Kinematic and Thermal SZ Cross-Correlations with LSST, AdvACT, and CMB-S4

Colin Hill
Columbia University
Junior Fellow, Simons Society of Fellows

w/ S. Ferraro, N. Battaglia, J. Liu, D. Spergel

LSST Cross-Correlation Spectacular
23 May 2016

1603.01608
1605.02722

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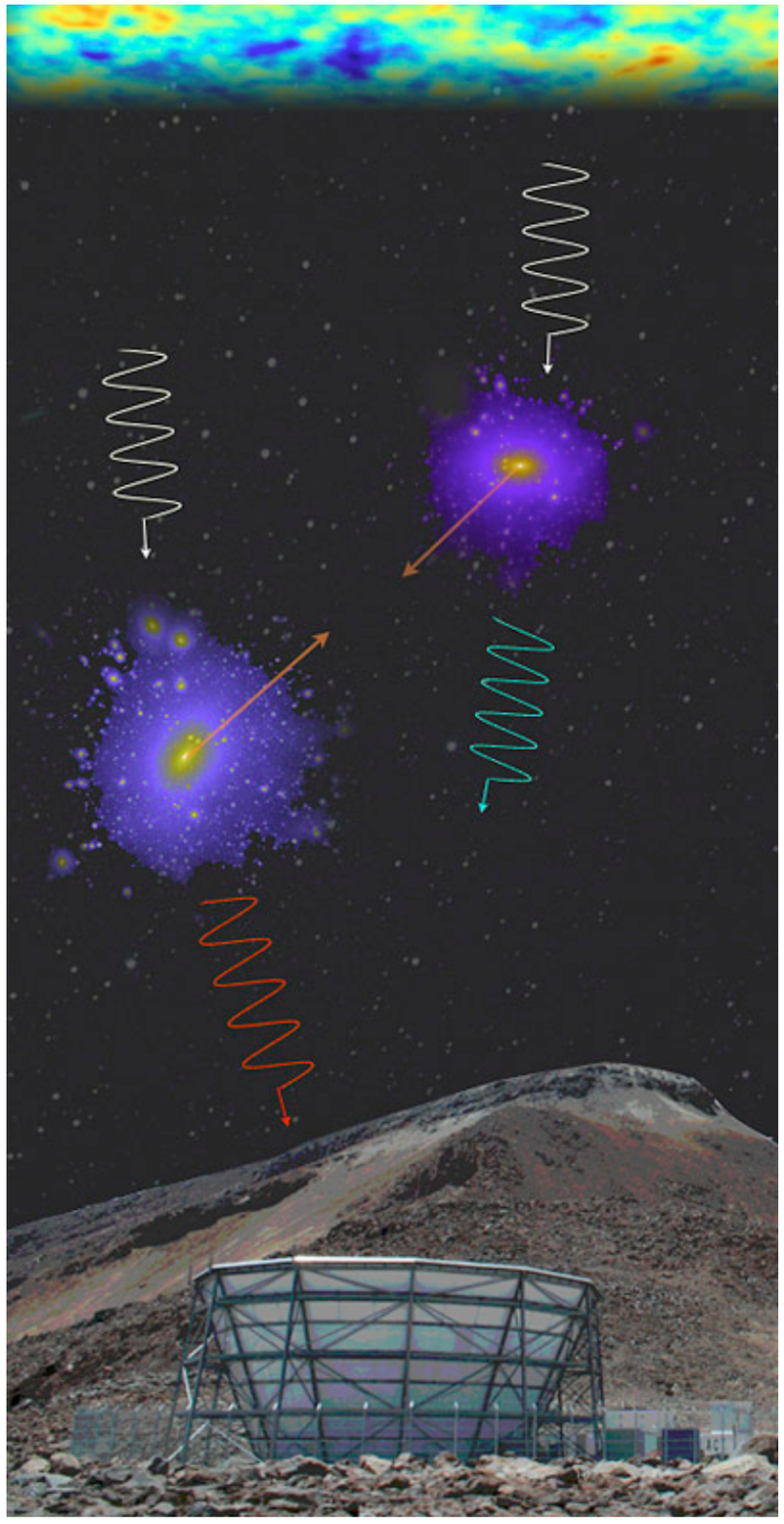
Kinematic SZ Effect



Sudeep Das/ACT

Kinematic Sunyaev-Zel'dovich Effect:
Doppler boosting of CMB photons
Compton-scattering off free electrons
with non-zero line-of-sight velocity

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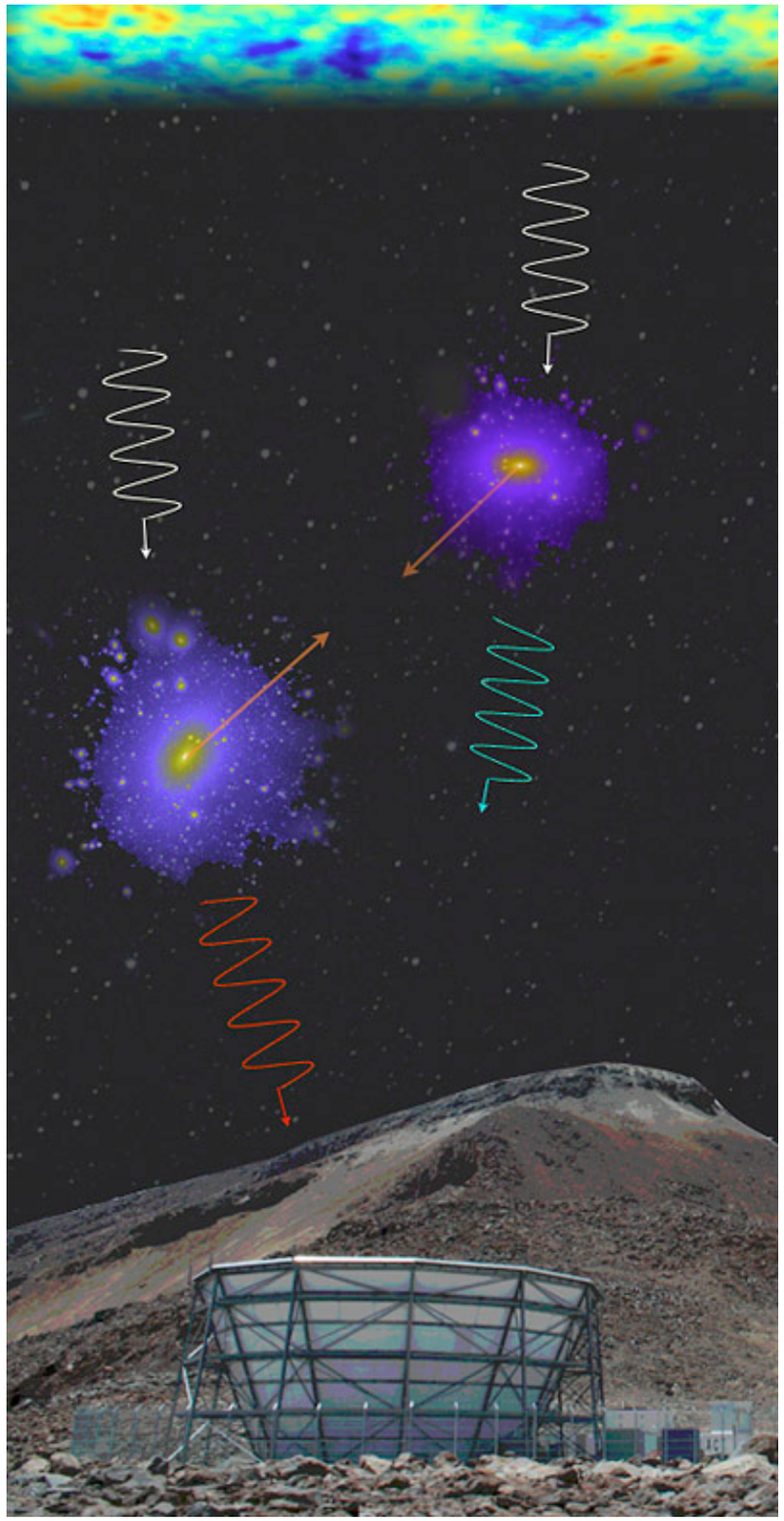
Kinematic SZ Effect



Sudeep Das/ACT

Kinematic Sunyaev-Zel'dovich Effect:
Doppler boosting of CMB photons
Compton-scattering off free electrons
with non-zero line-of-sight velocity

- Preserves blackbody CMB spectrum
- Probe of electron momentum field

$$\Theta^{\rm kSZ}(\hat{\mathbf{n}}) = -\frac{1}{c}\int_0^{\eta_{\rm re}} d\eta\, g(\eta)\, \mathbf{p}_e \cdot \hat{\mathbf{n}}$$

- Contributions from reionization and collapsed structures at late times
- Unbiased tracer of free electrons — a tool to find "missing baryons"

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kSZ with LSST

- Most common estimator: mean pairwise momentum

$$\hat{T}_{\rm kSZ} = \frac{\sum_{ij} c_{ij} T_{ij}}{\sum_{ij} c_{ij}^2} \qquad c_{ij} \equiv \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2} = \frac{(r_i - r_j)(1+\cos\theta)}{2\sqrt{r_i^2 + r_j^2 - 2 r_i r_j \cos\theta}}$$

- The challenge: photometric redshift errors

Also: Ferreira+ (1999); Hand+ (2012); Planck+ (2015); Flender+ (2015)

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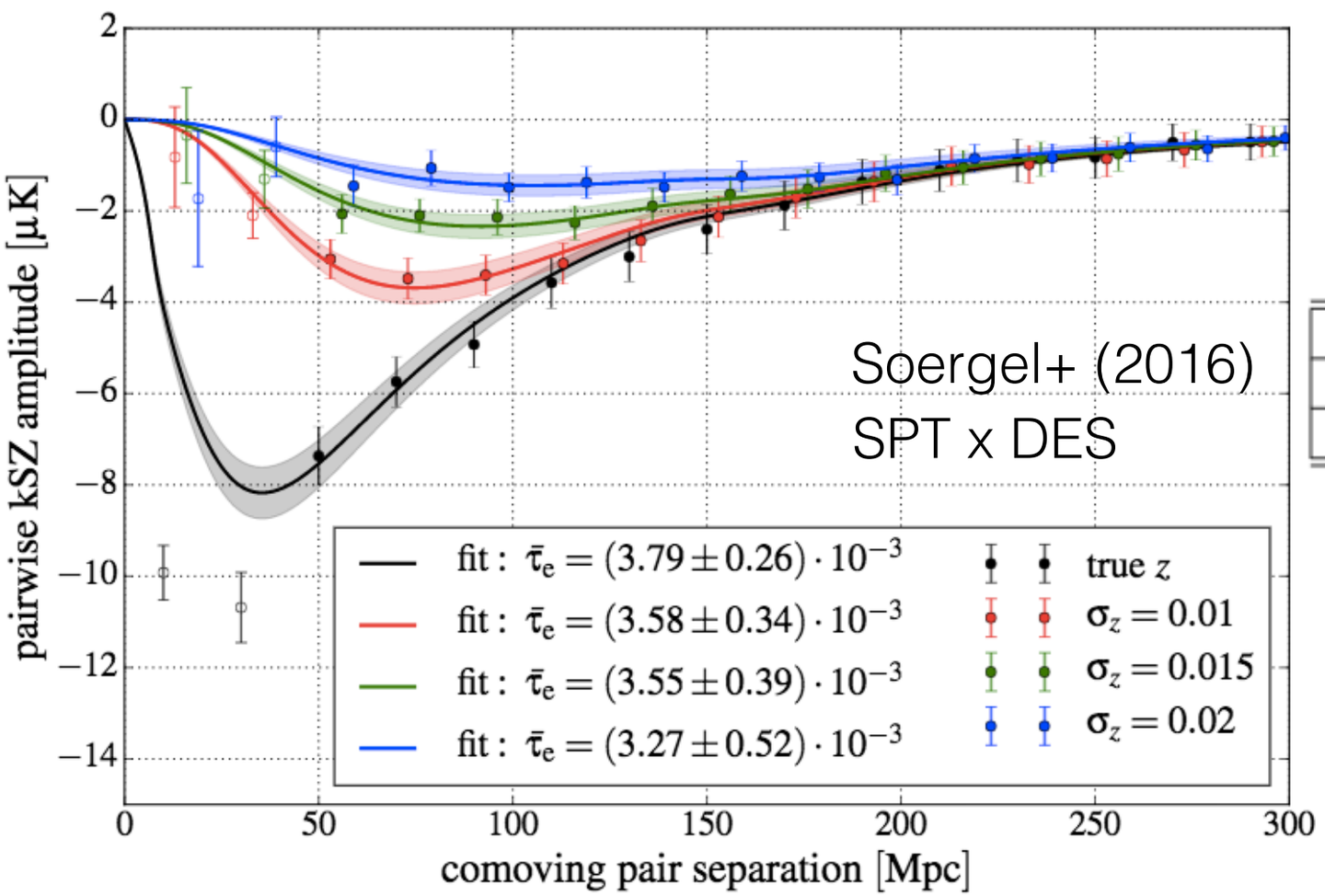

Soergel+ (2016)
SPT x DES

30-50% degradation in S/N compared to spec-z

	DES-*base* (photo-z)	DES-*base* (spec-z)
SPT-SZ	8.2σ (12%)	12.5σ (8.0%)
SPT-3G	18σ (5.5%)	26σ (3.9%)

Keisler & Schmidt (2013)

- Is there another way to use photometric data for kSZ?

