Title: Probing the Ionized Gas Thermodynamics in Distant Galaxies with the Sunyaev-Zelâ€™dovich Effect

Speakers: Aleksandra Kusiak

Series: Cosmology & Gravitation

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Abstract: The Sunyaev-Zel'dovich Effect--the Doppler boost of low-energy Cosmic Microwave Background photons scattering off free electrons--is an excellent probe of ionized gas residing in distant galaxies. Its two main constituents are the kinematic SZ effect (kSZ), where electrons have a non-zero line-of-sight (LOS) velocity and which probes the electron line-of-sight momentum, and the thermal SZ effect (tSZ), where electrons have high energies due to their temperature, and which probes the electron integrated pressure. These two effects provide complementary information to constrain the thermodynamic profile of gas residing in distant galaxies, which can be further used to understand feedback processes, a necessary ingredient to describe the evolution of the large-scale structure in our Universe. Both tSZ and kSZ can be measured in cross-correlation with large-scale structure. In this talk, I will discuss my past and ongoing measurements of the SZ-galaxy cross-correlation with unWISE galaxies, where to measure the kSZ effect I use the projected-fields estimator. unWISE is a galaxy catalog containing over 500 million galaxies on the full sky and consists of three subsamples of mean redshifts z=0.5, 1.1, 1.5, whose halo occupation distribution I have already constrained. If time permits, I will also present my work on mitigating foregrounds in the SZ cross-correlations, particularly the Cosmic Infrared Background (CIB).

Zoom link

Probing the Ionized Gas Thermodynamics in Distant Galaxies with the Sunyaev-Zel'dovich Effect

Aleksandra (Ola) Kusiak
Columbia University

January 18, 2024
Perimeter Institute

Work with Colin Hill, Boris Bolliet, Shivam Pandey, Will Coulton, Fiona McCarthy, Kristen Surrao, Alex Krolewski, Simone Ferraro & many others; ACT and DES teams

Today's talk

1. CMB and its late-time anisotropies
2. SZ effect
3. Projected-fields kSZ
   a. Theory
   b. unWISE x Planck
4. New era for SZ
   a. Halo-model & comparison to sims
   b. SZ with ACT DR6
5. Combining with tSZ to constrain gas thermodynamics
6. Future directions

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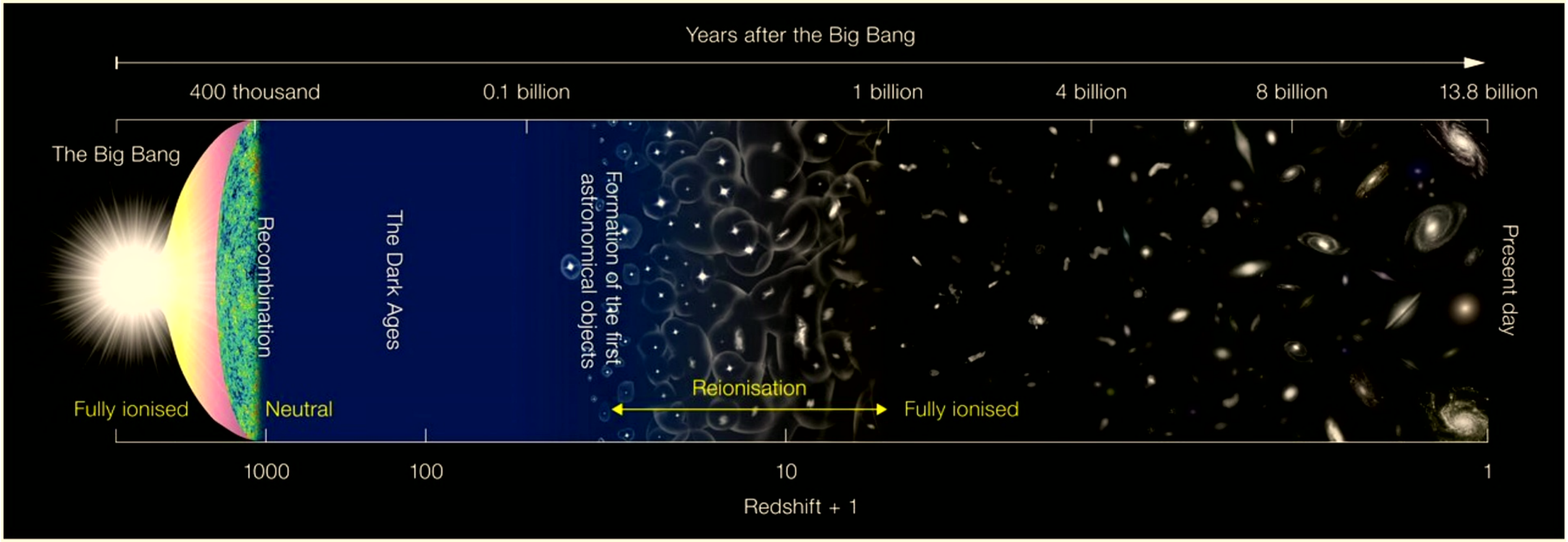
Cosmic Microwave Background



Credits: ESO

CMB carries a wealth of information about early times

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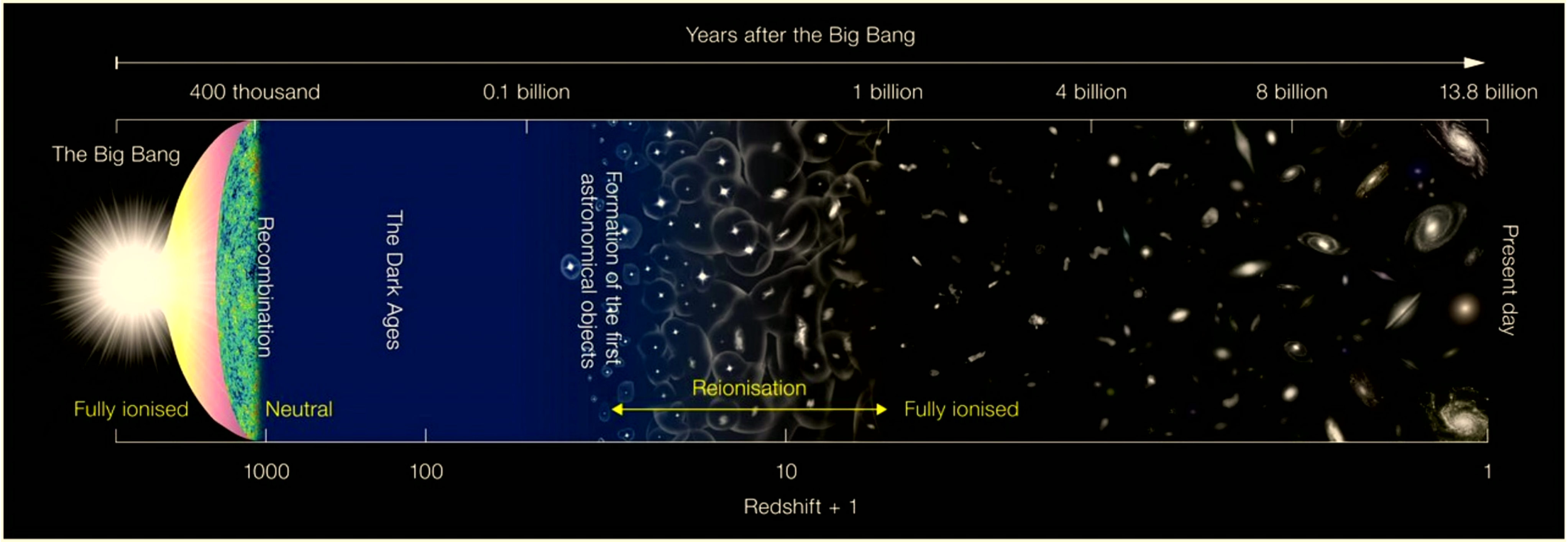
Cosmic Microwave Background



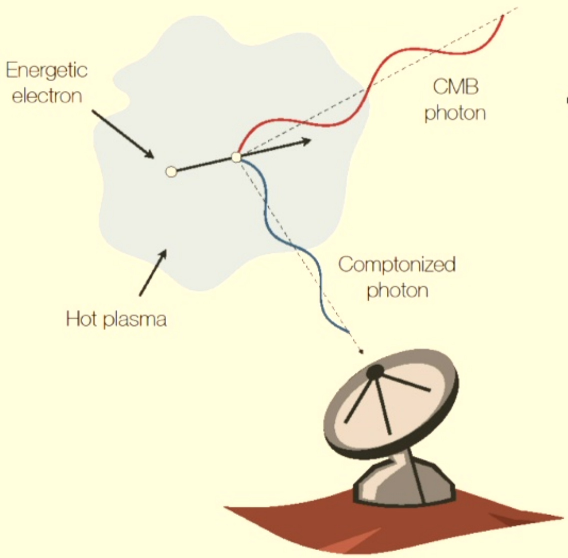
Credits: ESO

CMB photons in late Universe:

- Deflect from matter: CMB gravitational lensing→probe of total mass

Sunyaev–Zel'dovich (SZ) Effect

SZ effect - the inverse-Compton **scattering** of the Cosmic Microwave Background (CMB) photons off free electrons



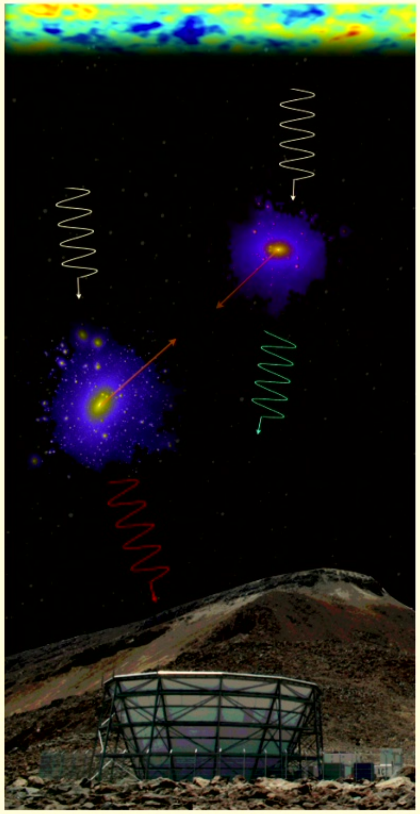
tSZ effect

Thermal (tSZ)

- electrons have high temperatures
- $\propto$ **electron integrated pressure**
- "dense" structures (galaxies)
- unique frequency dependence

Kinematic (kSZ)

- electrons have non-zero velocity
- $\propto$ **electron momentum /mass density**
- Traces distribution of baryons and velocities on large scales
- Preserves primary CMB blackbody spectrum



kSZ effect

Credits: ACT collaboration

Sunyaev & Zeldovich 1972

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The tSZ effect

$$\frac{\Delta T(\vec{\theta}, M, z)}{T_{\rm CMB}} = g_\nu \frac{\sigma_T}{m_e c^2} \int_{\rm LOS} P_e\left(\sqrt{l^2 + d_A^2|\vec{\theta}|^2}, M, z\right) dl\,,$$

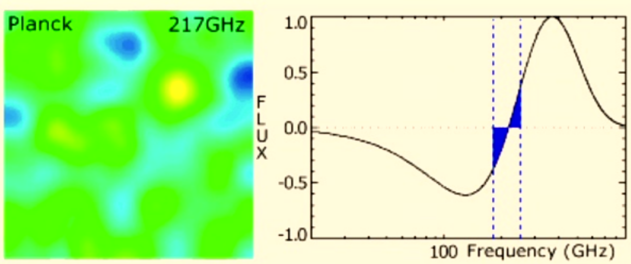
Frequency-dependence

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

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

Compton-y

- Pressure profile of the electron gas



Can use tSZ unique spectral dependence to separate it from other signals and make tSZ (Compton-y) maps from multifrequency experiments using the Internal Linear Combination (ILC) method

The kSZ effect

$$\Theta^{\mathrm{kSZ}}(\hat{\mathbf{n}}) = -\sigma_{\mathrm{T}} \int \frac{d\eta}{1+z} e^{-\tau} n_e(\hat{\mathbf{n}},\eta)\, \mathbf{v_e}(\hat{\mathbf{n}},\eta) \cdot \hat{\mathbf{n}}.$$

Electron number density
(astrophysics)

- Distribution of baryons & gas density profiles
- Missing baryons (traces gas both in the CGM and IGM)

Electron velocity
(cosmology)

$$\mathbf{v}(\mathbf{k}) = i\frac{faH\delta(\mathbf{k})}{k}\hat{\mathbf{k}},$$

- Large-scale velocities
- Linear theory:
  - Underlying matter density
  - Growth rate of Large Scale Structure (LSS)

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The kSZ effect

$$\Theta^{\rm kSZ}\left(\hat{\mathbf{n}}\right) = -\sigma_{\rm T} \int \frac{d\eta}{1+z} e^{-\tau} n_e\left(\hat{\mathbf{n}}, \eta\right) \mathbf{v_e}\left(\hat{\mathbf{n}}, \eta\right) \cdot \hat{\mathbf{n}}.$$

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Probe of cosmological parameters, **neutrinos**, DE and gravity

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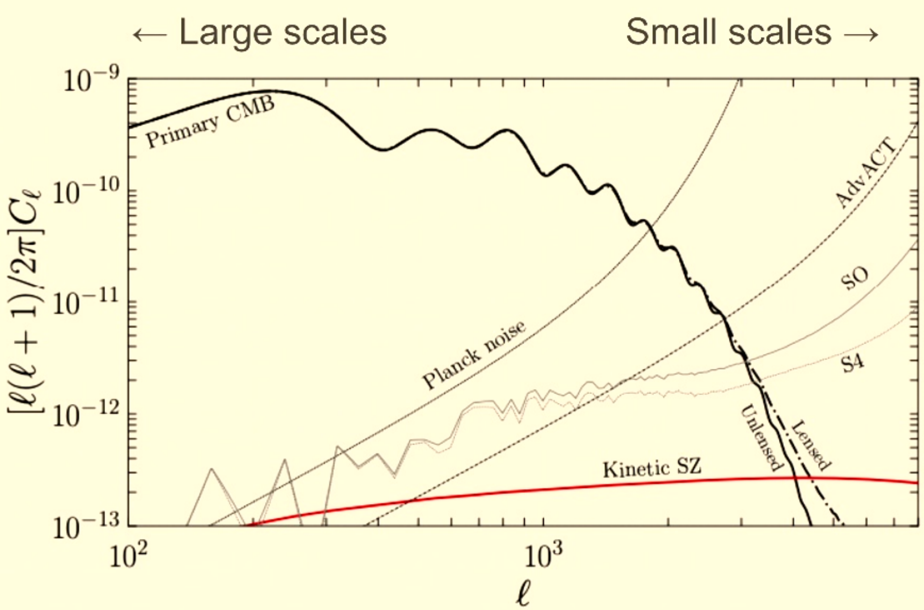
Detecting kSZ: combine with LSS

- kSZ is a small signal
- Not possible to isolate kSZ solely based on frequency dependance (as for tSZ)
- Statistical estimators w/ LSS:
  1. Pairwise kSZ
     a. First kSZ detection in ACT+BOSS Hand+12
     b. Planck, SPT, ACT, Vavagiakis+21
  2. Velocity-weighted stacking
     a. Planck, ACT DR5, Schaan+21, Amodeo+21,
  3. Velocity-reconstruction
     a. No measurements yet, Munchmeyer+19,



kSZ in comparison with primary CMB and noise (from Bolliet et al. (2022))

> Mathematically equivalent (Smith+18) and require spectroscopic redshifts

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Projected-fields kSZ^2-LSS estimator

Main 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, e.g. galaxies, galaxy/CMB lensing

But <kSZ x LSS> vanishes! (electron velocity)

Solution: Square the kSZ field

Projected-field kSZ^2-LSS:

1. Construct a clean T map & apply Wiener filter
2. Cross-correlate with *projected* (2D) LSS tracer
3. But <T x LSS> vanishes!
4. Solution: measure **$\langle T^2 \times LSS \rangle$**

No redshift estimates needed!

Doré et al. (2004); DeDeo et al. (2005); Hill et al.(2016), Ferraro et al. (2016), Kusiak et al. (2021), Bolliet et al. (2022), Patki et al. (2023)

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What do we measure with projected-fields?

kSZ-induced temperature shift in the CMB:

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

2

Gas density profile

x

projected galaxy overdensity:

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

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

Redshift distribution of LSS tracer

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

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

See Raagini Patki's work on including all terms in the bispectrum

Doré et al. (2004); DeDeo et al. (2005); Hill et al.(2016), Ferraro et al. (2016), Kusiak et al. (2021), Bolliet et al. (2022), Patki et al. (2023)

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What can we learn from the kSZ?

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

- $C_\ell^{\mathrm{kSZ}^2 \times \delta_g}$: <T^2 x g>
- f_b: baryon fraction
- f_{free}: free electron fraction
- v_{rms}: large-scale velocity dispersion

Large scale limit: <u>baryon abundance can be constrained!</u>

Halo model: <u>shape of gas density profile</u>

Upcoming CMB experiments!

