CMB weak lensing: introduction to the quadratic estimators

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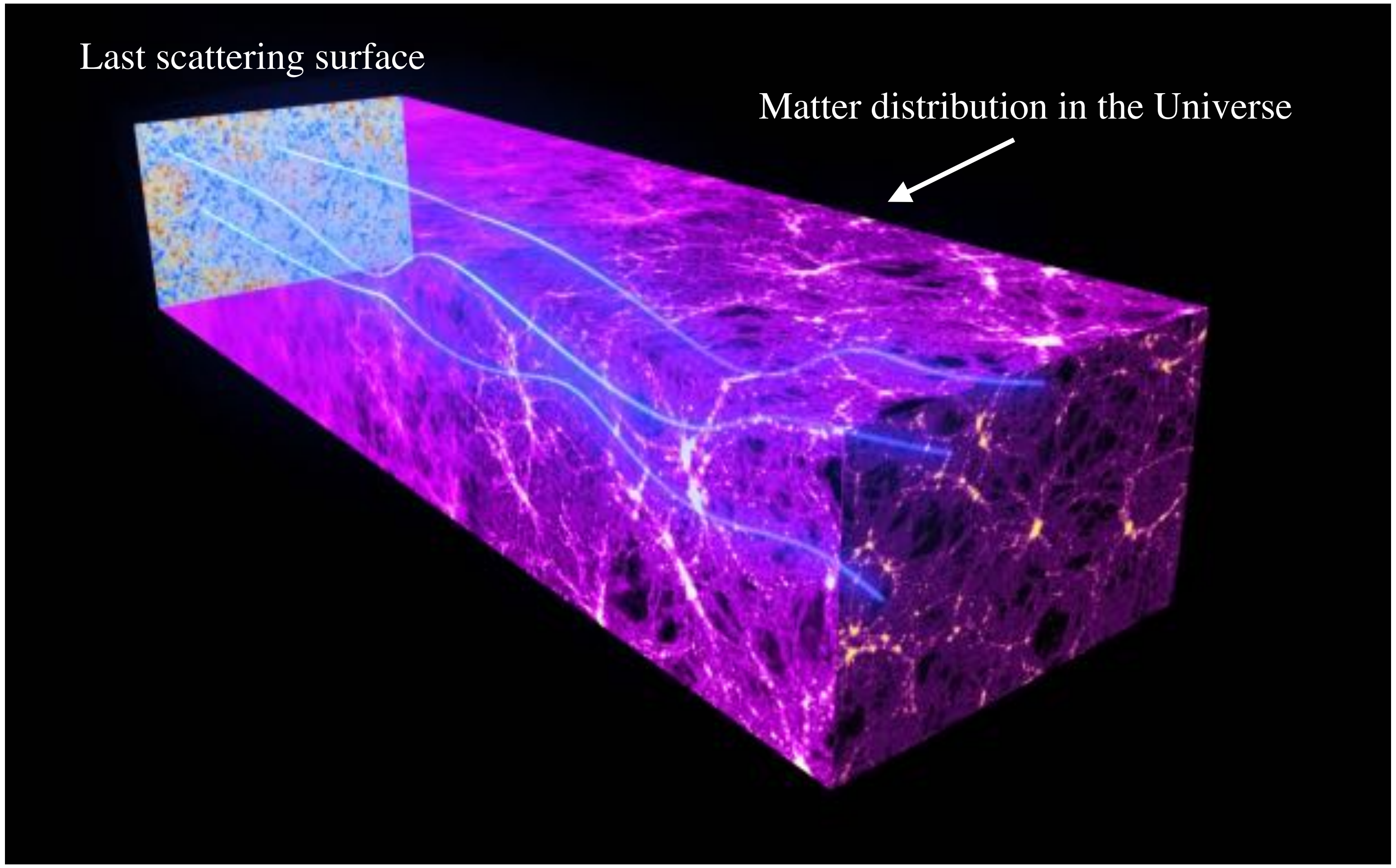
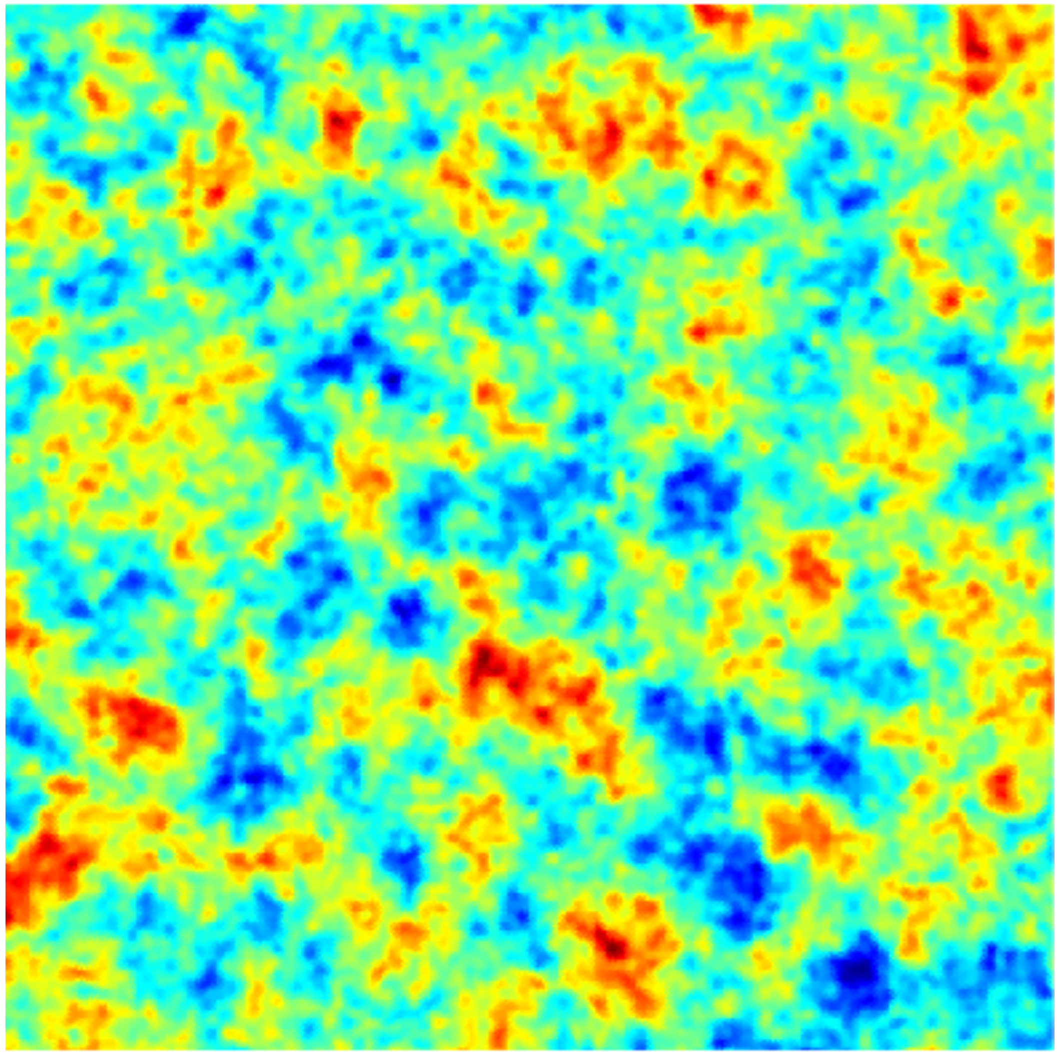
Weak lensing of the CMB

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



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 $\kappa = \frac{1}{2}L(L+1)\phi$)

