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

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- 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-*y* 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

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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*

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Cosmic Microwave ~~Background~~ Backlight

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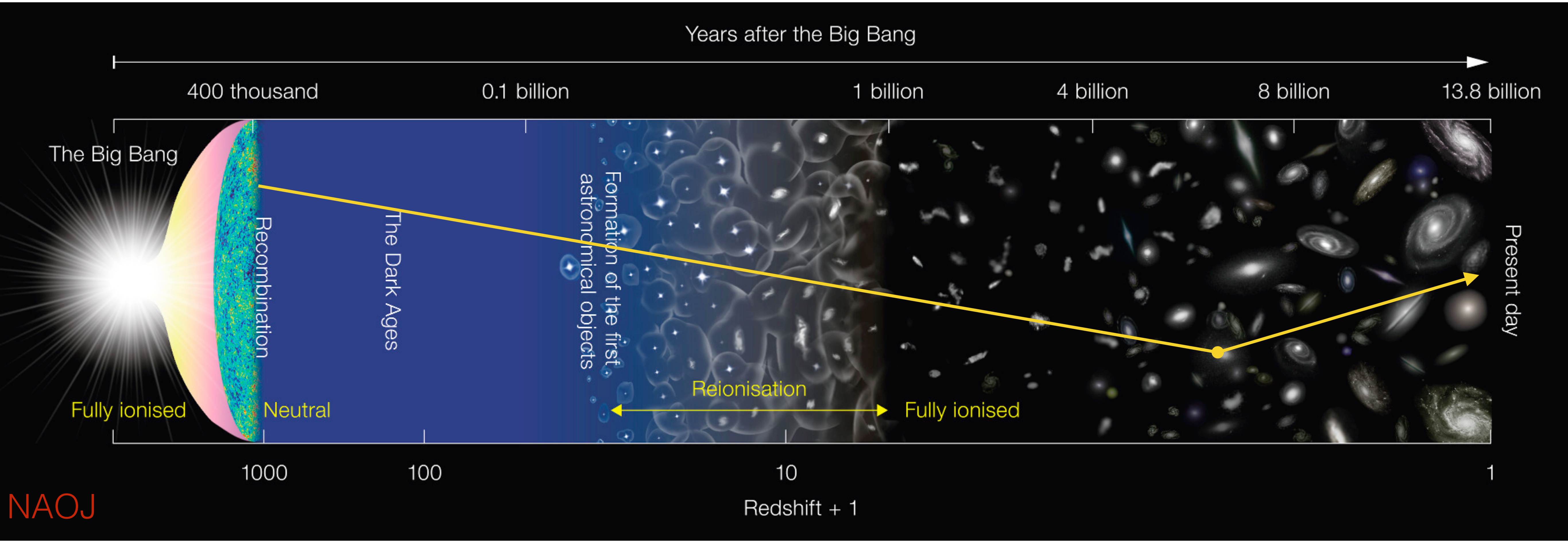
Cosmic Microwave Backlight

Secondary Anisotropies



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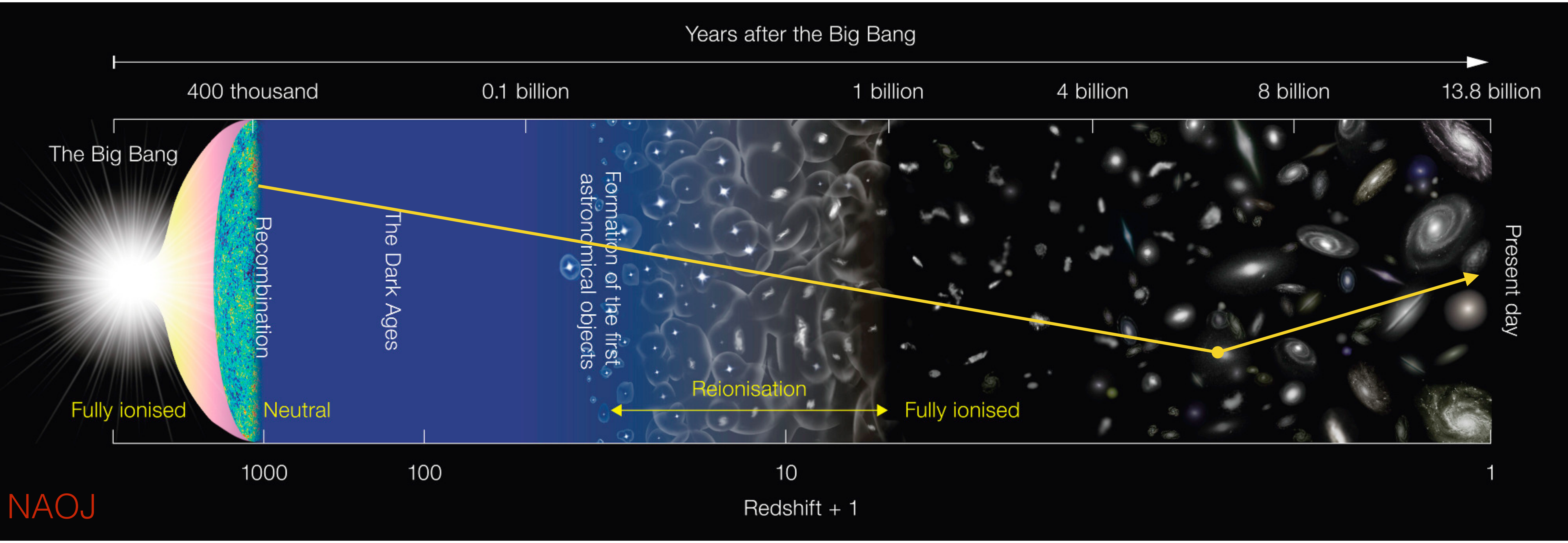
Cosmic Microwave Backlight

Secondary Anisotropies



- Scattering: thermal / kinematic Sunyaev-Zel'dovich effect

redshift-independent

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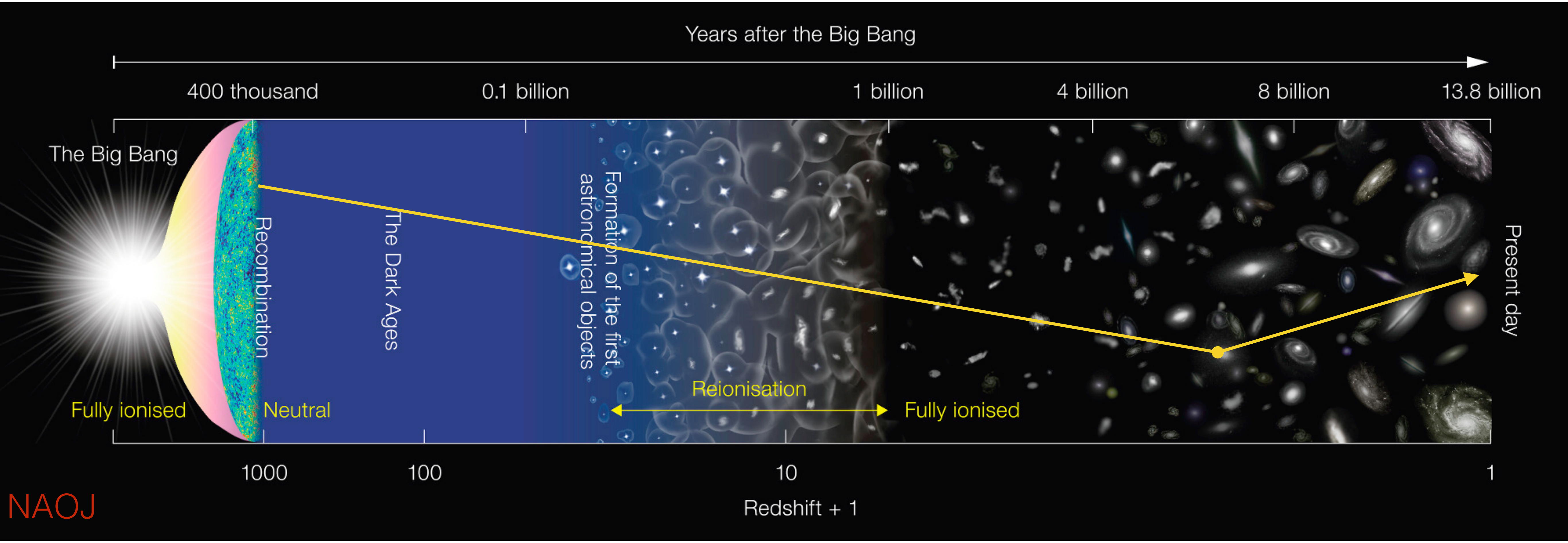
Secondary Anisotropies



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

CMB Lensing

→ Integrated Total Mass

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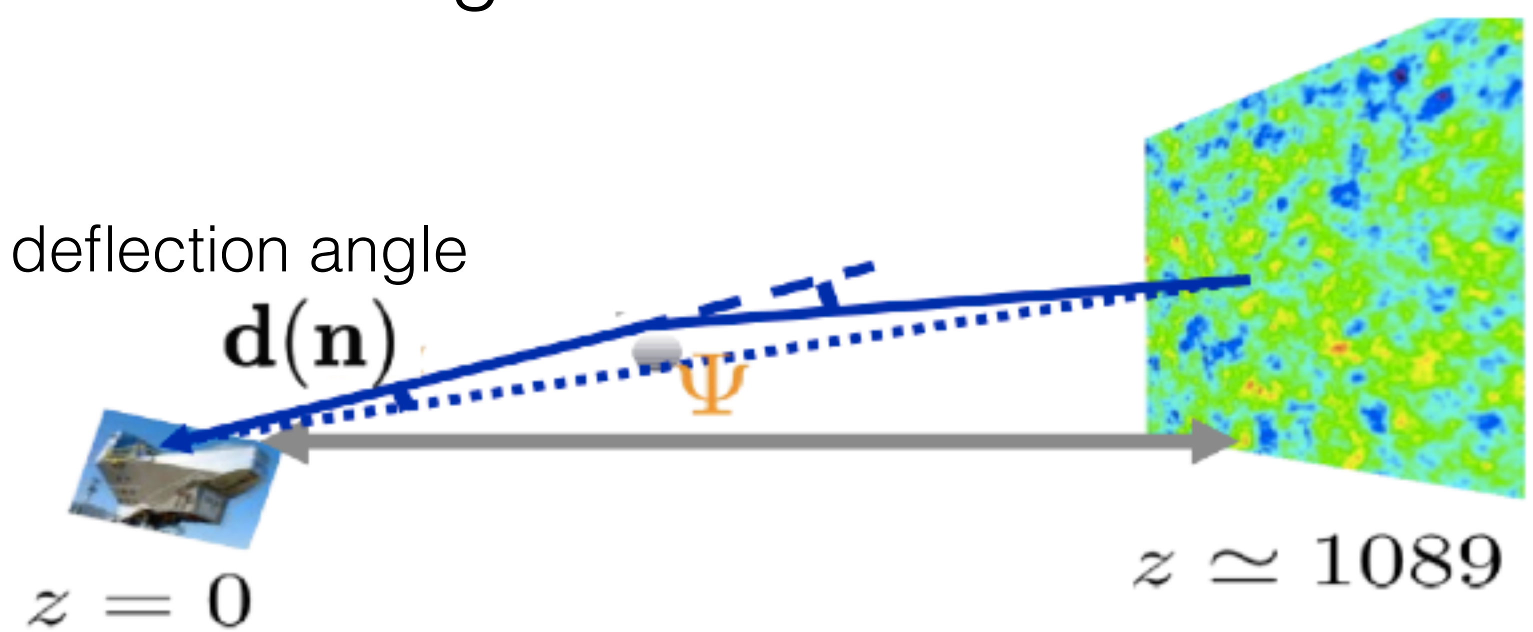
Re-mapping of CMB fluctuations (preserves blackbody form)

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



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

CMB Lensing

→ Integrated Total Mass

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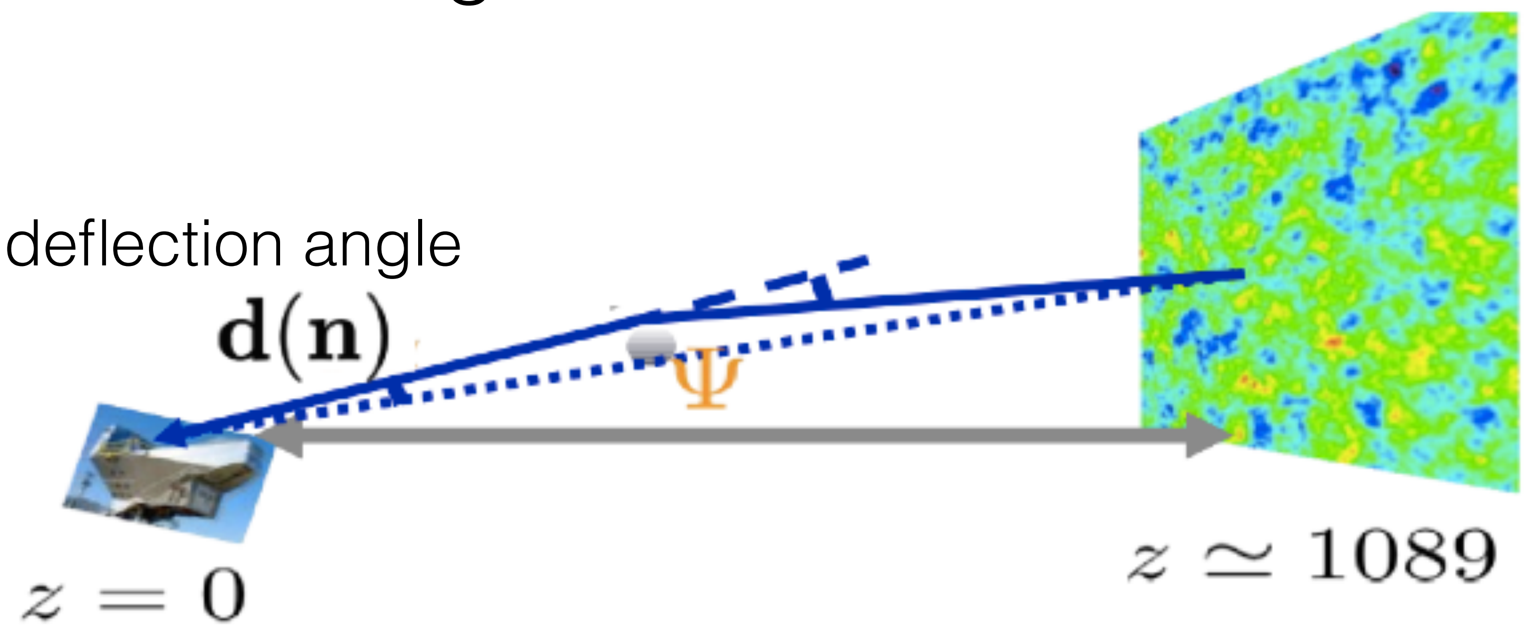

$$T(\hat{\mathbf{n}})_{\rm lensed} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\rm unlensed}$$

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

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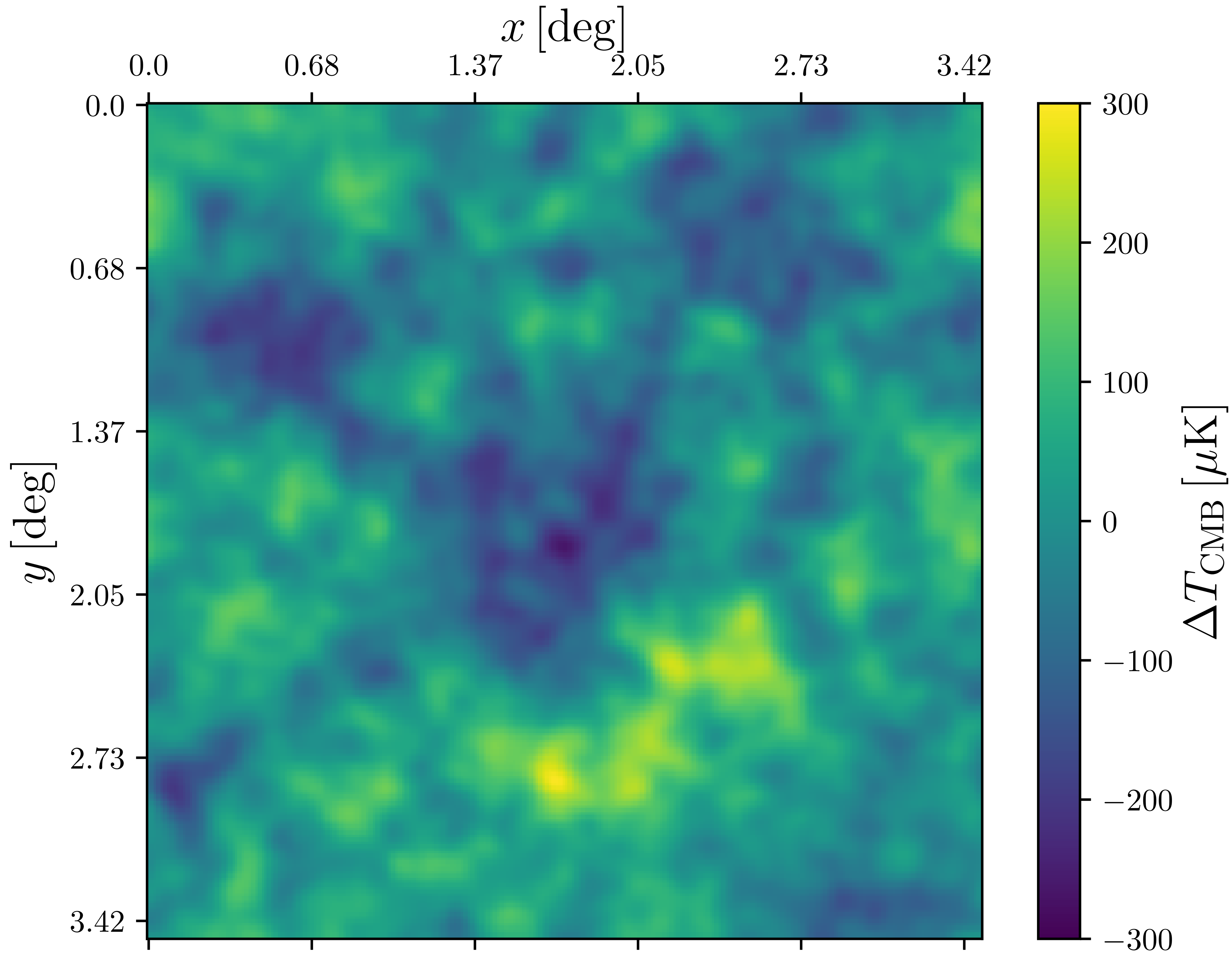
→ Integrated Total Mass



unlensed

CMB Lensing

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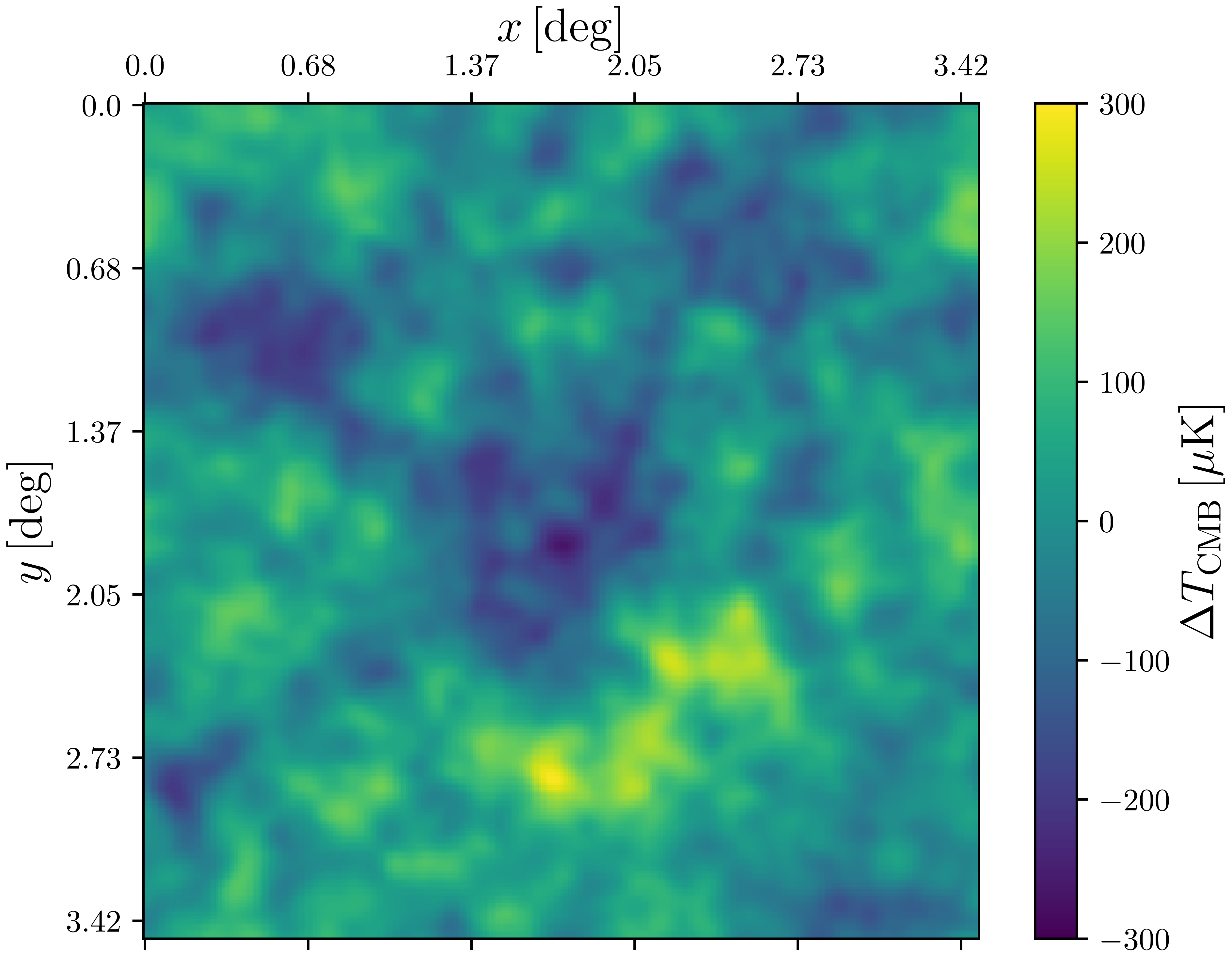
→ **Integrated Total Mass**



lensed

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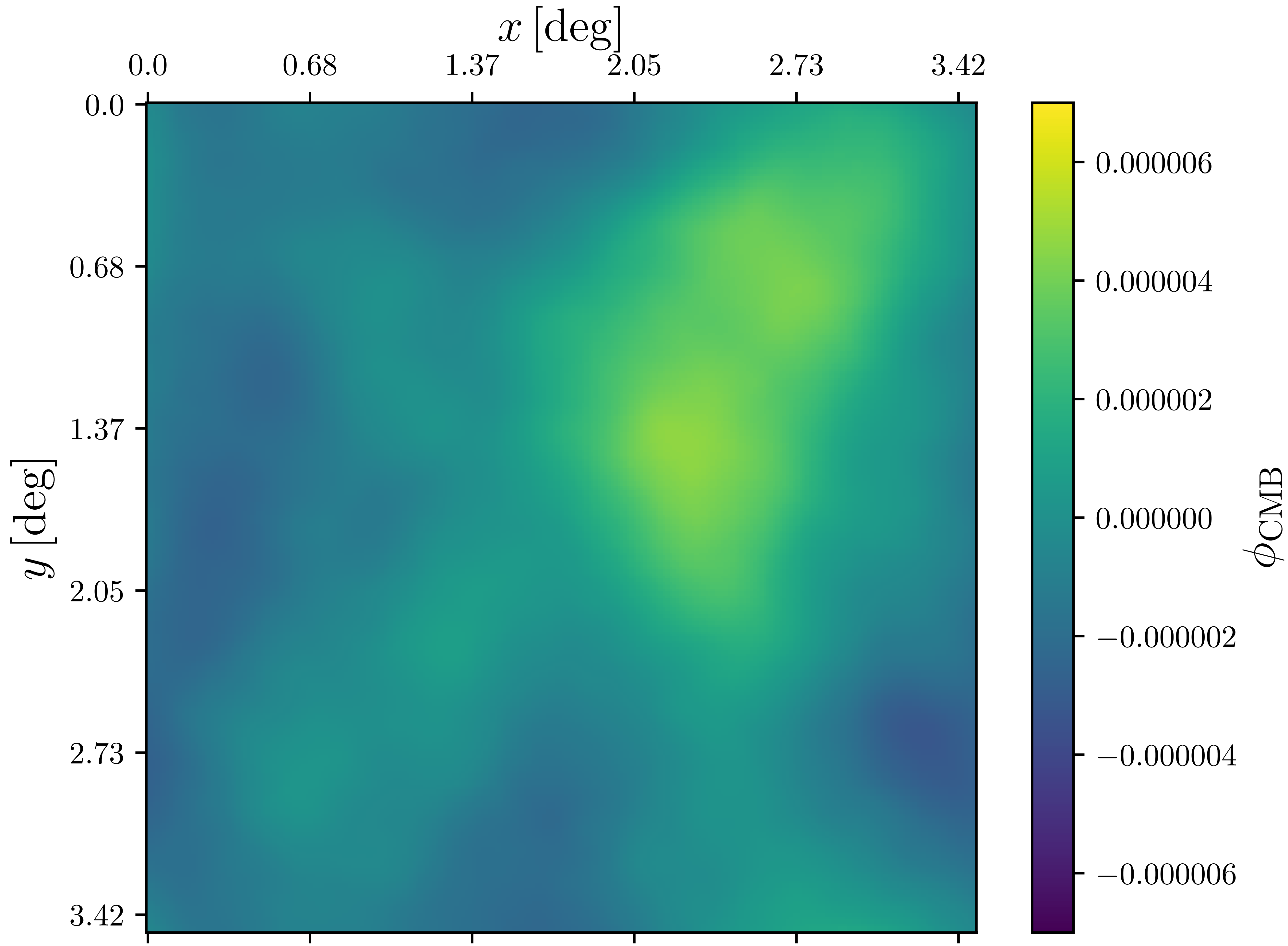
CMB Lensing

