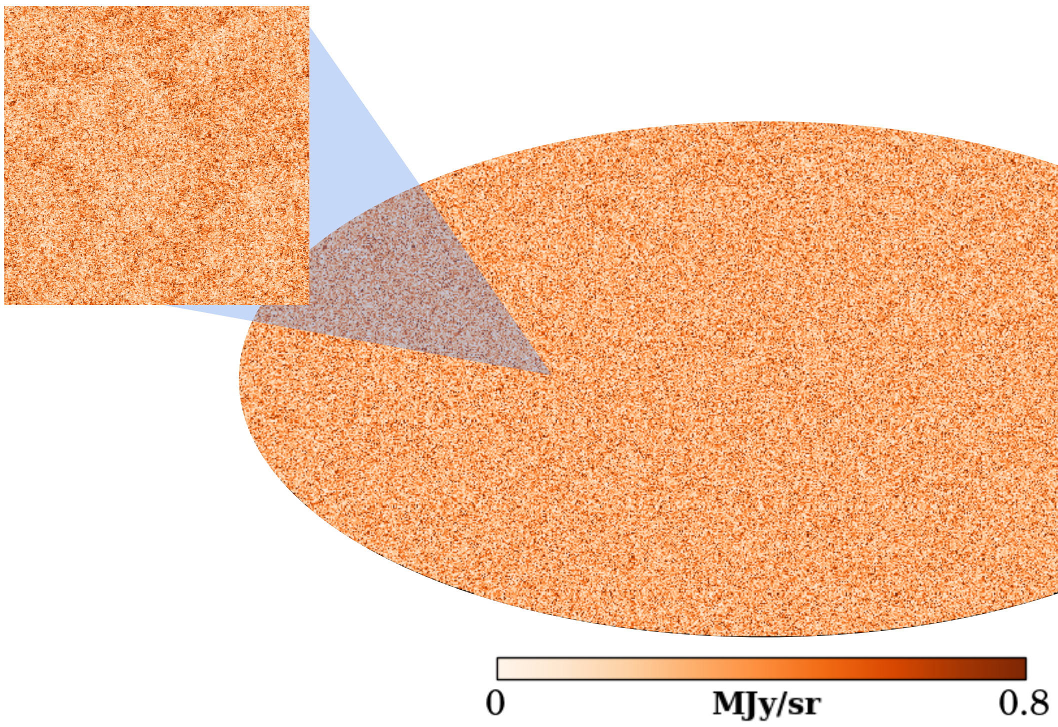
Exploring the Non-Gaussianity of the CIB & Its Gravitational Lensing

Open in Keynote for animations!



Jaemyoung (Jason) Lee

Cosmology from Home 2023

Collaborators: J. Richard Bond, Pavel Motloch, Alexander van Engelen, and George Stein

https://arxiv.org/abs/2304.07283

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- What is the CIB (Cosmic Infrared Background)?
- Websky Simulations

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- **Statistics of the Websky CIB maps**
- **Effect of lensing on CIB statistics**
- **Beyond n-point statistics**
- Correlation of the CIB with CMB lensing
- (Galaxy) environmental effects on CIB statistics

Results

- Conclusion & Why we care

Introduction

Cosmic Infrared Background (CIB)

- Emission of dust from star forming galaxies: traces galaxy formation, clustering, dark matter
- $z = 0$ to 4, Non-Gaussian (beyond power spectrum)

Cosmic Infrared Background (CIB)

- Emission of dust from star forming galaxies: traces galaxy formation, clustering, dark matter
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- CIB 2-point and 3-point measured by *Planck*, SPT (South Pole Telescope), and ACT (Atacama Cosmology Telescope) at 150 GHz ~ 850 GHz
- CMB foreground

Websky Peak Patch Simulations

- Based on Peak Patch and 2LPT
- Flux of each galaxy calculated according to a CIB halo model - depends only on the mass and redshift of the (sub)halo
- Normalized so that CIB power spectrum at 545 GHz, $\ell = 500$ match *Planck*'s

Websky Peak Patch Simulations

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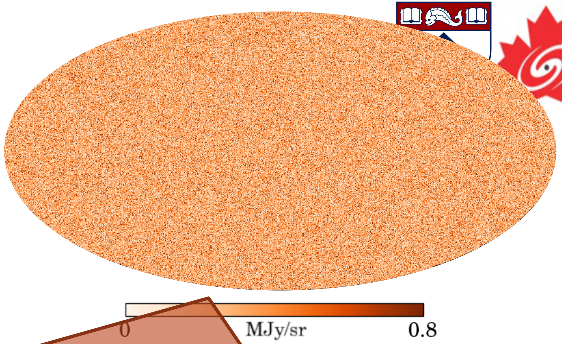
- Flux of each galaxy calculated according to a CIB halo model - depends only on the mass and redshift of the (sub)halo
- Normalized so that CIB power spectrum at 545 GHz, $\ell = 500$ match *Planck*'s
- Lensing convergence (κ) maps - integrated over the appropriately weighted density field along line of sight

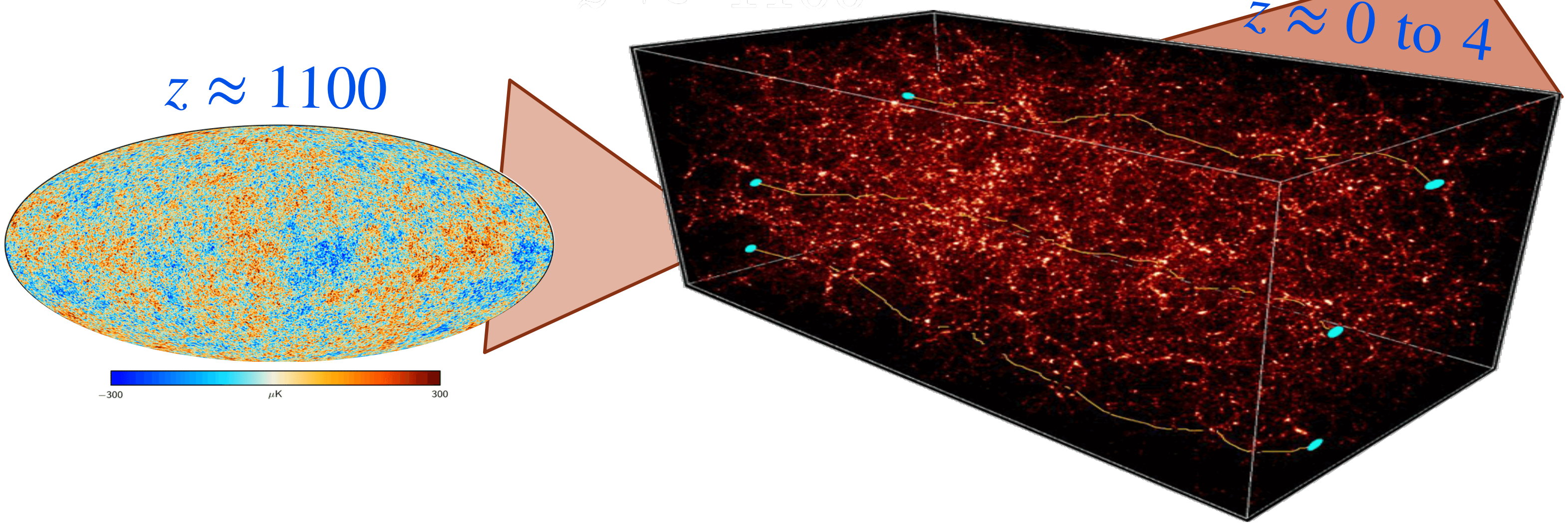
- Stein et al. (2020) - https://iopscience.iop.org/article/10.1088/1475-7516/2020/10/012/pdf , https://mocks.cita.utoronto.ca/index.php/WebSky_Extragalactic_CMB_Mocks for more info

Methodology

Lensing of the CIB

➢ Observed CIB distorted as photon paths are deflected by gravity





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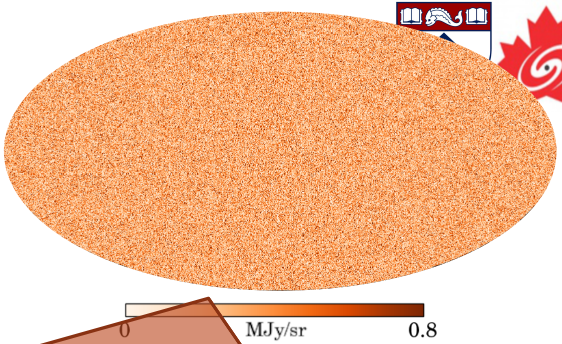