Caution: <T_{CMB}^2 x LSS> 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 et al.(2016), Ferraro et al. (2016), Kusiak et al. (2021), Bolliet et al. (2022), Patki et al. (2023)

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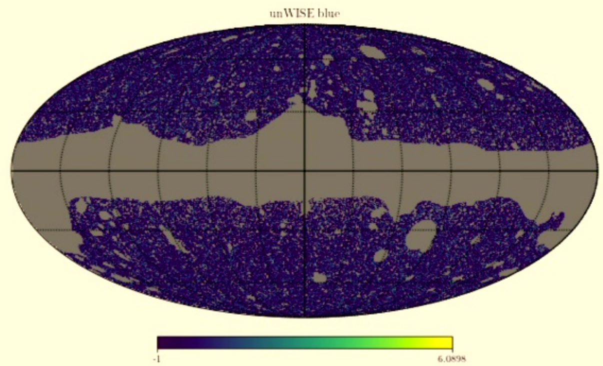
Projected-fields kSZ with unWISE and Planck

CMB:

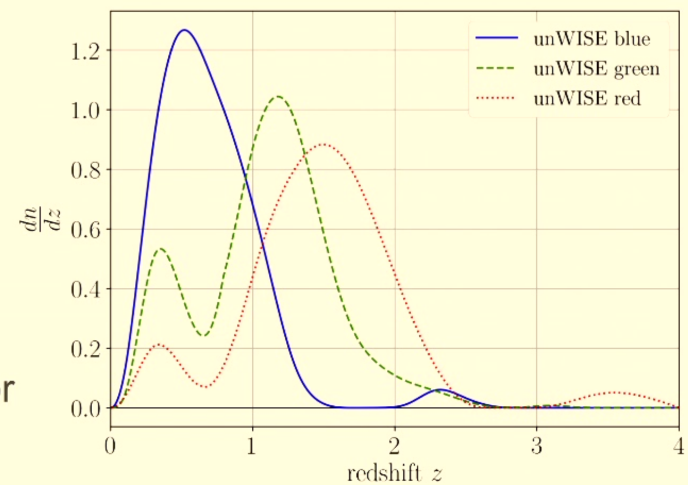
- LGMCA map (tSZ-deprojected)
- Planck SMICA map



unWISE	$\bar{z}$	δ_z	$\bar{n}$
blue	0.6	0.3	3409
green	1.1	0.4	1846
red	1.5	0.4	144

unWISE catalog (Krolewski et al. 2020):

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



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 **CIB cleaning** ell-dependent method and extensive testing for foreground contamination
- **Validating** the results with different map combinations

Kusiak et al. 2021

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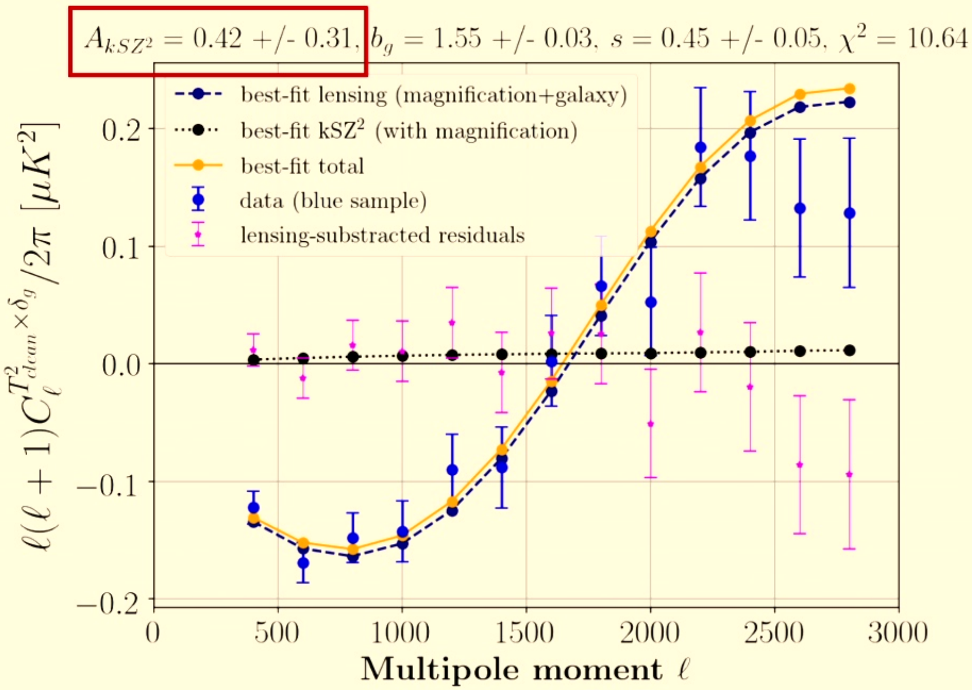
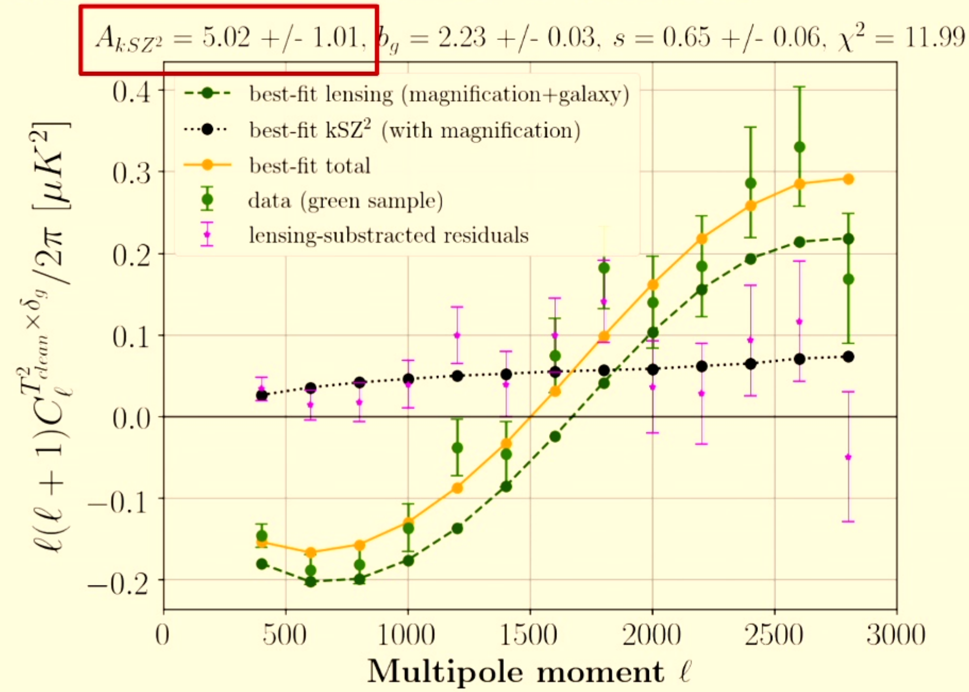
Projected-fields kSZ with unWISE and Planck





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

+Red (highest redshift kSZ detection)

Overall S/N ~5.5

No missing baryons!

Kusiak et al. 2021

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unWISE Halo Occupation Distribution (HOD)

HOD model from Zheng et al., Zehavi et al.

Central and satellite galaxies:

$$N_c(M) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M - \log M_{\mathrm{min}}}{\sqrt{2}\sigma_{\log M}}\right)\right], \qquad N_s(M) = \left(\frac{M - M_0}{M_1'}\right)^{\alpha_s},$$

Power Spectra in the halo model:

$$C_\ell^{ij} = C_\ell^{ij,1\mathrm{h}} + C_\ell^{ij,2\mathrm{h}}$$

$$C_\ell^{ij,1\mathrm{h}} = \int_{z_{\mathrm{min}}}^{z_{\mathrm{max}}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega} \int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathrm{d}M \frac{\mathrm{d}N}{\mathrm{d}M\mathrm{d}V} u_\ell^i(M,z) u_\ell^j(M,z),$$

$$C_\ell^{ij,2\mathrm{h}} = \int_{z_{\mathrm{min}}}^{z_{\mathrm{max}}} \mathrm{d}z \frac{\mathrm{d}^2V}{\mathrm{d}z\mathrm{d}\Omega} \left|\int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathrm{d}M_i \frac{\mathrm{d}n}{\mathrm{d}M_i} b(M_i,z) u_\ell^i(M_i,z)\right| \left|\int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathrm{d}M_j \frac{\mathrm{d}n}{\mathrm{d}M_j} b(M_j,z) u_\ell^j(M_j,z)\right| P_{\mathrm{lin}}\left(\frac{\ell + \frac{1}{2}}{\chi}, z\right), \quad (5)$$

