Prospects for Kinematic Sunyaev-Zeldovich Measurements from South Pole Telescope

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Work done with Yuuki Omori, Gil Holder, Nathan Whitehorn, Tom Crawford and the entire SPT collaboration

Based on on ongoing SPT x SPIRE work.

Prospects (*and Challenges*) for Kinematic Sunyaev-Zeldovich Measurements from South Pole Telescope (*and Future CMB Experiments*)

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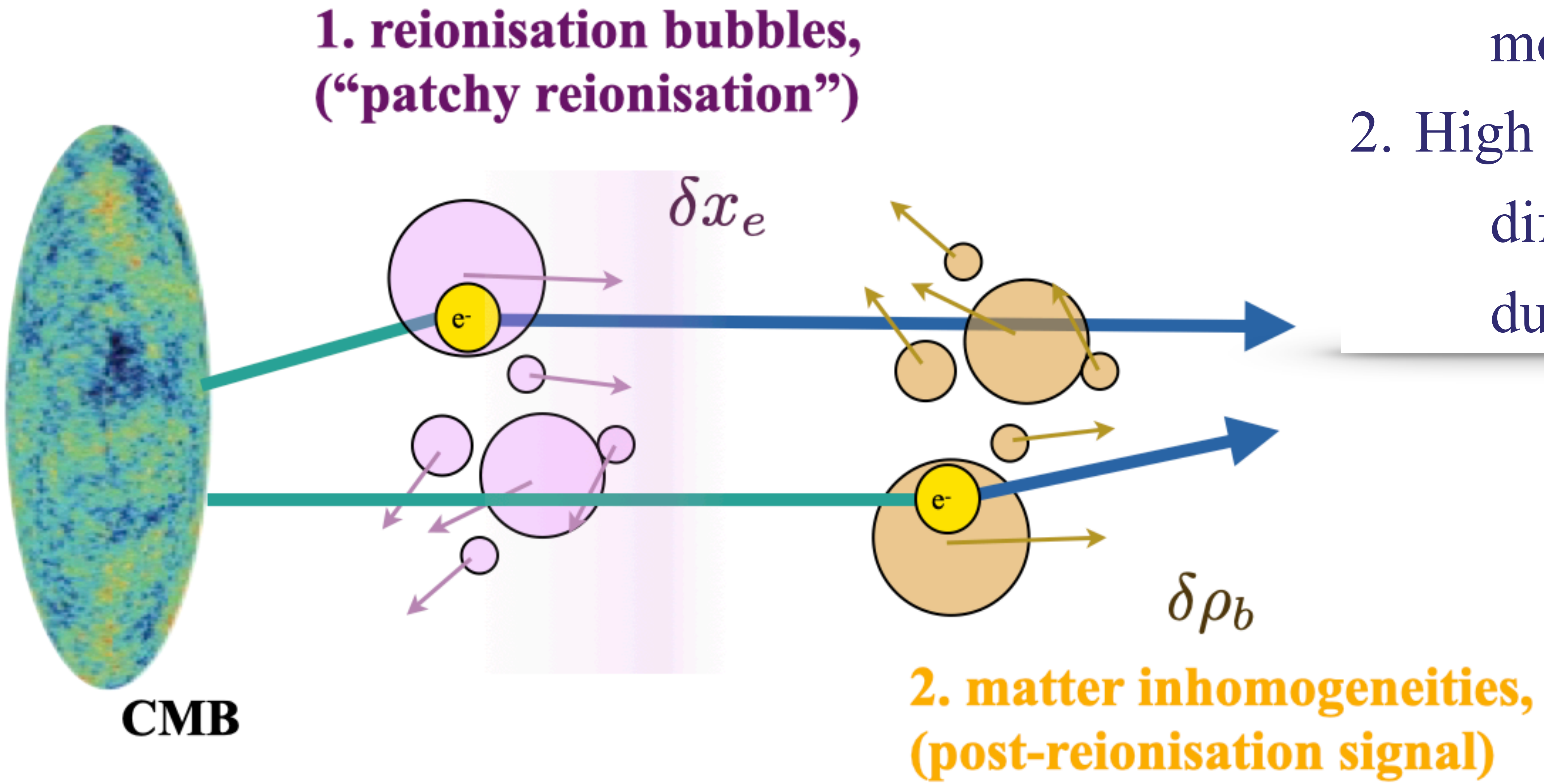
Based on on ongoing SPT x SPIRE work and Raghunathan & Omori 2023, ApJ (arXiv:2304.09166).

Kinematic Sunyaev–Zeldovich (kSZ) effect

Doppler boosting of CMB photons due to free electrons ***in motion***.



Two sources:

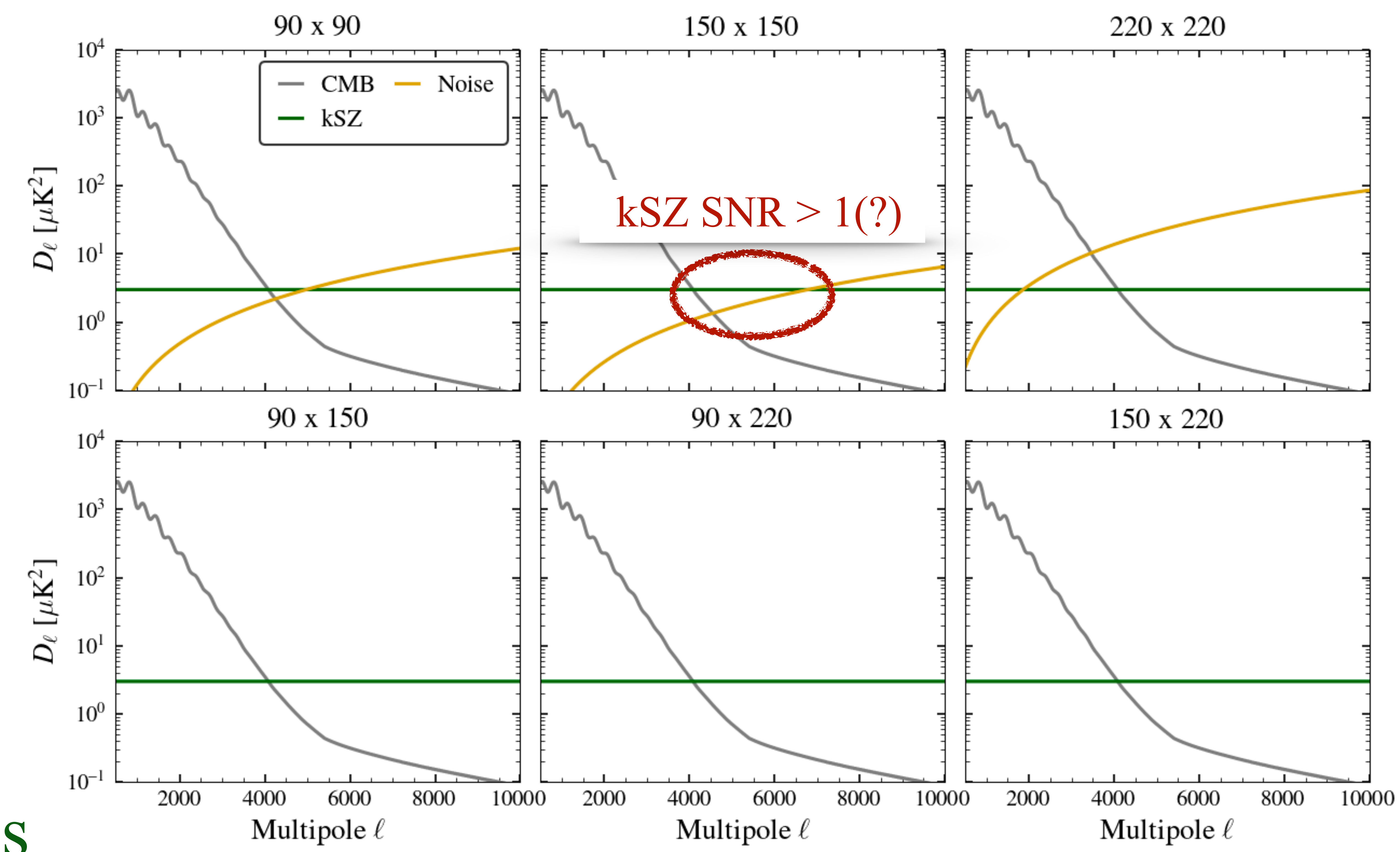
1. Low redshift or late-time or post-reionisation kSZ: Bulk motion haloes.
2. High redshift or early-time or reionisation kSZ: Spatial differences in ionisation fractions in the Universe during the epoch of reionisation (z>~6).

Image: Christian Reichardt

Small-scale temperature power spectra

kSZ is larger than CMB on small scales and has the same BB spectrum as the CMB.

Power spectra



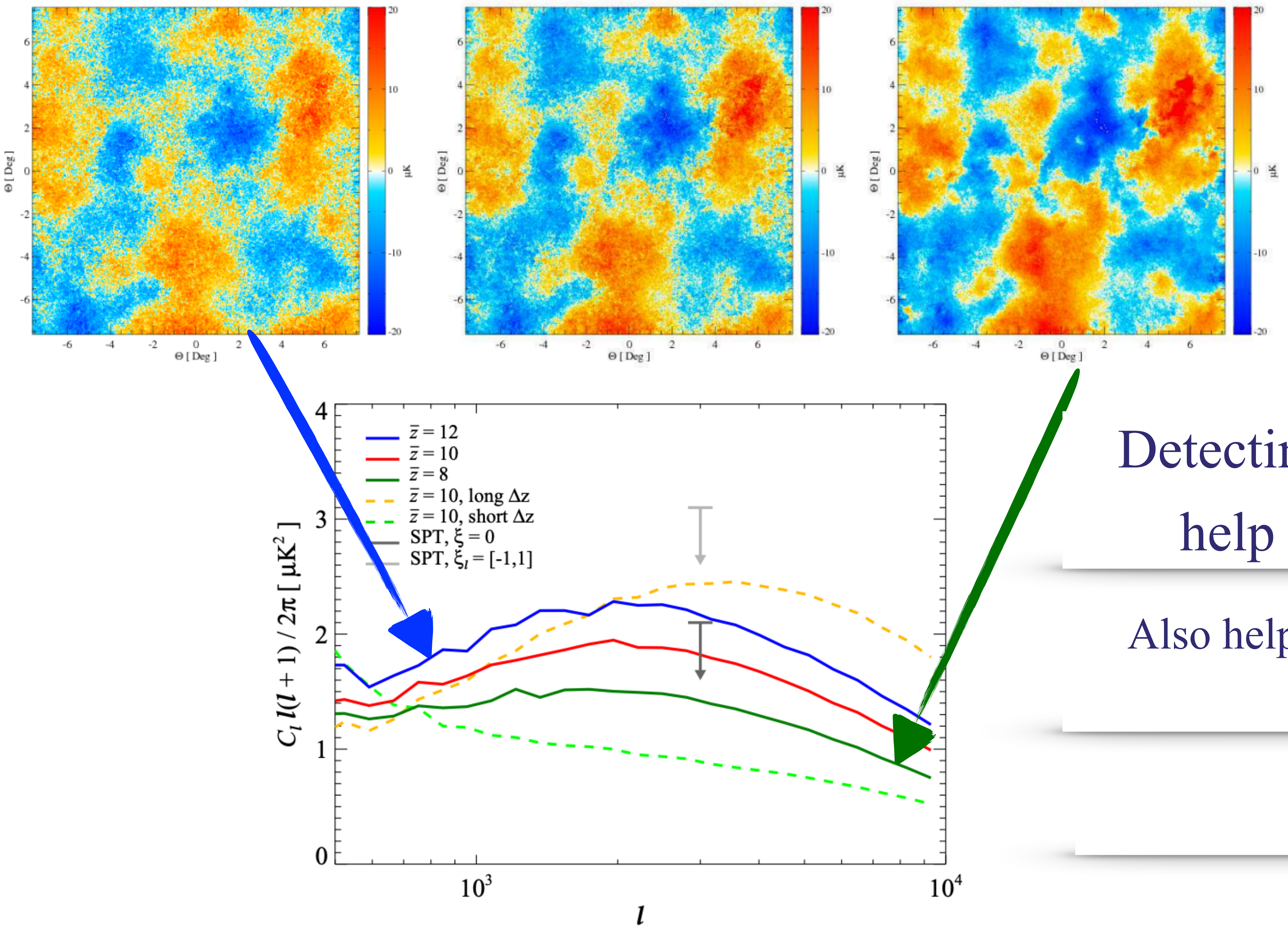
Large-scales

Small-scales

Reichardt et al. 2021, ApJ (arXiv: 2002.06197).

Noise: SPT-3G expectation.

Kinematic Sunyaev–Zeldovich Power Spectrum: Probe of Reionisation



Battaglia et al. 2013, ApJ (arXiv: 1211.2832).

Detecting the kSZ power spectrum will help us contain reionisation physics.

Also helps in understanding the velocity field in the low-z Universe.