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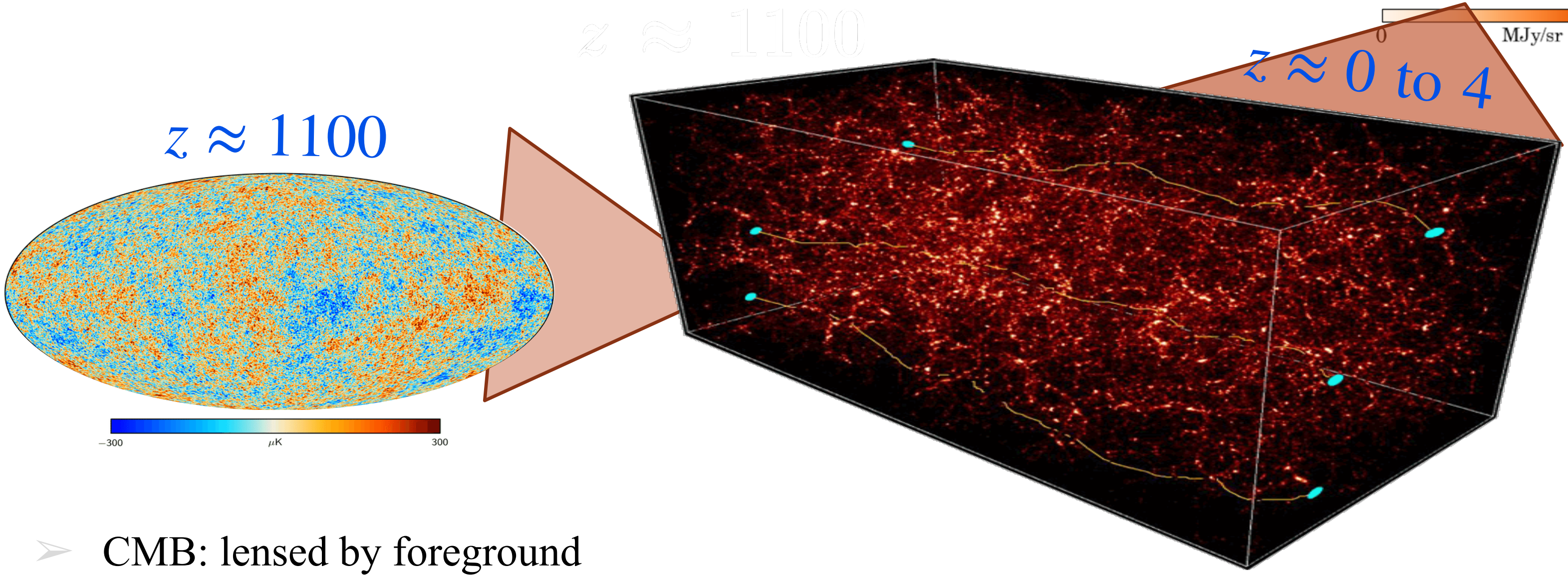
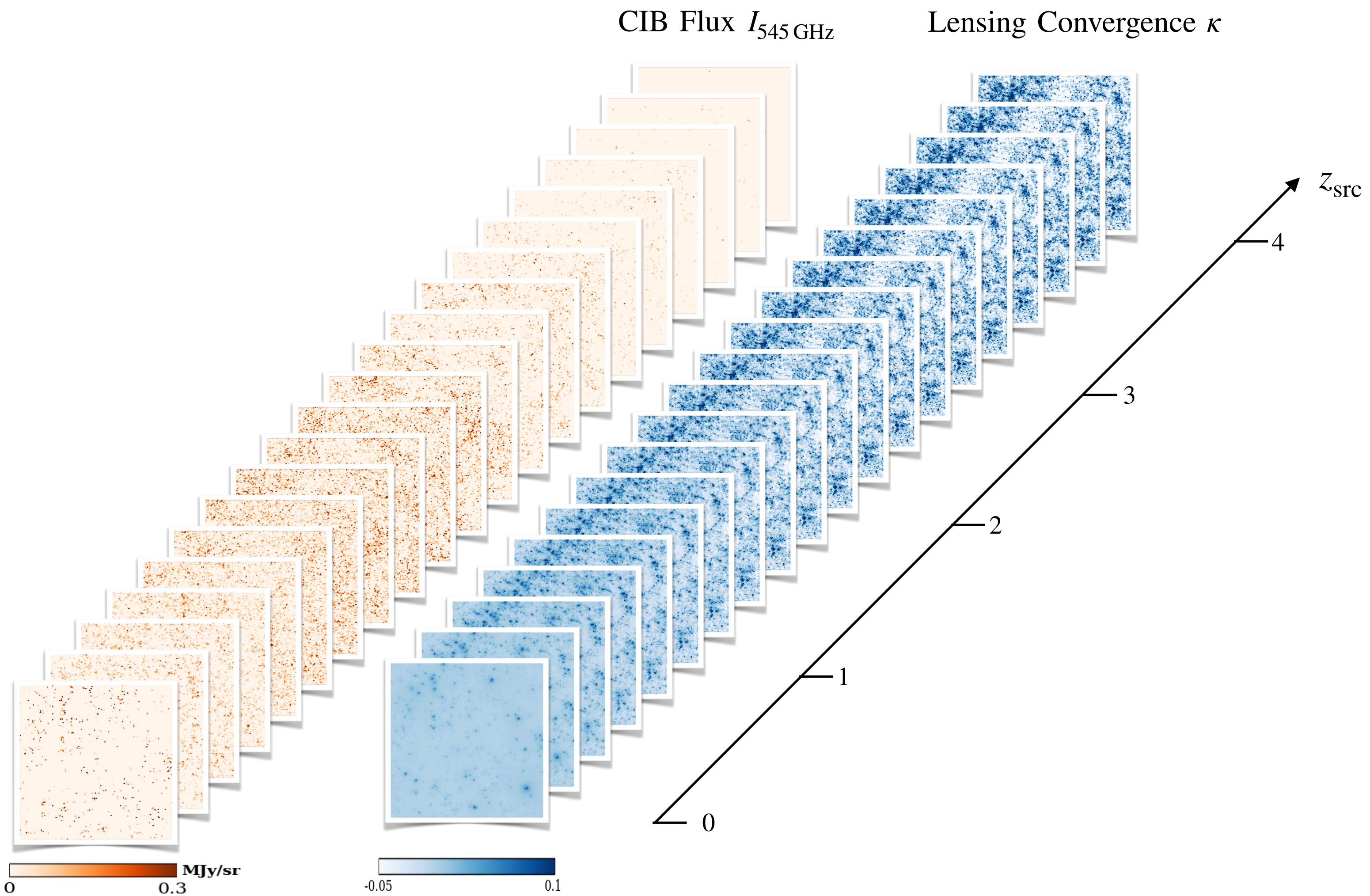
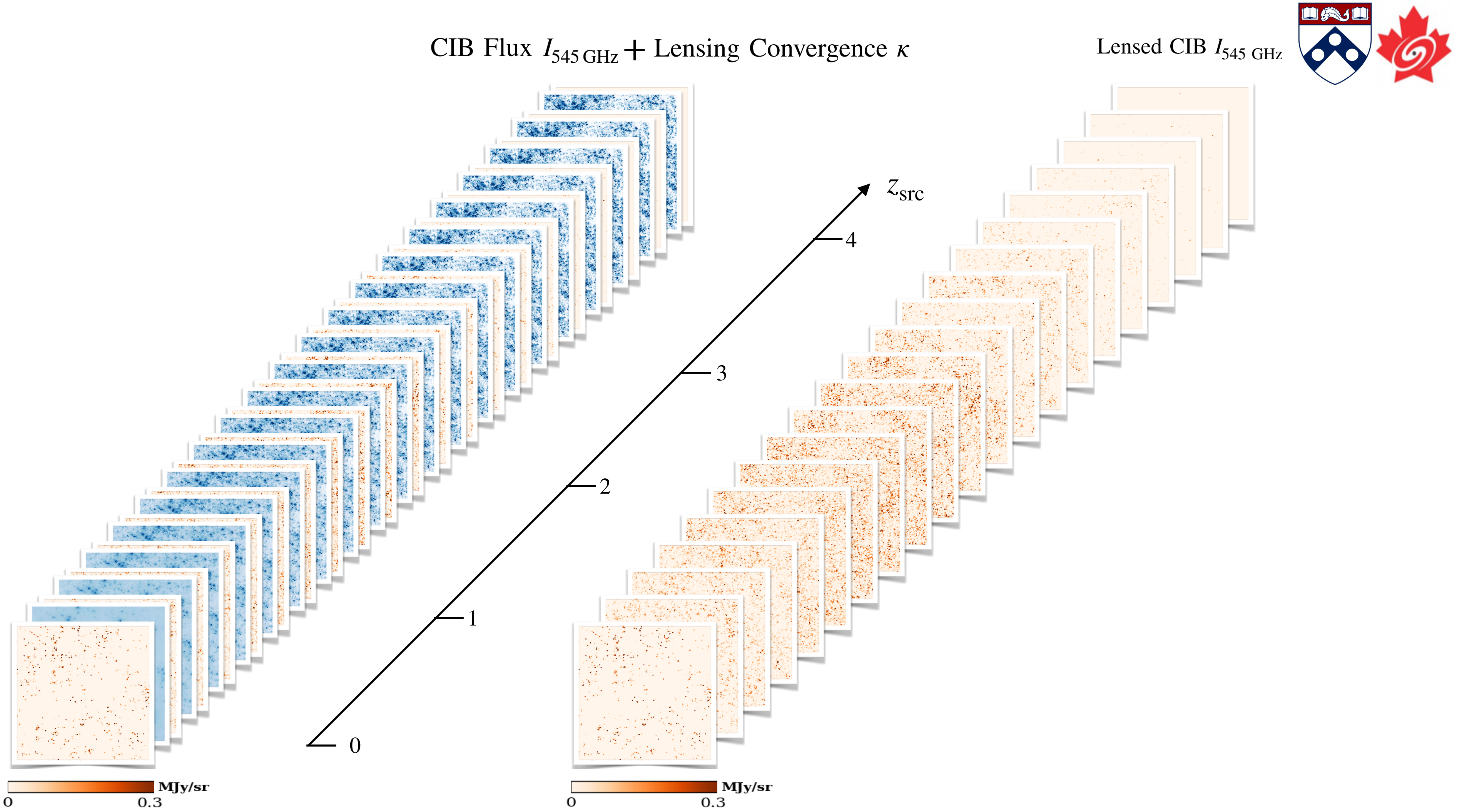


- CMB: lensed by foreground
- CIB: lensed by sources contributing to the CIB (self-lensing)
- Complicates CIB lensing analysis => motivation for simulation studies



CIB Flux $I_{545\,\mathrm{GHz}}$
Lensing Convergence κ
z_{src}
4
3
2
1
0
MJy/sr
0
0.3
-0.05
0.1



