Towards Cosmology with the Projected-Fields kSZ estimator

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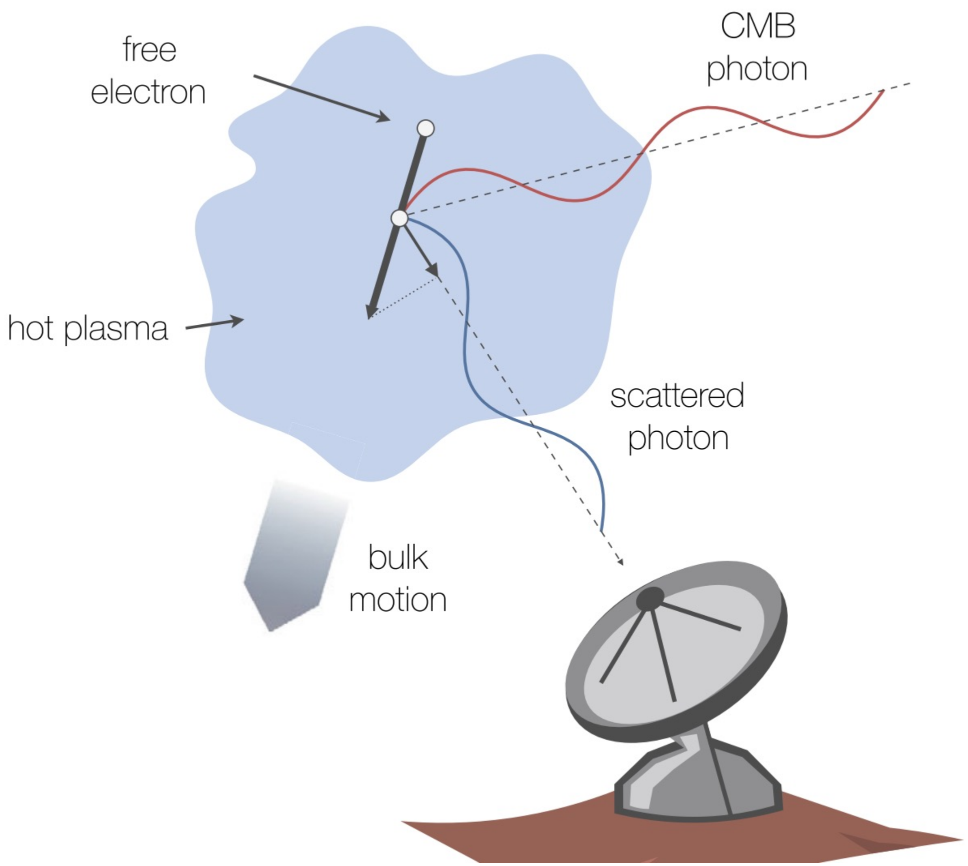
with Nick Battaglia & Simone Ferraro

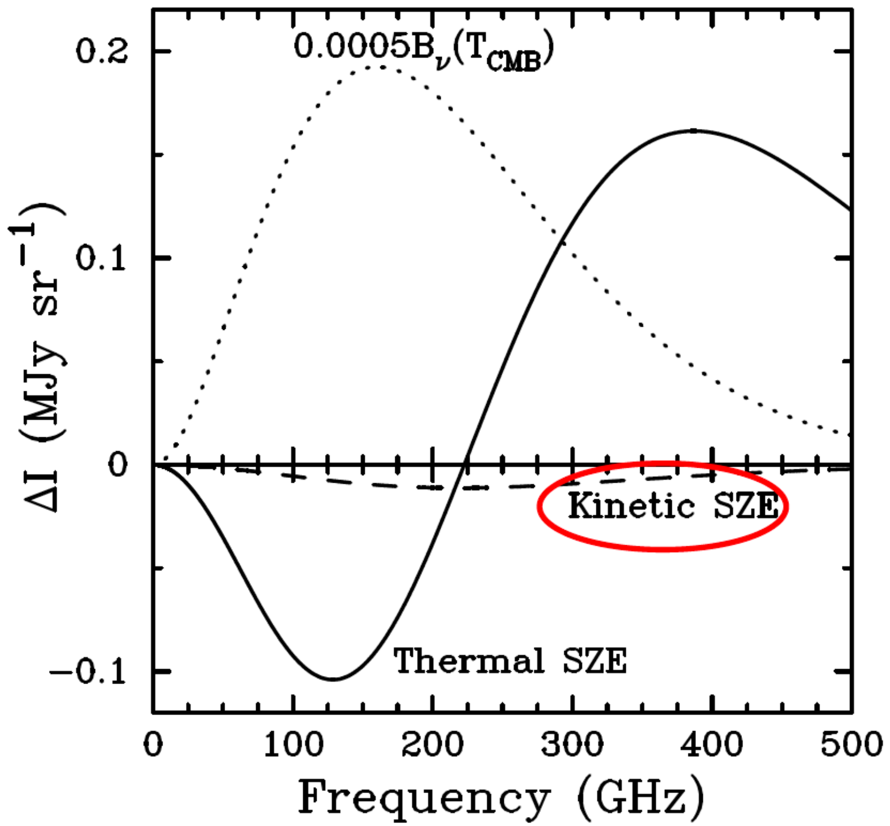
Outline

- Detecting the kSZ with Projected-fields
- Improved model for the Projected-fields estimator
- Cosmological dependence of the Projected-fields kSZ estimator
- Future Directions & Summary

The kinetic Sunyaev-Zel'dovich (kSZ) effect



- Dominates over primary CMB at: $\ell > \sim 4000$
- Equally likely ± ; maintains blackbody spectrum



→ Lowest order: Relative shift in blackbody $T_{\rm CMB} \propto \mathbf{p_e} = (1+\delta_e)\mathbf{v}_e$

Source: Mroczkowski+2019

The kSZ effect

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

→ Degeneracy: Astrophysics (gas density) × Cosmology (velocity)

Astrophysics:

- Abundance of baryons (z):

  → missing ?

- Distribution of baryons:

  → gas density profile

Cosmology:

- Peculiar velocities – scales > RSD
- Linear theory

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

& phenomenological:

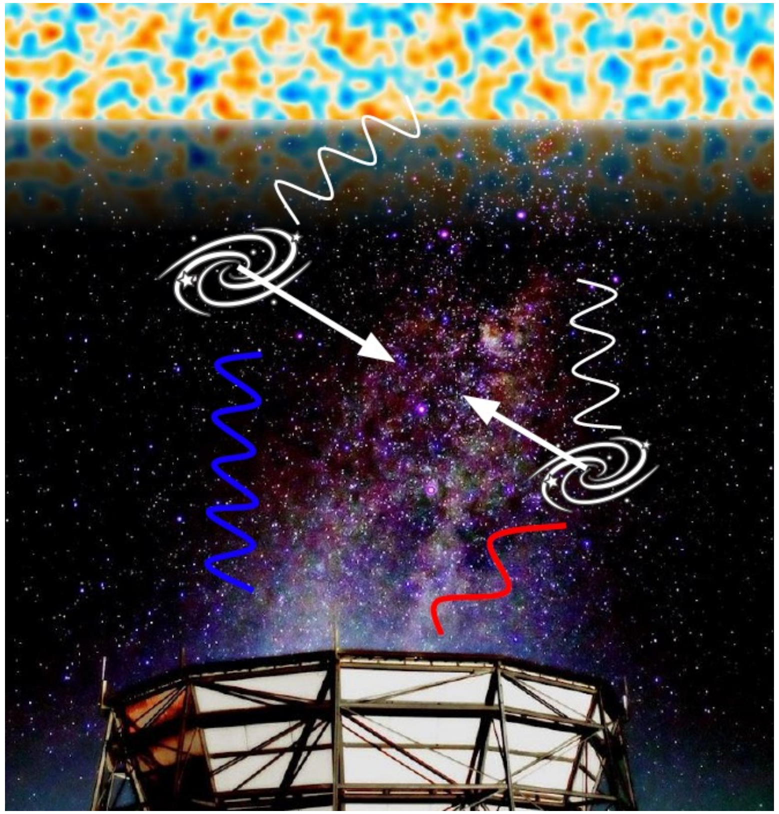
→ trace total matter density
→ growth rate of LSS

Detecting the kSZ: combine with LSS data

- *Cannot* isolate: by ILC, + reionization signal

- Statistical estimators:

1. Pairwise kSZ:
   - 1st kSZ detection in ACT+BOSS,
   - *Planck*, SPT, ACT-DR5, ..
2. Velocity-weighted stacking:
   - *Planck*, ACT, -DR5
3. Velocity reconstruction:
   - No measurements yet, probe for f_{NL}



Sources: e.g. Hand+12, Vavagiakis+21, Soergel+16, Schaan+21, Amodeo+21, Munchmeyer+19, ..

Detecting the kSZ: combine with LSS data

- *Cannot* isolate: by ILC, + reionization signal

- Statistical estimators:

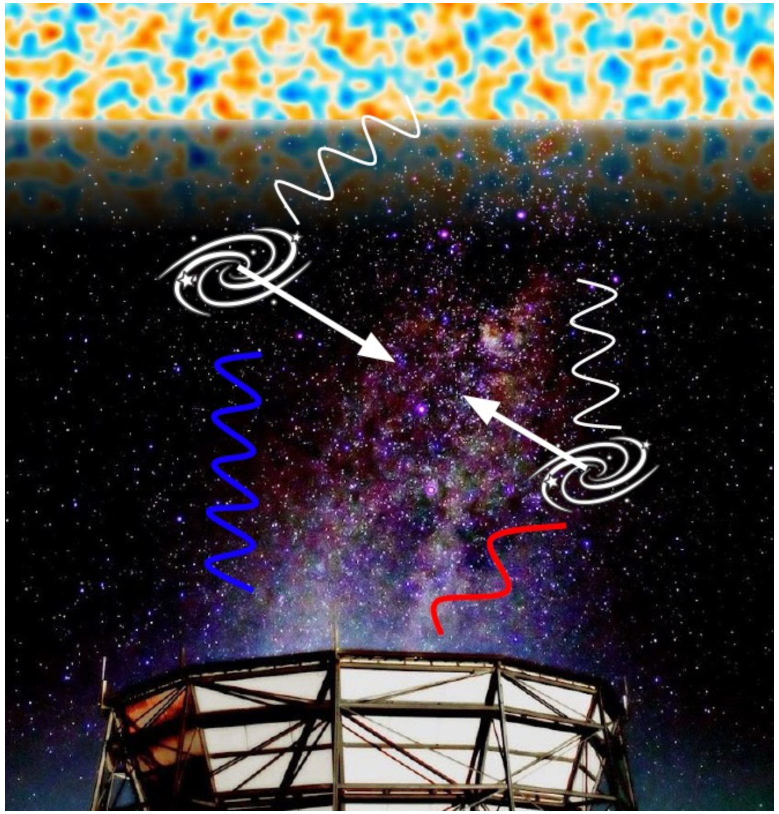
1.

Mathematically equivalent [Smith+18]
&

2.

Key:
Require accurate spectroscopic redshifts

3.



Sources: e.g. Hand+12, Vavagiakis+21, Soergel+16, Schaan+21, Amodeo+21, Munchmeyer+19, ..

Projected-fields kSZ estimator

Projected-field of LSS tracers:

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

→ Does *not* need accurate redshifts: e.g. photometric galaxies, lensing, 21-cm, ..

Take a *cleaned* CMB map → *filter* it to select *small* scales
→ <u>*square*</u> it in real space → before cross-correlating with LSS:

$$C_\ell^{\mathrm{kSZ}^2\times\delta_g} = \int_0^{\eta_{\max}} \frac{d\eta}{\eta^2} W^g(\eta) g^2(\eta) \mathcal{T}\left(j = \frac{\ell}{\eta}, \eta\right)$$

