Multi-Tracer CMB Delensing

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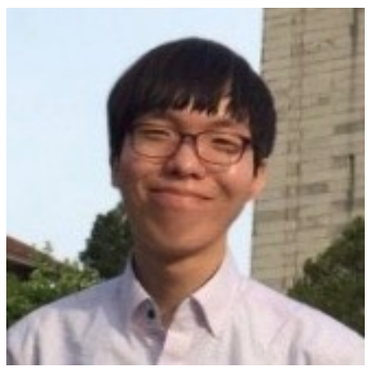
w/ B. Yu and B. Sherwin



UC-Berkeley: B-Mode from Space
6 December 2017

1705.02332
PRD in press

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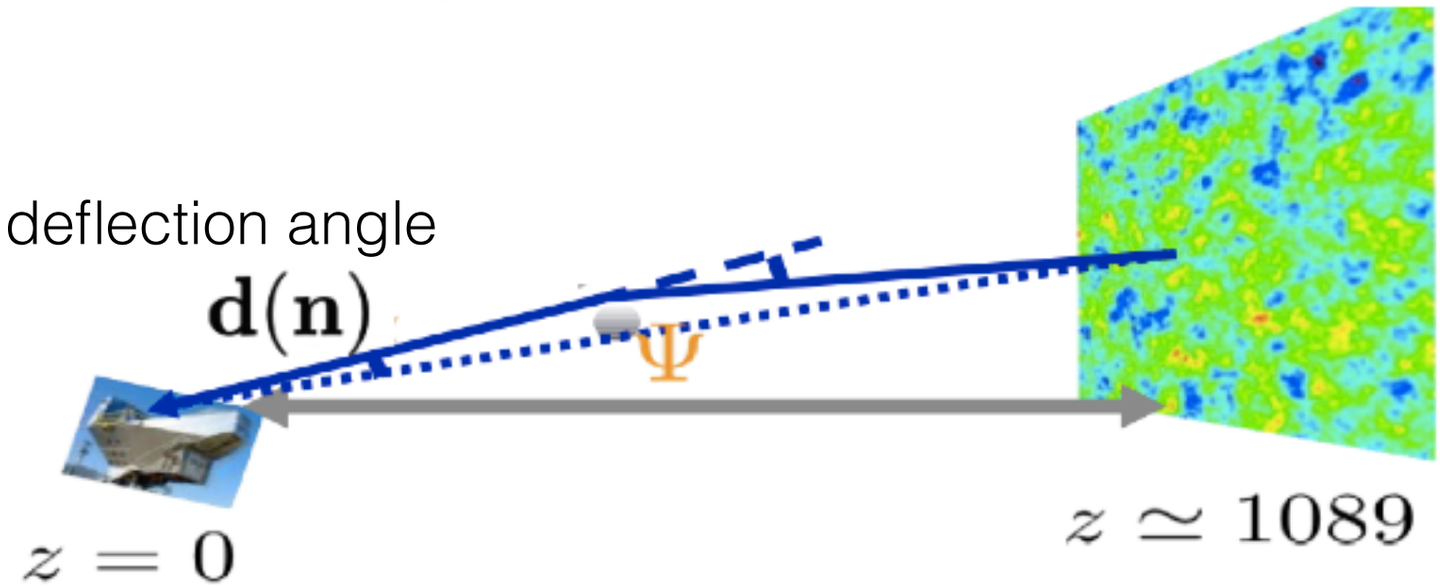
CMB Lensing

Re-mapping of CMB fluctuations (preserves blackbody form)

Many (~50) small random deflections lead to a net deflection (~2-3 arcmin), coherent on ~deg scales



$$T(\hat{\mathbf{n}})_{\rm lensed} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\rm unlensed}$$

Quadratic reconstruction:

$$\phi(\vec{\mathbf{L}}) \sim T(\vec{\ell})T(\vec{\mathbf{L}} - \vec{\ell})$$

lensing potential

$$\vec{\mathbf{d}} = \nabla\phi$$

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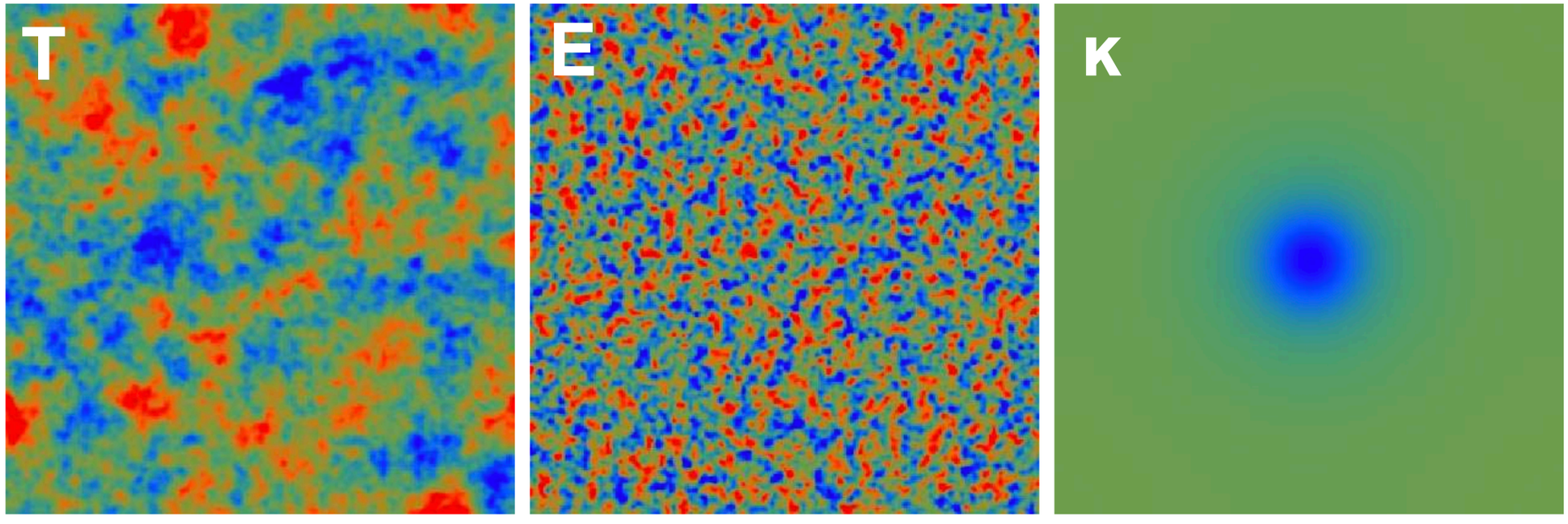
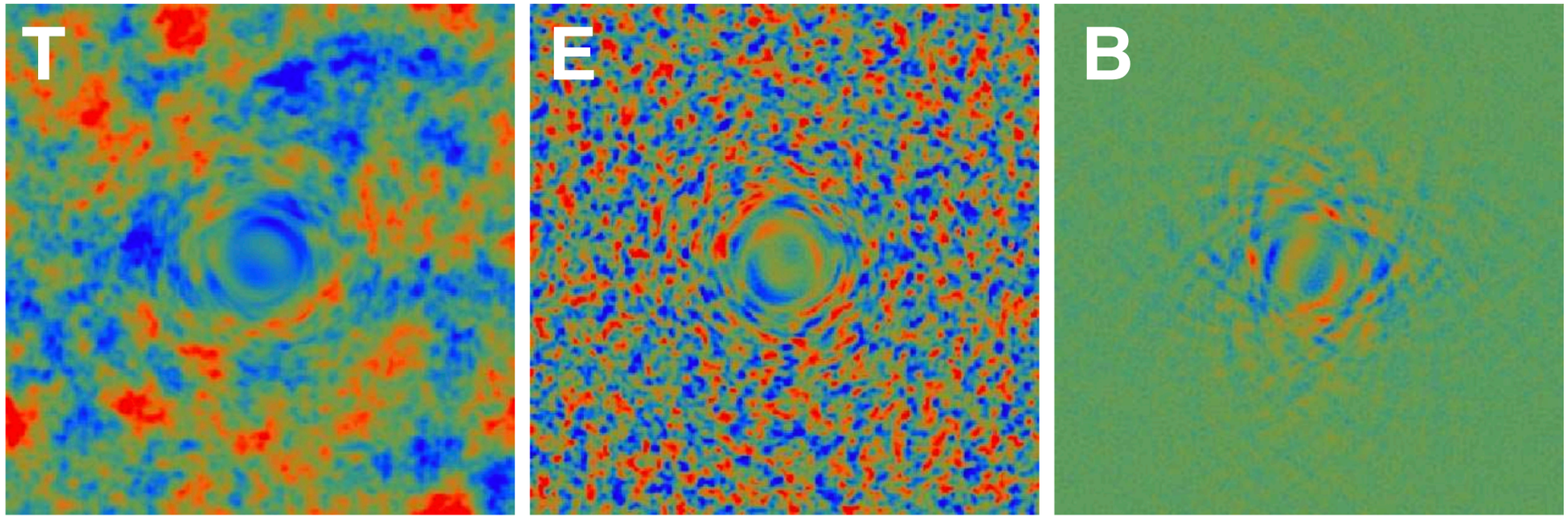
CMB Lensing

