Title: Weak lensing: globally optimal estimator and a new probe of the high-redshift Universe

Speakers: Abhishek Maniyar

Series: Cosmology & Gravitation

Date: November 02, 2021 - 11:00 AM

URL: https://pirsa.org/21110000

Abstract: In recent years, weak lensing of the cosmic microwave background (CMB) has emerged as a powerful tool to probe fundamental physics. The prime target of CMB lensing surveys is the lensing potential, which is reconstructed from observed CMB temperature T and polarization E and B fields. In this talk, I will show that the classic Hu-Okamoto (HO02) estimator used for the lensing potential reconstruction is not the absolute optimal lensing estimator that can be constructed out of quadratic combinations of T, E and B fields. Instead, I will derive the global-minimum-variance (GMV) lensing quadratic estimator and show explicitly that the HO02 estimator is suboptimal to the GMV estimator.

Rapidly expanding field of the line intensity mapping (LIM) promises to revolutionise our understanding of the galaxy formation and evolution. Although primarily a tool for galaxy astrophysics, LIM technique can be used as a cosmological probe and I will point out one such application in rest of the talk. I will show that a linear combination of lensing maps from the cosmic microwave background (CMB) and from line intensity maps (LIMs) allows to exactly null the low-redshift contribution to CMB lensing, and extract only the contribution from the Universe from/beyond reionization. This would provide a unique probe of the Dark Ages, complementary with 21 cm. I will quantify the interloper bias (which is a key hurdle to LIM techniques) to LIM lensing for the first time, and derive a "LIM-pair" estimator which nulls it exactly.

In the end, I will show some results for prospects of observing the Doppler boosted CIB emission and its applications.

Weak lensing: globally optimal estimator and a new probe of the high-redshift Universe

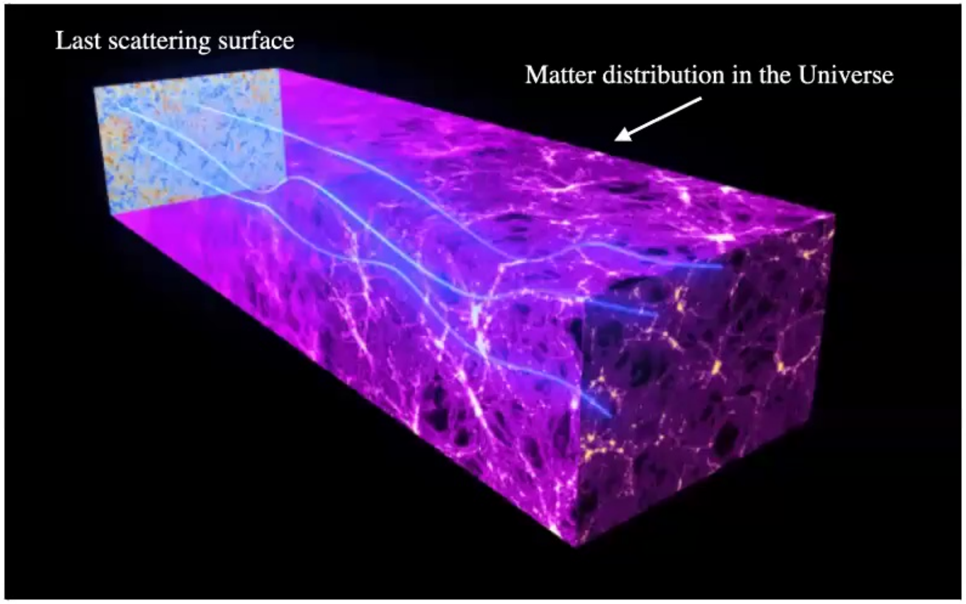
Abhishek S. Maniyar
CCPP, NYU

Cosmology seminar, PITP
2nd November 2021
😊 Virtual ☹️

View Zoom Add Slide Play Keynote Live Table Chart Text Shape Media Comment Collaborate Format Animate Document

Weak lensing of the CMB

- Distribution of the foreground matter fluctuations deflects CMB photons
- What we see is a distorted CMB map



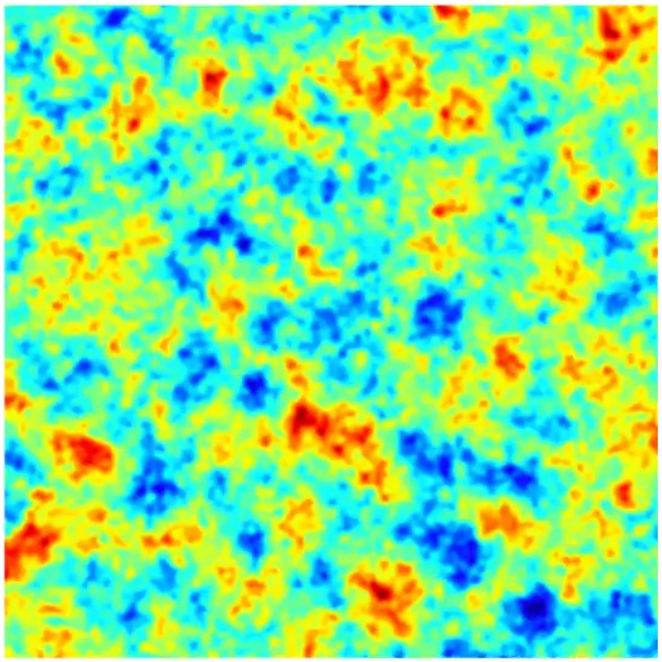
Abhishek Maniyar, CCPP (NYU)

Weak lensing: globally optimal estimator

In collaboration with: Yacine Ali-Haïmoud, Julien Carron, Antony Lewis, Mathew Madhavacheril

Phys. Rev. D103, 083524 (2021)

Weak lensing of the CMB



credit: https://www.earlyuniverse.org/neutrinos/

$$T(\hat{n}) = T^0(\hat{n} + d)$$

lensed map ↗

unlensed map ↑

deflection angle ↖

$$d = \nabla\phi$$ ← lensing potential

Reconstruction of ϕ (or $\kappa = \frac{1}{2}L(L+1)\phi$

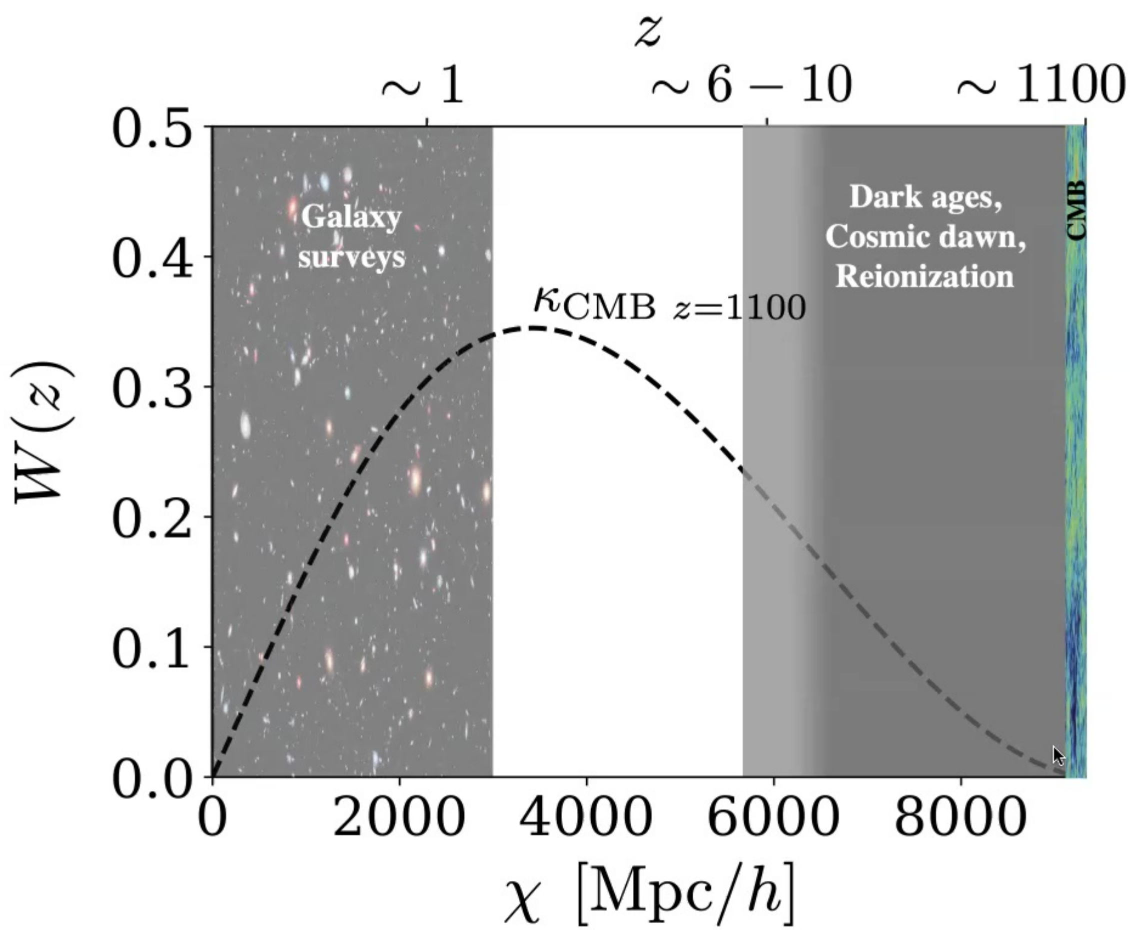
↓

Projected mass distribution along the line of sight
=> projected map of the matter in the Universe!

Reconstructing the density field with lensing

- κ probes projected mass density
- Reconstructing κ => major cosmology goal of CMB experiments
- $\kappa = \frac{1}{2}L(L+1)\phi$

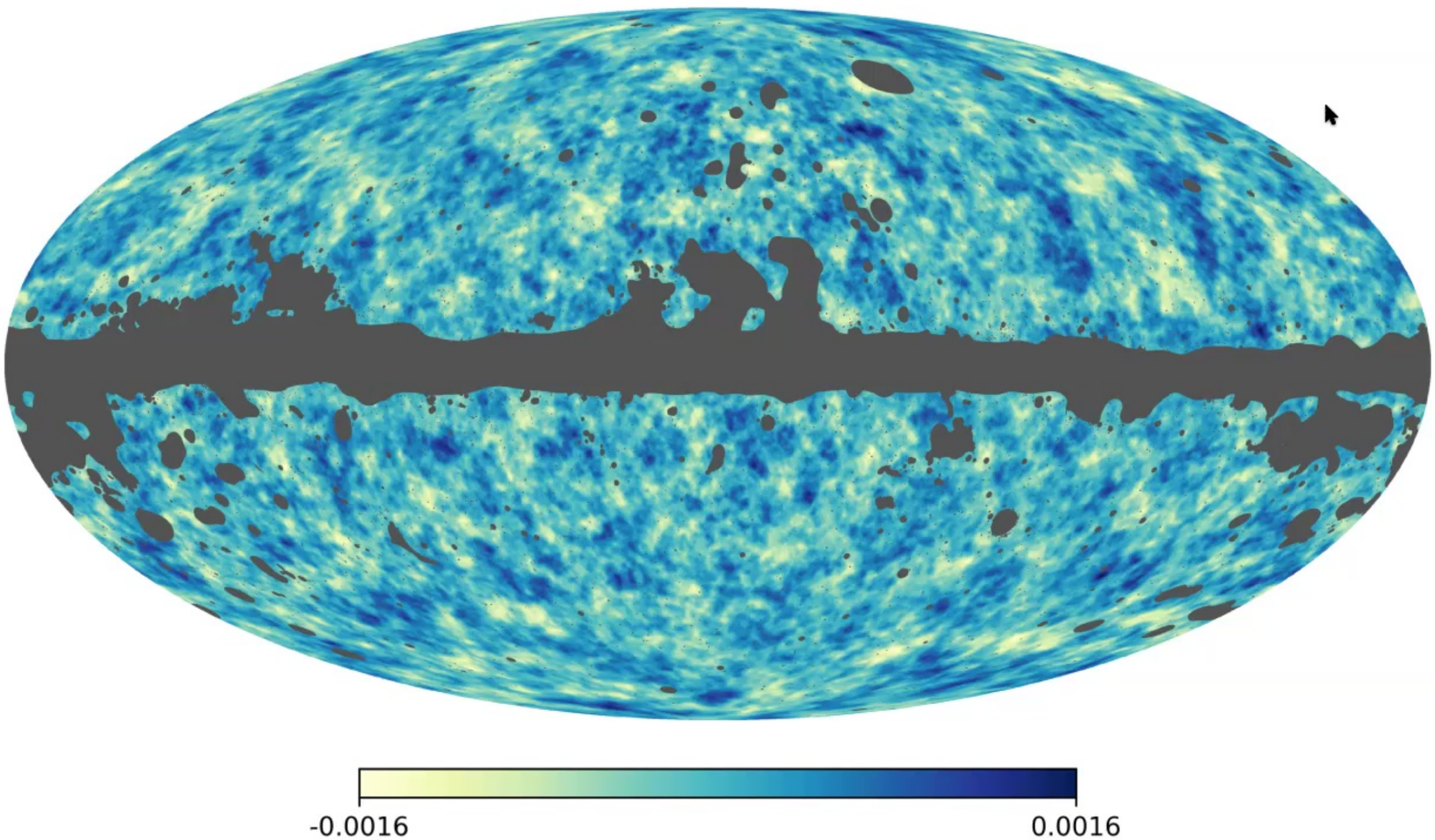
Lensing potential



Abhishek Maniyar, CCPP (NYU)