However …

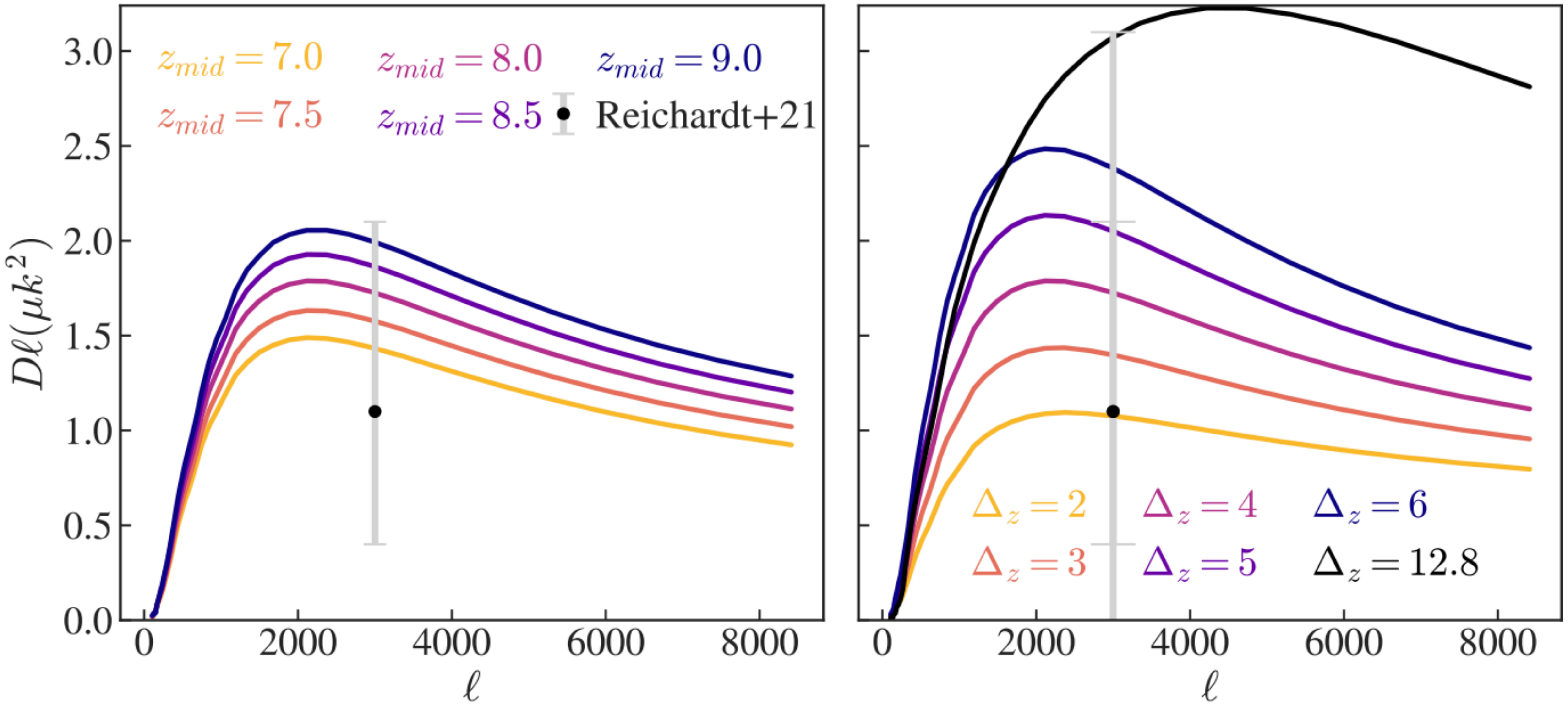
Kinematic Sunyaev–Zeldovich Power Spectrum: Probe of Reionisation

However, we only have a 3σ measurement of the total kSZ power spectrum (with SPT-SZ).

(Reichardt et al. 2021, ApJ, arXiv: 2002.06197).

And it was obtained by using templates. (i.e:) One data point at \ell = 3000.

Makes constraining reionisation physics hard.

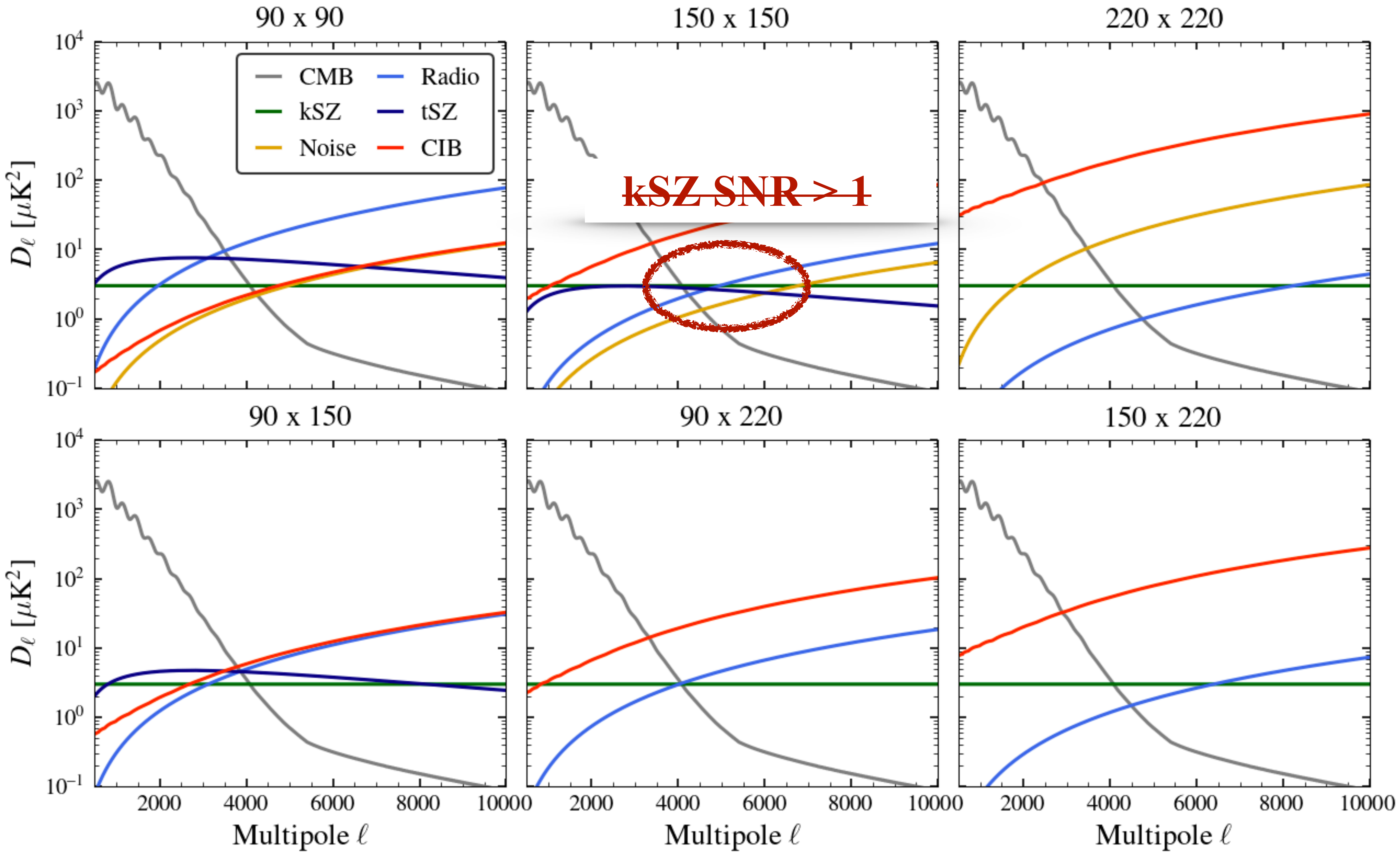


Chen et al. 2022, ApJ (arXiv: 2203.04337)

kSZ Power Spectrum Measurements

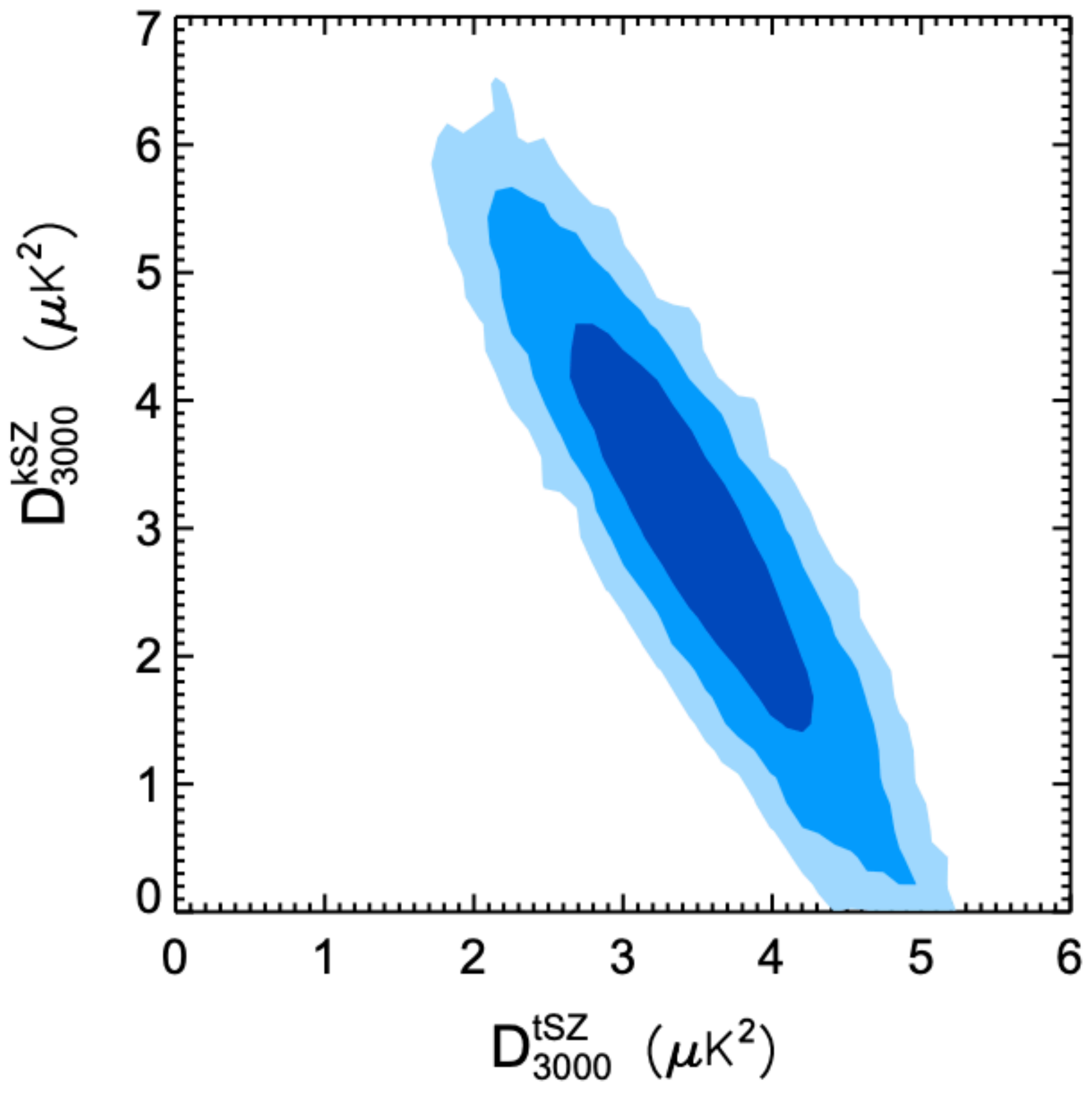
Foregrounds, particularly CIB, fully swamps the kSZ SNR.

Foregrounds are also degenerate with the kSZ signal. So we should not be using templates.



Reichardt et al. 2021, ApJ (arXiv: 2002.06197).

kSZ Power Spectrum Measurements: Current Experiments

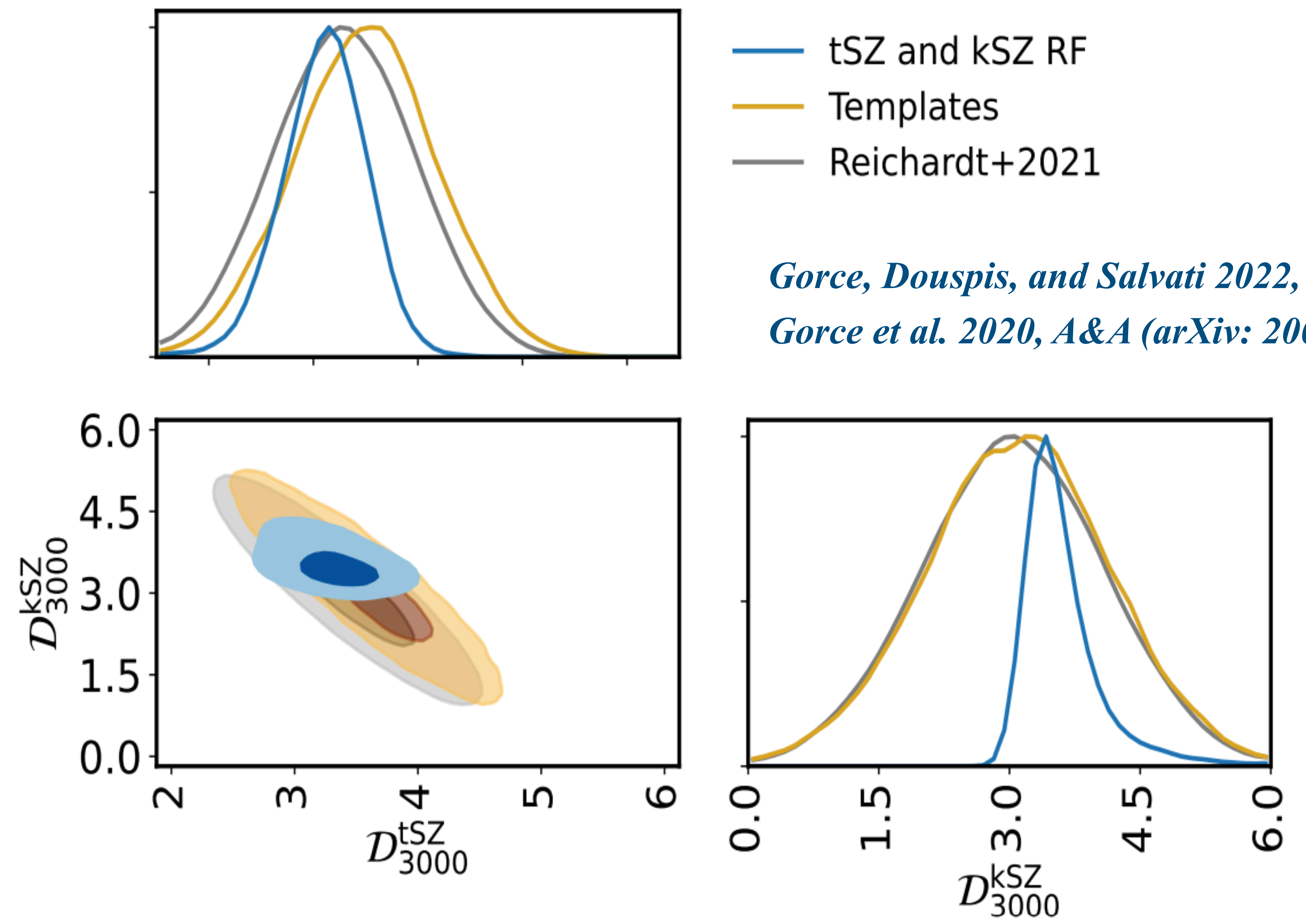


Reichardt et al. 2021, ApJ (arXiv: 2002.06197).

3σ evidence of the total kSZ power spectrum. tSZ template from Shaw et al. 2010.

Shaw et al. 2010, ApJ (arXiv: 1006.1945).