unlensed



lensed



$$B^{\rm lens}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}') E(\mathbf{l}') \kappa(\mathbf{l}-\mathbf{l}') \qquad W(\mathbf{l},\mathbf{l}') = \frac{2\mathbf{l}'\cdot(\mathbf{l}-\mathbf{l}')}{|\mathbf{l}-\mathbf{l}'|^2}\sin(2\varphi_{\mathbf{l},\mathbf{l}'})$$

Hu & Okamoto (2001)

Zaldarriaga & Seljak (1998)

CMB Lensing: *r* Foreground

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delensing = suppression of lensing B-mode sample variance by removing these modes from the map

$$\sigma(r) \sim C_l^{BB} + N_l^{BB}$$

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CMB Lensing: *r* Foreground

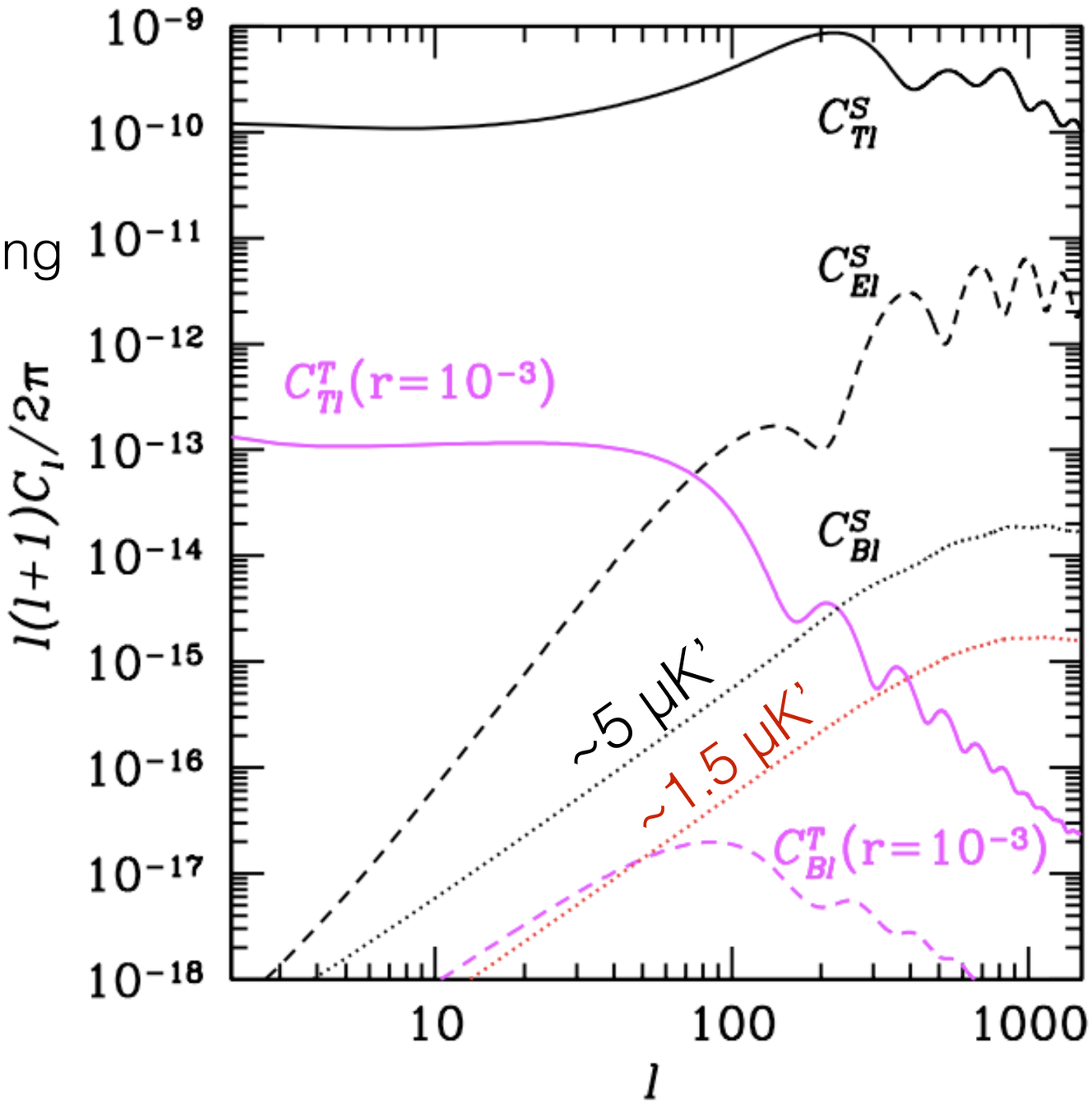
Knox & Song (2002)

$r_{\rm lim} = 6 \times 10^{-4}$

without delensing

$r_{\rm lim} = 6 \times 10^{-5}$

w/ ideal QE delensing



Lensing BB PS

post-delensing w/ ideal exp. (QE)

BB PS (r=10^{-3})

Zaldarriaga & Seljak (1998); Lewis+ (2001); Kesden+ (2002); Knox & Song (2002)

CMB Lensing: *r* Foreground

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delensing = suppression of lensing B-mode sample variance by removing these modes from the map

$$\sigma(r) \sim C_l^{BB} + N_l^{BB}$$

what data can be used to delens B-mode maps?

→ **any tracer of the CMB lensing potential**

$$\hat{B}^{\rm lens}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}') f(\mathbf{l},\mathbf{l}') E^N(\mathbf{l}') I(\mathbf{l}-\mathbf{l}')$$