View Zoom Add Slide Play Keynote Live Table Chart Text Shape Media Comment Collaborate Format Animate Document

Planck lensing reconstruction map



Planck 2018

Abhishek Maniyar, CCPP (NYU)

Quadratic estimators

$$\langle x^0(\mathbf{l})x^0(\mathbf{l}')\rangle \equiv (2\pi)^2\delta(\mathbf{l}-\mathbf{l}')C_\ell^0 \xrightarrow[\text{lensing}]{\text{No}} \text{Different multipoles uncorrelated}$$

$$x^0 = T, E, B$$

$$\langle x(\mathbf{l})x'(\mathbf{l}')\rangle_{\text{fixed } \phi} = f_\alpha(\mathbf{l},\mathbf{l}')\phi(\mathbf{L}) \xrightarrow{\text{lensing}}$$

Lensing induces correlations between different multipoles!

$$\mathbf{L} = \mathbf{l} + \mathbf{l}' \qquad \mathbf{l} \neq -\mathbf{l}' \qquad x, x' = T, E, B$$

$$\alpha = \{TT, TE, EE, TB, EB, BB\}$$

- Appropriate average of pairs of multipoles can be used to estimate the deflection field!
- Pairs of multipoles => quadratic estimator!

Abhishek Maniyar, CCPP (NYU)

Quadratic estimators

$$\langle x^0(\mathbf{l})x^0(\mathbf{l}')\rangle \equiv (2\pi)^2\delta(\mathbf{l}-\mathbf{l}')C_\ell^0 \xrightarrow[\text{lensing}]{\text{No}} \text{Different multipoles uncorrelated}$$

$$x^0 = T, E, B$$

$$\langle x(\mathbf{l})x'(\mathbf{l}')\rangle_{\text{fixed }\phi} = f_\alpha(\mathbf{l},\mathbf{l}')\phi(\mathbf{L}) \xrightarrow{\text{lensing}}$$ Lensing induces correlations between different multipoles!

$$\mathbf{L} = \mathbf{l} + \mathbf{l}' \quad \mathbf{l} \neq -\mathbf{l}' \quad x, x' = T, E, B$$

$$\alpha = \{TT, TE, EE, TB, EB, BB\}$$

$$\phi(\mathbf{L}) \propto \int_{\mathbf{l}\neq\mathbf{l}'} F(\mathbf{l},\mathbf{l}')x(\mathbf{l})x'(\mathbf{l}')$$

- Appropriate average of pairs of multipoles can be used to estimate the deflection field!
- Pairs of multipoles => quadratic estimator!

Several Quadratic Estimators of the CMB weak lensing

- Hu and Okamoto (2002): HO02
- Okamoto and Hu (2003): OH03
- Global minimum variance estimator: GMV
- Suboptimal quadratic estimator: SQE

→ Used in the final data analysis

Abhishek Maniyar, CCPP (NYU)

HO02

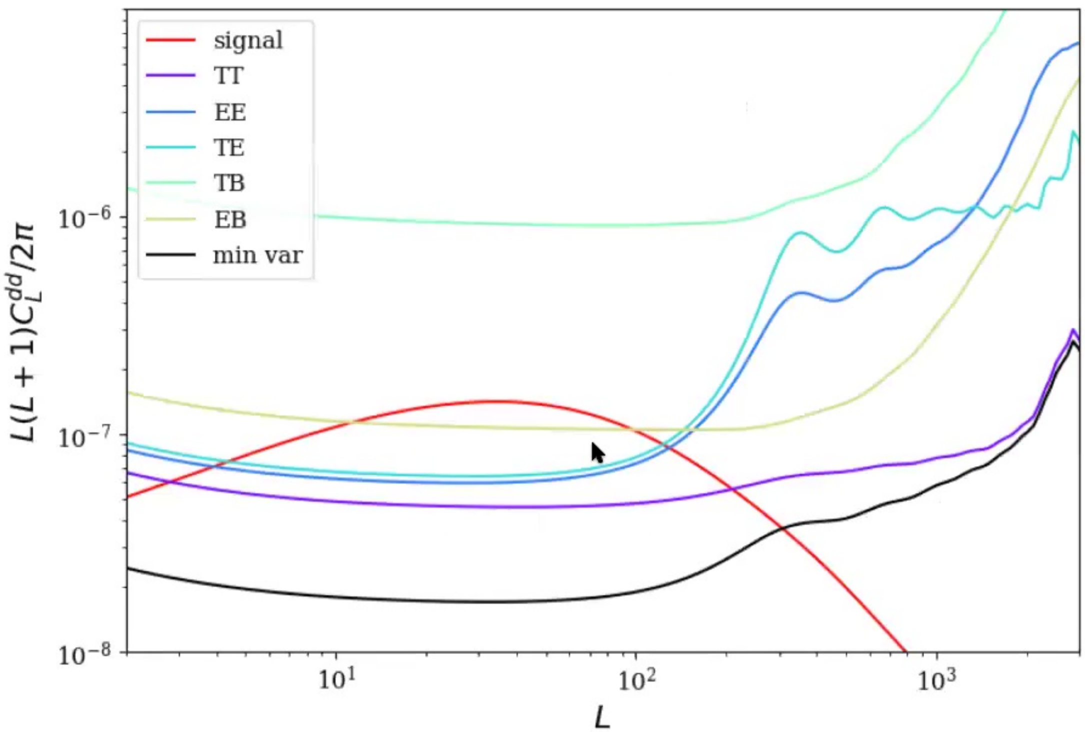
$$\hat{\phi}(\boldsymbol{L}) \propto \int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} F_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2) X(\boldsymbol{l}_1) Y(\boldsymbol{l}_2)$$

- 5 minimum variance estimators: $\hat{\phi}_{TT}$, $\hat{\phi}_{EE}$, $\hat{\phi}_{TE}$, $\hat{\phi}_{TB}$, $\hat{\phi}_{EB}$
- Final estimator: minimum variance linear combination of individual estimators

$$\hat{\phi}_{\text{HO02}} = w_{TT}\hat{\phi}_{TT} + w_{EE}\hat{\phi}_{EE} + w_{TE}\hat{\phi}_{TE} + w_{TB}\hat{\phi}_{TB} + w_{EB}\hat{\phi}_{EB}$$

$$w_{TT} + w_{EE} + w_{TE} + w_{TB} + w_{EB} = 1$$

HO02: SO-like experiment



- Individual TT, EE, TE, TB, and EB estimators
- MV estimator out of combination of individual estimators
- Temperature dominated data

Abhishek Maniyar, CCPP (NYU)

GMV

- HO02 consider the correlations between different XY pairs **after** integrating over l_1 and l_2
- GMV: Account for these correlations at each l_1 and l_2
- Less noisy than HO02 and best possible minimum variance quadratic estimator!

$$\phi_{\rm mv} \propto \int \Big(F_{TT} T(\mathbf{l}) T(\mathbf{l}') + F_{EE} E(\mathbf{l}) E(\mathbf{l}') + F_{TE} T(\mathbf{l}) E(\mathbf{l}') + F_{TB} T(\mathbf{l}) B(\mathbf{l}') + F_{EB} E(\mathbf{l}) B(\mathbf{l}') \Big)$$

GMV

GMV

$$\hat{\phi}(\boldsymbol{L}) = \int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} X^i(\boldsymbol{l}_1)\Xi_{ij}(\boldsymbol{l}_1, \boldsymbol{l}_2)X^j(\boldsymbol{l}_2),$$

$$[\boldsymbol{\Xi}(\boldsymbol{l}_1, \boldsymbol{l}_2)] = \frac{\lambda(L)}{2}[\boldsymbol{C}_{l_1}]^{-1}[\boldsymbol{f}(\boldsymbol{l}_1, \boldsymbol{l}_2)][\boldsymbol{C}_{l_2}]^{-1}$$

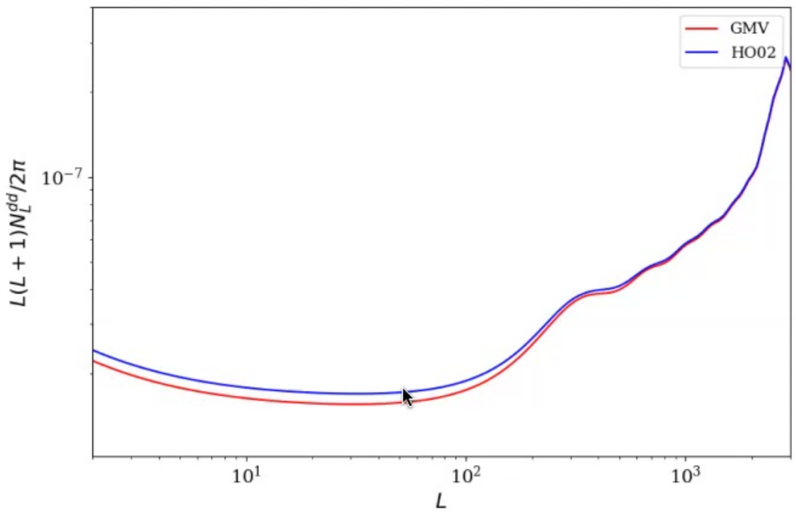
HO02

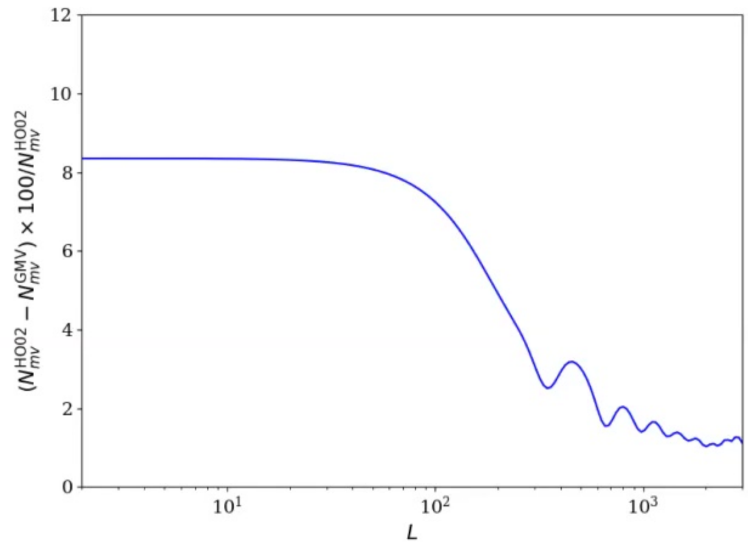
$$\int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} F_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2)X(\boldsymbol{l}_1)Y(\boldsymbol{l}_2)$$

$$F_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2) = \lambda_{XY}(L)\,\frac{f_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2)}{(1+\delta_{XY})C^{XX}_{l_1}C^{YY}_{l_2}}$$

- $\boldsymbol{C}_l$ and $\boldsymbol{f}(\boldsymbol{l}_1, \boldsymbol{l}_2)$: 3 x 3 symmetric matrices
- Separable in l_1 and l_2 without any approximations! => FFT
- Previously derived, but erroneously described as equivalent to HO02 estimator!!

