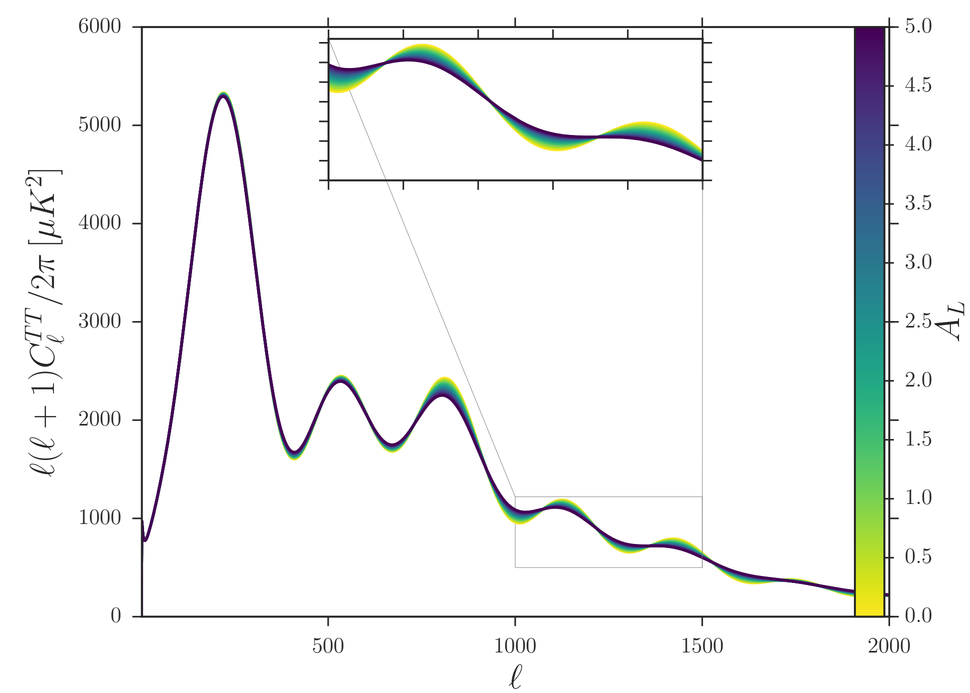
Lensing is consistent with ΛCDM predictions

Lensing smears the acoustic peaks in the primary CMB TT/TE/EE spectra (effect quantified by the *unphysical* parameter A_L)

$C_L^{\phi\phi}$ scaling



CMB peak smoothing scaling



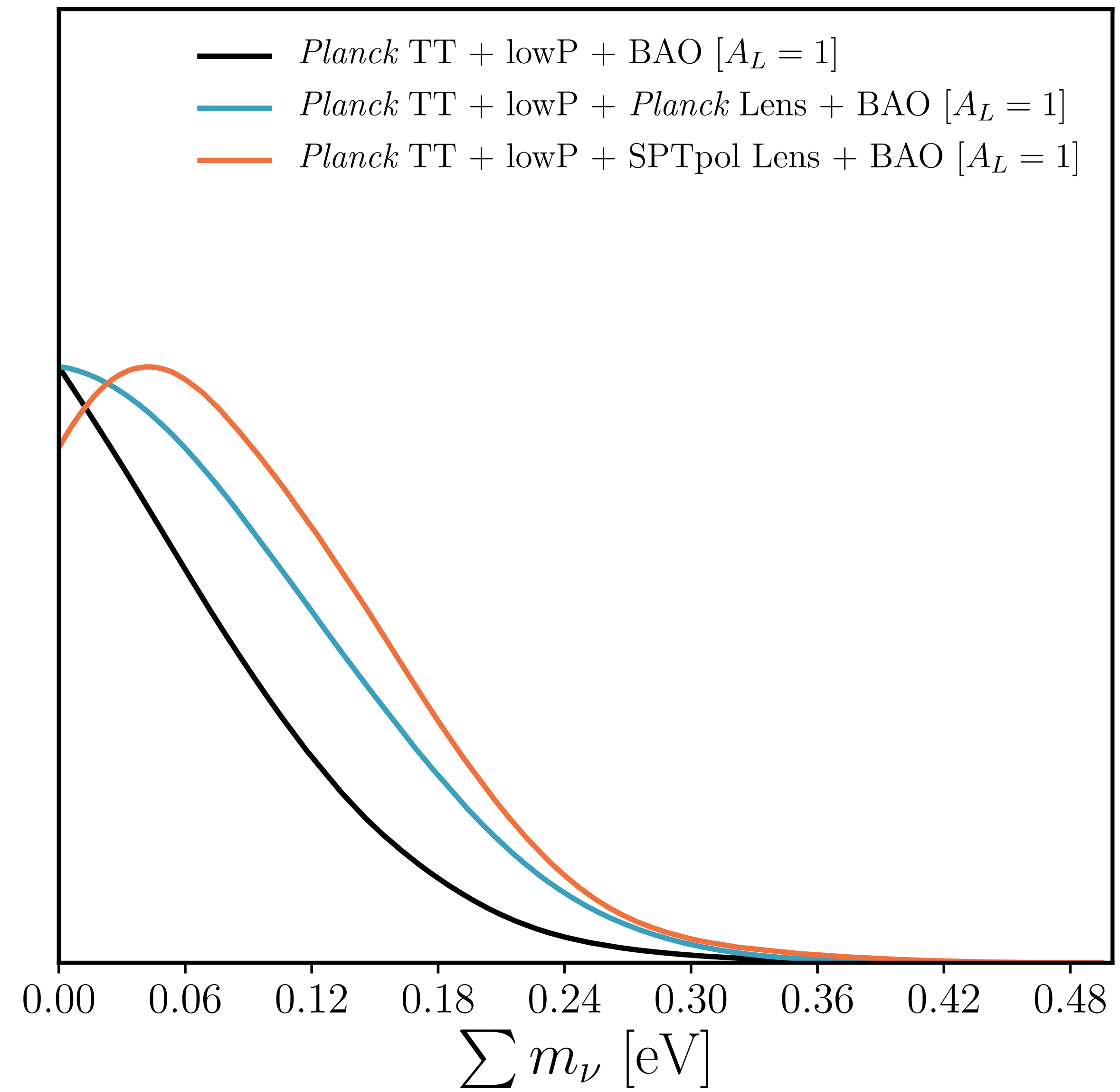
Massive neutrinos*

Massive neutrinos suppress the growth of structure below the neutrino free-streaming length, resulting in a scale-dependent suppression of $C_L^{\phi\phi}$

