CMB Foregrounds:

Problems, Parameterizations, and Progress

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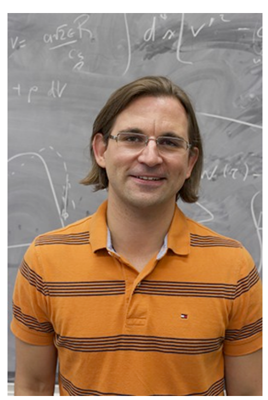
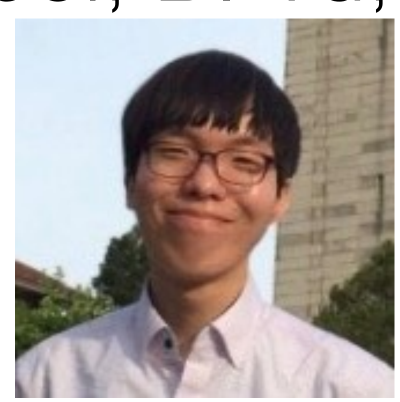
CCA

w/ J. Chluba, M. Abitbol, B. Yu, B. Sherwin






TeVPA, Columbus, OH

7 August 2017

1701.00274
1705.01534

1705.02332
1705.06751

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Outline

- CMB Foregrounds
- Generalized Parameterizations
  - Application: PIXIE Spectral Distortions
- CMB Lensing: signal and foreground

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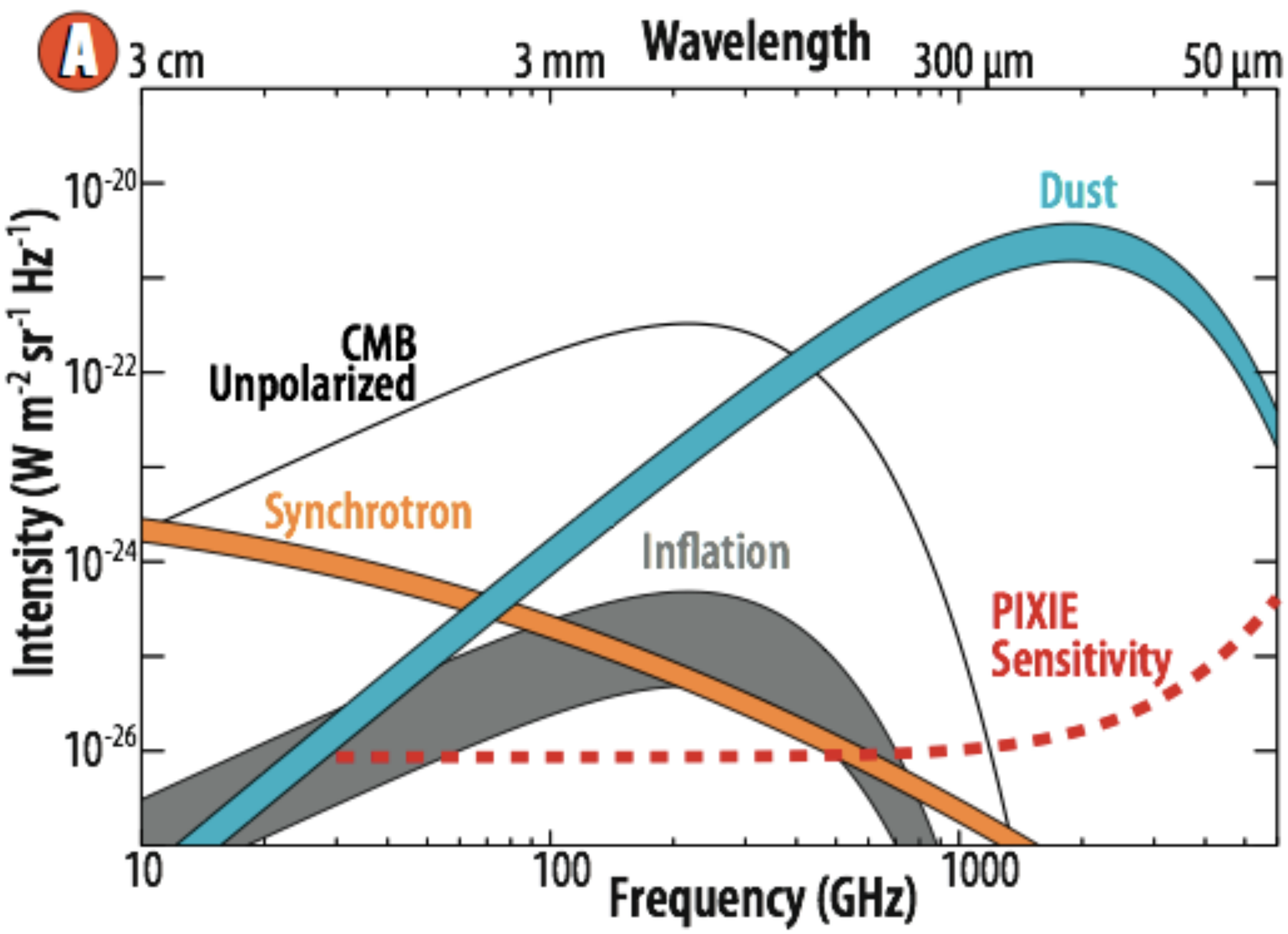
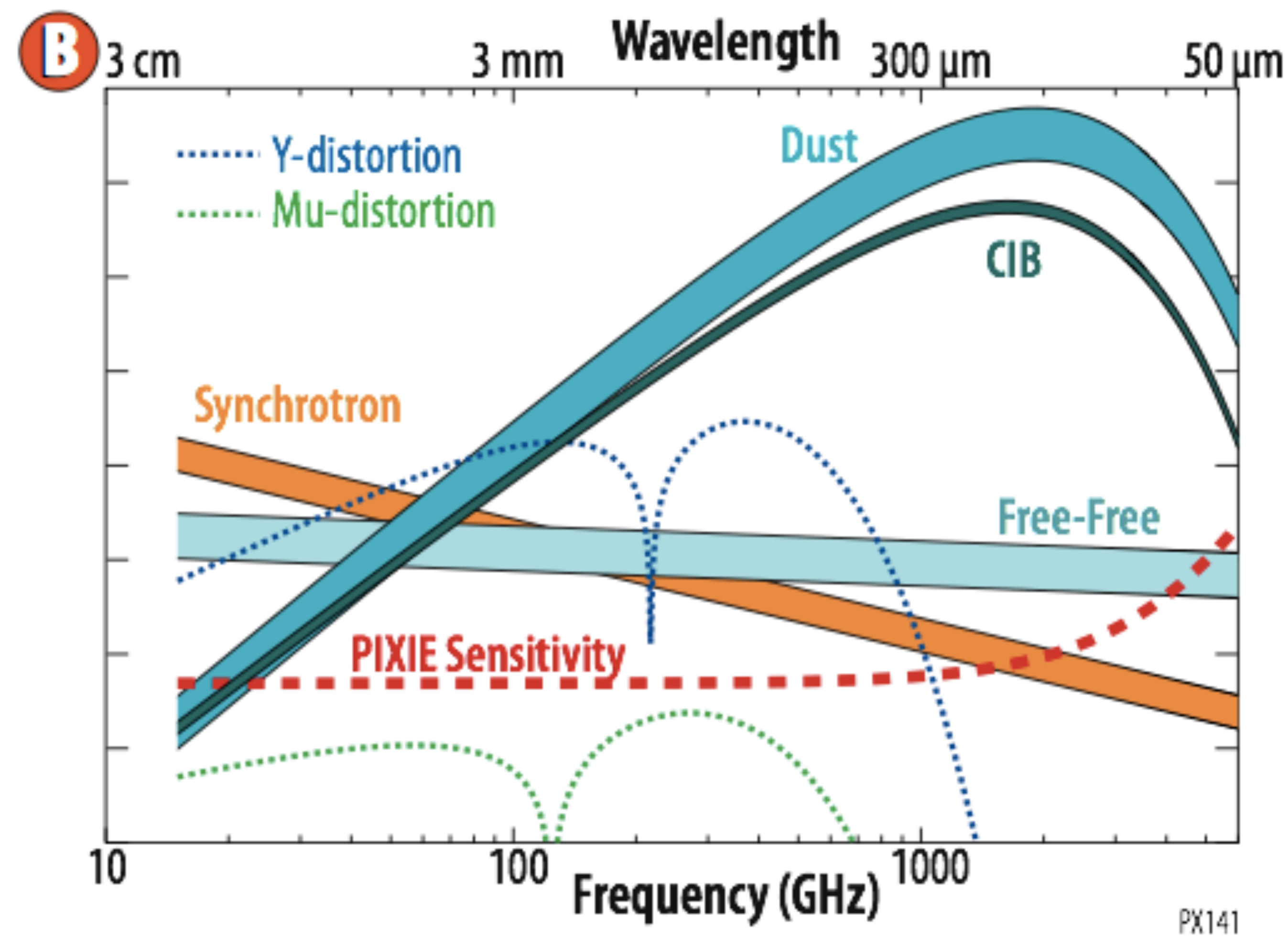
CMB Foregrounds

Polarization



Temperature



+ Radio sources
+ Anomalous microwave emission?
(+ Atmosphere)

+ Lensed CMB
+ Kinematic SZ
+ Anomalous microwave emission
+ Radio sources
(+ Atmosphere)

Kogut+ (2016); Abitbol, Chluba, **JCH**, & Johnson (2017)