*Replacing the template-fitting approach for tSZ/kSZ, **Gorce, Douspis, and Salvati 2022 were able to break tSZ / kSZ degeneracy** and improve the kSZ SNR by x2.*

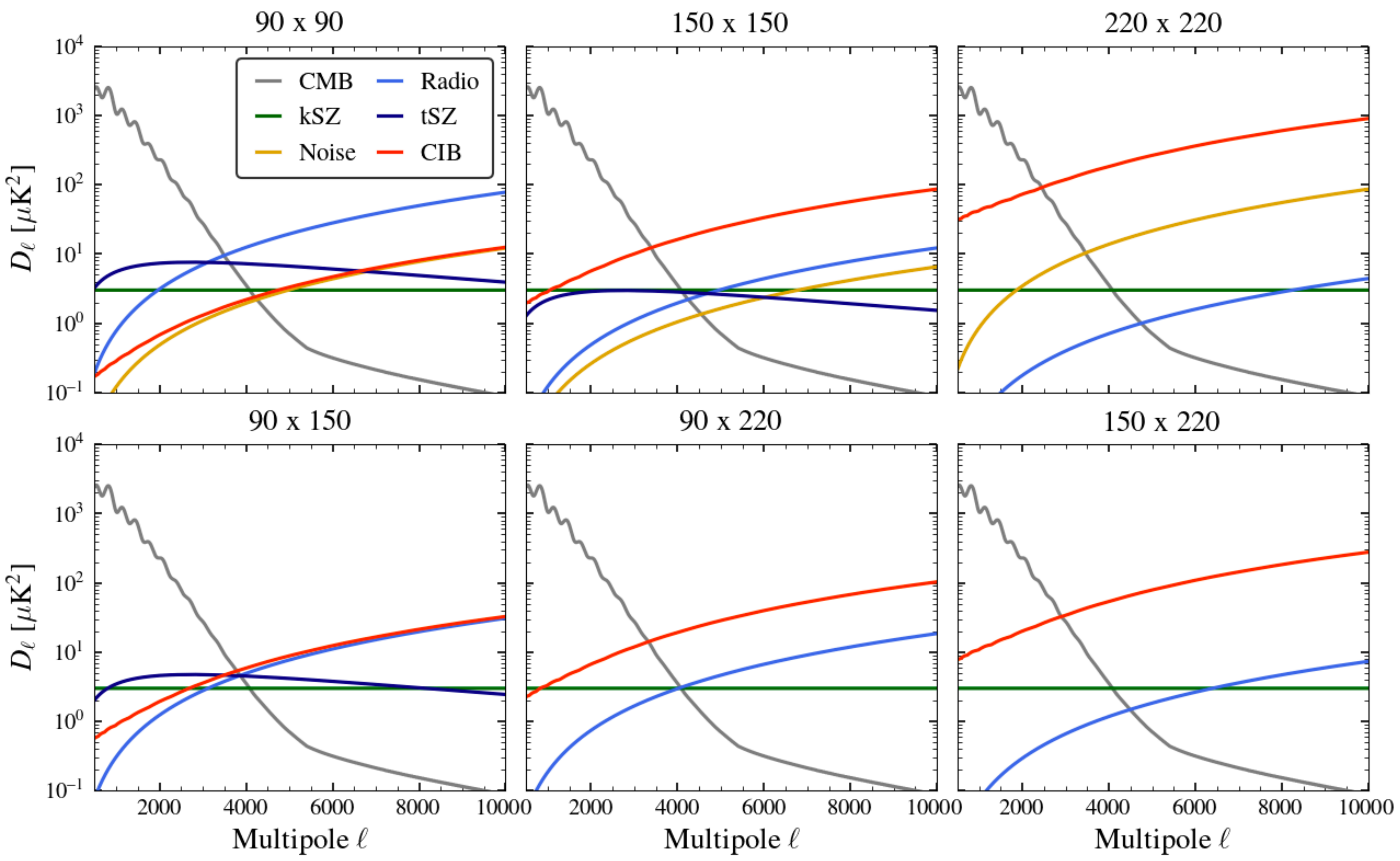


Gorce, Douspis, and Salvati 2022, A&A (arXiv: 2202.08698).
Gorce et al. 2020, A&A (arXiv: 2004.06616).

Also see talk by **Marian Douspis** on Monday.

kSZ Power Spectrum Measurements: Current Experiments

Foregrounds are frequency dependent. So combining data from multiple bands should help for the kSZ detection.

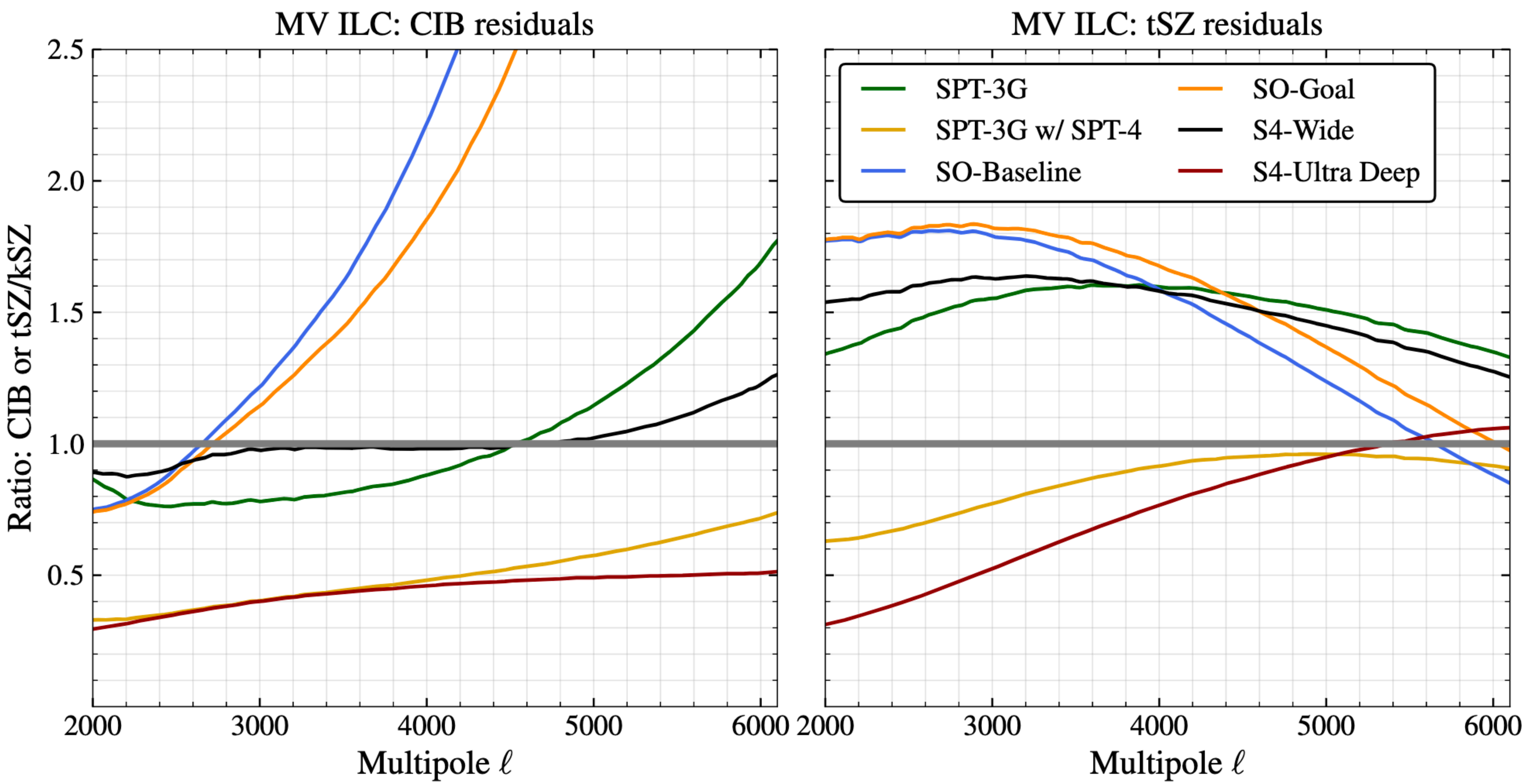


Reichardt et al. 2021, ApJ (arXiv: 2002.06197).

kSZ Power Spectrum Measurements: Future Experiments (MV ILC)

Combining data from multiple bands to reduce the overall (noise + foregrounds) variance in the CMB maps.

But, this is not optimal for foreground mitigation. ***Details of CIB and tSZ modelling are still important for kSZ.***

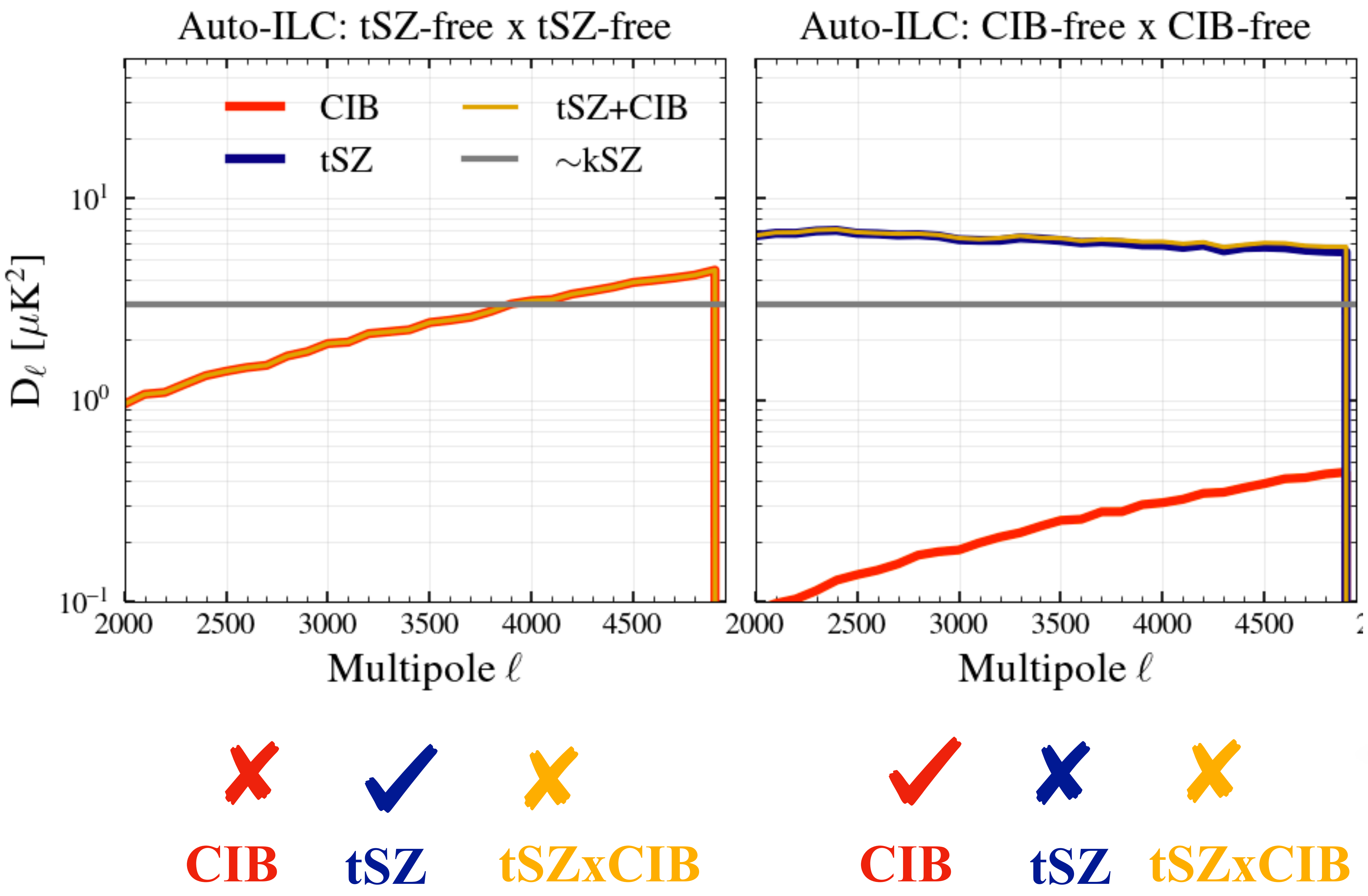


Raghunathan & Omori 2023, ApJ (arXiv:2304.09166).

kSZ Power Spectrum Measurements: Future Experiments (Constrained ILC)

Can we use constrained ILC to get rid of the foreground signals? **No.**

Low-noise Multi-band Futuristic survey



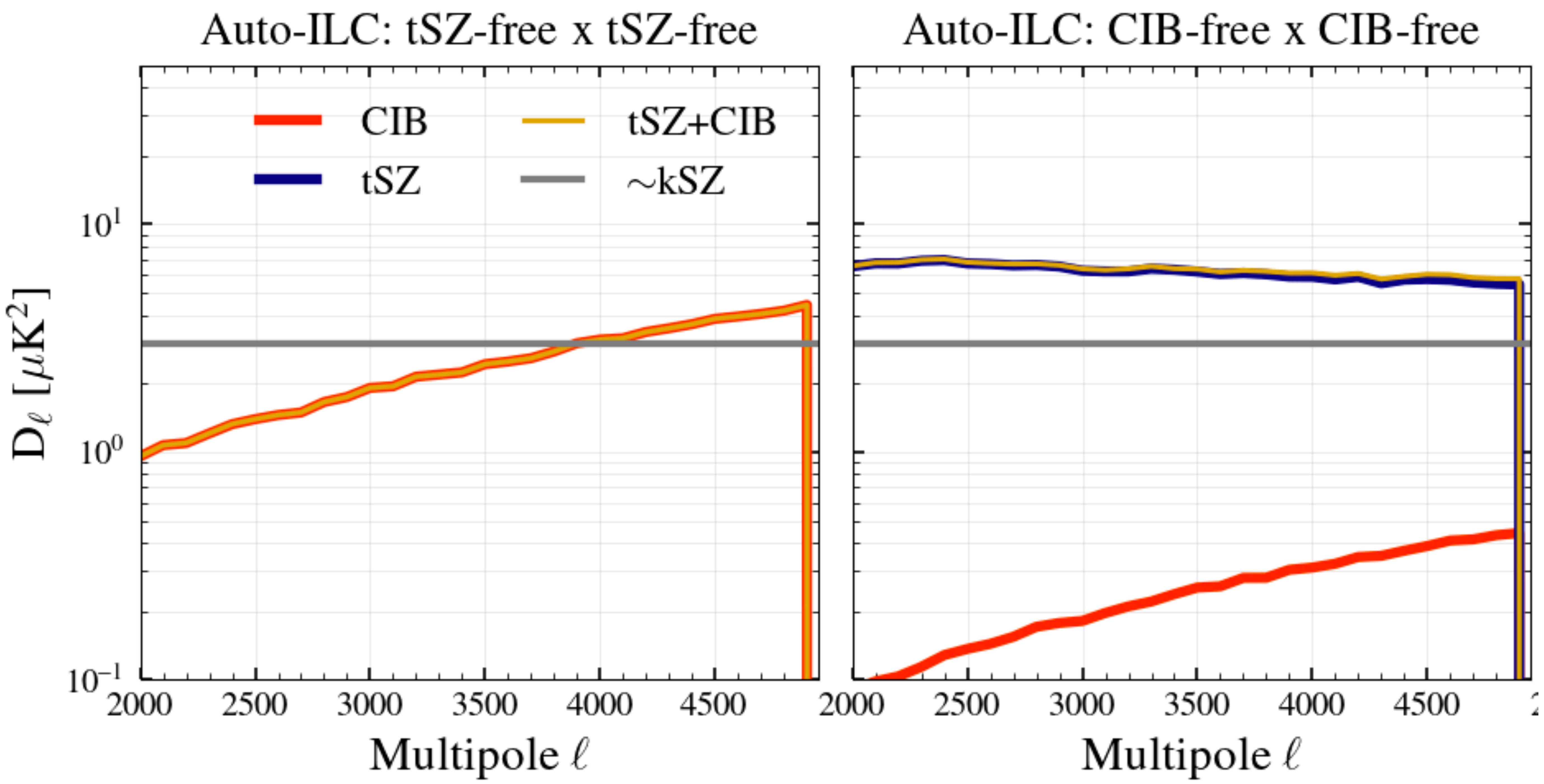
Also see talk by **Kristen Surrao on Wednesday** for foreground mitigation with external datasets (galaxy surveys) using the correlation between tSZ/CIB and LSS tracers.