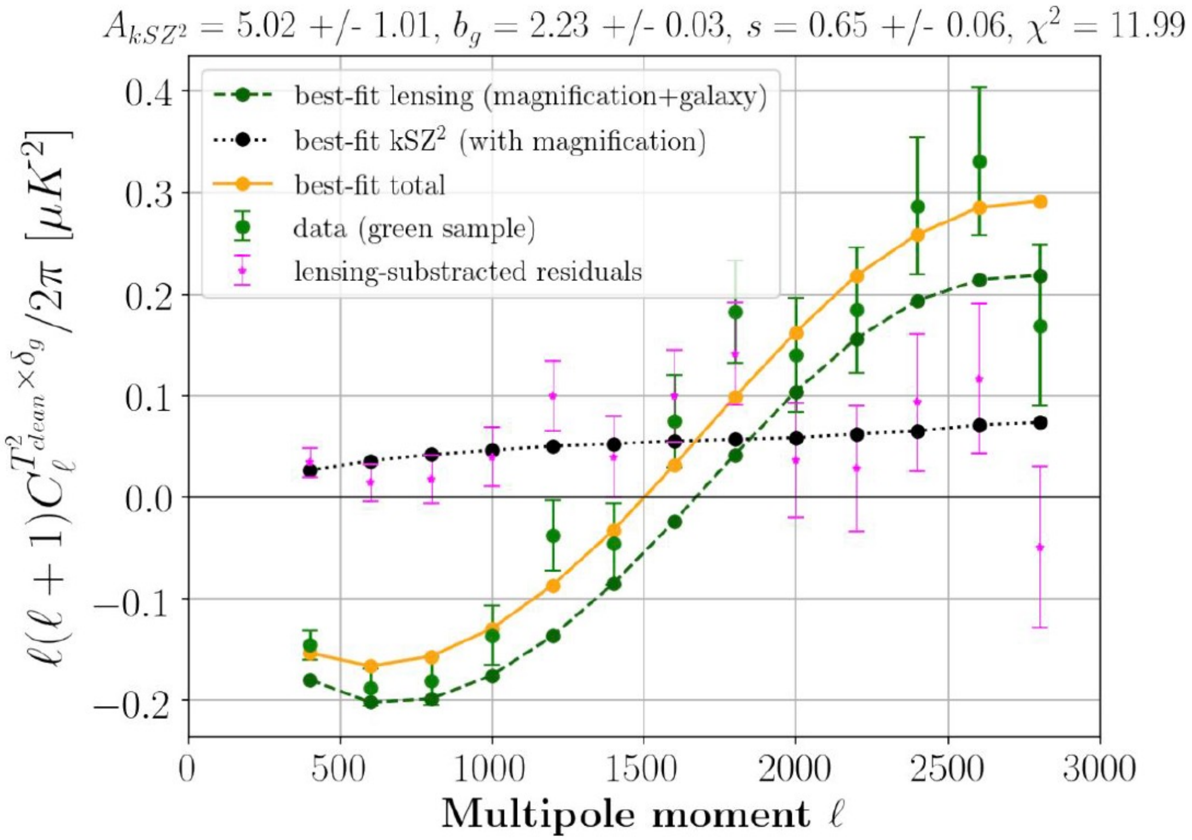
Dore+04, DeDeo+05

$$\mathcal{T}(j,\eta) = \int \frac{d^2\mathbf{q}}{(2\pi)^2} f(q\eta) f(|\mathbf{j}+\mathbf{q}|\eta) \boxed{B_{p_{\hat{\mathbf{n}}}p_{\hat{\mathbf{n}}}\delta}(\mathbf{q}, -\mathbf{j}-\mathbf{q}, \mathbf{j}).}$$

Projected-fields estimator

- 1^{st} measurement: [Hill+2016, Ferraro+2016]
  Planck data + WISE galaxies ~3σ
- 2^{nd} measurement: [Kusiak+2021]
  Planck data + unWISE galaxies ~5σ
- Amplitude → baryon fraction

- Forecasts for constraints on baryon density profile [Bolliet+2022]
- Thus: as a probe of astrophysics



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Existing Approximate Model for $B_{p_n p_n \delta}$

DeDeo+2005: *Ansatz* for high-ℓ limit of $C_\ell^{\mathrm{kSZ}^2 \times \delta_g}$, only in its high-$k_1, k_2, k_3$ limit.

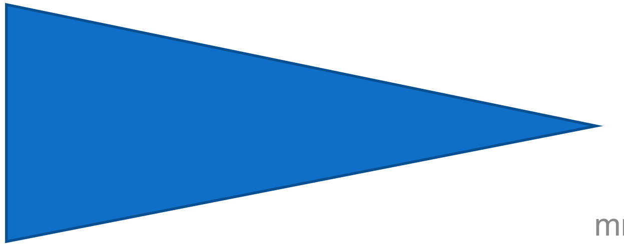
Terms	Geometric scaling
$\langle v^i(\mathbf{k}) v^j(\mathbf{k}')\rangle\langle\delta(\mathbf{k}_1-\mathbf{k})\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	1
$\langle v^i(\mathbf{k})\delta(\mathbf{k}_1-\mathbf{k})\rangle\langle v^j(\mathbf{k}')\delta(\mathbf{k}_2-\mathbf{k}')\delta(\mathbf{k}_3)\rangle$	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 $B_{p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}} \delta}(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3})$,

$$\int \frac{d^3k}{(2\pi)^3}\left[1-\mu_1\mu_2\right] P_{vv}(k) B_{\delta\delta\delta}(\mathbf{k_1}-\mathbf{k}, \mathbf{k_2}+\mathbf{k}, \mathbf{k_3})$$

$$B^{\mathrm{approx}}_{p_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}} \delta}(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3}) \approx \frac{1}{3} v_{\mathrm{rms}}^2 B_{\delta\delta\delta}(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3})$$

(Neglected)



Issues:
1) Convolution
2) Squeezed triangles
3) Only applicable for astrophysics

Our Improved Model for $B_{p_n p_n \delta}$

The *first* rigorous derivation, accounting for <u>all</u> triangles

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

$$\int \frac{d^3k}{(2\pi)^3}\left[\underline{\sqrt{1-\mu_1^2}\sqrt{1-\mu_2^2}}\right] P_{vv}(k) B_{\delta\delta\delta}(\mathbf{k_1}-\mathbf{k}, \mathbf{k_2}+\mathbf{k}, \mathbf{k_3})$$

$+$

We calculate and include these
3 higher-order terms
for the first time

Numerical Evaluation:

- Fitting function for matter bispectrum:
- Speed-up using emulators

$$B_{\delta\delta\delta}(k_1,k_2,k_3) = \sum_{cyc} 2F_2(k_1,k_2,k_3)P_{\delta\delta}(k_1)P_{\delta\delta}(k_2)$$

Forecasts for surveys

- Assume *realistic* post-ILC noise models for: Simons Observatory (SO) & CMB-S4

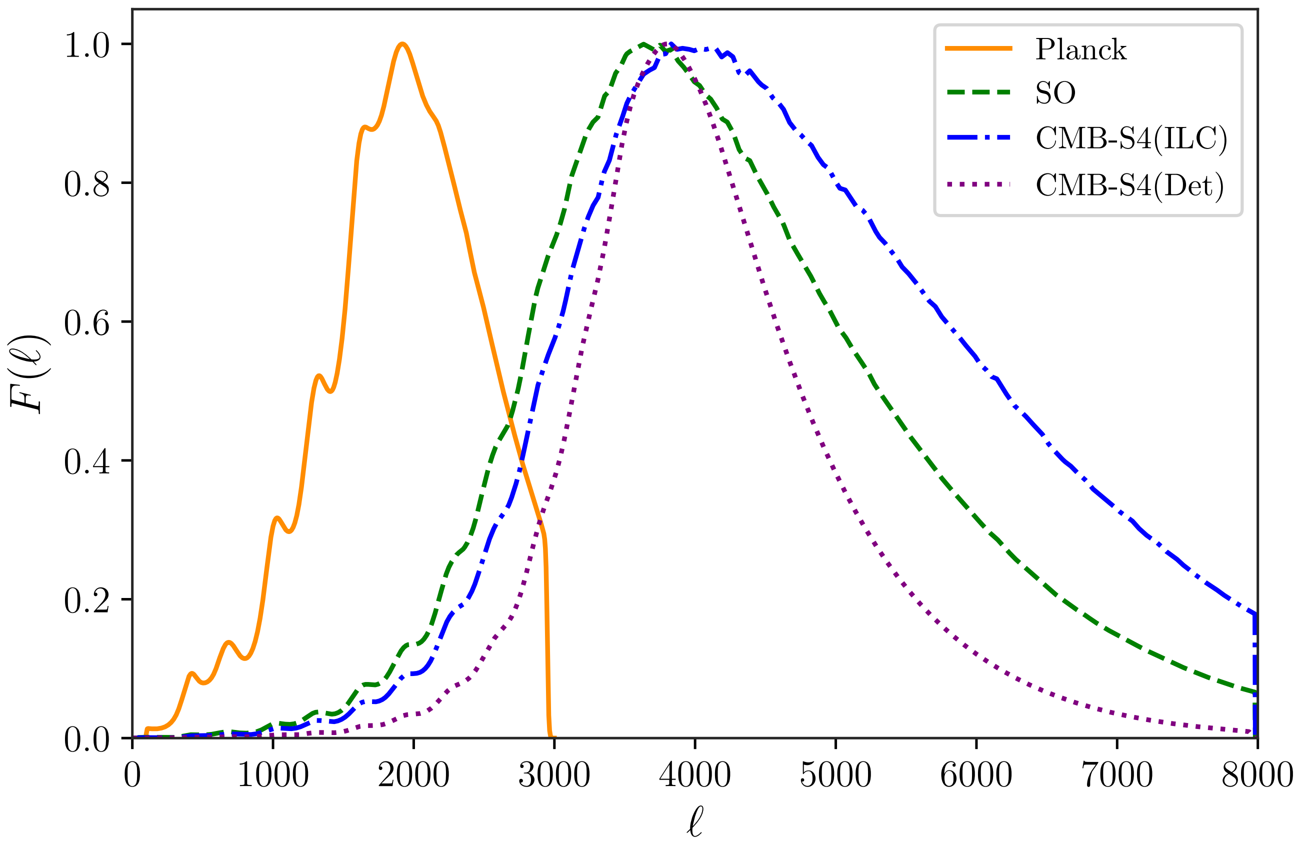
- Photometric galaxies – $\Delta z = 0.1$

