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

Aleksandra (Ola) Kusiak
Columbia University

November 14, 2023
LBNL, Research Progress Meeting

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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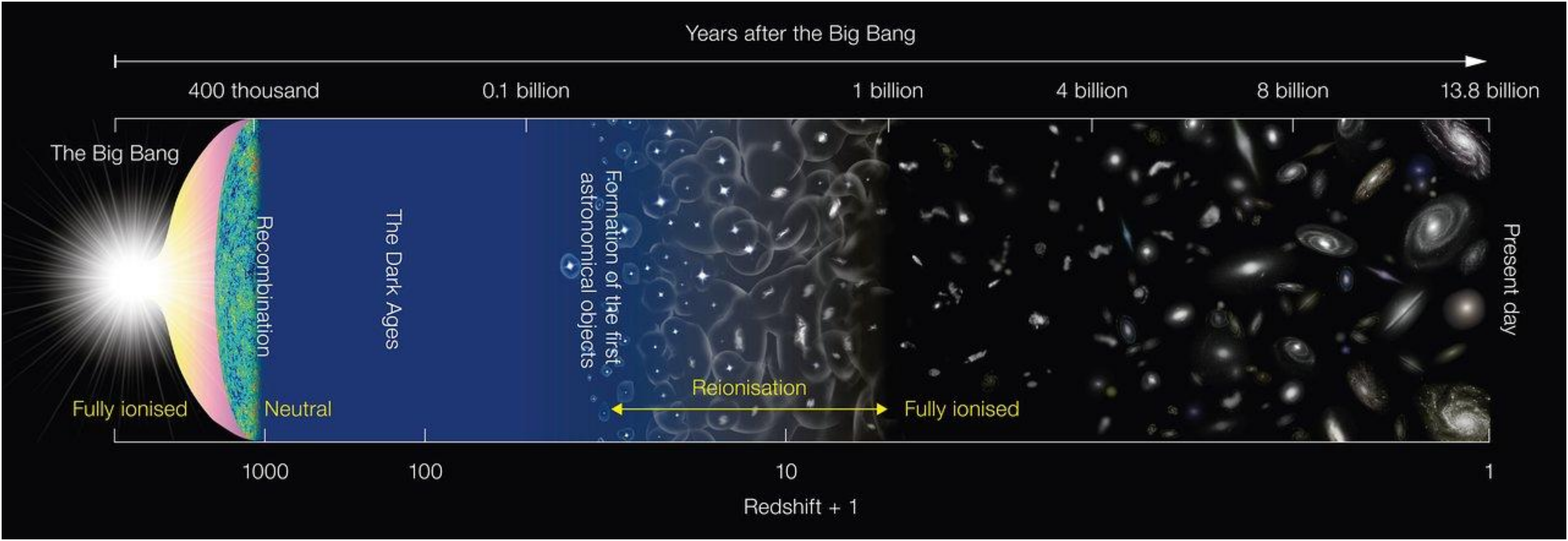
Cosmic Microwave Background



Credits: ESO

CMB carries a wealth of information about early times

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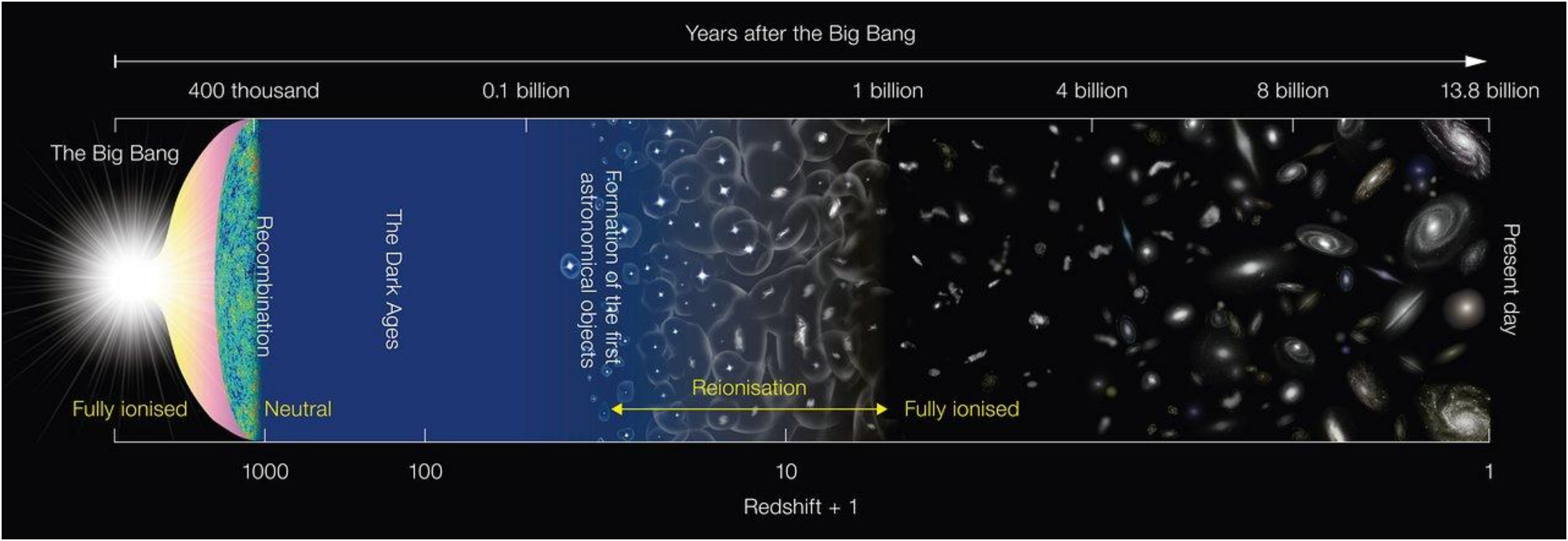

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CMB carries a wealth of information about early times

But also about late-time Universe!

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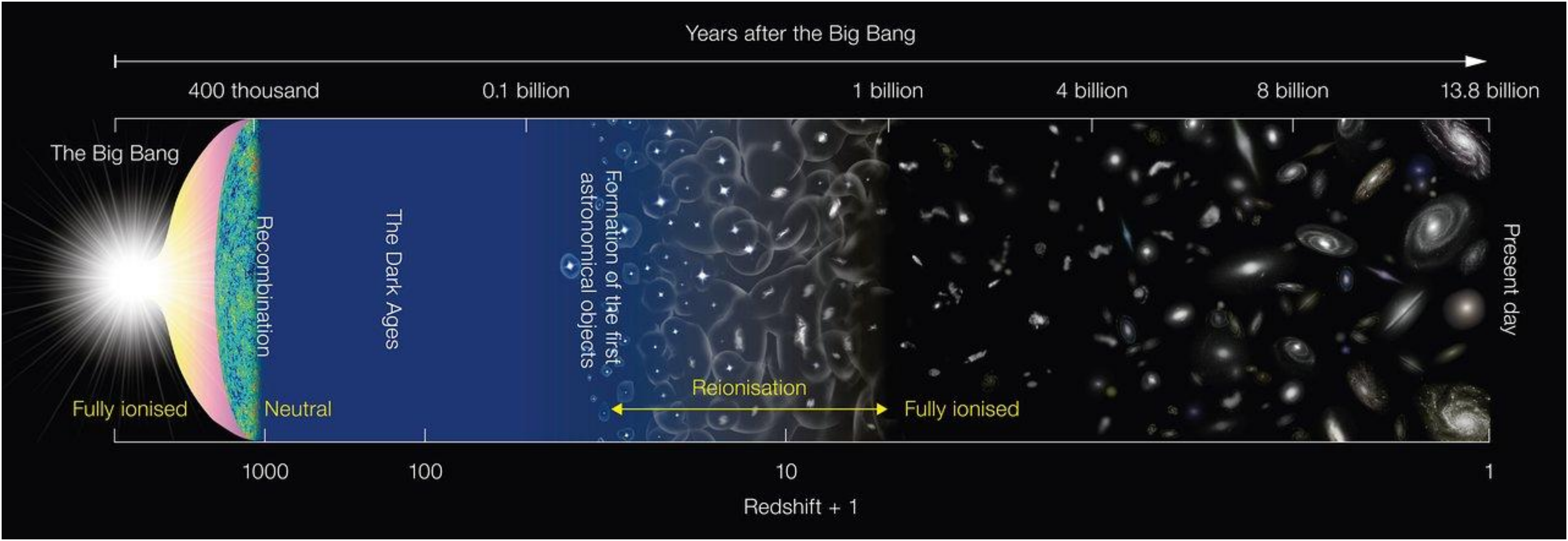