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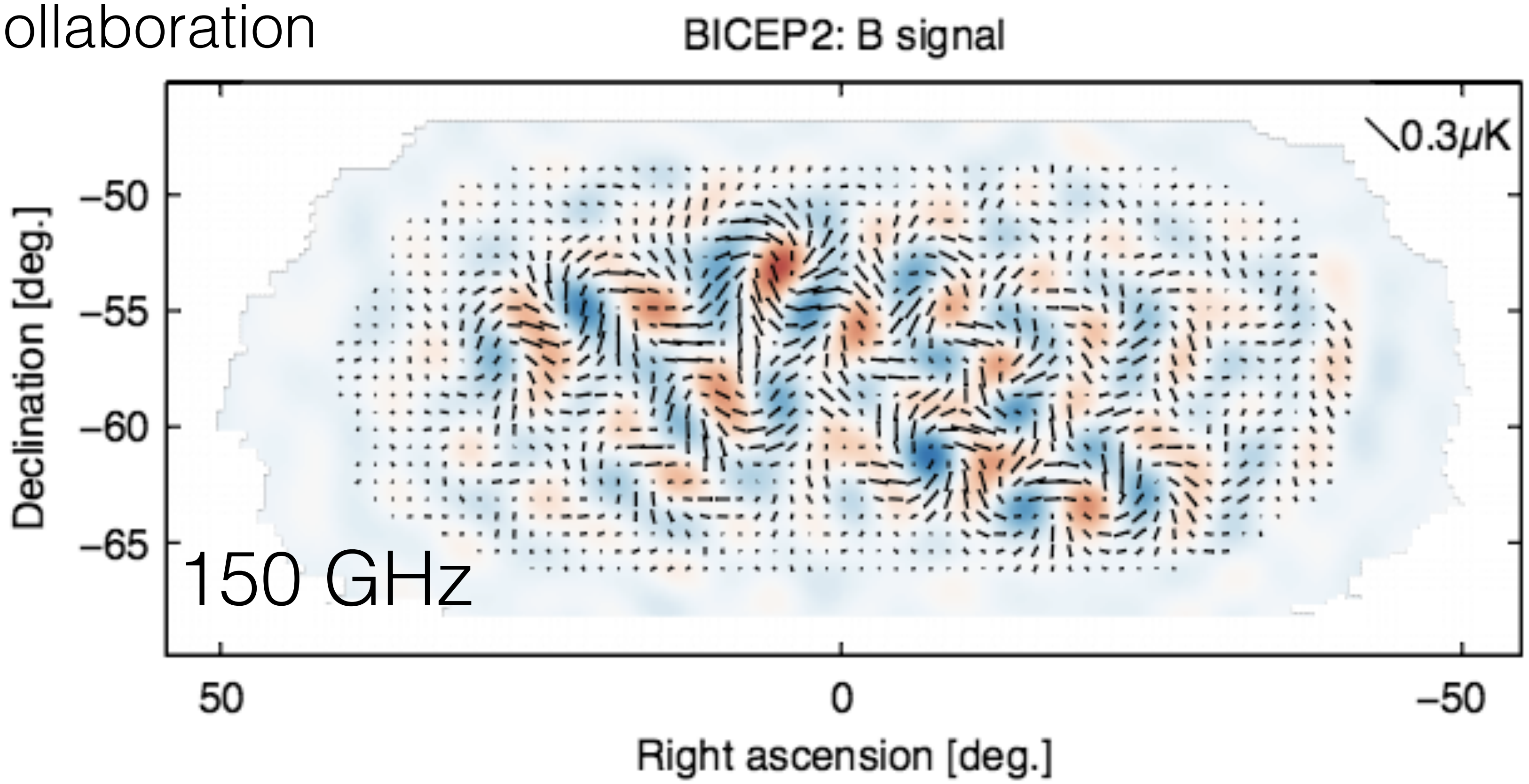
B-modes

BICEP2
Collaboration



B-modes

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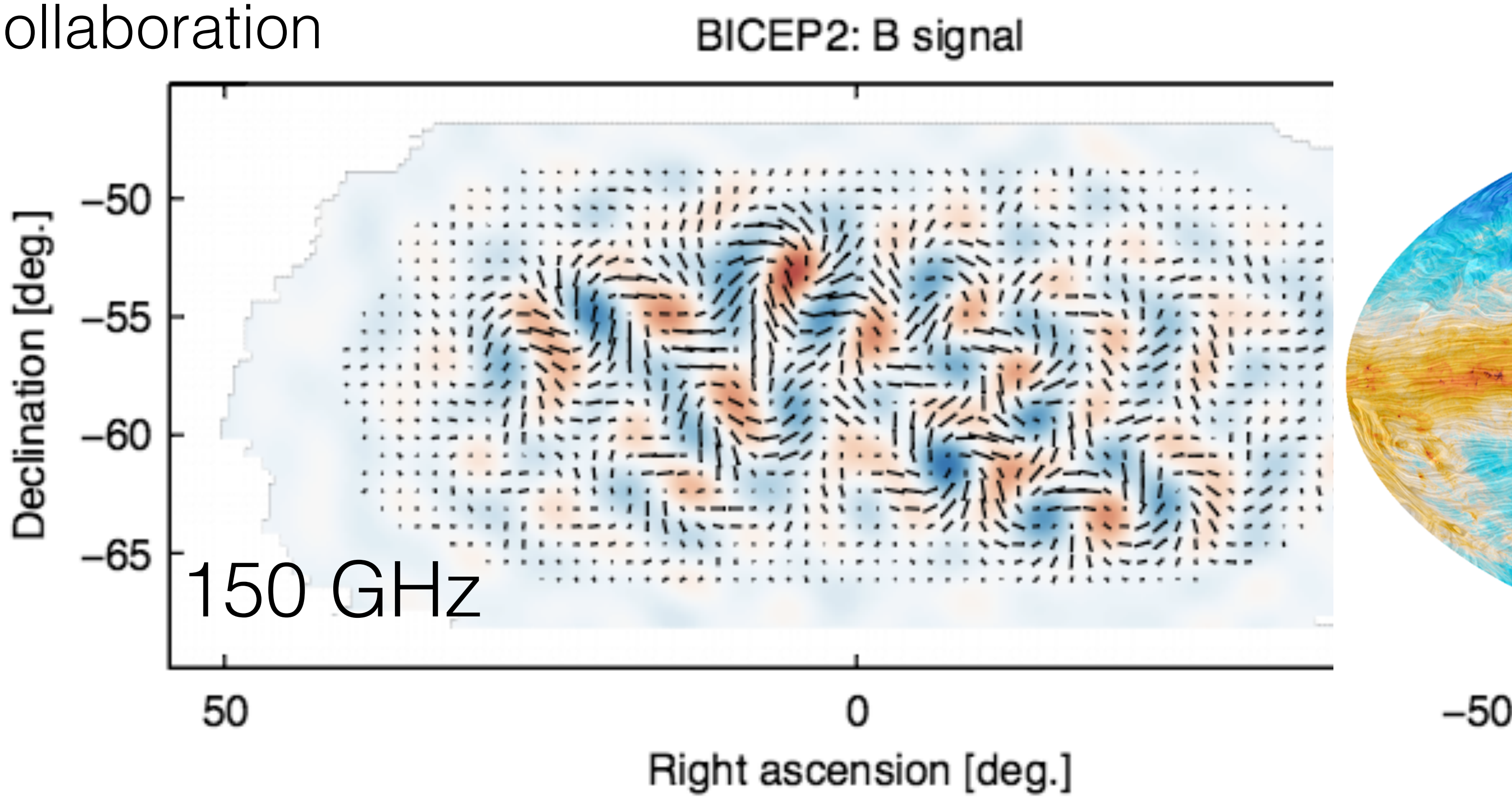
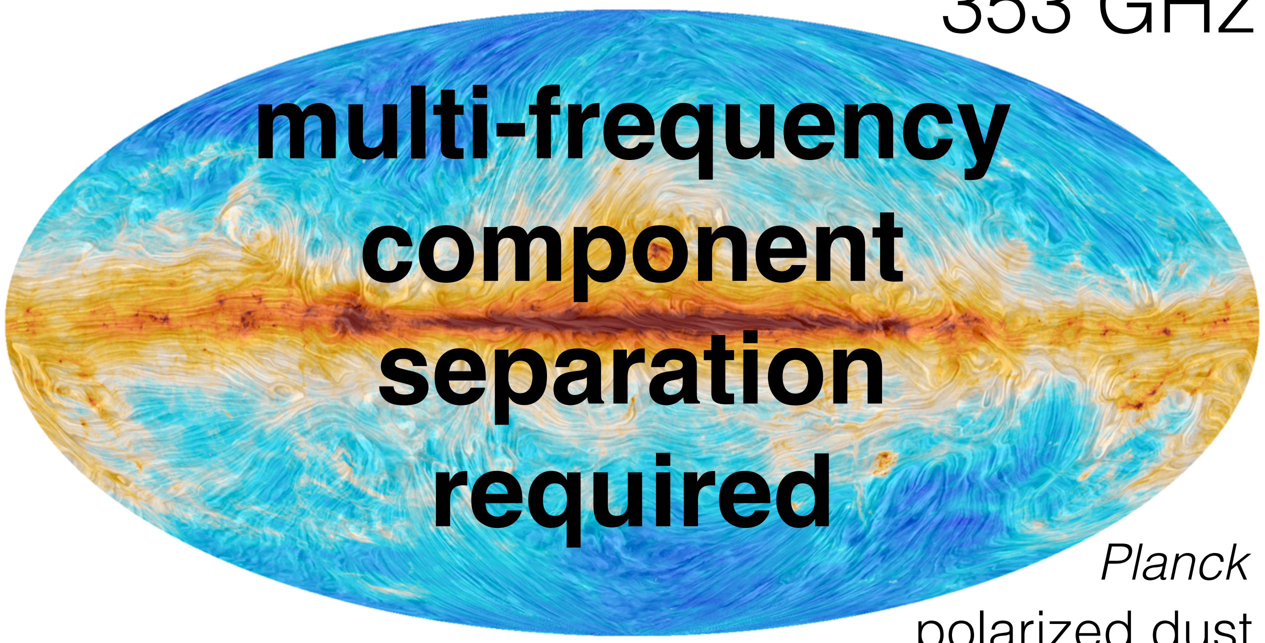
BICEP2
Collaboration