→ Integrated Total Mass



input lensing potential

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

ray-traced N-body sim. [Liu, JCH+ (2016)]

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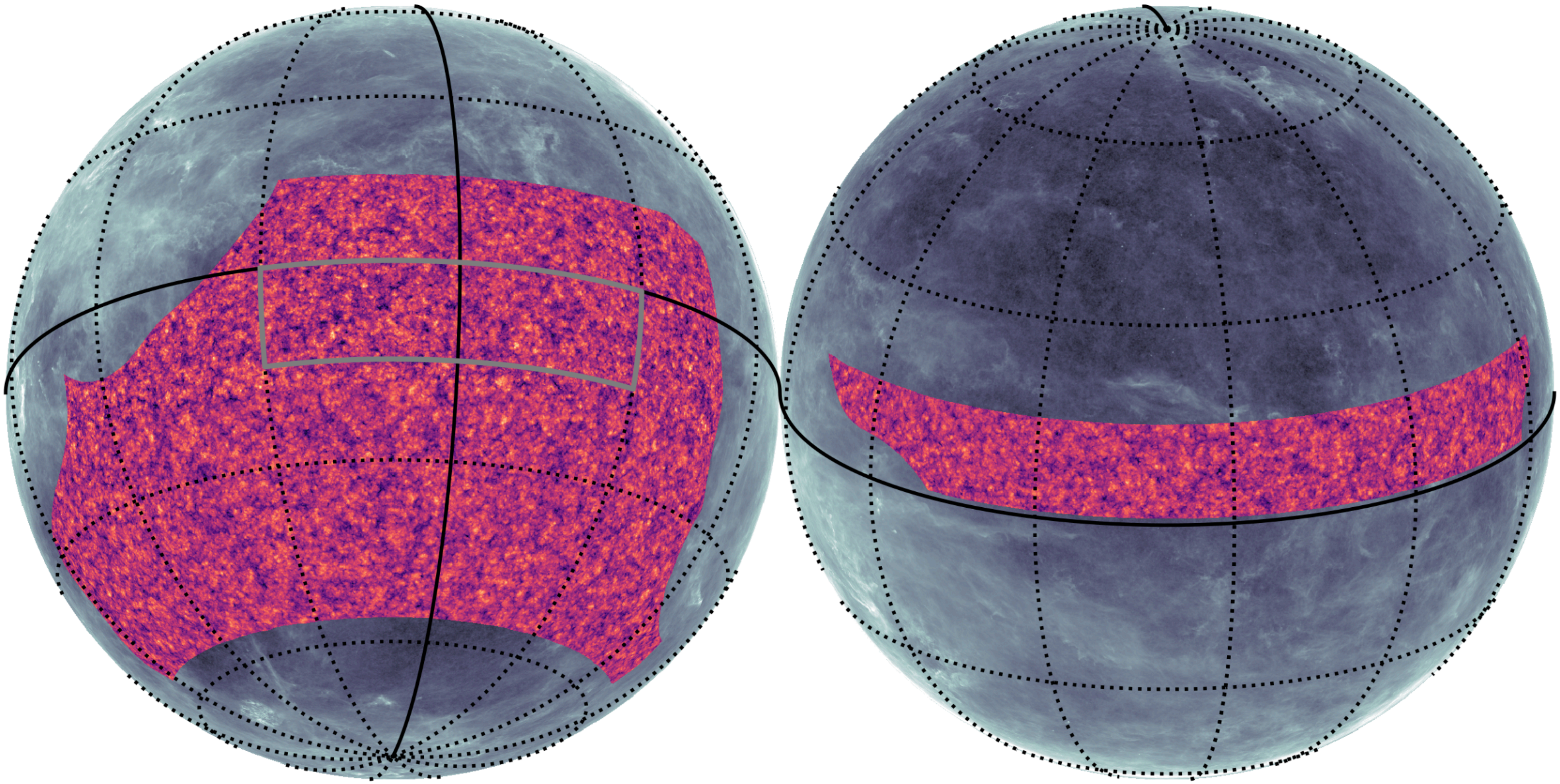
CMB Lensing

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)

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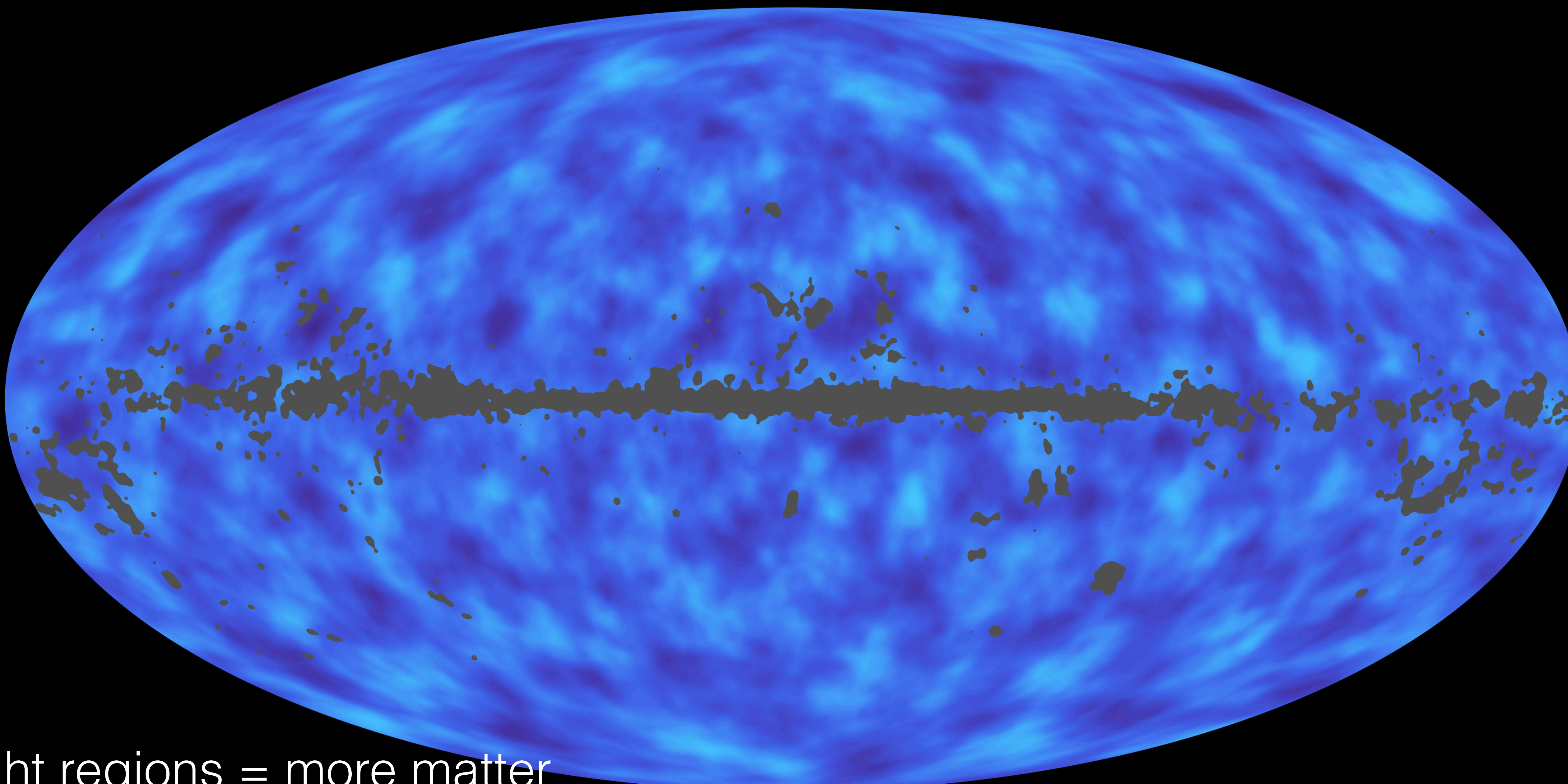
CMB Lensing

State of the art: *Planck*



light regions = more matter
dark regions = less matter

Planck Collaboration (2016); most recent update (PR4) in Carron et al. (2022)

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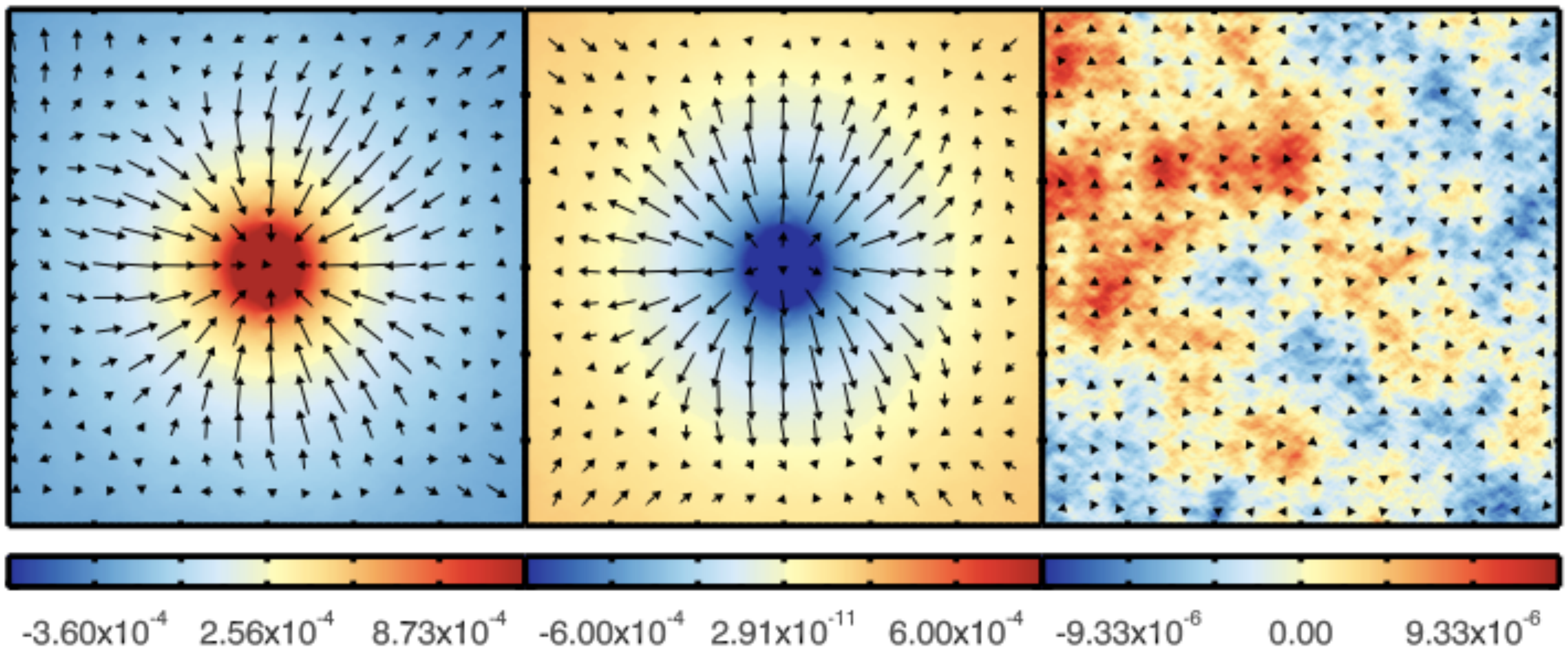
Cosmic Infrared Background

cumulative emission of dusty, star-forming galaxies over cosmic time

strongly correlated with CMB lensing (and partially correlated w/ tSZ and other fields)

545 GHz



Planck XVIII (2013)

Compton-*y* Maps from Planck PR4 with **pyilc**

McCarthy & JCH (to appear)

Thermal SZ Extraction

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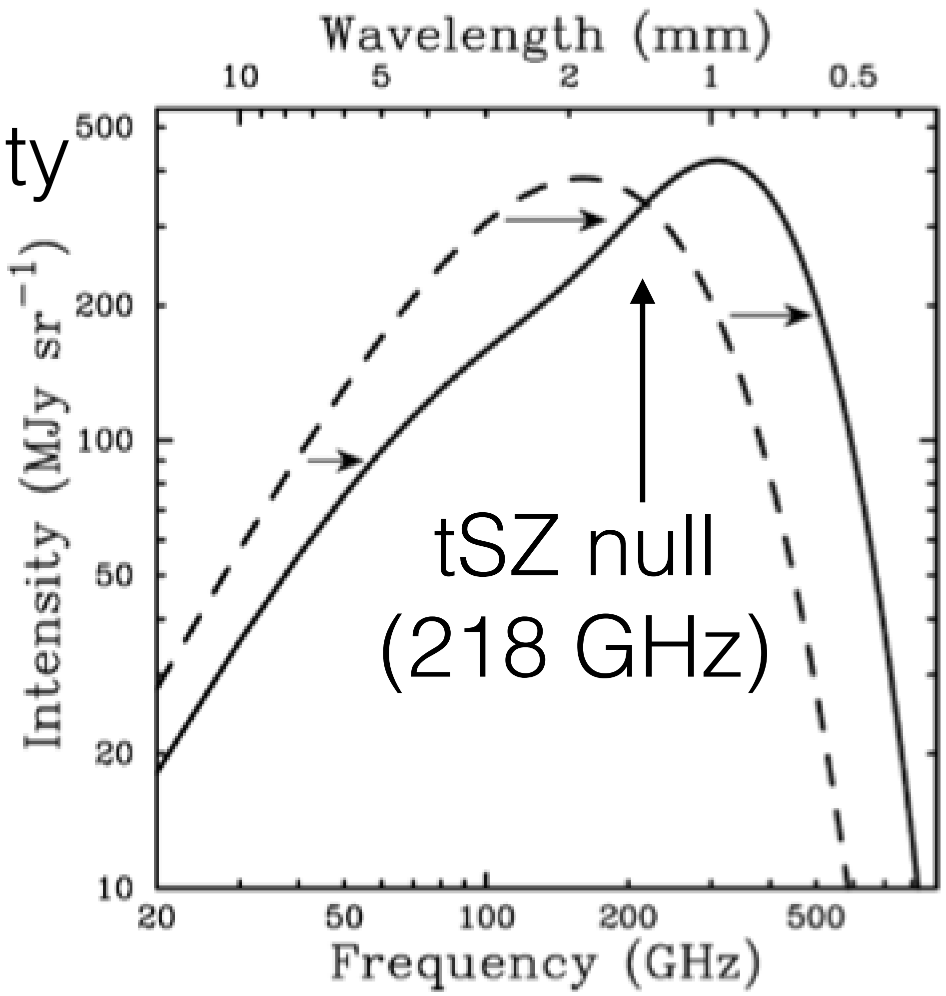
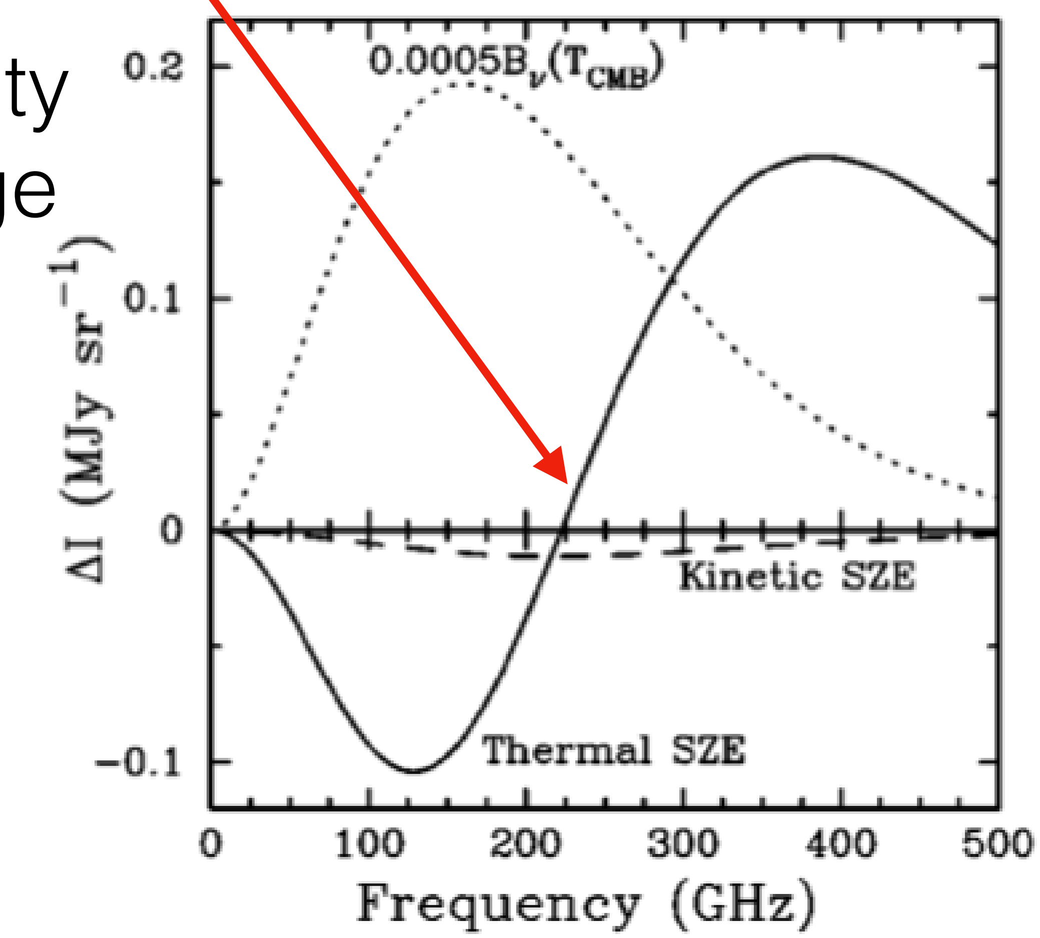
Utilize unique spectral signature of tSZ effect

intensity



frequency

intensity
change



frequency

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

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

Figures: Carlstrom+ (2002)

Thermal SZ Extraction

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Internal Linear Combination

relatively agnostic approach, flexible choice of domain

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

i ⟷ frequency

observed temperature fluctuation | component of interest | noise+ contaminants

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

Thermal SZ Extraction

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Internal Linear Combination

relatively agnostic approach, flexible choice of domain

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

i ⟷ frequency

observed temperature fluctuation — component of interest — noise+ contaminants

minimum-variance estimator with unit response to desired component:

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

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

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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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

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

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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

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

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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

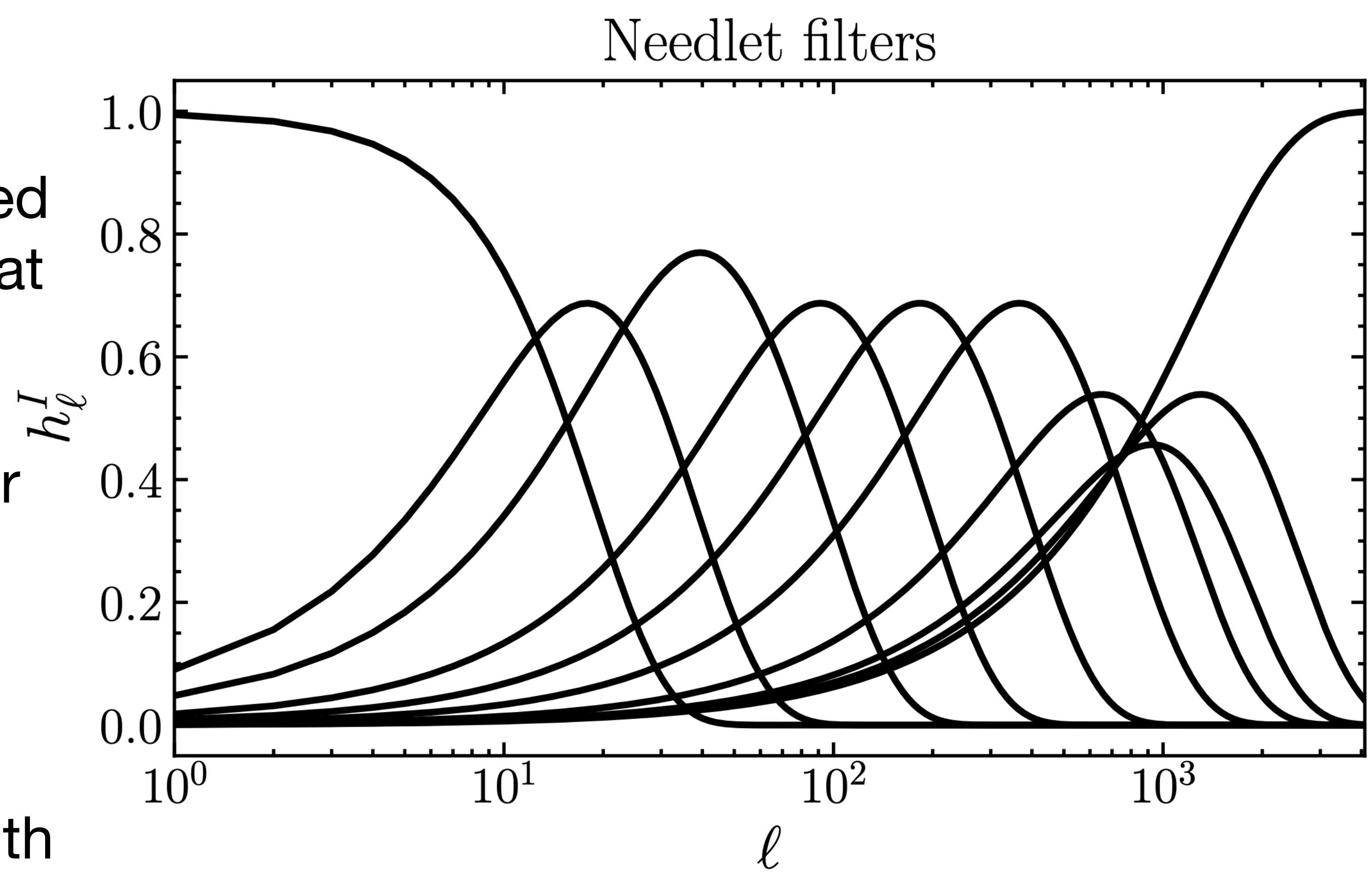
2) Compute the freq.-freq. covariance matrix in real-space domain of specified size centered on each pixel (for maps at each needlet scale)

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)

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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:

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

McCarthy & JCH (to appear)

code will appear on GitHub with paper

Thermal SZ Extraction

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CIB cleaning: moment deprojection

Idea: suppose the fundamental SED describing dust emission is indeed a modified blackbody (MBB). Variations in the MBB parameters (β,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.