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CMB photons in late Universe:

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

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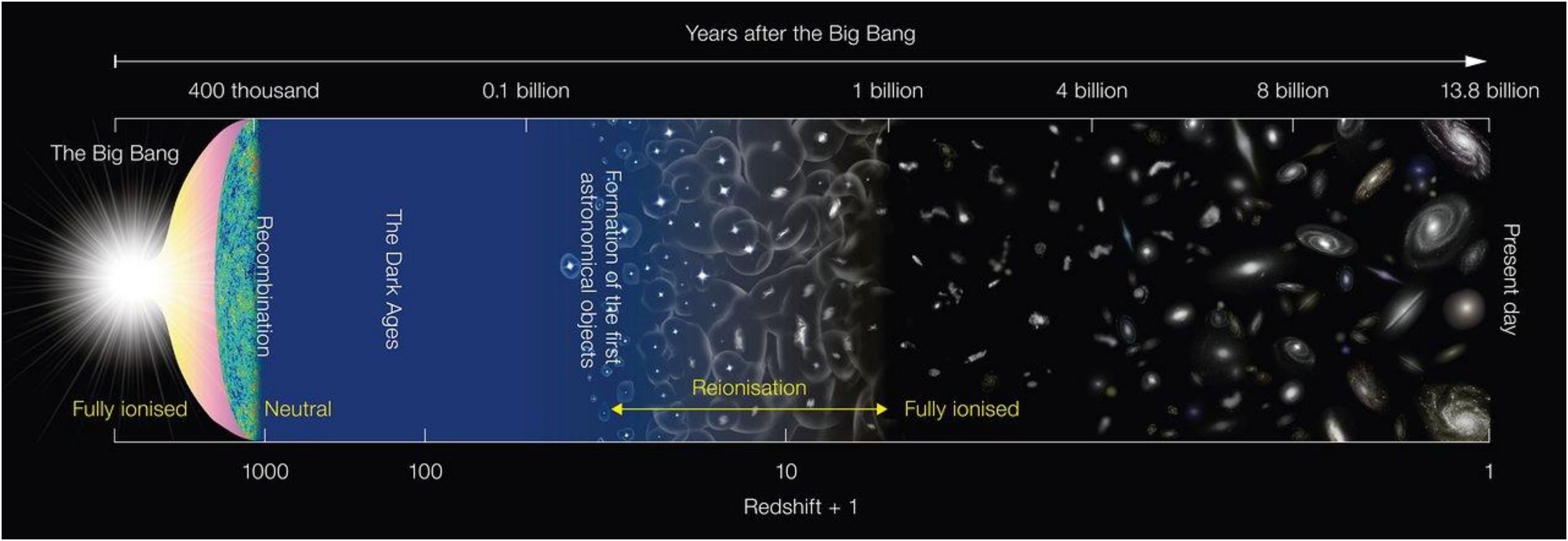

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CMB photons in late Universe:

- Deflect from matter: CMB gravitational lensing→probe of total mass
- Scatter off free electrons (“gas”/ “baryons”): Sunyaev–Zel’dovich Effect→probe of baryons

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Sunyaev–Zel’dovich (SZ) Effect

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

Sunyaev & Zeldovich 1972

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Thermal (tSZ) **Kinematic (kSZ)**

Sunyaev & Zeldovich 1972

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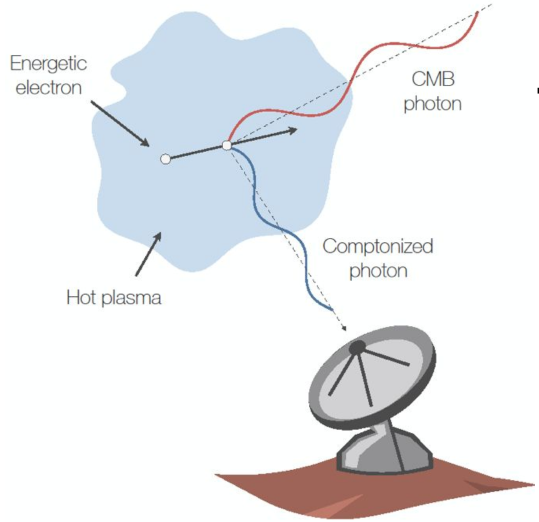

tSZ effect

Thermal (tSZ)

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

Kinematic (kSZ)

Sunyaev & Zeldovich 1972

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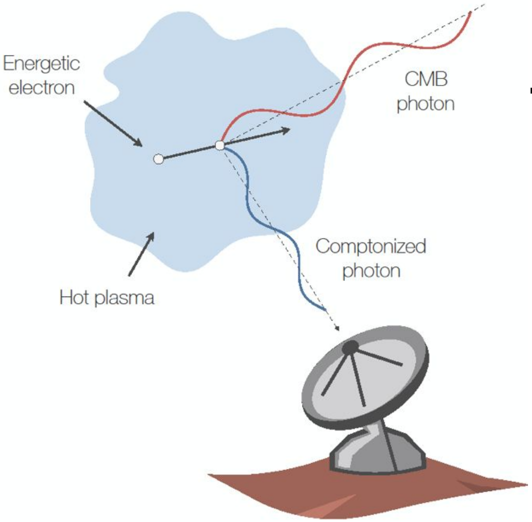


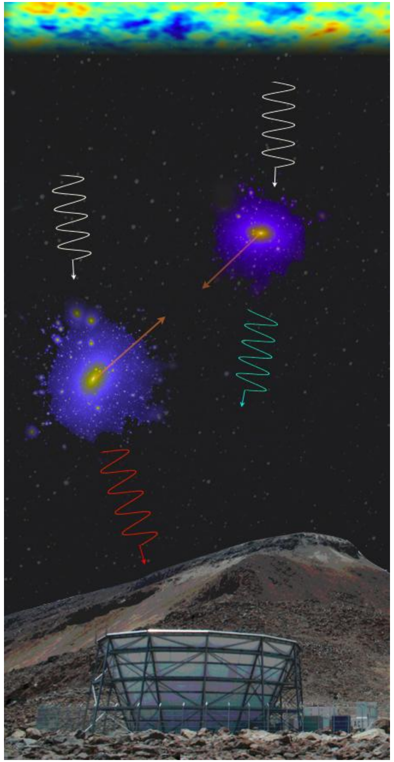
tSZ effect

Thermal (tSZ)

- electrons have high temperatures
- ∝ **electron integrated pressure**
- “dense” structures (galaxies)
- unique frequency dependence

Kinematic (kSZ)

- electrons have non-zero velocity
- ∝ **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

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

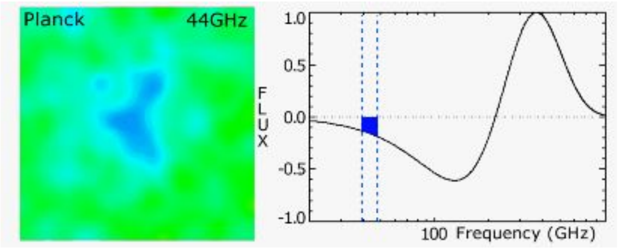
Frequency-dependence

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

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

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

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

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)

The kSZ effect

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

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Probe of cosmological parameters, **neutrinos** (see later), DE and gravity

