Cosmological Parameter Forecasts for a CMB-HD Survey

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Stony Brook University

Cosmological Parameter Forecasts for a CMB-HD Survey

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Image credit: ACT Collaboration

Outline

1. Introduction
2. Forecasting Methods and Data
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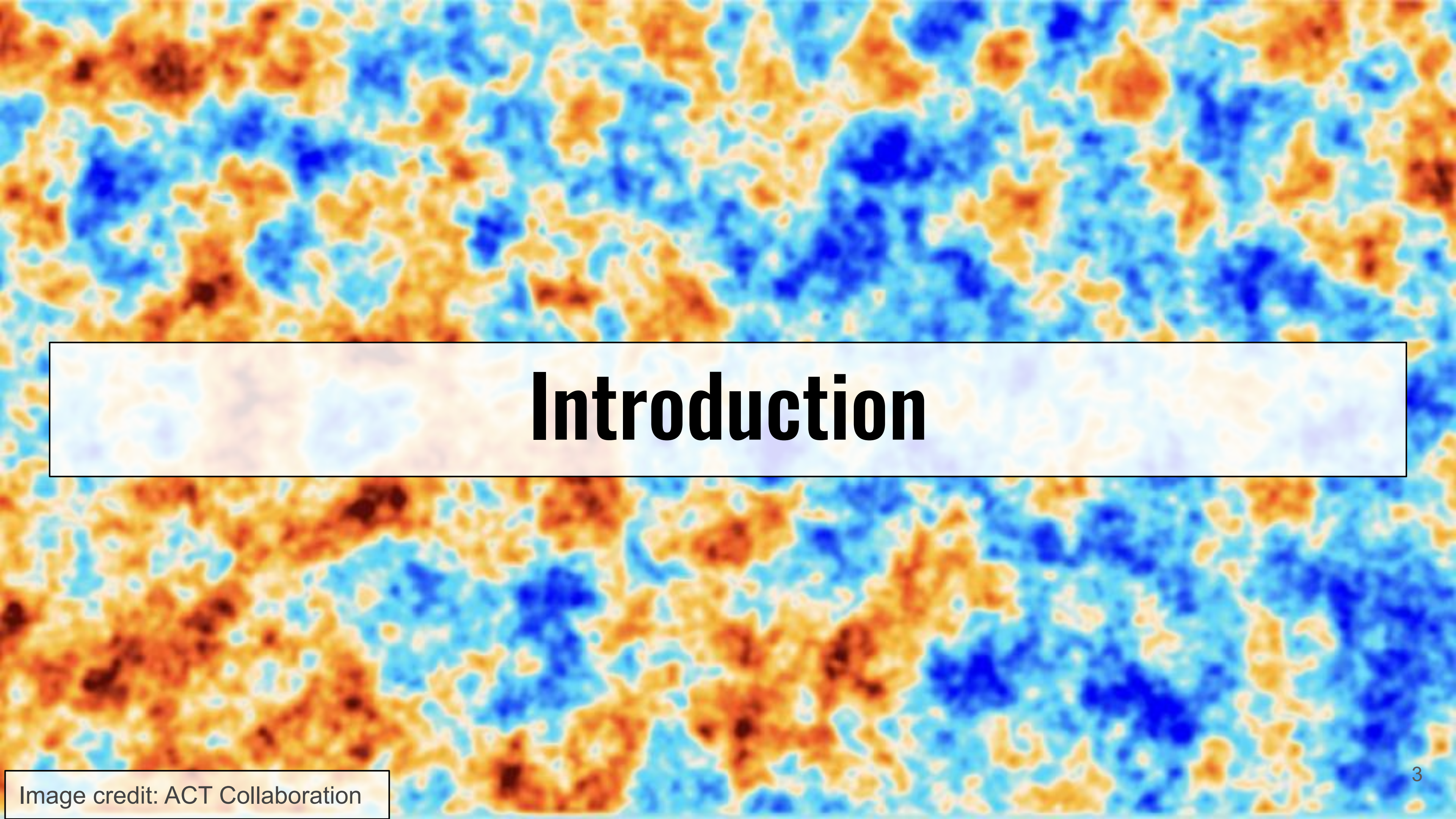
4. Summary

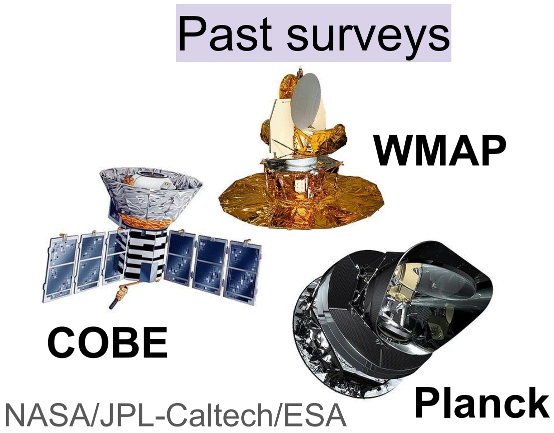
Image credit: ACT Collaboration

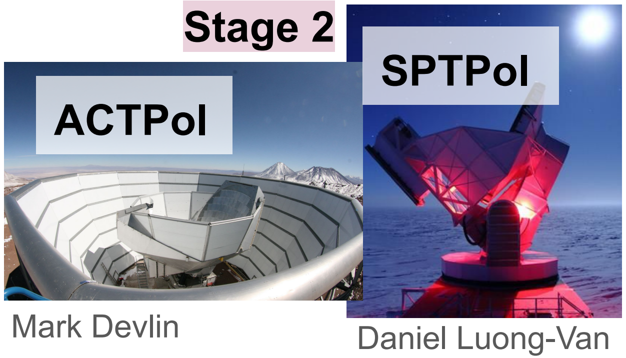


Introduction

Image credit: ACT Collaboration

Timeline of CMB Observations





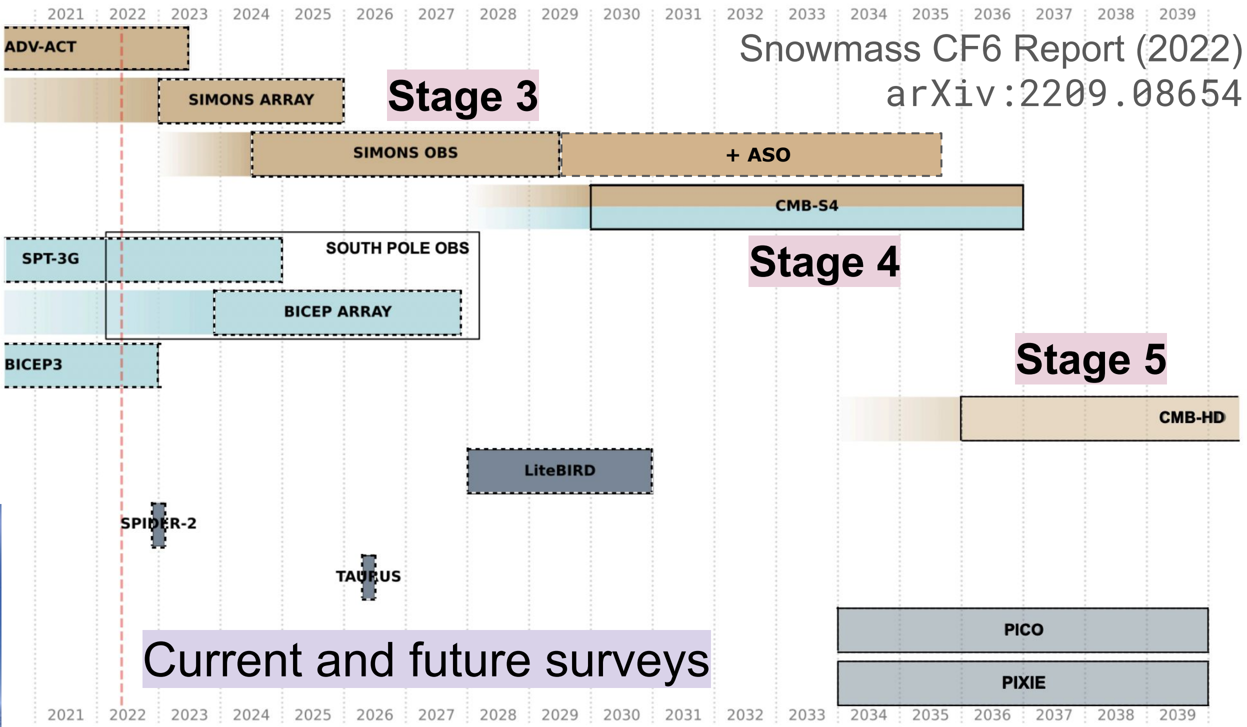


Figure 6-5. *Timeline of current and future ground-based CMB experiments. For context, the timeline also includes a few sub-orbital and satellite experiments in grey. Dashed boxes indicate fully-funded facilities. The fade-in regions indicate commissioning periods, while the boxes indicate full survey observations.*

Image credit: Debra Kellner

Stage-5 CMB: CMB-HD

CMB-HD is a proposed low-noise, high-resolution millimeter-wave survey over half the sky.

- 6 times higher resolution & 3 times lower noise than CMB-S4
- Will measure angular scales $30 < \ell < 20{,}000$
- 7 frequencies from 30 to 350 GHz
- Will be located in the Atacama desert in Chile

Forecasts will assume 90 & 150 GHz data over 60% of the sky, plus delensing, baryonic feedback, and DESI BAO.

Frequency (GHz)	30	40	90	150	220	280	350
Resolution (arcmin)	1.25	0.94	0.42	0.25	0.17	0.13	0.11
White noise level (μK-arcmin)[a]	6.5	3.4	0.7	0.8	2.0	2.7	100.0

[a] Sensitivity is for temperature maps. For polarization maps, the noise is $\sqrt{2}$ higher.

(Snowmass 2021 CMB-HD White Paper; arXiv:2203.05728)

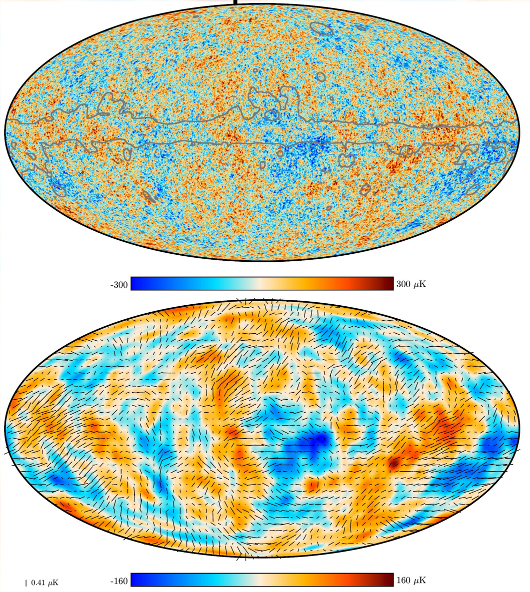
CMB HD

cmb-hd.org

CMB Anisotropies

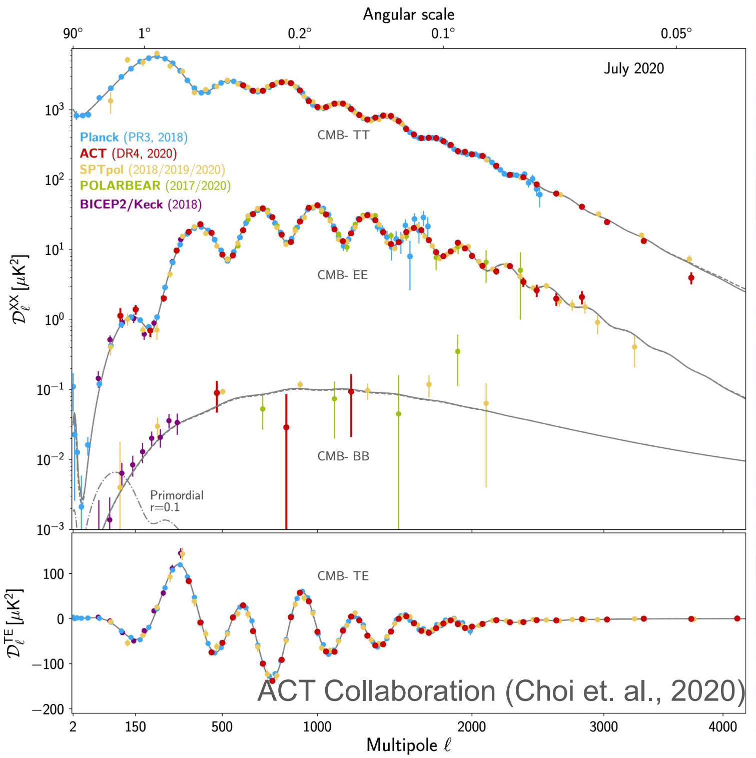
Maps → **Power spectra** → **Parameters**