Chluba, JCH, Abitbol (2017); McCarthy & JCH (to appear)

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MBB:

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

First-order moments:

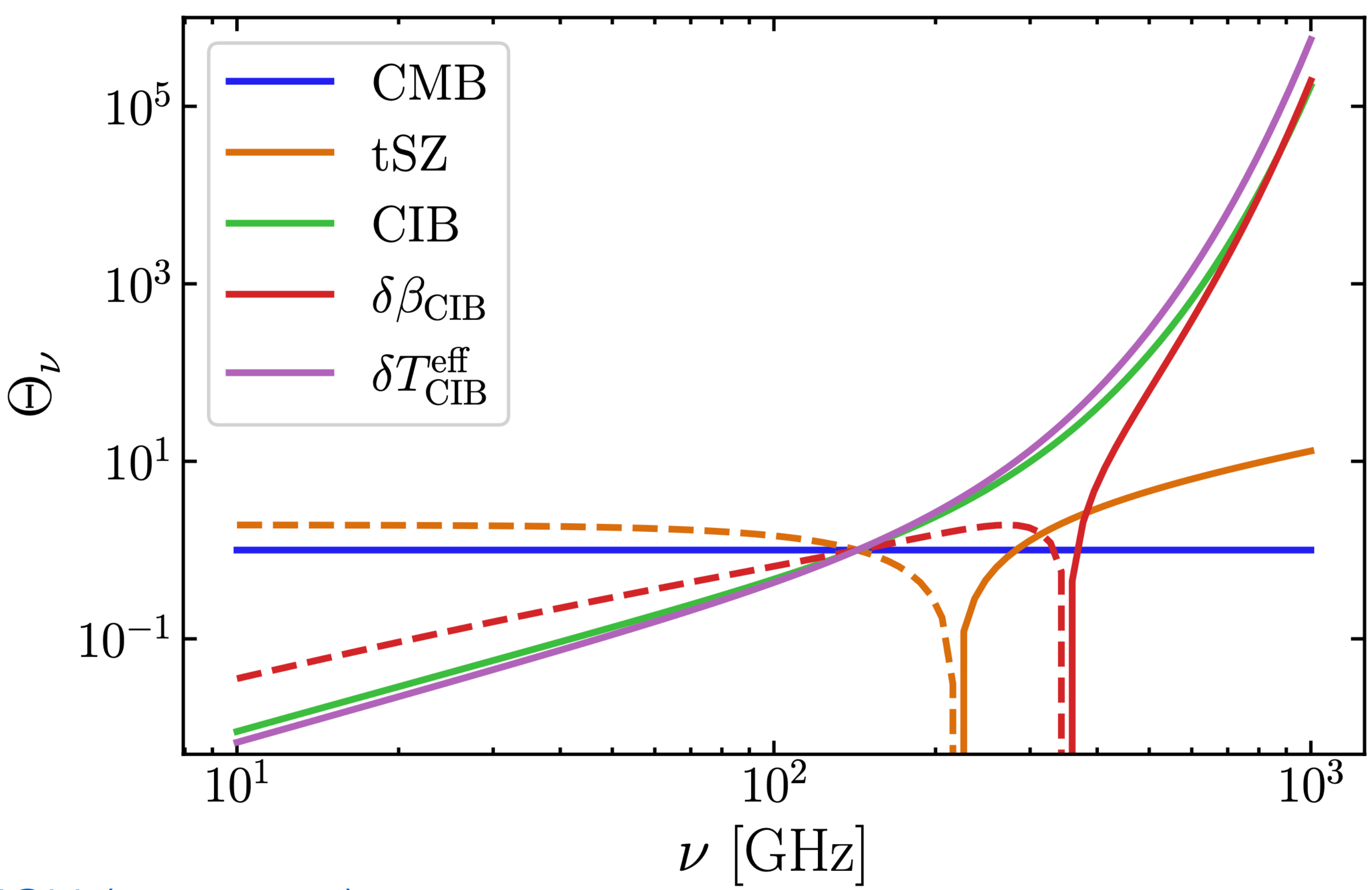
$$\frac{\partial I_\nu^{\rm CIB}(\hat{n})}{\partial \beta} = \ln\left(\frac{\nu}{\nu_0}\right) I_\nu^{\rm CIB}(\hat{n})\,;$$

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

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

ν_0 = 353 GHz

Component SEDs [normalized]



Chluba, JCH, Abitbol (2017); McCarthy & JCH (to appear)

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CIB cleaning: moment deprojection

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

McCarthy & JCH (to appear); Planck Collaboration XXX (2014)

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Thermal SZ Extraction

CIB cleaning: moment deprojection

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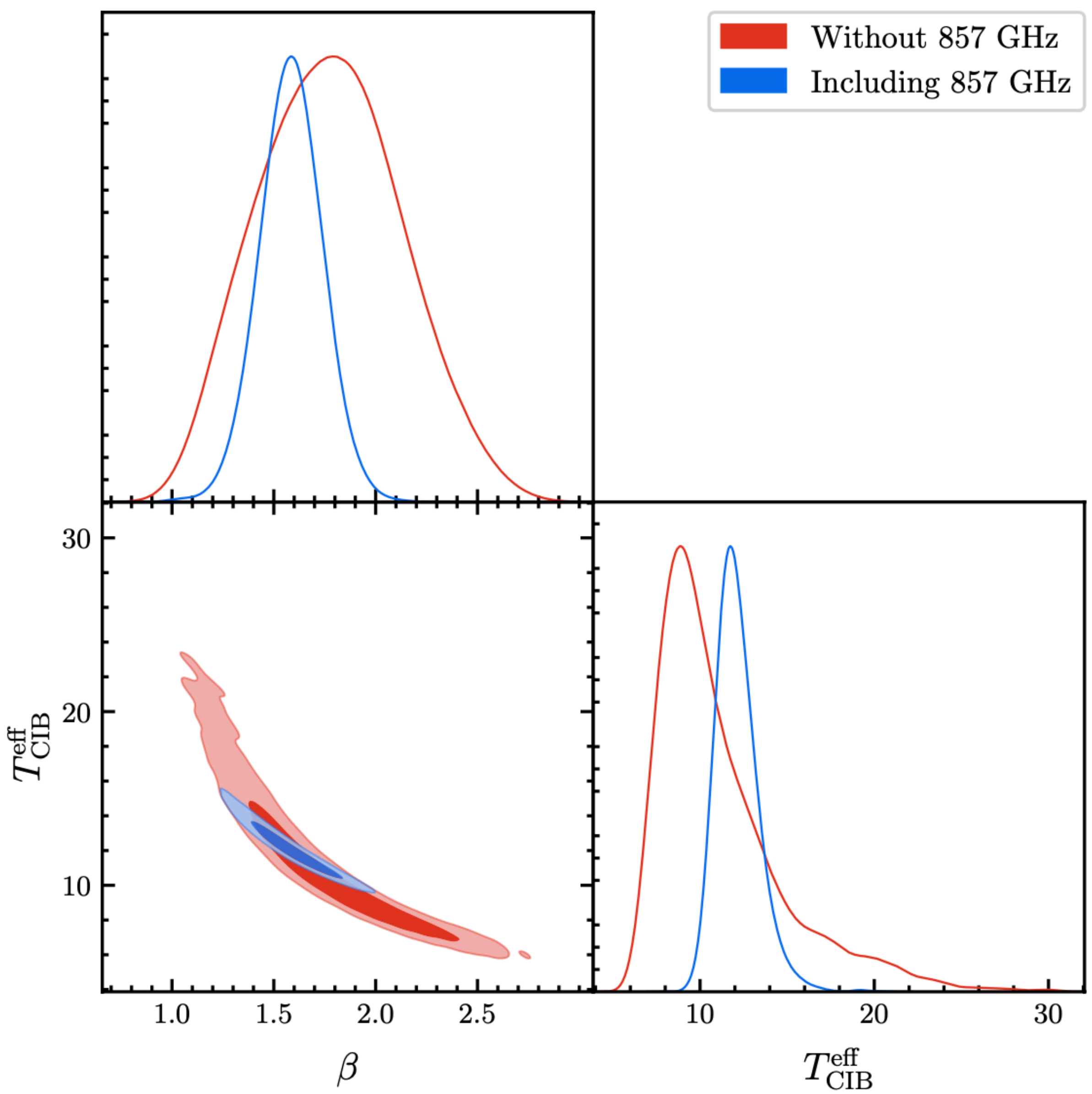

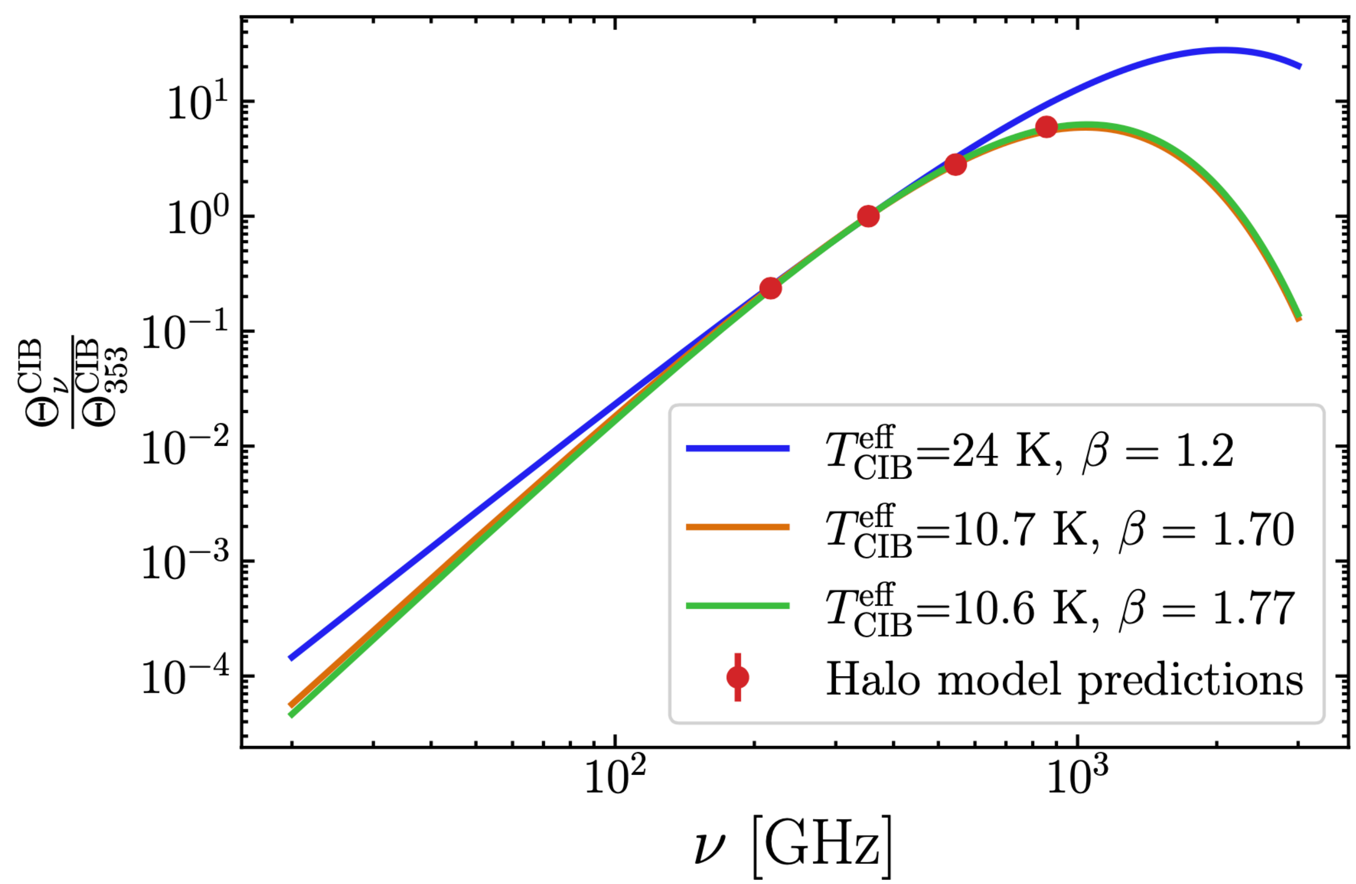

Later in our analysis we will draw (β,$T^{\rm eff}$) samples from this posterior to test the sensitivity of our CIB deprojections to the assumed MBB SED

McCarthy & JCH (to appear)

Thermal SZ Extraction

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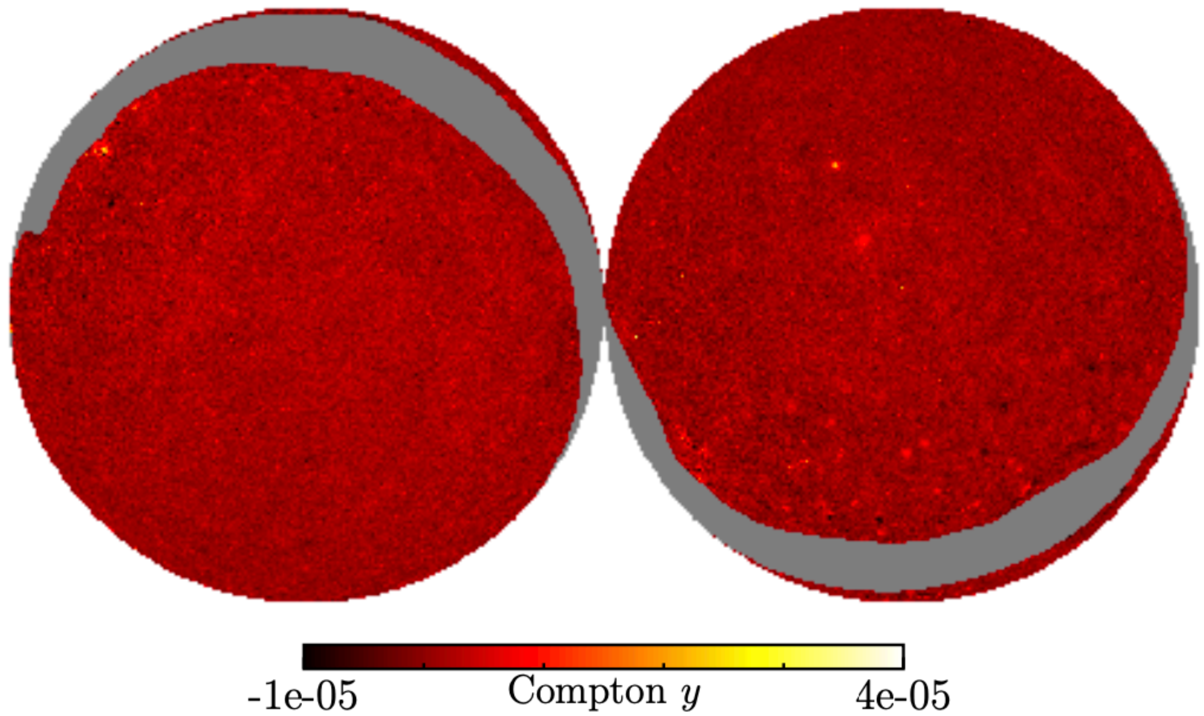
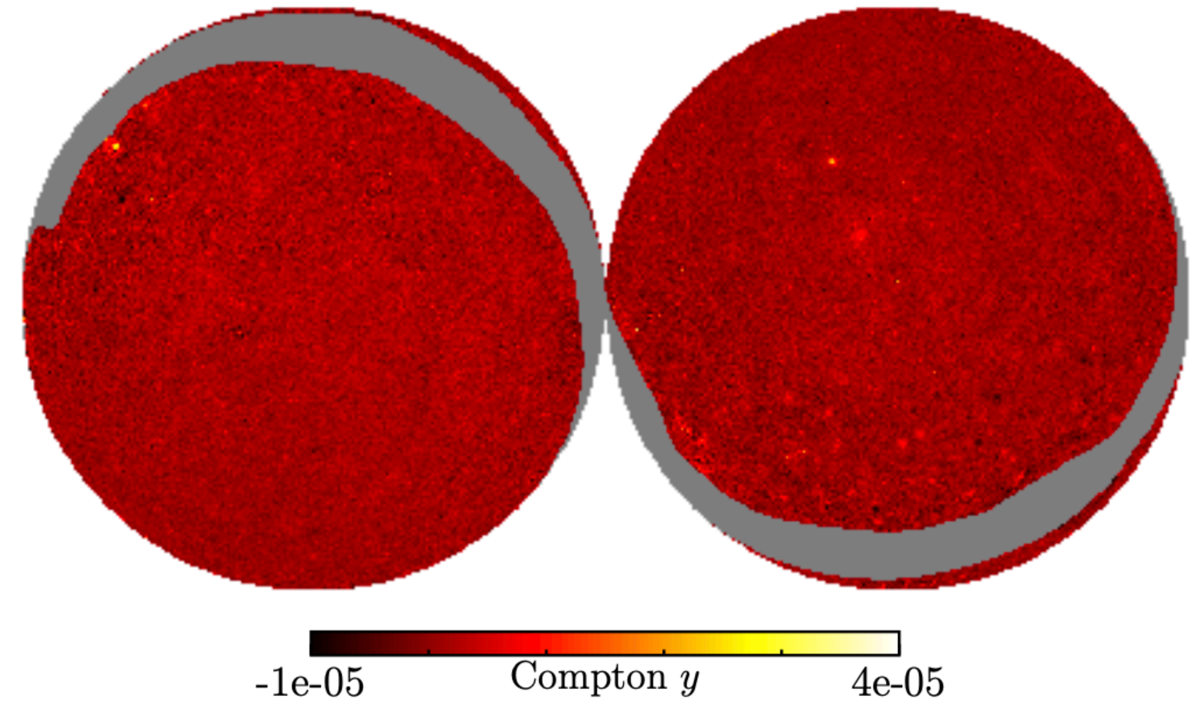
Application to Planck PR4 (NPIPE) maps

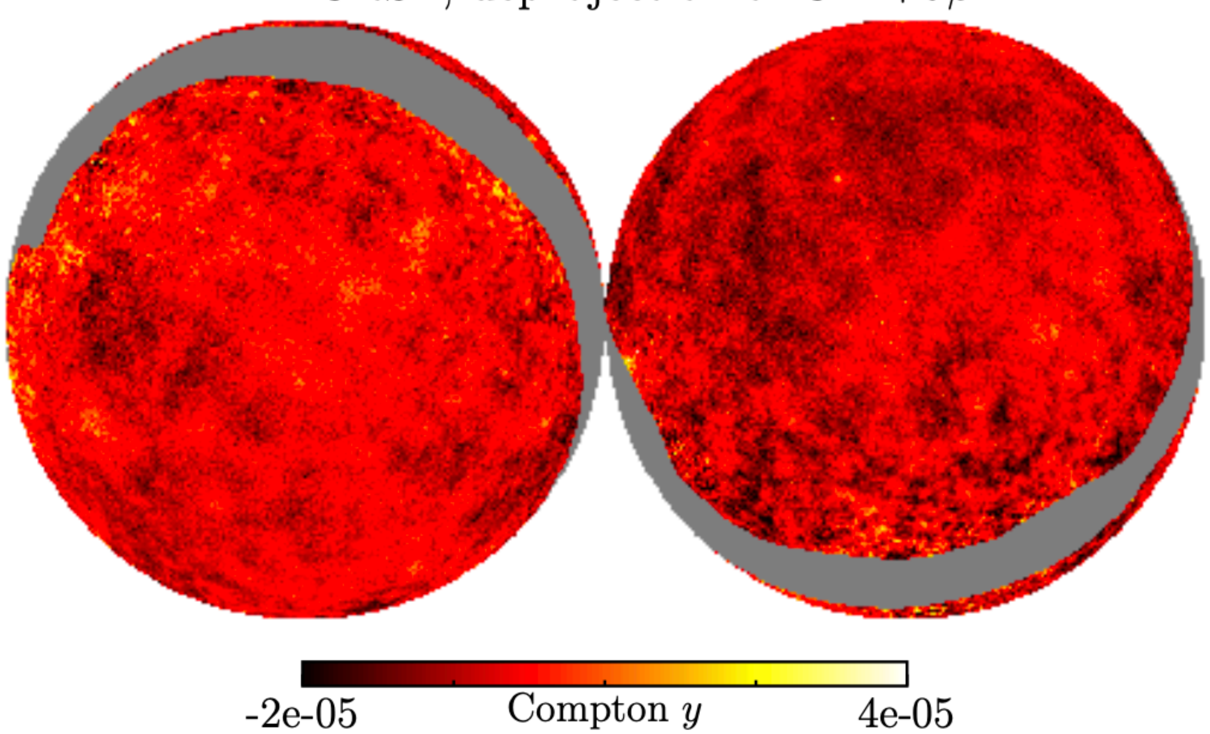
NILC tSZ; no deprojection



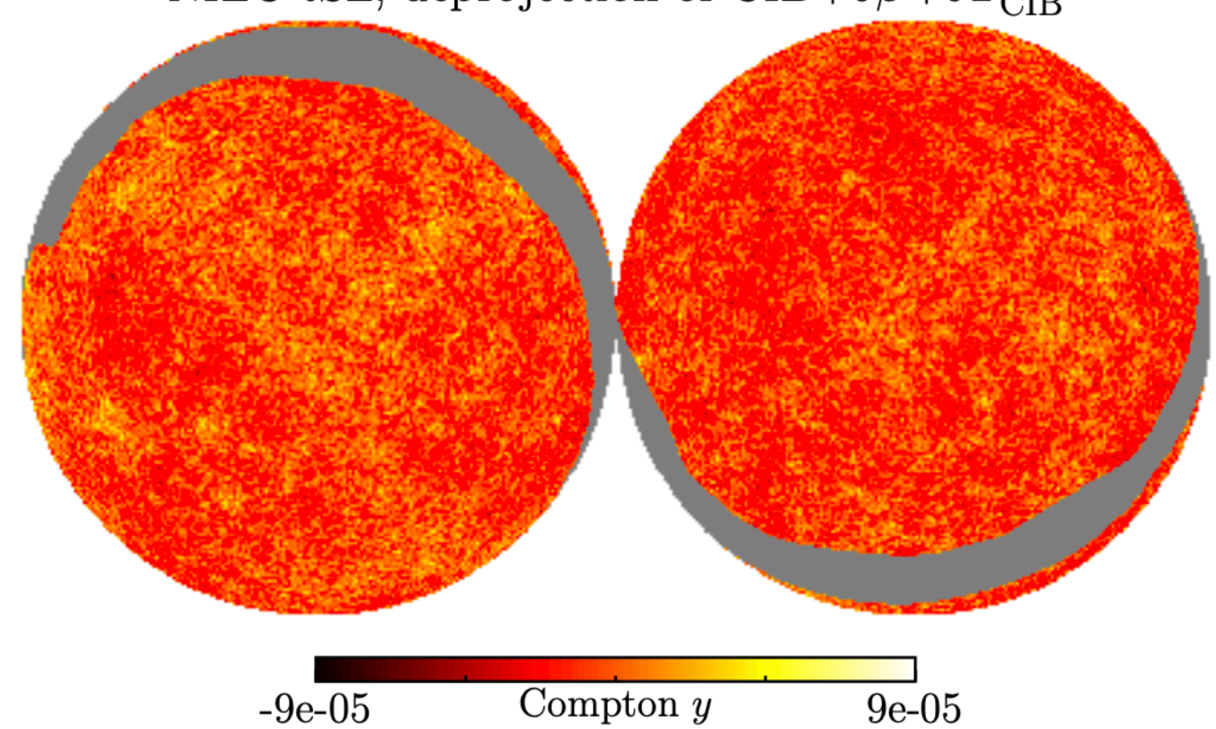
NILC tSZ; deprojection of CIB



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



NILC tSZ; deprojection of CIB+$\delta\beta$+$\delta T^{\rm eff}_{\rm CIB}$



McCarthy & JCH (to appear)

