Projected-field kSZ

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CMB-S4 collaboration meeting 8/11

Work with Colin Hill, Boris Bolliet, Simone Ferraro and Alex Krolewski

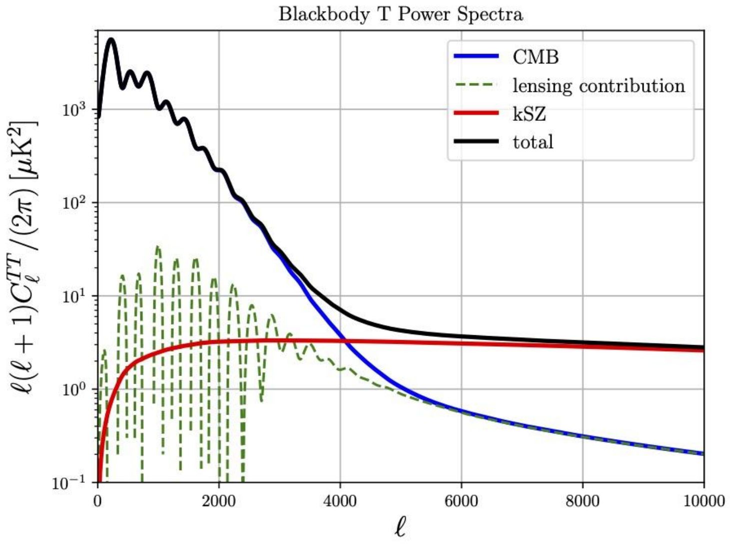
Projected Field kSZ estimator

Idea: **foreground-cleaned** blackbody CMB temperature map contains kSZ information

kSZ signal traces the overall mass distribution, and thus can be detected by cross-correlating it with any large-scale structure (LSS) field

1. Construct a clean T map and apply Wiener filter
2. Cross-correlate with *projected* (2D) galaxy number density map
3. But <T x g> vanishes!
4. Solution: measure <T^2 x g>

No redshift estimates needed!



Credits: Colin Hill
kSZ power spectrum from Battaglia et al simulations

Dore+2004, DeDeo+2005, Hill+2016, Ferraro+2016, Kusiak+2021

kSZ^2-LSS estimator:

kSZ-induced temperature shift in the CMB:

$$\Theta^{\mathrm{kSZ}}(\hat{\boldsymbol{n}}) = -\int_0^{\eta_{re}} d\eta\, g(\eta)\, \boldsymbol{p_e}\cdot\hat{\boldsymbol{n}}$$
$$= -\sigma_T \int_0^{\eta_{re}} \frac{d\eta}{1+z} e^{-\tau} n_e(\hat{\boldsymbol{n}},\eta)\boldsymbol{v_e}\cdot\hat{\boldsymbol{n}},$$

projected galaxy overdensity:

$$\delta_g(\hat{\boldsymbol{n}}) = \int_0^{\eta_{\max}} d\eta W_g(\eta)\delta_m(\eta\hat{\boldsymbol{n}},\eta),$$

$W_g(\eta)$ =$b_g(\eta)$ *$p(\eta)$ - projection kernel

$$C_\ell^{\mathrm{kSZ}^2\times\delta_g} = \frac{1}{c^2}\int_0^{\eta_{\max}} \frac{d\eta}{\eta^2} W_g(\eta) g^2(\eta)\mathcal{T}(k=\frac{\ell}{\eta},\eta), \quad (6)$$

$$\mathcal{T}(k,\eta) = \int \frac{d^2\boldsymbol{q}}{(2\pi^2)} f(q\eta) f(|\boldsymbol{k}+\boldsymbol{q}|\eta) B_{\delta_g p_{\hat{\boldsymbol{n}}} p_{\hat{\boldsymbol{n}}}}(\boldsymbol{k},\boldsymbol{q},-\boldsymbol{k}-\boldsymbol{q}). \quad (7)$$

$$B_{\delta_g p_{\hat{\boldsymbol{n}}} p_{\hat{\boldsymbol{n}}}} = \frac{1}{3} v_{\mathrm{rms}}^2 B_{\mathrm{m}}^{\mathrm{NL}}\,.$$