CIB Flux $I_{545\,\mathrm{GHz}}$ + Lensing Convergence κ
Lensed CIB $I_{545\,\mathrm{GHz}}$
z_{src}
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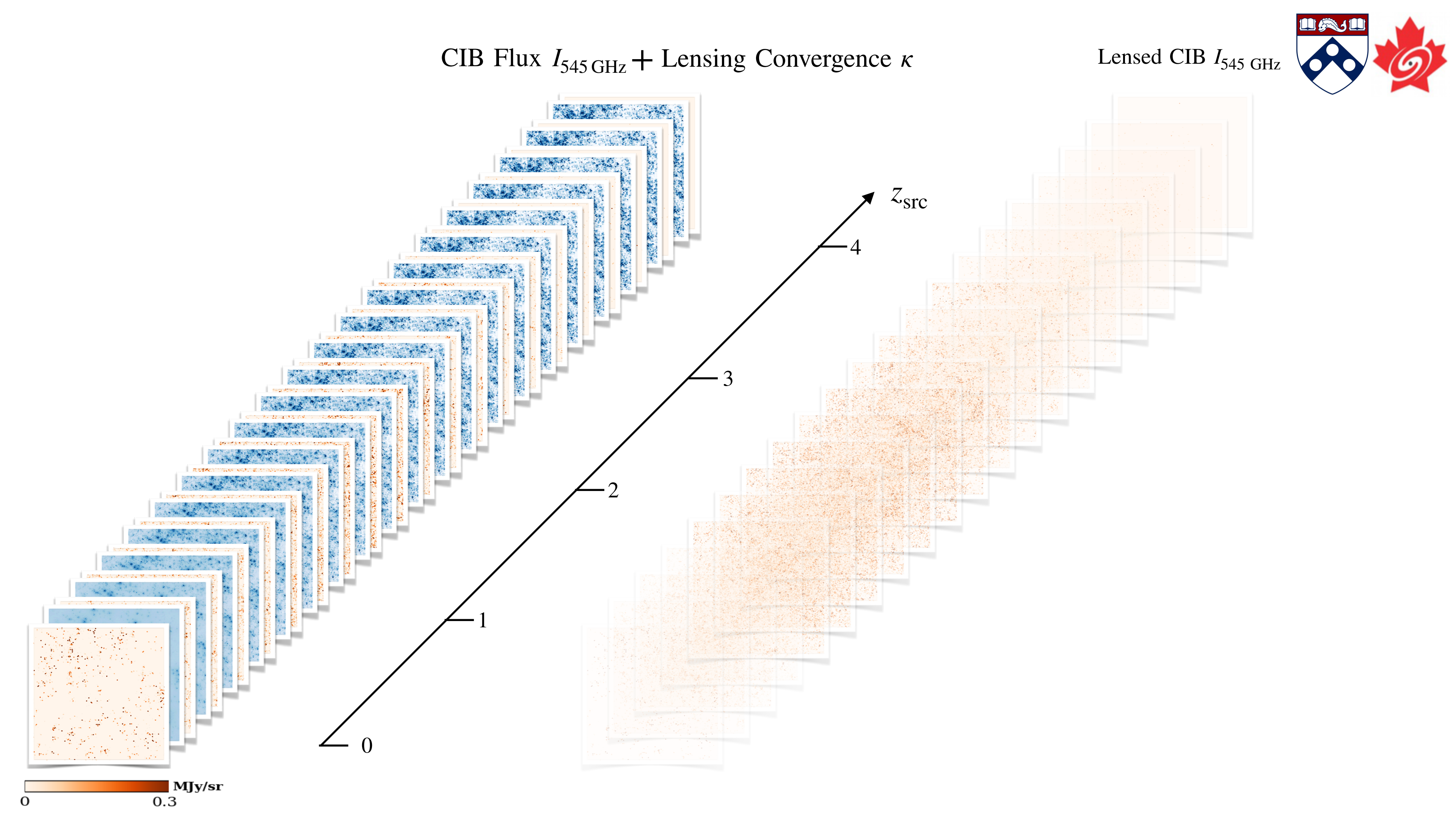
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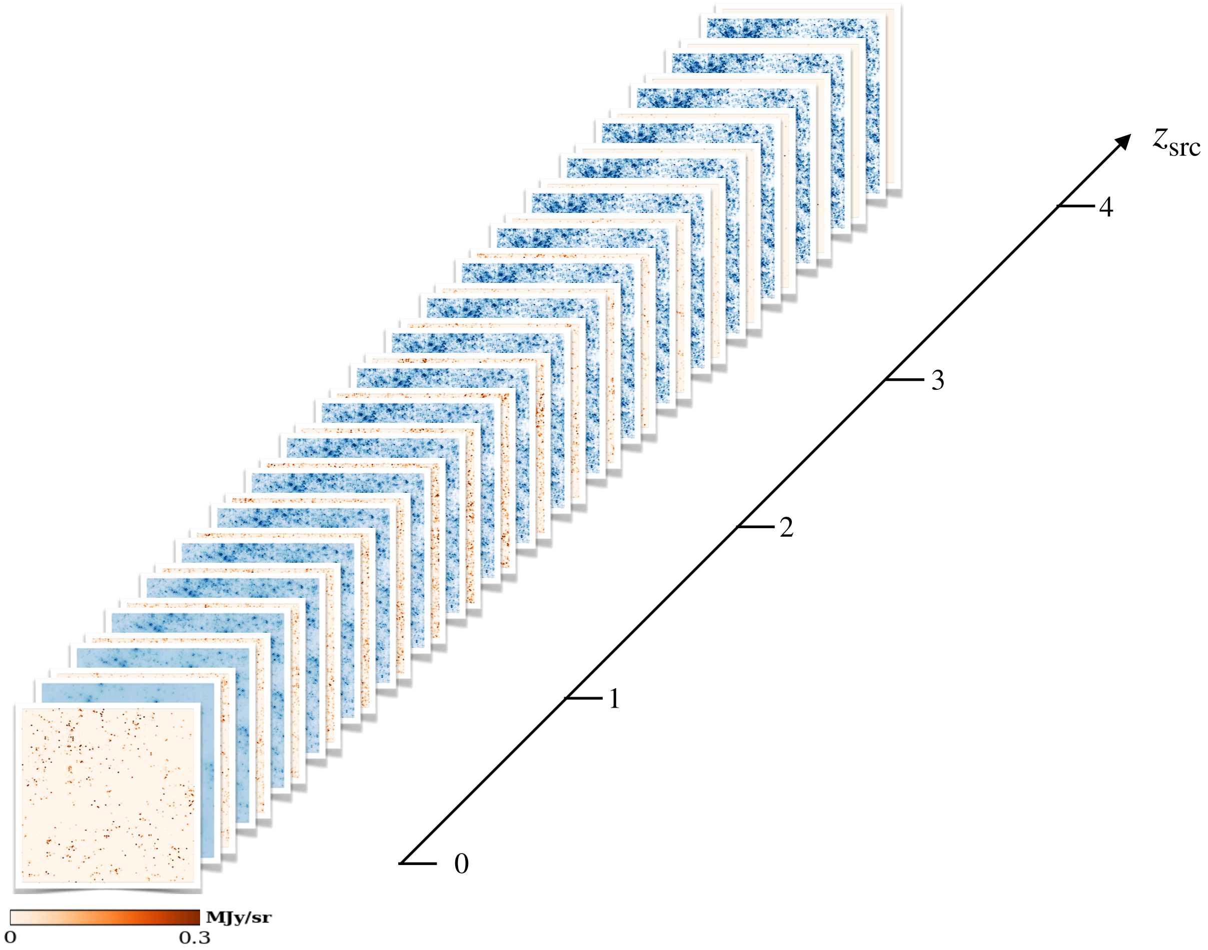
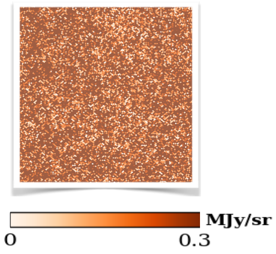
CIB Flux $I_{545\,\mathrm{GHz}}$ + Lensing Convergence κ



Total Lensed CIB $I_{545\ \mathrm{GHz}}$



How we lens the CIB: Deflection-magnification method

- Smooth κ maps with a beam of $\left(\sqrt{3}N_{\mathrm{SIDE}}\right)^{-1}$ (pixel-size) to mitigate strong-lensing
- Galaxies deflected by an amount given by $\nabla \phi_{z_i}$ (Lewis 2005)

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- Galaxies then magnified by $\mu = \left[(1-\kappa)^2 - \gamma^2\right]^{-1}$ rather than $(1+2\kappa)$
  - 3% difference at $\kappa = 0.1$
  - 30% difference at $\kappa = 0.3$

