Enhancing CMB+kSZ Power Spectrum Measurements by Removing CIB and tSZ Contamination with LSS

Kristen Surrao
Grenoble mm Universe, June 2023
Work with Ola Kusiak and Colin Hill

Motivation: measuring kSZ is challenging. Can we improve it by removing tSZ and CIB?

Idea: Use the external LSS data that is correlated with both CIB and tSZ to remove those contaminants to enhance CMB+kSZ measurements using ILC methods

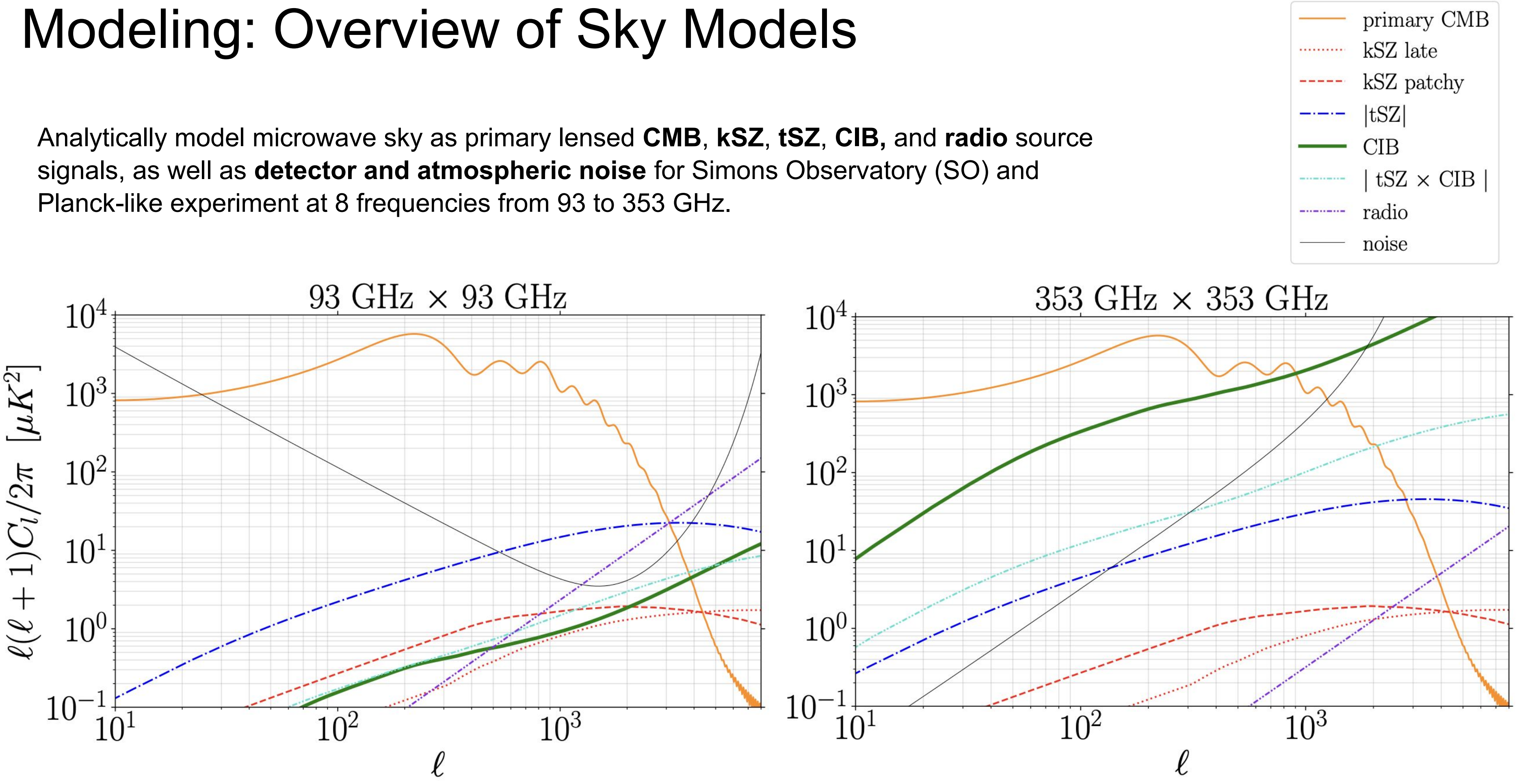
Key: Two-point correlation function of LSS with CMB + kSZ vanishes

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

Modeling choices

Modeling: Overview of Sky Models

Analytically model microwave sky as primary lensed **CMB**, **kSZ**, **tSZ**, **CIB,** and **radio** source signals, as well as **detector and atmospheric noise** for Simons Observatory (SO) and Planck-like experiment at 8 frequencies from 93 to 353 GHz.



Computed in the halo model with class_sz (Boris Bolliet)

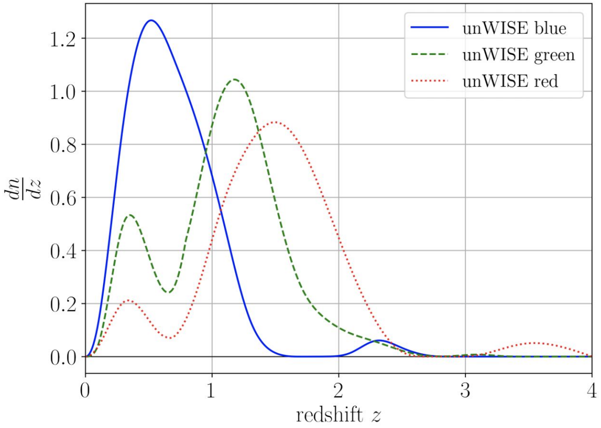
Modeling: *unWISE* Galaxies

- ***unWISE* galaxy catalog (Krolewski+ 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)
  - Coarse dn/dz via cross-correlation with spectroscopic surveys

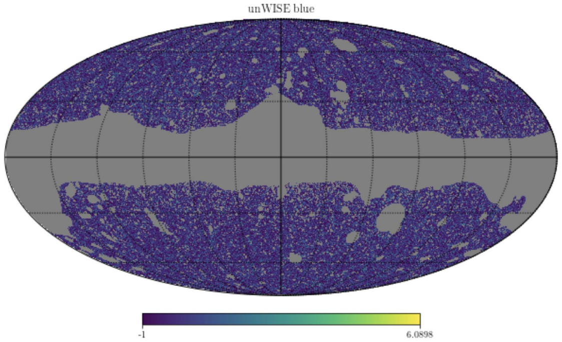
Number density of galaxies

unWISE	$\bar{z}$	δ_z	$\bar{n}_g$ [deg^{-2}]
blue	0.6	0.3	3409
green	1.1	0.4	1846
red	1.5	0.4	144

