Title: Lensing reconstruction using line intensity maps

Date: May 01, 2018 02:30 PM

URL: http://pirsa.org/18050012

Abstract: <p>Gravitational lensing of the cosmic microwave background has emerged as a powerful cosmological probe, made possible by the development and characterization of nearly-optimal estimators for extracting the lensing signal from temperature and polarization maps. One can ask whether similar tools can be applied to upcoming "intensity maps" of emission lines at other wavelengths (e.g. 21cm). In this talk, I will present recent work in this direction, focusing in particular on the impact of gravitational nonlinearities on standard quadratic lensing estimators. I will show how these nonlinearities can provide a significant contaminant to lensing reconstruction, even for observations at reionization-era redshifts, but will also describe how this contamination can largely be mitigated by modifying the lensing estimator. Finally, I will present estimates for the detectability of lensing in ongoing and future intensity mapping surveys.</p>

Lensing reconstruction from line intensity maps

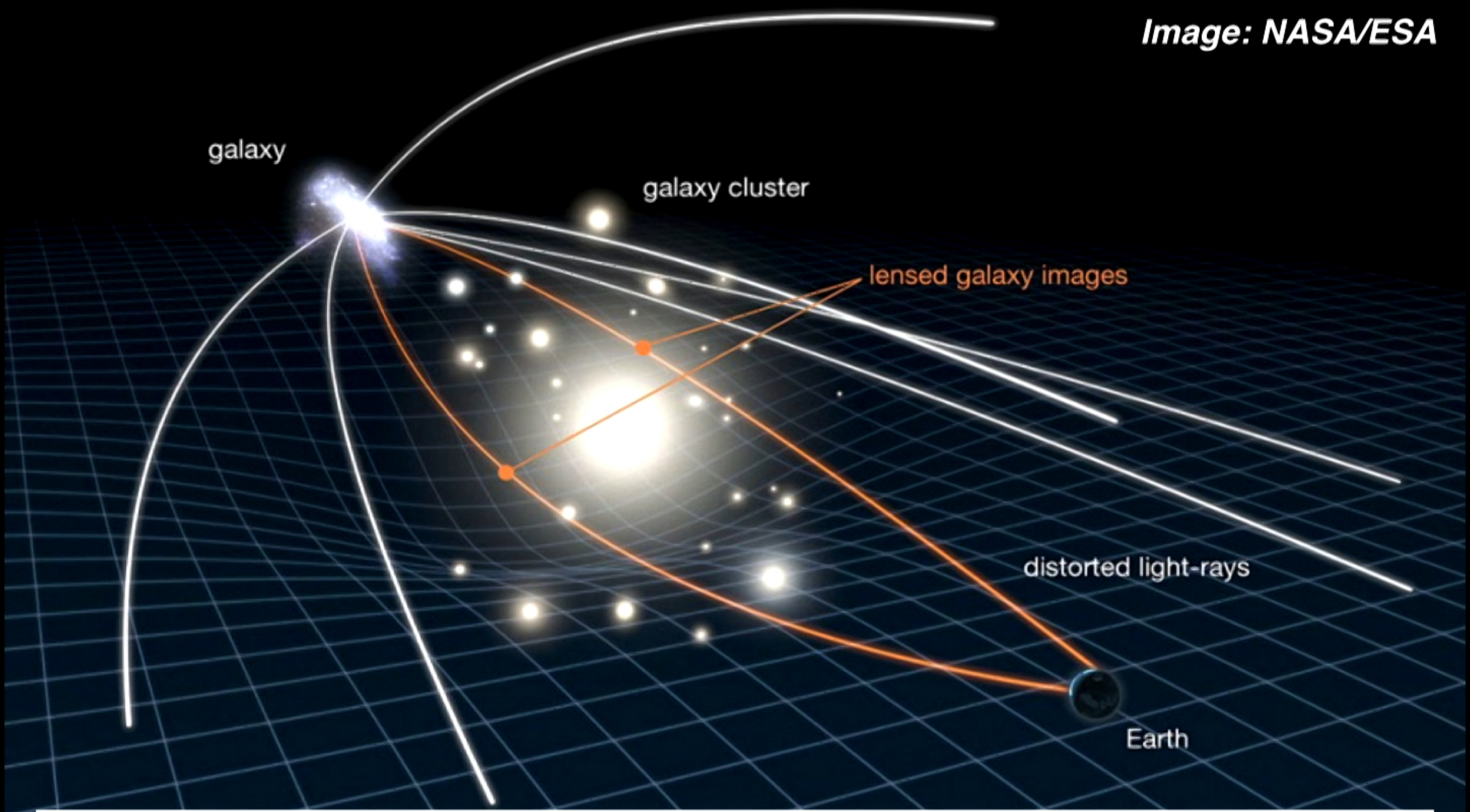
Simon Foreman
Canadian Institute for Theoretical Astrophysics

with
Alex van Engelen, Daan Meerburg, Joel Meyers

based on arXiv:1803.04975

Perimeter Institute Cosmology Seminar
May 1, 2018

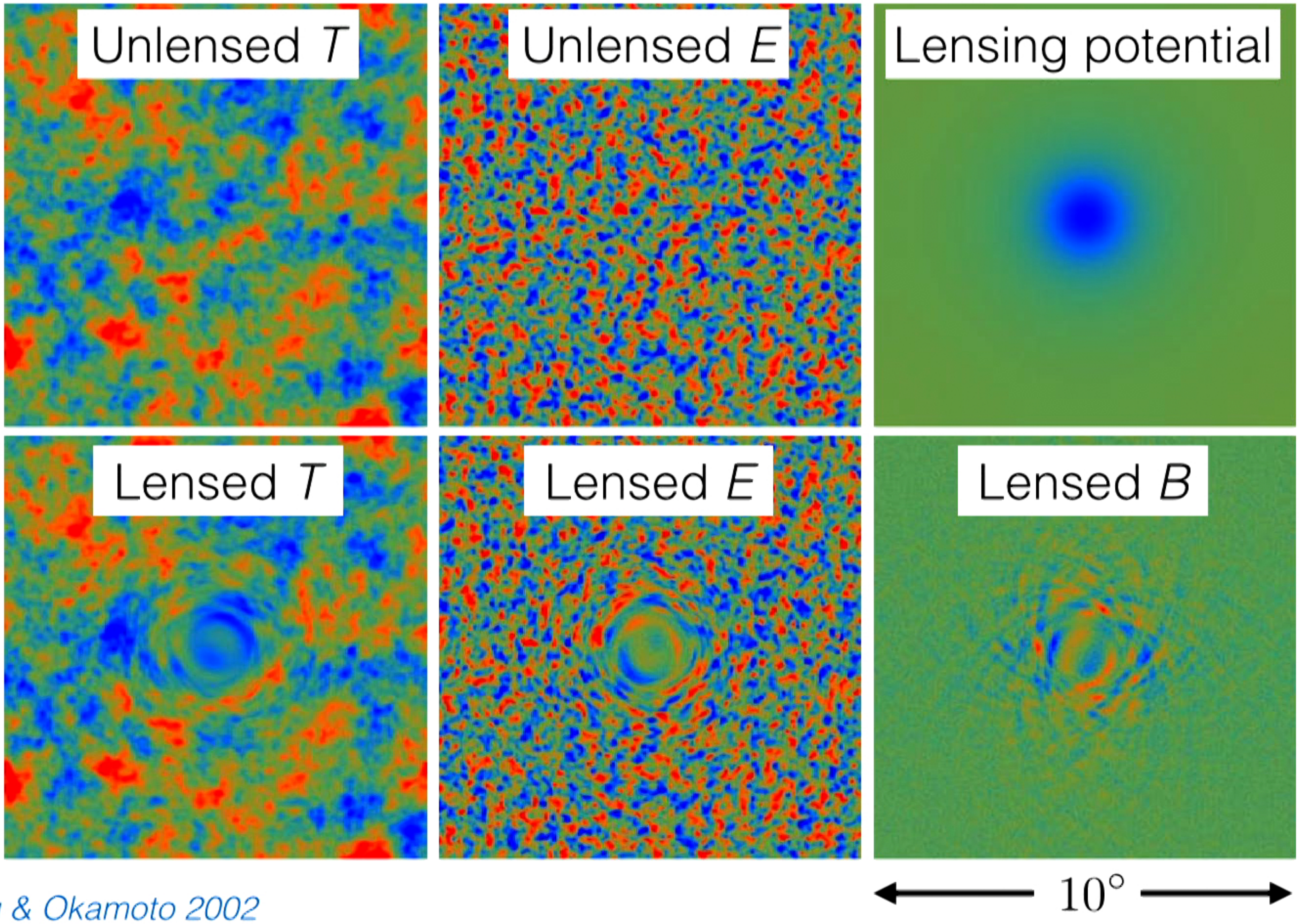
A cartoon of gravitational lensing



Directly traces low-redshift structure

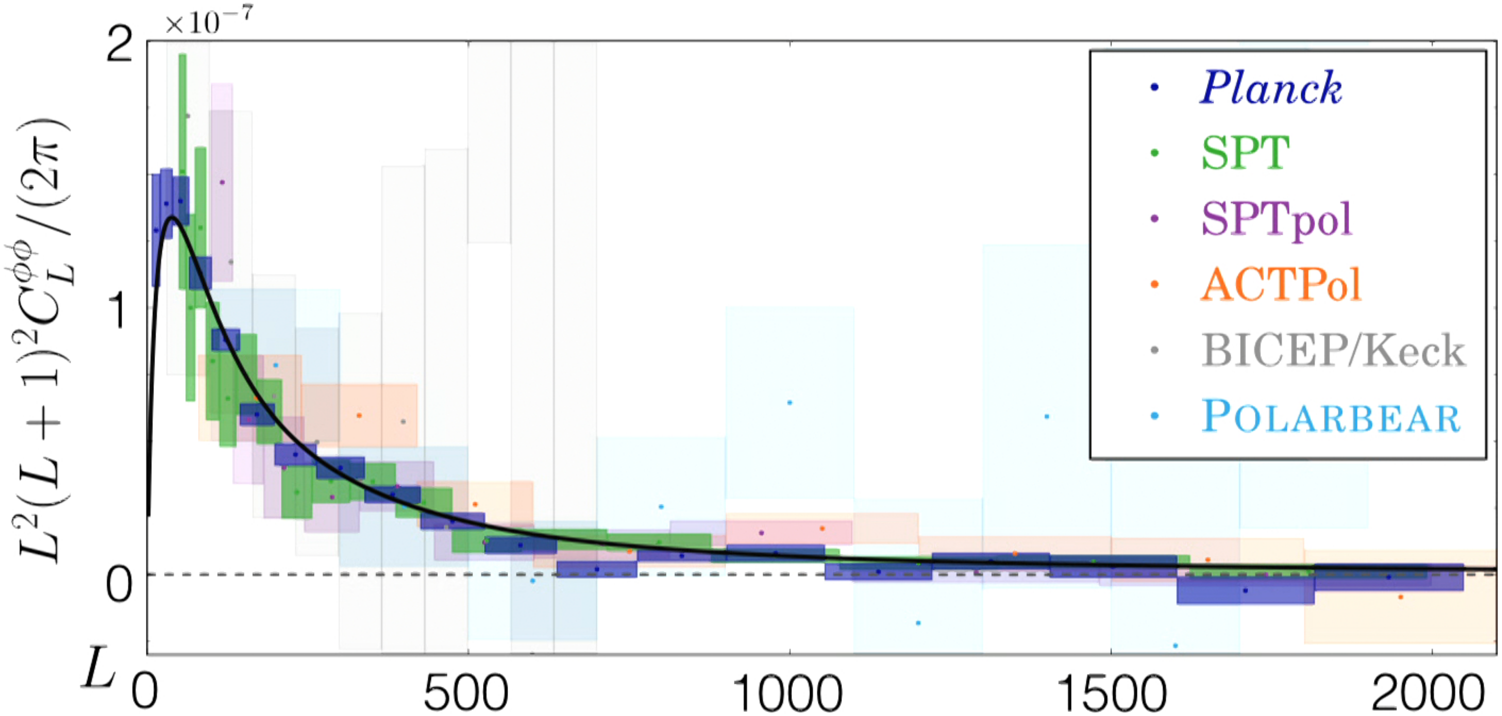
→ Neutrino masses, structure growth, cross-correlations

