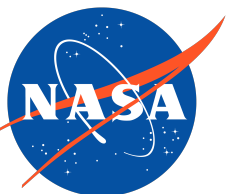


# Detection of Thermal SZ — CMB Lensing Cross-Correlation in *Planck* Legacy Data

Colin Hill

Columbia University

mm Universe  
Grenoble - LPSC  
26 June 2023



to appear w/ F. McCarthy (arXiv: this week)  
to appear w/ F. McCarthy (arXiv: next week)

# Columbia/CCA Talks This Week

Colin Hill  
Columbia



- Ola Kusiak: Probing the Ionized Gas Thermodynamics in unWISE Galaxies with the Sunyaev-Zel'dovich Effect

Wednesday, 2:10 pm, Room 9

- Kristen Surrao: Enhancing Kinematic Sunyaev-Zel'dovich Power Spectrum Measurements by Removing CIB Contamination Using unWISE Galaxies

Wednesday, 2:20 pm, Amphitheatre

- Alina Sabyr: Compton- $\gamma$  distortion: CMB constraints and new prospects with CIB

Thursday, 4:20 pm, Room 9

- Fiona McCarthy: Constraints on primordial non-Gaussianity from halo bias measured through CMB lensing cross-correlations

Wednesday, 3:00 pm, Amphitheater

- Boris Bolliet (now @Cambridge): class\_sz: a fast and accurate code for SZ and cross-correlations

Monday, 3:30 pm, Amphitheatre



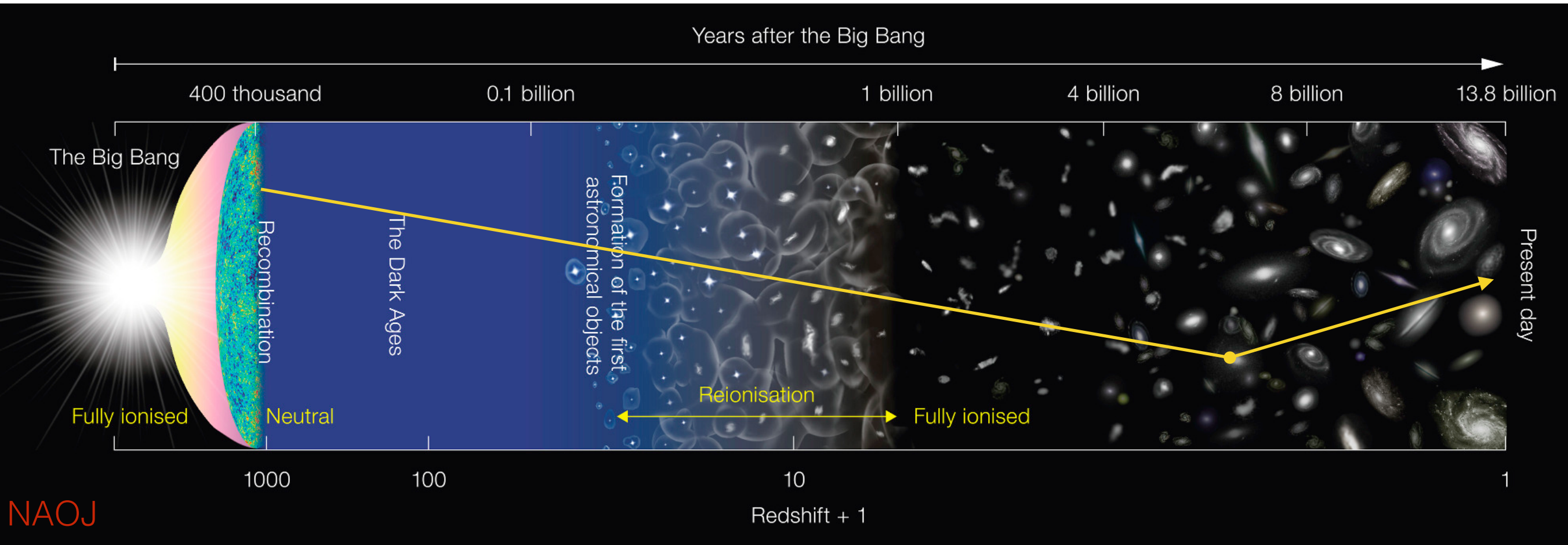
# Outline

- New Compton- $y$  Maps from *Planck* PR4
  - Flexible CIB Deprojection
  - Public Code: `pyilc`
- Robust Detection of Thermal SZ — CMB Lensing Cross-Correlation
- New Compton- $y$  Maps from ACT DR6 + *Planck*

# Cosmic Microwave ~~Background~~ Backlight

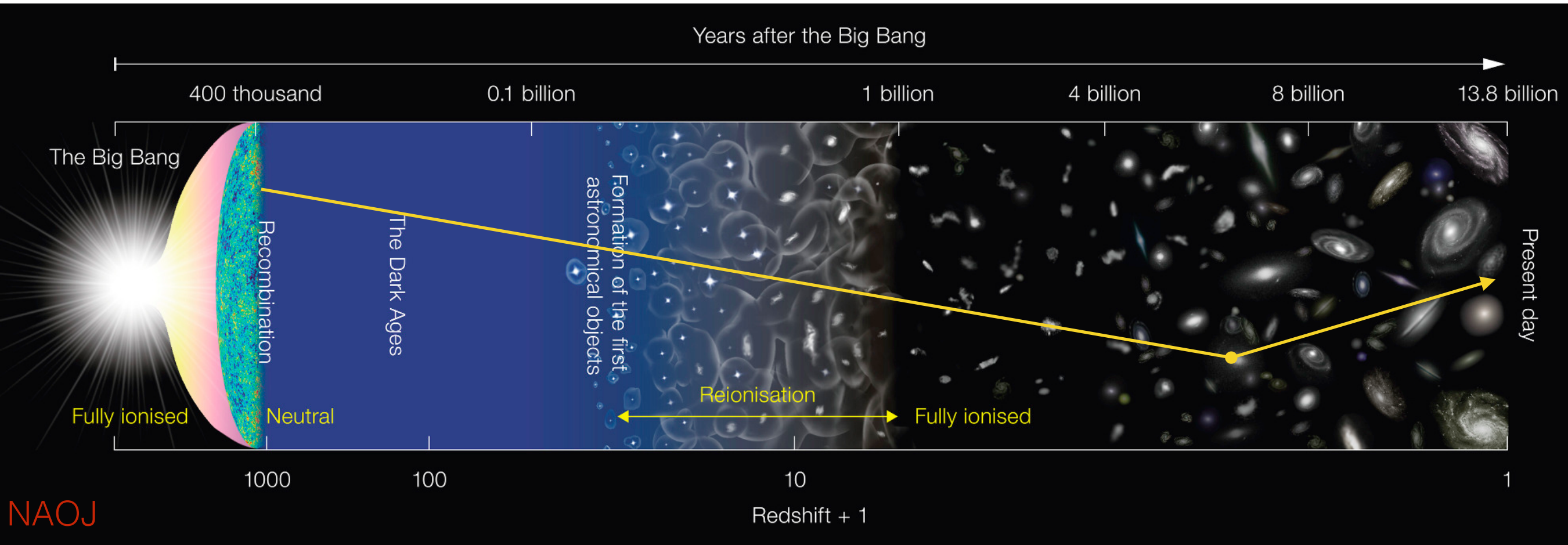
# Cosmic Microwave Backlight

## Secondary Anisotropies



# Cosmic Microwave Backlight

## Secondary Anisotropies

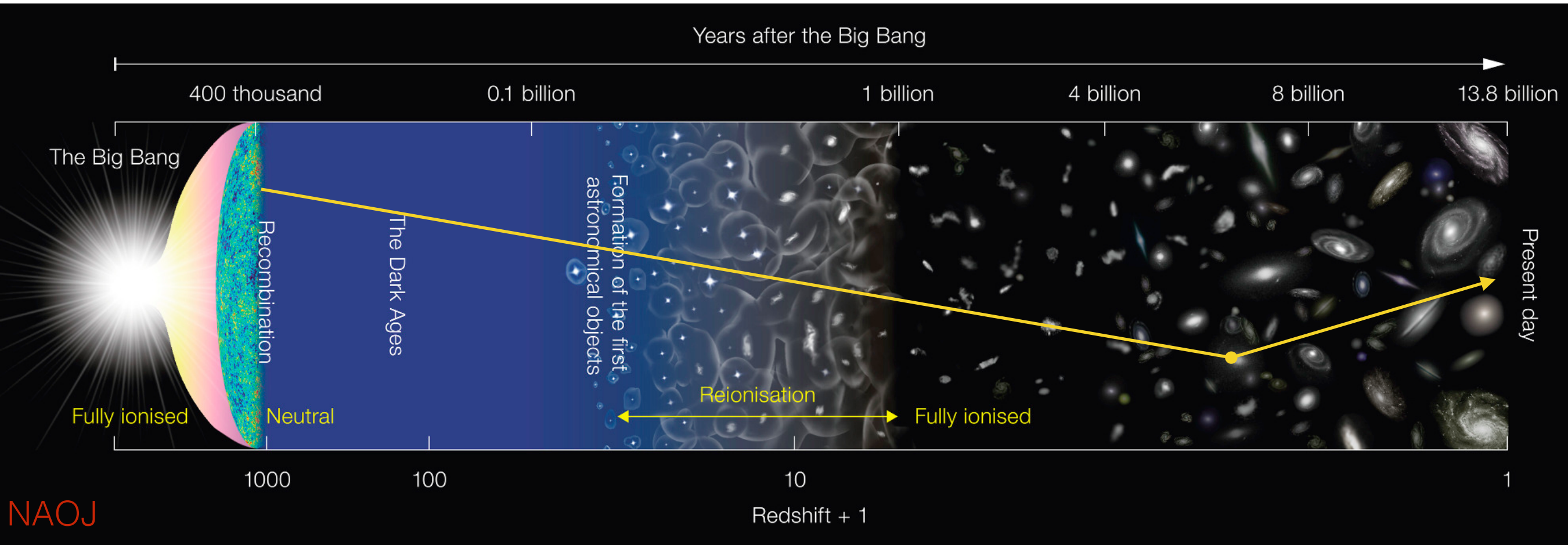


- Scattering: thermal / kinematic Sunyaev-Zel'dovich effect  
**redshift-independent**



# Cosmic Microwave Backlight

## Secondary Anisotropies



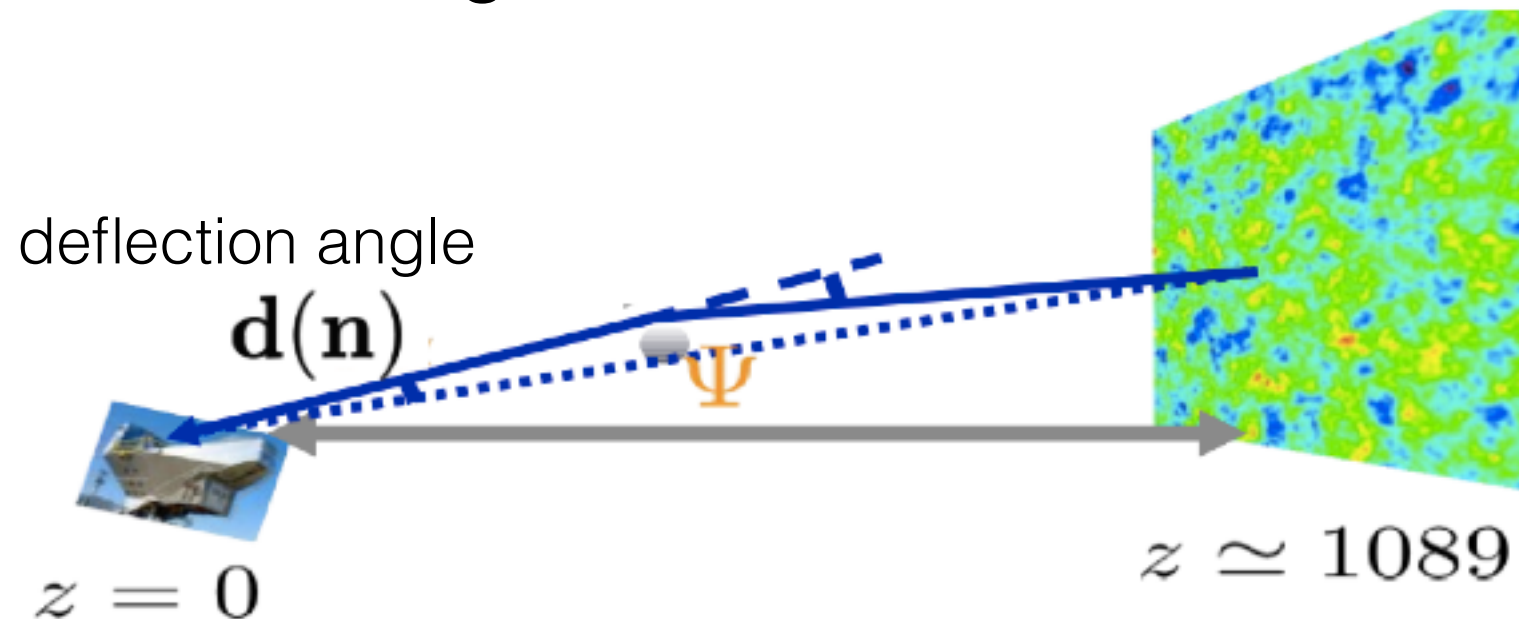
- Scattering: thermal / kinematic Sunyaev-Zel'dovich effect
- Deflection: gravitational lensing

# CMB Lensing

→ **Integrated Total Mass**

Re-mapping of CMB fluctuations (preserves blackbody form)

Many ( $\sim 50$ ) small random deflections lead to a net deflection ( $\sim 2-3$  arcmin), coherent on  $\sim$ deg scales



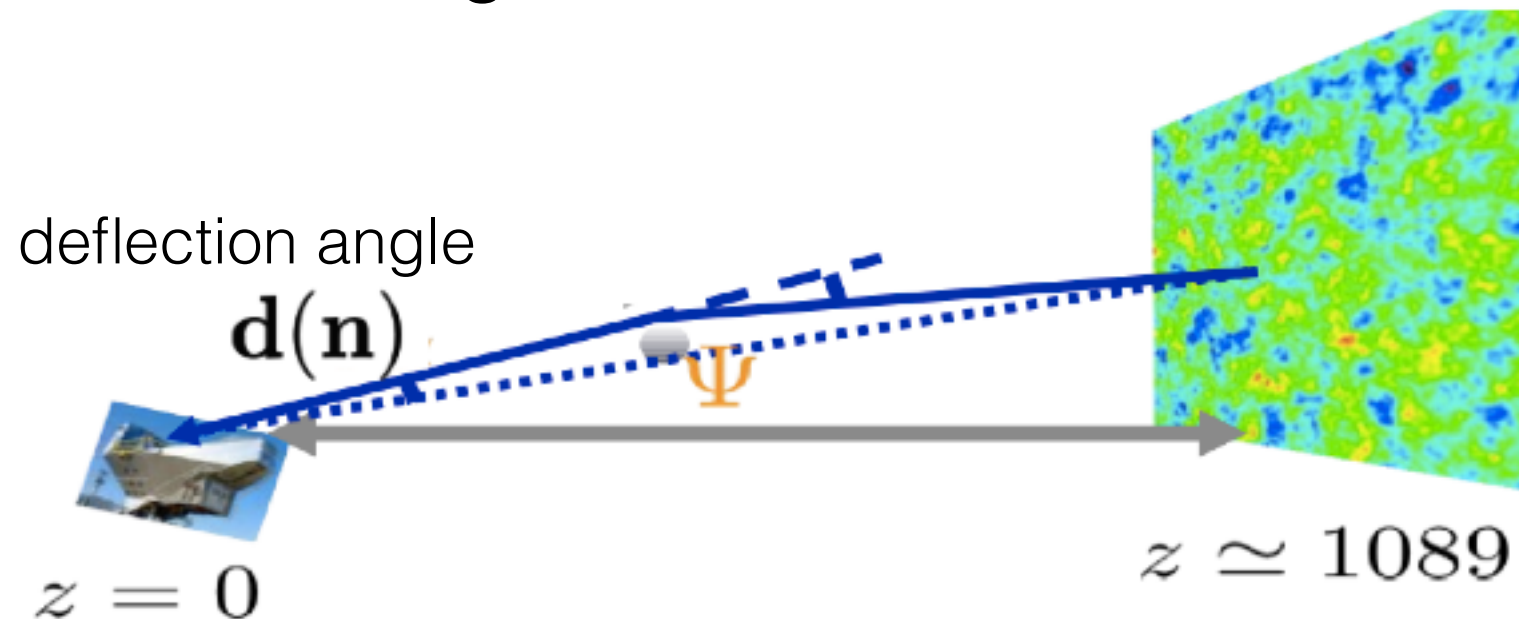
$$T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}}$$

# CMB Lensing

## → Integrated Total Mass

Re-mapping of CMB fluctuations (preserves blackbody form)

Many ( $\sim 50$ ) small random deflections lead to a net deflection ( $\sim 2$ - $3$  arcmin), coherent on  $\sim$ deg scales



$$T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}}$$

Quadratic  
reconstruction:

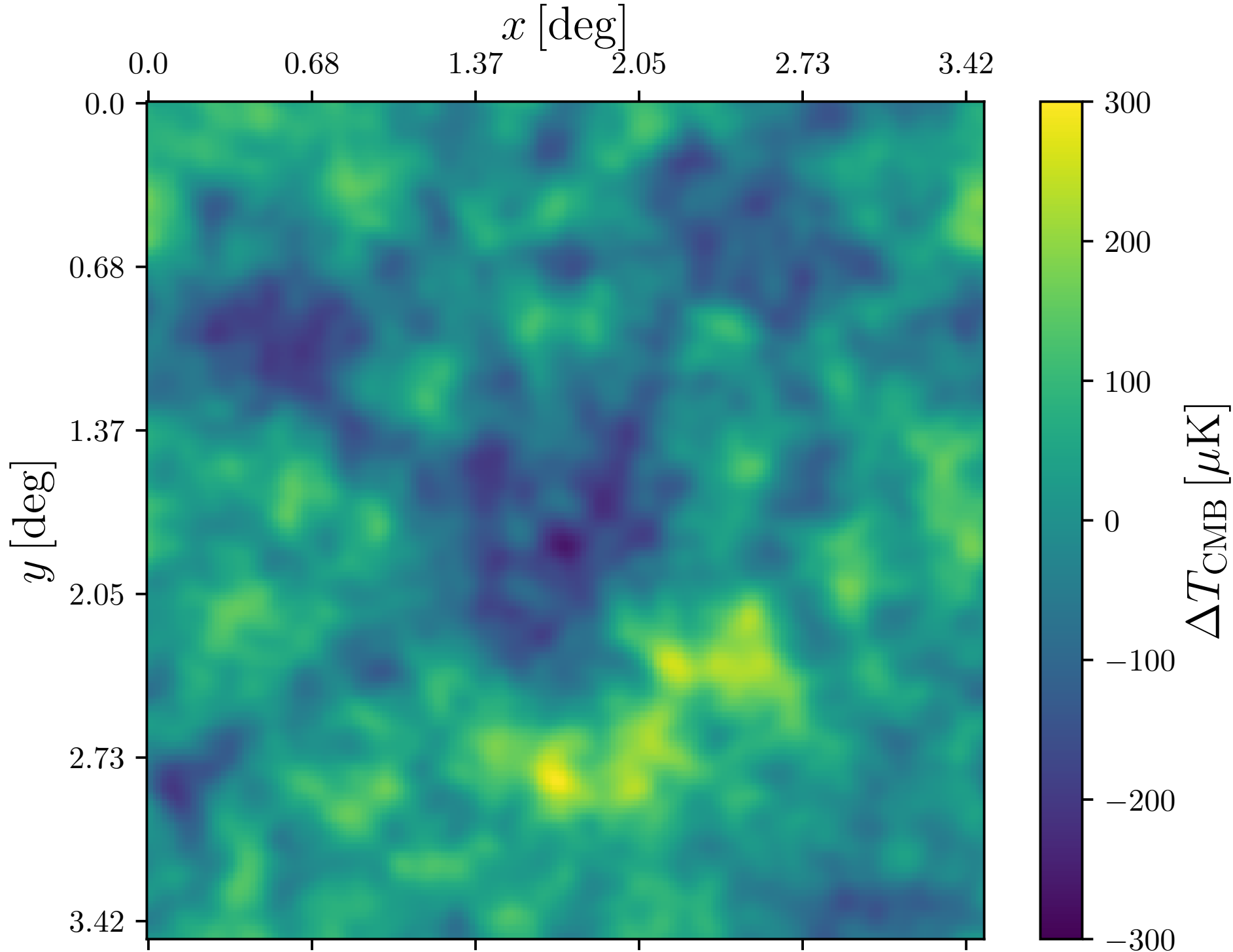
$$\phi(\vec{\mathbf{L}}) \sim T(\vec{\ell})T(\vec{\mathbf{L}} - \vec{\ell})$$