Temperature

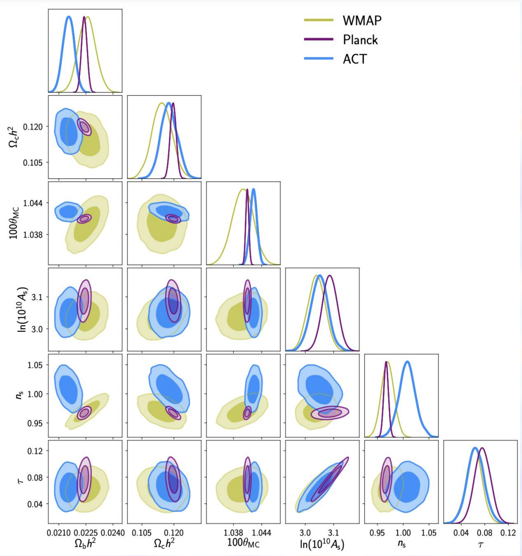


Polarization

ESA and the Planck Collaboration (2018)



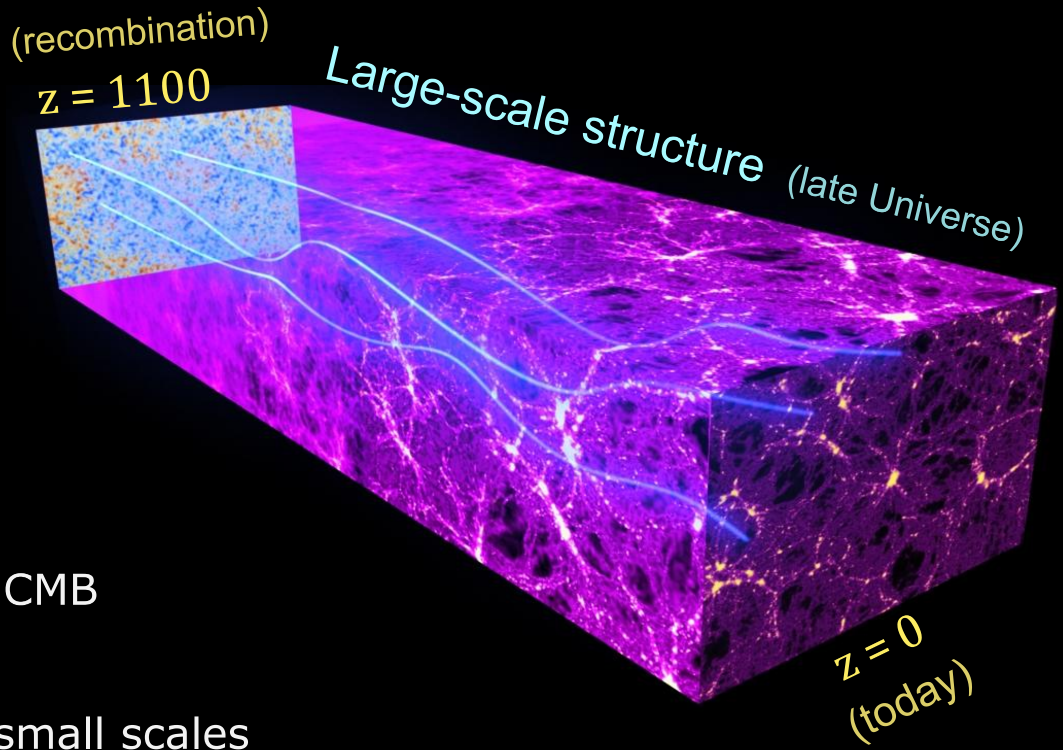
ACT Collaboration (Choi et. al., 2020)



ACT Collaboration (Aiola et. al., 2020)

CMB Lensing

Probes the matter distribution using the primary CMB as the backlight, without relying on baryonic tracers.



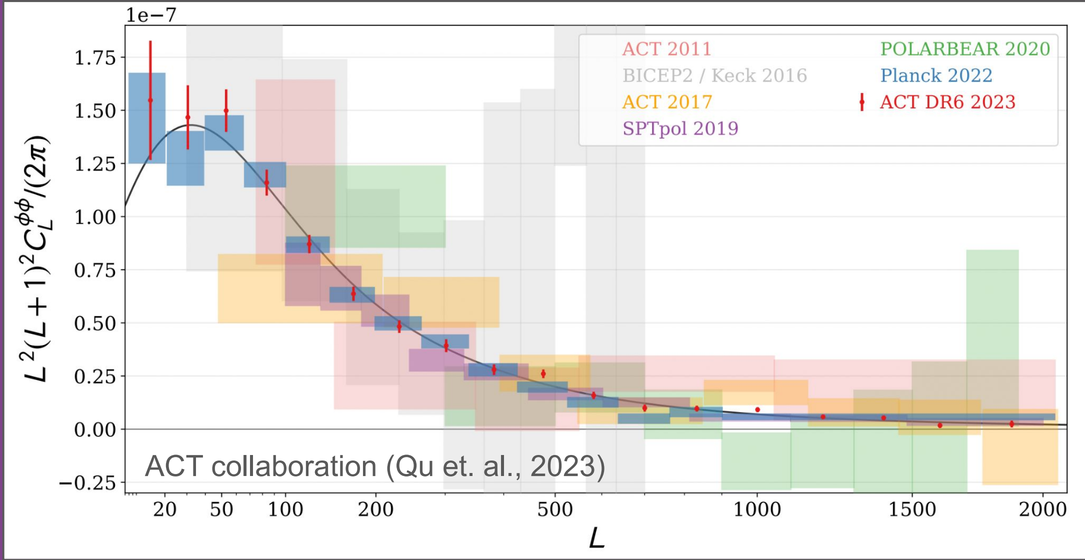
- Couples modes of the primary CMB
- Smooths the acoustic peaks
- Transfers power from large to small scales
- Converts E-mode polarization into B-modes

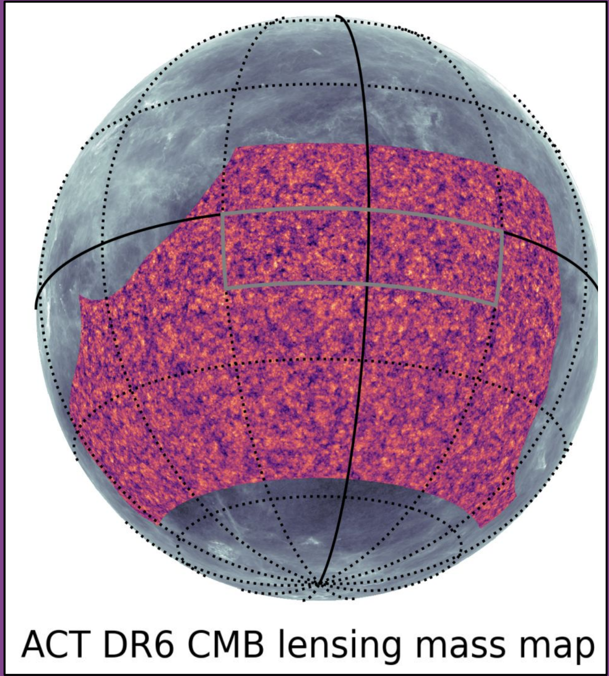
A. Lewis & A. Challinor (2006)

CMB Lensing Reconstruction

Use the lensed CMB to reconstruct a map of the gravitational lensing potential

→ Measure CMB lensing power spectrum
→ Delens the CMB





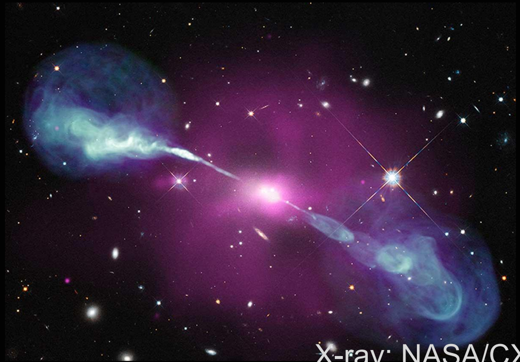
ACT collaboration (Madhavacheril et. al., 2023)