Low angular resolution lensing: CMB



Hu & Okamoto 2002

Low angular resolution lensing: CMB



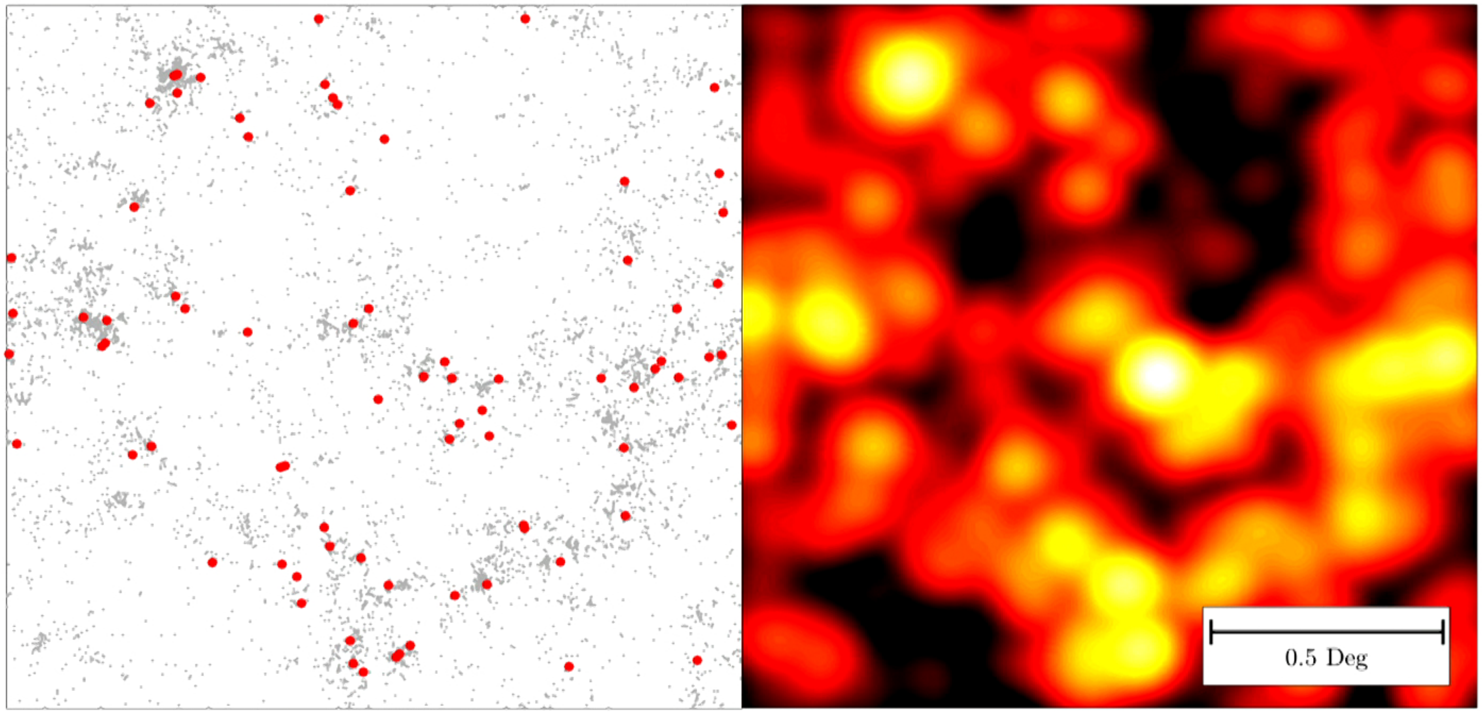
State of the art in CMB lensing:
40σ detection in Planck, 15σ in SPT+Planck, 7.1σ in ACTpol

CMB-S4: projected ~500σ detection

figure: Alex van Engelen

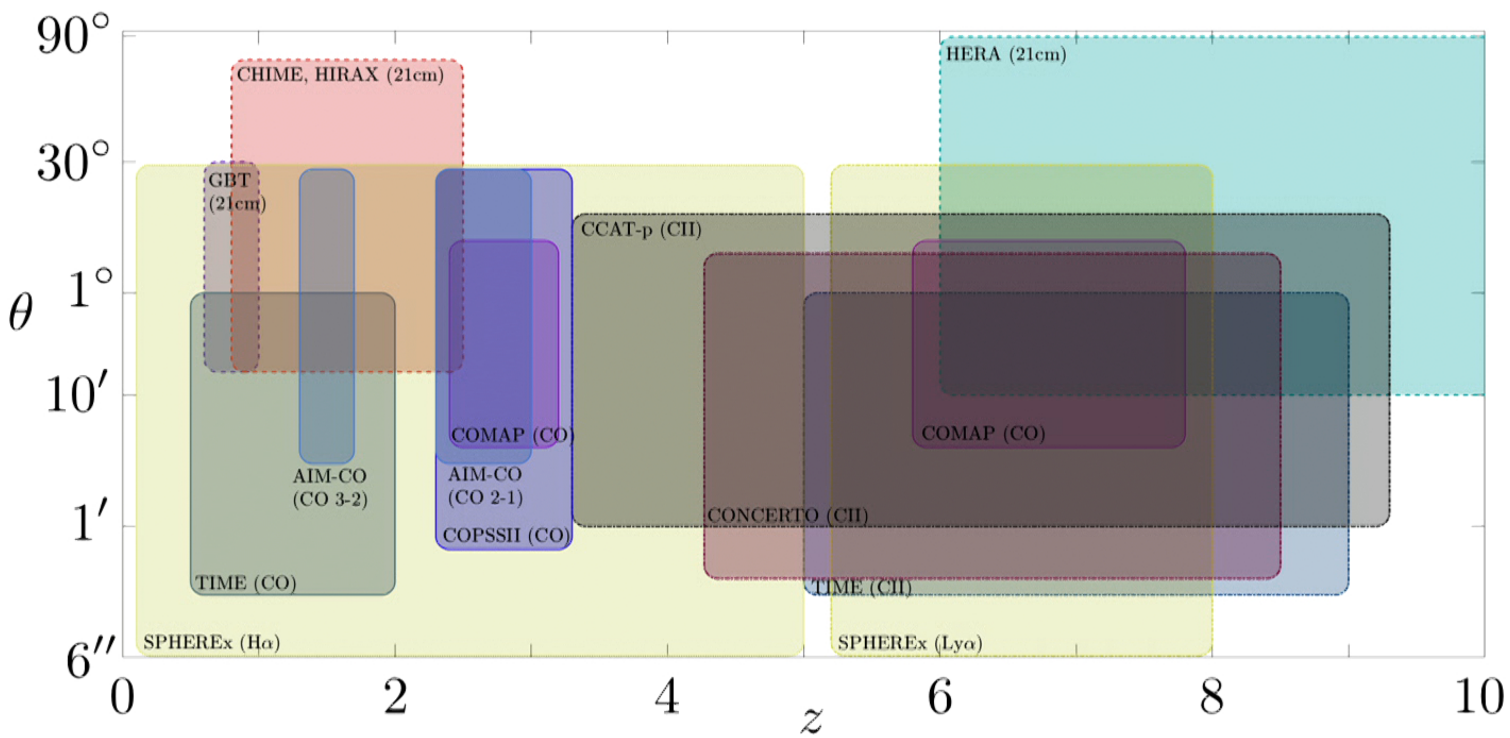
Low angular resolution lensing: the future?

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

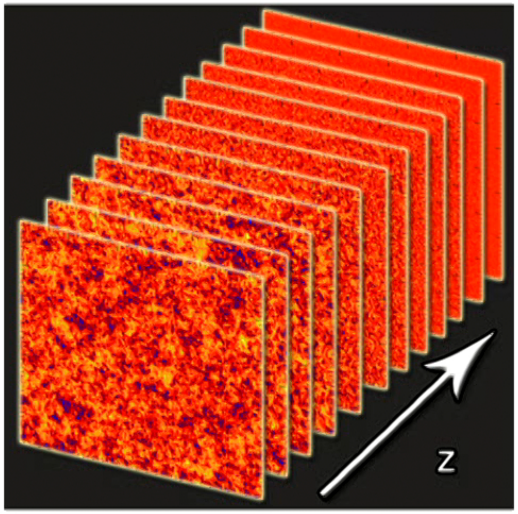


figure: Romeo et al. 2017

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
→ another window on the low-redshift universe!