Kusiak, Surrao, and Hill 2023 (arXiv: 2303.08121)

kSZ Power Spectrum Measurements: Future Experiments (Constrained ILC)

Can we use constrained ILC to get rid of the foreground signals? **No.**

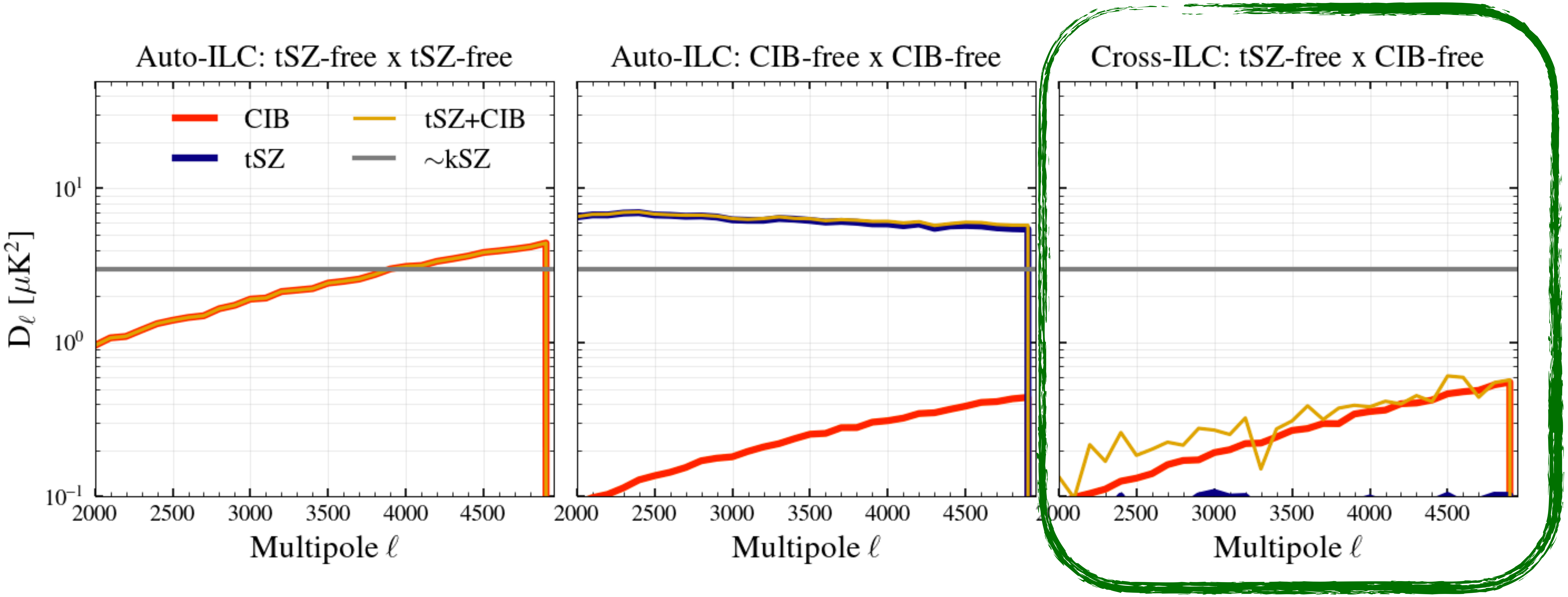
Jointly nulling tSZ and CIB also does not help.



CIB ✗ **tSZ** ✓ **tSZxCIB** ✗ **CIB** ✓ **tSZ** ✗ **tSZxCIB** ✗

Cross-ILC Technique for Future kSZ Power Spectrum Measurements

Cross-ILC technique of obtaining the cross power spectrum measurement from tSZ-free and CIB-free helps!



CIB ✗	tSZ ✓	tSZxCIB ✗	CIB ✓	tSZ ✗	tSZxCIB ✗	CIB ✓	tSZ ✓	tSZxCIB ✓

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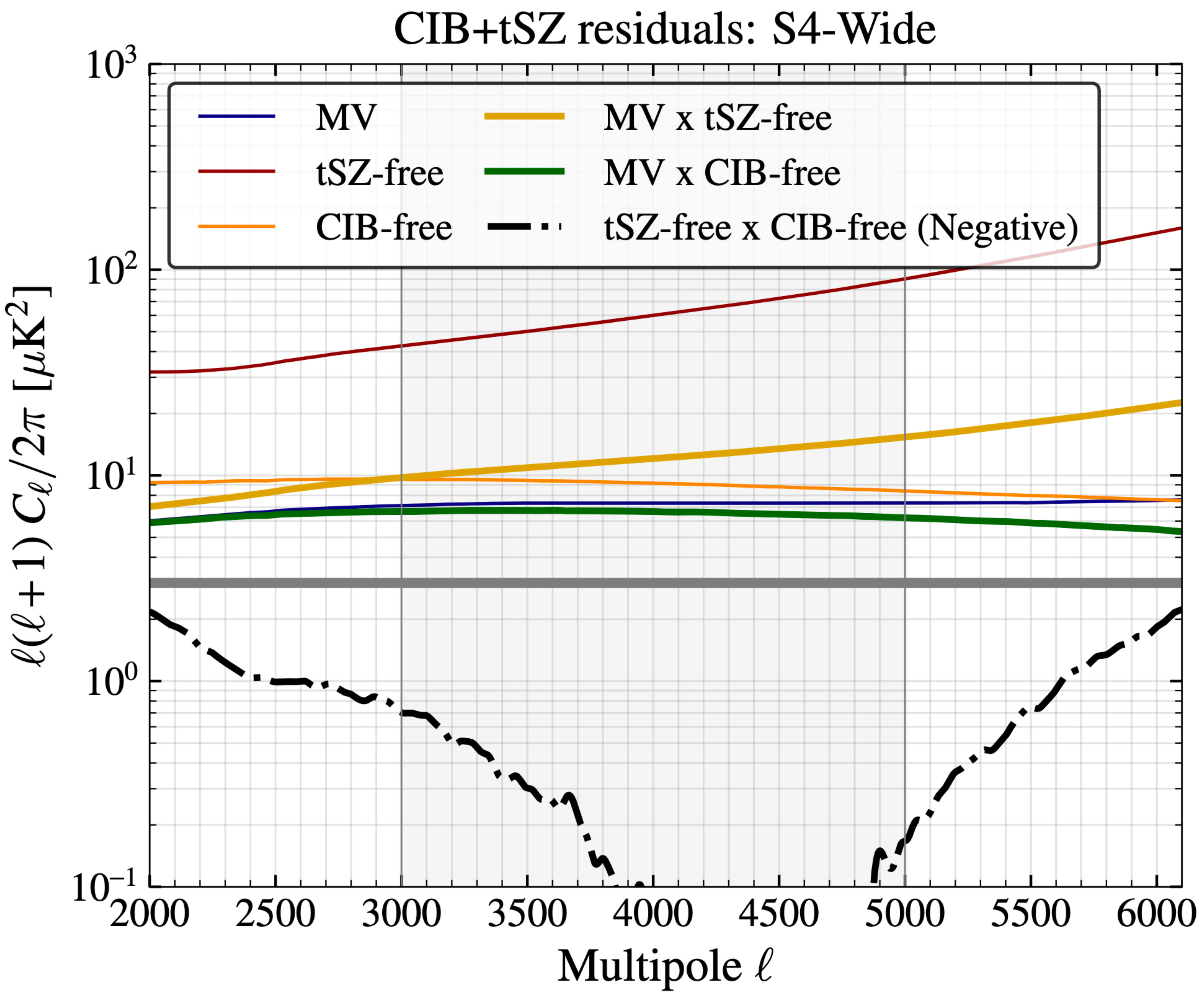
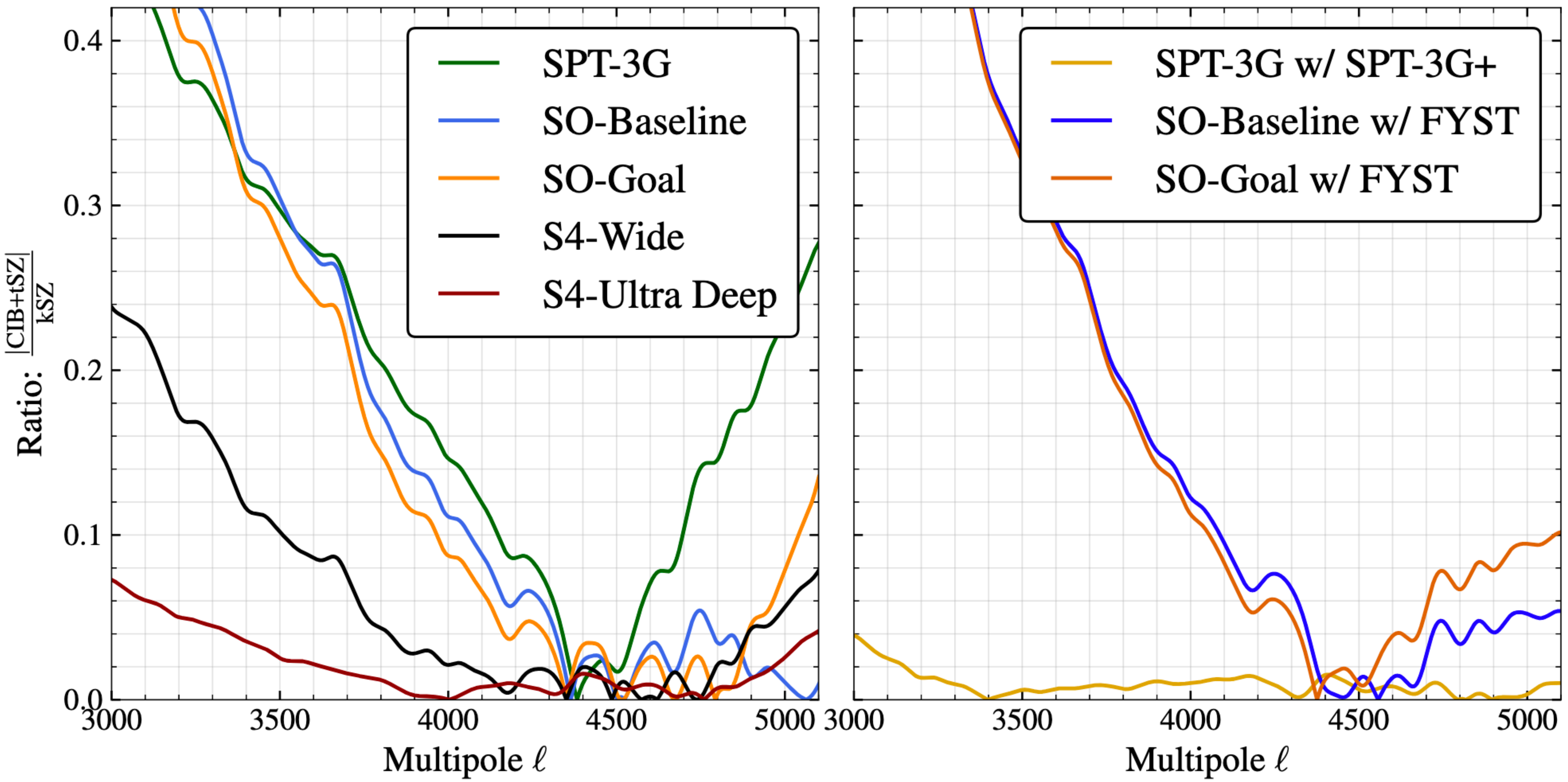