Also: Ferreira+ (1999); Hand+ (2012); Planck+ (2015); Flender+ (2015)

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kSZ Methods

- All detections thus far rely on cross-correlations

- Standard estimators:
  - mean pairwise momentum statistic
  (Hand+2012, Planck+2015, Soergel+2016)
  - velocity field reconstruction + stacking
  (Planck+2015, Schaan+2015)

$$\tilde{p}_{\rm pair}(r) = \frac{\sum_{i<j}(\mathbf{p}_i \cdot \hat{\mathbf{r}}_i - \mathbf{p}_j \cdot \hat{\mathbf{r}}_j)c_{ij}}{\sum_{i<j} c_{ij}^2}$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{v} + f \boldsymbol{\nabla} \cdot [(\boldsymbol{v} \cdot \hat{\boldsymbol{n}})\, \hat{\boldsymbol{n}}] = -aHf\, \frac{\delta_g}{b}$$

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- Both methods require spectroscopic data (or very good photo-*z*)

- Hand+ (ACT/BOSS): N=27000 f_{sky}=0.008 3σ
  Planck+ (SDSS): N=260000 f_{sky}=0.15 1.8-3.7σ
  Schaan+ (ACTPol/BOSS): N=26000 f_{sky}=0.016 3.3σ
  Soergel+ (SPT/DES): N=6700 f_{sky}=0.03 4σ

- Our method (Planck/WMAP/WISE): N=46 million f_{sky}=0.45 3.8-4.5σ

JCH+ (2016); Ferraro, JCH+ (2016)

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Novel kSZ Estimator

Main idea: CMB T already contains kSZ information

- Ideal frequency-cleaned CMB temperature map contains contributions from:
  - ISW (L<100) + RS/non-linear ISW (higher L, but small)
  - Primordial T (2<L<3000)
  - kSZ (primarily L>2000)

Dore+ (2004); DeDeo+ (2005); JCH+ (2016); Ferraro, JCH+ (2016)

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- Construct extremely clean T map, then Wiener filter for kSZ

- Cross-correlate with LSS tracer (*projected* in 2D)
  - But <T x LSS> vanishes because of $\mathbf{v} \longleftrightarrow -\mathbf{v}$ symmetry
  - Simplest fix: square in real space, measure $\langle T^2 \times \mathrm{LSS} \rangle$
  - Measures a particular squeezed 3-pt function: $\langle \delta \mathbf{pp} \rangle$
  - Caution: CMB lensing leakage (quadratic in T)

Dore+ (2004); DeDeo+ (2005); JCH+ (2016); Ferraro, JCH+ (2016)

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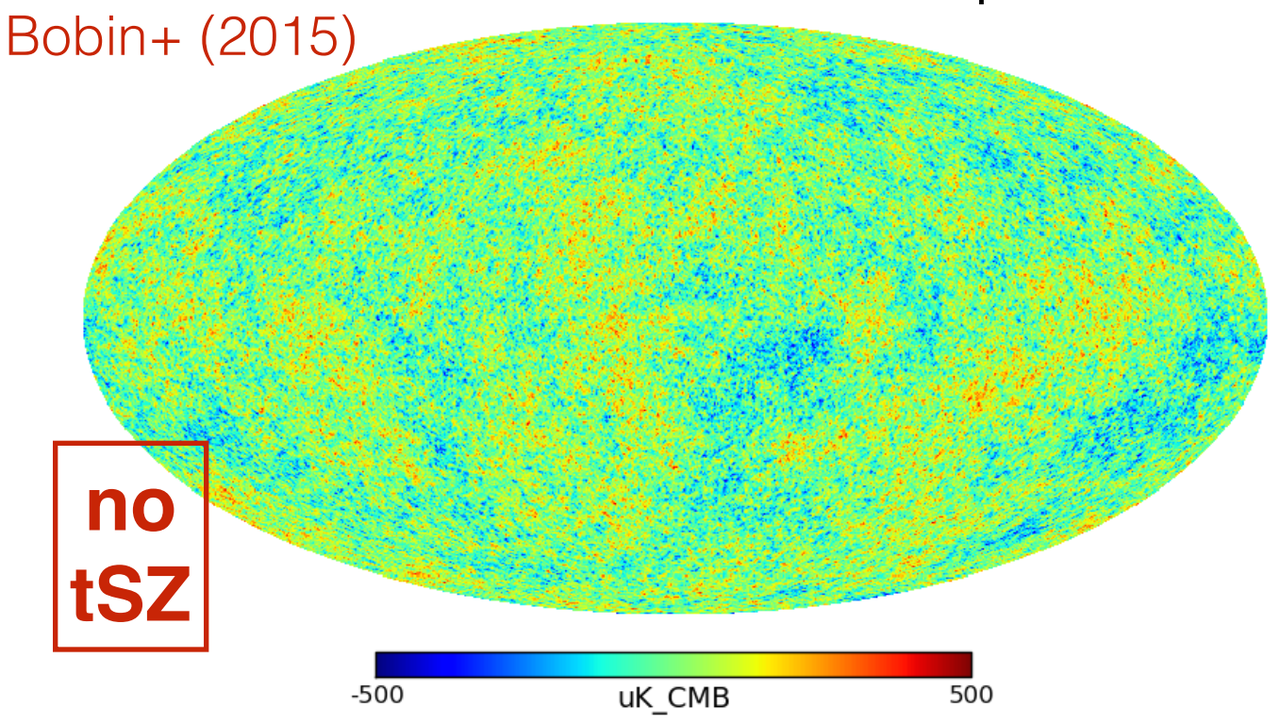
Data Analysis

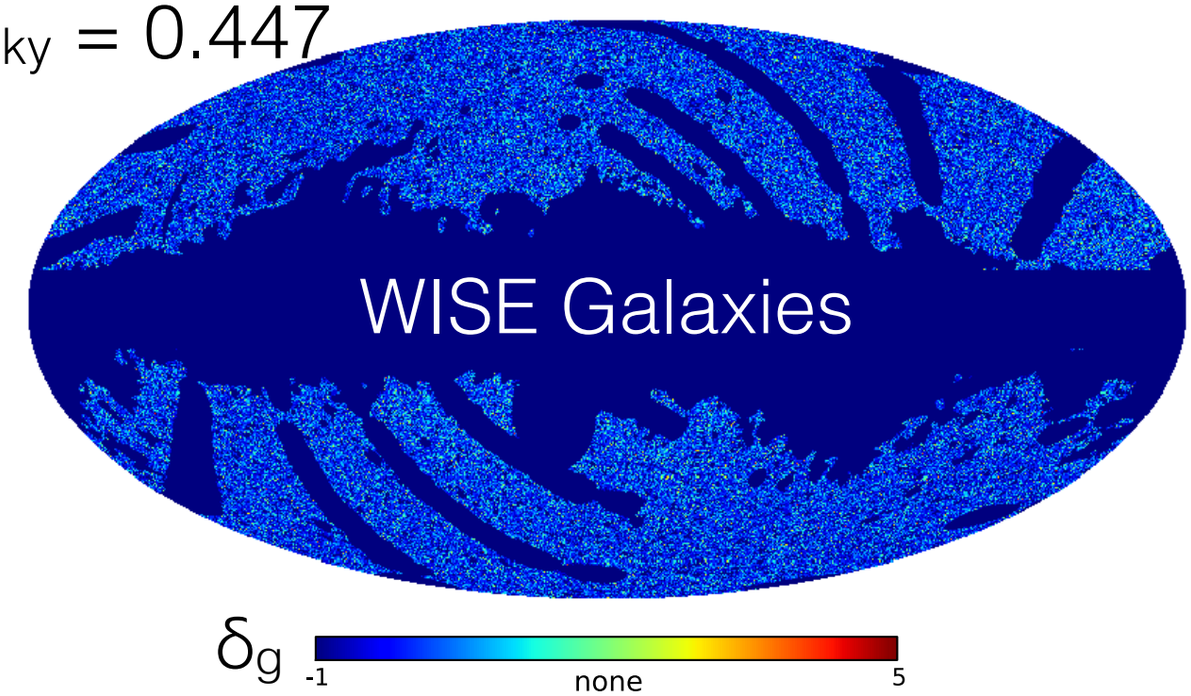
Planck/WMAP + WISE

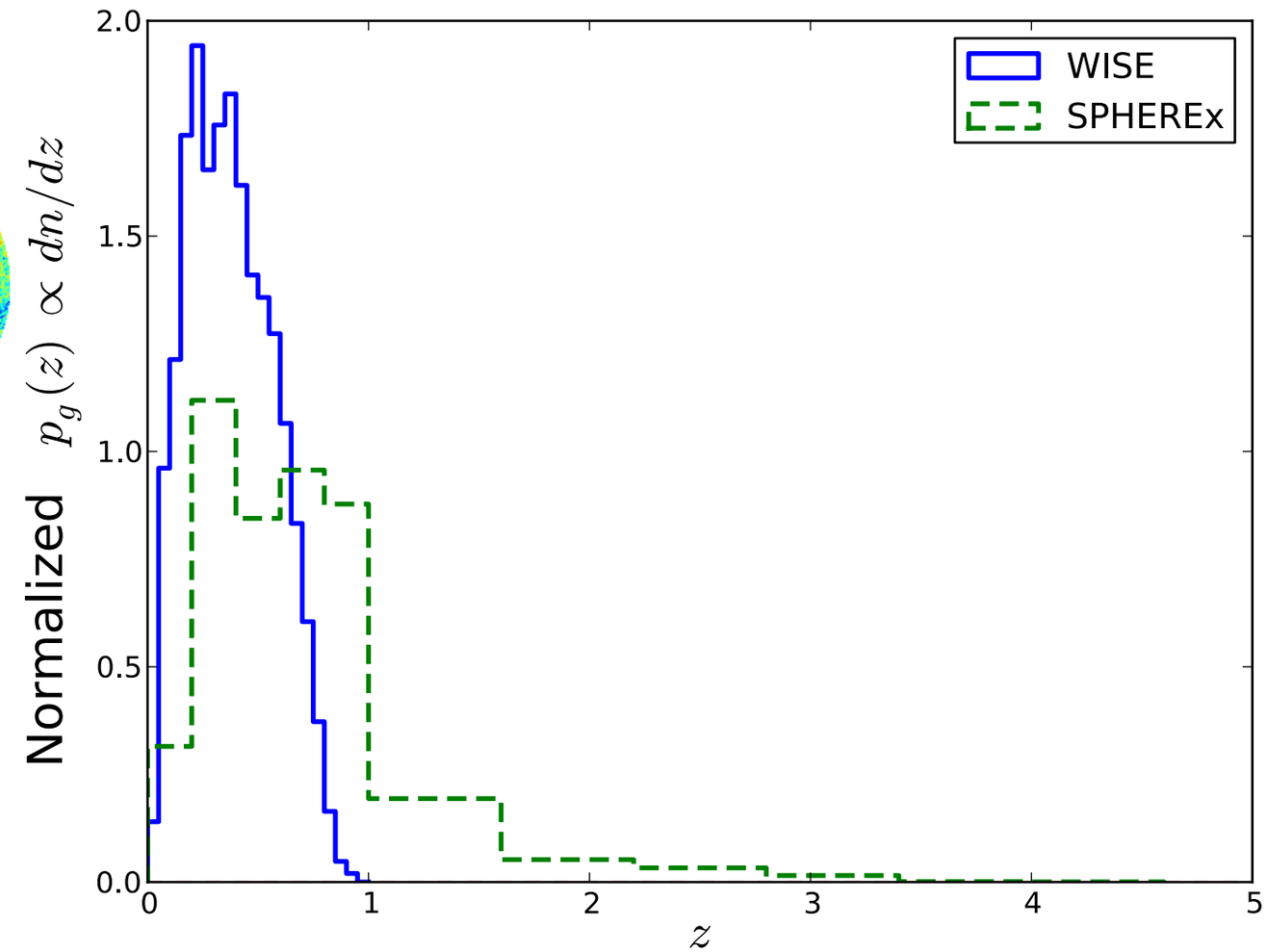
"LGMCA" CMB Map

Bobin+ (2015)



f_{sky} = 0.447





N_{gal} ~ 46 million

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

L ~ L*

JCH+ (2016)

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Planck/WMAP + WISE

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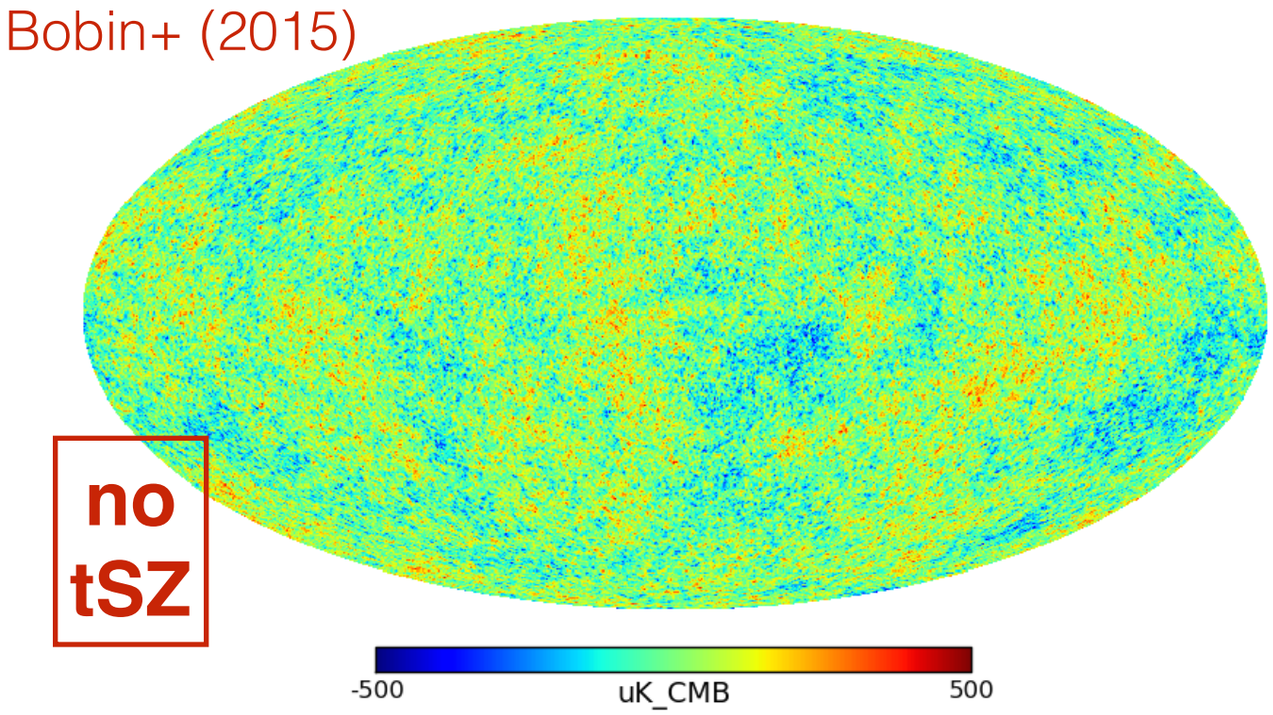