Doré et al. (2004); DeDeo et al. (2005); Hill & Ferraro et al.(2016)

What can we get from the kSZ?

$$C_\ell^{\mathrm{kSZ}^2 \times \delta_g} \propto f_b^2 f_{\mathrm{free}}^2 \times \frac{1}{3} v_{\mathrm{rms}}^2 \times \text{(galaxy bias, etc)}$$

<T^2 x g> — baryon fraction — free electron fraction — large-scale velocity dispersion

Baryon abundance can be constrained!

- Caution: <T_{CMB}^2 x g> receives important contribution from CMB lensing that must also be accounted for (Hill+2016, Ferraro+2016)

Doré et al. (2004); DeDeo et al. (2005); Hill & Ferraro et al.(2016)

Total Model

measured

kSZ signal

kSZ-magnification bias

$$C_\ell^{T^2\times\delta_g} = A_{\mathrm{kSZ}^2} b_g C_\ell^{\mathrm{kSZ}^2\times\delta_g} + A_{\mathrm{kSZ}^2}(5s-2)C_\ell^{\mathrm{kSZ}^2\times\mu_g} + b_g \Delta C_\ell^{T^2\times\delta_g} + (5s-2)\Delta C_\ell^{T^2\times\mu_g} \quad (21)$$

CMB weak lensing

CMB lensing-magnification bias

- 3 free parameters: kSZ^2 amplitude A_{kSZ2}, galaxy bias b_g, and magnification response s.
- A_{kSZ2}= 1 corresponds to the fiducial model.

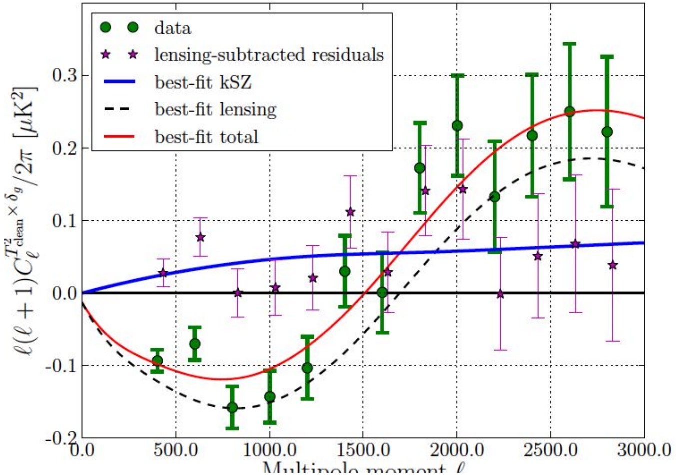
kSZ with WISE (Hill et al.)

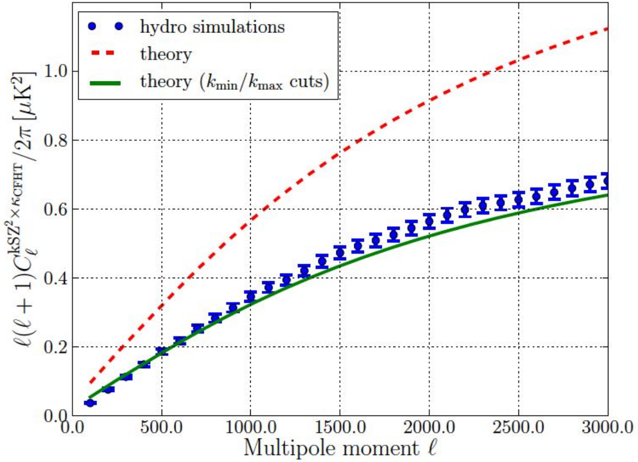
For the first time applied to data in Hill et al.

- **LGMCA** map (based on Planck and WMAP):
  - tSZ deprojected
  - dust-cleaned
- **WISE** catalog at redshift z~0.4
- Overall signal to noise: 3.8-4.5

$(f_b/0.158)\ (f_{free}/1.0) = \mathbf{1.48 +/- 0.19}$

No missing baryons!