Thermal SZ Extraction

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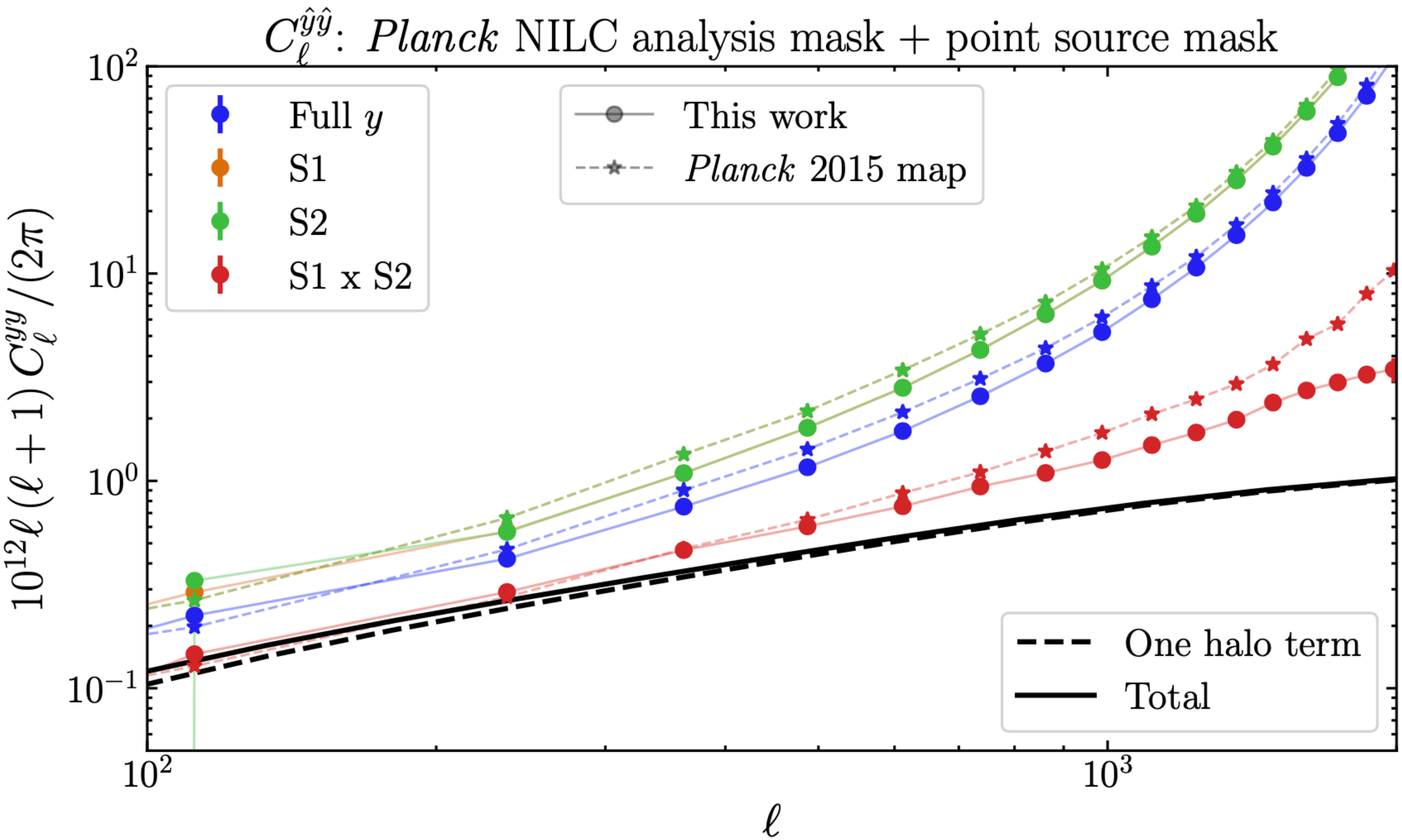
Application to Planck PR4 (NPIPE) maps



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

McCarthy & JCH (to appear); see also Tanimura+(2022) and Chandran+(2023) [consistent results]

Thermal SZ Extraction

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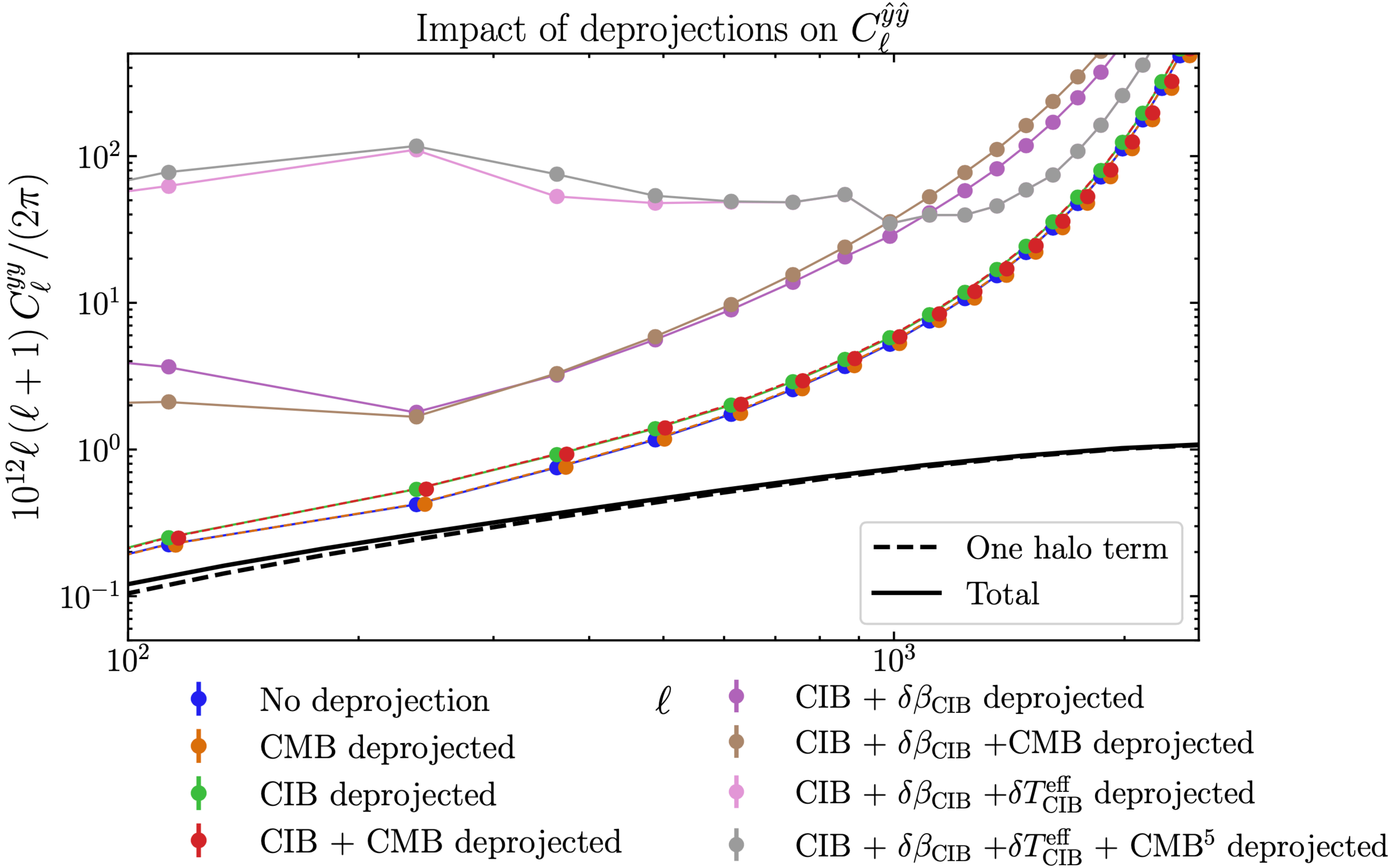
Application to Planck PR4 (NPIPE) maps



McCarthy & JCH (to appear)

Thermal SZ
x
CMB Lensing

tSZ x CMB Lensing

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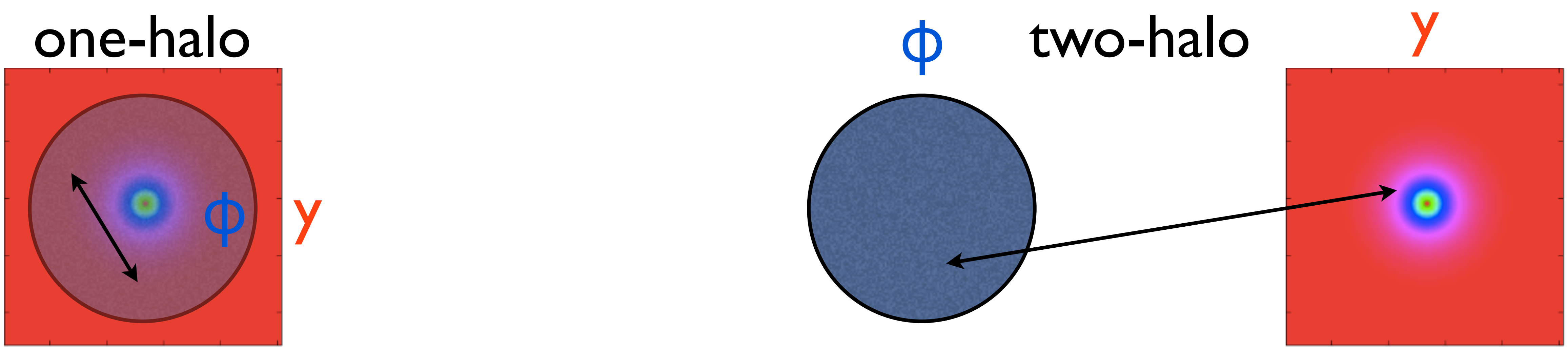
Theory: halo model

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



dominates on small scales

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

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)

JCH & Spergel (2014); McCarthy & JCH (to appear)

https://github.com/CLASS-SZ/class_sz

tSZ x CMB Lensing

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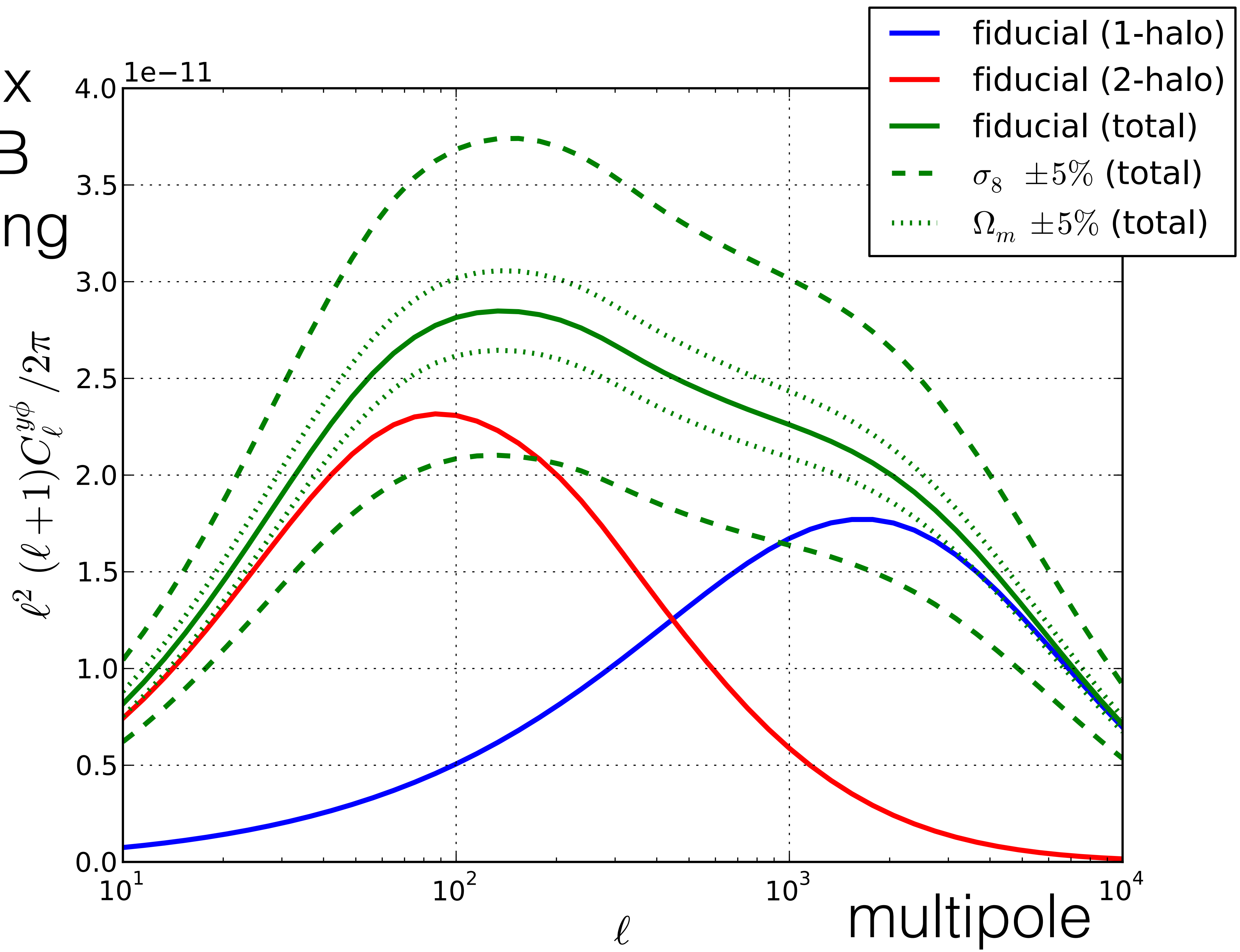
Theory: halo model

tSZ x CMB Lensing PS



multipole

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

JCH & Spergel (2014); McCarthy & JCH (to appear)

tSZ x CMB Lensing

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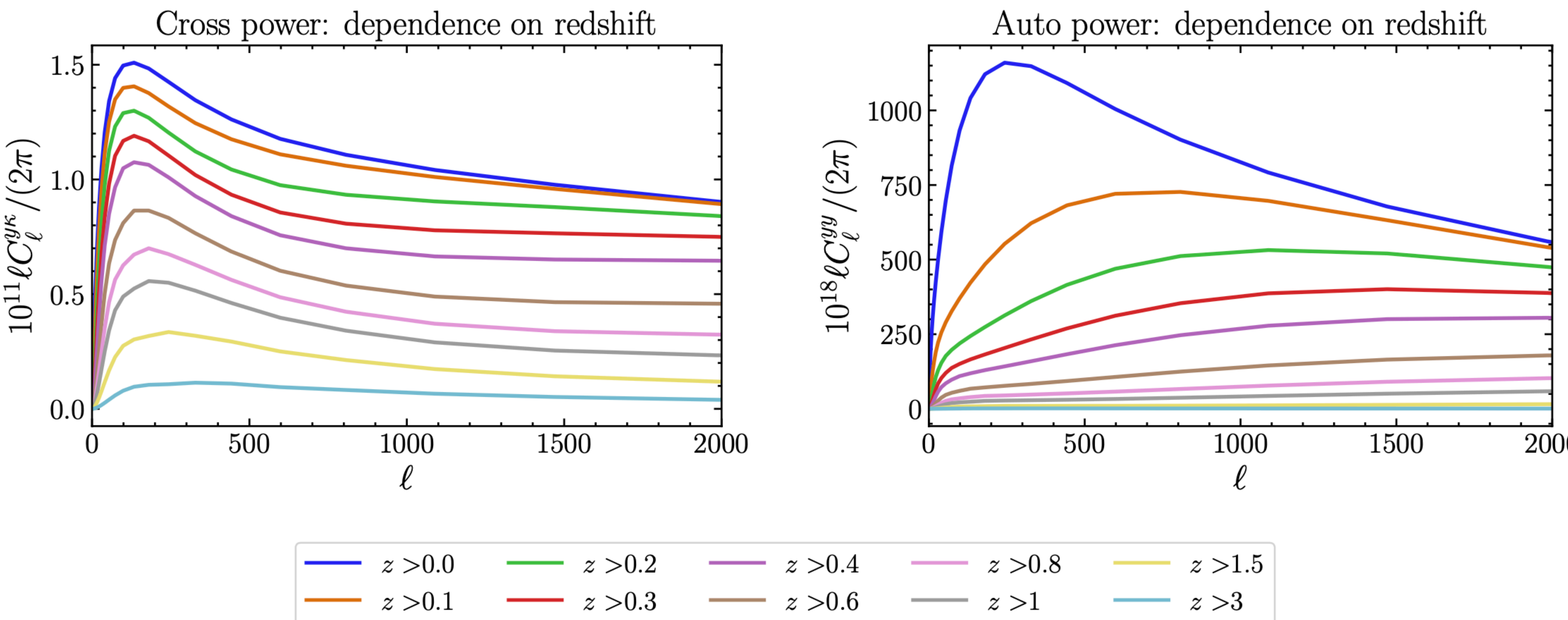
Theory: origin of the signal

y x ϕ_{CMB} cross-power

yy auto-power



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

JCH & Spergel (2014); McCarthy & JCH (to appear)

tSZ x CMB Lensing

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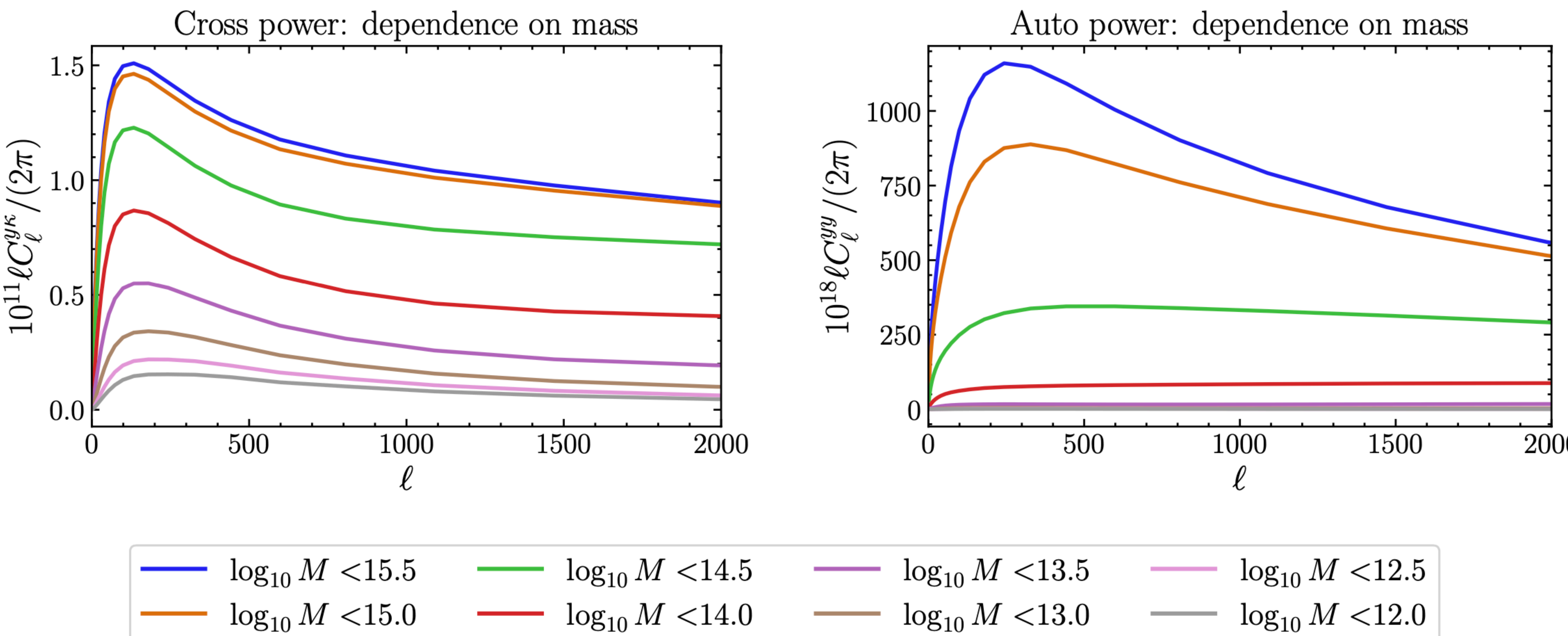
Theory: origin of the signal

y x ϕ_{CMB} cross-power | yy auto-power



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

JCH & Spergel (2014); McCarthy & JCH (to appear)

tSZ x CMB Lensing

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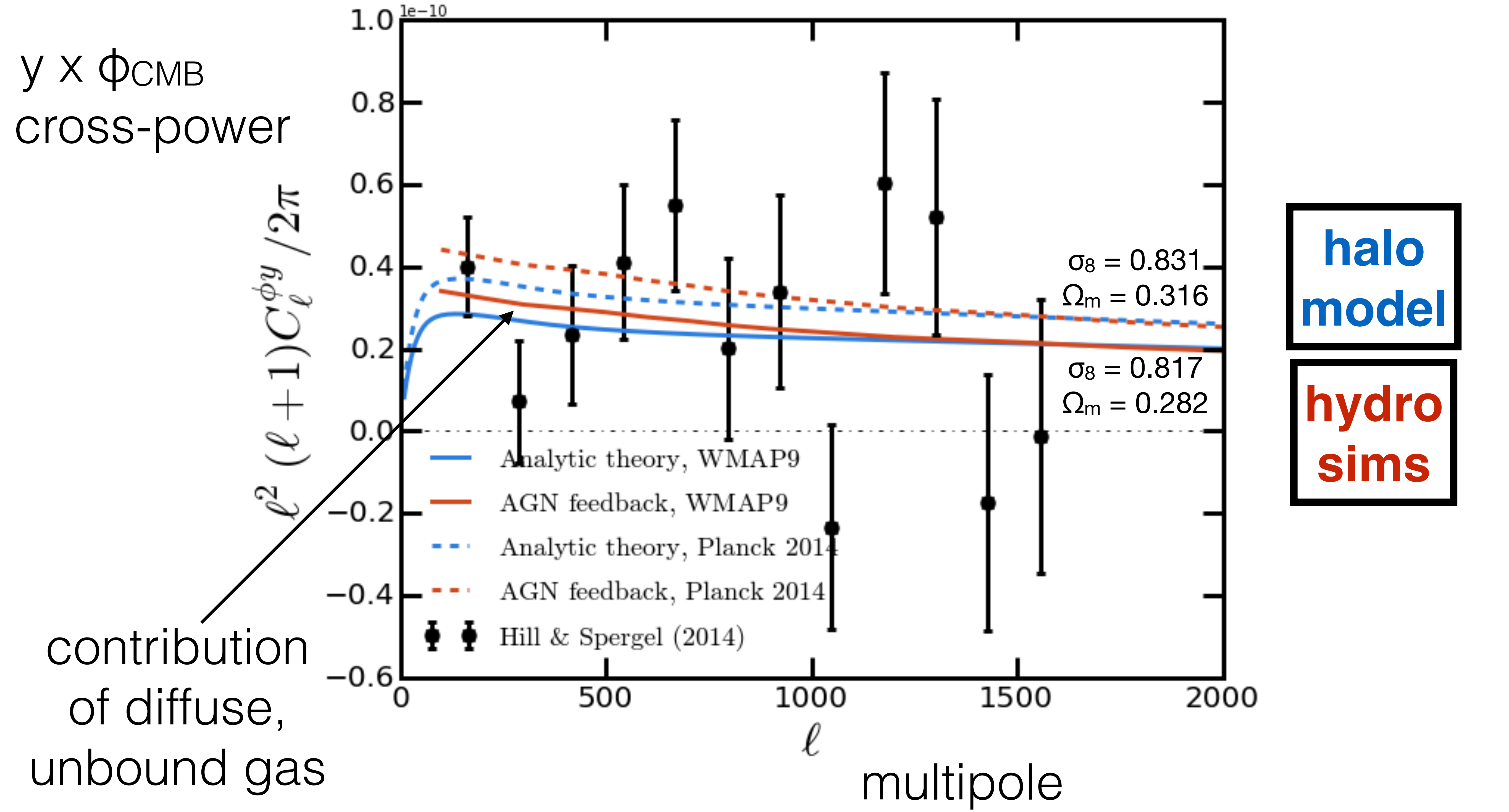
Theory: origin of the signal