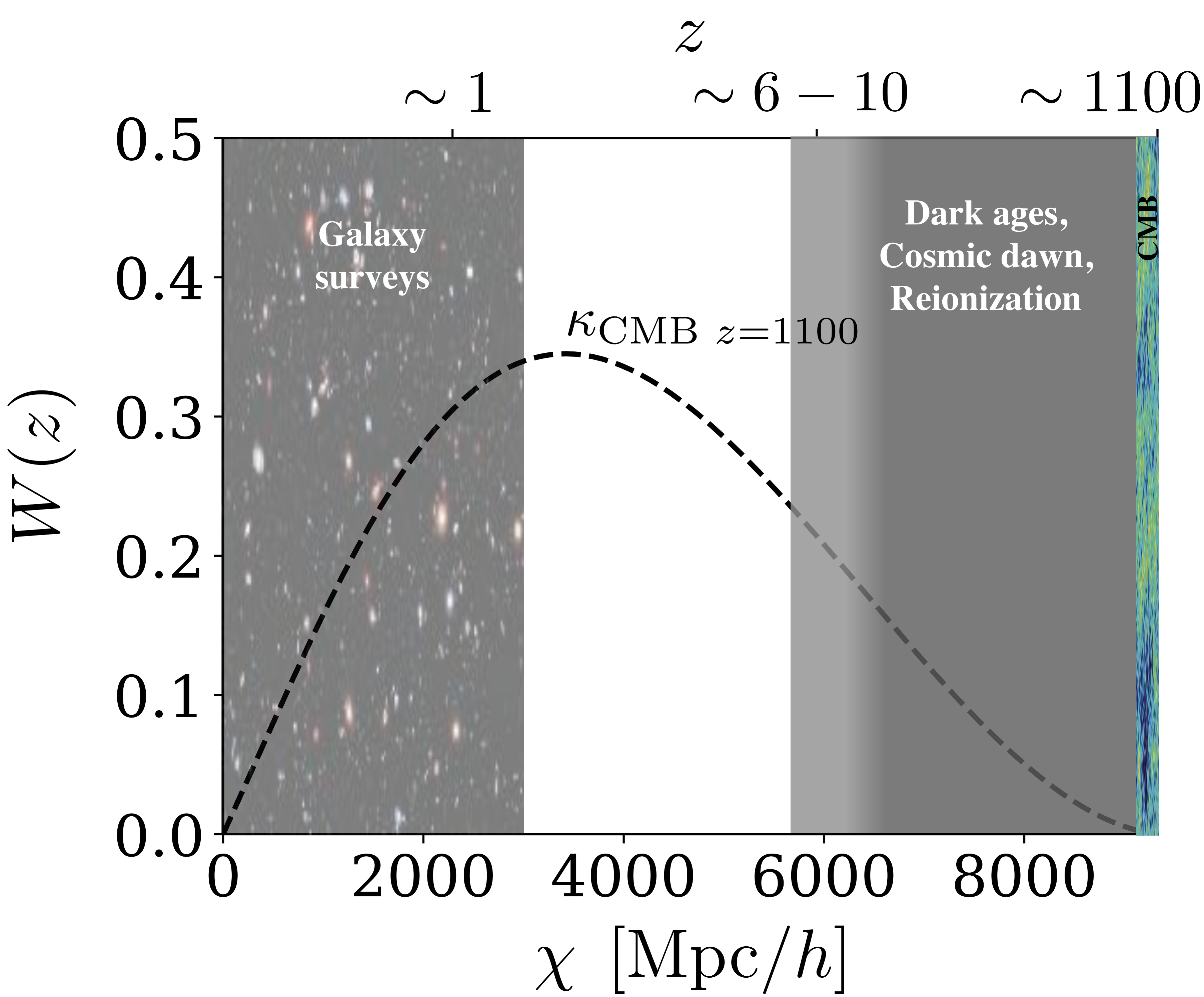
↓

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

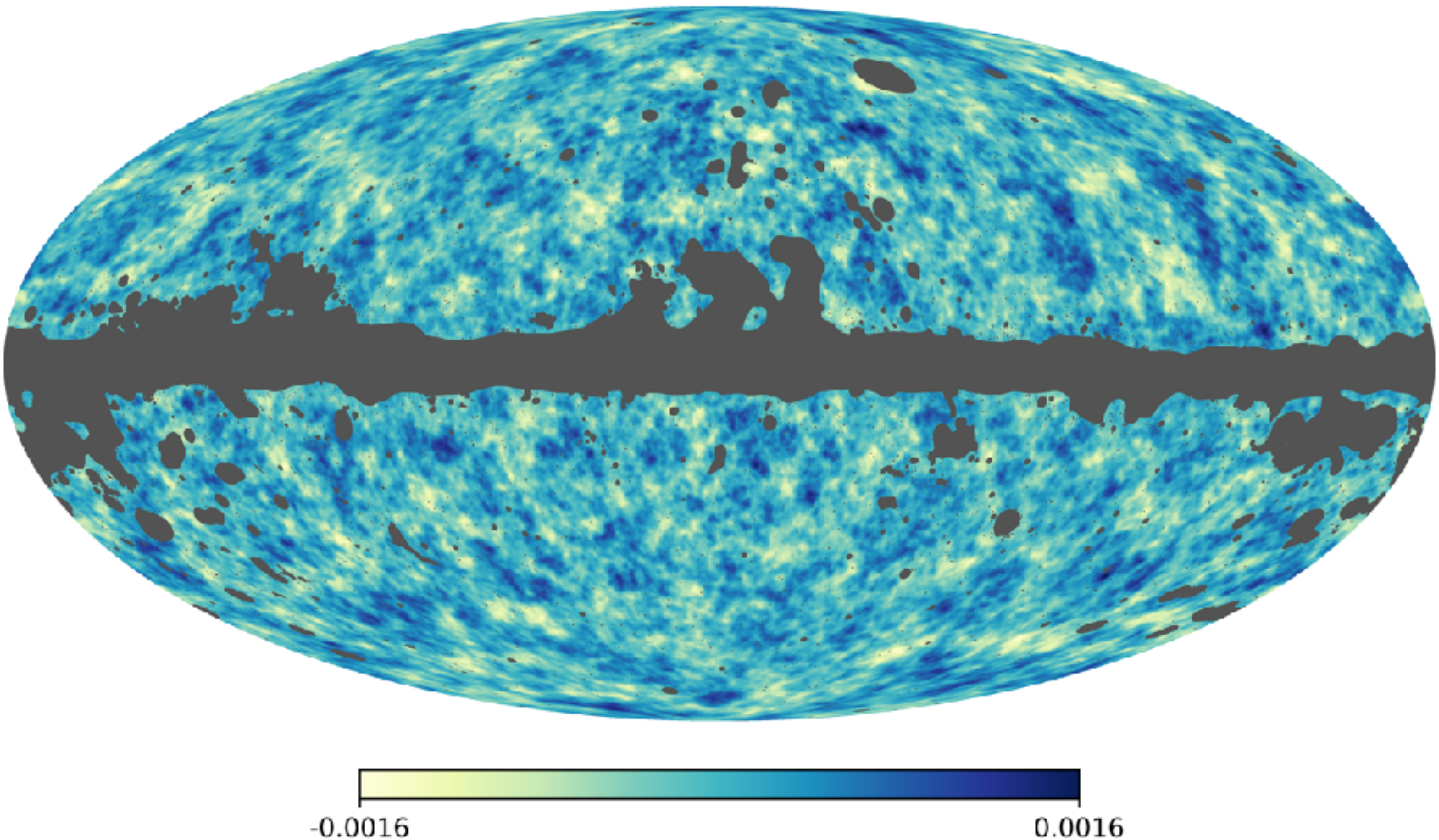
Reconstructing the density field with lensing

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

Lensing potential



Planck lensing reconstruction map



Planck 2018

Quadratic estimators

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

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

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

Lensing induces correlations between different multipoles!