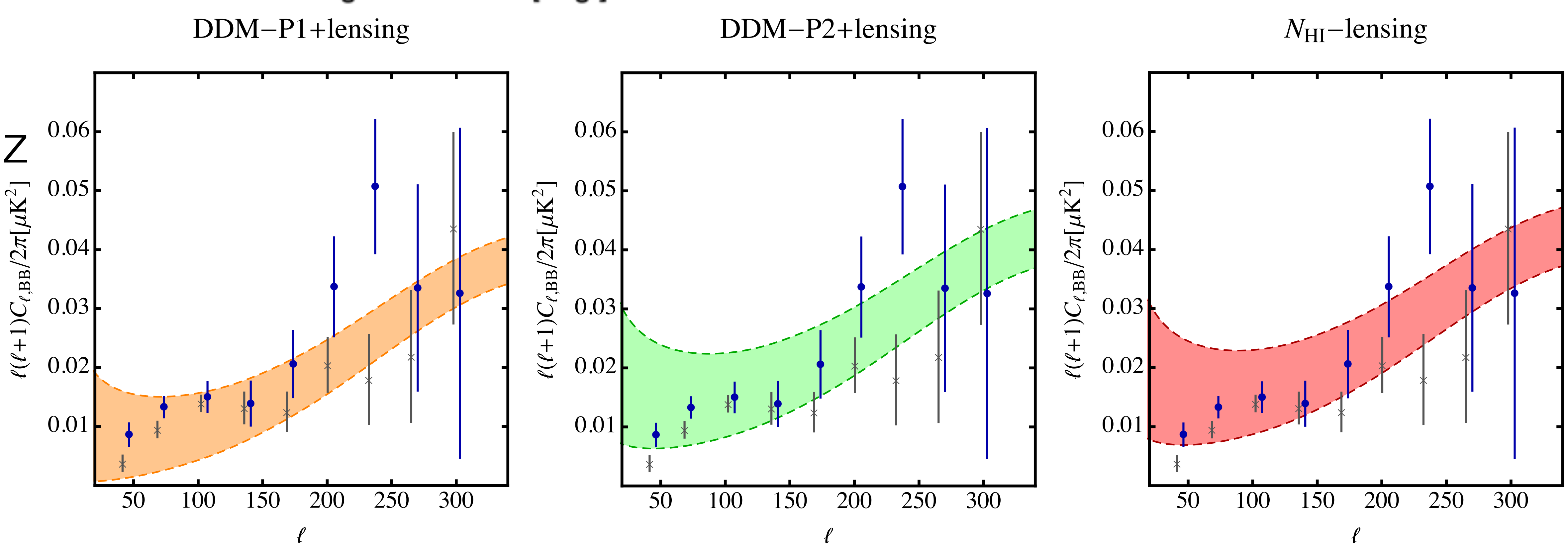


353 GHz



Planck
polarized dust

150 GHz
BB
PS



Flauger, **JCH**, & Spergel (2014)

Multipole

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New Parameterizations

Flexible, general models are needed for ~nK precision data

beam and line-of-sight averages are inevitable

→ superposition of spectral shapes, leading to new behavior

Chluba, **JCH**, and Abitbol (2017)

New Parameterizations

Flexible, general models are needed for ~nK precision data

beam and line-of-sight averages are inevitable

→ superposition of spectral shapes, leading to new behavior

consider Taylor expansion of SED

$\bar{\boldsymbol{p}}$ = averaged parameters

$$
\begin{aligned}
I_\nu(\boldsymbol{p}) = I_\nu(\bar{\boldsymbol{p}}) &+ \sum_i (p_i - \bar{p}_i)\, \partial_{\bar{p}_i} I_\nu(\bar{\boldsymbol{p}}) \\
&+ \frac{1}{2!} \sum_i \sum_j (p_i - \bar{p}_i)(p_j - \bar{p}_j)\, \partial_{\bar{p}_i} \partial_{\bar{p}_j} I_\nu(\bar{\boldsymbol{p}}) \\
&+ \frac{1}{3!} \sum_i \sum_j \sum_k (p_i - \bar{p}_i)(p_j - \bar{p}_j)(p_k - \bar{p}_k)\, \partial_{\bar{p}_i} \partial_{\bar{p}_j} \partial_{\bar{p}_k} I_\nu(\bar{\boldsymbol{p}}) \\
&+ \dots \qquad (3)
\end{aligned}
$$

new SED behavior generated by beam- and LOS-averaging coupling to derivatives of fundamental SED

can be captured by *moments* of underlying parameter distribution functions

Chluba, **JCH**, and Abitbol (2017)

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New Parameterizations

Flexible, general models are needed for ~nK precision data

beam and line-of-sight averages are inevitable

→ superposition of spectral shapes, leading to new behavior

Example: modified blackbody SED

$$I_\nu(A_0, \alpha, T) = A_0\,(\nu/\nu_0)^\alpha\,\nu^3/(\mathrm{e}^{h\nu/kT} - 1) \qquad \boldsymbol{p} = \{A_0, \alpha, \beta = 1/T\}$$

$$\langle I_\nu \rangle = \frac{\bar{A}_0\,(\nu/\nu_0)^{\bar{\alpha}}\nu^3}{\mathrm{e}^x - 1}\left\{1 + \frac{1}{2}\,\omega^{\mathrm{d}}_{22}\ln^2(\nu/\nu_0) + \omega^{\mathrm{d}}_{23}\ln(\nu/\nu_0)\,Y_1(x) + \frac{1}{2}\,\omega^{\mathrm{d}}_{33}Y_2(x) + \frac{1}{6}\,\omega^{\mathrm{d}}_{222}\ln^3(\nu/\nu_0) + \frac{1}{2}\,\omega^{\mathrm{d}}_{223}\ln^2(\nu/\nu_0)Y_1(x) + \frac{1}{2}\,\omega^{\mathrm{d}}_{233}\ln(\nu/\nu_0)Y_2(x) + \frac{1}{6}\,\omega^{\mathrm{d}}_{333}Y_3(x) + \dots\right\}$$

$$\bar{\alpha} = \frac{\langle A_0(\boldsymbol{r})\,\alpha(\boldsymbol{r})\rangle}{\bar{A}_0}, \qquad \frac{1}{\bar{T}} = \frac{\langle A_0(\boldsymbol{r})/T(\boldsymbol{r})\rangle}{\bar{A}_0}$$

$$\omega^{\mathrm{d}}_{2\ldots23\ldots3} = \frac{\left\langle A_0(\boldsymbol{r})[(\alpha(\boldsymbol{r}) - \bar{\alpha}]^k\,[(\bar{T}/T(\boldsymbol{r}) - 1]^m\right\rangle}{\bar{A}_0}.$$

$$Y_k = [(-\beta)^k\partial^k_\beta I_\nu]/I_\nu$$
$$Y_1(x) = x\,\mathrm{e}^x/(\mathrm{e}^x - 1)$$
$$Y_2(x) = Y_1(x)\,x\coth(x/2)$$

note cross-terms between spectral index and temp.

Chluba, **JCH**, and Abitbol (2017)

New Parameterizations

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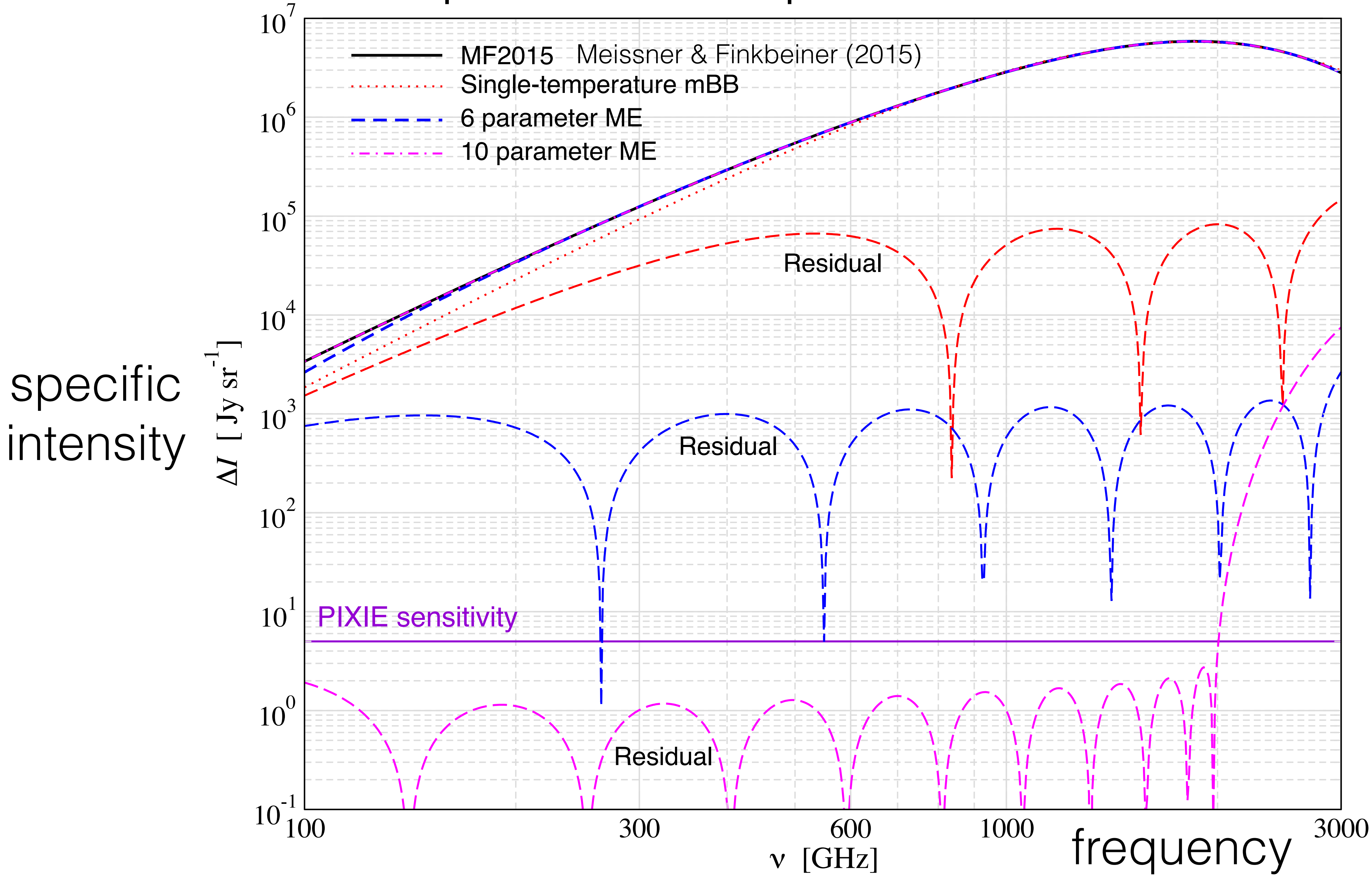
Example: two-component dust model



moment expansion is agnostic — can capture broad range of parameter distributions

