Gravitational lensing of line intensity maps

(and a few related topics)

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with

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based on 1803.04975, 1811.00529

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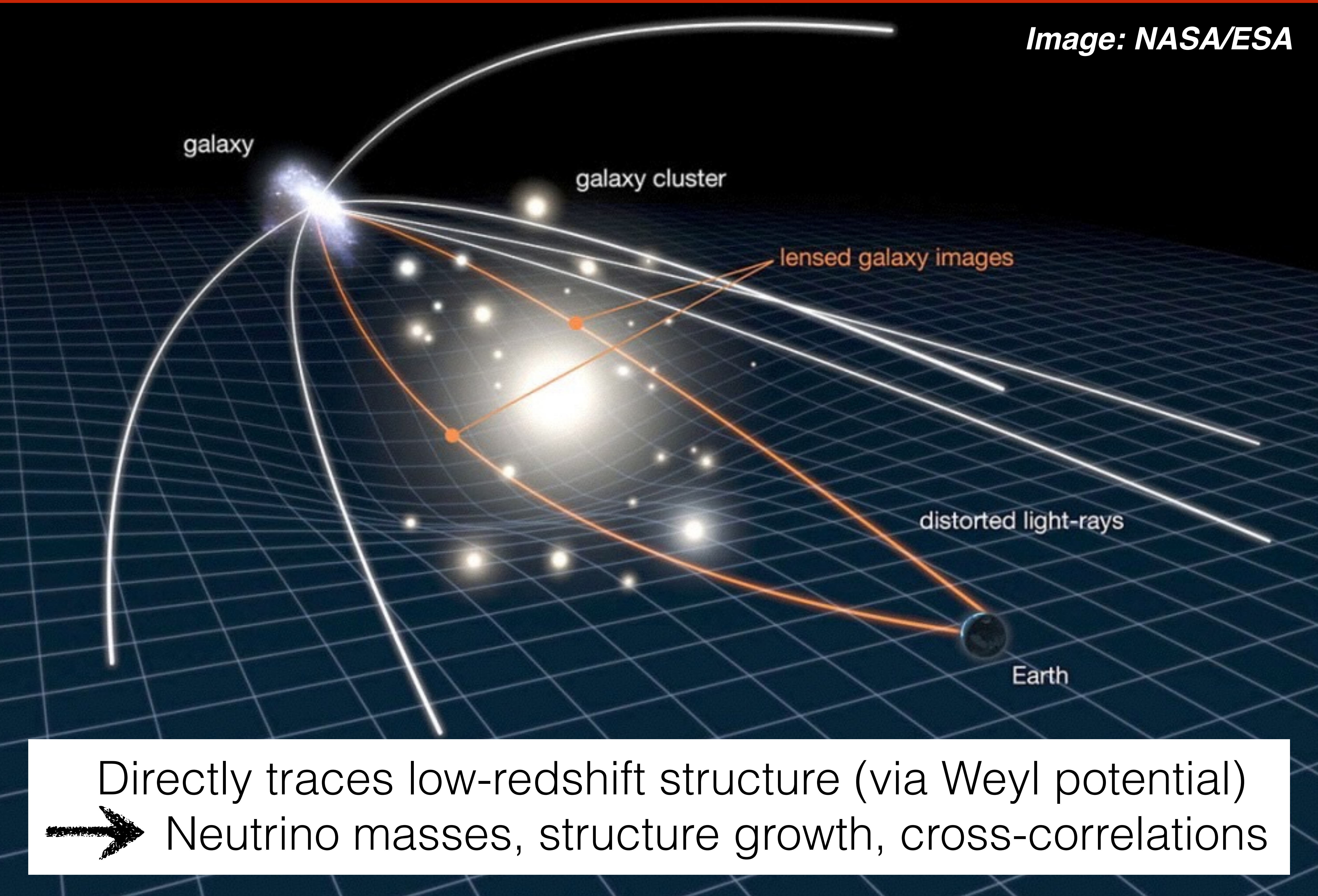
Canadian Institute for Theoretical Astrophysics

L'institut Canadien d'astrophysique théorique

LBL INPA Seminar

November 30, 2018

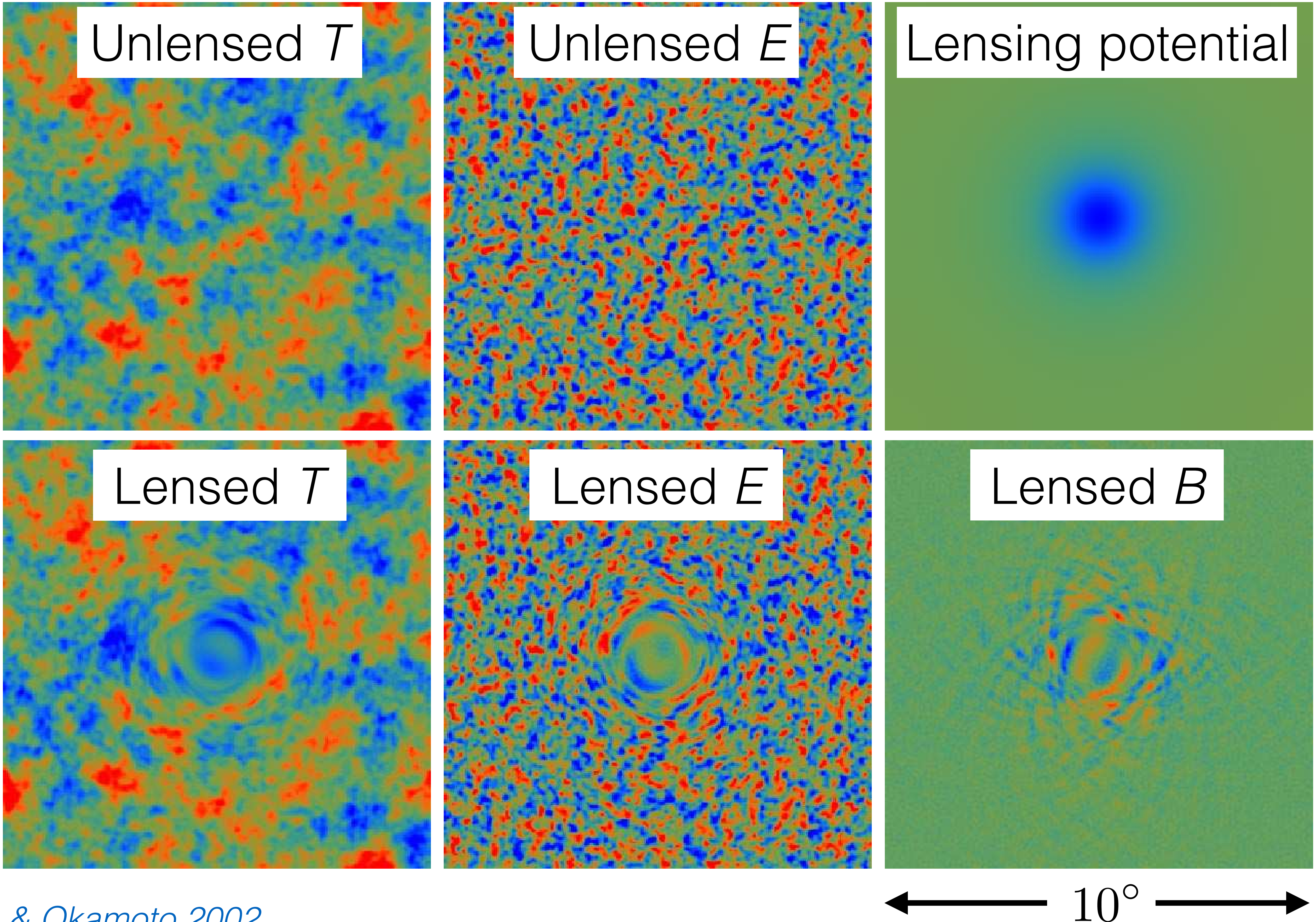
A cartoon of gravitational lensing



Directly traces low-redshift structure (via Weyl potential)

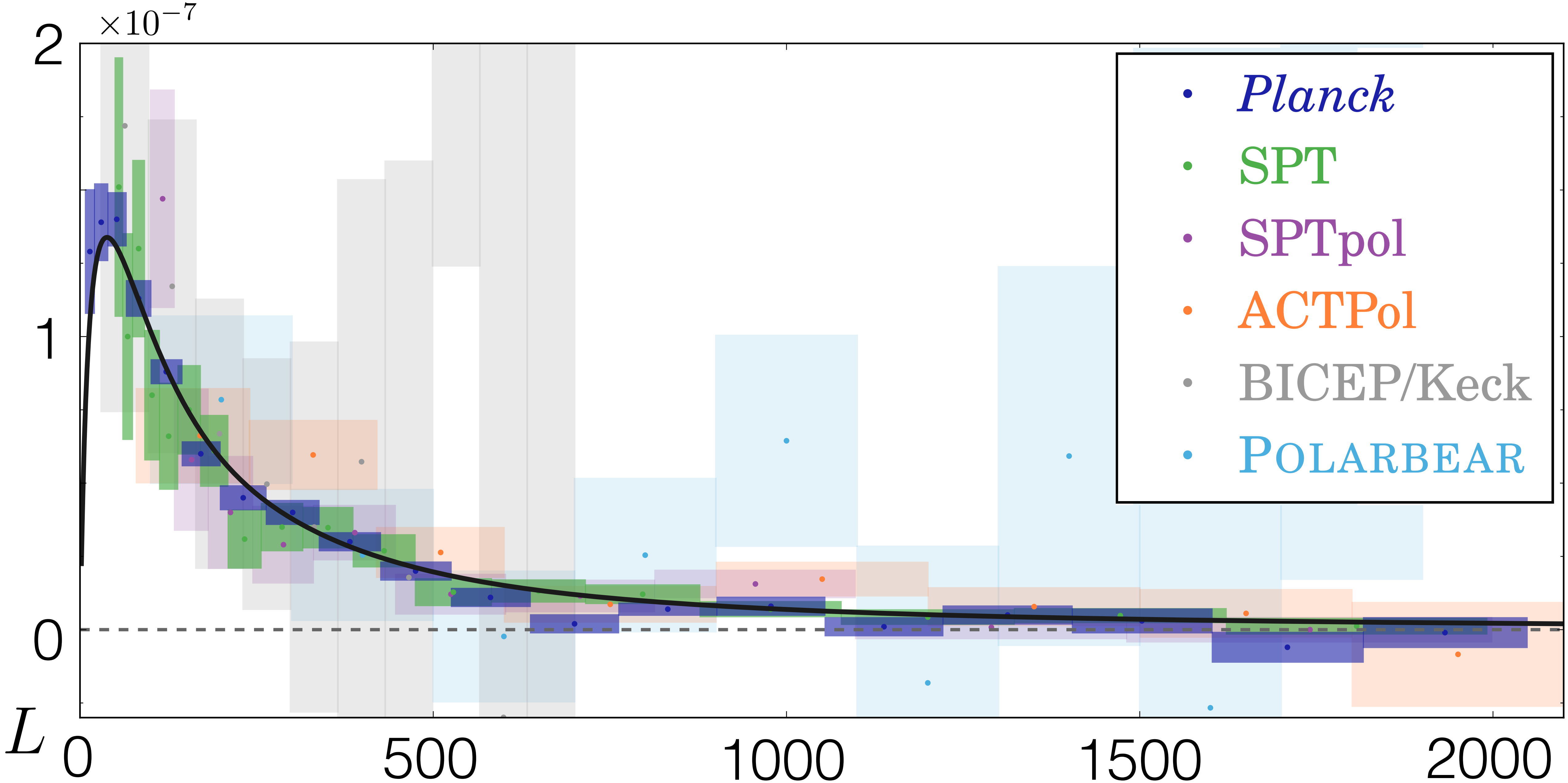
→ Neutrino masses, structure growth, cross-correlations