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

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

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

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

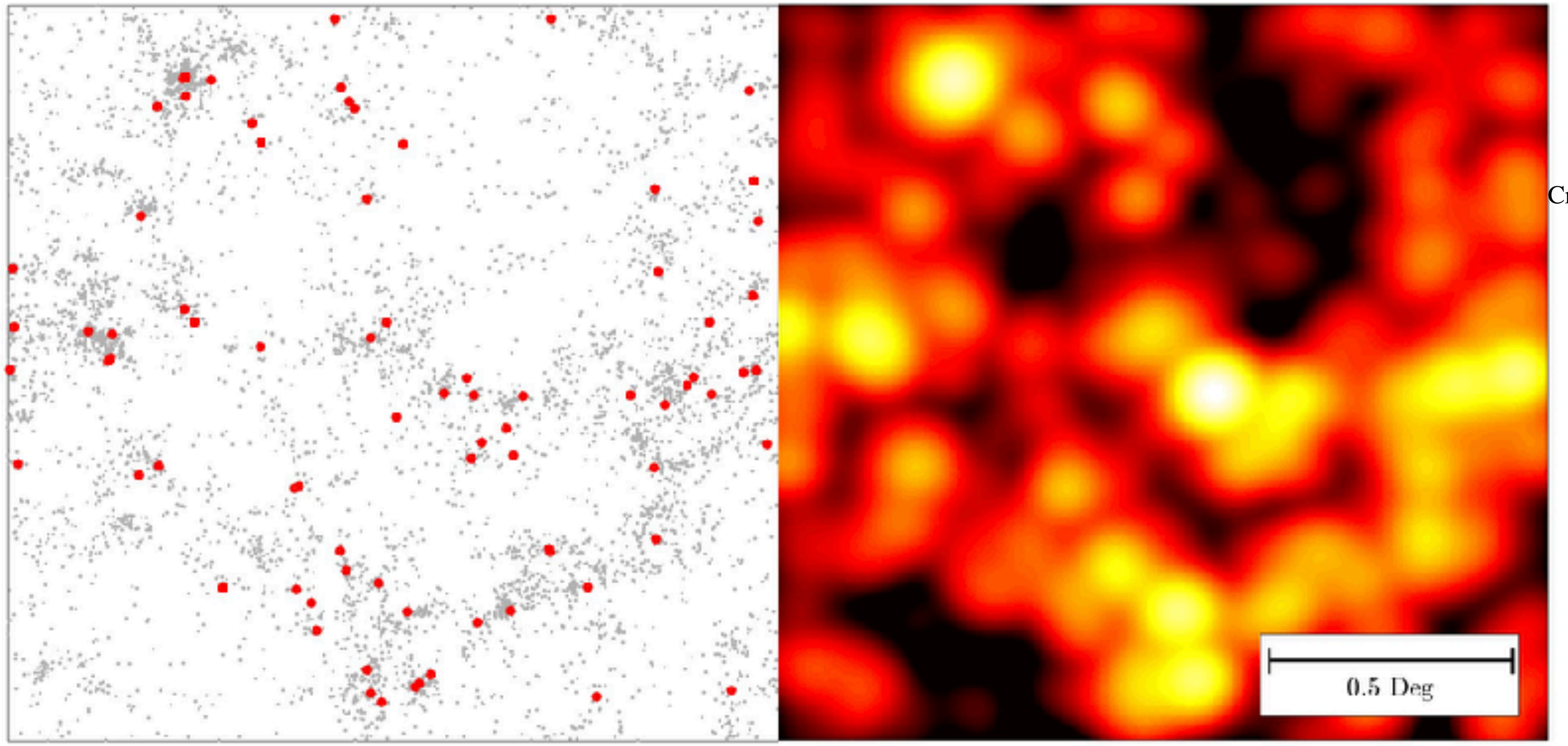
A new probe of the high-redshift Universe: nulling CMB lensing with interloper-free "LIM-pair" lensing

In collaboration with: Emmanuel Schaan & Anthony Pullen

Phys. Rev. D105.083509 (2022)

Line intensity mapping

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



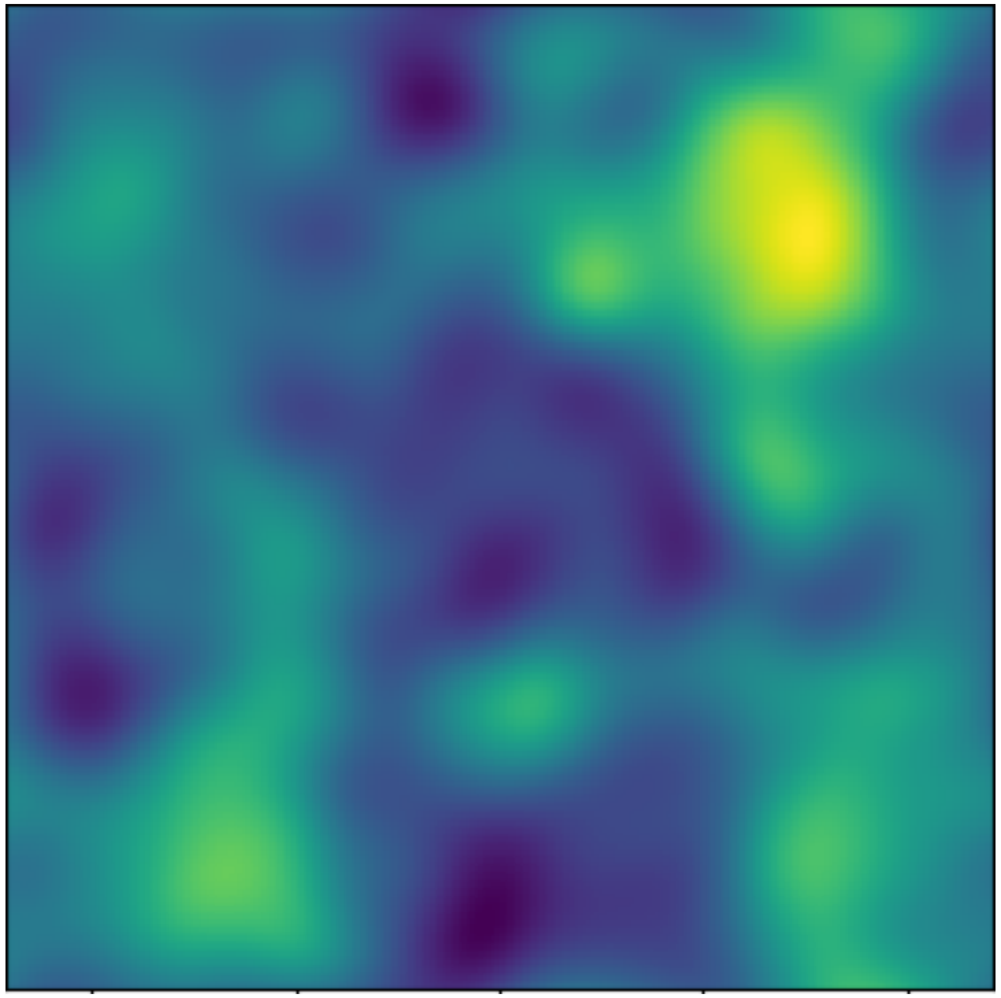
Credit: Patrick Breysse

Faint Galaxies | Bright Galaxies | Line Emission

A probe of high redshift Universe!