lensing potential

$$\vec{\mathbf{d}} = \nabla \phi$$

# CMB Lensing

→ Integrated Total Mass

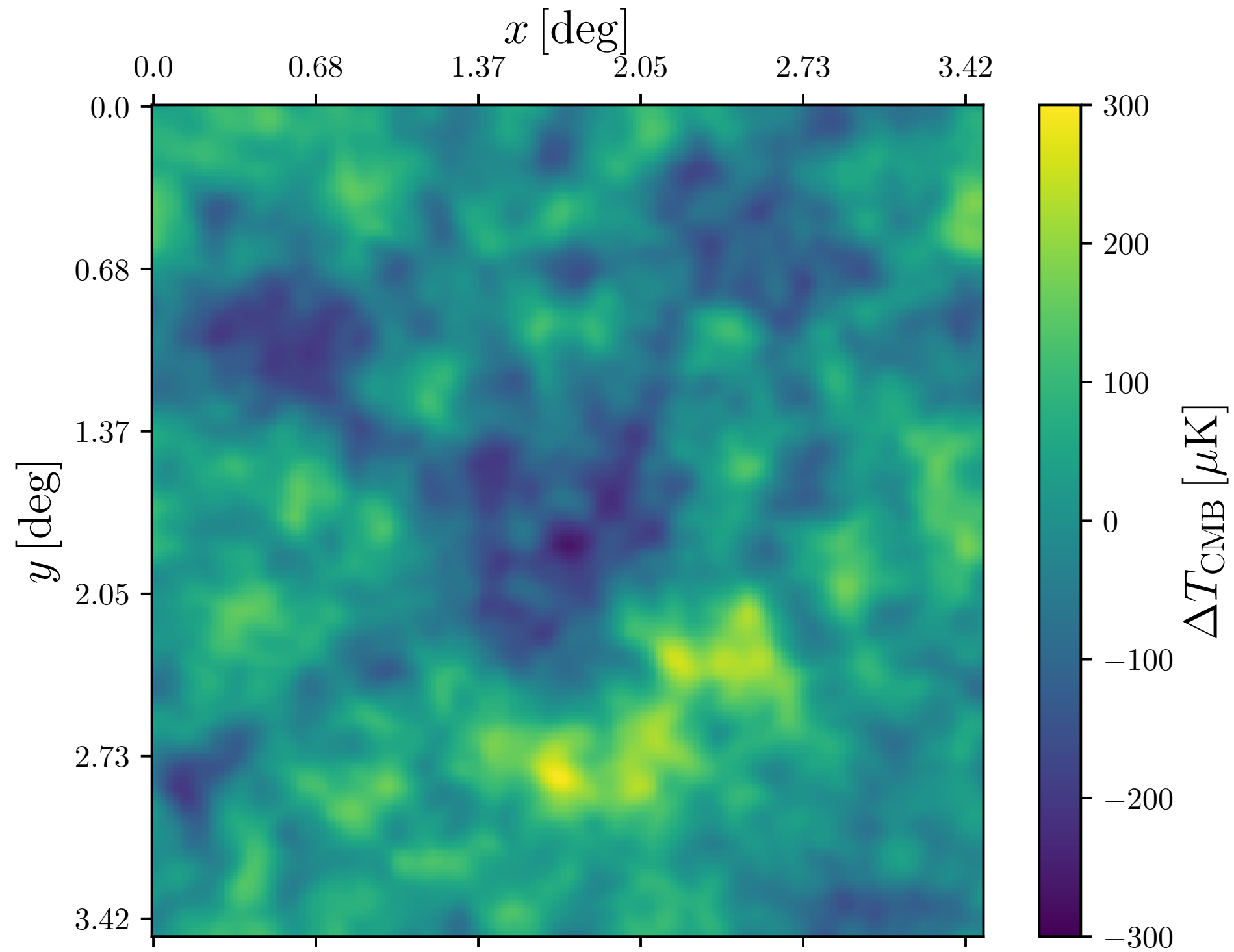


**unlensed**



# CMB Lensing

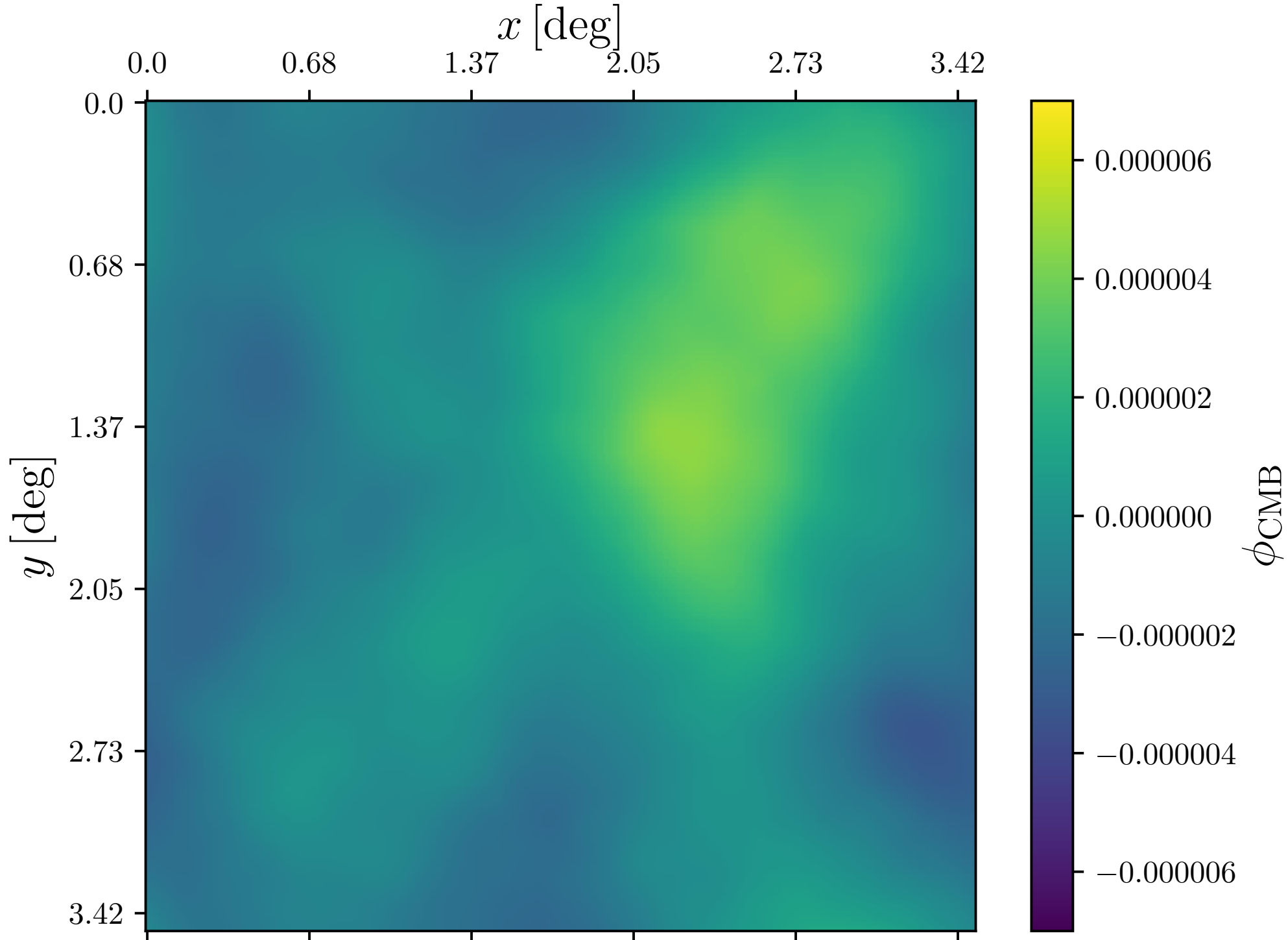
→ Integrated Total Mass



**lensed**

# CMB Lensing

→ Integrated Total Mass



**input lensing potential**

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

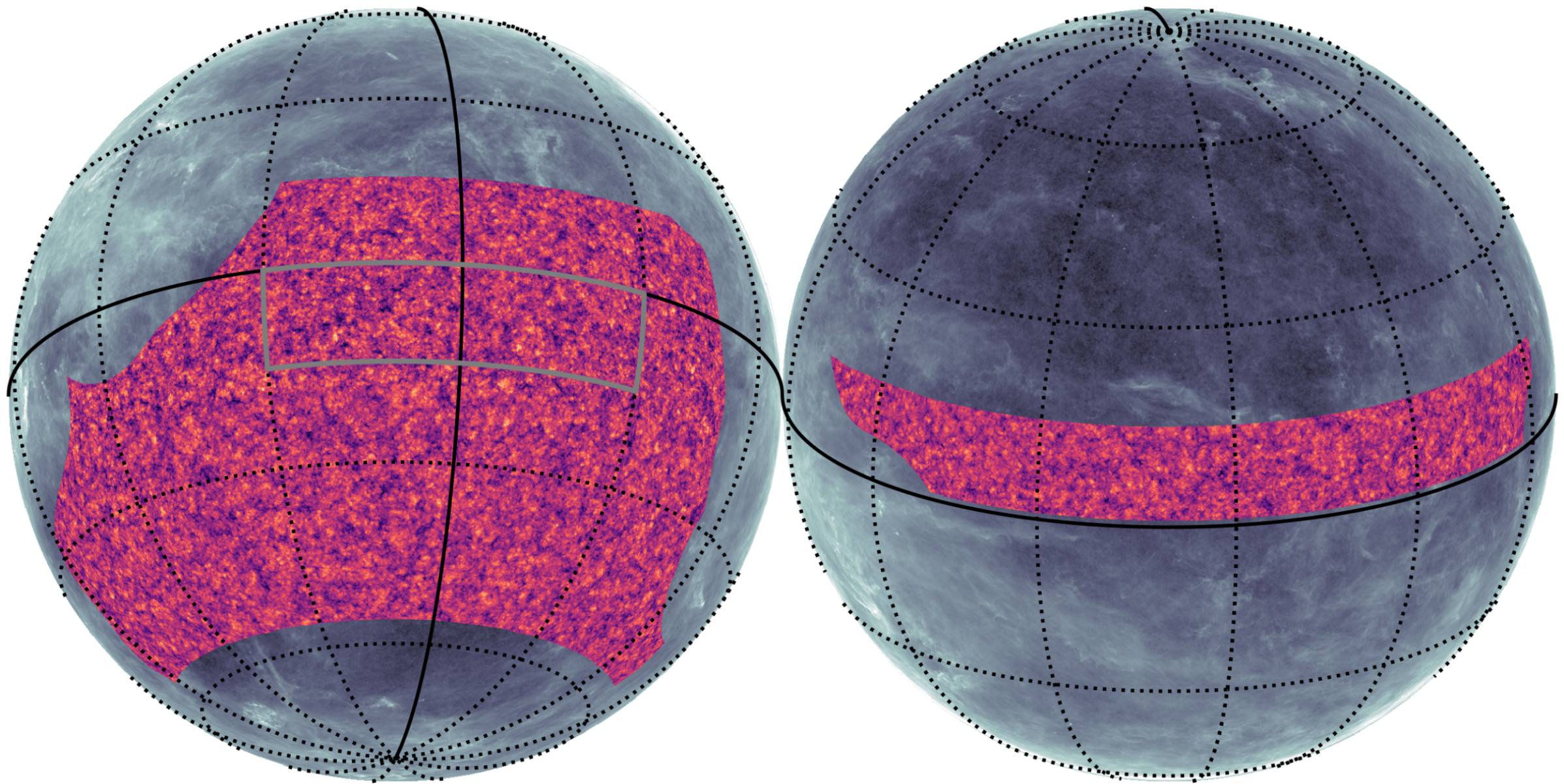




# CMB Lensing

State of the art: ACT DR6

ACT DR6 CMB lensing mass map



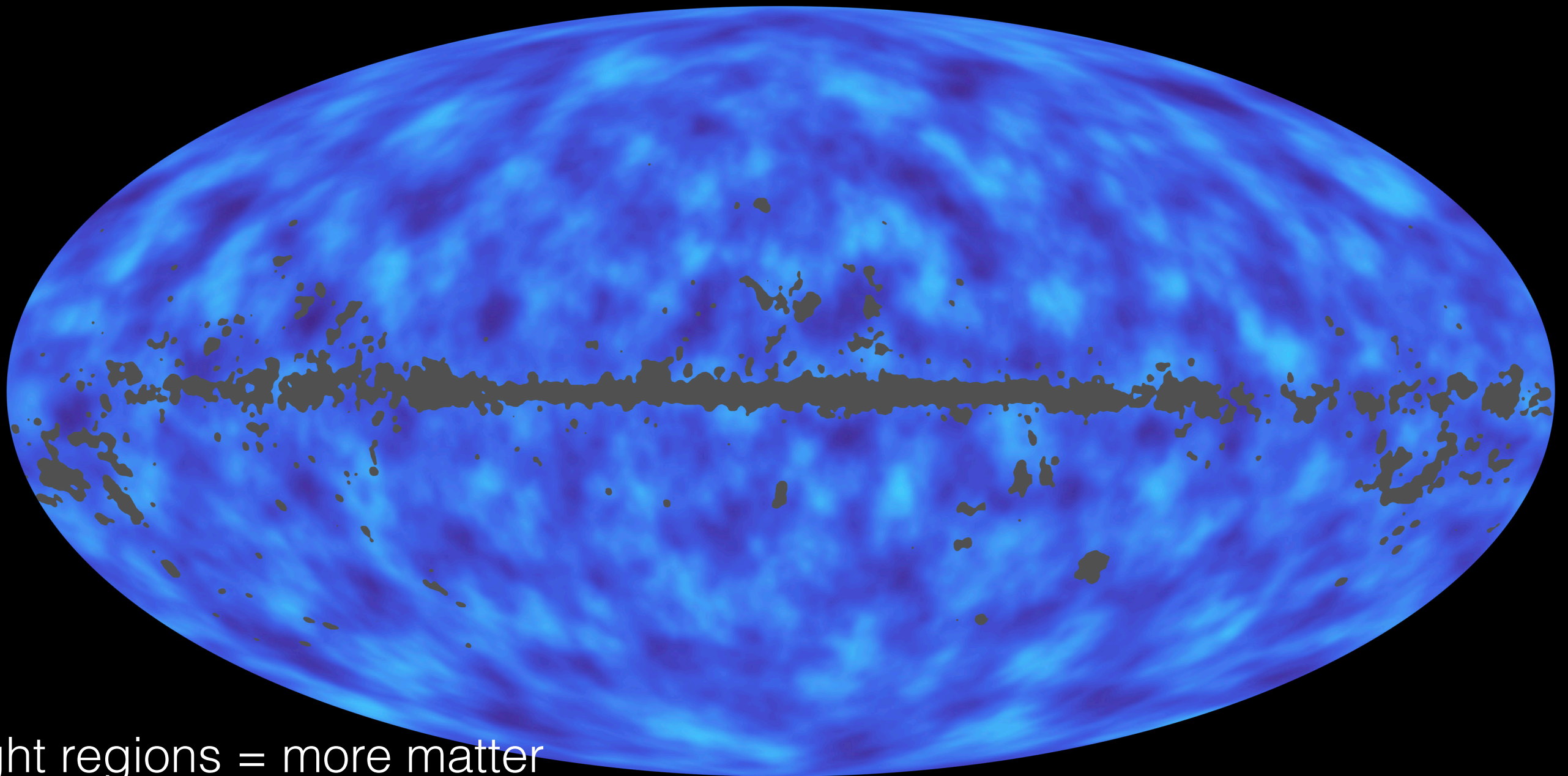
light regions = more matter; dark regions = less matter

[Qu et al. \(2023\)](#); [Madhavacheril et al. \(2023\)](#); [MacCrann et al. \(2023\)](#)



# CMB Lensing

State of the art: *Planck*

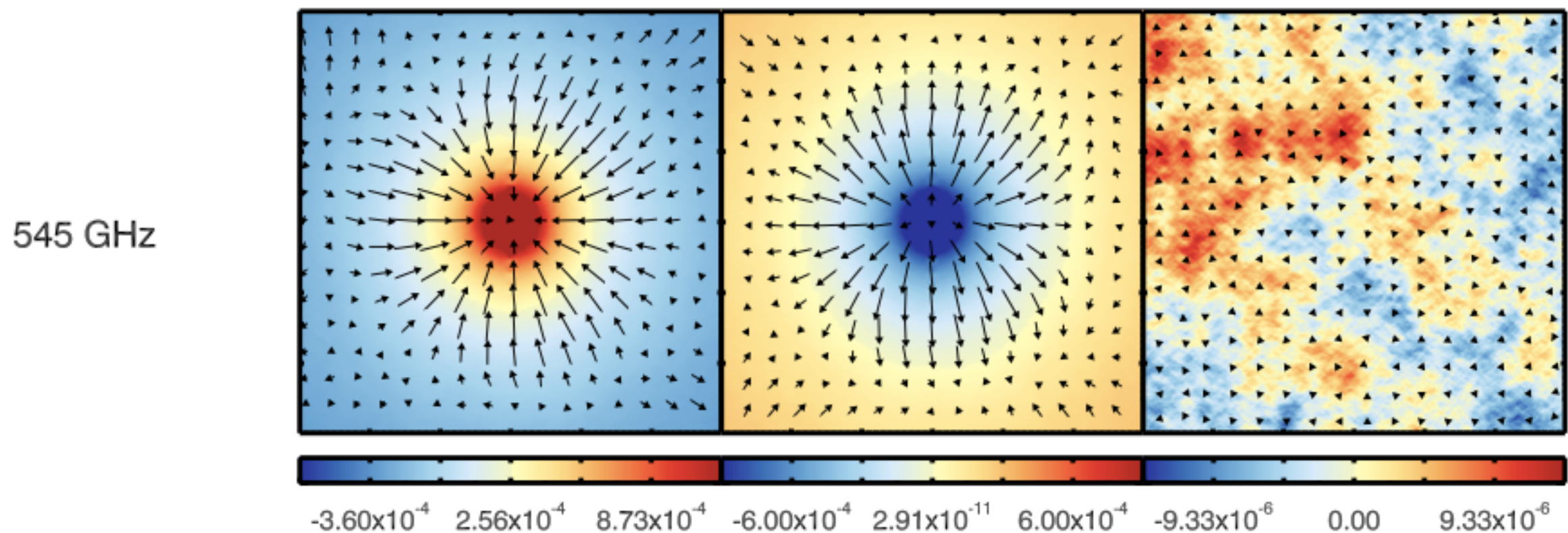


light regions = more matter  
dark regions = less matter

# Cosmic Infrared Background

Colin Hill  
Columbia

cumulative emission of dusty, star-forming galaxies over cosmic time  
strongly correlated with CMB lensing (and partially correlated w/ tSZ  
and other fields)



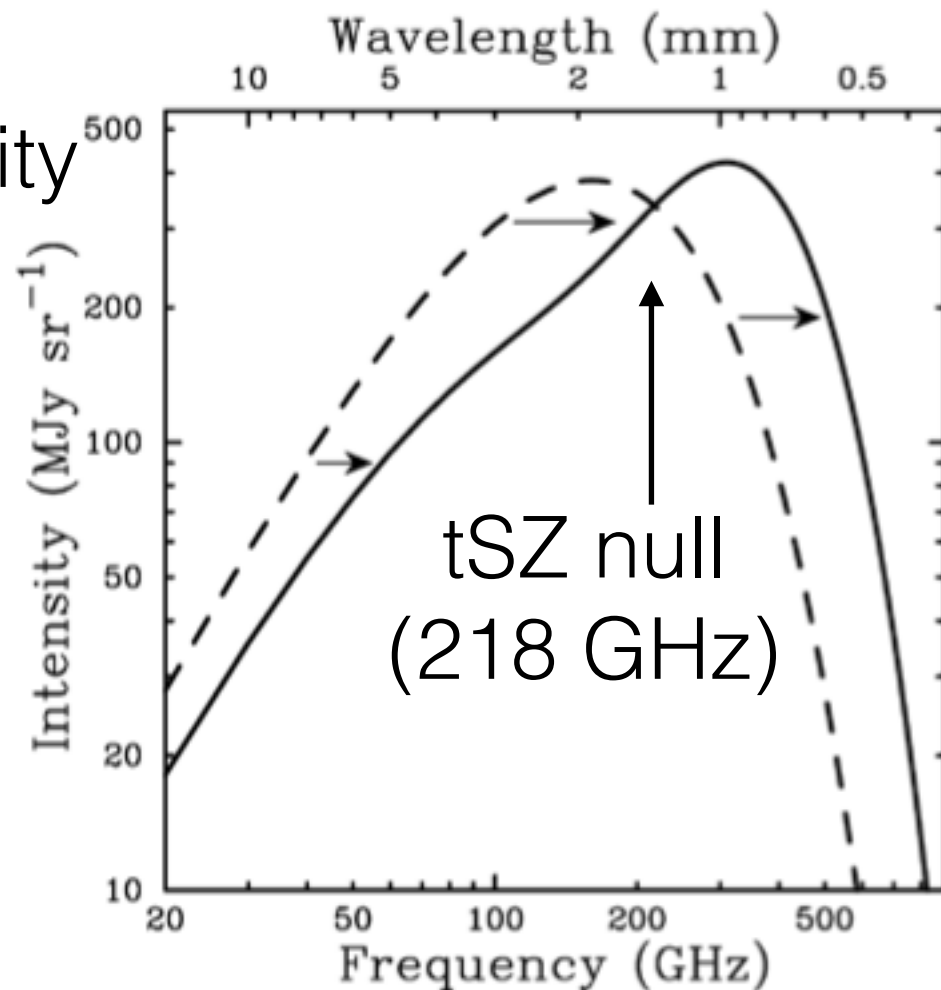


# Compton- $y$ Maps from Planck PR4 with `pyilc`

# Thermal SZ Extraction

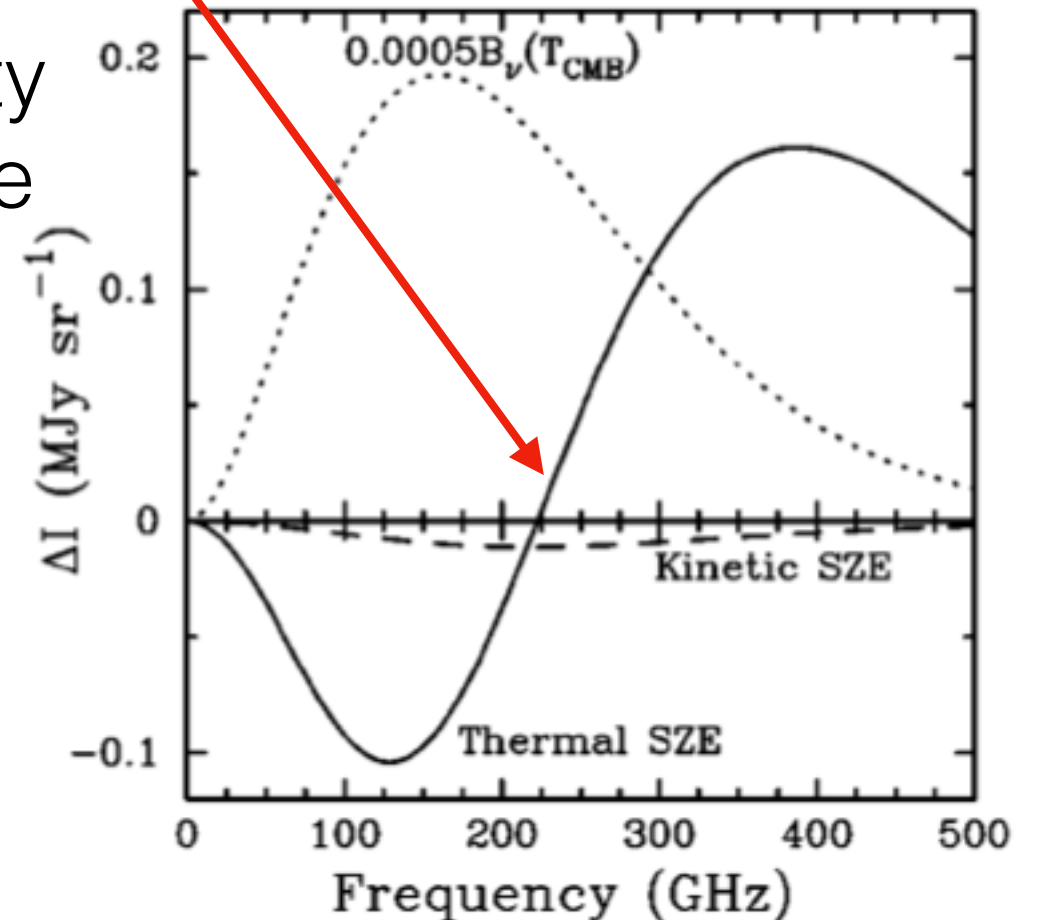
Utilize unique spectral signature of tSZ effect

intensity



frequency

intensity  
change



frequency

$$g_\nu = x \coth\left(\frac{x}{2}\right) - 4$$

$$x \equiv \frac{h\nu}{k_B T_{CMB}}$$

# Thermal SZ Extraction

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Columbia

## Internal Linear Combination

relatively agnostic approach, flexible choice of domain

$$\Delta T_i(p) = a_i y(p) + n_i(p) \quad i \longleftrightarrow \text{frequency}$$

observed temperature  
fluctuation

component  
of interest

noise+  
contaminants



# Thermal SZ Extraction

Colin Hill  
Columbia

## Internal Linear Combination

relatively agnostic approach, flexible choice of domain

$$\Delta T_i(p) = a_i y(p) + n_i(p) \quad i \longleftrightarrow \text{frequency}$$

observed temperature  
fluctuation

component  
of interest

noise+  
contaminants

minimum-variance estimator with unit response to desired component:

$$\hat{y}(p) = w_i \Delta T_i(p) \quad w_j = \frac{a_i (\hat{R}^{-1})_{ij}}{a_k (\hat{R}^{-1})_{kl} a_l}$$

$$\hat{R}_{ij} = N_{\text{pix}}^{-1} \sum_p \Delta T_i(p) \Delta T_j(p)$$

flexibility = choice of domain on which to compute freq.-freq. covariance

e.g., Eriksen+(2004); Delabrouille+(2009); Remazeilles+(2011); JCH & Spergel (2014)

# Thermal SZ Extraction

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Columbia

## Constrained Internal Linear Combination

extension: explicitly remove other component(s) as well

$$\Delta T_i(p) = a_i y(p) + b_i s(p) + n_i(p)$$

observed temperature  
fluctuation

component  
of interest

component  
to remove

noise + other  
contaminants

# Thermal SZ Extraction

Colin Hill  
Columbia

## Constrained Internal Linear Combination

extension: explicitly remove other component(s) as well

$$\Delta T_i(p) = a_i y(p) + b_i s(p) + n_i(p)$$

observed temperature  
fluctuation

component  
of interest

component  
to remove

noise + other  
contaminants

minimum-variance estimator with unit response to desired component  
and zero response to undesired component:

$$w_j = \frac{\left( b_k (\hat{R}^{-1})_{kl} b_l \right) a_i (\hat{R}^{-1})_{ij} - \left( a_k (\hat{R}^{-1})_{kl} b_l \right) b_i (\hat{R}^{-1})_{ij}}{\left( a_k (\hat{R}^{-1})_{kl} a_l \right) \left( b_m (\hat{R}^{-1})_{mn} b_n \right) - \left( a_k (\hat{R}^{-1})_{kl} b_l \right)^2}$$

- can be extended to explicitly remove N components
- advantage: can remove contaminants that could bias some analysis
- disadvantage: variance in final ILC map is larger

# Thermal SZ Extraction

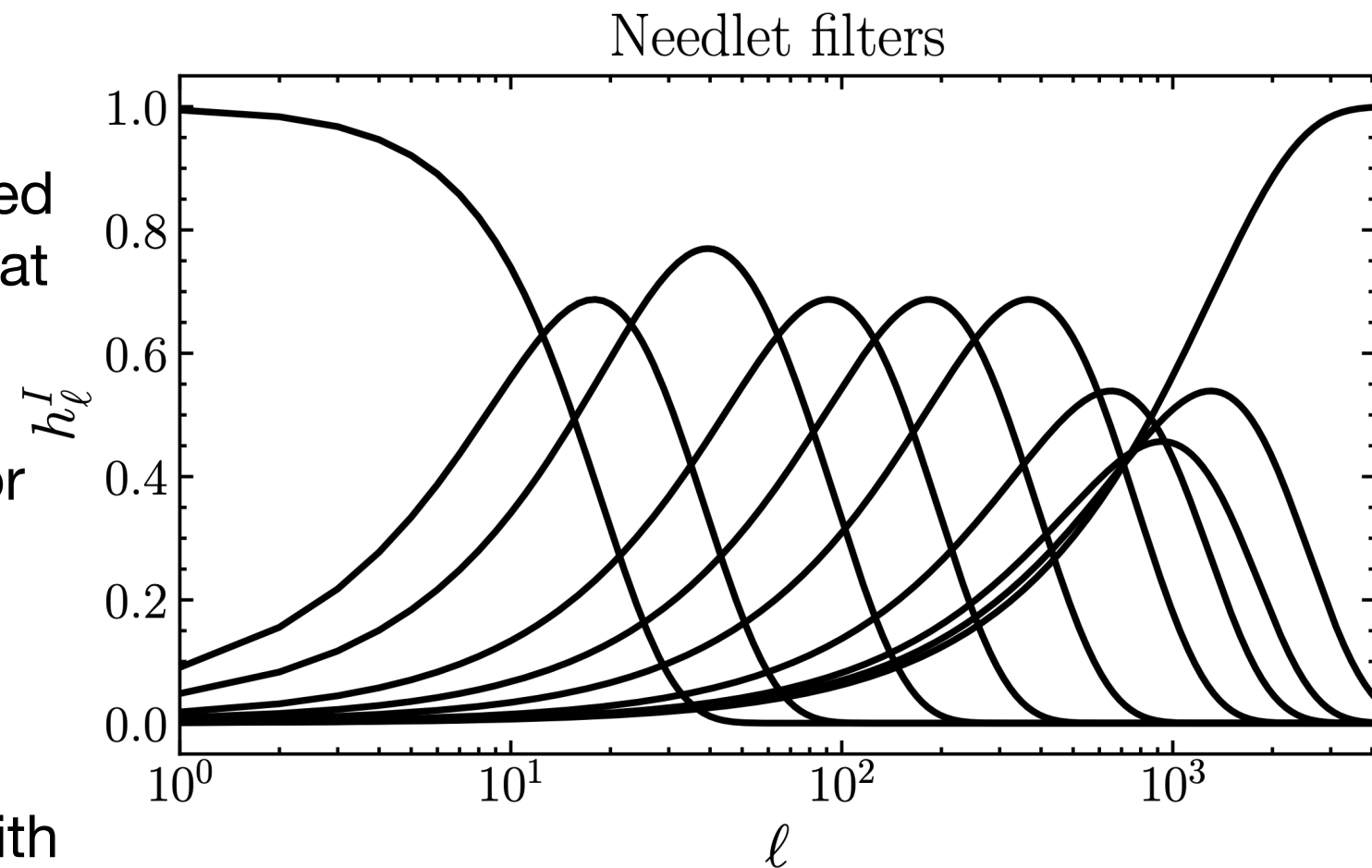
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Columbia

## Needlet Internal Linear Combination

Needlets allow localization of ILC weights in both harmonic and pixel space

### Steps:

- 1) Filter each frequency map with each harmonic-space needlet filter
- 2) Compute the freq.-freq. covariance matrix in real-space domain of specified size centered on each pixel (for maps at each needlet scale)
- 3) Compute ILC weights at each pixel (for maps at each needlet scale)
- 4) Obtain per-scale ILC maps
- 5) Filter each per-scale ILC map again with the needlet filters
- 6) Co-add ILC maps from all needlet scales to obtain final NILC map



e.g., Eriksen+(2004); Delabrouille+(2009); Remazeilles+(2011); JCH & Spergel (2014)



# Thermal SZ Extraction

**pyilc**

flexible, extensible NILC code in Python

Needlet ILC in Python

**Features:**

- Trivial installation, requires only healpy
- Many component SEDs available (CMB, tSZ, CIB, synchrotron, ..) + easy to add more
- Easy to define any type of needlet filters
- Delta-function or realistic passbands can be used
- Gaussian beams or arbitrary ell-dependent beams can be used
- Automatically determines which frequency maps to use at a given needlet scale, given their beams
- Covariances are computed only once and then cached for future use, allowing many constrained ILCs (“deprojections”) to be run at ~zero additional computational expense
- Automatically determines the size of the real-space domains to be used in computing the freq.-freq. covariance matrix at each needlet scale, by requiring the number of modes to be large enough to keep the “ILC bias” below a fixed tolerance:

$$\frac{b_{\text{ILC}}}{\langle s^2 \rangle} = \frac{|1 + N_{\text{deproj}} - N_{\text{freq}}|}{N_{\text{modes}}}$$

# Thermal SZ Extraction

Colin Hill  
Columbia

CIB cleaning: moment deprojection

**Idea: suppose the fundamental SED describing dust emission is indeed a modified blackbody (MBB). Variations in the MBB parameters ( $\beta, T$ ) across the sky and along the line of sight will generically produce new spectral shapes that are described by higher-order moments in a Taylor expansion of the fundamental SED.**

# Thermal SZ Extraction

Colin Hill  
Columbia

## CIB cleaning: moment deprojection

Idea: suppose the fundamental SED describing dust emission is indeed a modified blackbody (MBB). Variations in the MBB parameters ( $\beta, T$ ) across the sky and along the line of sight will generically produce new spectral shapes that are described by higher-order moments in a Taylor expansion of the fundamental SED.