Redshift Distribution



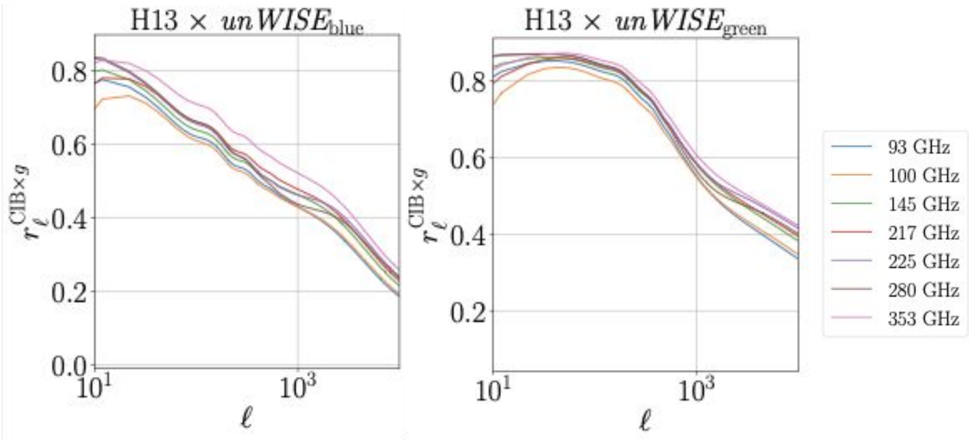
Galaxy overdensity map (*unWISE* blue)



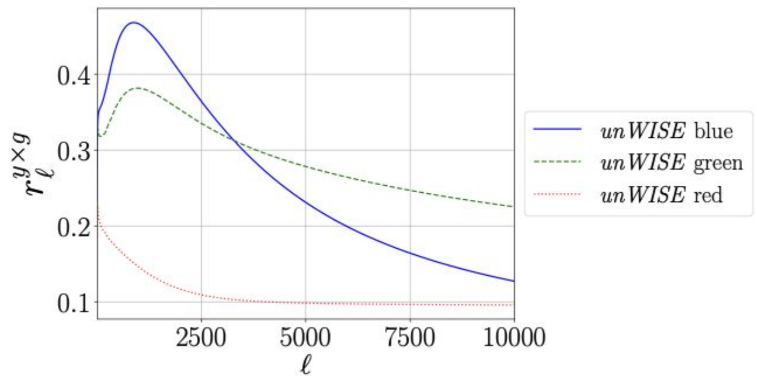
We model *unWISE* halo occupation distribution (HOD) = galaxy clustering model based on Kusiak+ 2022

unWISE correlates with CIB and tSZ fields

CIB x *unWISE*:



Compton-y x *unWISE*:



unWISE

- great tracer of the CIB
- also partially traces tSZ

Internal Linear Combination (ILC): Theory

Standard ILC

Internal Linear Combination (ILC)–standard method to construct a map of the signal of interest and optionally deproject (=remove) some other contaminant components

$$\hat{T}^{\mathrm{ILC}}_{\ell m} = \sum_i w^i_\ell T^i_{\ell m}$$

temperature map at i[th] frequency

Minimization subject to **one constraint:**

- Minimize variance

$$\sigma^2_{\hat{T}^{\mathrm{ILC}}_{\ell m}\hat{T}^{\mathrm{ILC}}_{\ell m}} = \sum_{i,j} w^i_\ell w^j_\ell \left(\hat{R}_\ell\right)_{ij}$$

Frequency-frequency covariance matrix from data

- Unit response to signal of interest

$$\sum_i w^i_\ell a_i = 1$$

SED of signal of interest

Solution for the weights:

$$w^i_\ell = \frac{\left(\hat{R}^{-1}_\ell\right)_{ij} a_j}{\left(\hat{R}^{-1}_\ell\right)_{km} a_k a_m}$$

Constrained ILC

Solution for the weights:

$$w_\ell^j = \frac{\left(b_k(\hat{R}_\ell^{-1})_{kl}b_l\right) a_i(\hat{R}_\ell^{-1})_{ij} - \left(a_k(\hat{R}_\ell^{-1})_{kl}b_l\right) b_i(\hat{R}_\ell^{-1})_{ij}}{\left(a_k(\hat{R}_\ell^{-1})_{kl}a_l\right)\left(b_m(\hat{R}_\ell^{-1})_{mn}b_n\right) - \left(a_k(\hat{R}_\ell^{-1})_{kl}b_l\right)^2}$$

Minimization subject to **two constraints:**

- Minimize variance

$$\sigma^2_{\hat{T}^{\mathrm{ILC}}_{\ell m}\hat{T}^{\mathrm{ILC}}_{\ell m}} = \sum_{i,j} w_\ell^i w_\ell^j \left(\hat{R}_\ell\right)_{ij}$$