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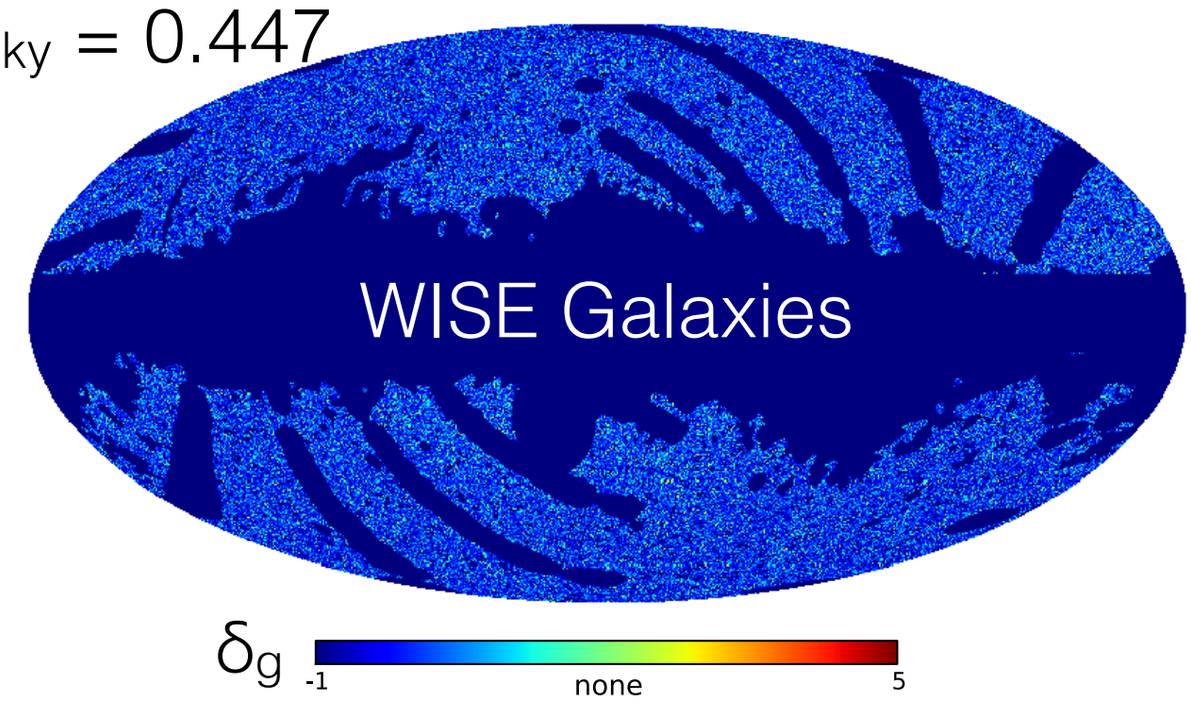
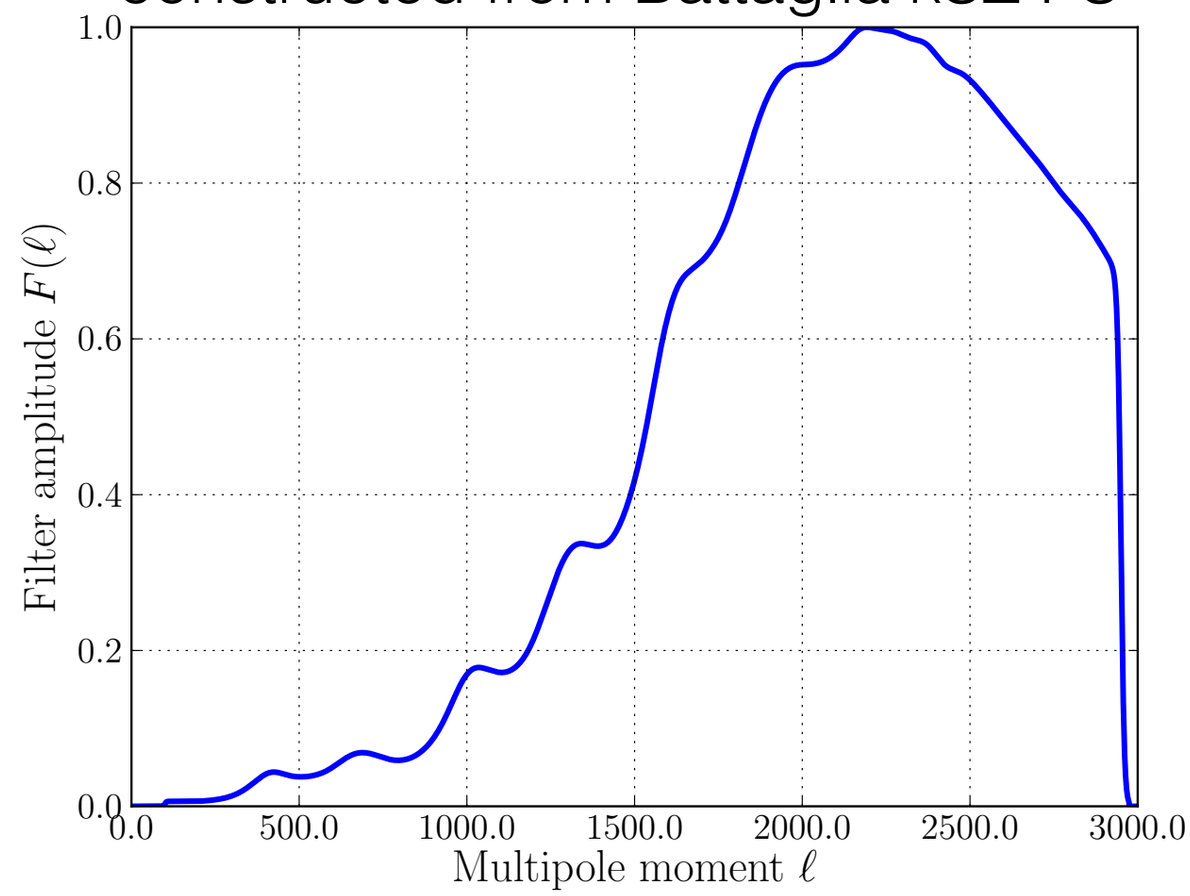


Wiener filter

constructed from Battaglia kSZ PS



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JCH+ (2016)

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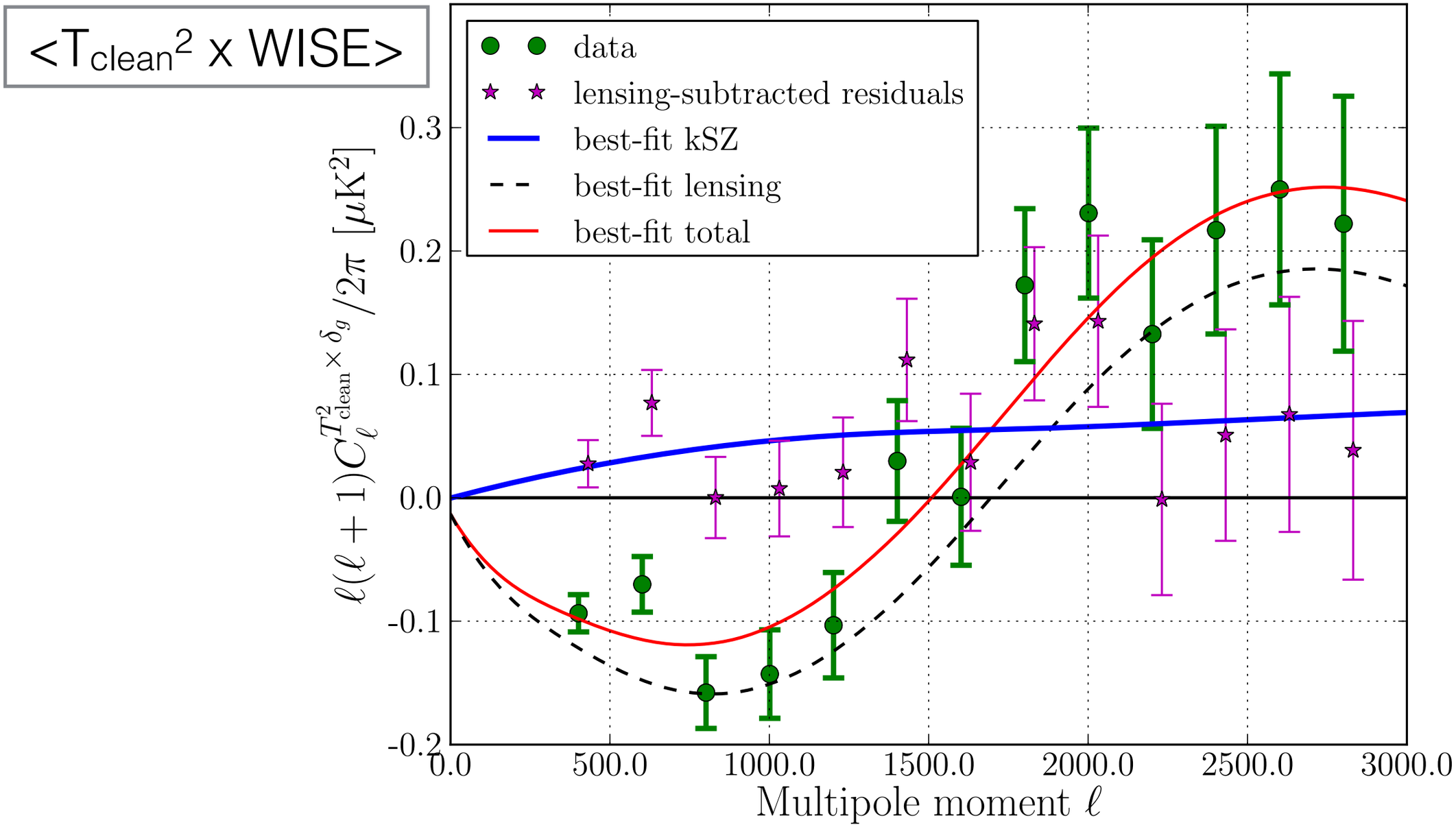
Data Analysis

Detection



JCH+ (2016)

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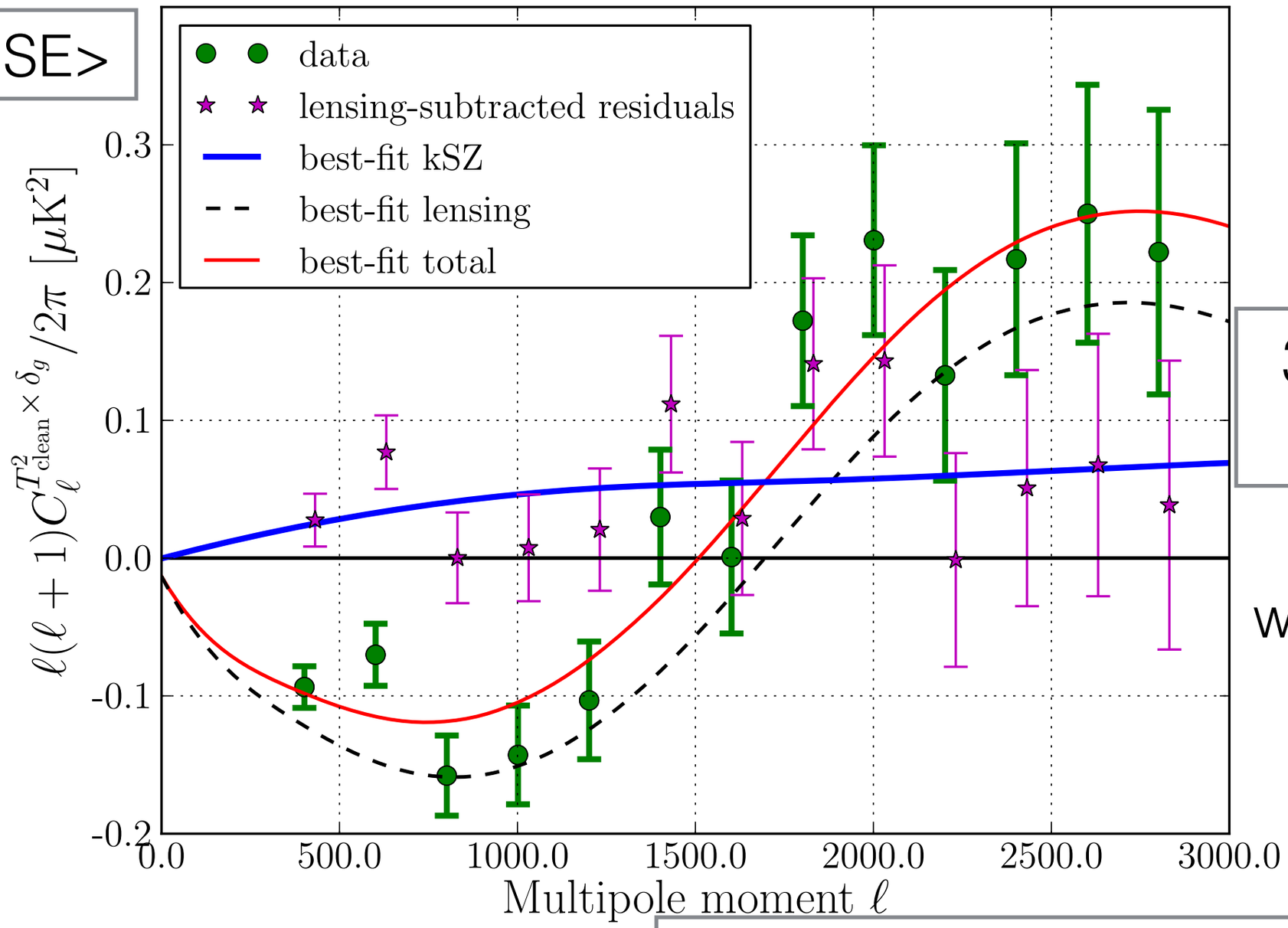
Data Analysis

Detection

<T_{clean}^2 x WISE>



3.8σ kSZ² detection

model fits well (p=0.28)

$$\left(C_\ell^{\mathrm{kSZ}^2\times\delta_g}\right)_{\mathrm{measured}} = b_g \mathcal{A}_{\mathrm{kSZ}^2} \left(C_\ell^{\mathrm{kSZ}^2\times\delta_g}\right)_{\mathrm{fiducial}}$$

A_{kSZ} = 2.18 +/- 0.57
b_g = 1.10 +/- 0.11

JCH+ (2016)