Interlopers & continuum

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



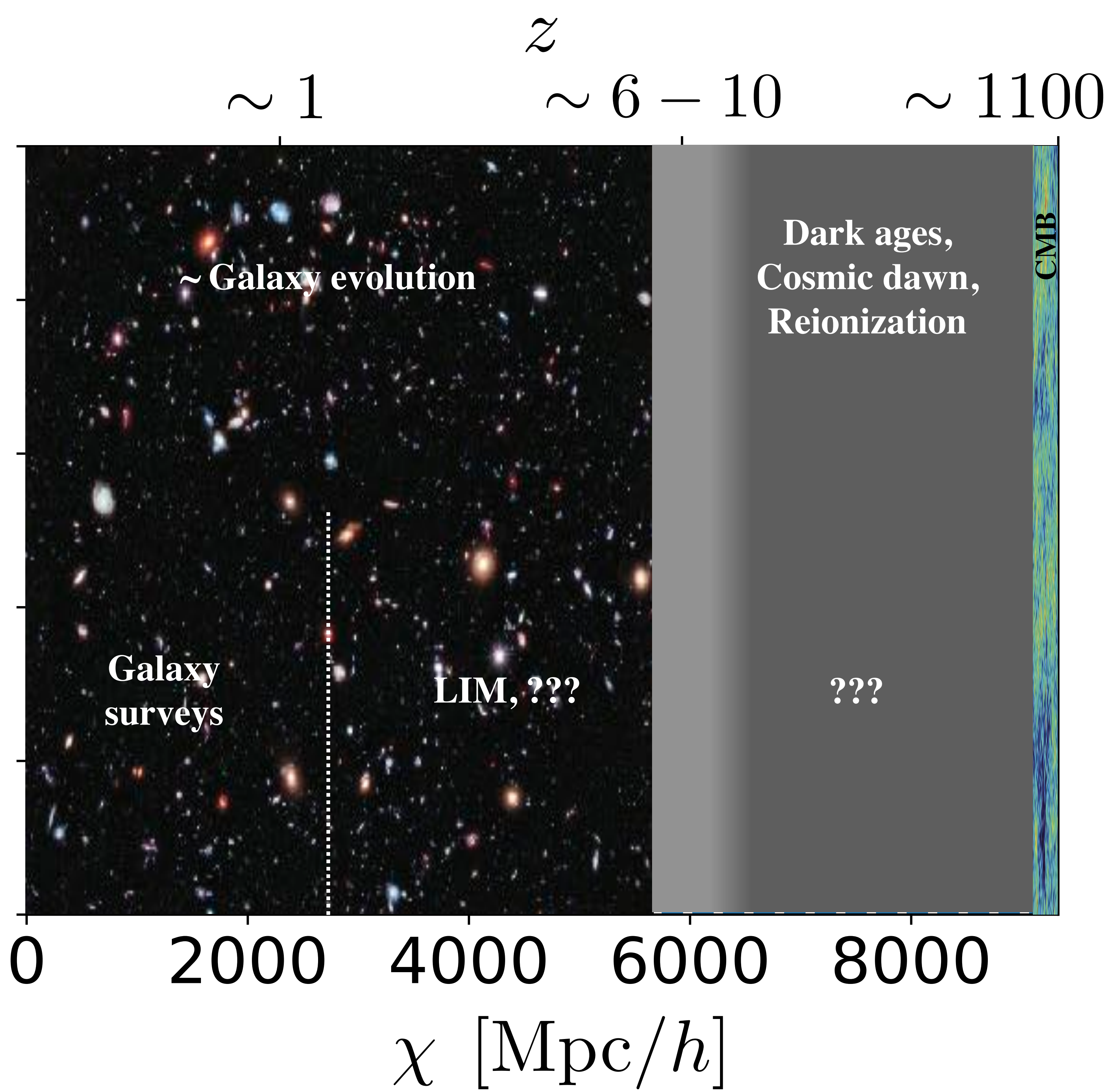
500 GHz

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

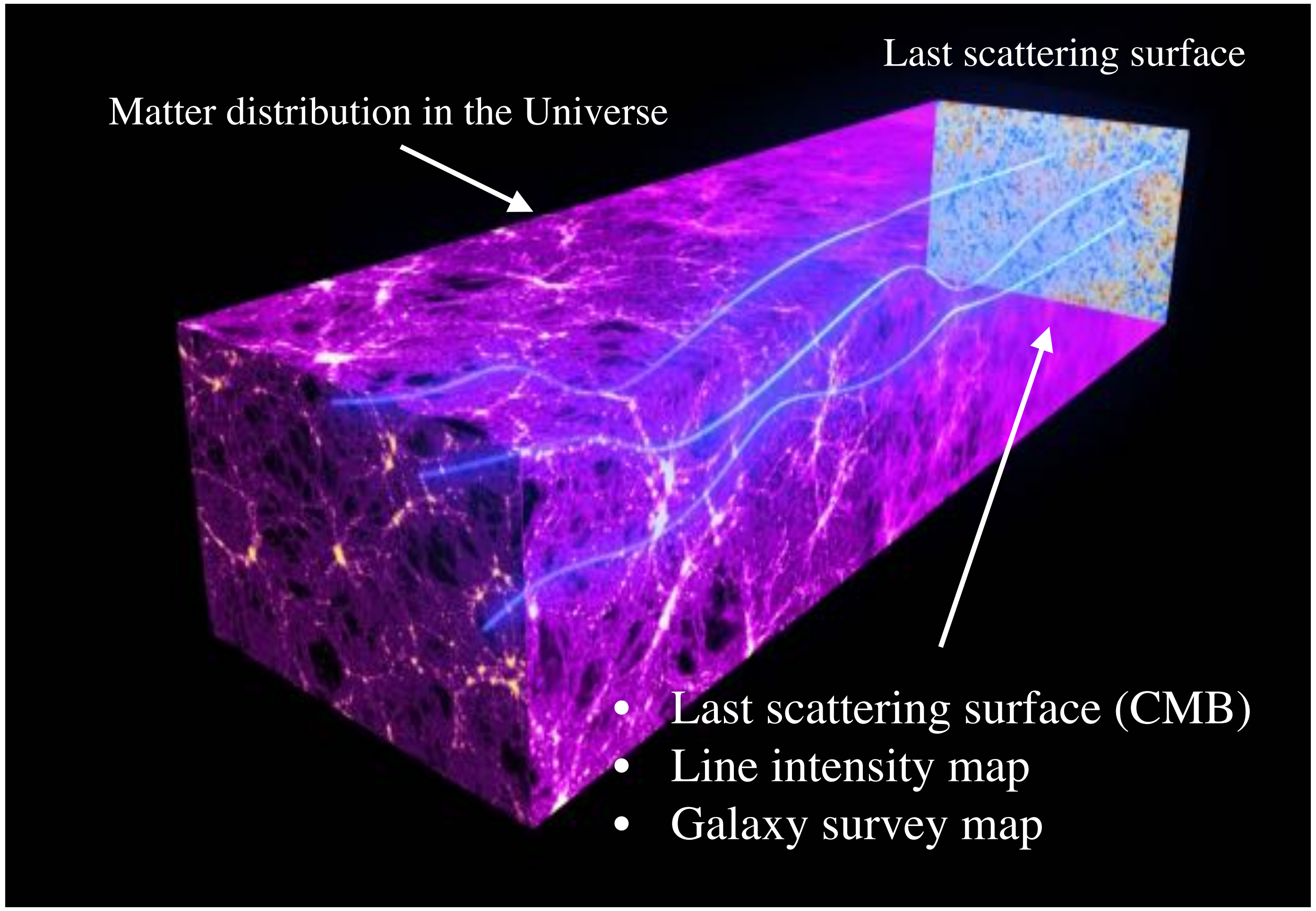
Also continuum emission: Cosmic Infrared Background, Milky Way!