- **Unit response** to signal of interest

$$\sum_i w_\ell^i a_i = 1$$

- Deproject **one** contaminant

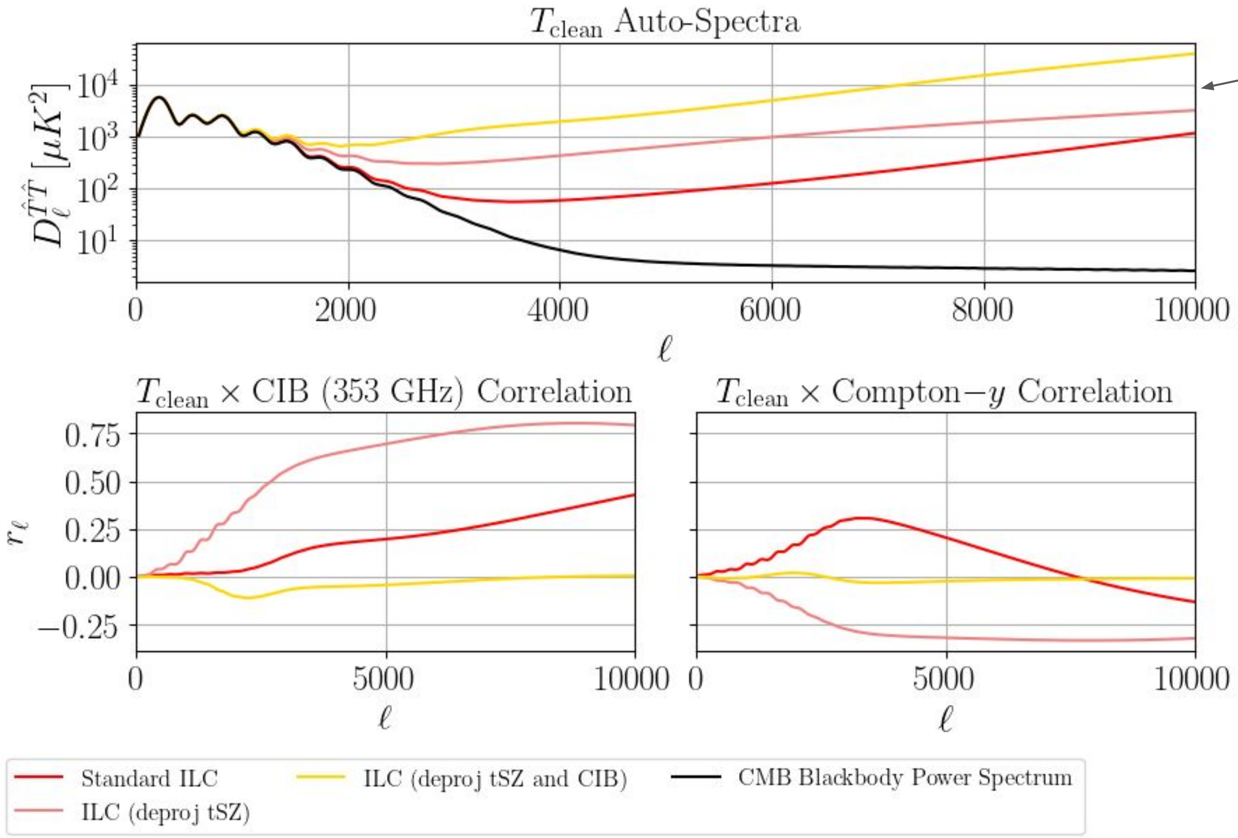
$$\sum_i w_\ell^i b_i = 0$$

SED of component to deproject

- Solution can be generalized to N deprojected components
- Generally, (except tSZ) we don't know the exact SED of the contaminant
- No free lunch!
    - deprojecting/adding a constraint increases the noise of the final map

Standard and Constrained ILC Results

Deprojection increases noise



New Methods

Overview of New Methods

1. ILC with tracers as additional input “frequency” maps
2. de-CIB
3. ILC requiring tracers to have zero correlation with the cleaned map

Overview of New Methods

1. **ILC with tracers as additional input “frequency” maps**
2. de-CIB
3. ILC requiring tracers to have zero correlation with the cleaned map

ILC with Tracers as Additional Input “Frequency” Maps

- Use the fact that the CMB and kSZ fields have zero “response” in the tracer maps

$$\boxed{\hat{T}^{\mathrm{ILC}}_{\ell m} = \sum_{i=1}^{N} w^i_\ell T^i_{\ell m} + \sum_{i=1}^{N_g} w^{N+i}_\ell g_{i,\ell m}}$$

Spectral response vector for signal of interest

$$\boldsymbol{a} \leftarrow \boldsymbol{a} + \underbrace{[0, ..., 0]}_{N_g}$$

ILC with Tracers as Additional Input "Frequency" Maps

- Use the fact that the CMB and kSZ fields have zero "response" in the tracer maps

$$\boxed{\hat{T}^{\rm ILC}_{\ell m} = \sum_{i=1}^{N} w^i_\ell T^i_{\ell m} + \sum_{i=1}^{N_g} w^{N+i}_\ell g_{i,\ell m}}$$

Spectral response vector for signal of interest

$$\boldsymbol{a} \leftarrow \boldsymbol{a} + \underbrace{[0, ..., 0]}_{N_g}$$

$$\sum_{i=1}^{N+N_g} w^i_\ell a_i = \sum_{i=1}^{N} w^i_\ell a_i = 1$$

ILC with Tracers as Additional Input "Frequency" Maps

- Use the fact that the CMB and kSZ fields have zero "response" in the tracer maps

$$\boxed{\hat{T}^{\rm ILC}_{\ell m} = \sum_{i=1}^{N} w^i_\ell T^i_{\ell m} + \sum_{i=1}^{N_g} w^{N+i}_\ell g_{i,\ell m}}$$

Spectral response vector for signal of interest

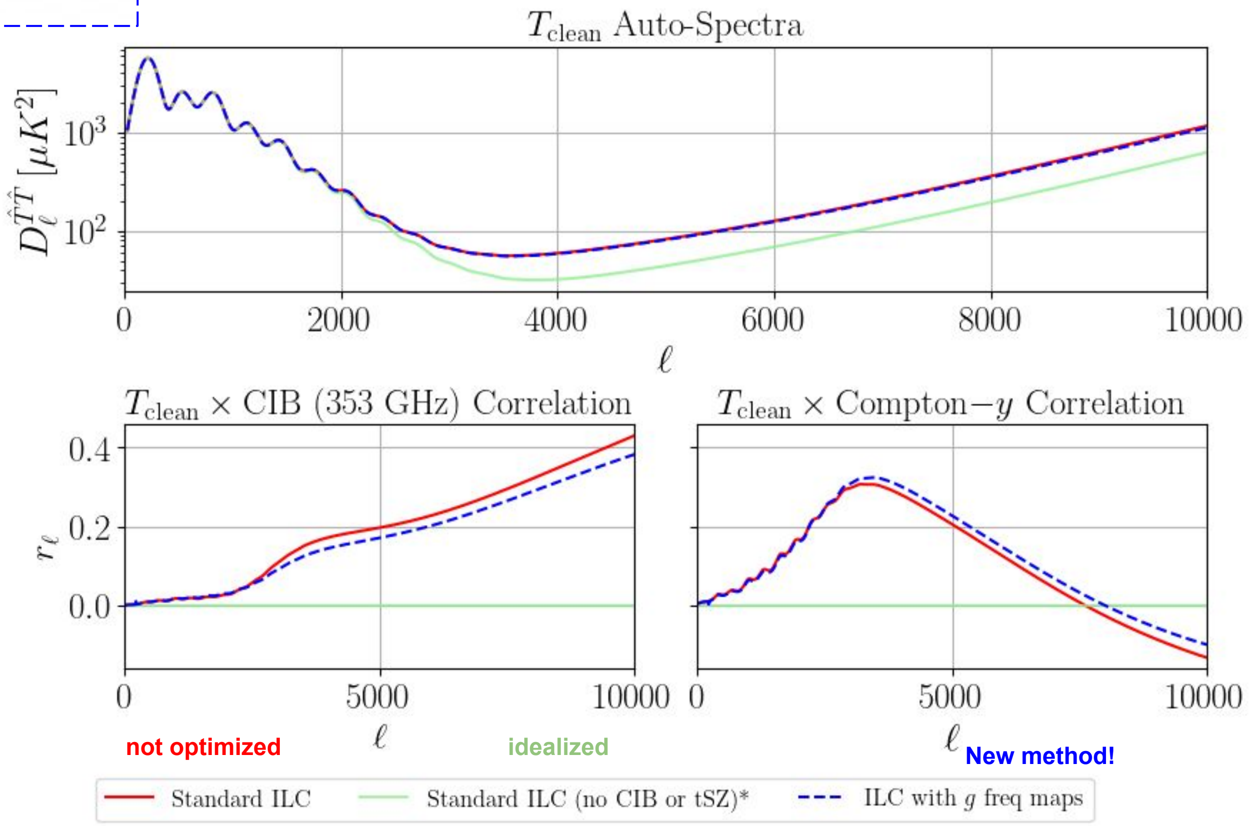
$$\boldsymbol{a} \leftarrow \boldsymbol{a} + \underbrace{[0, \ldots, 0]}_{N_g} \quad \Longrightarrow \quad \sum_{i=1}^{N+N_g} w^i_\ell a_i = \sum_{i=1}^{N} w^i_\ell a_i = 1$$