A. Lewis & A. Challinor (2006); D. Green et. al. (2017)

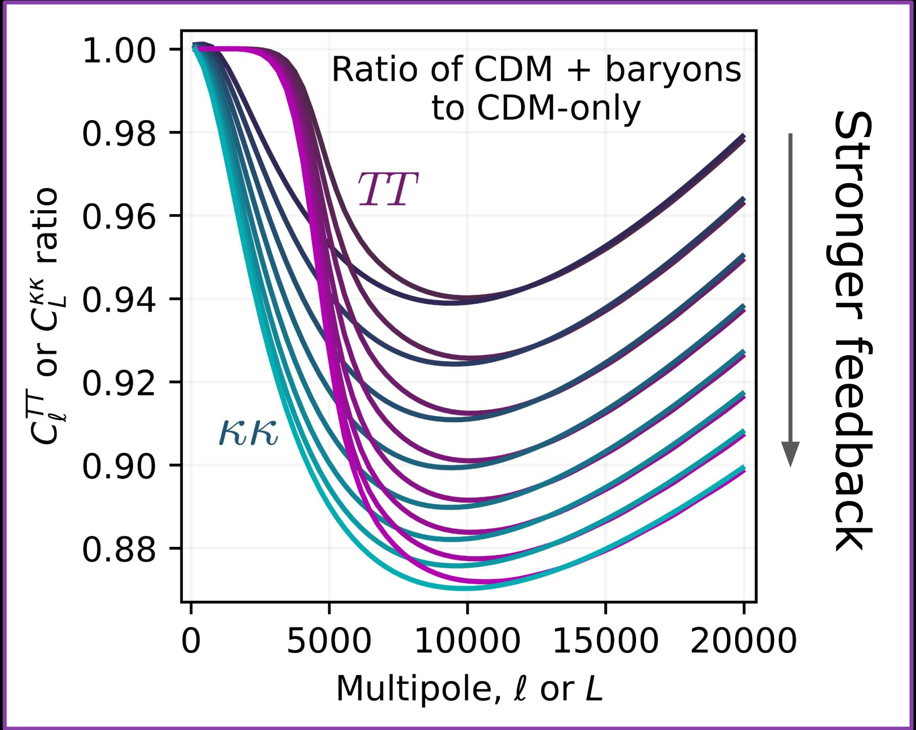
Baryonic Feedback

Baryonic feedback processes change the matter distribution on small scales

- Can be probed by small-scale CMB lensing



X-ray: NASA/CXC/SAO
visual: NASA/STScI
radio: NSF/NRAO/VLA



A. Mead et. al. (2020)

Forecasting Methods and Data

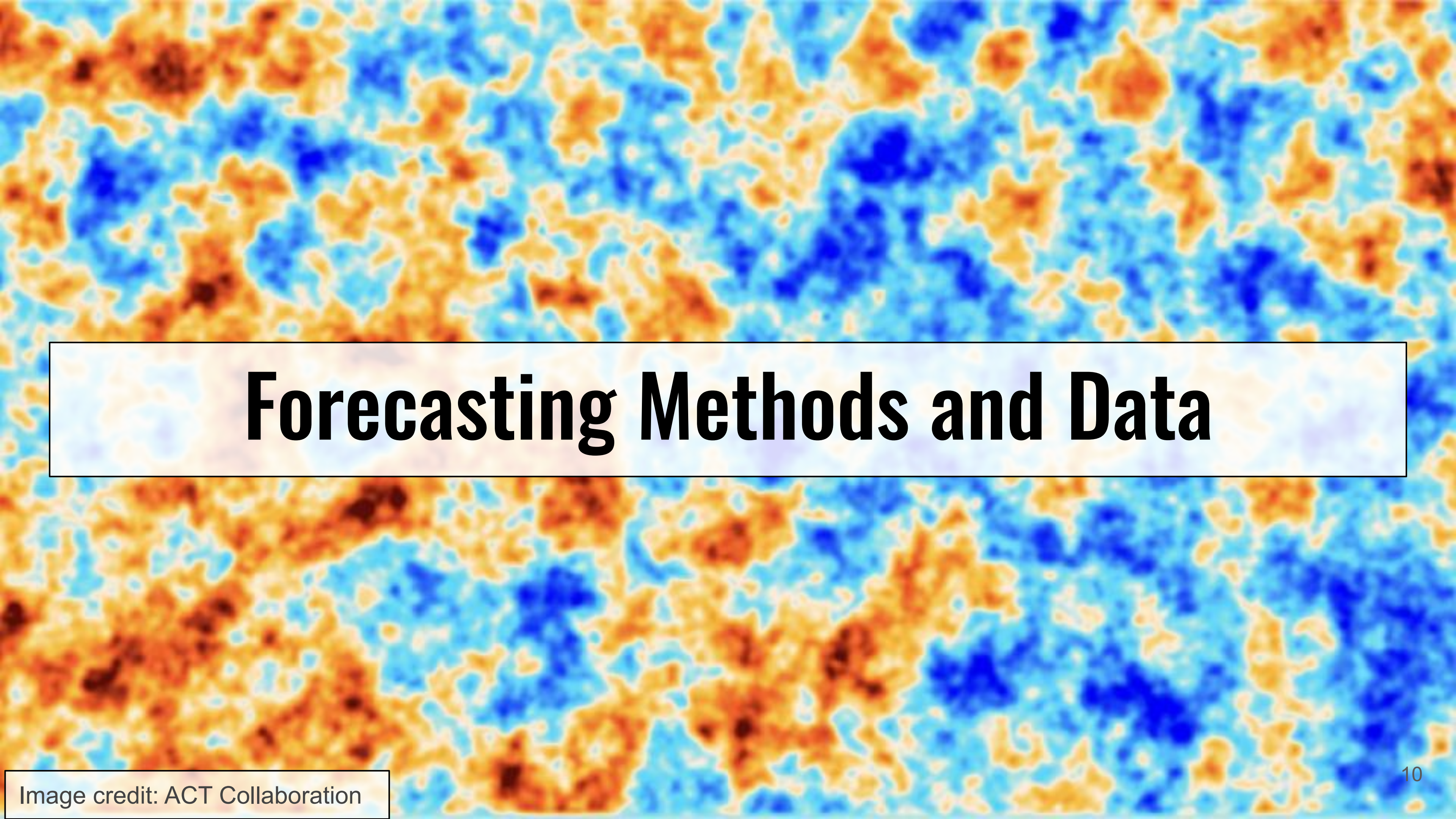
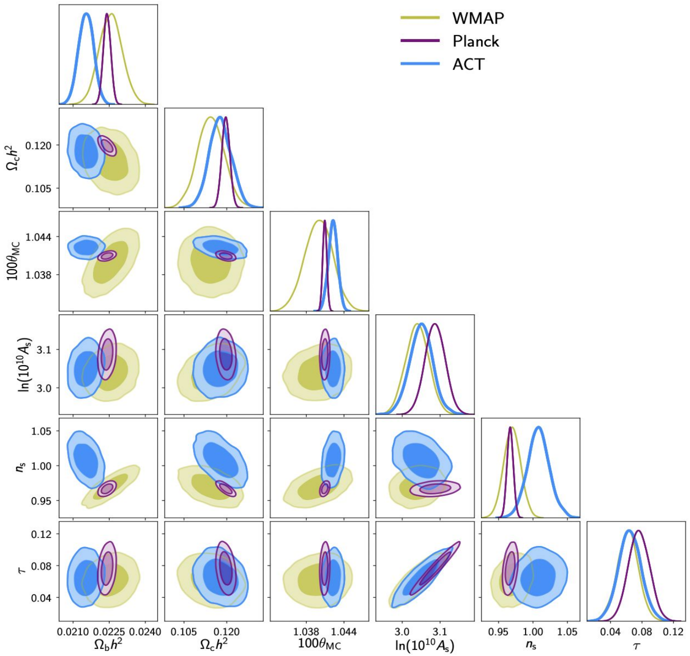


Image credit: ACT Collaboration

Forecasting Methods



ACT Collaboration (Aiola et. al., 2020)

8-parameter model: $\Lambda\text{CDM} + N_{\text{eff}} + \sum m_\nu$

+ prior $\sigma(\tau) = 0.007$ from *Planck* (2018)

Data from CMB-HD + DESI BAO

(A. Aghamousa et. al., 2016)

Fisher matrix: baseline method

- Quick, but assumes Gaussian parameter posteriors

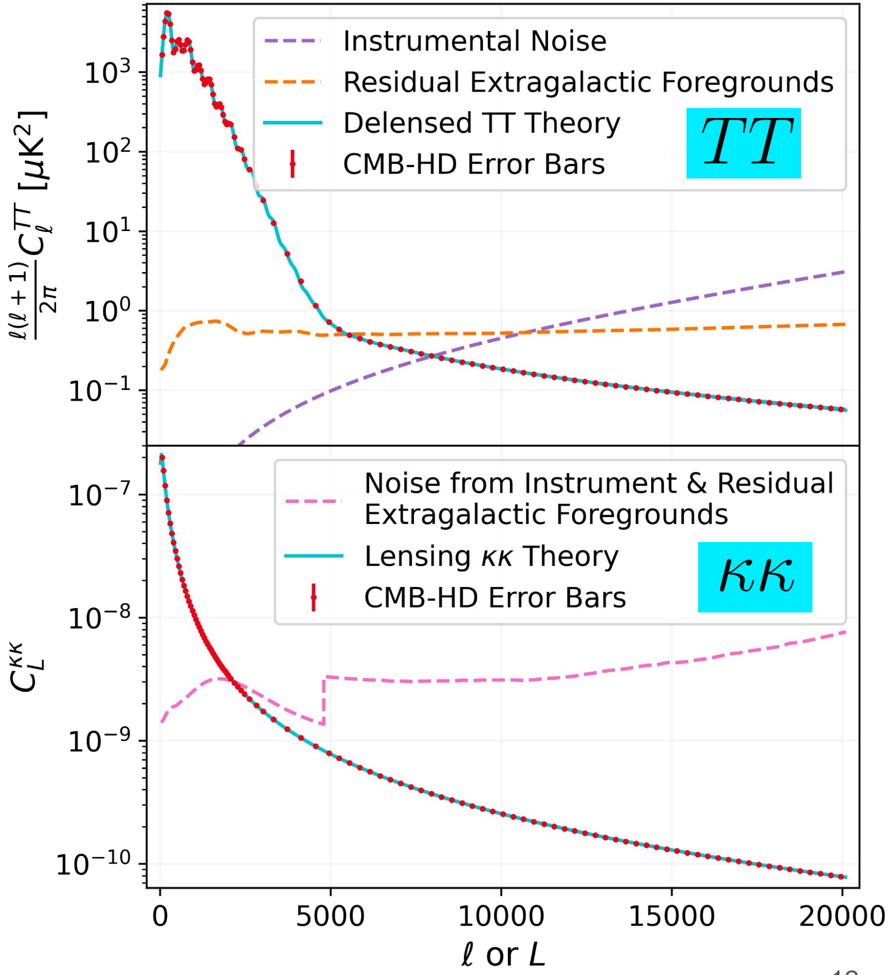
Markov chain Monte Carlo (MCMC): used to check Fisher

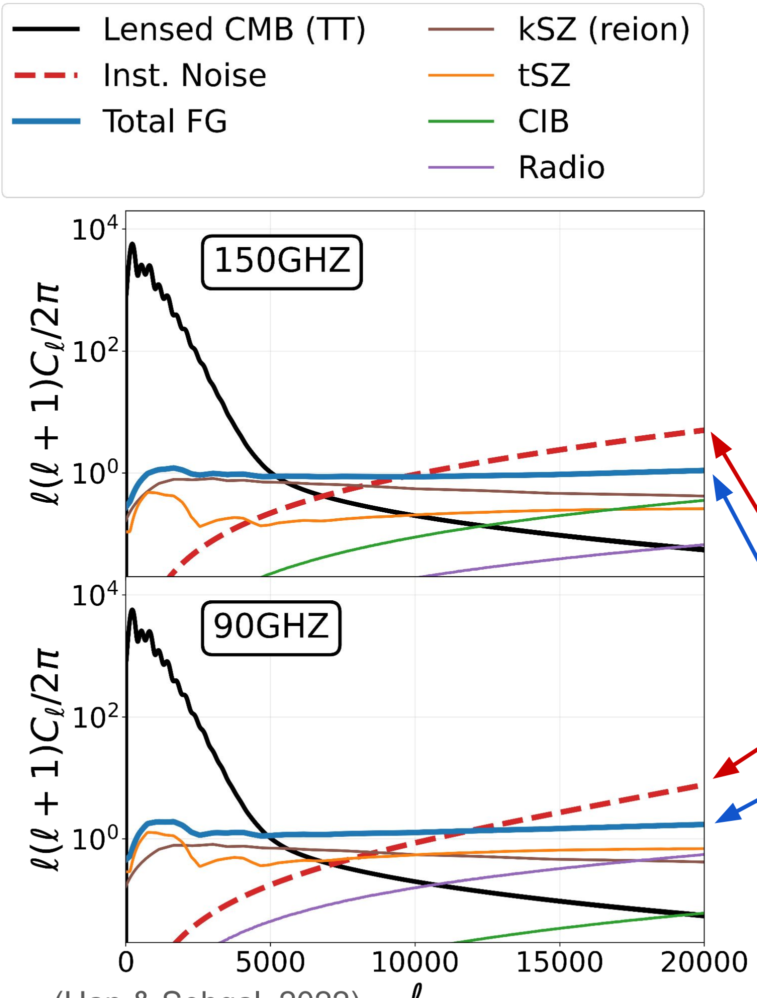
- Slower, but can recover non-Gaussian parameter posteriors