kernel — optimal filter — obs. E mode — lensing tracer

crucial for low-resolution space missions

Cosmic Infrared Background

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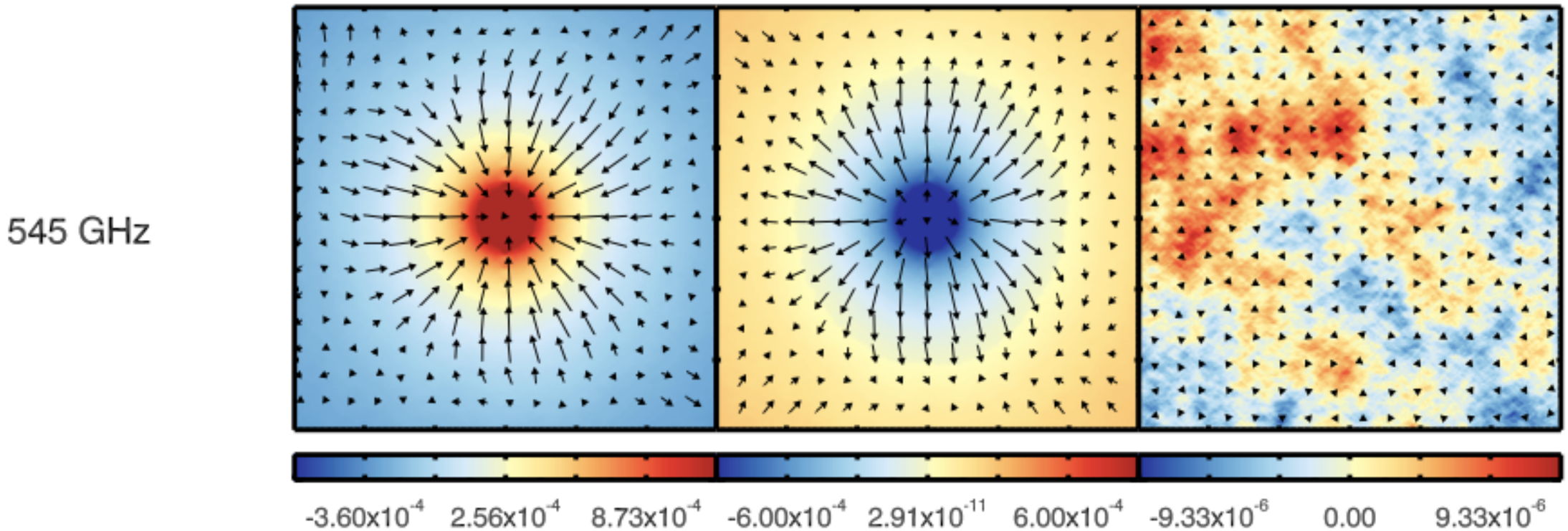
cumulative emission of dusty, star-forming galaxies over cosmic time

strongly correlated with CMB lensing



arrows = lensing deflection
color = CIB intensity

Planck XVIII (2013)

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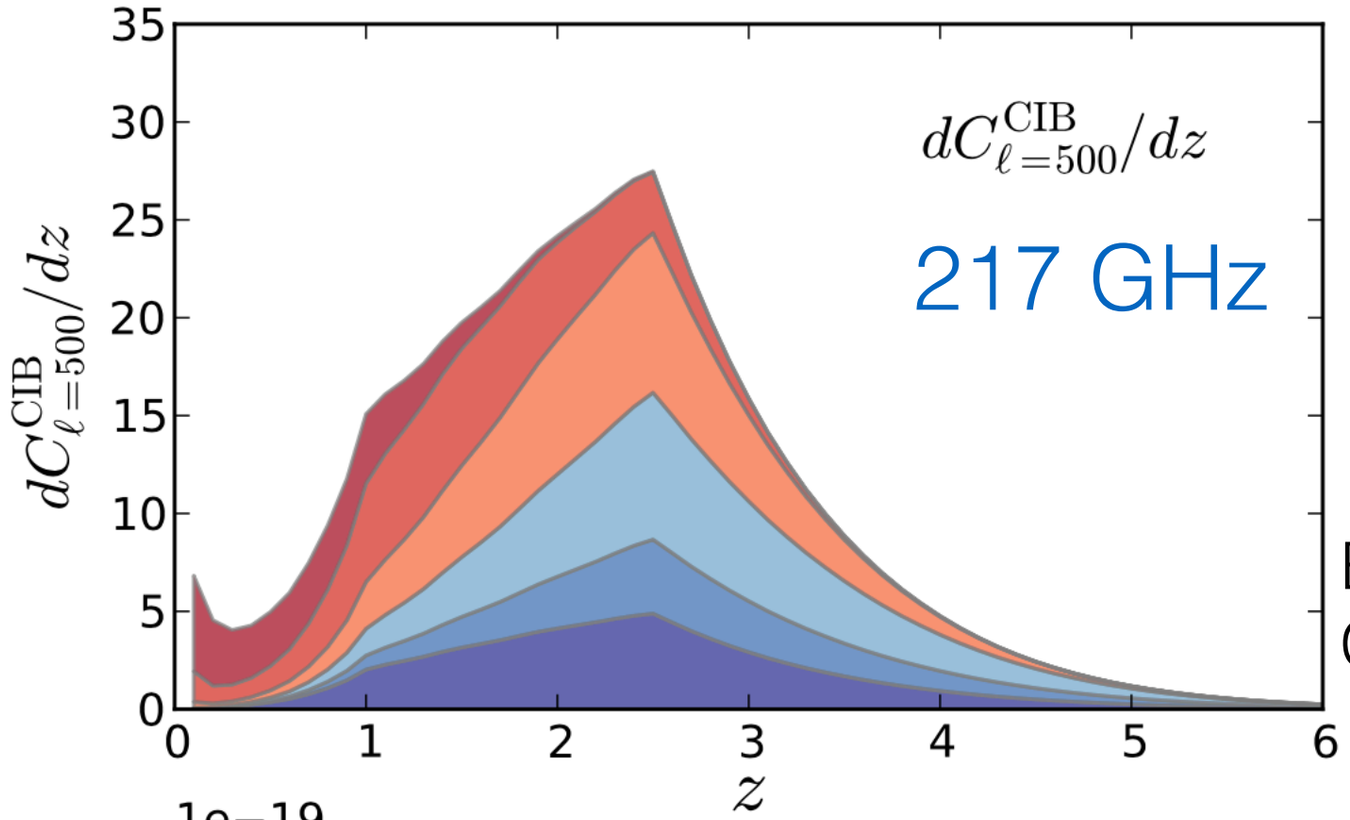
differential redshift contributions to PS



Bethermin+ (2012)
CIB model

Planck XVIII (2013)

Multi-Tracer Delensing

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- goal: combine LSS data sets to optimize delensing performance

  delensing efficiency ⟷ correlation coefficient with true κ

$$C_l^{\kappa\kappa} \to (1-\rho_l^2) C_l^{\kappa\kappa}$$

- limitations:
  - foreground contributions to LSS tracer maps
  - noise in reconstructed CMB lensing maps
  - missing redshift overlap of tracers with true lensing potential

Sherwin & Schmittfull (2015); Simard+ (2015)

see also Larsen+ (2016)

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- optimal combination of tracers: $I = \sum_i c_i I_i$

$$c_i = \sum_j (\mathbf{C}^{-1})_{ij} C_l^{\kappa I_j}$$

matrix of tracer auto- and cross-correlations

Sherwin & Schmittfull (2015); Simard+ (2015)

see also Larsen+ (2016)