$\sum m_\nu < 0.20$ eV (95%), (PLANCKTT + LOWP) + BAO

$\sum m_\nu < 0.23$eV (PLANCKTT + LOWP + BAO + SPTPOL lensing, 95%),

$\sum m_\nu < 0.22$eV (PLANCKTT + LOWP + BAO + *Planck* lensing, 95%),



*we consider one single family of massive neutrinos

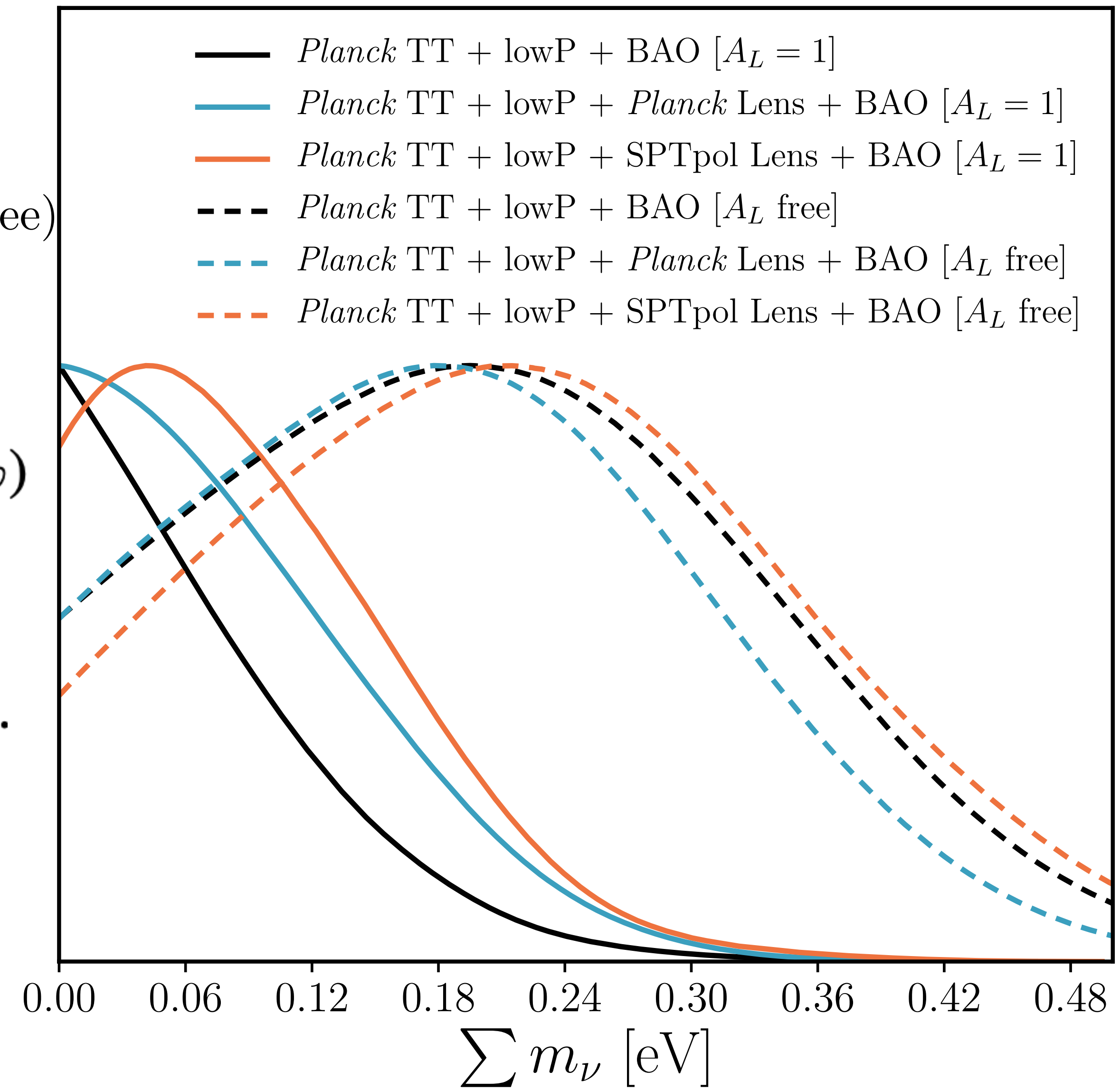
Massive neutrinos*

We can remove the primary CMB sensitivity to lensing by marginalising over A_L

$\sum m_\nu < 0.430\mathrm{eV}(95\%)$ (PLANCKTT + LOWP $[A_L]$free)

$\sum m_\nu < 0.45\mathrm{eV}$ (PLANCKTT + LOWP + BAO + SPTPOL lensing$[A_L$ free], 95%)

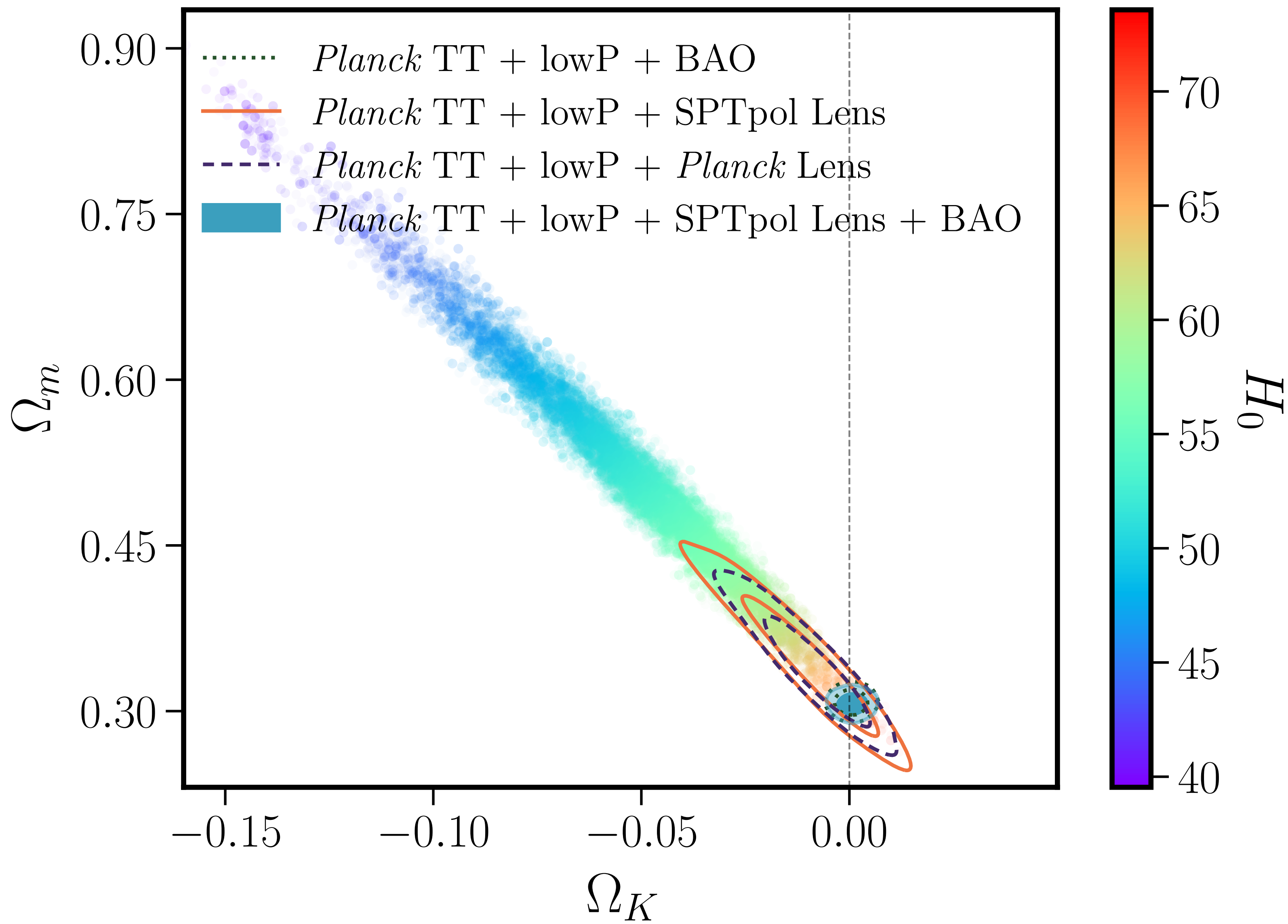
$\sum m_\nu < 0.39\mathrm{eV}$ (PLANCKTT + LOWP + BAO + *Planck* lensing$[A_L$ free], 95%).



