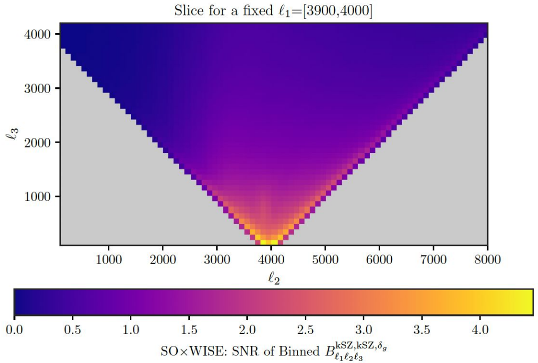
A Novel Bispectrum extracting the Kinematic SZ effect using Projected Fields

arXiv: 2411.11974

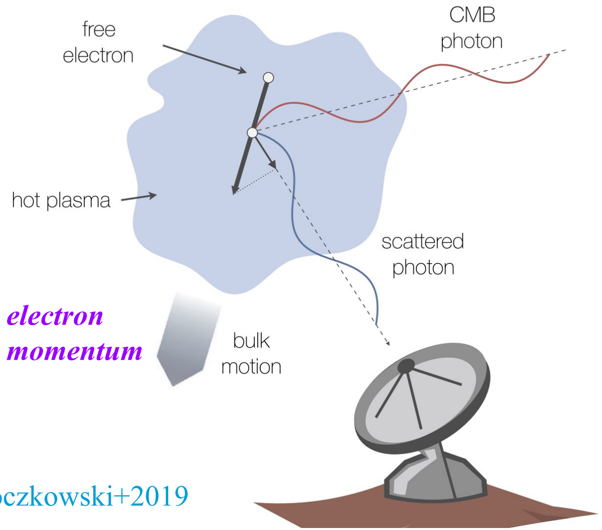
Raagini Patki
Cornell University

with
Nick Battaglia & Colin Hill



June 25, 2025
mm Universe 2025 | University of Chicago

Why study the kSZ effect?



Source: Mroczkowski+2019

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

Astrophysics (gas density) × **Cosmology** (velocity)

- *Abundance* of baryons (z)
- *Distribution* of baryons: density profile:

  How extended? feedback?

$\Updownarrow$

- Peculiar velocities – probe *large* scales!

$\rightarrow$ trace total matter density $\mathbf{v}(\mathbf{k}) = i\frac{faH\delta(\mathbf{k})}{k}\hat{\mathbf{k}},$

$\rightarrow$ growth rate of LSS

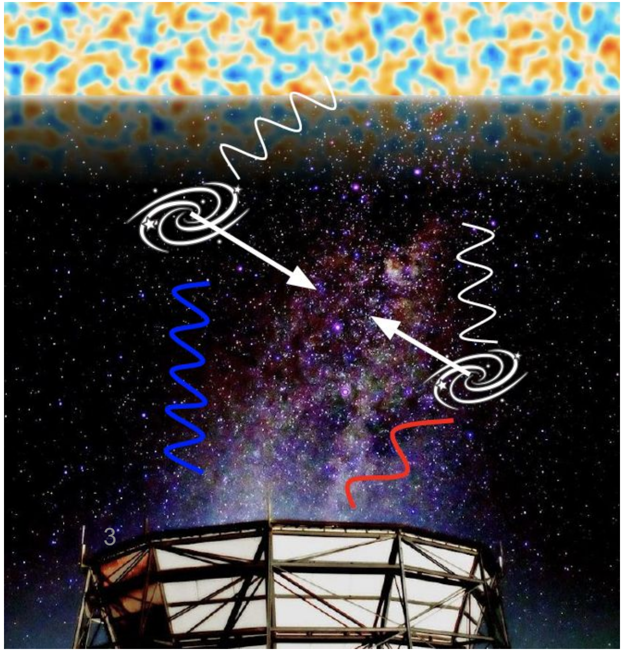
- *Neutrino masses, dark energy, gravity, f_{NL}!*

Detecting the kSZ: (how to) use LSS data?