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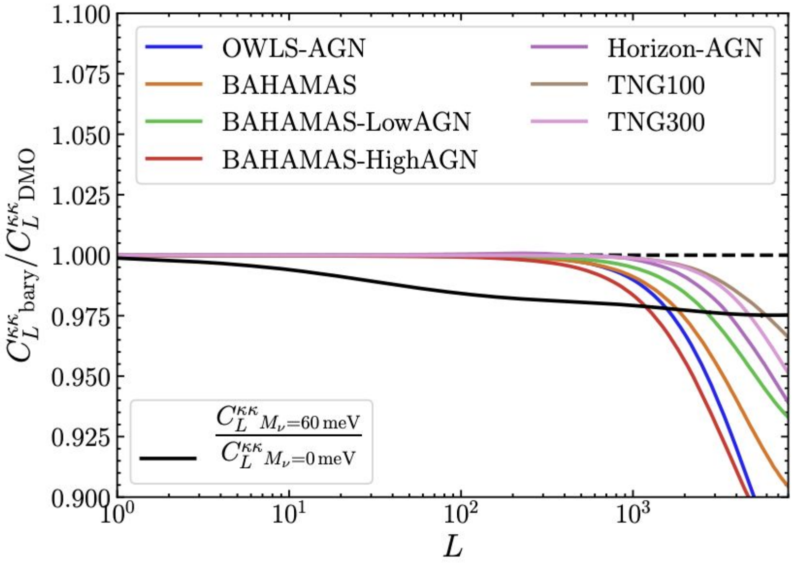
Electron number density
(astrophysics)

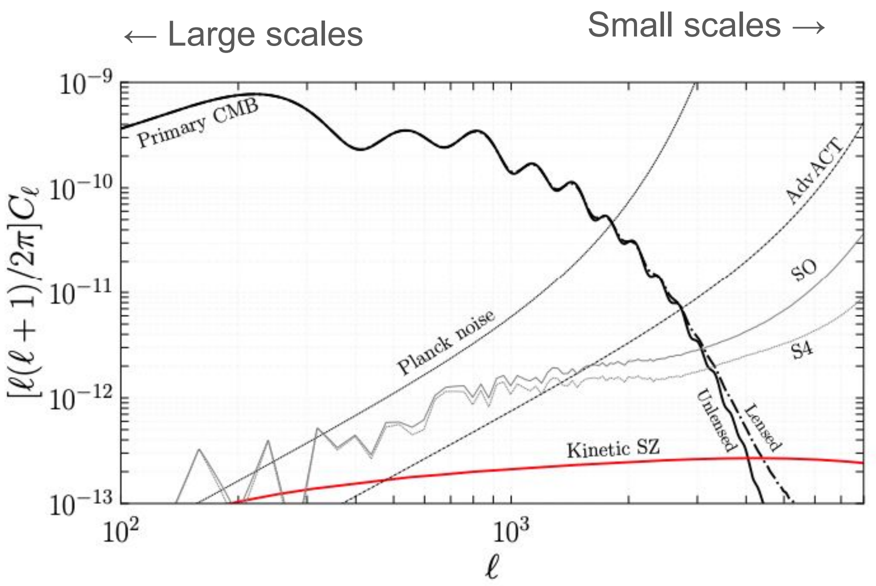
Combine kSZ (density)+tSZ (pressure)+CMB and galaxy lensing (mass) to constrain **baryonic feedback** (gas dynamics, star formation, AGNs) → necessary to constrain, e.g., **neutrino** masses from CMB lensing



The effect of **baryons** on the CMB lensing power spectrum (from McCarthy et al.)

Detecting kSZ: combine with LSS

- kSZ is a small signal
- Not possible to isolate kSZ solely based on frequency dependance (as for tSZ)



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

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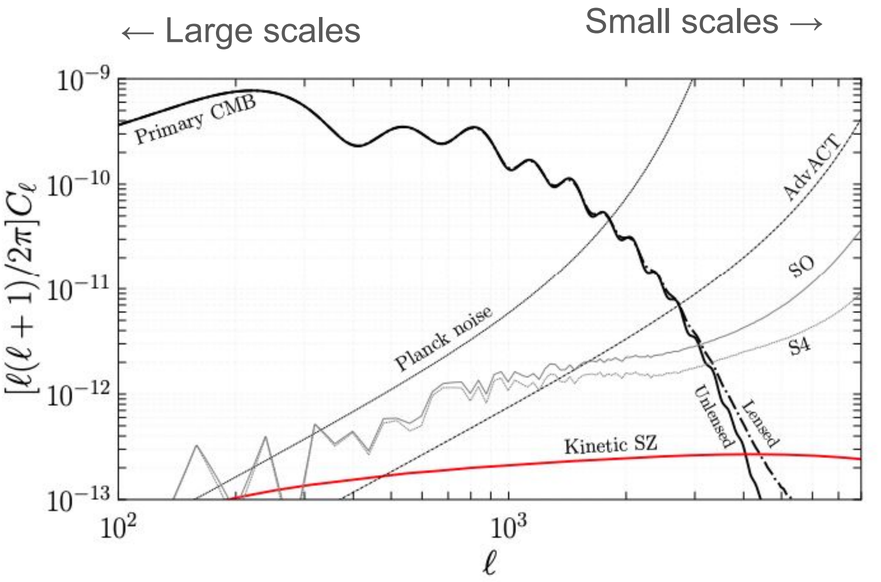
- Statistical estimators w/ LSS:
  1. Pairwise kSZ
     a. First kSZ detection in ACT+BOSS Hand+12
     b. Planck, SPT, ACT, Vavagiakis+21
  2. Velocity-weighted stacking
     a. Planck, ACT DR5, Schaan+21, Amodeo+21,
  3. Velocity-reconstruction
     a. No measurements yet, Munchmeyer+19,



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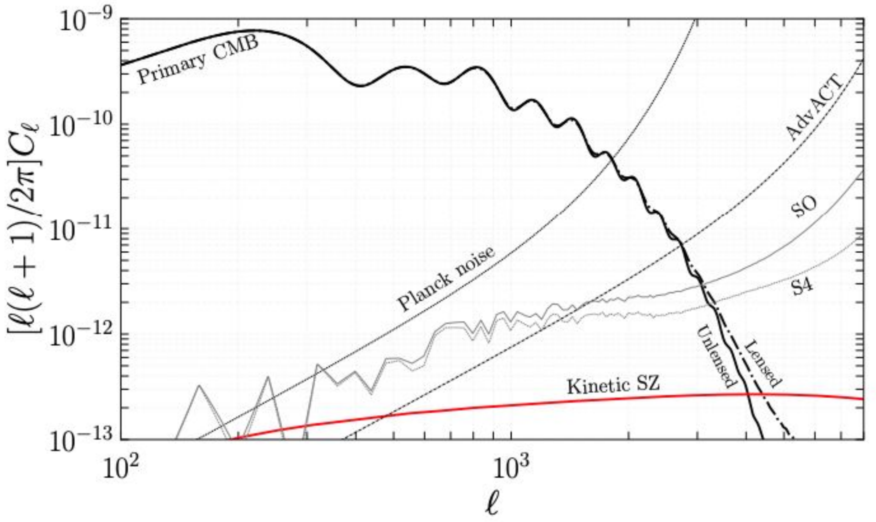
Mathematically equivalent (Smith+18) and require spectroscopic redshifts

← Large scales   Small scales →



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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

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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Solution: Square the kSZ field

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<u>Projected-field kSZ^2-LSS:</u>

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 **<T^2 x LSS>**

<u>No redshift estimates needed!</u>

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)

What do we measure with projected-fields?

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What do we measure with projected-fields?

kSZ-induced temperature shift in the CMB:

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

Gas density profile

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Gas density profile

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

Redshift distribution of LSS tracer

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Gas density profile

x

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<u>Redshift distribution</u> of LSS tracer

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

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

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)

What can we learn from the kSZ?

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What can we learn from the kSZ?

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

<T[2] x g>

baryon fraction

free electron fraction

large-scale velocity dispersion

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

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

Upcoming CMB experiments!