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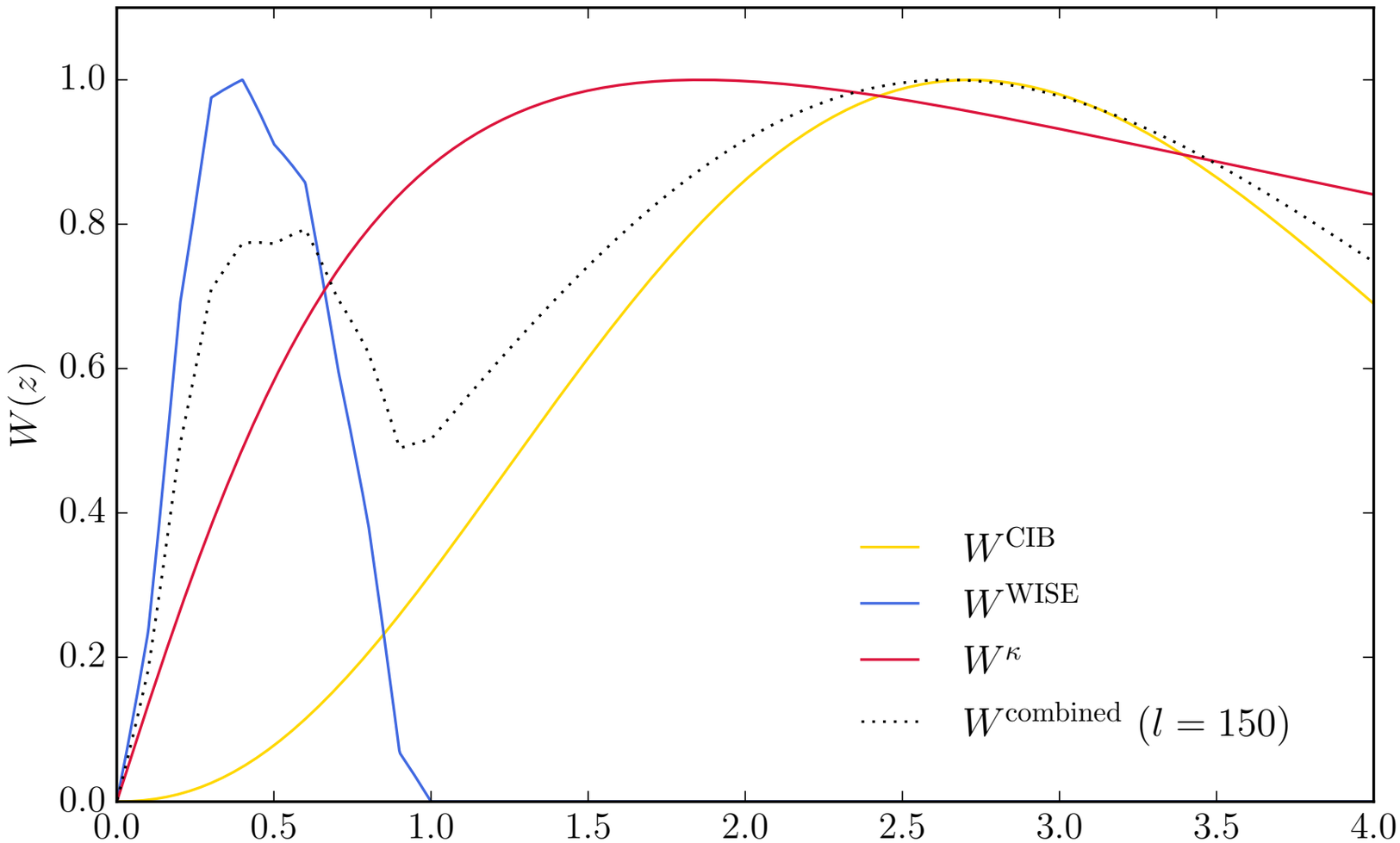
Multi-Tracer Delensing

estimate lensing B-mode using multi-tracer large-scale structure data

$$\hat{B}^{\rm lens}(\mathbf{l}) = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W(\mathbf{l},\mathbf{l}') f(\mathbf{l},\mathbf{l}') E^N(\mathbf{l}') I(\mathbf{l}-\mathbf{l}') \qquad B^{\rm res} = B^{\rm lens} - \hat{B}^{\rm lens}$$

Tracers = {**CIB** [Planck GNILC 353 GHz], **WISE** galaxies, **Planck** κ}

redshift kernel



Yu, **JCH**, and Sherwin (2017)

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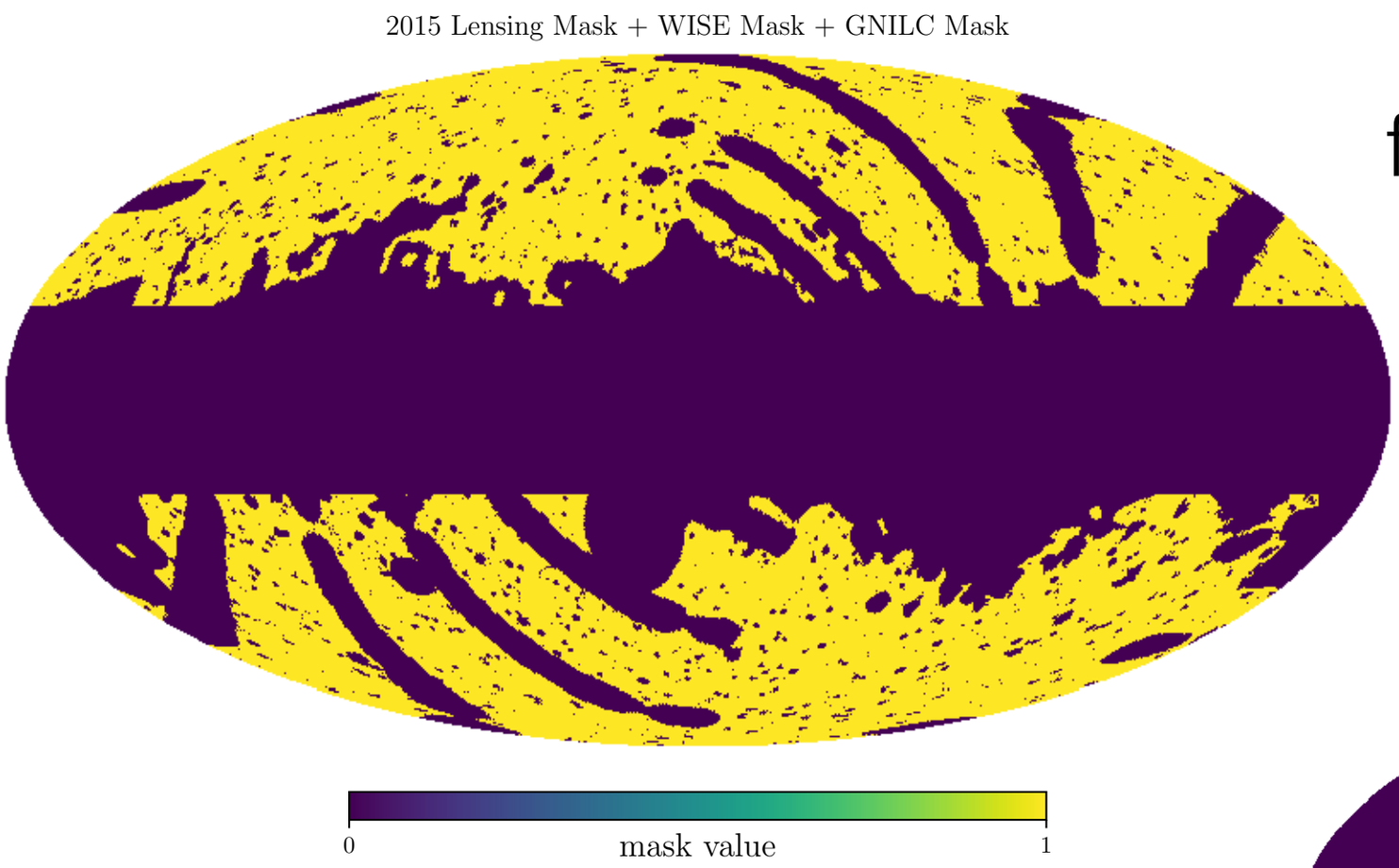
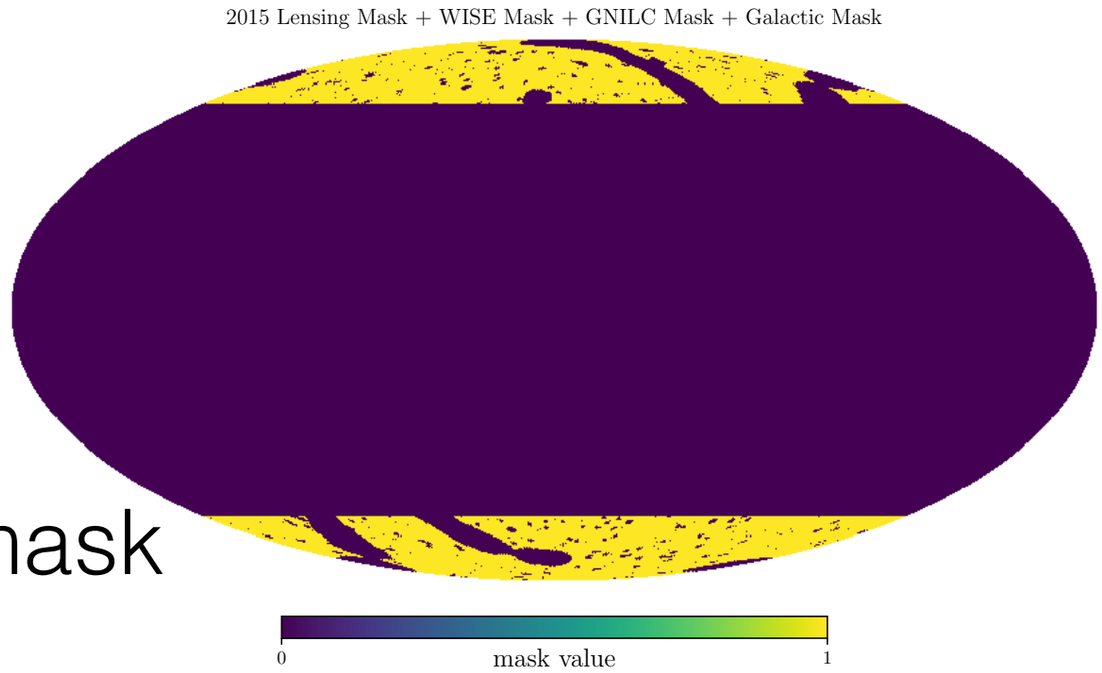
Multi-Tracer Delensing