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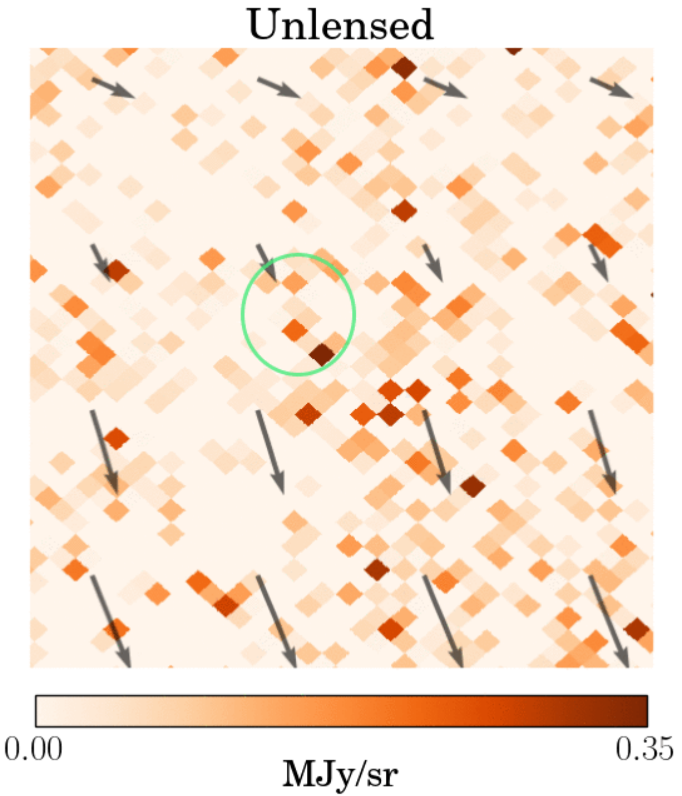
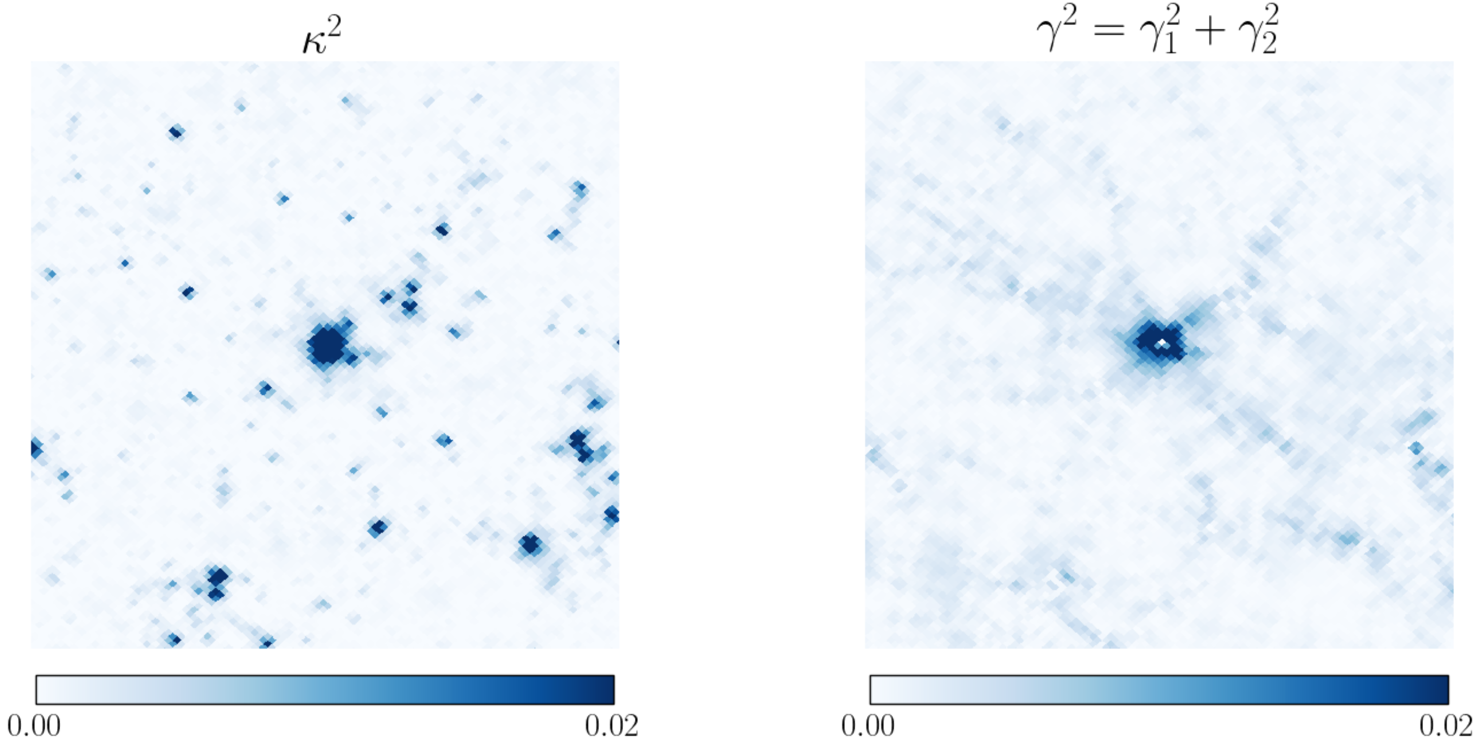


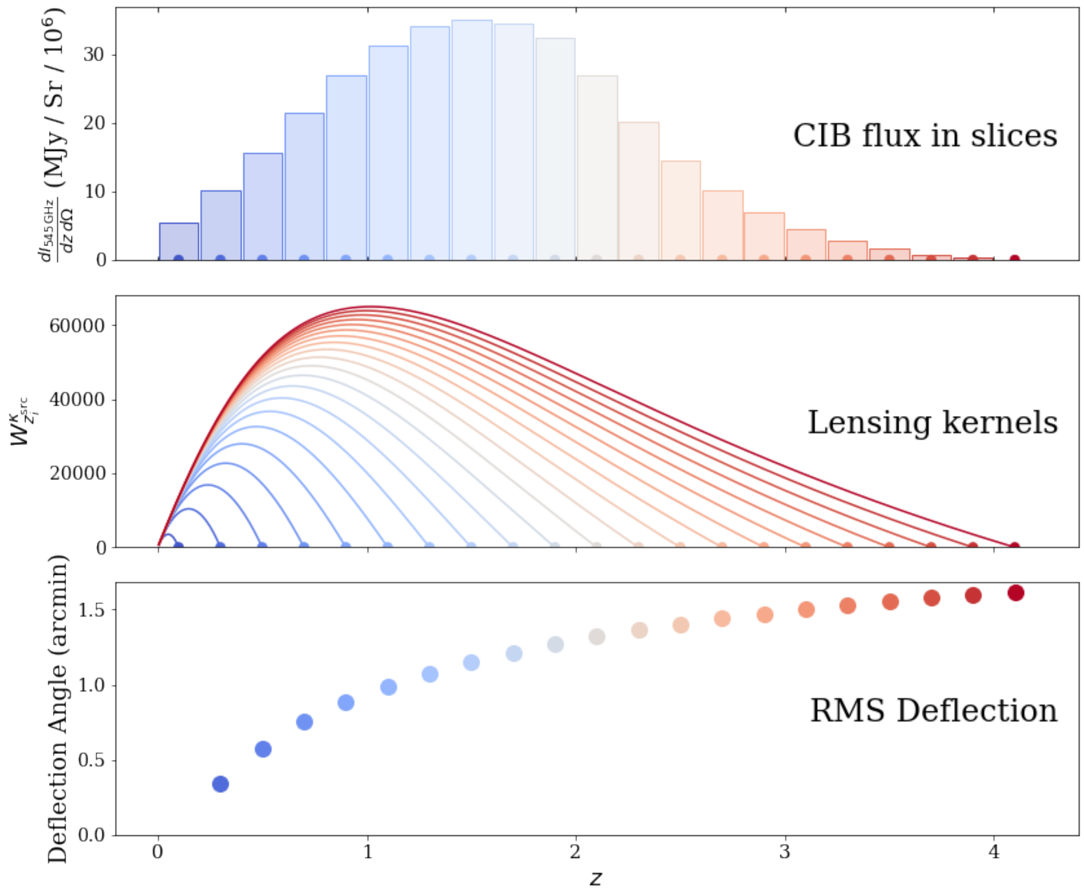
0.5° by 0.5° patch of CIB at 545 GHz

Lensing convergence and shear

$z = 1.0 \sim 1.2$



Websky CIB



CIB flux in slices
Lensing kernels
RMS Deflection
$\frac{dI_{545\,\mathrm{GHz}}}{dz\,d\Omega}$ (MJy / Sr / 10^6)
$W^{\kappa}_{z_i^{\mathrm{src}}}$
Deflection Angle (arcmin)
z

Filtered Statistics

- Variance: $S_2^{\ell_c} = < \left(\Delta T^{\ell_c}(x)\right)^2 >$
- Skewness: $S_3^{\ell_c} = < \left(\Delta T^{\ell_c}(x)\right)^3 >$
- Kurtosis: $S_4^{\ell_c} = < \left(\Delta T^{\ell_c}(x)\right)^4 > - \ 3\left(S_2^{\ell_c}\right)^2$
  - ℓ_c : ℓ – band center

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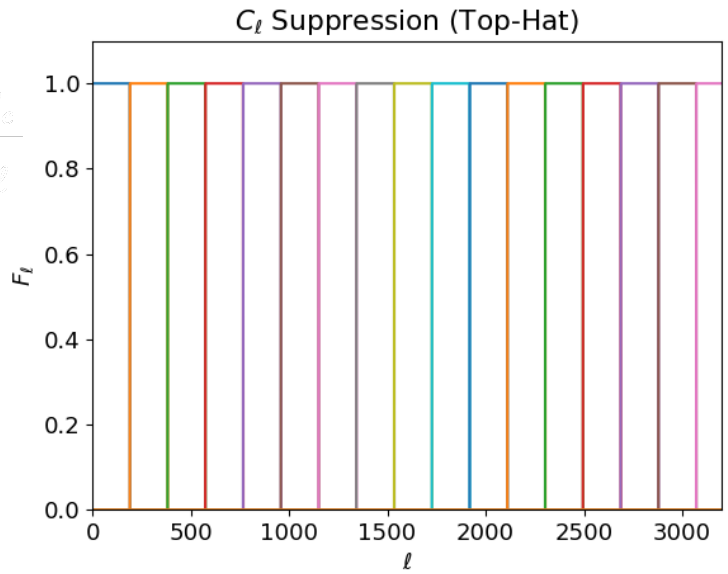

Filtered Statistics to poly-spectra

- (Roughly) equilateral configuration
  - $C_{\ell_c} \approx S_2^{\ell_c} \left(\sum_{\ell_c - \Delta\ell/2}^{\ell_c + \Delta\ell/2} \frac{2\ell + 1}{4\pi} \right)^{-1}, \quad \because S_2^{\ell_c} = \sum_{\ell_c - \Delta\ell/2}^{\ell_c + \Delta\ell/2} \frac{2\ell + 1}{4\pi} C_\ell$
  - $b_{\ell_c, \ell_c, \ell_c} \approx 2\sqrt{3}\pi^3 S_3^{\ell_c} (\Delta\ell)^{-3} \ell_c^{-1} \propto S_3^{\ell_c} \ell_c^{-1}$
  - $t_{\ell_c, \ell_c, \ell_c, \ell_c} \propto S_4^{\ell_c} \ell_c^{-2}$

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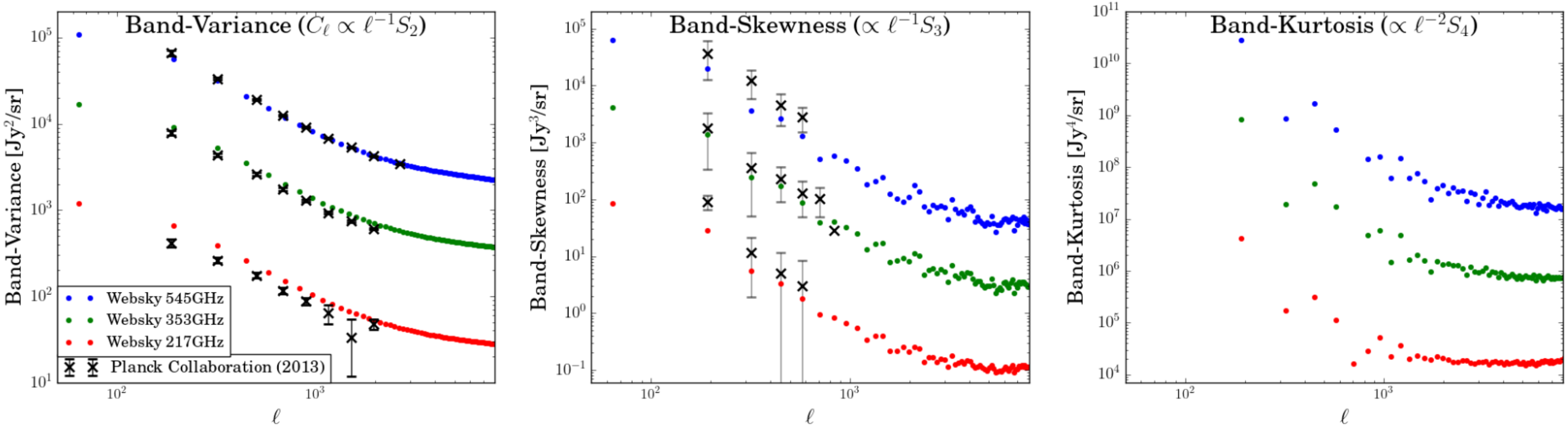
- Binning: $\Delta\ell = 640$ (default), $\Delta\ell = 128$ (vs. *Planck*)
- 8 minutes on Niagara cluster for $N_{\mathrm{SIDE}} = 4096$, default binning (about 20 bins)