Understanding a contaminant for e.g. nG constraints

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

Outline

1. Review of quadratic CMB lensing estimator

2. Extension of estimator to 3d
   - *impact of gravitational nonlinearities*

3. Reducing gravitational effects in variance: "bias-hardening"

4. Forecasts

Review of CMB lensing

Lensing re-maps angular coordinates of temperature:

$$T(\vec{\theta}) = \tilde{T}(\vec{\theta} + \vec{\nabla}\phi(\vec{\theta})) \approx \tilde{T}(\vec{\theta}) + \vec{\nabla}\phi(\vec{\theta}) \cdot \vec{\nabla}\tilde{T}(\vec{\theta})$$

$$\phi \sim \int_0^{\chi_s} \frac{\chi_s - \chi}{\chi_s \chi} \Phi(\chi \hat{n}, z[\chi])$$

In harmonic space:

$$T(\vec{\ell}) \approx \tilde{T}(\vec{\ell}) - \int_{\vec{\ell}'} \vec{\ell}' \cdot (\vec{\ell} - \vec{\ell}') \tilde{T}(\vec{\ell}') \phi(\vec{\ell} - \vec{\ell}')$$

Lensing induces off-diagonal mode-couplings:

$$\left\langle T(\vec{\ell}) T(\vec{L} - \vec{\ell}) \right\rangle \approx (2\pi)^2 \delta_D(\vec{L}) \tilde{C}_L + f(\vec{\ell}, \vec{L} - \vec{\ell}) \phi(\vec{L})$$

estimator $\longrightarrow$

$$\frac{T(\vec{\ell}) T(\vec{L} - \vec{\ell})}{f(\vec{\ell}, \vec{L} - \vec{\ell})} \approx \phi(\vec{L})$$

Optimal quadratic estimator

Naive estimator: $\hat{\phi}(\vec{L}) = \dfrac{T(\vec{\ell})T(\vec{L}-\vec{\ell})}{f(\vec{\ell},\vec{L}-\vec{\ell})}$

Can do better by inverse-variance weighting:

$$\hat{\phi}(\vec{L}) = N_L \int_{\vec{\ell}} \frac{f(\vec{\ell},\vec{L}-\vec{\ell})}{2C_\ell^{\rm tot} C_{|\vec{L}-\vec{\ell}|}^{\rm tot}} T(\vec{\ell})T(\vec{L}-\vec{\ell})$$

Power spectrum of reconstructed lensing map:

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

Hu 2001

Outline

1. Review of quadratic CMB lensing estimator
    - *exploits mode-couplings induced by lensing*
    - *connected 4-pt function → lensing potential power spectrum*
2. **Extension of estimator to 3d**
3. Reducing gravitational effects in variance: “bias-hardening”
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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:

$$C_\ell(k_\parallel) = \mathcal{L}^{-1}\chi^{-2} P_I\left(\sqrt{\ell^2/\chi^2 + k_\parallel^2}\right)$$

(Easier to account for correlations this way)

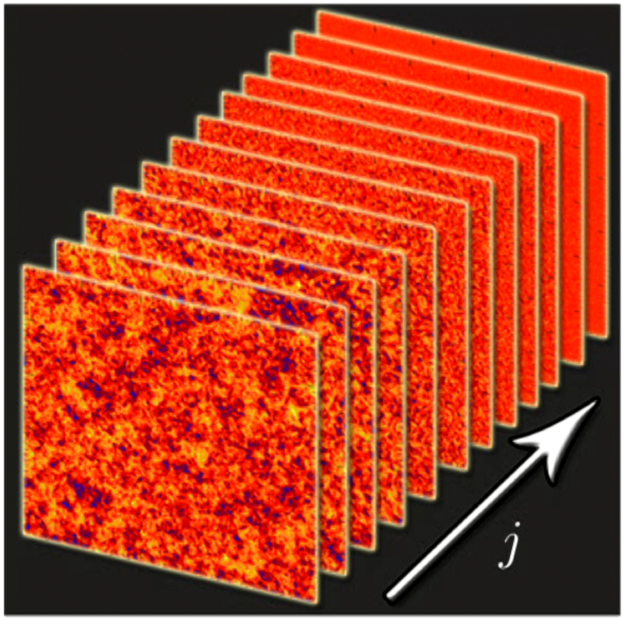
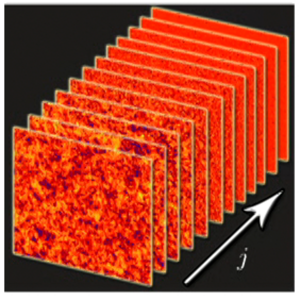


figure: Romeo et al. 2017

Zahn & Zaldarriaga 2006; Pourtsidou & Metcalf 2014

3d lensing estimator

Can construct estimator for each j:



$$\hat{\phi}(\vec{L}, k_\parallel) = N_{\phi\phi}(L, k_\parallel) \times \int_{\vec{\ell}} \frac{f_\phi(\vec{\ell}, \vec{L}-\vec{\ell}, k_\parallel)}{2C_\ell^{\rm tot}(k_\parallel)C_{|\vec{L}-\vec{\ell}|}^{\rm tot}(k_\parallel)} I(\vec{\ell}, k_\parallel) I(\vec{L}-\vec{\ell}, -k_\parallel)$$

Power spectra of reconstructed ϕ maps:

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

Can coadd j's to beat down noise in maps:

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

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**

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

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

$$+ \int_{\vec{\ell}_1} \int_{\vec{\ell}_2} (\cdots)(\cdots) \left\langle \tilde{I} \tilde{I} \tilde{I}^* \tilde{I}^* \right\rangle_{\rm c}$$ **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

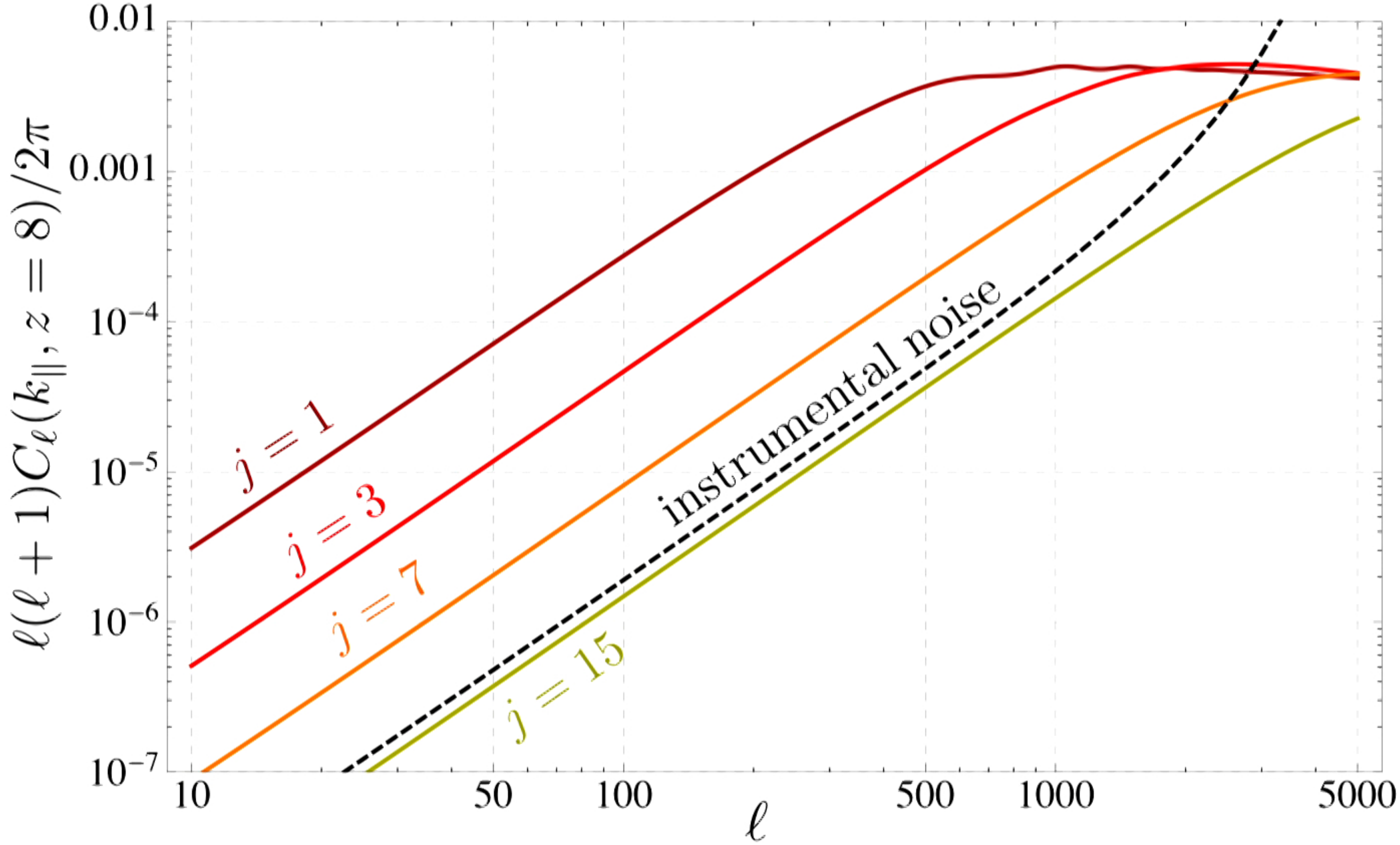
We will:

- suppose that $\tilde{I} = b\delta_{\mathrm{m}}$
- use tree-level PT for the connected 4-pt function