- High-resolution CMB maps: ACT, SPT, → SO
- Cannot isolate: by ILC alone; +reionization kSZ

- Different kSZ estimators: 3D ‘**tomography**’ type:

1. Pairwise kSZ:
   - ACT DR6 + SDSS, SPT + DES
2. Velocity-weighted stacking:
   - ACT DR6 + DESI
3. Velocity reconstruction:
   - ACT DR6 + DESI-LRGs, SDSS



Sources: e.g. Hand+12, Soergel+22, Vavagiakis+21, Schaan+21, Hadzhiyska+24, McCarthy+24, Lague+24

Detecting the kSZ: (how to) use LSS data?

- High-resolution CMB maps: ACT, SPT, → SO
- Cannot isolate: by ILC alone; +reionization kSZ

- Different kSZ estimators: 3D ‘**tomography**’ type:

1.

2.

3.

Mathematically equivalent to:

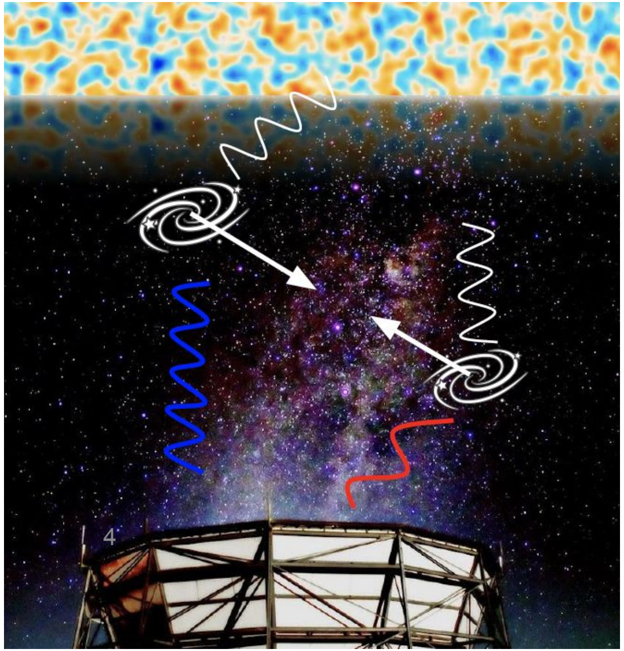
< T g g >

[Smith+18]

&

Key:

Require estimates of *individual* redshifts of galaxies



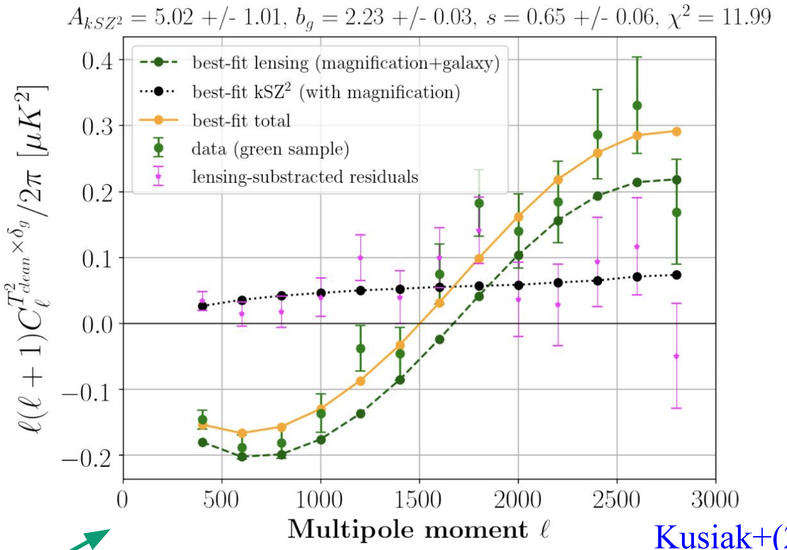
Sources: e.g. Hand+12, Soergel+22, Vavagiakis+21, Schaan+21, Hadzhiyska+24, McCarthy+24, Lague+24

Instead: use *Projected-Fields* of LSS tracers?

$$\delta_g(\hat{\mathbf{n}}) = \int_0^{\eta_{\max}} d\eta\, W^g(\eta)\, \delta_m(\eta\hat{\mathbf{n}}, \eta)$$