High redshift universe

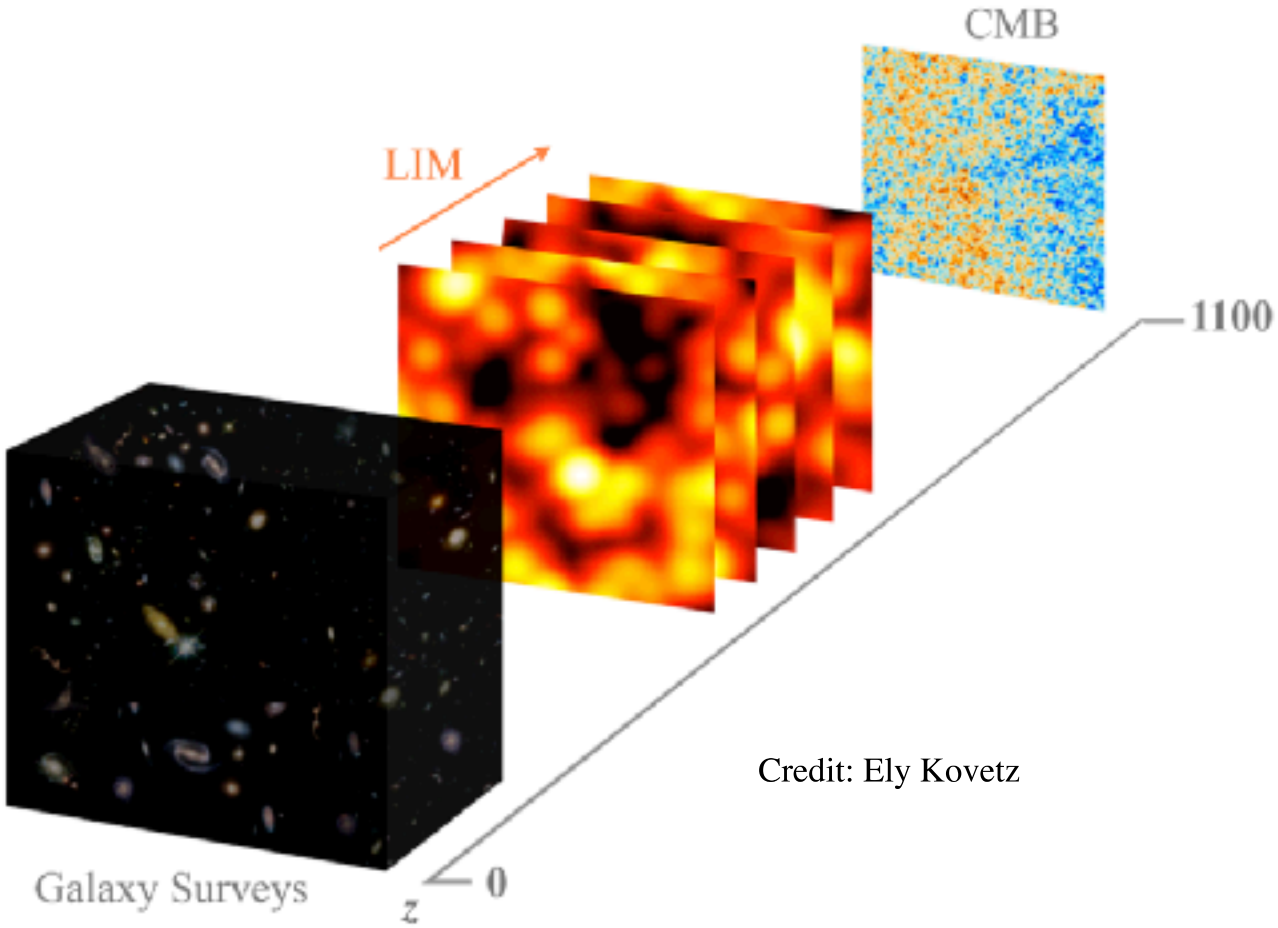
- Galaxy surveys: matter density field at z < ~1.5
- LIM at high redshifts?
  - Continuum foregrounds render modes perpendicular to LOS $k_{\parallel} \simeq 0$ unusable for cosmology
- Constructing matter density field at z > ~1.5 quite difficult
- Cosmic dawn, dark ages even more difficult
- Some new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



Weak lensing of the CMB/LIM/Galaxies



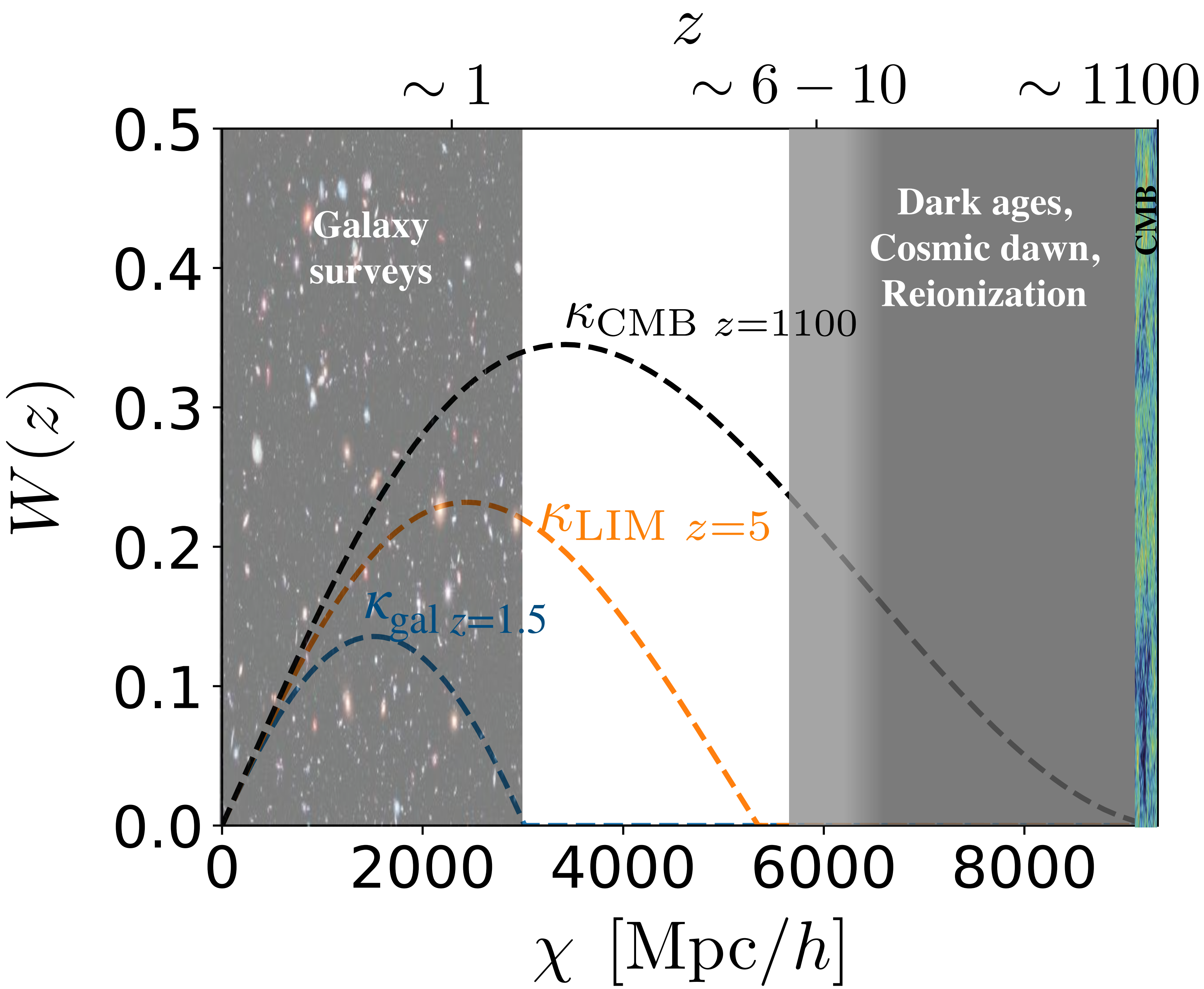
- Last scattering surface (CMB)
- Line intensity map
- Galaxy survey map



Credit: Ely Kovetz

Reconstructing the density field with lensing

- κ probes projected mass density



But..

