Component Maps

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1603.01608 1605.02722
1705.06751 1802.08230

+in prep.

Component-separated maps: What are they good for?

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Reminder: Parameters

Component-separated CMB maps do not form the basis of standard cosmological parameter estimation pipelines

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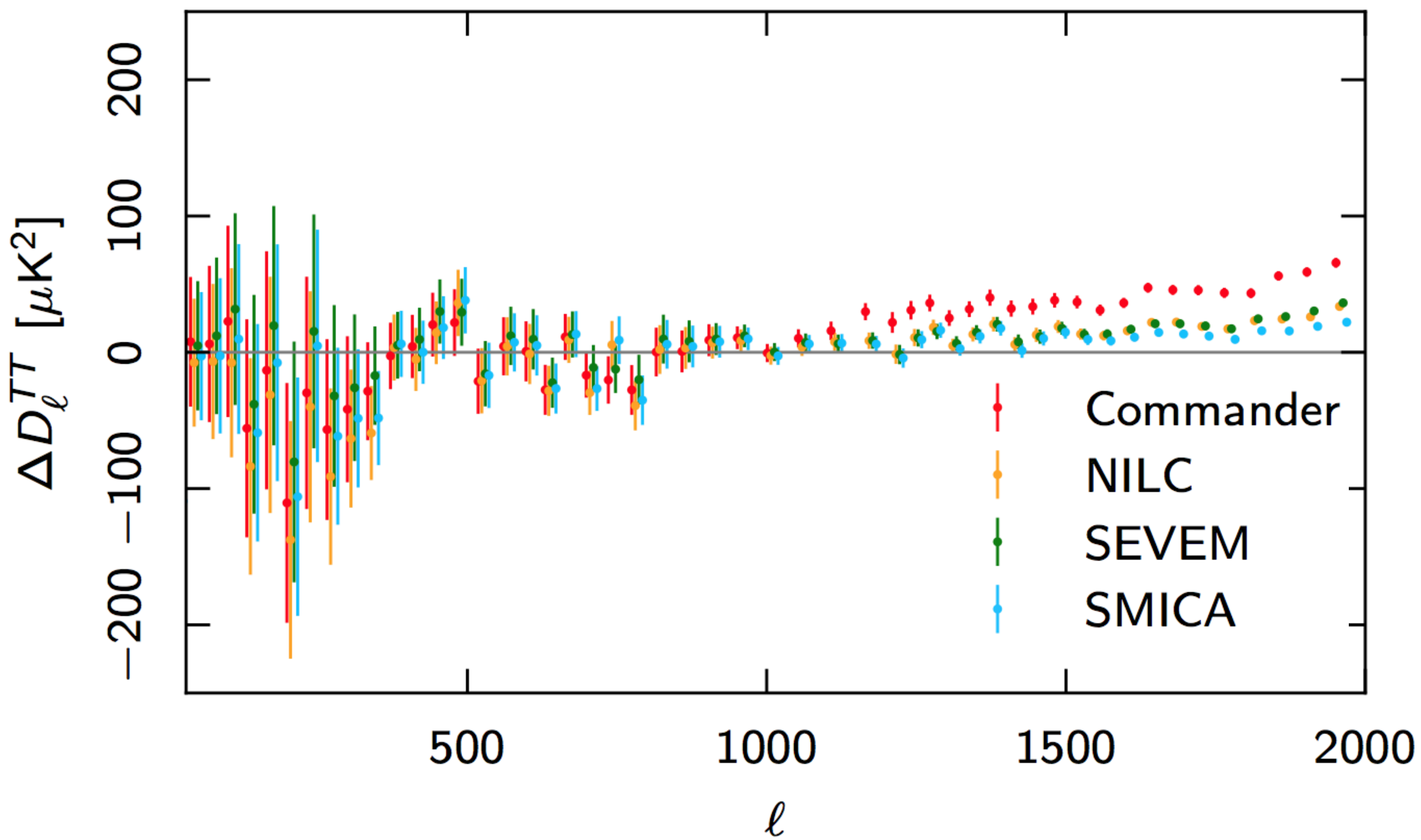
Reminder: Parameters

Component-separated CMB maps do not form the basis of standard cosmological parameter estimation pipelines



Characterizing residuals is difficult and model-dependent
Is using the additional information at the map level worth it?

Planck IX (2015)

Planck Component-Separated CMB Maps

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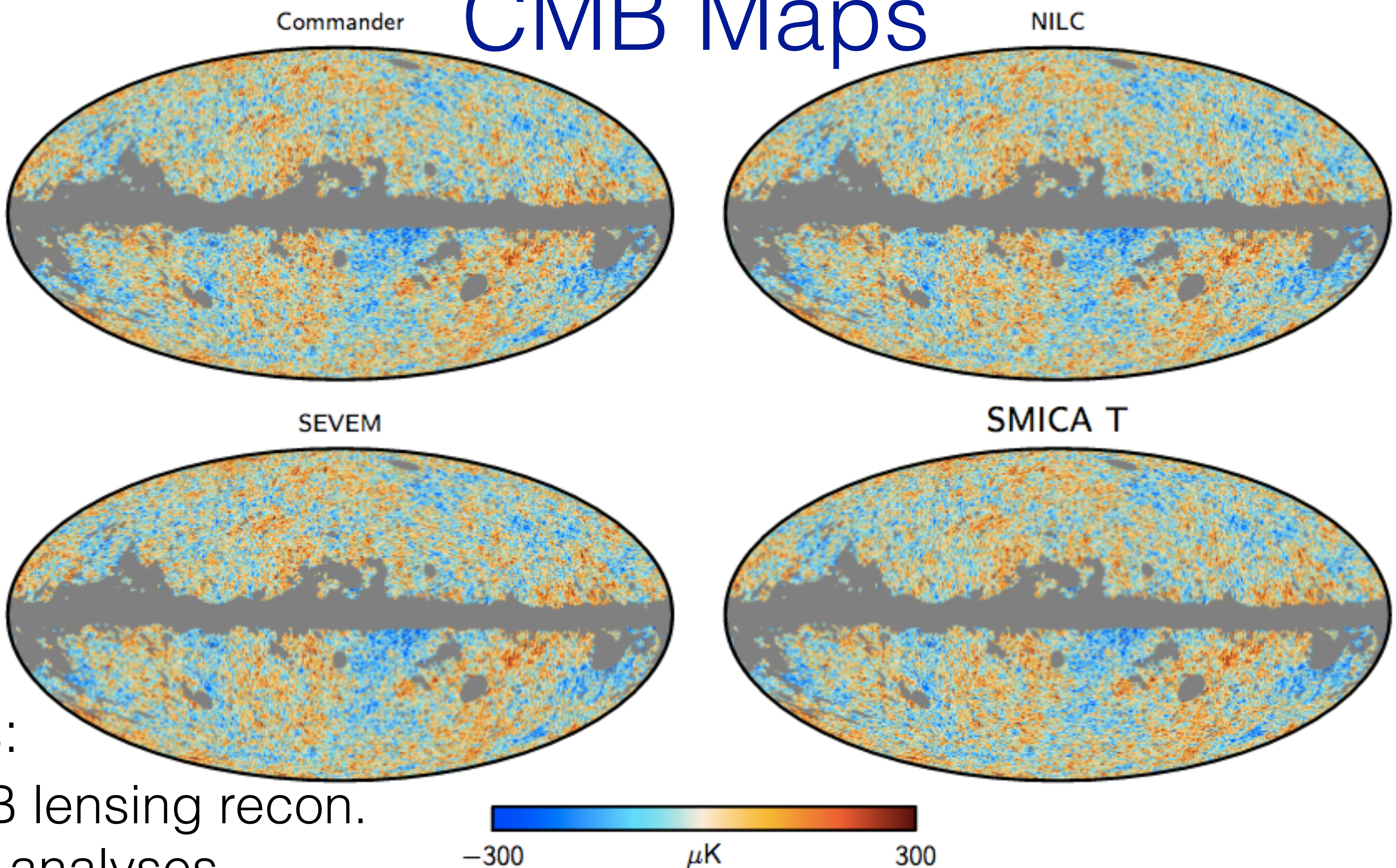

Uses:

- CMB lensing recon.
- ISW analyses
- Primordial non-Gaussianity analyses
- Constraints on large-scale anomalies, topological defects, …
- Cross-correlations (e.g., kSZ)

Planck IX (2015)

Component Maps

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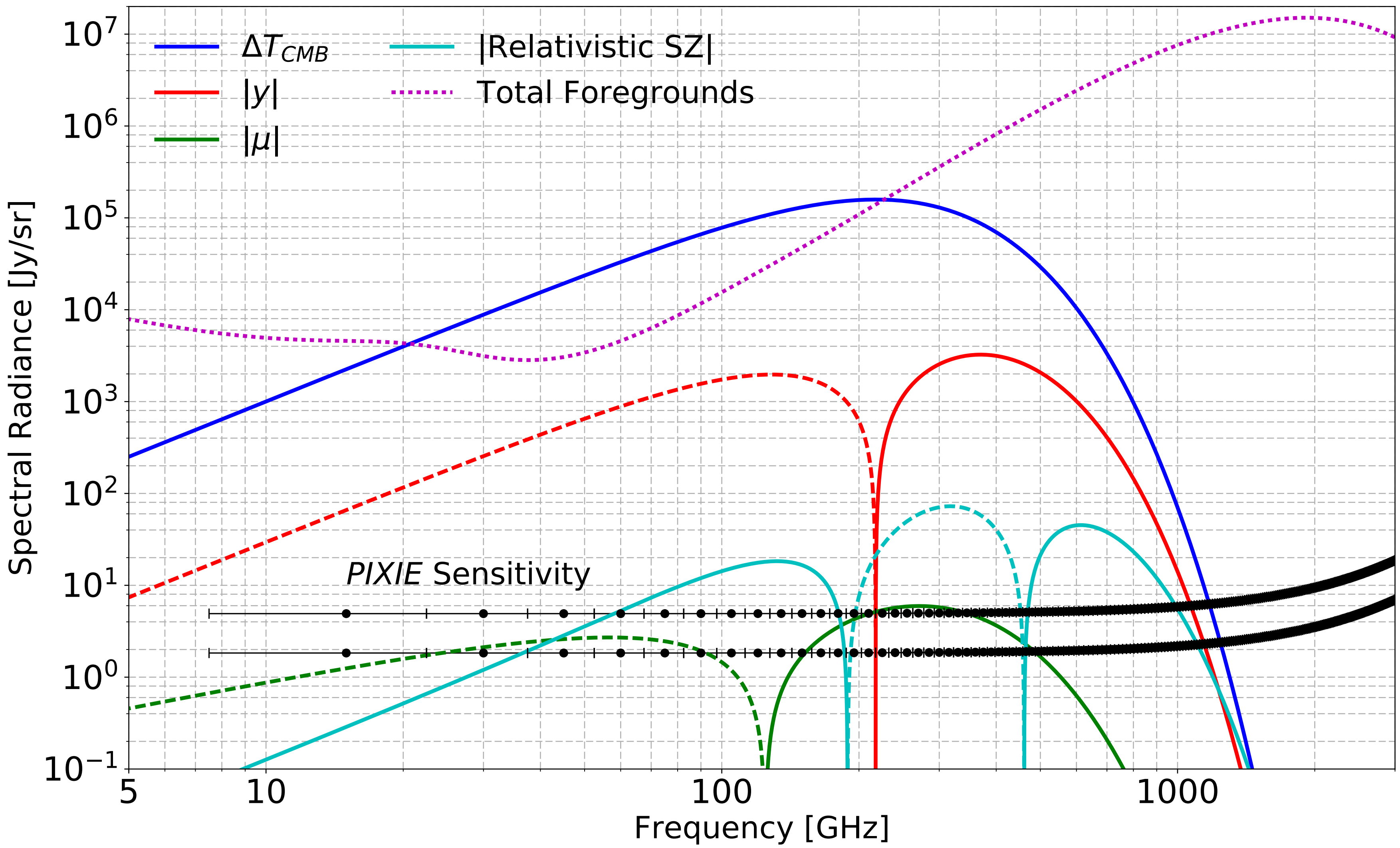
- Blackbody temperature: Lensed CMB + ISW + kSZ + RS
- Blackbody polarization: Lensed CMB + polarized SZ
- Non-blackbody:
  * Thermal SZ (*y*-type distortion)
  * Relativistic SZ
  * μ-type distortion



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Component Maps

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- Blackbody polarization: Lensed CMB + polarized SZ
- Non-blackbody:
  * Thermal SZ (y-type distortion)
  * Relativistic SZ
  * μ-type distortion
- Model-dependent:
  * Cosmic infrared background
  * Dust
  * Synchrotron
  * etc.