*we consider one single family of massive neutrinos

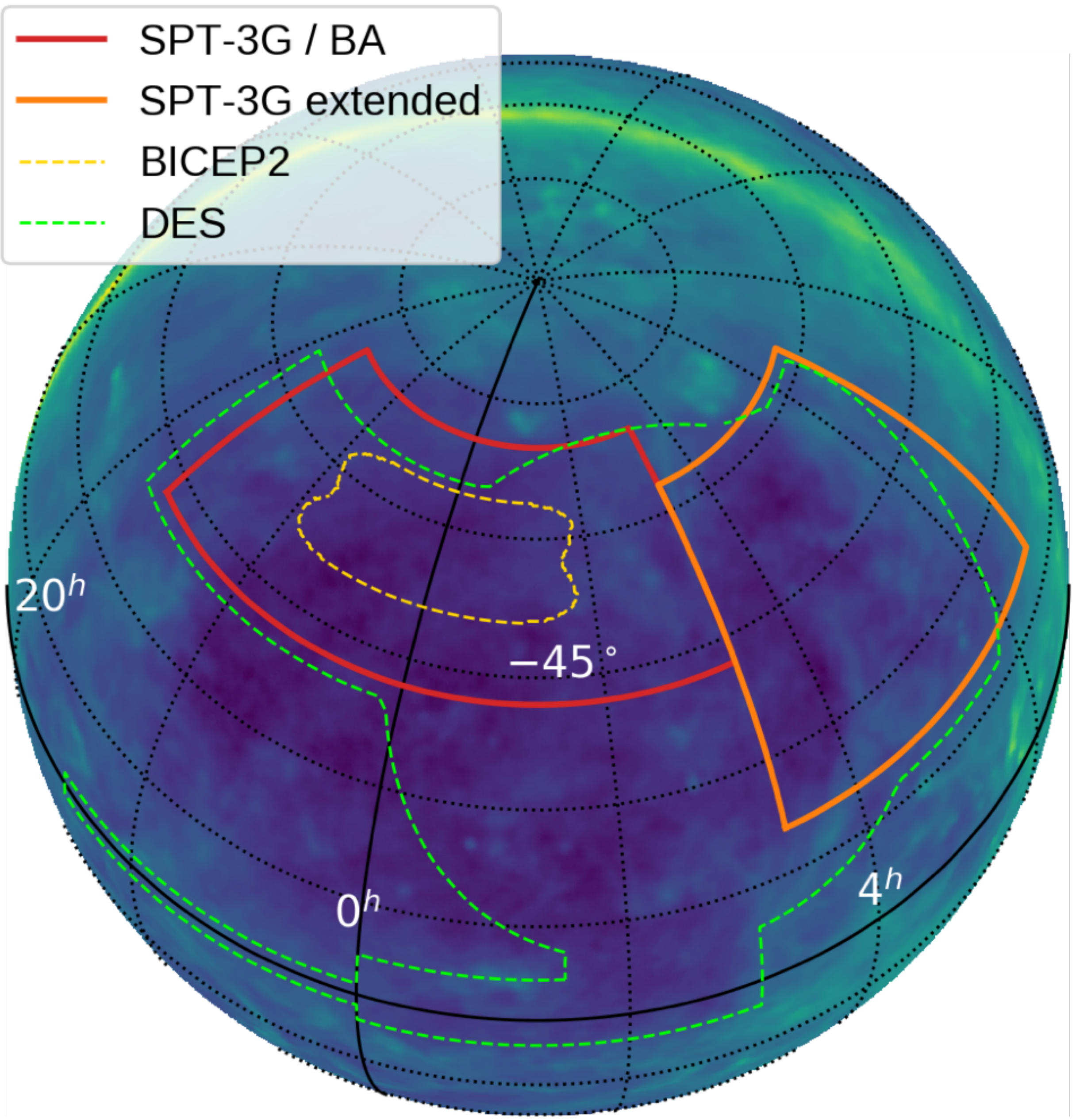
Curvature

Primary CMB affected by the geometrical degeneracy: models with similar matter content and angular-diameter distance to the last-scattering surface will produce nearly indistinguishable CMB power spectra…but lensing can break it!



Lensing measurements consistent with a flat LCDM model

The SPT-3G 1500 deg² Survey



Credit: A. Anderson

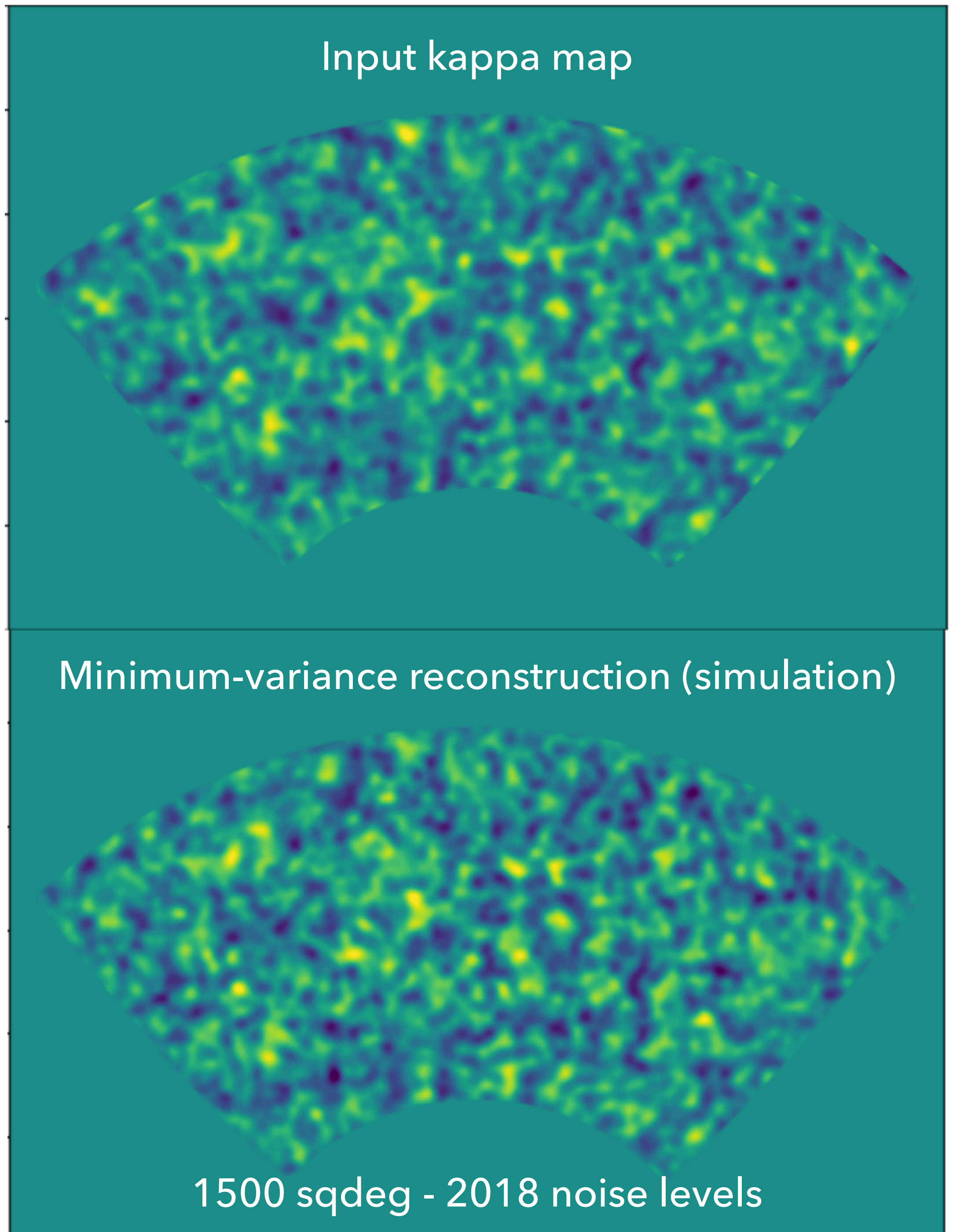
Deep survey complements measurements from a wide survey. For SPT-3G:

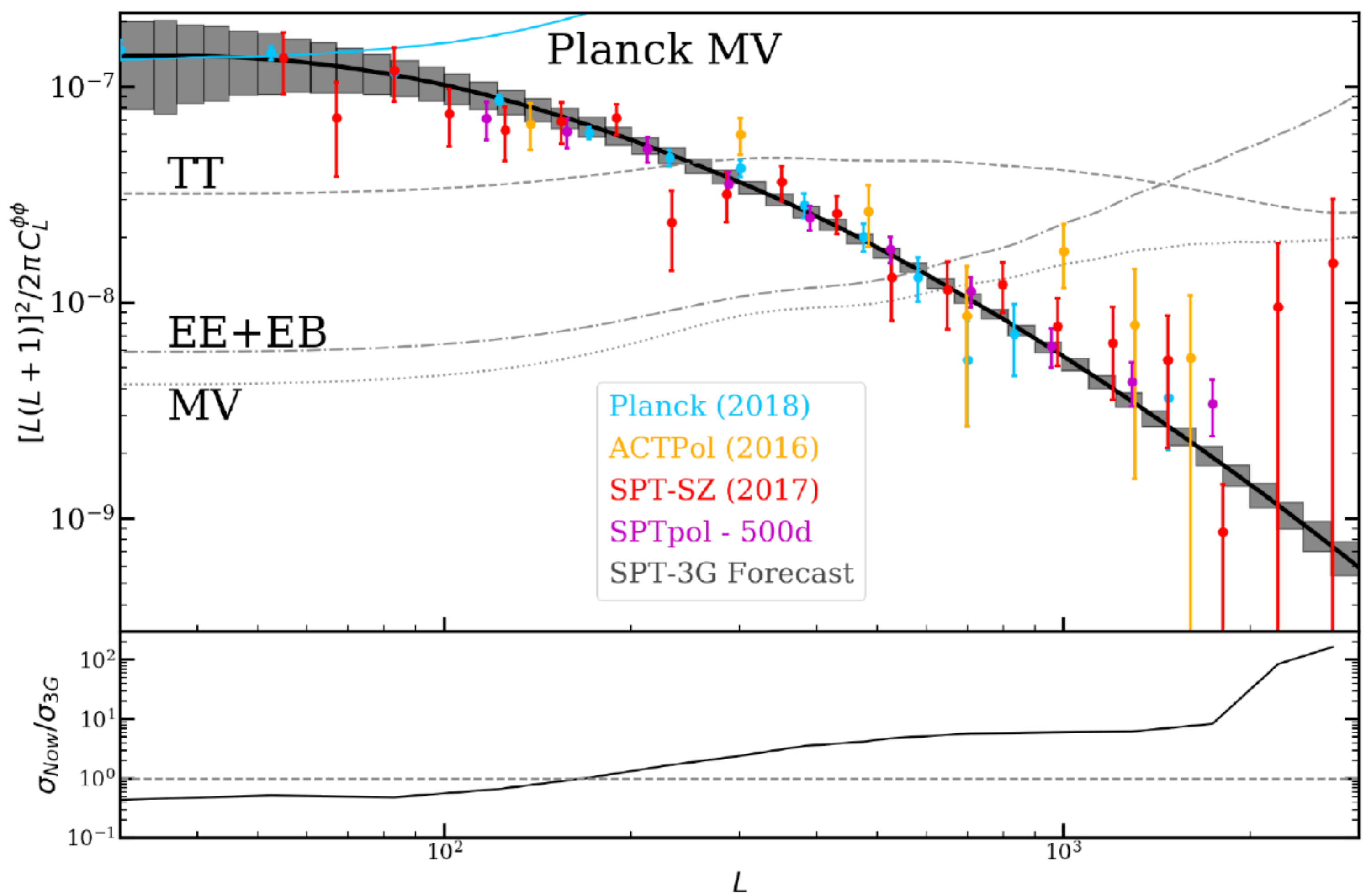
- ***Damping Tail Physics:*** *Improve S/N of CMB power spectra by factors of > ~10 at ℓ>2500 over current constraints*
- ***CMB lensing:*** *cross-correlations, cluster lensing, de-lensing σ(r) ~ 0.0025*
- ***Clusters:*** *More efficient at finding high-z clusters, discovering clusters at z > 2, proto-clusters out to z > 4*
- ***Transients:*** *Daily observations of 1500 deg² field provide new window into mm-wave transients (e.g., GRBs, FRBs), and mJy-level monitoring of 1000s of blazars*
- ***and more!***

	Obs. Years	Area (deg²)	95 GHz (uK-arcmin)	150 (uK-arcmin)	220 (uK-arcmin)
SPT-3G *(projected)*	2017-23	1500	3.0	2.2	8.8

CMB lensing with SPT-3G

Analysis of the 2018 data is underway (led by Zhaodi Pan at UChicago), S/N expected to increase by ~1.5x