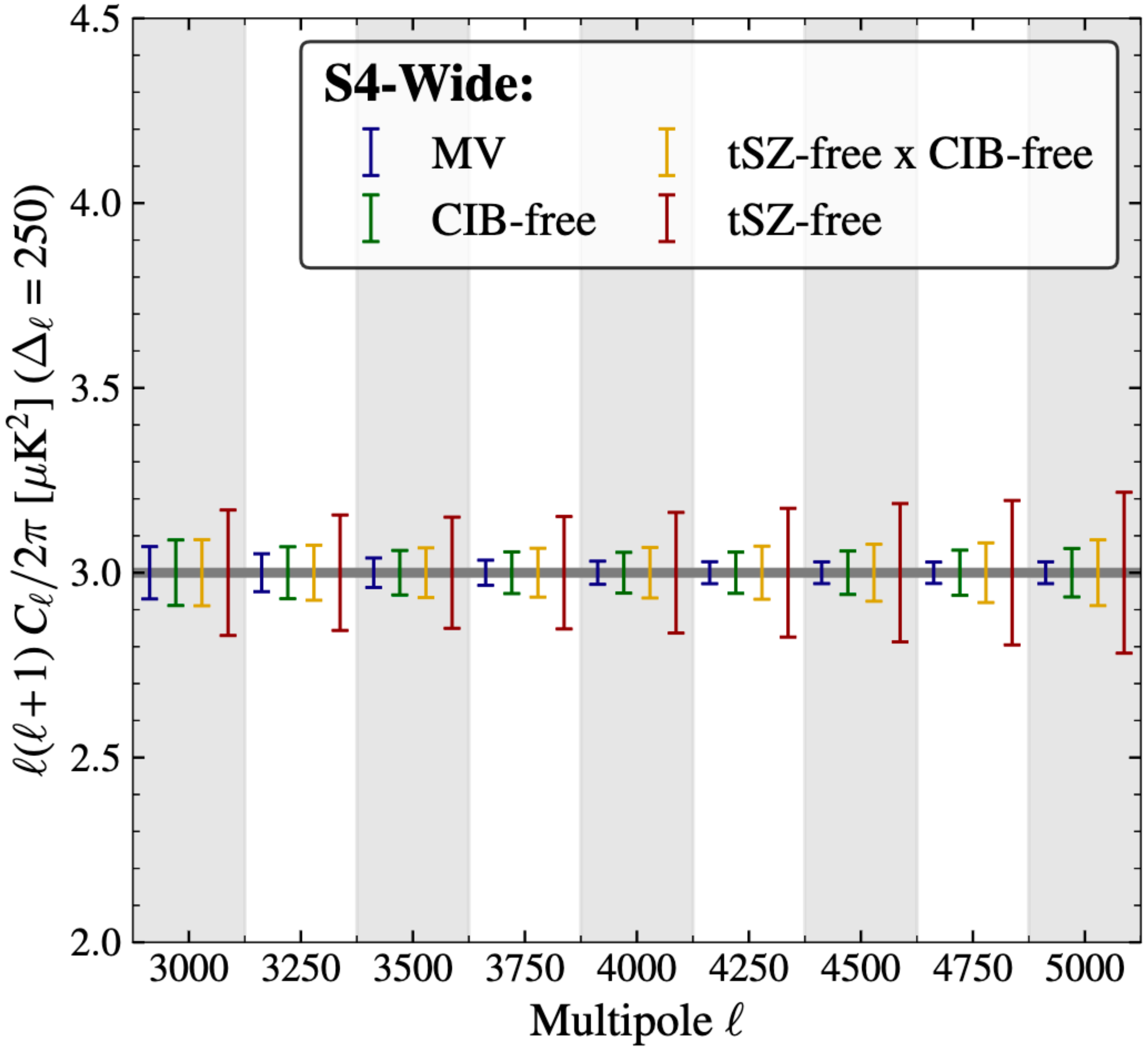
Cross-ILC Technique for Future kSZ Power Spectrum Measurements

tSZ-free x CIB-free: CIB and tSZ foregrounds are **>x5 lower than kSZ at \ell>=3700** for all experiments!



Cross-ILC Technique for Future kSZ Power Spectrum Measurements

Uncertainties are higher for cross-ILC but we have excellent control on foreground systematics



Code and Data Products: https://github.com/sriniraghunathan/cross_ilc_methods_paper

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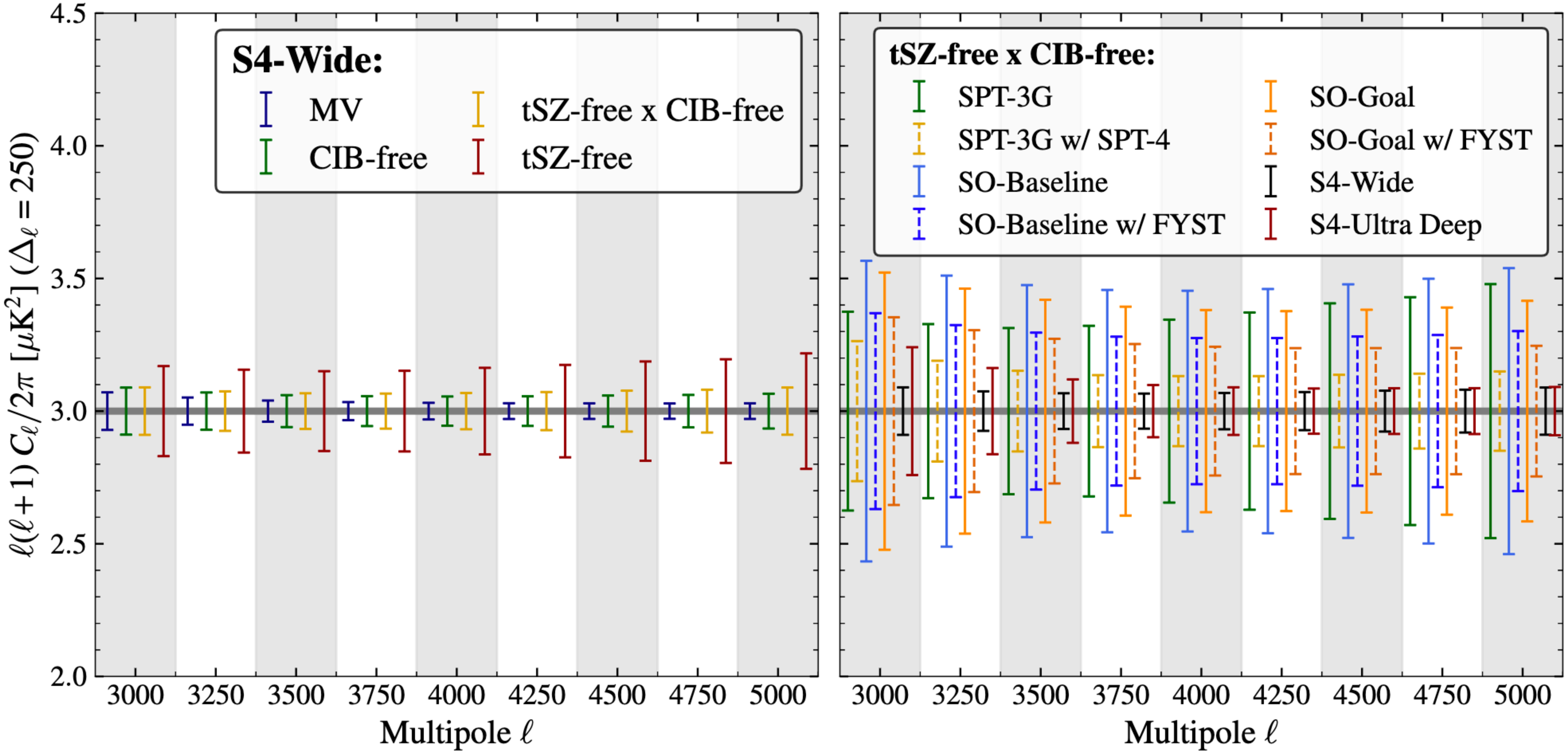

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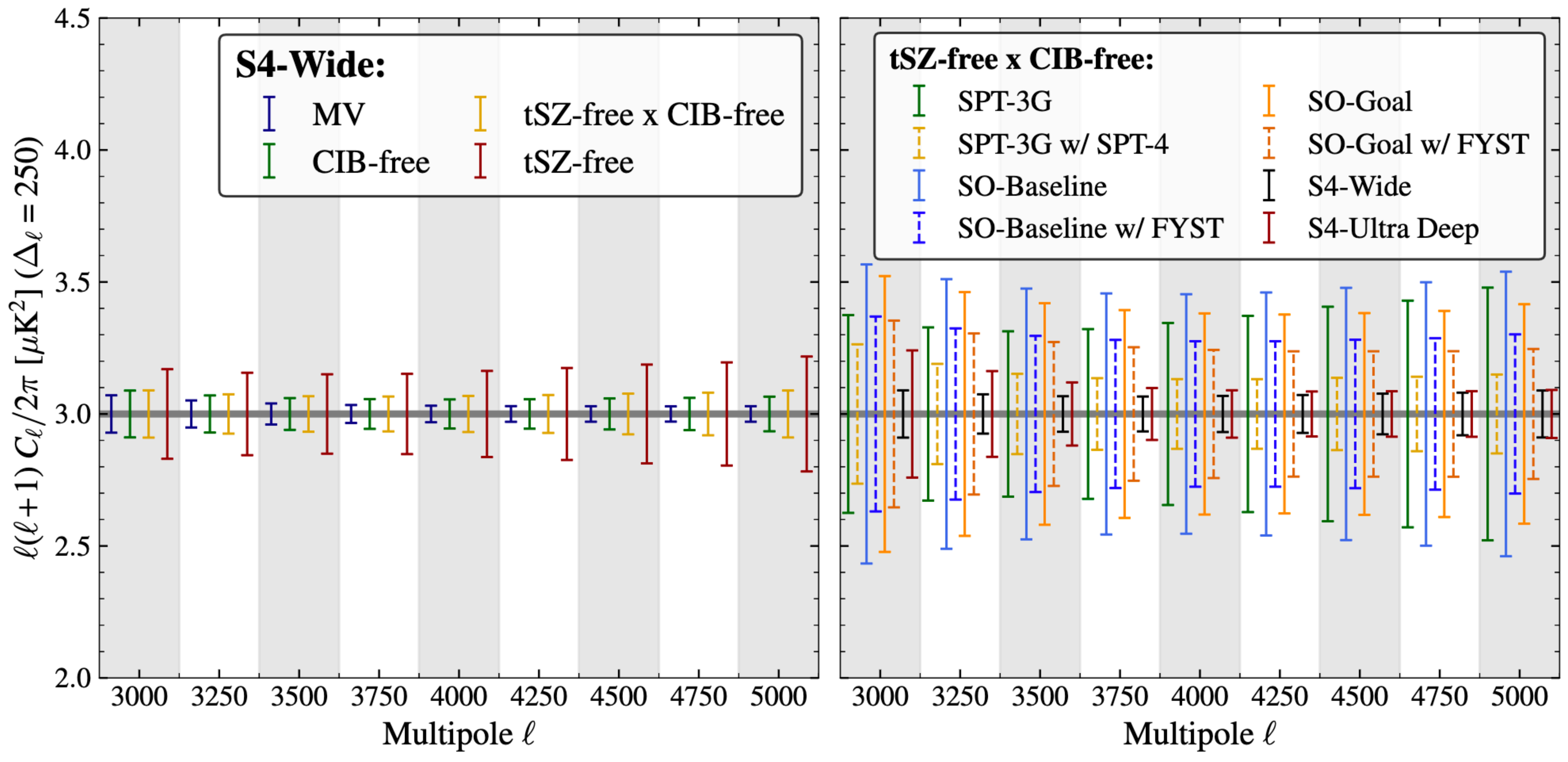


Experiment	f_{sky}	kSZ SNR
SPT-3G	0.036	20
SPT-3G w/ SPT-4		35
SO	0.4	25
CMB-S4	0.5	85

Next few years.

This decade.

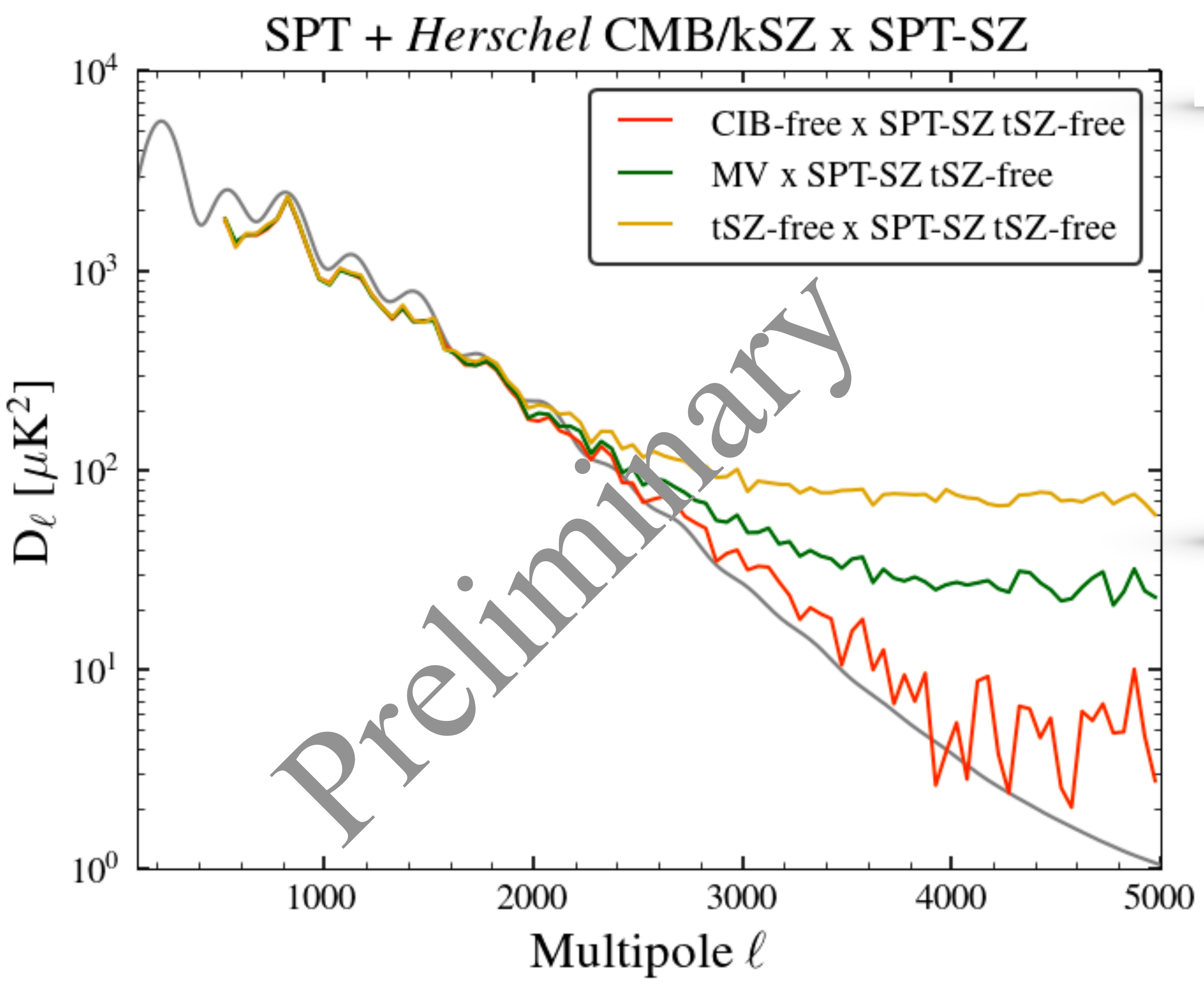
Future.