$$T \sim F_2^2(\cdots) + F_3(\cdots)$$

- incorporate foregrounds with a hard $k_{||}$ cut

SKA1-Low: signal curves for different $k_\parallel$ values

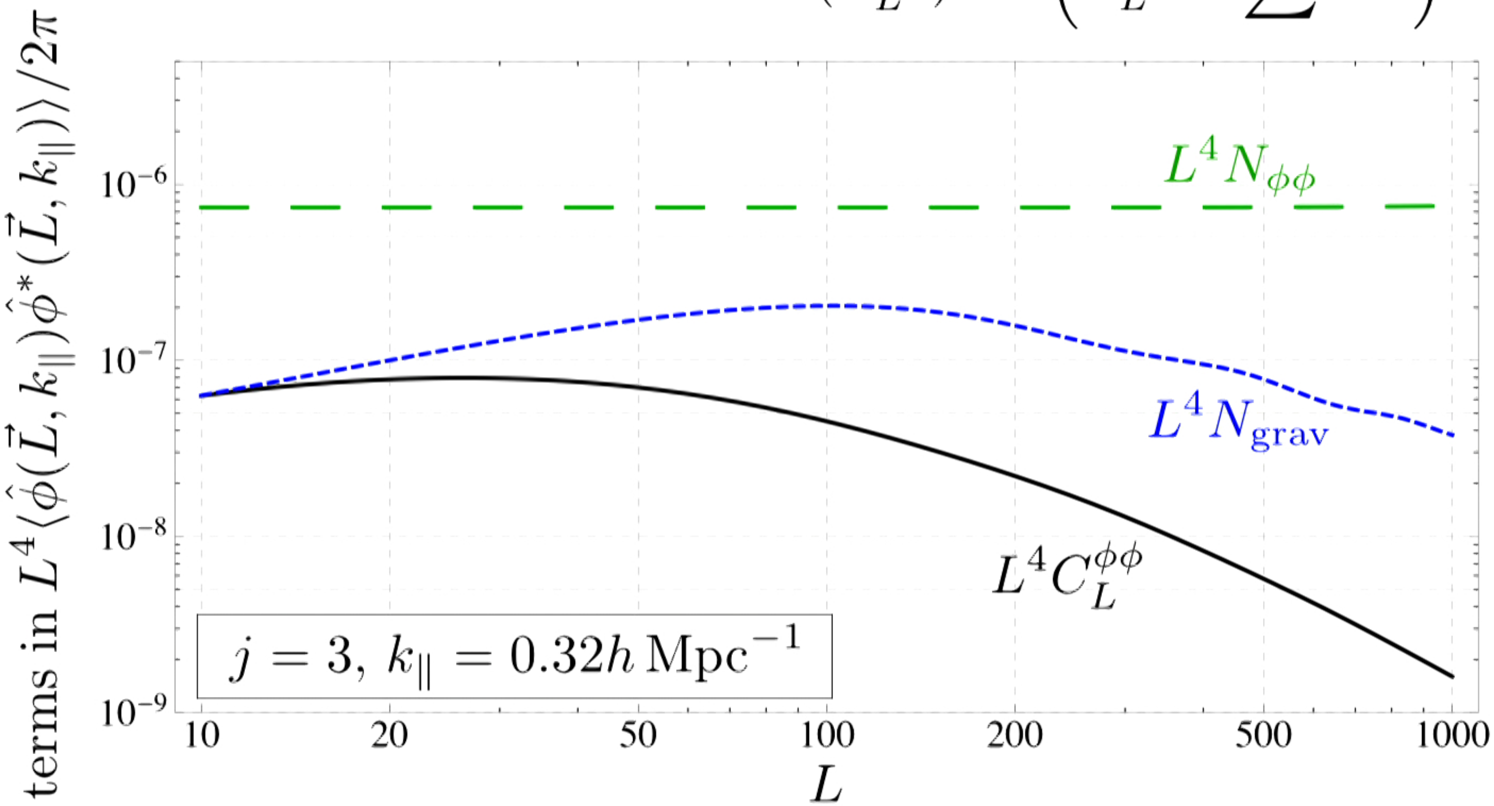


Lensing estimator for single $k_\parallel$

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

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

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



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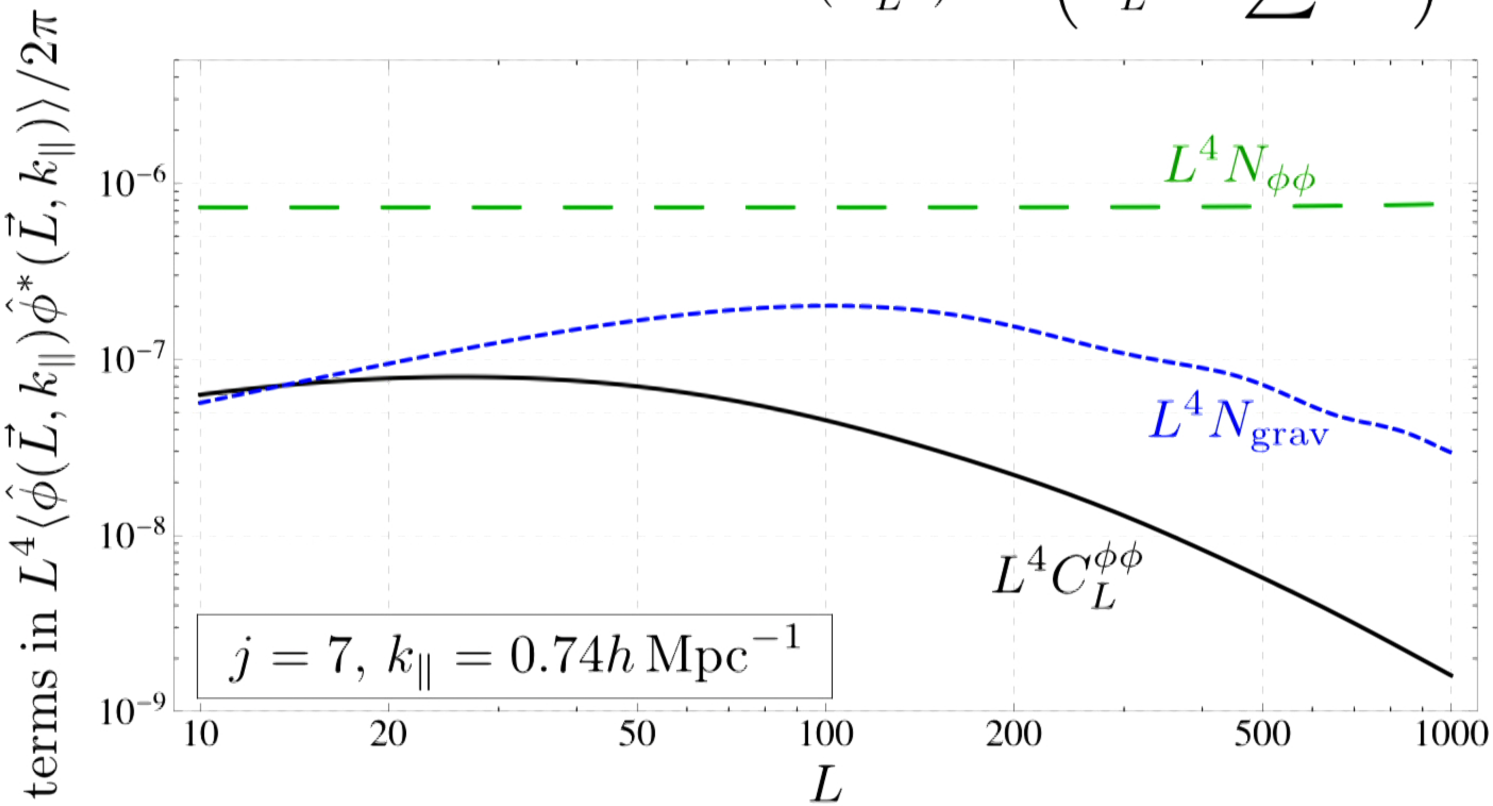
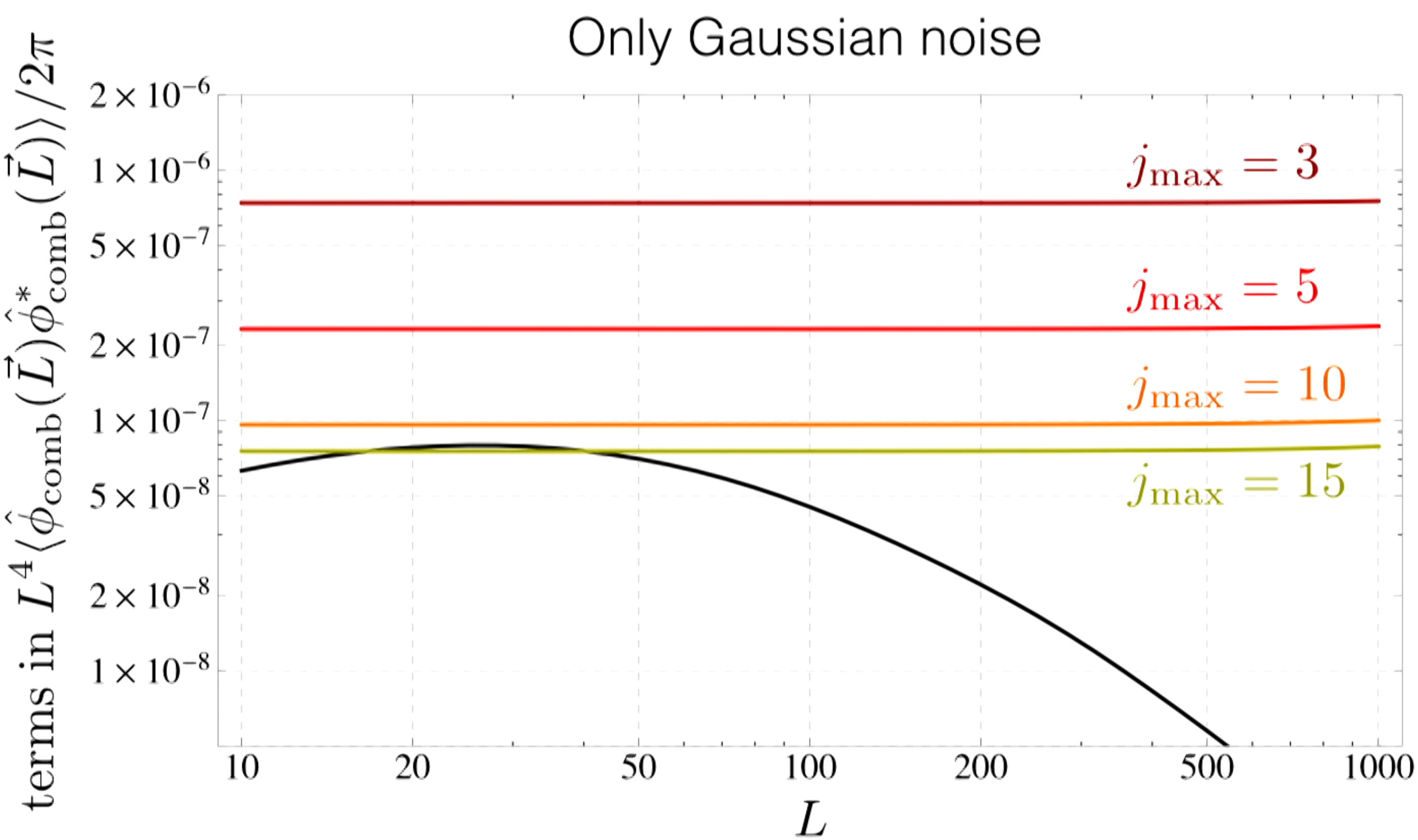