Standard ILC solution with modified covariance

$$w^i_\ell = \frac{\left(\hat{R}^{-1}_\ell\right)'_{ij} a_j}{\left(\hat{R}^{-1}_\ell\right)'_{km} a_k a_m} \qquad \left(\hat{R}^\ell\right)' = \begin{bmatrix} \hat{R}^\ell & X_\ell \\ X^T_\ell & G_\ell \end{bmatrix}$$

ILC with Tracers as Additional Input "Frequency" Maps: Results

$$\hat{T}^{\mathrm{ILC}}_{\ell m} = \sum_{i=1}^{N} w^i_\ell T^i_{\ell m} + \sum_{i=1}^{N_g} w^{N+i}_\ell g_{i,\ell m}$$



Overview of New Methods

1. ILC with tracers as additional input “frequency” maps
2. **de-CIB**
3. ILC requiring tracers to have zero correlation with the cleaned map

de-CIB

Idea taken from delensing, following
Yu, Hill, Sherwin 2017

1. Find the linear combination of LSS tracer samples most highly correlated with CIB at i^{th} frequency:

$$g^i_{\ell m} = \sum_a c^i_{a,\ell}\, g^a_{\ell m}$$

Optimal combination of tracers at i^{th} frequency

Different tracers, e.g. *unWISE* blue, green, red

de-CIB

Idea taken from delensing, following
Yu, Hill, Sherwin 2017

1. Find the linear combination of LSS tracer samples most highly correlated with CIB at ith frequency:

$$g^i_{\ell m} = \sum_a c^i_{a,\ell}\, g^a_{\ell m}$$

Optimal combination of tracers at ith frequency

Different tracers, e.g. *unWISE* blue, green, red

2. Starting from an ILC map, subtract the fraction of tracers that's contained in the CIB at each frequency:

ILC

$$\boxed{T^{\rm clean}_{\ell m} = \sum_i w^i_\ell (T^i_{\ell m} - f^i_\ell g^i_{\ell m})}$$

de-CIB

Idea taken from delensing, following
Yu, Hill, Sherwin 2017

1. Find the linear combination of LSS tracer samples most highly correlated with CIB at i$^{\text{th}}$ frequency:

$$g^i_{\ell m} = \sum_a c^i_{a,\ell}\, g^a_{\ell m}$$

Optimal combination of tracers at i$^{\text{th}}$ frequency

Different tracers, e.g. *unWISE* blue, green, red

2. Starting from an ILC map, subtract the fraction of tracers that's contained in the CIB at each frequency:

ILC

$$\boxed{T^{\rm clean}_{\ell m} = \sum_i w^i_\ell (T^i_{\ell m} - f^i_\ell g^i_{\ell m})}$$

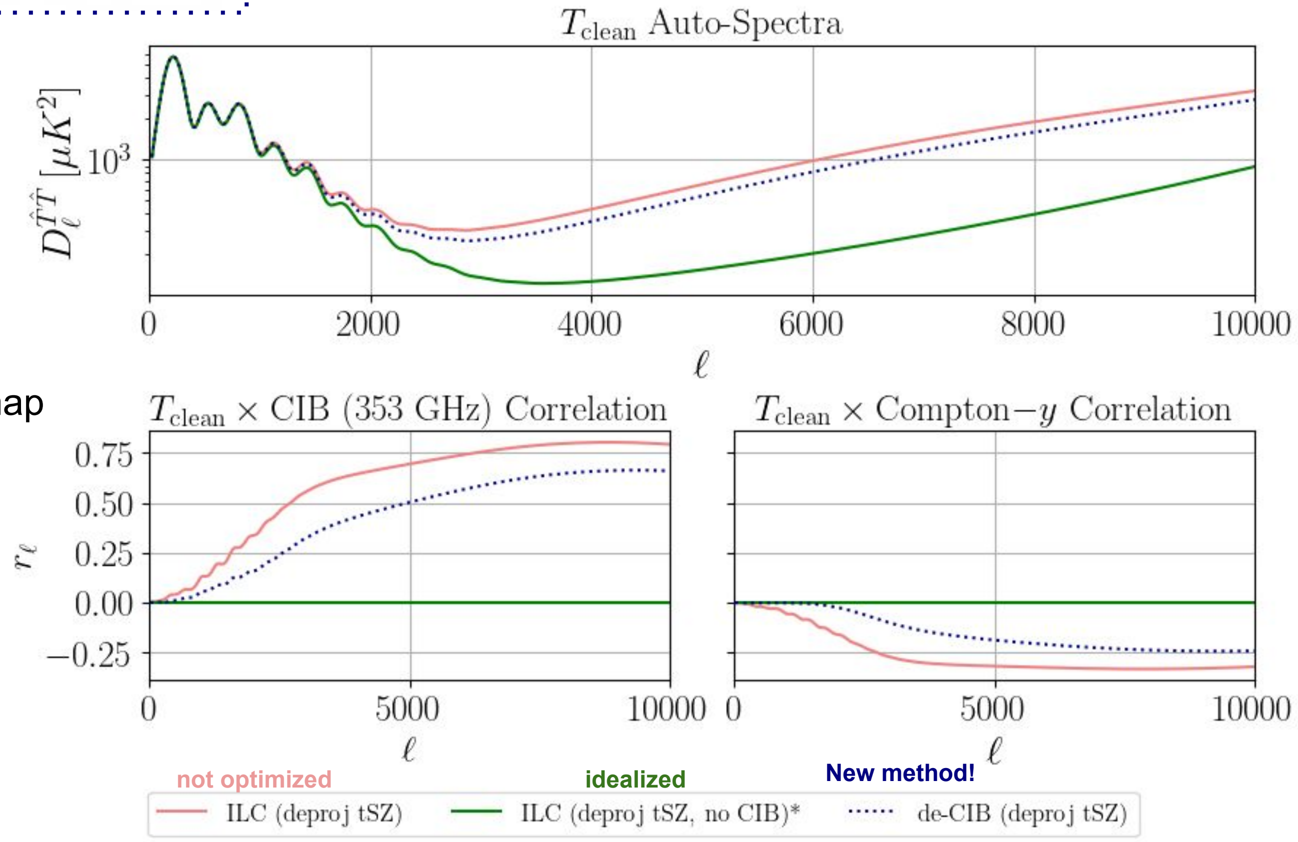
The fraction of tracers contained in the CIB at each frequency (from delensing: minimize the variance of the final map) is