Results

Websky CIB statistics (vs. *Planck*)



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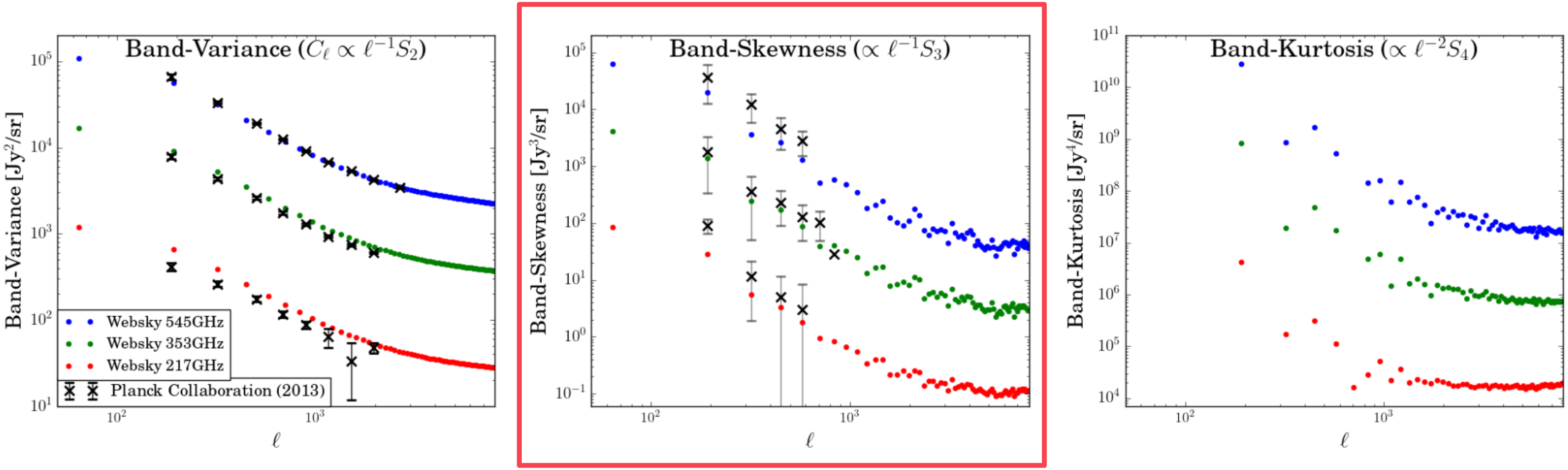
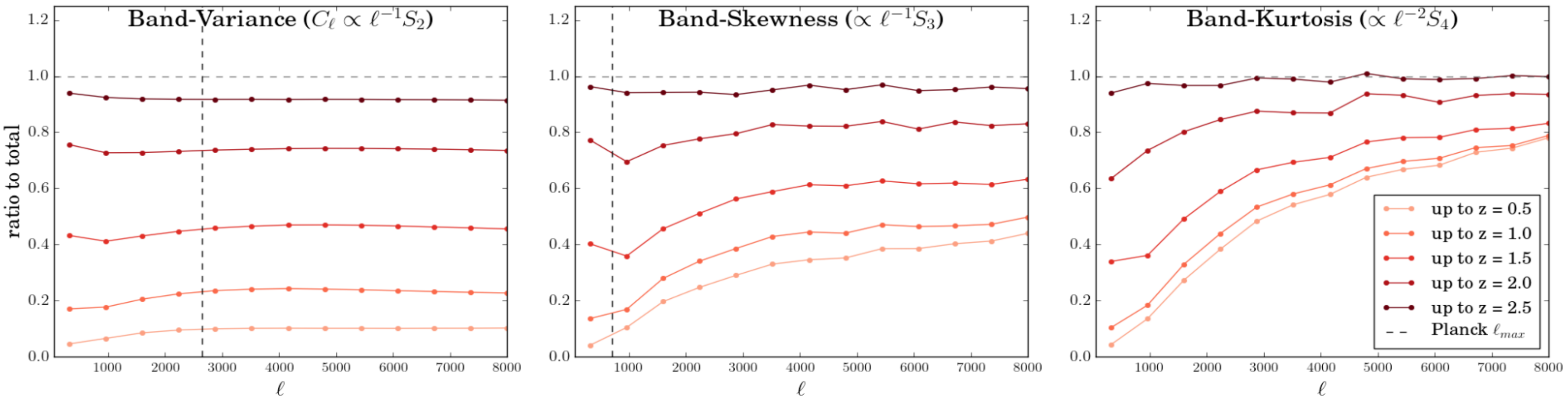


- ➢ To exclude very bright, nearby sources, flux cuts applied (same as *Planck* values)
- ➢ Websky CIB bispectra are generally within *Planck* error bars => nontrivial!!

Websky CIB statistics (redshift breakdown)



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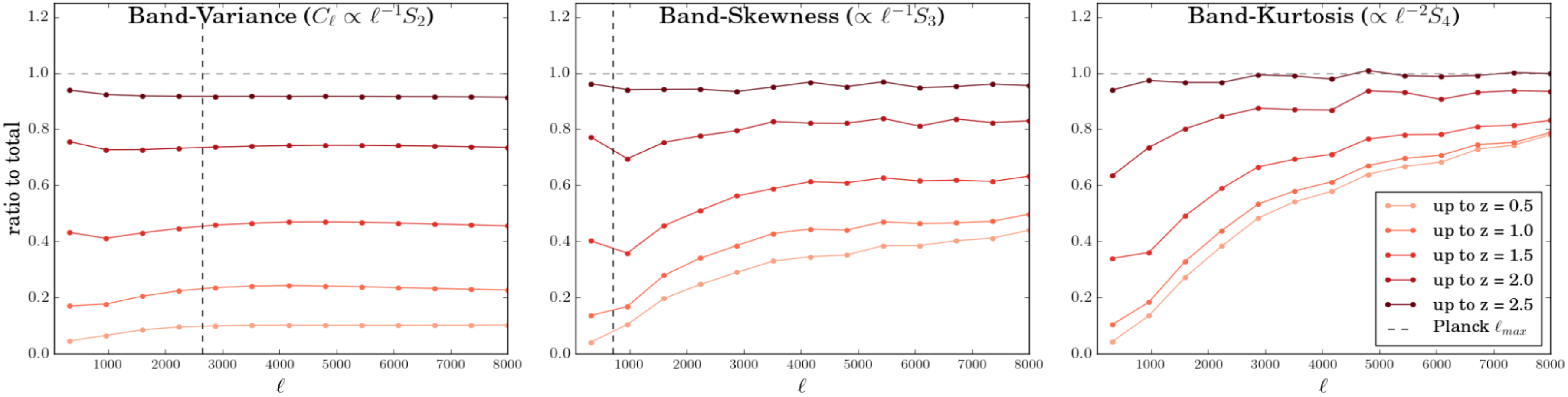
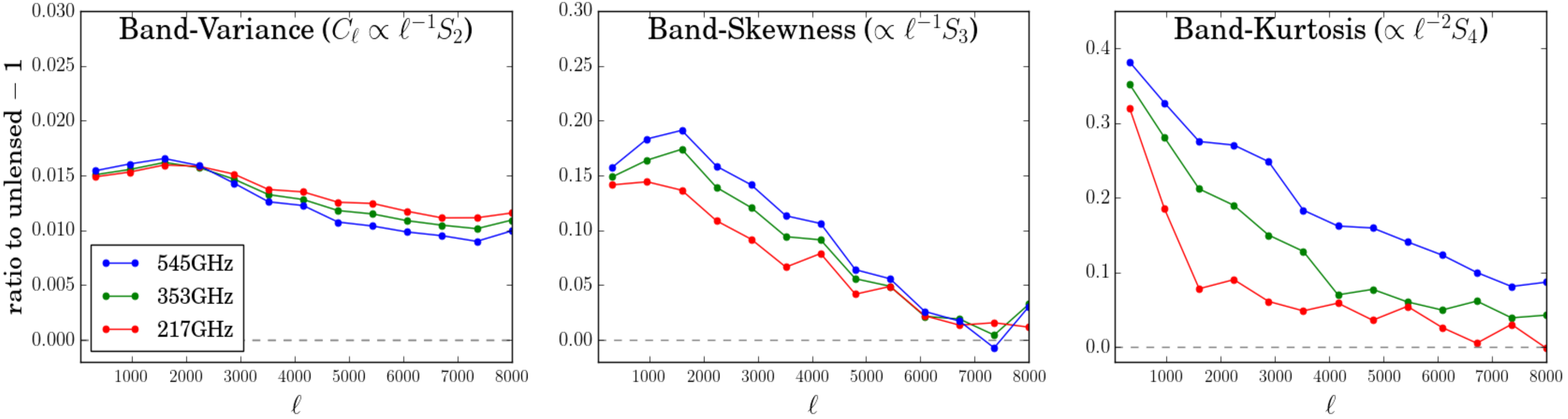


- ➢ Most of the CIB statistics come from $z < 2.5$
- ➢ For 3-point and 4-point, large contribution from low-z, especially at high-ℓ
- ➢ Bright, nearby sources (flux cuts) important for the change in 3-point and 4-point due to lensing