Low angular resolution lensing: CMB



Hu & Okamoto 2002

Low angular resolution lensing: CMB



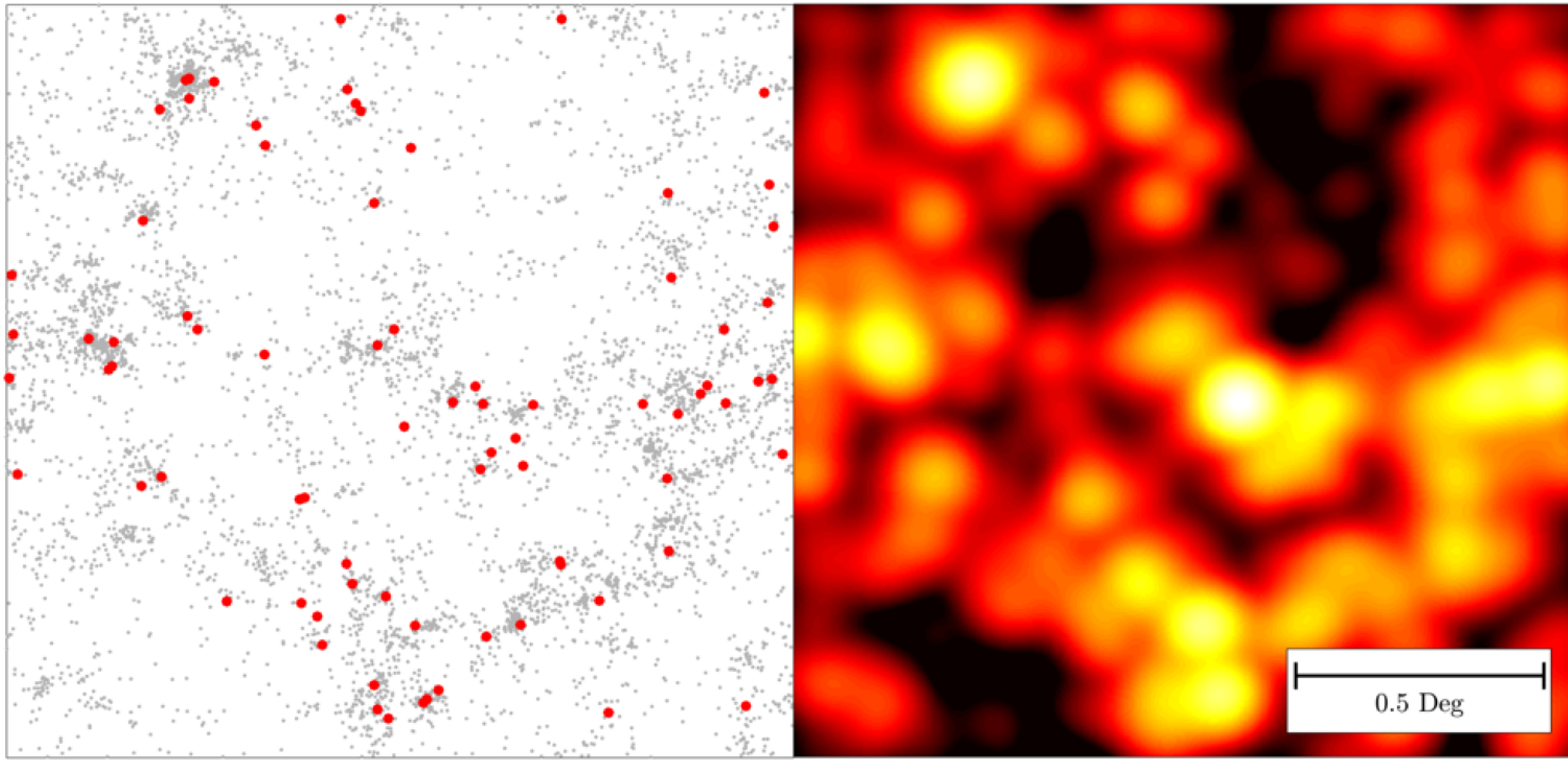
State of the art in CMB lensing:
40σ detection in Planck, 15σ in SPT+Planck, 7.1σ in ACTpol

CMB-S4: projected ~500σ detection

figure: Alex van Engelen

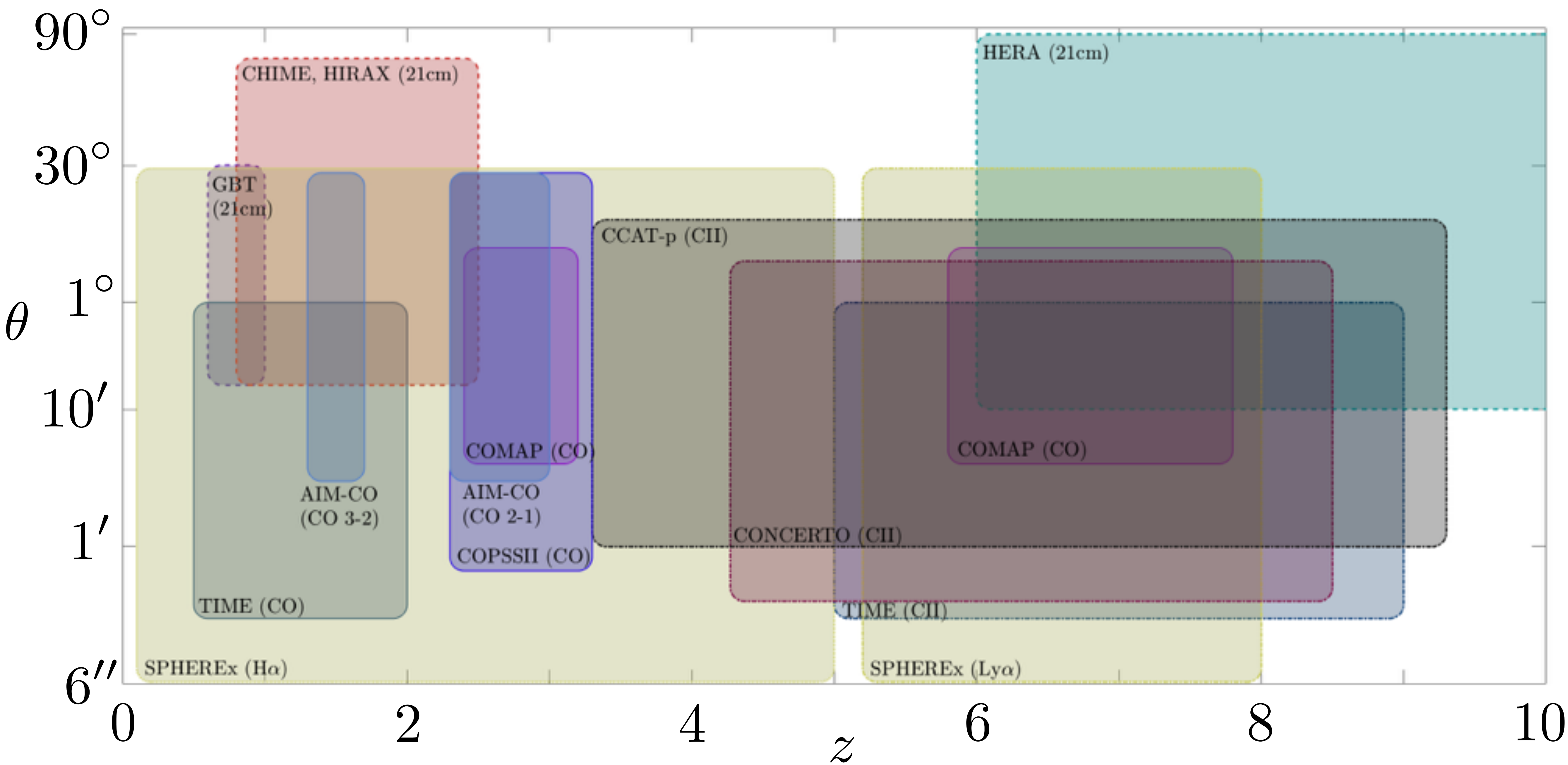
Low angular resolution lensing: the future?

Low angular resolution maps can also be made at other wavelengths: “(line) intensity mapping”



Kovetz et al. 2017 (figure: Patrick Breysse)

The landscape of line intensity mapping experiments



Observations planned for 21cm, CO, CII, …

Kovetz et al. 2017 (figure: Ely Kovetz & Patrick Breysse)

The promise of lensing reconstruction from intensity maps

Line intensity maps provide many 2d screens for lensing reconstruction

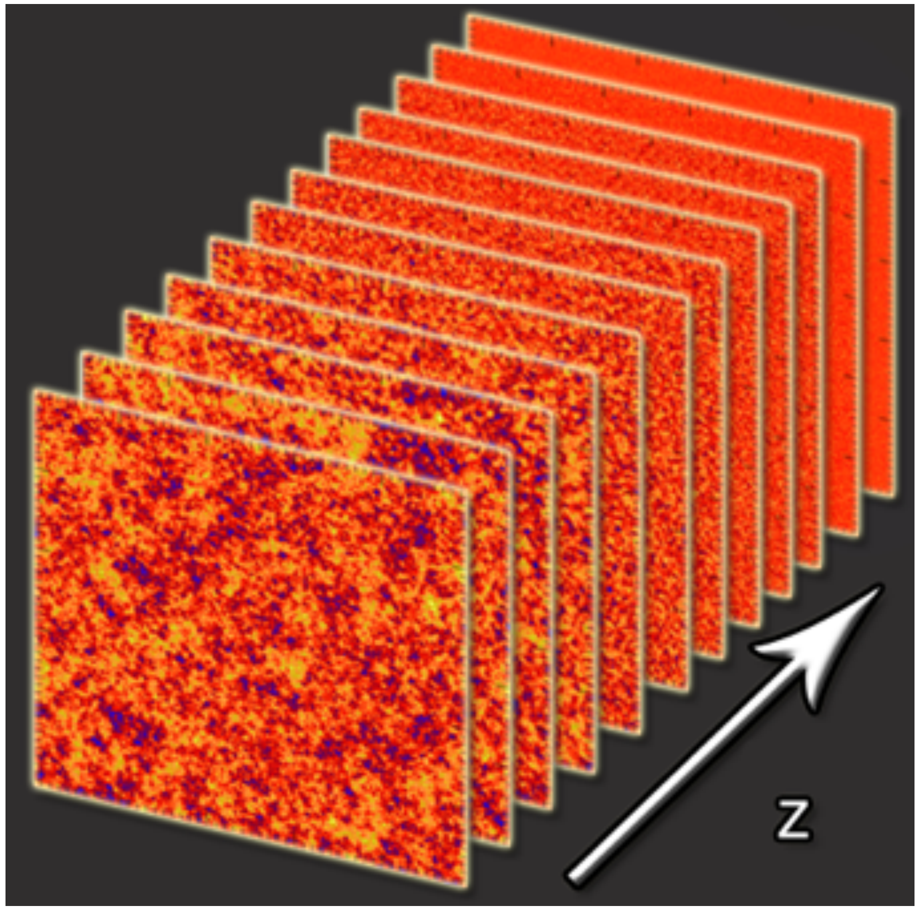


figure: Romeo et al. 2017

Closely-spaced screens

→ potentially high S/N on lensing

Widely-spaced sets of screens

→ different lensing kernels for tomography

Different systematics than CMB or galaxy lensing

Understanding a contaminant for e.g. nG constraints

Cooray 2004; Pen 2004; Zahn & Zaldarriaga 2006; Metcalf & White 2009; …

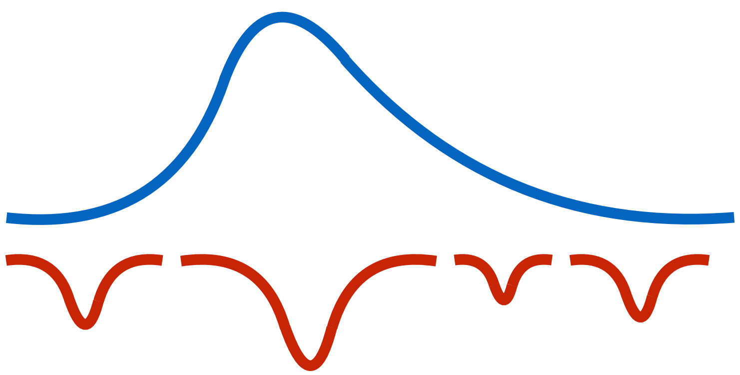
Outline

1. How CMB lensing is measured
2. Extension of method to 3d
   - *impact of gravitational nonlinearities*
3. Reducing gravitational effects in variance: "bias-hardening"
4. Forecasts
5. ** Recent work: CMB temperature reconstruction

Review of CMB lensing

Lensing potential: projection of gravitational potentials

$$\phi \sim \int_0^{\chi_{\rm s}} d\chi \, \underline{W(\chi)} \, \underline{\Phi(\chi\hat{n}, z[\chi])}$$



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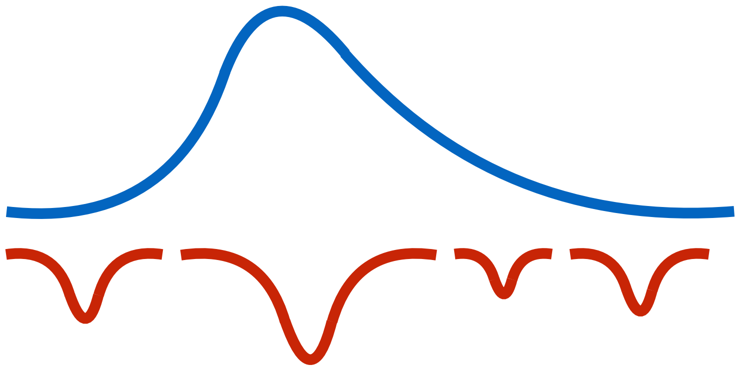

Unlensed CMB: different Fourier modes are uncorrelated

$$\left\langle T(\vec{\ell}_1) T^*(\vec{\ell}_2) \right\rangle = (2\pi)^2 \delta_{\rm D}(\vec{\ell}_1 - \vec{\ell}_2) C_{\ell_1}^{(\rm unlensed)}$$