Raghunathan & Omori 2023, ApJ (arXiv:2304.09166).

Code and Data Products: https://github.com/sriniraghunathan/cross_ilc_methods_paper

Ongoing work: SPT x SPIRE (Preliminary)

Combining SPT (90/150/220 GHz) with *Herschel* SPIRE (600/857 GHz) datasets.



Cross-correlating current ILC maps with SPT-SZ tSZ-free map.

Bleem et al. 2021, ApJ, (arXiv: 2102.05033).

No noise bias / tSZ correlation in any of the curves.

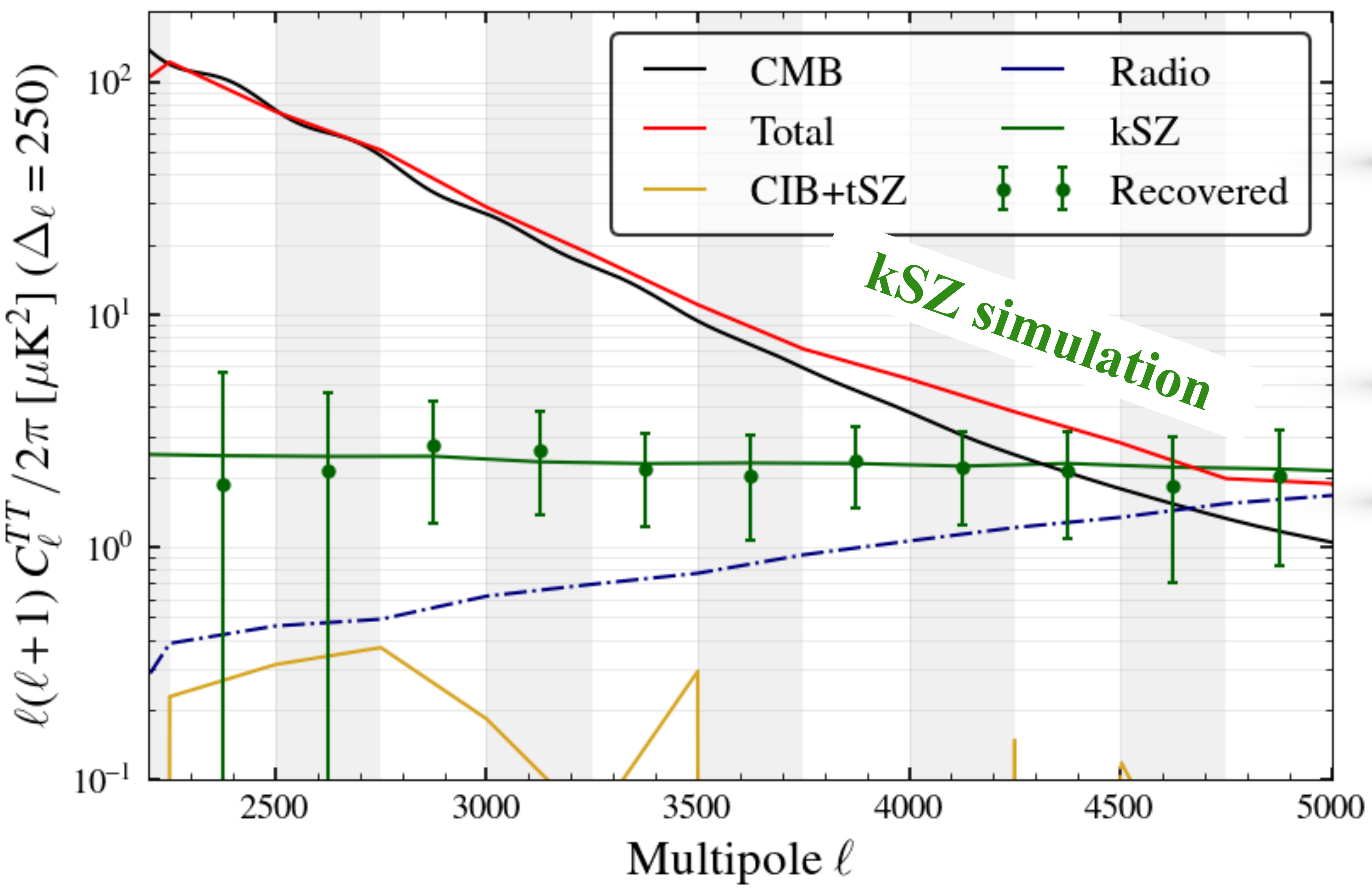
CIB residuals:

tSZ-free x tSZ-free > MV x tSZ-free > CIB-free x tSZ-free

Raghunathan et al., SPT/SPIRE Collaboration (in prep).

Ongoing work: SPT x SPIRE (Preliminary)

Combining SPT (90/150/220 GHz) with *Herschel* SPIRE (600/857 GHz) datasets.



Radio residuals dominate the small-scales but they are relatively easy to model.

kSZ SNR >7$\boldsymbol{\sigma}$ for $D_l \sim 3\ \mu K^2$.

Note: This is using a 100 sq. degree field.

Raghunathan et al., SPT/SPIRE Collaboration (in prep).

kSZ Power Spectrum: Expected reionisation constraints

Joint TT/EE/TE constraints on:

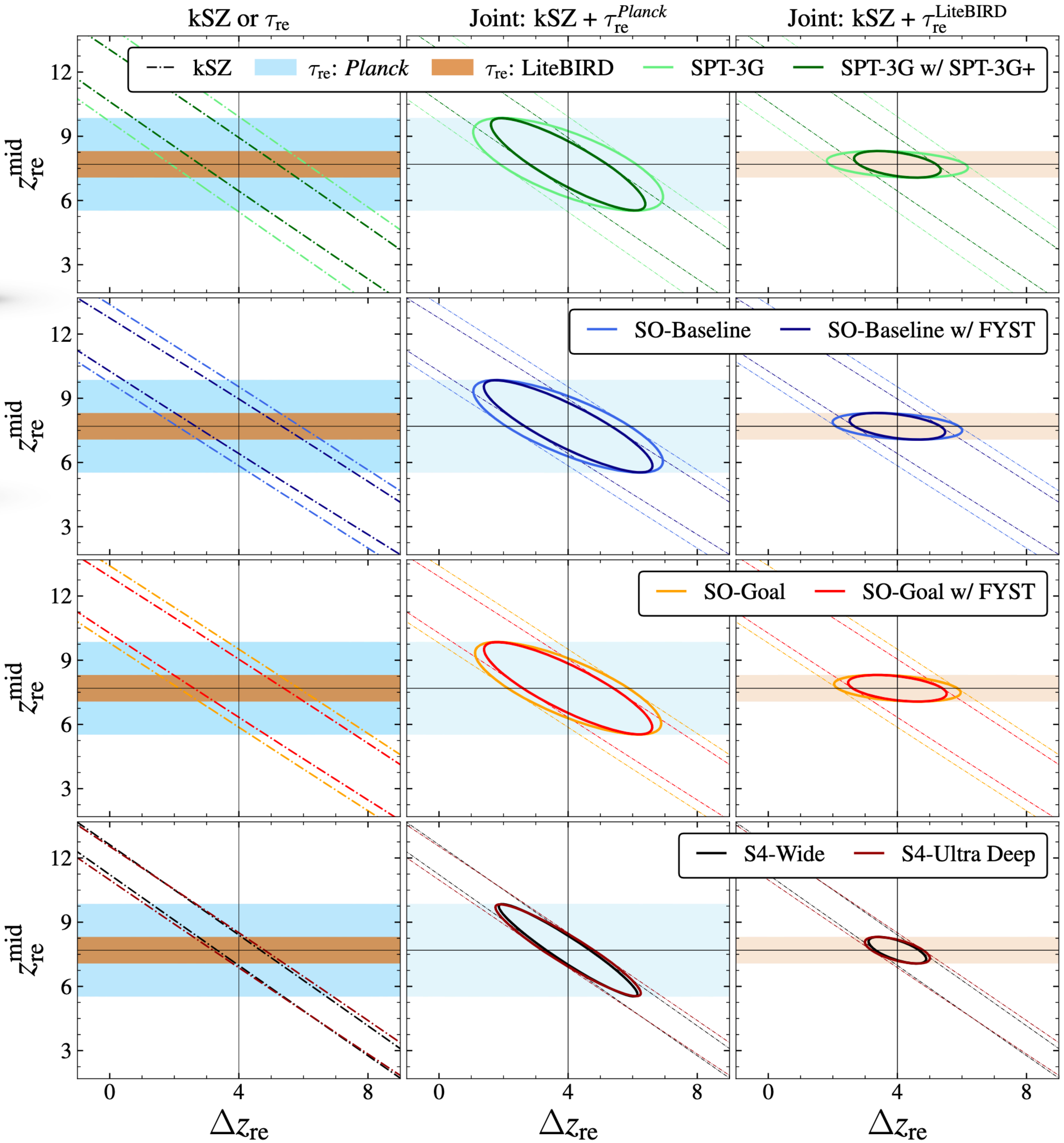
ΛCDM (6 parameters) +
foregrounds (3 parameters) +
late-time kSZ (2 parameters) +
reionisation (2 parameters).

Priors:

- τ_{re}: *Planck* or LiteBIRD.
- Late-time kSZ: 10 per cent.

$\sigma(\Delta z) \sim 1.5$ or 0.5 depending on the choice of prior on τ (*Planck* vs LiteBIRD).

Note that this is unconstrained currently by *Planck*.



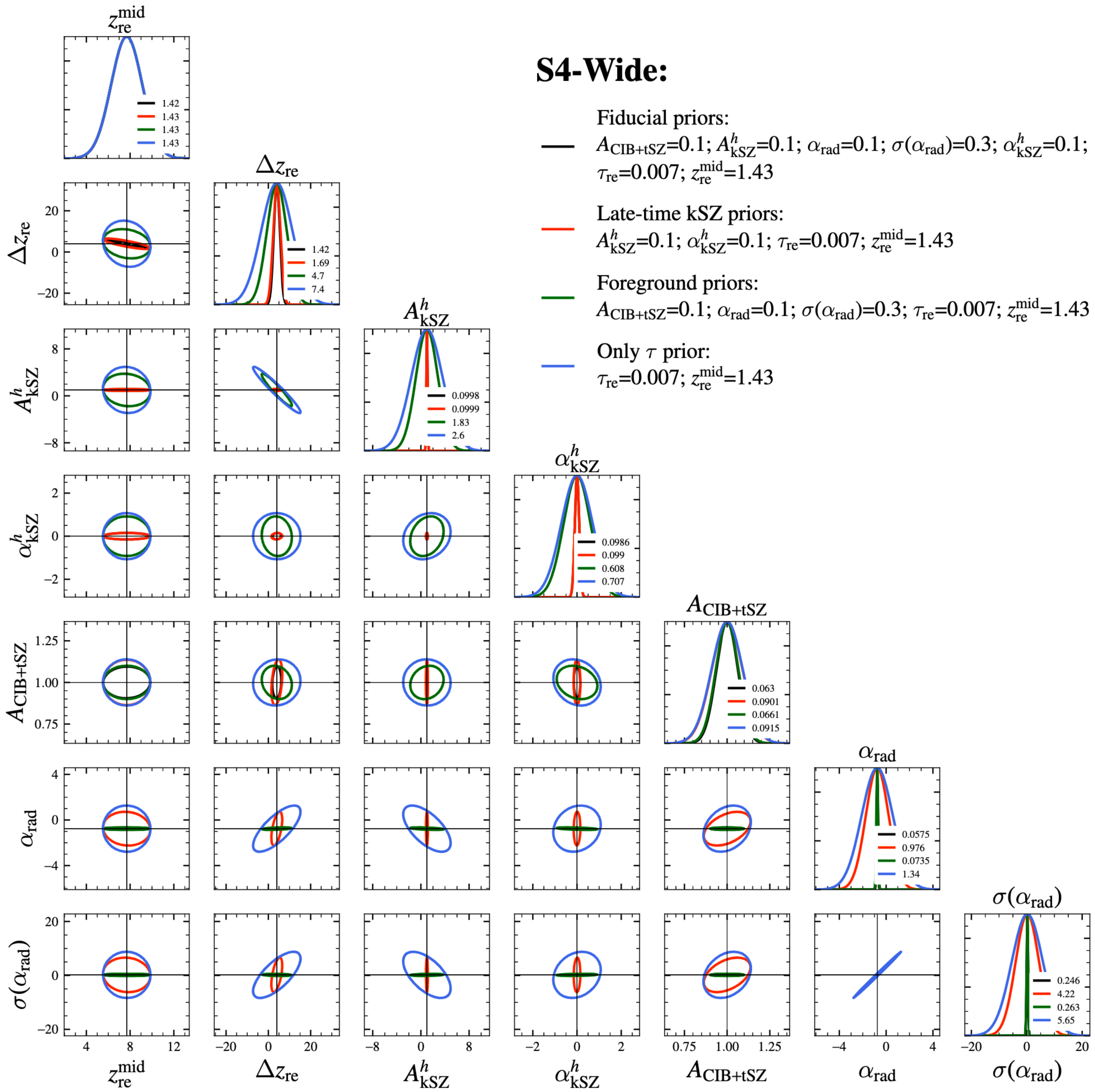
Raghunathan & Omori 2023, ApJ (arXiv:2304.09166).