GMV: SO-like experiment





- 8-10% smaller noise than HO02 on small L
- More information out of the same maps!

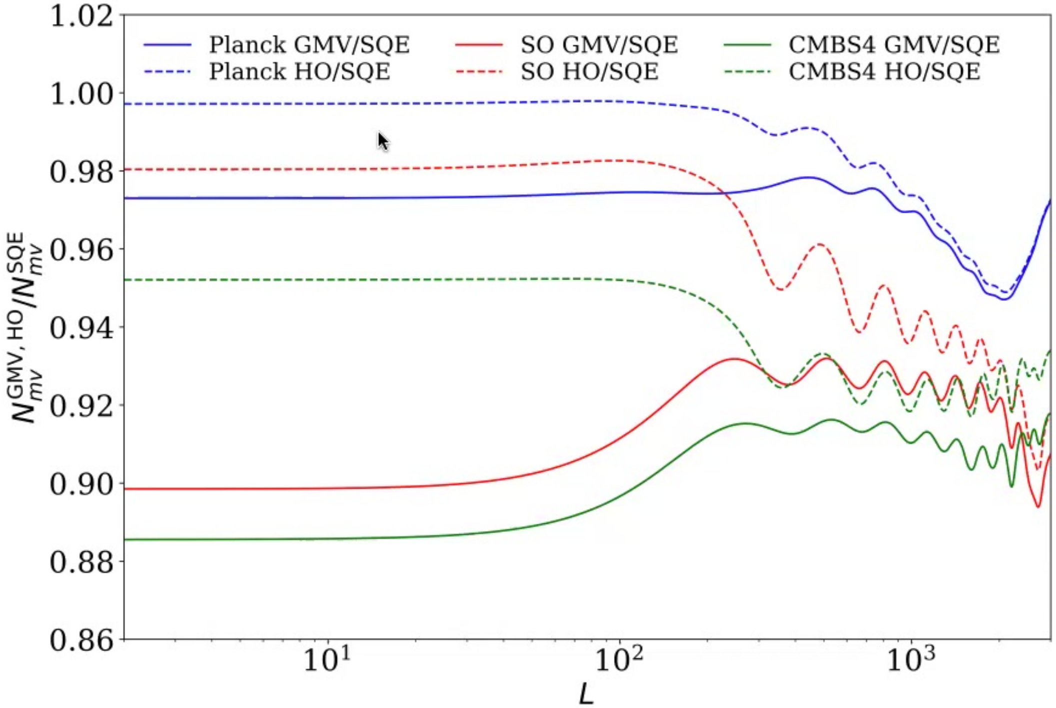
SQE

$$\hat{\phi}(\boldsymbol{L}) = \int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} X^i(\boldsymbol{l}_1)\Xi_{ij}(\boldsymbol{l}_1, \boldsymbol{l}_2)X^j(\boldsymbol{l}_2), \qquad [\boldsymbol{\Xi}(\boldsymbol{l}_1, \boldsymbol{l}_2)] = \frac{\lambda(L)}{2}[\boldsymbol{C}_{l_1}]^{-1}[\boldsymbol{f}(\boldsymbol{l}_1, \boldsymbol{l}_2)][\boldsymbol{C}_{l_2}]^{-1}$$

- Planck (2016, 2020) and SPT (2019) use an approximated version: SQE
- $C_l^{TE} = 0$ in $\boldsymbol{C}_l$
- Allows to deal with cut-sky setup with lower computational cost
- Preserves separability in l_1 and l_2
- 3% noise penalty for Planck
- Suboptimal to HO02 as well!

Abhishek Maniyar, CCPP (NYU)

Comparison of all estimators



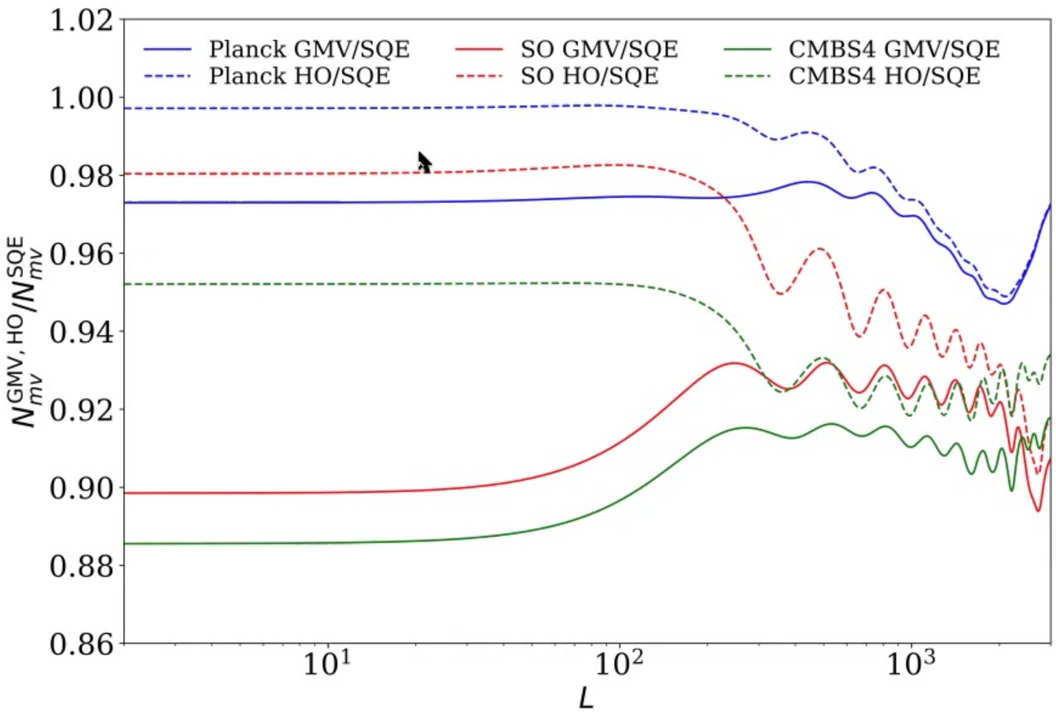
- SQE to GMV difference:
  - 3-6% for Planck-like experiments
  - 11-12% for SO-like experiments
- Should motivate use of full covariance matrix rather than setting $C_l^{TE} = 0$

Abhishek Maniyar, CCPP (NYU)

Conclusions

- HO02 optimisation procedure does not lead to absolute minimum-variance QE
- GMV is the global minimum-variance QE
- Arguments applicable to full-sky as well
- Cross-correlation studies of lensing, delensing will benefit by smaller noise on reconstruction: GMV

Comparison of all estimators



- SQE to GMV difference:
  - 3-6% for Planck-like experiments
  - 11-12% for SO-like experiments
- Should motivate use of full covariance matrix rather than setting $C_l^{TE} = 0$

Abhishek Maniyar, CCPP (NYU)

SQE

$$\hat{\phi}(\boldsymbol{L}) = \int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} X^i(\boldsymbol{l}_1)\Xi_{ij}(\boldsymbol{l}_1, \boldsymbol{l}_2)X^j(\boldsymbol{l}_2), \qquad [\boldsymbol{\Xi}(\boldsymbol{l}_1, \boldsymbol{l}_2)] = \frac{\lambda(L)}{2}[\boldsymbol{C}_{l_1}]^{-1}[\boldsymbol{f}(\boldsymbol{l}_1, \boldsymbol{l}_2)][\boldsymbol{C}_{l_2}]^{-1}$$

- Planck (2016, 2020) and SPT (2019) use an approximated version: SQE
- $C_l^{TE} = 0$ in $\boldsymbol{C}_l$
- Allows to deal with cut-sky setup with lower computational cost
- Preserves separability in l_1 and l_2
- 3% noise penalty for Planck
- Suboptimal to HO02 as well!

Abhishek Maniyar, CCPP (NYU)

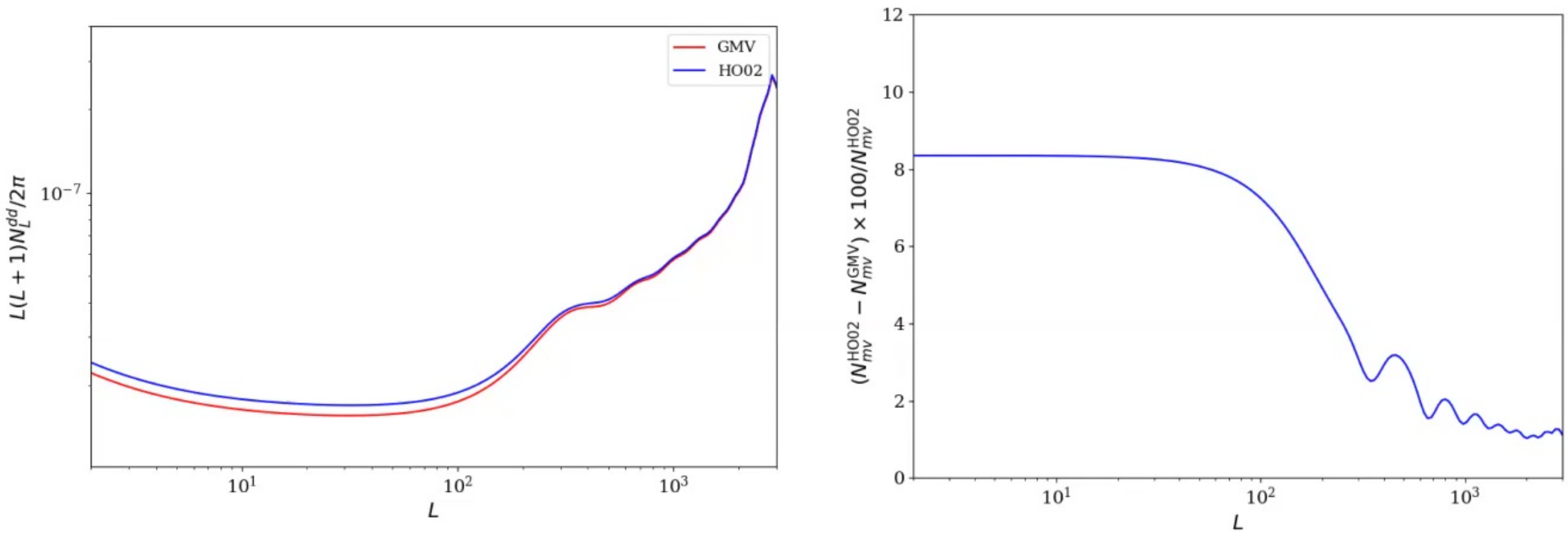
SQE

$$\hat{\phi}(\boldsymbol{L}) = \int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} X^i(\boldsymbol{l}_1)\Xi_{ij}(\boldsymbol{l}_1, \boldsymbol{l}_2)X^j(\boldsymbol{l}_2), \qquad [\boldsymbol{\Xi}(\boldsymbol{l}_1, \boldsymbol{l}_2)] = \frac{\lambda(L)}{2}[\boldsymbol{C}_{l_1}]^{-1}[\boldsymbol{f}(\boldsymbol{l}_1, \boldsymbol{l}_2)][\boldsymbol{C}_{l_2}]^{-1}$$

- Planck (2016, 2020) and SPT (2019) use an approximated version: SQE
- $C_l^{TE} = 0$ in $\boldsymbol{C}_l$
- Allows to deal with cut-sky setup with lower computational cost
- Preserves separability in l_1 and l_2
- 3% noise penalty for Planck
- Suboptimal to HO02 as well!