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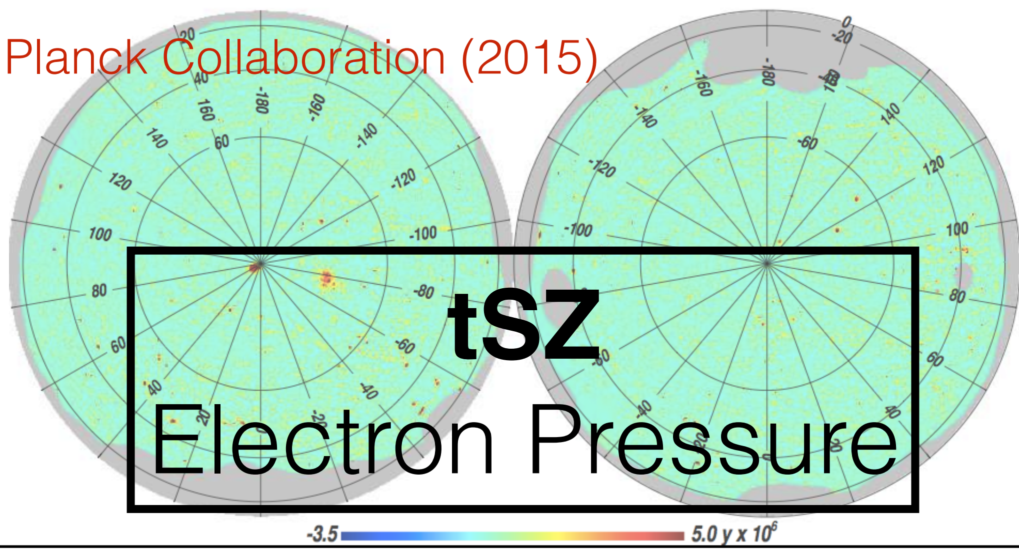
Cosmic Microwave Backlight

Secondary Anisotropies

Planck Collaboration (2015)



tSZ

Electron Pressure

- **Cosmology from tSZ-selected cluster counts**
- **Cosmology from *y*-map statistics + x-corr.**
- **Galaxy formation gastrophysics from tSZ stacking analyses (e.g., AGN feedback)**

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Cosmic Microwave Backlight

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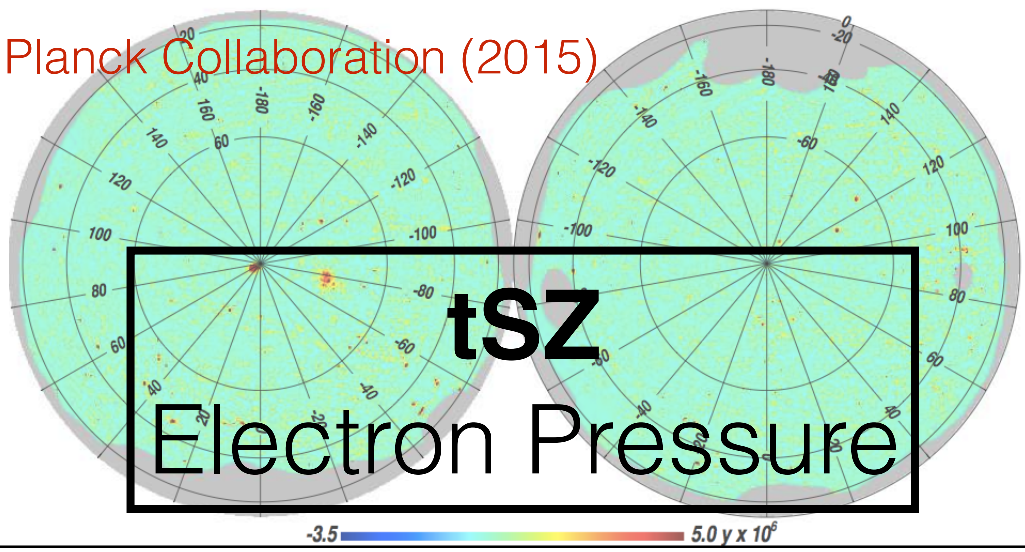

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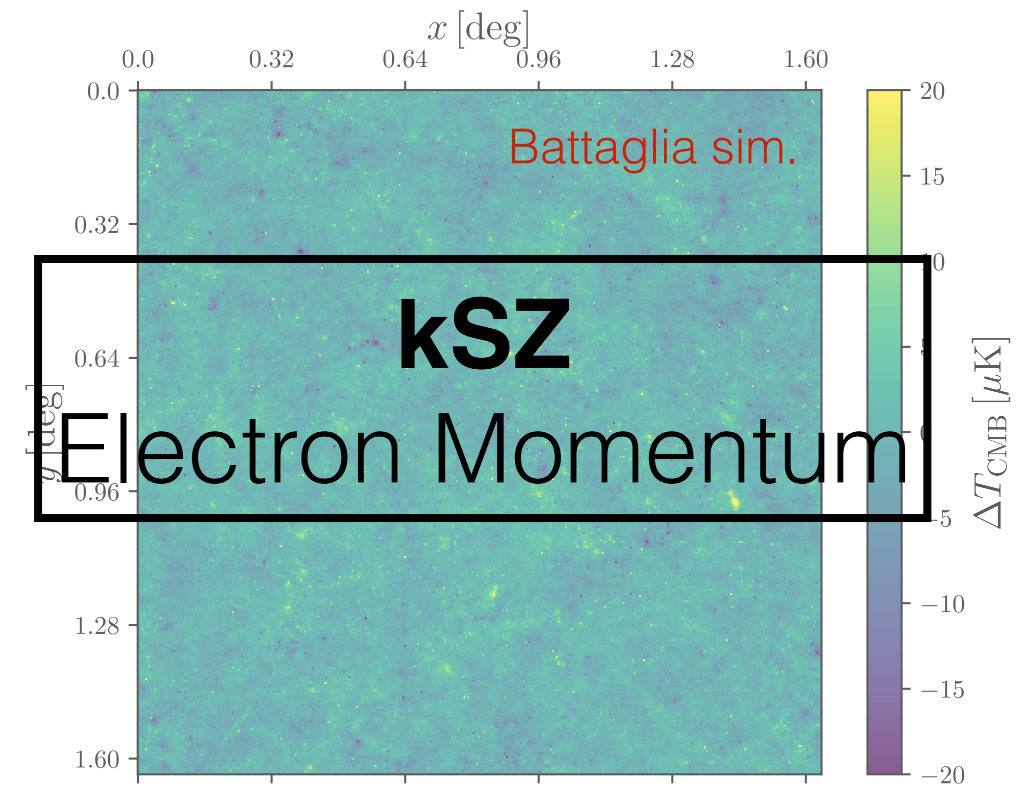

kSZ

Electron Momentum

- **Probe gas distribution ("missing baryons")**
- **Galaxy formation gastrophysics**
- **Cosmology from velocity field (growth of structure)**

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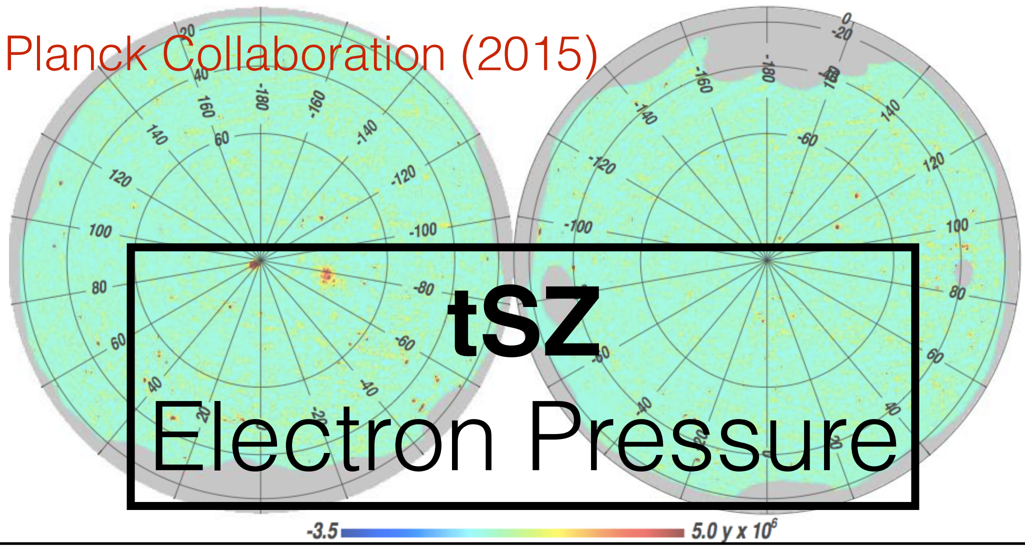
Cosmic Microwave Backlight

Secondary Anisotropies

Planck Collaboration (2015)



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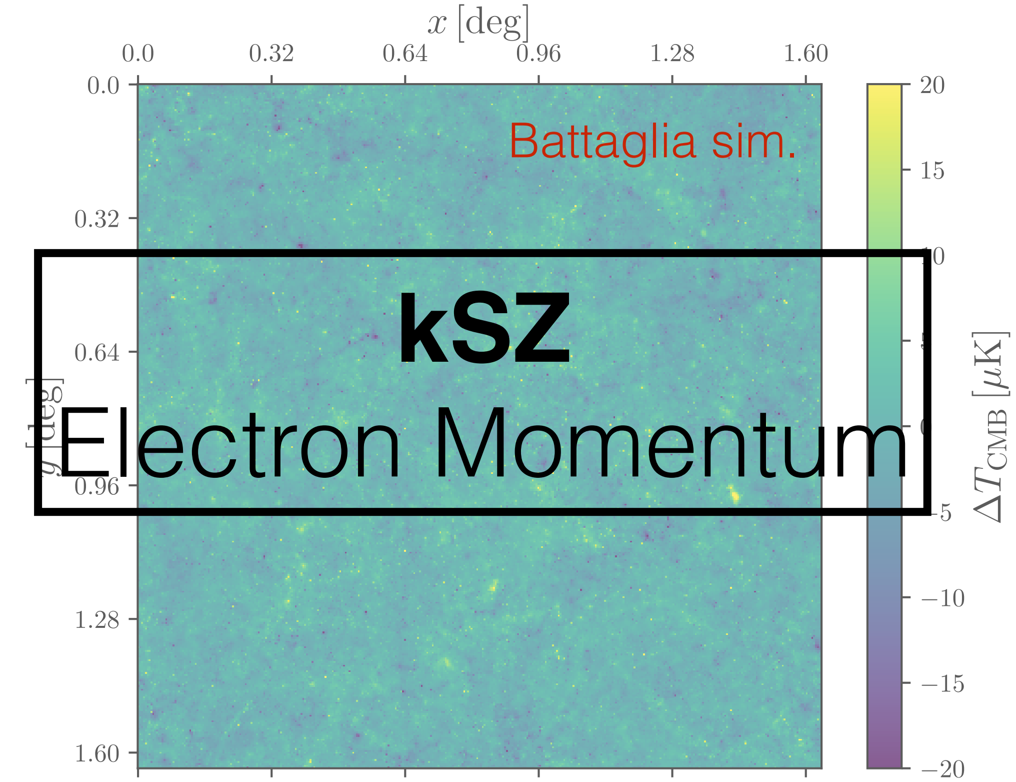

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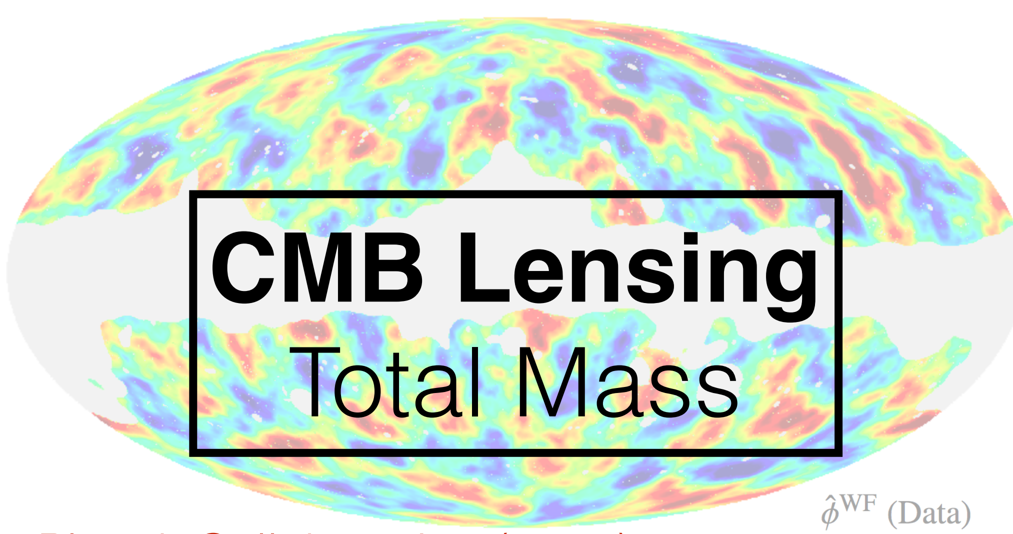

Planck Collaboration (2015)

- **Cosmology from κ power spectrum + other stats.**
- **Calibrate halo mass - observable relations**
- **Astrophysics+cosmology via cross-correlations**
- **Delensing of B-mode maps**

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CMB Lensing: Foregrounds and Component Separation

Foreground Challenges

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CMB lensing: first step is foreground cleaning

- Temperature lensing reconstruction
  - CIB
  - Thermal SZ
  - Kinematic SZ
  - Point sources
  - Galactic dust
  - Other Galactic foregrounds

correlated w/ lensing field!

- Polarization lensing reconstruction (dominates S/N for PICO/S4)
  - Polarized Galactic dust
  - Polarized Galactic synchrotron
  - Point sources

?