CMB-HD Data: Power Spectra

Lensed or delensed CMB *TT*, *TE*, *EE*, *BB* power spectra + CMB lensing $\kappa\kappa$ power spectrum

- Multipoles $\ell \in [1000, 20000]$
  - (Multipoles $\ell \in [30, 1000]$ from ASO)
- Combined noise + foregrounds from 90 and 150 GHz channels





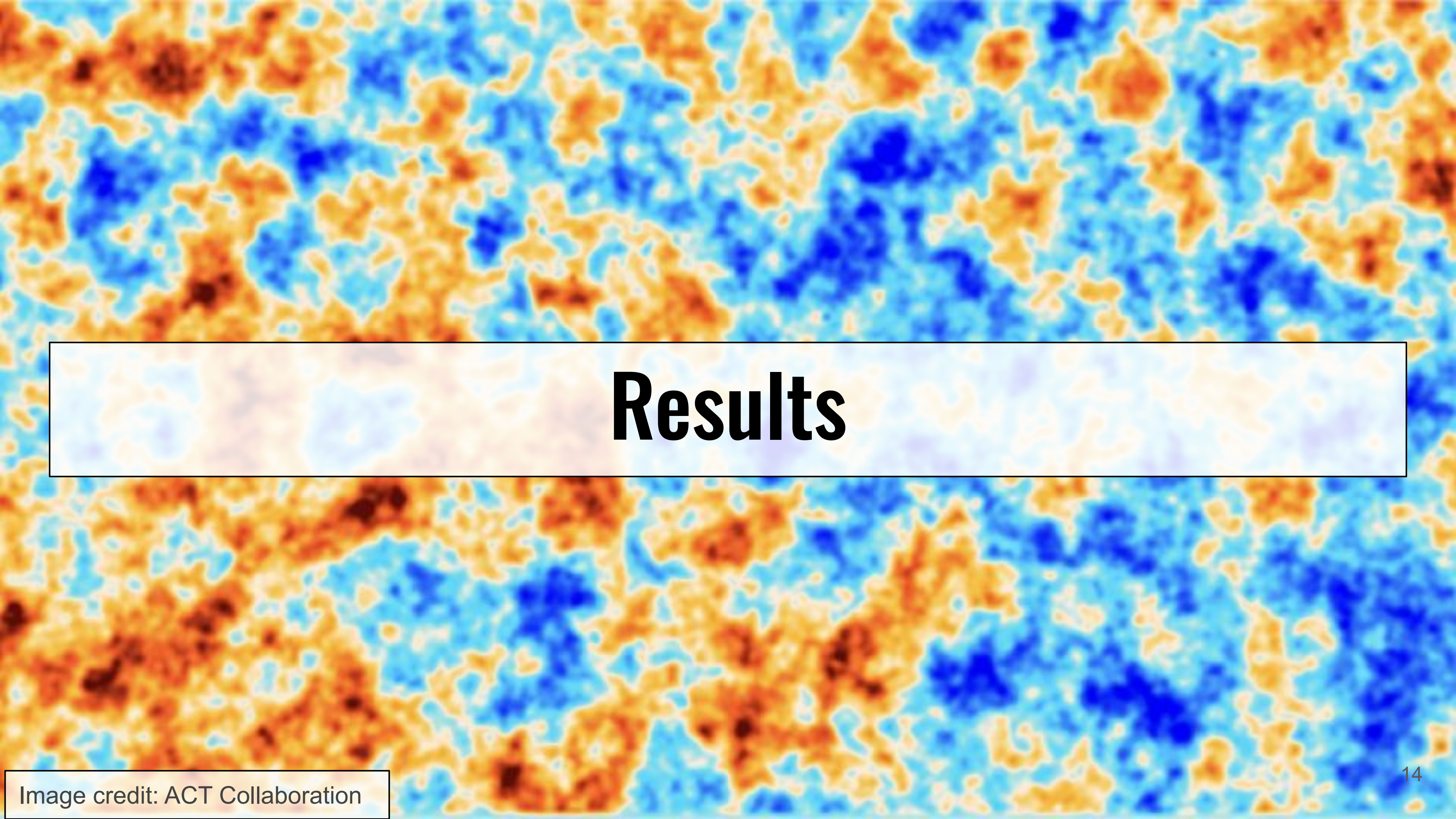
(Han & Sehgal, 2022)

Instrumental Noise and Residual Extragalactic Foregrounds

On small scales, the CMB and lensing signals are contaminated by extragalactic foreground emission.

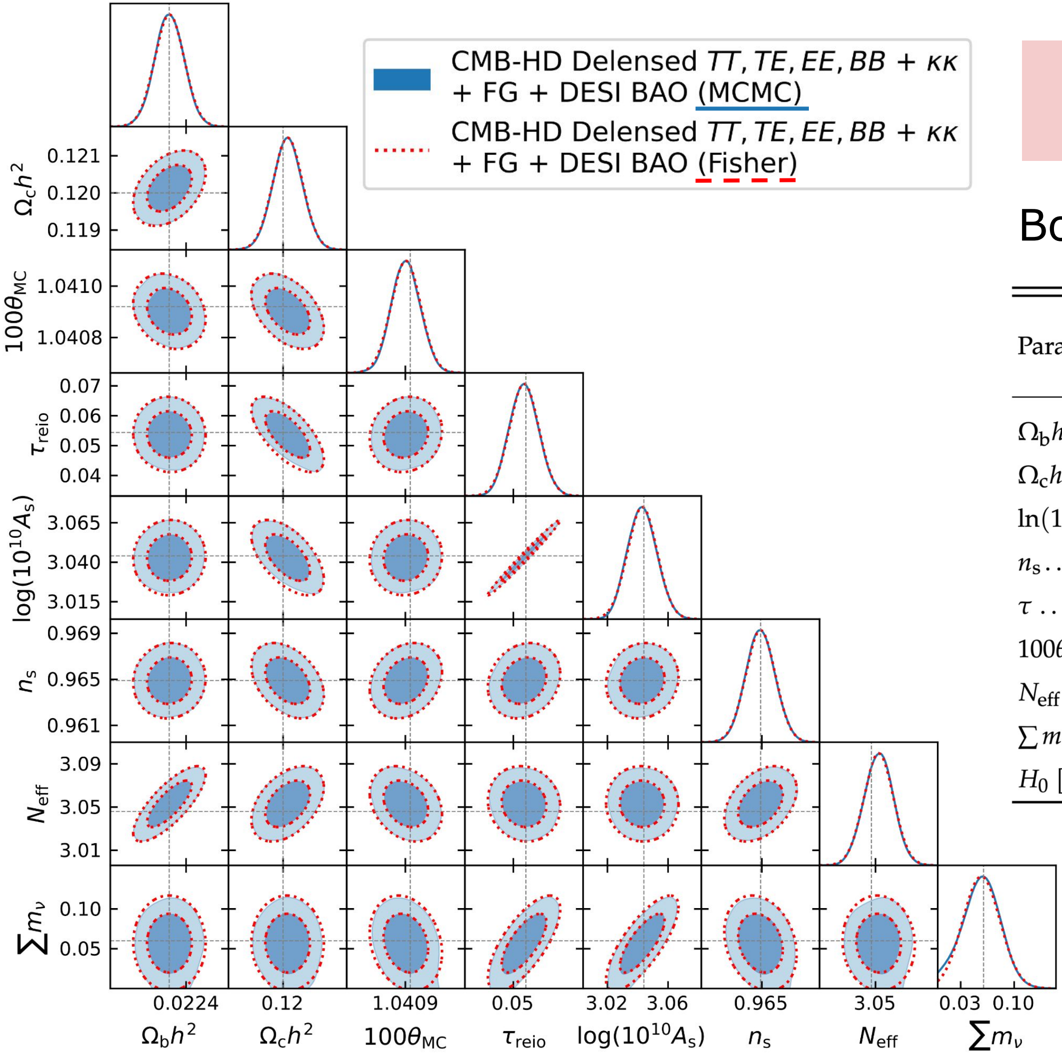
CMB noise at 90 and 150 GHz includes:

- *TT, TE, EE, BB*: instrumental noise
- *TT*: residual extragalactic foregrounds



Results

Image credit: ACT Collaboration

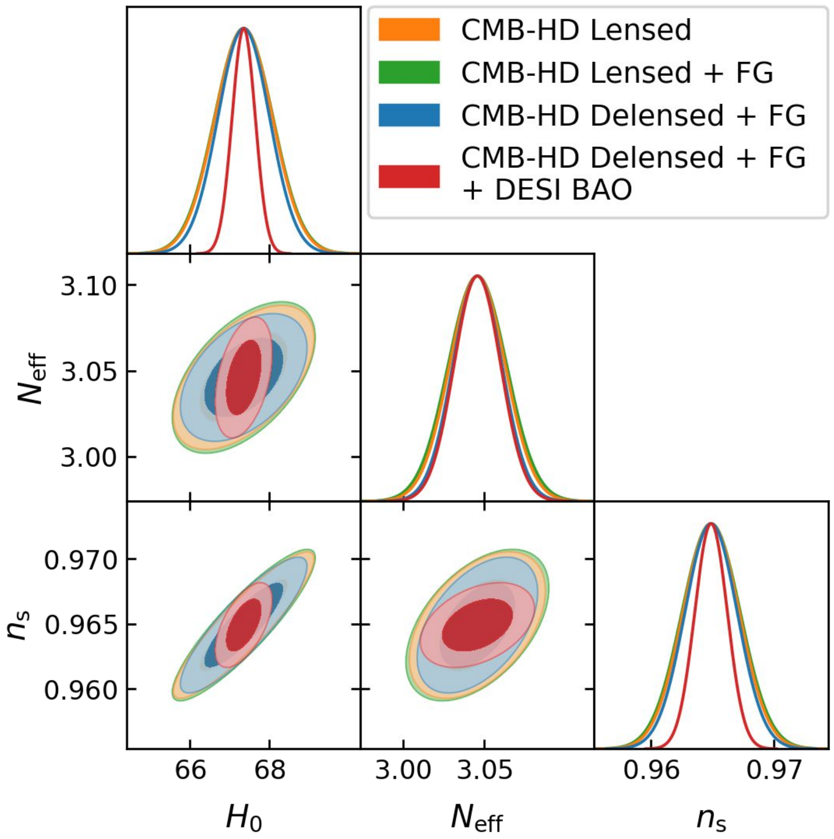


Fisher vs. MCMC

Both methods give consistent results:

Parameter	Fiducial	MCMC 1σ error	Fisher 1σ error	Fisher / MCMC
$\Omega_b h^2$	0.022370	0.0000258	0.0000263	1.02
$\Omega_c h^2$	0.12000	0.000410	0.000414	1.01
$\ln(10^{10} A_s)$	3.044	0.00953	0.00974	1.02
n_s	0.9649	0.00133	0.00134	1.01
τ	0.0544	0.00505	0.00515	1.02
$100\theta_{MC}$	1.040920	0.0000583	0.0000598	1.03
N_{eff}	3.046	0.0139	0.0143	1.03
$\sum m_\nu$ [eV]	0.060	0.0243	0.0244	1.00
H_0 [km s^{-1} Mpc^{-1}]	67.36	0.284	0.293	1.03