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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$\langle T^2$ x g$\rangle$

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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: $\langle T_{\mathrm{CMB}}^2$ x LSS$\rangle$ receives important contribution from CMB lensing that must also be accounted for (Hill+2016, Ferraro+2016)

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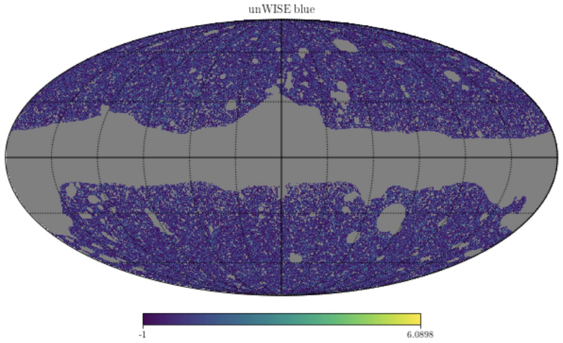
Projected-fields kSZ with unWISE and Planck

CMB:

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

unWISE catalog (Krolewski et al. 2020):

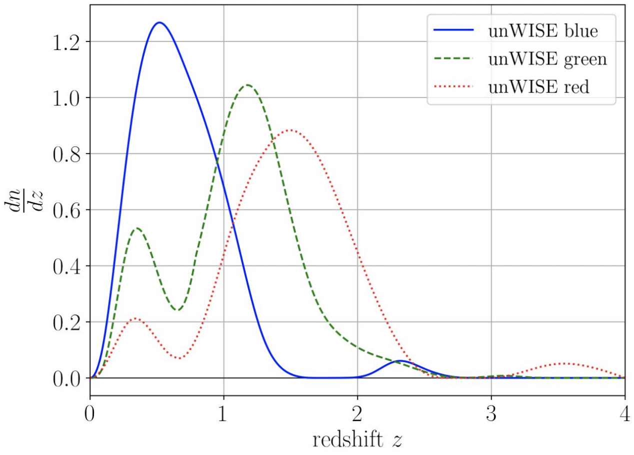
- Based on WISE and NEOWISE
- Over 500 million galaxies on the full sky
- 3 subsamples: blue (z=0.6), green (z=1.1), and red (z=1.5)



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

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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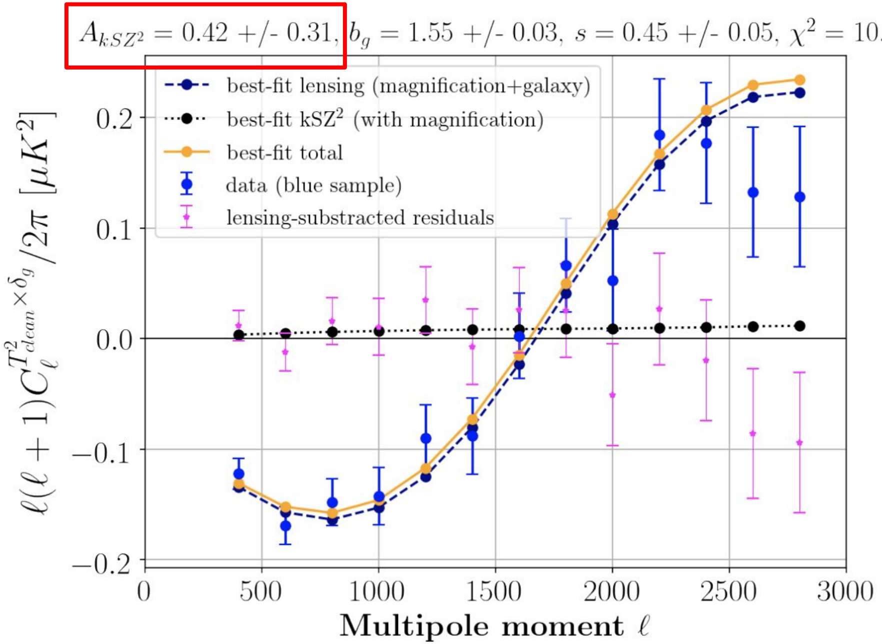
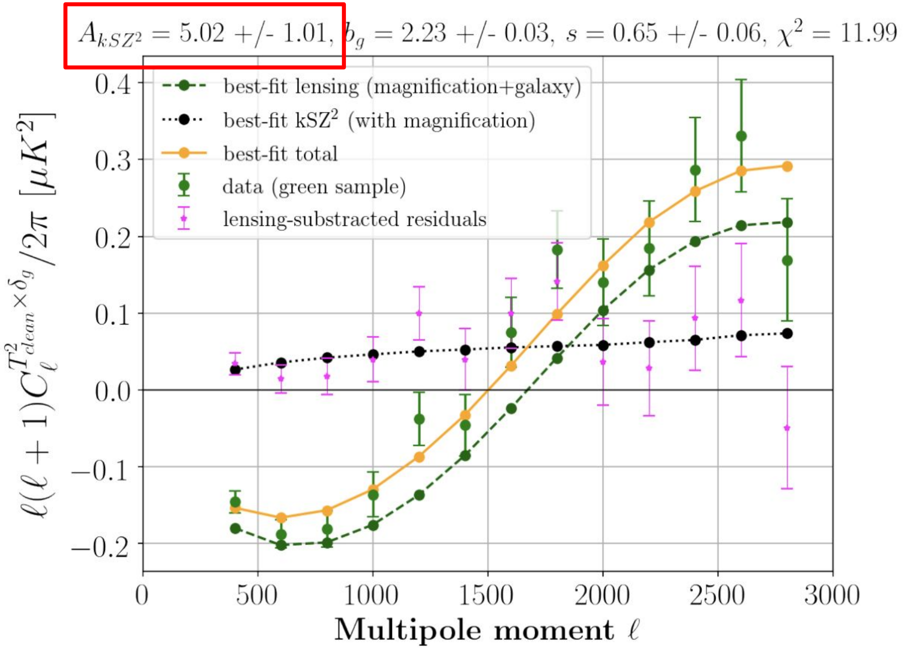
Projected-fields kSZ with unWISE and Planck





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:

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

Power Spectra in the halo model:

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

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

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

Galaxy overdensity:

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

Galaxy kernel

Mean number density of galaxies

Kusiak et al. 2022

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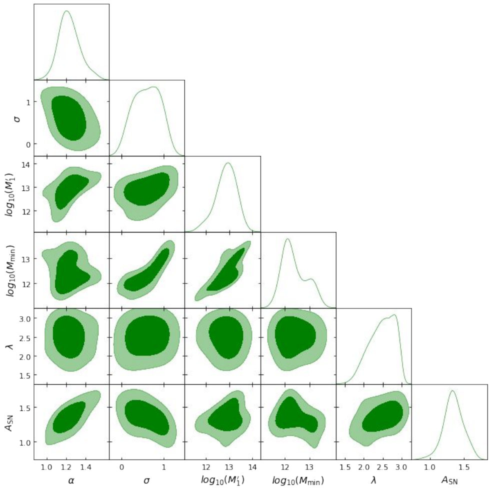
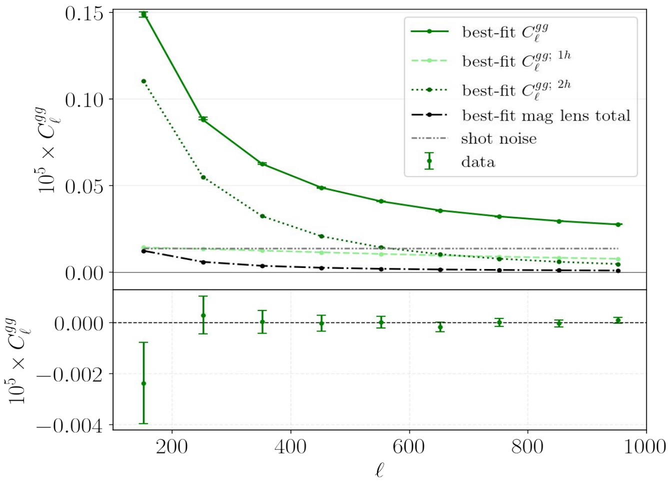
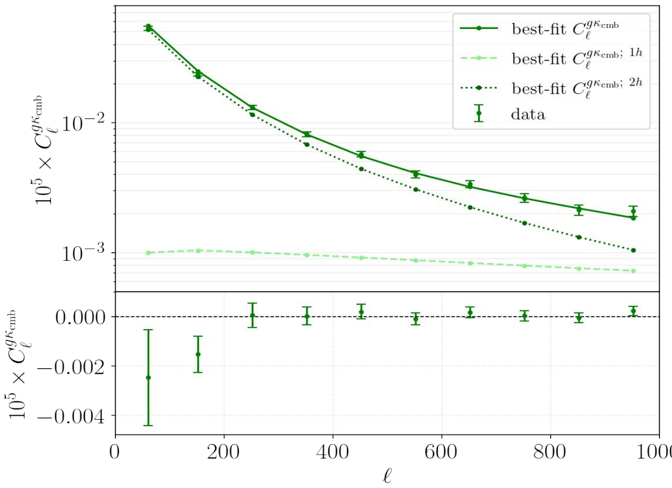
unWISE Halo Occupation Distribution (HOD)