Abhishek Maniyar, CCPP (NYU)

GMV: SO-like experiment



- 8-10% smaller noise than HO02 on small L
- More information out of the same maps!

GMV

GMV

$$\hat{\phi}(\boldsymbol{L}) = \int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} X^i(\boldsymbol{l}_1)\Xi_{ij}(\boldsymbol{l}_1, \boldsymbol{l}_2)X^j(\boldsymbol{l}_2),$$

$$[\boldsymbol{\Xi}(\boldsymbol{l}_1, \boldsymbol{l}_2)] = \frac{\lambda(L)}{2}[\boldsymbol{C}_{l_1}]^{-1}[\boldsymbol{f}(\boldsymbol{l}_1, \boldsymbol{l}_2)][\boldsymbol{C}_{l_2}]^{-1}$$

HO02

$$\int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} F_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2)X(\boldsymbol{l}_1)Y(\boldsymbol{l}_2)$$

$$F_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2) = \lambda_{XY}(L)\ \frac{f_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2)}{(1+\delta_{XY})C^{XX}_{l_1}C^{YY}_{l_2}}$$

- $\boldsymbol{C}_l$ and $\boldsymbol{f}(\boldsymbol{l}_1, \boldsymbol{l}_2)$: 3 x 3 symmetric matrices
- Separable in l_1 and l_2 without any approximations! => FFT
- Previously derived, but erroneously described as equivalent to HO02 estimator!!

Abhishek Maniyar, CCPP (NYU)

SQE

$$\hat{\phi}(\boldsymbol{L}) = \int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} X^i(\boldsymbol{l}_1)\Xi_{ij}(\boldsymbol{l}_1, \boldsymbol{l}_2)X^j(\boldsymbol{l}_2), \qquad [\boldsymbol{\Xi}(\boldsymbol{l}_1, \boldsymbol{l}_2)] = \frac{\lambda(L)}{2}[\boldsymbol{C}_{l_1}]^{-1}[\boldsymbol{f}(\boldsymbol{l}_1, \boldsymbol{l}_2)][\boldsymbol{C}_{l_2}]^{-1}$$

- Planck (2016, 2020) and SPT (2019) use an approximated version: SQE
- $C_l^{TE} = 0$ in $\boldsymbol{C}_l$
- Allows to deal with cut-sky setup with lower computational cost
- Preserves separability in l_1 and l_2
- 3% noise penalty for Planck
- Suboptimal to HO02 as well!

Abhishek Maniyar, CCPP (NYU)

A new probe of the high-redshift Universe: nulling CMB lensing with interloper-free "LIM-pair" lensing

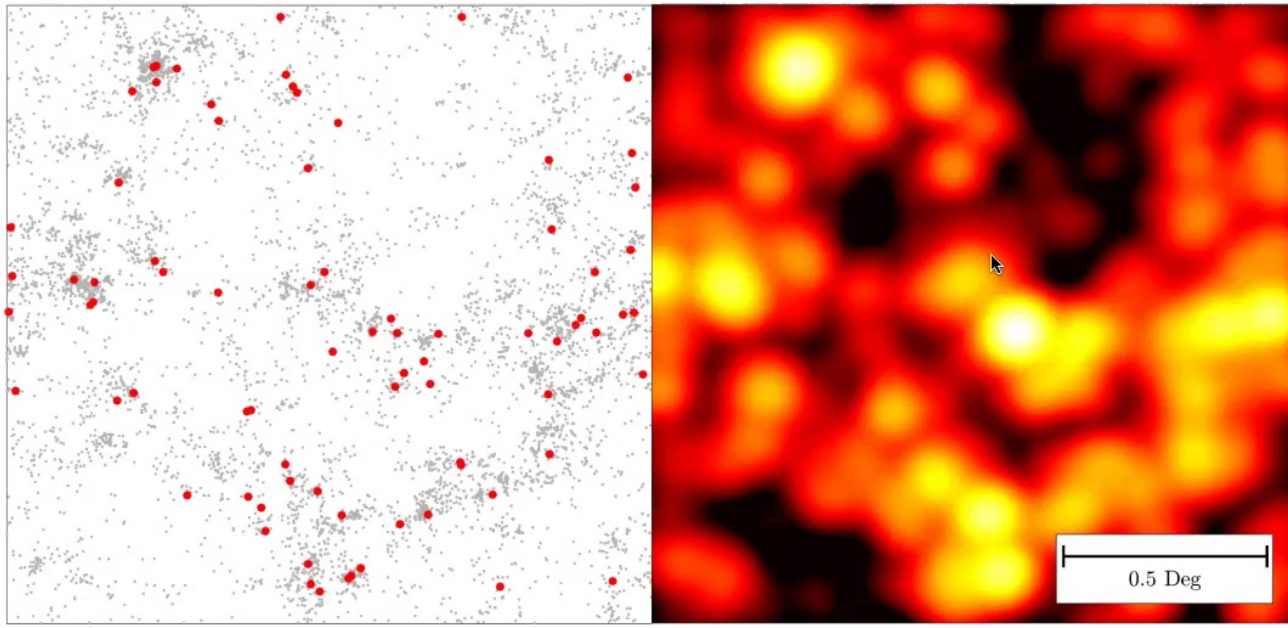
In collaboration with: Emmanuel Schaan & Anthony Pullen

arXiv:2106.09005

Abhishek Maniyar, CCPP (NYU)

Line intensity mapping

Measures **aggregate intensity** in large 2D pixels in multiple frequency bins



Credit: Patrick Breysse

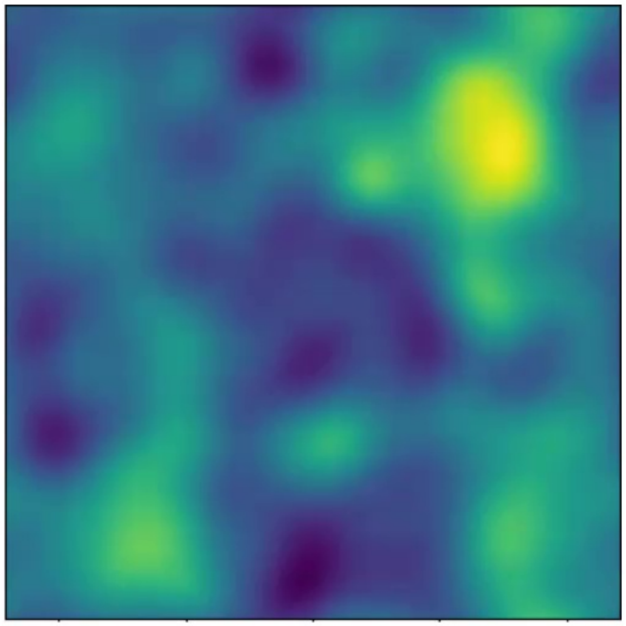
Faint Galaxies Bright Galaxies Line Emission

A probe of high redshift Universe!

Abhishek Maniyar, CCPP (NYU)

Interlopers & continuum

What we aim to measure is emission from a specific atomic or molecular line transition

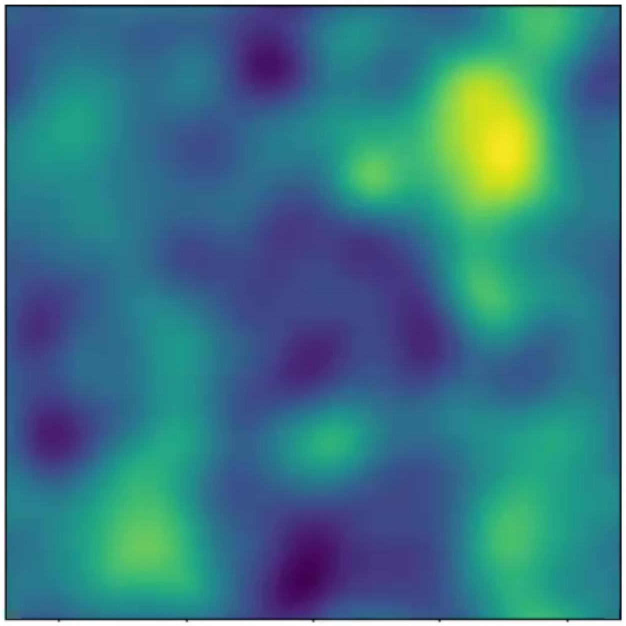


500 GHz

Line	Rest frame ν [GHz]	z for [420-650] GHz
[CII]	1901	2.5 - 3.6
CO J=5-4	576.3	0.0 - 0.4
CI J=1-0	492	0.0 - 0.2
CI J=2-1	809	0.4 - 1.0

Interlopers & continuum

What we aim to measure is emission from a specific atomic or molecular line transition



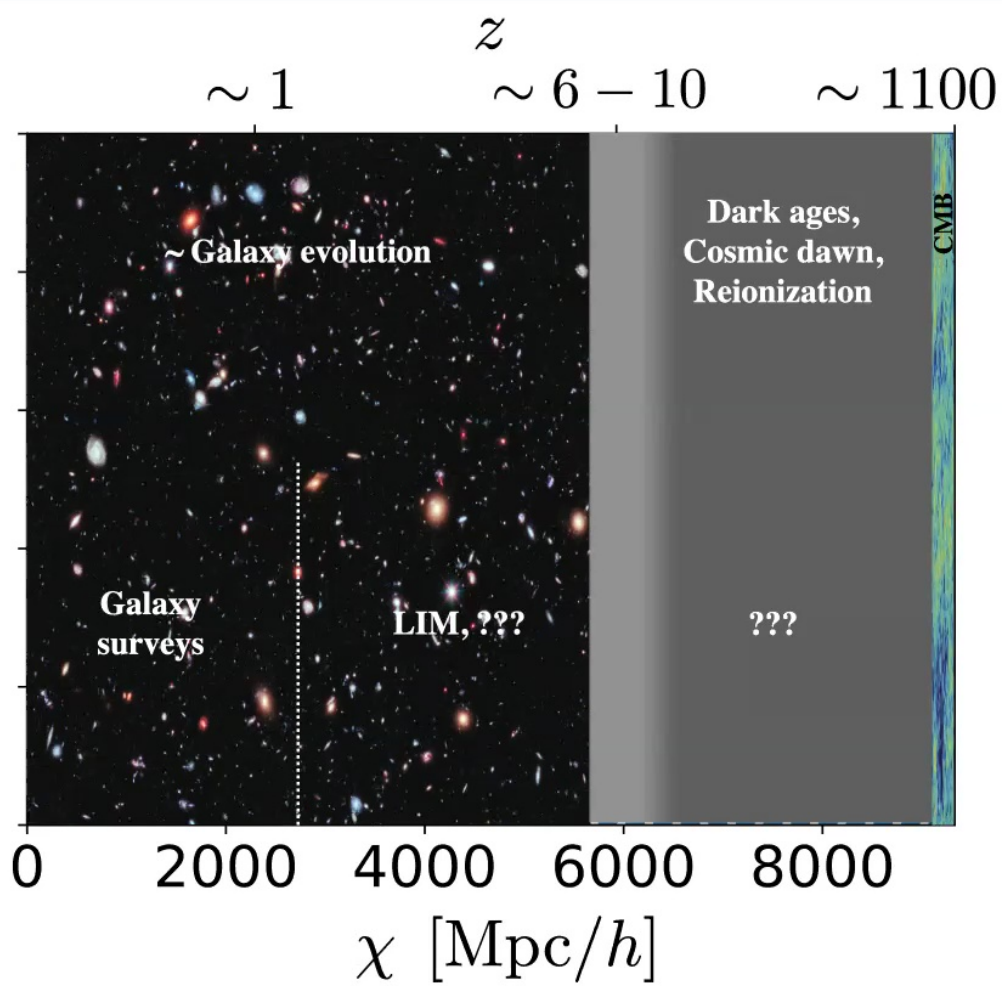
500 GHz

Line	Rest frame ν [GHz]	z for [420-650] GHz
[CII]	1901	2.5 - 3.6
CO J=5-4	576.3	0.0 - 0.4
CI J=1-0	492	0.0 - 0.2
CI J=2-1	809	0.4 - 1.0

Also continuum emission: Cosmic Infrared Background, Milky Way!