Lensing estimator, combining signal from several j's



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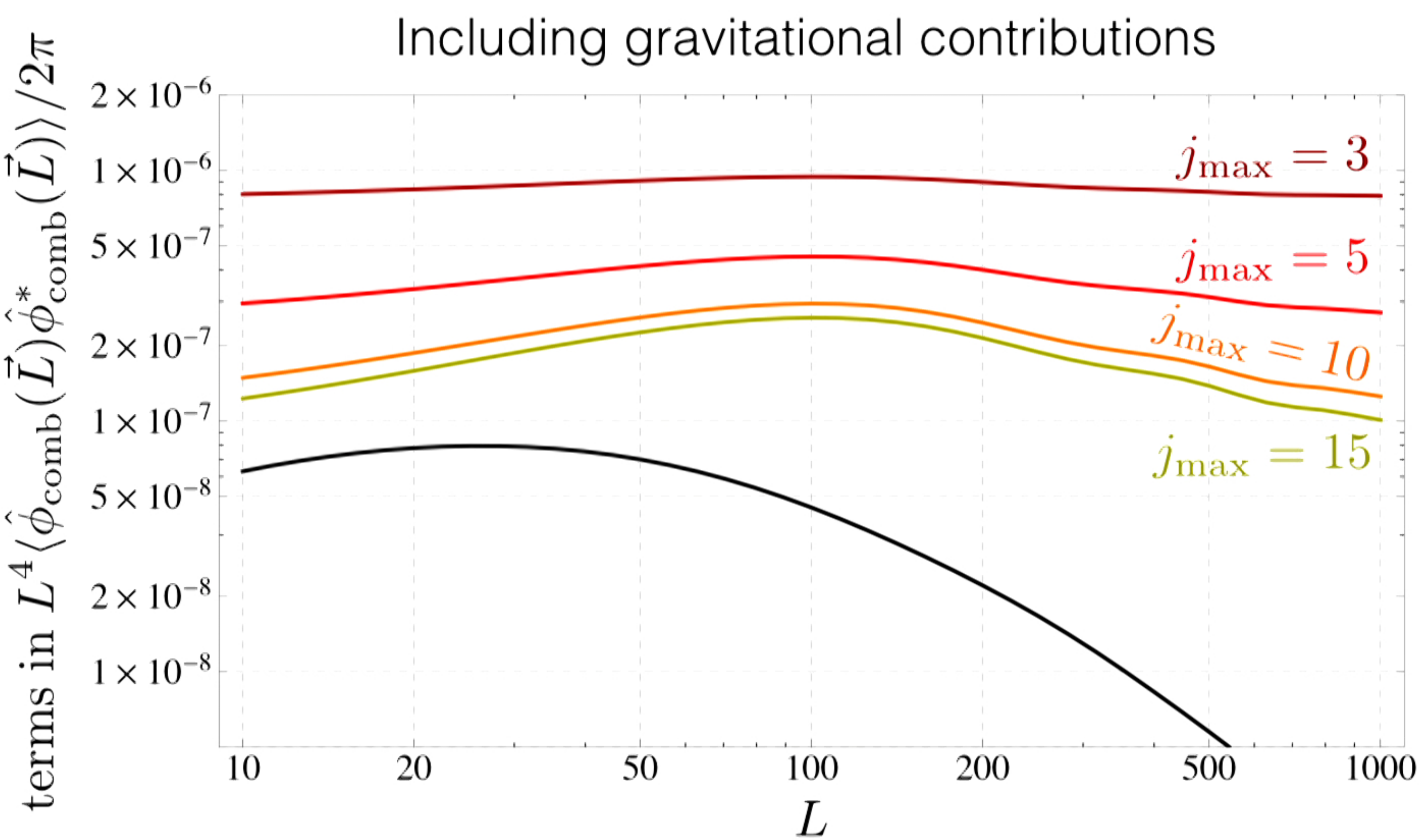

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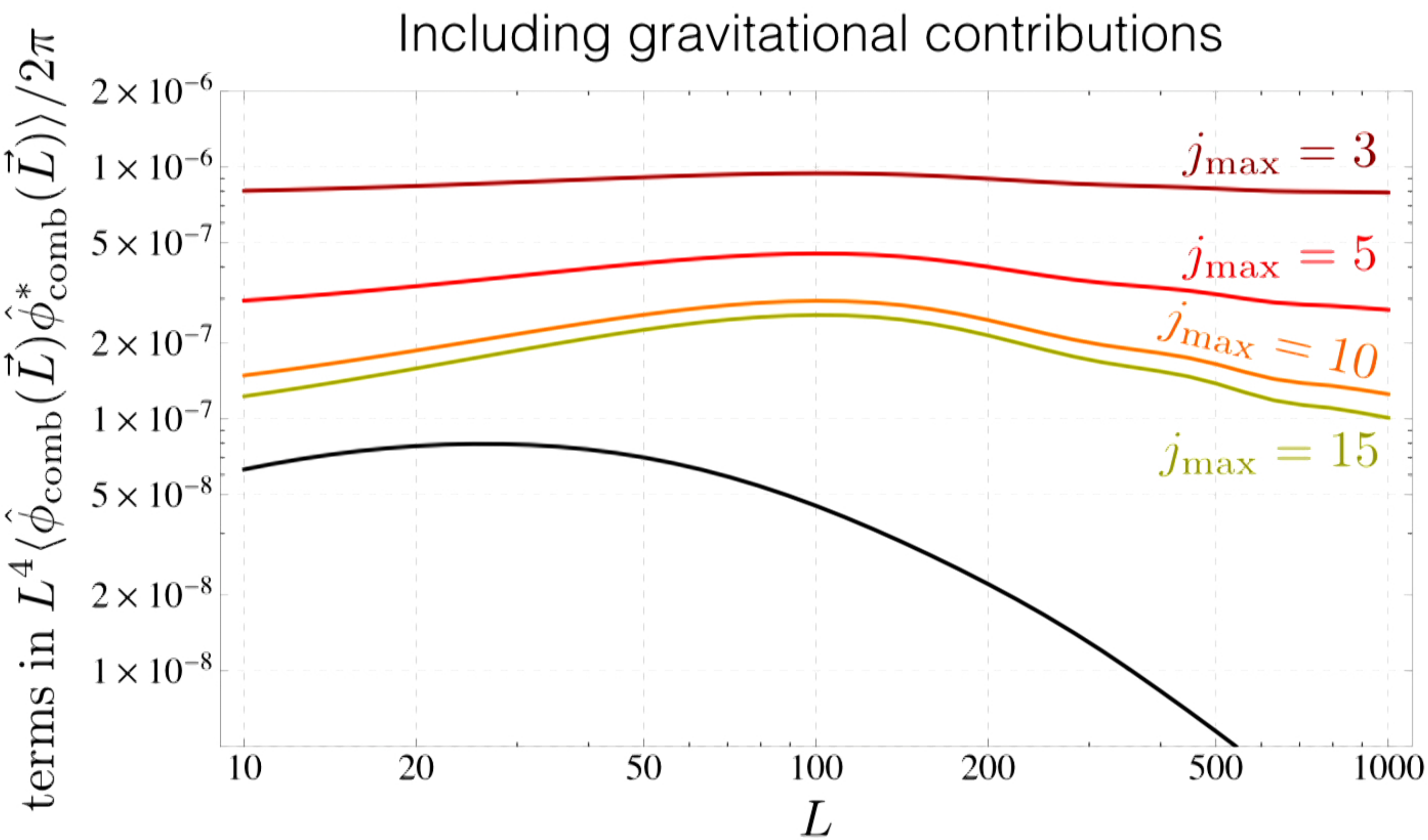

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   - *exploits mode-couplings induced by lensing*
   - *connected 4-pt function → lensing potential power spectrum*
2. Extension of estimator to 3d
   - *apply 2d estimator to maps with different $k_\parallel$ values*
   - *gravity adds noise, that is correlated between $k_\parallel$s*
3. **Reducing gravitational effects in variance: "bias-hardening"**
4. Forecasts

Lensing and gravity both induce mode-coupling

$$I(\vec{\ell}, k_{\|}) \sim \delta_1(\vec{\ell}/\chi, k_{\|})$$ **linear**

$$- \int_{\vec{\ell}'} \vec{\ell}' \cdot (\vec{\ell} - \vec{\ell}') \delta_1(\vec{\ell}'/\chi, k_{\|}) \phi(\vec{\ell} - \vec{\ell}')$$ **lensing**

$$+ \int_{\vec{q}} F_2(\vec{q}, \vec{k} - \vec{q}) \delta_1(\vec{q}) \delta_1(\vec{k} - \vec{q}) \Big|_{\vec{k} = (\vec{\ell}/\chi, k_{\|})}$$ **gravity**

Contributions to power spectrum of reconstructed ϕ

Schematically, $I \sim \delta + \delta\phi + \delta\delta + \cdots$

What do we get in $\left\langle \hat{\phi}\hat{\phi} \right\rangle \sim \langle IIII \rangle$?

$\langle\delta\delta\rangle\,\langle\delta\delta\rangle$	$\longrightarrow$	$N_{\phi\phi}$	**Gaussian noise**
$\langle\delta\,\delta\phi\;\;\delta\,\delta\phi\rangle$	$\longrightarrow$	$(\cdots)C_L^{\phi\phi}$	**signal!**
$\langle\delta\,\delta\phi\;\;\delta\,\delta\phi\rangle$	$\longrightarrow$	$N_{\phi\phi}^{(1)}$	**connected lensing bias**
$\langle\delta\,\delta\delta\;\;\delta\,\delta\delta\rangle$	$\longrightarrow$	$(\cdots)P_\delta(L/\chi)$	**coupling to long modes**
$\langle\delta\,\delta\delta\;\;\delta\,\delta\delta\rangle$	$\longrightarrow$	$N_{\rm grav}^{(c)}$	**connected coupling to long modes**

These terms have the same form!

$$\langle \delta\,\delta\phi \;\; \delta\,\delta\phi \rangle \longrightarrow (\cdots) C_L^{\phi\phi}$$

signal!

$$\langle \delta\,\delta\delta \;\; \delta\,\delta\delta \rangle \longrightarrow (\cdots) P_\delta(L/\chi)$$

coupling to long modes

Bias-hardened estimators

Define ϕ and δ estimators like so:

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

Then define new estimators as solutions of linear system:

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

However, new estimator has 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 $k_{\|}$