Battaglia, JCH, Murray (2015)

tSZ x CMB Lensing

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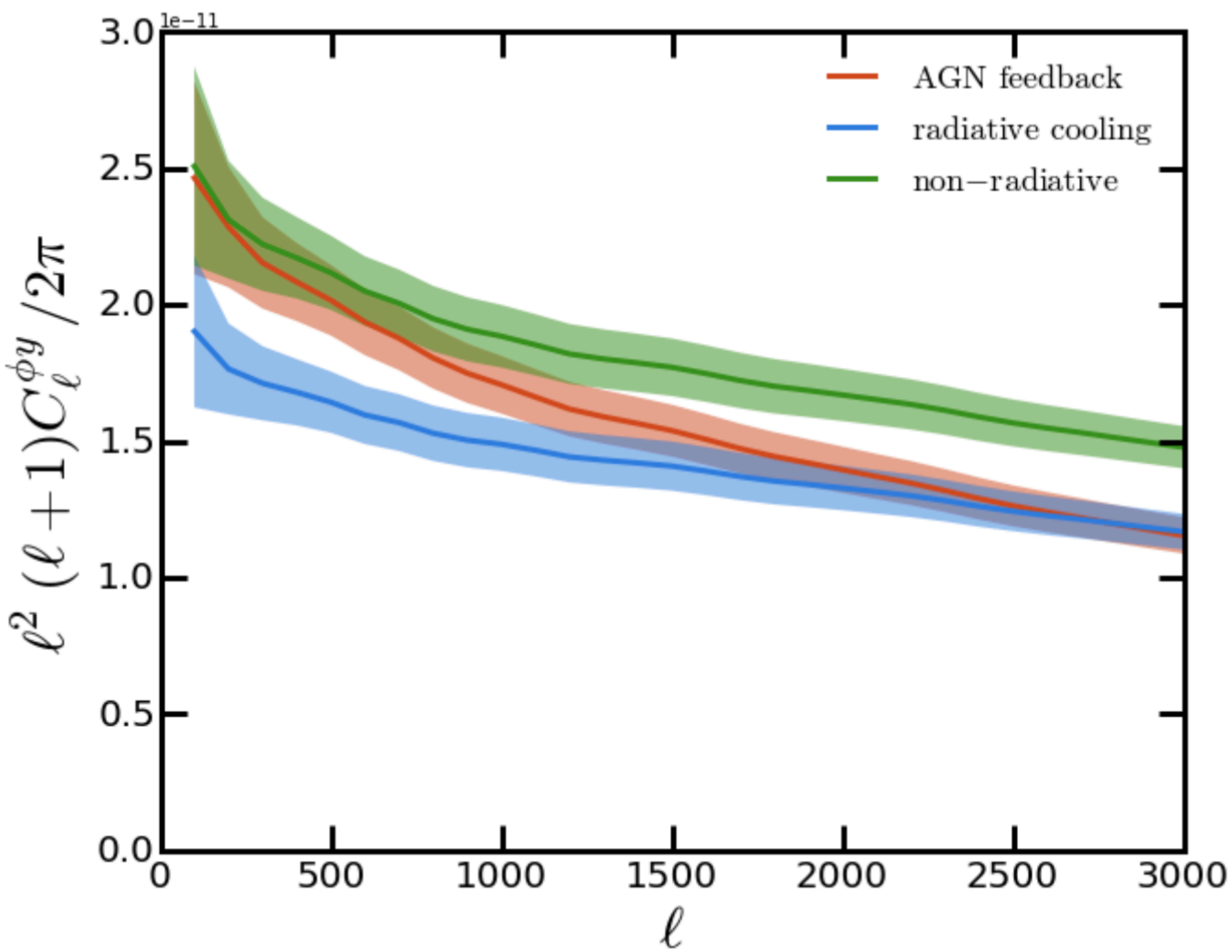
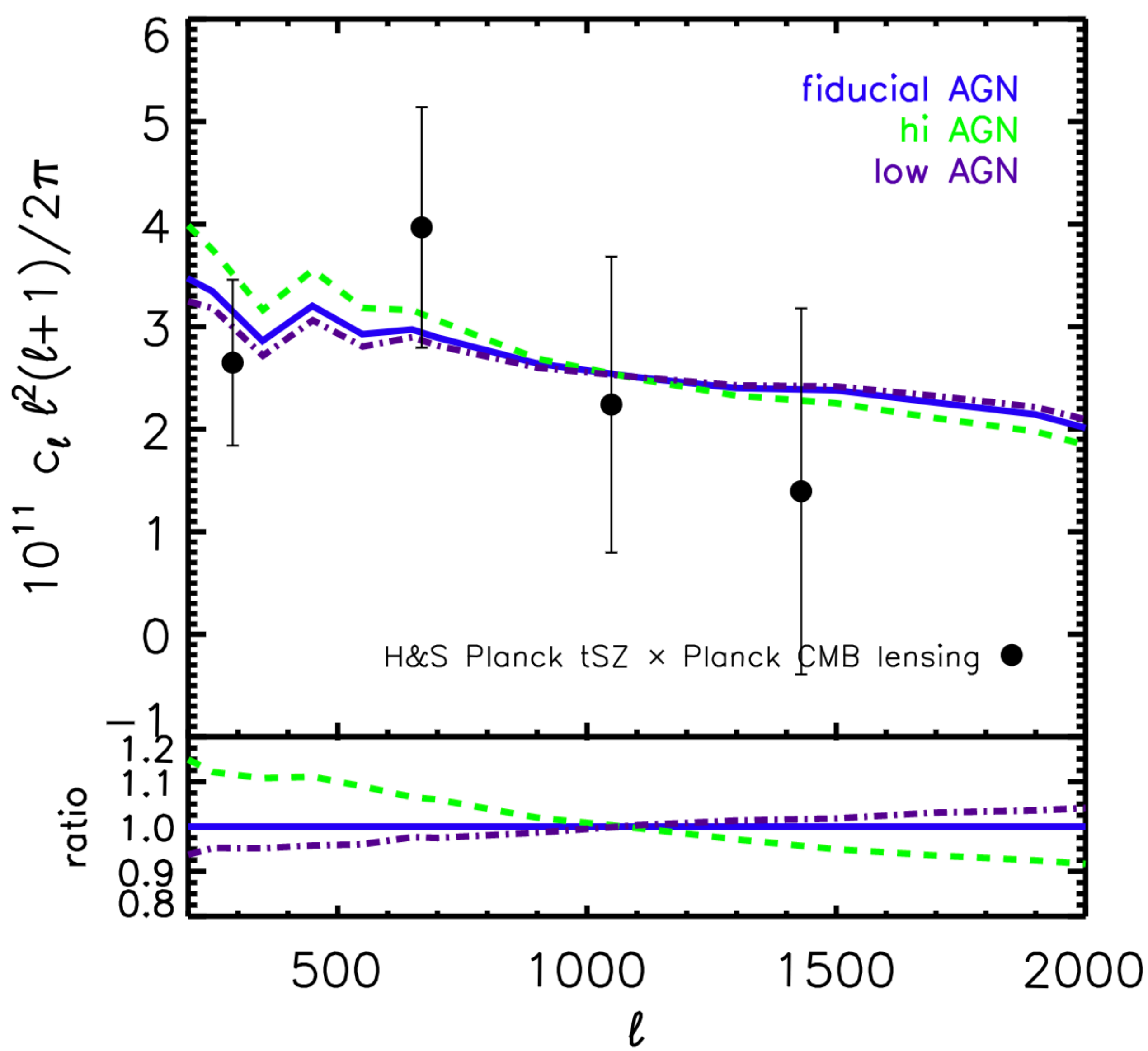
Theory: sensitivity to gastrophysics/feedback modeling





Battaglia, JCH, Murray (2015); Ian McCarthy+(2017) [BAHAMAS]; Schaye+(2023) [FLAMINGO]

tSZ x CMB Lensing

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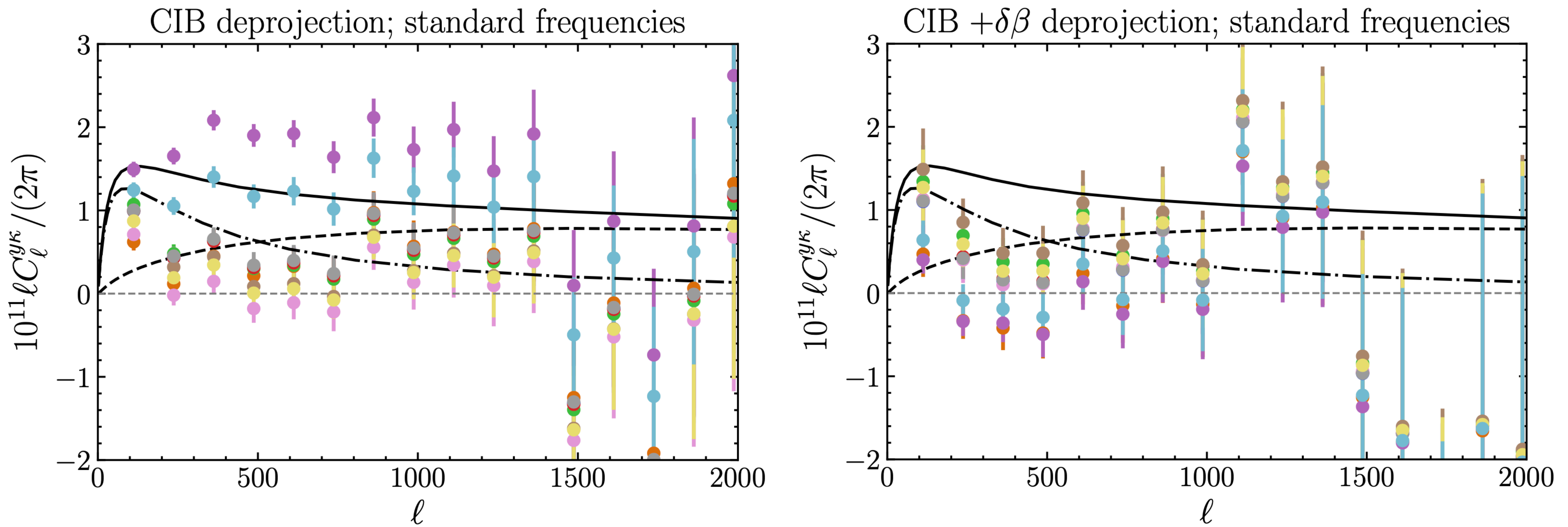
Cross-correlation of pyilc *y*-maps with PR4 CMB lensing maps

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



Colored points = different (β, T^{eff}) values used in CIB MBB SED

McCarthy & JCH (to appear)

tSZ x CMB Lensing

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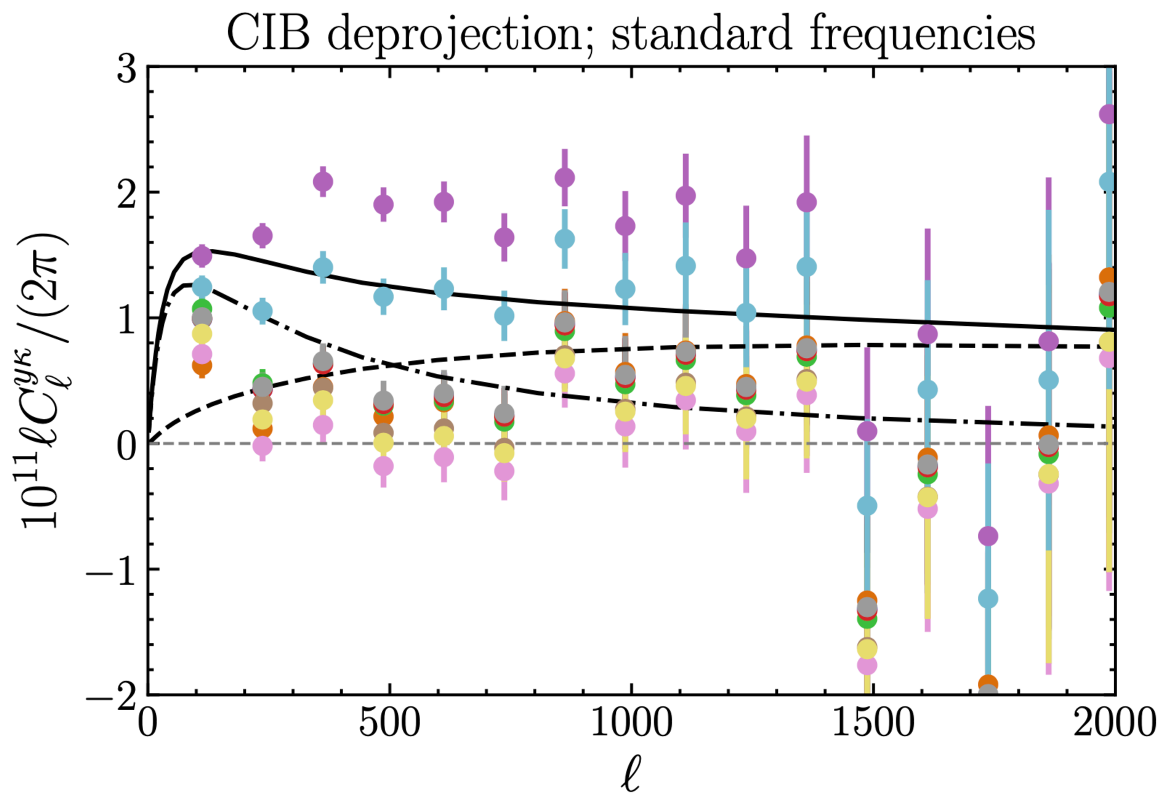
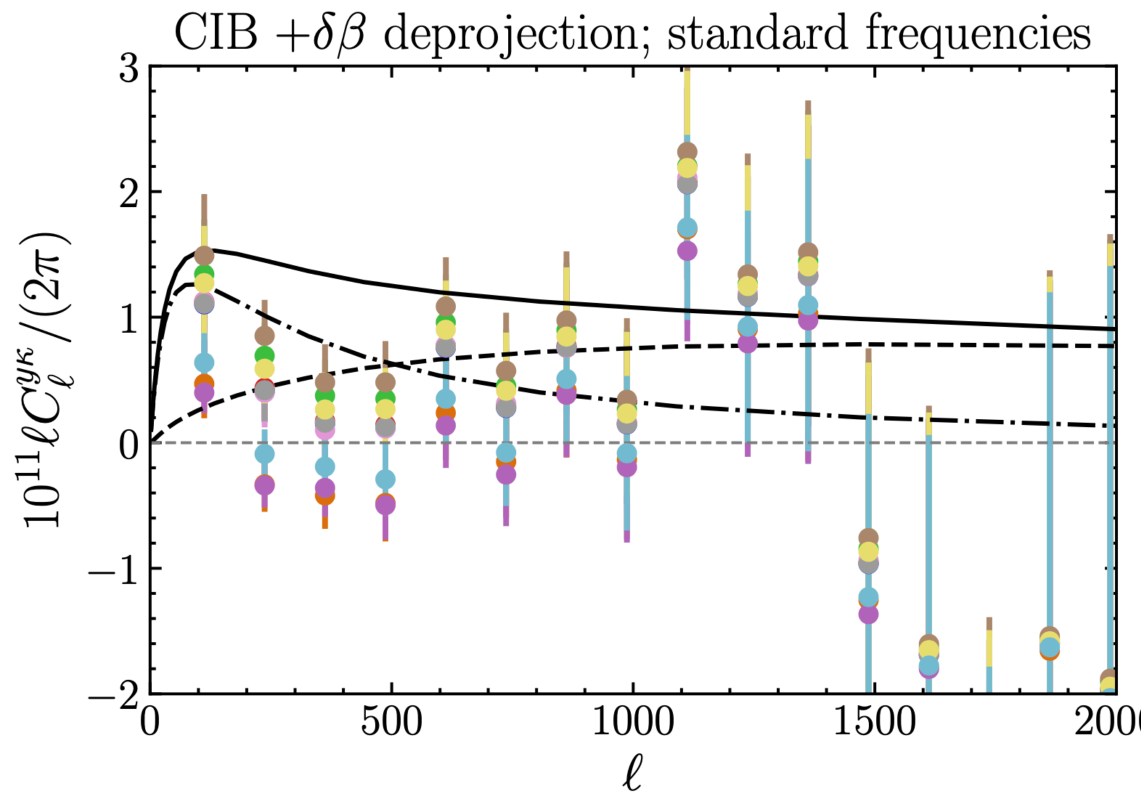
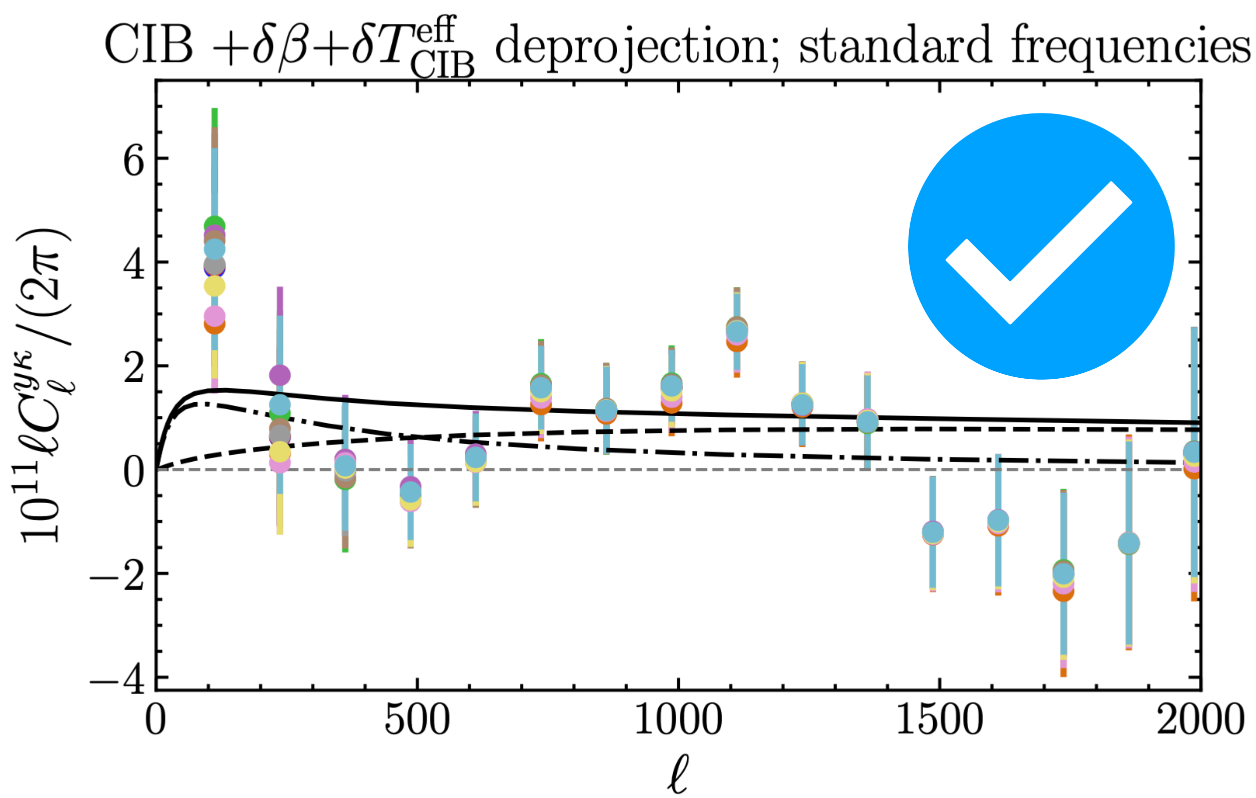
Multi-moment CIB deprojection required to obtain stable/robust measurement







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

Also validated on detailed mm-wave sky simulations

tSZ x CMB Lensing

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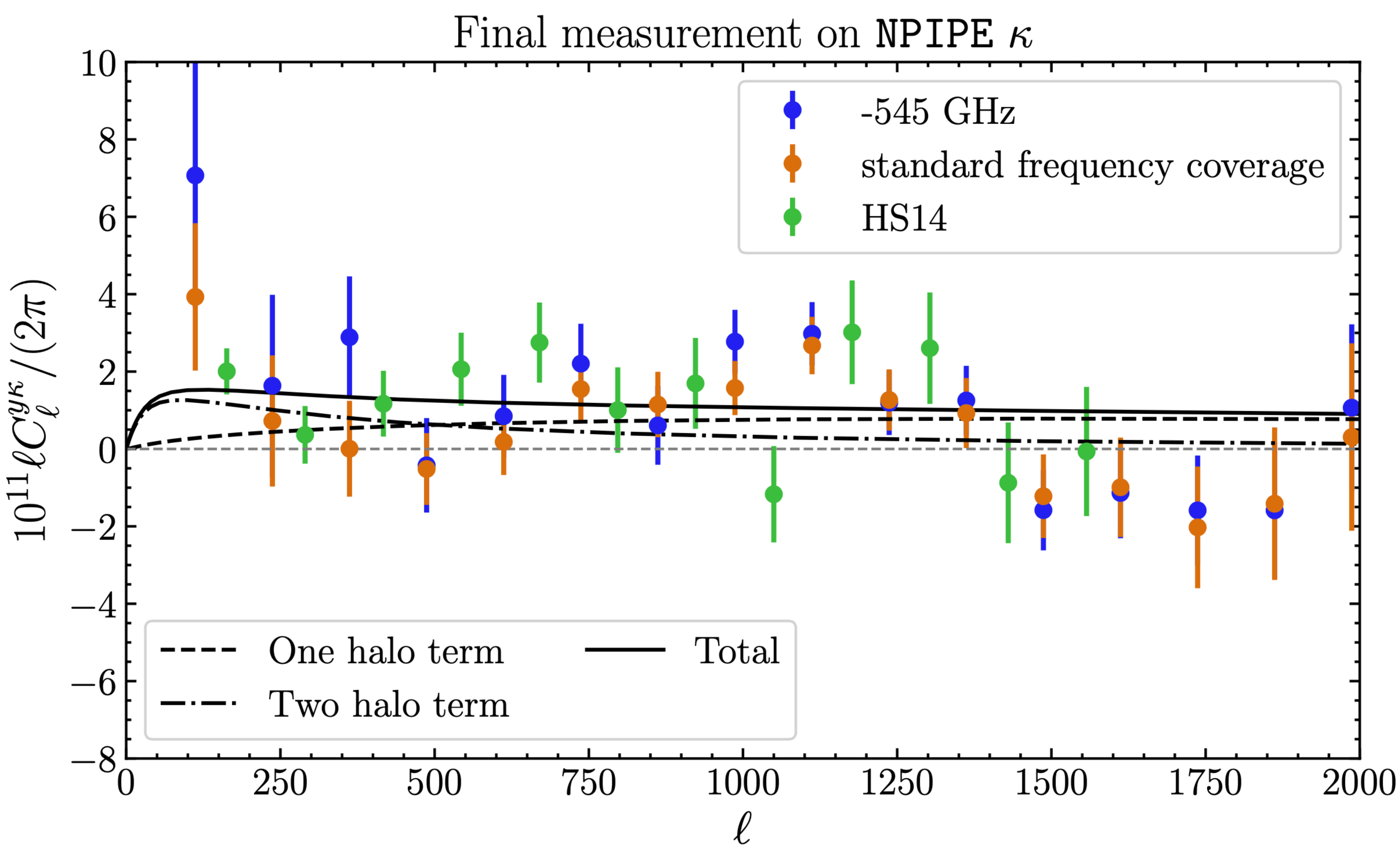
Cross-correlation of pyilc *y*-maps with PR4 CMB lensing maps