High redshift universe

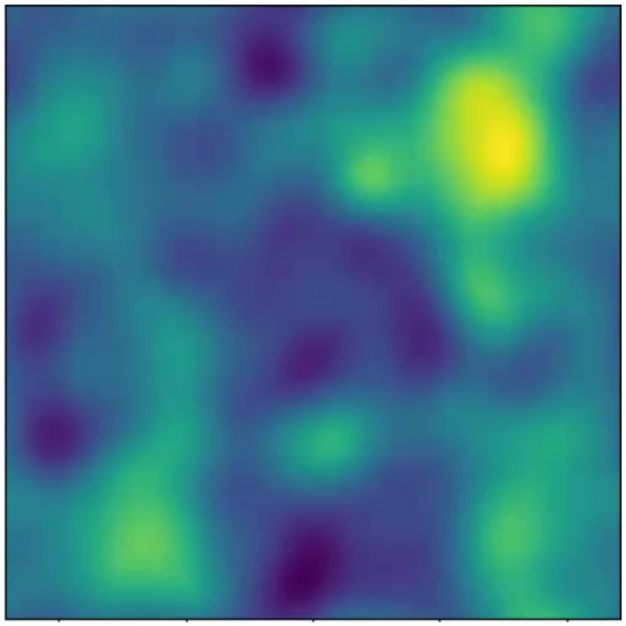
- Galaxy surveys: matter density field at z < ~1.5
- LIM at high redshifts?
  - ✶ Continuum foregrounds render modes perpendicular to LOS $k_{||} \simeq 0$ unusable for cosmology
- Constructing matter density field at z > ~1.5 quite difficult
- Cosmic dawn, dark ages even more difficult
- Some new probe?



Abhishek Maniyar, CCPP (NYU)

Interlopers & continuum

What we aim to measure is emission from a specific atomic or molecular line transition

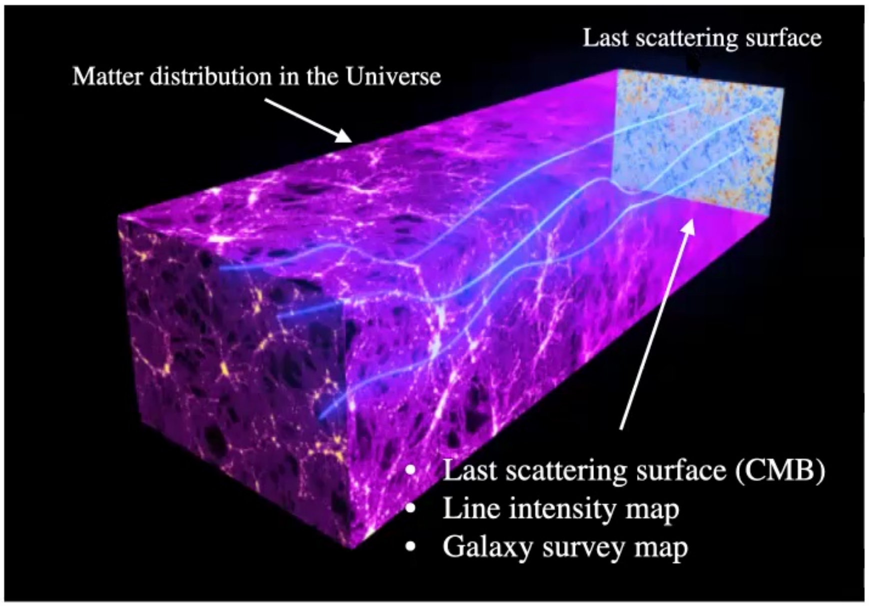


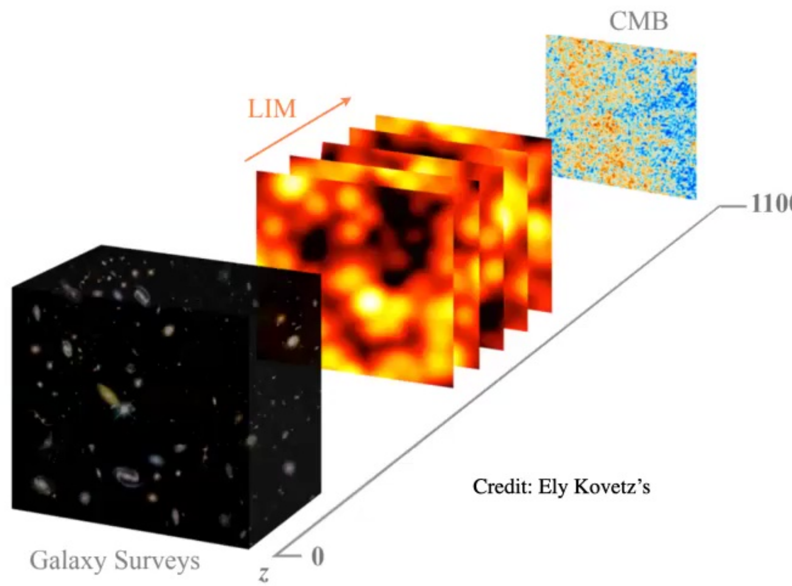
500 GHz

Line	Rest frame ν [GHz]	z for [420-650] GHz
[CII]	1901	2.5 - 3.6
CO J=5-4	576.3	0.0 - 0.4
CI J=1-0	492	0.0 - 0.2
CI J=2-1	809	0.4 - 1.0

Also continuum emission: Cosmic Infrared Background, Milky Way!

Weak lensing of the CMB/LIM/Galaxies



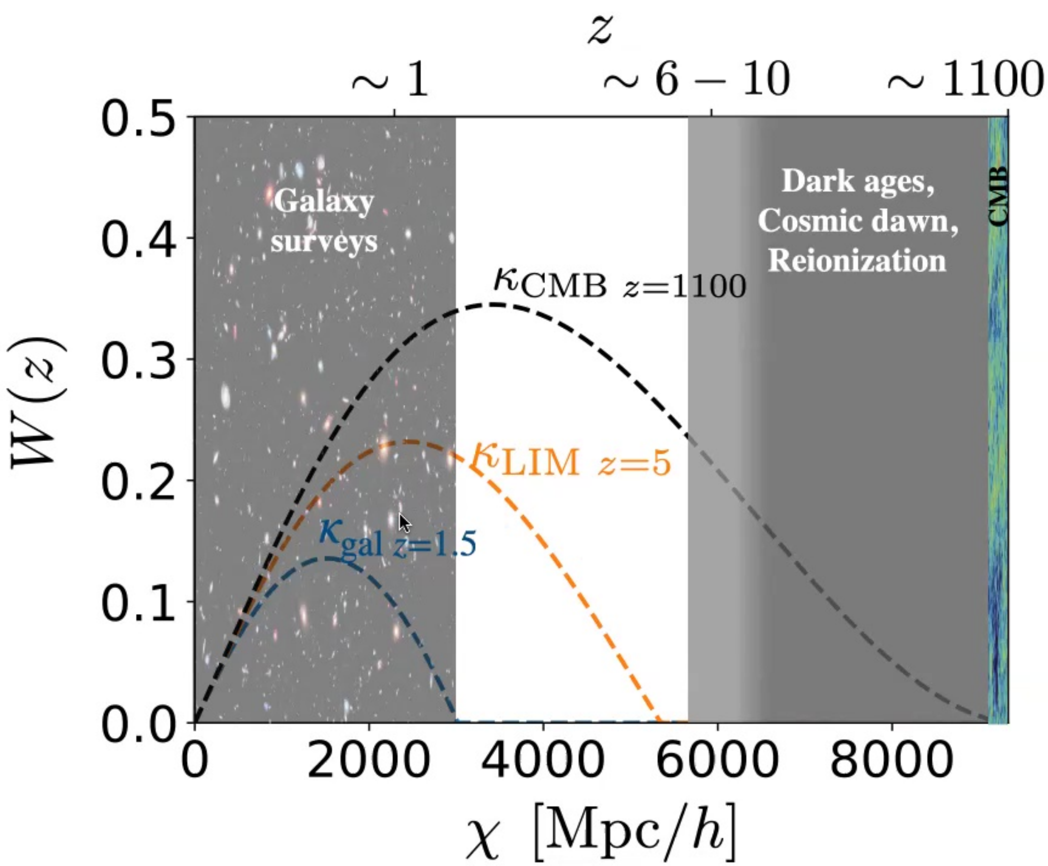


Credit: Ely Kovetz's

Abhishek Maniyar, CCPP (NYU)

Reconstructing the density field with lensing

- κ probes projected mass density



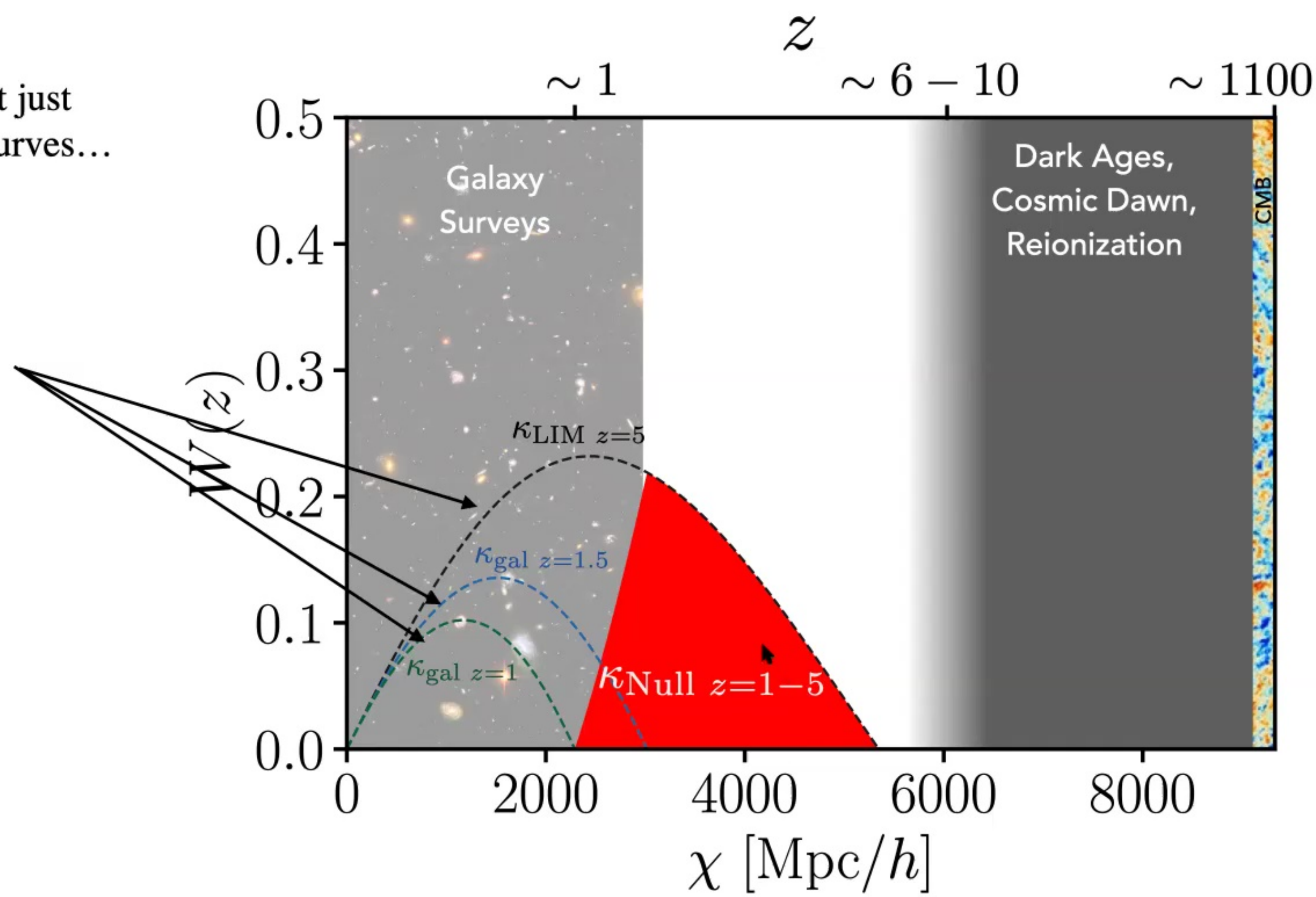
Abhishek Maniyar, CCPP (NYU)

But..