- *without requiring redshifts of individual LSS tracers* → only need a rough dn/dz
- Applicable to:
  - *Photometric galaxies* - with large photo-z errors (e.g. (un)WISE, Rubin)
  - CMB/galaxy lensing convergence, quasars, 21-cm
- But: $\langle \mathrm{kSZ} \times \delta_g \rangle \approx 0$
- *Solution*? So far:

$$\langle \mathrm{kSZ}^2 \times \delta_g \rangle$$



Kusiak+(2021)

Measurements in Planck data using WISE or unWISE galaxies

Doré+(2004); DeDeo+(2005), Ferraro+(2016), Hill+(2016), La Plante+(2022), Bolliet+(2022), **Patki+(2023)**

$\rightarrow$ A New $\langle \mathrm{kSZ} \times \mathrm{kSZ} \times \delta_g \rangle$ Bispectrum

arXiv: 2411.11974

Take a *cleaned* CMB map
$\rightarrow$ Take **a full 3-point cross-correlation**
in **harmonic space: < TTg >**
2 CMB maps with 1 projected-field (LSS)

- Previous kSZ^2 estimator: compression & convolution across triangle shapes
- Binned bispectrum => richer info, better scale separation across 'triangle *modes*'
- Better control: modeling uncertainties

$$B^{\mathrm{kSZ,kSZ},\delta_g}_{\ell_1\ell_2\ell_3} = b(\ell_1)b(\ell_2)\int_0^{\eta_{\max}} \frac{d\eta}{\eta^4} W^g(\eta) g^2(\eta) \boxed{B_{p_{\hat{n}}p_{\hat{n}}\delta}\left(\frac{\ell_1}{\eta}, \frac{\ell_2}{\eta}, \frac{\ell_3}{\eta}\right)}$$

3D **Binning** in harmonic space $\downarrow$

Why?

$$B^{\mathrm{kSZ,kSZ},\delta_g}_{abc} = \frac{\sum_{\substack{\ell_1\in\Delta_a \\ \ell_2\in\Delta_b \\ \ell_3\in\Delta_c}} \left(N_\Delta^{\ell_1\ell_2\ell_3} B^{\mathrm{kSZ,kSZ},\delta_g}_{\ell_1\ell_2\ell_3}\right)}{N_{abc}}$$

Bucher+2016, Coulton & Spergel 2019

Theoretical model & Analysis choices

Patki, Battaglia, & Ferraro: arXiv:2306.03127

- **Improved model** for underlying $B_{p_n p_n \delta}$ → accurate across **all shapes**:
- Faster computation: fitting fn for matter bispectrum, build emulators
- Forecasts: **SO and CMB-S4** - realistic post-ILC noise