determine optimal linear combination coefficients by fitting models to all measured auto- and cross-power spectra



fiducial mask
$f_{sky} = 0.43$



more restrictive mask
$f_{sky} = 0.11$

Yu, **JCH**, and Sherwin (2017)

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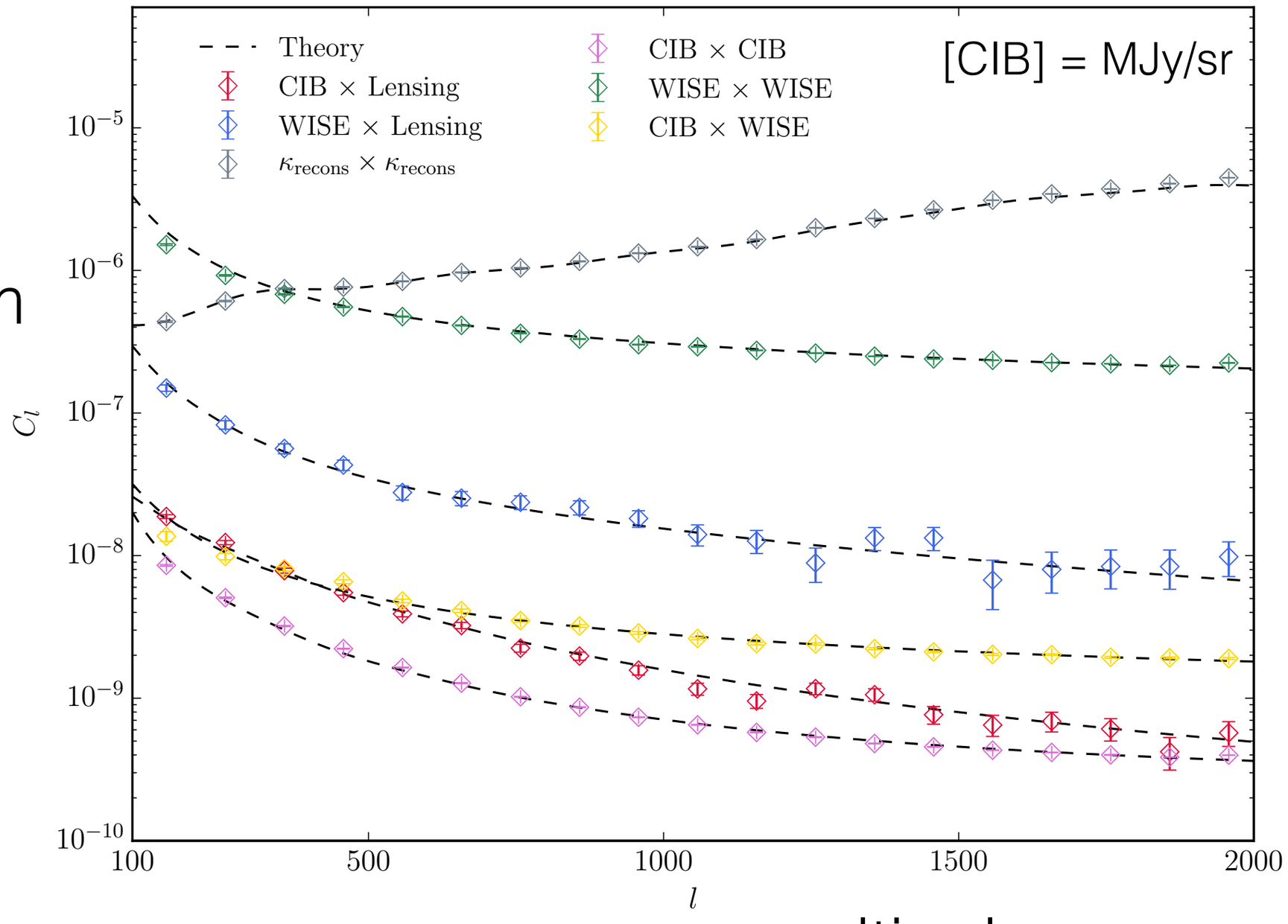
Multi-Tracer Delensing

determine optimal linear combination coefficients by fitting models to all measured auto- and cross-power spectra

power spectrum



multipole

models include signal (Limber), shot noise, and Galactic dust

Yu, **JCH**, and Sherwin (2017)