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CMB Lensing: Foregrounds

in principle, all biases can be removed via multi-frequency component separation — **except kinematic SZ**

biases κ auto-spectrum and LSS cross-correlations

Ferraro & **JCH** (2018)

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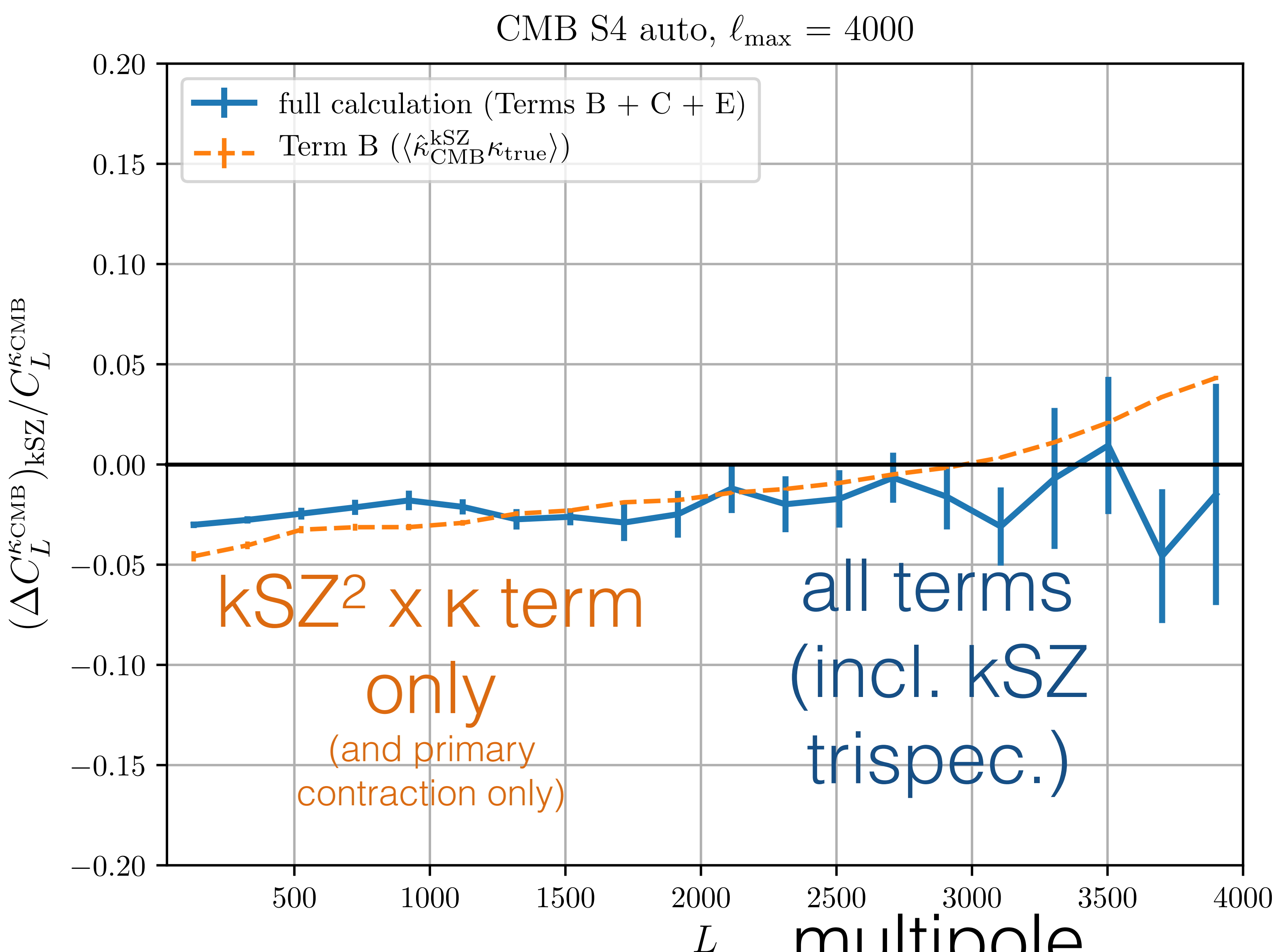
biases **κ auto-spectrum** and LSS cross-correlations

fractional bias to κ auto-correlation



multipole

would lead to non-negligible bias on neutrino mass

Ferraro & **JCH** (2018)

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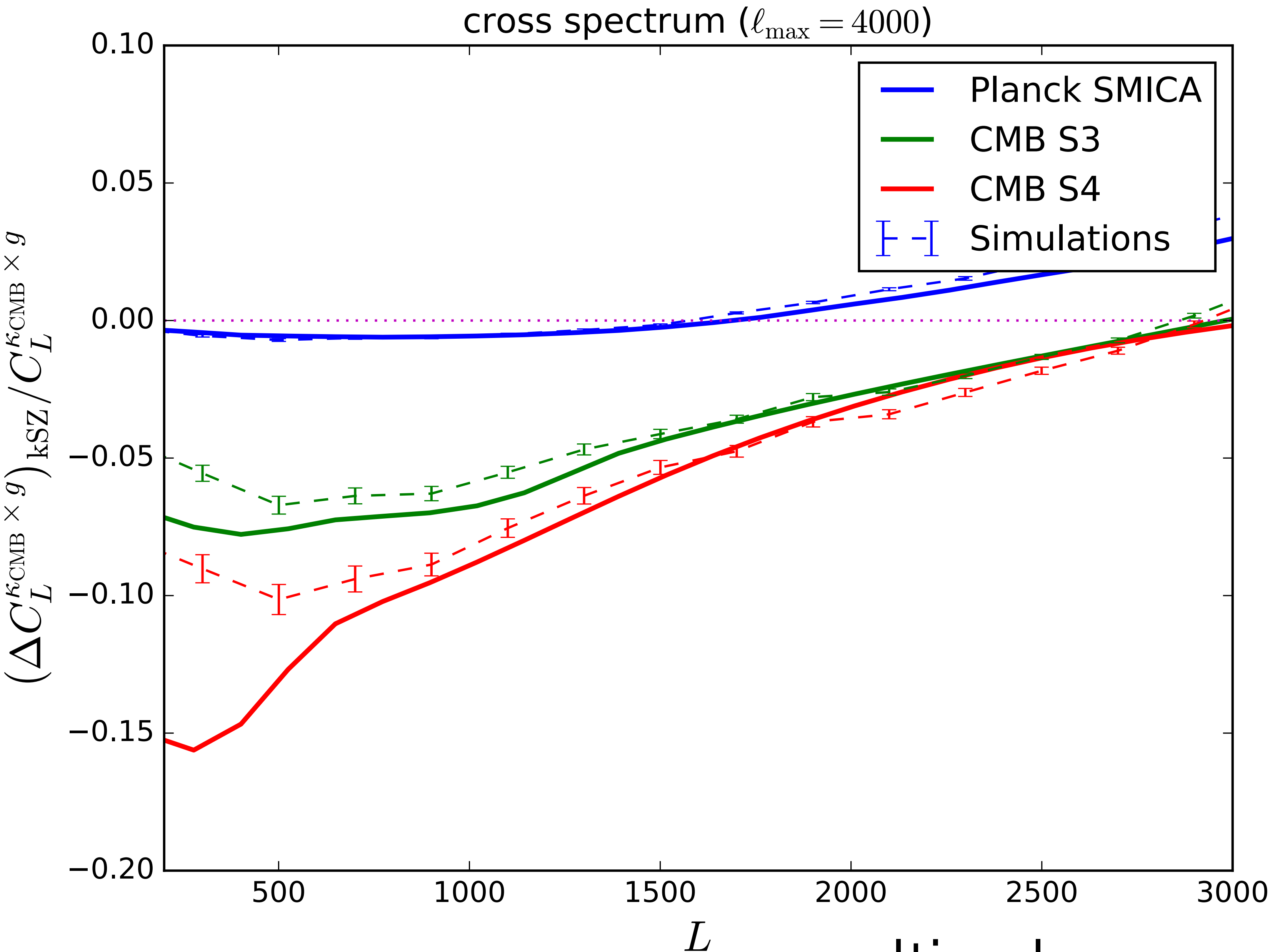
CMB Lensing: Foregrounds

in principle, all biases can be removed via multi-frequency component separation — **except kinematic SZ**

biases κ auto-spectrum and **LSS cross-correlations**

fractional bias to κ-galaxy cross-correlation



multipole

would lead to non-negligible bias on neutrino mass

Ferraro & **JCH** (2018)

CMB Lensing: Foregrounds

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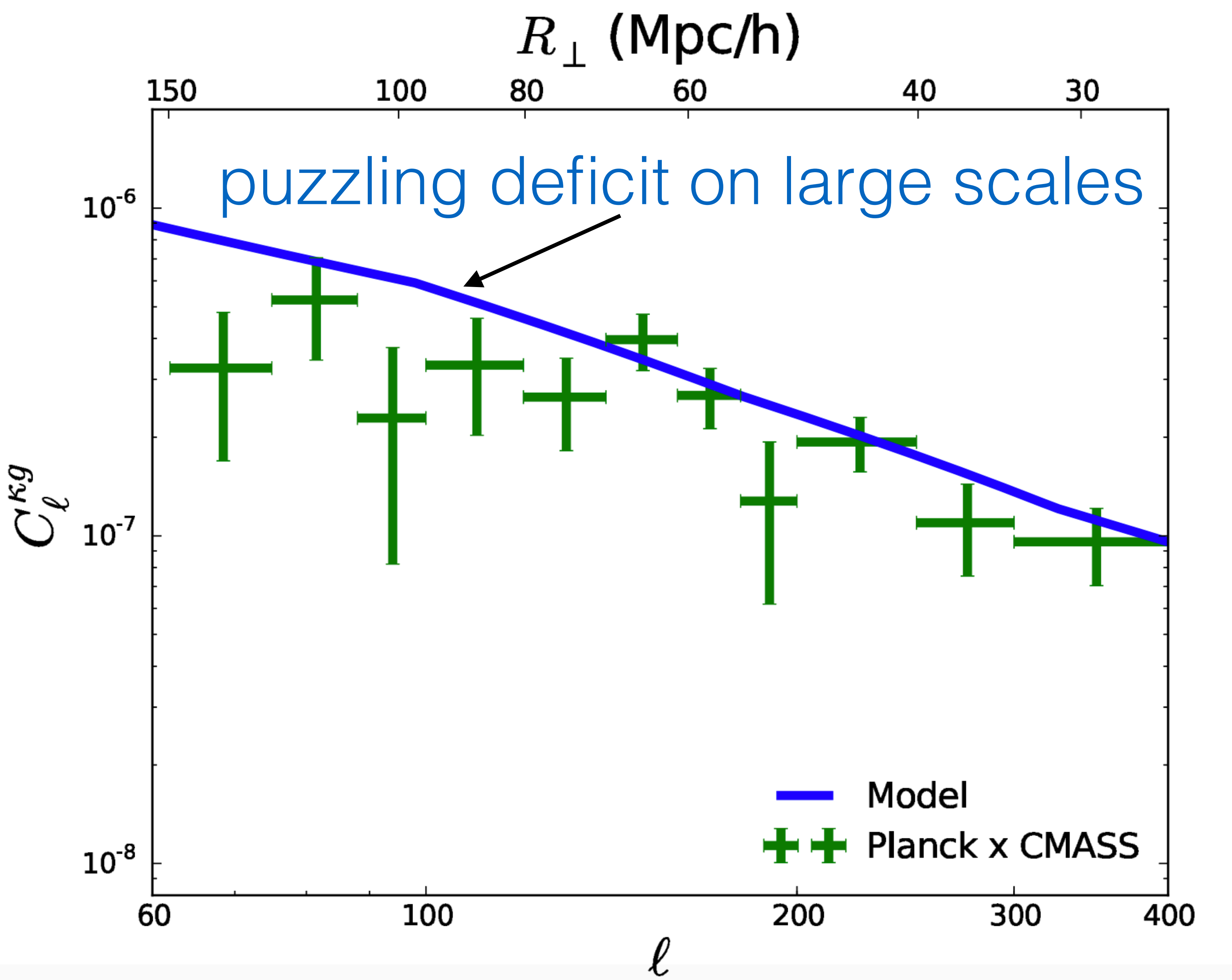
perhaps already signs of such biases in current measurements?

Planck κ cross-correlation w/ BOSS CMASS galaxy catalog



multipole

Pullen+ (2016); similar low-L deficit seen in WISE-κ cross-correlation **JCH**+ (2016)

CMB Lensing: Foregrounds

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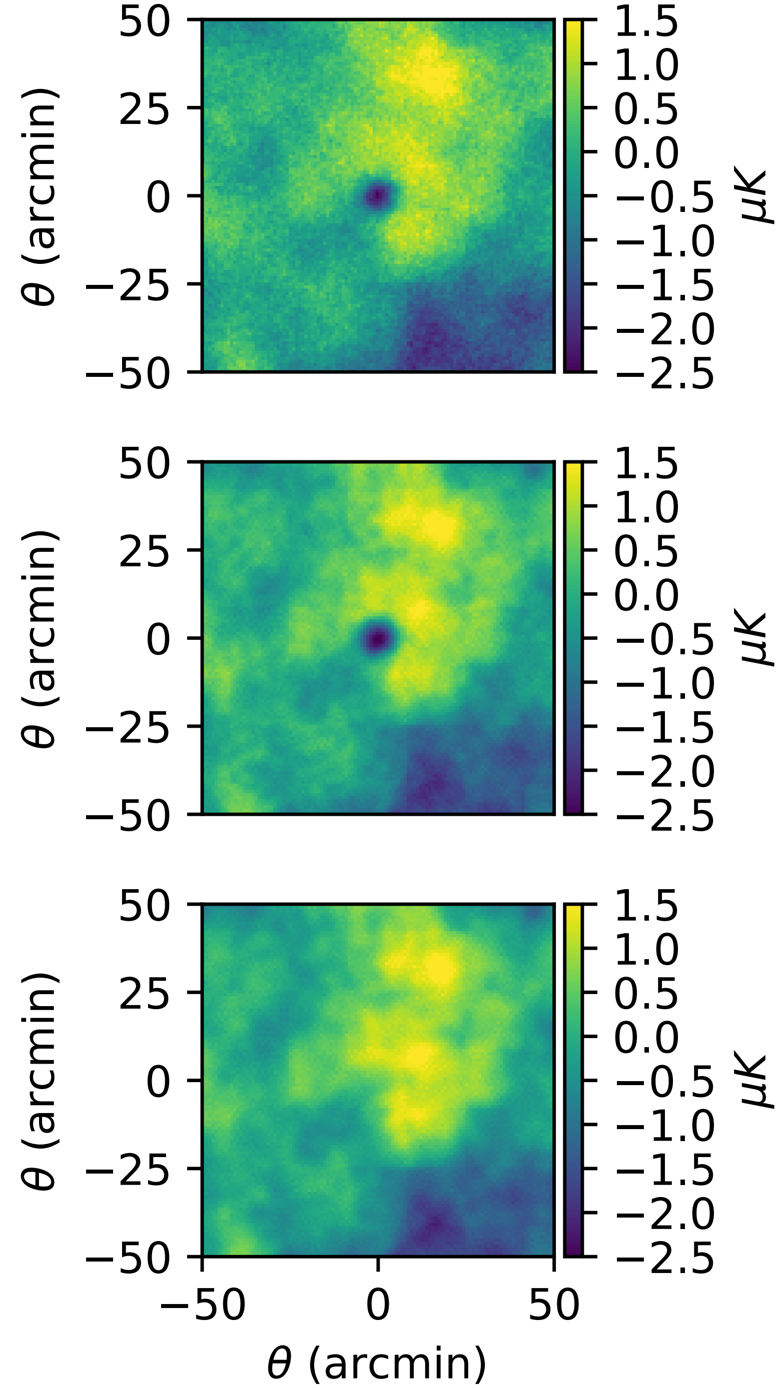
N.B. SMICA map used in Planck lensing reconstruction has significant tSZ residuals

stack on SDSS DR8 redMaPPer clusters



Planck 143 GHz

Planck SMICA CMB

LGMCA CMB (tSZ deprojected)

Madhavacheril & **JCH** (2018)

Asymmetric Lensing Recon.