Galaxy overdensity:

$$u_\ell^g(M,z) = W_g(z)\bar{n}_g^{-1}\left[N_c + N_s u_\ell^m(M,z)\right]$$

$W_g(z)$: Galaxy kernel

$\bar{n}_g$: Mean number density of galaxies

Kusiak et al. 2022

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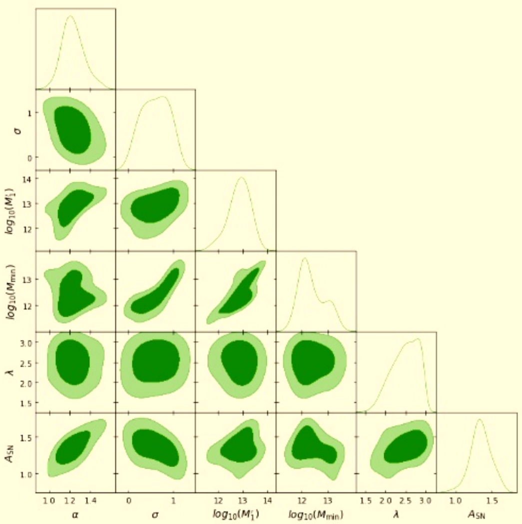
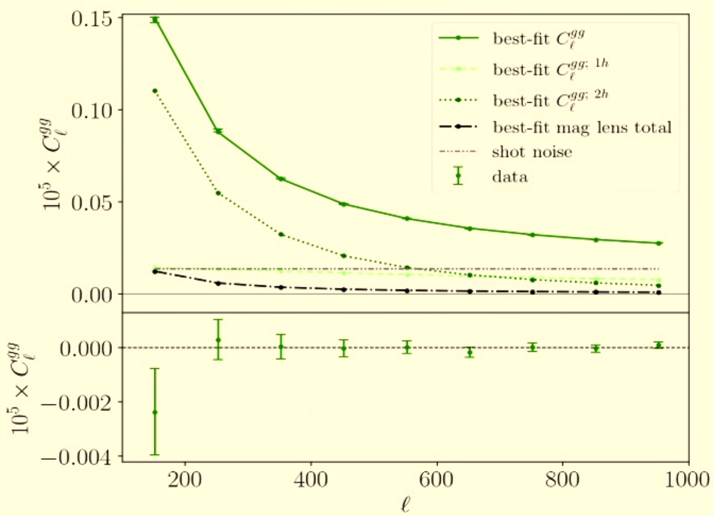
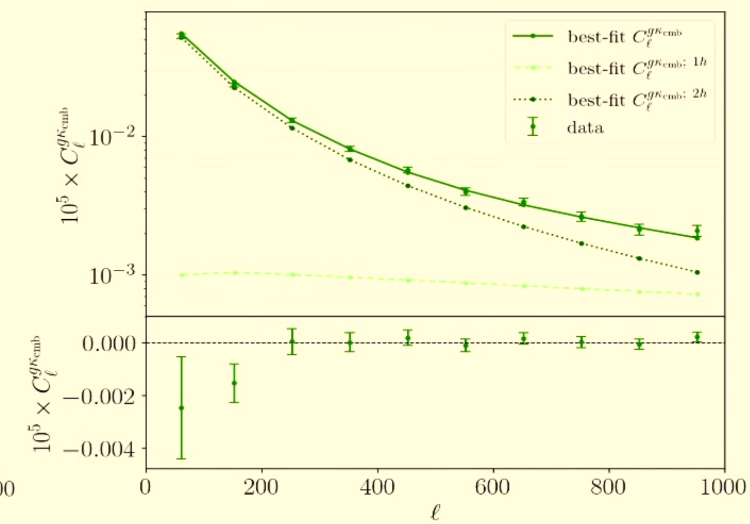
unWISE Halo Occupation Distribution (HOD)

Jointy fit unWISE **galaxy-galaxy (gg)** and Planck **CMB lensing-galaxy (kg)** power spectra from Krolewski *et al.* to our theory halo model, separately for each unWISE sample (blue, green, and red) to constrain **6 model parameters**

Results for unWISE green







\+ Bias, satellite fraction, Mh = 1.99, 1.86, 2.04 × 10^13 Msun/h

Kusiak et al. 2022

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unWISE is of great interest!

unWISE is of great interest recently:

- cosmology with unWISE-ACT DR6 lensing (Farren et al.)
- Detection of CMB lensing-galaxy bispectrum with unWISE (Farren et al. 2311.04213), used my HOD
- cosmology with the Gaia-unWISE Quasars and CMB lensing (Alonso et al.)

⇩

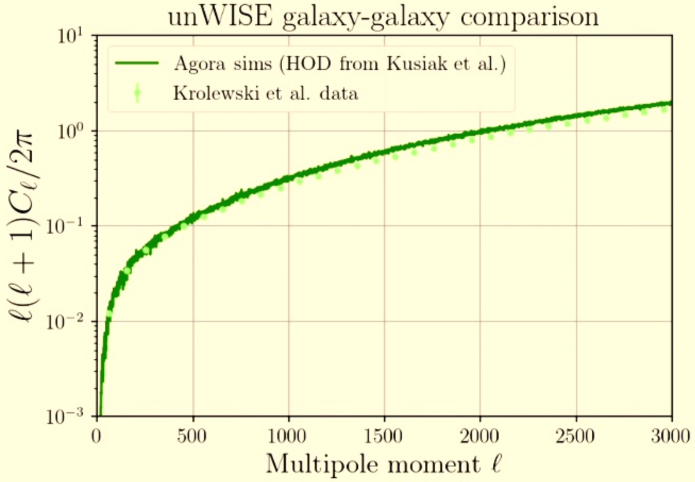
Missing realistic simulations

⇩

AGORA (Omori 2022)

- N-body, lightcones from MDPL2
- Coherently implemented components for cross-survey science

Comparison of Agora simulated halos populated with unWISE HOD (Kusiak et al.) with measurements from Krolewski et al.



will be of use for multiple projects:

- foreground (particularly CIB) in my ongoing SZ (kSZ^2 +tSZ) analyses
- Foregrounds in unWISE-CMB lensing (Farren et al. used Websky)
- Accuracy of the halo-model predictions

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Halo-model projected-fields kSZ² x LSS

$$C_\ell^{\mathrm{kSZ}^2 X} = \int \mathrm{d}v W^{\mathrm{kSZ}}(\chi)^2 W^X(\chi) T(\ell,\chi) \quad \text{with} \quad T(\ell,\chi) = \int \frac{\mathrm{d}^2\boldsymbol{\ell}'}{(2\pi)^2} w(\ell') w(|\boldsymbol{\ell}+\boldsymbol{\ell}'|) B_{\delta_e\delta_e X}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

- Halo model hybrid bispectrum

$$B_{\delta_e\delta_e X} = B^{1\mathrm{h}}_{\delta_e\delta_e X} + B^{2\mathrm{h}}_{\delta_e\delta_e X} + B^{3\mathrm{h}}_{\delta_e\delta_e X}$$

X - LSS tracer

$$B^{1\mathrm{h}}_{\delta_e\delta_e X} = \int \mathrm{d}n_1 \hat{u}^{\mathrm{e}}_{k_1}(m_1)\hat{u}^{\mathrm{e}}_{k_2}(m_1)\hat{u}^{X}_{k_3}(m_1)$$

1 halo

$$B^{2\mathrm{h}}_{\delta_e\delta_e X} = \int \mathrm{d}n_1 b^{(1)}(m_1)\hat{u}^{\mathrm{e}}_{k_1}(m_1)\hat{u}^{\mathrm{e}}_{k_2}(m_1) \int \mathrm{d}n_2 b^{(1)}(m_2)\hat{u}^{X}_{k_3}(m_2)P_L(k_3) + \text{perms}$$

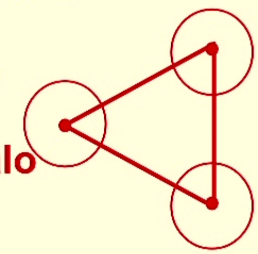
2 halo

$$B^{3\mathrm{h}}_{\delta_e\delta_e X} = 2\int \mathrm{d}n_1 b^{(1)}(m_1)\hat{u}^{\mathrm{e}}_{k_1}(m_1)P_L(k_1) \int \mathrm{d}n_2 b^{(1)}(m_2)\hat{u}^{\mathrm{e}}_{k_2}(m_2)P_L(k_2) \int \mathrm{d}n_3 b^{(1)}(m_3)\hat{u}^{X}_{k_3}(m_3)F_2(k_1,k_2,k_3)$$
$$+ \int \mathrm{d}n_1 b^{(1)}(m_1)\hat{u}^{\mathrm{e}}_{k_1}(m_1)P_L(k_1) \int \mathrm{d}n_2 b^{(1)}(m_2)\hat{u}^{\mathrm{e}}_{k_2}(m_2)P_L(k_2) \int \mathrm{d}n_3 b^{(2)}(m_3)\hat{u}^{X}_{k_3}(m_3) + \text{perms}$$

Liner matter power spectrum

Fourier transform of the gas density profile/tracer

3 halo



Implemented in halo-model code class-sz (Bolliet, AK, et al. 2023)

Bolliet,..., AK,… 2022; Bolliet, AK, et al. 2023

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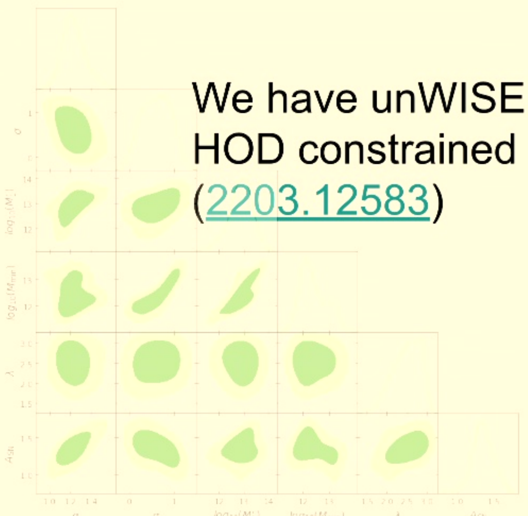
Halo-model kSZ^2 x LSS: forecasts