Effect of lensing on CIB statistics



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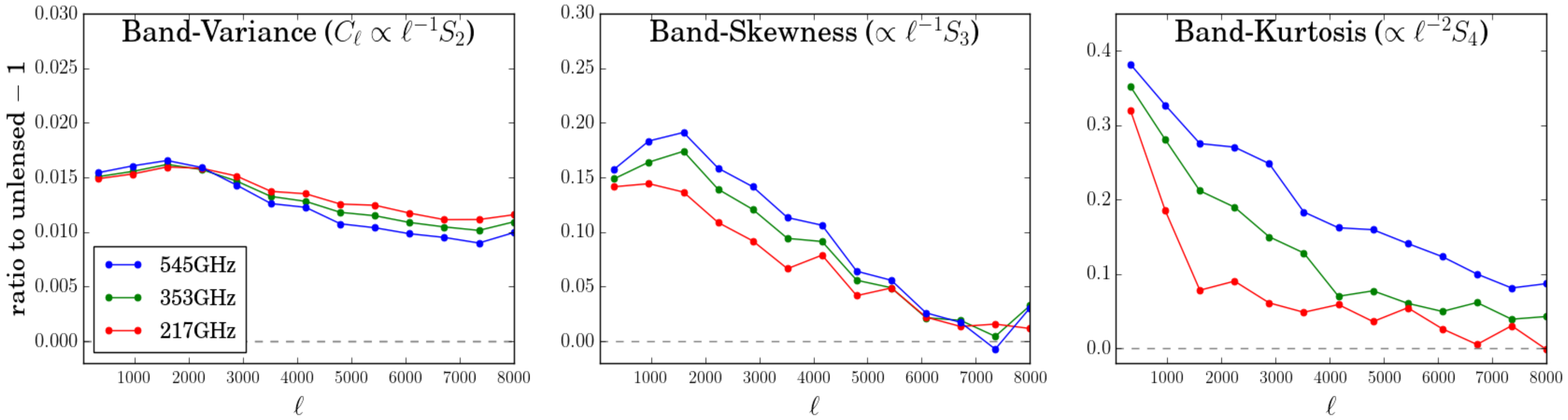
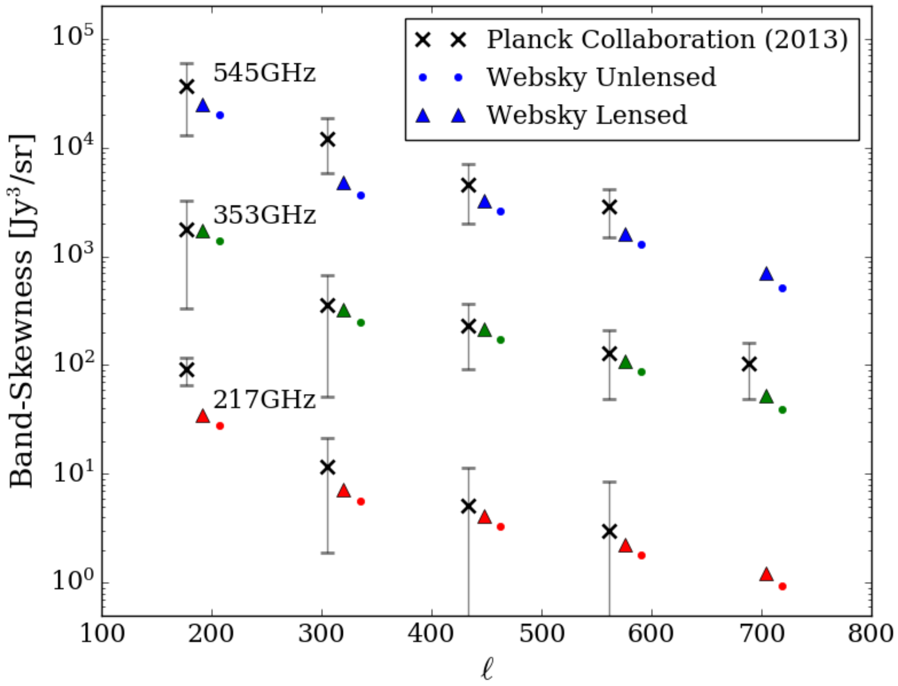


- ➢ Small power spectrum increase (~1.5%) as expected by Schaan et al. (2018), while 3-point and 4-point increases substantially at large scales
- ➢ More frequency dependence for the 3-point and 4-point (due to flux cut choices)

Effect of lensing on CIB statistics (3-point revisited)



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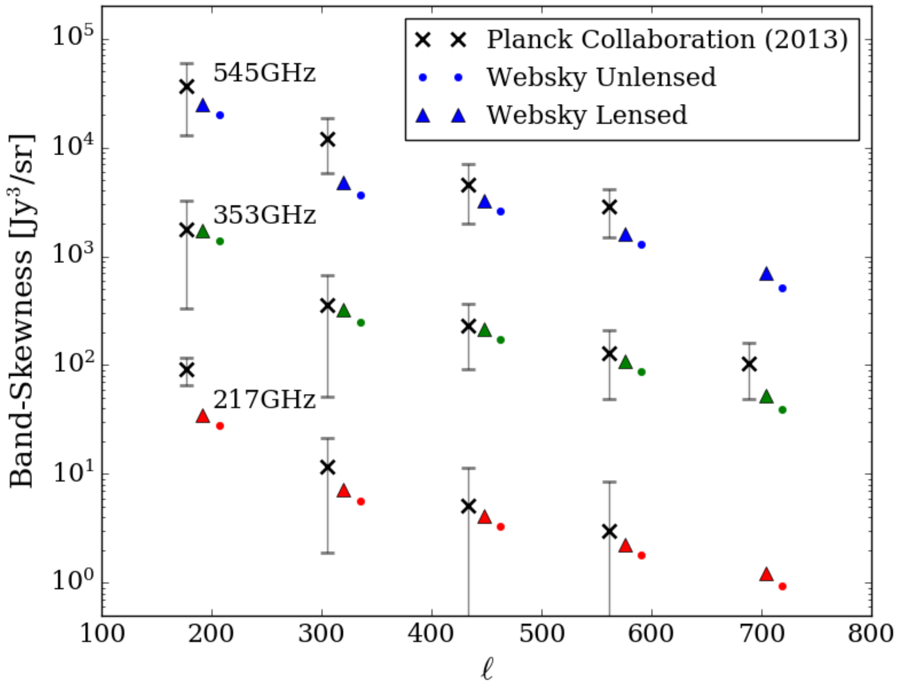
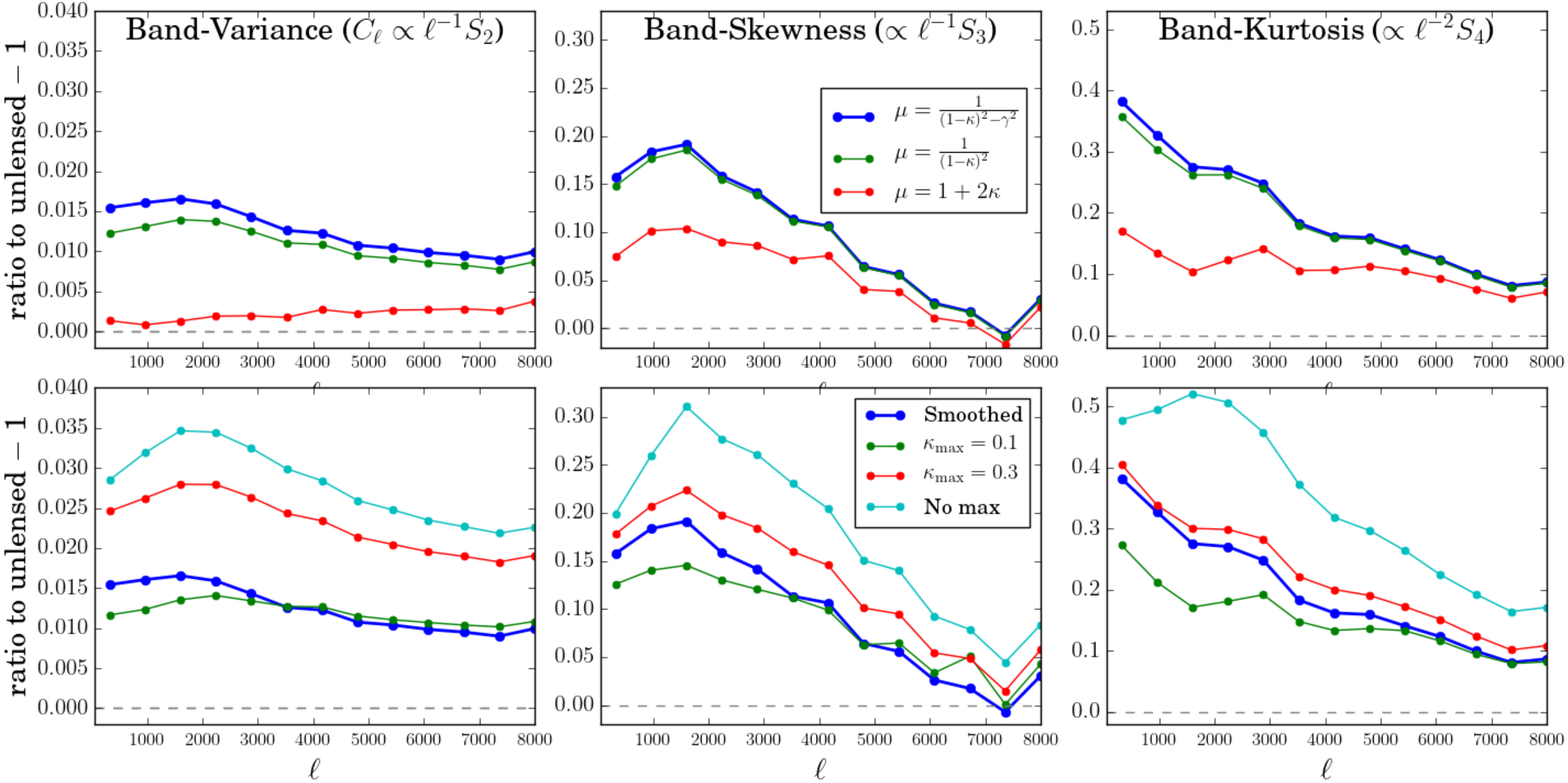