MBB:

$$I_{\nu}^{\text{CIB}}(\hat{n}) = \left( \frac{\nu}{\nu_0} \right)^{\beta+3} \frac{1}{e^{x_{\text{CIB}}} - 1} A^{\text{CIB}}(\hat{n})$$

First-order moments:

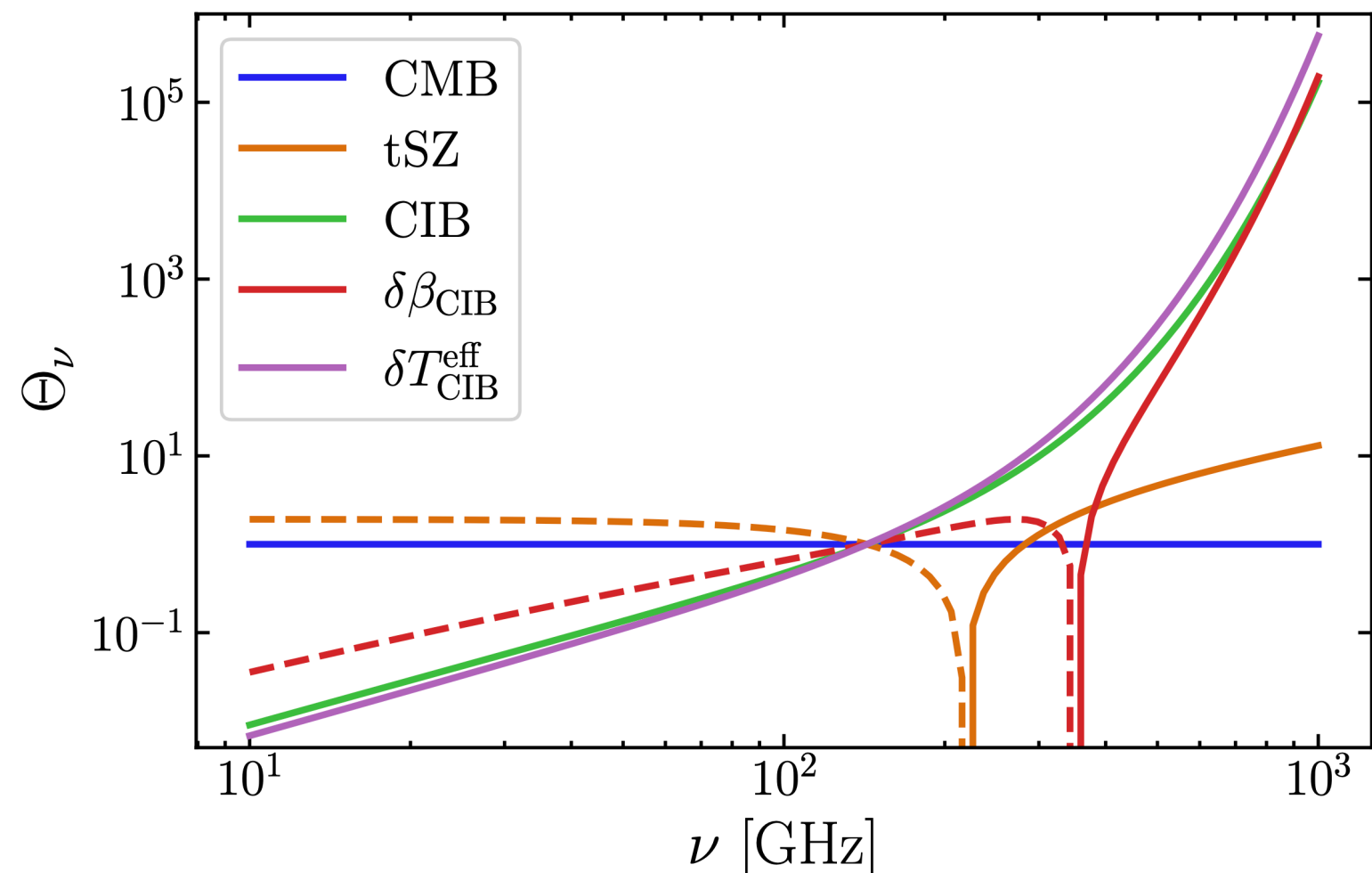
$$\frac{\partial I_{\nu}^{\text{CIB}}(\hat{n})}{\partial \beta} = \ln \left( \frac{\nu}{\nu_0} \right) I_{\nu}^{\text{CIB}}(\hat{n}) ;$$

$$\frac{\partial I_{\nu}^{\text{CIB}}(\hat{n})}{\partial T_{\text{CIB}}^{\text{eff}}} = I_{\nu}^{\text{CIB}}(\hat{n}) \frac{x_{\text{CIB}}}{T_{\text{CIB}}^{\text{eff}}} \frac{e^{x_{\text{CIB}}}}{e^{x_{\text{CIB}}} - 1}$$

$$x_{\text{CIB}} \equiv \frac{h\nu}{k_B T_{\text{CIB}}^{\text{eff}}}$$

$$\nu_0 = 353 \text{ GHz}$$

Component SEDs [normalized]



# Thermal SZ Extraction

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Columbia

CIB cleaning: moment deprojection

**MBB fit to CIB monopole SED predicted by best-fit halo model to CIB power spectra**

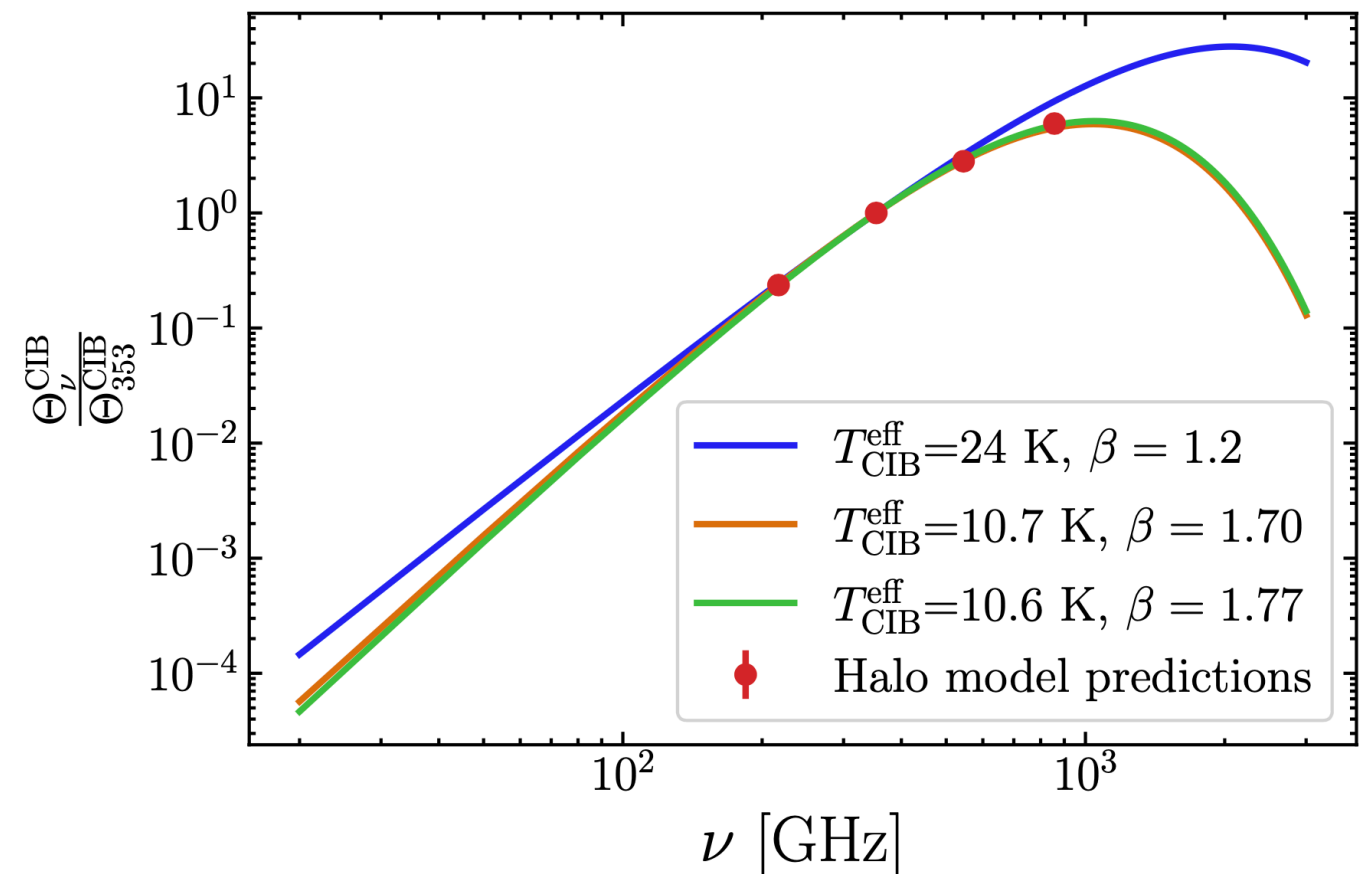
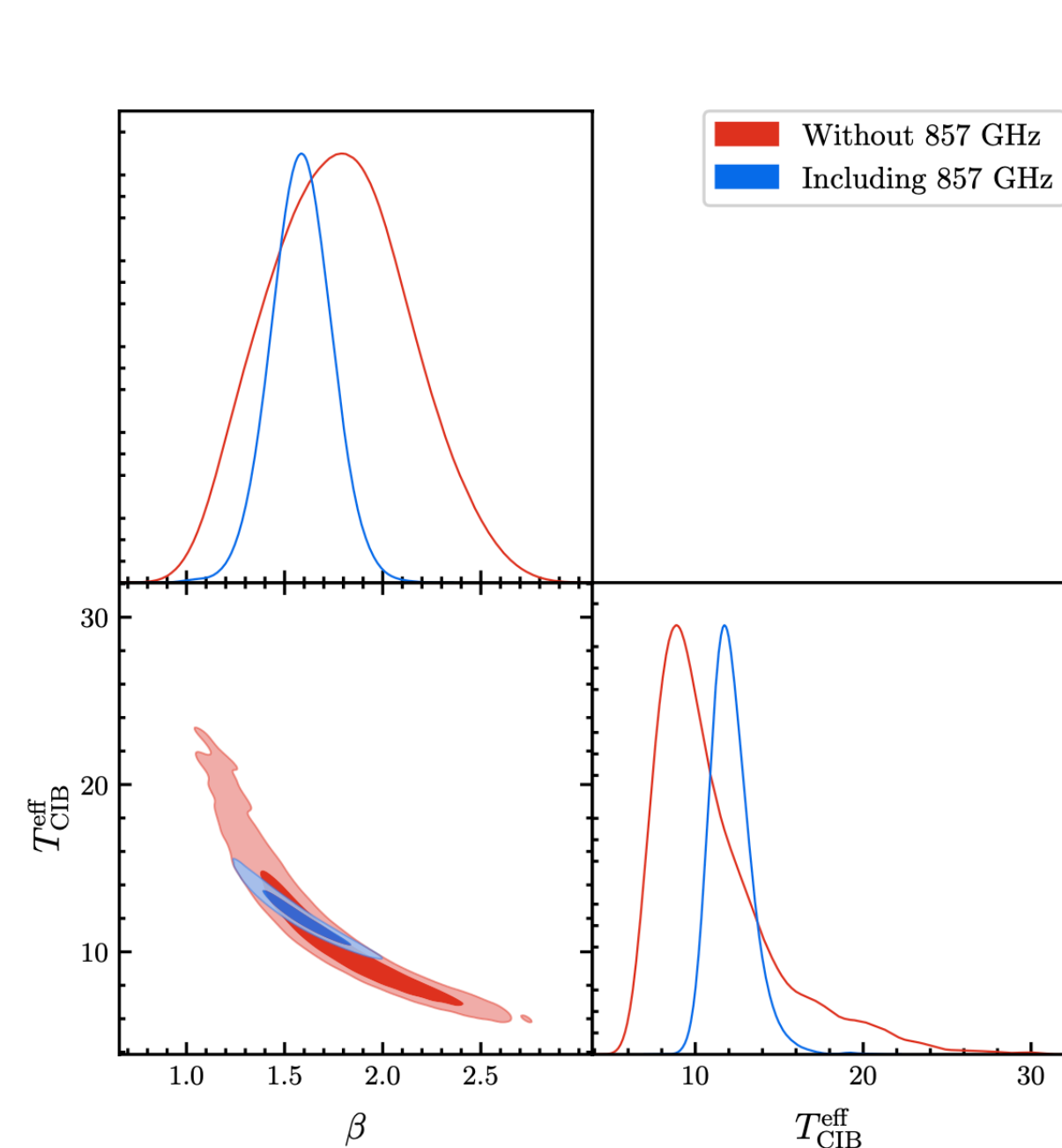


# Thermal SZ Extraction

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CIB cleaning: moment deprojection

**MBB fit to CIB monopole SED predicted by best-fit halo model to CIB power spectra**



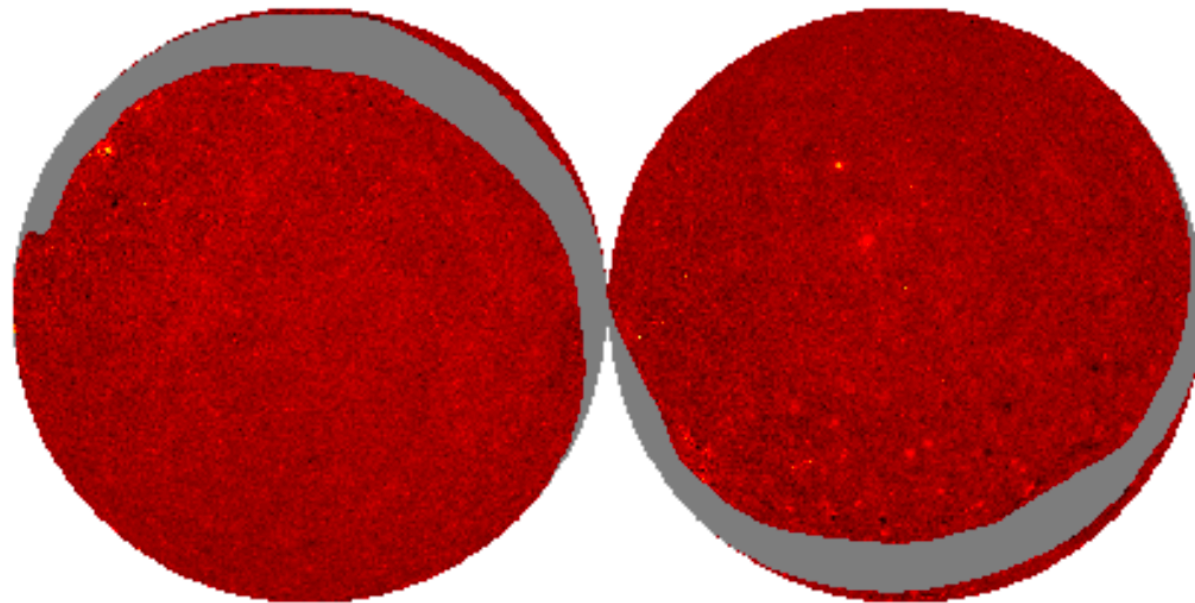
Later in our analysis we will draw  $(\beta, T_{\text{CIB}}^{\text{eff}})$  samples from this posterior to test the sensitivity of our CIB deprojections to the assumed MBB SED

# Thermal SZ Extraction

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Columbia

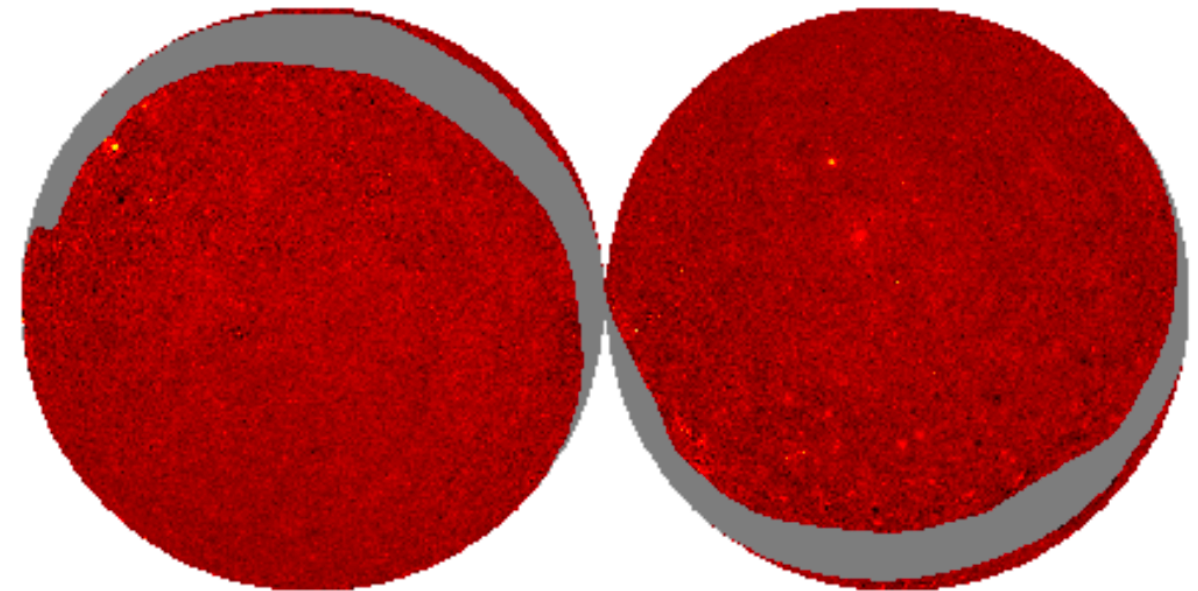
Application to Planck PR4 (NPIPE) maps

NILC tSZ; no deprojection



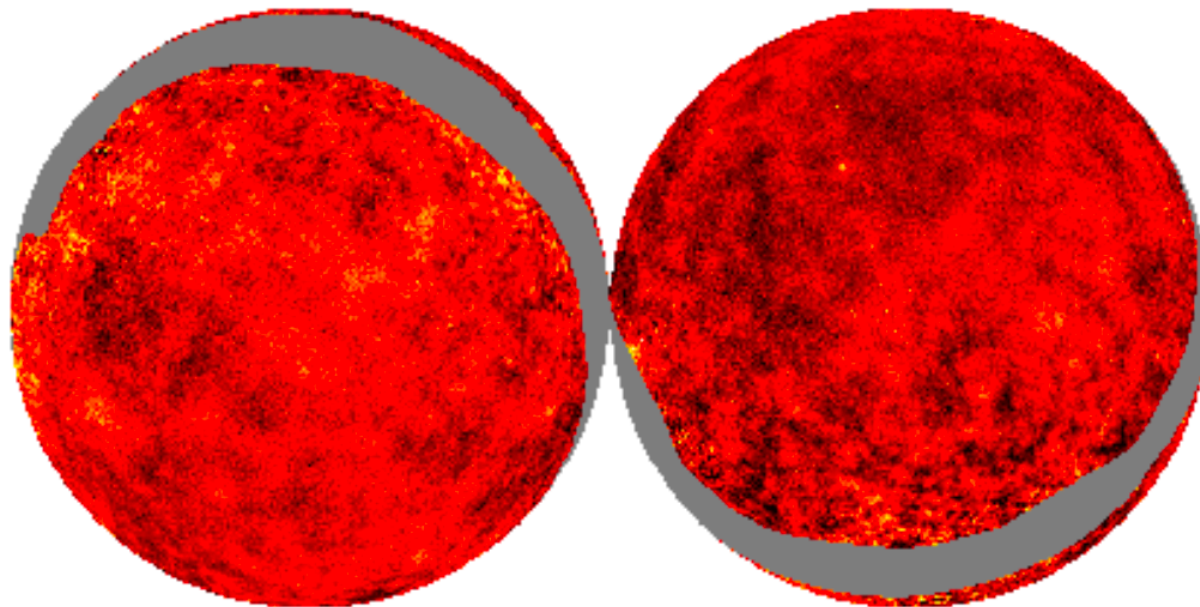
-1e-05 Compton  $y$  4e-05

NILC tSZ; deprojection of CIB



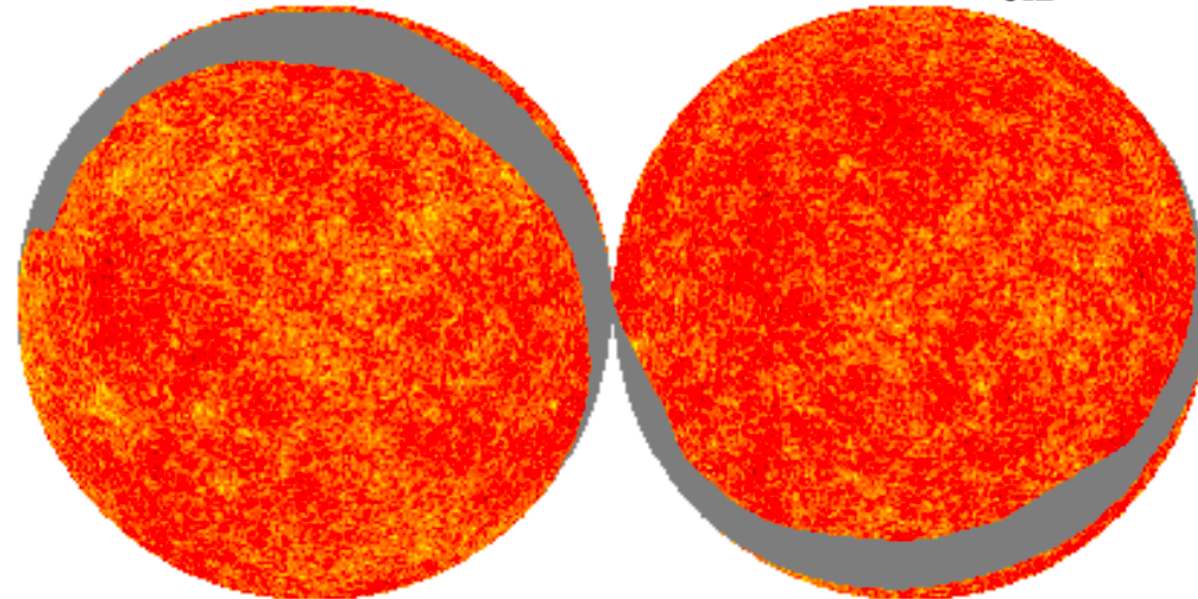
-1e-05 Compton  $y$  4e-05

NILC tSZ; deprojection of CIB+ $\delta\beta$



-2e-05 Compton  $y$  4e-05

NILC tSZ; deprojection of CIB+ $\delta\beta$ + $\delta T_{\text{CIB}}^{\text{eff}}$

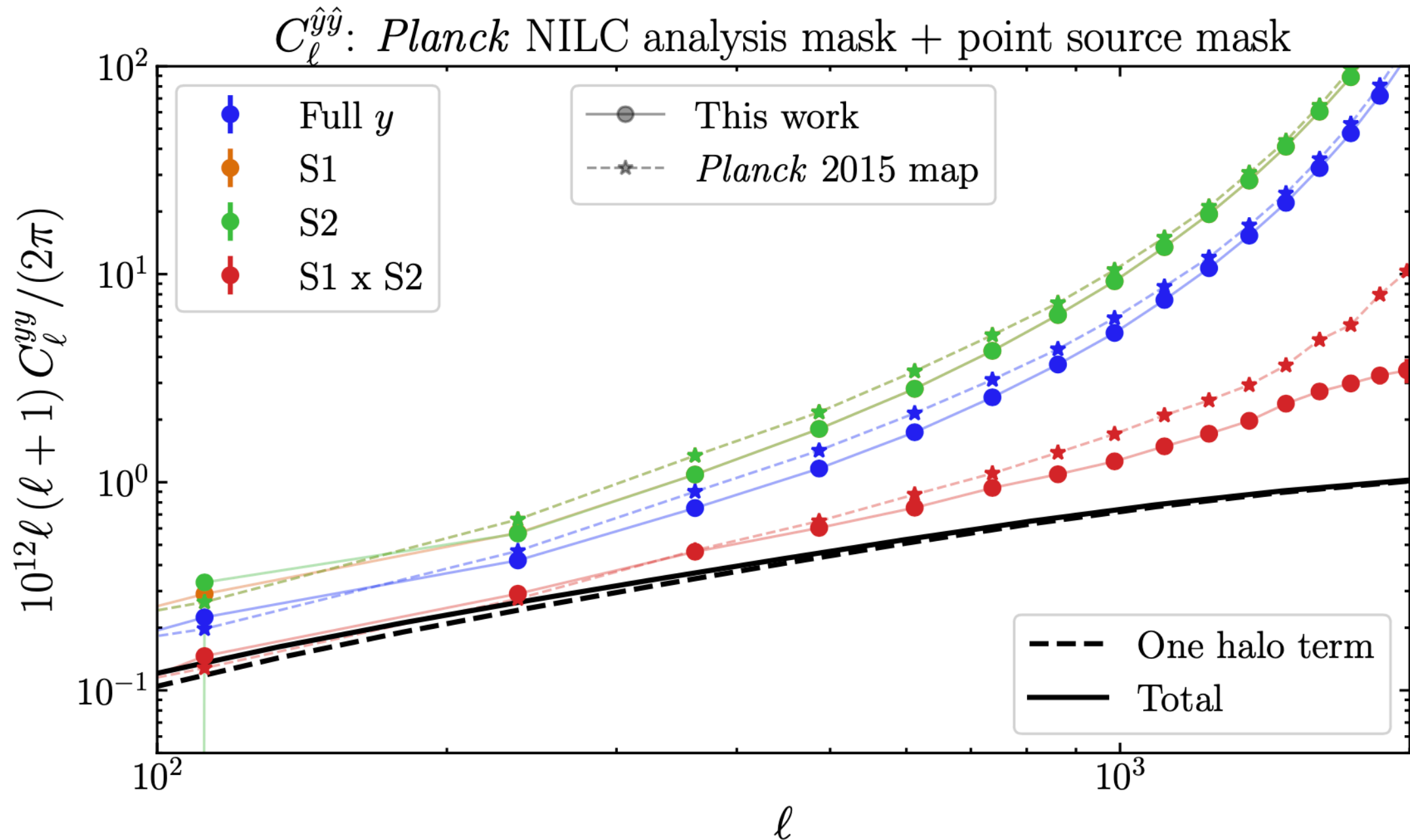


-9e-05 Compton  $y$  9e-05

# Thermal SZ Extraction

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Columbia

Application to Planck PR4 (NPIPE) maps



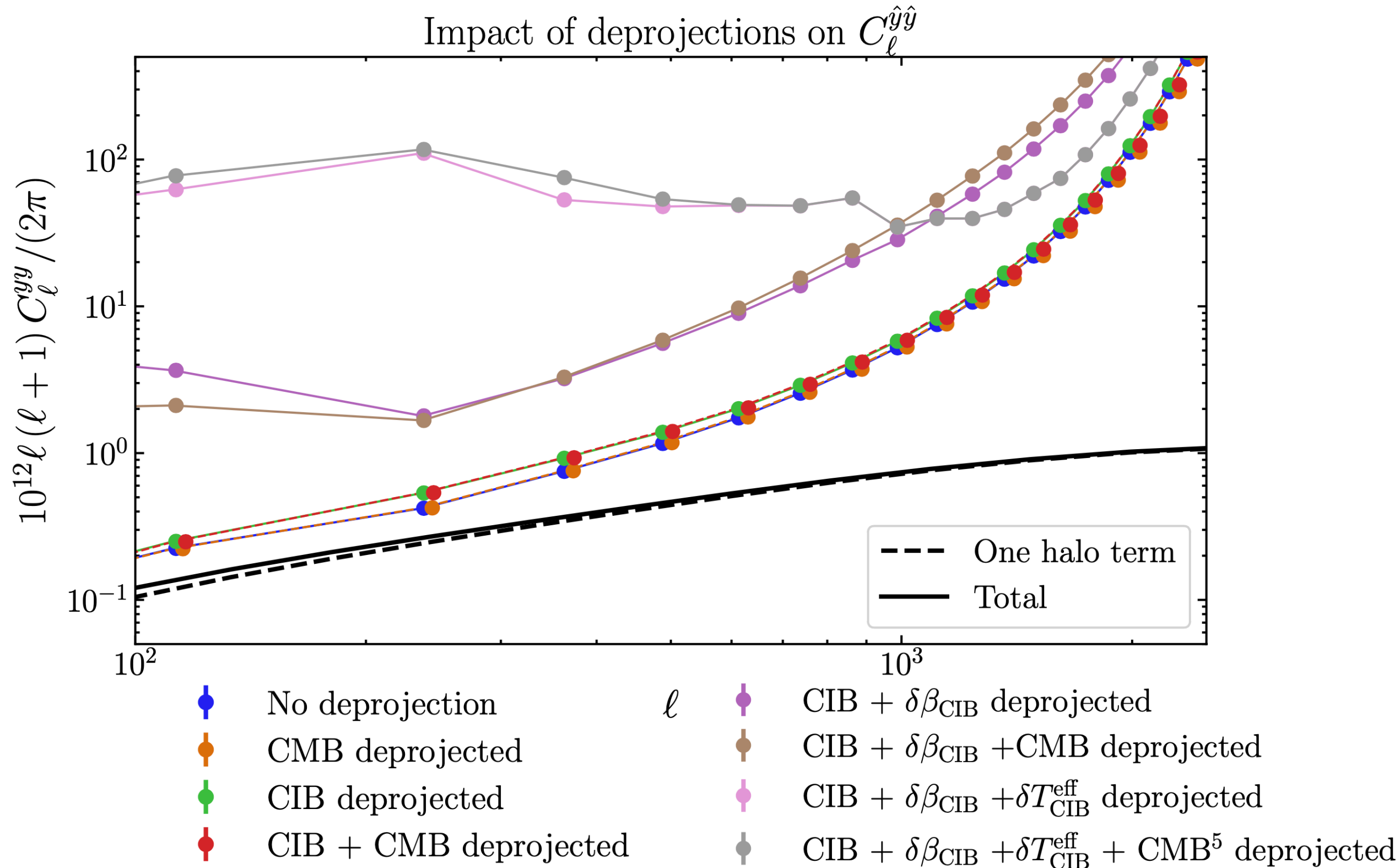
**~10-20% lower noise visible on small scales in auto-spectrum, and improved foreground cleaning visible in S1xS2 cross-spectrum (free of noise bias)**



# Thermal SZ Extraction

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Columbia

Application to Planck PR4 (NPIPE) maps



# Thermal SZ X CMB Lensing



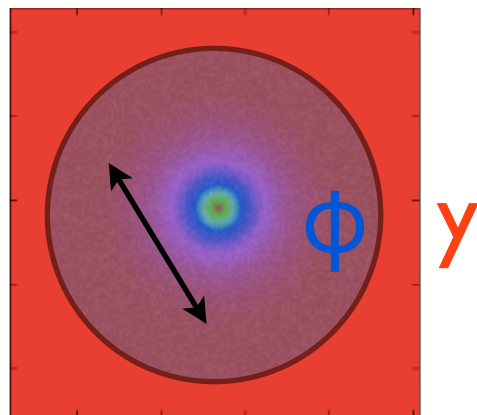
# tSZ x CMB Lensing

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Columbia

Theory: halo model

- Cross-spectrum can be derived similarly to tSZ auto-spectrum
- Need Fourier transform of both the  $y$ -profile and  $\phi$ - (lensing potential) profile (e.g., computed from NFW) for each halo
- Contributions from both one-halo and two-halo terms:

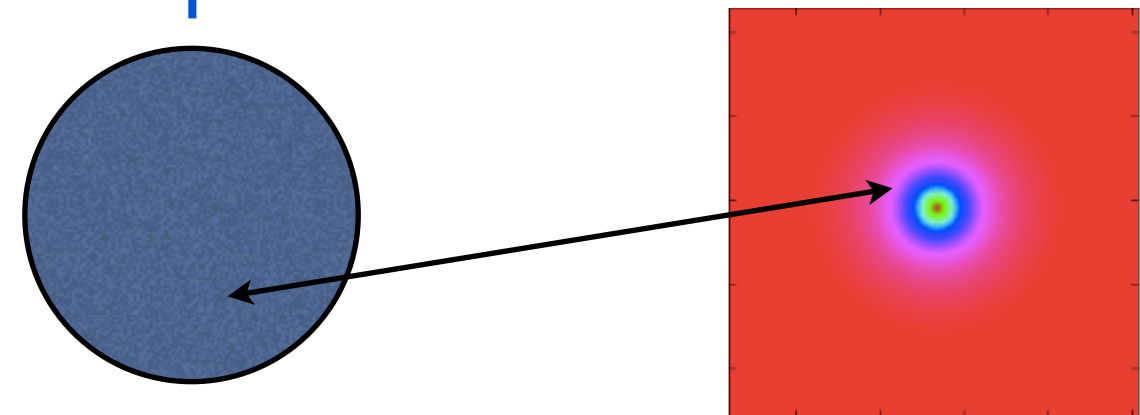
one-halo



dominates on small scales

sensitive to number of clusters and  
how gas pressure traces DM in  
clusters

$\phi$  two-halo



dominates on large scales

sensitive to how gas traces  
DM on large scales (amongst  
many things)

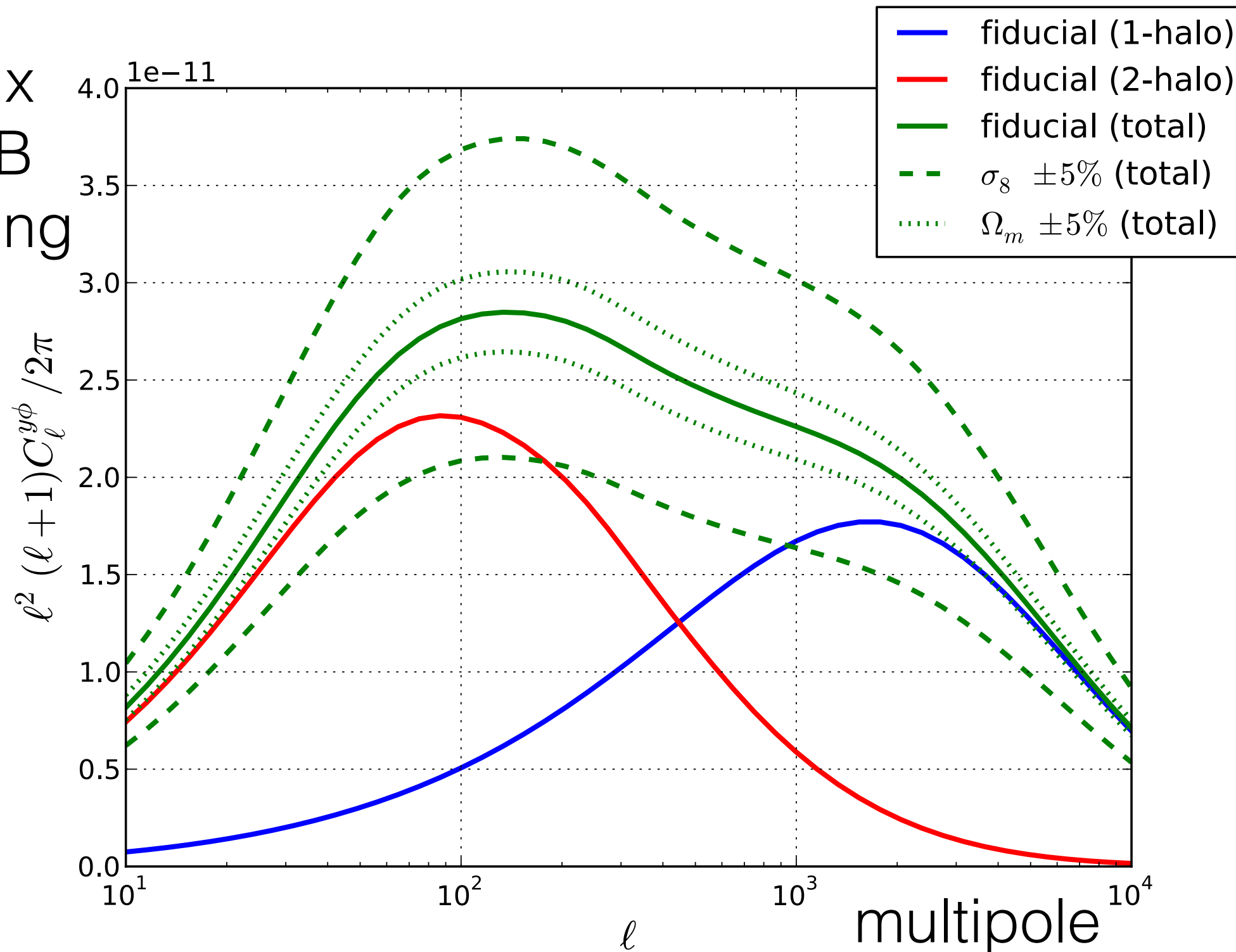
**All theory calculations performed with CLASS\_SZ (Bolliet+2022)**

# tSZ x CMB Lensing

Colin Hill  
Columbia

Theory: halo model

tSZ x  
CMB  
Lensing  
PS



**fiducial =**  
Battaglia+  
2012  
pressure  
profile  
+  
Tinker+2008  
HMF  
+  
Tinker+2010  
halo bias

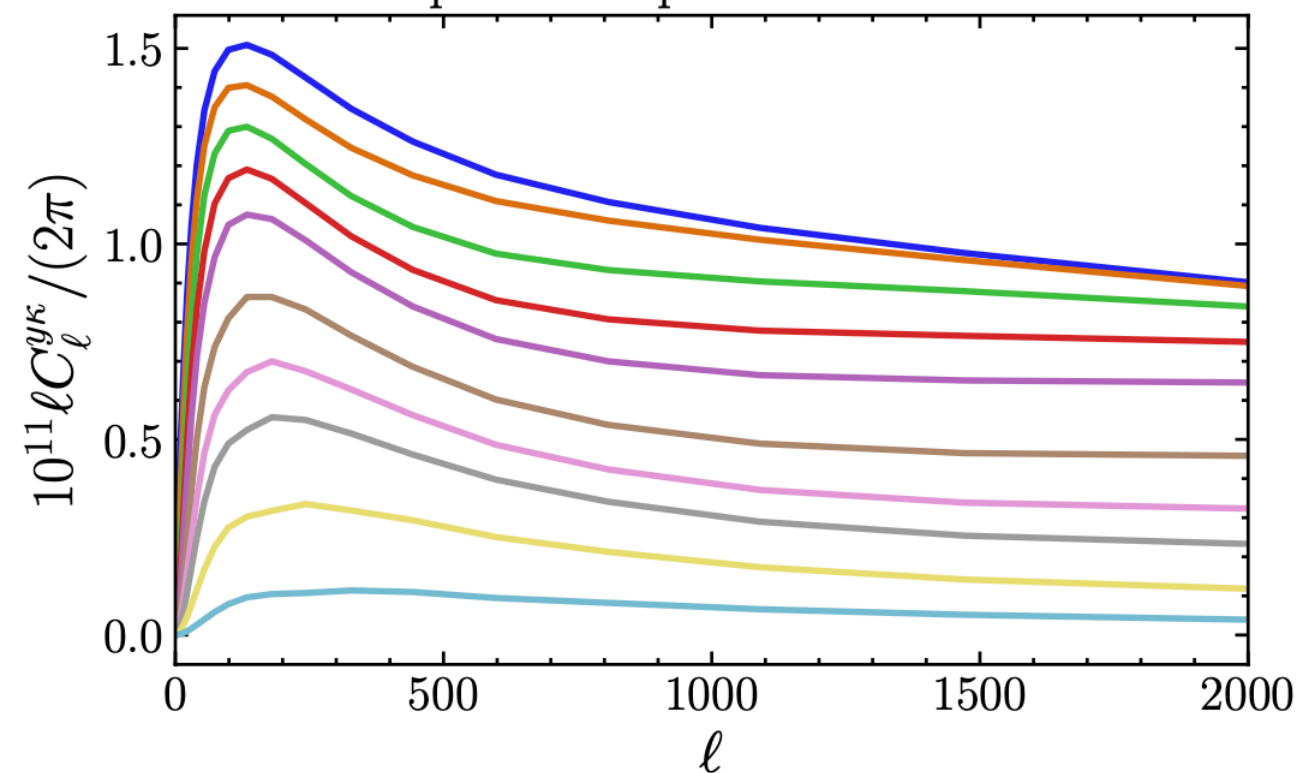
# tSZ x CMB Lensing

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Columbia

Theory: origin of the signal

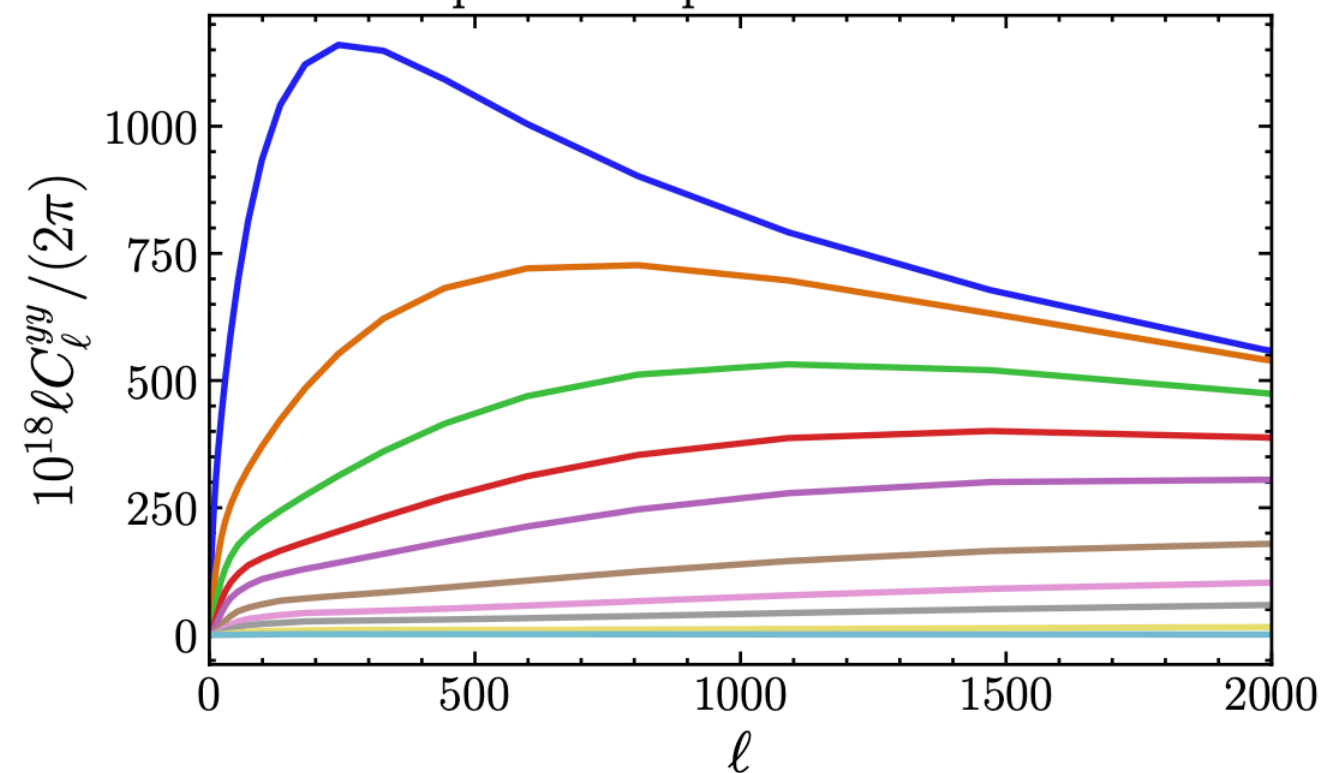
$y \times \phi_{\text{CMB}}$   
cross-power

Cross power: dependence on redshift



$yy$   
auto-power

Auto power: dependence on redshift



At  $\ell=2000$ : ~25% of cross-power signal from  $z > 1$  (cf. < 10% of auto-power signal)

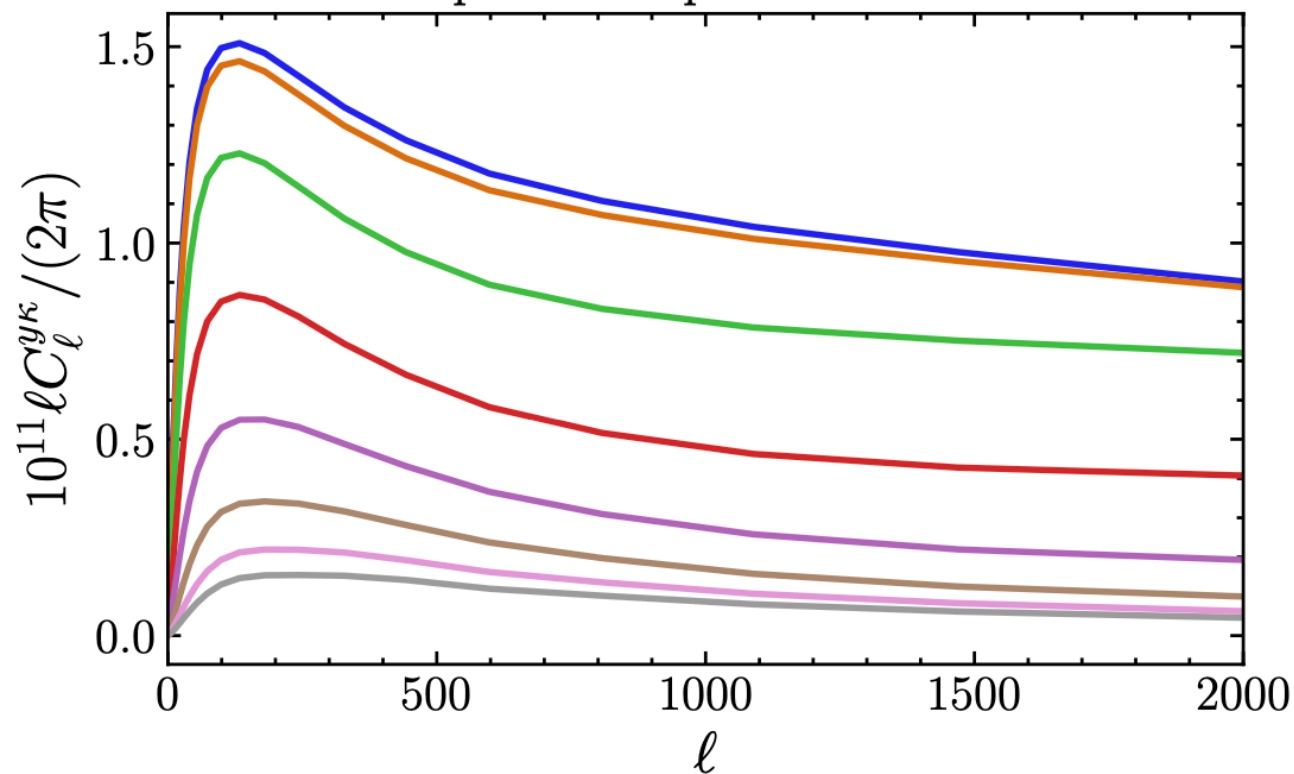
# tSZ x CMB Lensing

Colin Hill  
Columbia

Theory: origin of the signal

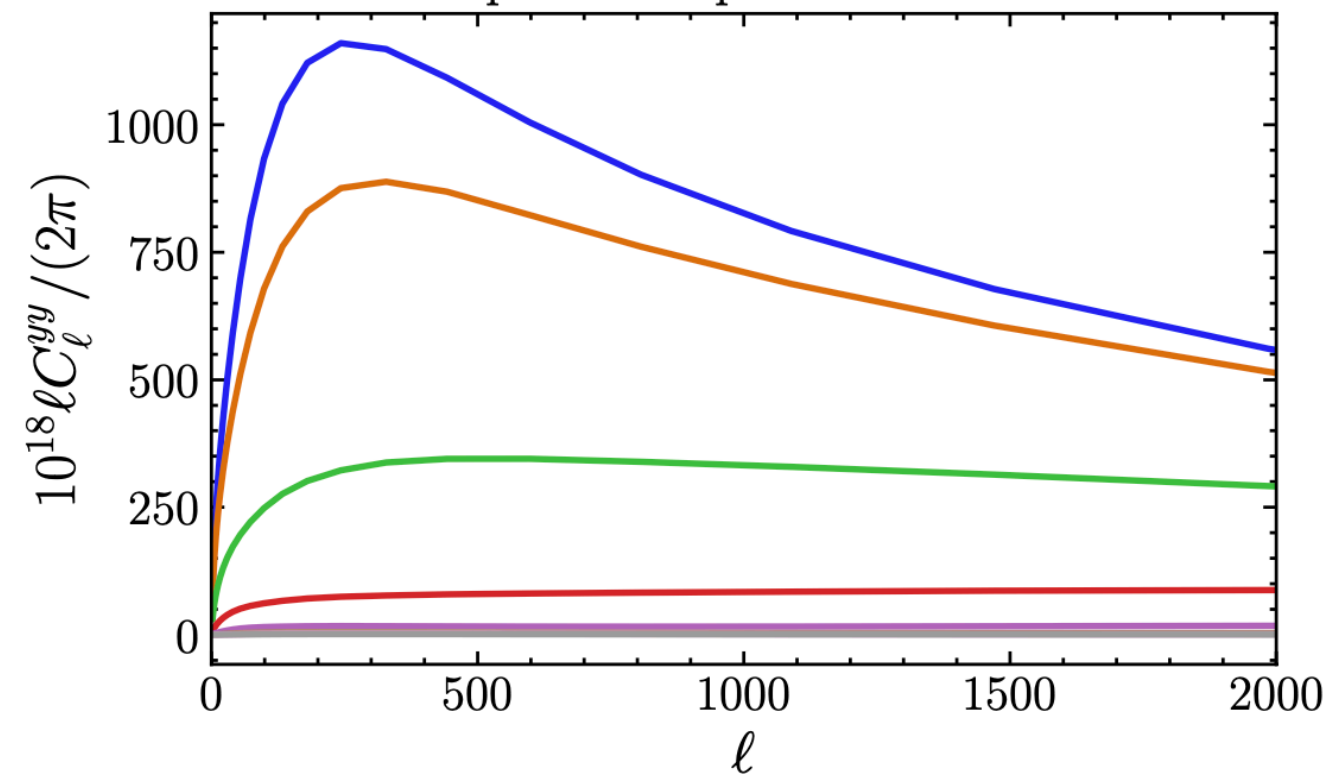
$y \times \phi_{\text{CMB}}$   
cross-power

Cross power: dependence on mass



$yy$   
auto-power

Auto power: dependence on mass



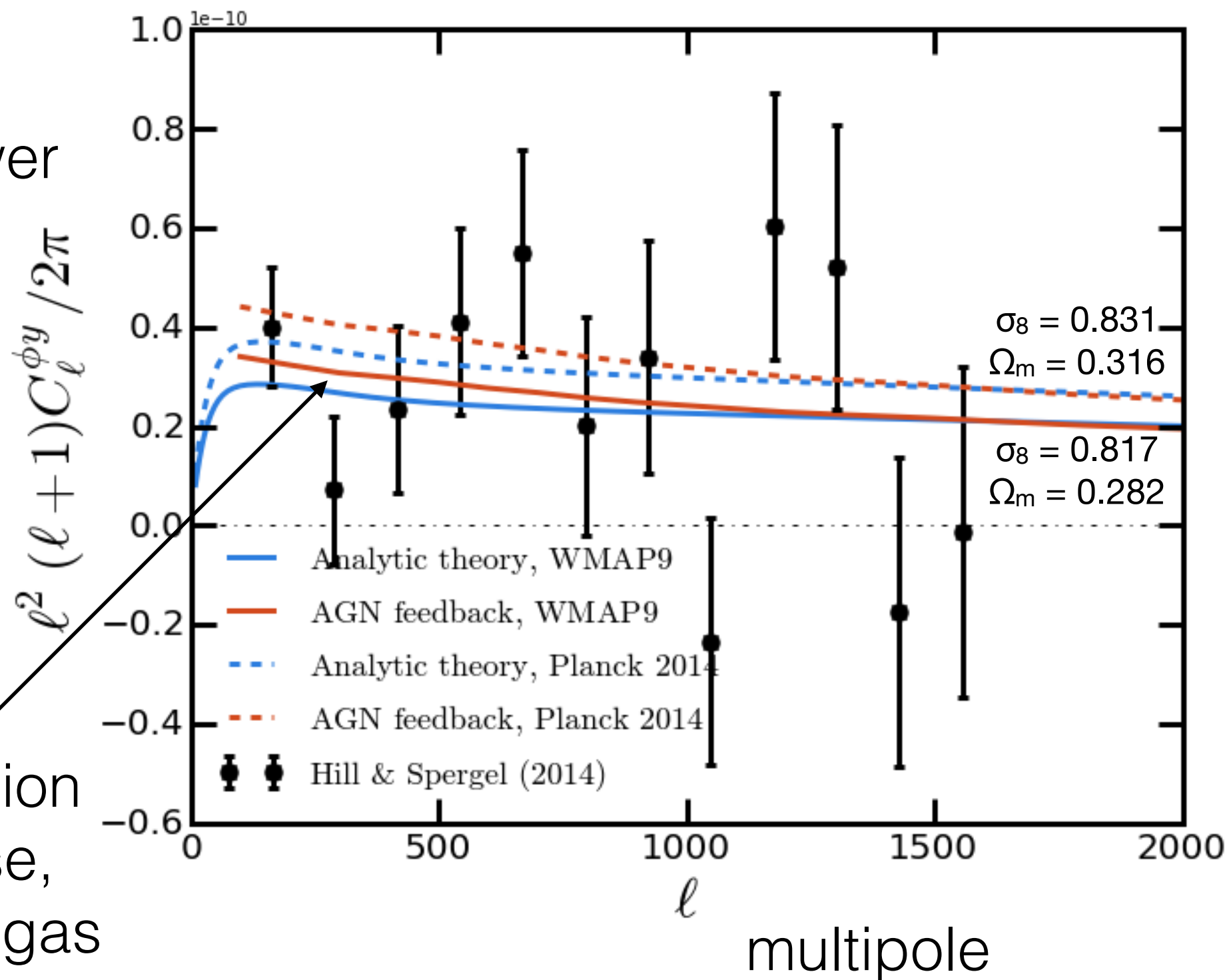
At  $\ell=2000$ :  $\sim 25\%$  of cross-power signal from  $M < 10^{13.5} M_{\text{sun}}/h$  (cf.  $< 3\%$  of auto-power)

# tSZ x CMB Lensing

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Columbia

Theory: origin of the signal

$y \times \phi_{\text{CMB}}$   
cross-power



**halo  
model**

**hydro  
sims**

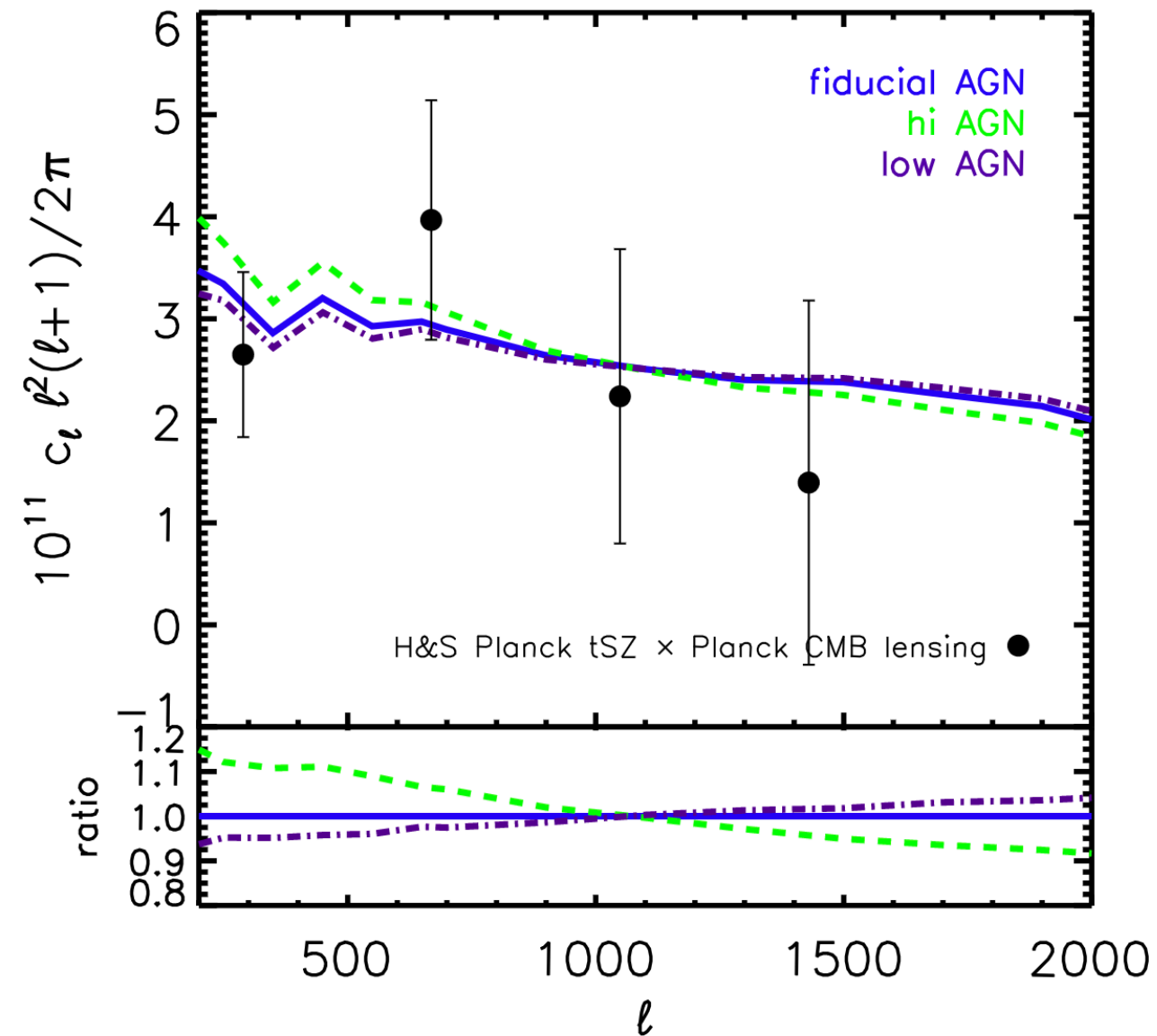
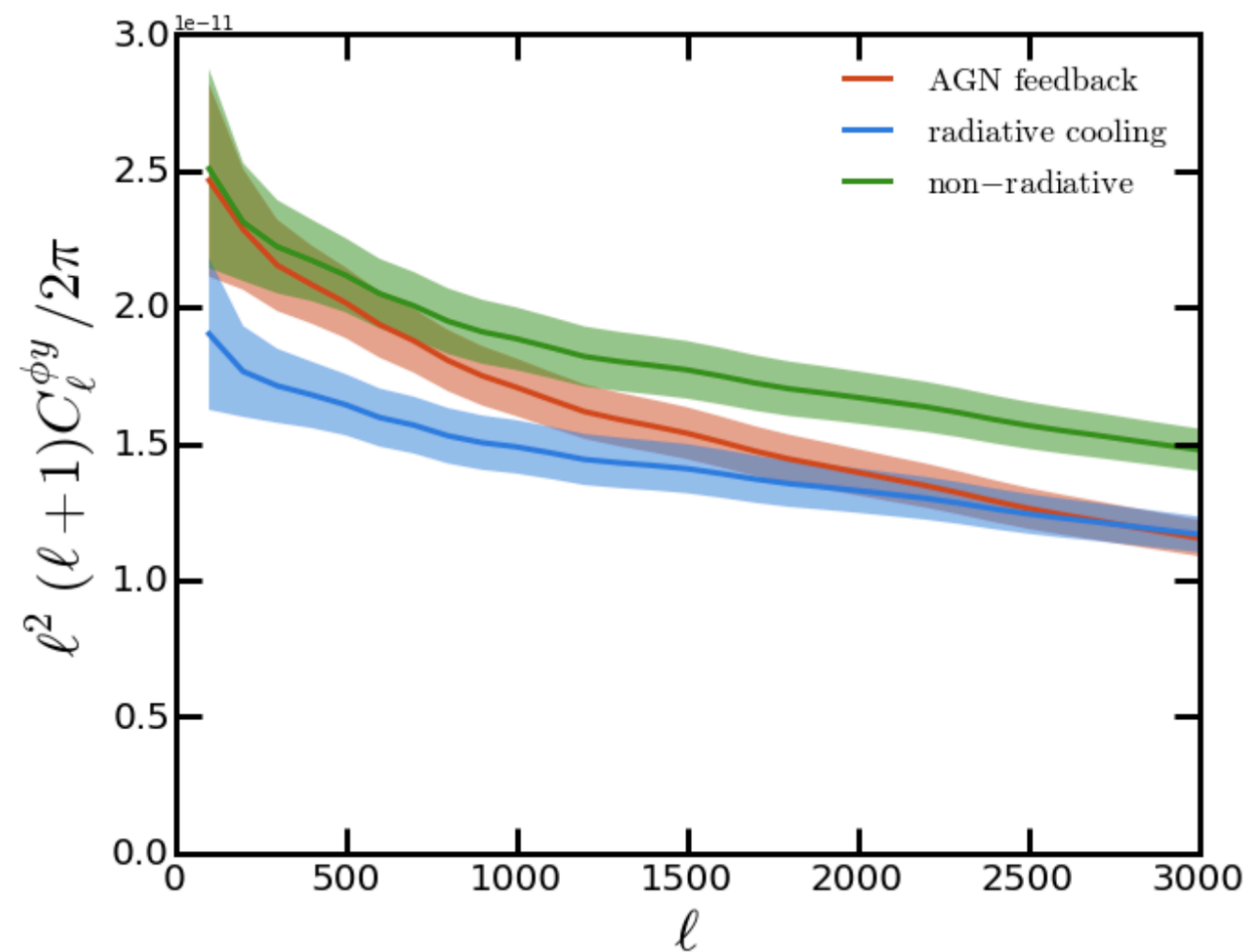
contribution  
of diffuse,  
unbound gas