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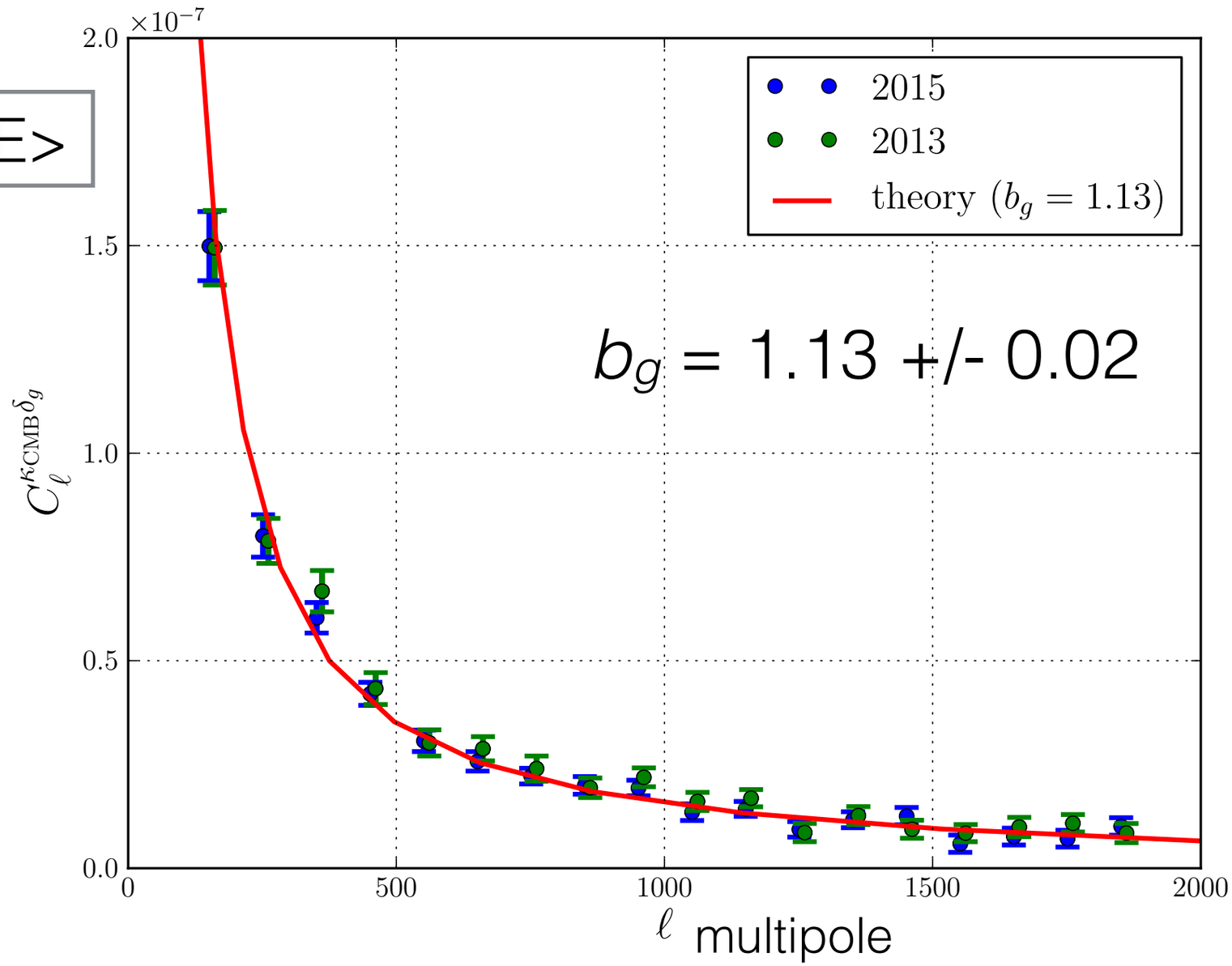
Data Analysis

External constraint on WISE galaxy bias from κ_{CMB}

<κ_{CMB} x WISE>



Consistent bias values are also an important test for the <T^2 x WISE> framework

JCH+ (2016)

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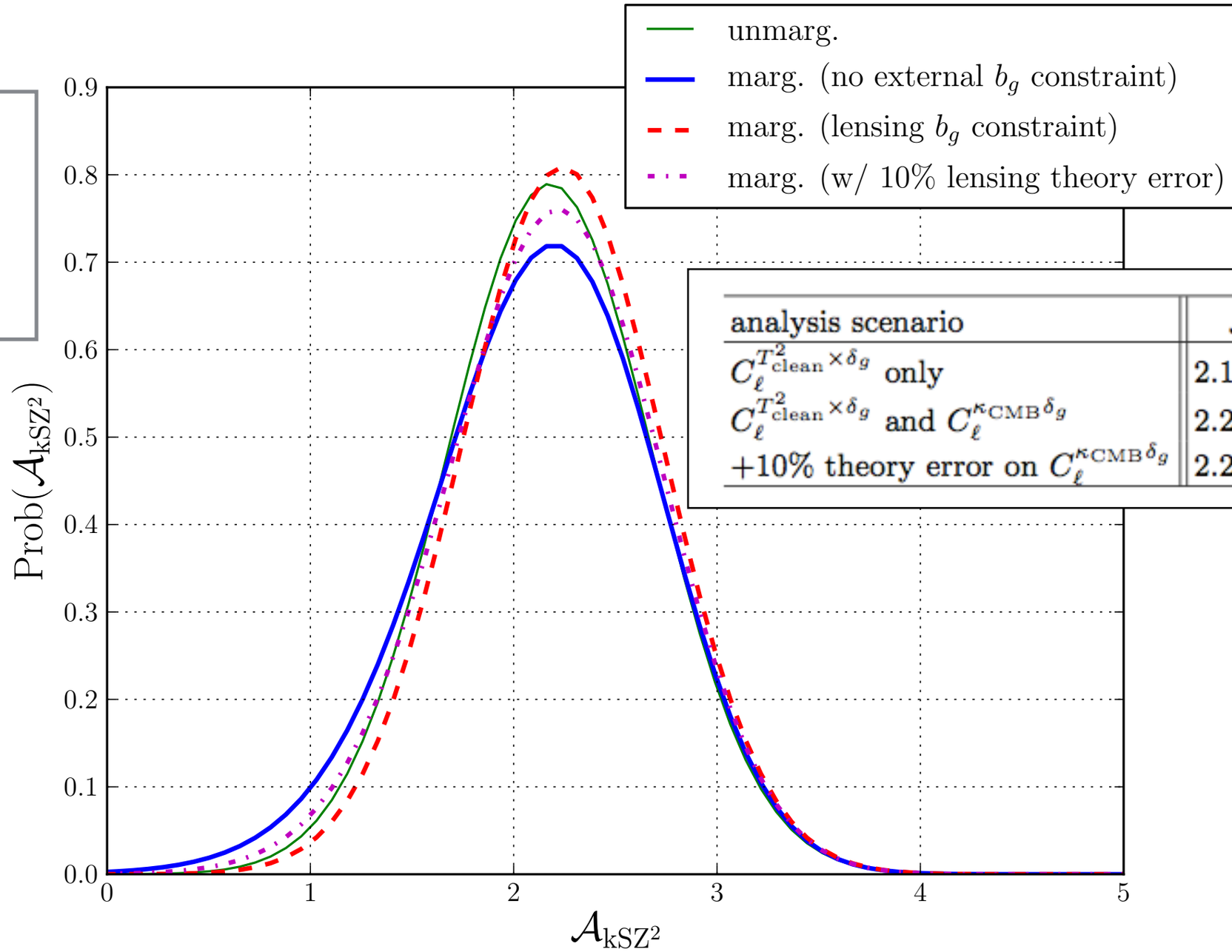
Interpretation

3.8-4.5σ
kSZ^2
detection



analysis scenario	$\mathcal{A}_{\mathrm{kSZ}^2}$	b_g
$C_\ell^{T^2_{\mathrm{clean}}\times\delta_g}$ only	2.18 ± 0.57	1.10 ± 0.11
$C_\ell^{T^2_{\mathrm{clean}}\times\delta_g}$ and $C_\ell^{\kappa_{\mathrm{CMB}}\delta_g}$	2.24 ± 0.50	1.13 ± 0.02
+10% theory error on $C_\ell^{\kappa_{\mathrm{CMB}}\delta_g}$	2.21 ± 0.53	1.11 ± 0.08

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

N.B. theoretical systematics at ~10s% (e.g., NL bispectrum, σ_8/parameters, …)

JCH+ (2016); Ferraro, JCH+ (2016)

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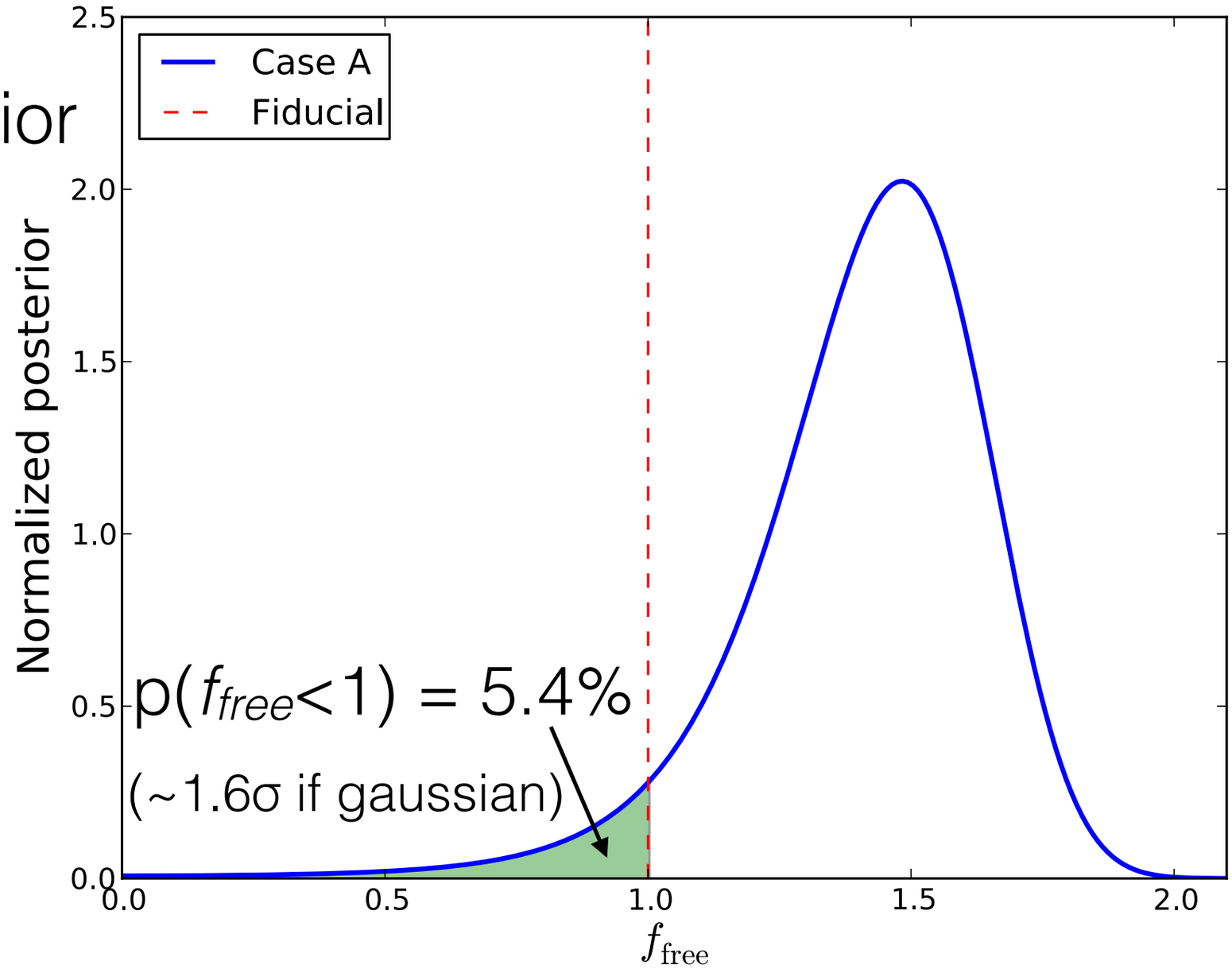
Interpretation

f_{free} posterior



(for fiducial analysis w/ no external b_g info)

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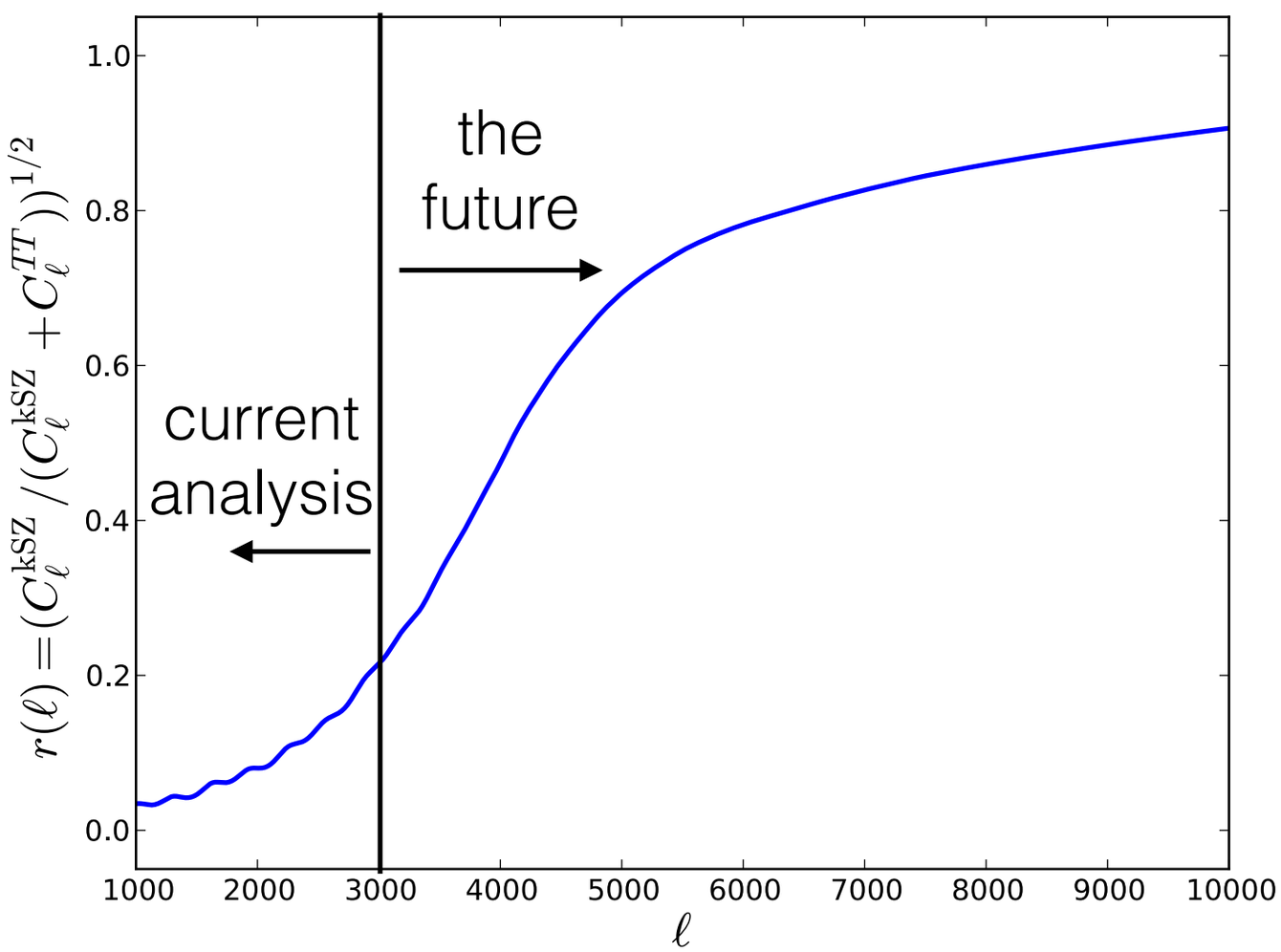
Forecasts/Outlook