$$f^i_\ell \equiv \frac{C_\ell^{{\rm CIB}_i, g^i}}{C_\ell^{g^i, g^i}} = \frac{\sum_a c^i_{a,\ell} C_\ell^{{\rm CIB}_i, g_a}}{\sum_{a,b} c^i_{a,\ell} c^i_{b,\ell} C_\ell^{g_a g_b}}$$

de-CIB: Results

$$T_{\ell m}^{\text{clean}} = \sum_i w_\ell^i (T_{\ell m}^i - f_\ell^i g_{\ell m}^i)$$

de-CIB is applied to tSZ-deprojected ILC map



Overview of New Methods

1. ILC with tracers as additional input “frequency” maps
2. de-CIB
3. **ILC requiring tracers to have zero correlation with the cleaned map**

ILC with Zero-Tracer-Correlation Constraint

Start from an ILC, and explicitly require the output map to have zero cross-correlation with the tracer map:

$$\boxed{\langle T_{\ell m}^{\mathrm{ILC}} g_{\ell m} \rangle = 0 \Longleftrightarrow \sum_i w_\ell^i \langle T_{\ell m}^i g_{\ell m} \rangle = 0}$$

ILC with Zero-Tracer-Correlation Constraint

Start from an ILC, and explicitly require the output map to have zero cross-correlation with the tracer map:

$$\boxed{\langle T_{\ell m}^{\mathrm{ILC}} g_{\ell m} \rangle = 0 \Longleftrightarrow \sum_i w_\ell^i \langle T_{\ell m}^i g_{\ell m} \rangle = 0}$$

Def. $c_i^\ell \equiv \langle T_{\ell m}^i g_{\ell m} \rangle = C_\ell^{ig}$

$$\Longrightarrow \quad \sum_i w_\ell^i c_i^\ell = 0$$

similar to usual constrained ILC!

ILC with Zero-Tracer-Correlation Constraint

Start from an ILC, and explicitly require the output map to have zero cross-correlation with the tracer map:

$$\boxed{\langle T^{\mathrm{ILC}}_{\ell m} g_{\ell m}\rangle = 0 \Longleftrightarrow \sum_i w^i_\ell \langle T^i_{\ell m} g_{\ell m}\rangle = 0}$$

Def. $c^\ell_i \equiv \langle T^i_{\ell m} g_{\ell m}\rangle = C^{ig}_\ell$ $\Rightarrow$ $$\sum_i w^i_\ell c^\ell_i = 0$$

similar to usual constrained ILC!

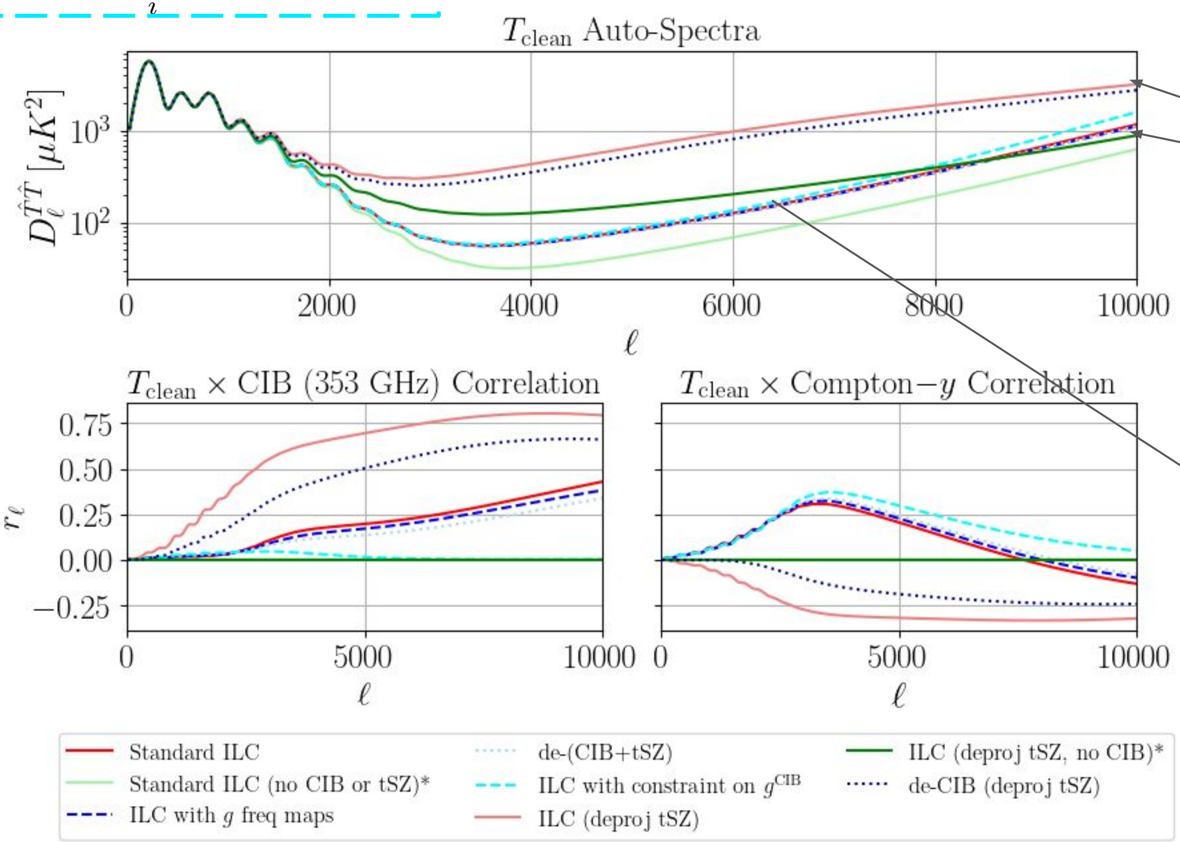
- This is a **spatial** deprojection instead of the usual **spectral** deprojection
- Can be applied to a (spectral) tSZ-deprojected ILC or can spatially deproject both tSZ and CIB, i.e., using

$$b^\ell_i \equiv \langle T^i_{\ell m} g^{\mathrm{tSZ}}_{\ell m}\rangle \text{ and } c^\ell_i \equiv \langle T^i_{\ell m} g^{\mathrm{CIB}}_{\ell m}\rangle$$

ILC with Zero-Tracer-Correlation Constraint: Results

$$\boxed{\langle T^{\rm ILC}_{\ell m} g_{\ell m}\rangle = 0 \iff \sum_i w^i_\ell \langle T^i_{\ell m} g_{\ell m}\rangle = 0}$$

(no tSZ-deprojection)



Compare with 2 constraints: ILC (deproj tSZ) and ILC (deproj tSZ, no CIB)

Spatial deprojection – noise behaves differently!