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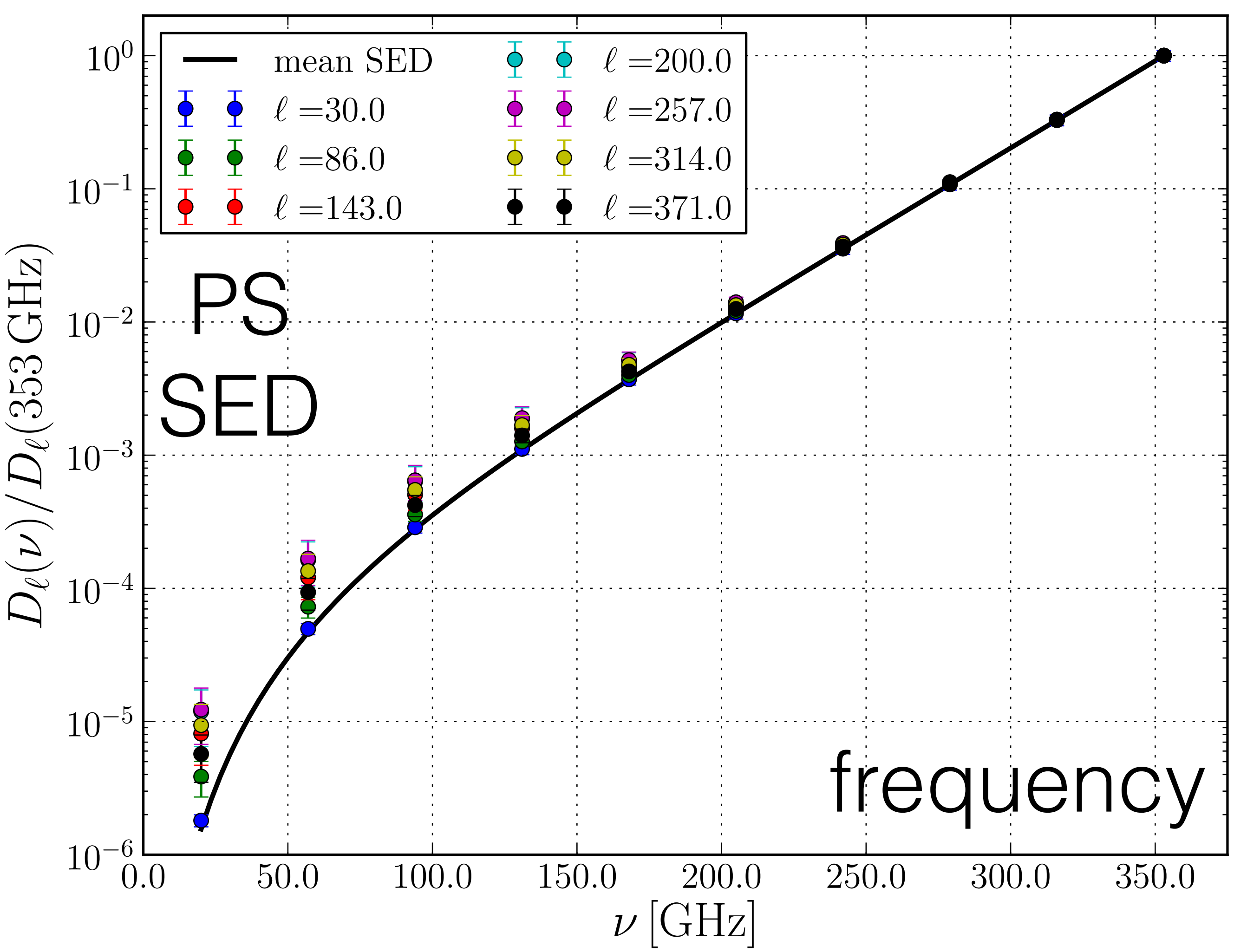
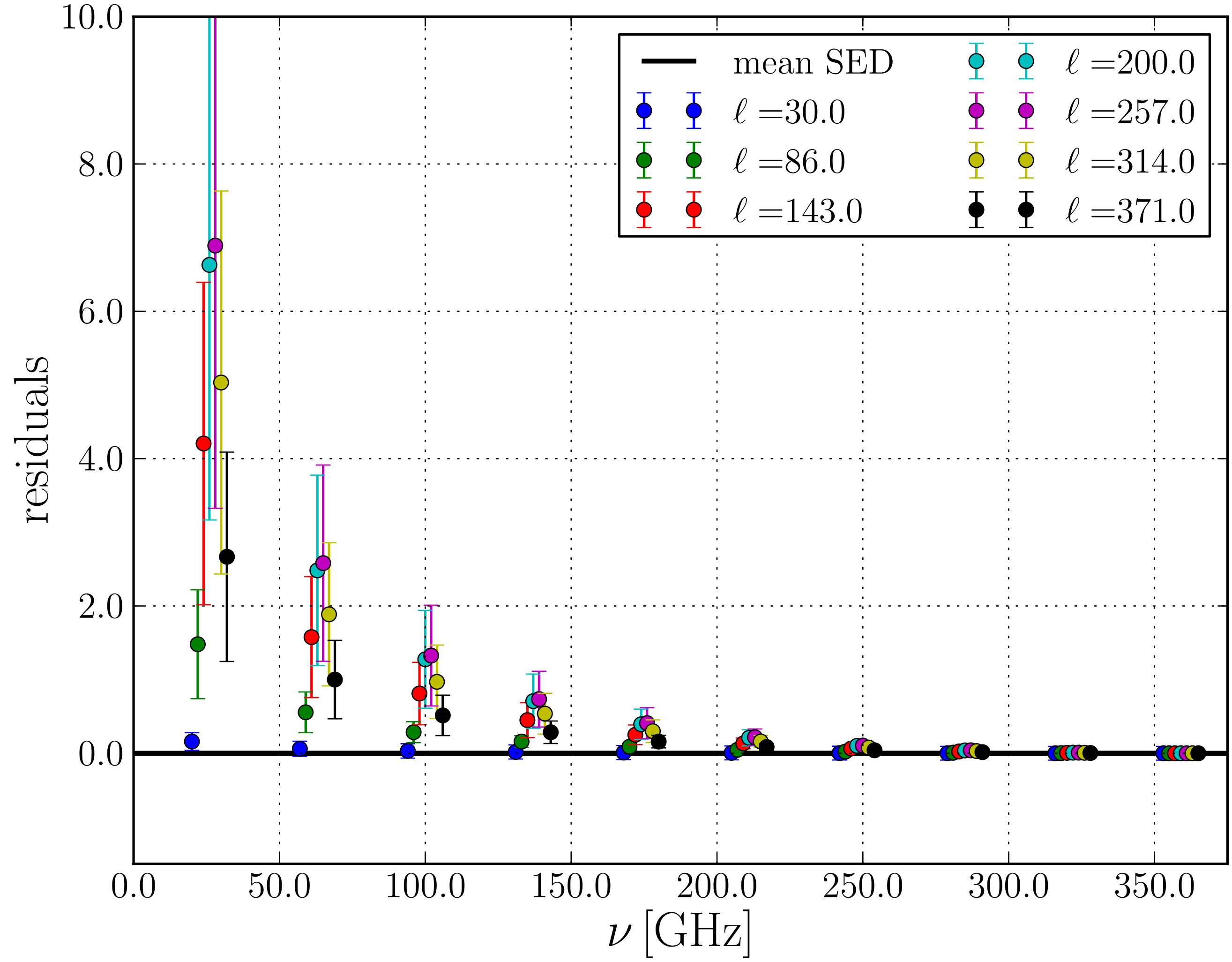
New Parameterizations

Example: suppose dust SED is simple modified blackbody everywhere, but spectral index varies on ~deg scales





simple extrapolations can lead to highly inaccurate results

moment method allows such variations to be captured without *a priori* assumptions