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

McCarthy & JCH (to appear)

tSZ x CMB Lensing

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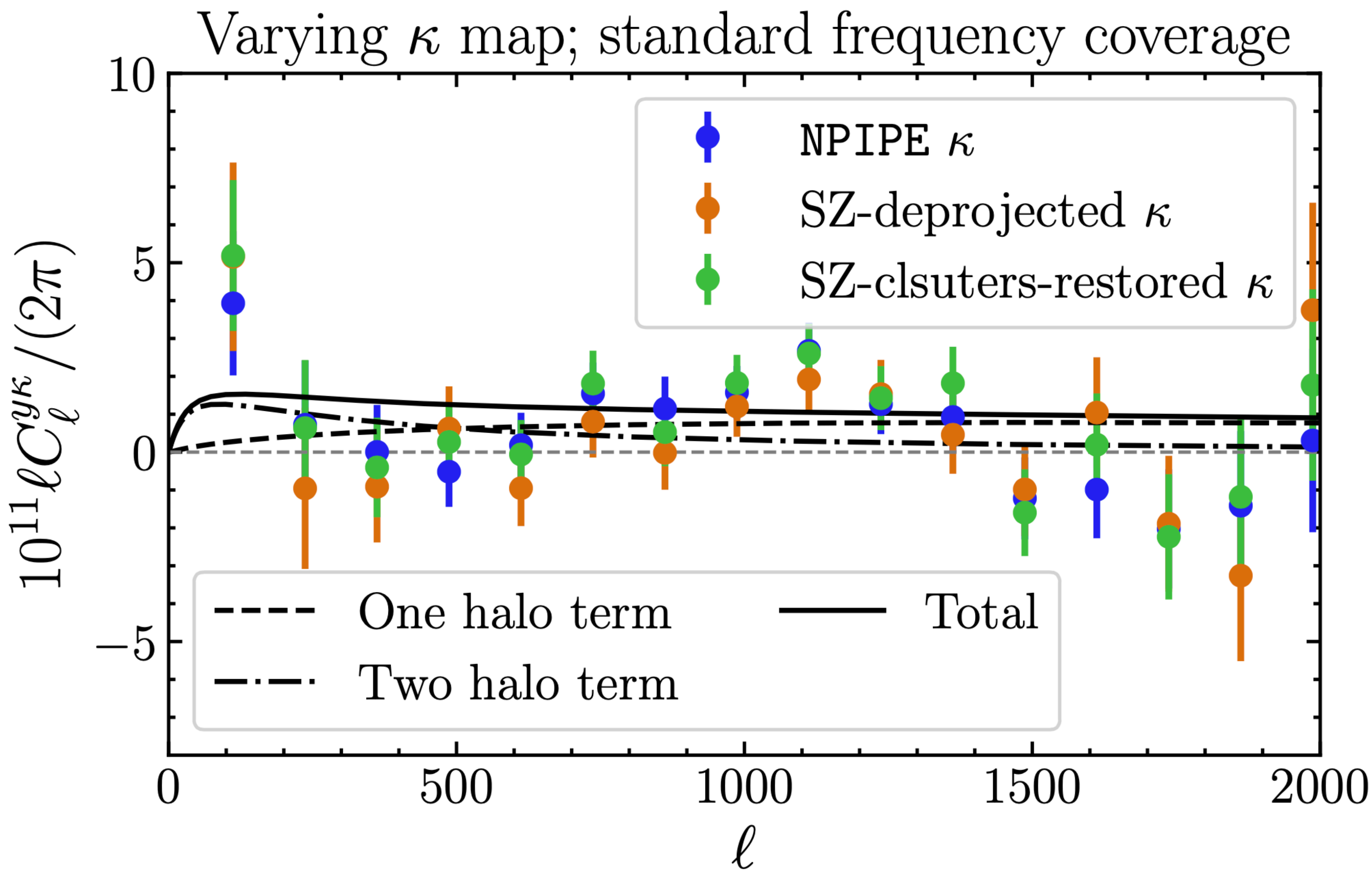
Cross-correlation of pyilc *y*-maps with PR4 + PR3 CMB lensing maps



Measurement is also robust to analysis variations in the κ reconstruction:

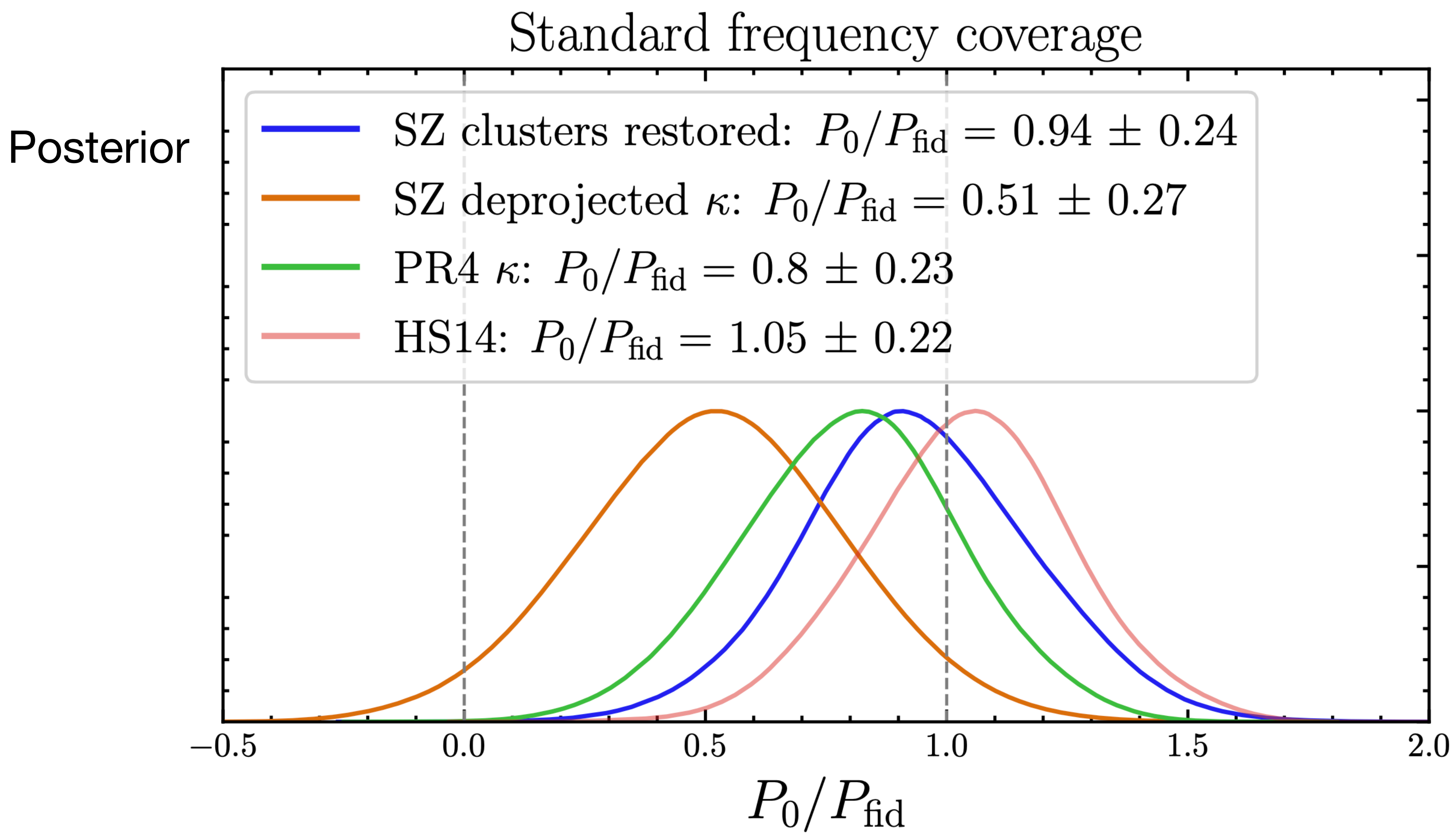
- Reconstruction on tSZ-deprojected CMB map (avoids <yyy> bias in cross-correlation)
- Reconstruction with signal restored at location of tSZ-detected clusters (masked by default)

McCarthy & JCH (to appear)

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 ~ 4 (similar to HS14 due to enormous CIB deprojection penalty)

McCarthy & JCH (to appear)

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, ++]

McCarthy & JCH (to appear)

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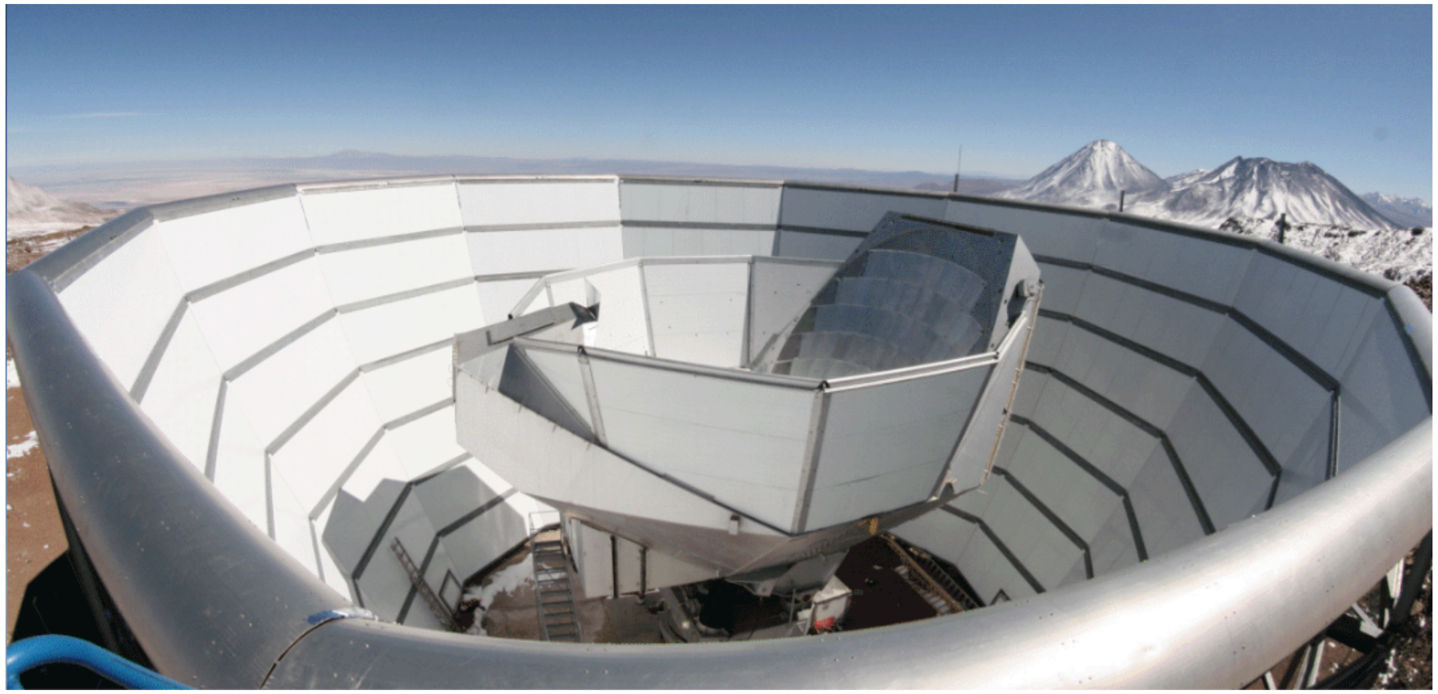
ACT DR6: Compton-y Maps



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

William Coulton,[1] Mathew S. Madhavacheril,[2,3] Adriaan J. Duivenvoorden,[1,4] J. Colin Hill,[5,1]

+ ACT Collaboration

Coulton+ (to appear) [ACT Collaboration]

ACT Data Release 6

Colin Hill
Columbia

High-sensitivity, arcminute-resolution maps at 90/150/220 GHz covering ~17,000 deg^2

- Qu et al. (2023): Reconstructed CMB lensing maps
- Madhavacheril et al. (2023): Cosmology from CMB lensing

S_8 = 0.840 ± 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

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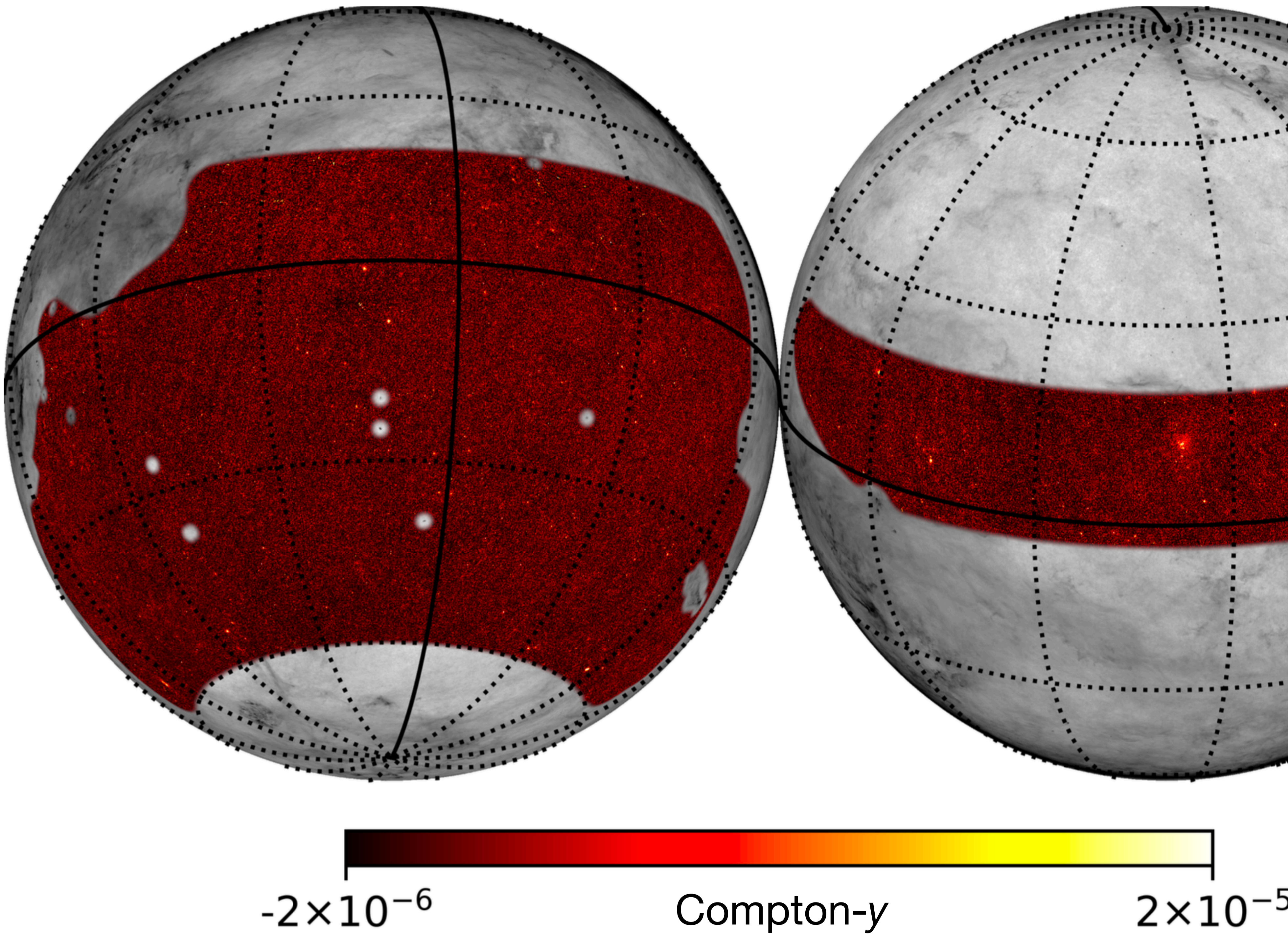
Columbia

ACT + Planck NPIPE



Coulton+ (to appear) [ACT Collaboration]

ACT DR6 NILC *y*-map

Colin Hill
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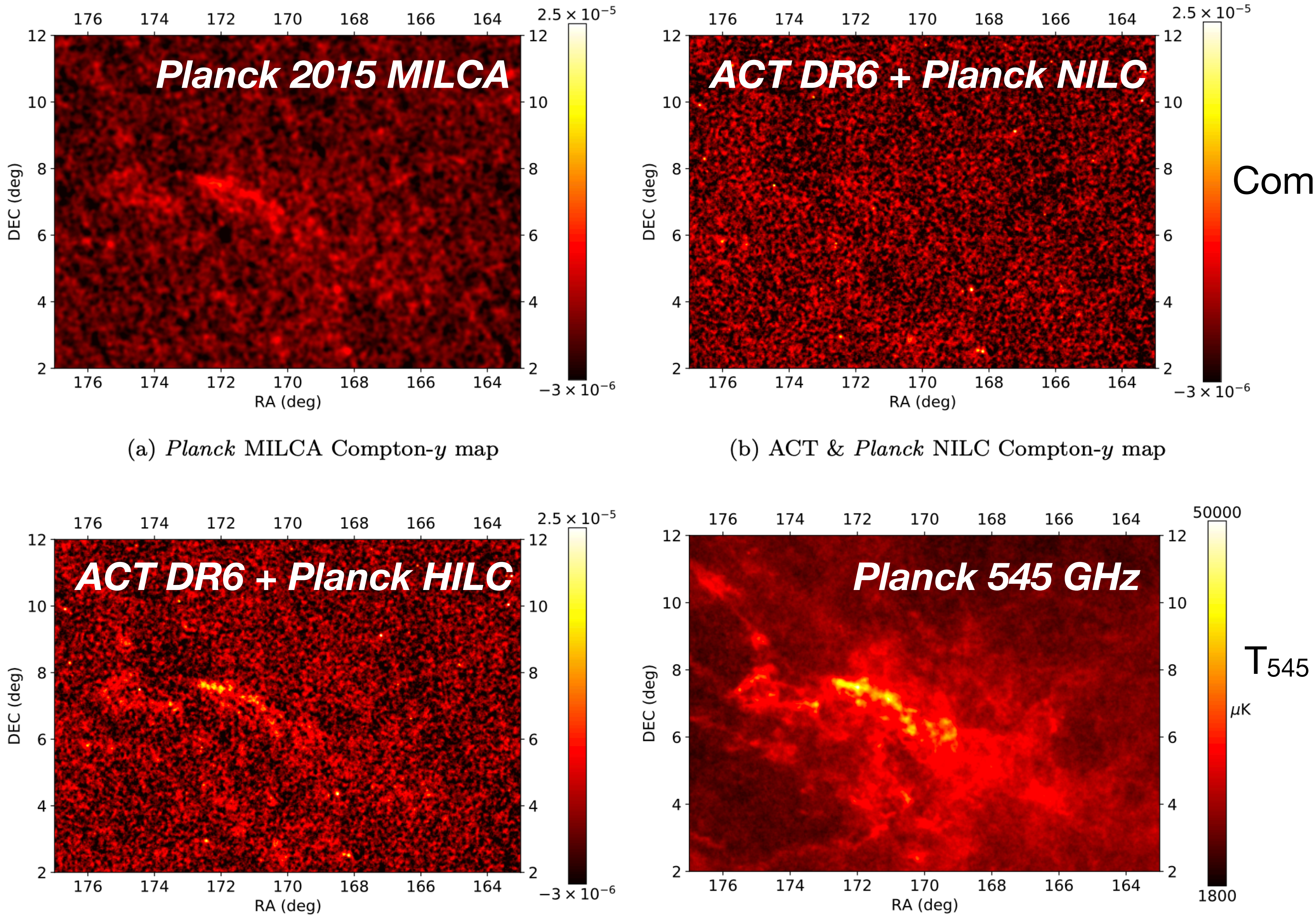
ACT + Planck NPIPE



(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

Coulton+ (to appear) [ACT Collaboration]

ACT DR6 NILC *y*-map

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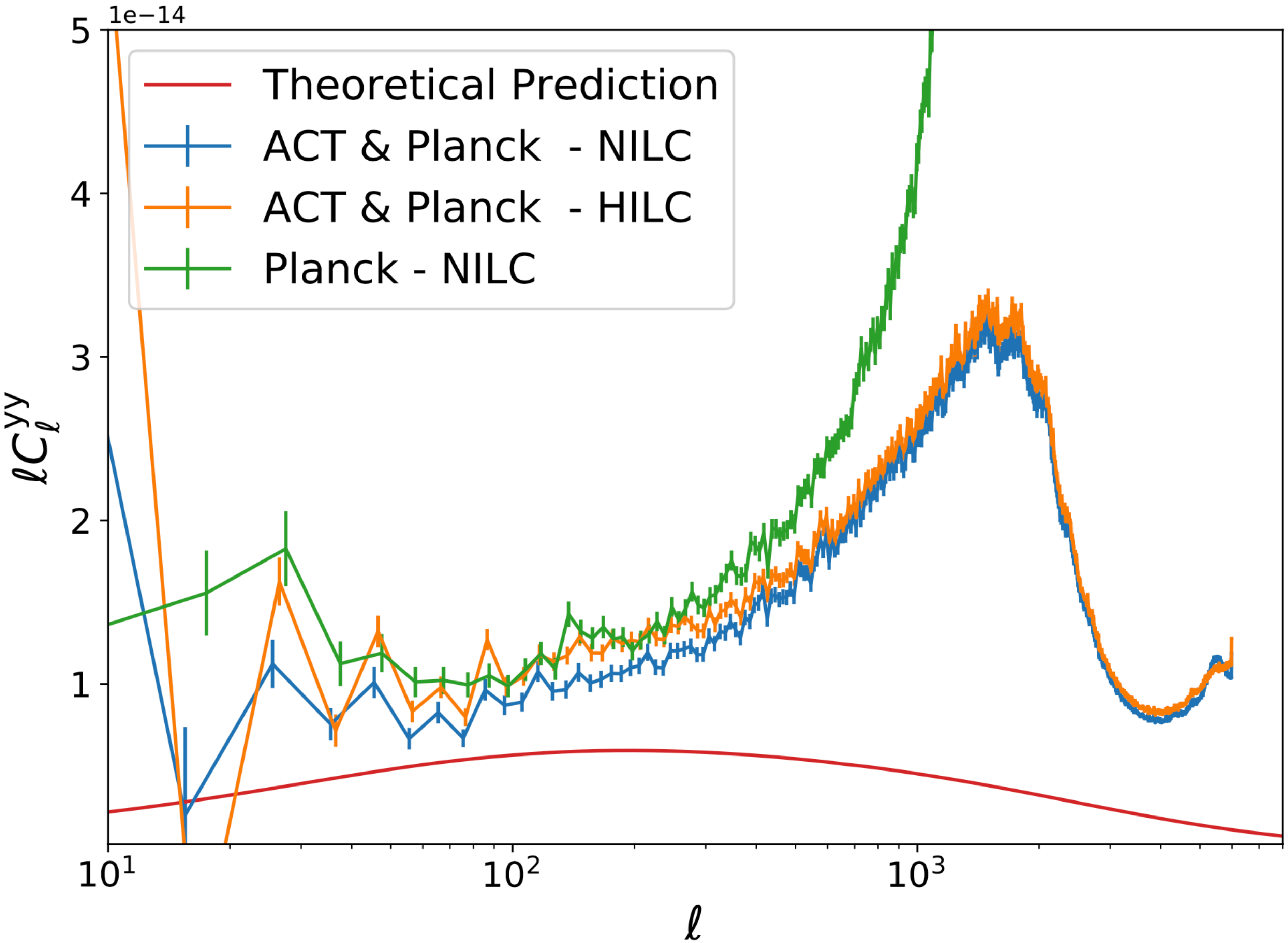
Columbia