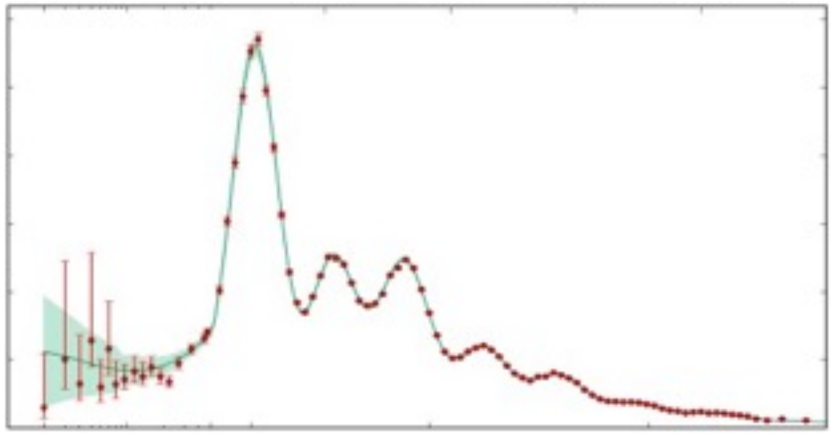

figure: ESA

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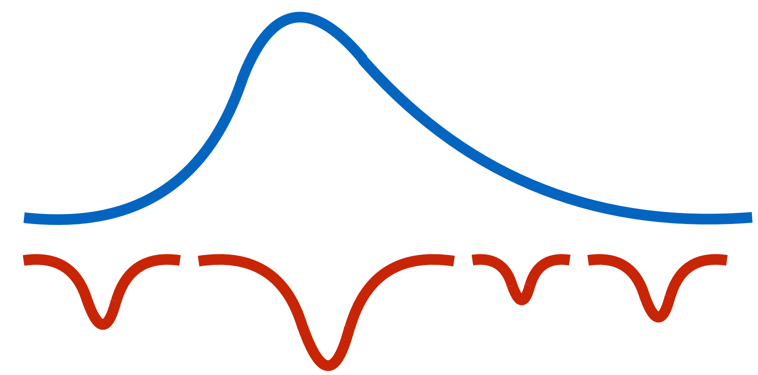

Unlensed CMB: different Fourier modes are uncorrelated

$$\left\langle T(\vec{\ell}_1)T^*(\vec{\ell}_2)\right\rangle = (2\pi)^2\delta_\mathrm{D}(\vec{\ell}_1 - \vec{\ell}_2)C_{\ell_1}^{(\mathrm{unlensed})} + f(\vec{\ell}_1, \vec{\ell}_2)\phi(\vec{\ell}_1 - \vec{\ell}_2)$$

Lensed CMB: different Fourier modes become correlated

Review of CMB lensing

Can use this correlation to construct an *estimator* for ϕ:

$$\hat{\phi}_{\vec{\ell}}(\vec{L}) = \frac{T(\vec{\ell})T^*(\vec{\ell}-\vec{L})}{f(\vec{\ell},\vec{\ell}-\vec{L})}$$

Review of CMB lensing

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Can do better by inverse-variance weighting:

$$\hat{\phi}(\vec{L}) = N_L \sum_{\vec{\ell}} \frac{\hat{\phi}_{\vec{\ell}}(\vec{L})}{\mathrm{Var}\left[\hat{\phi}_{\vec{\ell}}(\vec{L})\right]}$$

Hu 2001

Review of CMB lensing

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Power spectrum of reconstructed ϕ map:

$$\left\langle \hat{\phi}(\vec{L})\hat{\phi}^*(\vec{L}) \right\rangle = C_L^{\phi\phi} + N_L + \cdots$$

Hu 2001

Review of CMB lensing

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Power spectrum of reconstructed ϕ map:

$$\left\langle \hat{\phi}(\vec{L})\hat{\phi}^*(\vec{L}) \right\rangle = \underline{C_L^{\phi\phi}} + \underline{N_L} + \cdots$$

$$\left(\quad \left\langle \hat{\phi}\hat{\phi} \right\rangle \sim \langle TTTT \rangle \sim \underbrace{\langle TT \rangle^2}_{\textbf{Gaussian}} + \underbrace{\langle TTTT \rangle_{\mathrm{c}}}_{\textbf{non-Gaussian}} \quad \right)$$

Hu 2001

Outline

1. How CMB lensing is measured
    - *exploits mode-couplings induced by lensing*
    - *connected 4-pt function → lensing potential power spectrum*
2. **Extension of method to 3d**
3. Reducing gravitational effects in variance: "bias-hardening"
4. Forecasts

Observations in 3d

3d intensity field, observed within comoving thickness $\mathcal{L}$:

$$I(\vec{x}_\perp, x_\parallel) \longrightarrow I(\vec{\ell}, k_\parallel)\,, \qquad k_\parallel = \frac{2\pi}{\mathcal{L}} j\,, \quad j = 0, 1, 2, \ldots$$

Angular power spectrum
for given j:

$$C_\ell(k_\parallel) \propto P_I\left(\sqrt{\ell^2/\chi^2 + k_\parallel^2}\right)$$

(Easier to account for
correlations this way)

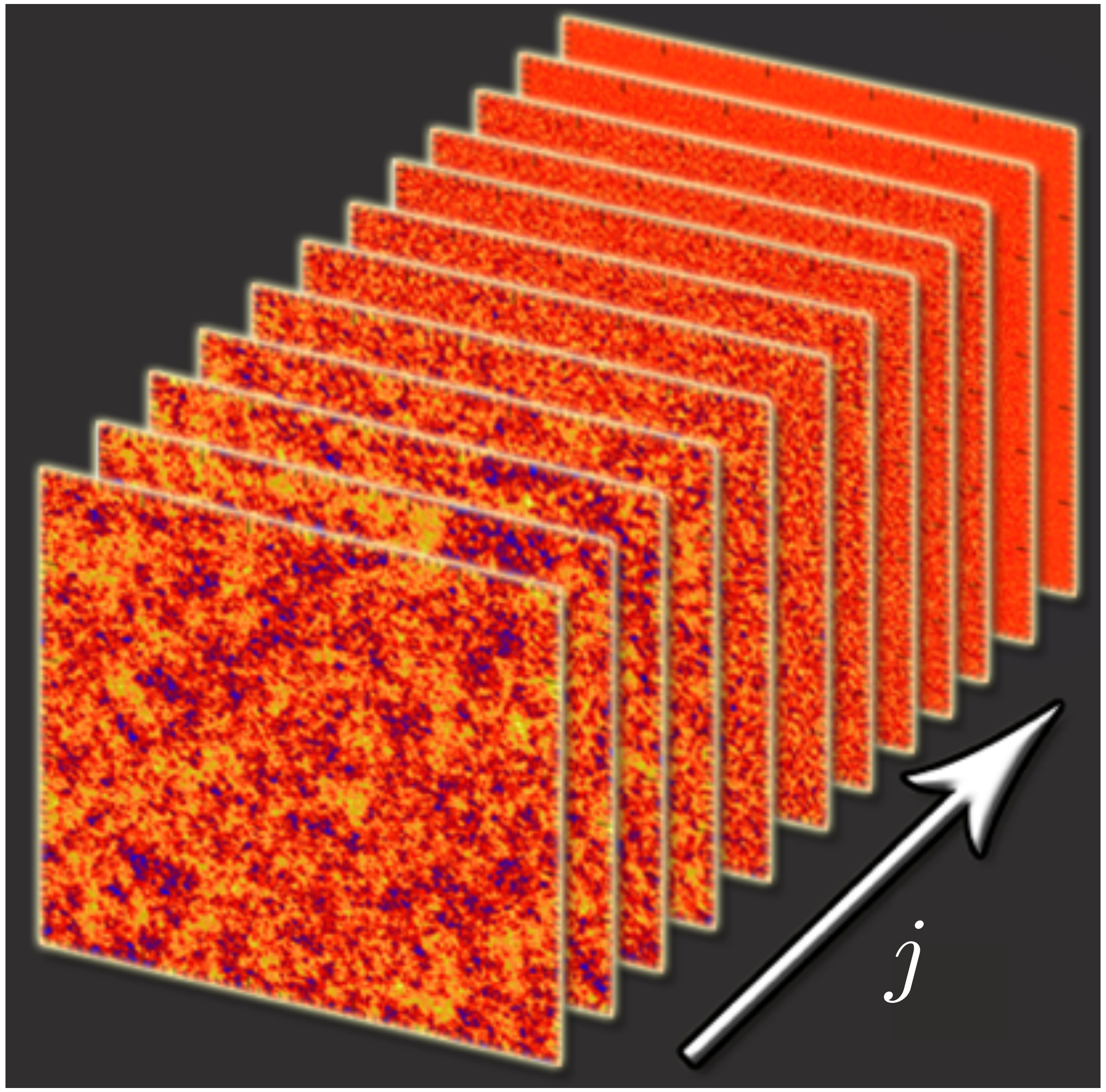
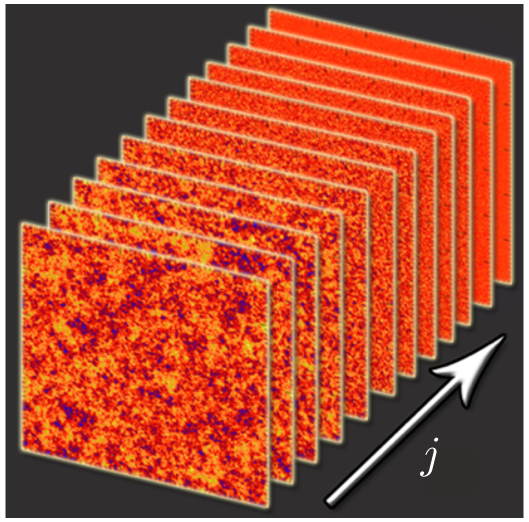


figure: Romeo et al. 2017

Zahn & Zaldarriaga 2006; Pourtsidou & Metcalf 2014

3d lensing estimator

Can construct estimator for each j:



$$\hat{\phi}(\vec{L}, k_{||}) = N_{\phi\phi}(L, k_{||}) \times \int_{\vec{\ell}} g(\vec{\ell}, \vec{L} - \vec{\ell}) I(\vec{\ell}, k_{||}) I(\vec{L} - \vec{\ell}, -k_{||})$$

Power spectra of reconstructed ϕ maps:

$$\left\langle \hat{\phi}(\vec{L}, k_{||}) \hat{\phi}^*(\vec{L}, k_{||}) \right\rangle = C_L^{\phi\phi} + N_{\phi\phi}(\vec{L}, k_{||}) + \cdots$$

Can coadd j's to reduce noise in maps:

$$\longrightarrow \quad \mathrm{Var}[\hat{\phi}(\vec{L})] = \frac{1}{\sum_j N_{\phi\phi}^{-1}(L, k_{||})} \sim \frac{1}{j_{\max}} N_{\phi\phi}$$

Zahn & Zaldarriaga 2006; Pourtsidou & Metcalf 2014

However, we missed an important contribution!

$$\left\langle \hat{\phi}(\vec{L}, k_{\parallel 1})\hat{\phi}^*(\vec{L}, k_{\parallel 2}) \right\rangle$$

2-pt function of $\hat{\phi}$

$$\sim \int_{\vec{\ell}_1} \int_{\vec{\ell}_2} (\cdots)(\cdots) \left\langle I I I^* I^* \right\rangle$$

4-pt function of I

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$$\left\langle \hat{\phi}(\vec{L}, k_{\parallel 1}) \hat{\phi}^*(\vec{L}, k_{\parallel 2}) \right\rangle$$ **2-pt function of $\hat{\phi}$**

$$\sim \int_{\vec{\ell}_1} \int_{\vec{\ell}_2} (\cdots)(\cdots) \, \langle I I I^* I^* \rangle$$ **4-pt function of I**

$$\sim \delta_{k_{\parallel 1}, k_{\parallel 2}} N_{\phi\phi}(L, k_{\parallel 1})$$ **disconnected 4-pt**

$$+ \, C_L^{\phi\phi}$$ **connected 4-pt from lensing**

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$$+ C_L^{\phi\phi}$$ **connected 4-pt from lensing**

$$+ \int_{\vec{\ell}_1} \int_{\vec{\ell}_2} (\cdots)(\cdots) \left\langle \tilde{I} \tilde{I} \tilde{I}^* \tilde{I}^* \right\rangle_{\rm c}$$ **connected 4-pt of unlensed field**

If I traces $\delta_{\rm matter}$, $\left\langle \tilde{I} \tilde{I} \tilde{I}^* \tilde{I}^* \right\rangle_{\rm c} \sim \langle \delta\delta\delta\delta \rangle_{\rm c,\, gravity}$

Quantifying the gravitational contribution

Main goal: quantify impact of gravitational contributions ($\langle\delta\delta\delta\delta\rangle_{\rm c,gravity}$) on lensing estimator

Assumptions (21cm):