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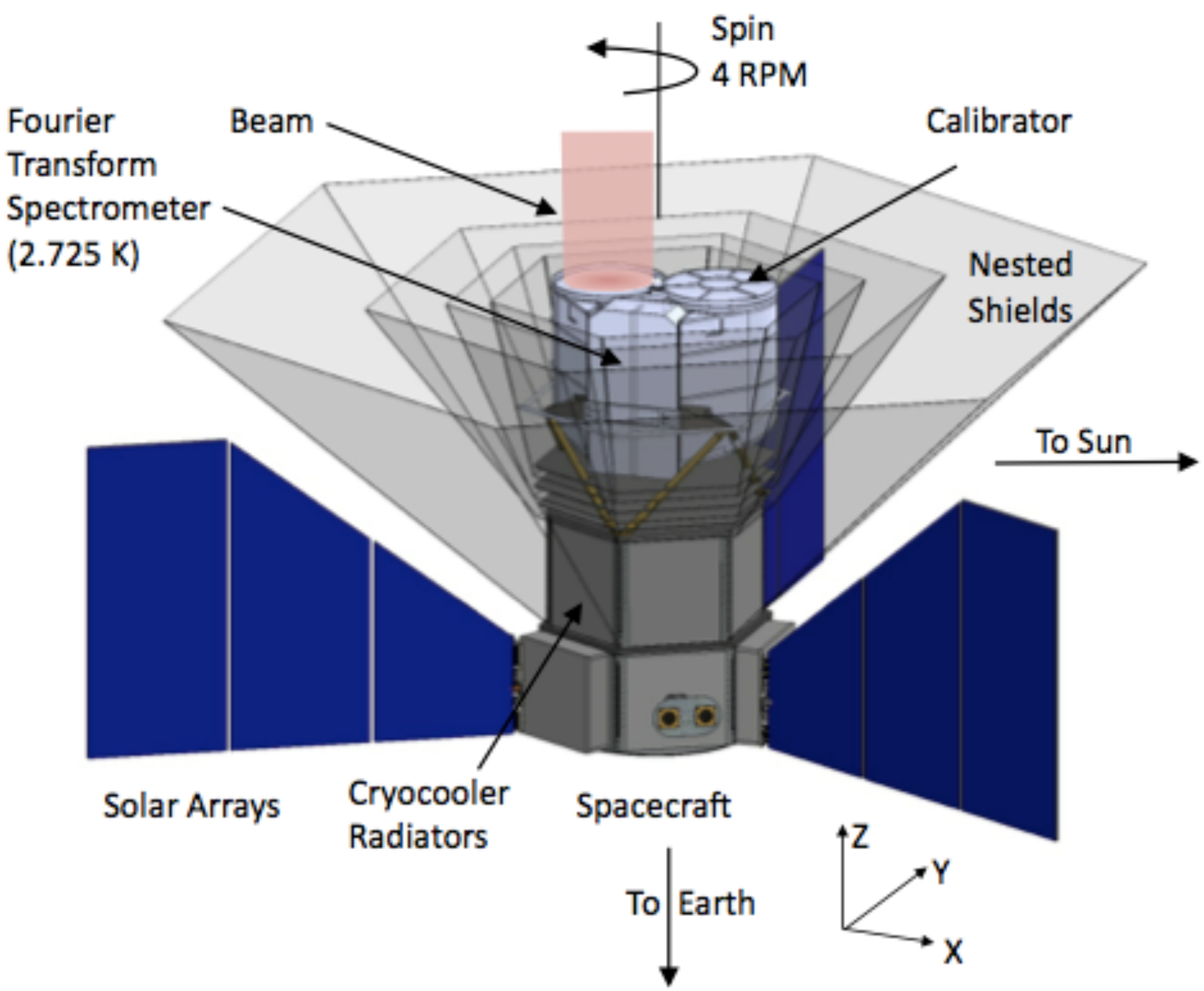
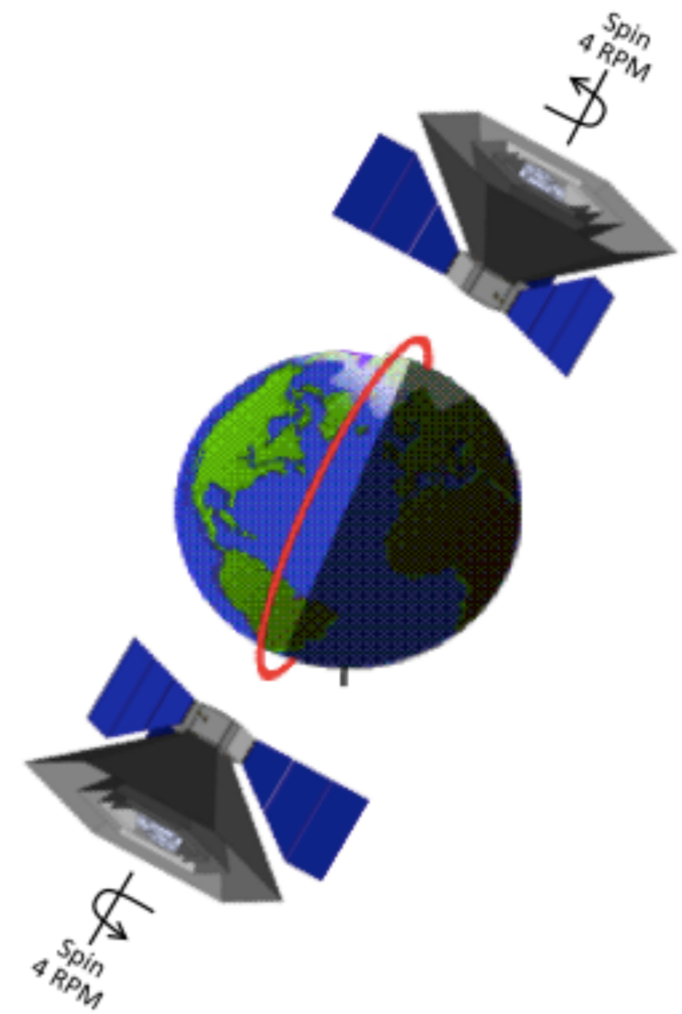
Application: *PIXIE* Forecasts

Primordial Inflation Explorer





~1000x more sensitive than COBE-FIRAS
15 GHz to 6 THz (400 channels)
High S/N detection of <y> + relativistic tSZ
Primordial B-mode science: $\sigma(r) \sim 6 \times 10^{-4}$

Mid-Ex proposal submitted Dec. 2016

Kogut+ (2011); **JCH**+ (2015); Calabrese+ (2016)

PIXIE Forecasts

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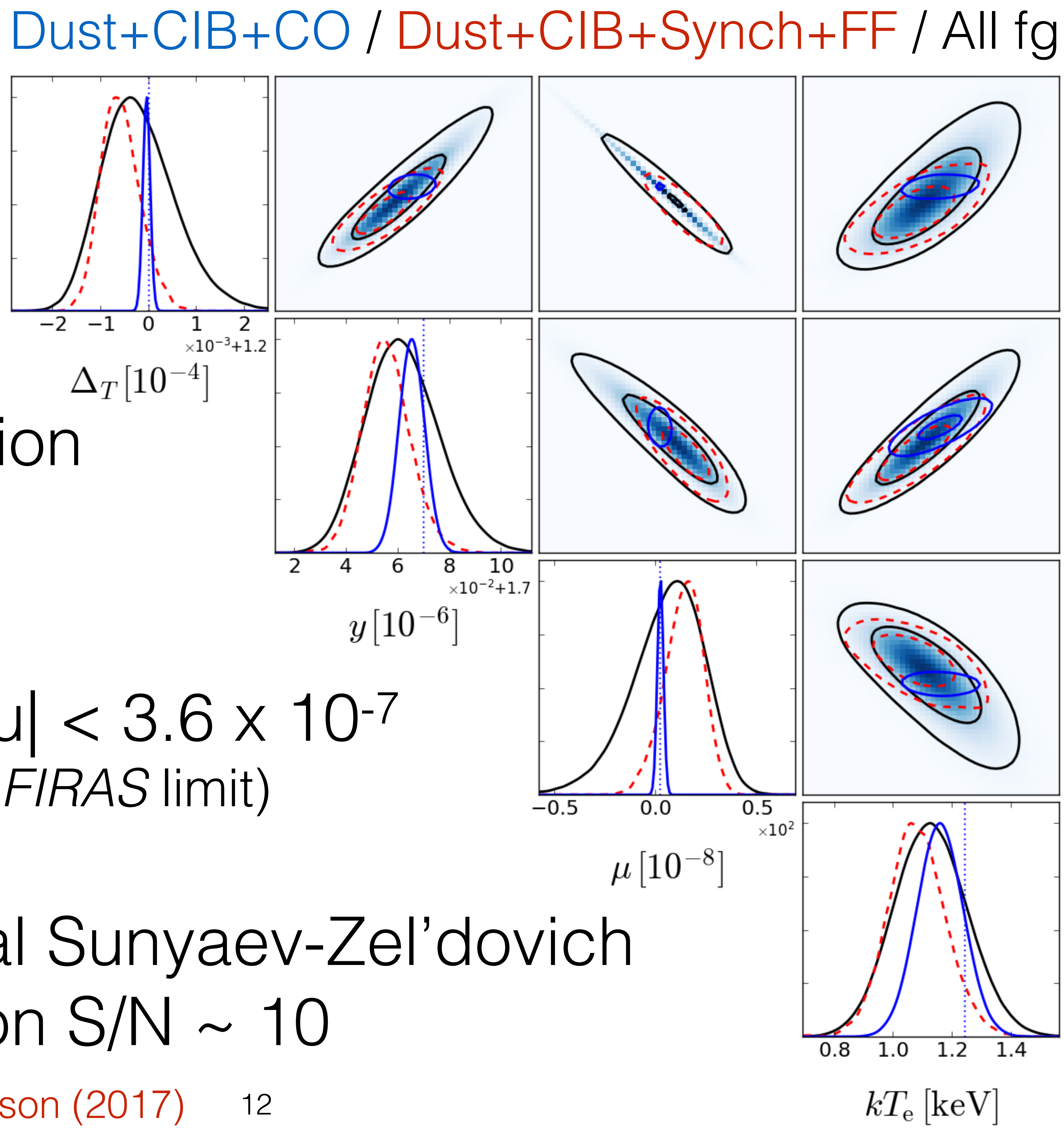
σ(T_{CMB}) ~ 100 nK
(S/N ~ 1.3 x 10^7)

Compton-y detection
S/N ~ 200

μ limit (95% CL): |μ| < 3.6 x 10^{-7}
(250x better than *FIRAS* limit)

Relativistic thermal Sunyaev-Zel'dovich
detection S/N ~ 10



Abitbol, Chluba, **JCH**, and Johnson (2017)

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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: $\phi(\vec{\mathbf{L}}) \sim T(\vec{\ell})T(\vec{\mathbf{L}} - \vec{\ell})$ $\quad \vec{\mathbf{d}} = \nabla\phi$