ACT + Planck NPIPE

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



Coulton+ (to appear) [ACT Collaboration]

ACT DR6 NILC *y*-map

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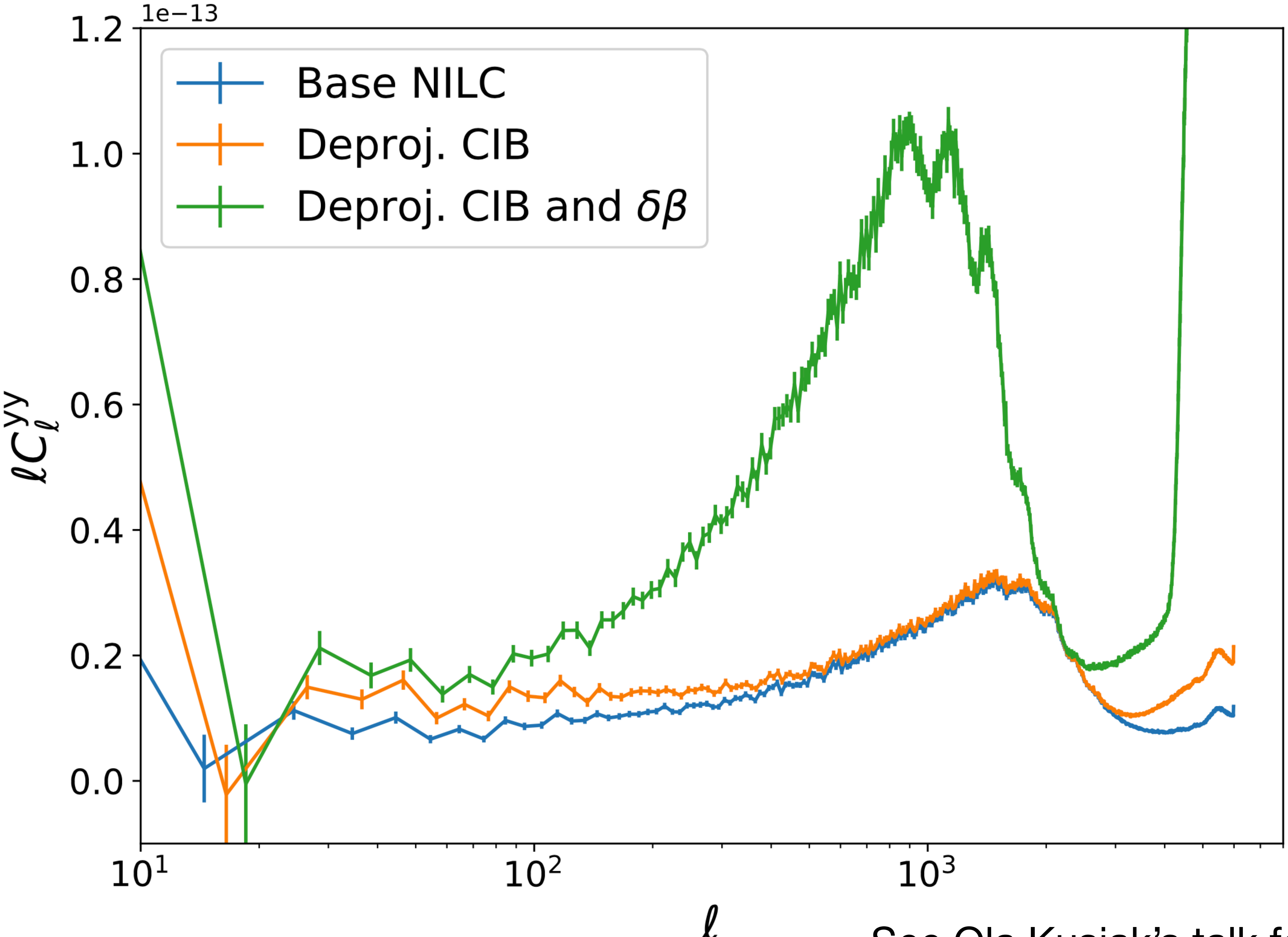
ACT + Planck NPIPE

Various CIB deprojection options also implemented



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

Coulton+ (to appear) [ACT Collaboration]

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 gastrophysics models to high-z, low-mass regime
4) ACT DR6 (+PR4) *y*-maps soon — unprecedented resolution and signal-to-noise across ~14,000 deg^2

Photo: D. Kellner

Thanks!

Bonus

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 κ map (with or without noise)

McCarthy & JCH (to appear)

tSZ x CMB Lensing

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Columbia

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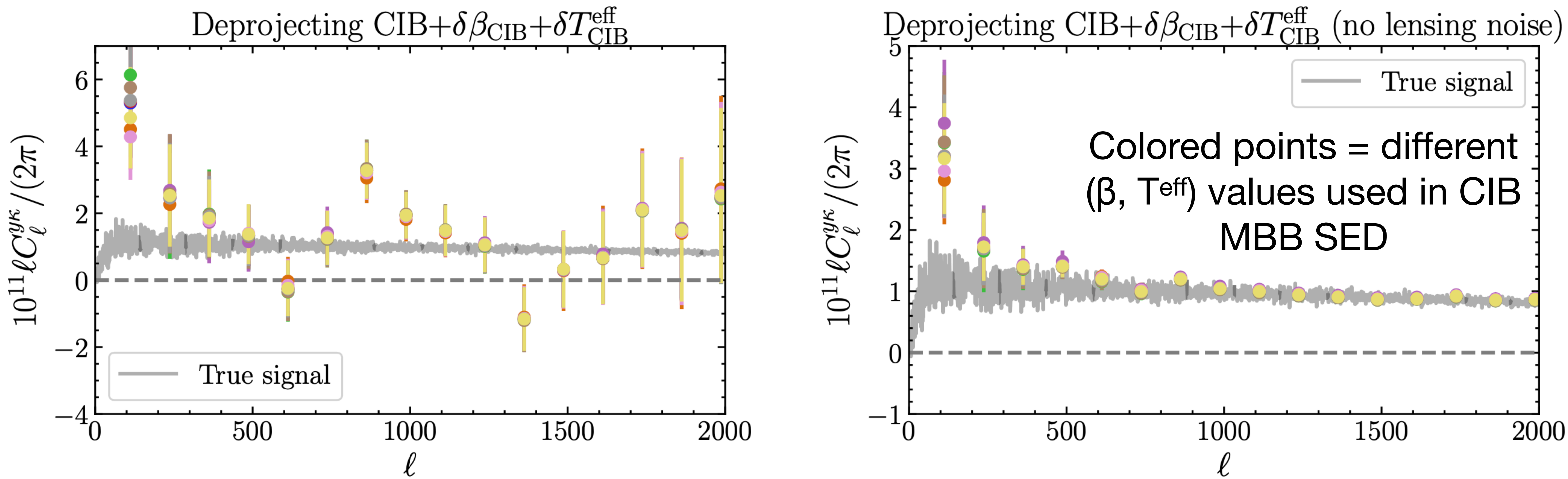

Only by deprojecting the CIB + both first moment SEDs is the measurement stable/ robust to the assumed MBB parameters of the CIB (β, $T^{\rm eff}$)

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

McCarthy & JCH (to appear)

tSZ x CMB Lensing

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

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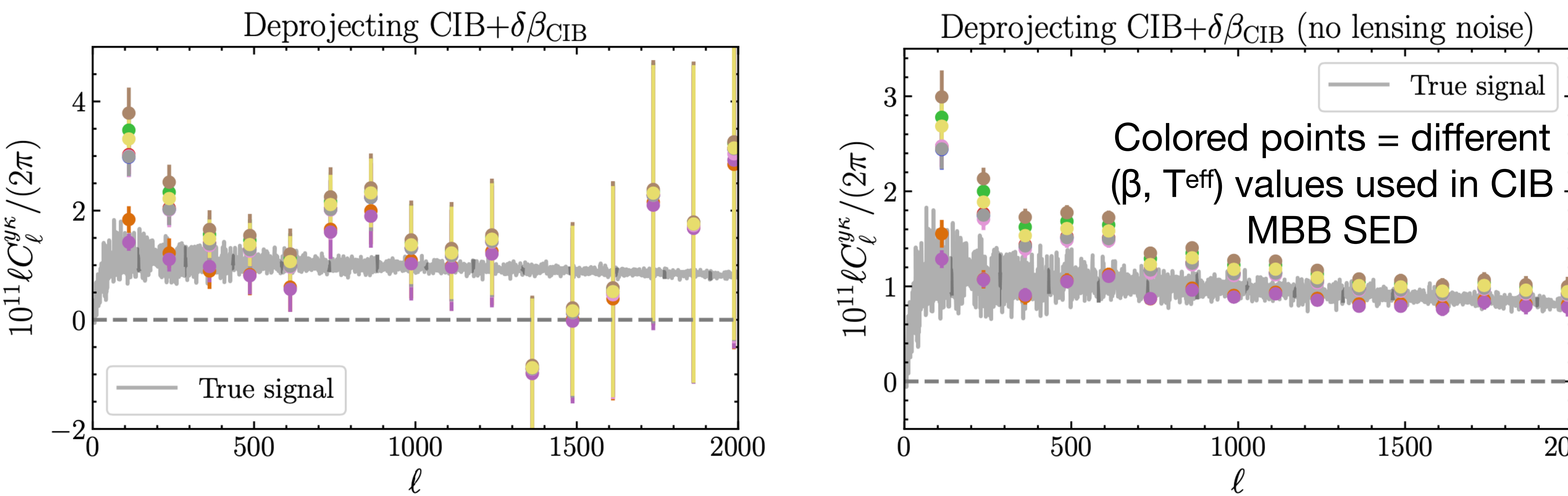


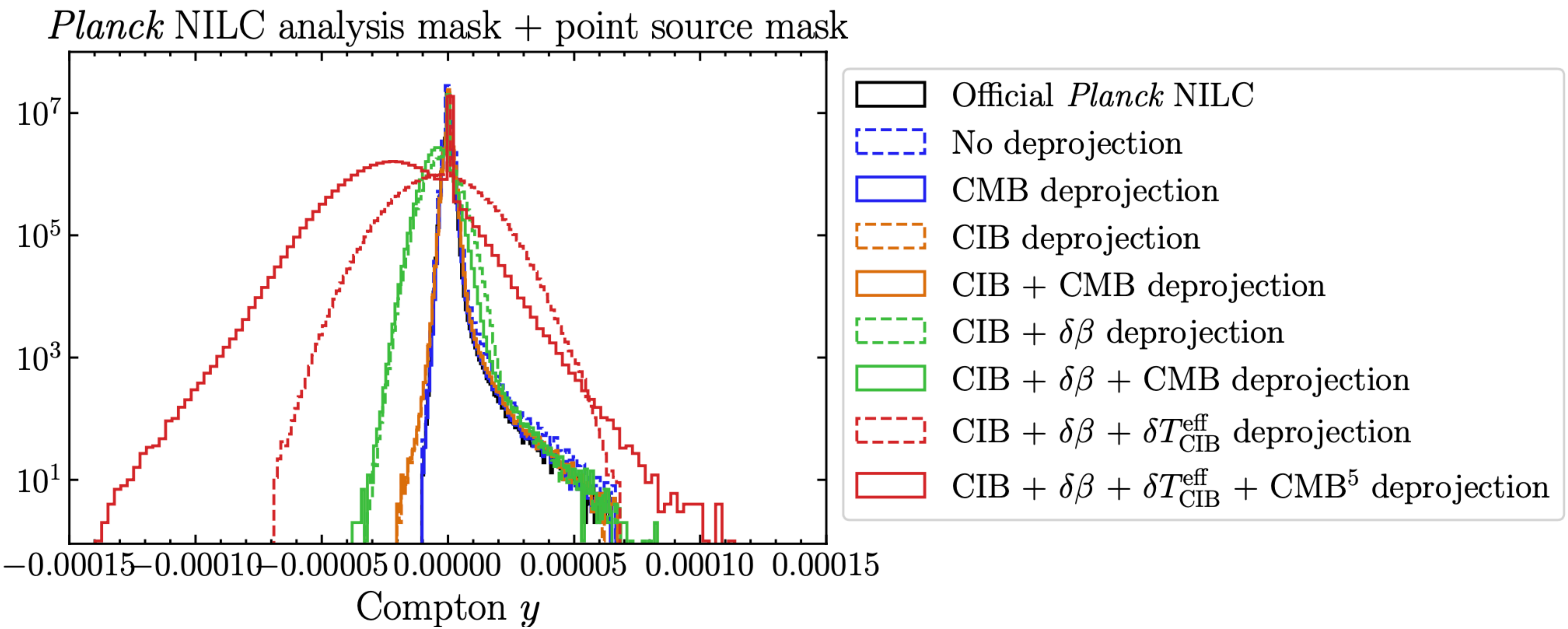
Even deprojecting the CIB + β first moment SED is not sufficient to yield a measurement stable/robust to the assumed MBB parameters of the CIB (β, $T_{\rm eff}$)

McCarthy & JCH (to appear)

Thermal SZ Extraction

Colin Hill
Columbia

Application to Planck PR4 (NPIPE) maps



McCarthy & JCH (to appear)

Thermal SZ Extraction

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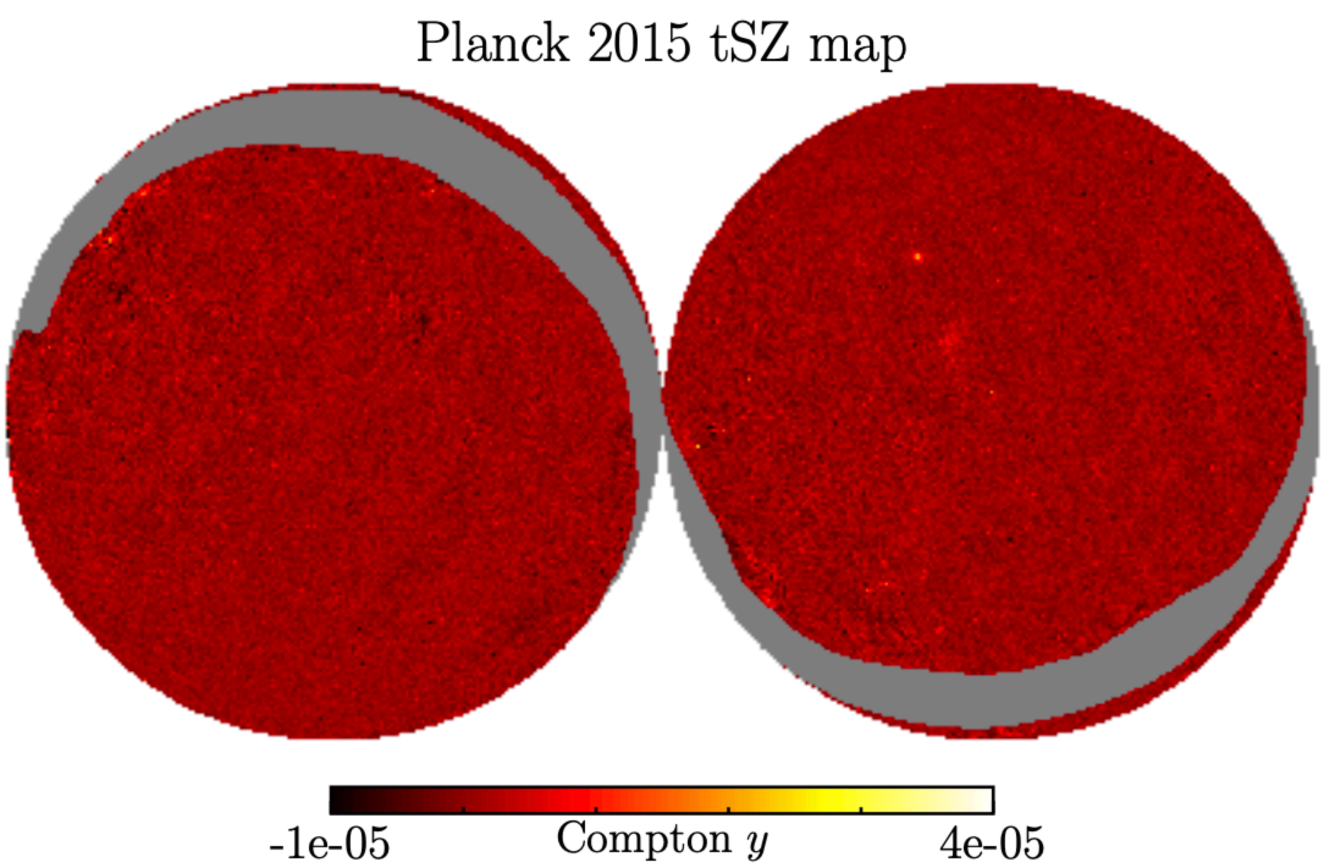
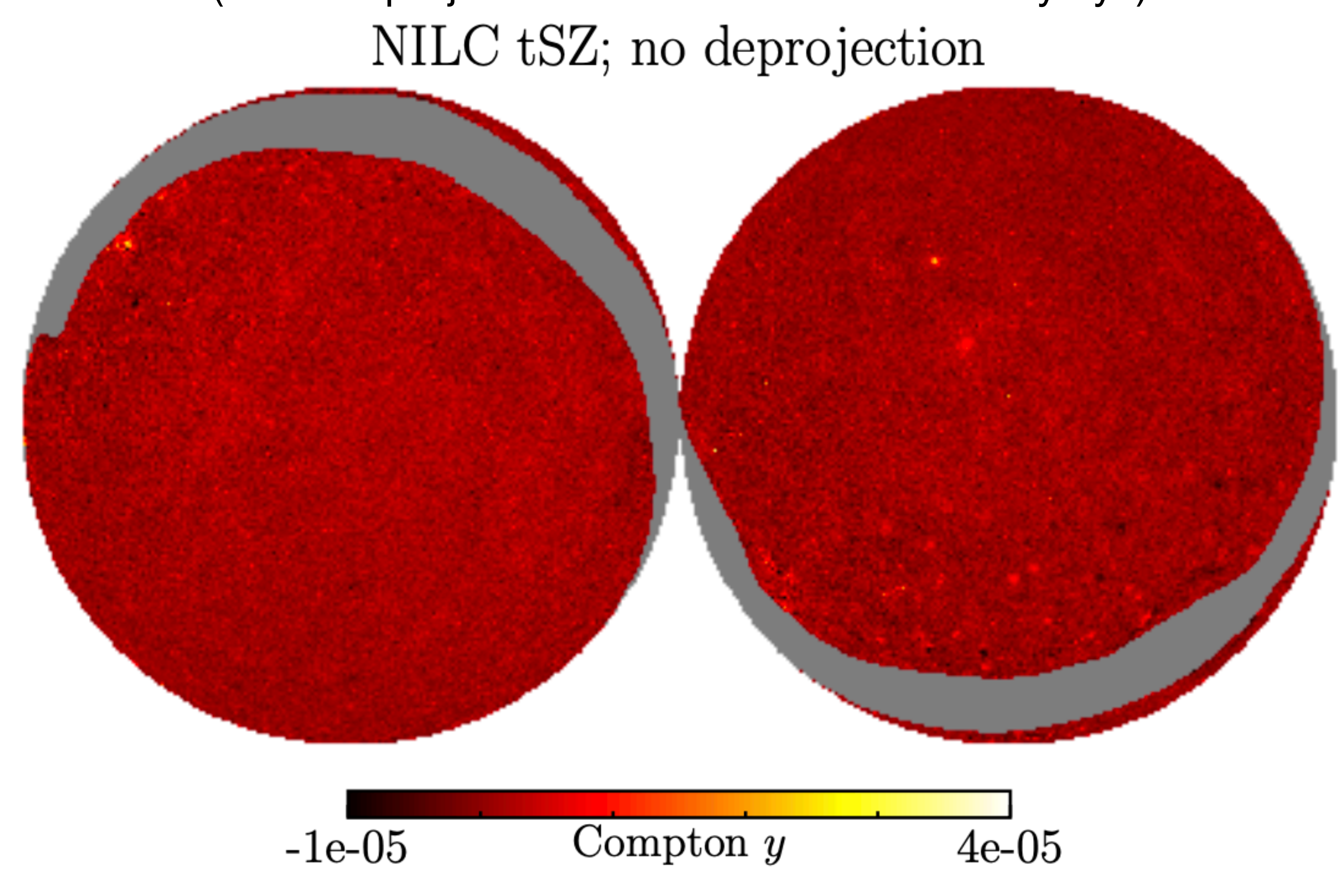
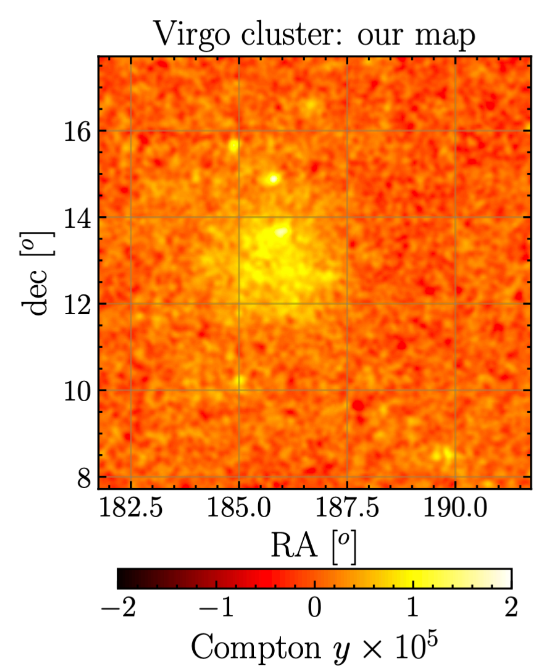
Comparison to official PR2 *y*-map

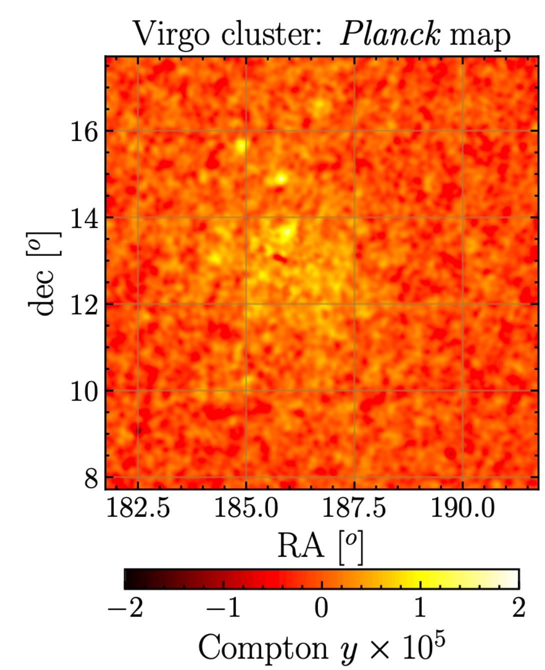
(CMB-deprojected version looks identical by eye)