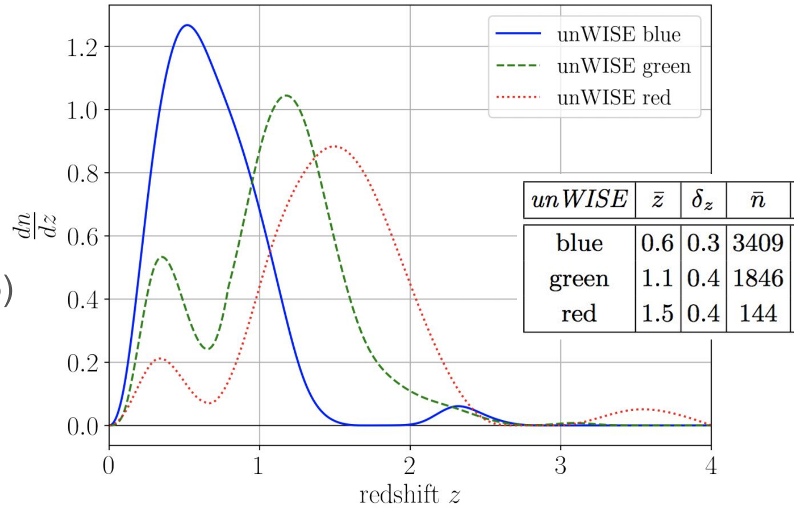
Hill+2016, Ferraro+2016

kSZ with unWISE

CMB: LGMCA map again + Planck SMICA map

unWISE catalog (Krolewski et al. 2020):

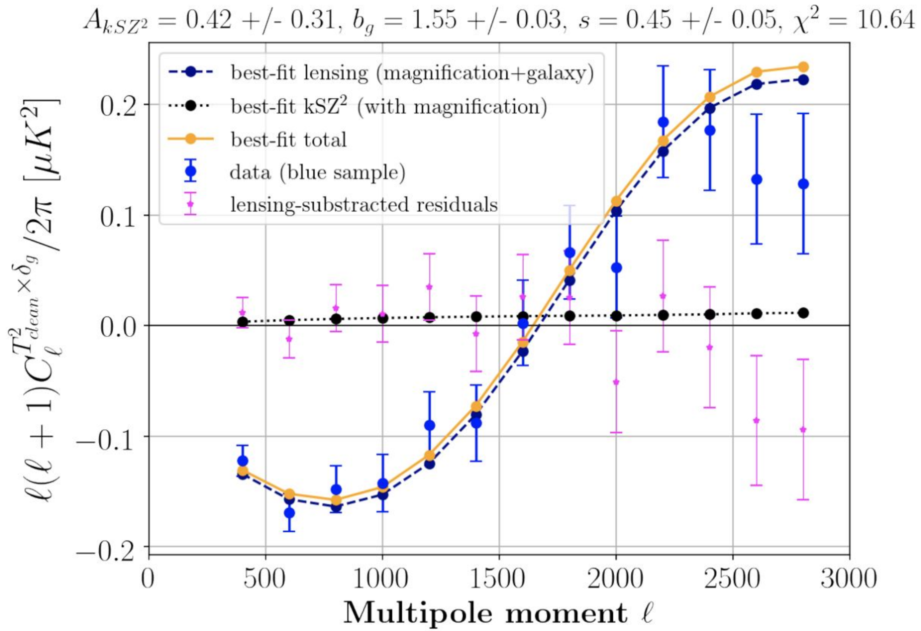
- Based on WISE and NEOWISE
- 3 subsamples: blue (z=0.6), green (z=1.1), and red (z=1.5)
- Over 500 million galaxies on the full sky