$\tilde{I} \sim b\,\delta_{\rm matter}$ (linearly biased tracer)

tree-level perturbation theory for grav. 4-pt. function

instrumental noise = thermal noise, set by T_{sys}, n_{base}, …

foregrounds kill modes with low $k_{||}$

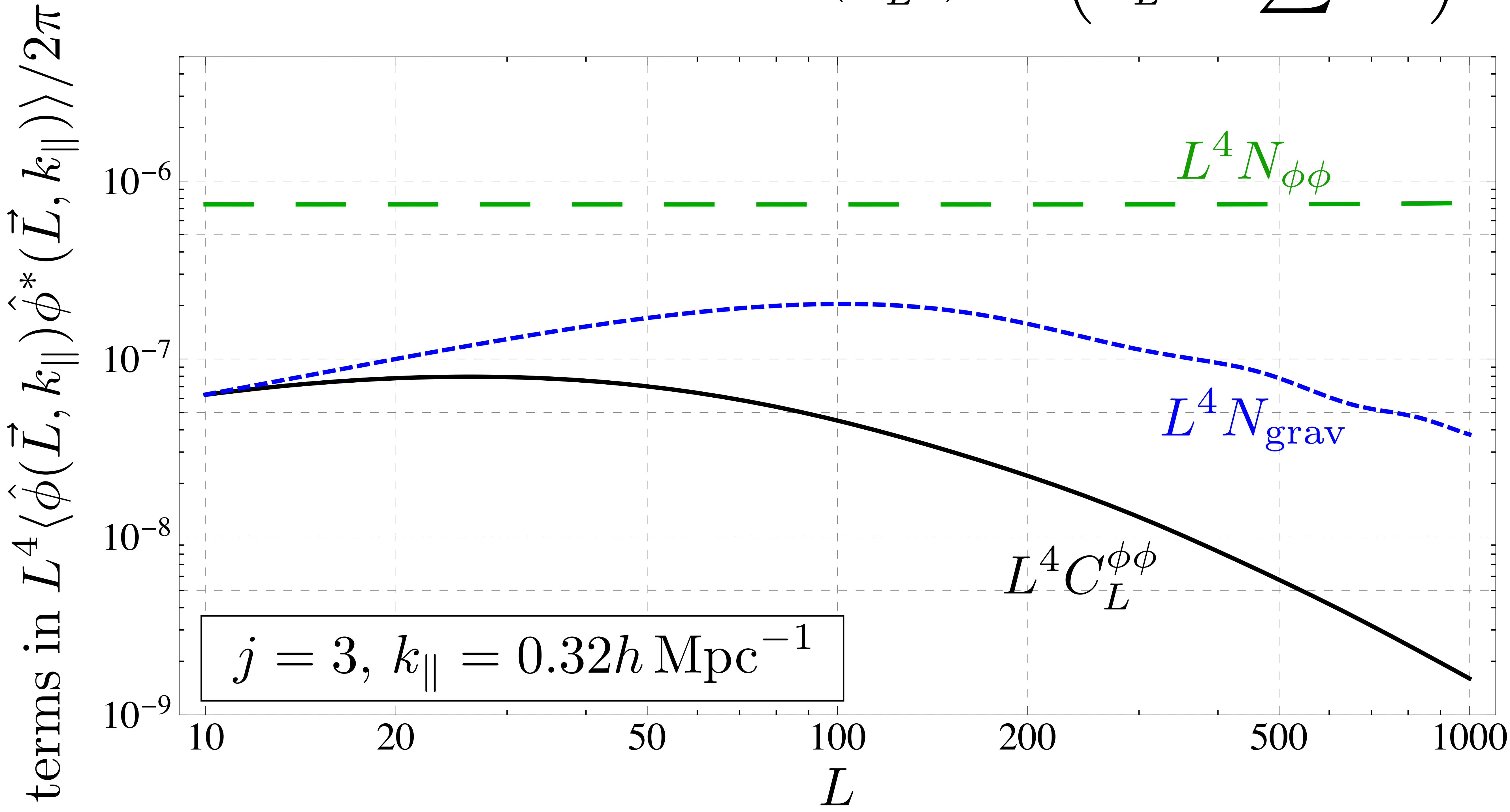
can cross-correlate with ~LSST

Lensing estimator for single $k_\parallel$

$N\ldots$ terms add both *bias* and *noise* to $C_L^{\phi\phi}$

$$\langle \hat{\phi}\hat{\phi}^* \rangle \propto C_L^{\phi\phi} + \sum N\ldots$$

$$\sigma(\hat{C}_L^{\phi\phi})^2 \propto \left(C_L^{\phi\phi} + \sum N\ldots \right)$$



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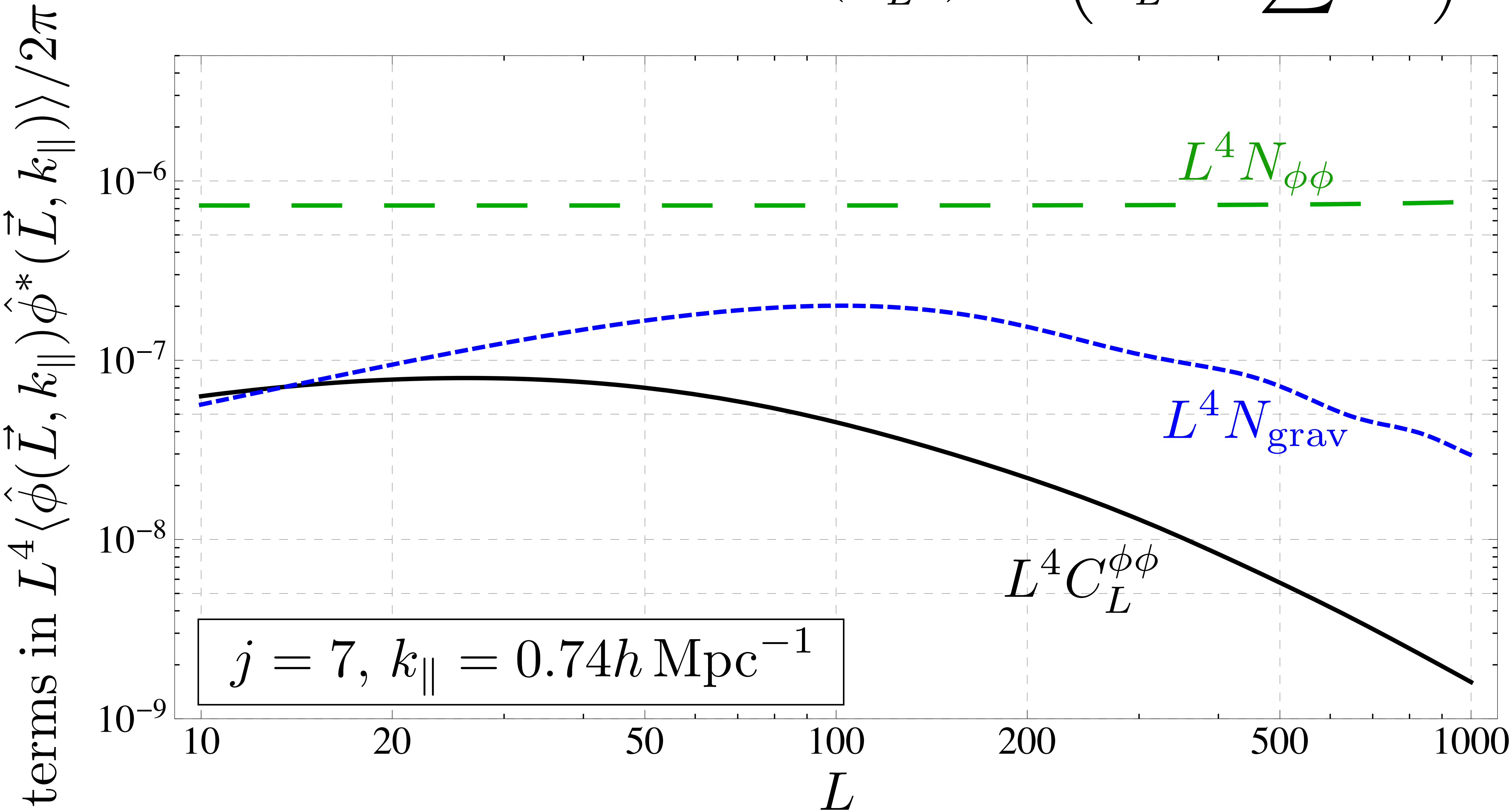

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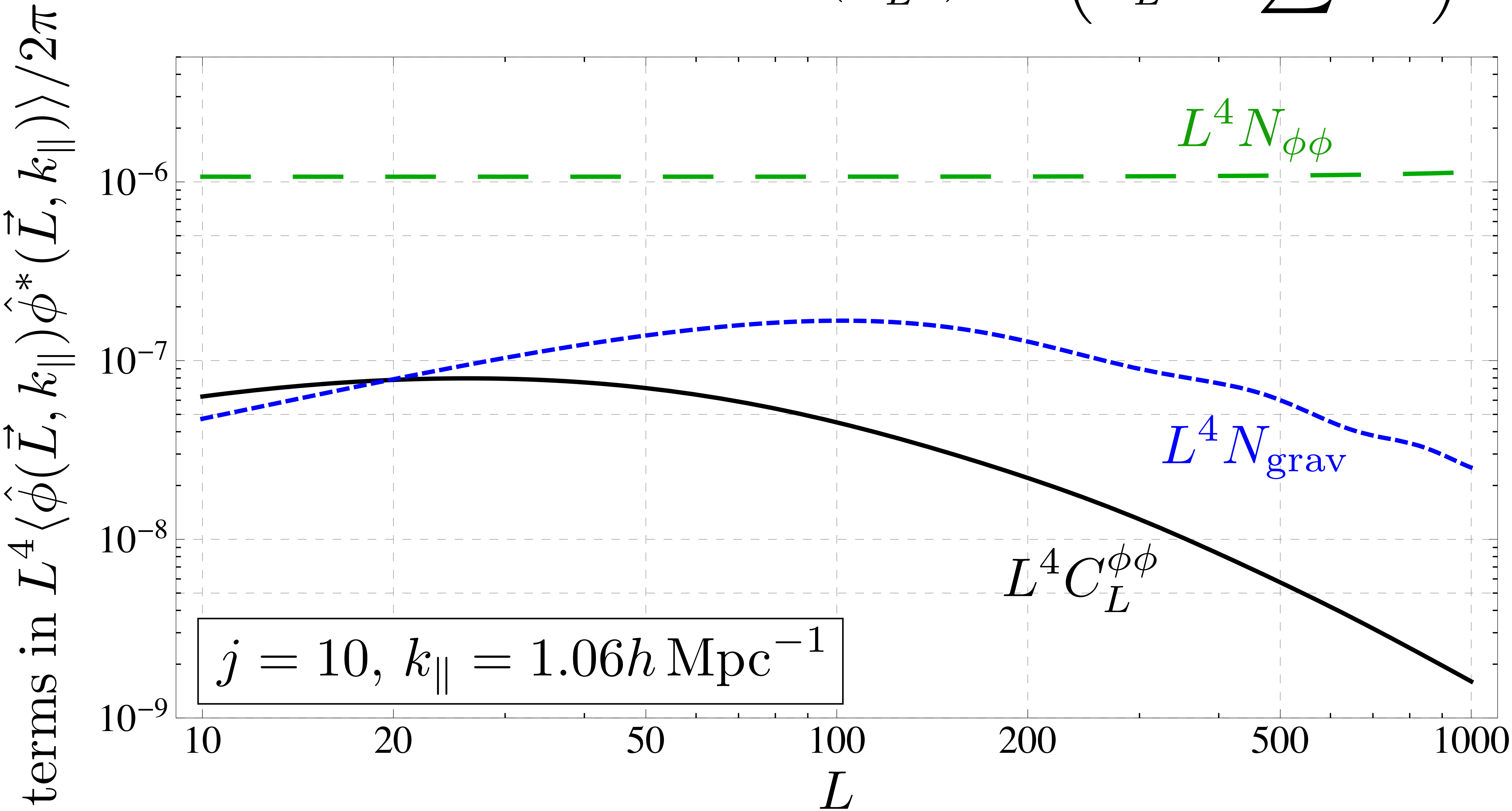