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Observation 1:

$$\kappa^{XY}(\boldsymbol{\theta}) = -\mathcal{F}^{-1}\left\{A^{XY}(\boldsymbol{L})\mathcal{F}\left\{\mathrm{Re}\left[\nabla\cdot\left[\boldsymbol{\nabla}X_f(\boldsymbol{\theta})Y_f(\boldsymbol{\theta})^*\right]\right]\right\}\right\}$$

T gradient saturates by ell~2000

Madhavacheril & **JCH** (2018)

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T gradient saturates by ell~2000

Observation 2:

$$\langle\tilde{\kappa}(\boldsymbol{\theta})\rangle = \langle\nabla\cdot\left[[\boldsymbol{\nabla}T^o(\boldsymbol{\theta})]_f T^o_f(\boldsymbol{\theta})\right]\rangle \tag{3}$$

$$= \langle\nabla\cdot[[\boldsymbol{\nabla}T_f(\boldsymbol{\theta}) + \boldsymbol{\nabla}F_f(\boldsymbol{\theta})][T_f(\boldsymbol{\theta}) + F_f(\boldsymbol{\theta})]]\rangle \tag{4}$$

$$= \langle\nabla\cdot[[\boldsymbol{\nabla}T_f(\boldsymbol{\theta})]T_f(\boldsymbol{\theta}))]\rangle + \langle\nabla\cdot[[\boldsymbol{\nabla}F_f(\boldsymbol{\theta})]F_f(\boldsymbol{\theta})]\rangle \tag{5}$$

only need to clean one leg to remove bias

Madhavacheril & **JCH** (2018)

Cause for Optimism

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foreground cleaning requirements may be less stringent than originally thought: we only need to foreground-clean one “leg” of the quadratic estimator (“asymmetric” lensing recon.)

Madhavacheril & **JCH** (2018)

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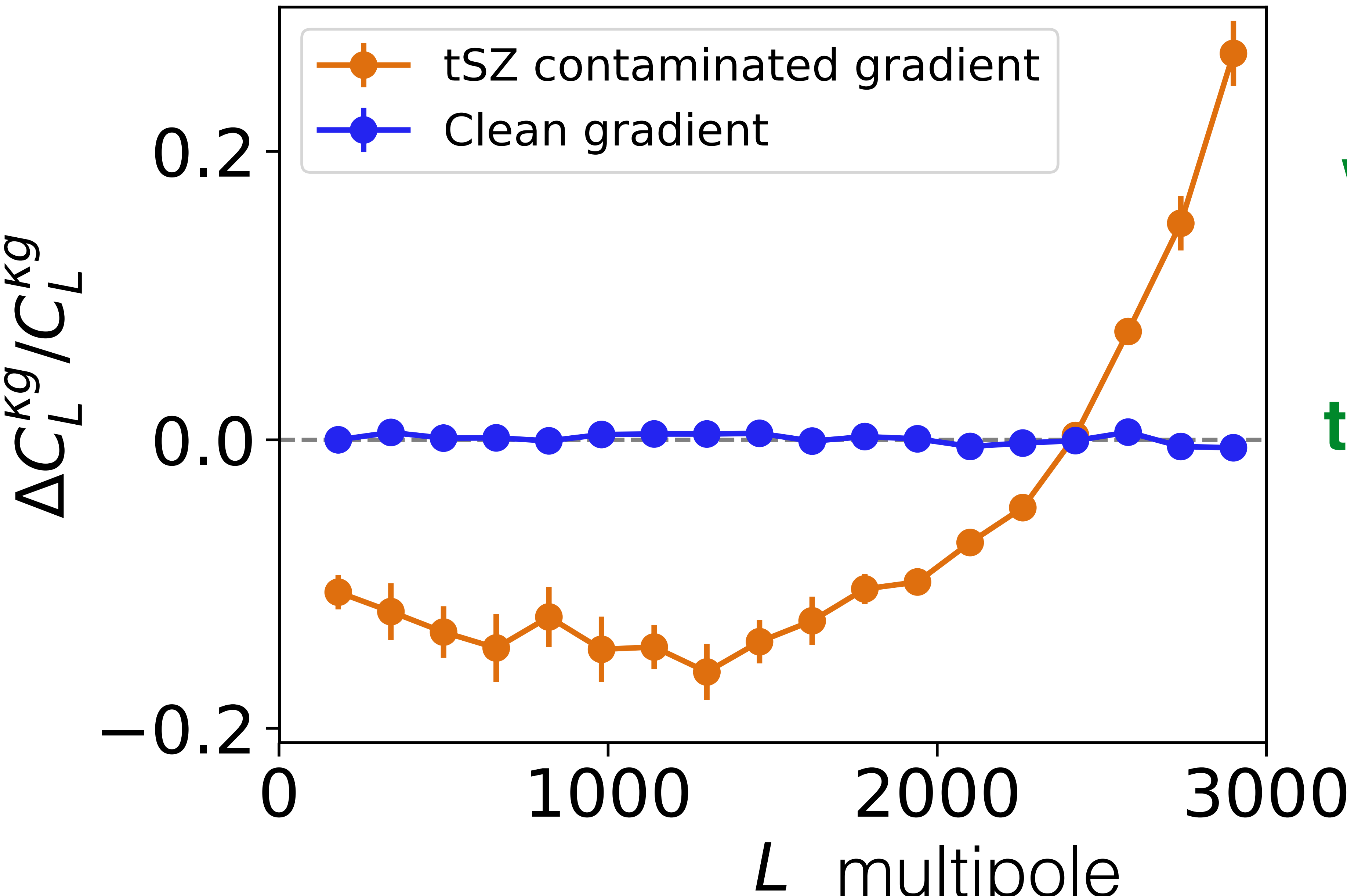
Cause for Optimism

foreground cleaning requirements may be less stringent than originally thought: we only need to foreground-clean one "leg" of the quadratic estimator ("asymmetric" lensing recon.)

PICO would be optimal mission to provide cleaned gradient maps

fractional bias to κ-galaxy cross-correlation



Madhavacheril & **JCH** (2018)

see also
Schaan & Ferraro (2018)

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More Fun with Cleaned CMB Maps: kSZ

Novel kSZ Estimator: kSZ^2xLSS

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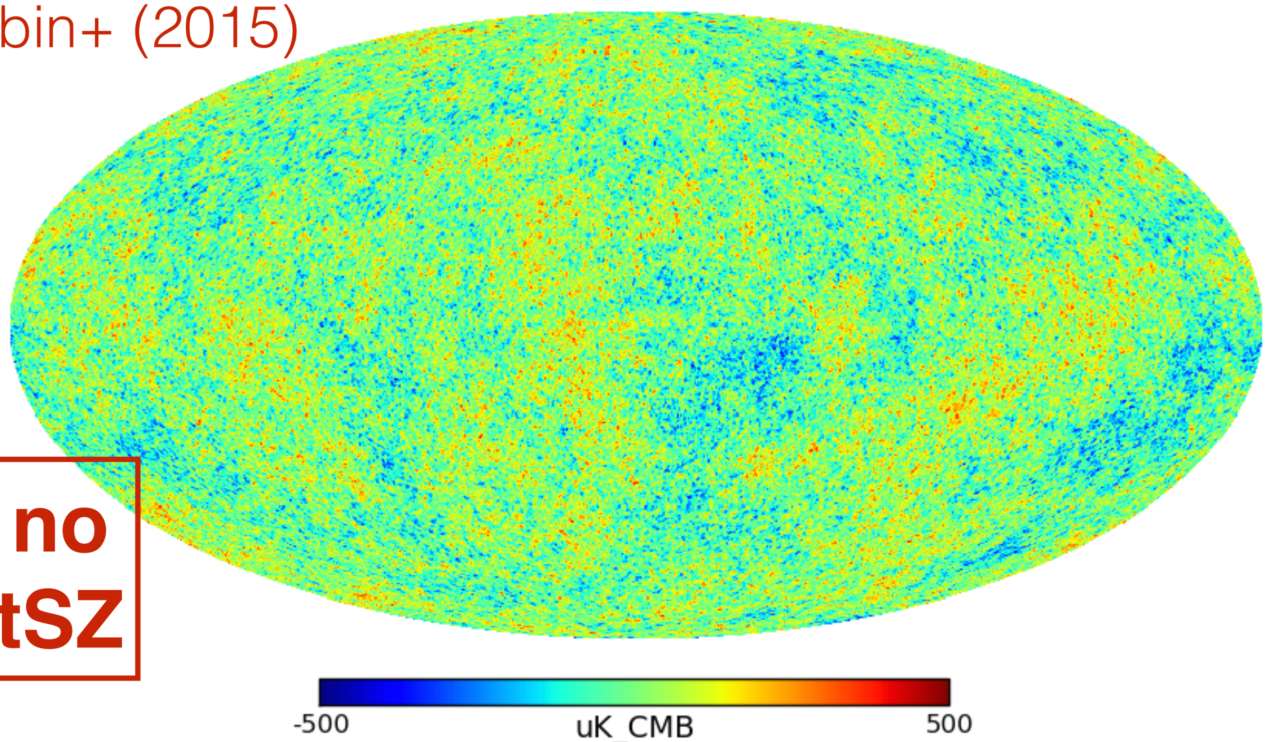
Planck/WMAP + WISE

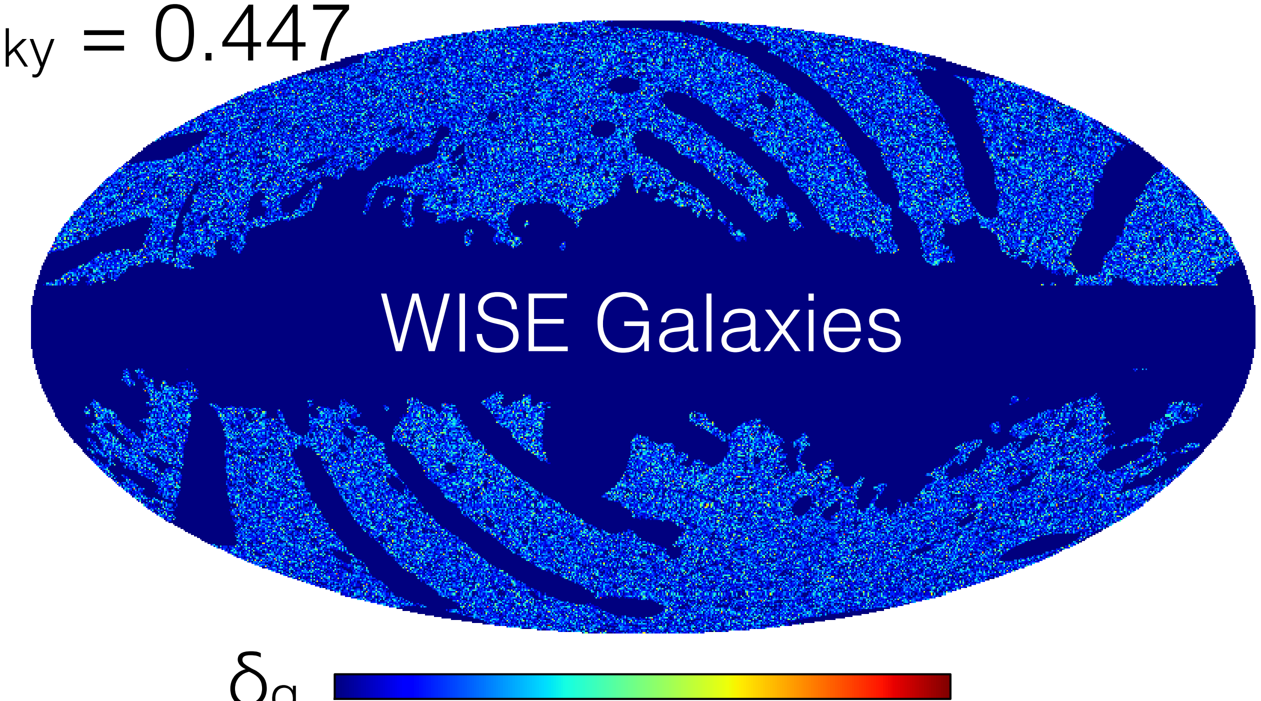
“LGMCA” CMB Map

Bobin+ (2015)