Ratio of parameter error bars from Fisher vs. MCMC

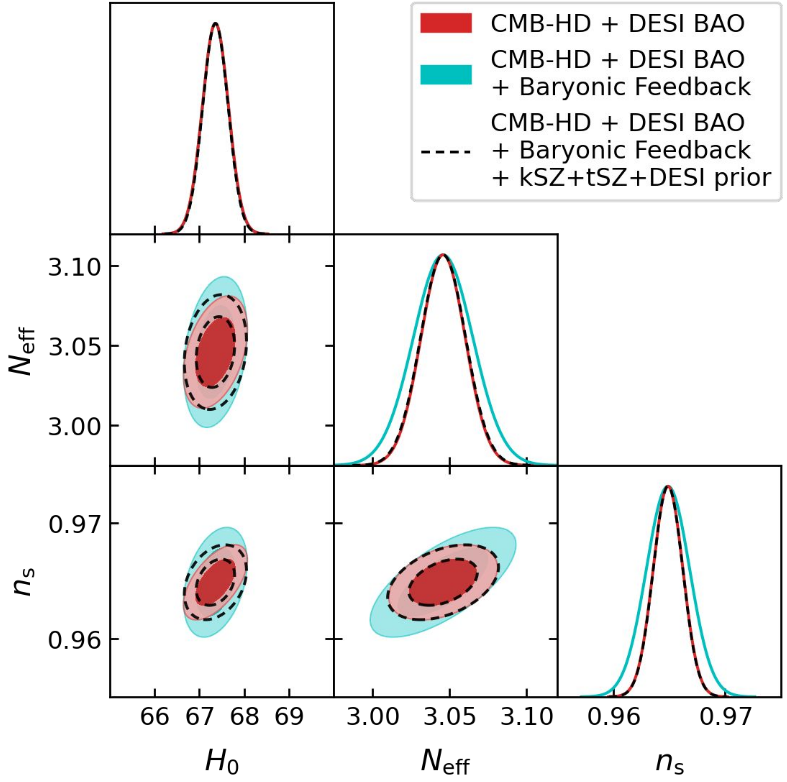


Fisher Forecasts

- **Residual extragalactic foregrounds**: slight increase in parameter errors
- **Delensing**: reduces parameter errors
- **BAO**: reduces parameter degeneracies

Baryonic feedback

Baryonic feedback strength characterized by parameter $\log_{10}(T_{\mathrm{AGN}}/\mathrm{K})$ (Mead et. al., 2020)

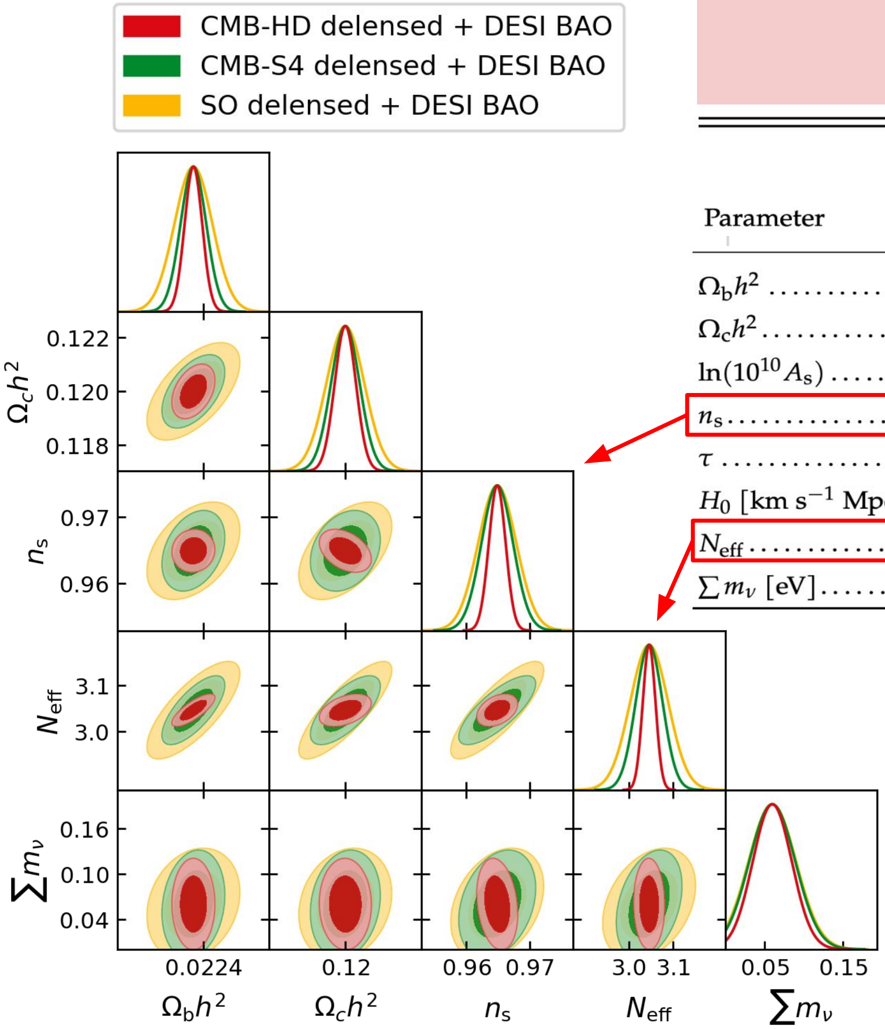


Assume CMB-HD SZ x CMB lensing can constrain $\log_{10}(T_{\mathrm{AGN}}/\mathrm{K})$ to 0.06%
(extrapolation from points below)

- 6% constraint from KiDS lensing x ACT+Planck tSZ (Tröster et. al., 2022)
- CMB-HD will have 25 times sky area of KiDS, at least an order of magnitude better lensing S/N, and 20 times deeper sensitivity than ACT+Planck

Marginalizing over the feedback model, including the SZ prior, does not change parameter errors

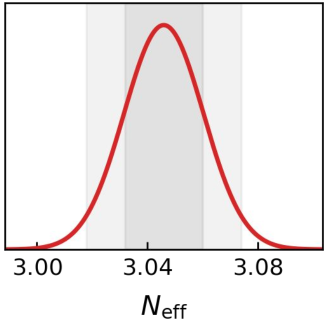
Parameter Results



Parameter	Fiducial	1σ Error	Ratio of 1σ Errors	
		CMB-HD	CMB-HD / SO	CMB-HD / CMB-S4
$\Omega_b h^2$	0.022370	0.000026	0.46	0.67
$\Omega_c h^2$	0.12000	0.00041	0.55	0.73
$\ln(10^{10} A_s)$	3.044	0.0098	0.84	0.86
n_s	0.9649	0.0013	0.43	0.52
τ	0.0544	0.0052	0.85	0.87
H_0 [km s^{-1} Mpc^{-1}]	67.36	0.29	0.81	0.91
$N_{\rm eff}$	3.046	0.014	0.33	0.47
$\sum m_\nu$ [eV]..........	0.06	0.025	0.83	0.86

Factor of two improvement on $\sigma(N_{\rm eff})$ and $\sigma(n_s)$

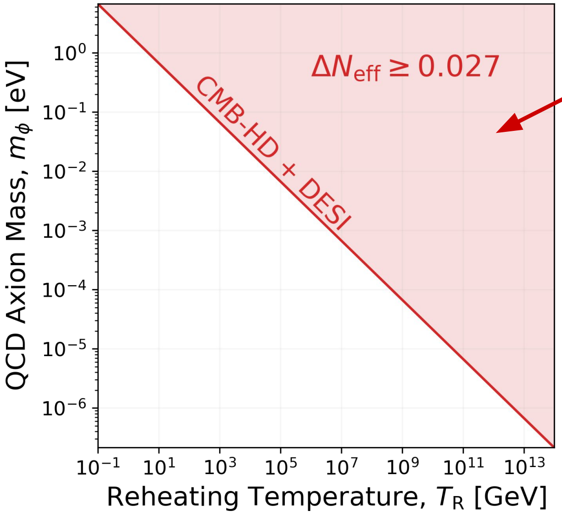
Effective Number of Relativistic Species



CMB-HD + DESI

$\sigma(N_{\rm eff}) = 0.014$

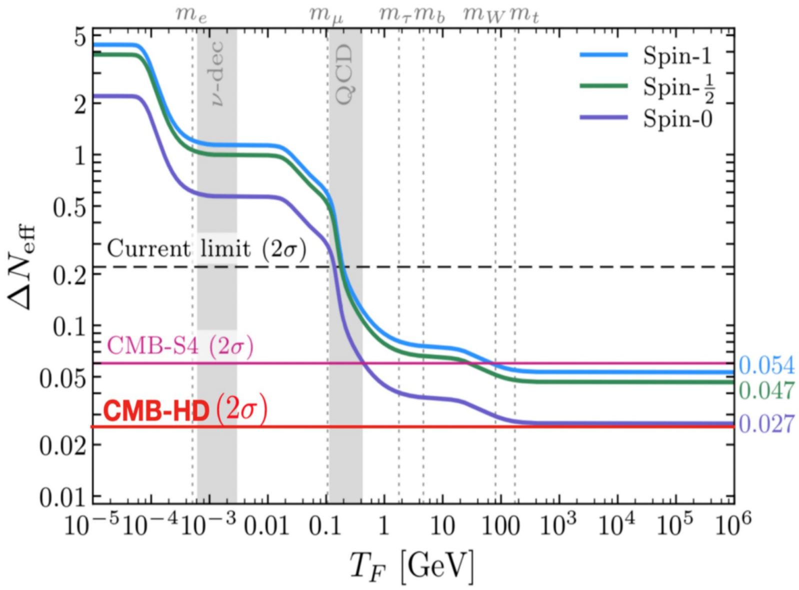
Can detect or rule out any new light particle that was in thermal equilibrium after inflation at 2σ.



Requires

$\Delta N_{\rm eff} \geq 0.027$

Can be ruled out by CMB-HD + DESI at 2σ

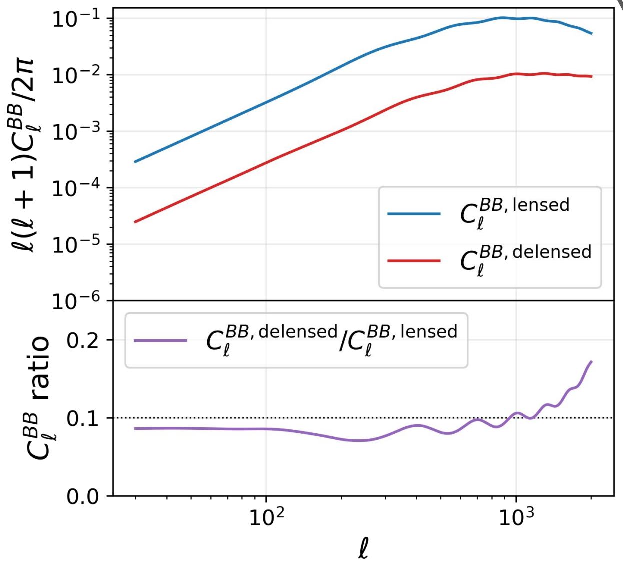


Snowmass 2021 CMB-HD White Paper (2203.05728)
original figure: Benjamin Wallisch (2018)