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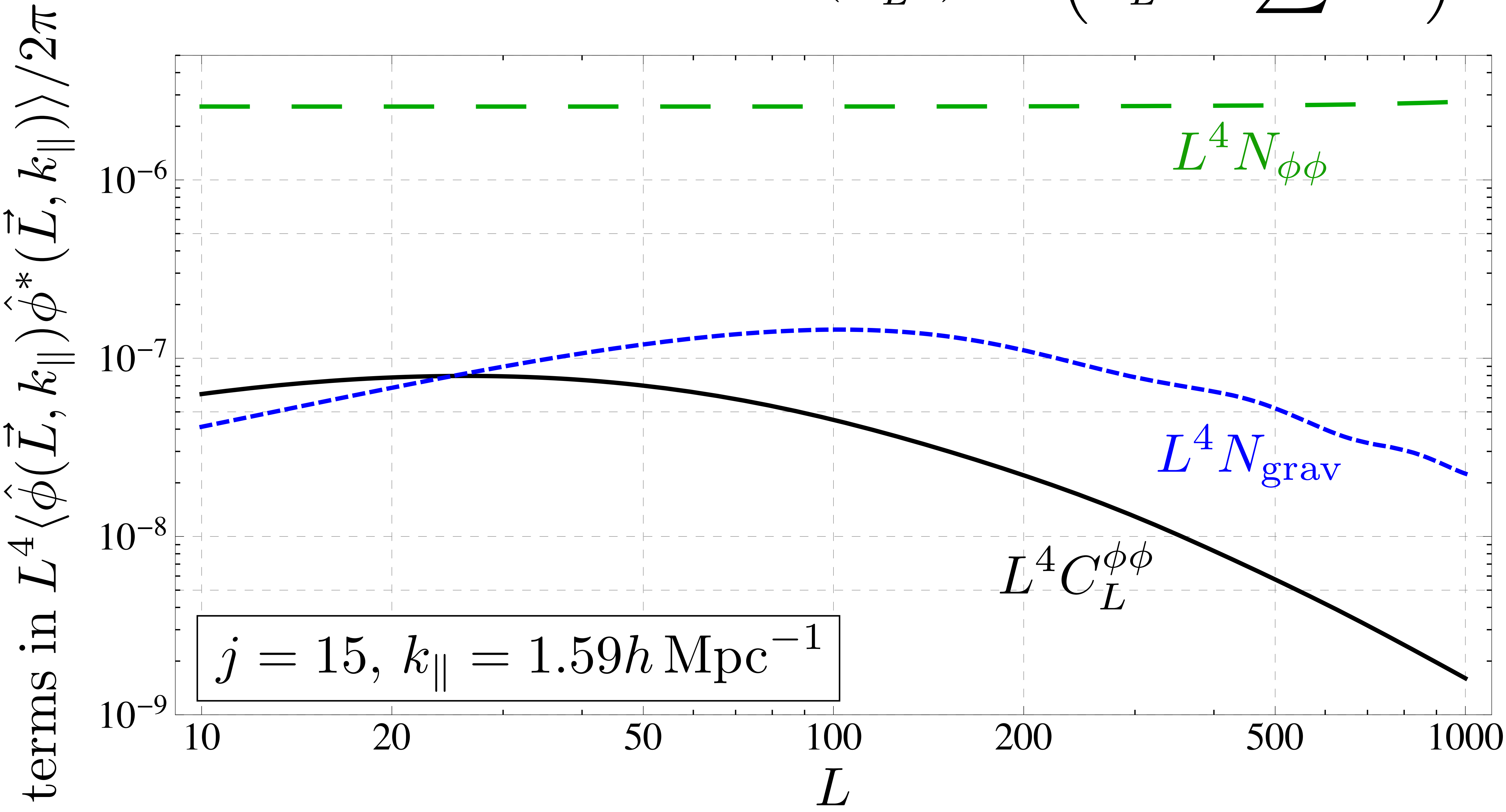
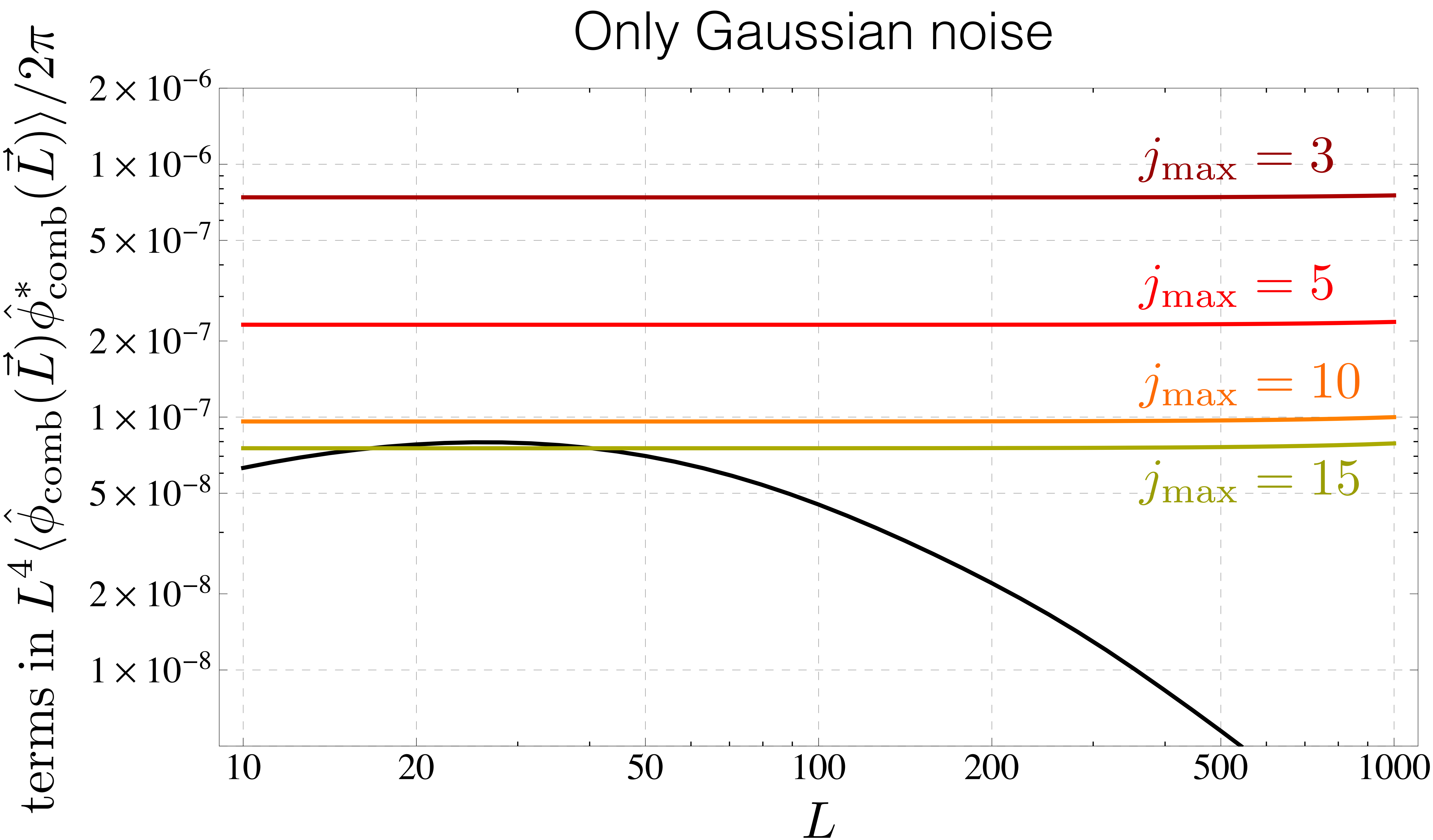


Lensing estimator, combining signal from several j's



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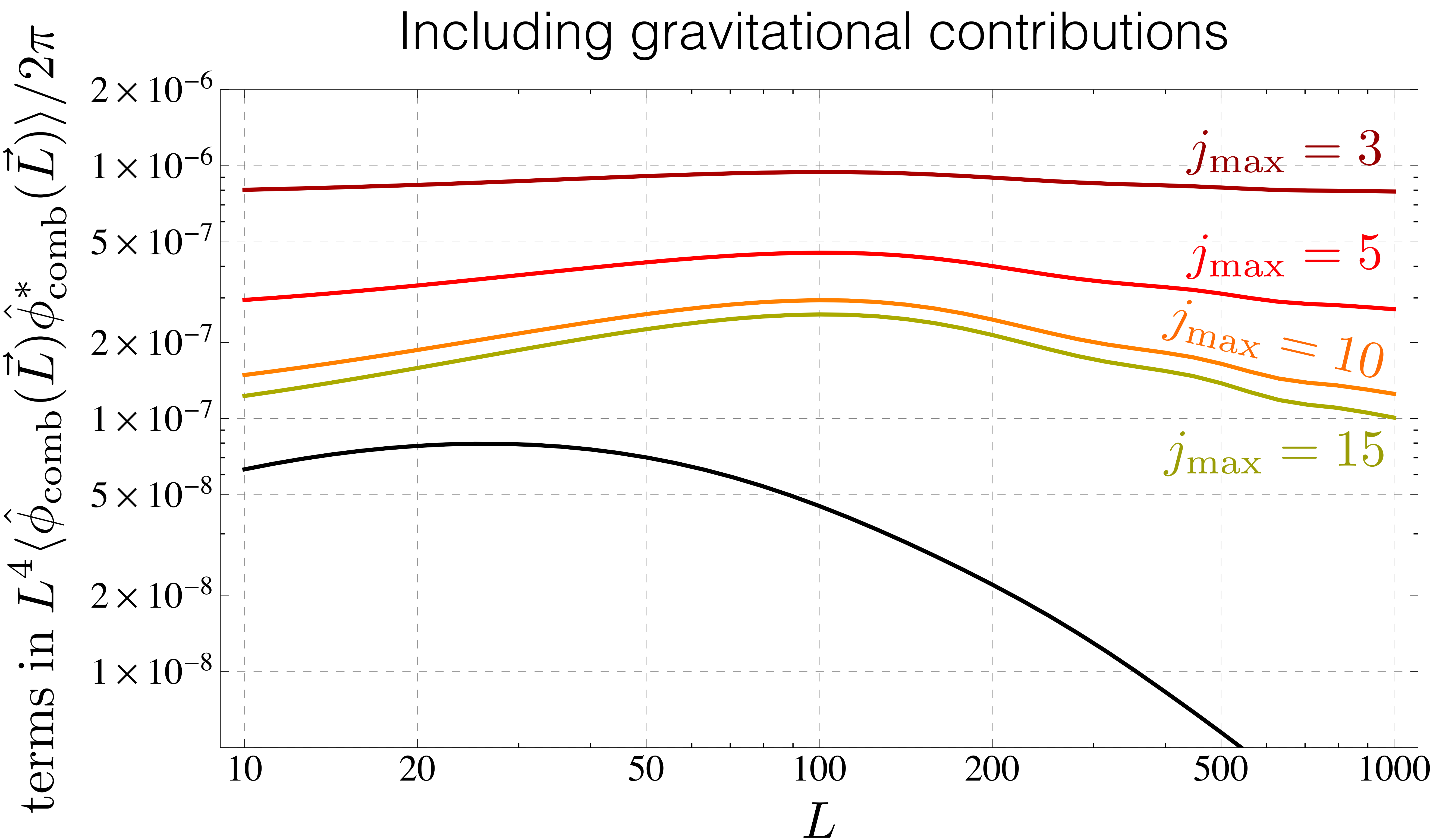

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   - *gravity adds noise, that is correlated between $k_\parallel$s*
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Lensing and gravity both induce mode-coupling

Unlensed intensity: different Fourier modes are uncorrelated

$$\left\langle I(\vec{\ell}_1, k_\parallel) I^*(\vec{\ell}_2, -k_\parallel) \right\rangle = (2\pi)^2 \delta_{\rm D}(\vec{\ell}_1 - \vec{\ell}_2) C_\ell^{\rm (unlensed)}(k_\parallel)$$

$$+ f_\phi(\vec{\ell}_1, \vec{\ell}_2) \phi(\vec{\ell}_1 - \vec{\ell}_2)$$

Lensed intensity: different Fourier modes become correlated

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$$+ f_\phi(\vec{\ell}_1, \vec{\ell}_2) \phi(\vec{\ell}_1 - \vec{\ell}_2)$$

$$+ f_\delta(\vec{\ell}_1, \vec{\ell}_2) \delta_{\rm m}(\vec{\ell}_1 - \vec{\ell}_2)$$

Lensed, nonlinear intensity: different Fourier modes become correlated

(can obtain $f_\delta(\vec{\ell}_1, \vec{\ell}_2)$ *from perturbation theory)*

Bias-hardened estimators

Define ϕ and δ estimators like so:

$$\hat{X}(\vec{L}) \sim \int_{\vec{\ell}} g_X(\vec{\ell}, \vec{L} - \vec{\ell}) I(\vec{\ell}) I(\vec{L} - \vec{\ell})$$

Each estimator is biased by the other field:

$$\begin{cases} \left\langle \hat{\phi} \right\rangle \sim \phi + (\cdots)\delta_1(\vec{L}/\chi) \\ \left\langle \hat{\delta} \right\rangle \sim (\cdots)\phi + \delta_1(\vec{L}/\chi) \end{cases}$$

Namikawa et al. 2013

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Define new estimators as solutions of linear system!

Namikawa et al. 2013

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Define new estimators as solutions of linear system!