Summary

- kSZ power spectrum is a good probe of the physics of reionisation.
  - Future measurements should focus on getting the entire kSZ power spectrum.
- Foregrounds, particularly CIB and tSZ are extremely important.
  - Modelling them is hard.
  - **Cross-ILC seems to return promising results**. ***Raghunathan & Omori 2023, ApJ (arXiv:2304.09166).***
- kSZ SNR for future experiments: ***Raghunathan & Omori 2023, ApJ (arXiv:2304.09166).***
  - 20 - 30 (new few years / this decade) - SPT and SO.
  - >80 (in the future by CMB-S4).
- On going SPT x *Herschel* SPIRE work:
  - High kSZ SNR (>6σ) expected with good control on foreground systematics from 100 sq. deg. data.
- Reionisation constraints using kSZ:
  - $\sigma(\Delta z) \sim 1.5$ or 0.5 depending on the choice of prior on τ.
  - Degeneracy between late-time and reionisation kSZ is important.
    - kSZ 4-pt may help. ***Smith & Ferraro, PRL (arXiv:1607.01769).***
    - de-late-time-kSZing using galaxy surveys may help. ***Foreman et al. 2023, PRD, (arXiv:2209.03973).***

Back up slides

Parameter degeneracies for CMB-S4



S4-Wide:

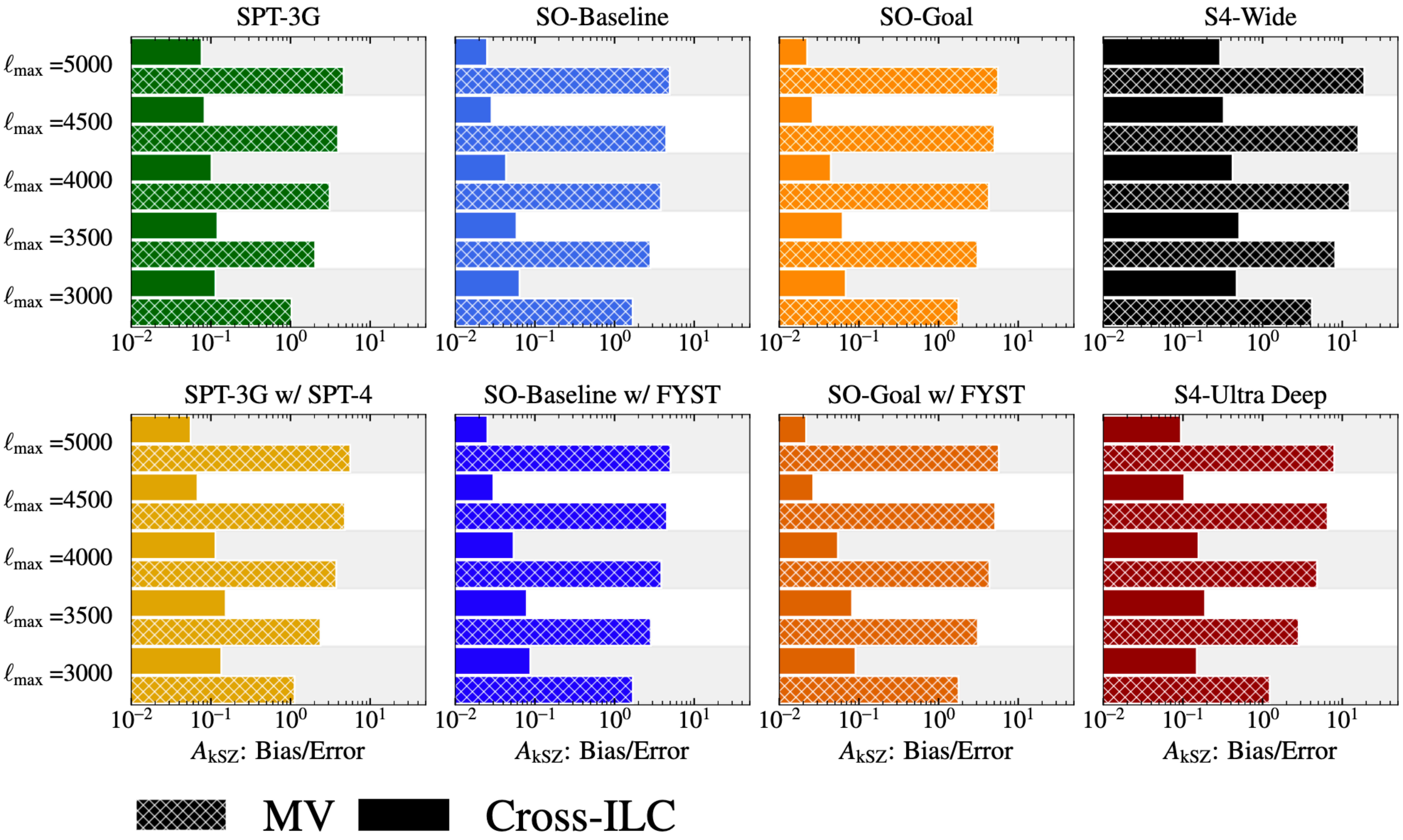
Fiducial priors:
$A_{\rm CIB+tSZ}$=0.1; $A^h_{\rm kSZ}$=0.1; $\alpha_{\rm rad}$=0.1; $\sigma(\alpha_{\rm rad})$=0.3; $\alpha^h_{\rm kSZ}$=0.1; $\tau_{\rm re}$=0.007; $z_{\rm re}^{\rm mid}$=1.43

Late-time kSZ priors:
$A^h_{\rm kSZ}$=0.1; $\alpha^h_{\rm kSZ}$=0.1; $\tau_{\rm re}$=0.007; $z_{\rm re}^{\rm mid}$=1.43

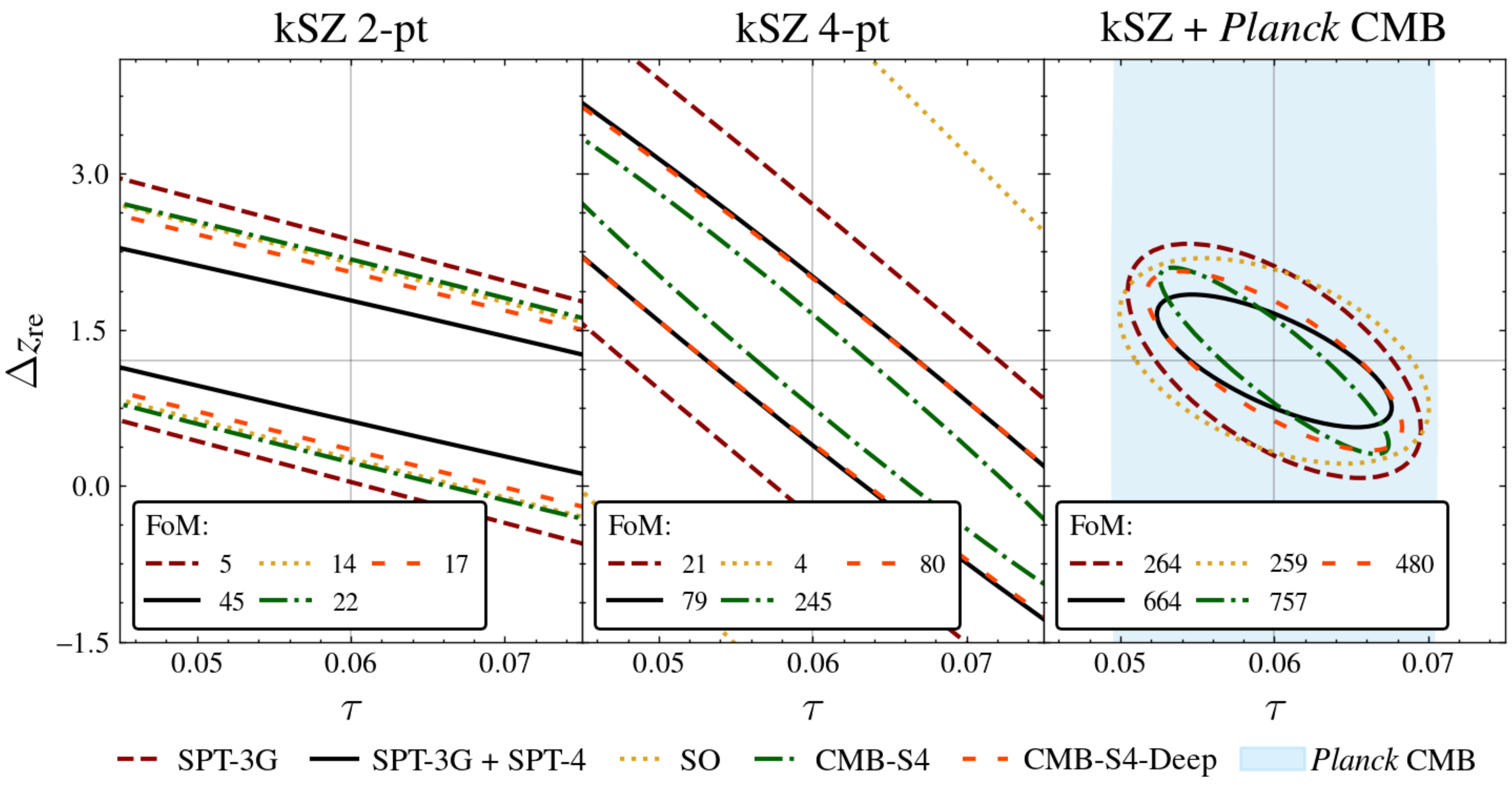
Foreground priors:
$A_{\rm CIB+tSZ}$=0.1; $\alpha_{\rm rad}$=0.1; $\sigma(\alpha_{\rm rad})$=0.3; $\tau_{\rm re}$=0.007; $z_{\rm re}^{\rm mid}$=1.43

Only τ prior:
$\tau_{\rm re}$=0.007; $z_{\rm re}^{\rm mid}$=1.43

Bias in kSZ reconstruction: MV ILC vs Cross-ILC



kSZ: 2-pt + 4-pt Constraints on Reionisation



Work done with Adam Anderson and SPT team.

Based on the formalism presented in Alvarez et al. 2021, PRD (arXiv: 2006.06594).

Constraints on optical depth: $\sigma(\tau)$ improves by 20 - 30 %. Complementary systematic check for *Planck* primary CMB measurement.

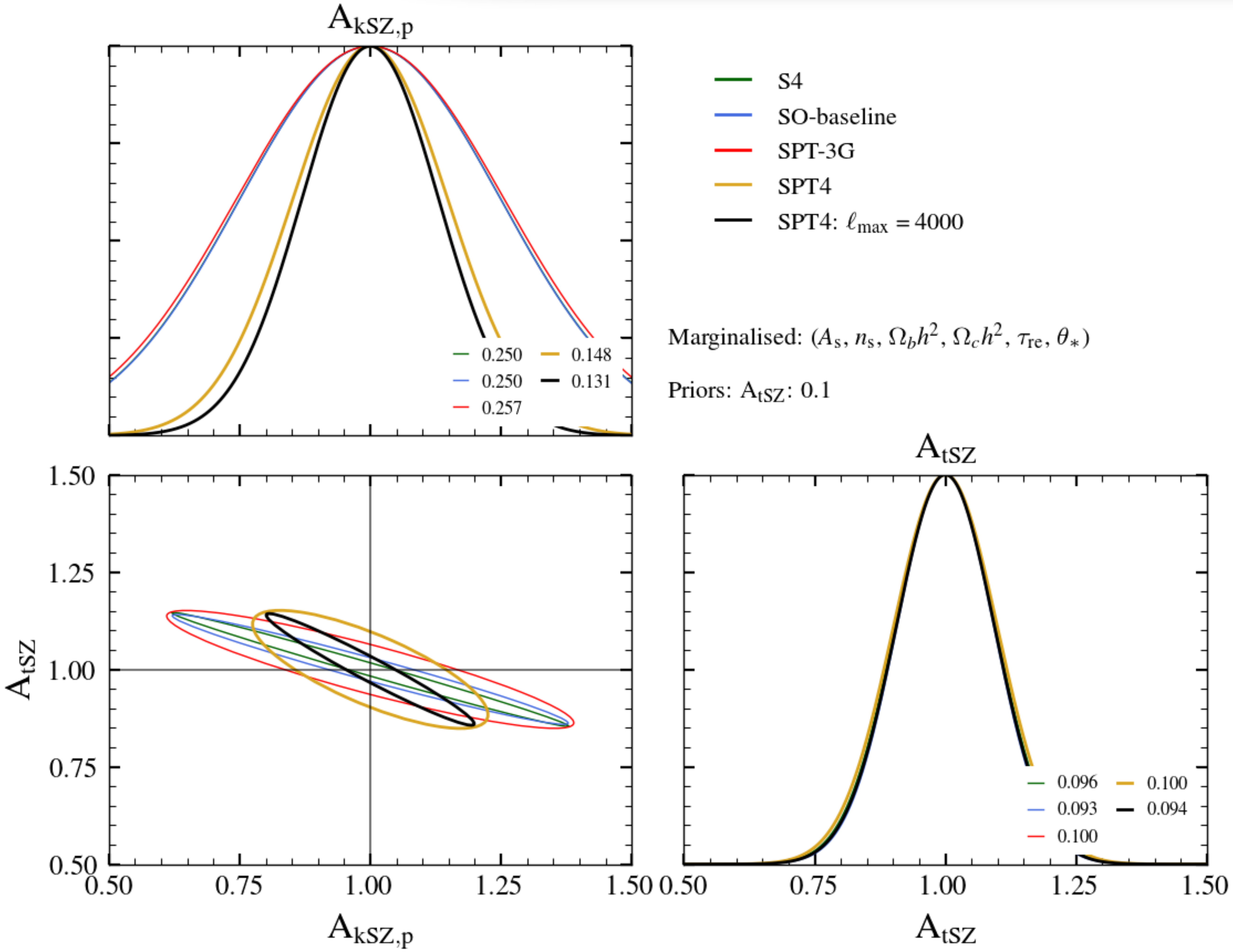
Constraints on the duration of reionisation: $\sigma(z_{\rm re}) = 0.42$. Unconstrained by *Planck*.