  WISE: 50 million; $z < 1$

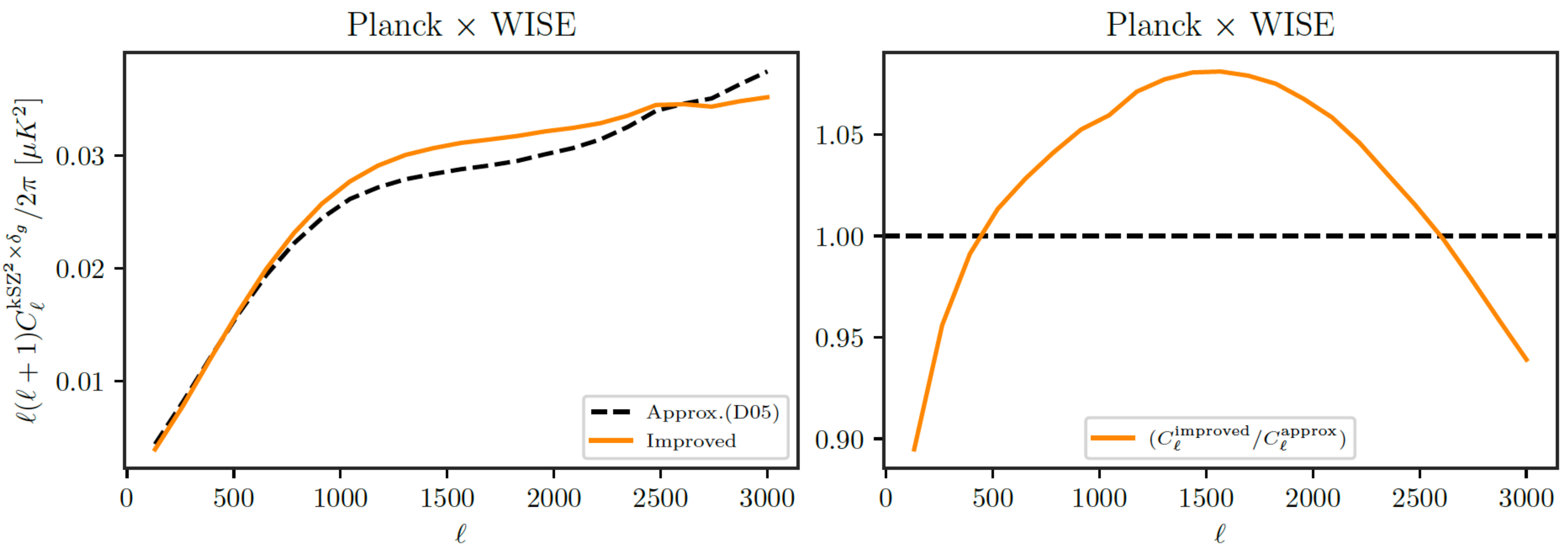
  VRO: ~ 4 billion; $z < 3$

- + include lensing contribution term

  [Ferraro+2016]