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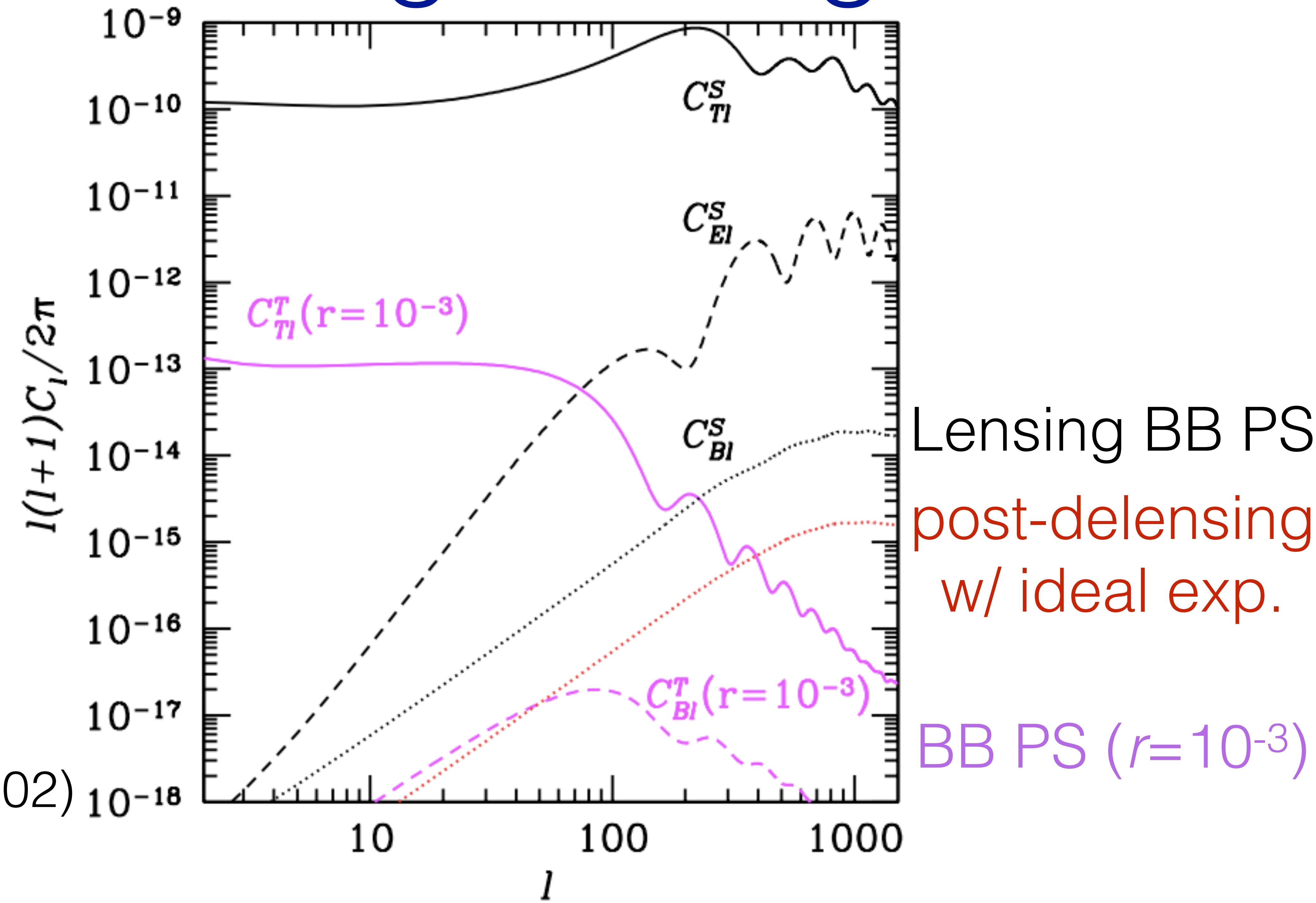
CMB Lensing: *r* Foreground



Knox & Song (2002)

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

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

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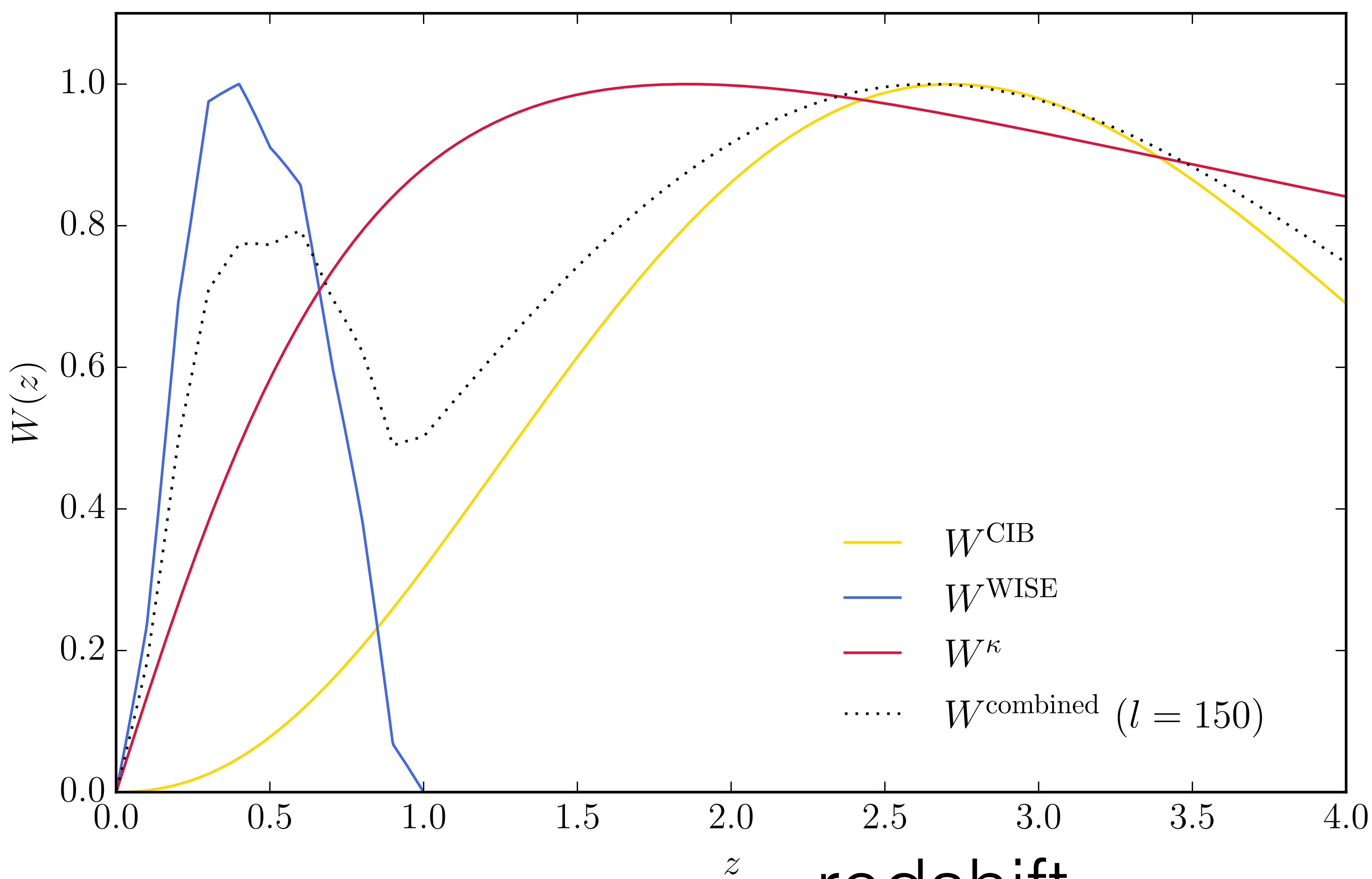
CMB Delensing

estimate lensing B-mode using multi-tracer LSS 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



redshift

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

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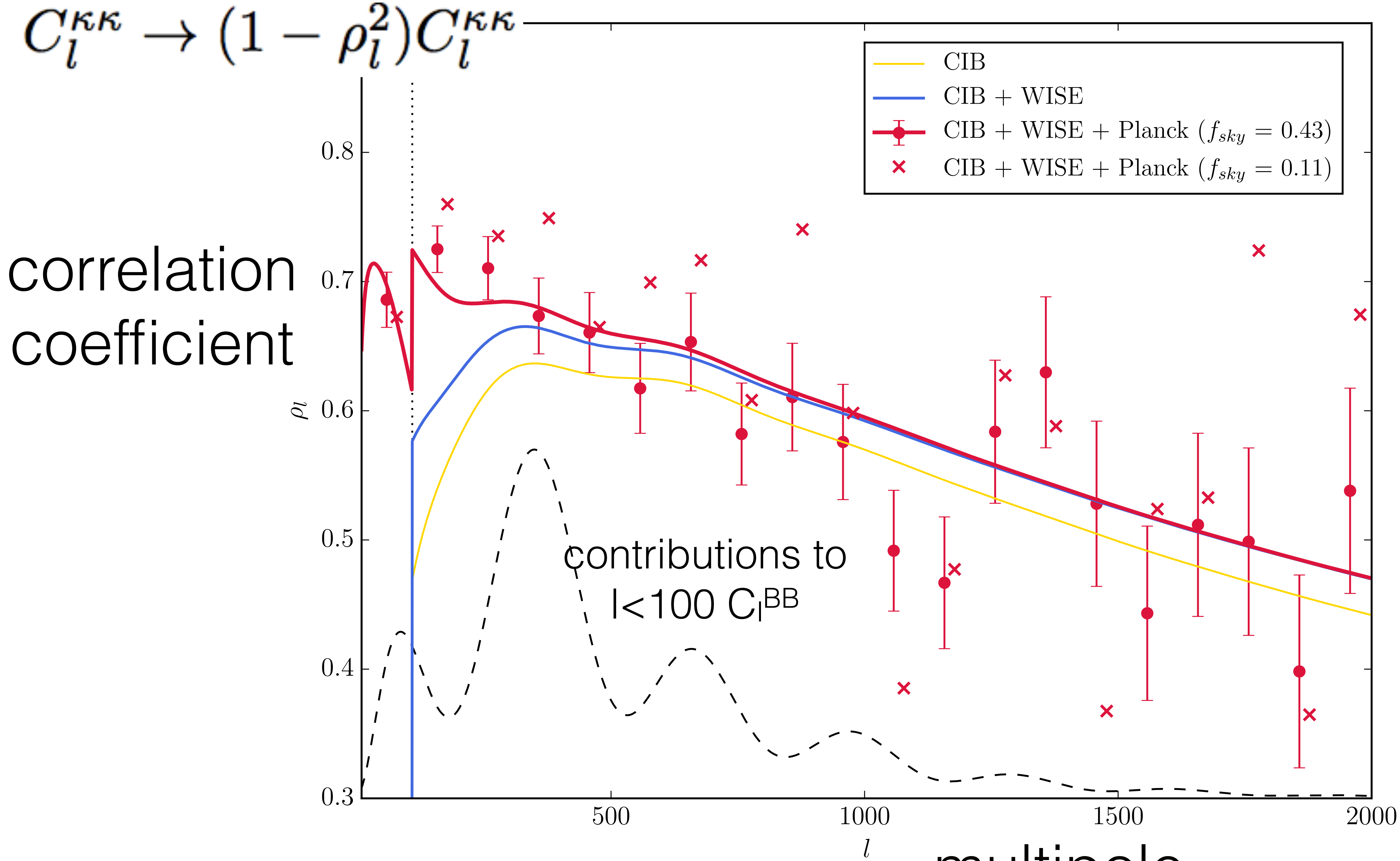
determine optimal linear combination coefficients by fitting models to all auto- and cross-power spectra