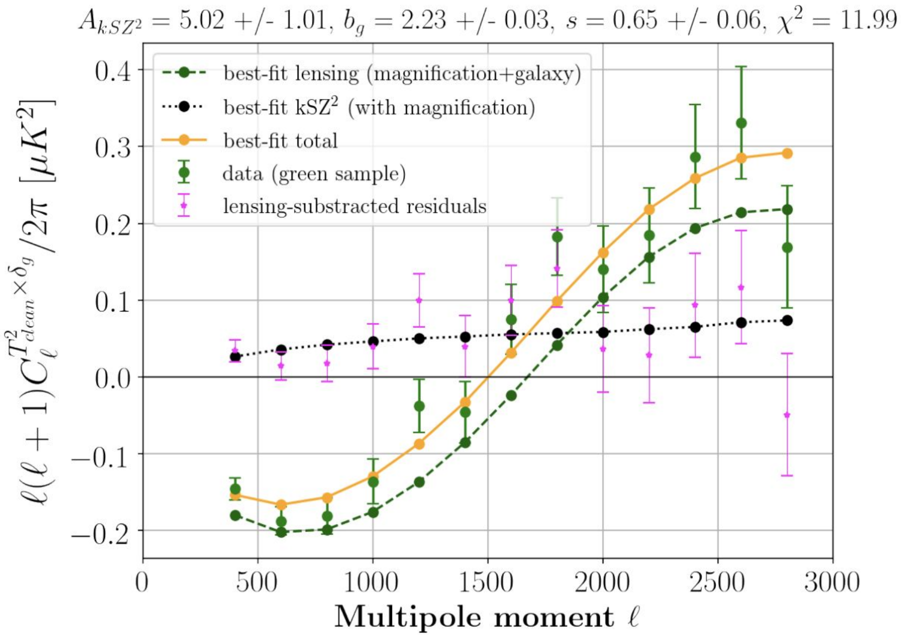


New aspects of the analysis:

- Included the **magnification bias** contributions
- **Asymmetric quadratic estimator** (multiplying two differently-cleaned CMB maps instead of squaring one map) to increase S/N
  - (LGMCA*SMICA) x unWISE, instead of ($LGMCA^2$) x unWISE
- New *l*-dependent ***α*-cleaning** method and extensive testing for foreground contamination
- **Validating** the results with different map combinations

Kusiak+2021





+Red (highest redshift kSZ detection)

Blue (z~0.6): $(f_b/0.158)\ (f_{free}/1.0) = 0.65$ +/- 0.24

Green (z~1.1): $(f_b/0.158)\ (f_{free}/1.0) = 2.24$ +/- 0.23

Red (z~1.5): $(f_b/0.158)\ (f_{free}/1.0) = 2.87$ +/- 0.56

Overall S/N ~5.5

No missing baryons!

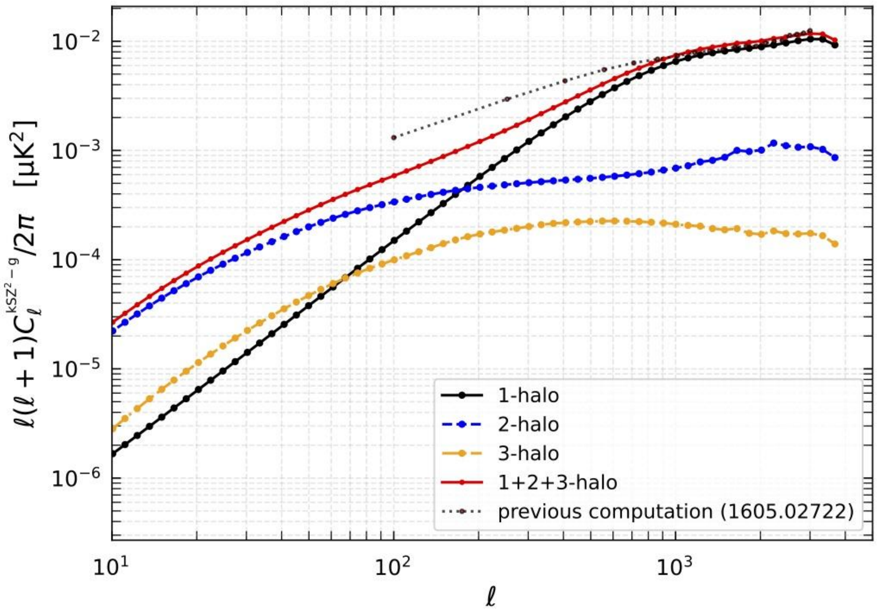
Kusiak+2021

Halo model (Bolliet et al. in prep)