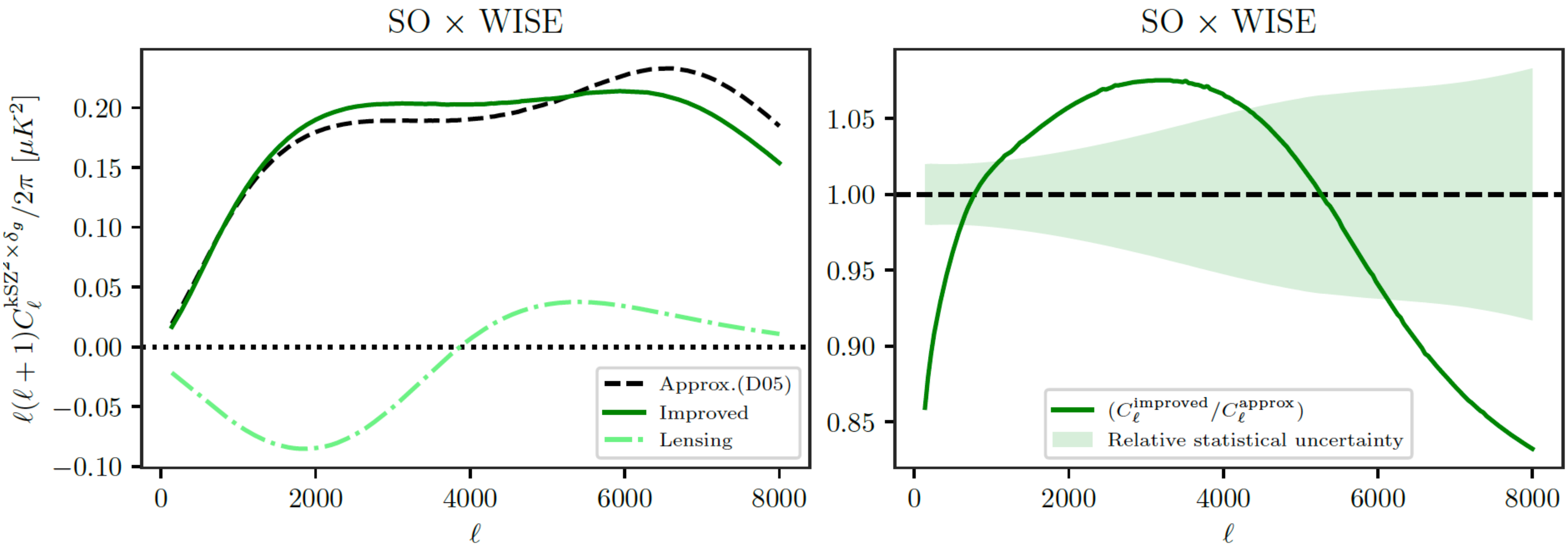
Wiener filters for CMB experiments



Current data: ***Planck***

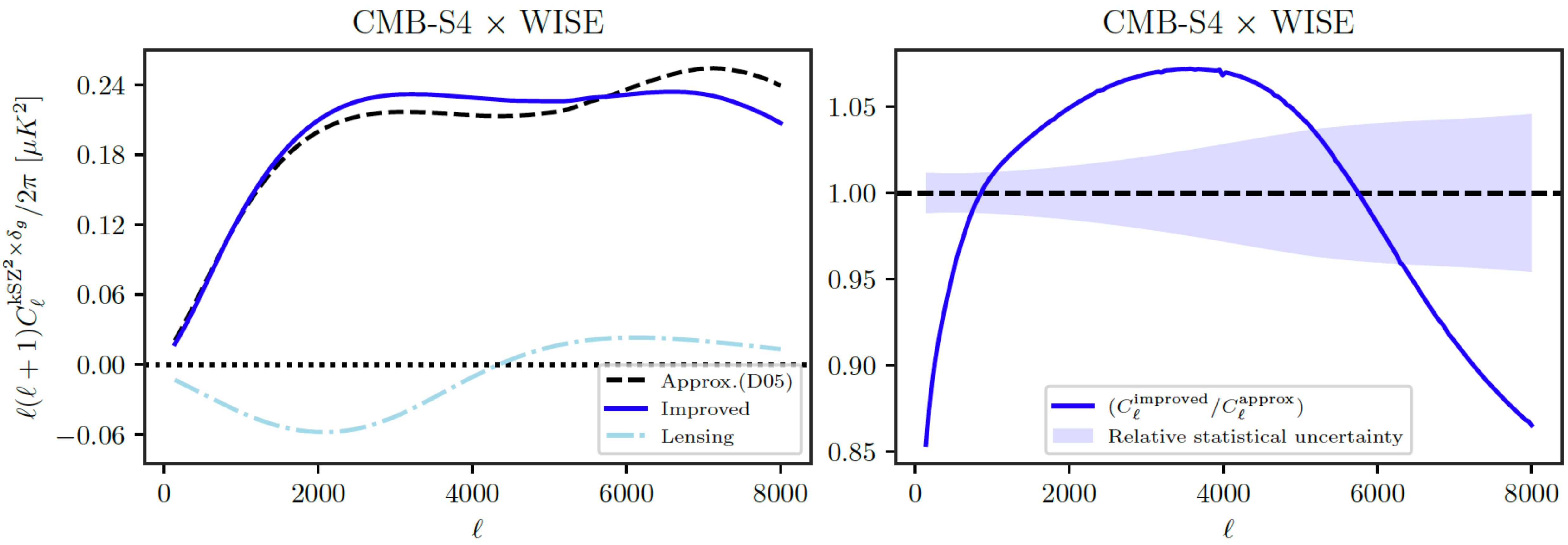
- ~ **5%** differences in predicted signal – SNR: 3-5
- Negligible compared to larger statistical errors
- Partially explains excess signal in (green) unWISE measurement

[Hill+2016, Kusiak+2021]



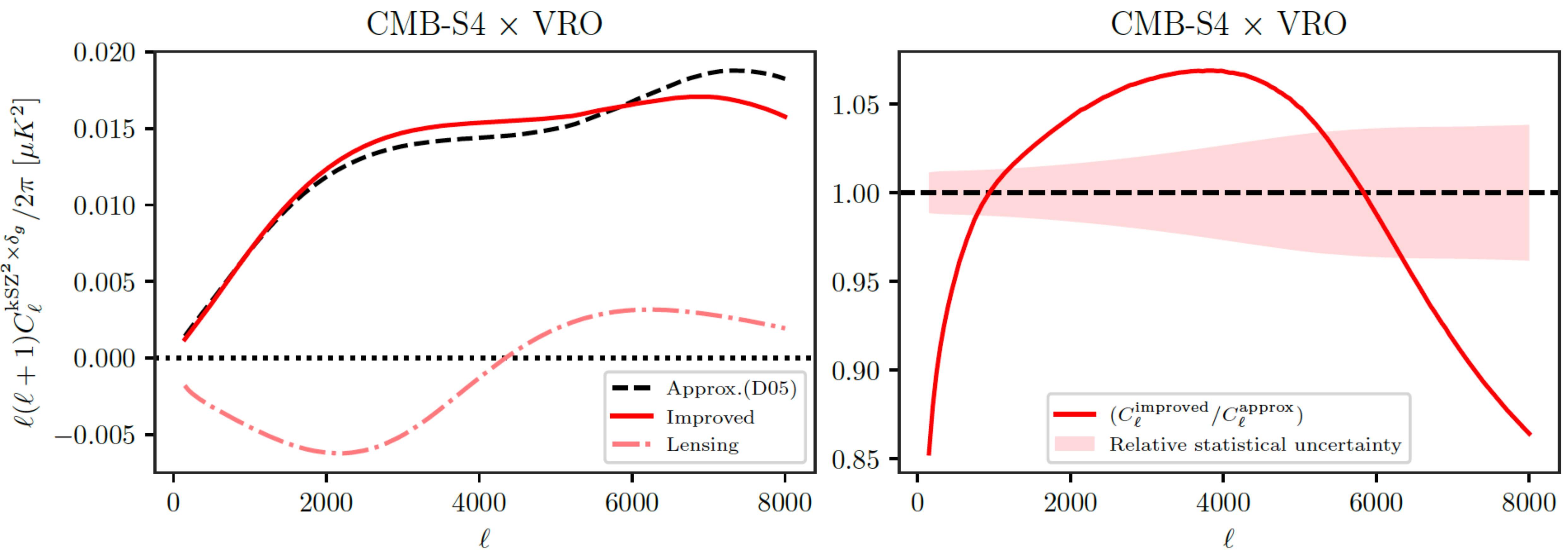
High-resolution CMB survey: **SO**

- Low statistical uncertainties → enormous forecasted **SNR: 110**
- ~ **15%** differences in predicted signal – **significant**
- **Scale-dependent** → impact shape → ***any*** parameter inference



CMB-S4 × WISE

- Low statistical uncertainties → enormous forecasted **SNR: 130**
- ~ **15%** differences in predicted signal – **significant**
- **Scale-dependent** → impact shape → ***any*** parameter inference



CMB-S4 × VRO

- Low statistical uncertainties → enormous forecasted **SNR: 180**
- ~ **15%** differences in predicted signal – **significant**
- **Scale-dependent** → impact shape → ***any*** parameter inference