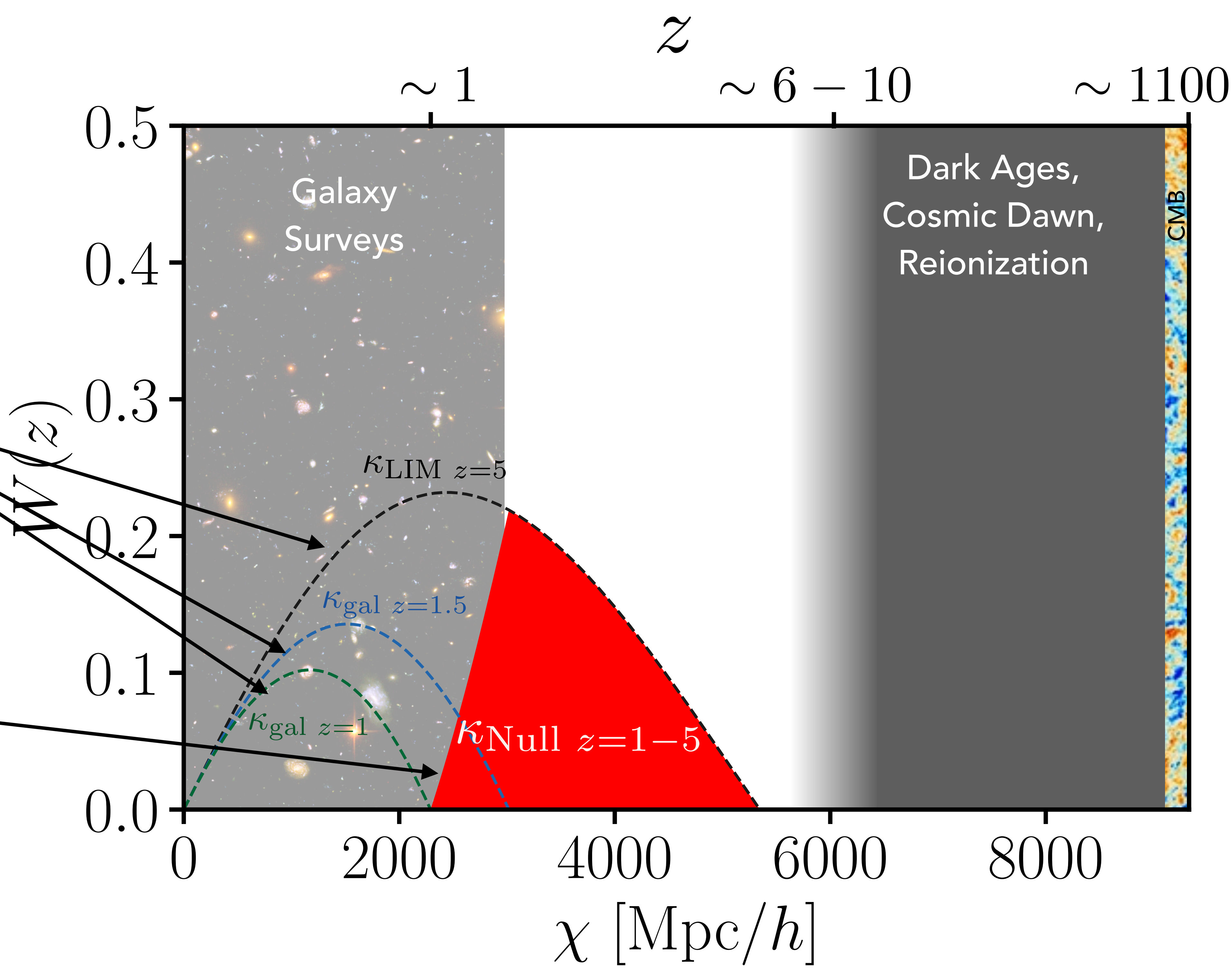
- How can we access the density field only for e.g. $1 < z < 5$?
- How can we access the density field only for e.g. $z > 5$?
- Galaxy surveys too expensive and limited at high redshifts

Nulling!

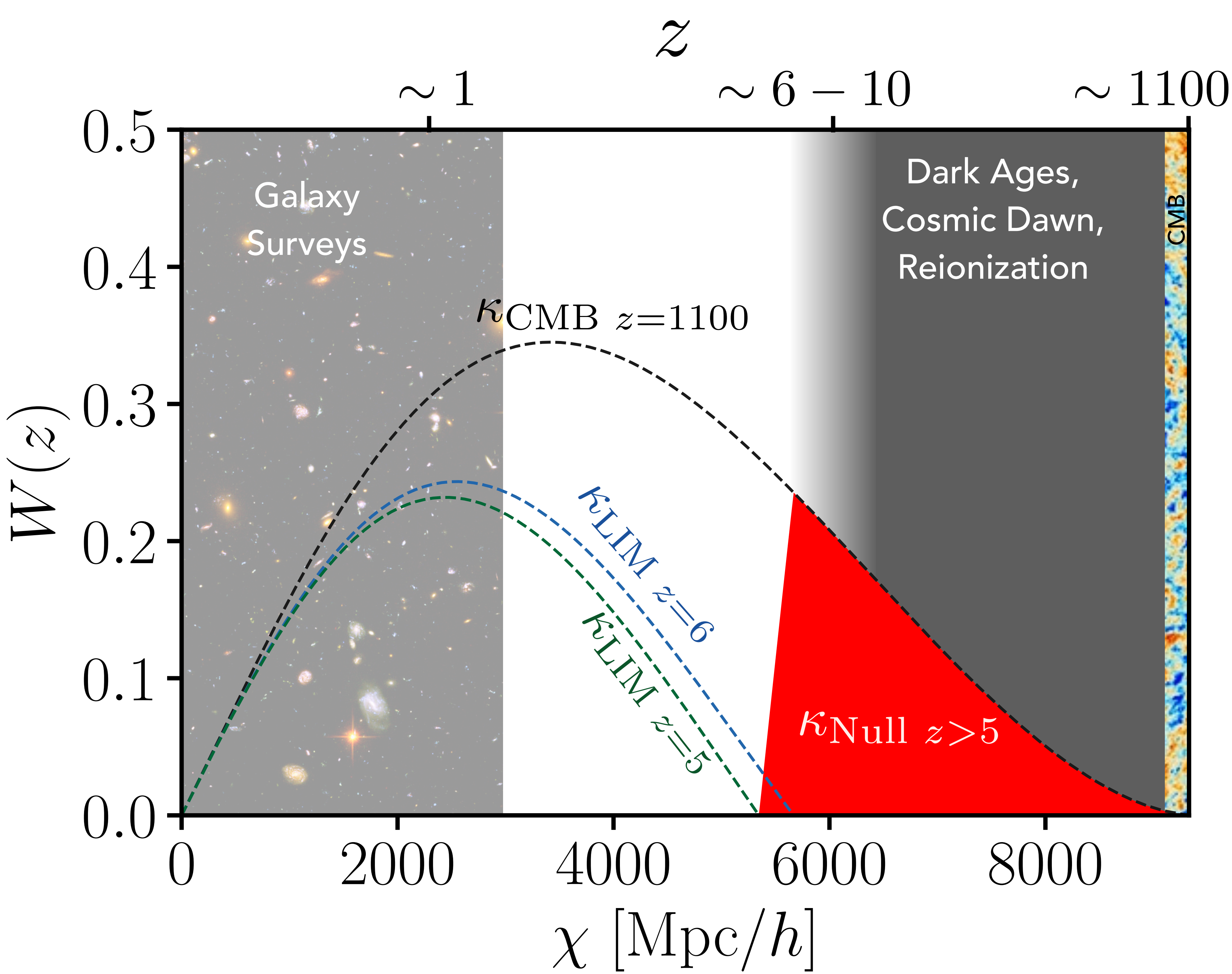
Can not just subtract curves…

2nd order polynomial in χ

Mathematically null for $\chi \leq \chi_1$!



Nulling!