- How can we access the density field only for e.g. $1 < z < 5$?
- How can we access the density field only for e.g. $z > 5$?
- Galaxy surveys too expensive and limited at high redshifts

Nulling!

Can not just subtract curves…

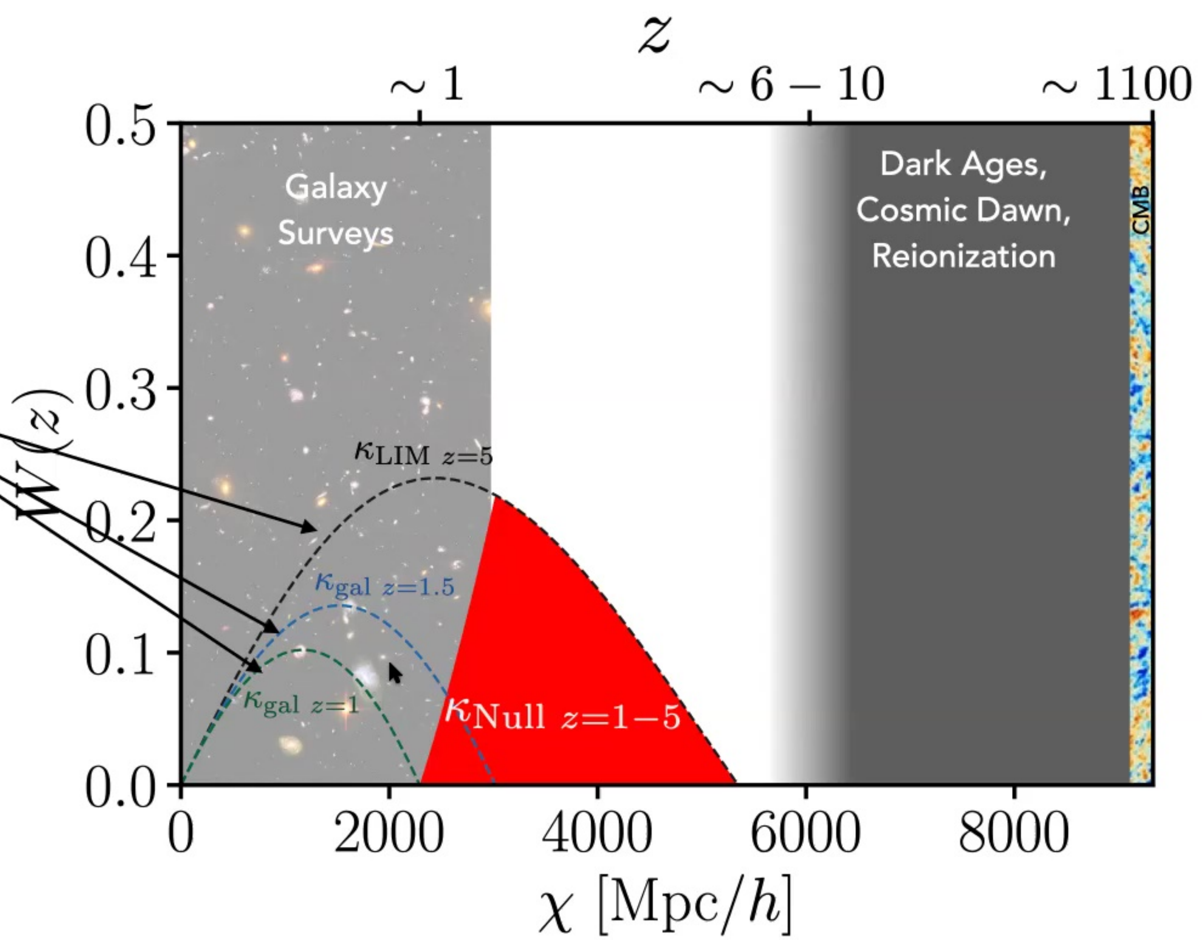


Abhishek Maniyar, CCPP (NYU)

Nulling!

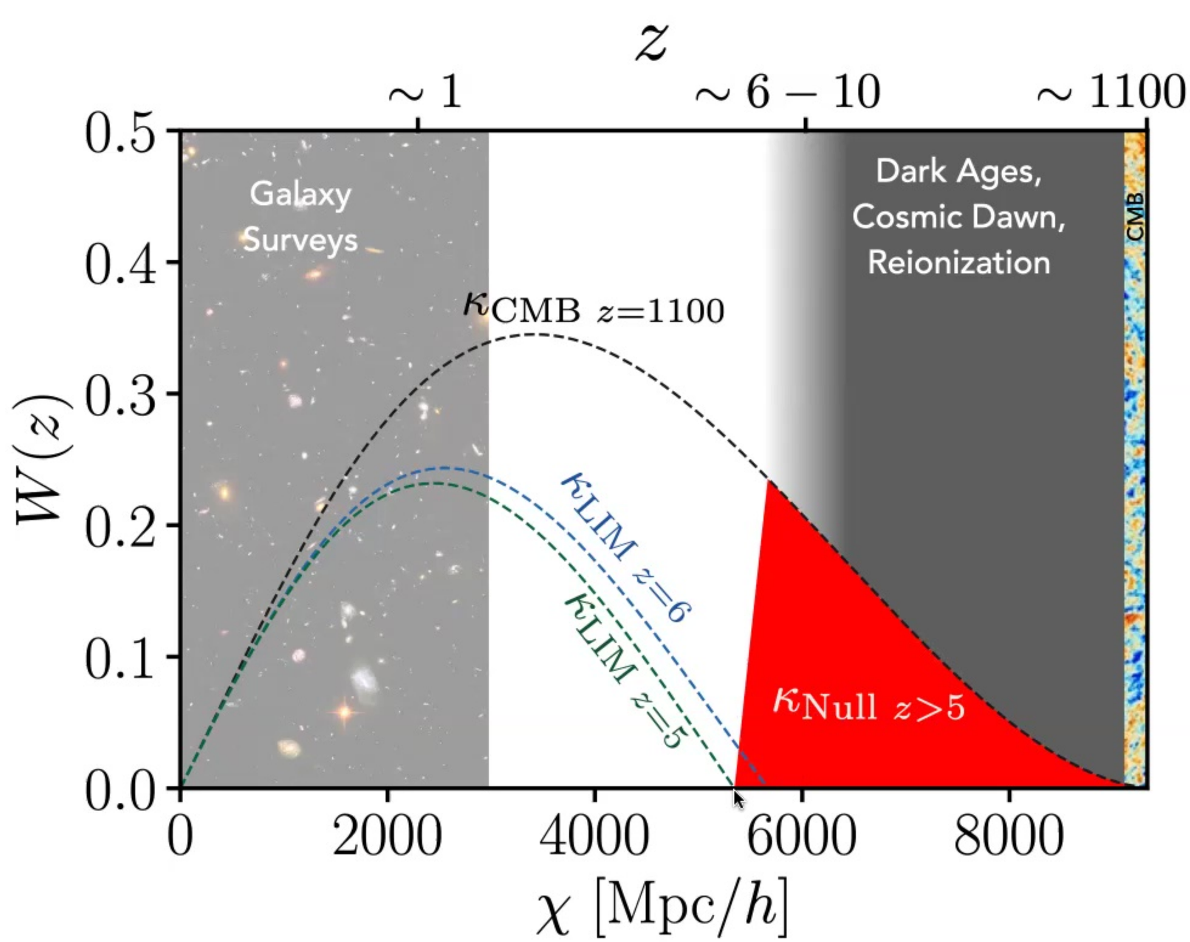
Can not just subtract curves…

2nd order polynomial in χ



Abhishek Maniyar, CCPP (NYU)

Nulling!



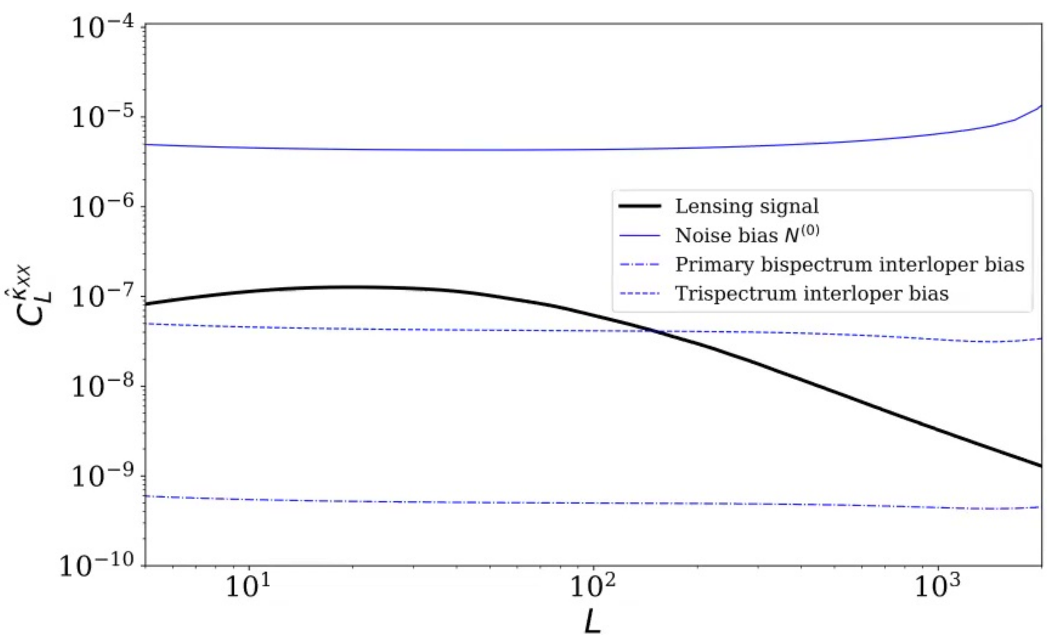
Abhishek Maniyar, CCPP (NYU)

LIM Lensing: issues!