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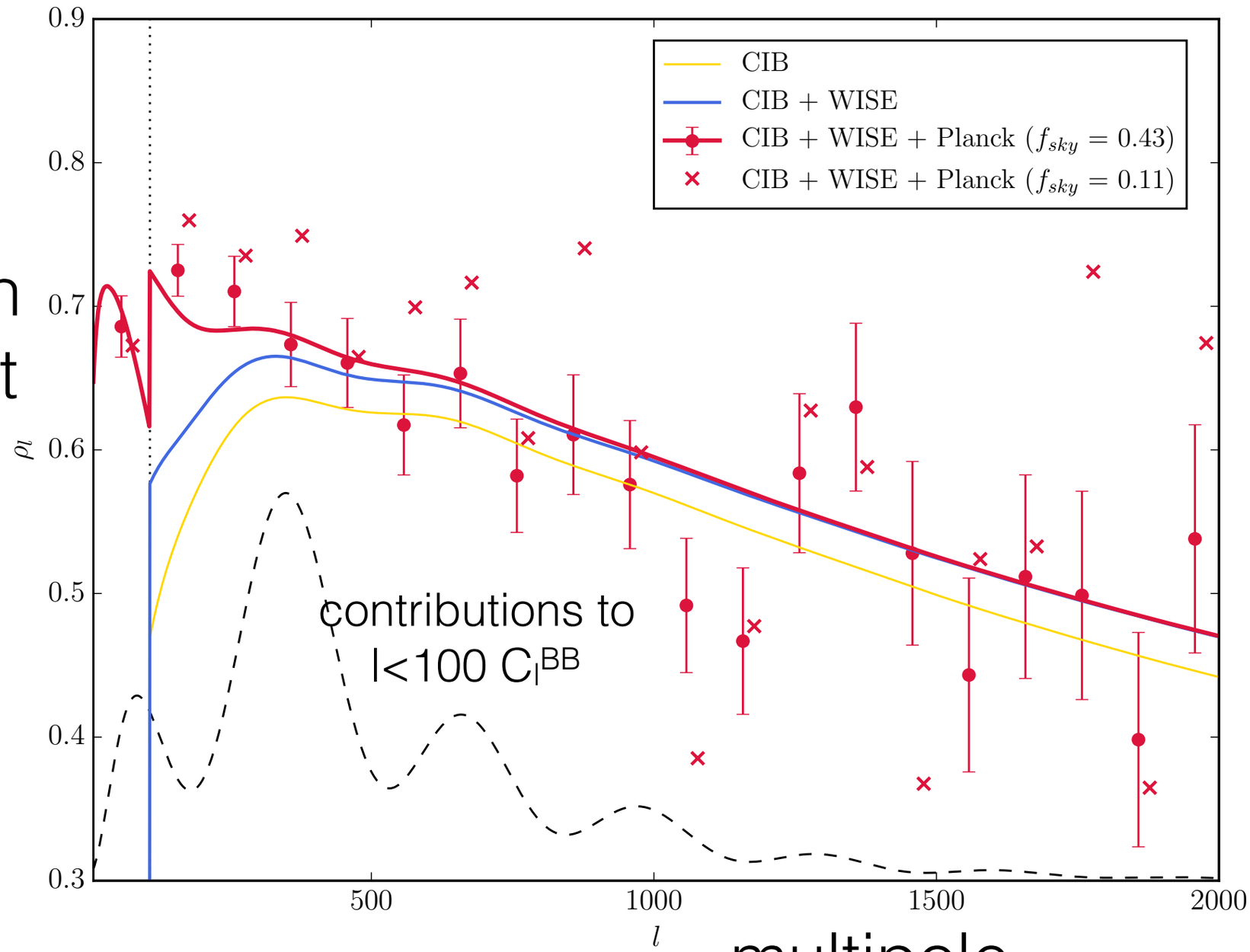
delensing efficiency ⟷ correlation coefficient with true κ

$$C_l^{\kappa\kappa} \to (1-\rho_l^2) C_l^{\kappa\kappa}$$

correlation coefficient



multipole

Yu, **JCH**, and Sherwin (2017)

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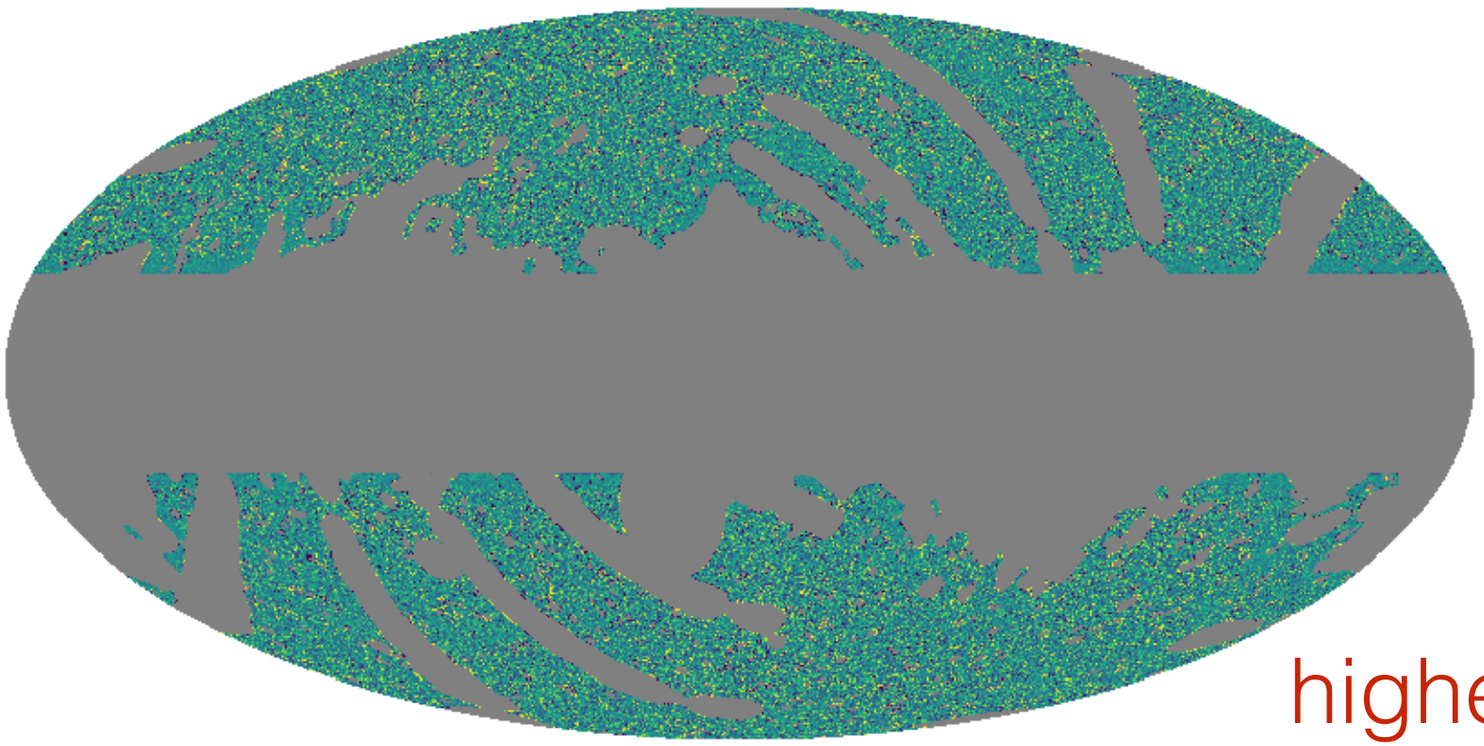
CIB
+
WISE