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

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unWISE is of great interest!

unWISE is of great interest recently:

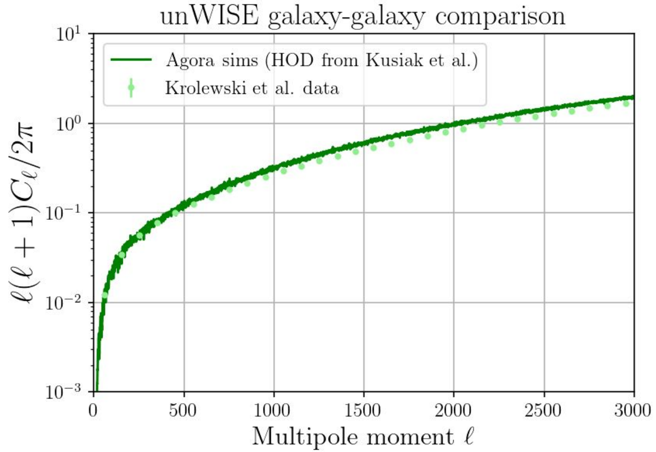
- cosmology with unWISE-ACT DR6 lensing (Farren et al.)
- Detection of CMB lensing-galaxy bispectrum with unWISE (Farren et al. 2311.04213), used my HOD
- cosmology with the Gaia-unWISE Quasars and CMB lensing (Alonso et al.)

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 kSZ^2 x LSS

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

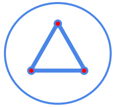
- Halo model hybrid bispectrum

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

X - LSS tracer

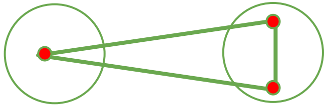
$$B^{1\mathrm{h}}_{\delta_e\delta_e X} = \int \mathrm{d}n_1 \hat{u}^{\mathrm{e}}_{k_1}(m_1)\hat{u}^{\mathrm{e}}_{k_2}(m_1)\hat{u}^{X}_{k_3}(m_1)$$

1 halo



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

2 halo

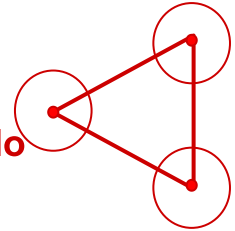


$$B^{3\mathrm{h}}_{\delta_e\delta_e X} = 2\int \mathrm{d}n_1 b^{(1)}(m_1)\hat{u}^{\mathrm{e}}_{k_1}(m_1)P_L(k_1) \int \mathrm{d}n_2 b^{(1)}(m_2)\hat{u}^{\mathrm{e}}_{k_2}(m_2)P_L(k_2) \int \mathrm{d}n_3 b^{(1)}(m_3)\hat{u}^{X}_{k_3}(m_3) F_2(k_1,k_2,k_3)$$
$$+ \int \mathrm{d}n_1 b^{(1)}(m_1)\hat{u}^{\mathrm{e}}_{k_1}(m_1)P_L(k_1)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

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

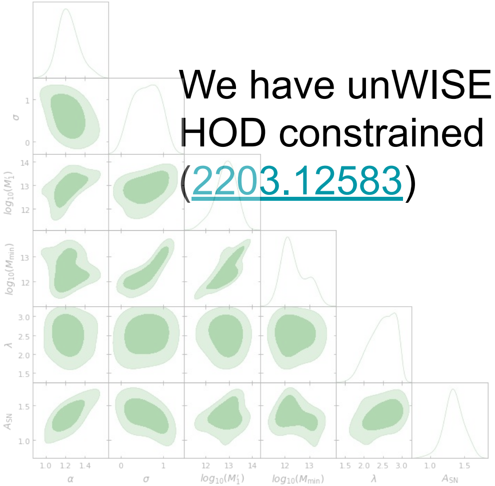
Halo-model kSZ^2 x LSS: forecasts

CMB:

- AdvACT, Simons Observatory and CMB-S4 temperature maps

LSS:

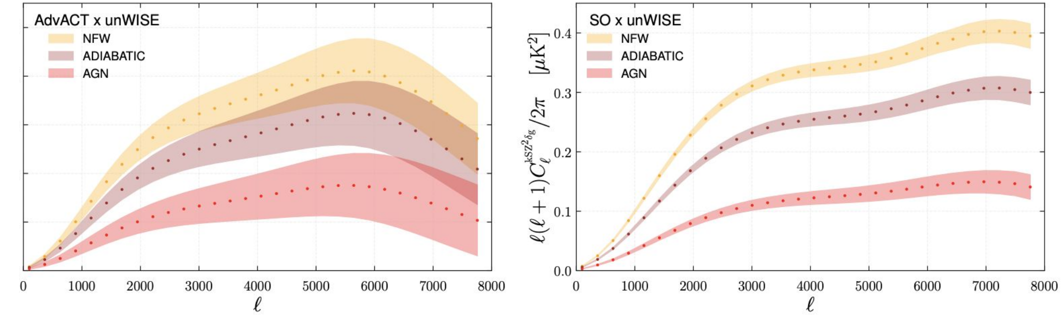
- Galaxy density (unWISE)
- Galaxy lensing (DES, VRO, Euclid)
- CMB lensing (SO, CMB-S4)



We have unWISE HOD constrained (2203.12583)

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

kSZ^2-unWISE forecasts



AdvACT: SNR ~ 17σ (ongoing)

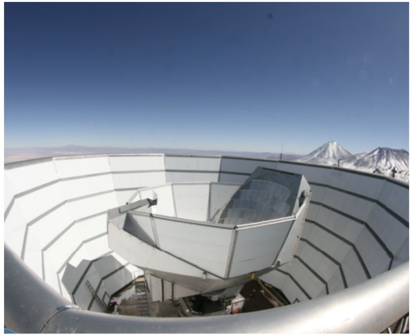
SO: SNR ~ 61σ

w/ *Euclid* galaxy lensing: SN ~19σ

w/ SO CMB lensing: SN ~16 σ

CMB-S4: ~100σ w/ unWISE, ~30σ w/Euclid galaxy lensing, ~35σ with CMB lensing

ACT DR6 data

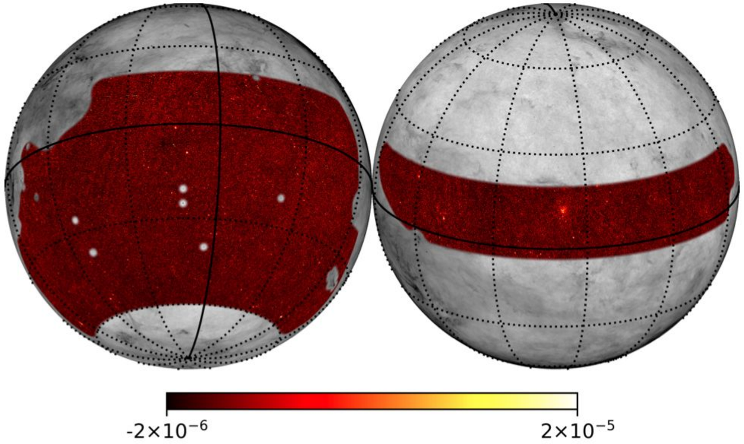


Atacama Cosmology Telescope (ACT) located on Cerro Toco in the Atacama Desert, Chile

ACT DR6 NILC maps include:

- CMB + kSZ blackbody
- Polarization
- Compton-y (tSZ) maps:
  - Various CIB deprojections

ACT DR6 Needlet ILC Compton-y (thermal SZ) map from Coulton et al.