- Non-linear nature of the LIM biases the inferred lensing from LIM
  - ➡ Bias hardened estimators (Foreman et al. 2018)
  - ➡ Modifying lensing weights to to down-weigh mode combinations coupled through nonlinear effects (Schaan et al. 2018)
- Continuum foregrounds like CIB or the Milky Way
  - ➡ Avoided by discarding the 3D Fourier modes with low $k_{||}$
- Interlopers?
  - ➡ Have not been addressed for LIM lensing
  - ➡ Bias the signal → $C_L^{\kappa\kappa}$

Abhishek Maniyar, CCPP (NYU)

LIM Lensing

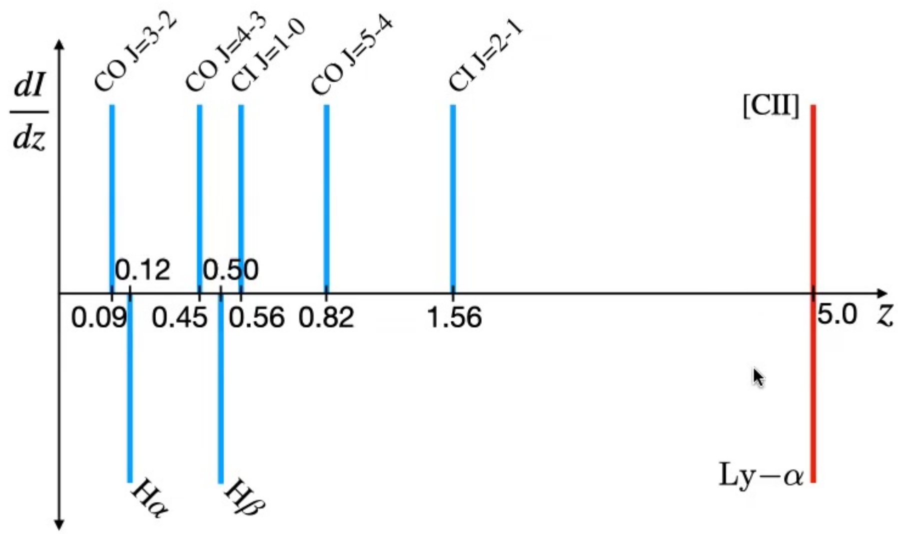


$X = \text{Ly}-\alpha$ at $z = 5$

- **Interloper contamination produces dominant non-Gaussian bias to lensing power spectrum**
- **Need a new estimator to get rid of the bias!**

Abhishek Maniyar, CCPP (NYU)

"LIM-pair" lensing!

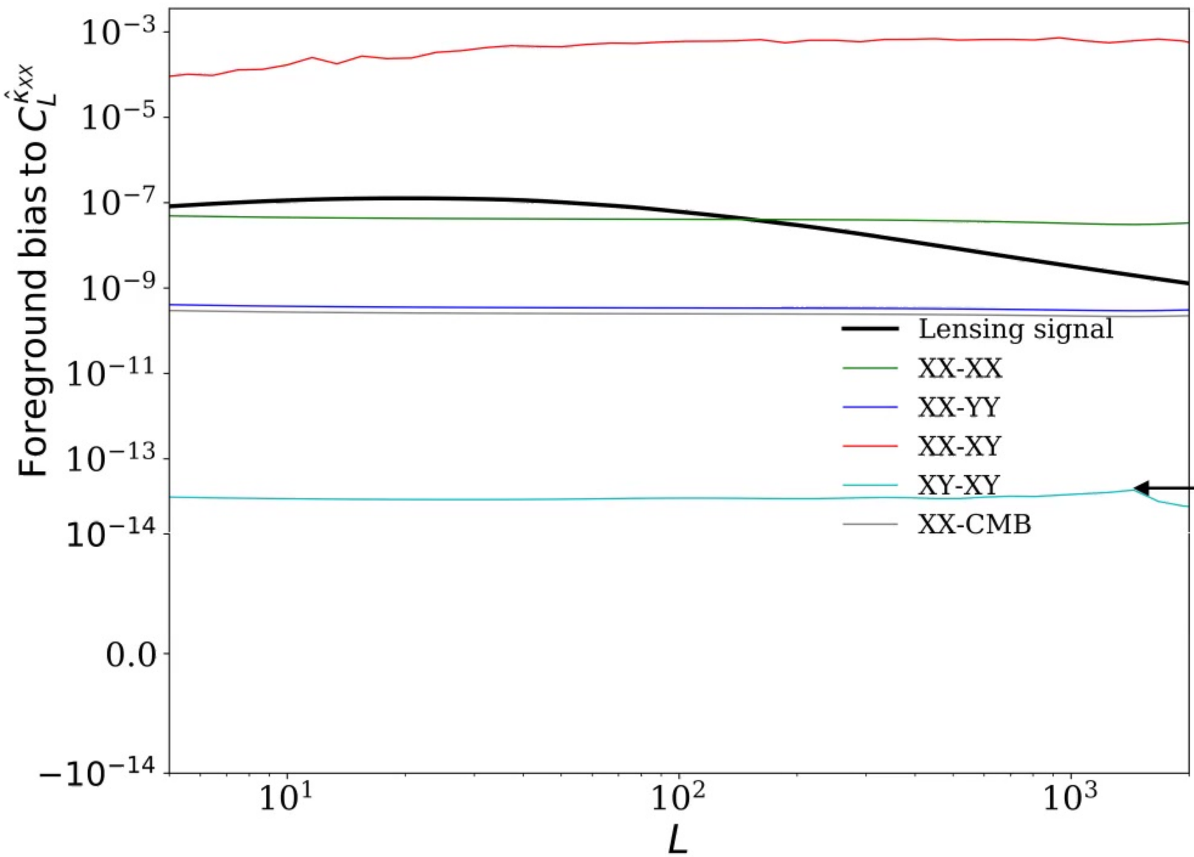


- Choose two target lines at the same redshift
- Only condition: interlopers should not overlap in redshift!

$$\kappa_{XY} \longrightarrow X, Y = [\mathrm{CII}], \mathrm{Ly}\!-\!\alpha, \ldots$$

Abhishek Maniyar, CCPP (NYU)

“LIM-pair” lensing!



X = Ly $-\alpha$

&

Y = [CII] or CMB

at

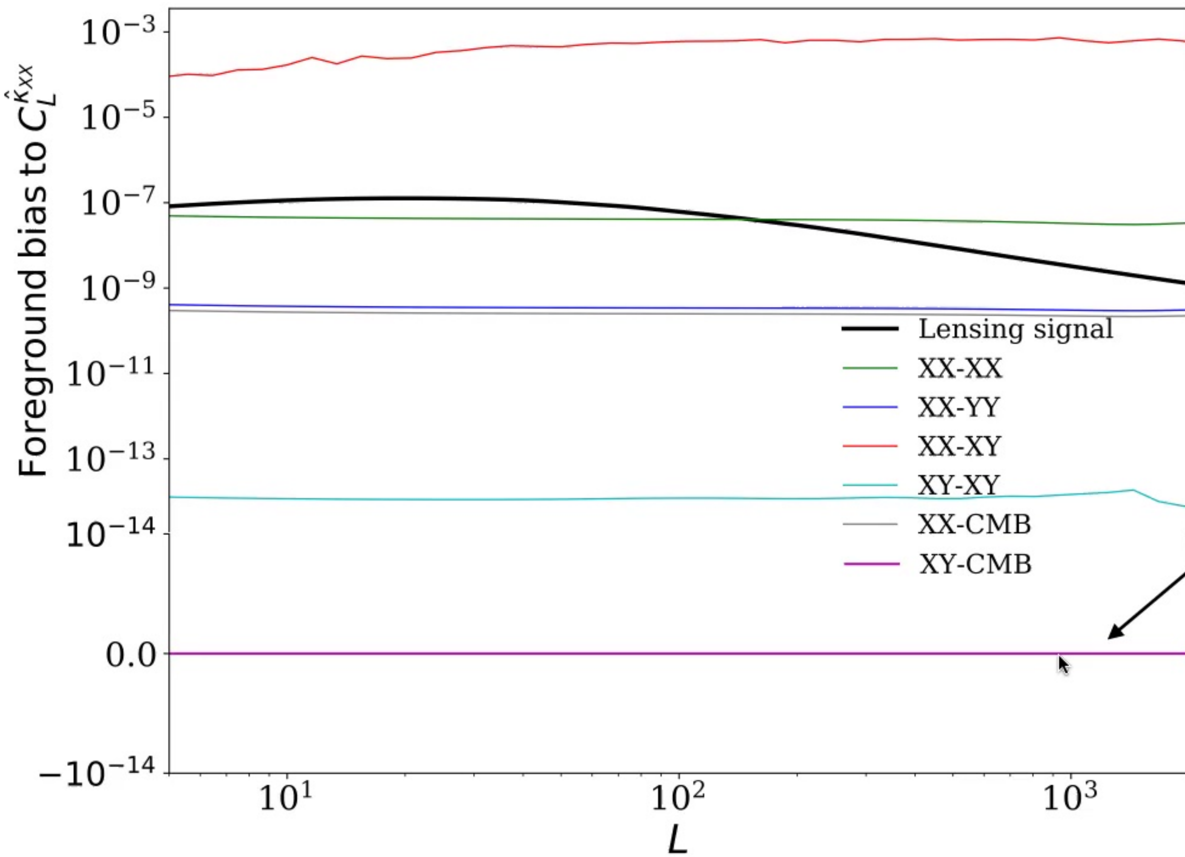
$z = 5$

XY is biased as well!

Secondary bispectrum bias

Abhishek Maniyar, CCPP (NYU)

“LIM-pair” lensing!



X = Ly$-\alpha$

&

Y = [CII] or CMB

at

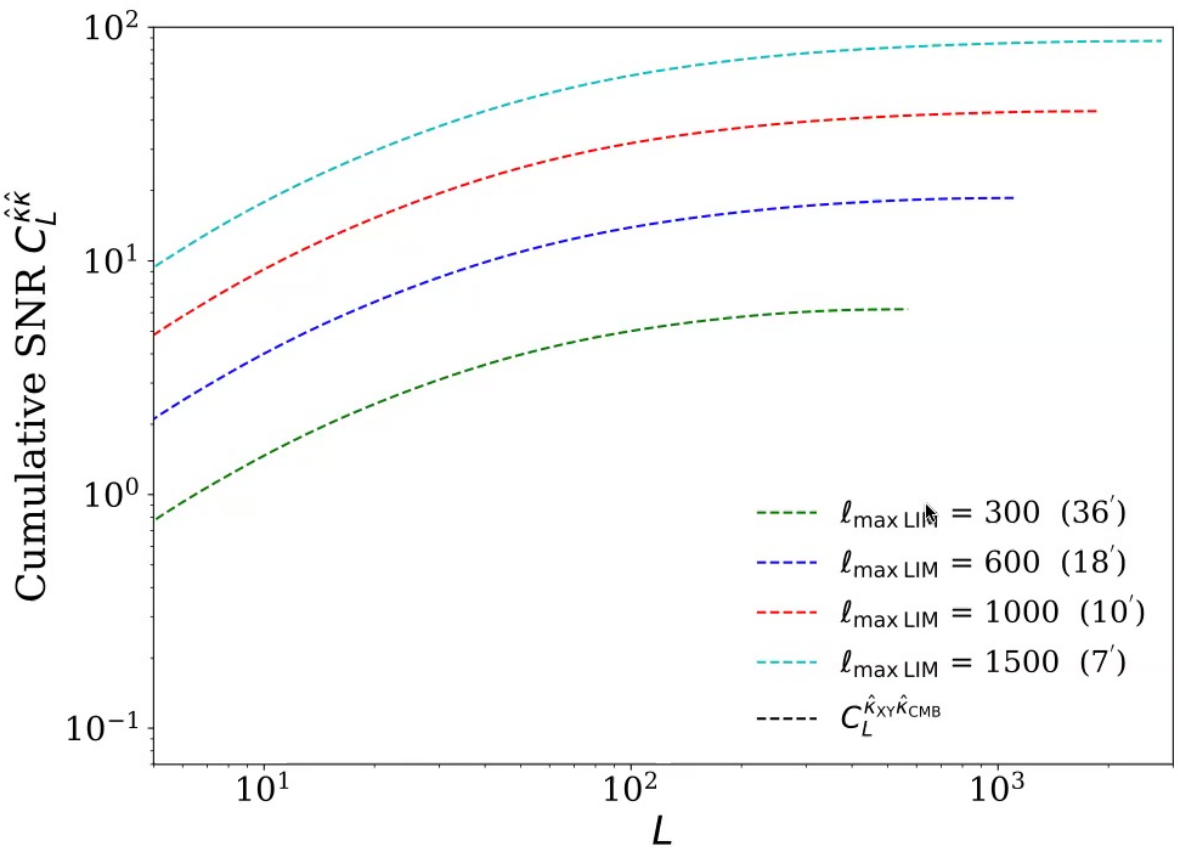
$z = 5$

$\langle \hat{\kappa}_{XY} \hat{\kappa}_{\rm CMB} \rangle$

Zero non-Gaussian bias!