Caveat:
increased variance

$$\mathrm{Var}\left[\hat{\phi}^{\mathrm{H}}\right] = \frac{N_{\phi\phi}}{1-\rho(\hat{\phi},\hat{\delta})^2} + \cdots$$

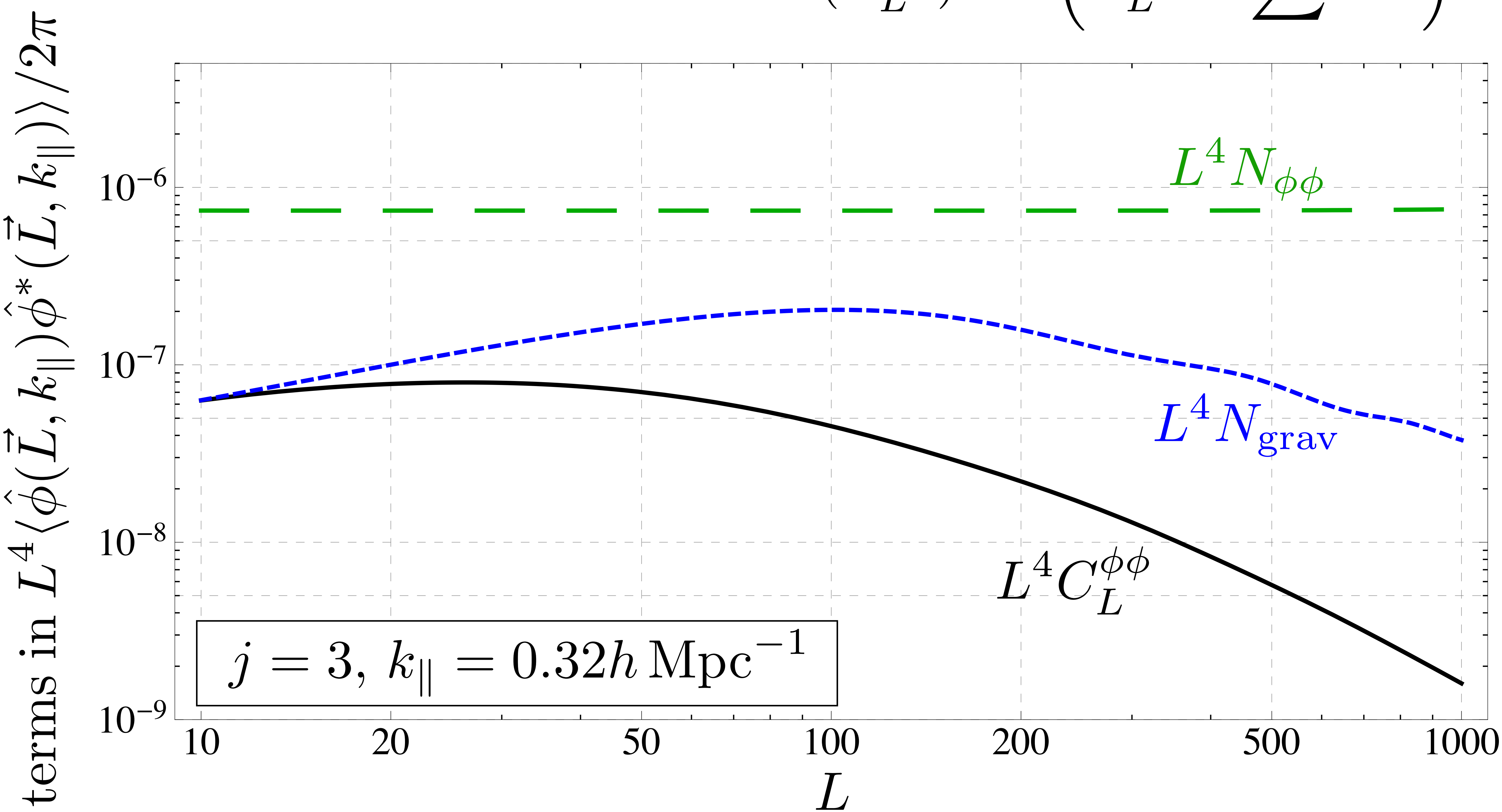
Namikawa et al. 2013

Previous lensing estimator for single $k_\parallel$

$N_{...}$ terms add both *bias* and *noise* to $C_L^{\phi\phi}$

$$\langle \hat\phi \hat\phi^* \rangle \propto C_L^{\phi\phi} + \sum N_{...}$$

$$\sigma(\hat C_L^{\phi\phi})^2 \propto \left(C_L^{\phi\phi} + \sum N_{...} \right)$$



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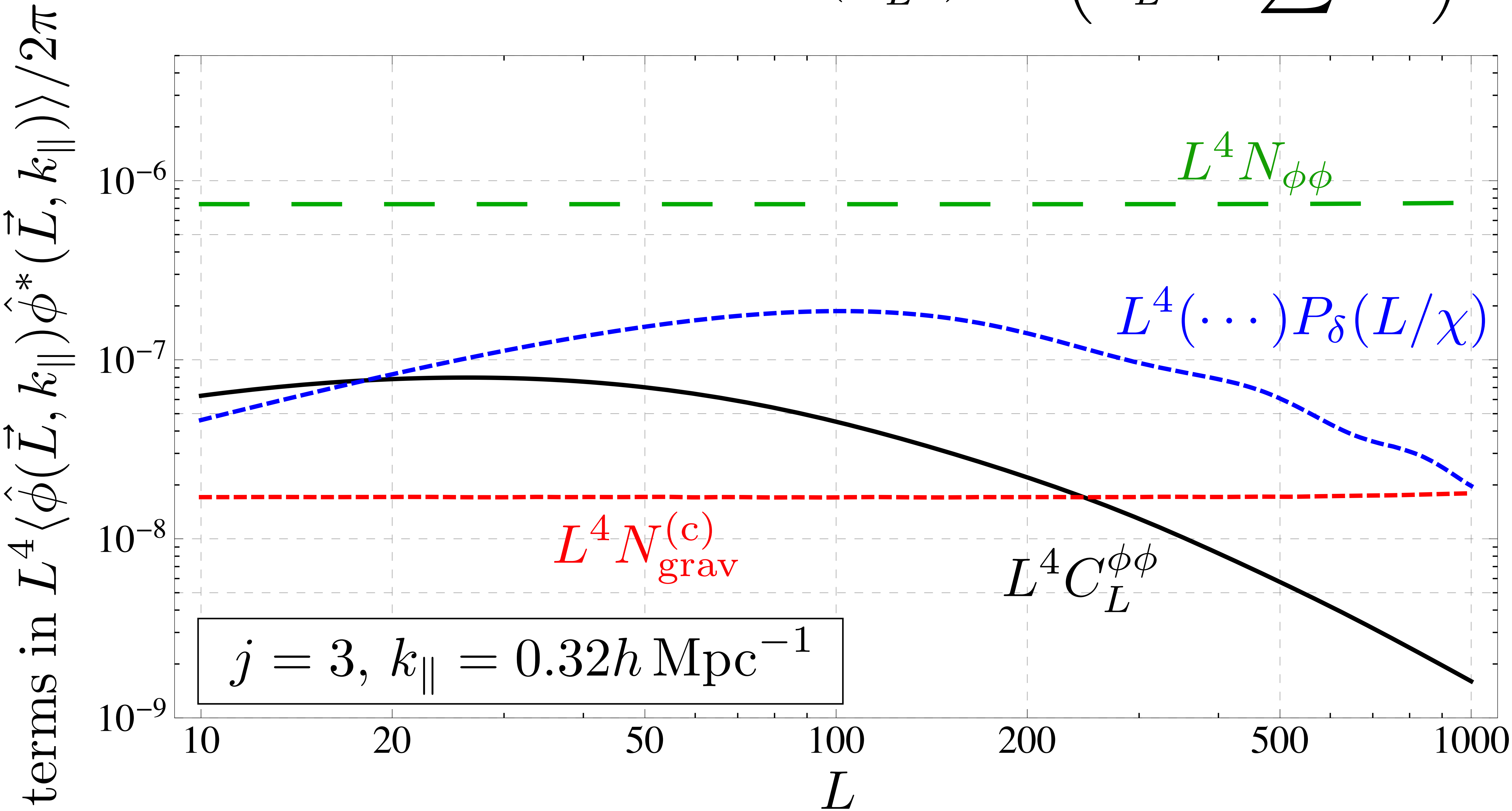

Bias-hardened lensing estimator for single $k_\parallel$

BH removes dominant bias at power-spectrum-level *and map-level*

$$\langle \hat{\phi}\hat{\phi}^* \rangle \propto C_L^{\phi\phi} + \sum N...$$

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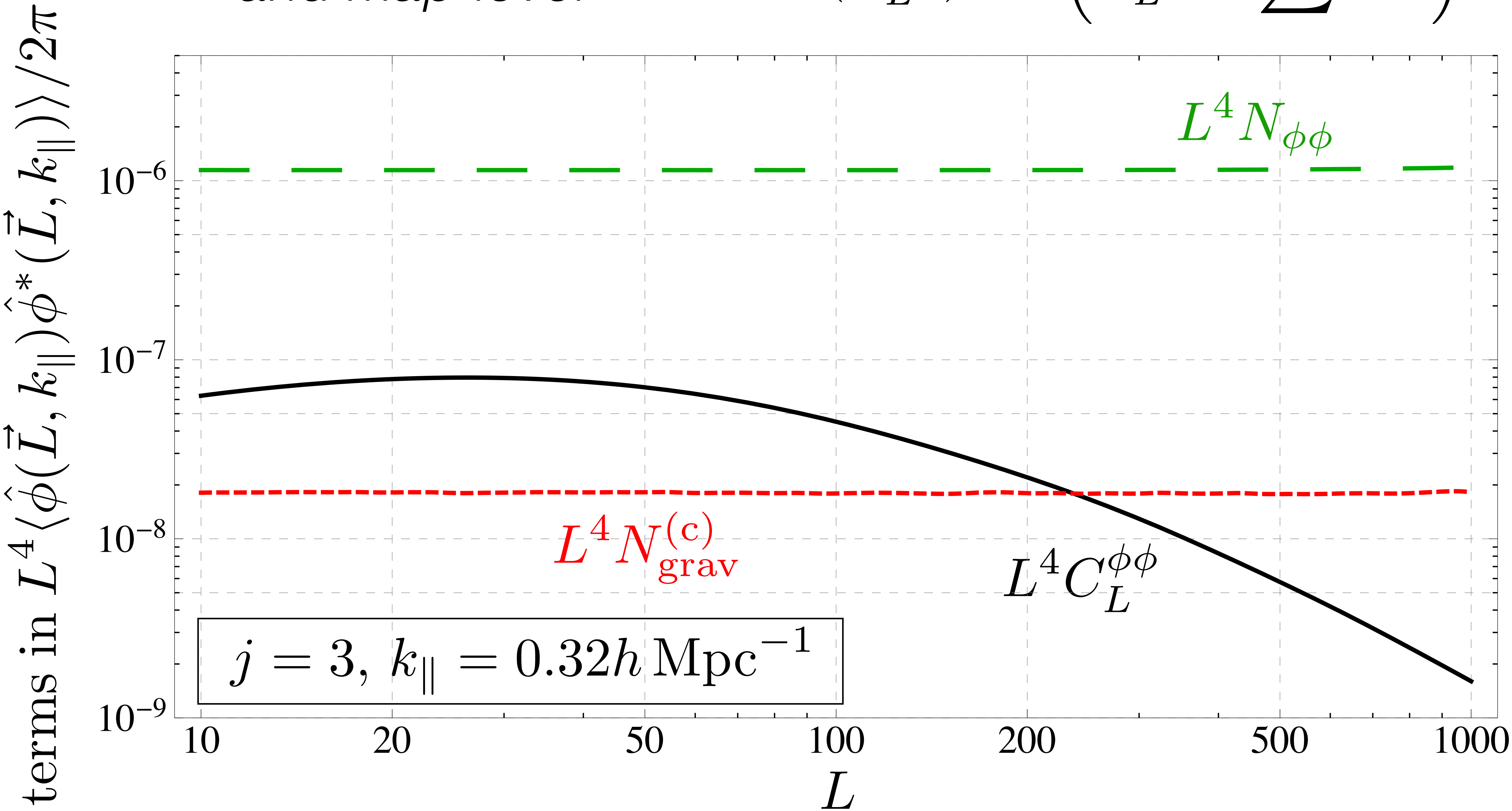
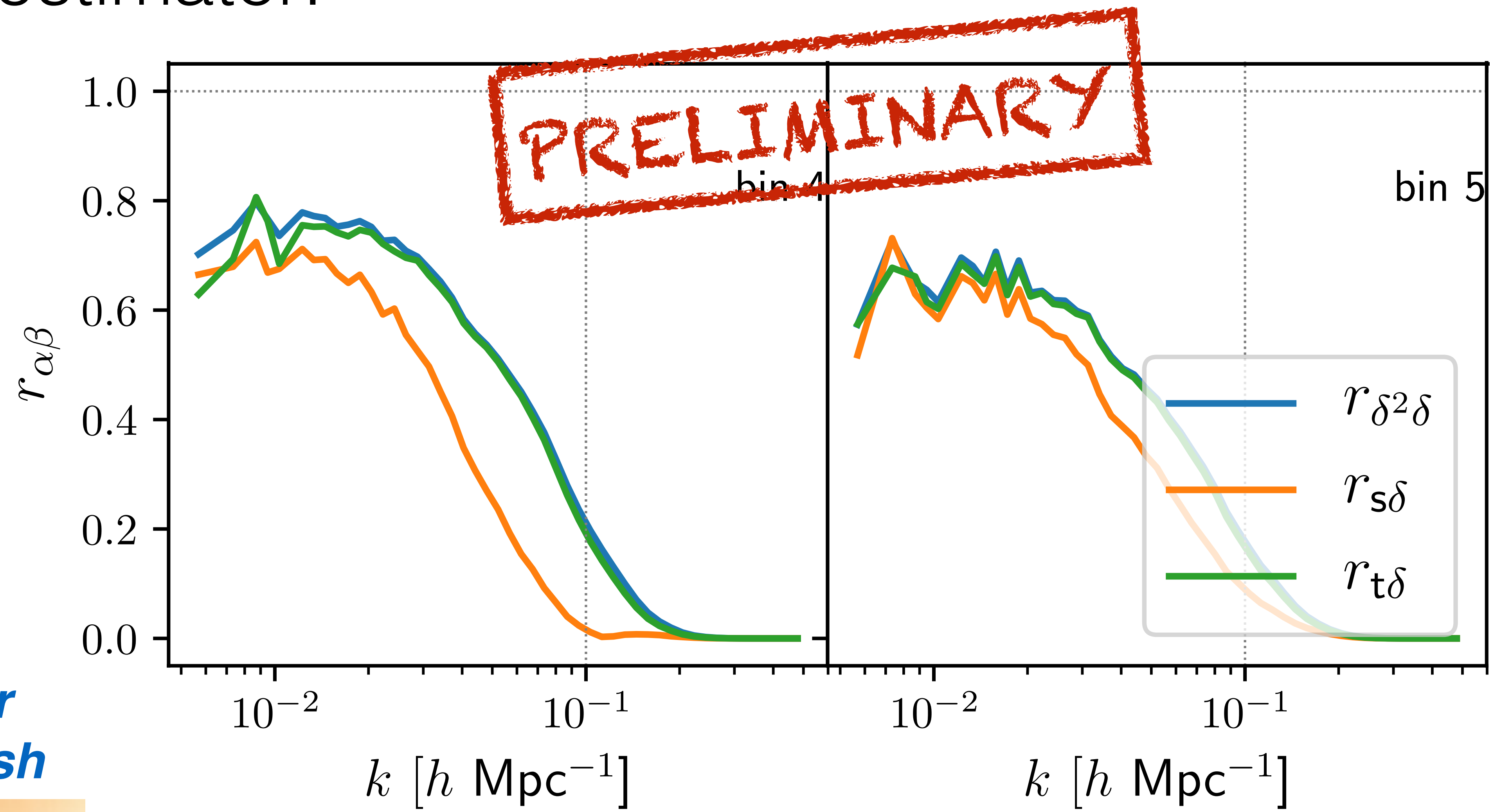