Large improvement expected with higher resolution

Cross-correlation coefficient of kSZ and blackbody T fields



Key issue:
multi-frequency component separation
➔AdvACT (+Planck)

Ferraro, JCH+ (2016)

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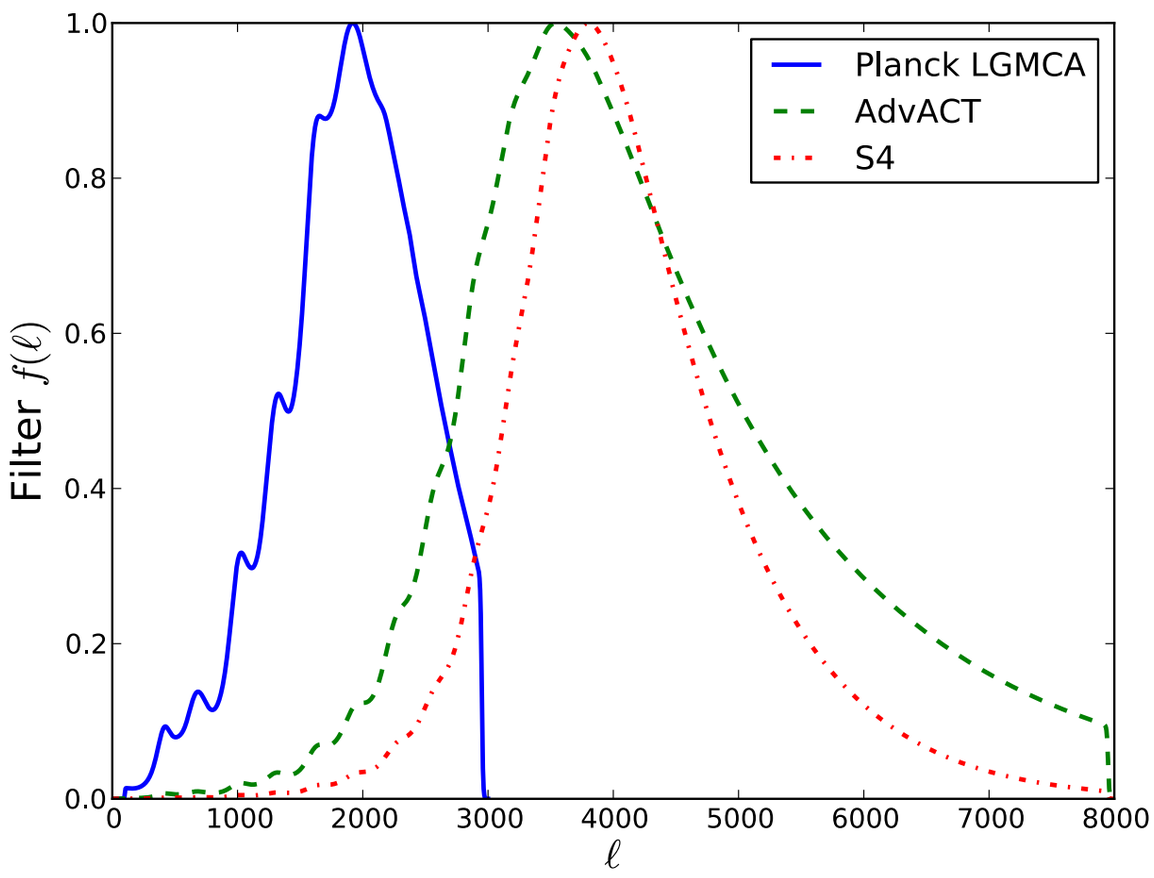
Forecasts/Outlook

Large improvement expected with higher resolution

CMB experiment	beam FWHM [arcmin]	effective noise[a] Δ_T [μK-arcmin]
Planck (2015 LGMCA map)	5	47
Advanced ACTPol	1.4	10
CMB-S4 (case 1) [b]	3	3
CMB-S4 (case 2)	1	3
CMB-S4 (case 3)	3	1
CMB-S4 (case 4)	1	1



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	$f_{\rm sky}$	ℓ range	$\left(\frac{\Delta f_{\rm free}}{f_{\rm free}}\right)^{-1}$
Planck × *WISE*	0.7	100 - 3000	5.2
Planck × *SPHEREx*	0.7	100 - 3000	5.4
Advanced ACTPol × *WISE*	0.5	100 - 8000	232
Advanced ACTPol × *SPHEREx*	0.5	100 - 8000	280
CMB-S4 (case 1) × *WISE*	0.5	100 - 8000	296
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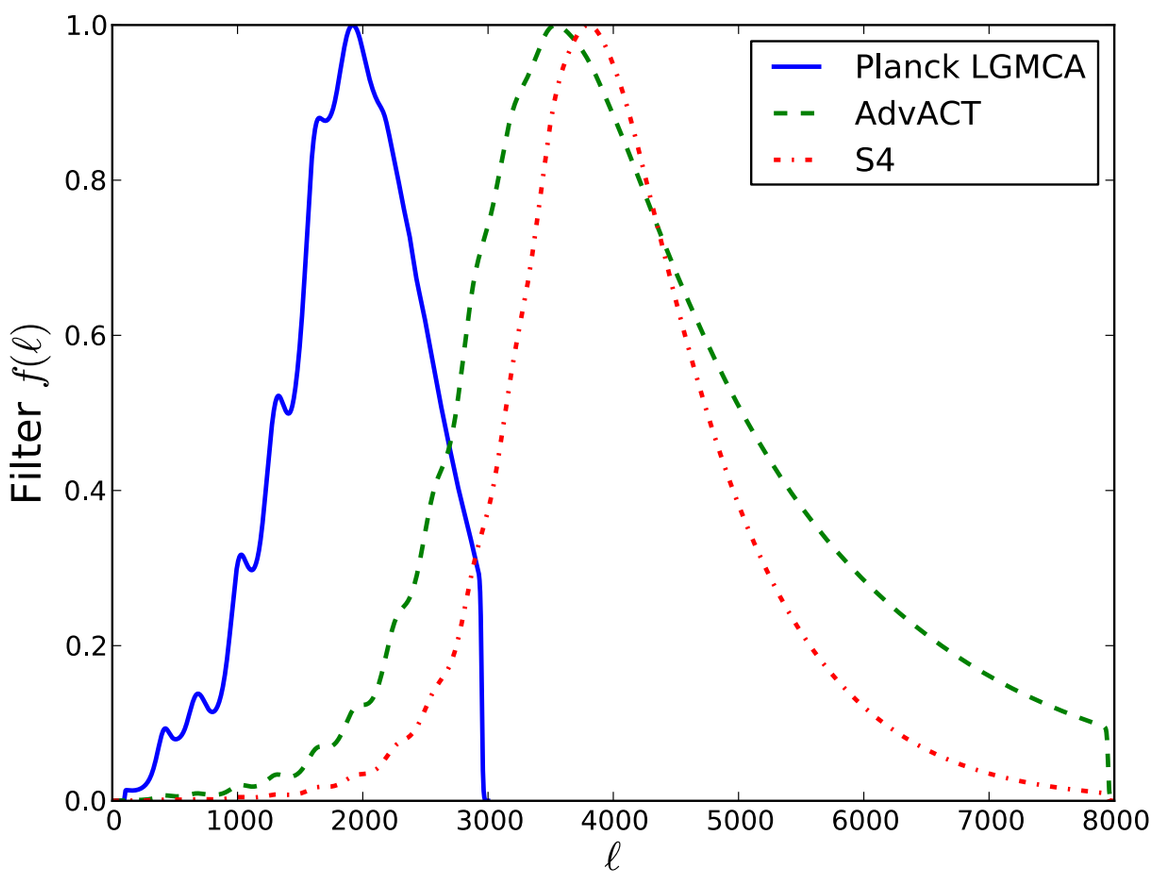

will likely be limited by component separation

Ferraro, JCH+ (2016)

Forecasts/Outlook

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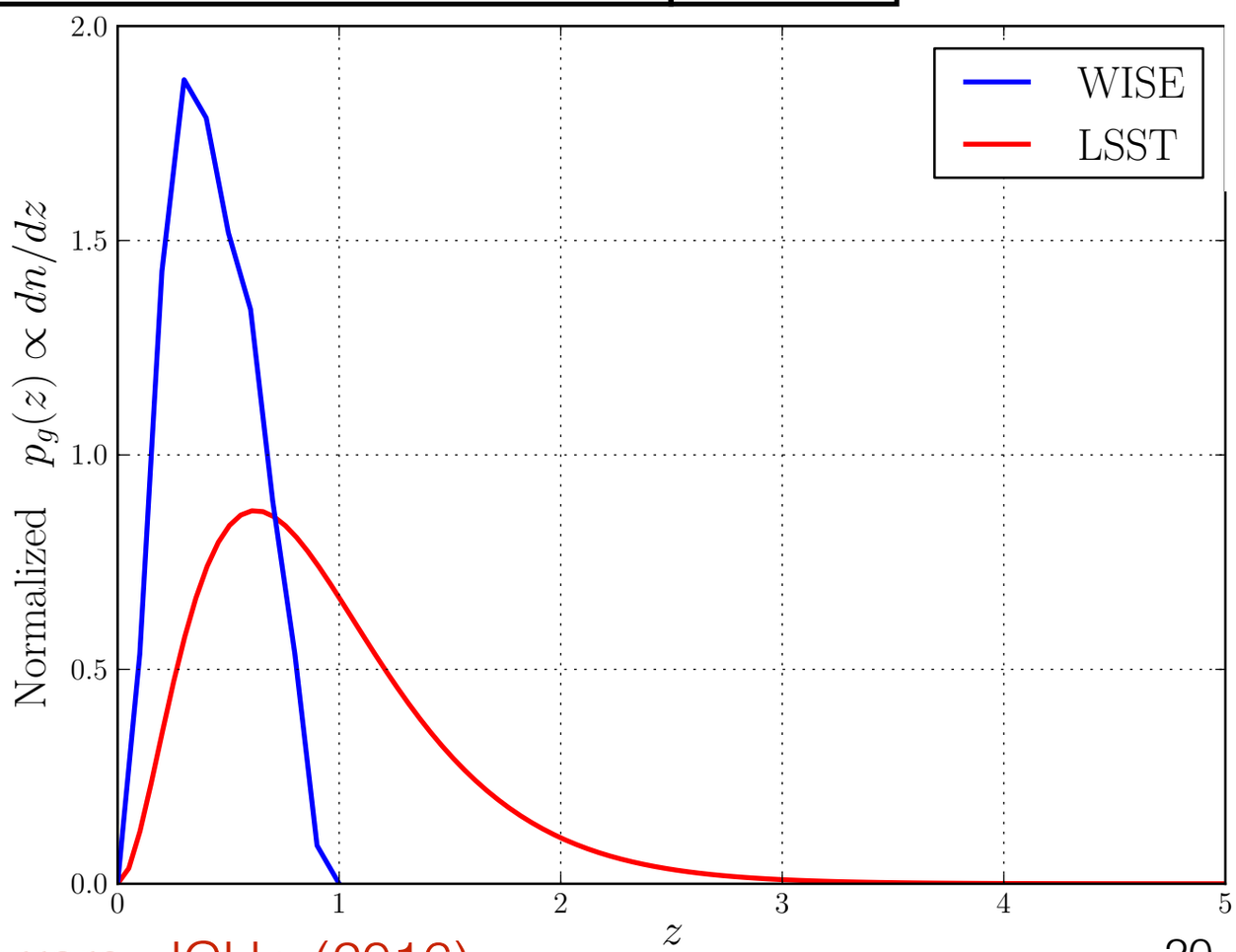
LSST f_{sky}=0.4; 26 gal/arcmin^2
preliminary

x AdvACT	326
x CMB-S4 (case 1)	402
x CMB-S4 (case 2)	1032
x CMB-S4 (case 3)	1006
x CMB-S4 (case 4)	1230



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Forecasts/Outlook

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

e.g.: AdvACT x DESI (pairwise): 20-50σ (Flender+2015)
AdvACT x LSST (proj. field): ~150σ (WISE ~100σ)

Unique possibility w/ projected fields: lensing maps as LSS tracer!

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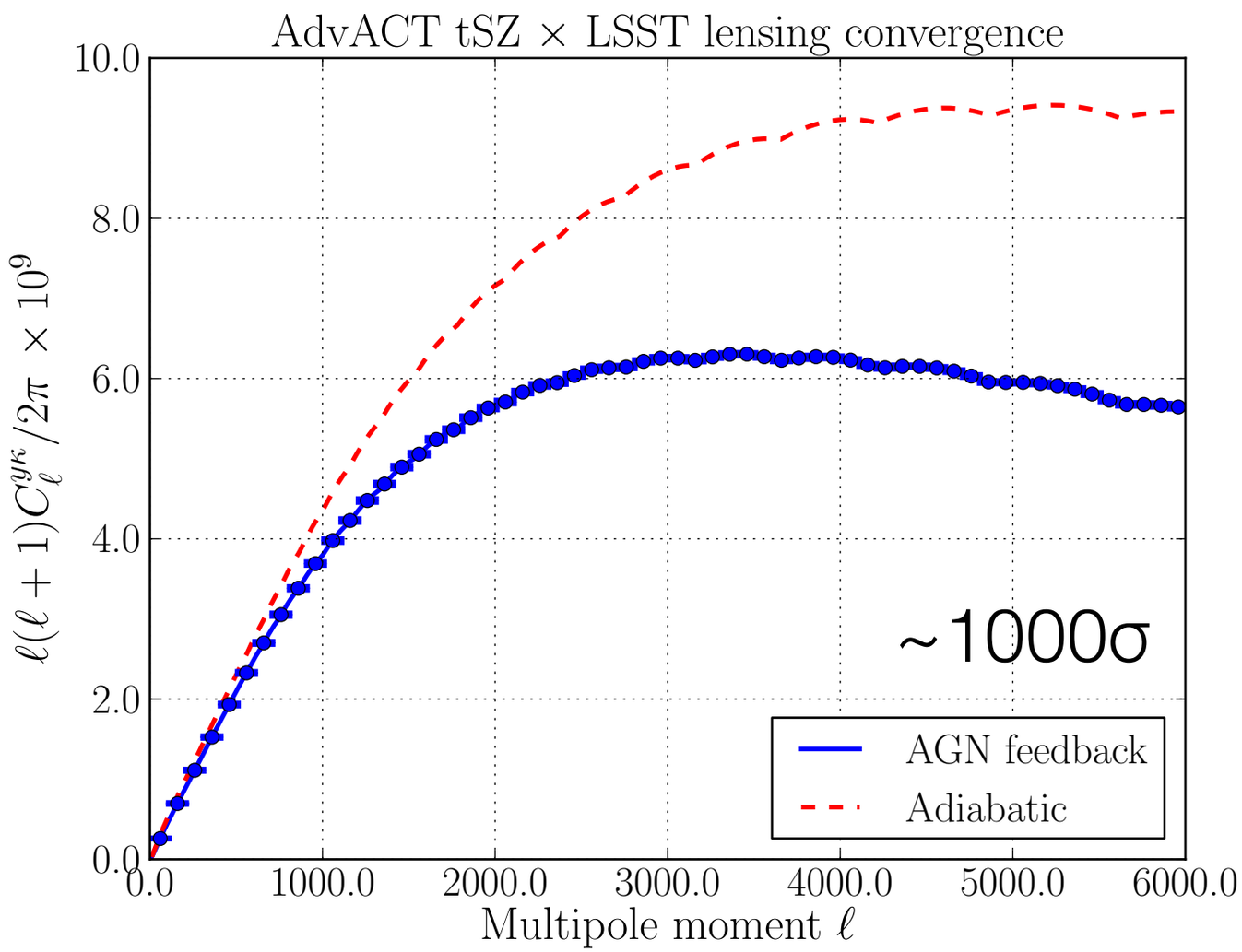

analogous to tSZ x LSST κ (shown here)

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What can we learn?