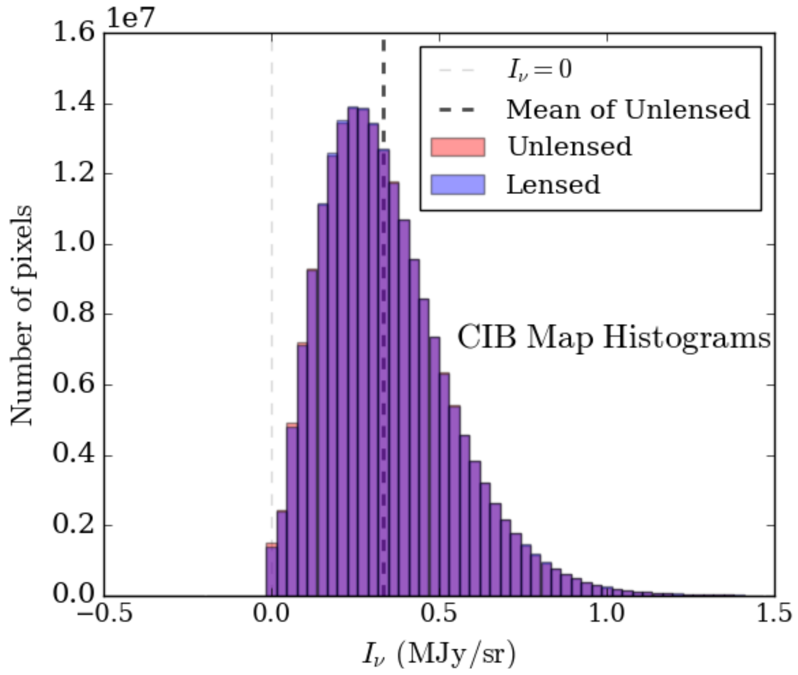
- Websky lensed values closer to *Planck* values
    - Lensing could be partially explain why unlensed Websky bispectra values are lower than *Planck's*

Effect of lensing on CIB statistics (different methods)



Beyond n-point statistics

Beyond n-point statistics (Histograms!)



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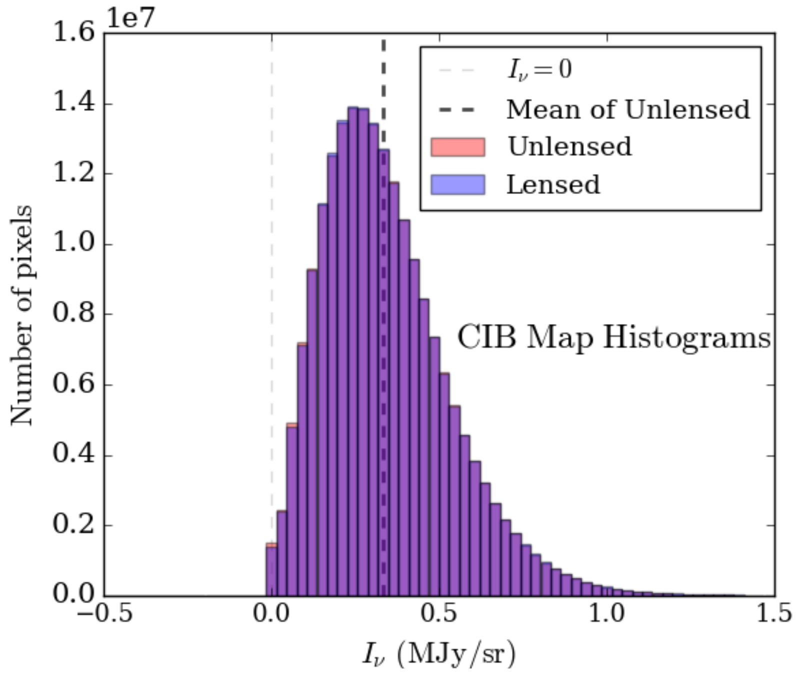
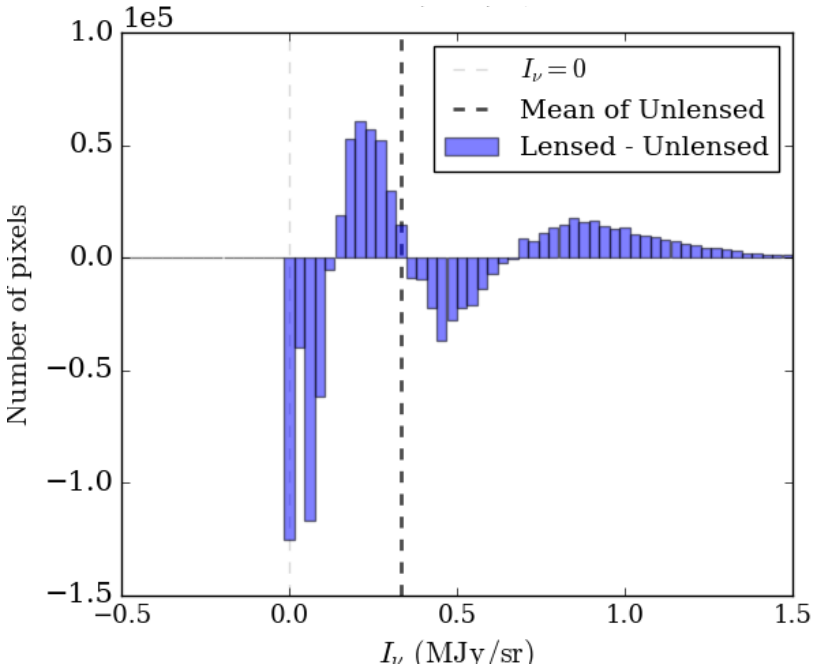
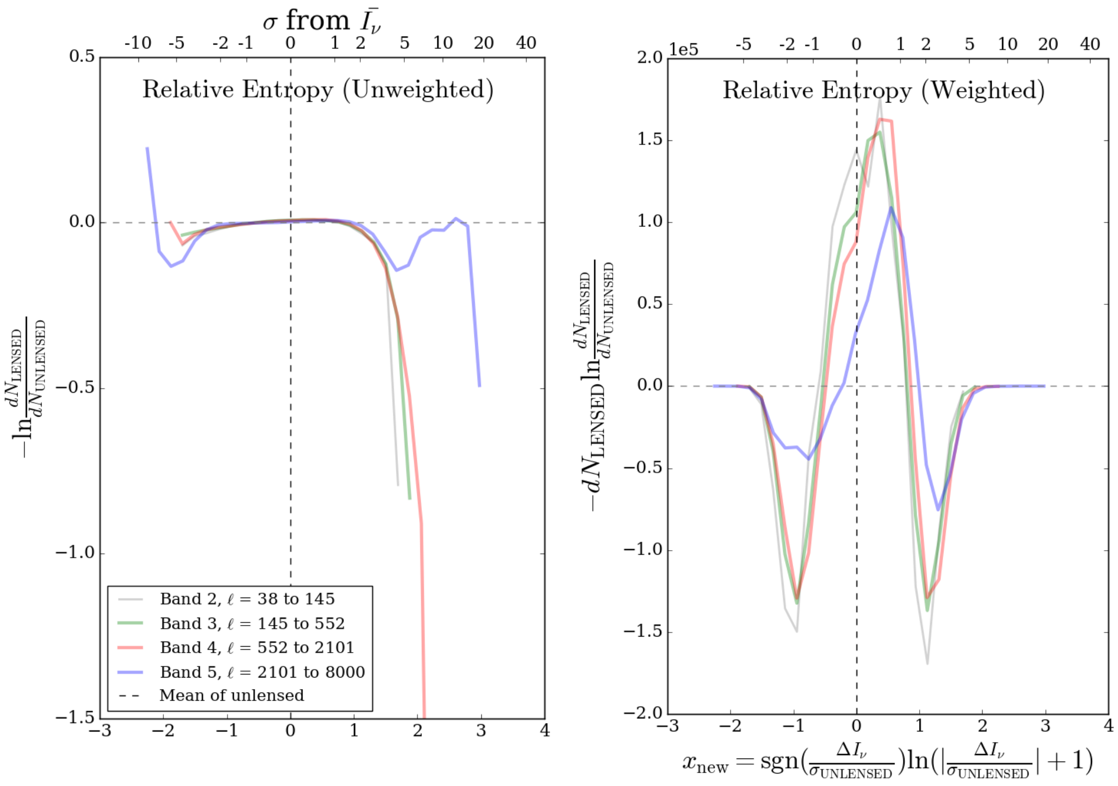




Beyond n-point statistics (Relative Entropy)

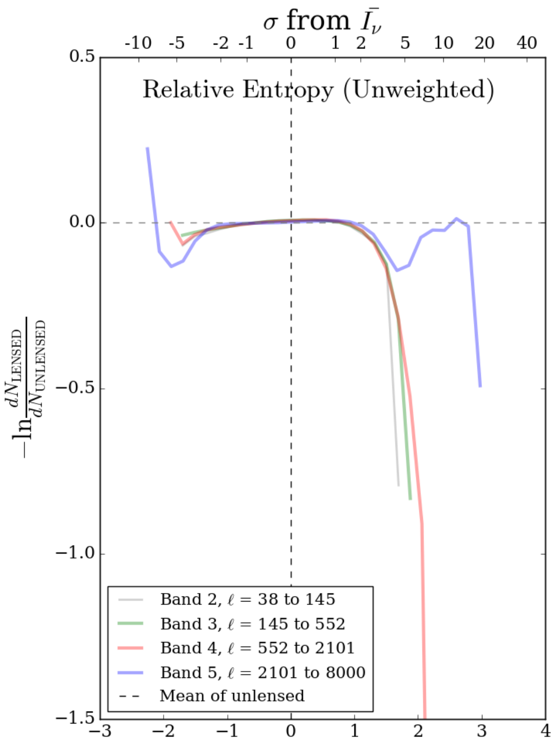
- Motivated from KL-divergence - $\sum P \ln \frac{P}{Q}$ $(P, Q$: PDFs)