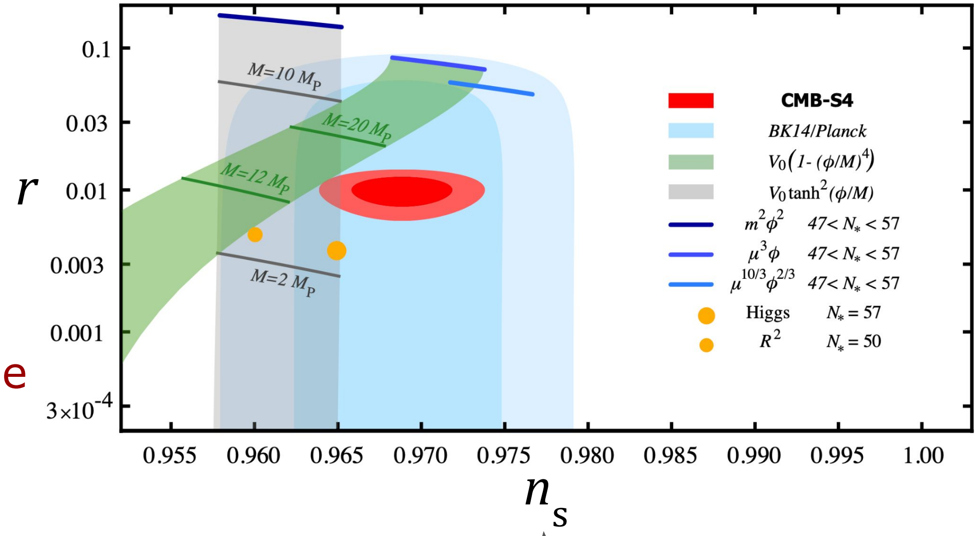
CMB-S4 Science Book (2016)

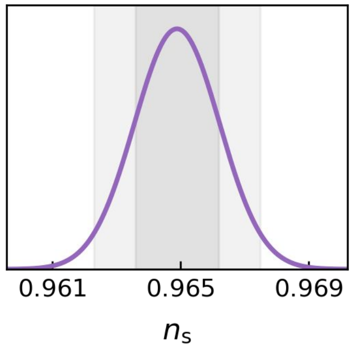
Inflation

CMB-HD Delensing



+Large-scale B-modes





CMB-HD + DESI

$\sigma(n_s) = 0.0013$

(2 x smaller than precursors)

Remove 90% of B-mode lensing over 60% of the sky

CMB-HD Forecasting Codes

github.com/CMB-HD

Both have options to include delensing, DESI BAO, and baryonic feedback.

hdlike :

- Compatible with CAMB and Cobaya
- Examples to easily reproduce HD forecasts and run new ones

hdfisher :

- Compatible with CAMB
  - Can vary any parameter that can be passed to `camb.set_params()`
- Example notebook to reproduce Fisher forecasts and plots
- Example notebook + python script to calculate a new Fisher matrix

Summary

- The low noise and high resolution of CMB-HD will lead to tight constraints on a $\Lambda\mathrm{CDM} + N_{\mathrm{eff}} + \sum m_\nu$ model
  - We find $\sigma(N_{\mathrm{eff}}) = 0.014$ and $\sigma(n_s) = 0.0013$ after including residual extragalactic foregrounds, delensing, and DESI BAO
- CMB-HD is sensitive to the effects of baryonic feedback on the small-scale matter distribution
- The CMB-HD likelihood and Fisher forecasting codes are publicly available at `github.com/CMB-HD`

Image credit: ACT Collaboration

Thank you!

Questions?

Image credit: ACT Collaboration

Extra slides

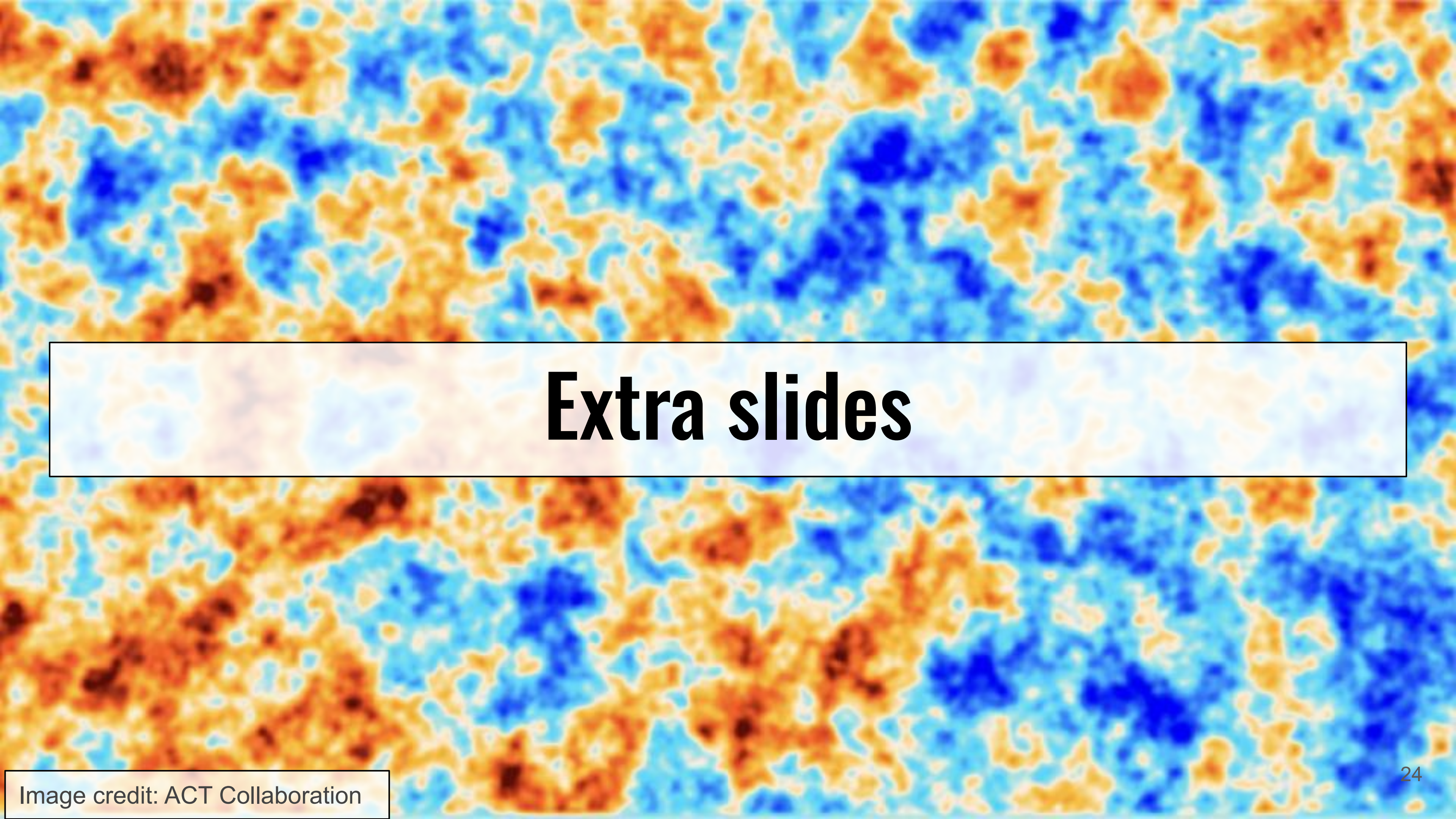
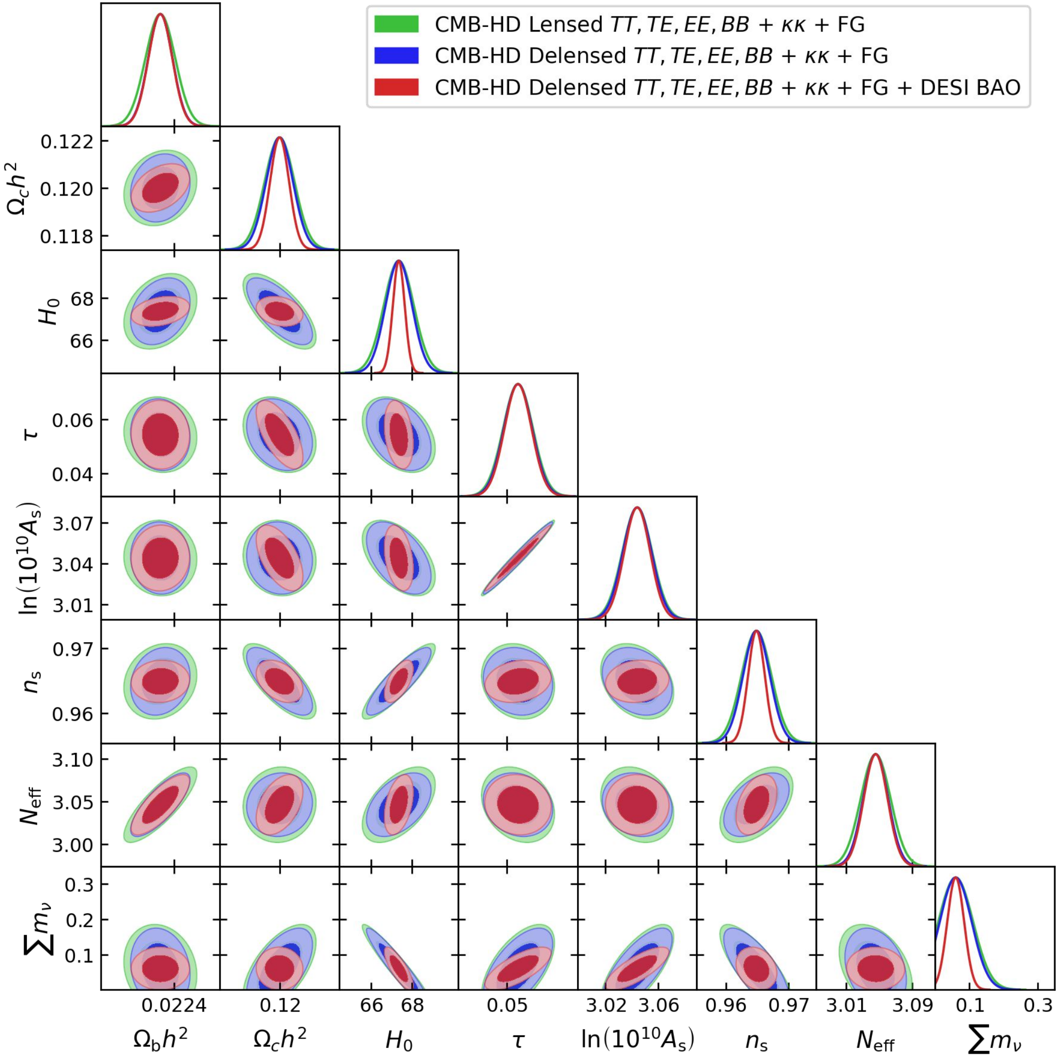