- Joint tSZ/kSZ measurements constrain n_e and T_e
  ⟶ precise baryon profiles + non-thermal pressure
- Tomographic breakdown
- Precise feedback constraints
- Low-z τ (improves reionization constraints)
- Growth of structure: dark energy/gravity/ massive neutrinos
  ⟶ potentially competitive with e.g. RSD (Alonso+2016)

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Thanks!

Bonus

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Novel kSZ Estimator

- Consider $\langle T_f^2(\mathbf{x})\ \delta_{\rm tr}(\mathbf{y})\rangle$

Filtered temperature squared in real space

Matter tracer (galaxies, AGNs, lensing convergence…)

- If only kSZ: $\sim \langle \delta v\ \delta v\ \delta_g \rangle$ → $b\delta$ for galaxies

$$\sim \langle vv\rangle\langle \delta\delta\delta_g\rangle + \langle v\delta\rangle\langle v\delta\delta_g\rangle + \ldots$$

Fourier Transform
Project along line of sight

$$C_\ell^{{\rm kSZ}^2\times\delta_g}$$

Assumptions (for now):
- Linear bias
- NL bispectrum fit
- Linear theory for $\delta \to v$
- Planck parameters

Doré et al (2003)
DeDeo et al (2005)
JCH, Ferraro et al (2016)
Ferraro, JCH et al (2016)

Planck x WISE Fisher ~ 3σ

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Novel kSZ Estimator

Why do this?

- Does **not** require spectroscopic LSS data! (not even photo-*z*, necessarily) — *projected fields*
- Can probe a wide range of physical scales — directly probe the baryon profile
- Halo mass estimates not needed to infer f_b
- For high-res experiments (e.g., AdvACT/CMB-S4), this estimator can yield very high S/N (because high-L T is kSZ)
- Complementary to other methods

JCH+ (2016); Ferraro, JCH+ (2016)

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Novel kSZ Estimator

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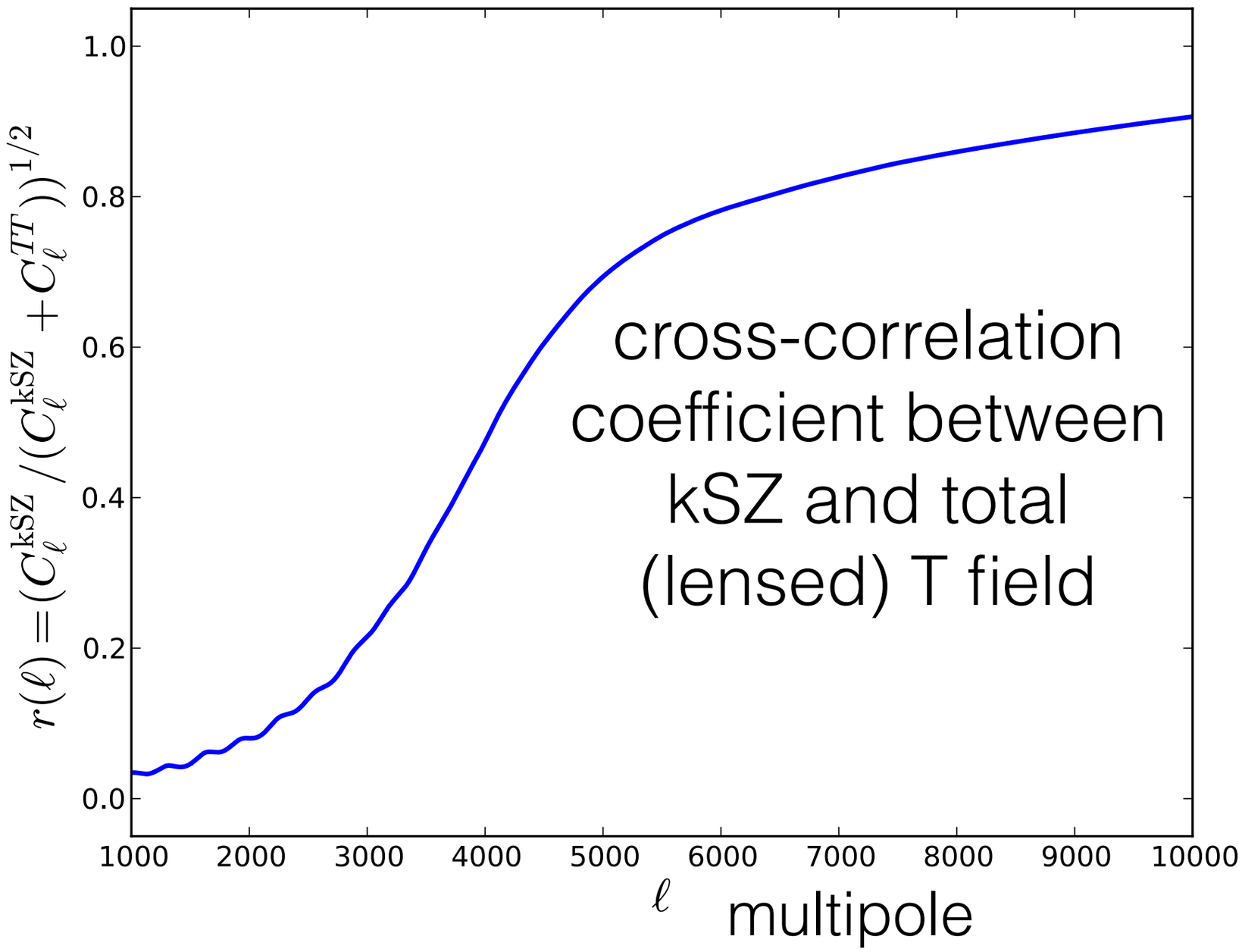

JCH+ (2016); Ferraro, JCH+ (2016)

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Novel kSZ Estimator

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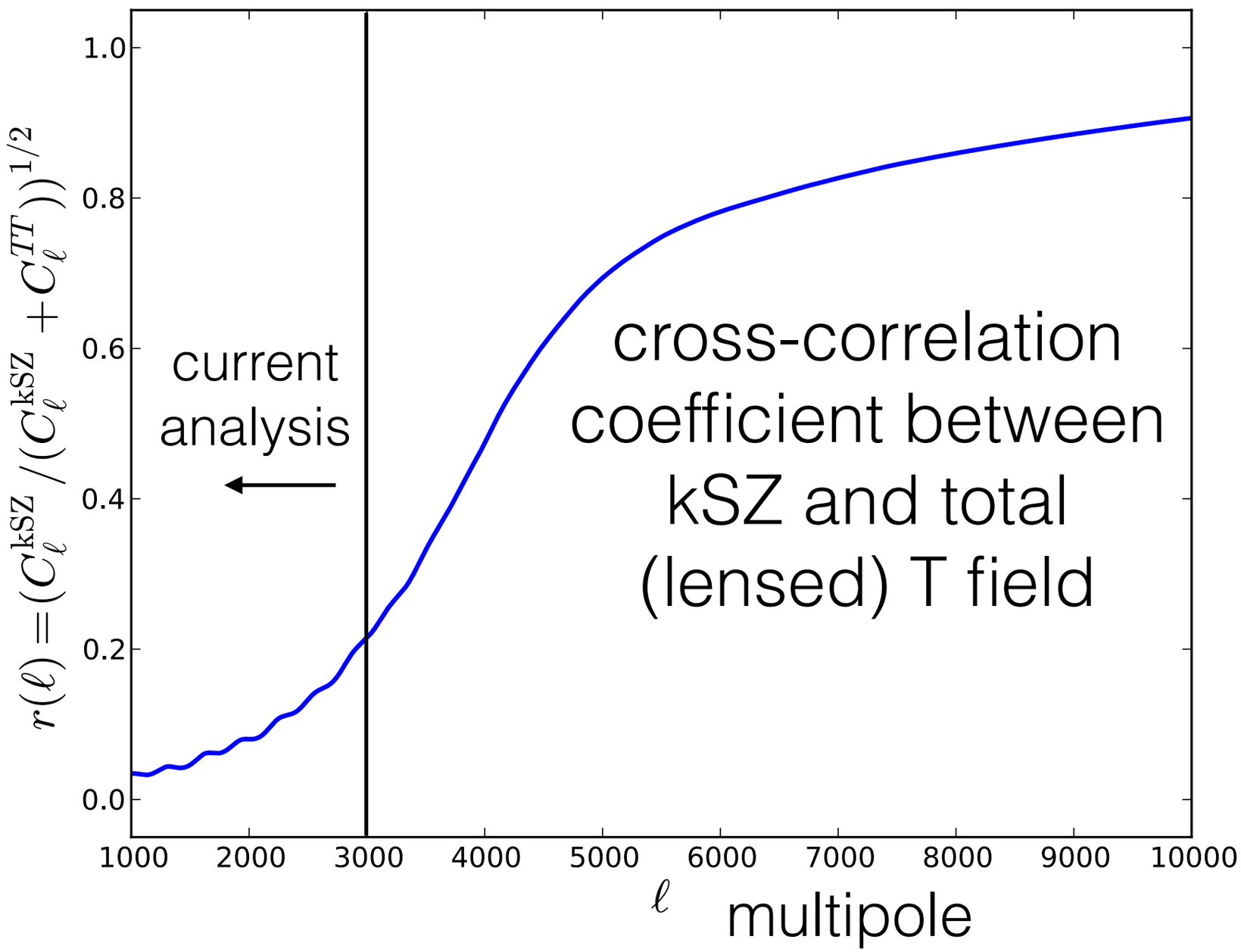

JCH+ (2016); Ferraro, JCH+ (2016)

Data Analysis

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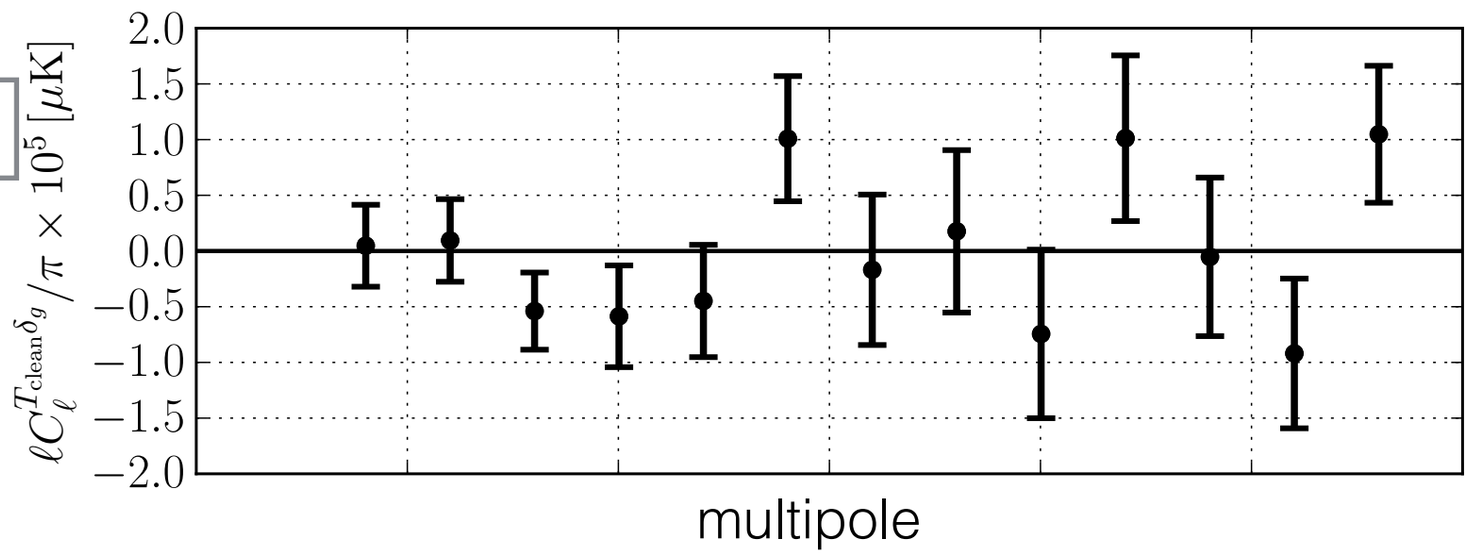
Extra Cleaning: Dust

- T_{dust} = CMB-free combination of 545 and 217 GHz (SFH14)
- $T_{clean} = (1+\alpha)T_{LGMCA} - \alpha * T_{dust}$ where α minimizes $\langle((1+\alpha)T_{LGMCA} - \alpha * T_{dust}) \times \mathrm{WISE}\rangle$ (α_{min} = -0.0002)

$\langle T_{clean} \times \mathrm{WISE}\rangle$

Test for any mean residual emission



p = 0.20
(p=0.08 w/ no cleaning)

Data Analysis

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$\langle T_{clean} \times \mathrm{WISE}\rangle$