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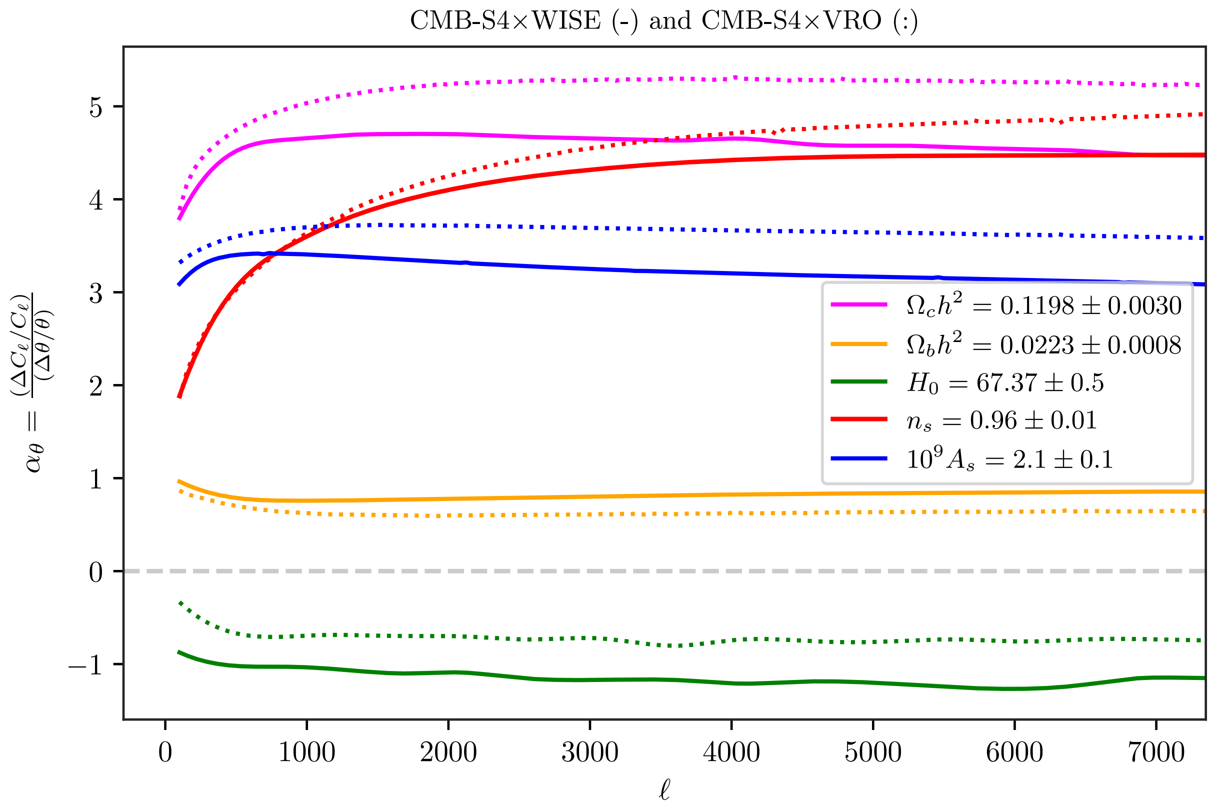
Cosmological Dependence

- Improved model → applicable beyond small-scales → cosmology
- Fisher formalism –

$$\boldsymbol{\theta}_{\min} = \{H_0, \Omega_b h^2, \Omega_c h^2, 10^9 A_s, n_s\} + \{A_{\mathrm{kSZ^2}}, b_g\}$$

- Assume: astrophysics ~known externally, with a flat prior on galaxy bias.
- $C_\ell^{\mathrm{kSZ}^2 \times \delta_g} \propto \sigma_8^{6-7}$

  → very sensitive to $\Omega_c h^2$ and A_s



Cosmological Dependence

- Fixed cosmology: forecasted SNRs = 110, 130, 180

  → sub-% level uncertainty on kSZ amplitude

- Note: For CMB-S4×WISE, assuming *detector-only* noise, SNR = 345
- Varying cosmology: Marginalizing over ΛCDM parameters + *Planck* CMB prior

  → ~ 7% uncertainty on kSZ amplitude

	$\%\Delta A_{\mathrm{kSZ}^2}$: 1σ % uncertainty on A_{kSZ^2}		
	SO × WISE	CMB-S4(ILC)× WISE	CMB-S4(ILC)× VRO
Fixed Cosmology	0.9	0.8	0.6
Varying ΛCDM + *Planck* prior	7.1	6.7	6.9
Varying ΛCDM + (low-ℓ *Planck*+high-ℓ CMB-S4) prior	5.9	5.6	5.9
Varying ΛCDM + (low-ℓ LiteBIRD+high-ℓ CMB-S4) prior	3.7	3.6	3.6

Sensitivity of $C_\ell^{\mathrm{kSZ}^2 \times \delta_g}$ to Neutrinos

Illustration - potential probe of cosmology + fundamental physics

- Include ΛCDM + Σm_ν in *initial* Fisher forecasts
- Why? Massive neutrinos imprint the LSS

- Effect of neutrinos:

1) Suppress the matter power spectrum

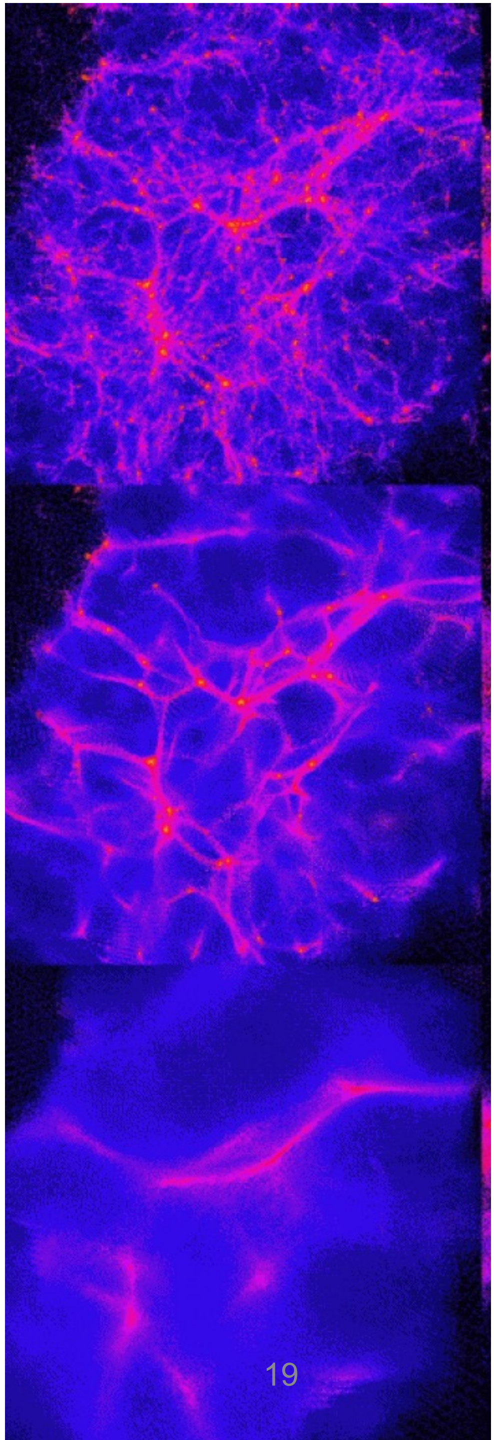
→ At first order, matter bispectrum: ~ twice the suppression