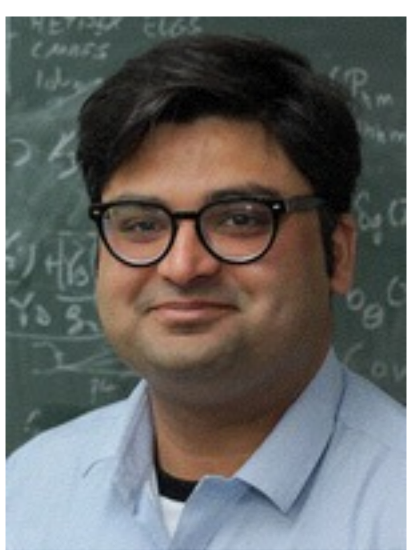
Removable mode-coupling from gravity - also interesting signal!

Can also reconstruct long density modes using quadratic estimator:

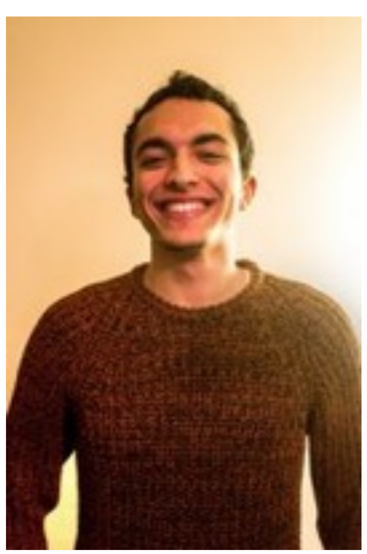
Cross-correlation between reconstruction and true modes



Muntazir M. Abidi



Omar Darwish



+ T. Baldauf, SF, D. Meerburg, B. Sherwin (work in progress)

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2. Extension of method to 3d
   - *apply 2d estimator to maps with different $k_\parallel$ values*
   - *gravity adds noise, that is correlated between $k_\parallel$s*
3. Reducing gravitational effects in variance: “bias-hardening”
   - *can remove dominant effect with modified lensing estimator*
   - *can increase noise, depending on observational setup*
4. **Forecasts**

Examples of 21cm interferometers

SKA: $3<z<27$ (SKA1-Low)

- large dish array w/ dense core
- facility, targeting cosmology + other astro

CHIME: $0.8<z<2.5$

- 4 20m x 100m cylinders
- dedicated instrument, targeting BAO + FRBs

HIRAX: $0.8<z<2.5$

- 32x32 close-packed 6m dishes
- dedicated instrument, targeting BAO + FRBs

Forecasts for 21cm surveys

S/N on lensing power spectra for 21cm surveys

	z	$f_{\rm sky}$	$\langle\kappa\kappa\rangle$	$\langle\kappa g_{\rm LSST}\rangle$	$\langle\kappa\gamma_{\rm LSST}\rangle$
SKA1-Low	$6 < z < 14$	6.5×10^{-4}	3.7	27	14
CHIME	$1.1 < z < 2.5$	0.5	0.26	35	28
HIRAX	$1.35 < z < 2.5$	0.5	0.98	46	36

lensing auto spectrum

lensing x ~LSST galaxy clustering

lensing x ~LSST galaxy lensing

Conclusion: cross-correlations might be worth a try!

Key factor: angular resolution

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Next-gen 21cm can do much better: see Cosmic Visions white paper!

Ansari et al (incl. SF), 1810.09572

Monty Python
1971

Another application of small-scale mode-couplings

Lensing estimator based on 3-pt correlation:

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$$\boxed{\widehat{\phi}_{\rm long} \sim \langle T_{\rm short}T_{\rm short}\rangle}$$

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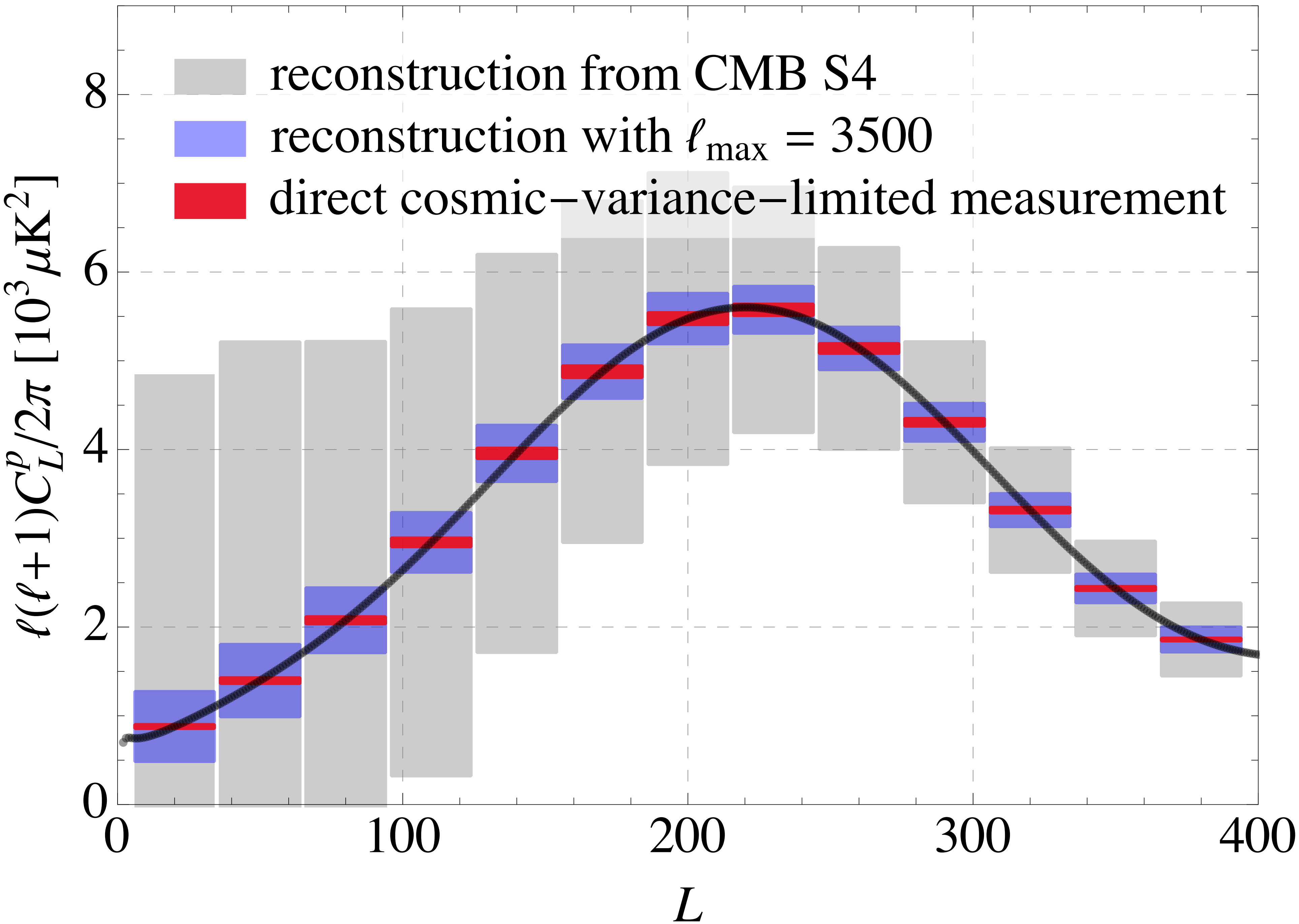
 & \boxed{\widehat{\phi}_{\text{long}} \sim \langle T_{\text{short}}T_{\text{short}}\rangle} \\
\langle T_{\text{long}}T_{\text{short}}\phi_{\text{short}}\rangle \arrow[r] & \boxed{\widehat{T}_{\text{long}} \sim \langle T_{\text{short}}\phi_{\text{short}}\rangle}
\end{tikzcd}$$

Same logic leads to **estimator for long T modes**

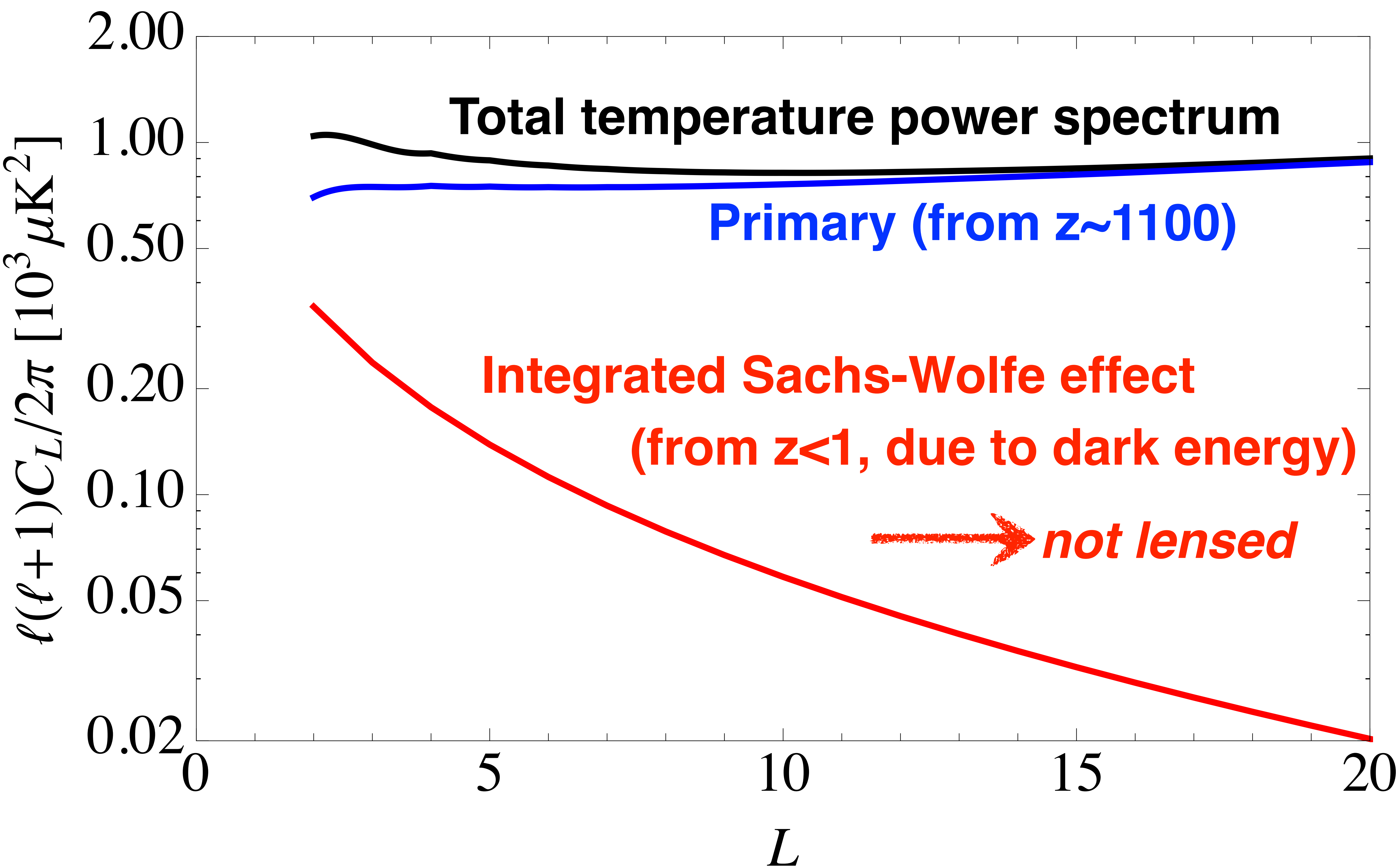
Reconstructing long modes of CMB temperature