CMB:

- AdvACT, Simons Observatory and CMB-S4 temperature maps

LSS:

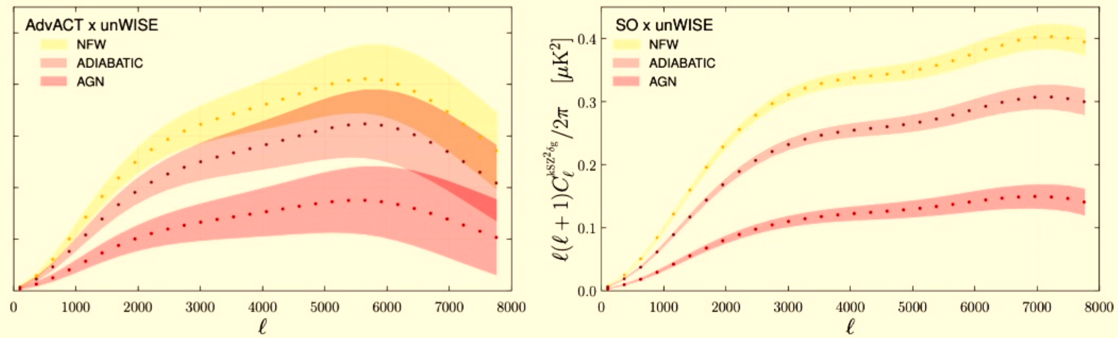
- Galaxy density (unWISE)
- Galaxy lensing (DES, VRO, Euclid)
- CMB lensing (SO, CMB-S4)



We have unWISE HOD constrained (2203.12583)

Bolliet,..., AK,... 2022

kSZ^2-unWISE forecasts



AdvACT: SNR ~ 17σ (ongoing)

SO: SNR ~ 61σ

SO:

w/ *Euclid* galaxy lensing: SN ~19σ
w/ SO CMB lensing: SN ~16 σ

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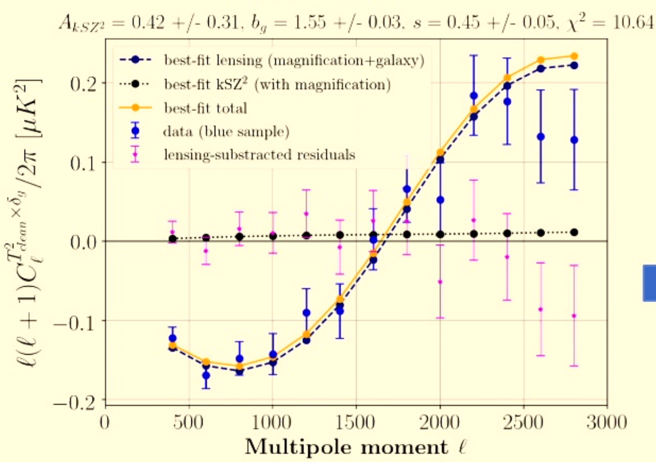
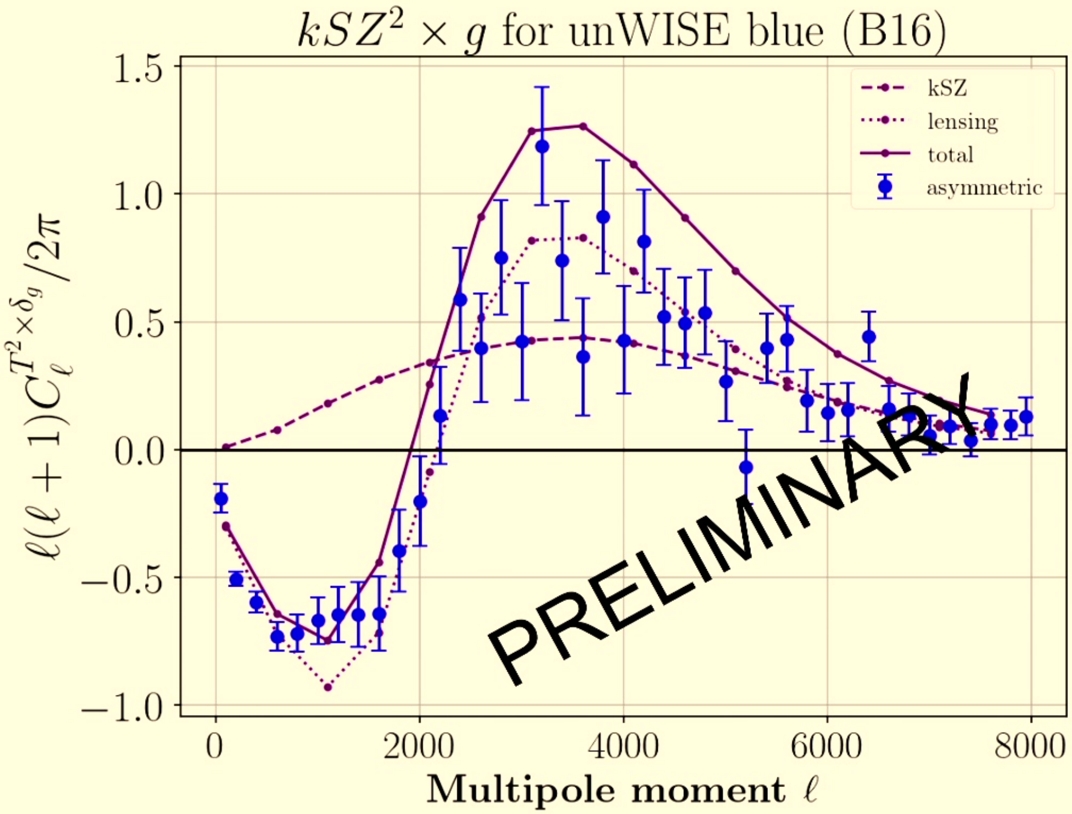
Projected-fields kSZ with unWISE and ACT DR6

With Planck





Measurement is lensing dominated

Theory curve is not a fit! (only used unWISE HOD, and B16 AGN gas density profile)

Goal: constrain unWISE **density profile**

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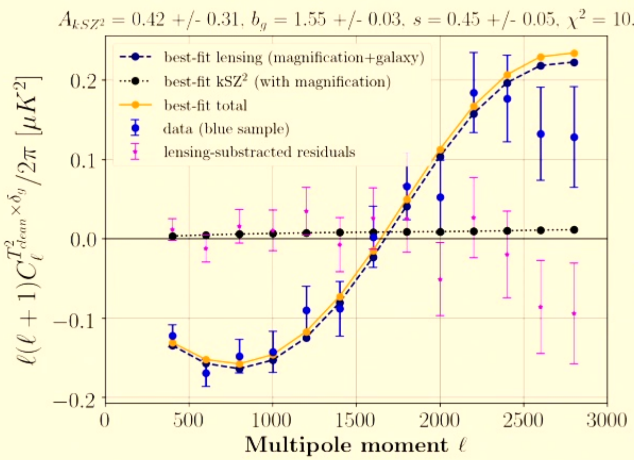
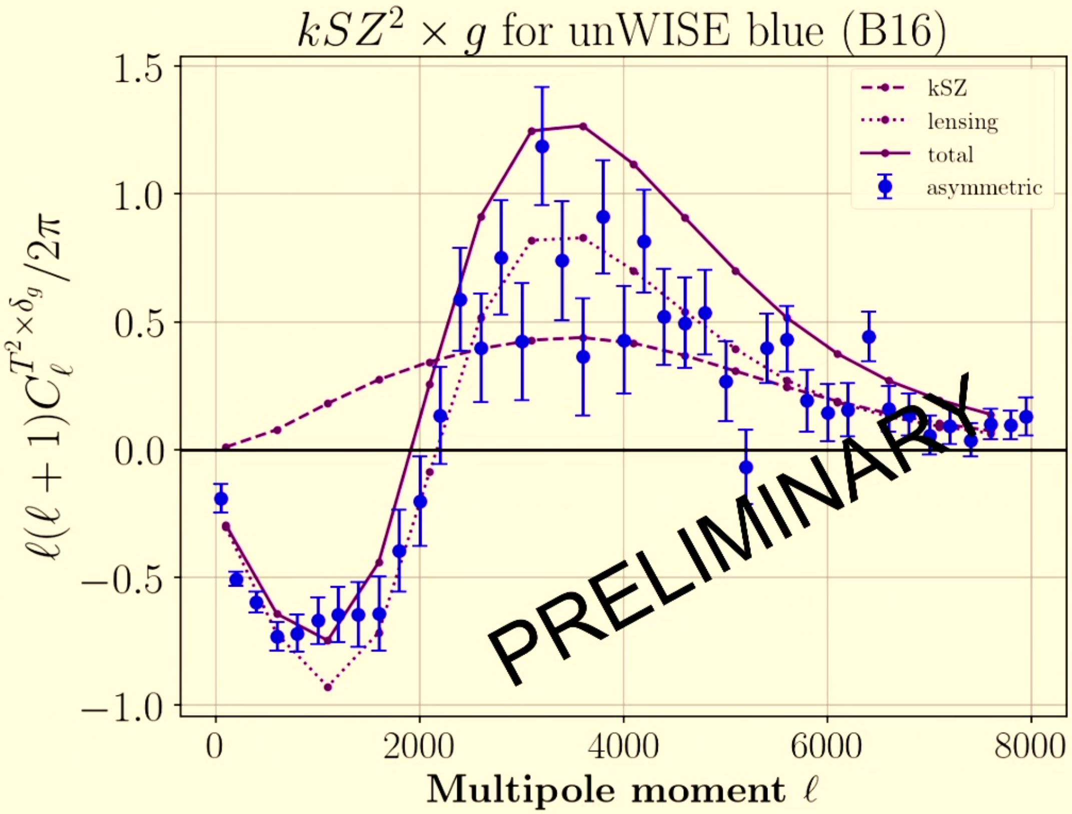
Projected-fields kSZ with unWISE and ACT DR6