# tSZ x CMB Lensing

Colin Hill  
Columbia

Theory: sensitivity to gasphysics/feedback modeling



# tSZ x CMB Lensing

Colin Hill  
Columbia

## Cross-correlation of pyilc $y$ -maps with PR4 CMB lensing maps

Validation of pipeline on detailed mm-wave sky simulations

- Simulations: Websky CMB+tSZ+CIB + PySM dust+synch+free-free+AME + Planck noise
- Processed through pyilc pipeline with various CIB deprojection choices
- Cross-correlated with true Websky  $\kappa$  map (with or without noise)

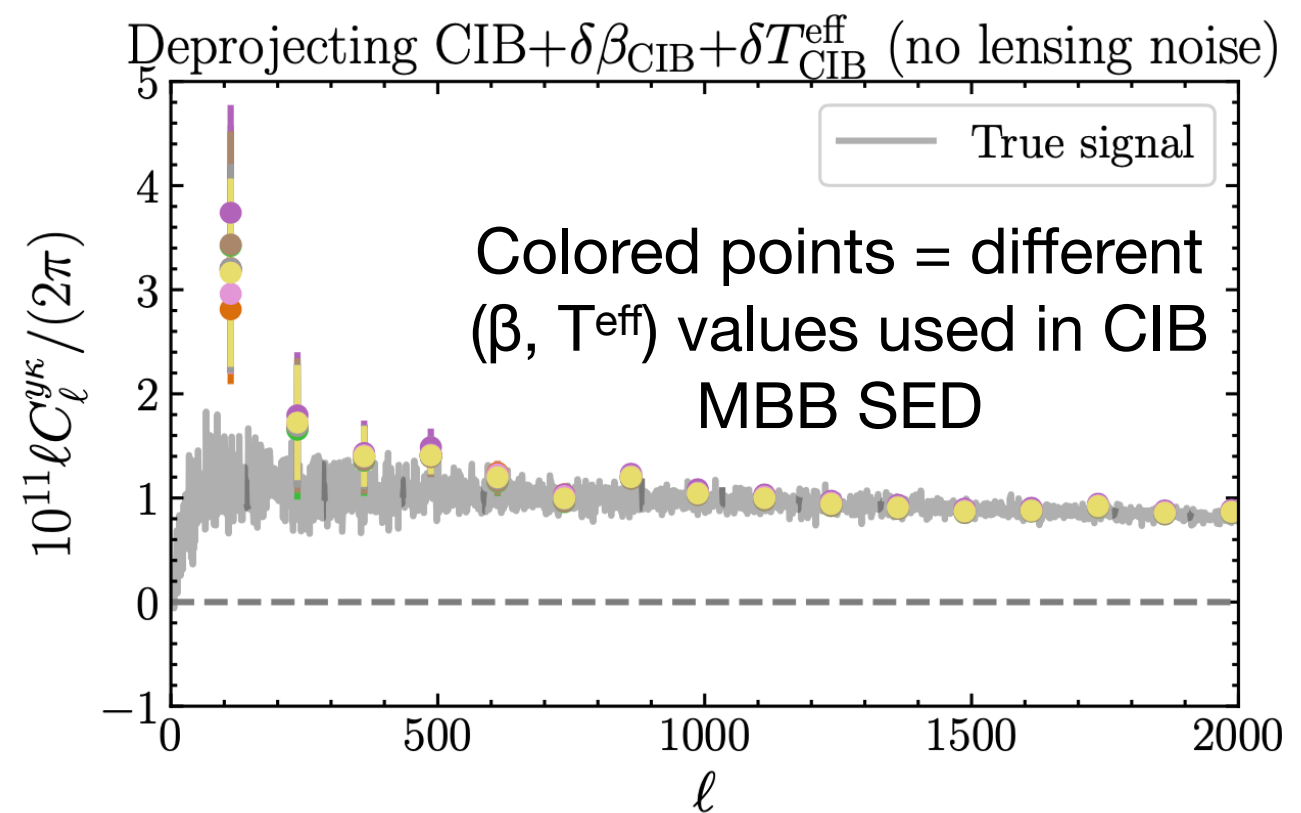
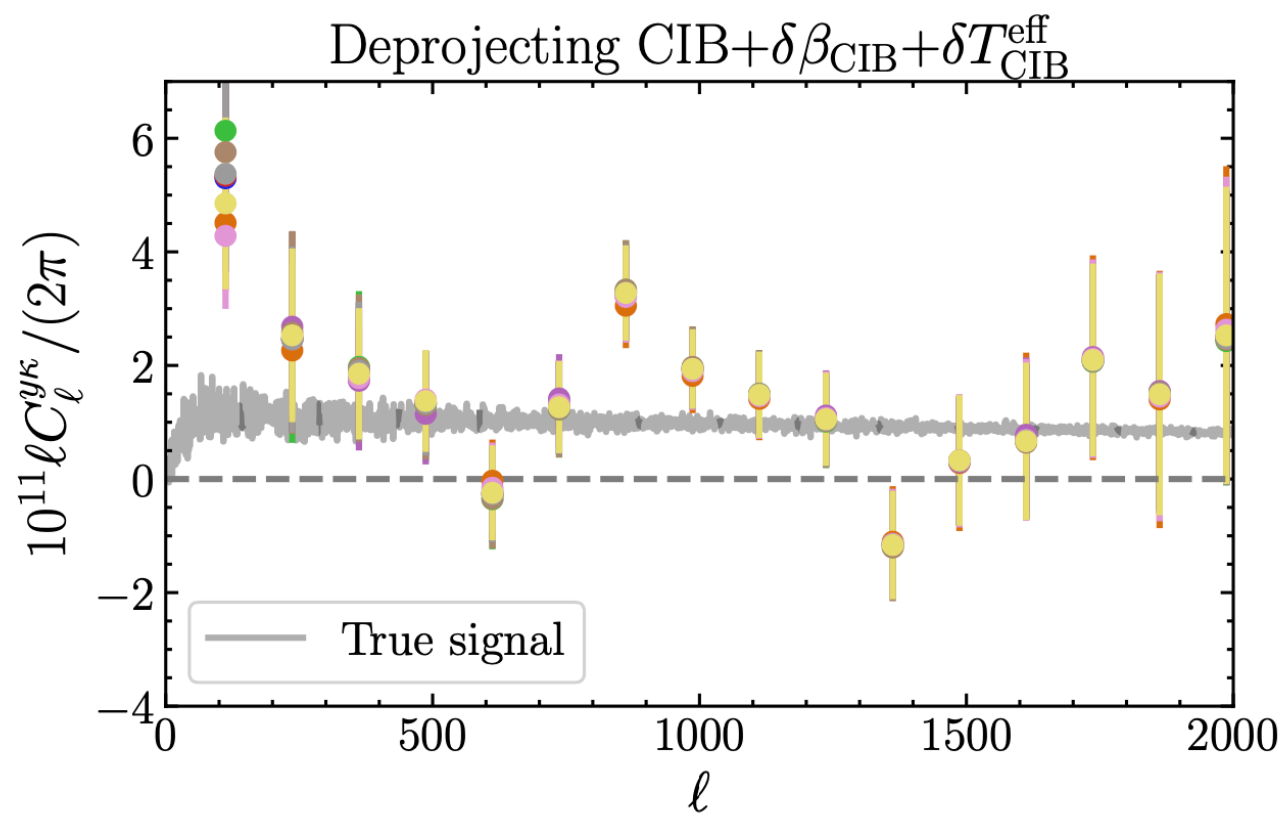
# tSZ x CMB Lensing

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## Cross-correlation of pyilc $y$ -maps with PR4 CMB lensing maps

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- Processed through pyilc pipeline with various CIB deprojection choices
- Cross-correlated with true Websky  $\kappa$  map (with or without noise)



**Only by deprojecting the CIB + both first moment SEDs is the measurement stable/robust to the assumed MBB parameters of the CIB ( $\beta$ ,  $T^{\text{eff}}$ )**

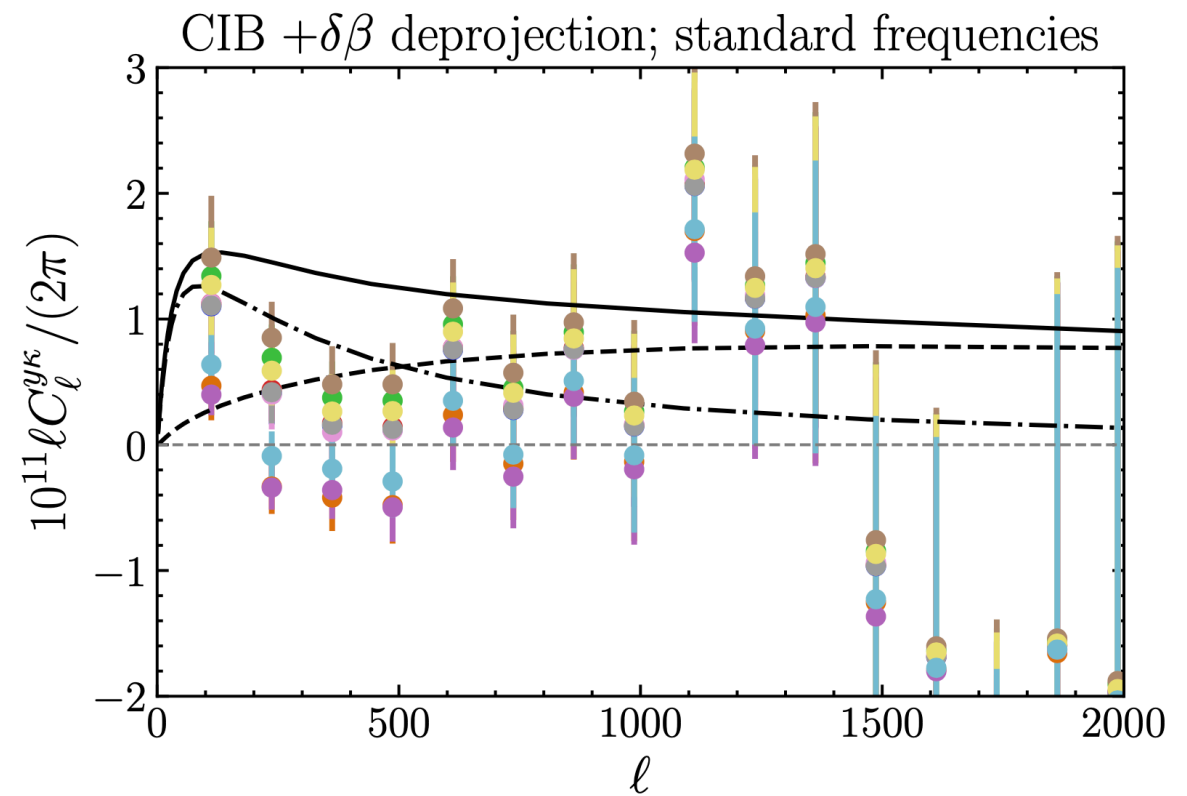
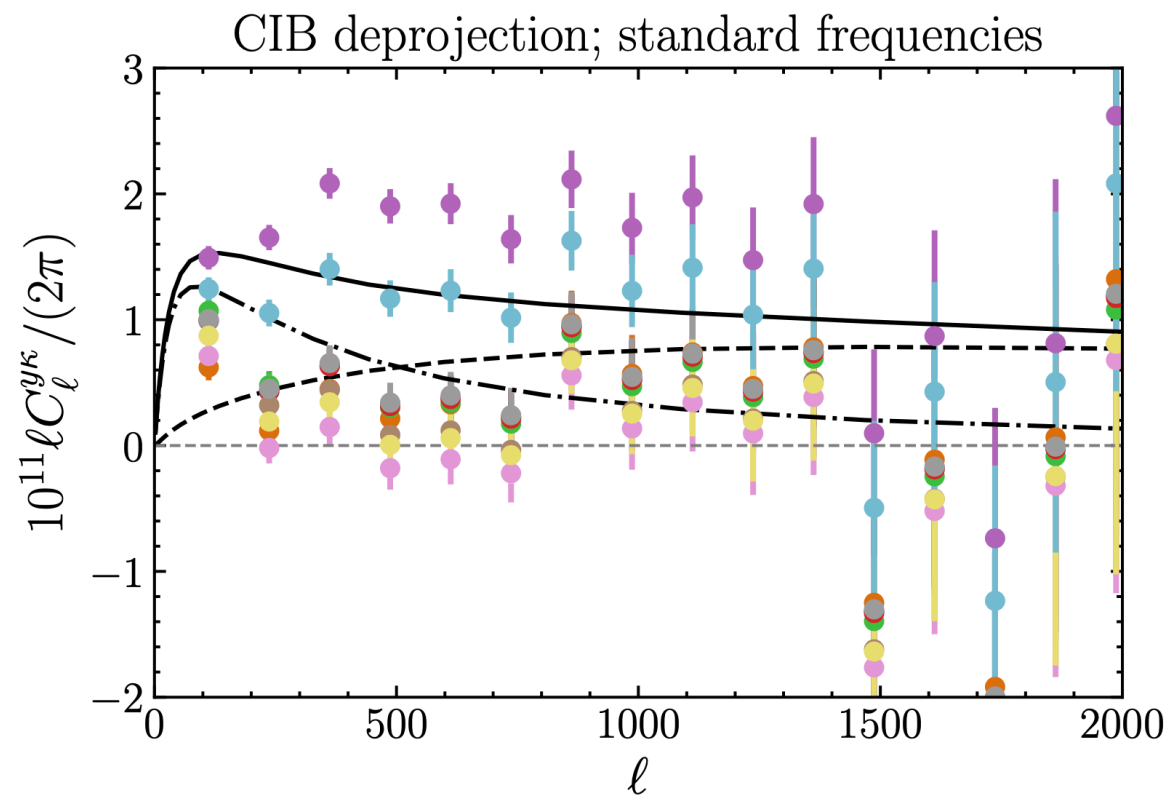
CMB is also deprojected in first five needlet scales (to mitigate potential ISW-lensing contribution)

# tSZ x CMB Lensing

Colin Hill  
Columbia

## Cross-correlation of pyilc $y$ -maps with PR4 CMB lensing maps

Multi-moment CIB deprojection required to obtain stable/robust measurement



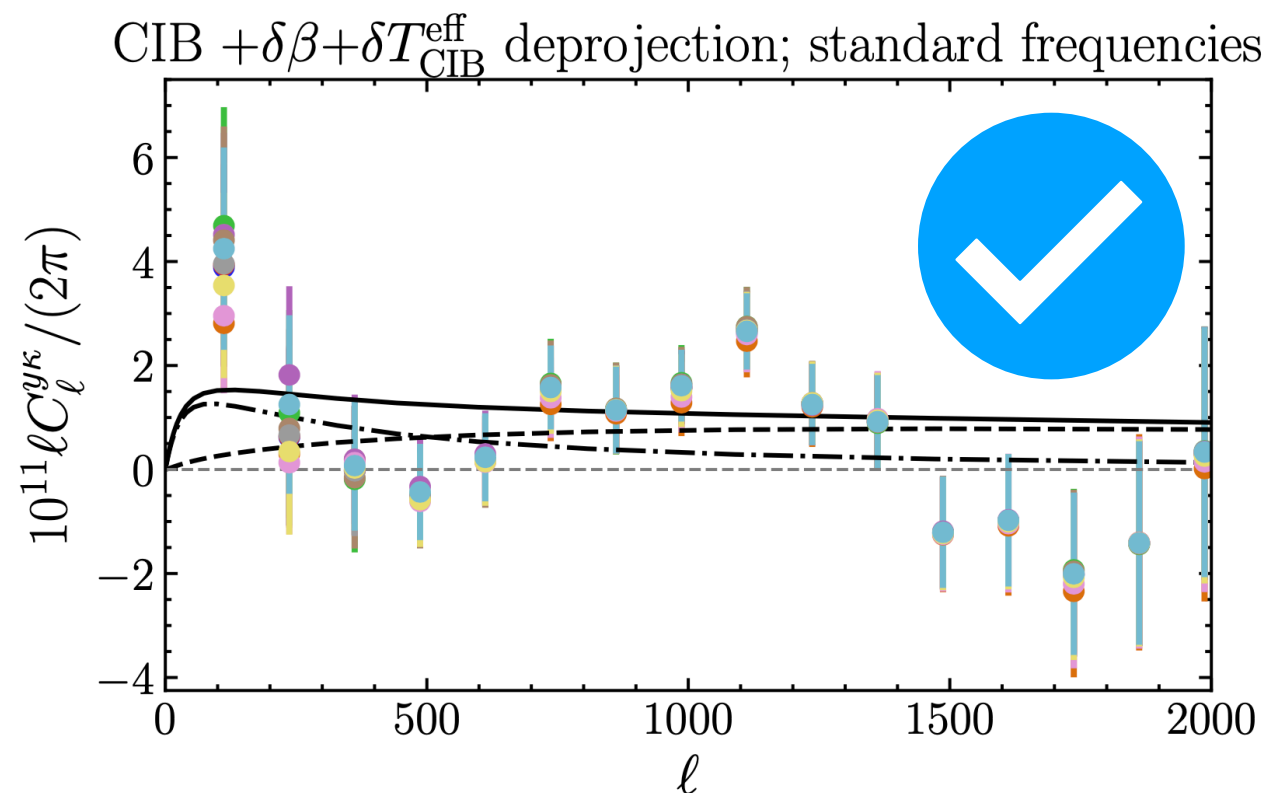
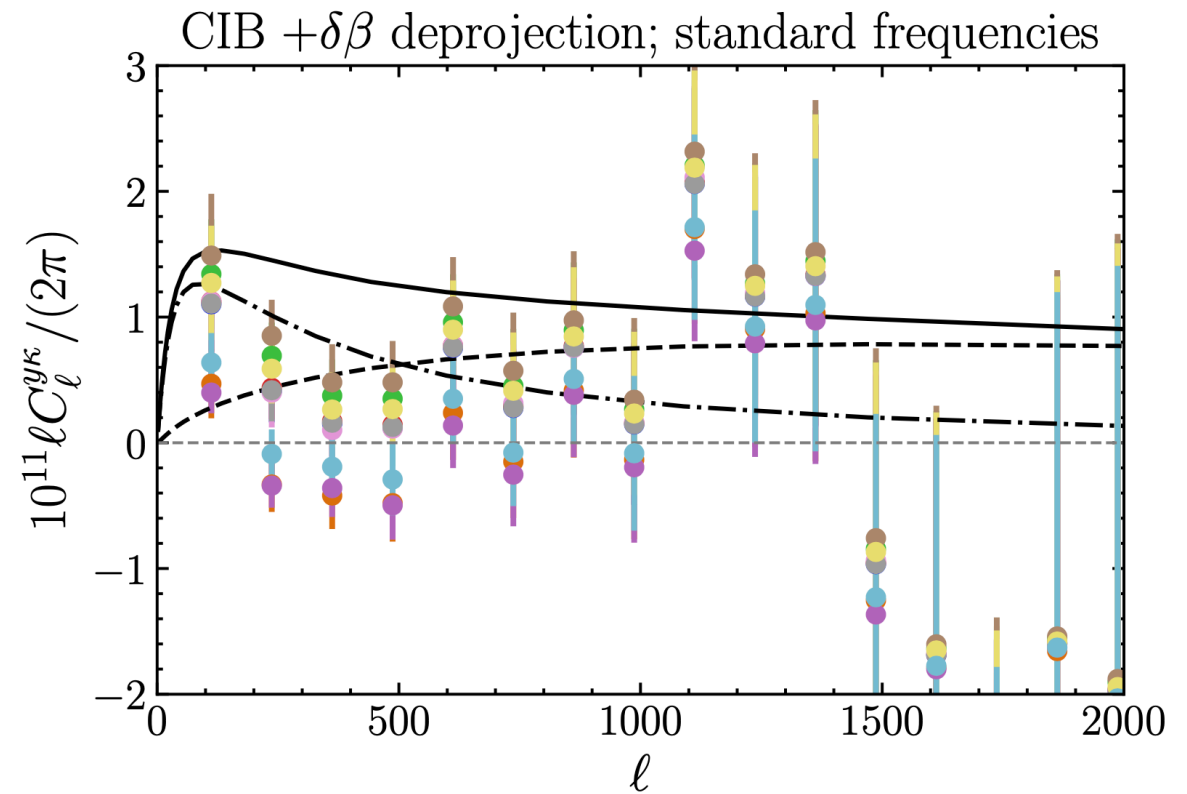
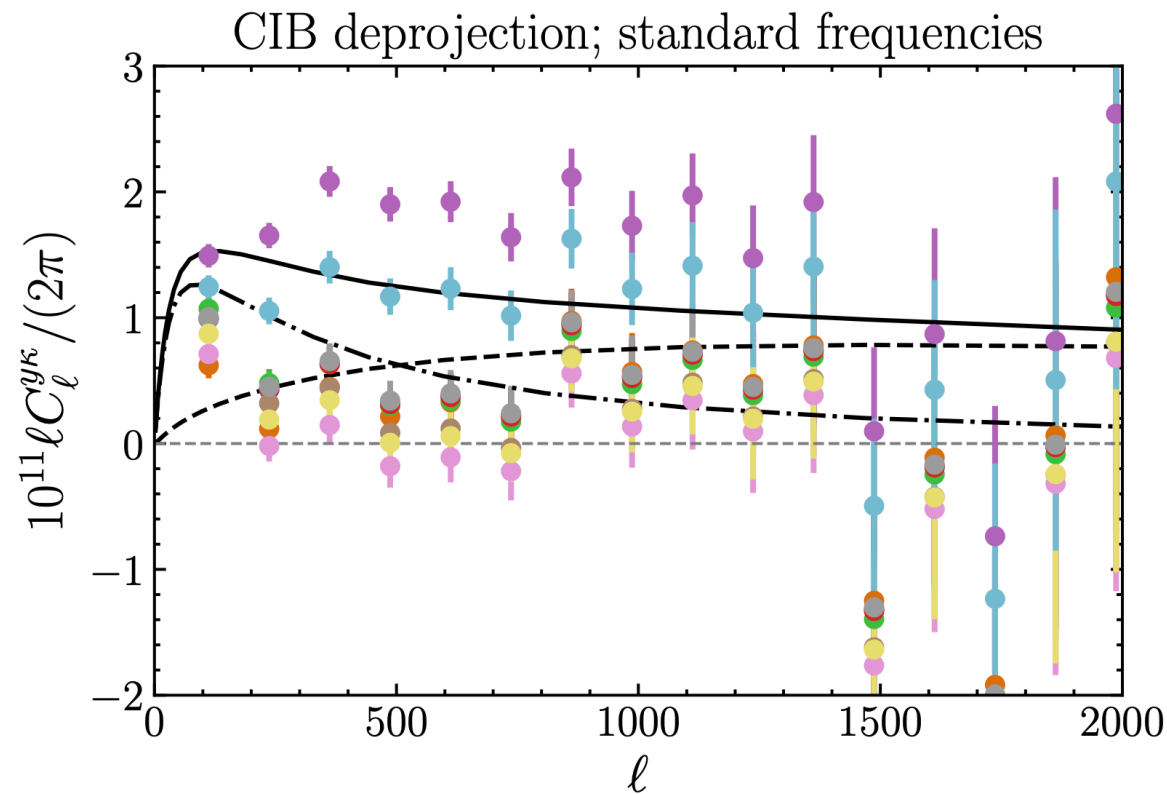
Colored points = different  
 $(\beta, T^{\text{eff}})$  values used in CIB  
MBB SED

# tSZ x CMB Lensing

Colin Hill  
Columbia

Cross-correlation of pyilc  $y$ -maps with PR4 CMB lensing maps

Multi-moment CIB deprojection required to obtain stable/robust measurement



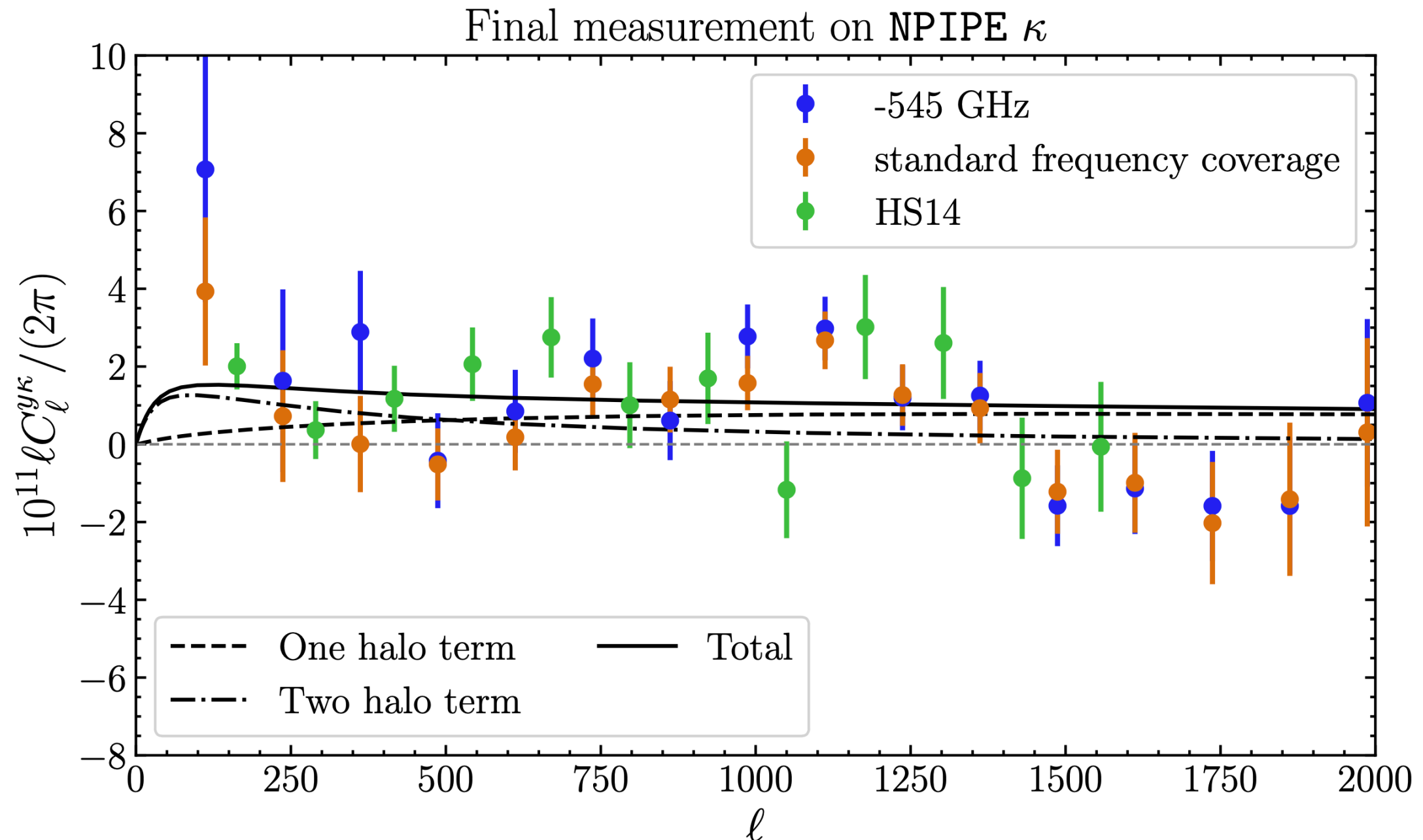
Colored points = different  
( $\beta$ ,  $T^{\text{eff}}$ ) values used in CIB  
MBB SED