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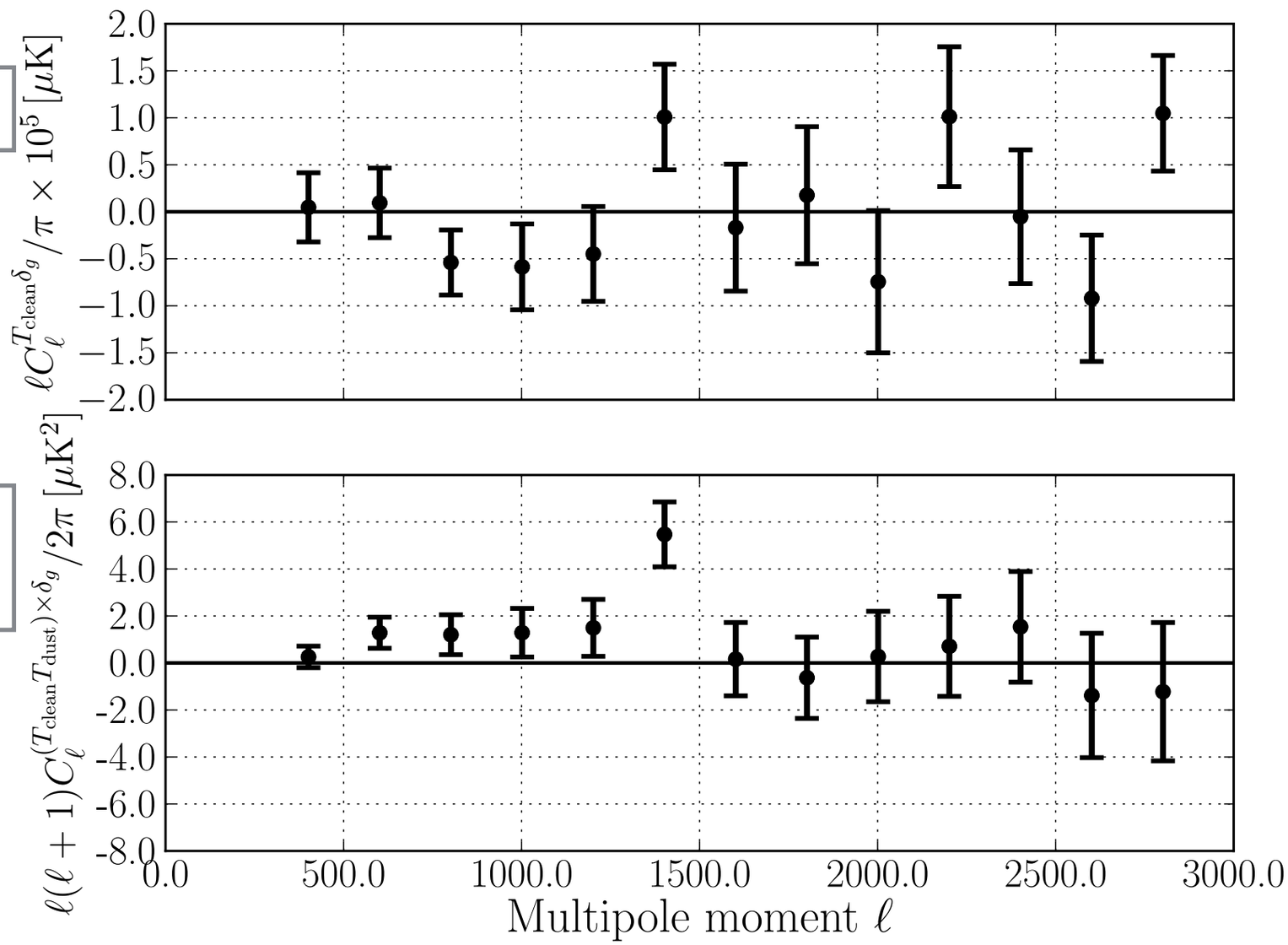

p = 0.20
(p=0.08 w/ no cleaning)

$\langle(T_{clean} * T_{dust}) \times \mathrm{WISE}\rangle$

Test for residual dust emission, including fluctuations

p = 0.02
but must rescale amplitude from 545 GHz to CMB channels

a factor ~400-500

+other null tests

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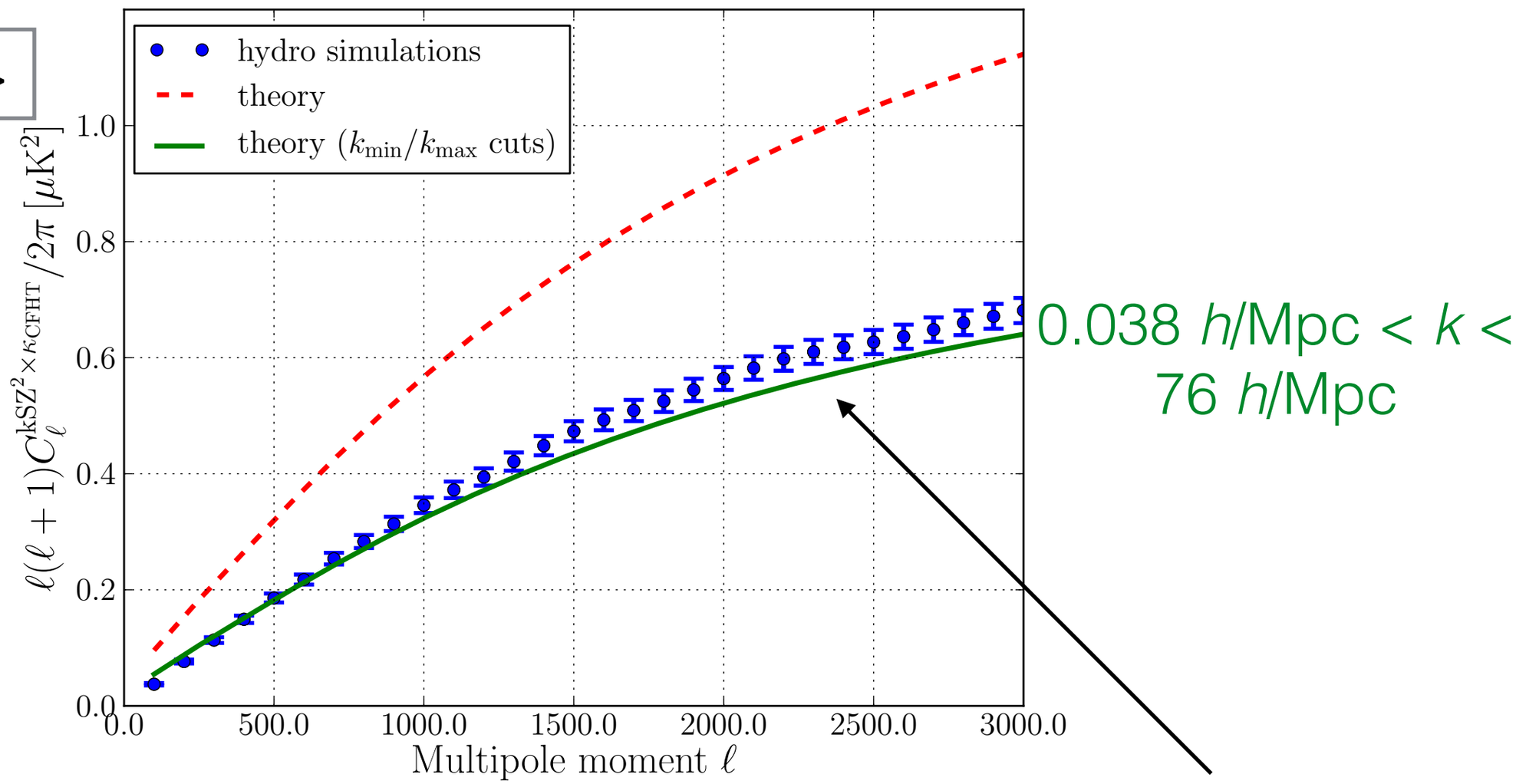
Simulation Tests

Comparison to Battaglia+ cosmological hydro sims.

sim. LSS tracer = CFHTLenS lensing convergence

<kSZ^2 x κ_{CFHT}>

(unfiltered)



must account for the effect of missing super-box long-wavelength modes on the velocity field (c.f. Park+ 2013)

(50% of <v_{rms}^2> comes from k < 0.06 h/Mpc)

Ferraro, JCH+ (2016)

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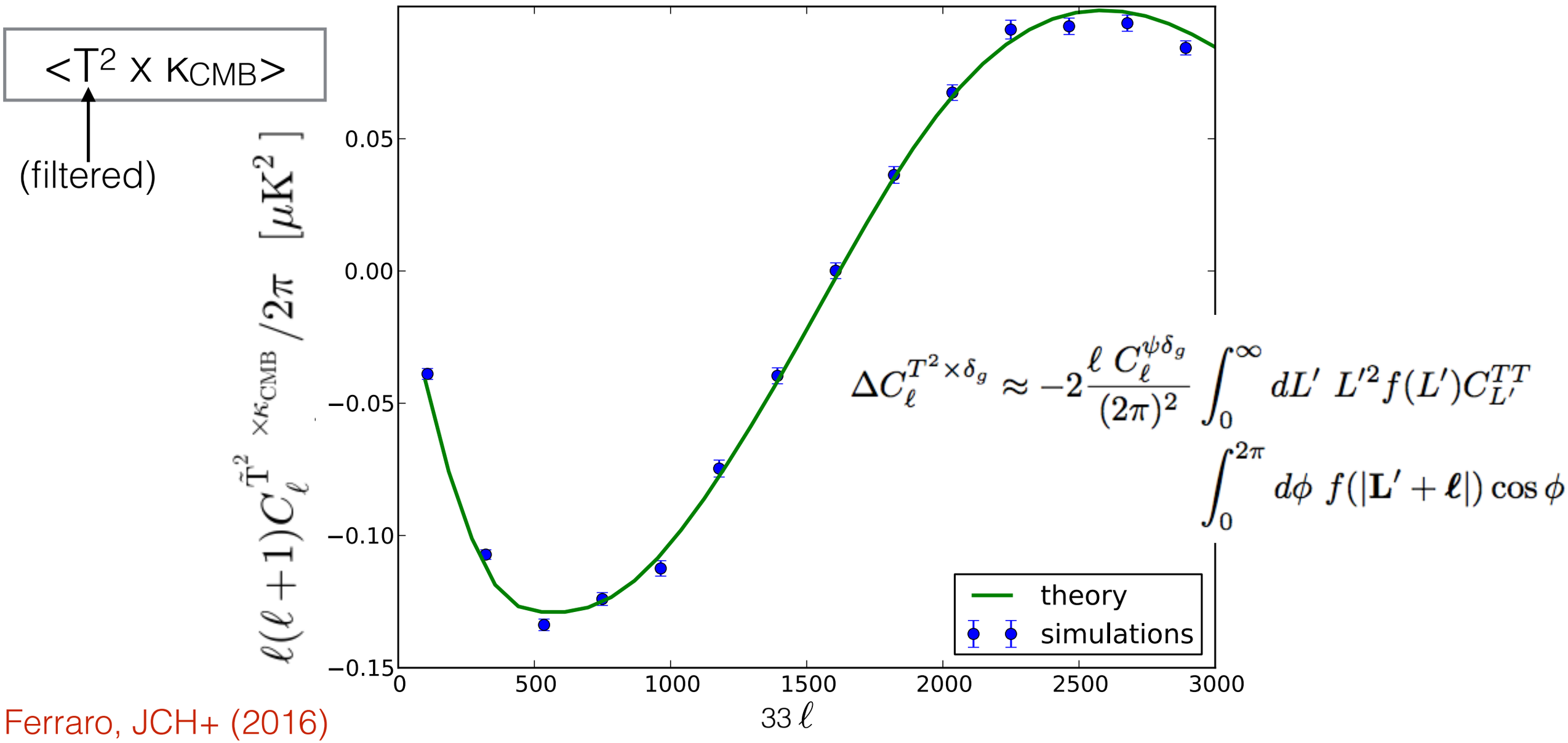
Columbia

Simulation Tests

Comparison to Sehgal+ sims (N-body/"painted gas")

sim. LSS tracer = CMB lensing convergence

verification of CMB lensing "leakage" calculation for kSZ^2



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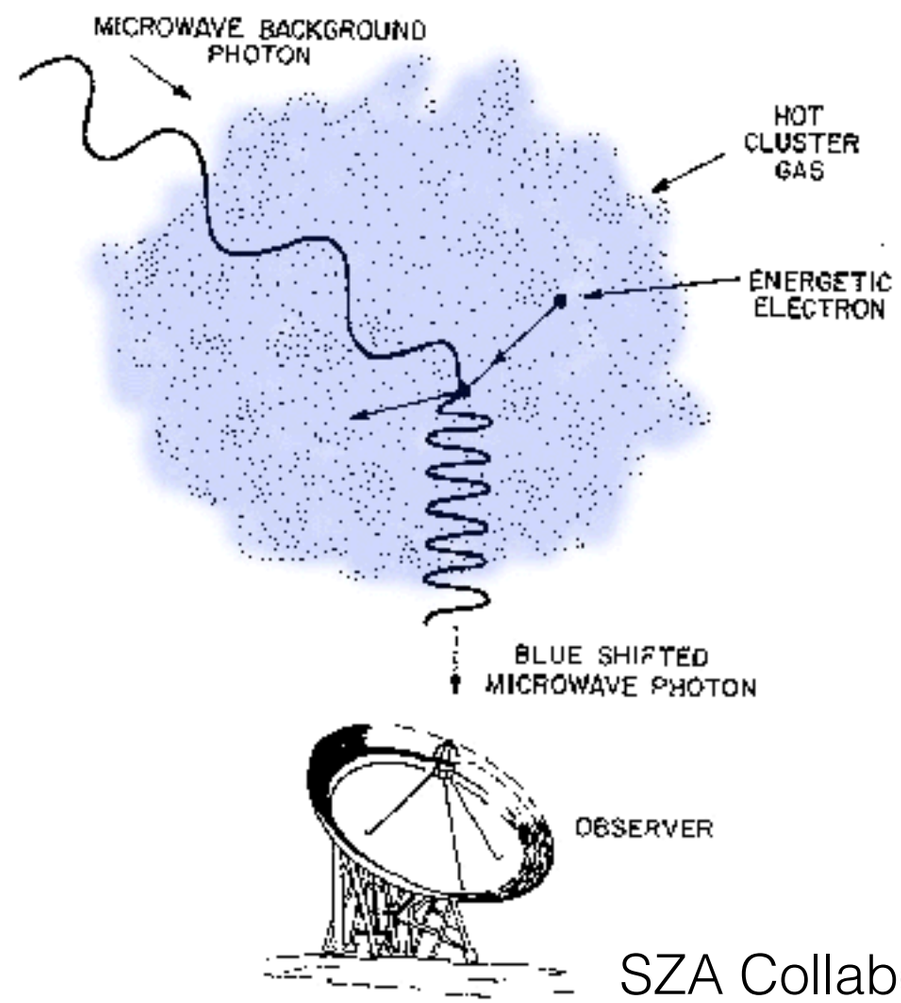
Thermal SZ Effect