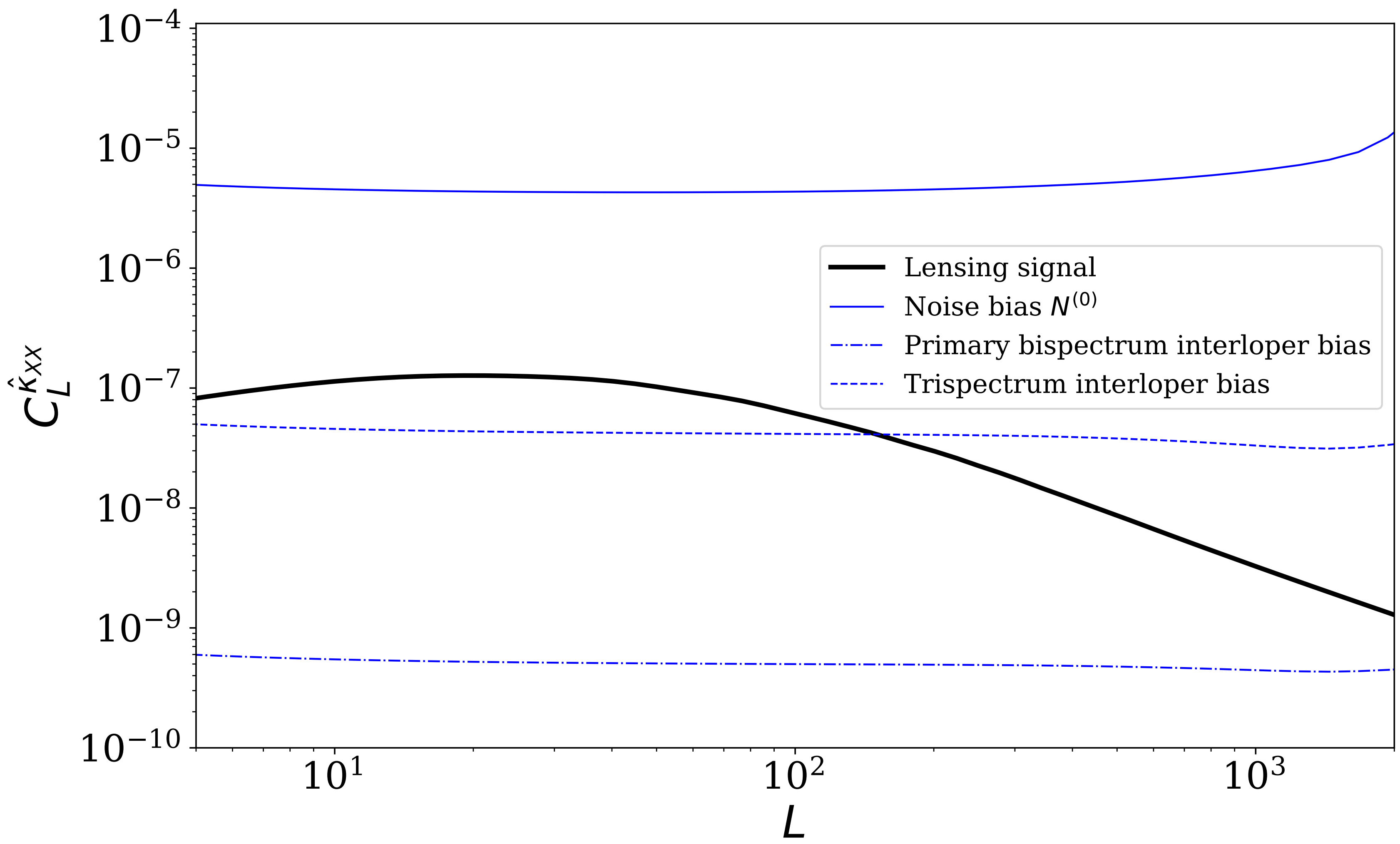


z
~ 1
$\sim 6-10$
~ 1100
0.5
0.4
0.3
0.2
0.1
0.0
$W(z)$
Galaxy Surveys
Dark Ages, Cosmic Dawn, Reionization
CMB
$\kappa_{\rm CMB}\ z{=}1100$
$\kappa_{\rm LIM}\ z{=}6$
$\kappa_{\rm LIM}\ z{=}5$
$\kappa_{\rm Null}\ z{>}5$
0
2000
4000
6000
8000
χ [Mpc/h]