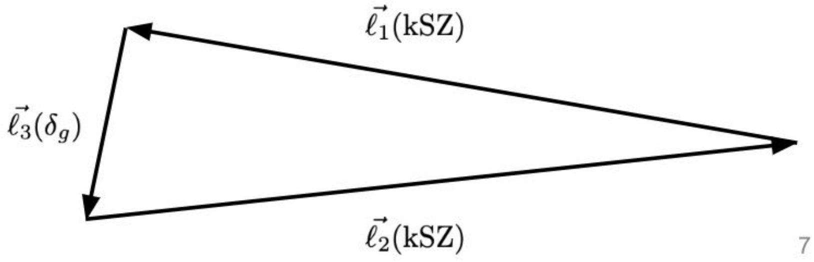
  $\ell_{\max}$ ~8000

- **WISE** galaxies - z < 1; ~ 50 mil

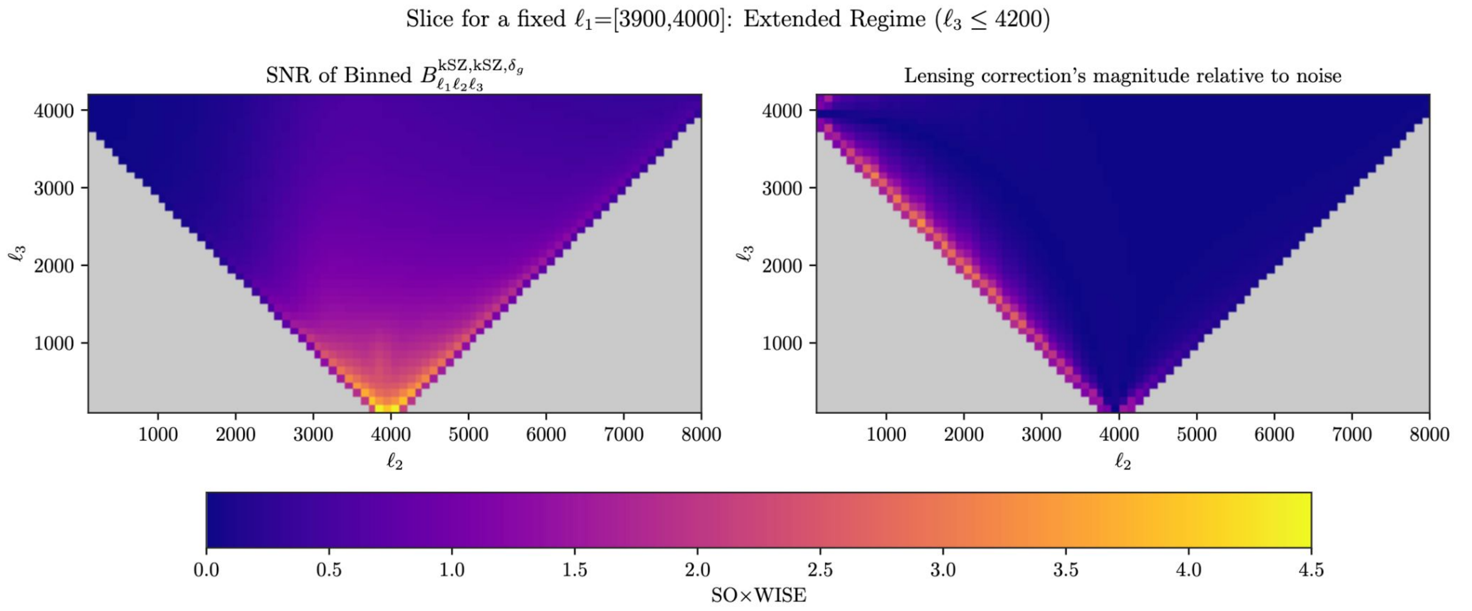
- For constraints: choose to restrict galaxy modes to linear scales $\ell_{\max} \sim 700$

Terms	Geometric scaling
$\langle v^i(\mathbf{k}) v^j(\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	1
$\langle v^i(\mathbf{k})\delta(\mathbf{k}_1-\mathbf{k})\rangle\langle v^j(\mathbf{k}')\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	0
$\langle v^i(\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k}) v^j(\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	k/k_2
$\langle\delta(\mathbf{k}_2-\mathbf{k}') v^j(\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k}) v^i(\mathbf{k})\delta(\mathbf{k}_3)\rangle$	0
$\langle\delta(\mathbf{k}_1-\mathbf{k}) v^j(\mathbf{k}')\rangle\langle v^i(\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	k/k_1
$\langle v^i(\mathbf{k})\delta(\mathbf{k}_3)\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}') v^j(\mathbf{k}')\rangle$	0
$\langle\delta(\mathbf{k}_3) v^j(\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}') v^i(\mathbf{k})\rangle$	0
$\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\rangle\langle v^i(\mathbf{k}) v^j(\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	$[-k+(k_1 \text{ or } k_2)]/k_3$
$\langle\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle\langle v^i(\mathbf{k}) v^j(\mathbf{k}')\delta(\mathbf{k}_1-\mathbf{k})\rangle$	0
$\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_3)\rangle\langle v^i(\mathbf{k}) v^j(\mathbf{k}')\delta(\mathbf{k}_2-\mathbf{k}')\rangle$	0

TABLE I. The ten terms in the Wick contraction of $\langle p_\perp p_\perp \delta\rangle \sim \langle\delta\mathbf{v}\delta\mathbf{v}\delta\rangle$ which contribute to $B_{p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}} \delta}(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3})$,