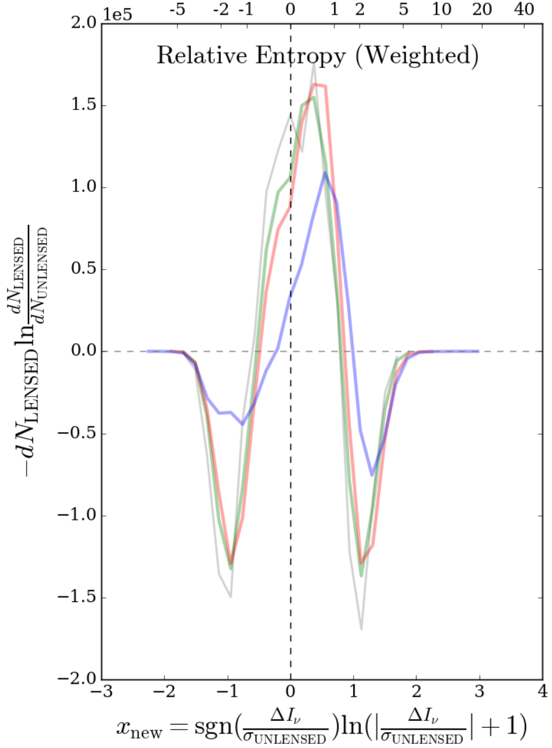
Beyond n-point statistics (Relative Entropy)



➢ $$\sum P \ln \frac{P}{Q}$$

Beyond n-point statistics (Relative Entropy)



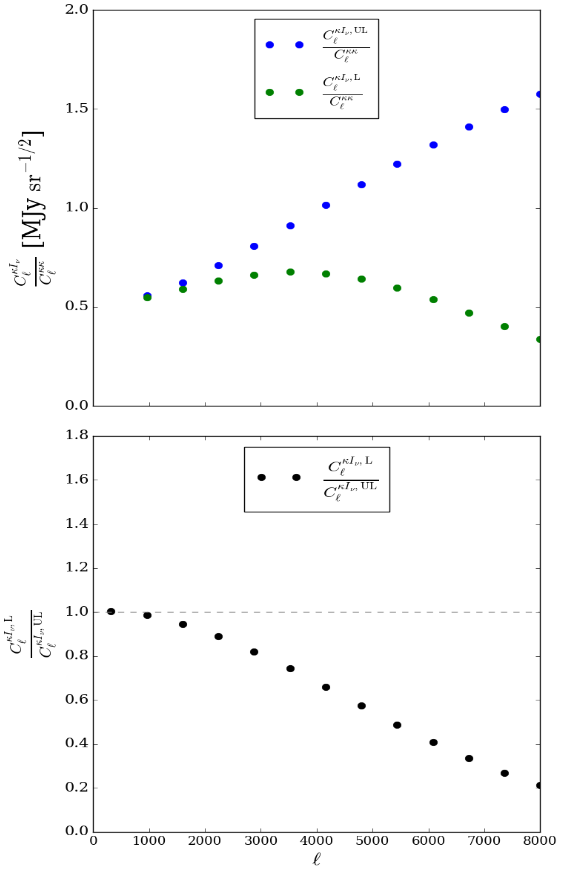


- $\sum P \ln \frac{P}{Q}$

$[\ln dN_{\mathrm{UNLENSED}} - \ln dN_{\mathrm{LENSED}}]_{\ell-\mathrm{band}}$
$= q_{\mathrm{lens,\ CIB}} \times [\mathrm{Template}_{\mathrm{UNWEIGHTED}}]_{\ell-\mathrm{band}}$

- Can plot a *spectra* of $q_{\mathrm{lens,\ CIB}}$ - tweak parameters and iterate until flat to constrain parameters

Correlation between CIB and CMB κ



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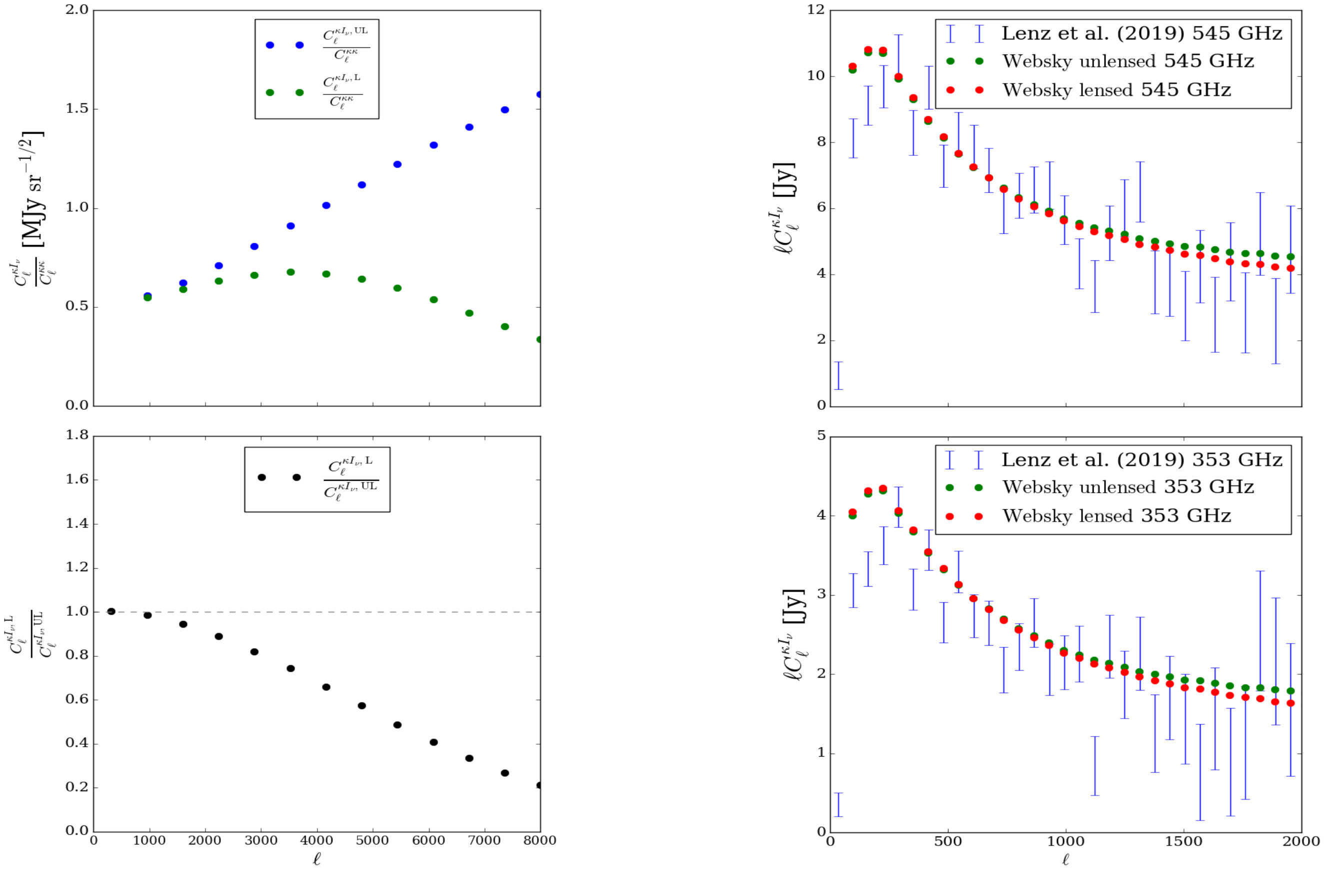

Environmental Effects on CIB statistics

- Galaxy luminosity only depends on mass in the halo model (approximation)
- To model environmental effects, multiplied flux of a galaxy by $\exp[\mathcal{N}(0,\sigma_{\ln L})]$
- Normalized map so that the power spectrum matches Websky at $\ell = 500$

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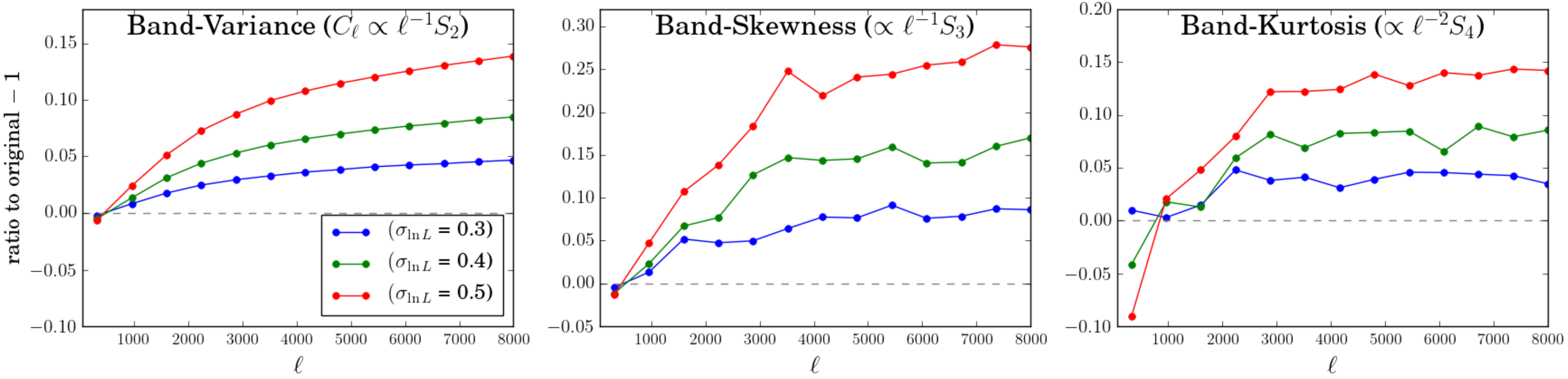

Conclusion & Why we care

- Websky CIB maps capture equilateral bispectra reasonably well
- CIB lensing increases power spectrum by ~1.5% and the 3-point and 4-point by 10~20% or more
- Relative entropy can be used to probe both intrinsic CIB parameters and lensing
- CIB lensing could potentially be detected through cross-correlation with CMB lensing
- Induced stochasticity can change CIB statistics

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- CIB non-Gaussianity provides extra information on top of power spectrum
- Lensing pipeline can be used for any 3-D intensity fields (21cm, Lyman-alpha, mm-wave intensity fields)
- CIB non-Gaussianity affects detection of primordial non-Gaussianity
- Change in CIB-non-Gaussianity due to lensing could be important for next-generation surveys

Thank you very much!

Questions/Comments?