GNILC 353 GHz + WISE co-add

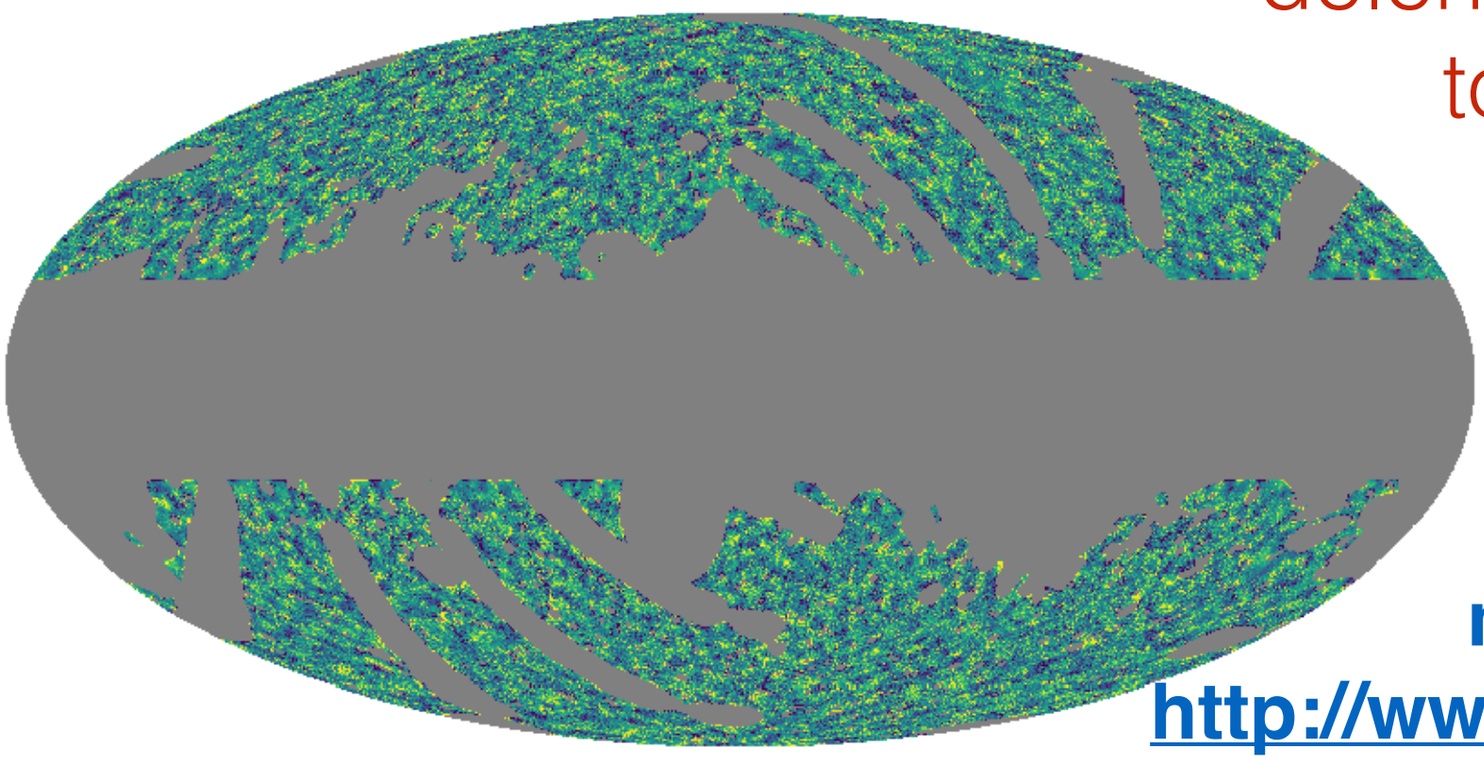


$f_{sky} = 0.43$

highest-fidelity delensing maps to date

CIB
+
WISE
+
Planck κ

GNILC 353 GHz + WISE + Planck lens co-add



maps:
http://www.sns.ias.edu/~jch/delens/

Yu, **JCH**, and Sherwin (2017)

Multi-Tracer Delensing

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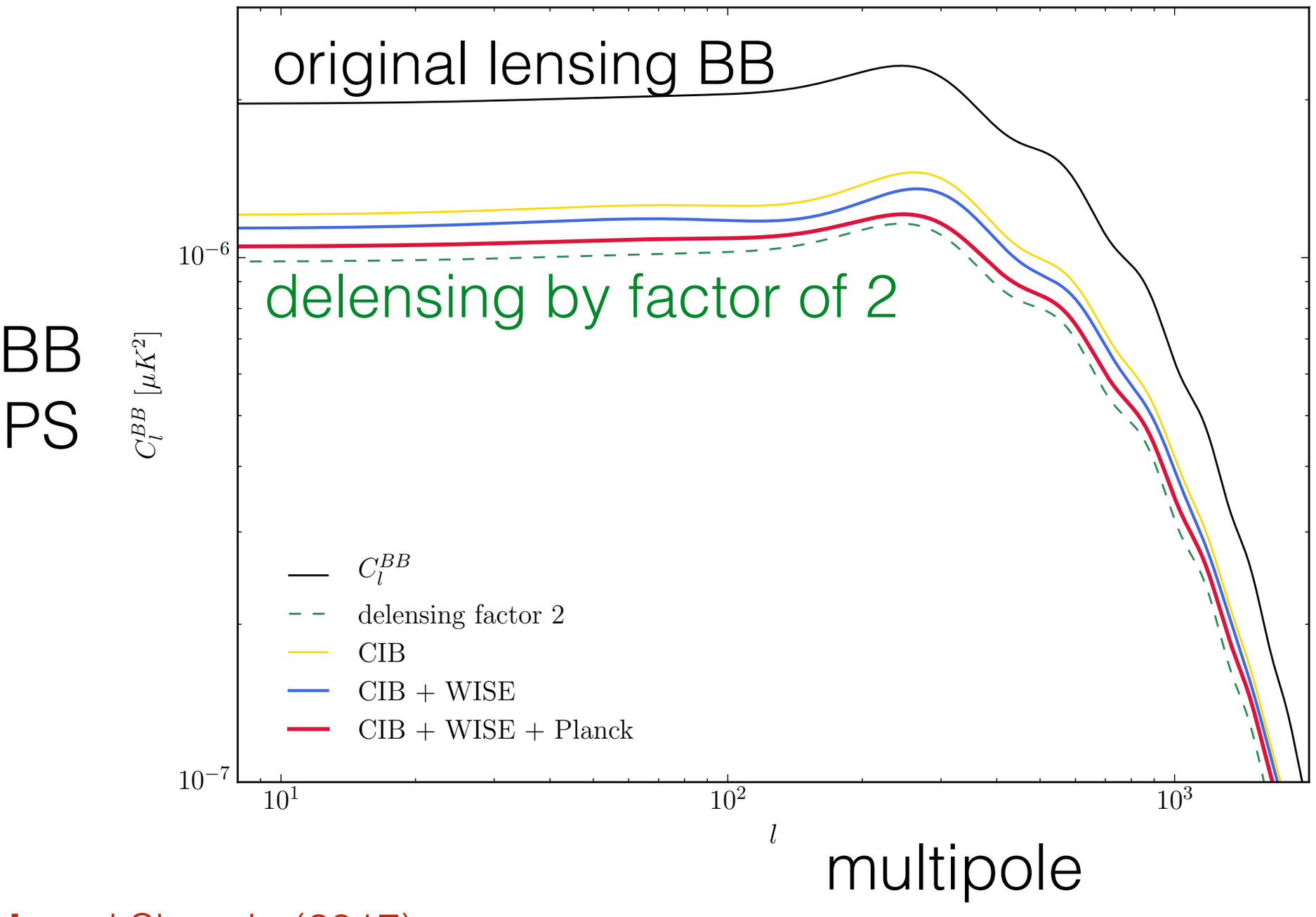
delensing factor ~2 on nearly half of the sky

→ **~2x decrease in σ(*r*) for low-noise surveys**



Yu, **JCH**, and Sherwin (2017)