Abhishek Maniyar, CCPP (NYU)

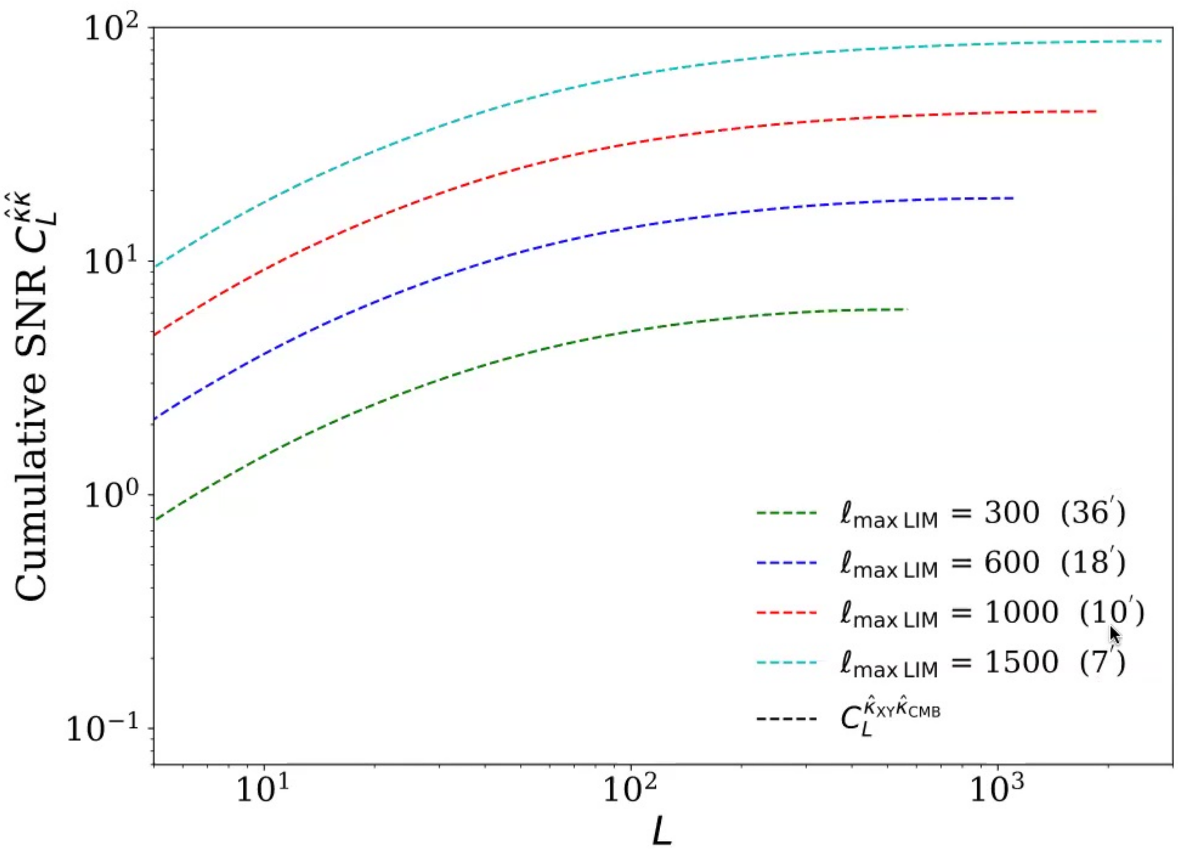
Can we detect $C_L^{\hat{\kappa}_{XY}\hat{\kappa}_{CMB}}$? SNR?



- f_sky = 40%
- Can be detected with very high SNR!

Abhishek Maniyar, CCPP (NYU)

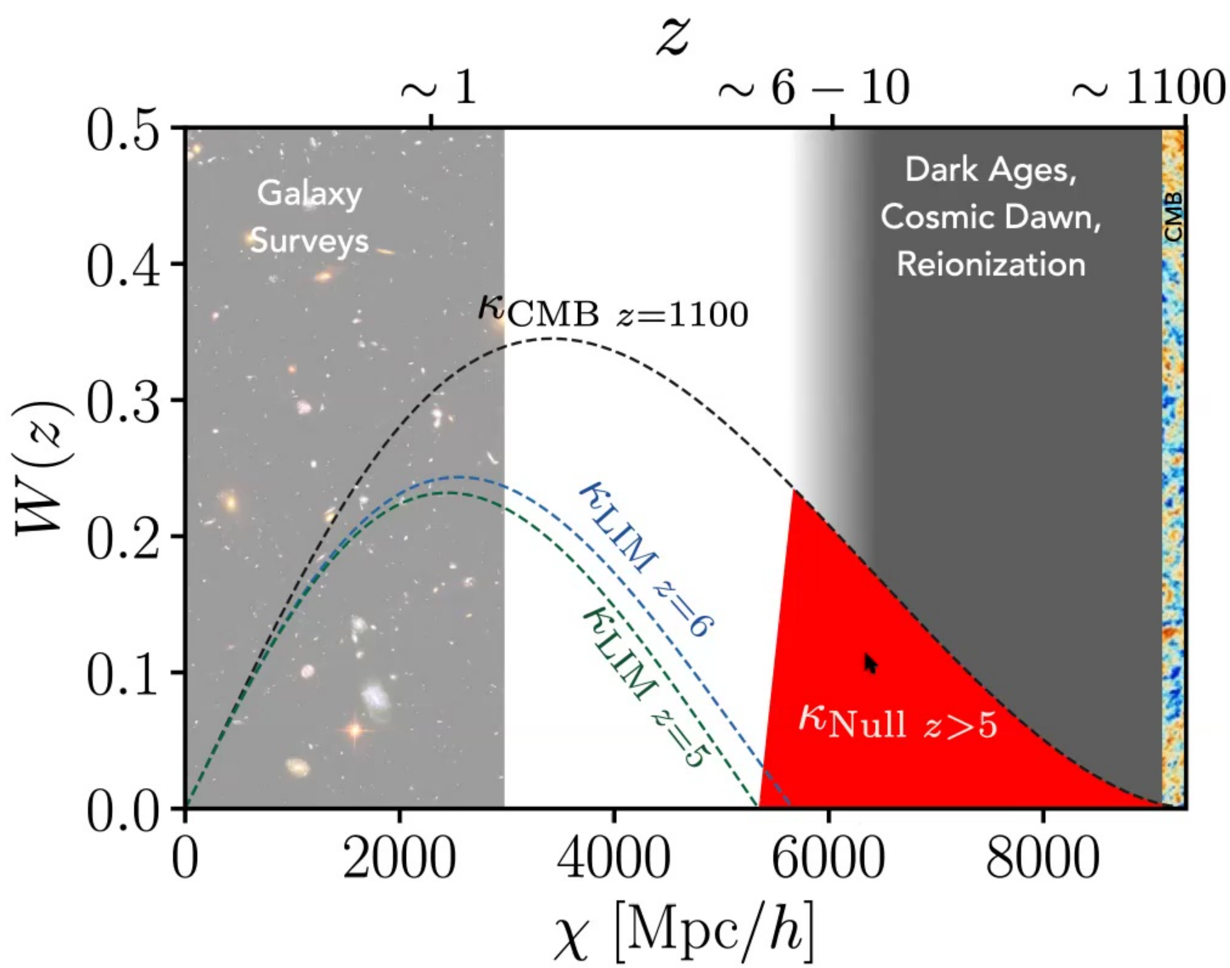
Can we detect $C_L^{\hat{\kappa}_{XY}\hat{\kappa}_{CMB}}$? SNR?



- f_sky = 40%
- Can be detected with very high SNR!

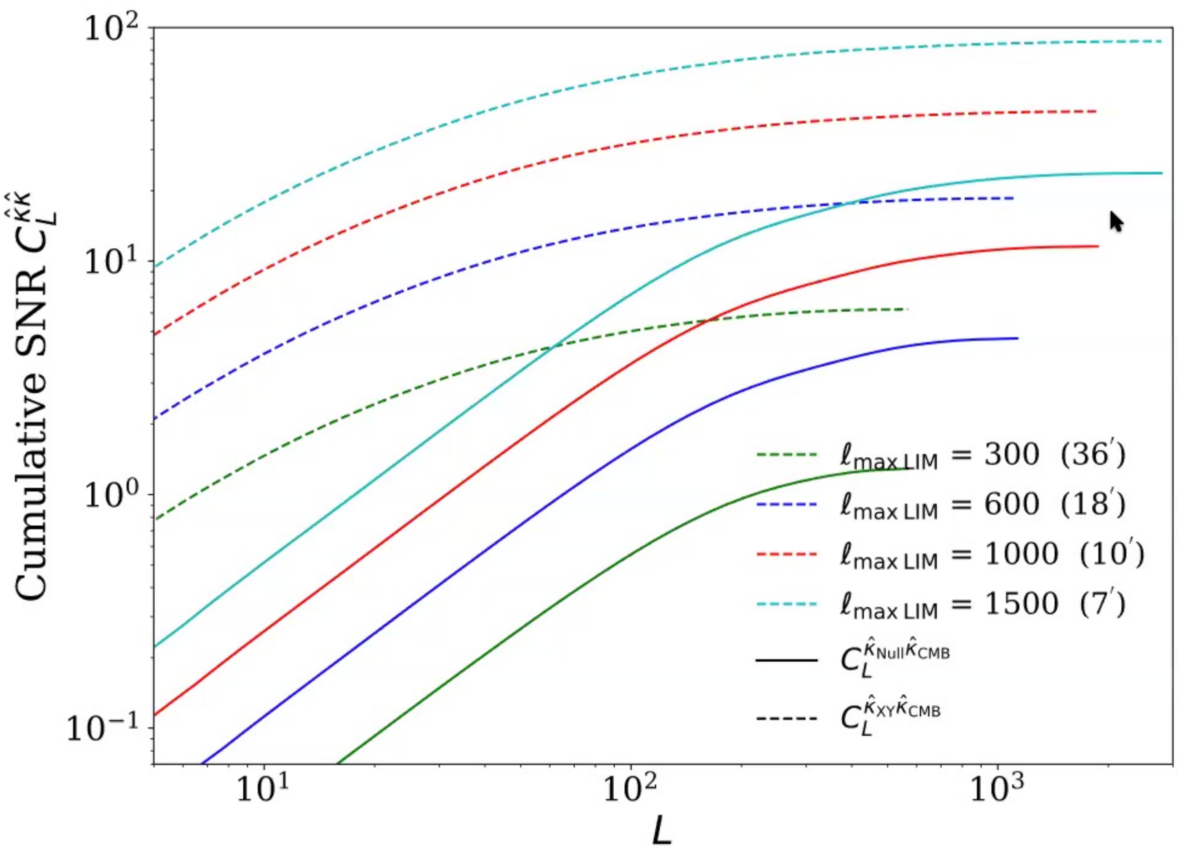
Abhishek Maniyar, CCPP (NYU)

Can we detect this? $C_L^{\hat{\kappa}_{\rm null}\hat{\kappa}_{\rm CMB}}$



Abhishek Maniyar, CCPP (NYU)

Can we detect this? $C_L^{\hat{\kappa}_{\text{null}}\hat{\kappa}_{\text{CMB}}}$ Yes!



- f_sky = 40%
- Would be possible to detect this signal well
- Angular resolution should not be an issue
- Probe of really high redshifts!

Abhishek Maniyar, CCPP (NYU)

Conclusions

- Non-Gaussian bias to LIM lensing from interlopers is quite high, quantified for the first time
- LIM pair estimator fixes it completely, independent of all the astrophysical uncertainties
- Nulling allows access to high redshift
- Combining with interloper cleaning techniques, the detection SNR will further increase
- $C_L^{\hat{\kappa}_{XY}\hat{\kappa}_{ZW}}$ very futuristic, but completely independent of the interloper bias as well independent of CMB!