no tSZ

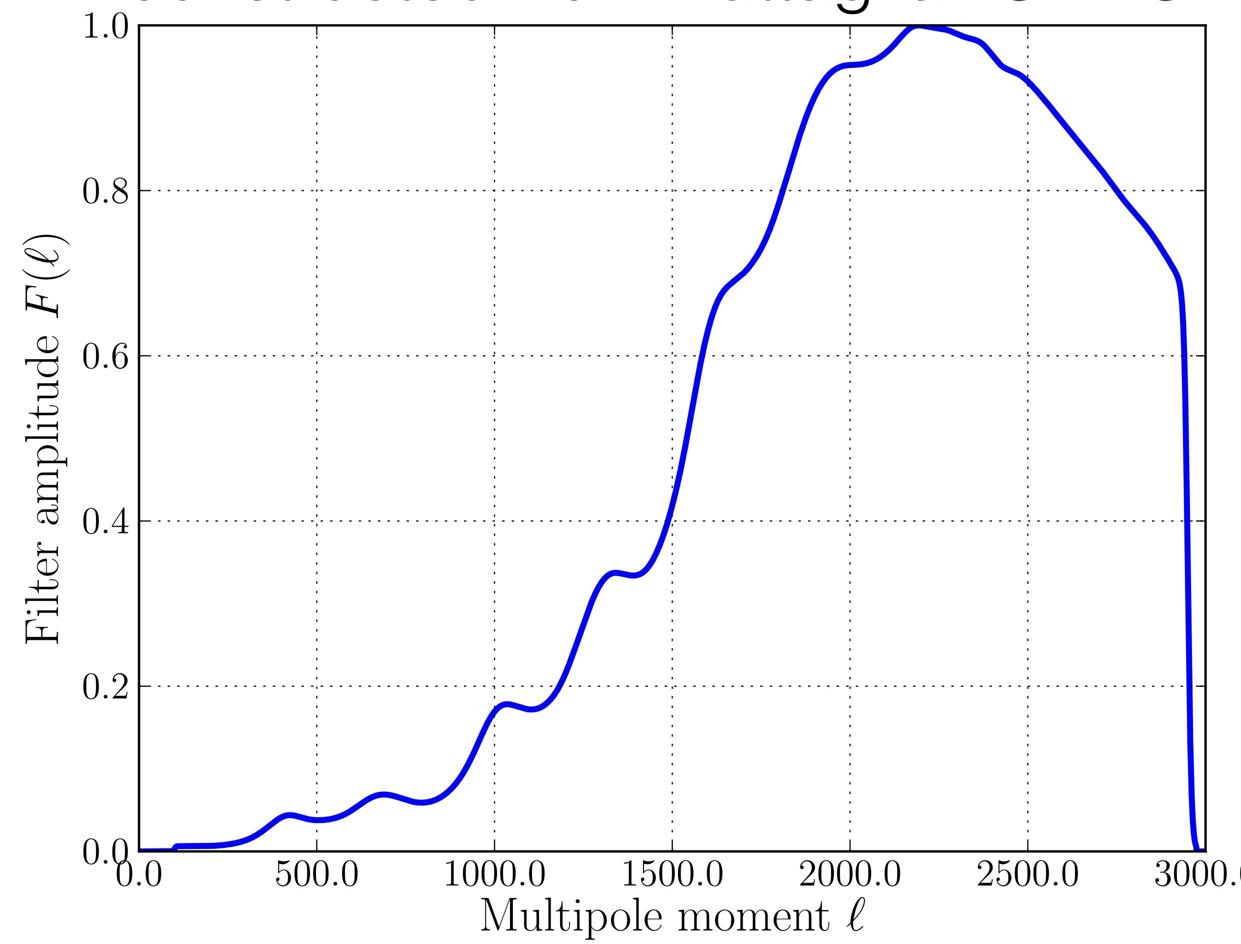
$f_{sky} = 0.447$



δ_g

Wiener filter

constructed from Battaglia kSZ PS



N_{gal} ~ 46 million

<z> ~ 0.4 (dn/dz from SDSS cross-match)

L ~ L*

M ~ (1–5) x 10^{12} M_{sun}

JCH+ (PRL 2016)

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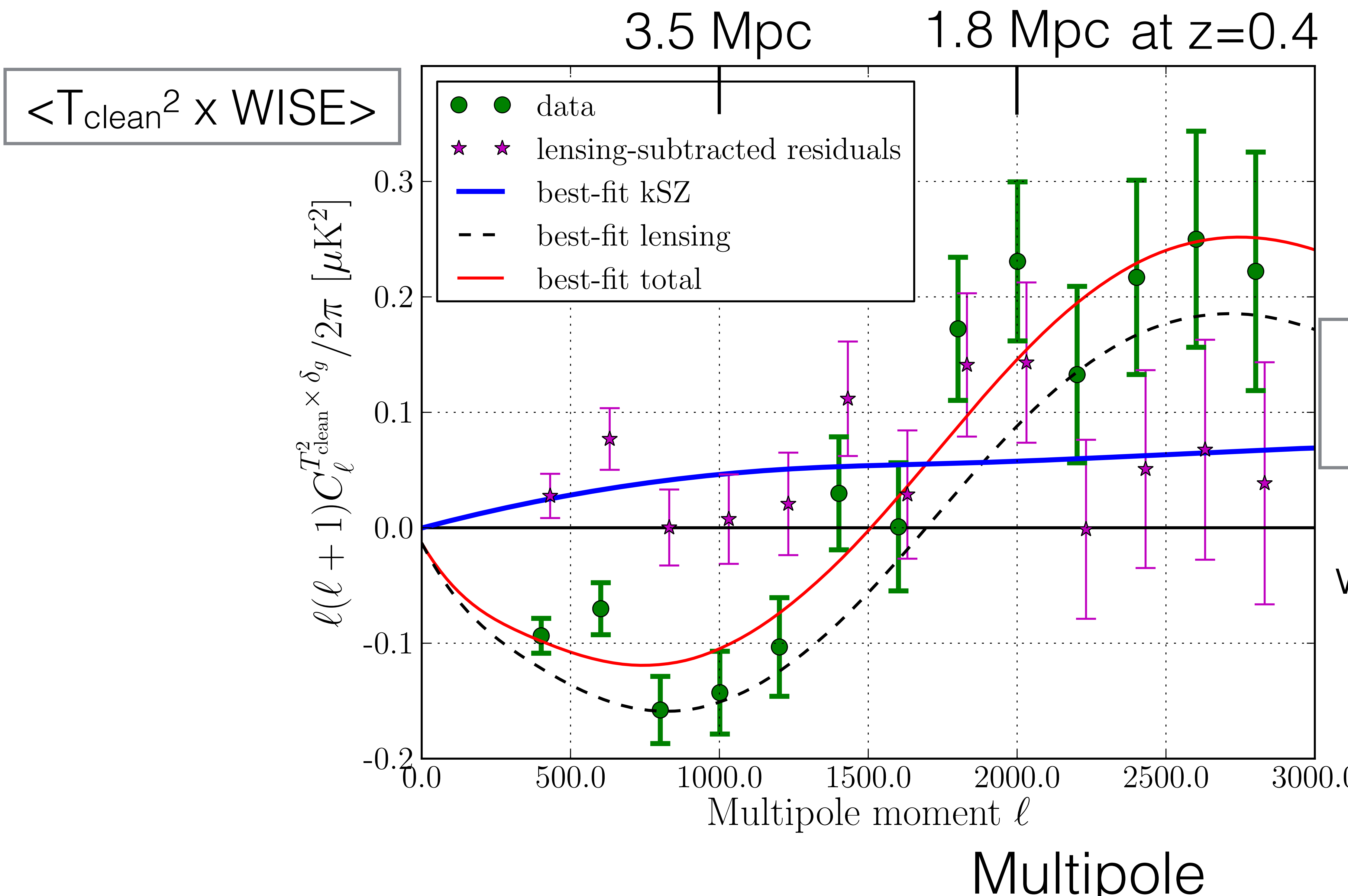
Novel kSZ Estimator

Detection (after further cleaning dust)

consistent with cosmic baryon abundance: $(f_b/0.155)\,(f_{\rm free}/1.0) = 1.48 \pm 0.19$



4σ kSZ² detection

model fits well (p=0.28)

JCH+ (PRL 2016)

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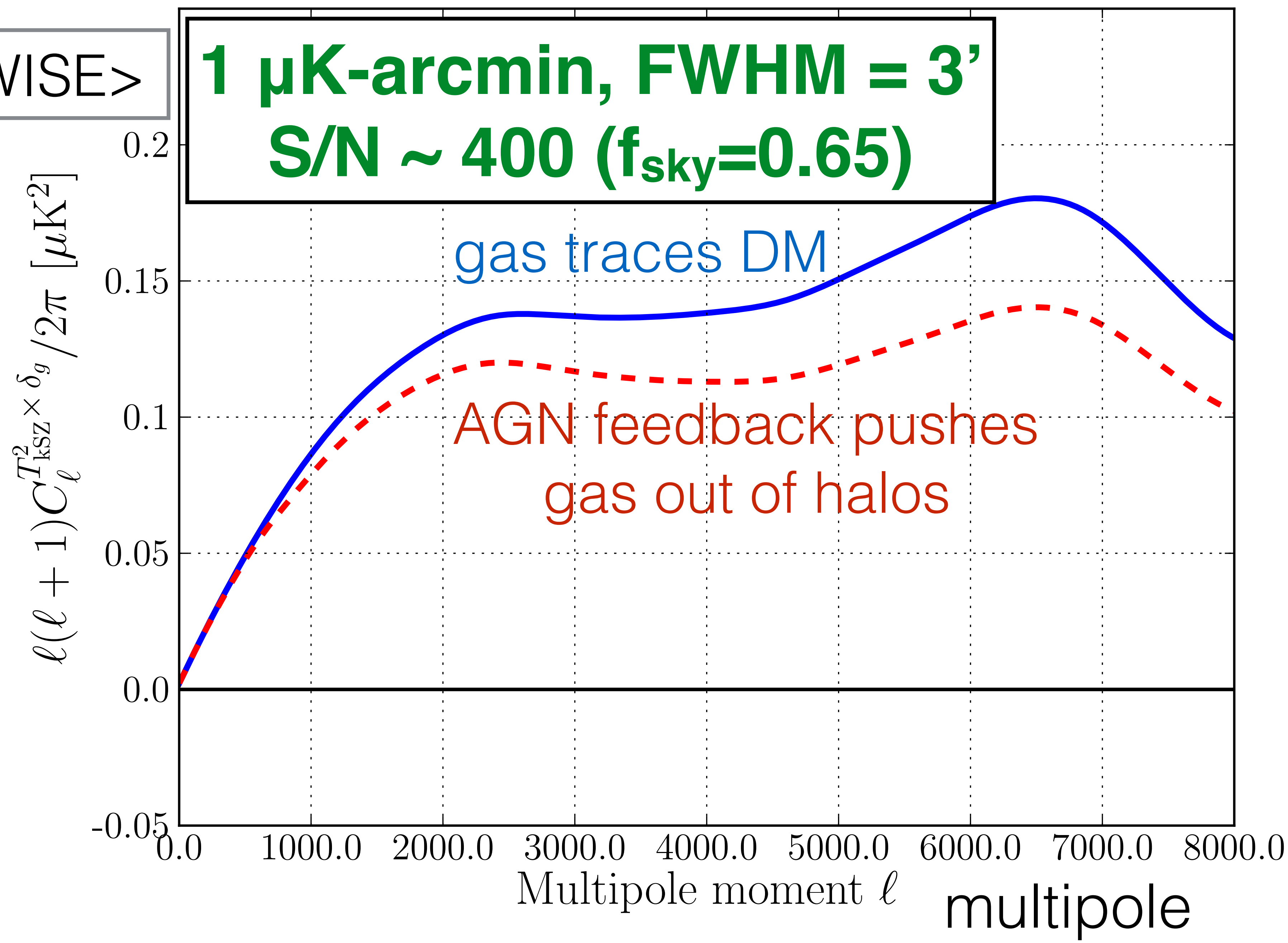
kSZ Outlook for PICO

Projected-field estimator opens a new window for kSZ measurements from photometric surveys

Strong sensitivity to AGN feedback models via gas distribution

<T_{kSZ}^2 x WISE>



high resolution and multi-frequency coverage is crucial for kSZ w/ PICO

many models to constrain/rule out: Horizon-AGN; cosmo-OWLS; Illustris; EAGLE; FIRE; Battaglia; …