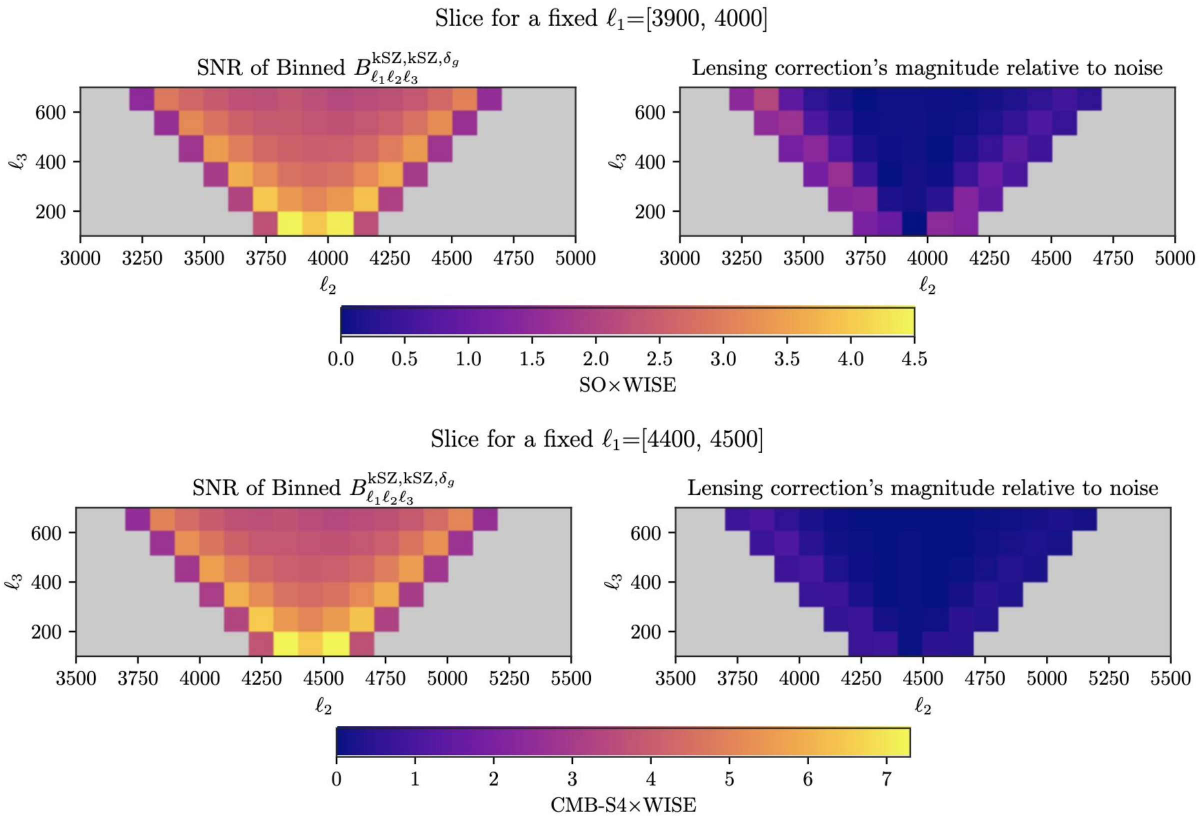
Extended regime: SNR and Lensing Correction



- Estimating covariance matrix analytically under weak non-Gaussianity,
  => SNR peaks for squeezed triangles: short LSS mode, 2 long CMB modes
- Correction due to CMB lensing: relatively small, peaks for different triangle shapes

Forecasts across shapes:

- No convolution => no mixing of scales/info
- Restricting LSS modes to linear regime retains highest SNR modes
- Lensing correction: small relative to signal for squeezed triangles



Detection Significance + *improvement:*

	$B^{\mathrm{kSZ,kSZ},\delta_g}$ (default)		$B^{\mathrm{kSZ,kSZ},\delta_g}$ (extended)		$C_\ell^{\mathrm{kSZ}^2\times\delta_g}$ [8]	
$\ell_{\max}$ of δ_g =	700		4200		8000	
	SO × WISE	CMB-S4× WISE	SO × WISE	CMB-S4× WISE	SO × WISE	CMB-S4× WISE
$\mathrm{SNR_{tot}}$	106	200	221	418	113	127

- **Cumulative SNR** across bins: comparable/higher than kSZ^2 method
- => **Robust** to HOD, nonlinear bias uncertainties
- No need to assume a theory template to detect
- **Potential future applications:**