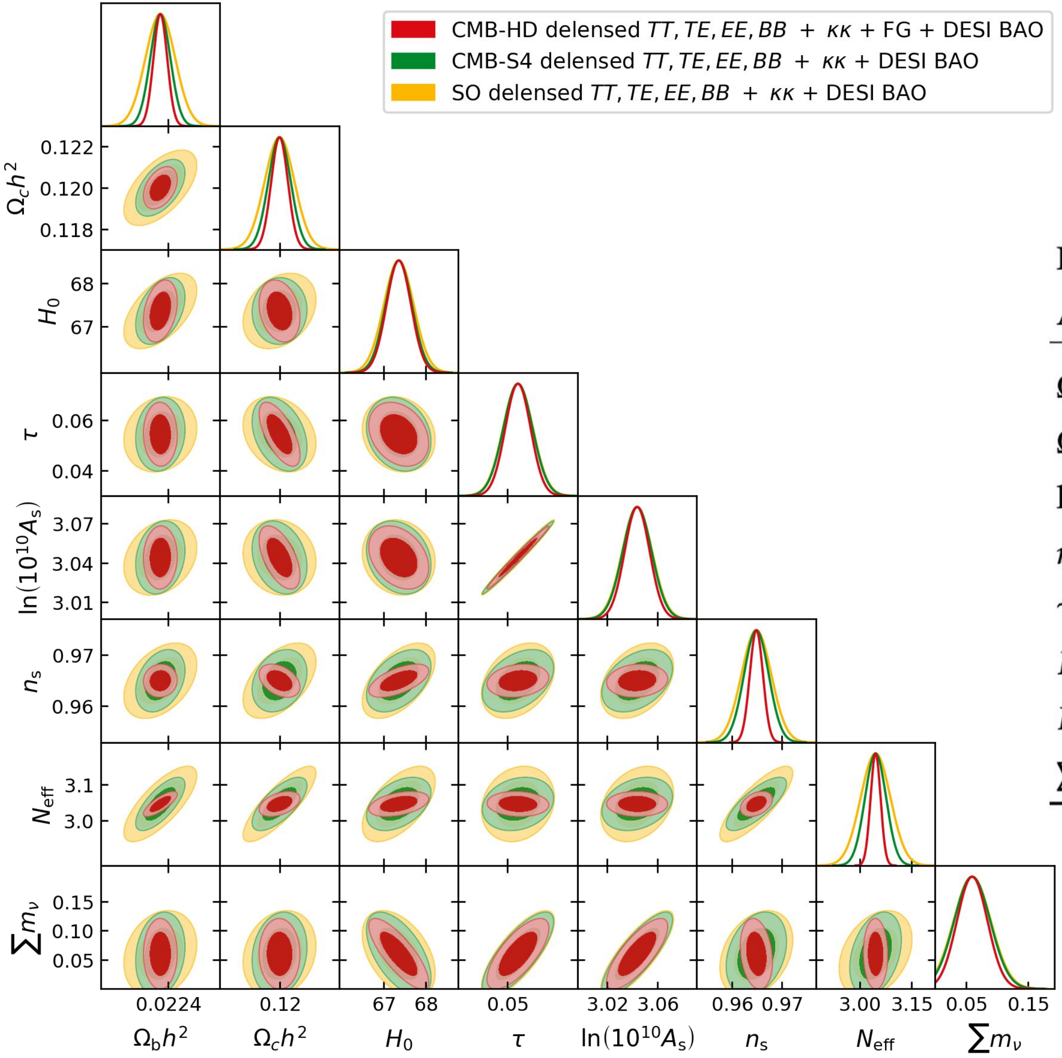
Image credit: ACT Collaboration



CMB-HD Lensed TT, TE, EE, BB + $\kappa\kappa$ + FG
CMB-HD Delensed TT, TE, EE, BB + $\kappa\kappa$ + FG
CMB-HD Delensed TT, TE, EE, BB + $\kappa\kappa$ + FG + DESI BAO
$\Omega_c h^2$
H_0
τ
$\ln(10^{10}A_s)$
n_s
N_{eff}
$\sum m_\nu$
$\Omega_b h^2$
0.0224
0.12
66 68
0.05
3.02 3.06
0.96 0.97
3.01 3.09
0.1 0.3

		$\ell_{\max}$, $L_{\max} = 20,000$				$\ell_{\max}$, $L_{\max} = 10,000$
Parameter ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	Fiducial	HD Lensed	HD Lensed + FG	HD Delensed + FG	**HD Delensed + FG + DESI BAO**	HD Delensed + FG + DESI BAO
$\Omega_{\rm b}h^2$	0.022370	0.000032	0.000033	0.000027	0.000026	0.000026
$\Omega_{\rm c}h^2$	0.12000	0.00064	0.00065	0.00058	0.00041	0.00041
$\ln(10^{10} A_{\rm s})$	3.044	0.011	0.011	0.011	0.0098	0.010
$n_{\rm s}$	0.9649	0.0023	0.0024	0.0021	0.0013	0.0014
τ	0.0544	0.0056	0.0057	0.0054	0.0052	0.0054
H_0 [km s^{-1} Mpc^{-1}]	67.36	0.72	0.74	0.65	0.29	0.29
$N_{\rm eff}$	3.046	0.017	0.018	0.015	0.014	0.015
$\sum m_\nu$ [eV]	0.06	0.050	0.051	0.047	0.025	0.026

Table IV. Forecasted cosmological parameter constraints from CMB-HD TT, TE, EE, BB and $\kappa\kappa$ power spectra for a ΛCDM + $N_{\rm eff} + \Sigma m_\nu$ model. All forecasts include a τ prior of $\tau = 0.054 \pm 0.007$ from *Planck* [1]. The first two columns list the parameters and their fiducial values. The following two columns list their forecasted marginalized 1σ uncertainties when using lensed spectra with or without foregrounds in the temperature maps. The fifth column shows the forecast when delensing the CMB spectra, and the sixth column shows the change when including DESI BAO data [16]. In each of these cases we use CMB and CMB lensing multipoles out to $\ell_{\max}, L_{\max} = 20,000$ for CMB-HD. The last column lists the same information as the sixth column, but instead using a maximum multipole of $\ell_{\max}, L_{\max} = 10,000$ for both CMB and CMB lensing power spectra. We see in particular that $n_{\rm s}$ and $N_{\rm eff}$ constraints are tightened when including multipoles beyond 10,000 for a CMB-HD type survey. We show corresponding forecasts for ΛCDM and ΛCDM + $N_{\rm eff}$ models in Appendix C.



Parameter ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	Fiducial	**HD Delensed + FG + DESI BAO**
$\Omega_b h^2$	0.022370	0.000026
$\Omega_c h^2$	0.12000	0.00041
$\ln(10^{10} A_s)$	3.044	0.0098
n_s	0.9649	0.0013
τ	0.0544	0.0052
H_0 [km s^{-1} Mpc^{-1}]	67.36	0.29
$N_{\rm eff}$	3.046	0.014
$\sum m_\nu$ [eV]	0.06	0.025

		1σ Error			Ratio of 1σ Errors	
Parameter ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	Fiducial	SO + DESI BAO	CMB-S4 + DESI BAO	CMB-HD + DESI BAO	CMB-HD / SO	CMB-HD / CMB-S4
$\Omega_{\rm b}h^2$	0.022370	0.000057	0.000039	0.000026	0.46	0.67
$\Omega_{\rm c}h^2$	0.12000	0.00074	0.00056	0.00041	0.55	0.73
$\ln(10^{10}A_{\rm s})$	3.044	0.012	0.011	0.0098	0.84	0.86
$n_{\rm s}$	0.9649	0.0030	0.0025	0.0013	0.43	0.52
τ	0.0544	0.0061	0.0060	0.0052	0.85	0.87
H_0 [km s^{-1} Mpc^{-1}]	67.36	0.36	0.32	0.29	0.81	0.91
$N_{\rm eff}$	3.046	0.043	0.030	0.014	0.33	0.47
$\sum m_\nu$ [eV]	0.06	0.030	0.029	0.025	0.83	0.86

Table III. Forecasted cosmological parameter constraints for a ΛCDM + $N_{\rm eff} + \Sigma m_\nu$ model from SO-like, CMB-S4-like, and CMB-HD-like delensed TT, TE, EE, BB and $\kappa\kappa$ power spectra when combined with DESI BAO. The first two columns list the parameters and their fiducial values. The following three columns list the forecasted marginalized 1σ uncertainties on each parameter for the three experiments, and the last two columns list the ratios of these values. The forecasts for CMB-HD include expected residual extragalactic foregrounds in the temperature power spectrum. All forecasts include a τ prior of $\tau = 0.054 \pm 0.007$ from *Planck* [1]. We find improvement in all parameters considered for a CMB-HD-like experiment compared to precursor surveys; we also find the most significant improvement for $n_{\rm s}$ and $N_{\rm eff}$, of about a factor of two or more. These forecasts are also depicted in Fig. 7.

Parameter	CDM	+ feedback	+ SZ prior
$\Omega_b h^2$	0.000026	0.000028	0.000027
$\Omega_c h^2$	0.00041	0.00046	0.00041
$\ln(10^{10} A_s)$	0.0095	0.010	0.010
n_s	0.0013	0.0021	0.0013
τ	0.0051	0.0056	0.0056
$100\theta_{MC}$	0.000058	0.000064	0.000060
N_{eff}	0.014	0.020	0.014
$\sum m_\nu$ [eV]	0.024	0.026	0.027
$\log_{10}(T_{AGN}/K)$ ...	—	0.040	0.0047
H_0 [km s^{-1} Mpc^{-1}]	0.28	0.29	0.27
σ_8	0.0033	0.0033	0.0033

Table V. Shown are the cosmological constraints from the combination of CMB-HD delensed TT, TE, EE, BB, and $\kappa\kappa$ power spectra with DESI BAO for the baseline ΛCDM + N_{eff} + $\sum m_\nu$ model, a ΛCDM + N_{eff} + $\sum m_\nu$ + baryonic feedback model from `HMCode-2020` [60], and a ΛCDM + N_{eff} + $\sum m_\nu$ + baryonic feedback model including a 0.06% prior on the feedback parameter $\log_{10}(T_{AGN}/K)$ expected from from a joint analysis of CMB-HD kSZ, tSZ, and lensing data (see Section V D for details). All results shown here are from the likelihood and MCMC chains as opposed to Fisher forecasts. We also include $100\theta_{MC}$, and separate the two derived parameters, H_0 and σ_8, which is the linear root-mean-square matter fluctuations today.

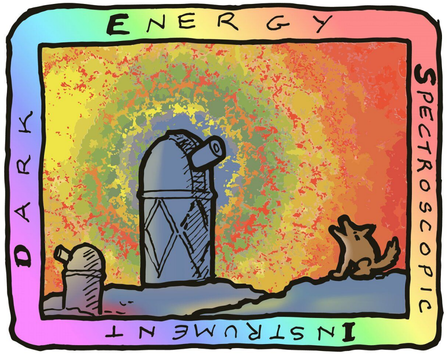
Parameter ΛCDM+$N_{\rm eff}$+$\sum m_\nu$	Fiducial	HD Lensed + FG + DESI BAO	HD Delensed + FG + DESI BAO
$\Omega_b h^2$	0.022370	0.000032	0.000026
$\Omega_c h^2$	0.12000	0.00045	0.00041
$\ln(10^{10} A_s)$	3.044	0.010	0.0098
n_s	0.9649	0.0014	0.0013
τ	0.0544	0.0055	0.0052
H_0 [km s^{-1} Mpc^{-1}]	67.36	0.30	0.29
$N_{\rm eff}$	3.046	0.017	0.014
$\sum m_\nu$ [eV]	0.06	0.025	0.025

Table IX. Here we compare the forecasted 1σ parameter constraints from lensed (third column) and delensed (fourth column) CMB-HD TT, TE, EE, BB and $\kappa\kappa$ power spectra when including DESI BAO in order to see how much improvement is gained from delensing alone. The parameter names and fiducial values are listed in the first and second columns, respectively. We find that delensing improves parameter constraints even after including DESI BAO, with the most improvement seen for $N_{\rm eff}$.