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





McCarthy & JCH (to appear); see also Tanimura+(2022) and Chandran+(2023)

Thermal SZ Extraction

Colin Hill
Columbia

Comparison to official PR2 *y*-map

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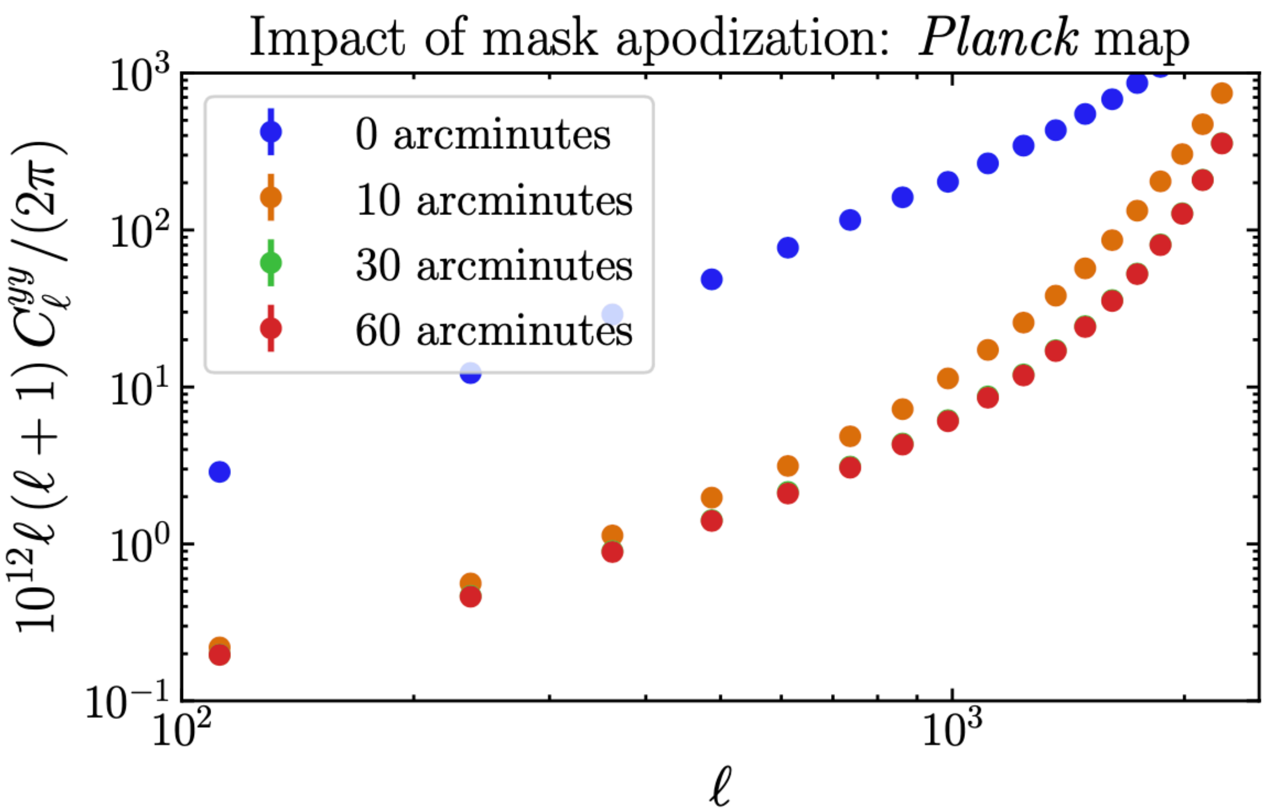

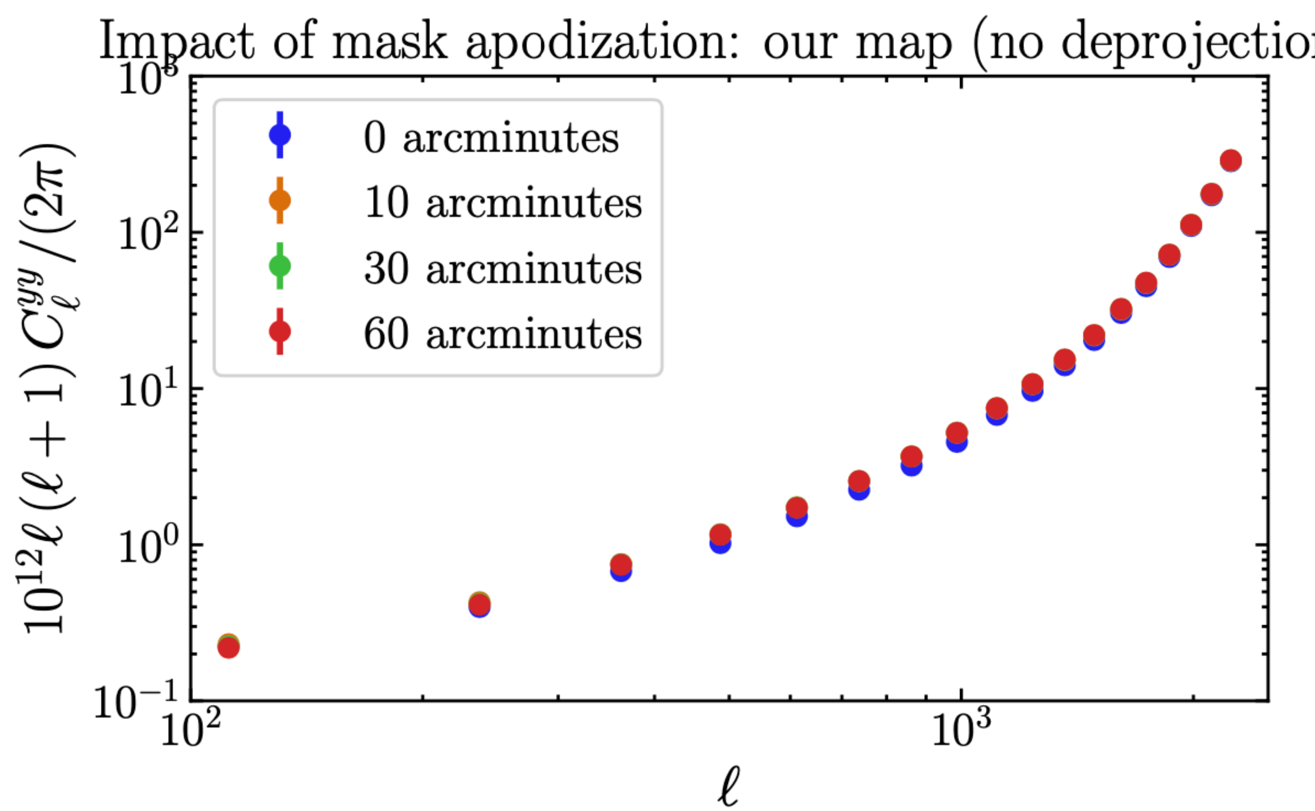

McCarthy & JCH (to appear); see also Tanimura+(2022) and Chandran+(2023)

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)

critical surface density for lensing

- One-halo term:

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

- Two-halo term:

matter power spectrum

$$C_\ell^{y\kappa,2h} = \int dz \frac{d^2V}{dz d\Omega} P_{lin}(\ell/\chi,z) \left[\int dM_1 \frac{dn}{dM_1} b(M_1,z) \tilde{y}_\ell(M_1,z)\right] \times \left[\int dM_2 \frac{dn}{dM_2} b(M_2,z) \tilde{\kappa}_\ell(M_2,z)\right],$$

halo bias

JCH & Spergel (2014); McCarthy & JCH (to appear)

tSZ x CMB Lensing

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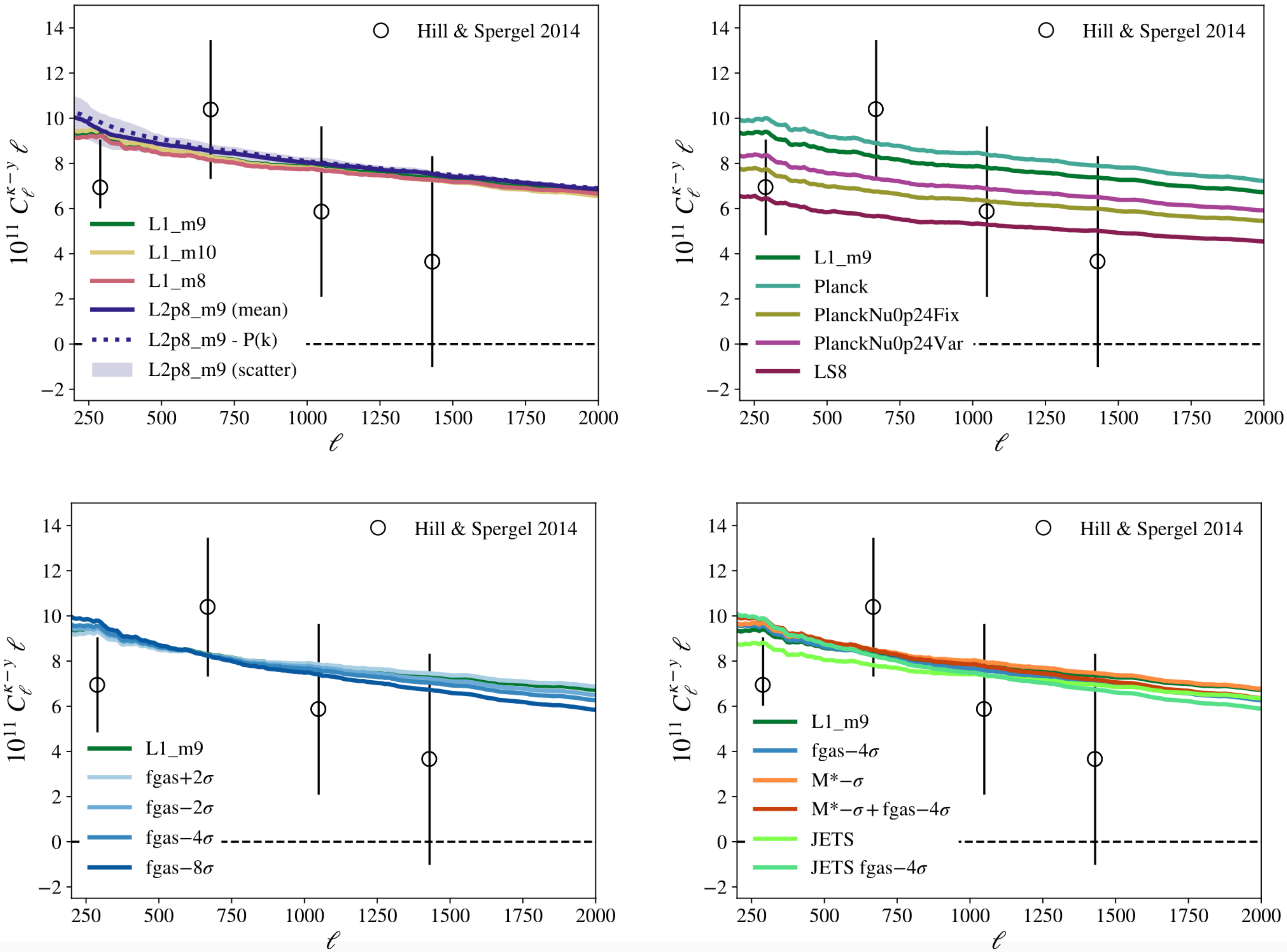
FLAMINGO simulations



Schaye+(2023)

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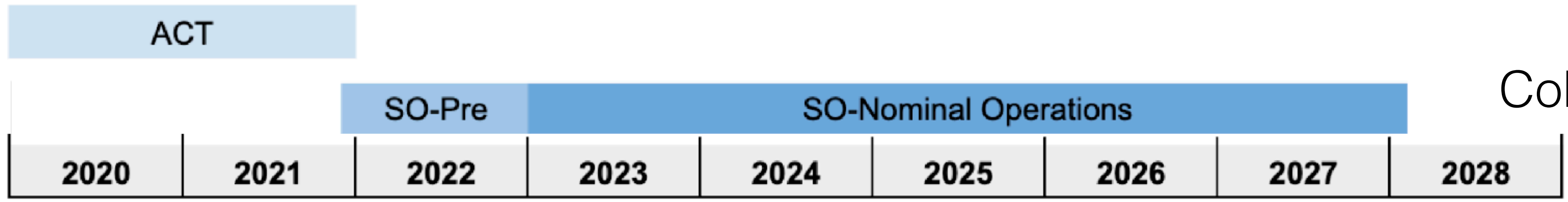
Next: ACT DR6

(target: later this year)



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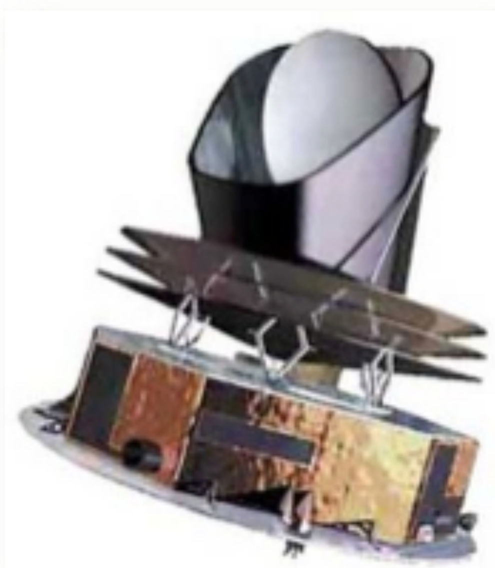
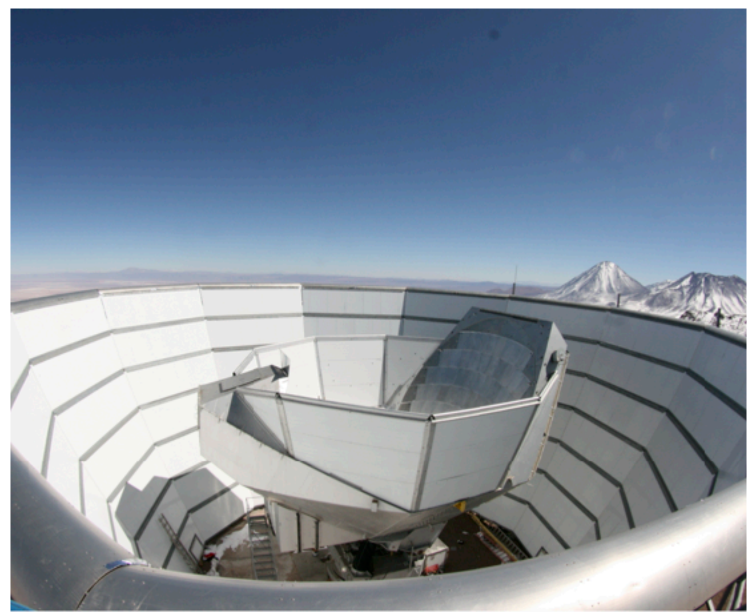
Planck → **Advanced ACT**





Final data 2018
100% sky

0.35 — 10 mm (9 bands)
5 — 33' resolution

Observations until 2022
40% sky
Noise ~3 times < Planck
1.4 — 10 mm (5 bands)
1 — 7' resolution

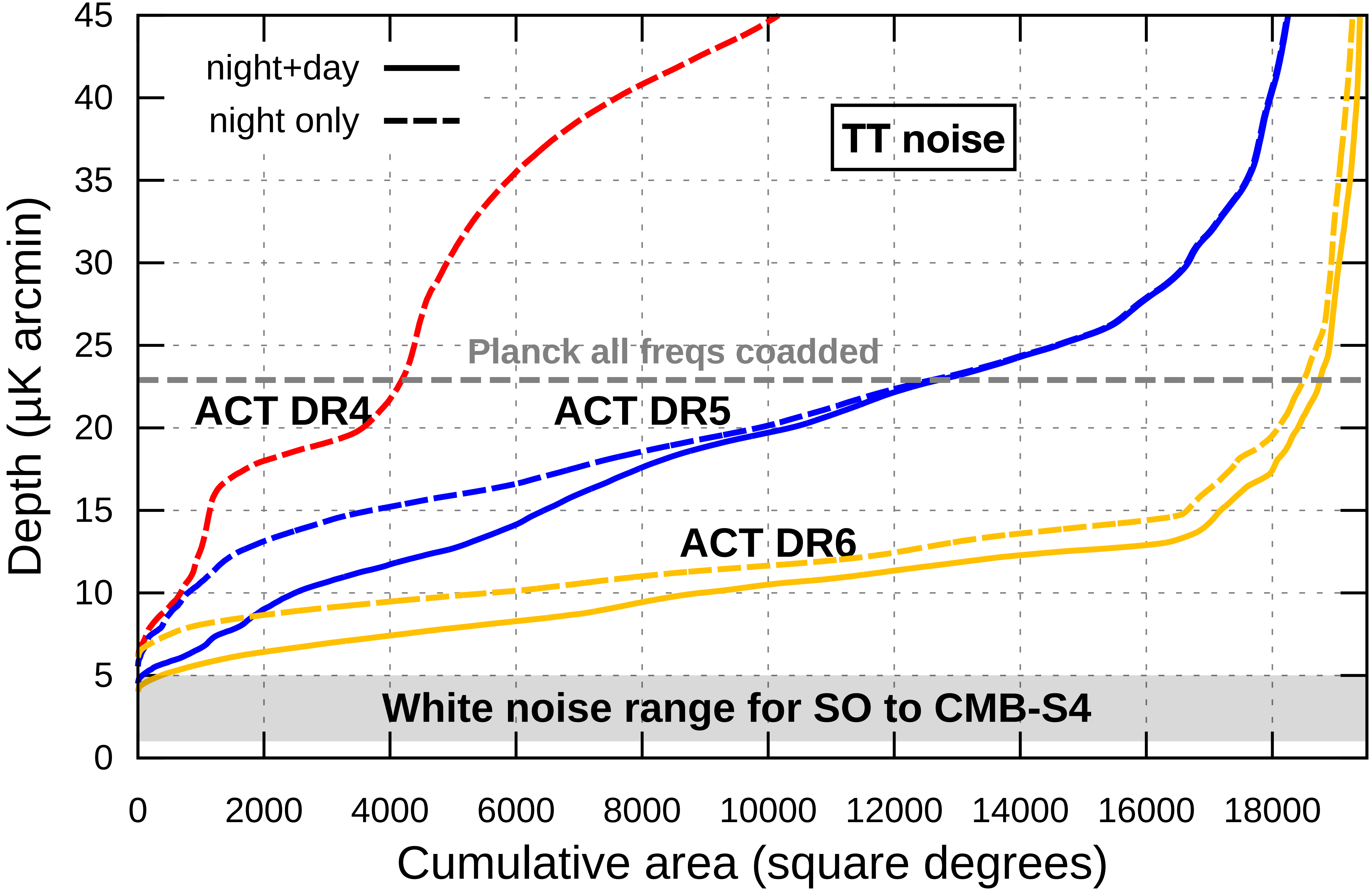
[South Pole Telescope - same timeframe]

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

$\sigma(H_0)$ ~ 0.5 km/s/Mpc in ΛCDM

DR6 Map Depth: T

Colin Hill
Columbia/CCA

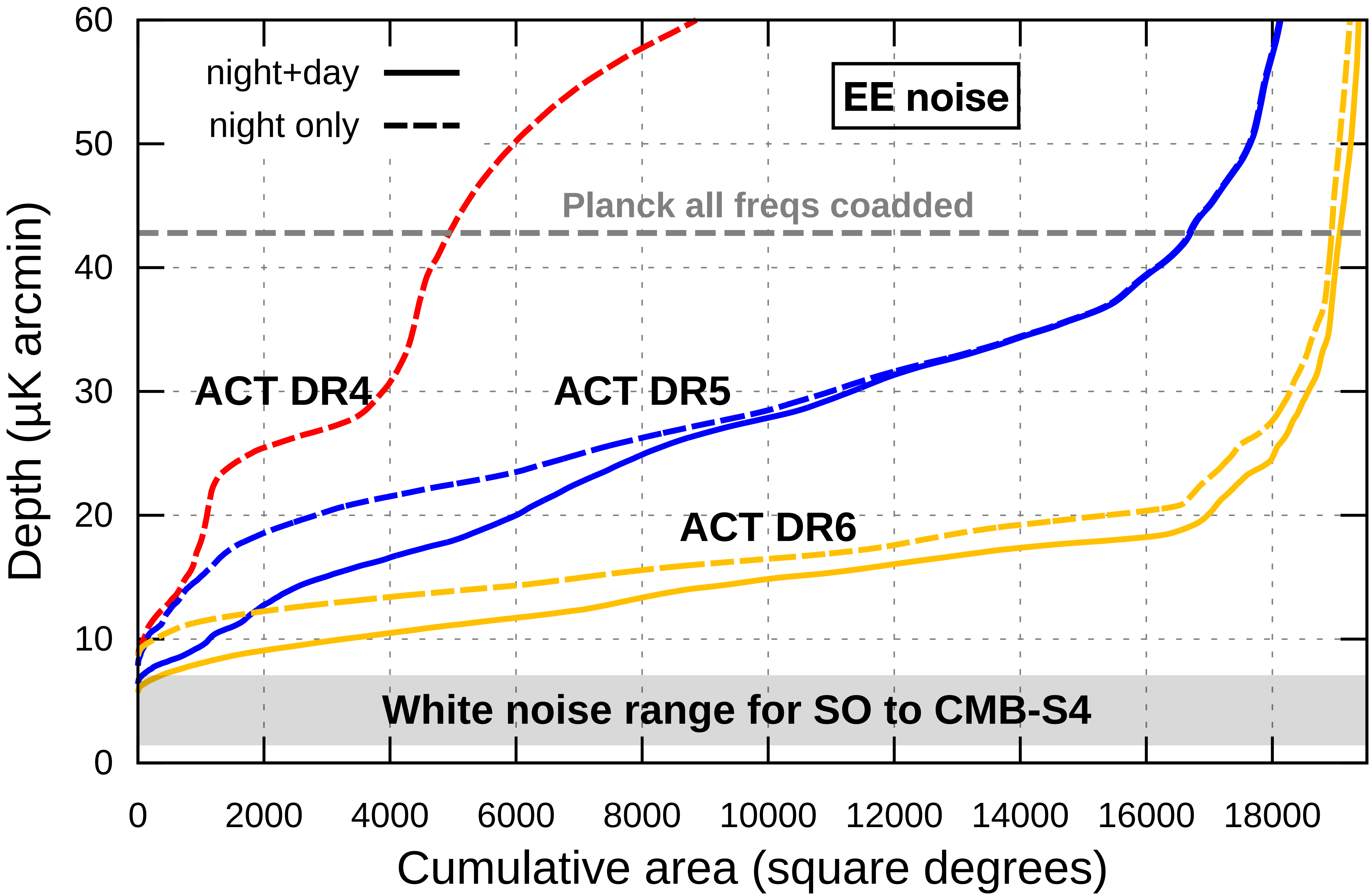


Credit:
S. Naess

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

Colin Hill
Columbia/CCA

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 >5x higher angular resolution

Colin Hill
Columbia

ACT DR6 Forecasts

ACT TT + TE + EE : precision cosmology beyond Planck

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

Large improvements in beyond-ΛCDM 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_{eff}, Σm_ν, σ_8, + beyond-ΛCDM models) — stay tuned!