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

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

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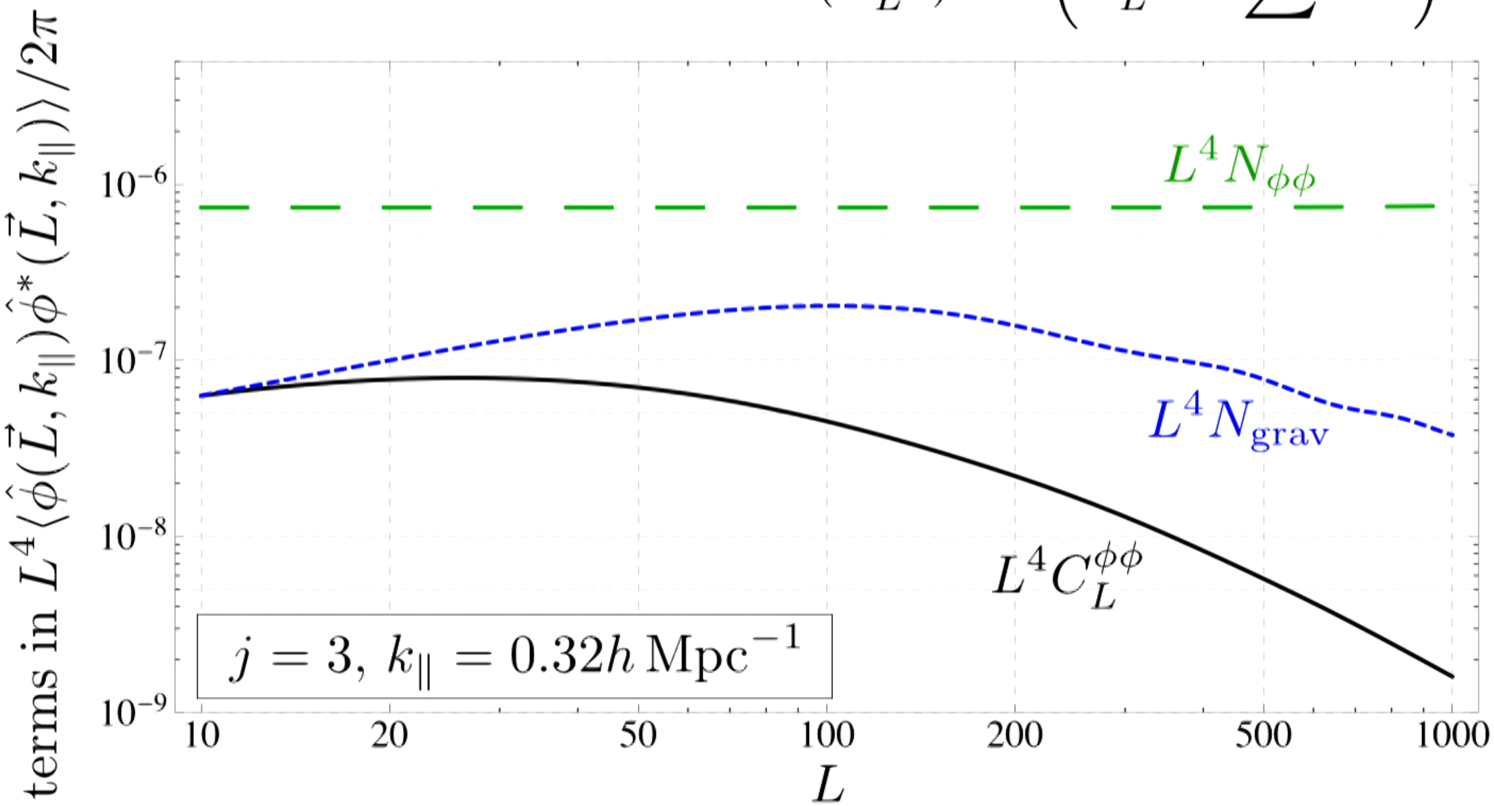

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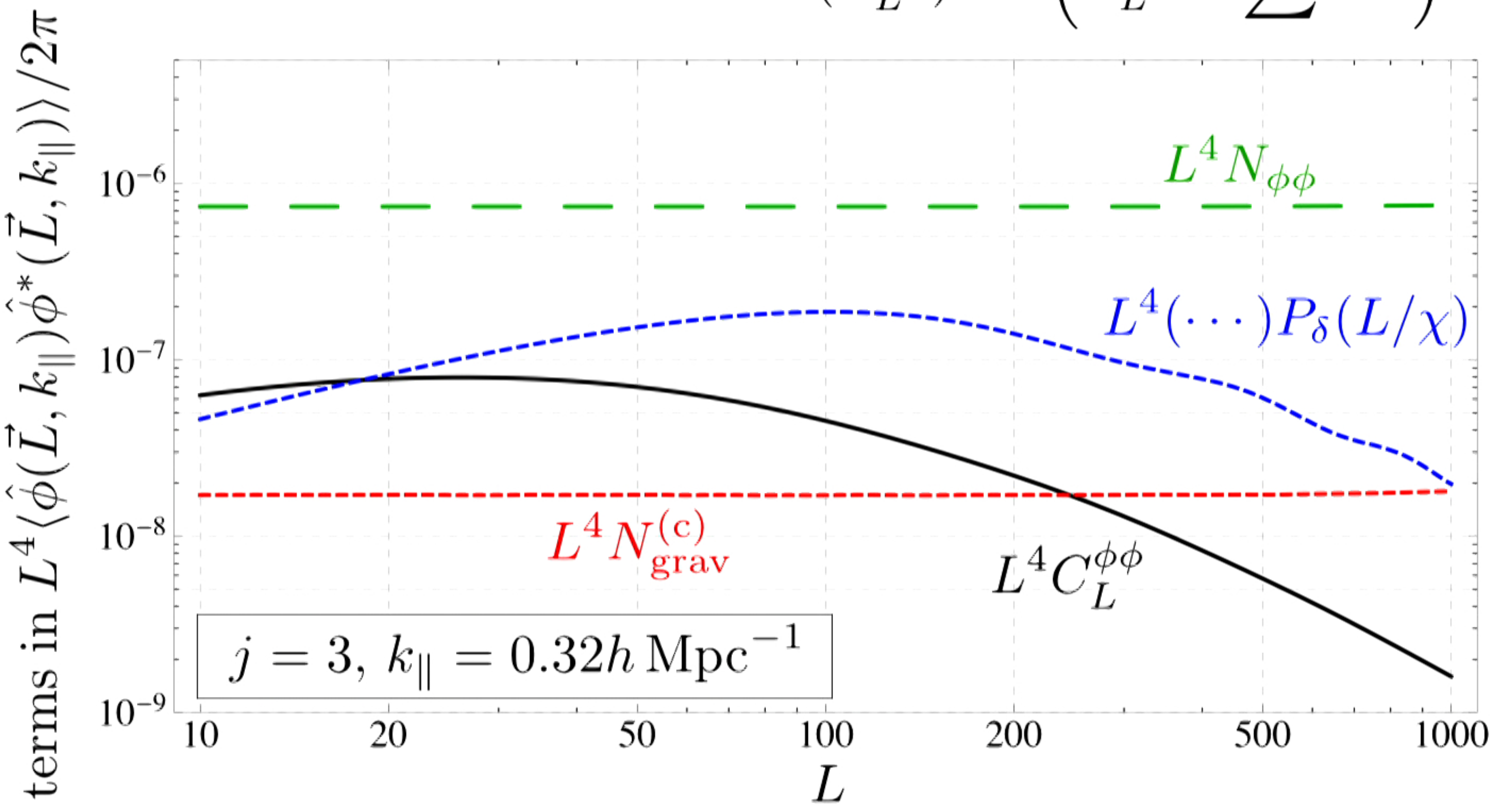

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$$\langle \hat\phi \hat\phi^* \rangle \propto C_L^{\phi\phi} + \sum N_{...}$$

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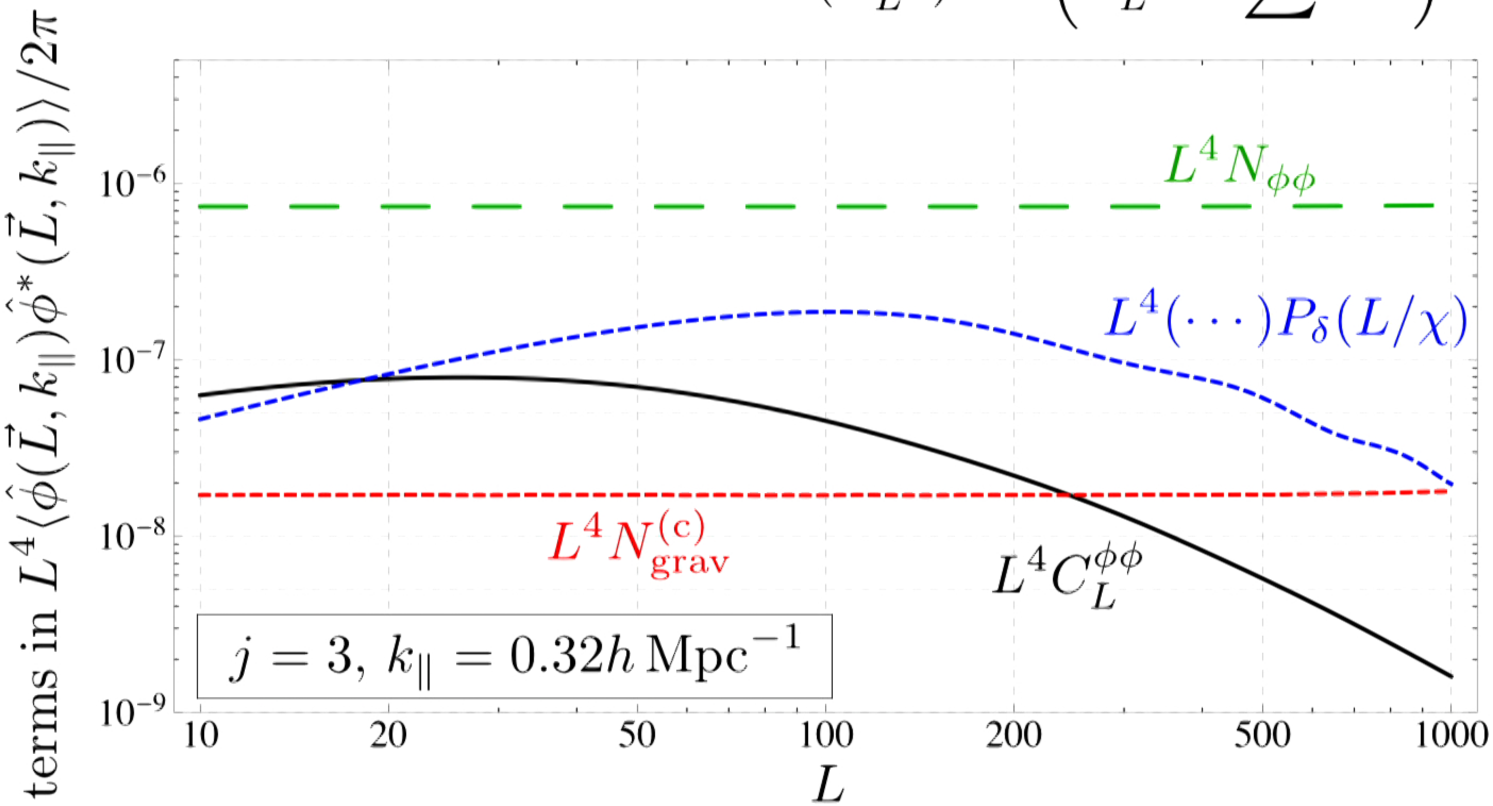
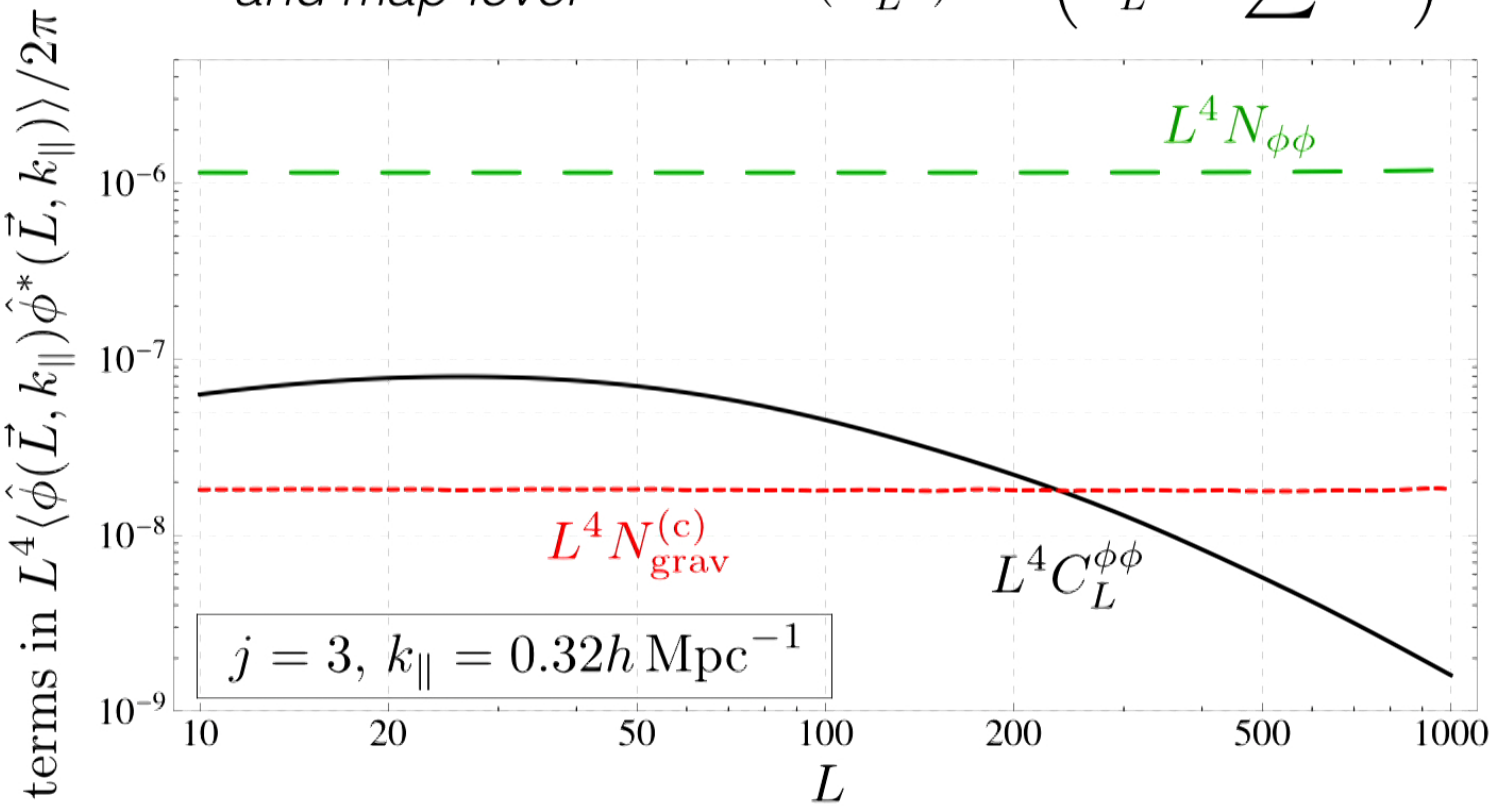