With Planck





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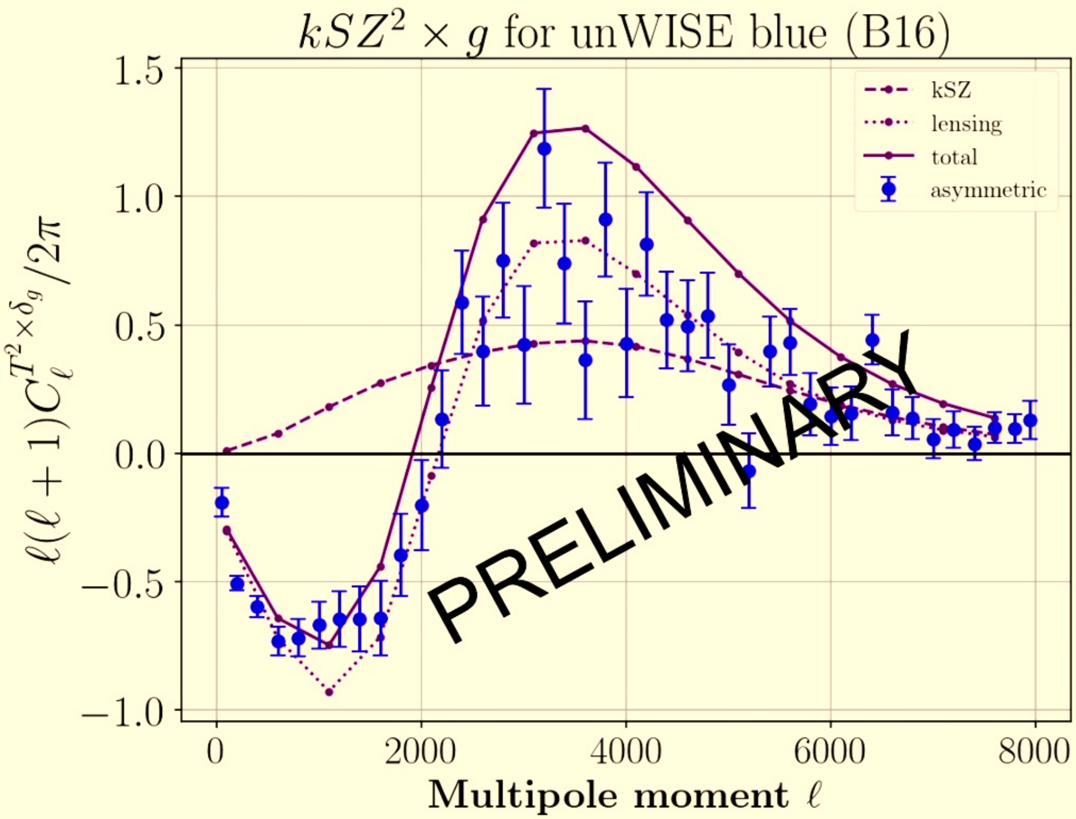
Projected-fields kSZ with unWISE and ACT DR6



Foregrounds:

- **tSZ:** asymmetric method
  - One leg is a tSZ-deprojected blackbody T map
- **CIB:** cleaning using the fact that <kSZxg>=0
  - Construct T_clean:

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

such that $\langle T_{\rm clean} \times g \rangle = 0$

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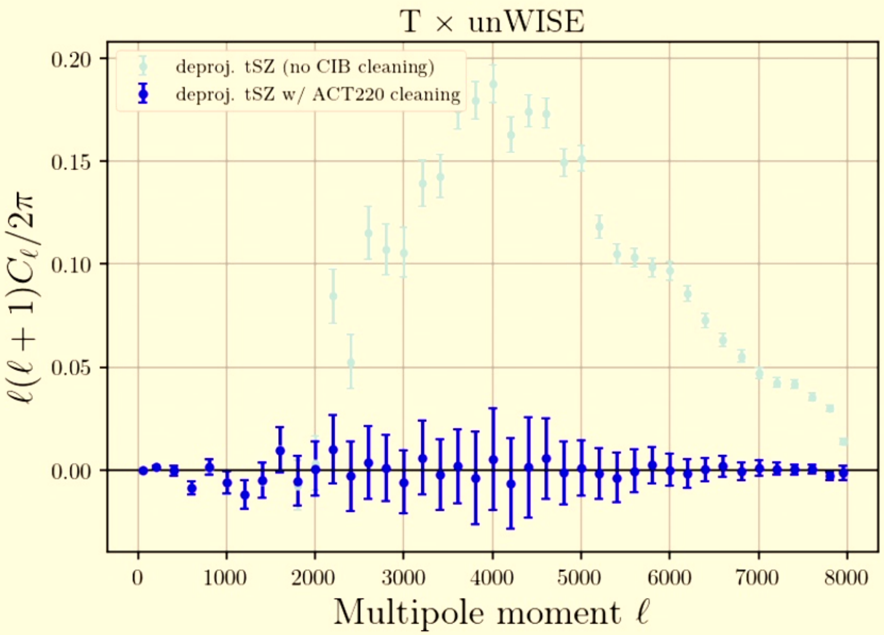
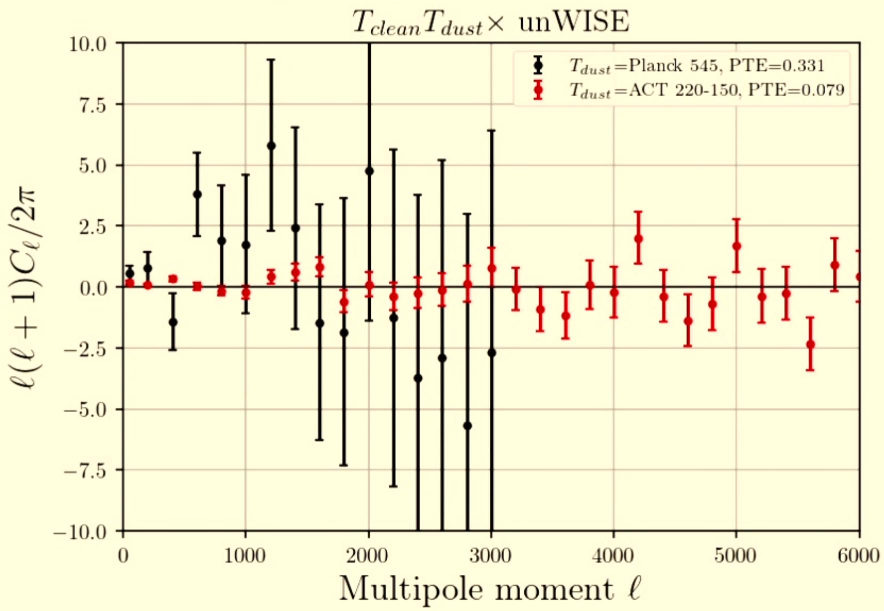
kSZ with unWISE and ACT DR6: Null tests

<T_clean x g> test



<T x g> is expected to be zero if T is truly blackbody (kSZ+CMB)