# tSZ x CMB Lensing

Colin Hill  
Columbia

Cross-correlation of pyilc  $y$ -maps with PR4 CMB lensing maps

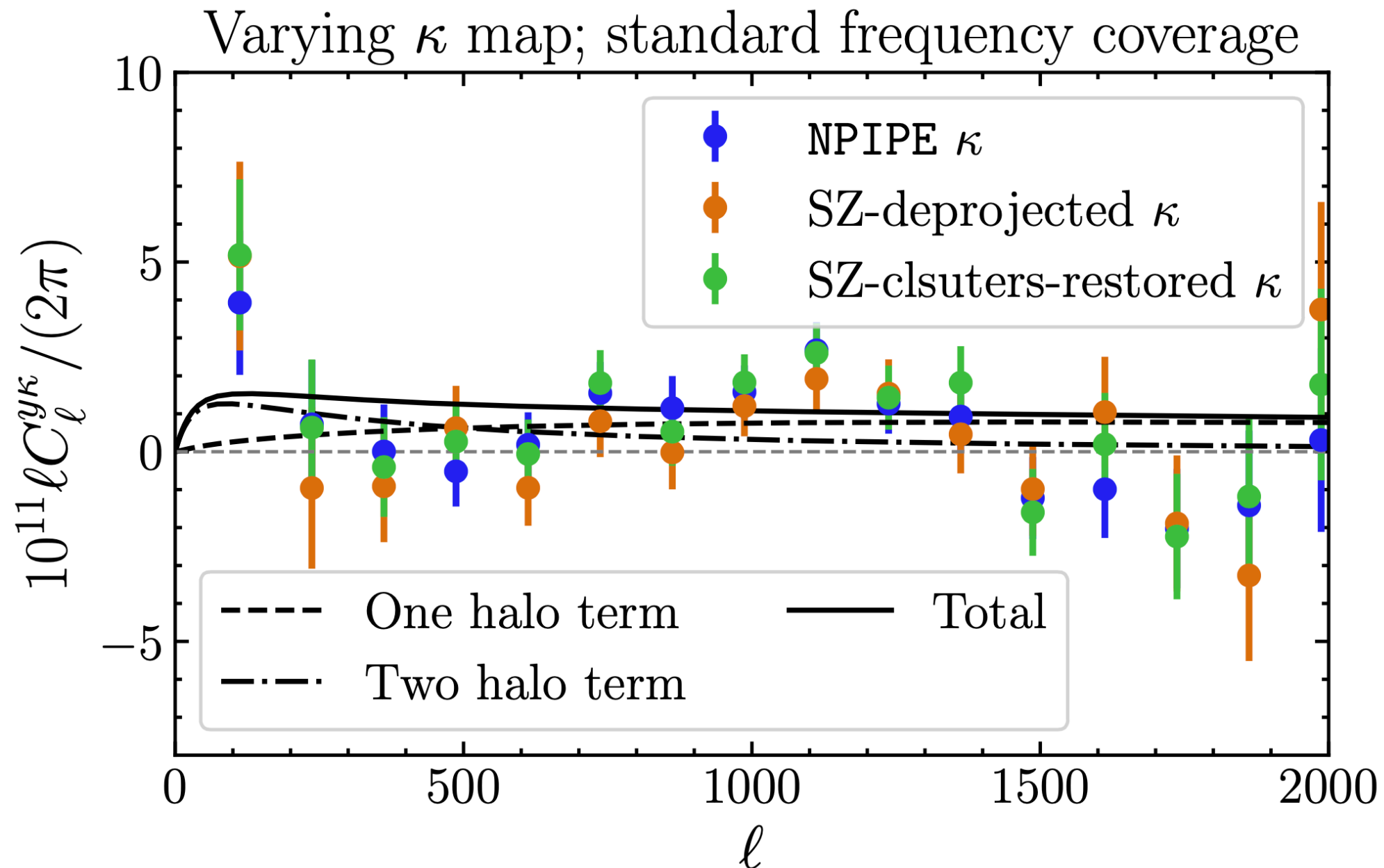


**Robustness comes at a cost: the multiple deprojections in the NILC lead to much larger noise in the  $y$ -map  $\rightarrow$  larger error bars in the cross-correlation**

# tSZ x CMB Lensing

Colin Hill  
Columbia

Cross-correlation of pyilc  $y$ -maps with PR4 + PR3 CMB lensing maps



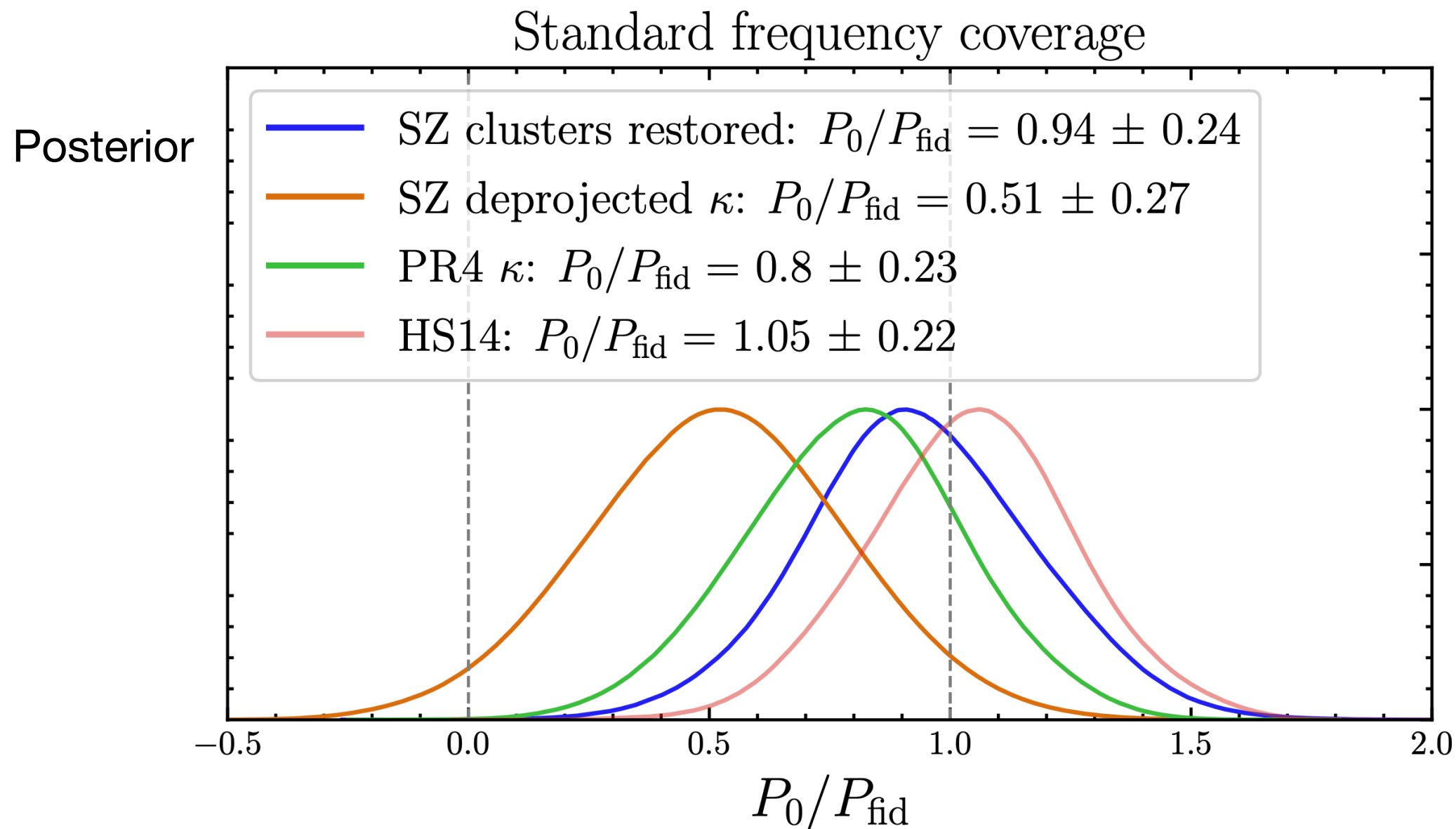
**Measurement is also robust to analysis variations in the  $\kappa$  reconstruction:**

- Reconstruction on tSZ-deprojected CMB map (avoids  $\langle yyy \rangle$  bias in cross-correlation)
- Reconstruction with signal restored at location of tSZ-detected clusters (masked by default)

# tSZ x CMB Lensing

Colin Hill  
Columbia

Interpretation: amplitude of pressure-mass relation



**Data are consistent with fiducial theoretical model (Battaglia+12 pressure profile)  
extrapolated into high-z, low-mass regime**

**Detection SNR  $\sim 4$  (similar to HS14 due to enormous CIB deprojection penalty)**

# tSZ x CMB Lensing

Colin Hill  
Columbia

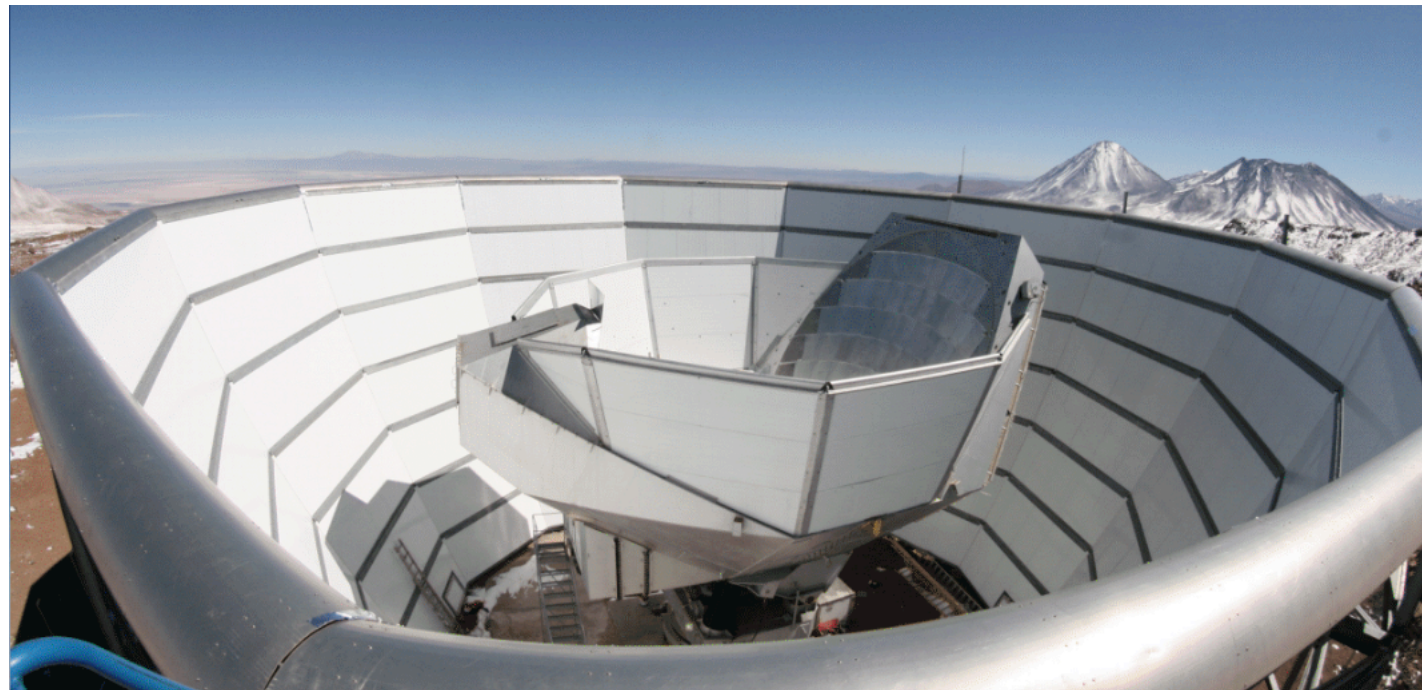
## Summary/Outlook

- We have learned an enormous amount about how to clean the CIB robustly and model-independently in tSZ cross-correlation measurements
- Implication: significant high-frequency coverage is needed in such measurements
- Use of 857 GHz can decrease the error bars, but we find that the final data points are not as stable/robust to CIB MBB SED variations
- Results are consistent with those of JCH & Spergel (2014), but *much* more robust (entire analysis pipeline validated on detailed sky simulations)
- Current gas pressure profile models calibrated at lower redshift and higher mass adequately describe tSZ x CMB lensing cross-correlation (and no sign of low  $S_8$ )

$$A = 0.80 \pm 0.23$$

- What's next: higher SNR measurement with ACT DR6 [Bolliet, Coulton, McCarthy, JCH, ++]

# ACT DR6: Compton- $\gamma$ Maps



**The Atacama Cosmology Telescope: High-resolution component-separated maps  
across one-third of the sky**

William Coulton,<sup>1</sup> Mathew S. Madhavacheril,<sup>2,3</sup> Adriaan J. Duivenvoorden,<sup>1,4</sup> J. Colin Hill,<sup>5,1</sup>

+ ACT Collaboration





# ACT Data Release 6

Colin Hill  
Columbia

High-sensitivity, arcminute-resolution maps at 90/150/220 GHz  
covering  $\sim 17,000 \text{ deg}^2$

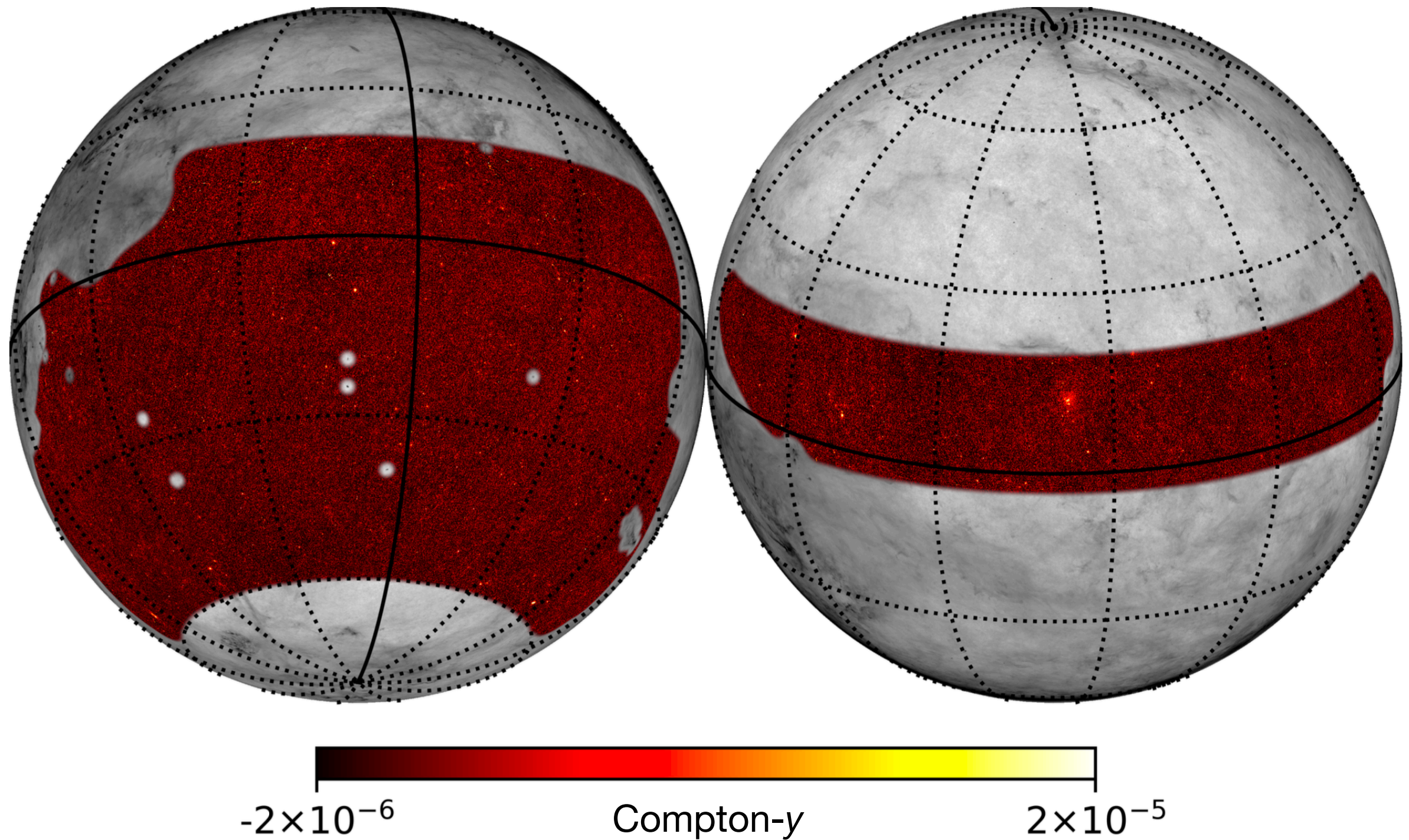
- Qu et al. (2023): Reconstructed CMB lensing maps
- Madhavacheril et al. (2023): Cosmology from CMB lensing  
 **$S_8 = 0.840 \pm 0.028$**
- MacCrann et al. (2023): Foreground mitigation for CMB lensing
- Coulton et al. (2023): Component-separated maps (y, T, E)
- Much more still to come, including:
  - Frequency map characterization and data release
  - Primary CMB TT, TE, EE power spectra
  - Cosmological constraints from CMB power spectra
  - Expanded tSZ cluster catalog
  - Cosmological constraints from cluster abundances (with DES and HSC weak lensing mass calibration)
  - and more