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

ACT DR6 data:

- ~arcmin resolution and lower noise than Planck
- ~⅓ of the sky
- includes Planck for additional frequency coverage

Coulton et al. 2023

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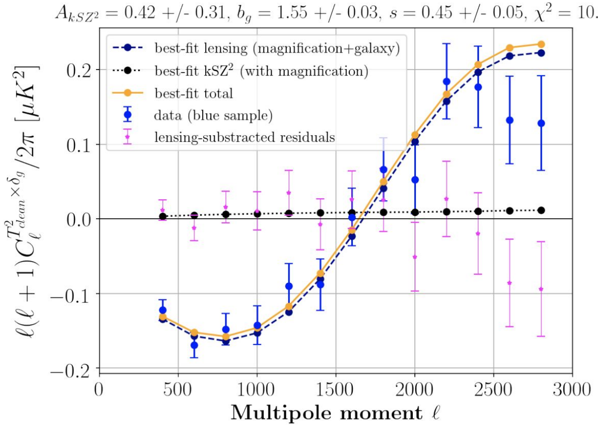
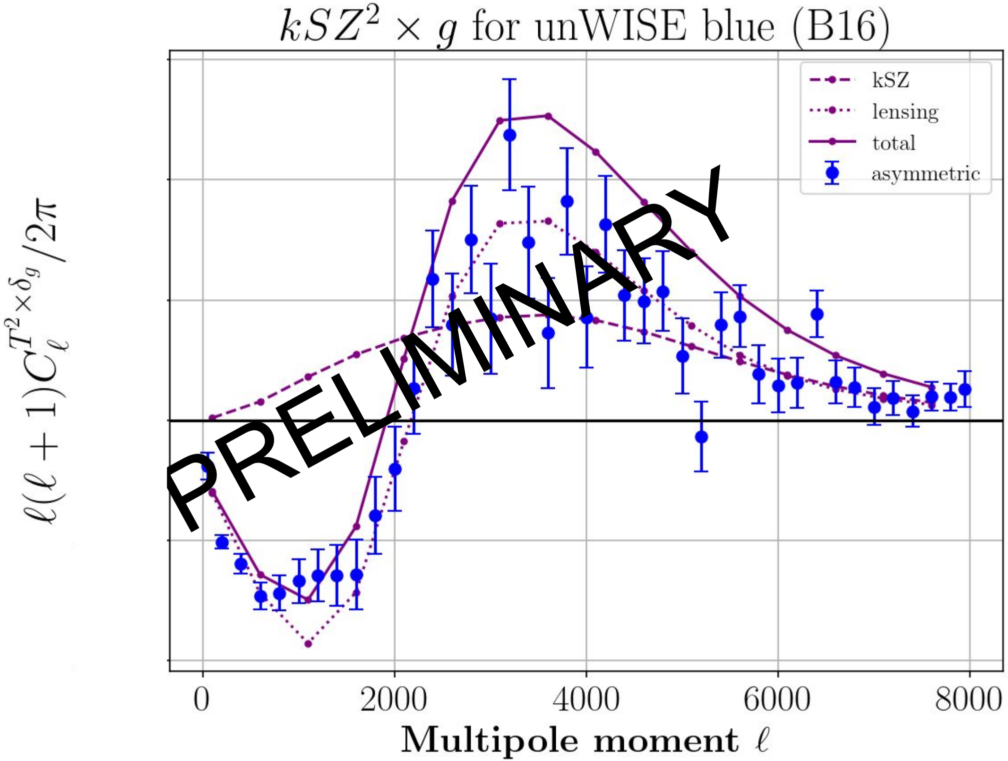
Projected-fields kSZ with unWISE and ACT DR6

With Planck



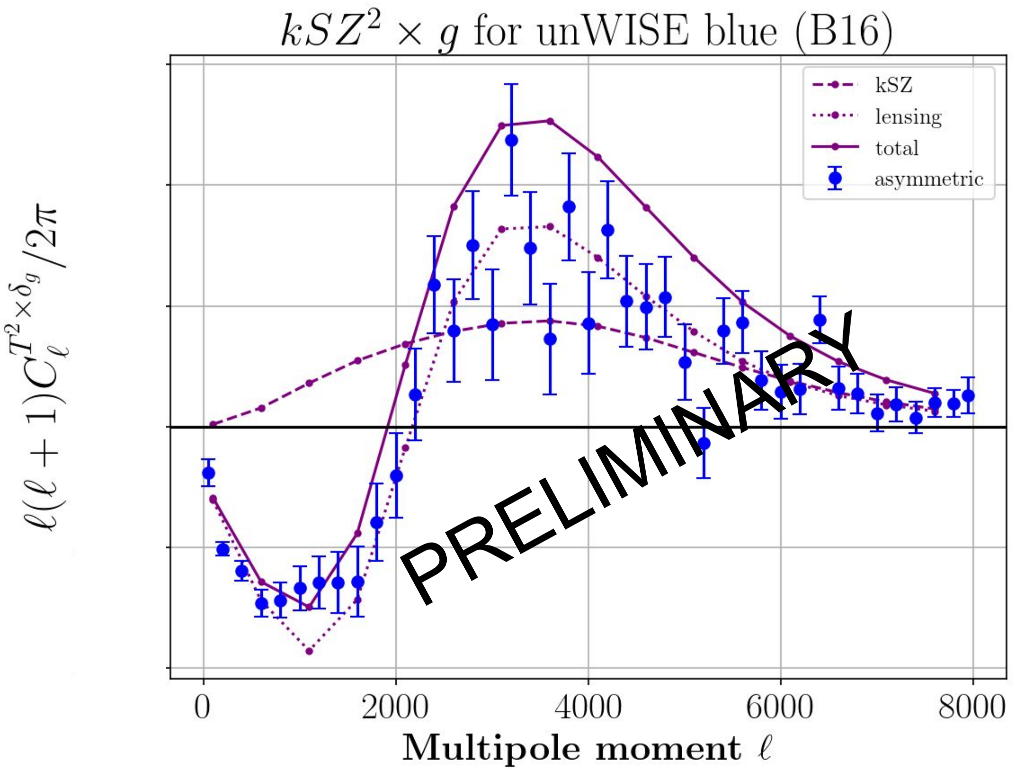


Measurement is lensing dominated

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

Goal: constrain unWISE **density profile**

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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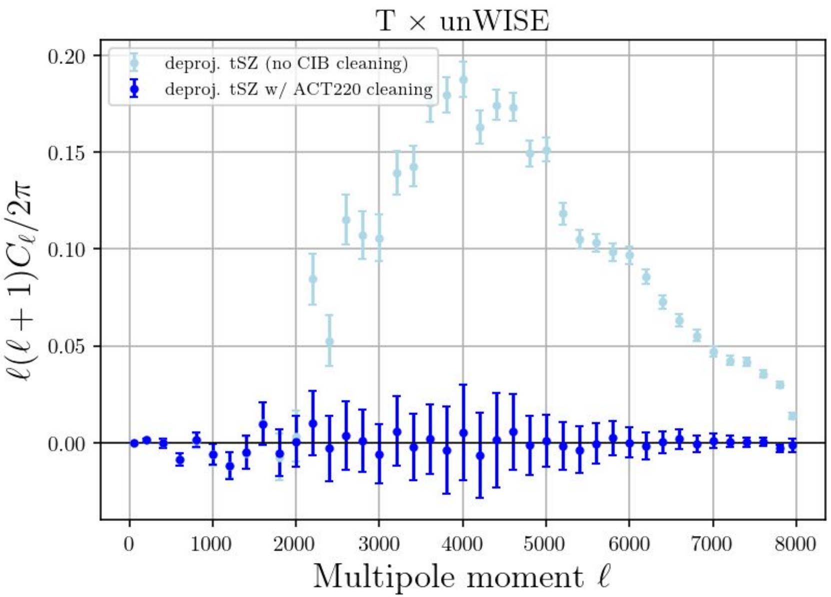
kSZ with unWISE and ACT DR6: Null tests