delensing efficiency ⟷ correlation coefficient with true κ

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



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

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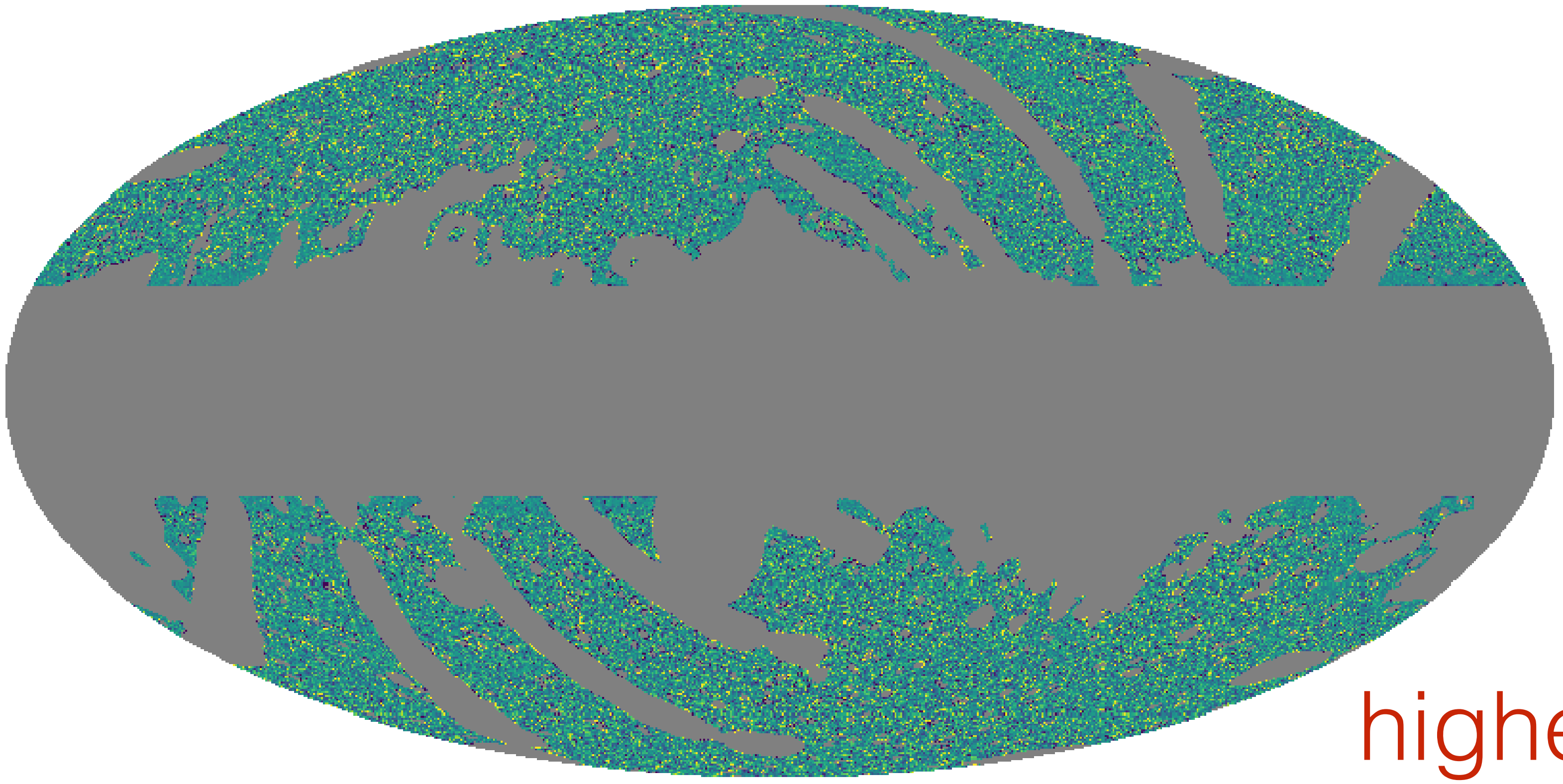
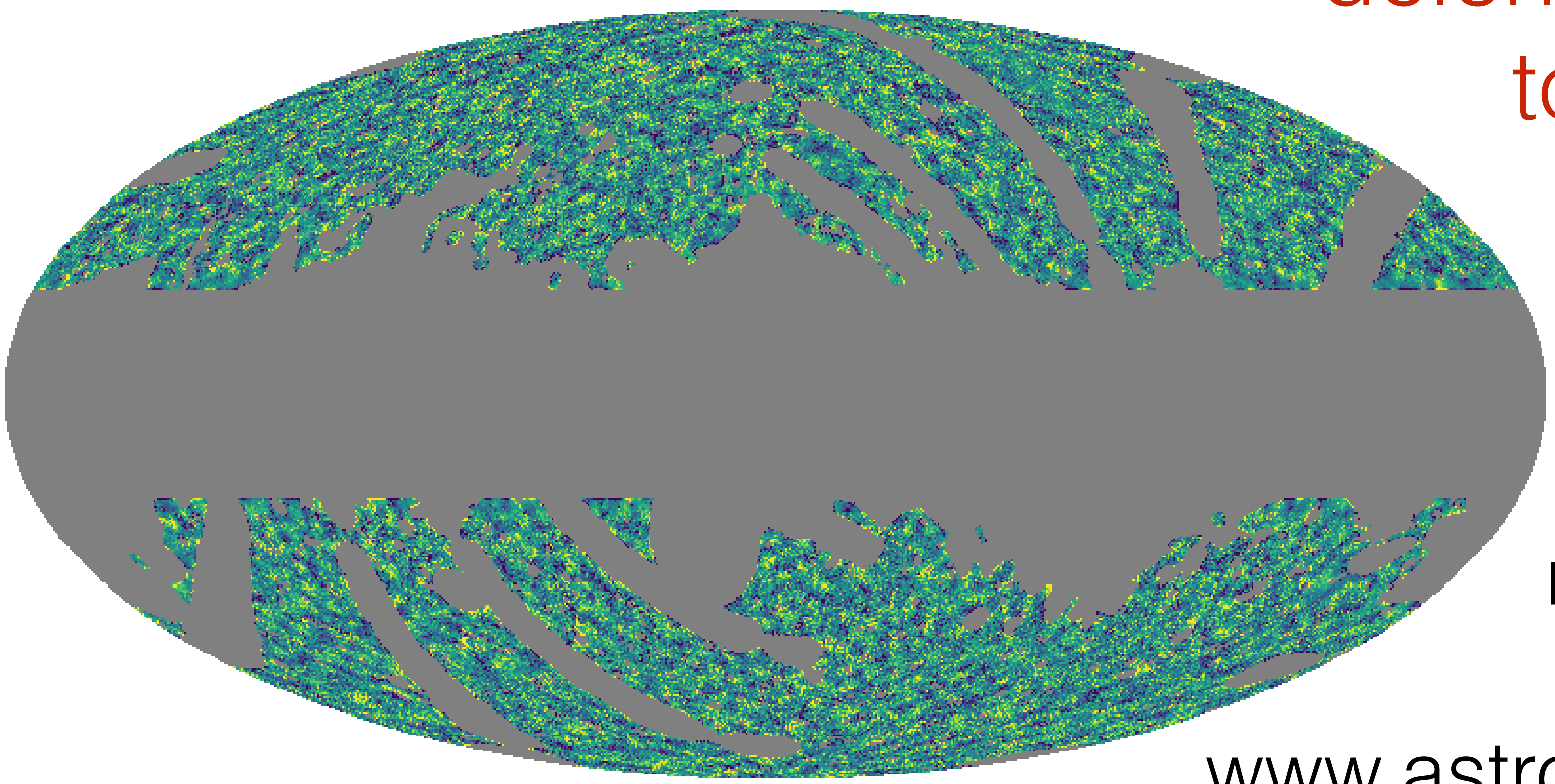
CIB
+
WISE



$f_{sky} = 0.43$



CIB
+
WISE
+
Planck κ

highest-fidelity delensing maps to date

maps: http://www.astro.princeton.edu/~jch/delens/

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

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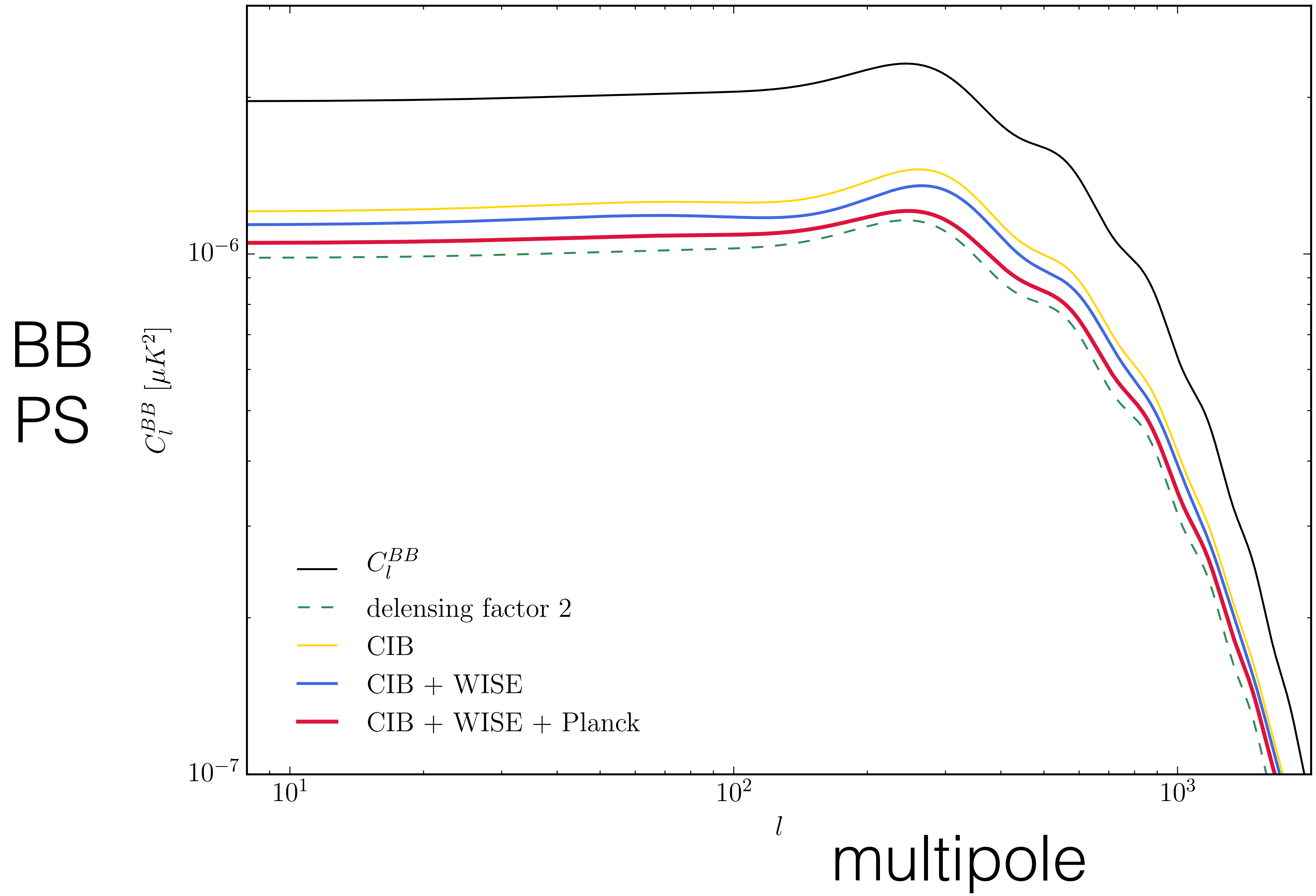
CMB Delensing