Covariance between 2-pt and 4-pt: Ignored.

kSZ / tSZ degenracies

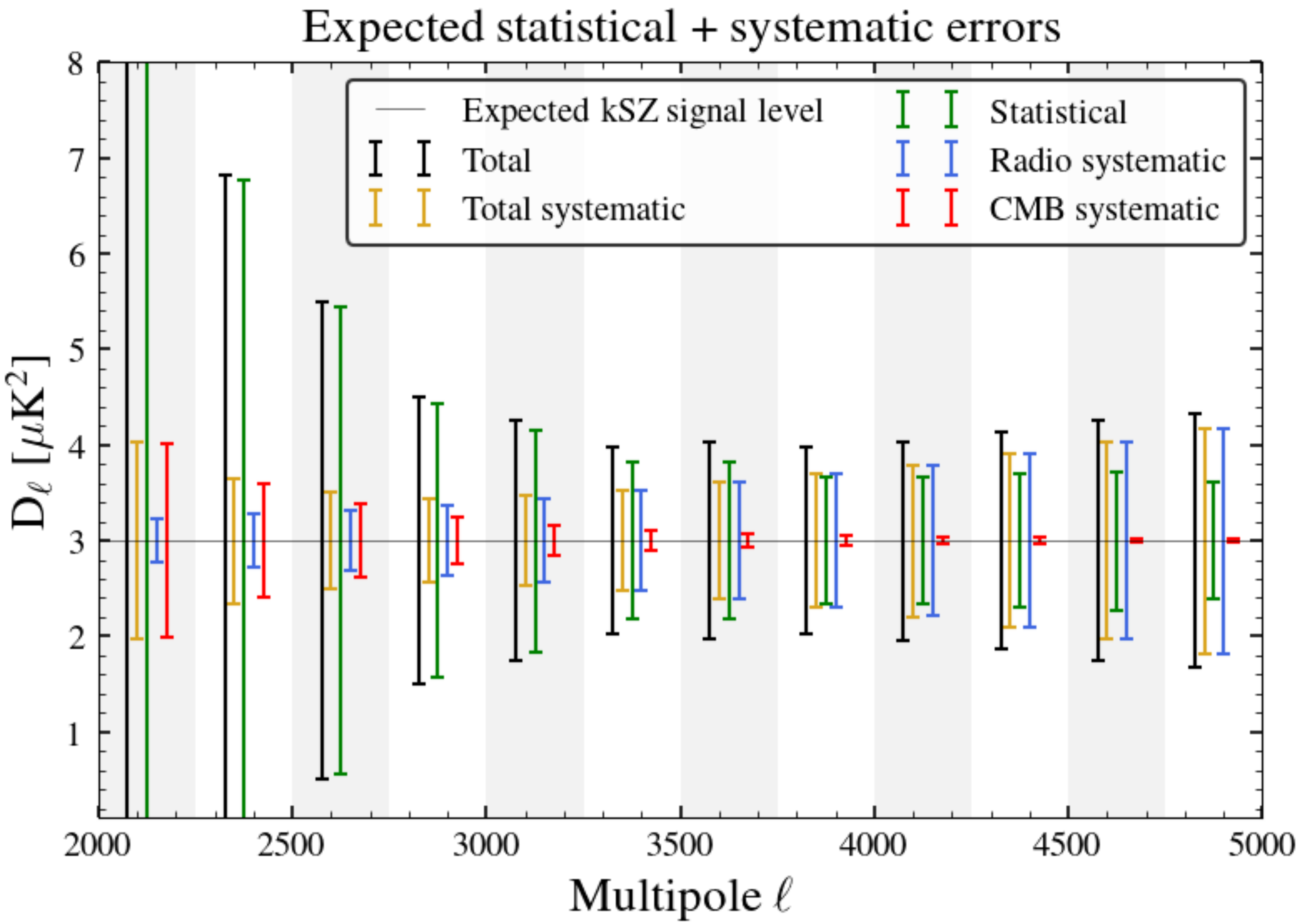
tSZ prior can come from tSZ bispectrum measurements but still assumes a template.

CIB assumed to be fully know below $\ell \le \ell_{max}$.



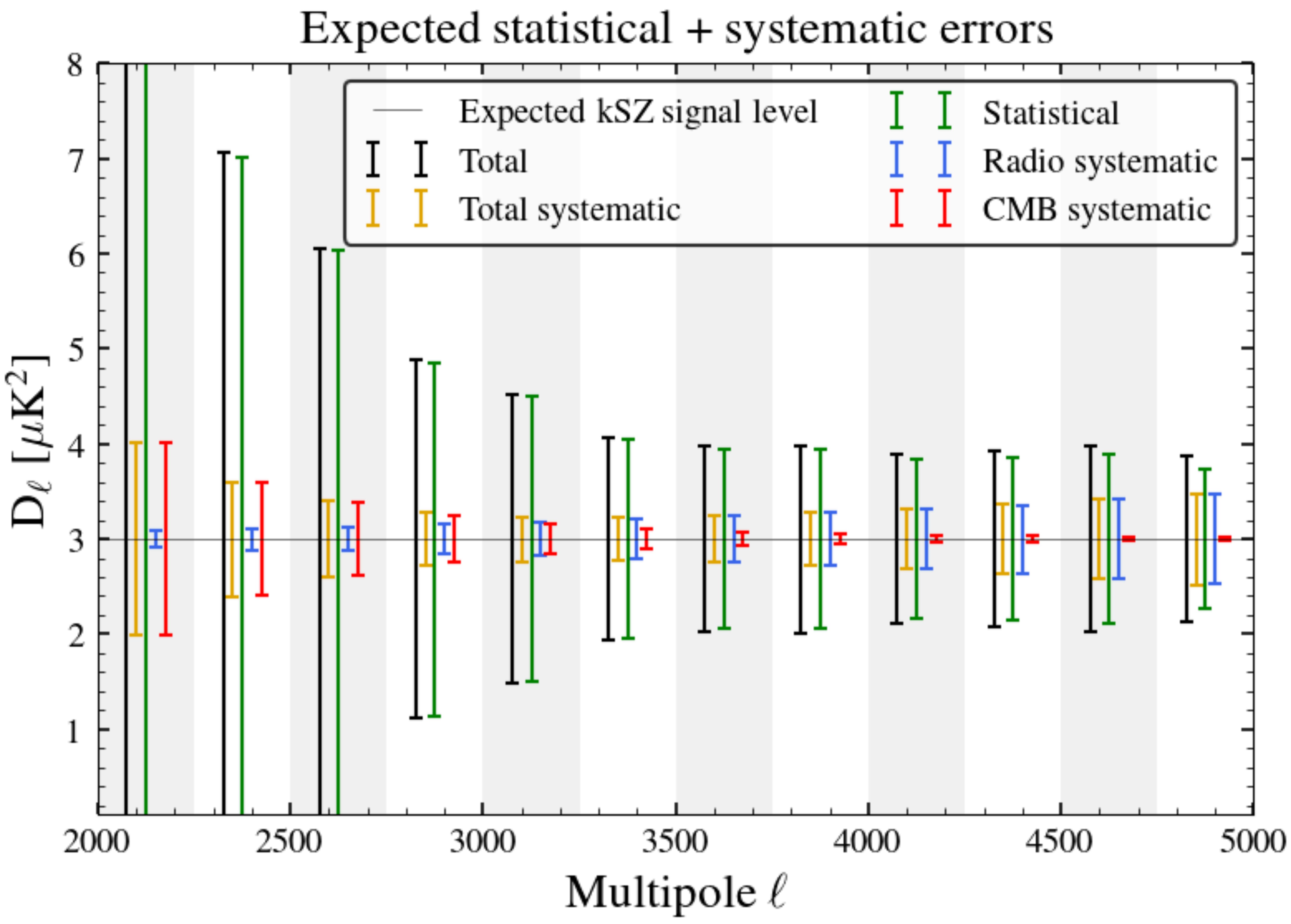
Ongoing work: SPT x SPIRE (Preliminary)

Source masking threshold = 4 mJy

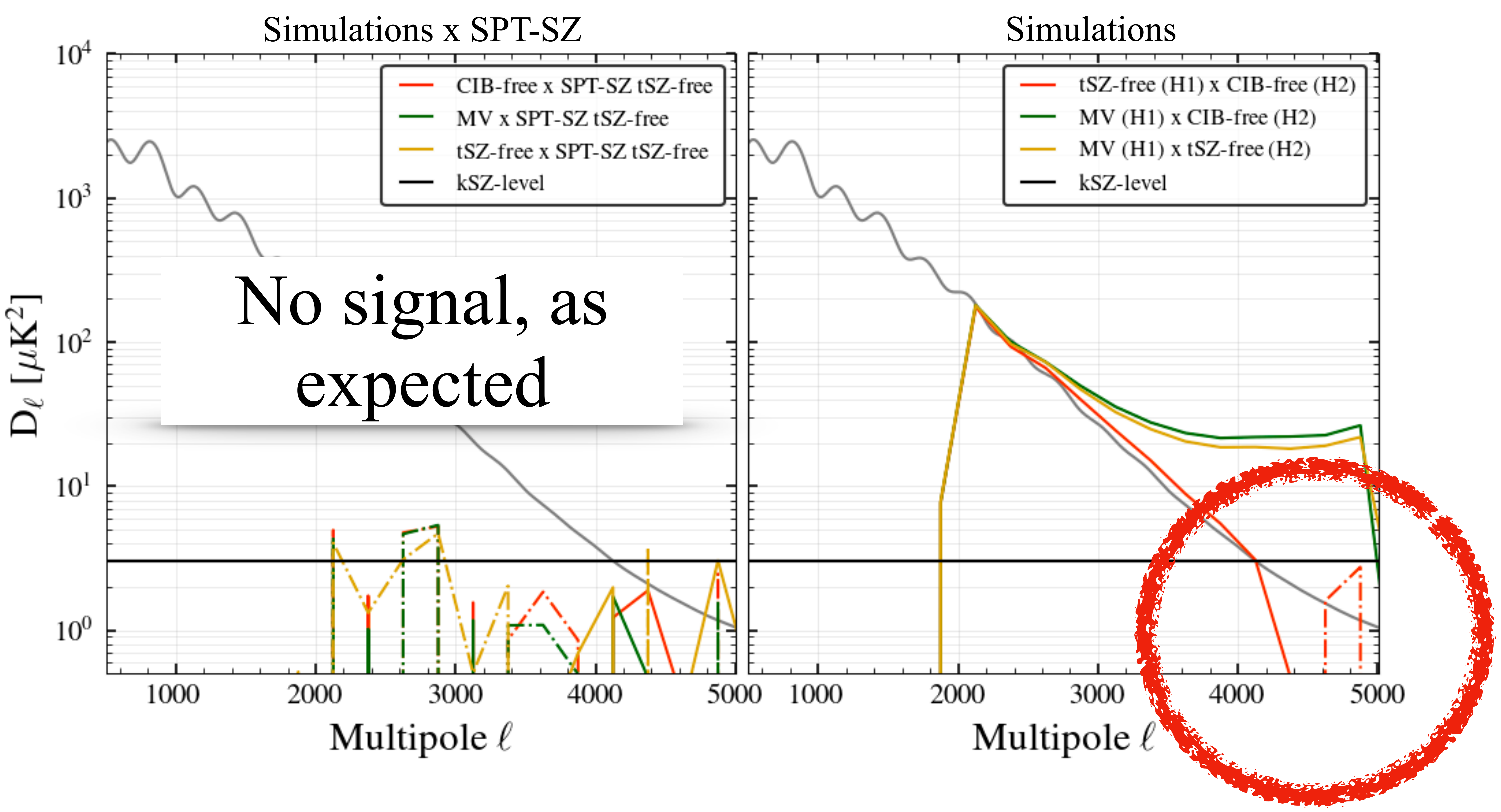


Ongoing work: SPT x SPIRE (Preliminary)

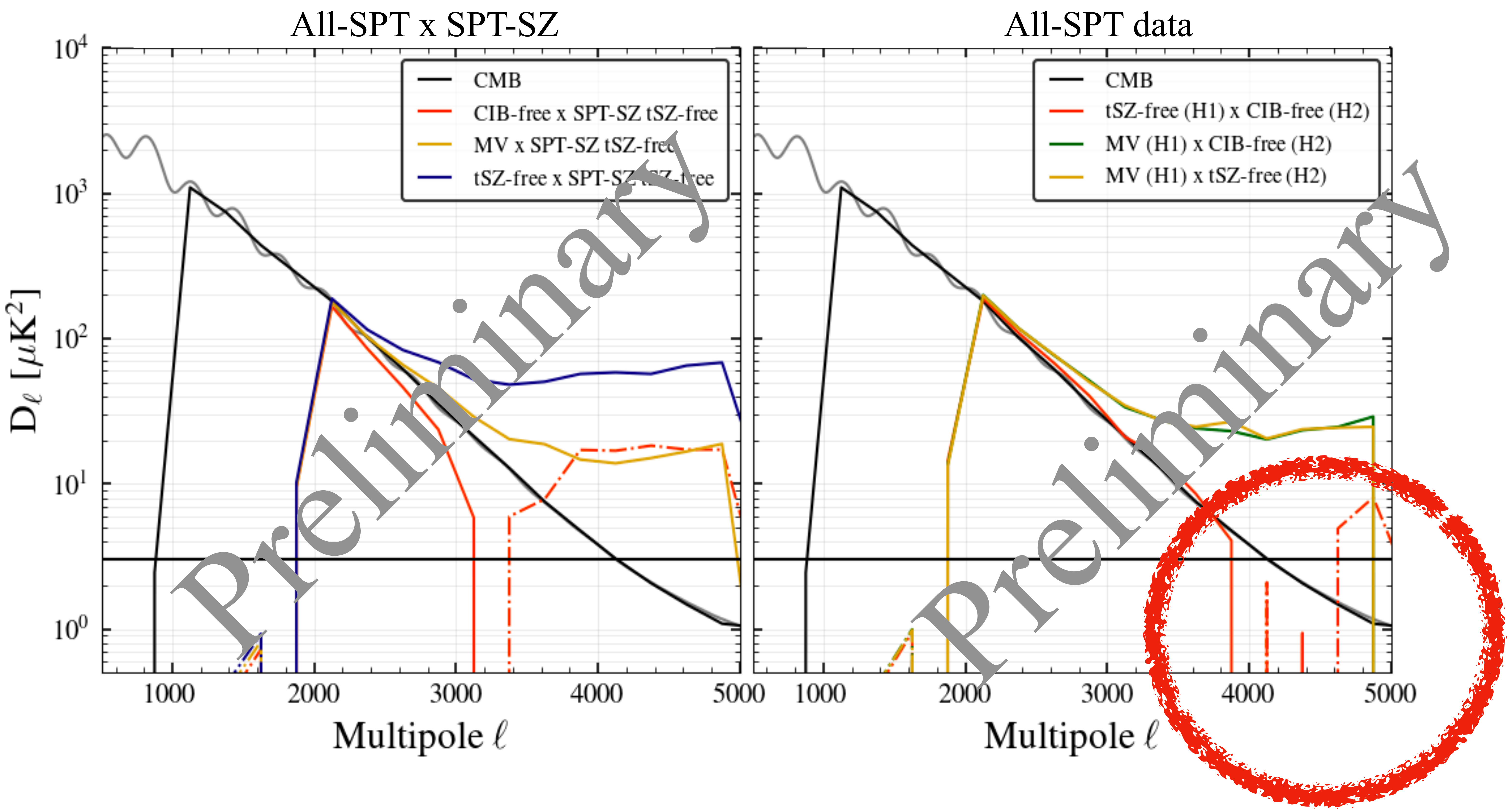
Source masking threshold = 2 mJy



Ongoing work: SPT x SPIRE (Preliminary)



Ongoing work: SPT x SPIRE (Preliminary)



Data has the same trend as simulations.

Raghunathan et al. SPT / Herschel (in prep).