  Constrain baryon abundance &/or density profile of baryons

$$\mathrm{SNR_{tot}} = \sqrt{\sum_{a,b,c} \frac{\left(B_{abc}^{\mathrm{kSZ,kSZ},\delta_g}\right)^2}{V_{abc}^{\mathrm{kSZ,kSZ},\delta_g}}}.$$

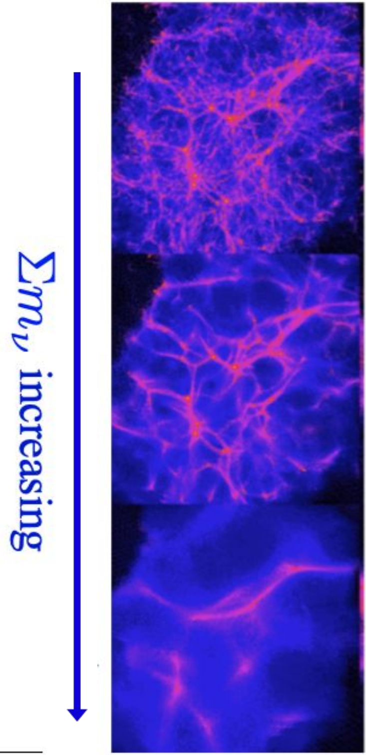
Probing Cosmology + ‘New Physics’!

- **Degeneracy** limits inference: baryon astrophysics $\longleftrightarrow$ cosmology

Q: Can we probe scale-dependent signatures at quasilinear scales?

- Include: free astrophysical amplitude: $A \propto \tau^2$
- <u>Initial</u> Fisher forecasts: ΛCDM + Σm_ν + A + linear galaxy bias
- Neutrinos imprint the kSZ:
  scale-dependent growth rate, and suppression of clustering
- Assuming an external prior on ΛCDM from primary CMB only:

	kSZ + *Planck* prior				kSZ + (SO or S4 + LiteBIRD) prior	
	$B^{\mathrm{kSZ,kSZ},\delta_g}$		$C_\ell^{\mathrm{kSZ}^2\times\delta_g}$ [14]		$B^{\mathrm{kSZ,kSZ},\delta_g}$	
	SO $\times$ WISE	CMB-S4$\times$ WISE	SO $\times$ WISE	CMB-S4$\times$ WISE	SO $\times$ WISE	CMB-S4$\times$ WISE
$\sigma(\Sigma m_\nu)$ [meV]	159	129	168	100	97	82



Source: Ben Moore

Conclusions and Future Outlook

- **Novel** projected-fields **kSZ bispectrum**: w/o individual LSS redshifts
- Improves upon existing 'kSZ^2 estimator': $\langle \mathrm{kSZ} \times \mathrm{kSZ} \times \delta_g \rangle$

  → Richer information content, better scale separation
- High SNR (esp squeezed triangles); **100-200σ** for SO, CMB-S4 with WISE
- Potential new, complementary probe of beyond-LCDM cosmology - or baryons!
- Next: model dependence on baryon density profile via Halo Model,

  tests on simulations → measurements with upcoming data!

arXiv: 2411.11974

Backup Slides

Projected-fields ‘ $\langle \mathrm{kSZ}^2 \times \delta_g \rangle$ ’ estimator:

***Existing* estimator:**

Take a *cleaned* CMB map
→ Wiener *filter (f)* to select scales
→ ***square*** it in real space
→ cross-correlate with projected-field (LSS)

$C_\ell^{\mathrm{kSZ}^2 \times \delta_g} =$

BUT, ***drawbacks*** -
Convolution (mixes scales)
&
Compresses across all ‘triangles’
(loss of info)

$f(|\mathbf{j}+\mathbf{q}|\eta) \boxed{B_{p_{\hat{\mathbf{n}}}p_{\hat{\mathbf{n}}}\delta}(\mathbf{q}, -\mathbf{j}-\mathbf{q}, \mathbf{j}).}$

Key statistic

+ Picks up a significant contribution from CMB **lensing** → must be accounted for

Doré+(2004); DeDeo+(2005), Bolliet+(2022), **Patki+(2023)**