Bias-hardened lensing estimator for single $k_{\|}$

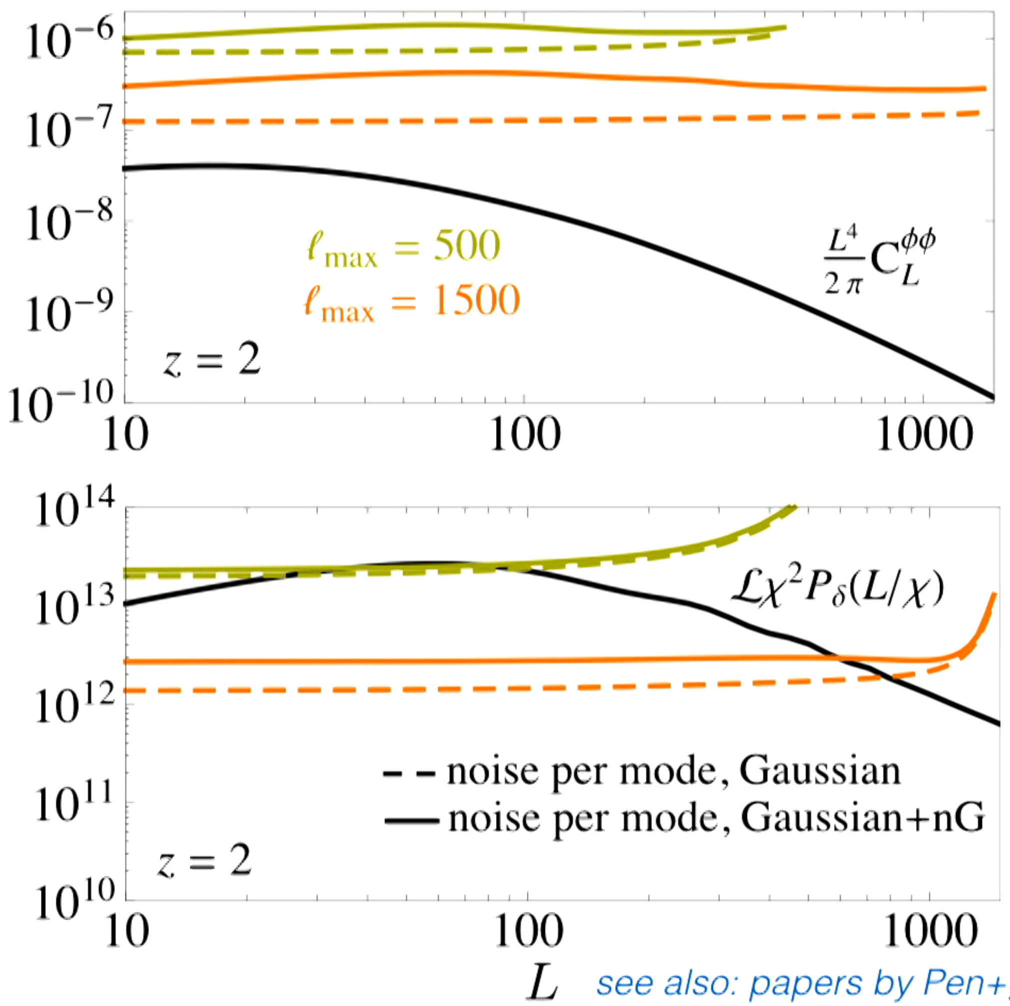
BH removes dominant bias at power-spectrum-level *and map-level*

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

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



"Tidal" reconstruction

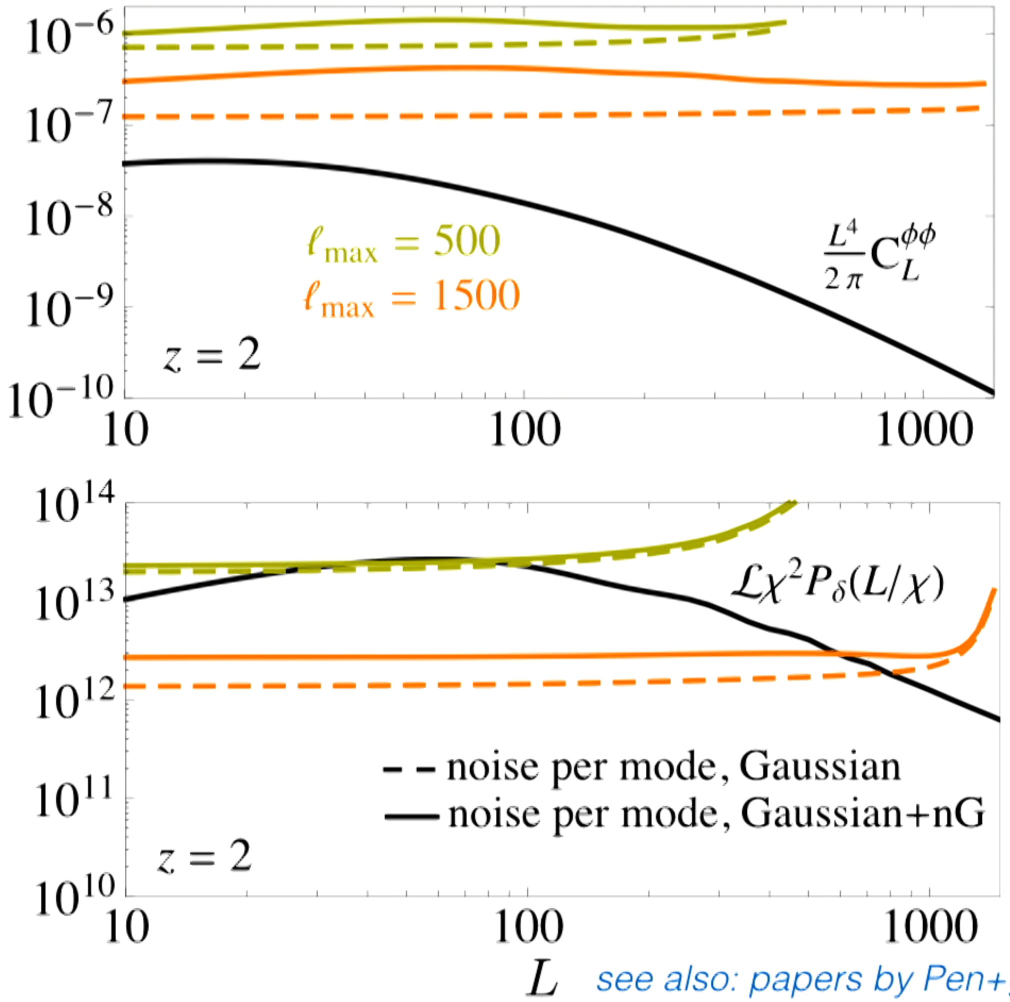


At low z, lensing is hard with quadratic estimators…

…but long density modes are recoverable with the same estimators!

see also: papers by Pen+group; SF et al., in progress

"Tidal" reconstruction



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   - *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 interferometers