<https://lambda.gsfc.nasa.gov/product/act/>

# ACT DR6 NILC $y$ -map

Colin Hill  
Columbia

ACT + Planck NPIPE

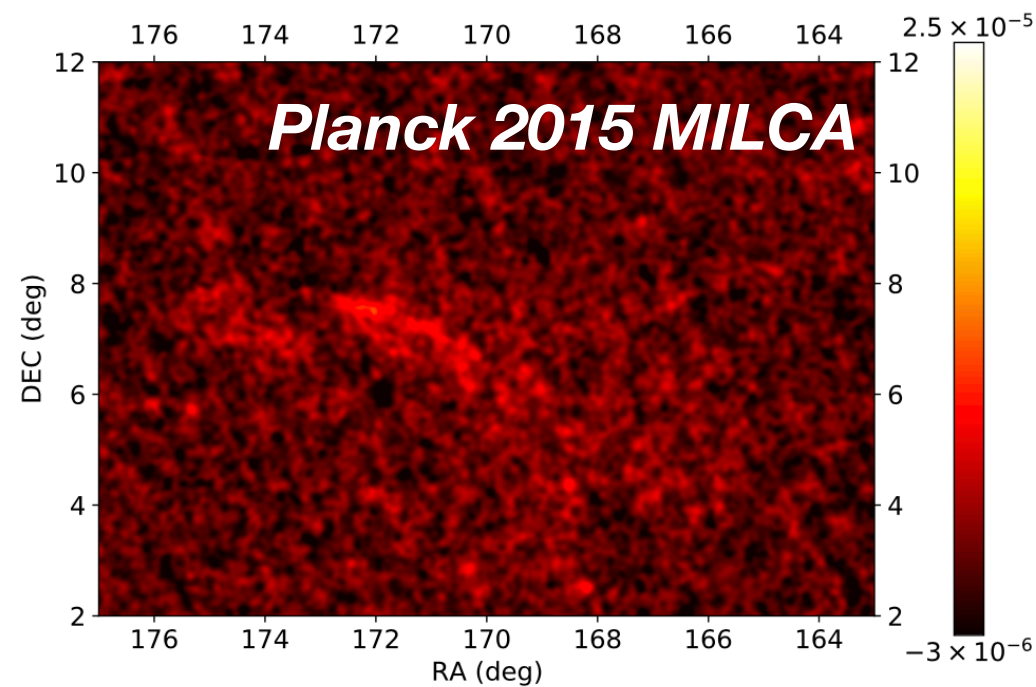




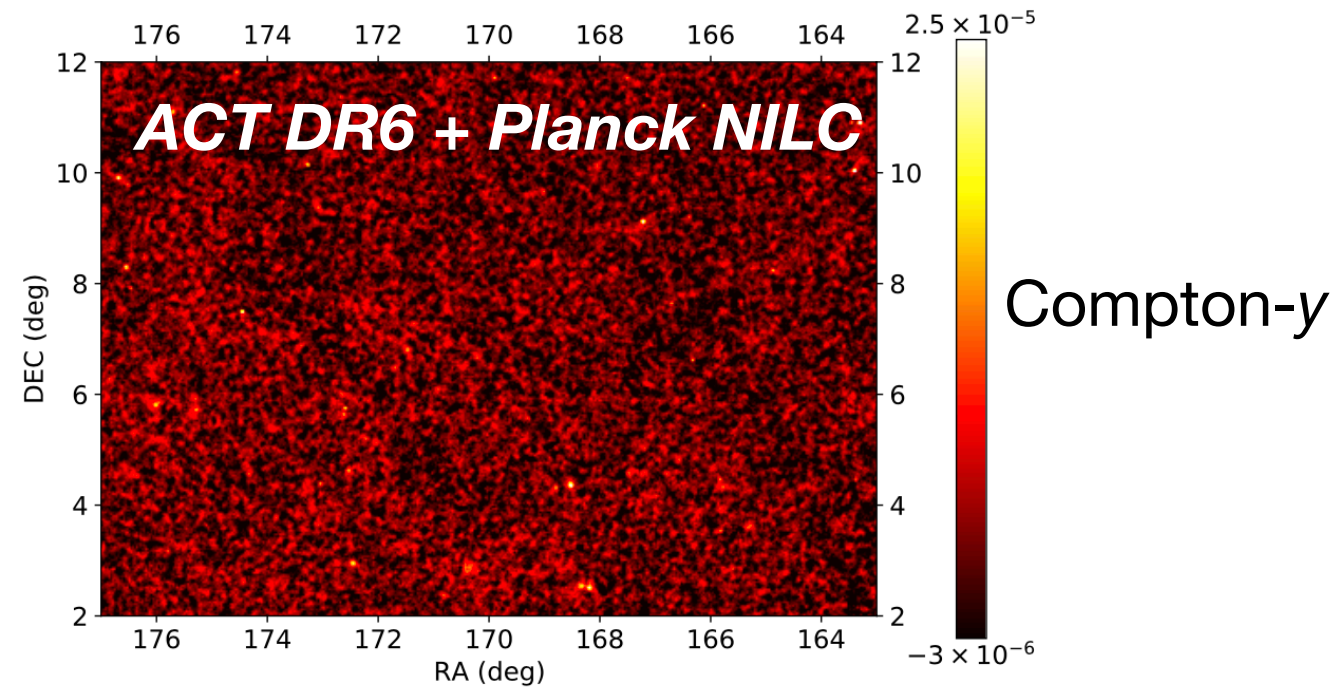
# ACT DR6 NILC $y$ -map

Colin Hill  
Columbia

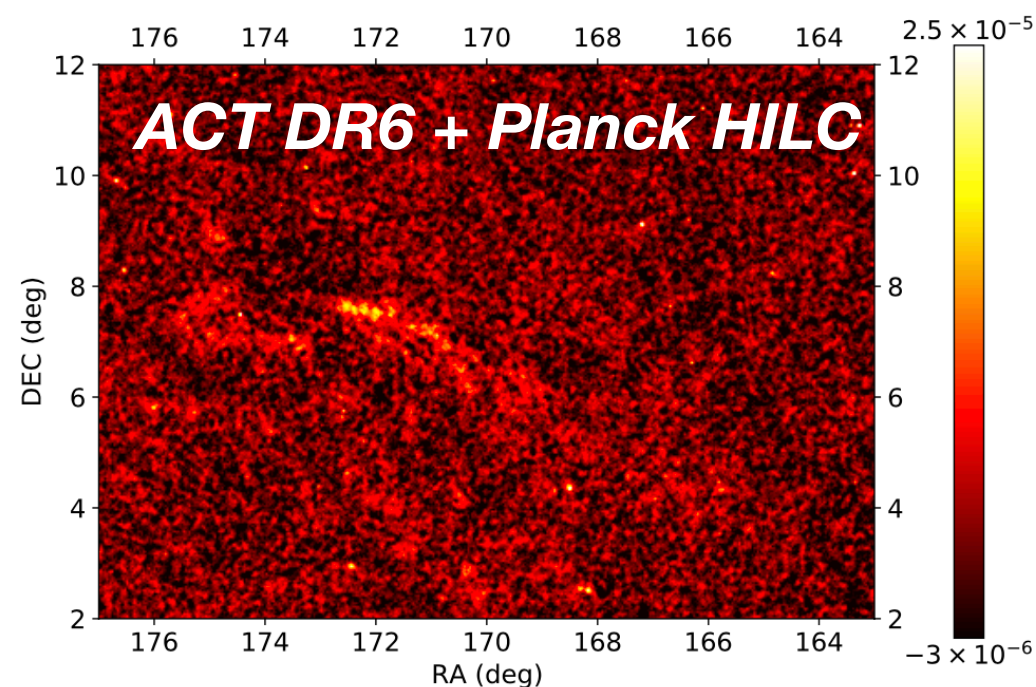
ACT + Planck NPIPE



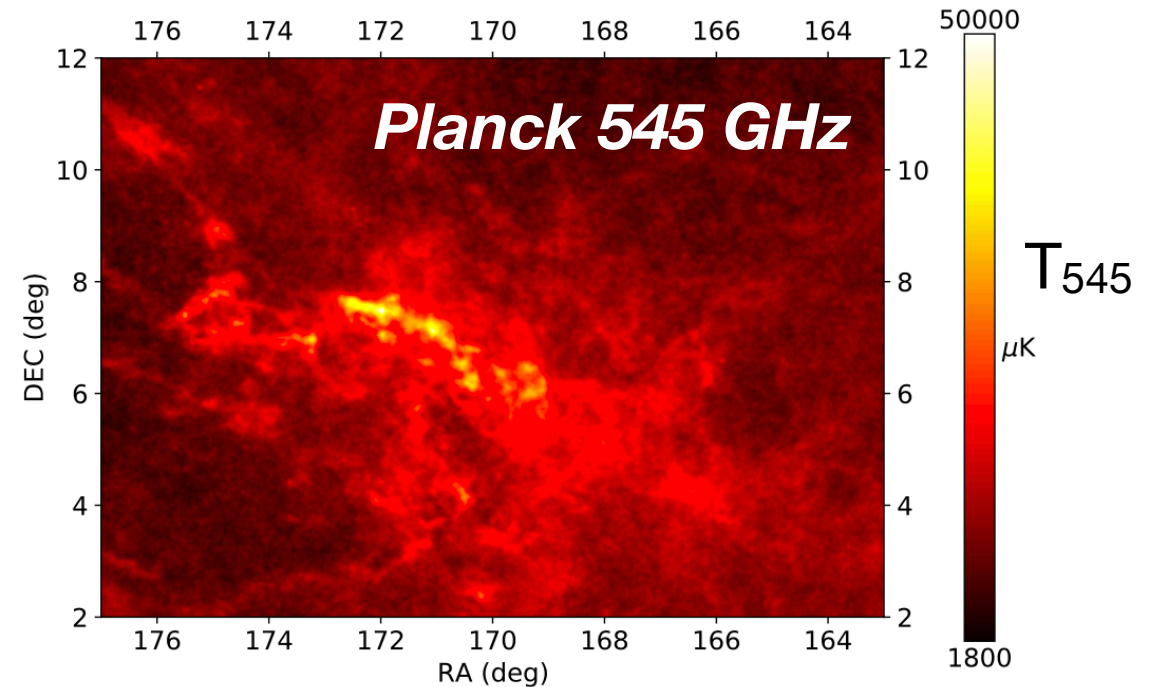
(a) *Planck* MILCA Compton- $y$  map



(b) ACT & *Planck* NILC Compton- $y$  map



(c) ACT & *Planck* Harmonic ILC Compton- $y$  map



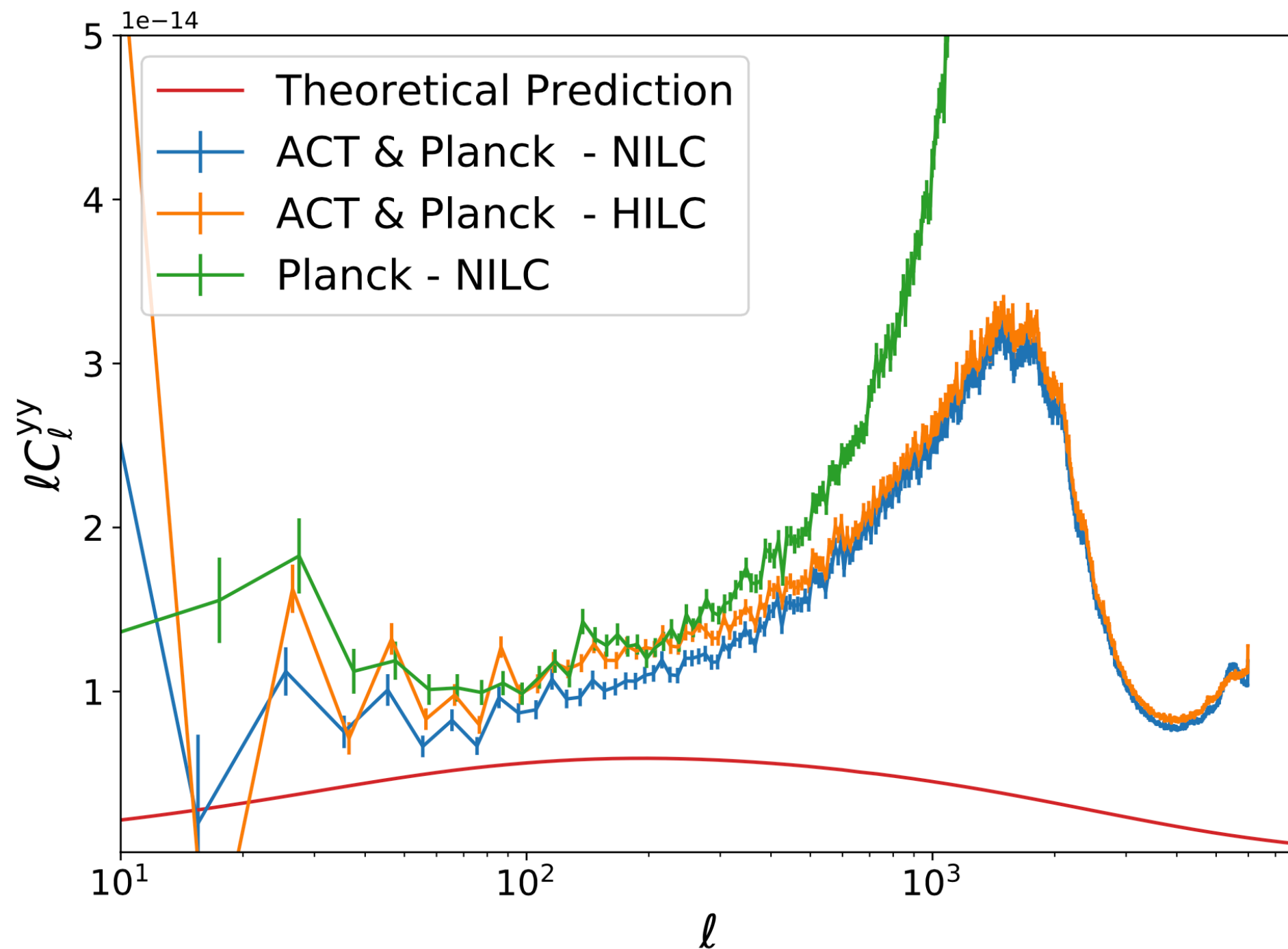
(d) *Planck* 545 GHz map

# ACT DR6 NILC $y$ -map

Colin Hill  
Columbia

ACT + Planck NPIPE

**Auto-power spectra of  $y$ -maps: enormous gains in SNR over *Planck*-only maps**

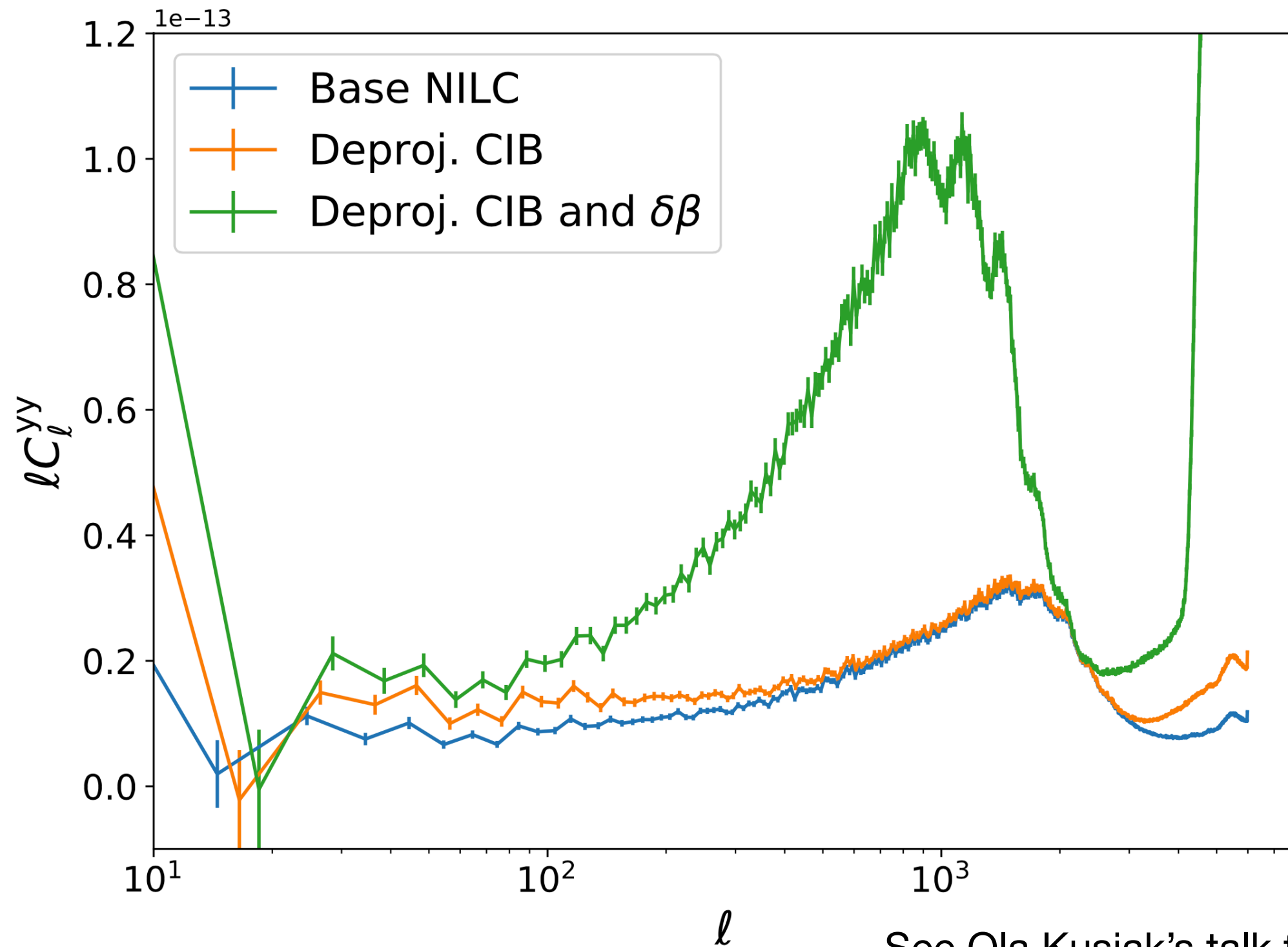


# ACT DR6 NILC $y$ -map

Colin Hill  
Columbia

ACT + Planck NPIPE

Various CIB deprojection options also implemented

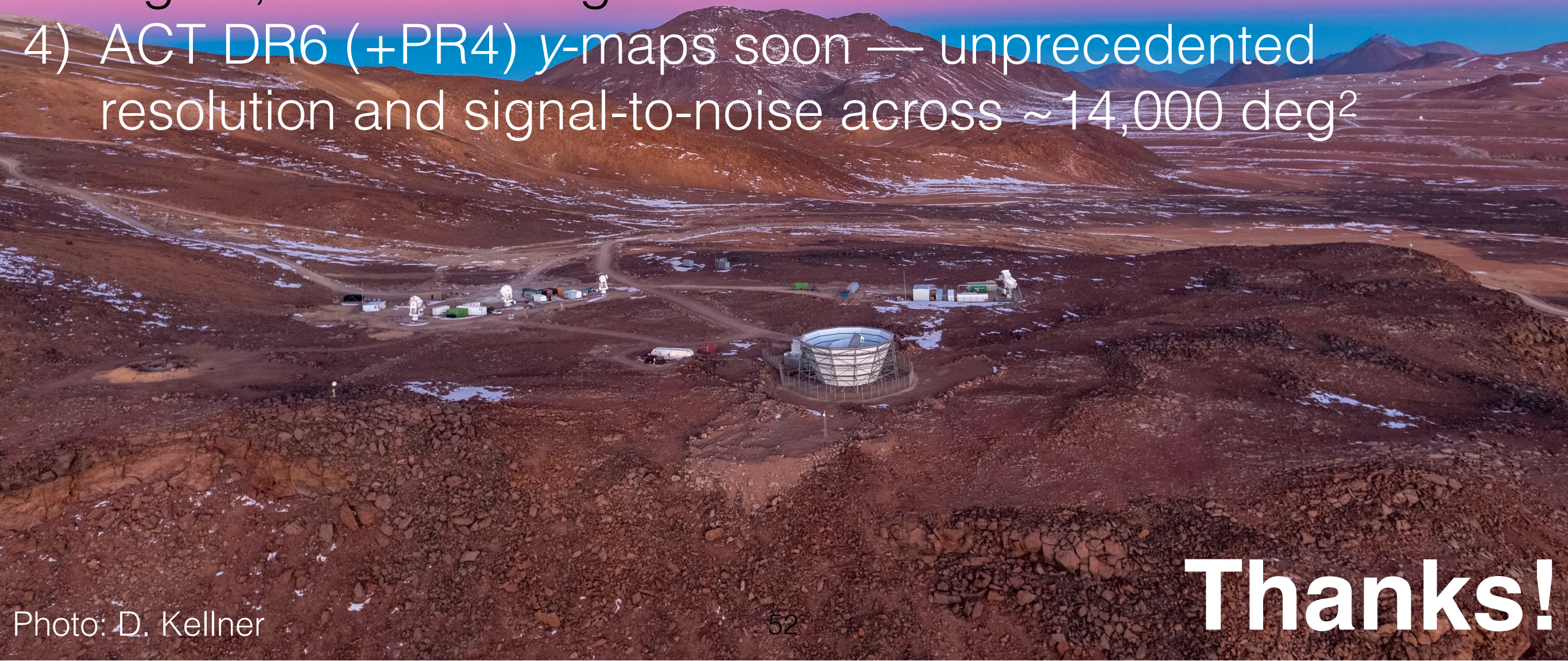


See Ola Kusiak's talk for early cross-correlation results using these maps



# Take-Home Messages

- 1) Flexible, robust NILC pipeline now publicly available: `pyilc`
- 2) CIB-deprojected  $y$ -maps from PR4 NPIPE data now publicly available
- 3) Robust PR4 tSZ x CMB lensing measurement is consistent with extrapolation of existing gas physics models to high- $z$ , low-mass regime
- 4) ACT DR6 (+PR4)  $y$ -maps soon — unprecedented resolution and signal-to-noise across  $\sim 14,000 \text{ deg}^2$



**Thanks!**



# Bonus

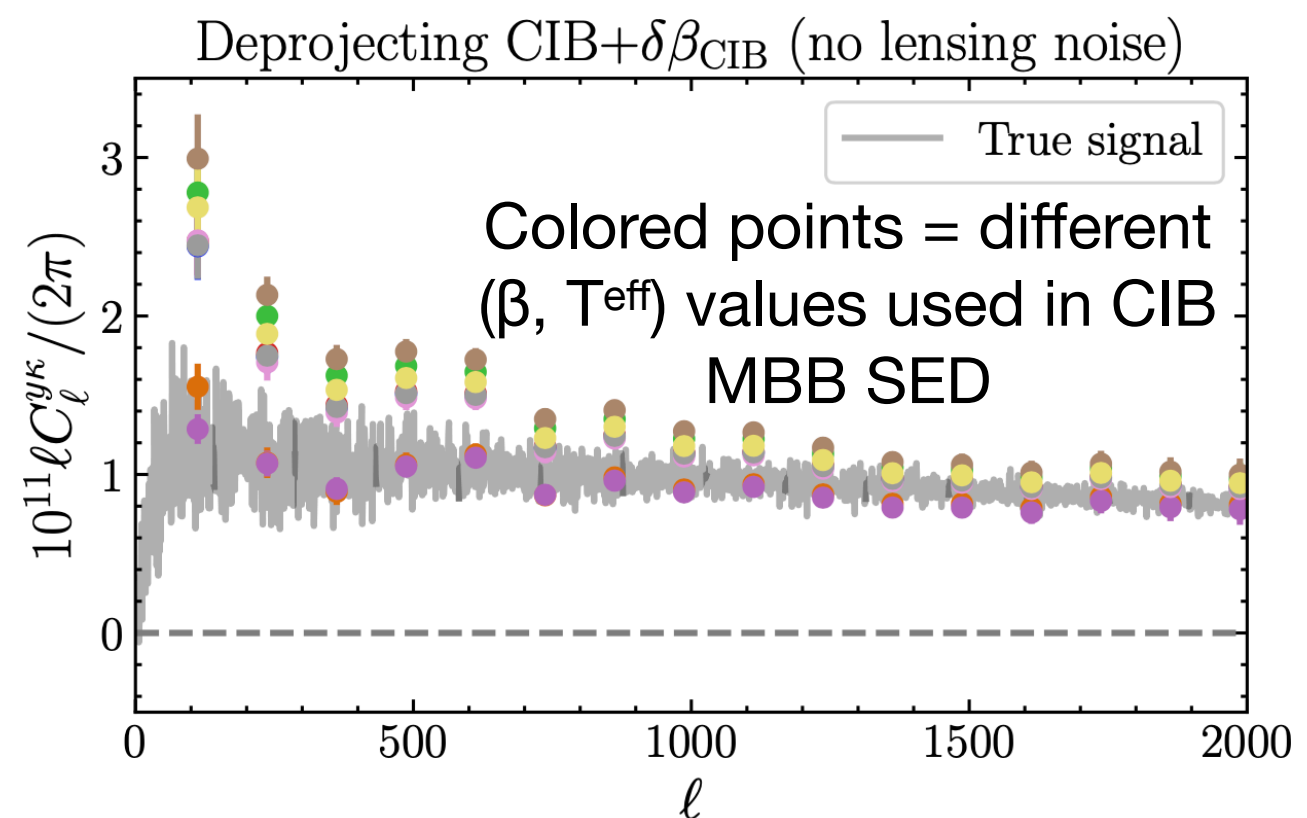
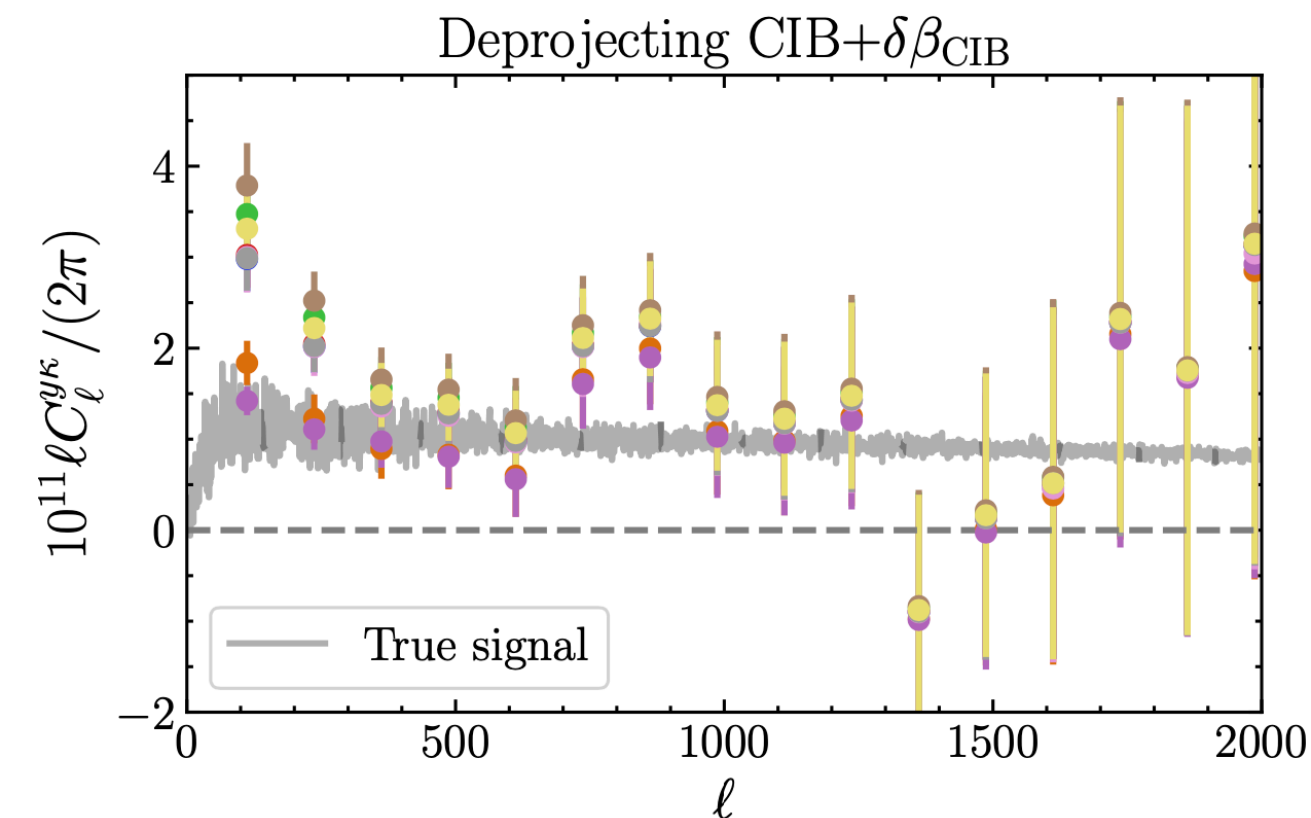
# tSZ x CMB Lensing

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Columbia

## Cross-correlation of pyilc $y$ -maps with PR4 CMB lensing maps

Validation of pipeline on detailed mm-wave sky simulations

- Simulations: Websky CMB+tSZ+CIB + PySM dust+synch+free-free+AME + Planck noise
- Processed through pyilc pipeline with various CIB deprojection choices
- Cross-correlated with true Websky  $\kappa$  map (with or without noise)



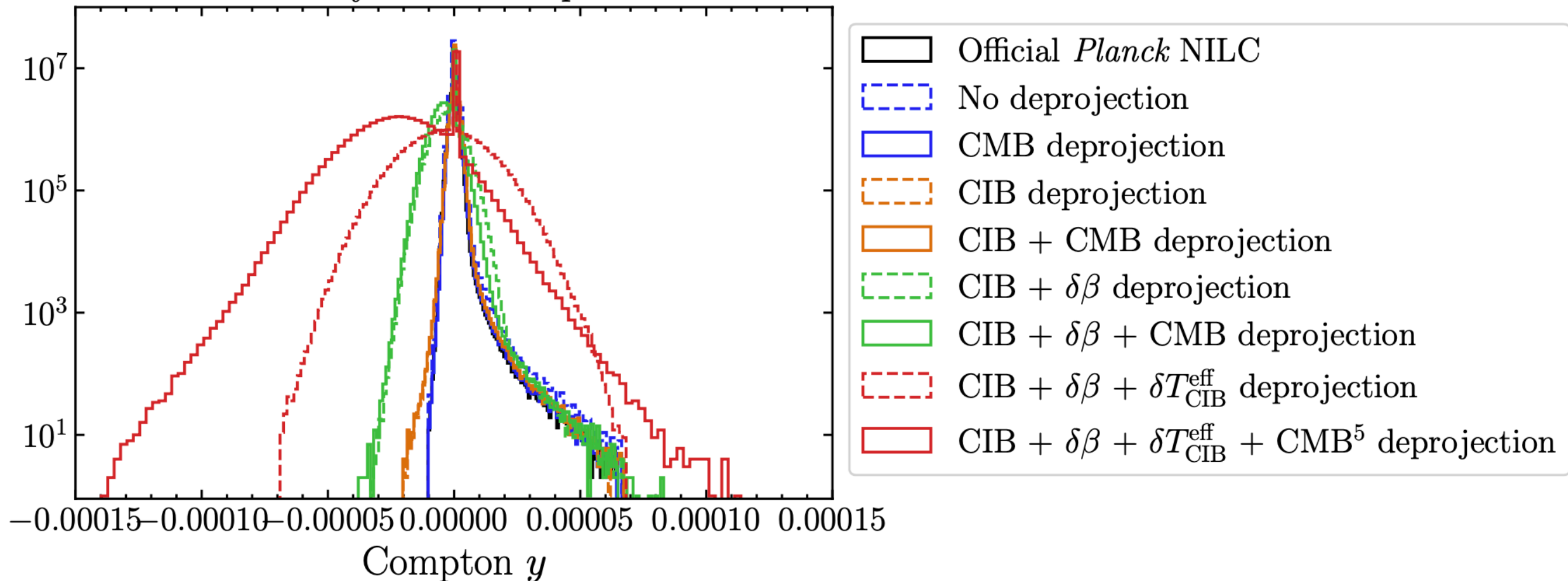
**Even deprojecting the CIB +  $\beta$  first moment SED is not sufficient to yield a measurement stable/robust to the assumed MBB parameters of the CIB ( $\beta, T^{\text{eff}}$ )**

# Thermal SZ Extraction

Colin Hill  
Columbia

Application to Planck PR4 (NPIPE) maps

*Planck* NILC analysis mask + point source mask



# Thermal SZ Extraction

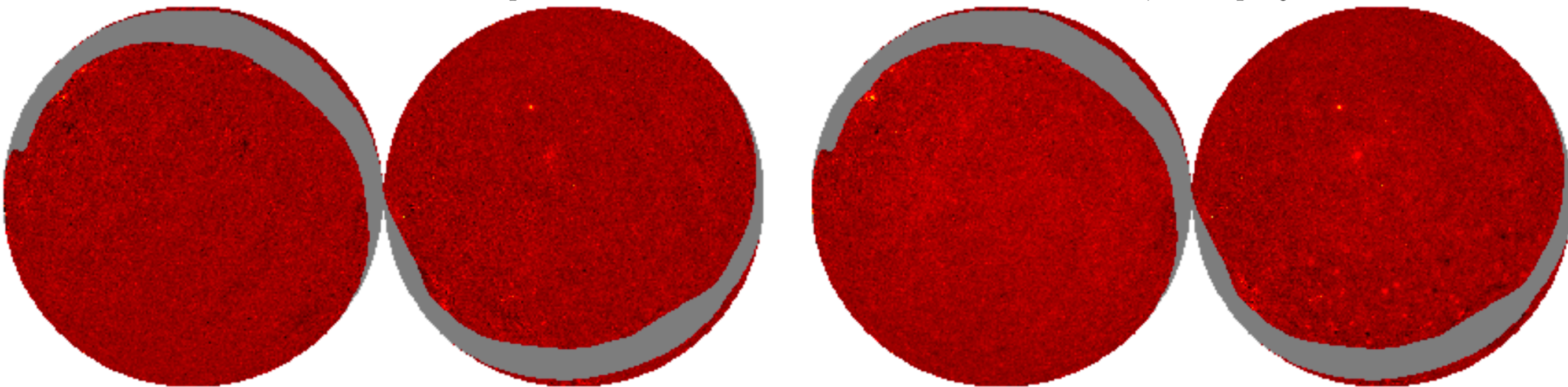
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Columbia

## Comparison to official PR2 $y$ -map

(CMB-deprojected version looks identical by eye)

Planck 2015 tSZ map

NILC tSZ; no deprojection

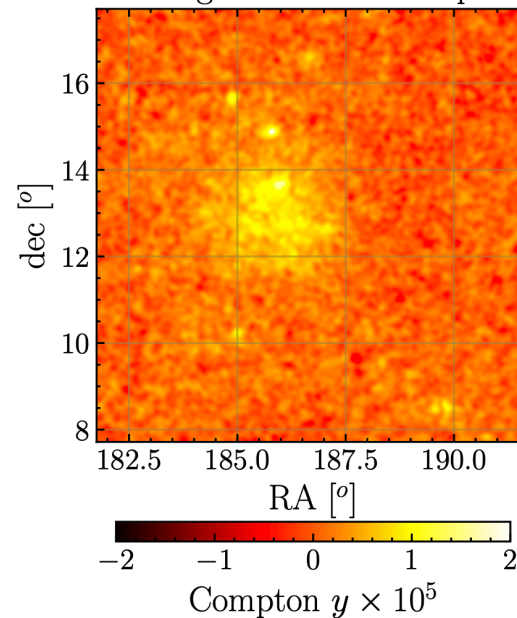


-1e-05 Compton  $y$  4e-05

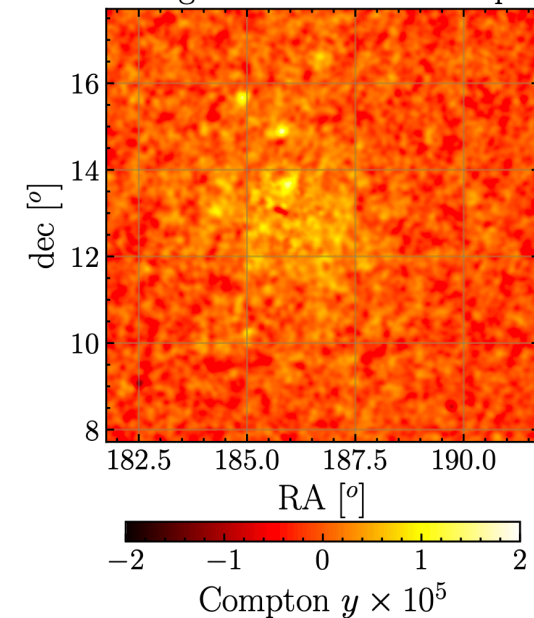
-1e-05 Compton  $y$  4e-05

We mask and inpaint source locations prior to running NILC — leads to significant improvement in behavior of weights and stability in power spectrum estimation