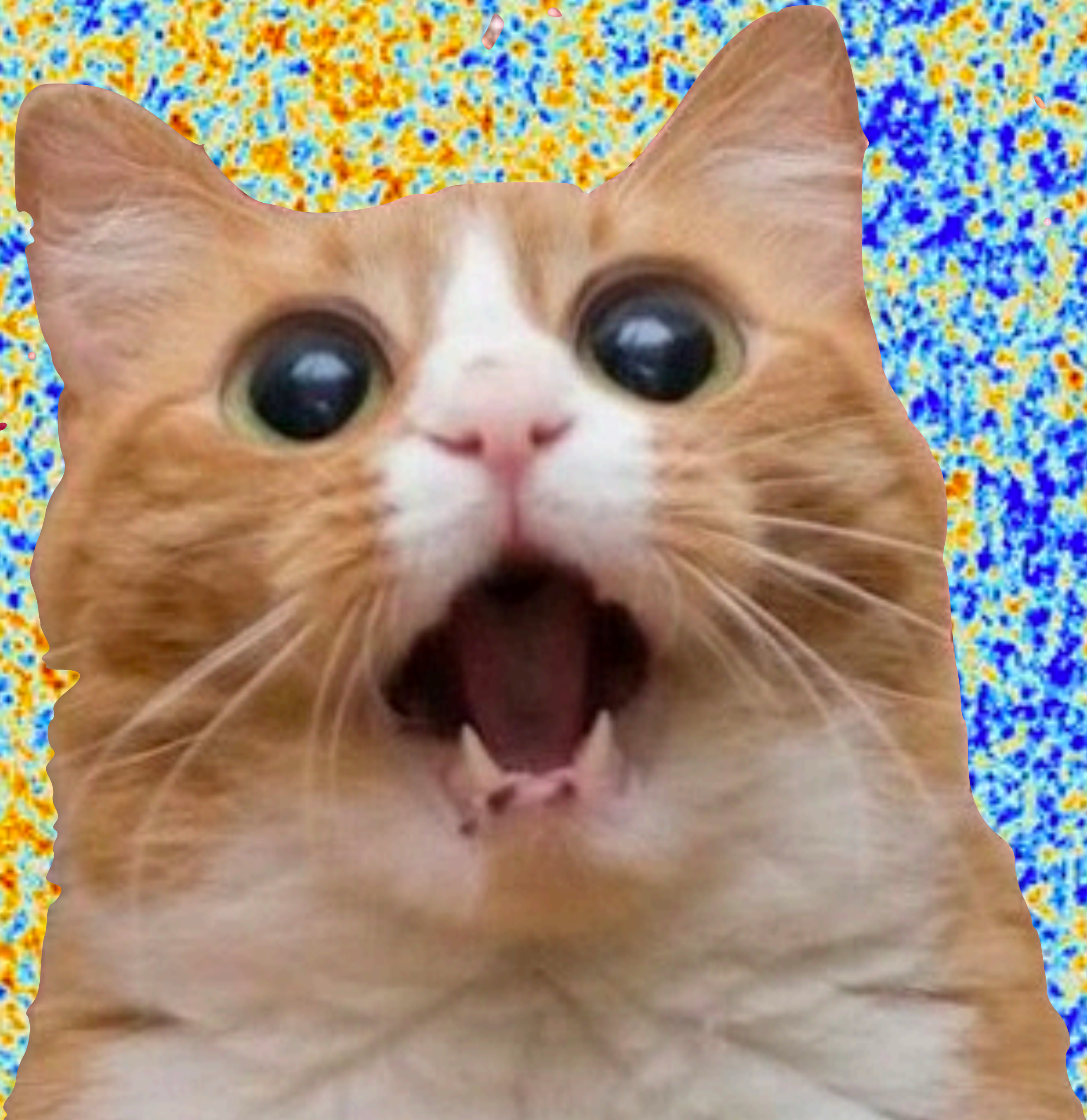


Projected uncertainties from full-survey depth

WRAP-UP

- SPTpol provides the most precise CMB Lensing measurement from the ground
- Cosmological constraints are comparable to Planck and consistent with LCDM
- SPT-3G: deep into our 3rd year of observation with 10x more detectors … stay tuned!

THANKS FOR LISTENING!



Priors

Table 1
Summary of the Priors Imposed on Each Cosmological Parameter in This Work, When Considering Either Lensing-only Data Sets or Also Including Primary CMB Measurements

Parameter	Lensing Only	Lensing + CMB
$\Omega_b h^2$	$\mathcal{N}(0.0222, 0.0005^2)$	$\mathcal{U}(0.005, 0.1)$
$\Omega_c h^2$	$\mathcal{U}(0.001, 0.99)$	$\mathcal{U}(0.001, 0.99)$
H_0 (km s^{-1} Mpc^{-1})	$\mathcal{U}(40, 100)$	$\mathcal{U}(40, 100)$
τ	0.055	$\mathcal{U}(0.01, 0.8)$
n_s	$\mathcal{N}(0.96, 0.02^2)$	$\mathcal{U}(0.8, 1.2)$
$\ln(10^{10}A_s)$	$\mathcal{U}(1.61, 3.91)$	$\mathcal{U}(1.61, 3.91)$
$\sum m_\nu$ (eV)	0.06	0.06 or $\mathcal{U}(0, 5)$
Ω_K	0	0 or $\mathcal{U}(-0.3, 0.3)$
A_L	1	1 or $\mathcal{U}(0, 10)$
$A_L^{\phi\phi}$	1	1 or $\mathcal{U}(0, 10)$

Note. Parameters that are fixed are reported by a single number. $\mathcal{U}(a, b)$ denotes a uniform distribution between $[a, b]$, while $\mathcal{N}(\mu, \sigma^2)$ indicates a Gaussian distribution with mean μ and variance σ^2.

THE UNIVERSITY OF MELBOURNE

CMB lensing likelihood correction

THE UNIVERSITY OF MELBOURNE

Fiducial cosmological parameters θ enter the CMB lensing likelihood in several ways:

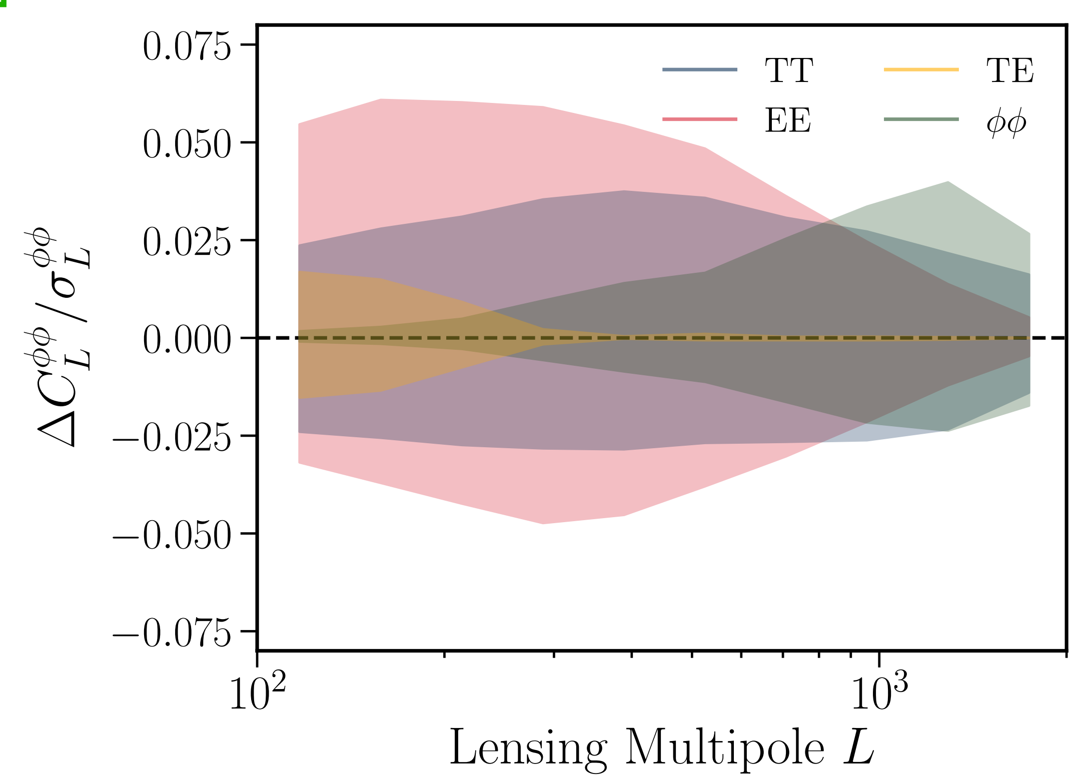
- Directly through the theory power spectrum $C_l^{\phi\phi}$
- Indirectly (non-linearly) through the CMB power spectra needed to calculate the response functions
- Indirectly (linearly) through $C_l^{\phi\phi}$ that appears in the N1 calculation