Thermal SZ Effect:
Change in temperature of CMB photons due to inverse Compton scattering off hot electrons, most of which are in the intracluster medium (ICM) of galaxy clusters



SZA Collaboration

$$\frac{\tilde{T}}{T_{\rm CMB}} = g_\nu \frac{\sigma_T}{m_e c^2} \int P_e(l) dl$$

temperature fluctuation

Spectral function

Electron pressure profile

Line-of-sight integral

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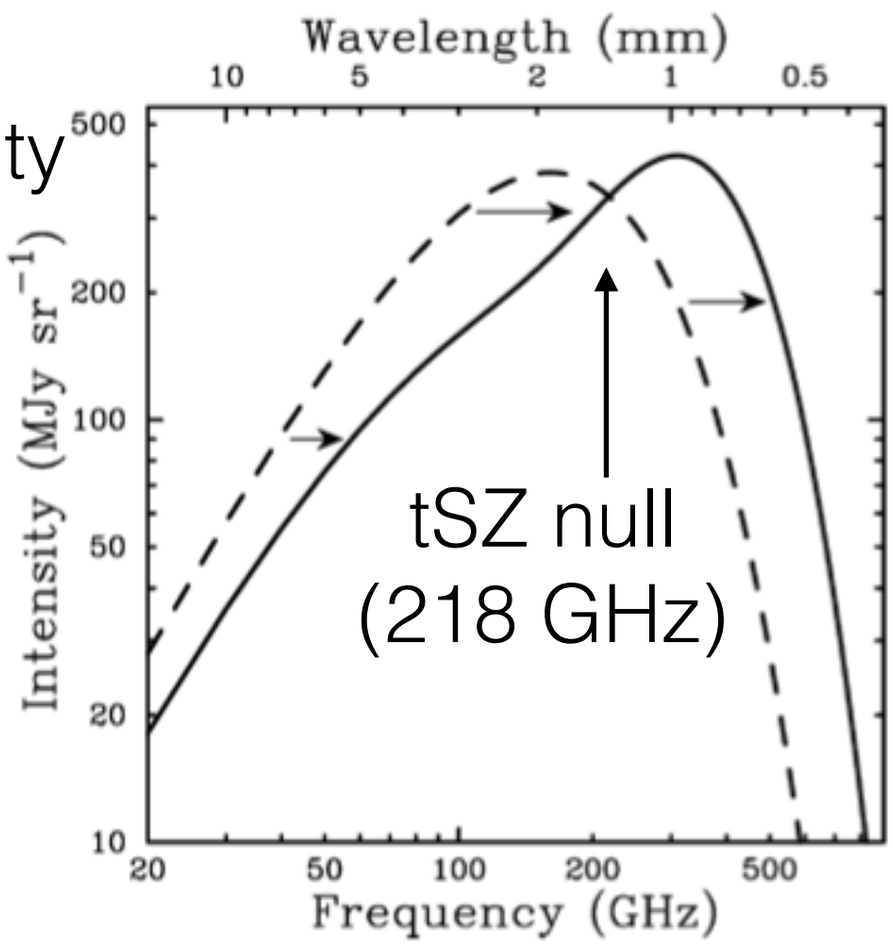
Thermal SZ Effect

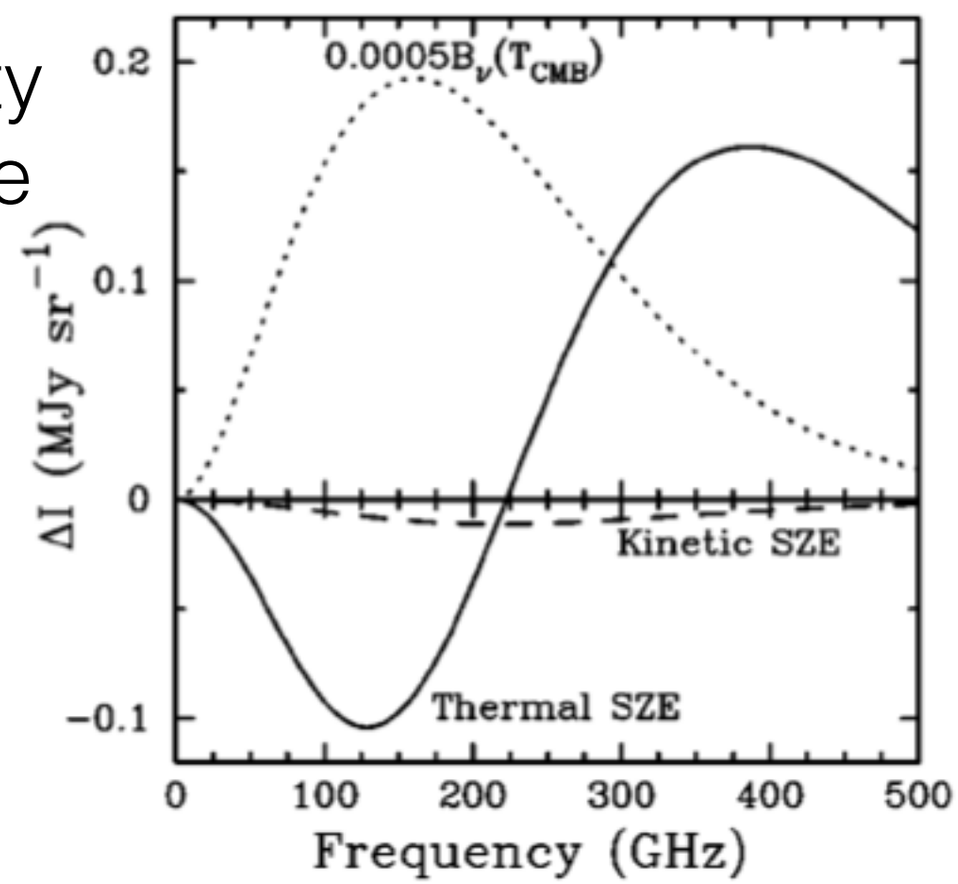
Unique spectral signature

intensity



frequency

intensity change



frequency

Carlstrom+ (2002)

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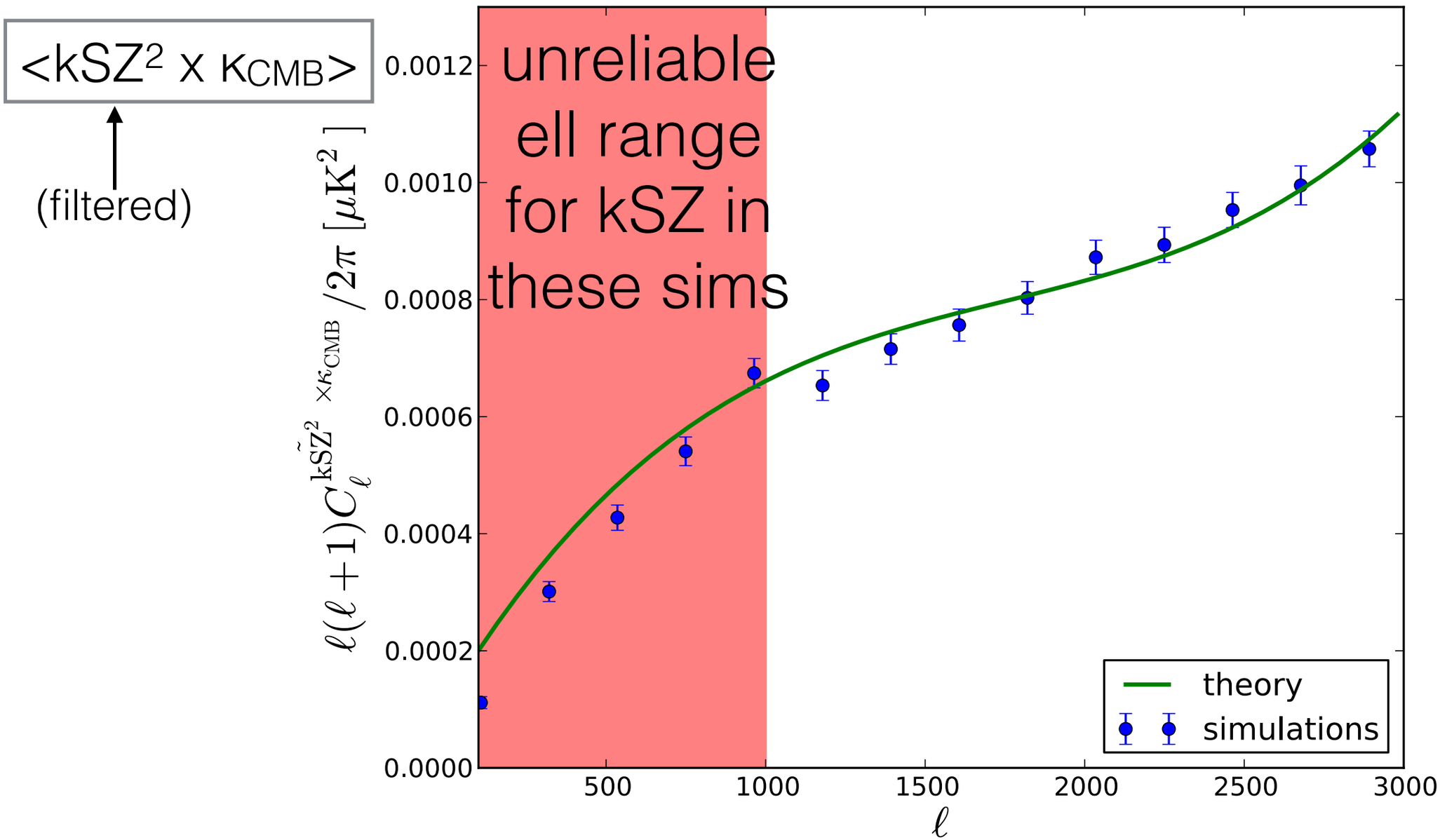
Simulation Tests

Comparison to Sehgal+ sims (N-body/"painted gas")

sim. LSS tracer = CMB lensing convergence



Ferraro, JCH+ (2016)

Interpretation

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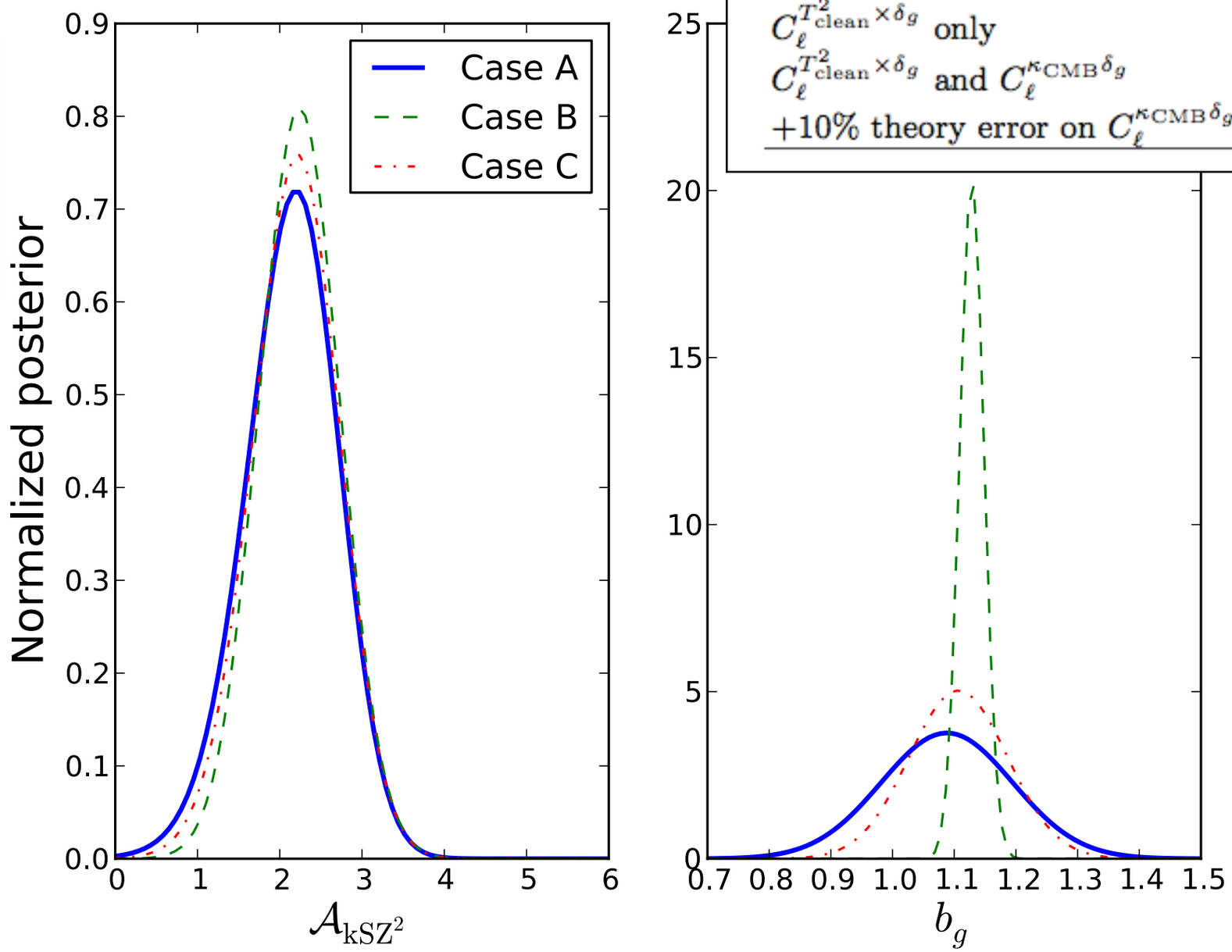
3.8-4.5σ kSZ² detection

analysis scenario	$\mathcal{A}_{\mathrm{kSZ}^2}$	b_g
$C_\ell^{T^2_{\mathrm{clean}}\times\delta_g}$ only	2.18 ± 0.57	1.10 ± 0.11
$C_\ell^{T^2_{\mathrm{clean}}\times\delta_g}$ and $C_\ell^{\kappa_{\mathrm{CMB}}\delta_g}$	2.24 ± 0.50	1.13 ± 0.02
+10% theory error on $C_\ell^{\kappa_{\mathrm{CMB}}\delta_g}$	2.21 ± 0.53	1.11 ± 0.08



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

N.B. theoretical systematics at ~10s% (e.g., NL bispectrum, σ_8/parameters, …)

JCH+ (2016); Ferraro, JCH+ (2016)