<T_dustT_clean x g> test

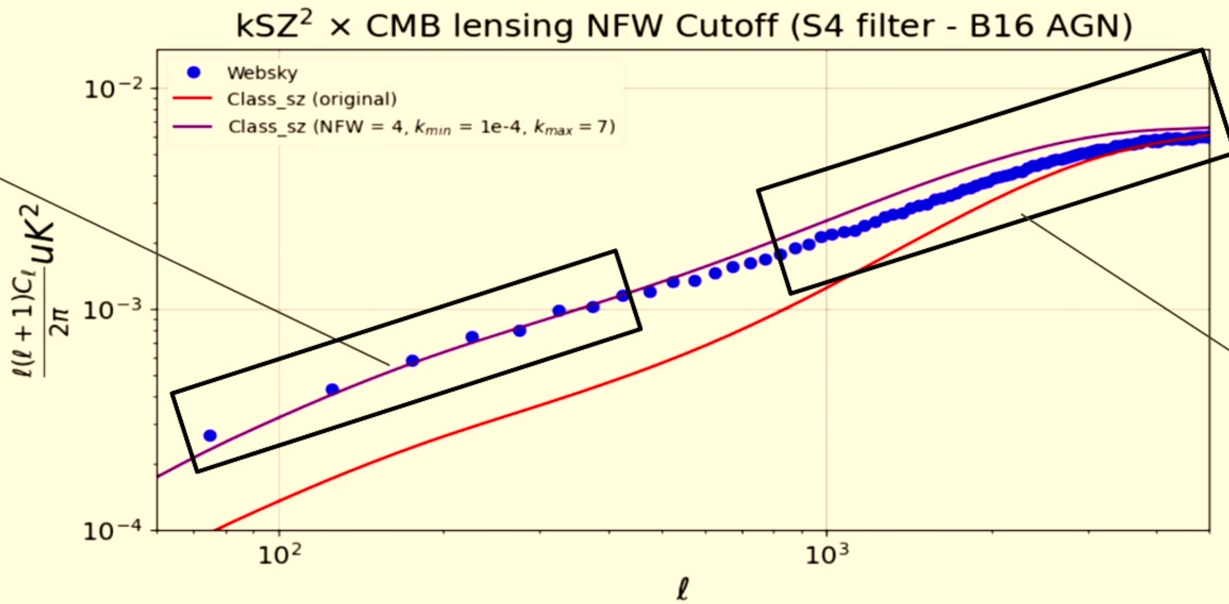


Very powerful test–it will pick up any residual CIB/tSZ contamination in T_clean

Projected-fields kSZ: Comparison to simulations

Lucie Afko
(Simons-NSBP summer intern at CCA, now at Duke)

Comparison of our kSZ^2 halo-model predictions computed with class_sz with Websky sims for CMB lensing as LSS tracer



Good agreement on large scales

Extra terms contributing to the bispectrum pointed out in Patki et al. 2023?

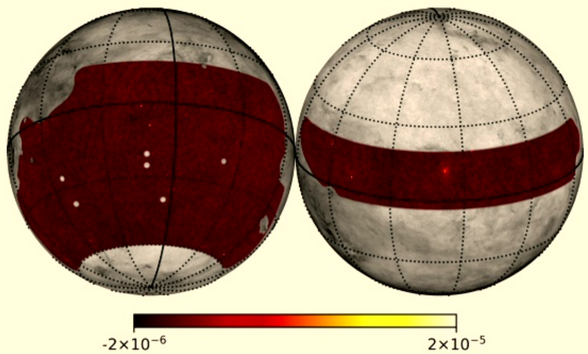
Michael Rodriguez
(Columbia Bridge Student)

Next step: galaxies as LSS tracer using AGORA simulated halos populated with unWISE HOD (Kusiak et al.)

Ola Kusiak, Columbia

tSZ with unWISE and ACT DR6

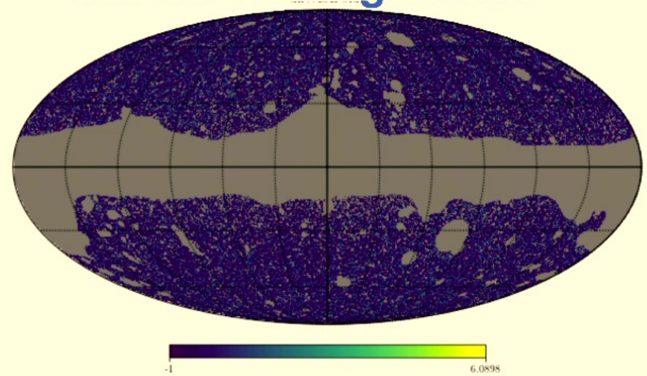
ACT DR6 (tSZ) Compton-y map



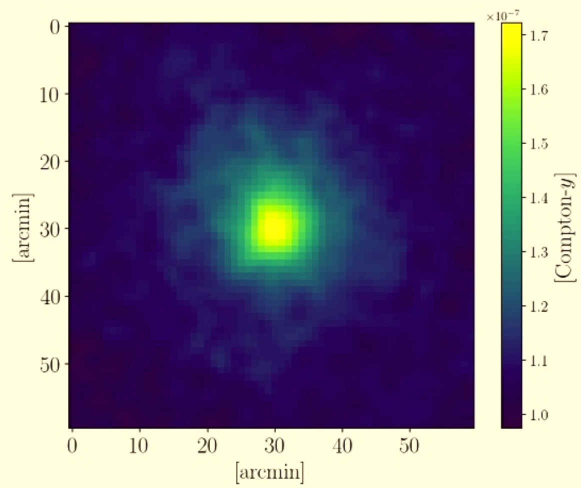
(a) ACT & *Planck* NILC Compton-y map.

x

unWISE blue galaxies



Measure the tSZ x unWISE (y x g) to constrain unWISE **pressure profile**



Compton-y map from ACT DR4 stacked at the location of unWISE galaxies

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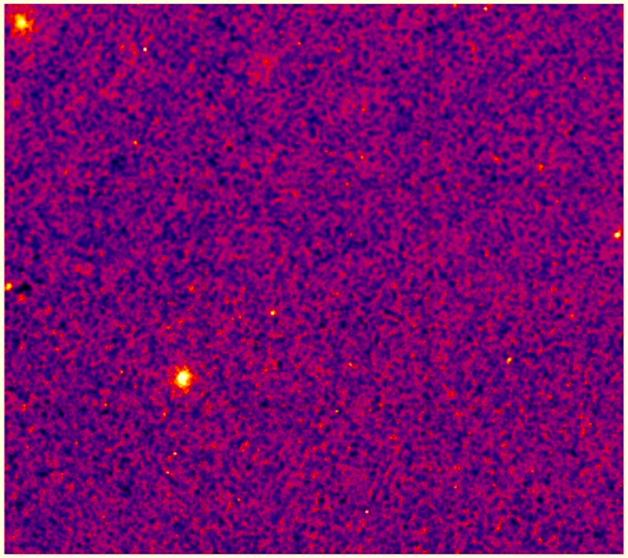
ACT DR6 tSZ (Compton-y) map



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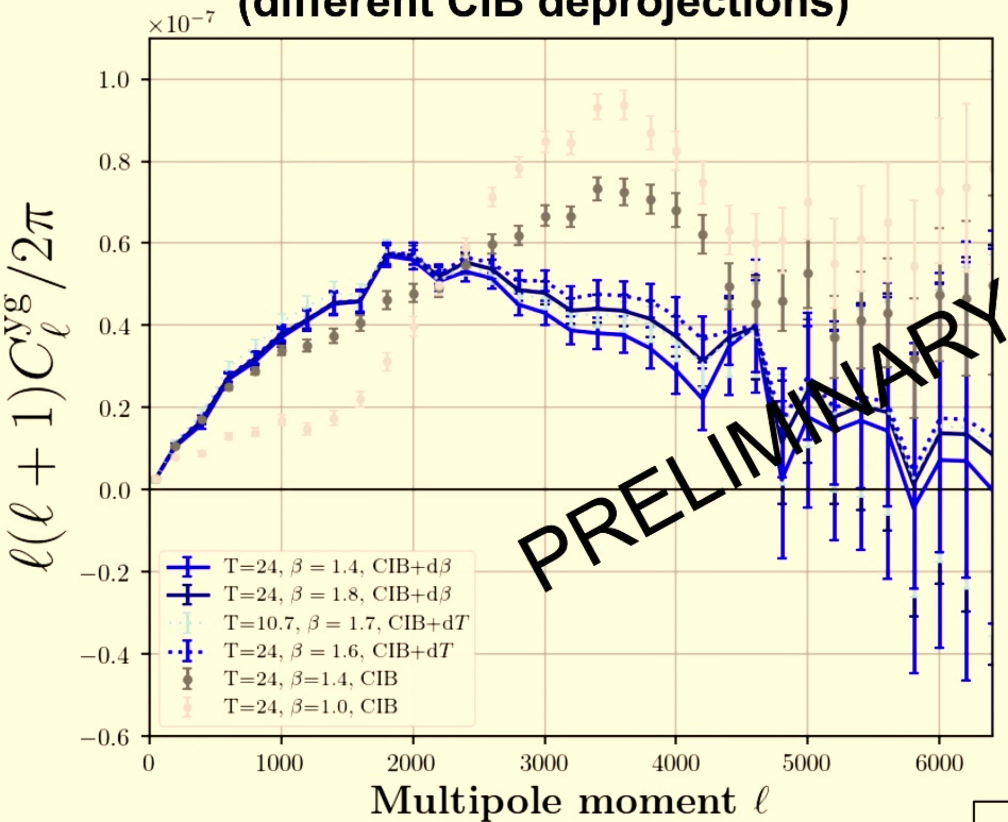
tSZ with unWISE and ACT DR6

tSZ for ACT DR6 and unWISE blue (y x g) (different CIB deprojections)