Parameter		ℓ_{max}, L_{max} for HD Delensed + FG + DESI BAO				
ΛCDM+N_{eff}+$\sum m_\nu$	Fiducial	1000	3000	5000	10,000	20,000
$\Omega_b h^2$	0.022370	0.00016	0.000039	0.000027	0.000026	0.000026
$\Omega_c h^2$	0.12000	0.0024	0.00054	0.00042	0.00041	0.00041
$\ln(10^{10} A_s)$	3.044	0.014	0.011	0.011	0.010	0.0098
n_s	0.9649	0.0048	0.0023	0.0018	0.0014	0.0013
τ	0.0544	0.0065	0.0060	0.0057	0.0054	0.0052
H_0 [km s^{-1} Mpc^{-1}]	67.36	0.80	0.32	0.29	0.29	0.29
N_{eff}	3.046	0.15	0.030	0.018	0.015	0.014
$\sum m_\nu$ [eV]	0.06	0.037	0.029	0.028	0.026	0.025

Table X. Shown are the forecasted 1σ uncertainties from delensed CMB-HD TT, TE, EE, BB and $\kappa\kappa$ spectra plus DESI BAO, when varying the maximum multipole ℓ_{max} or L_{max} for the CMB spectra. The parameter names and fiducial values are listed in the first and second columns, respectively, while the remaining columns list the 1σ parameter errors for the given maximum multipole. We see that to obtain $\sigma(n_s) = 0.0013$ and $\sigma(N_{eff}) = 0.014$, for example, requires the full range of multipoles out to 20,000.

DESI BAO Data

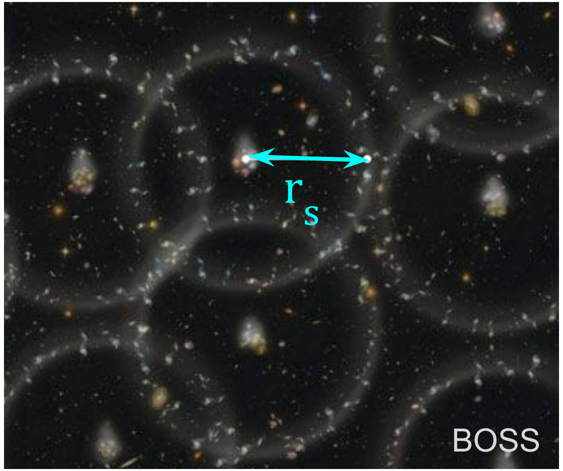


Forecast combination of CMB-HD and DESI BAO data:

- Mock DESI measurements of $r_s / d_V(z)$, where

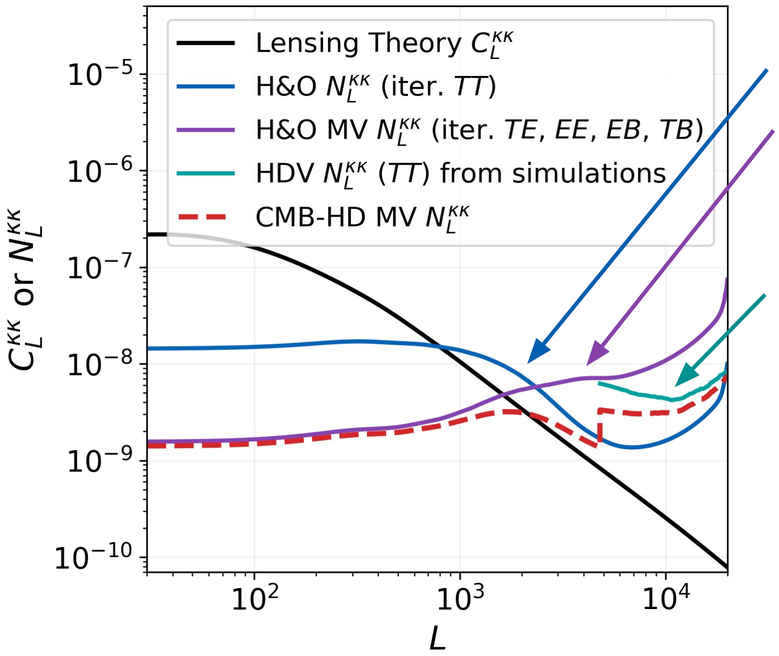
$$d_V(z) \equiv \left[(1+z)^2 d_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$ (Eisenstein et al., 2005)

- Derived from DESI forecasts for their baseline $(0.65 < z < 1.85)$ and bright $(0.05 < z < 0.45)$ galaxy surveys over 14,000 square degrees (Aghamousa et. al., 2016)



Lensing Noise

Minimum-variance combination of *TT*, *TE*, *EE*, *EB*, *TB* quadratic estimators



TT for $\mathrm{L} < 5000$ and
TE, *EE*, *EB*, *TB* on all scales:

- H&O estimator (Hu & Okamoto, 2002)
- Iterative delensing lowers noise (Hotinli et. al., 2021)

TT for $\mathrm{L} > 5000$:

- HDV estimator (Hu, DeDeo, & Vale, 2007)
- From simulations (Han & Sehgal, 2022)

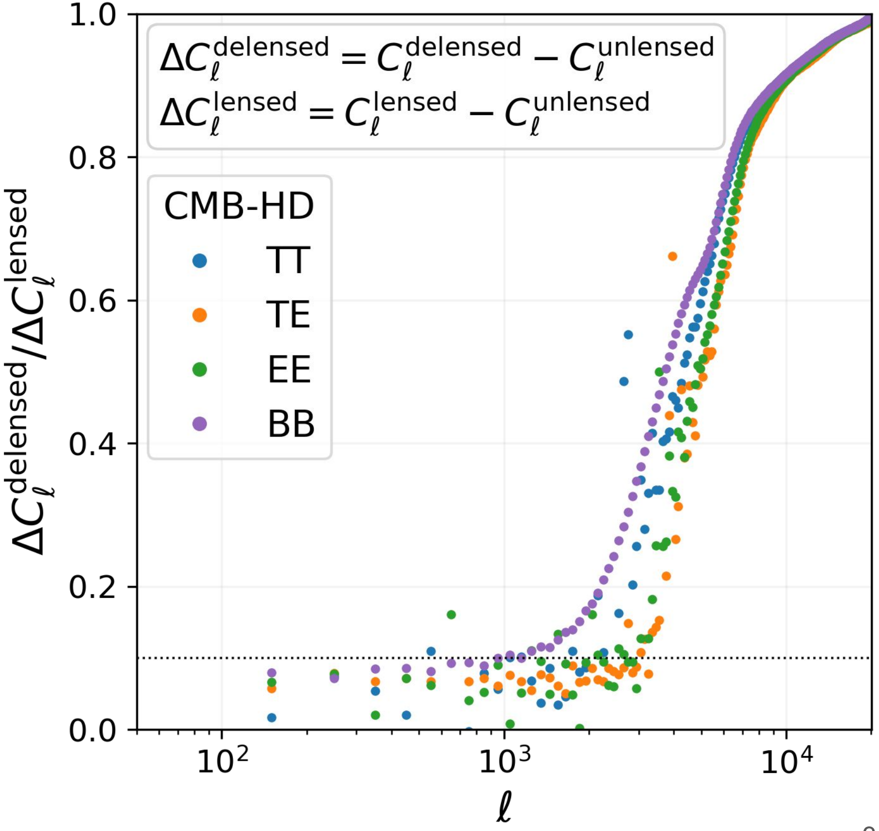
Delensing

Use reconstructed lensing map to delens the observed CMB.

- Gain sharpened picture of the universe at z = 1100.

Combine delensed CMB *TT, TE, EE, BB* power spectra with CMB lensing $\kappa\kappa$ power spectrum to replace the lost lensing information.

Fraction of lensing removed from the CMB power spectra:

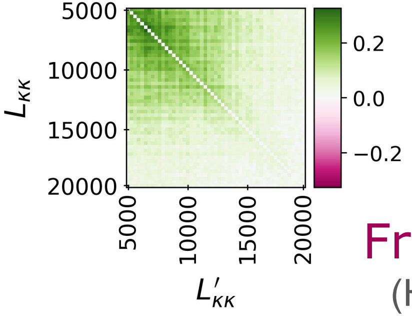


CMB-HD Data:
Covariance Matrix

Off-diagonal elements are from lensing-induced correlations

(Diagonal elements are not shown)

Lensing x Lensing

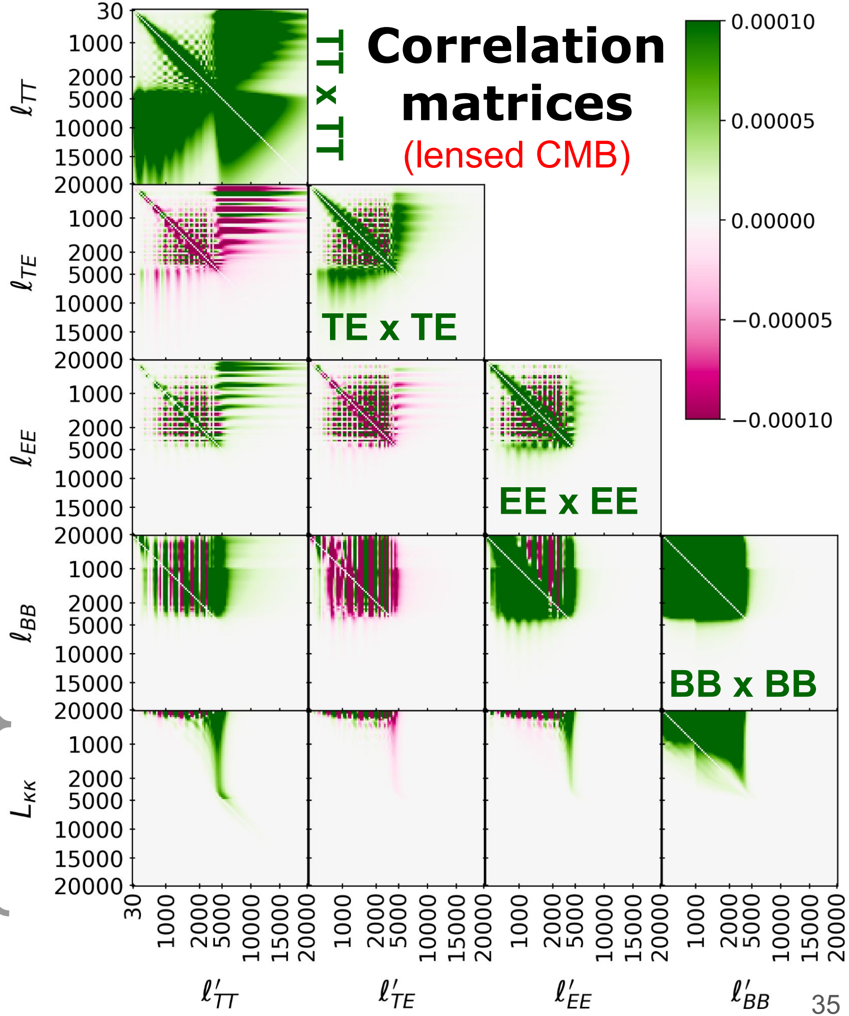


From simulations
(Han & Sehgal, 2022)

Analytic
(Hotinli et. al., 2021)

CMB x CMB

CMB x Lensing



CMB-HD Data:
Covariance Matrix

Off-diagonal elements are from lensing-induced correlations

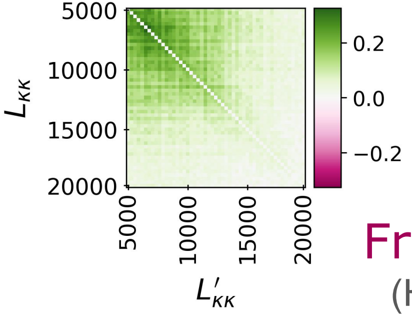
(Diagonal elements are not shown)

CMB x CMB

Analytic
(Hotinli et. al., 2021)

CMB x Lensing

Lensing x Lensing



From simulations
(Han & Sehgal, 2022)