Corrections

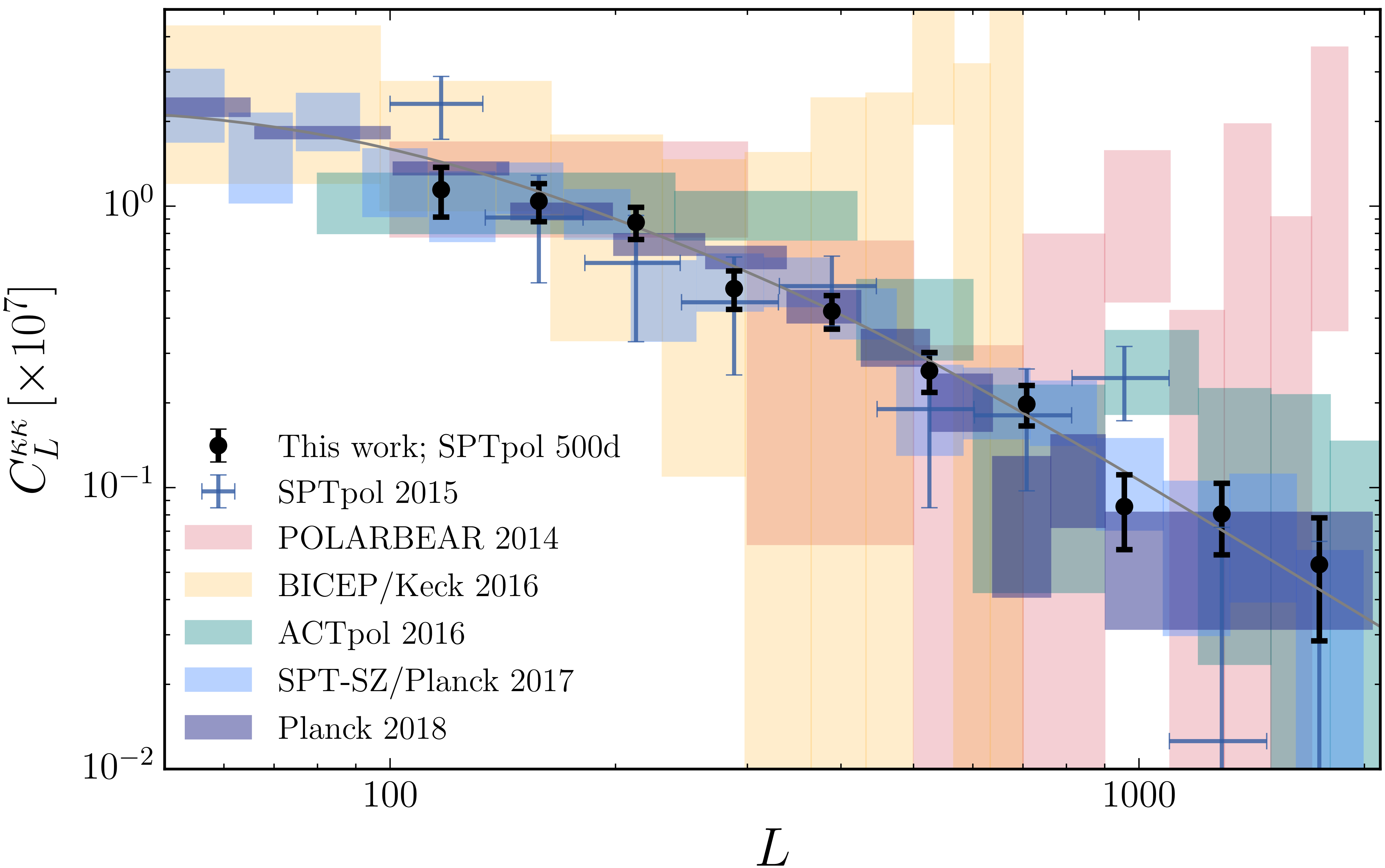
$$
\begin{aligned}
C_L^{\phi\phi} = \boxed{C_L^{\phi\phi}|_\theta} &+ \sum_{XY,WZ} w_L^{XY} w_L^{ZW} \sum_{j\in[TT,TE,EE]} \boxed{\frac{\partial \ln(\mathcal{R}^{XY}\mathcal{R}^{ZW})}{\partial C^j_{L'}}} C_L^{\phi\phi}|_{\rm fid}(C^j_{L'}|_\theta - C^j_{L'}|_{\rm fid}) + \\
&\sum_{XY,WZ} w_L^{XY} w_L^{ZW} \boxed{\frac{\partial N_L^{1,XYZW}}{\partial C_{L'}^{\phi\phi}}} (C_{L'}^{\phi\phi}|_\theta - C_{L'}^{\phi\phi}|_{\rm fid}) \\
= C_L^{\phi\phi}|_\theta &+ \sum_{j\in[TT,TE,EE,\phi\phi]} M^j_{LL'}(C^j_{L'}|_\theta - C^j_{L'}|_{\rm fid})
\end{aligned}
$$

Likelihood

$$
\begin{aligned}
&-2\ln\mathcal{L}_\phi(\mathbf{\Theta}) \\
&= \sum_{ij}[\hat{C}^{\phi\phi}_{L_b^i} - C^{\phi\phi,\rm th}_{L_b^i}(\mathbf{\Theta})]\mathbb{C}^{-1}_{L_b^i L_b^j}[\hat{C}^{\phi\phi}_{L_b^j} - C^{\phi\phi,\rm th}_{L_b^j}(\mathbf{\Theta})].
\end{aligned}
$$