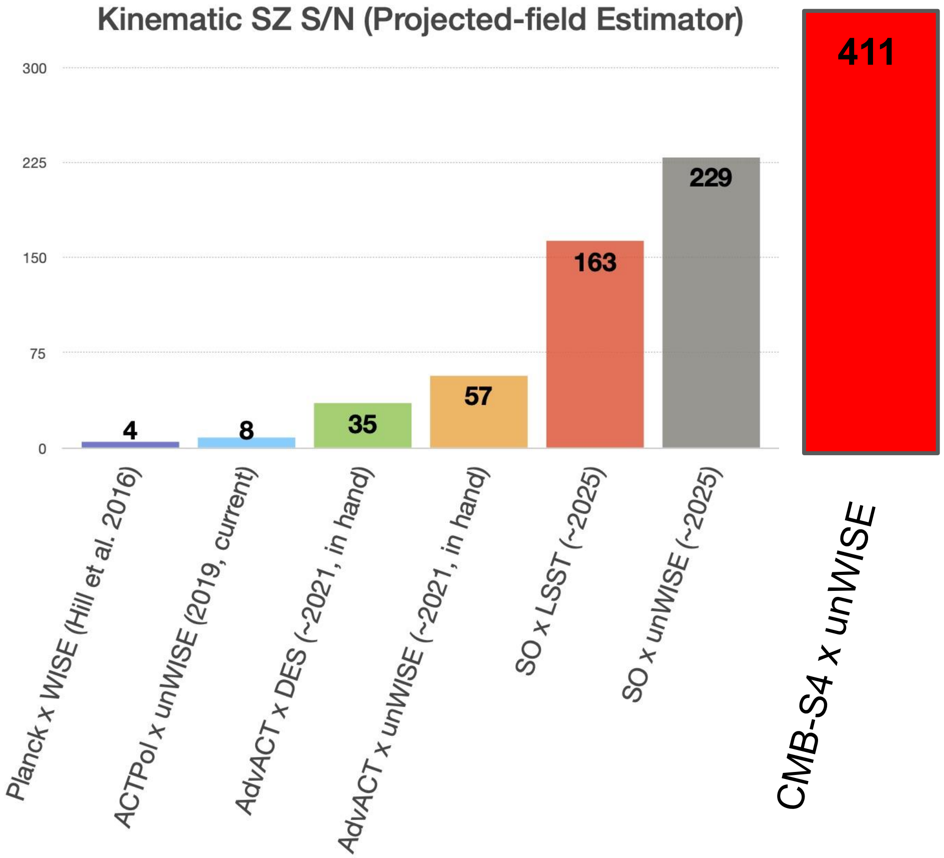
Follow-up paper with the Halo Model (Boris Bolliet class-sz)

Halo Model opens the door to probe the interior of halos (also need high-resolution data → prospects for CMB-S4),

Parametric models for the gas distribution needed for comparisons with the hydro sims



Prospects



Ferraro+2016

Projected-field kSZ: summary

The estimator does not require redshifts!
Can also be used with other LSS tracers, e.g., shear maps (not done before, exciting!)

- once we measure kSZ (number density), add tSZ (pressure) + lensing (total mass) to infer the thermodynamic information of the intergalactic gas →
- interpret the results with hydro sims (Illustris-TNG, OWLS, etc.) to calibrate the feedback processes

l-dependent α-cleaning method

- Look for α that nulls the cross-correlation of **δ** and ((1+α)TLGMCA - αTdust)
- Find α for each bin separately and interpolate over all *l*'s
- Construct clean CMB map

$$T_{\text{clean}} = (1 + \alpha_{\text{min}})T_{\text{LGMCA}} - \alpha_{\text{min}}T_{\text{dust}} \,,$$

Consistent with constant α cleaning results