<T_clean x g> test



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

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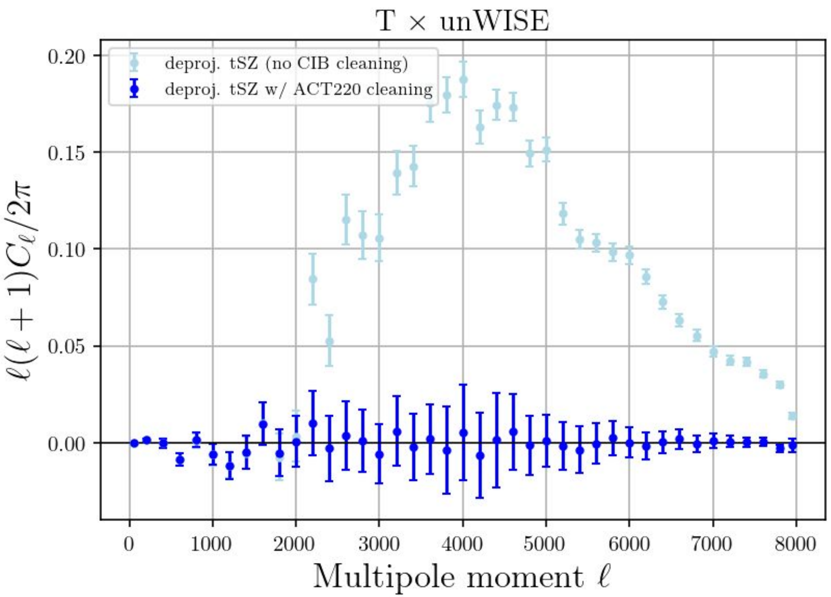
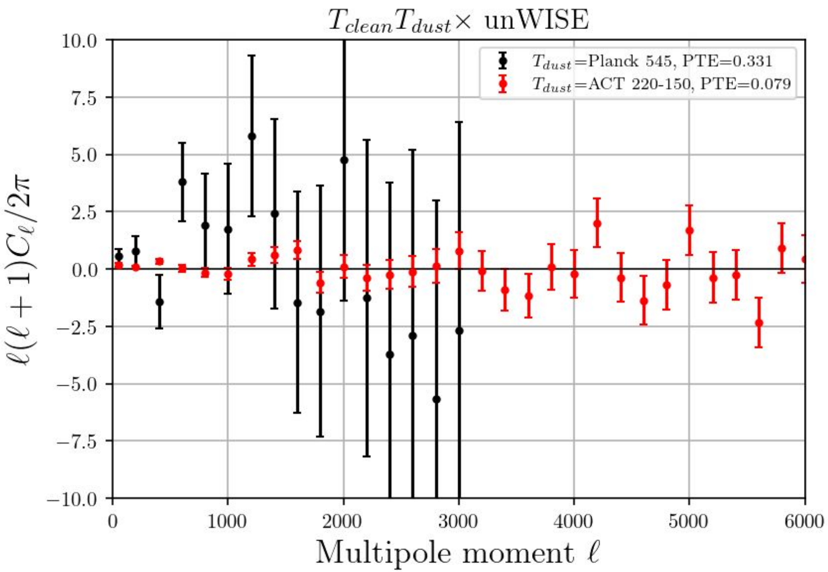
kSZ with unWISE and ACT DR6: Null tests

<T_clean x g> test



<T_dustT_clean x g> test



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

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

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Projected-fields kSZ as a probe of cosmology and fundamental physics

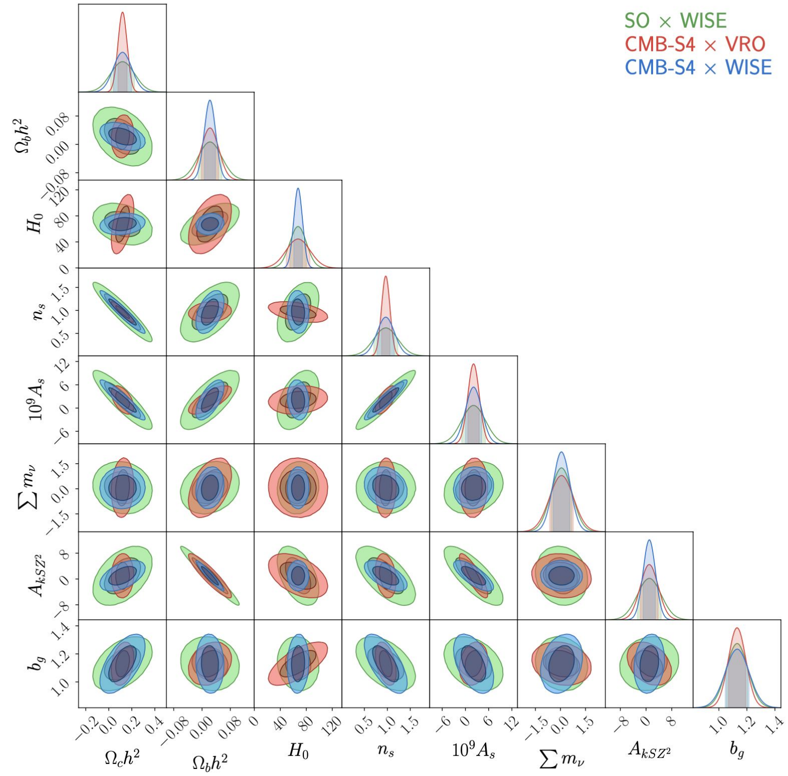
Patki et al. used the improved the kSZ estimator and put constraints on cosmological ΛCDM parameters + $\sum m_\nu$

- Assuming realistic post-ILC noise:

	kSZ + *Planck* + 1% b_g prior		
	SO × WISE	CMB-S4(ILC)× WISE	CMB-S4(ILC)× VRO
$\sigma(\Sigma m_\nu)$ [meV]	168	100	254

- Assuming *detector-only* noise:

CMB-S4 × WISE: $\sigma(\sum m_\nu)$ = 38 meV



Full bispectrum to ensure clear separation of large (cosmology) and small (astrophysics) scales?

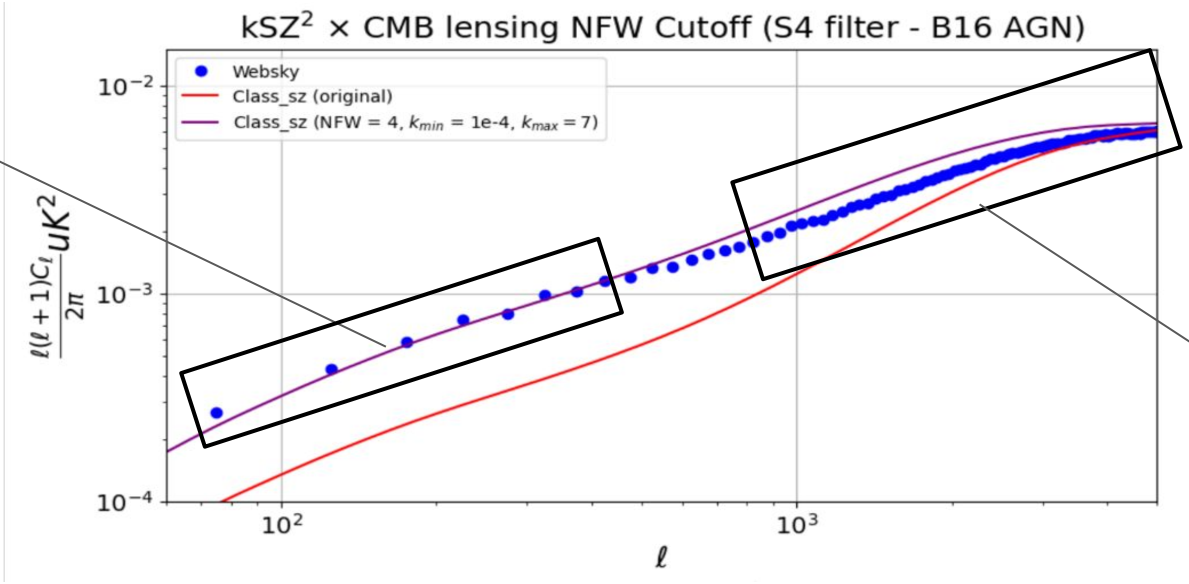
Patki et al. 2023

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.)