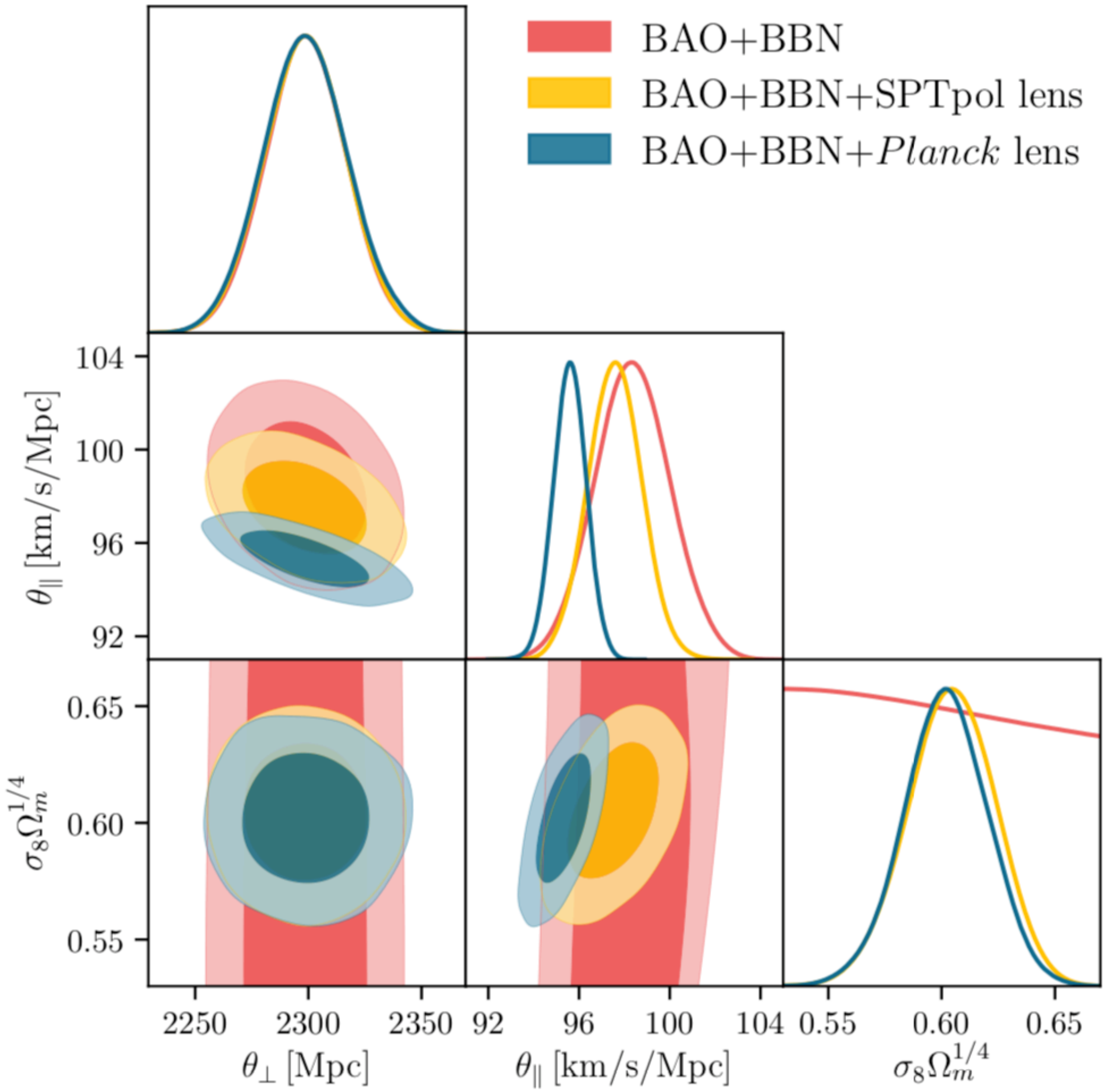


Other CMB lensing power spectra



More on the BAO + CMB Lensing (+BBN)

THE UNIVERSITY OF MELBOURNE



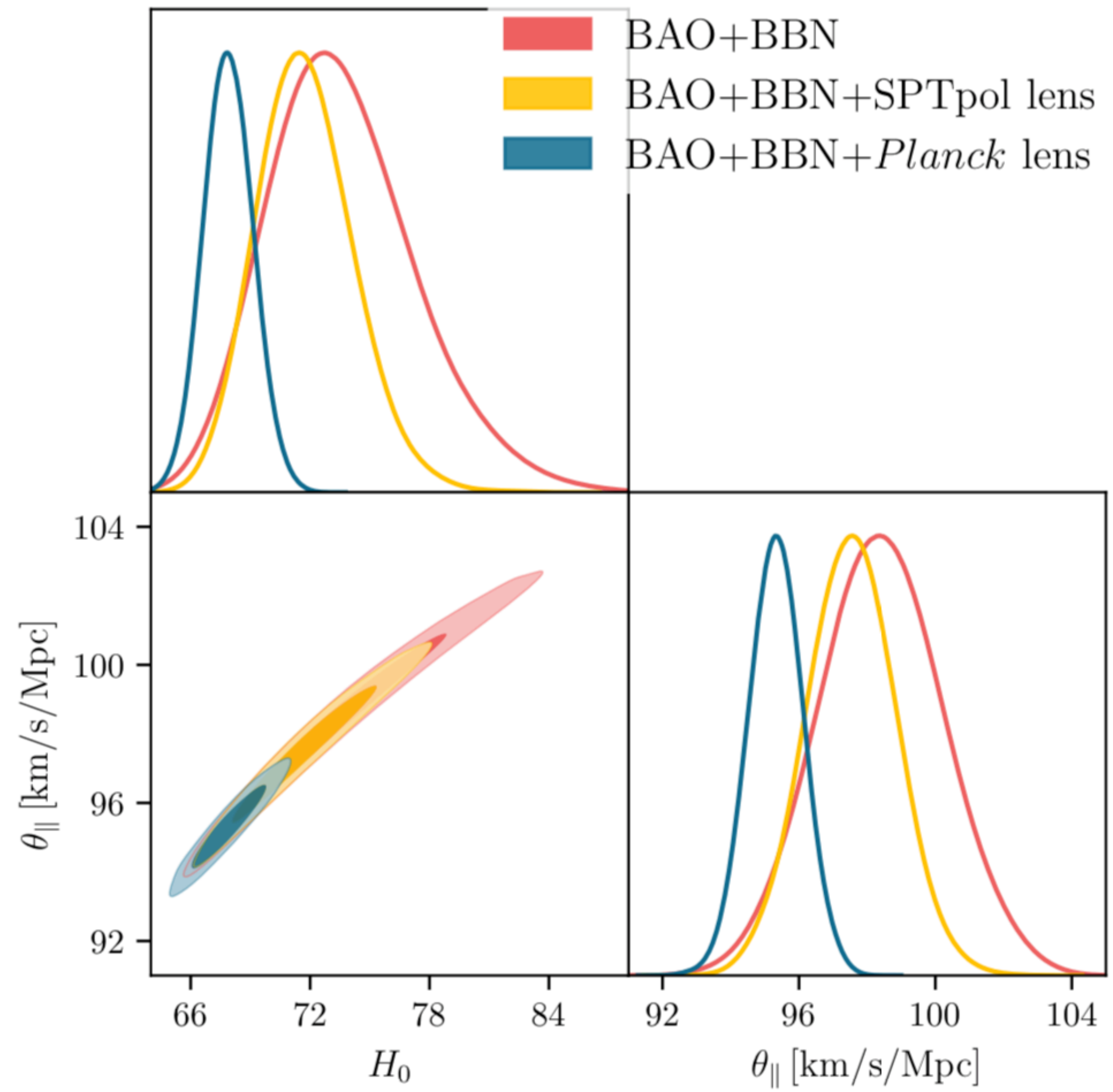
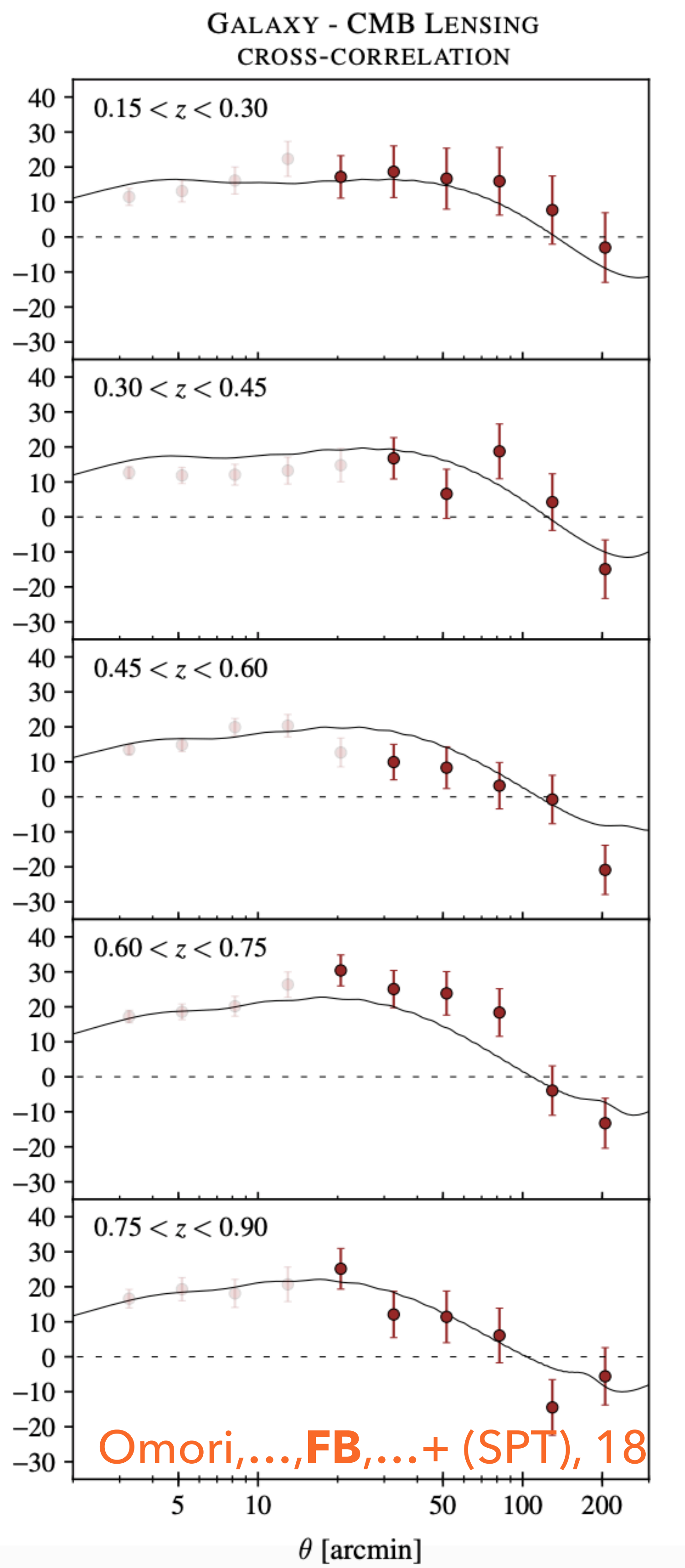