Summary

- Three new methods to remove CIB and tSZ contamination using LSS tracers to enhance kSZ+CMB
- Methods have various trade-offs depending on metrics one cares about
- Theoretical models provided for forecasting purposes but methods can be applied to data
- Results here are just for *unWISE*—can actually combine several tracers (DES, BOSS/eBOSS, 2MASS, or CMB/galaxy lensing)!
- Future surveys (LSST, DESI, Euclid) will have more galaxies and give even better results
- Future directions: test on sims and apply to data (ACT + *unWISE*)

arXiv:2303.08121

Backup Slides

Modeling: CIB

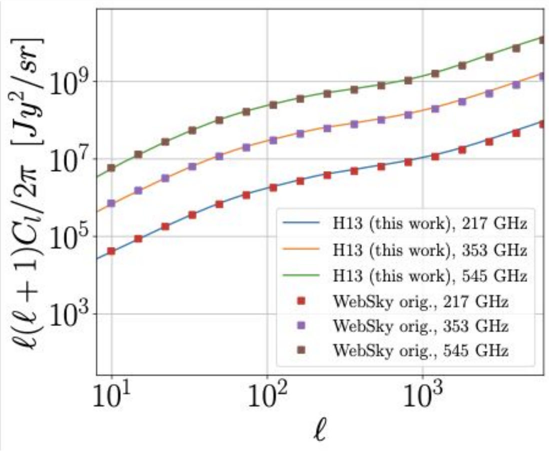
Two models based on the standard Shang et al. CIB model:

- Planck 2014 paper (P14)
- Herschel 2013 paper (H13); also in WebSky simulations

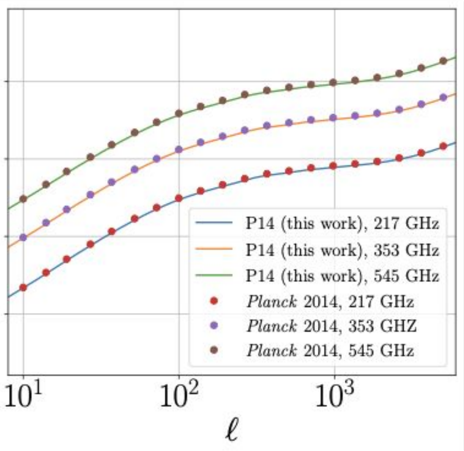
Parameter	Parameter description	Value
L_0	Normalization of L–M relation	7.0×10^{-8} Jy Mpc$^2/M_\odot$/Hz
$\alpha^{\rm CIB}$	Redshift evolution of dust temperature	0.36
T_0	Dust temperature at $z=0$	24.4 K
$\beta^{\rm CIB}$	Emissivity index of SED	1.75
$\gamma^{\rm CIB}$	Power law index of SED at high frequency	1.7
$\log_{10}(M_{\rm eff}^{\rm CIB}/M_\odot)$	Most efficient halo mass	12.6
$\log_{10}(M_{\rm min}^{\rm CIB}/M_\odot)$	Minimum halo mass to host a galaxy	10
σ^2_{L-M}	Distribution of of halo masses sourcing CIB emission	0.5
$\delta_{\rm CIB}$	Redshift evolution of L–M relation	3.6
z_p	Plateau redshift of L–M relation	10^{100}

Different values of the Shang et al. CIB parameters

H13



P14



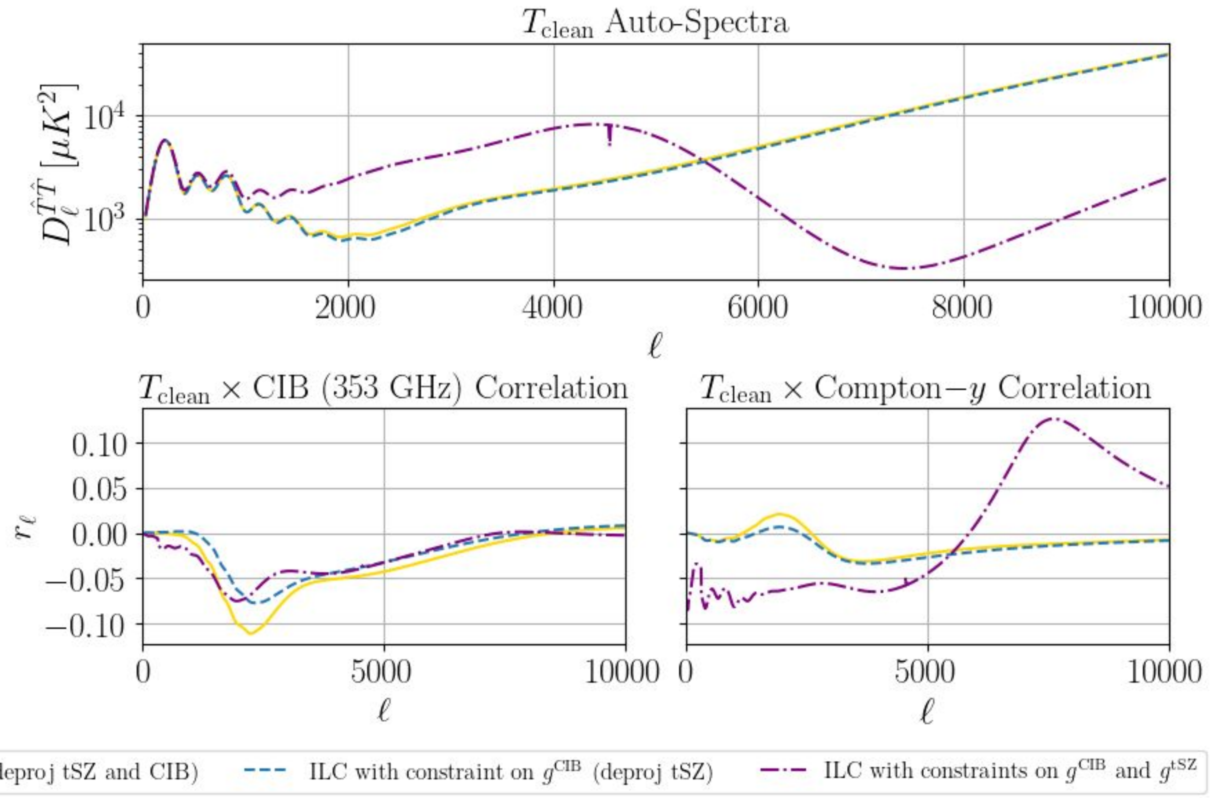
ILC w/ 2 Zero-Tracer-Corr Constraints (3 constraints): Results