Main worry is the **Cosmic Infrared Background (CIB) contamination**:

- deproject CIB=modified blackbody parametrized by β and T:

  MBB:

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

- Deproject CIB, but also first-moment of the SED parameters (Chluba+ 2017, McCarthy & Hill 2023)

Analysis done in the halo model with class_sz (Bolliet, AK, et al. 2023) using unWISE HOD to constrain unWISE **pressure profile**

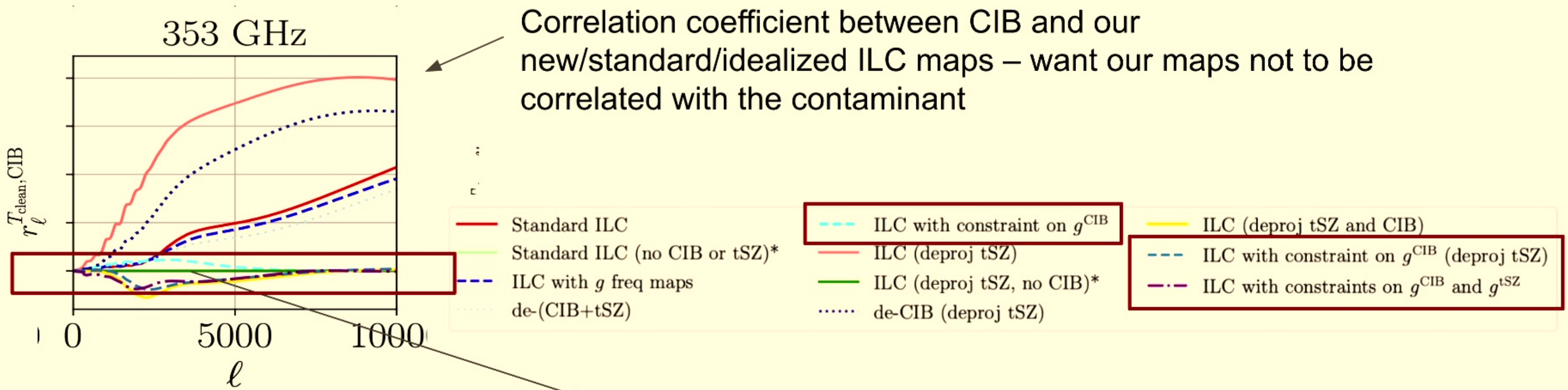
Best measurement of y x g at ell > 1500! (SNR ~ 100)

deCIBing

Do the opposite: Use the external LSS data (=unWISE) that correlates with both CIB and tSZ to remove those contaminants to enhance CMB+kSZ measurements using ILC methods

Key: Two-point correlation function of LSS with CMB + kSZ vanishes

- electron velocity as likely to be positive as to be negative, thus kSZ-LSS vanishes



Correlation coefficient between CIB and our new/standard/idealized ILC maps – want our maps not to be correlated with the contaminant

Improvements are already non-negligible

Kusiak, Surrao, Hill 2023

Ola Kusiak, Columbia

Combine tSZ+kSZ to constrain thermodynamics

1. Finalize kSZ and tSZ measurements for unWISE with ACT DR6

2. Combine kSZ (density), add tSZ (pressure) + lensing (total mass) to infer the **thermodynamic** information of the intergalactic gas

kSZ + tSZ + lensing = thermodynamics of electron gas

Density

Pressure

Mass

As done in, e.g., Amodeo et al. and Schaan et al.

→ interpret the results with hydro sims (Illustris-TNG, OWLS, etc.) to calibrate the **feedback processes**

need understanding of feedback to enable Stage-IV **neutrino mass constraints** from CMB lensing (**CMB-S4**) and galaxy weak lensing (**LSST**)

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Future plans

1. Projected-fields kSZ with ACT DR6/**SO x unWISE**
   - also with *Euclid* gal. lensing (SN ~19), and SO CMB lensing (SN ~16)
   - DESI, *Euclid,* LSST, SPHEREx, prepare for CMB-S4
2. Joint kSZ + tSZ + lensing to **constrain feedback**
3. unWISE
   - Improving dNdz (currently one of the modeling systematics)
   - Use **simulated unWISE galaxies** from Agora to test foregrounds and biases in various cross-correlations (SZ, CMB lensing…)
4. **Foreground mitigation** techniques (deCIBing)-crucial for upcoming surveys
   - deCIBing methods with *Euclid*: ~50% improvements
   - New methods crucial to obtain cosmological constraints from kSZ!

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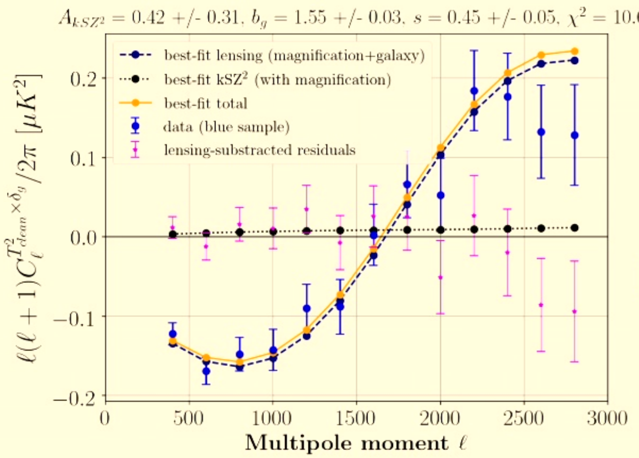
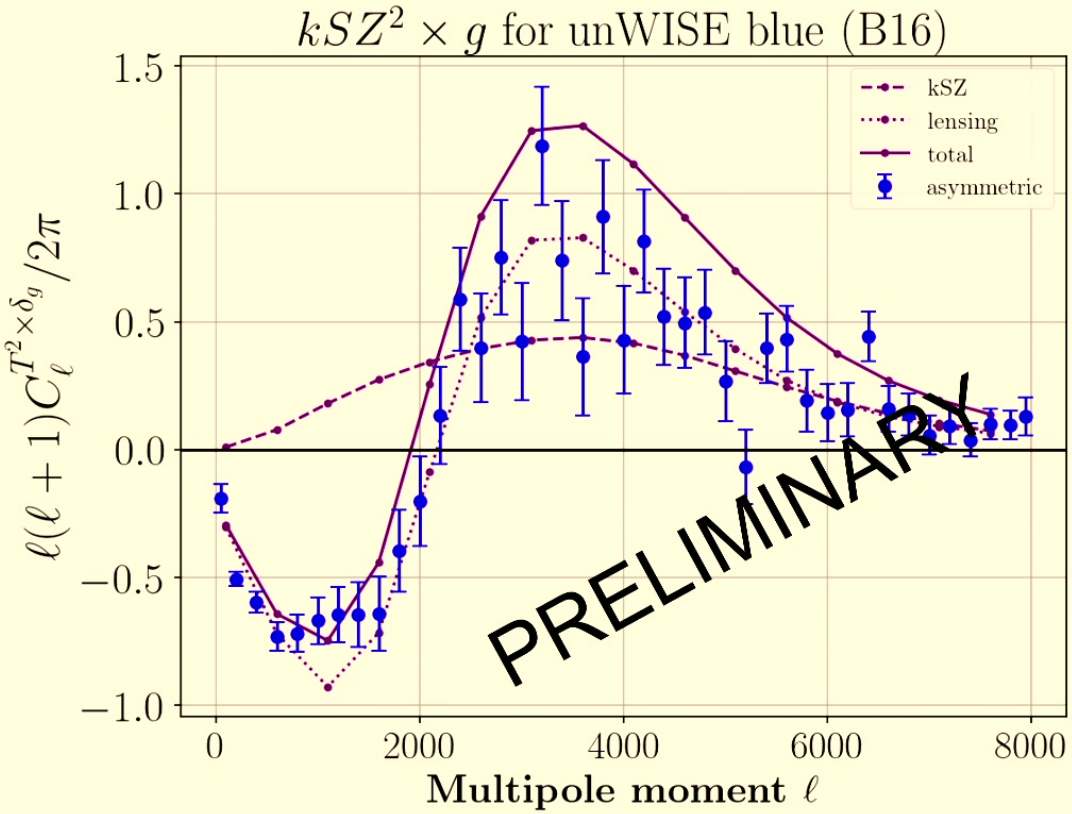
Projected-fields kSZ with unWISE and ACT DR6

With Planck





Measurement is lensing dominated

Theory curve is not a fit! (only used unWISE HOD, and B16 AGN gas density profile)

Goal: constrain unWISE **density profile**