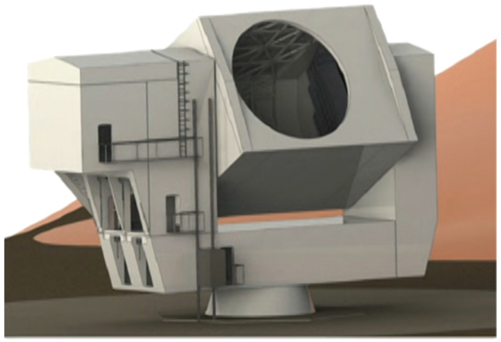
S/N on lensing power spectra for 21cm surveys

	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: total detection significance will be weak at best (for these surveys)

- Cross-correlations with LSST*: worth a try!
  ** or a sparser survey*

Example of single-dish IM survey

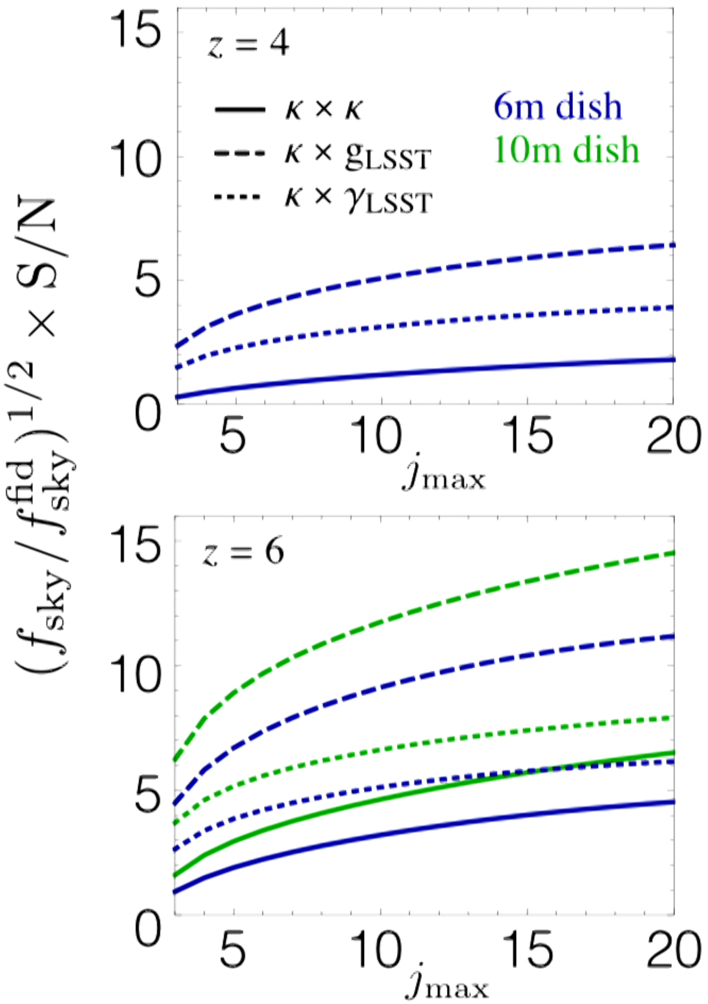


CCAT-prime IM survey: $3.3<z<9.3$

- measure 158 μm [CII] fine-structure line
- goal: map star-forming regions at high redshift
- modeling of signal is *very* uncertain

Images: Mike Niemack

Forecasts for single-dish CII IM survey



- $j_{\rm max}$ parameterizes noise level ($\ell_{\rm max}$ fixed by $D_{\rm dish}, \lambda_{\rm obs}$)
- Auto/cross detectability depends on S/N of IM signal, and $f_{\rm sky}$

Dreaming big: a "stage 2" 21cm survey

What might the next generation of 21cm surveys look like?

Slosar, SF et al, Cosmic Visions 21cm white paper - coming soon!

"Stage 1": HIRAX, $0.8<z<2.5$

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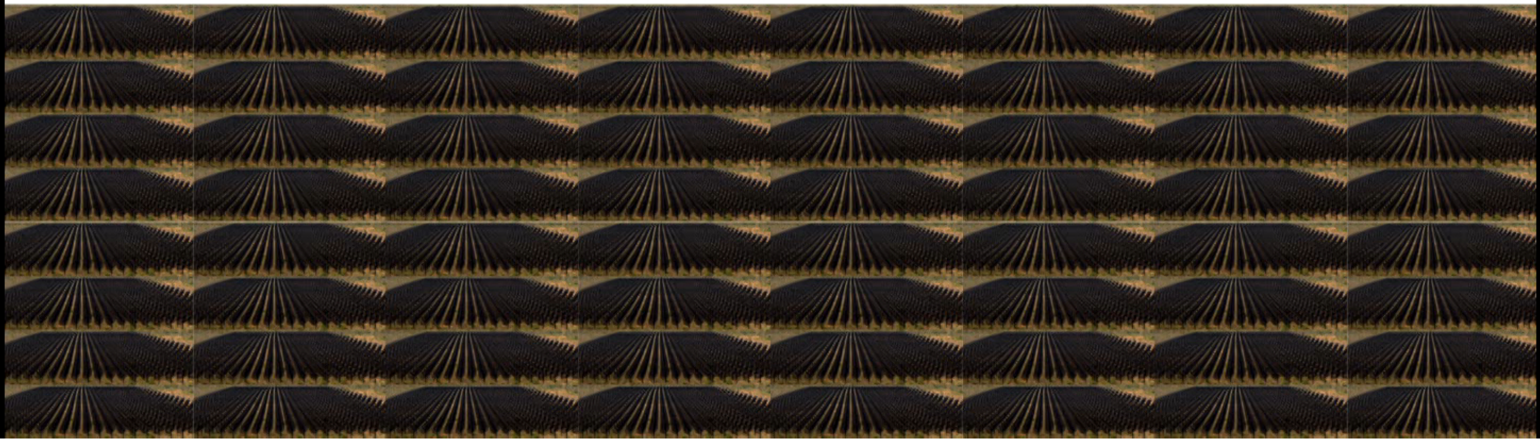
"Stage 1": HIRAX, 0.8<z<2.5

"Stage 2"(?): 64 x HIRAX, 2<z<6



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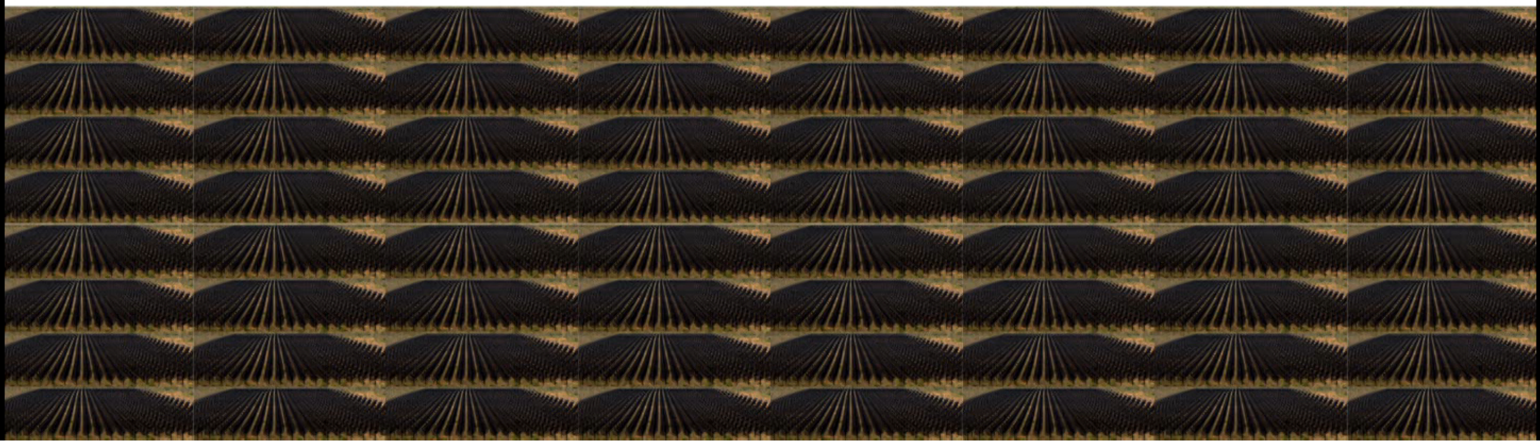
“Stage 2”(?): 64 x HIRAX, 2<z<6



Dreaming big: a "stage 2" 21cm survey

What might the next generation of 21cm surveys ***do***?

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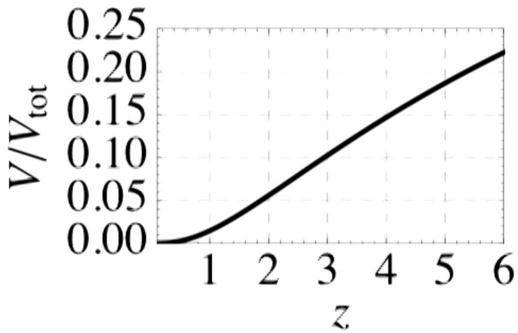
- Measure ~3x the volume of optical/IR galaxy surveys (many more linear modes!)



- Measure cosmic expansion history at 2<z<6
- Constrain features in the primordial power spectrum
- Constrain primordial non-Gaussianity via the bispectrum of large-scale structure

Dreaming big: a “stage 2” 21cm survey

What might the next generation of 21cm surveys ***do***?

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PRELIMINARY

S/N on lensing or tidal reconstruction power spectra

quantity / experiment	CMB S4	21-cm-S2, no wedge	21-cm-S2, with wedge
Lensing × LSST galaxies	367	466	300
Lensing × LSST shear	178	263	191
Lensing auto	353	84	6
Tidal reconstruction auto	-	1408	291

- 21cm lensing cross correlations:
  ~competitive with CMB-S4!
- tidal reconstruction: large S/N

Dreaming big: a “stage 2” 21cm survey

July 30 - August 1, 2018 www.bnl.gov/tra2018/

2018 Workshop on Tremendous Radio Arrays

General Workshop Registration (Deadline: July 16, 2018 11:59 PM)

Begin Workshop Registration

Motivation

Tremendous Radio Arrays will bring together the US and international communities interested in a large scale, dedicated, second generation 21-cm intensity mapping experiment. This workshop will provide an overview of the current state of the art and discuss the scientific drivers, technological challenges and programmatic issues that need to resolved before this experiment can become reality.

Workshop Dates
July 30–August 1, 2018

Event ID
38727

Workshop Venue
Brookhaven National Laboratory
Upton, NY 11973 USA

Workshop Location
Physics Department (Bldg. 510)
Large Seminar Room

Map and Directions

Conclusions

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   - *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!*
   - *an imagined "stage 2" 21cm survey would compete with CMB-S4 in lensing precision*