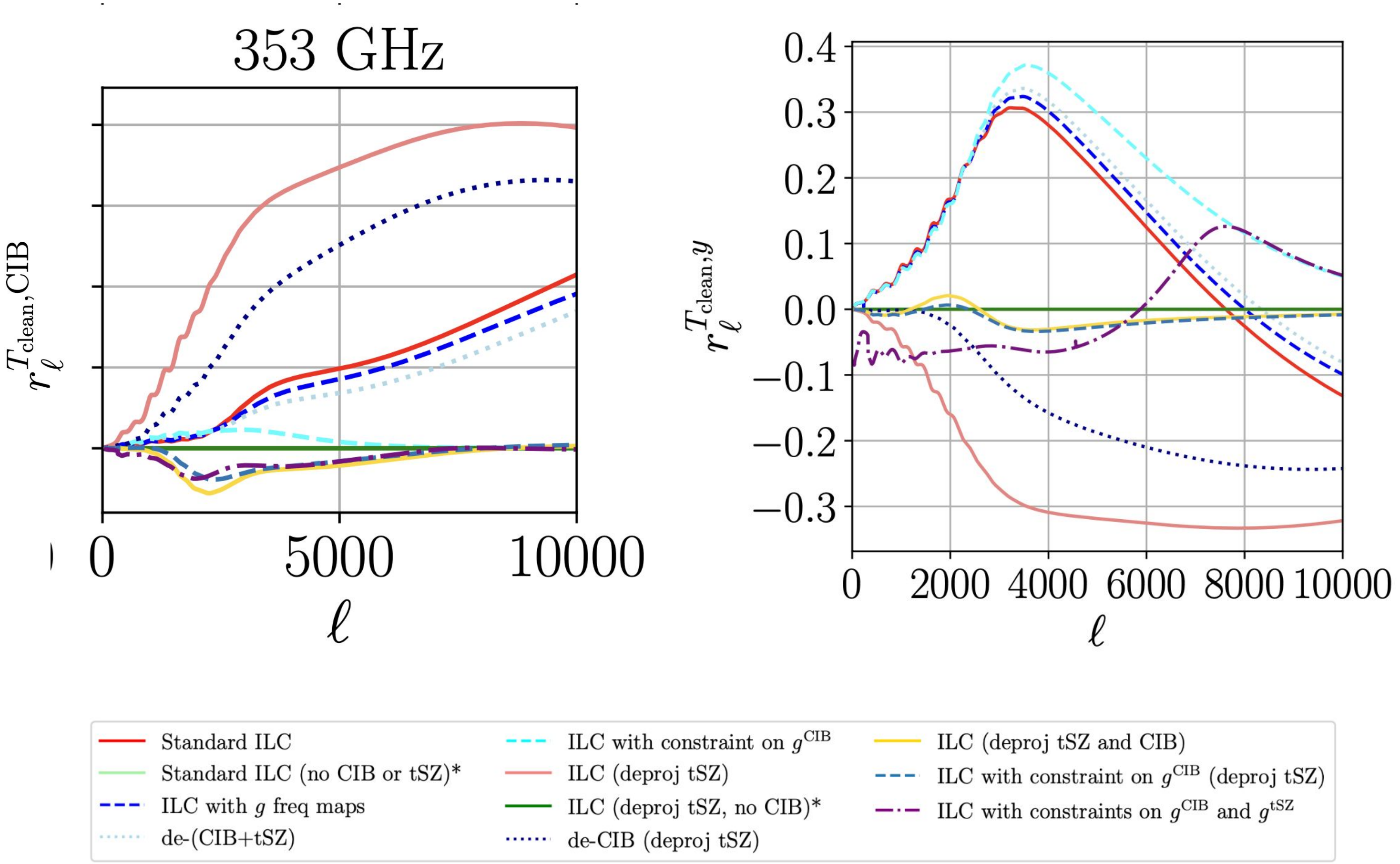
$$\langle T^{\mathrm{ILC}}_{\ell m} g_{\ell m}\rangle = 0 \Longleftrightarrow \sum_i w^i_\ell \langle T^i_{\ell m} g_{\ell m}\rangle = 0\,.$$

The shape of the new ILC (purple)

→CIB and tSZ highly correlated at small scales

→ spatially deprojecting two highly correlated tracers allows both to be deprojected for the price of one