Multi-Tracer Delensing

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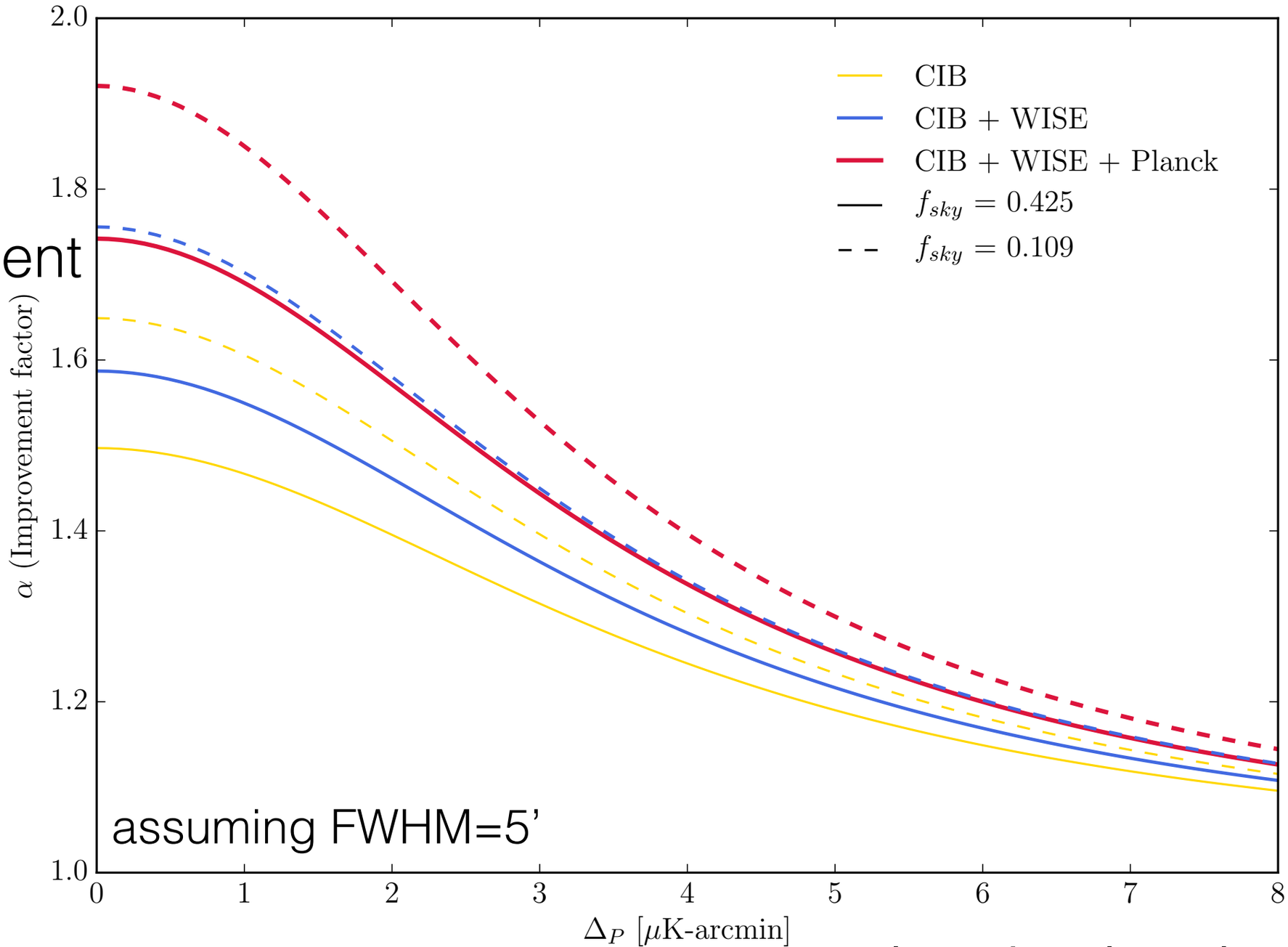
delensing factor ~2 on nearly half of the sky

→ **~2x decrease in σ(*r*) for low-noise surveys**

improvement in σ(r)



pol. noise level

Yu, **JCH**, and Sherwin (2017)

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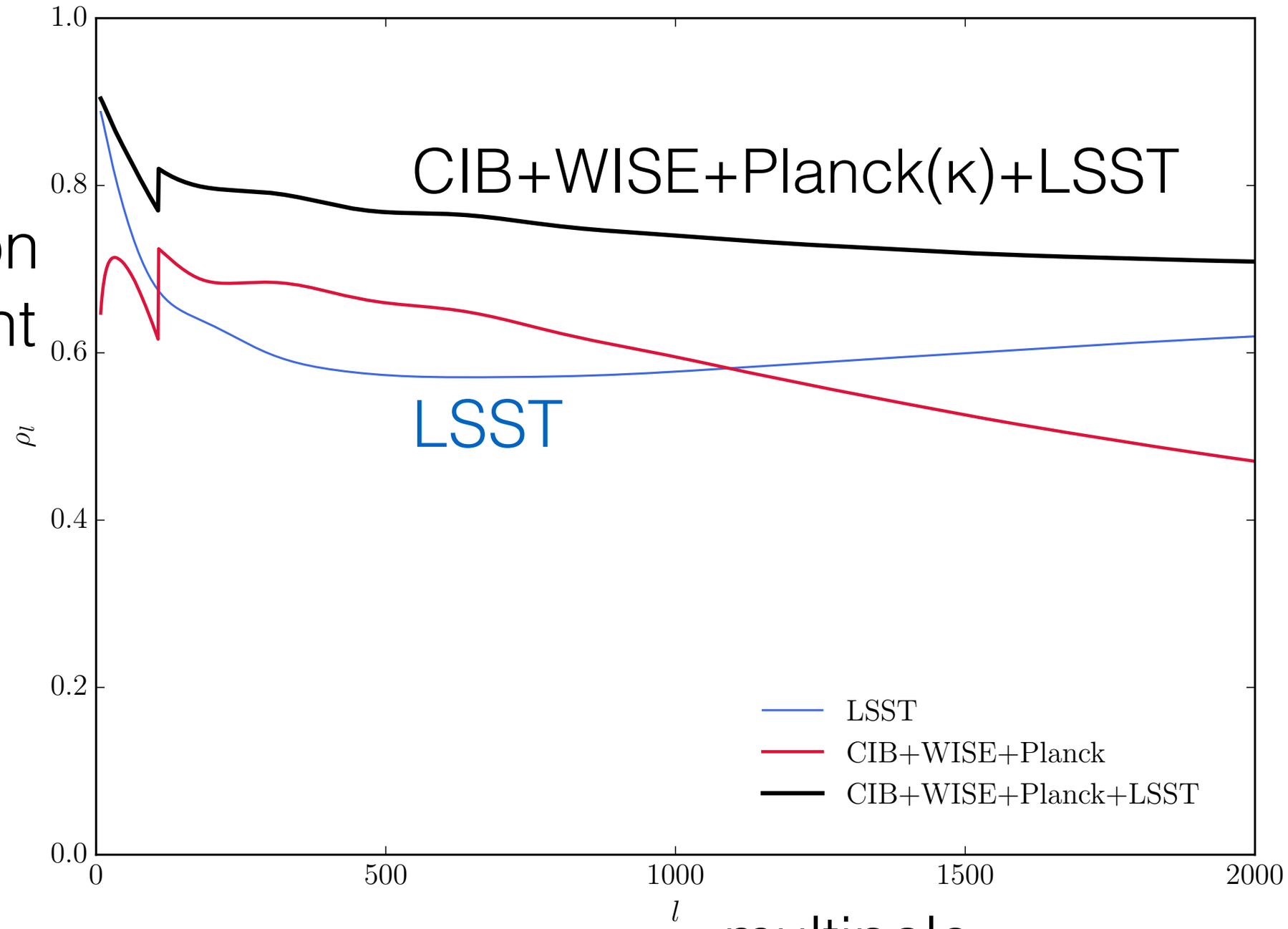
Outlook: LSST

~80+% correlation coefficient with CMB lensing

→ delensing fraction of ~60%



Yu, **JCH**, and Sherwin (2017)

see also Schmittfull & Seljak (2017)

Summary + Future

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- Multi-tracer maps from current data can delens B-mode foreground well enough to reduce σ(*r*) by factor of ~2.

- LSS delensing will be crucial for low-res. space missions.

- Improvements:
  - Combining CIB frequencies? GNILC CIB maps strongly correlated

correlation coefficients

	545			353		
	$f_{sky} = 0.4$	$f_{sky} = 0.1$	(Planck 13)	$f_{sky} = 0.4$	$f_{sky} = 0.1$	(Planck 13)
857	0.983	0.986	(0.949)	0.968	0.970	(0.911)
545		1		0.995	0.995	(0.983)
353		...			1	

TABLE I. Frequency decoherence of the CIB for $150 < l < 1000$. For comparison, we include the values from Planck 2013 CIB paper in bracket. For $l > 1000$, we find that CIB channels are more correlated with a more restrictive mask.

see also Mak+ (2017)

Summary + Future

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- Multi-tracer maps from current data can delens B-mode foreground well enough to reduce σ(*r*) by factor of ~2.

- LSS delensing will be crucial for low-res. space missions.

- Improvements:
  - Combining CIB frequencies? More work needed on CIB/Galactic dust component separation (HI?)
  - Optimal redshift re-weighting of tracer samples (LSST)
  - Include more tracers (tSZ at low-z, QSOs at high-z, …)

- Questions:
  - Foreground cleaning - delensing cross-talk: will we delens component-separated B-mode maps? foreground analysis currently at PS level
  - Residual foreground effects even in LSS delensing? (e.g., polarized CIB, Galactic dust)
  - Likelihood for delensed maps