FIG. 1. The posterior distributions of the data sets BAO+BBN, BAO+BBN+SPTpol lensing, BAO+BBN+*Planck* lensing in the parameter basis $[\theta_{\perp}, \theta_{\parallel}, \sigma_8\Omega_m^{1/4}]$ which is native to the BAO and CMB lensing measurements. The posteriors for the combined BAO+BBN+*Planck* lensing+SPTpol lensing data set are not shown for clarity as they are qualitatively close to those from BAO+BBN+*Planck* lensing.

FIG. 2. The posterior distributions of the data sets BAO+BBN, BAO+BBN+SPTpol lensing, BAO+BBN+*Planck* lensing for H_0 and $\theta_{\parallel}$. The differences observed in H_0 are highly correlated with the differences in $\theta_{\parallel}$, which suggests a common origin in the parallel BAO measurements.

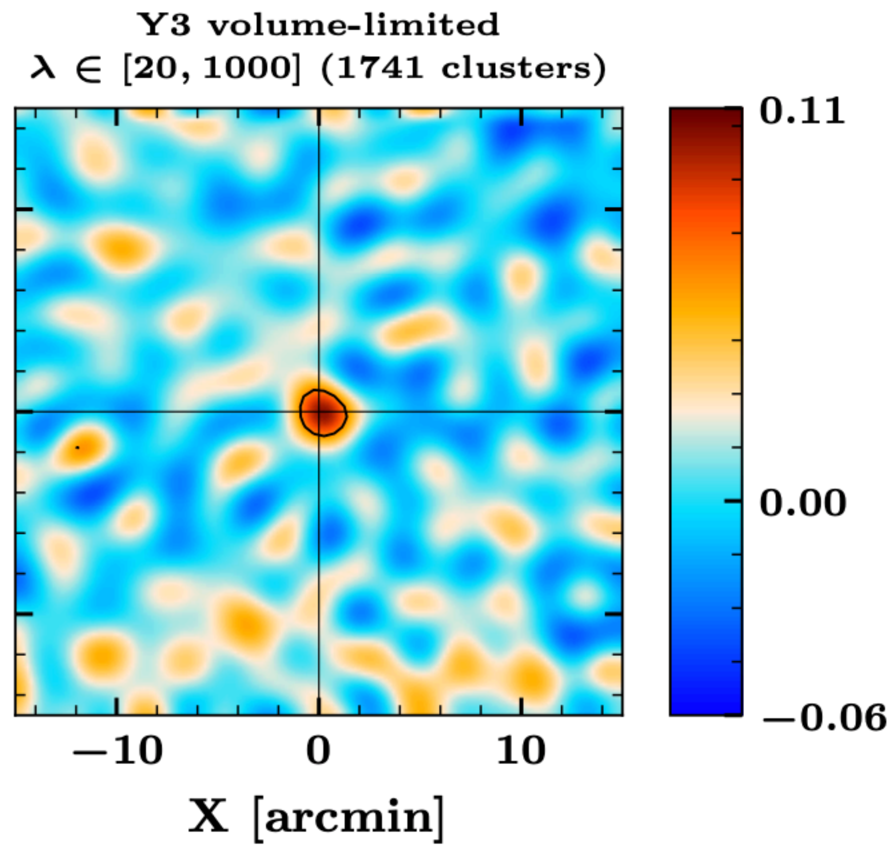
Wu+20

Other lensing measurements w/ SPT



Omori,…,**FB**,…+ (SPT), 18

Cluster lensing



Raghunathan ,…,**FB**,…+ (SPT), 18