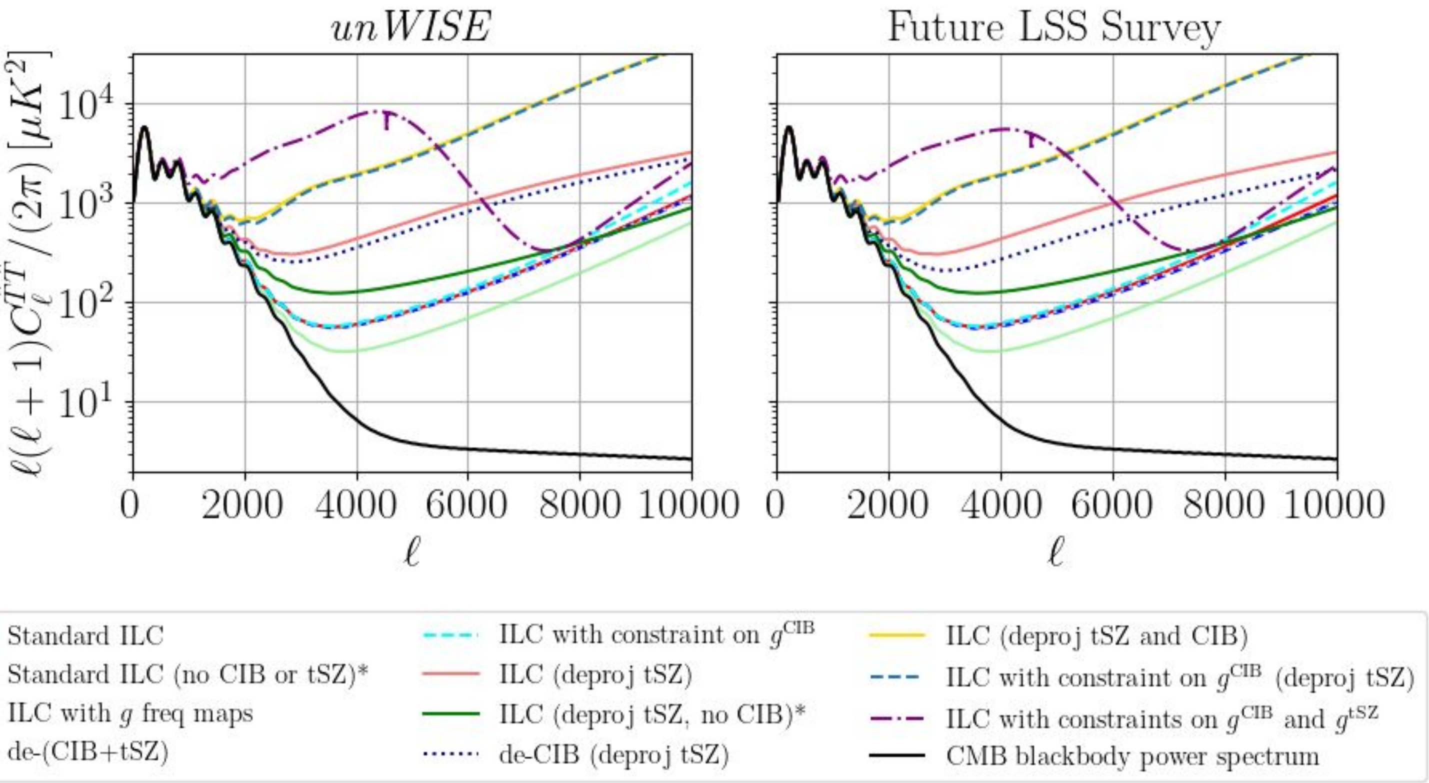


353 GHz
$r_\ell^{T_{\rm clean},{\rm CIB}}$
0
5000
10000
ℓ
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
$r_\ell^{T_{\rm clean},y}$
0
2000
4000
6000
8000
10000
ℓ
Standard ILC
Standard ILC (no CIB or tSZ)*
ILC with g freq maps
de-(CIB+tSZ)
ILC with constraint on $g^{\rm CIB}$
ILC (deproj tSZ)
ILC (deproj tSZ, no CIB)*
de-CIB (deproj tSZ)
ILC (deproj tSZ and CIB)
ILC with constraint on $g^{\rm CIB}$ (deproj tSZ)
ILC with constraints on $g^{\rm CIB}$ and $g^{\rm tSZ}$

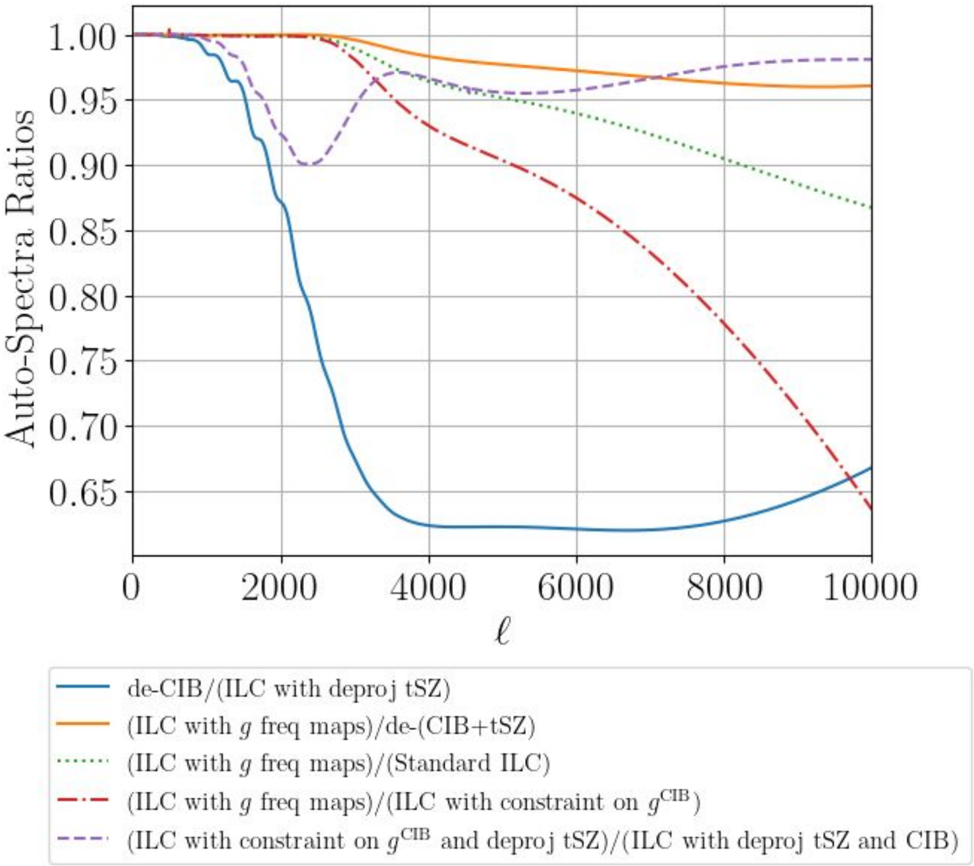
SNR

	H13 CIB Model (using *unWISE*)	P14 CIB Model (using *unWISE*)	H13 CIB Model (future LSS survey)	P14 CIB Model (future LSS survey)
Standard ILC	115.32	115.25	115.32	115.25
Standard ILC (no CIB or tSZ)*	202.74	202.74	202.74	202.74
ILC with g freq maps	116.80	116.75	120.04	118.37
de-(CIB+tSZ)	116.49	116.69	117.90	118.11
ILC with constraint on g^{CIB}	110.67	95.43	110.58	96.65
ILC (deproj tSZ)	19.43	25.17	19.43	25.17
ILC (deproj tSZ, no CIB)*	62.21	62.21	62.21	62.21
de-CIB (deproj tSZ)	23.22	25.52	29.25	25.93
ILC (deproj tSZ and CIB)	5.94	7.33	5.94	7.33
ILC with constraint on g^{CIB} (deproj tSZ)	6.36	8.47	6.34	8.43
ILC with constraints on g^{CIB} and g^{tSZ}	18.74	6.66	19.72	6.60

unWISE vs. Future LSS Surveys



Ratios



Auto-Spectra Ratios
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0
2000
4000
6000
8000
10000
ℓ
de-CIB/(ILC with deproj tSZ)
(ILC with g freq maps)/de-(CIB+tSZ)
(ILC with g freq maps)/(Standard ILC)
(ILC with g freq maps)/(ILC with constraint on g^{CIB})
(ILC with constraint on g^{CIB} and deproj tSZ)/(ILC with deproj tSZ and CIB)