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Thermal SZ

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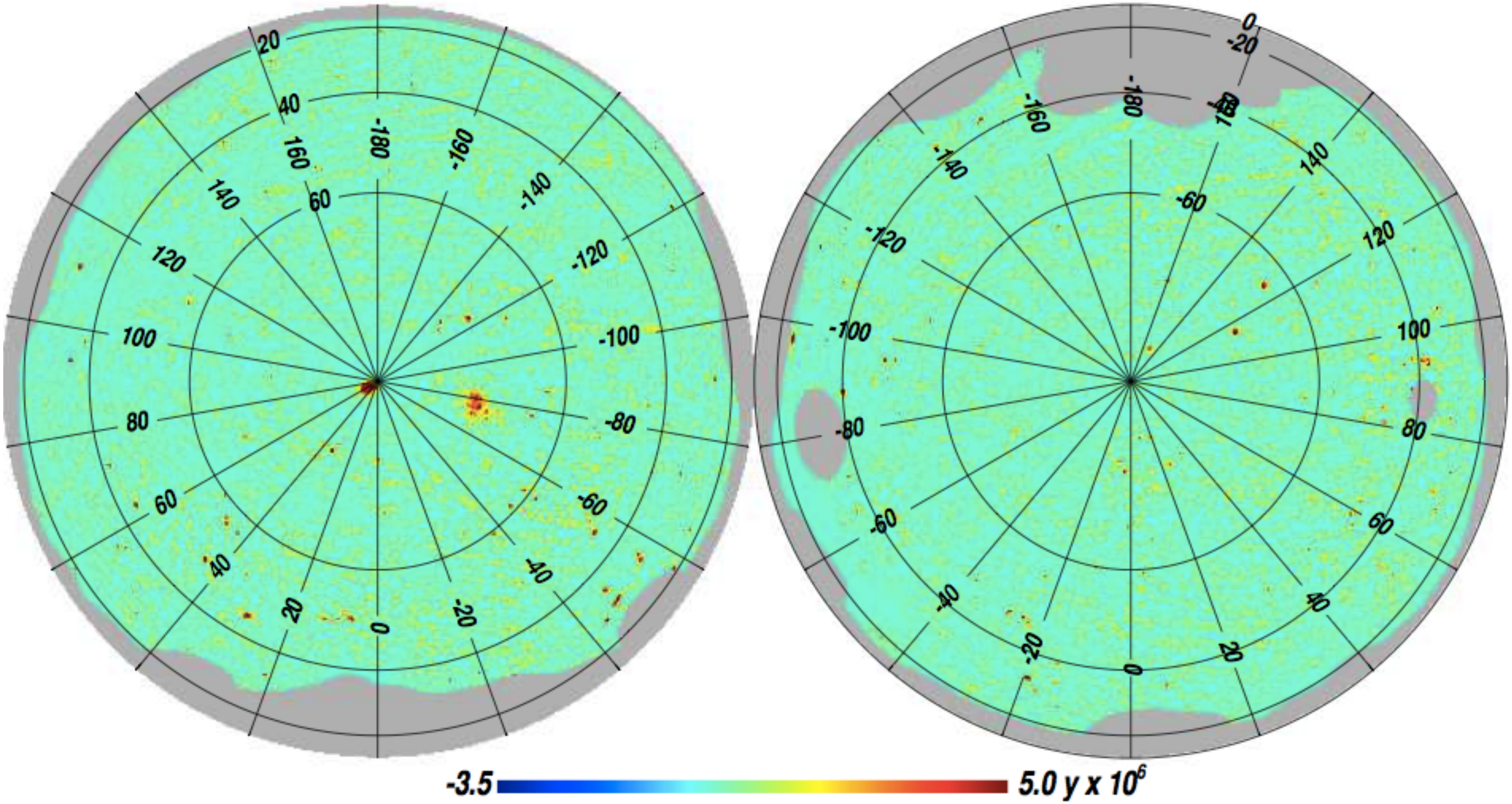
Planck tSZ ILC Maps

Needlet ILC Compton-y map



key difference w.r.t. CMB analysis: some contaminants (e.g., CIB) are correlated with the signal of interest

Planck XXII (2015)

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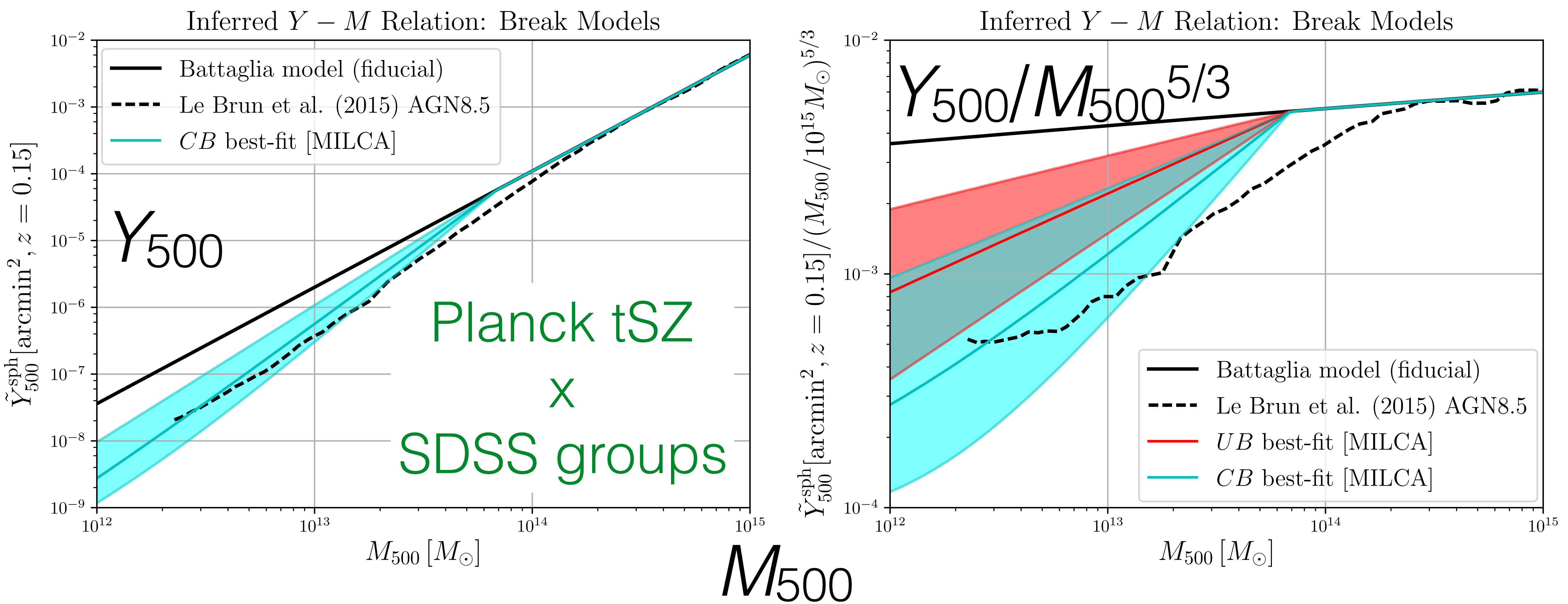
Y-M Self-Similarity

Bias in tSZ stacking analyses due to neglected two-halo term?

Hint of break from self-similar mass dependence



Improvements with better frequency coverage and higher resolution

JCH, Baxter, Lidz, Jain, & Greco (2017)

1706.03753

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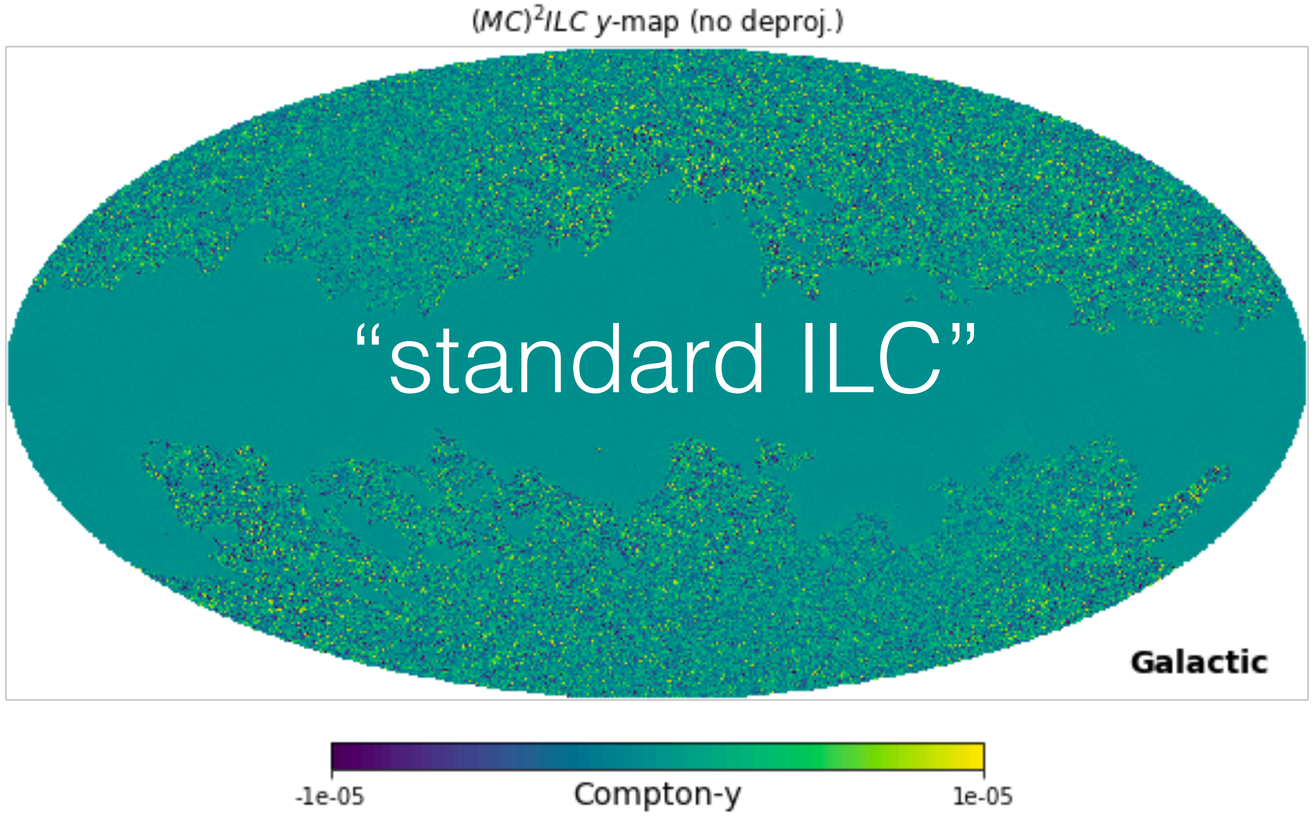
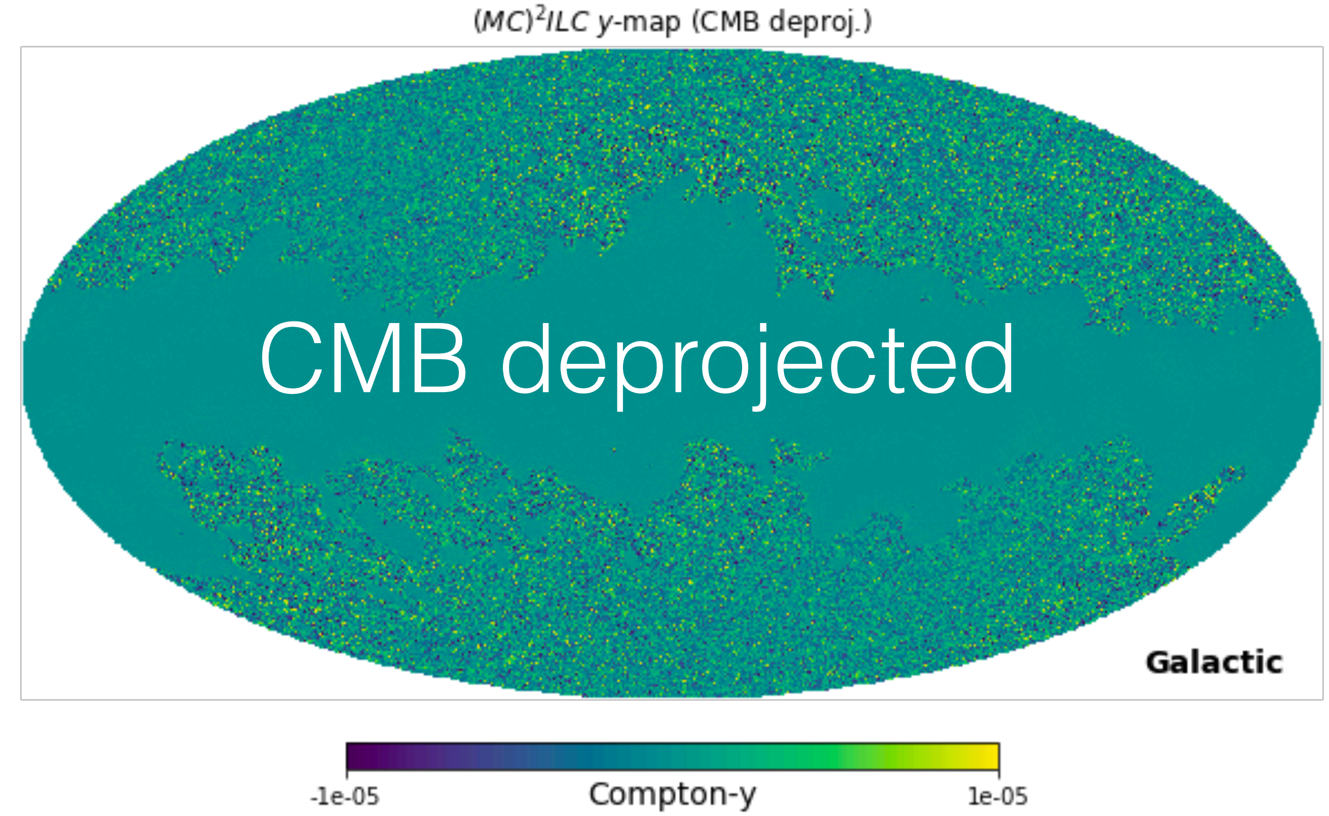
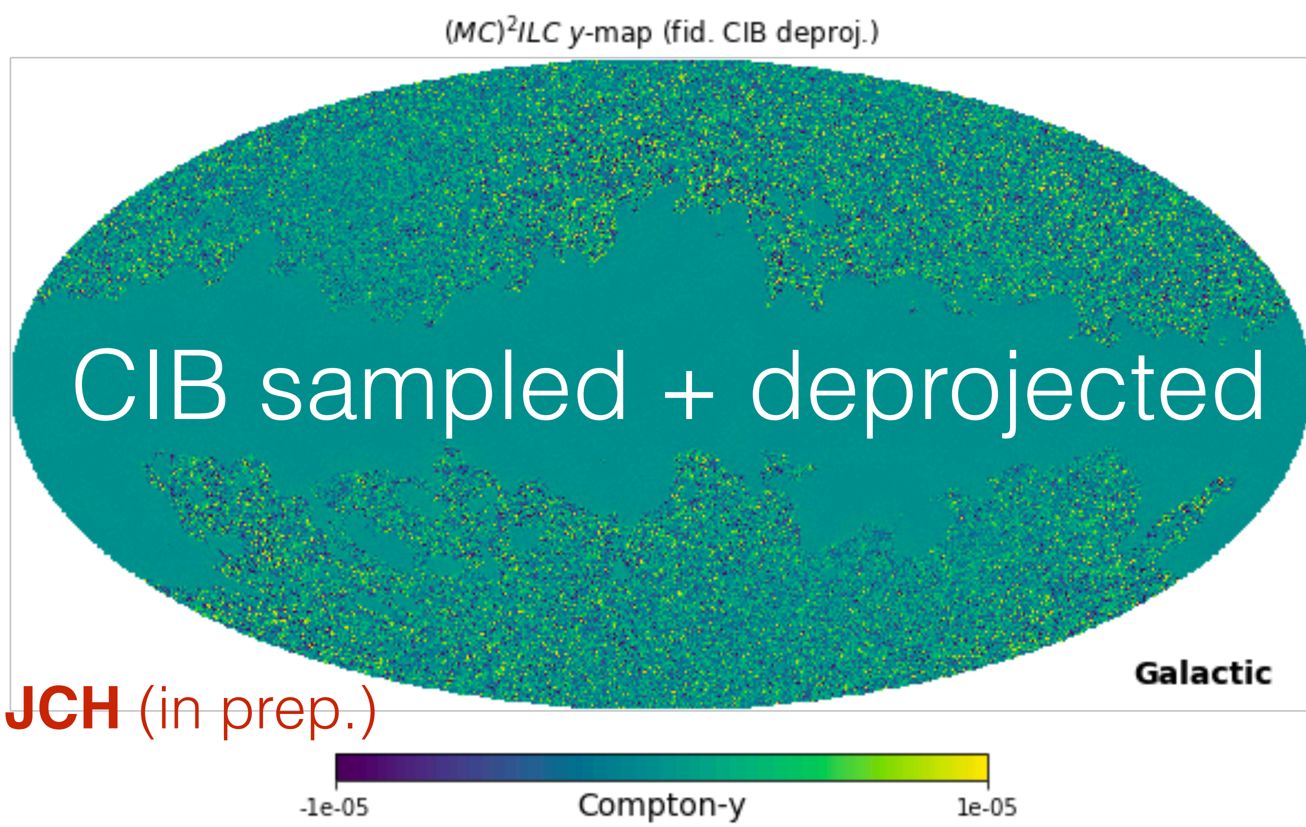
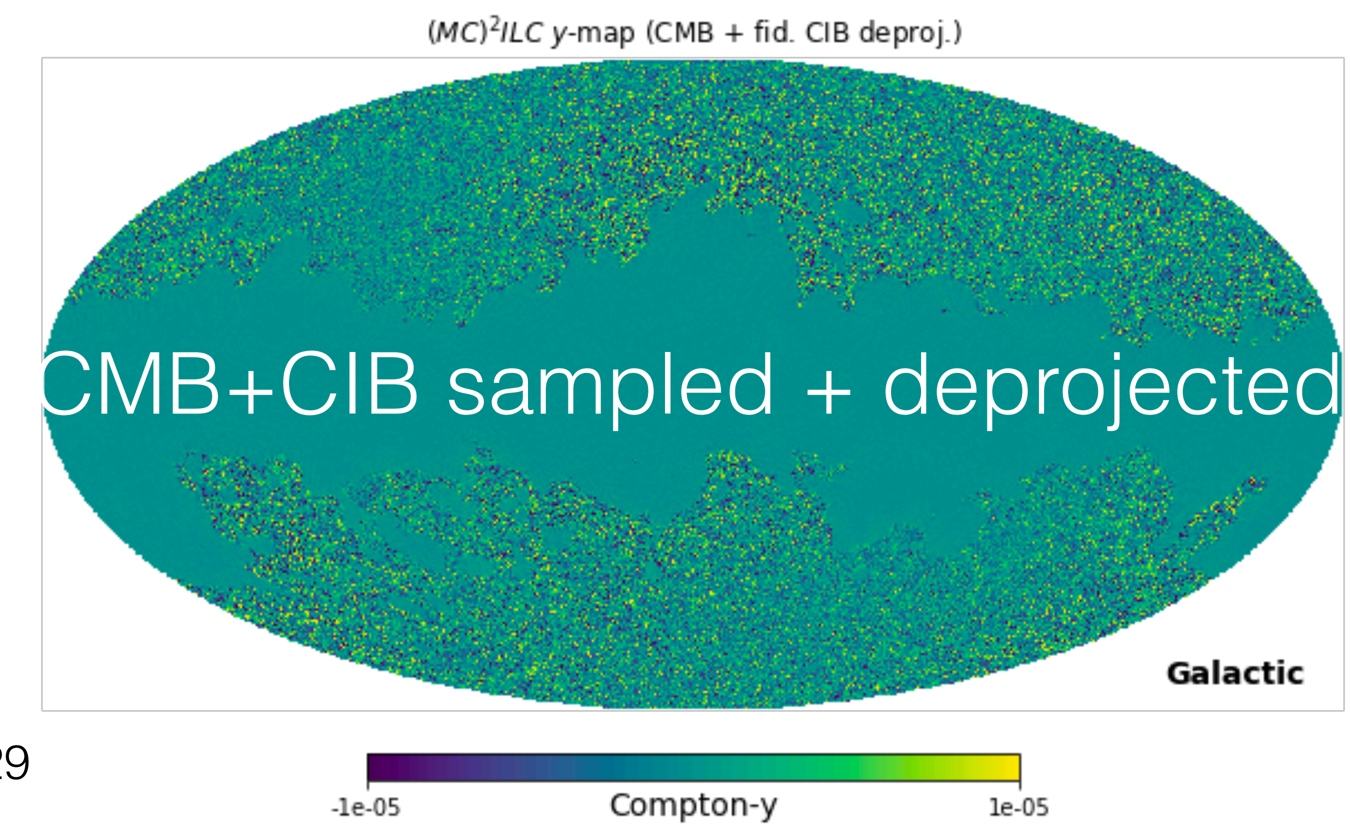
New Approach