Virgo cluster: our map



Virgo cluster: *Planck* map



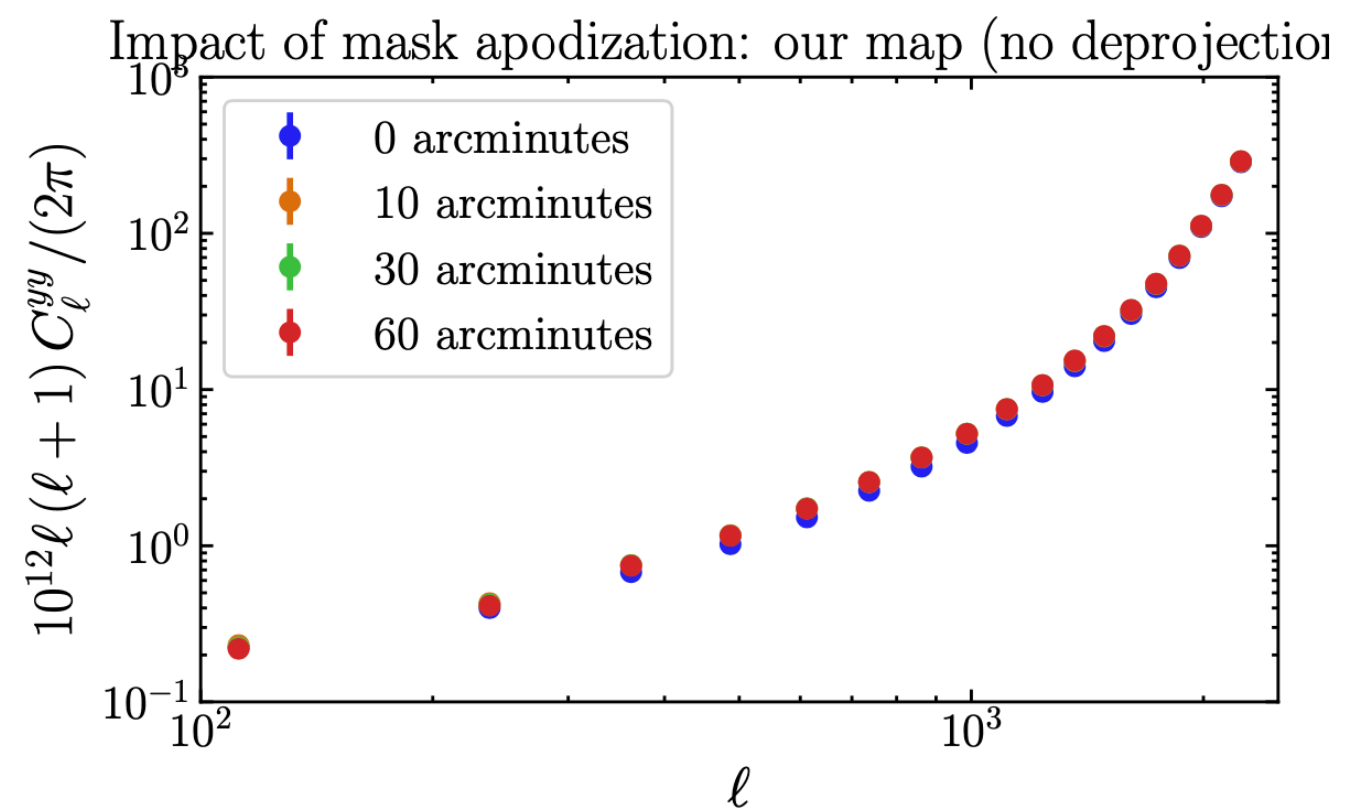
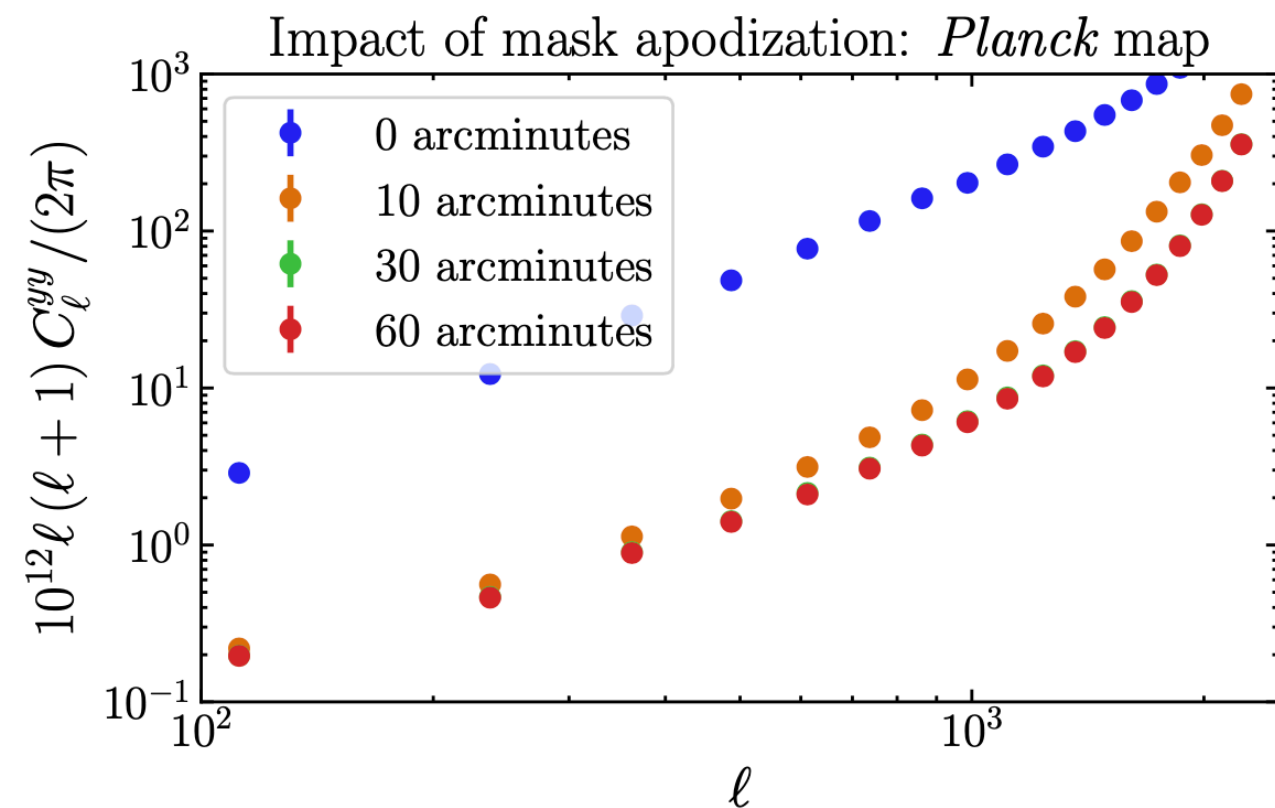


# Thermal SZ Extraction

Colin Hill  
Columbia

## Comparison to official PR2 $y$ -map

We mask and inpaint source locations prior to running NILC — leads to significant improvement in behavior of weights and stability in power spectrum estimation



# tSZ x CMB Lensing

Colin Hill  
Columbia

Theory: halo model

- Cross-spectrum can be derived similarly to tSZ auto-spectrum
- Need Fourier transform of convergence profile of each halo:

$$\tilde{\kappa}_\ell(M, z) = \frac{4\pi r_s}{\ell_s^2} \int dx x^2 \frac{\sin((\ell + 1/2)x/\ell_s)}{(\ell + 1/2)x/\ell_s} \frac{\rho(x; M, z)}{\Sigma_{crit}(z)}$$

density profile (NFW) →  $\rho(x; M, z)$   
critical surface density for lensing →  $\Sigma_{crit}(z)$

- One-halo term:

$$C_\ell^{y\kappa, 1h} = \int dz \frac{d^2 V}{dz d\Omega} \int dM \frac{dn}{dM} \tilde{y}_\ell(M, z) \tilde{\kappa}_\ell(M, z)$$

- Two-halo term:

$$C_\ell^{y\kappa, 2h} = \int dz \frac{d^2 V}{dz d\Omega} P_{lin}(\ell/\chi, z) \left[ \int dM_1 \frac{dn}{dM_1} b(M_1, z) \tilde{y}_\ell(M_1, z) \right] \times$$

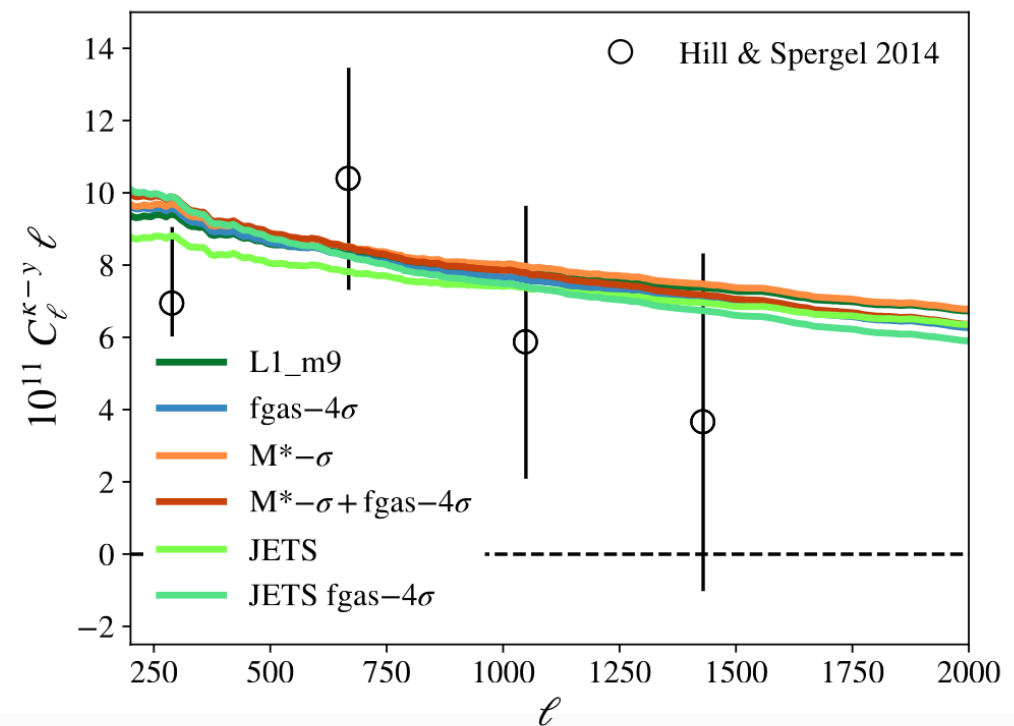
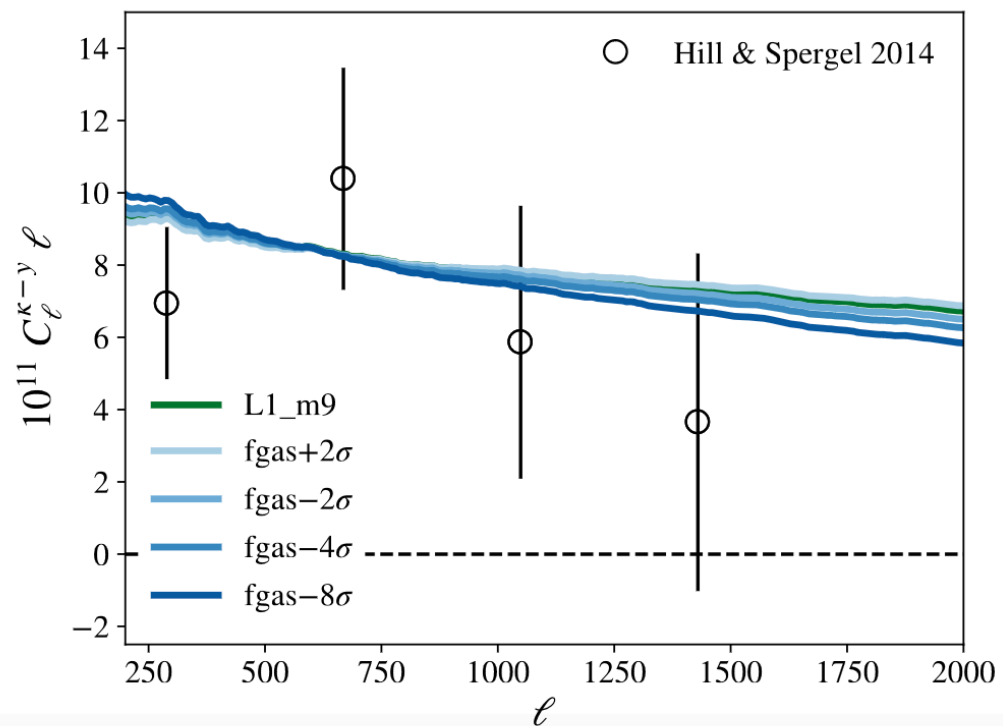
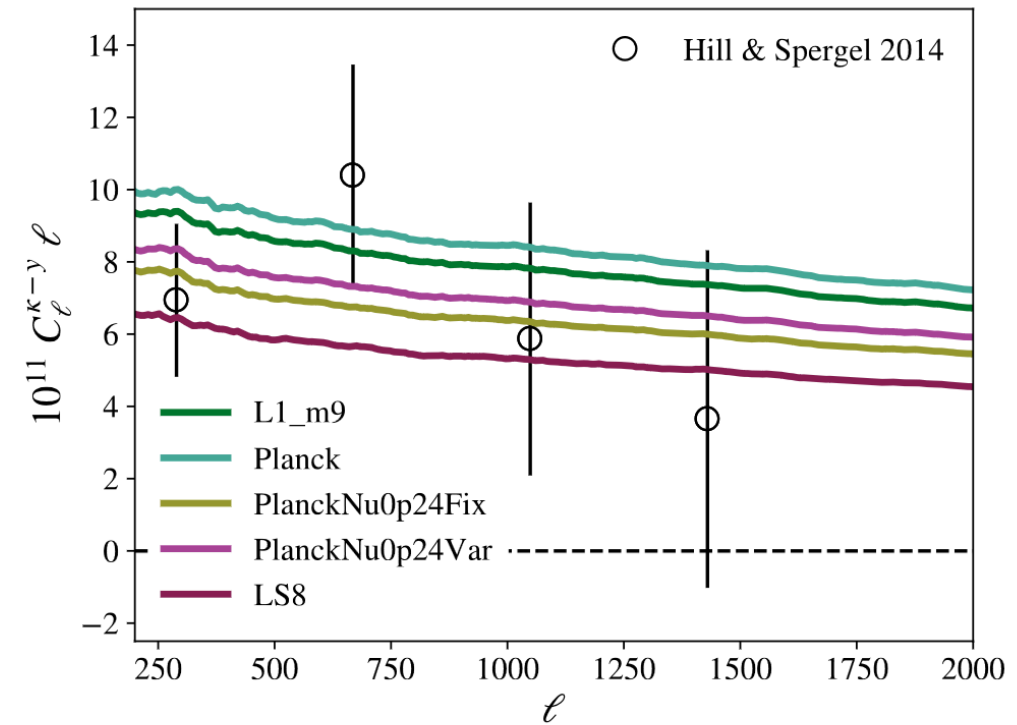
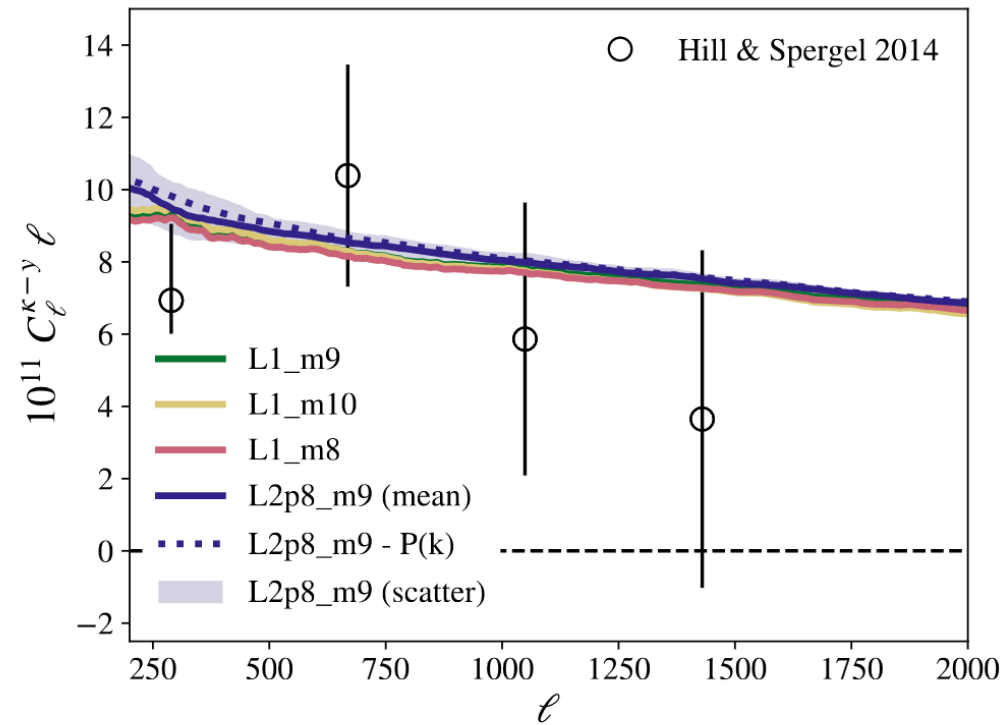
matter power spectrum →  $P_{lin}(\ell/\chi, z)$   
halo bias →  $b(M_1, z)$

$$\left[ \int dM_2 \frac{dn}{dM_2} b(M_2, z) \tilde{\kappa}_\ell(M_2, z) \right],$$

# tSZ x CMB Lensing

Colin Hill  
Columbia

## FLAMINGO simulations



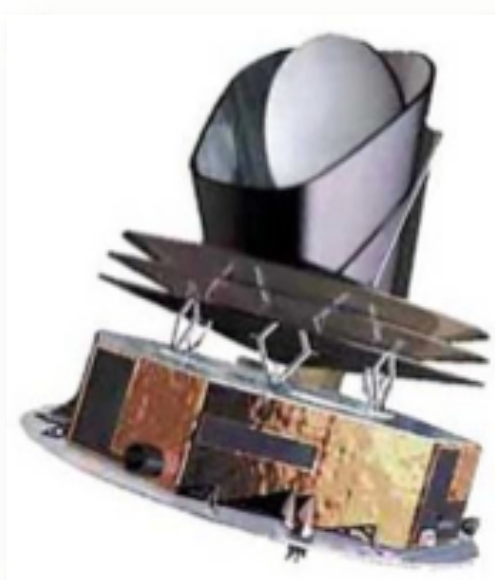
# Next: ACT DR6

(target: later this year)



|      |      | SO-Pre | SO-Nominal Operations |      |      |      |      |      |
|------|------|--------|-----------------------|------|------|------|------|------|
| 2020 | 2021 | 2022   | 2023                  | 2024 | 2025 | 2026 | 2027 | 2028 |

Planck

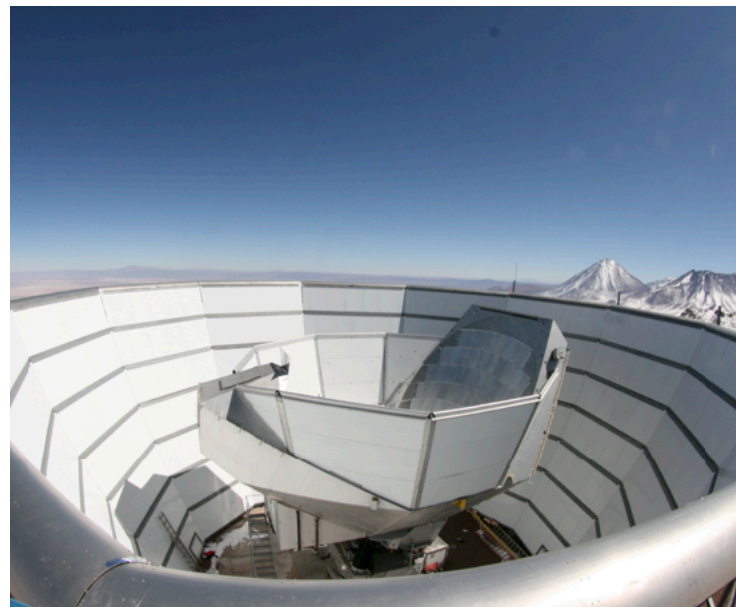
**Advanced ACT**

Final data 2018

100% sky

0.35 — 10 mm (9 bands)

5 — 33' resolution



Observations until 2022

40% sky

Noise ~3 times &lt; Planck

1.4 — 10 mm (5 bands)

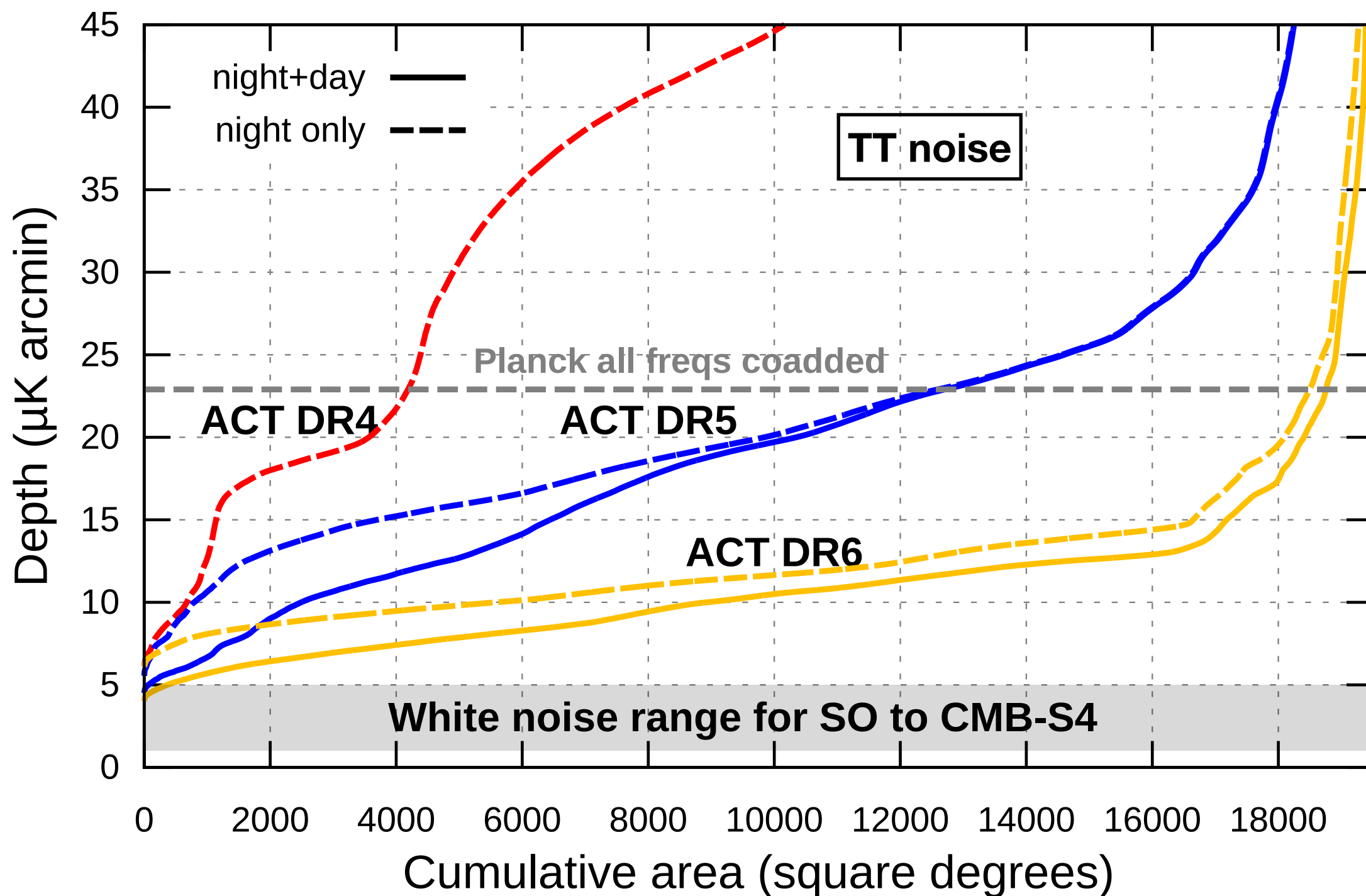
1 — 7' resolution

*[South Pole Telescope - same  
timeframe]*

ACT DR4 only comprises data collected through 2016 — we have >5x as much data already on disk, collected through 2022

**$\sigma(H_0) \sim 0.5 \text{ km/s/Mpc}$   
in  $\Lambda\text{CDM}$**

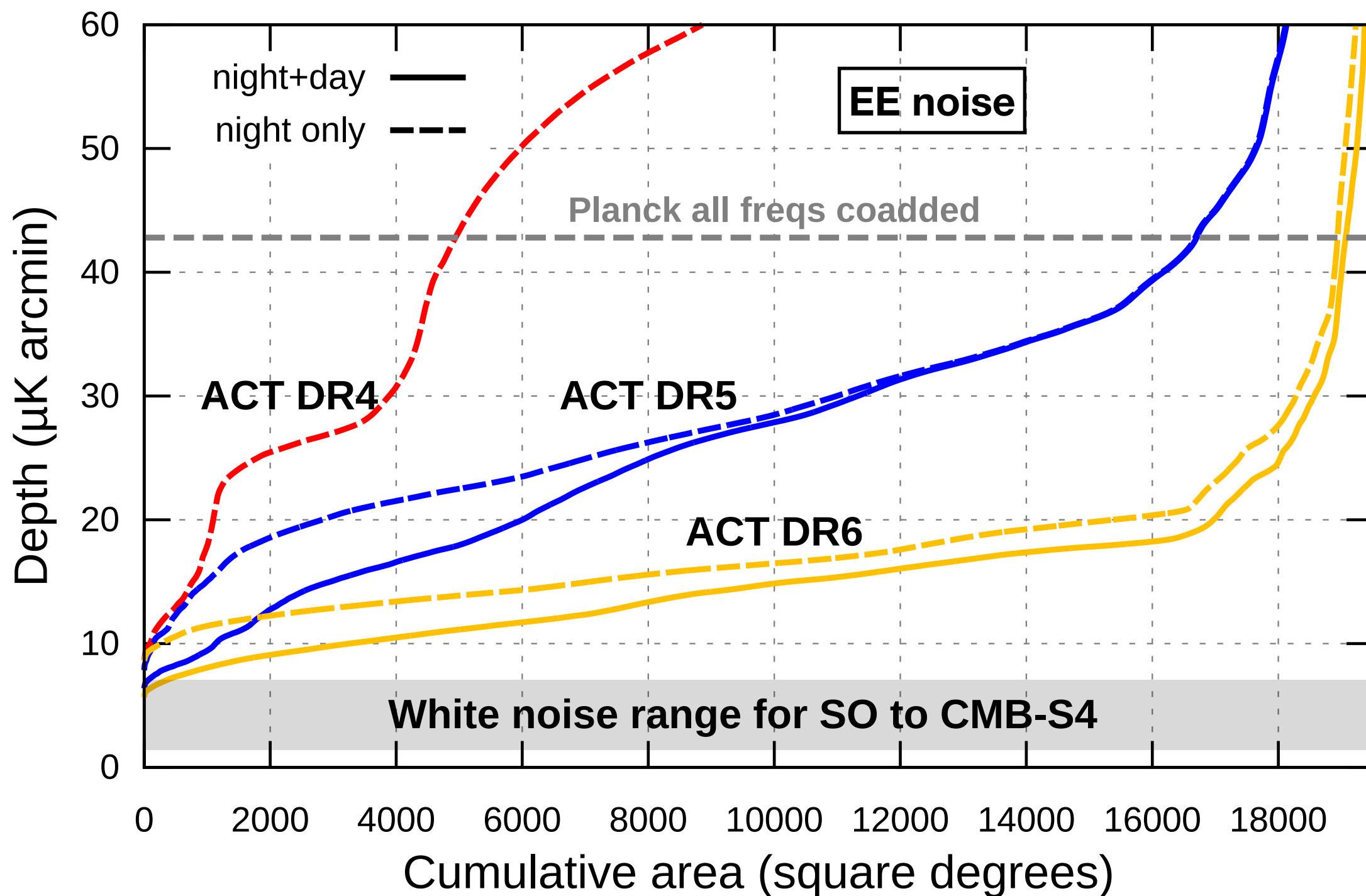
# DR6 Map Depth: T



Credit:  
S. Naess

ACT DR6 maps are significantly deeper (i.e., more sensitive) than Planck on nearly 40% of the sky, with  $>5\times$  higher angular resolution

# DR6 Map Depth: E



Credit:  
S. Naess

ACT DR6 maps are significantly deeper (i.e., more sensitive) than Planck on nearly 40% of the sky, with  $>5\times$  higher angular resolution

# ACT DR6 Forecasts

***ACT TT + TE + EE : precision cosmology beyond Planck***

|                          | ACT DR4 | ACT DR4 +<br>WMAP | Planck | Planck +<br>ACT DR6 |
|--------------------------|---------|-------------------|--------|---------------------|
| $\sigma(H_0)$            | 1.5     | 1.1               | 0.5    | 0.4                 |
| $\sigma(n_s)$            | 0.015   | 0.006             | 0.004  | 0.003               |
| $\sigma(N_{\text{eff}})$ | 0.4     | 0.3               | 0.2    | 0.1                 |

Large improvements in beyond- $\Lambda$ CDM parameters:  
~2x increase in sensitivity to new light relic particles



***PRELIMINARY FORECAST***

**Upcoming ACT DR6 precision cosmology constraints will surpass those from Planck ( $H_0$ ,  $N_{\text{eff}}$ ,  $\Sigma m_\nu$ ,  $\sigma_8$ , + beyond- $\Lambda$ CDM models) — stay tuned!**