Cross-correlate high-res. temperature + lensing maps

→ Recover large-angle temperature information



CMB temperature power spectrum: low-z contribution



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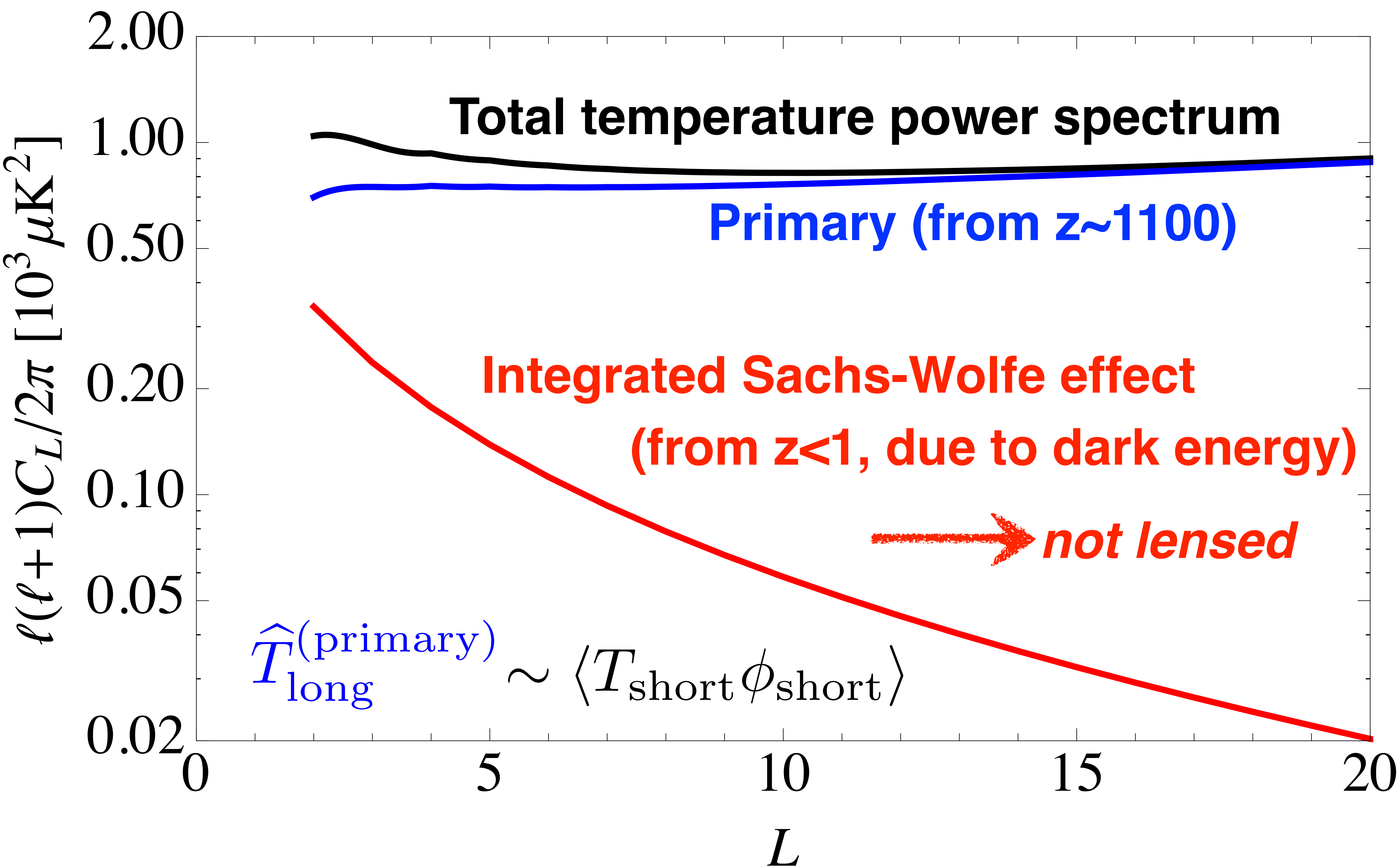

Reconstruction improves measurements of ISW effect

Subtract reconstructed *T* from directly measured *T*

→ Isolate ISW contribution (with lower noise)

Our (simplistic) forecasts:

Consider CV-limited measurements of T, ϕ *up to* $\ell_{\max}$

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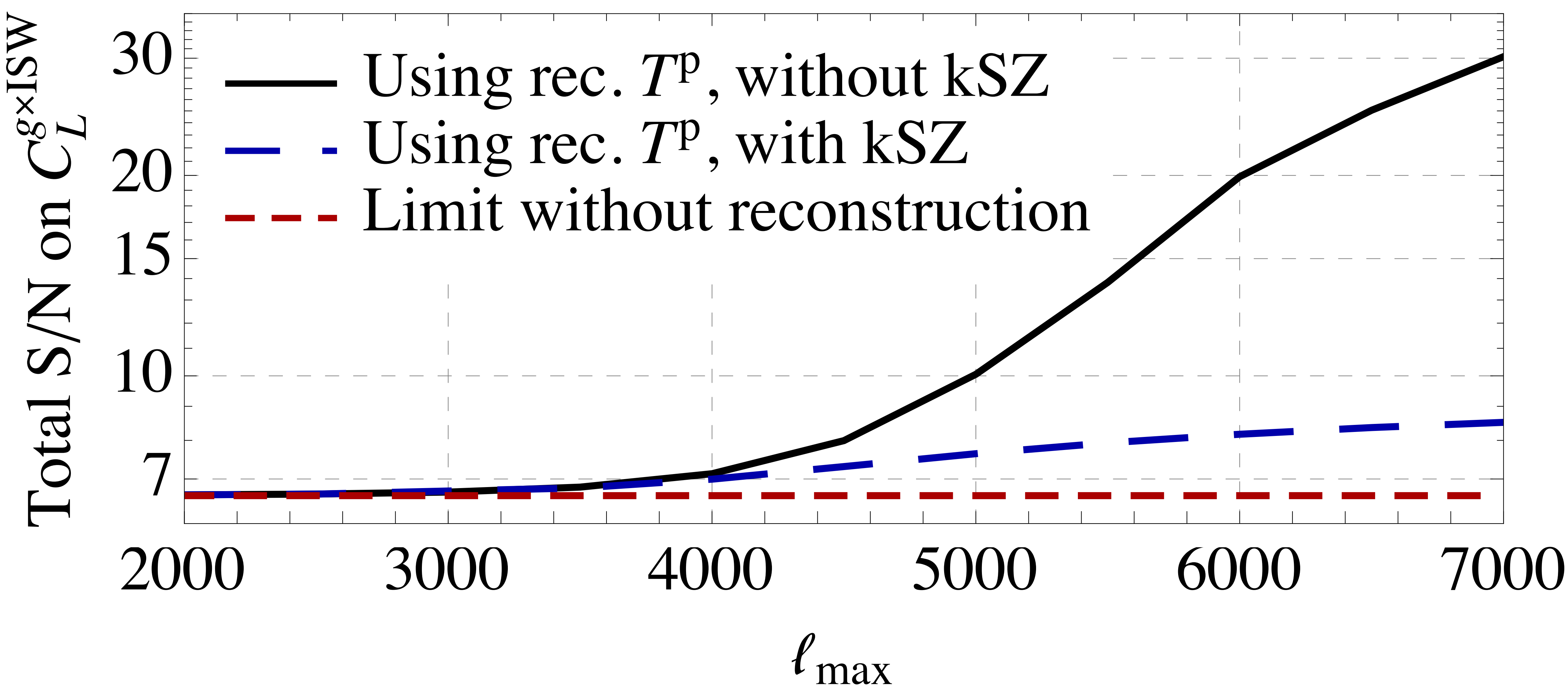

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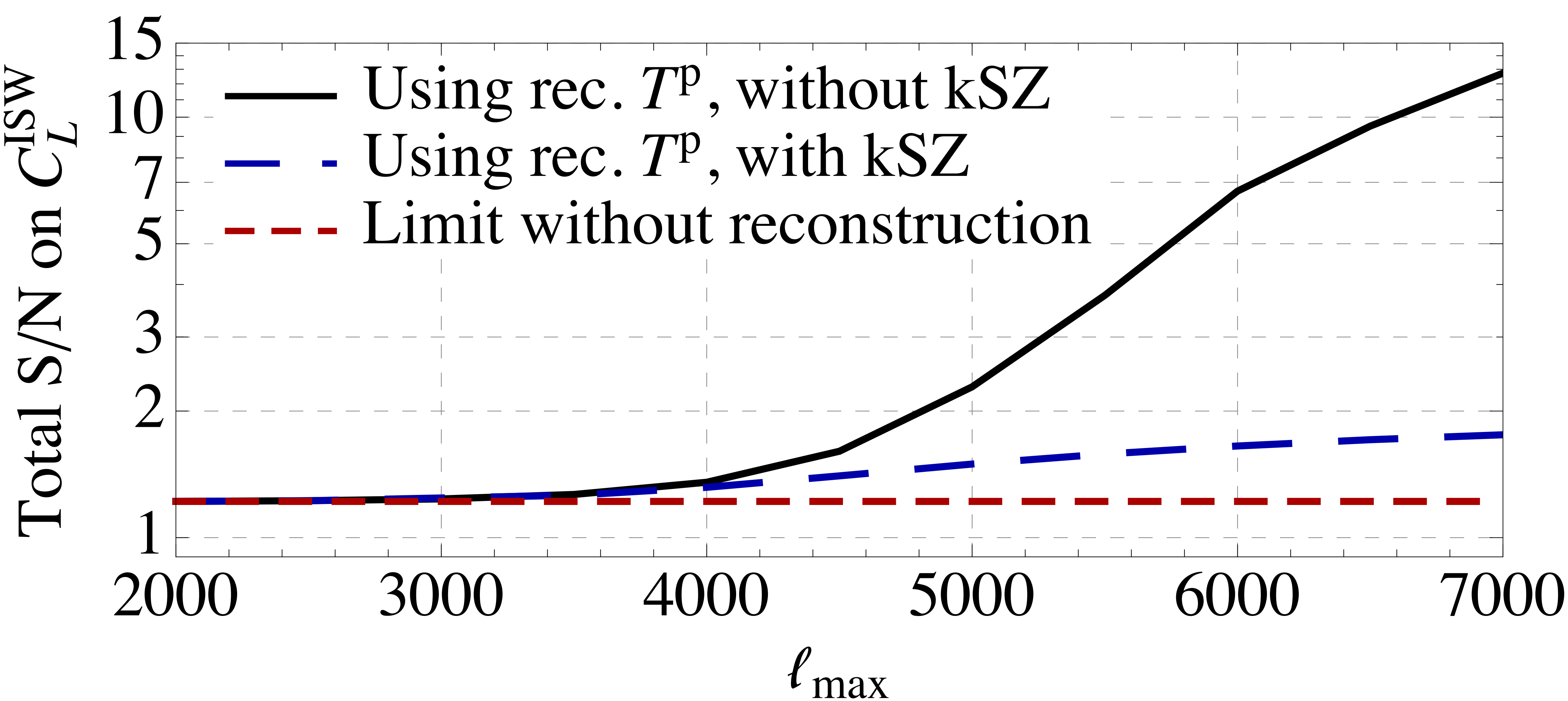

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- Need to clean kSZ + other T secondaries at small scales

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Dec

12

The CMB in HD: The Low-noise High-resolution Frontier

Date & Time

December 12 - 14, 2018

Add to Calendar

Location

Flatiron Institute, 162 Fifth Avenue

The CMB still contains a wealth of information about the cosmology and fundamental physics of our Universe. Unlocking all the information likely necessitates opening up a new window of CMB observations over a significant portion of the sky (~10%) that is of much lower noise (0.1 uK-arcmin) and higher resolution (10 to 20 arcsec) than previous CMB surveys. Such ultra-deep, high-resolution CMB measurements could potentially provide a novel way to map small scale dark matter, allowing, for example, a new probe of dark matter's particle properties. They would also open a new window on galaxy cluster physics through the thermal and kinetic SZ effects and high-z cluster detection, and on extragalactic mm/submm source populations. In addition, such observations would push the boundaries of our knowledge about the early Universe, dark energy, reionization, and galaxy evolution.

Conclusions

1. How CMB lensing is measured
   - *exploits mode-couplings induced by lensing*
   - *connected 4-pt function → lensing potential power spectrum*
2. Extension of method to 3d
   - *apply 2d estimator to maps with different $k_\parallel$ values*
   - *gravity adds noise, that is correlated between $k_\parallel$s*
3. Reducing gravitational effects in variance: "bias-hardening"
   - *can remove dominant effect with modified lensing estimator*
   - *can increase noise, depending on observational setup*
4. Forecasts
   - *first detections may be possible in the near term!*
   - *future promise: "stage 2" 21cm survey could compete with CMB-S4 in lensing precision*