New tSZ map pipeline: (MC)²ILC (here applied to Planck data)









JCH (in prep.)

Simulations
+
Ongoing Analysis

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Sky Model: Temperature

Model constructed from full-sky numerical sims. + data

Components:

N_{side}=4096

- Lensed CMB (via N-body simulation [Born-approx.])
- Thermal Sunyaev-Zel'dovich
- Kinematic Sunyaev-Zel'dovich
- Cosmic infrared background (CIB)
- Radio point sources (flux cut = 7 mJy at 150 GHz)

tSZ and CIB rescaled to match recent data

Sehgal et al. (2010);
Planck Collaboration (2016)

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Model constructed from full-sky numerical sims. + data

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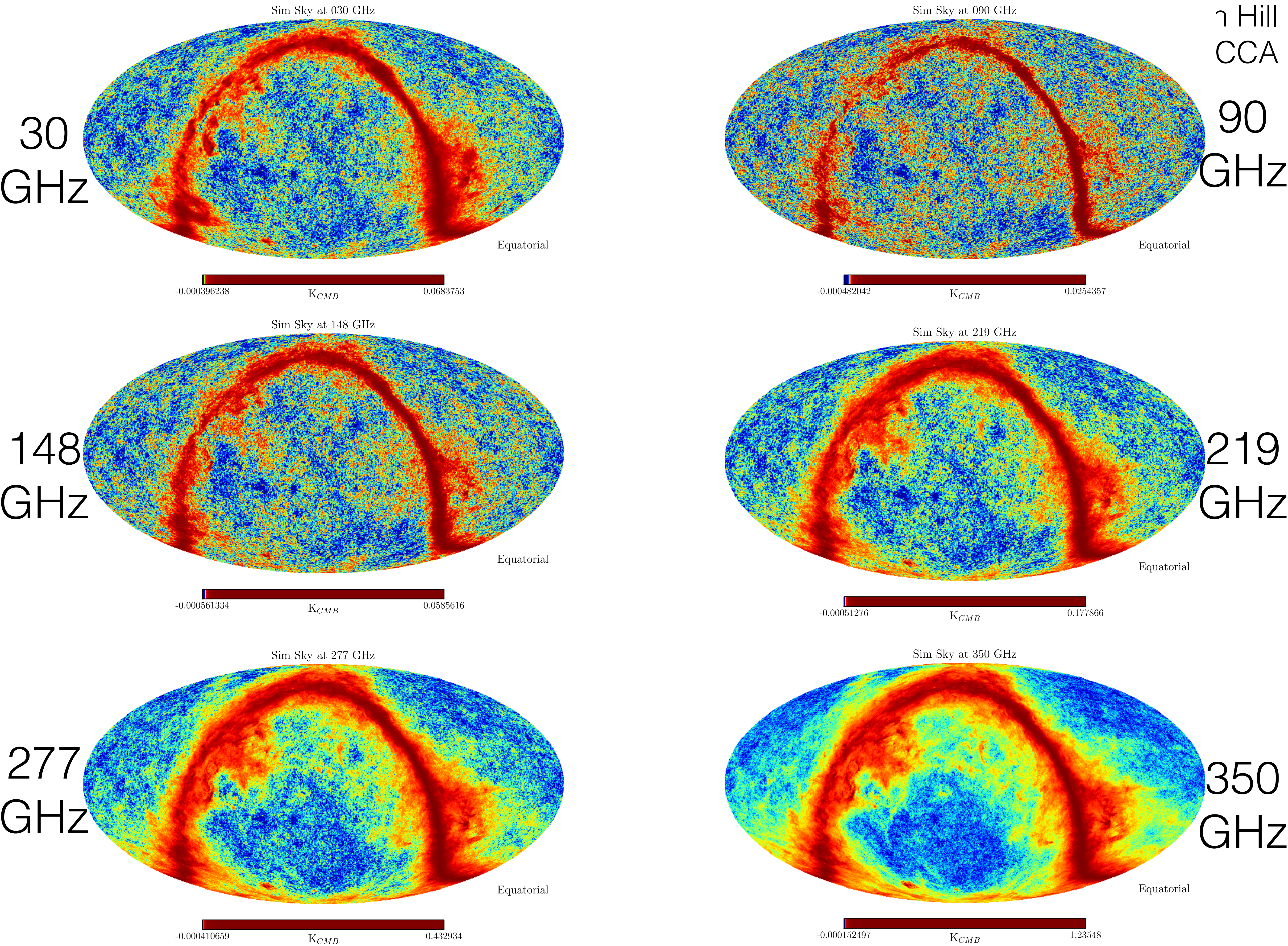
- Radio point sources (flux cut = 7 mJy at 150 GHz)
- Galactic dust
- Galactic synchrotron (Planck Commander template)
- Galactic free-free (Planck Commander template)
- Galactic anomalous microwave emission (Planck Commander)

tSZ and CIB rescaled to match recent data

caveat: no power in Commander above ell~400

All components are properly correlated

Sehgal et al. (2010);
Planck Collaboration (2016)



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Sim Sky at 030 GHz
30 GHz
Equatorial
-0.000396238
K$_{CMB}$
0.0683753
Sim Sky at 090 GHz
90 GHz
Equatorial
-0.000482042
K$_{CMB}$
0.0254357
Sim Sky at 148 GHz
148 GHz
Equatorial
-0.000561334
K$_{CMB}$
0.0585616
Sim Sky at 219 GHz
219 GHz
Equatorial
-0.00051276
K$_{CMB}$
0.177866
Sim Sky at 277 GHz
277 GHz
Equatorial
-0.000410659
K$_{CMB}$
0.432934
Sim Sky at 350 GHz
350 GHz
Equatorial
-0.000152497
K$_{CMB}$
1.23548

Thermal SZ x CIB

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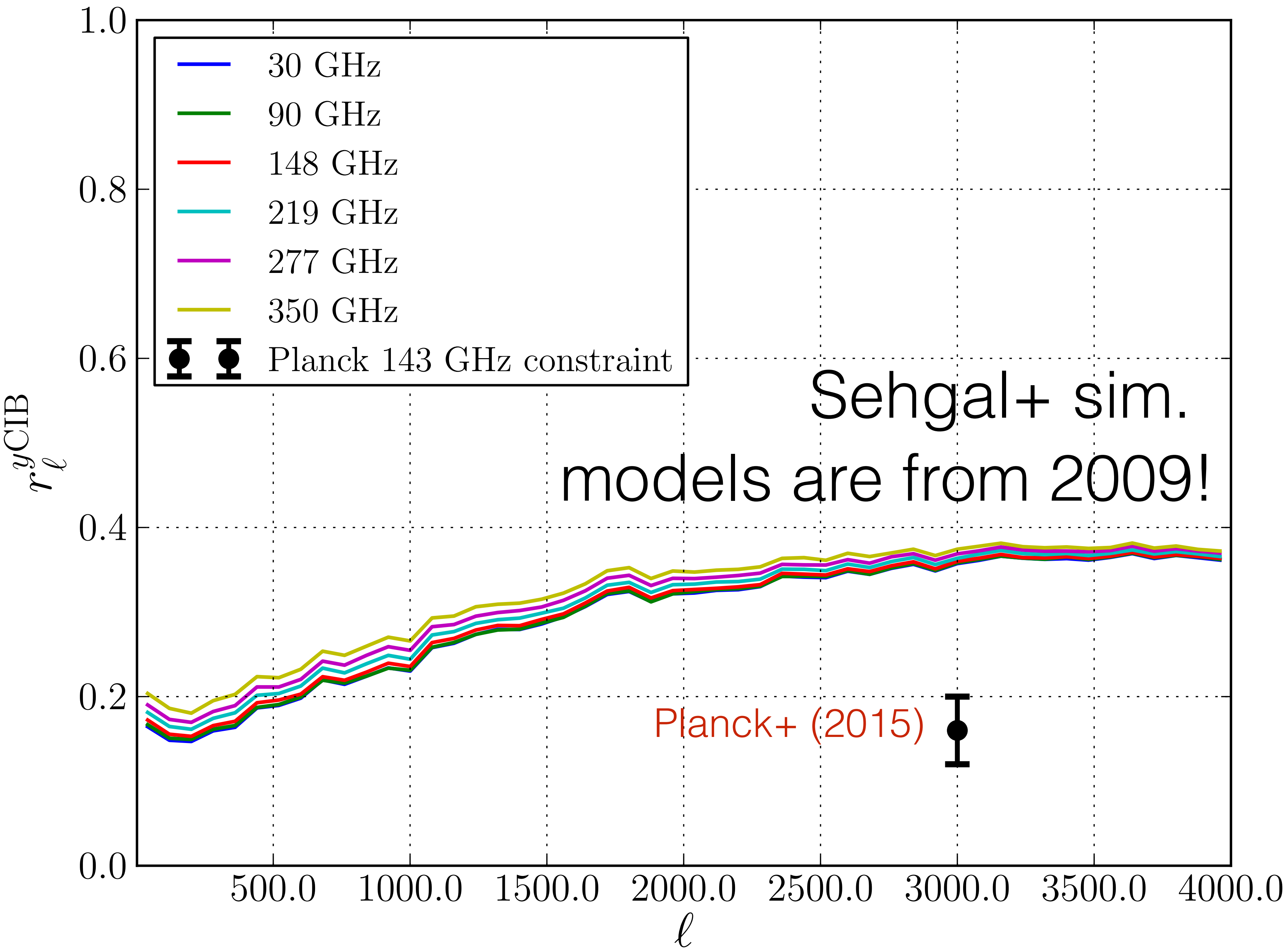
Need simulations that capture all of these correlations in order to reliably forecast + validate pipelines!

tSZ x CIB corr. coeff.