2) Induce scale-dependence in growth rate of LSS → velocities

$$f \equiv \frac{d\ln D(a)}{d\ln a}$$

Kiakotou+08

Σm_ν increasing



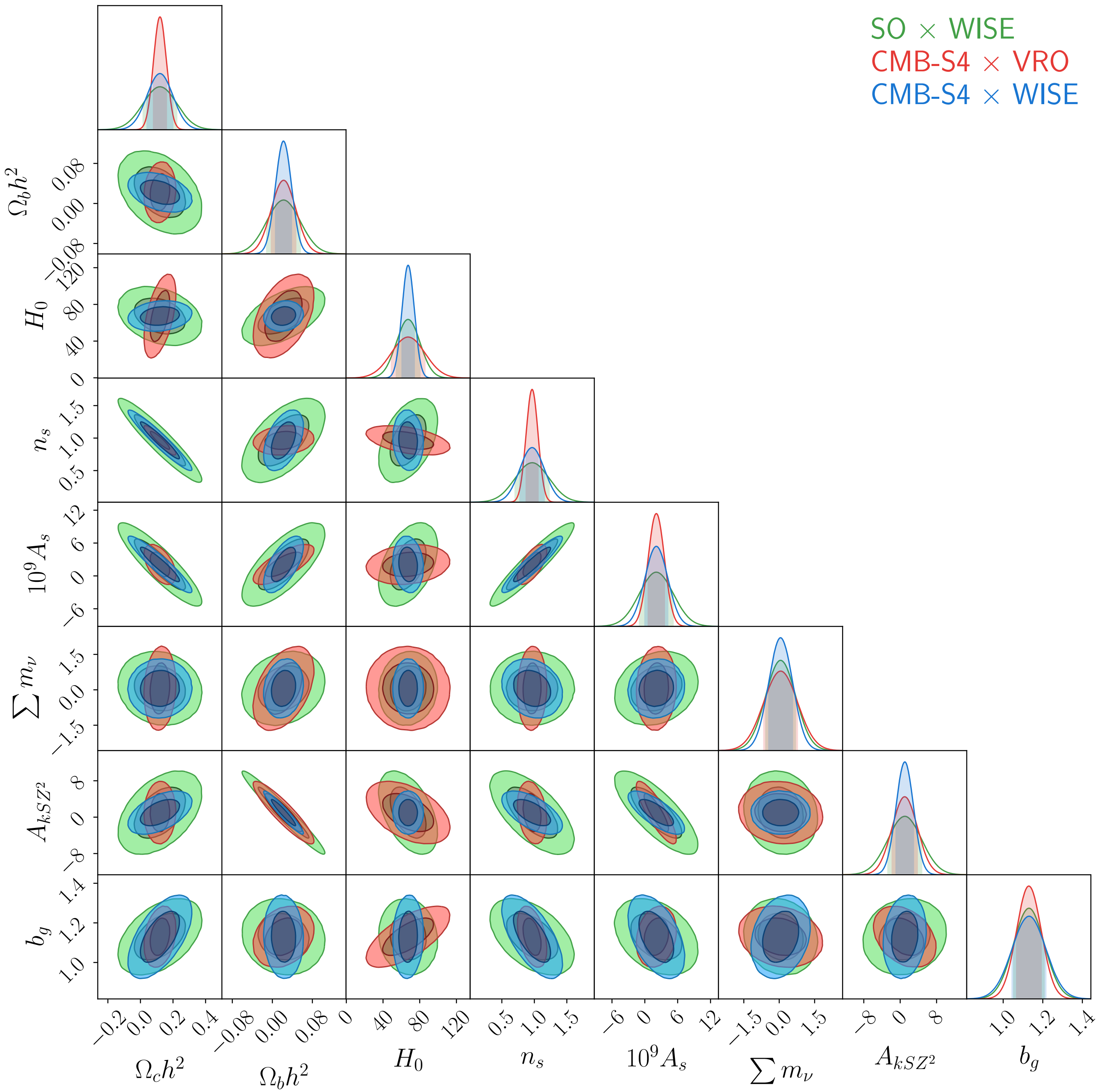
Source: Ben Moore

Parameter dependence: kSZ-only

CMB-S4×WISE > SO×WISE

CMB-S4×WISE vs CMB-S4×VRO:

→ much of signal comes from $z < 0.5$



Parameter constraints:

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

- Primary *Planck* priors on ΛCDM only, *realistic noise* in CMB maps.
- Forecasts with pairwise-kSZ: ~ 220 meV (Stage III) and 96 meV (Stage IV) Mueller+15

- Idealistic scenario: *detector-only noise* in CMB-S4 (×WISE) –
  All errors improve, $\sigma(\Sigma m_\nu) = 38$ meV → Alternative cleaning methods possible?

- → kSZ as a complementary probe of neutrinos (and possibly other extensions)
  among other upcoming CMB+LSS probes: CMB lensing, BAO, shear, …

Mishra-Sharma+2018,
Dvorkin+2019

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Future Directions

- Incorporating our improved model within the Halo Model `class_sz`:
  [Bolliet+2022] → include realistic baryon density profile

- Including non-linear galaxy bias – determined externally,
  + accounting for effect of extensions

- Optimal redshift-weighting – taking subsamples

- Faster computation for MCMC – emulator framework?
  → Joint astrophysics + cosmology analyses in future