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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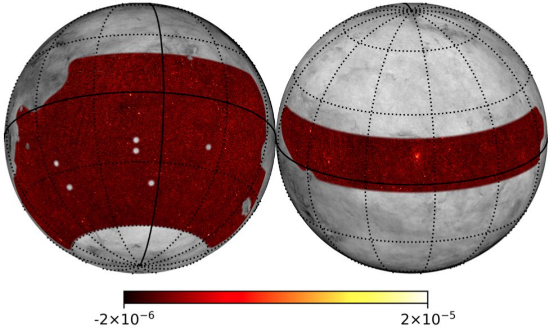
tSZ with unWISE and ACT DR6

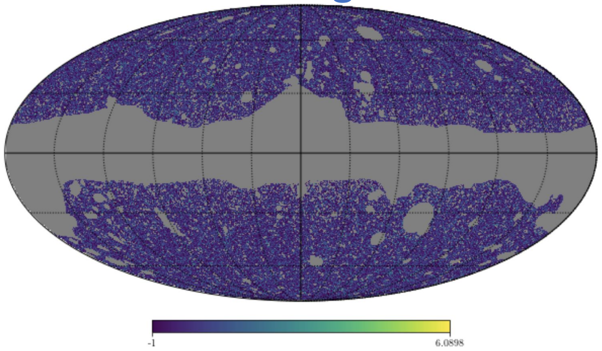
ACT DR6 (tSZ) Compton-y map



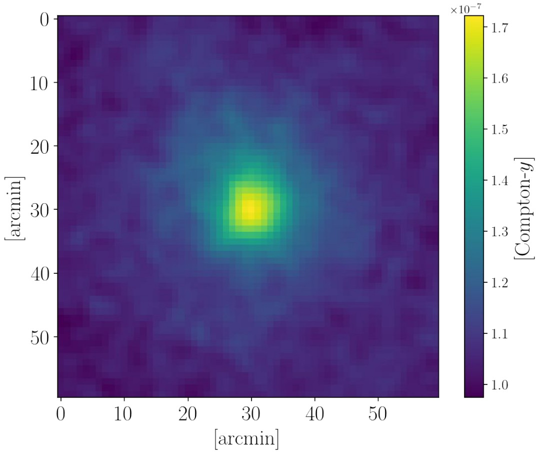
(a) ACT & *Planck* NILC Compton-y map.

x

unWISE blue galaxies



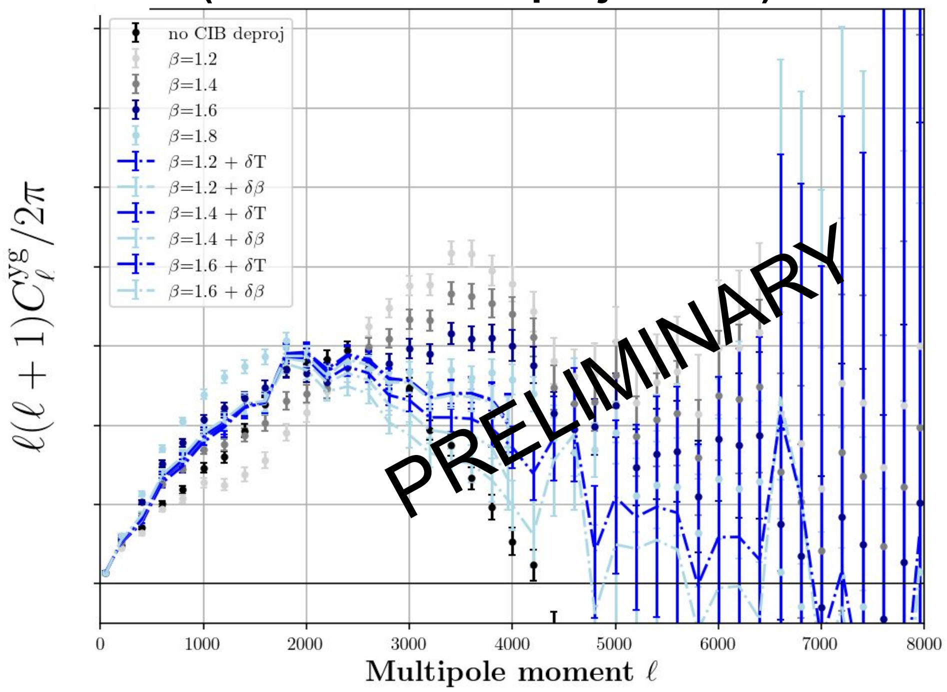
Measure the tSZ x unWISE (y x g) to constrain unWISE **pressure profile**



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

tSZ with unWISE and ACT DR6

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



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

Main worry is the **CIB contamination**:

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

  MBB:

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

- different versions of the CIB deprojected in the ILC
  - Deproject CIB assuming the MBB SED, but also dβ/dT (Chluba+ 2017, McCarthy & Hill 2023)

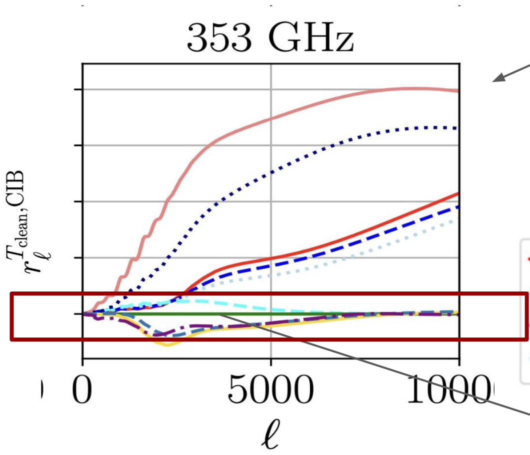
Analysis done in the halo model with class_sz (Bolliet, AK, et al.) and unWISE HOD to constrain unWISE **pressure profile**

deCIBing

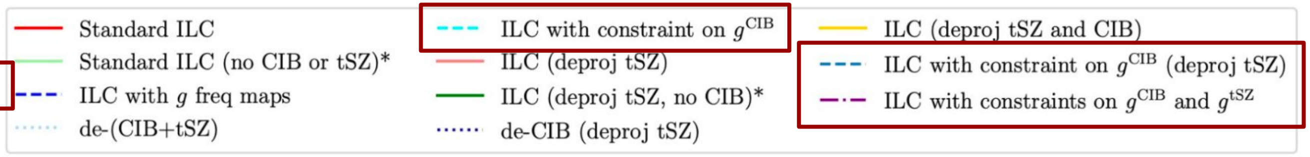
Do the opposite: Use the external LSS data (=unWISE) that correlates with both CIB and tSZ to remove those contaminants to enhance CMB+kSZ measurements using ILC methods

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

Come to CMB Lunch on Friday if you want to learn more!

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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 processes to enable Stage-IV **neutrino mass constraints** from CMB lensing (**CMB-S4**) and galaxy weak lensing (**LSST**)

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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**

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** (approved project), LSST, prepare for CMB-S4
2. Joint kSZ + tSZ + lensing to **constrain feedback**
3. unWISE
   - Improving dNdz with DESI (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!