CIB Decorrelation

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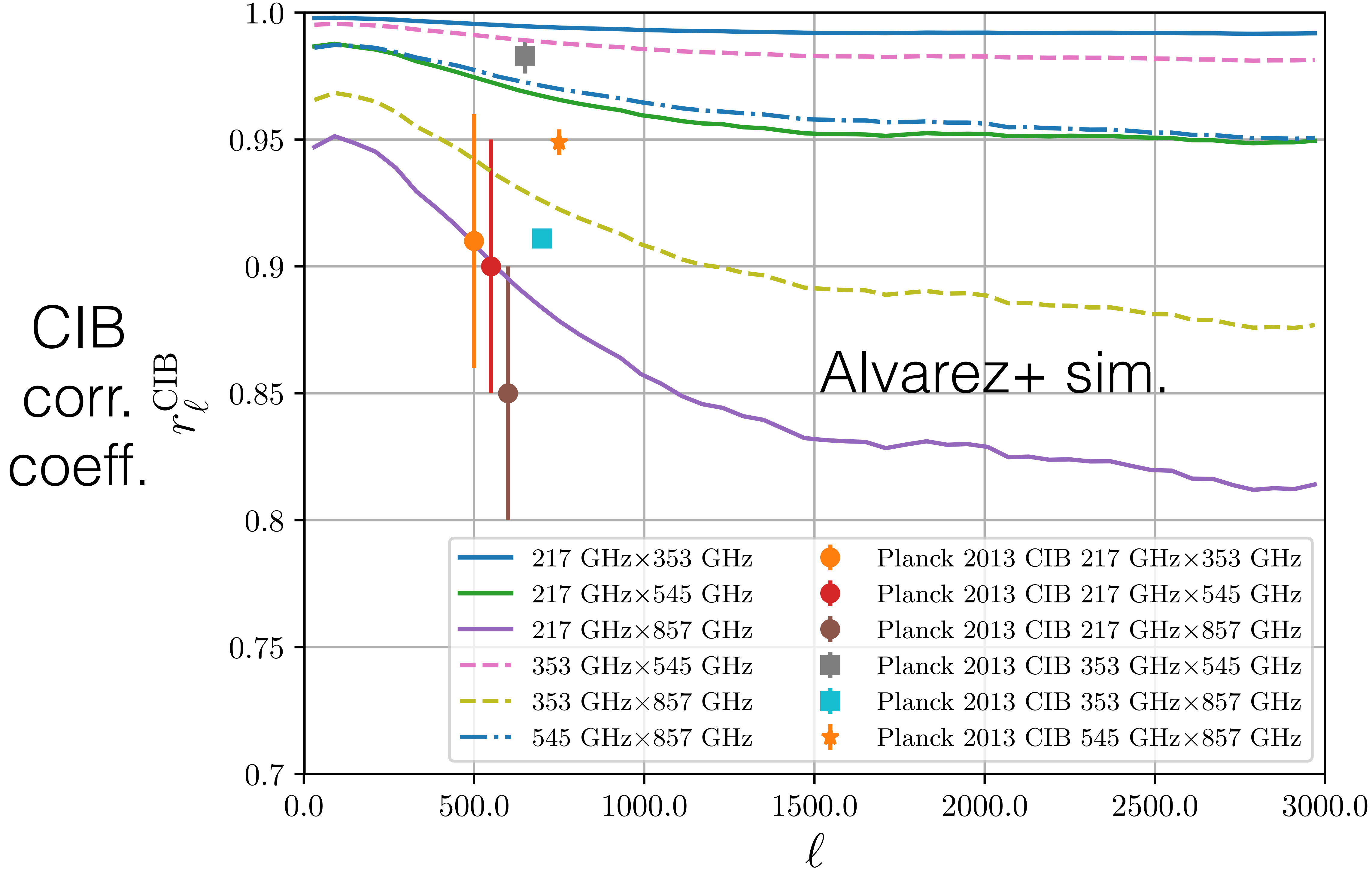
CIB decorrelation may ultimately limit high-ell tSZ/kSZ component separation



Planck+ (2013); Alvarez/CITA Peak-Patch Sim.

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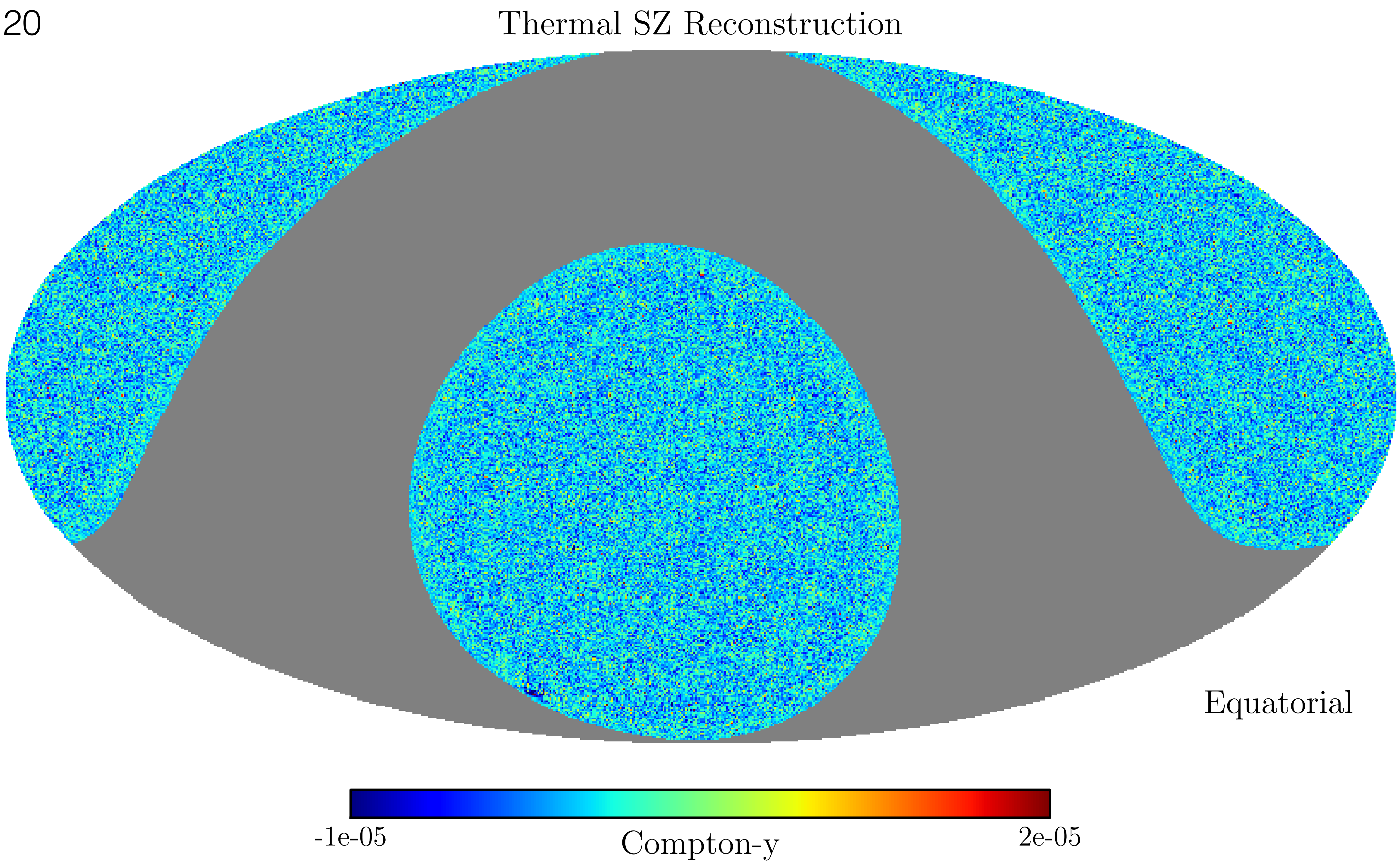
Example: ~AdvACT Thermal SZ

harmonic-space ILC

no ell<20



PICO tSZ and Beyond

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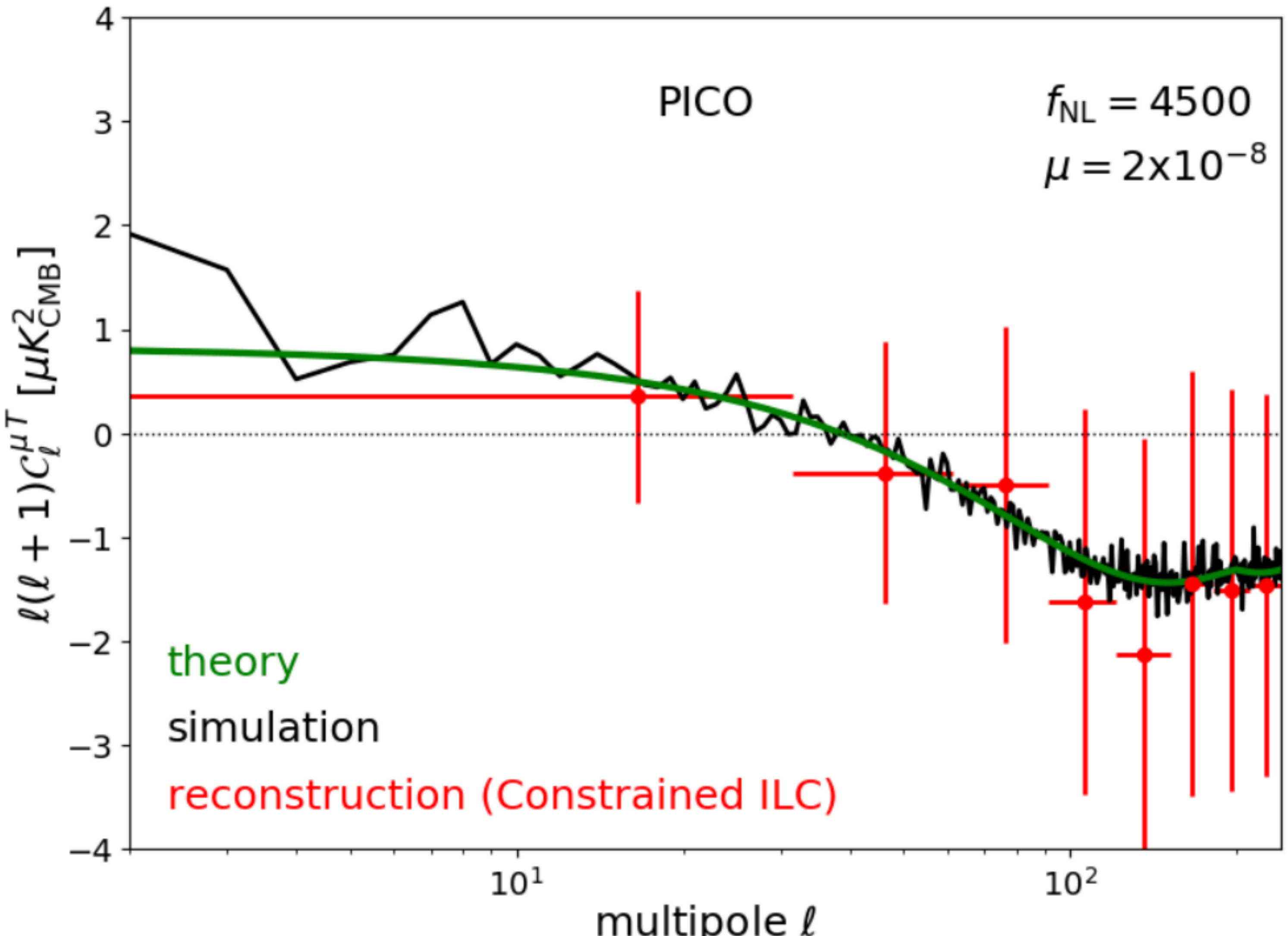
- PICO will unambiguously reconstruct the tSZ field on moderate to large angular scales — strong complementarity with SO/S4
- PICO will detect relativistic SZ at high significance — direct constraints on electron temperature
- Beyond: μ distortion maps with PICO will probe f_{NL} via μT cross-correlation



Remazeilles & Chluba (2018)

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Thank you