delensing factor ~2 on nearly half of the sky

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



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

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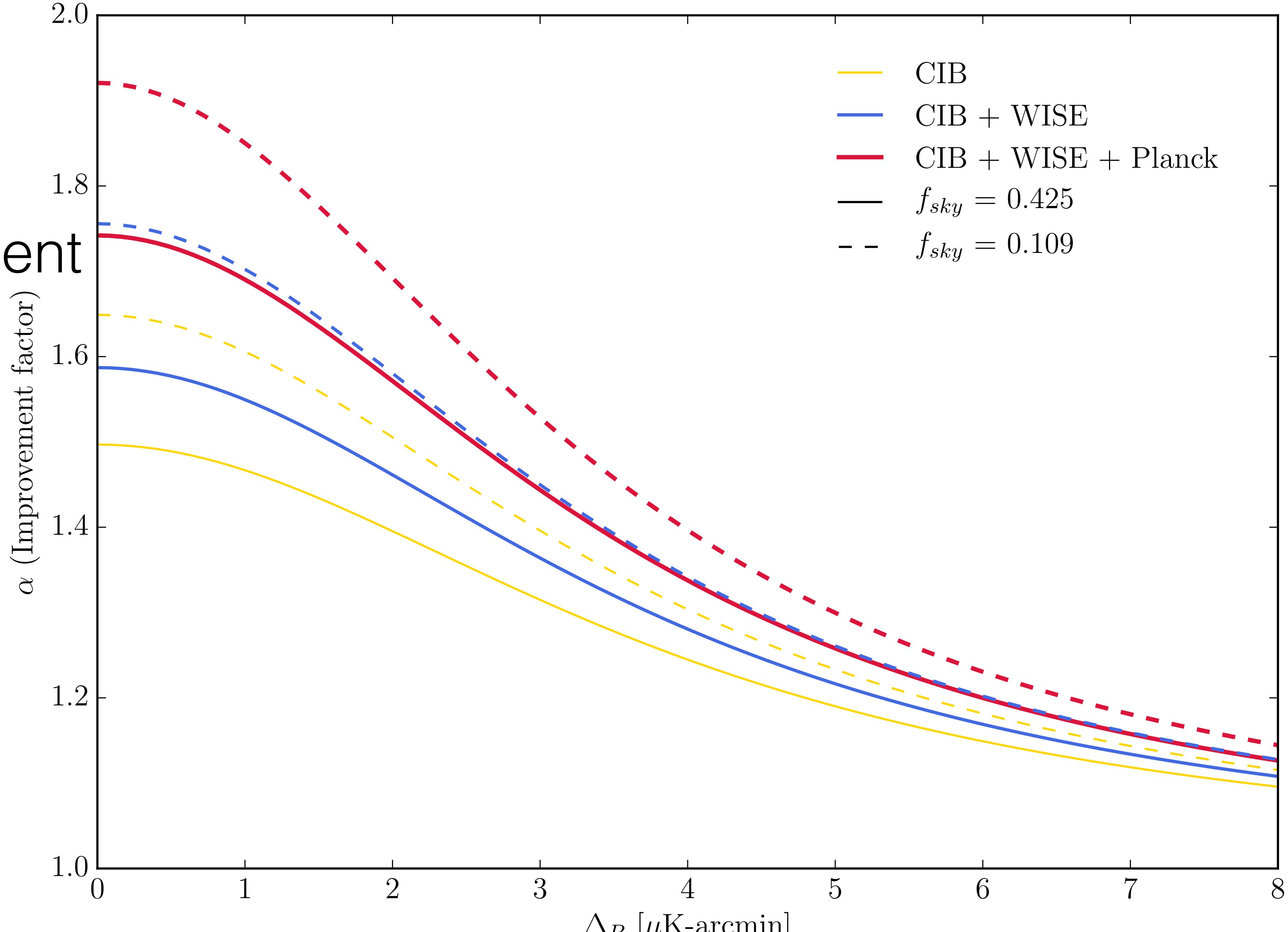

improvement in σ(r)

pol. noise level

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

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Conclusions

- Flexible, systematic foreground parameterizations are needed to robustly interpret upcoming polarization and spectral distortion measurements.

- *PIXIE* will detect Compton-y and relativistic tSZ distortions at high significance, even in the presence of foregrounds. μ constraints will improve upon *FIRAS* by factor of ~250.

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

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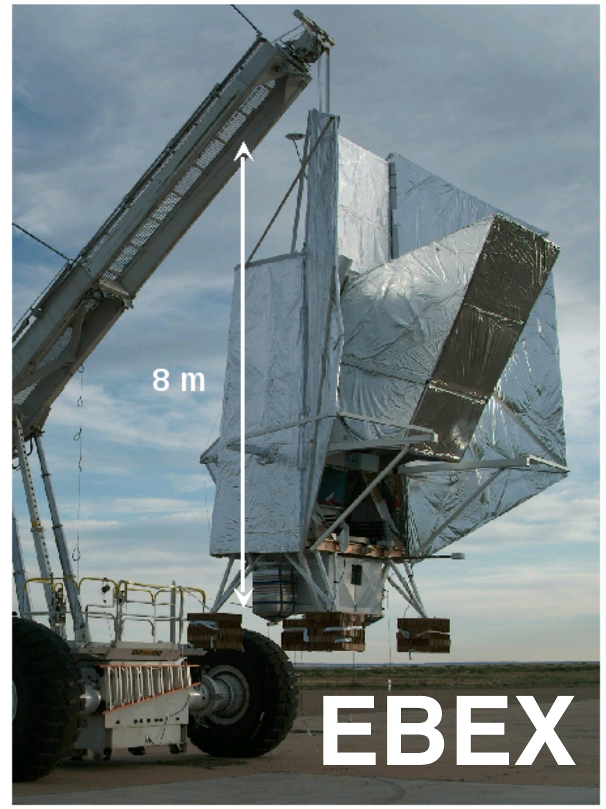

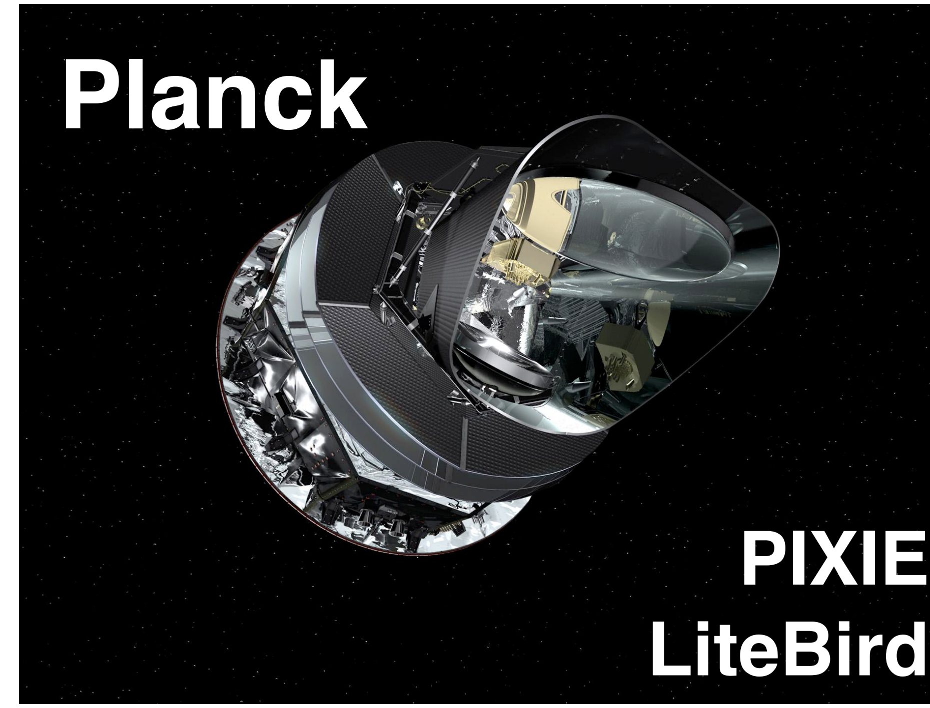

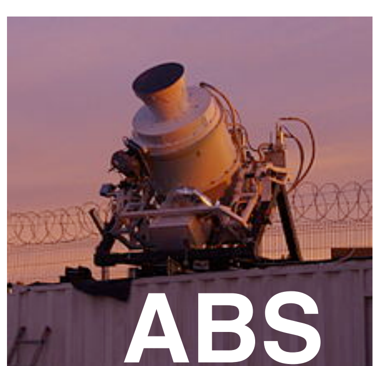

Thanks!