Take Home

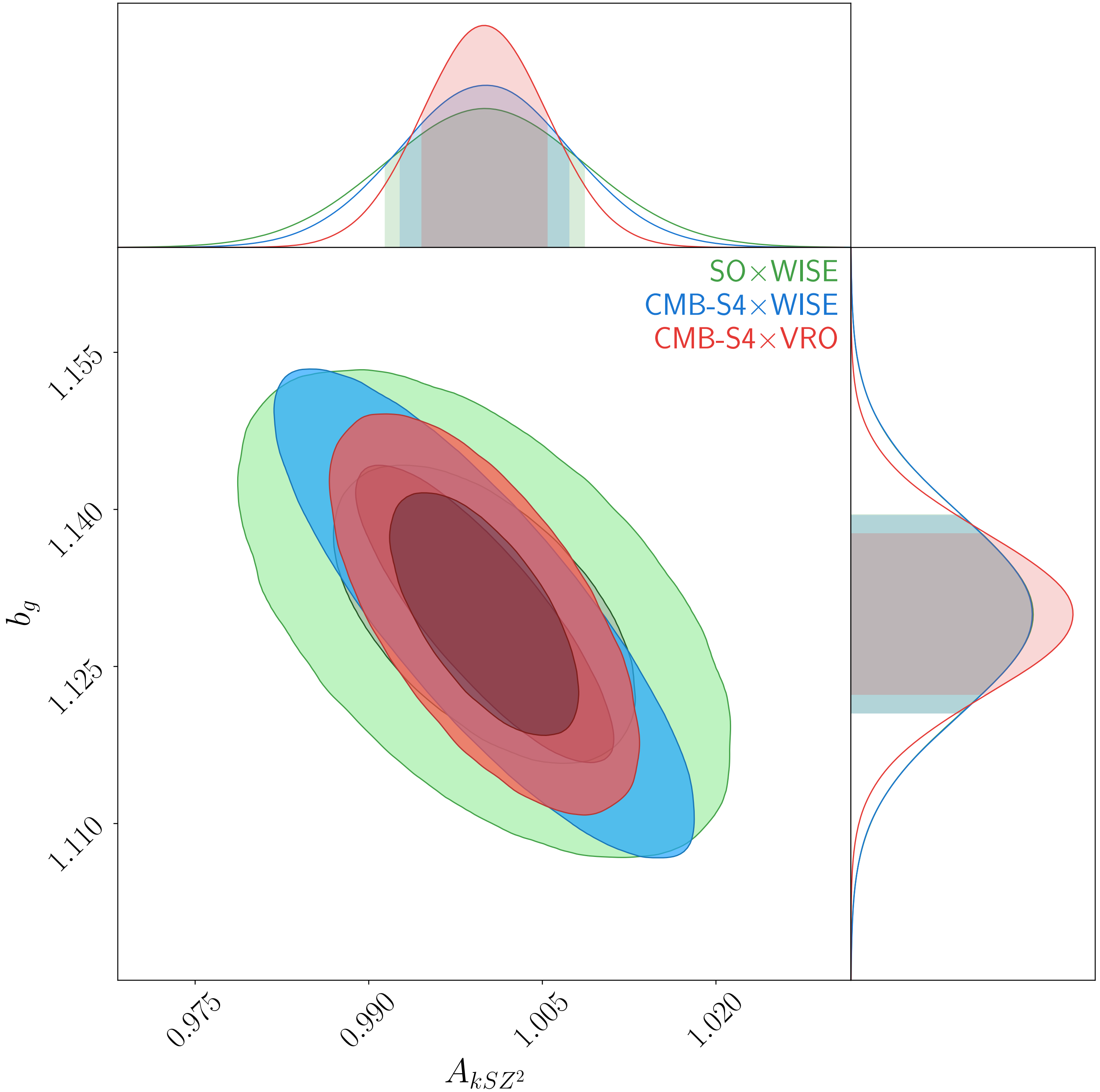
arXiv:2306.03127

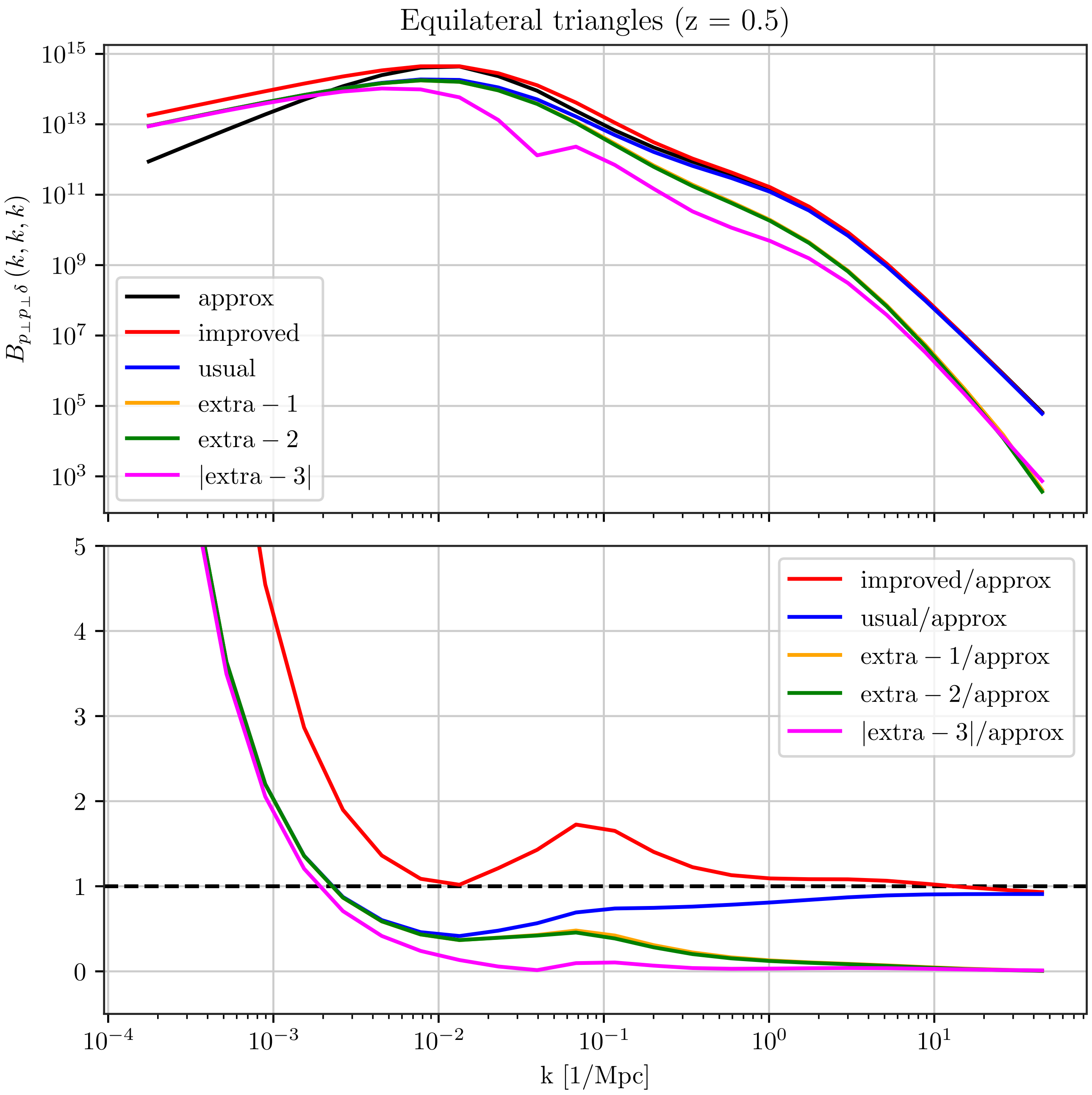
- Projected-fields kSZ estimator → does not need spectroscopic redshifts
- Our improved model → necessary to avoid biases in future measurements with SO, CMB-S4, ..
- Allows us to study the cosmological dependence of the signal,

  Marginalized uncertainty on amplitude:

  sub-% → ~7% with a *Planck* prior
- Projected-fields kSZ: a complementary probe of cosmology

Backup Slides


SO×WISE
CMB-S4×WISE
CMB-S4×VRO
b_g
1.155
1.140
1.125
1.110
0.975
0.990
1.005
1.020
A_{kSZ^2}


Equilateral triangles (z = 0.5)
$B_{p_\perp p_\perp \delta}(k,k,k)$
approx
improved
usual
extra − 1
extra − 2
|extra − 3|
improved/approx
usual/approx
extra − 1/approx
extra − 2/approx
|extra − 3|/approx
k [1/Mpc]