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 → $C_L^{\kappa\kappa}$

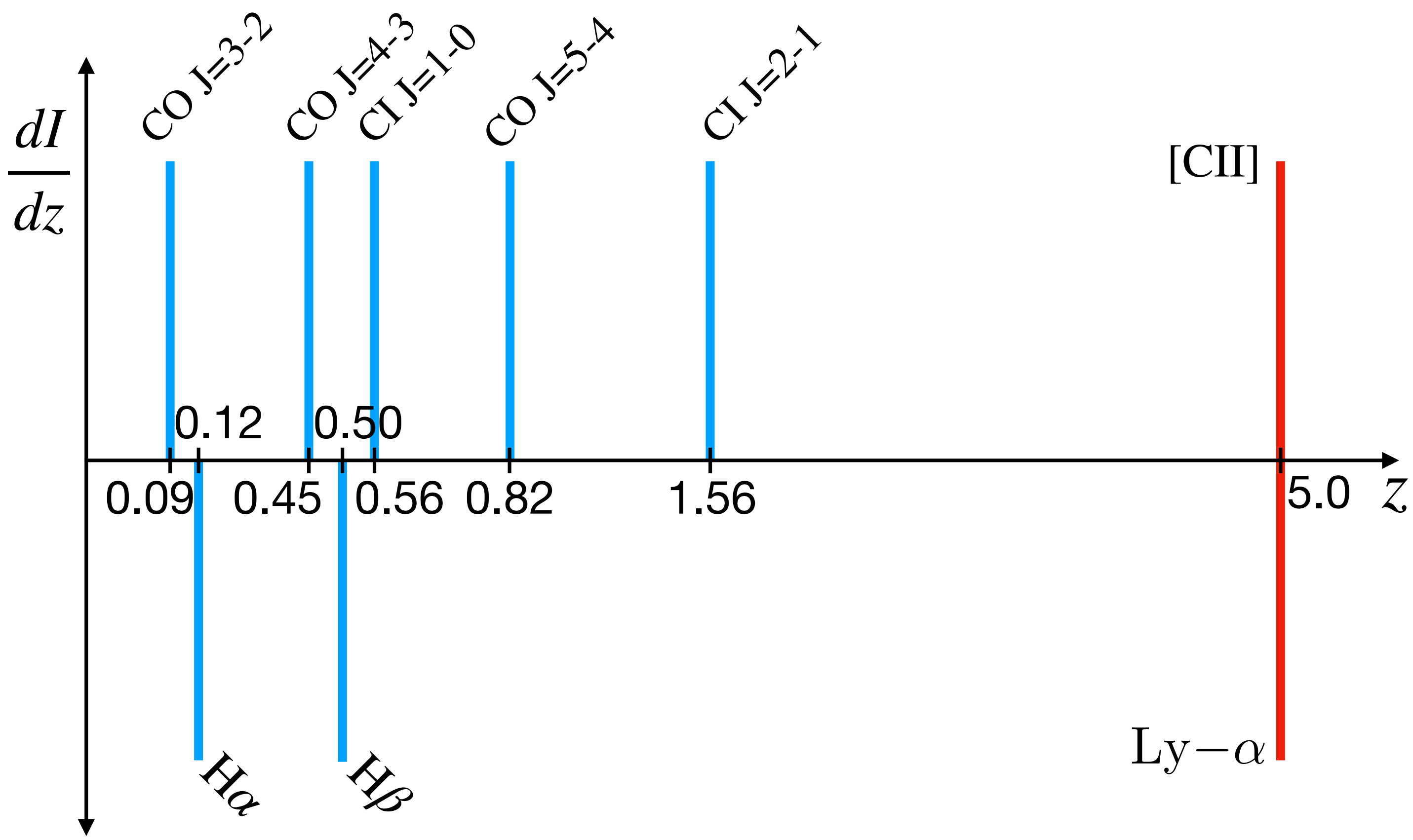
LIM Lensing



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

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

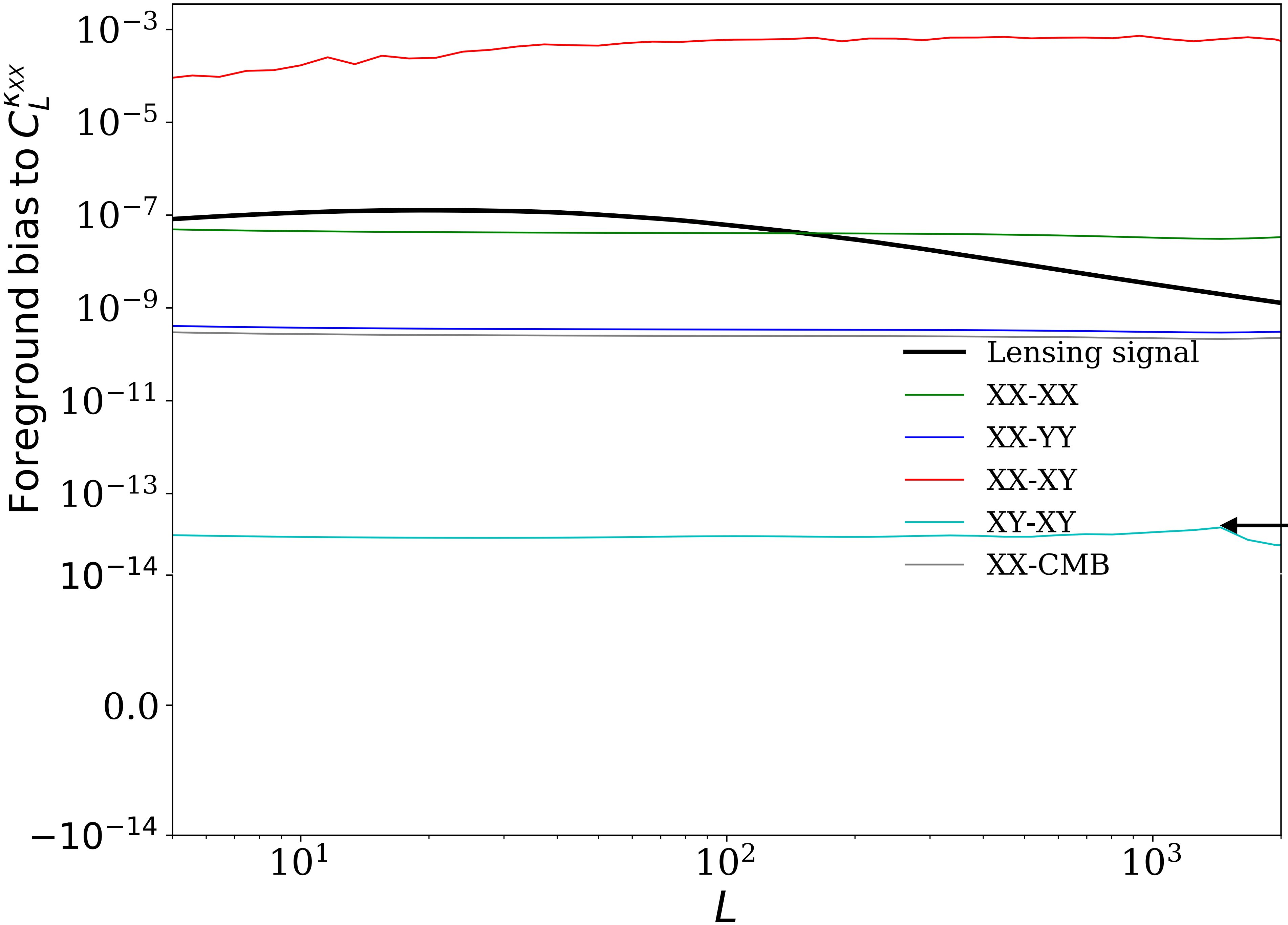
"LIM-pair" lensing!



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

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

"LIM-pair" lensing!



X = Ly$-\alpha$

&

Y = [CII] or CMB

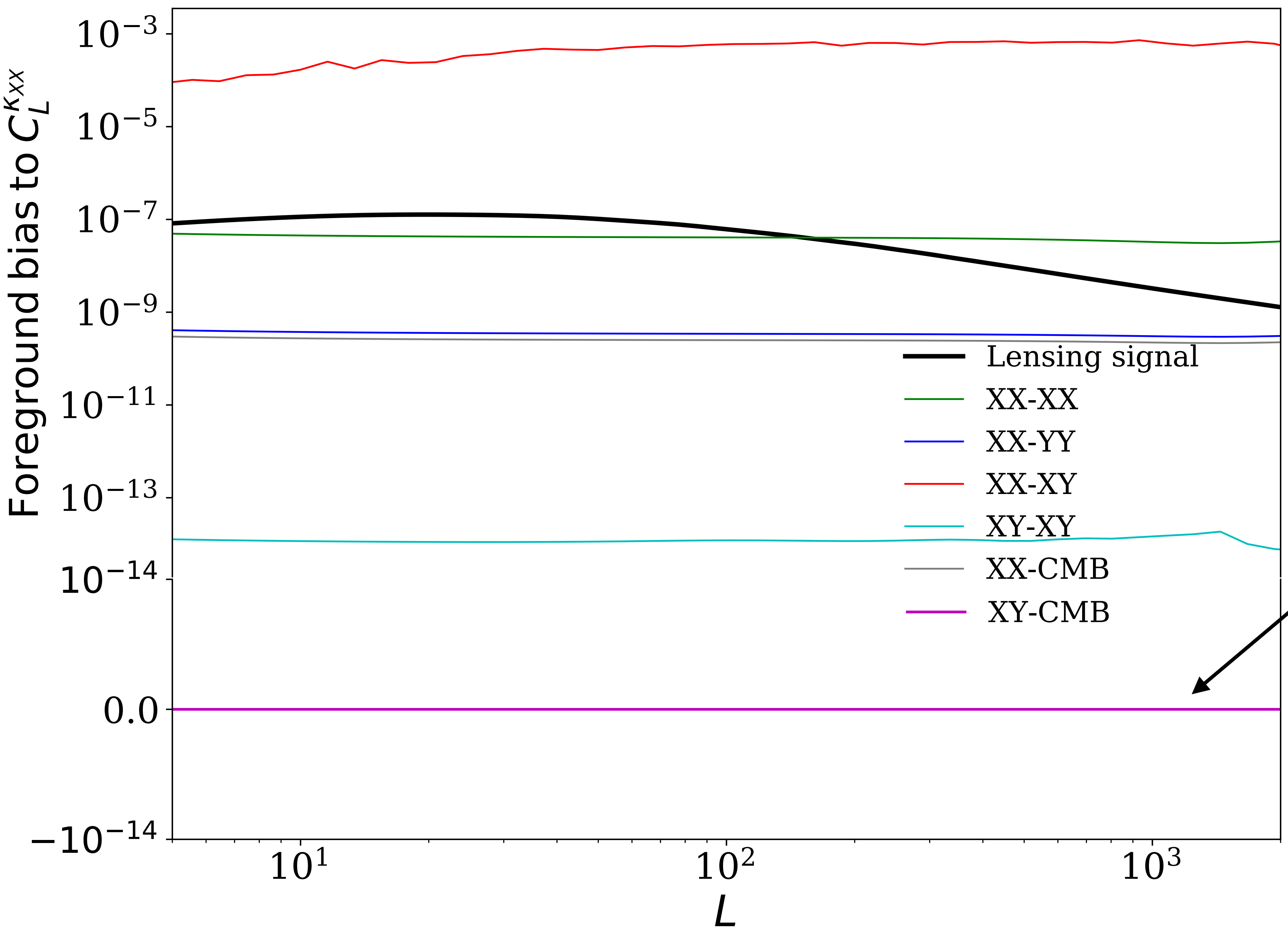
at

$z = 5$

XY is biased as well!

Secondary bispectrum bias

“LIM-pair” lensing!



X = Ly$-\alpha$

&

Y = [CII] or CMB

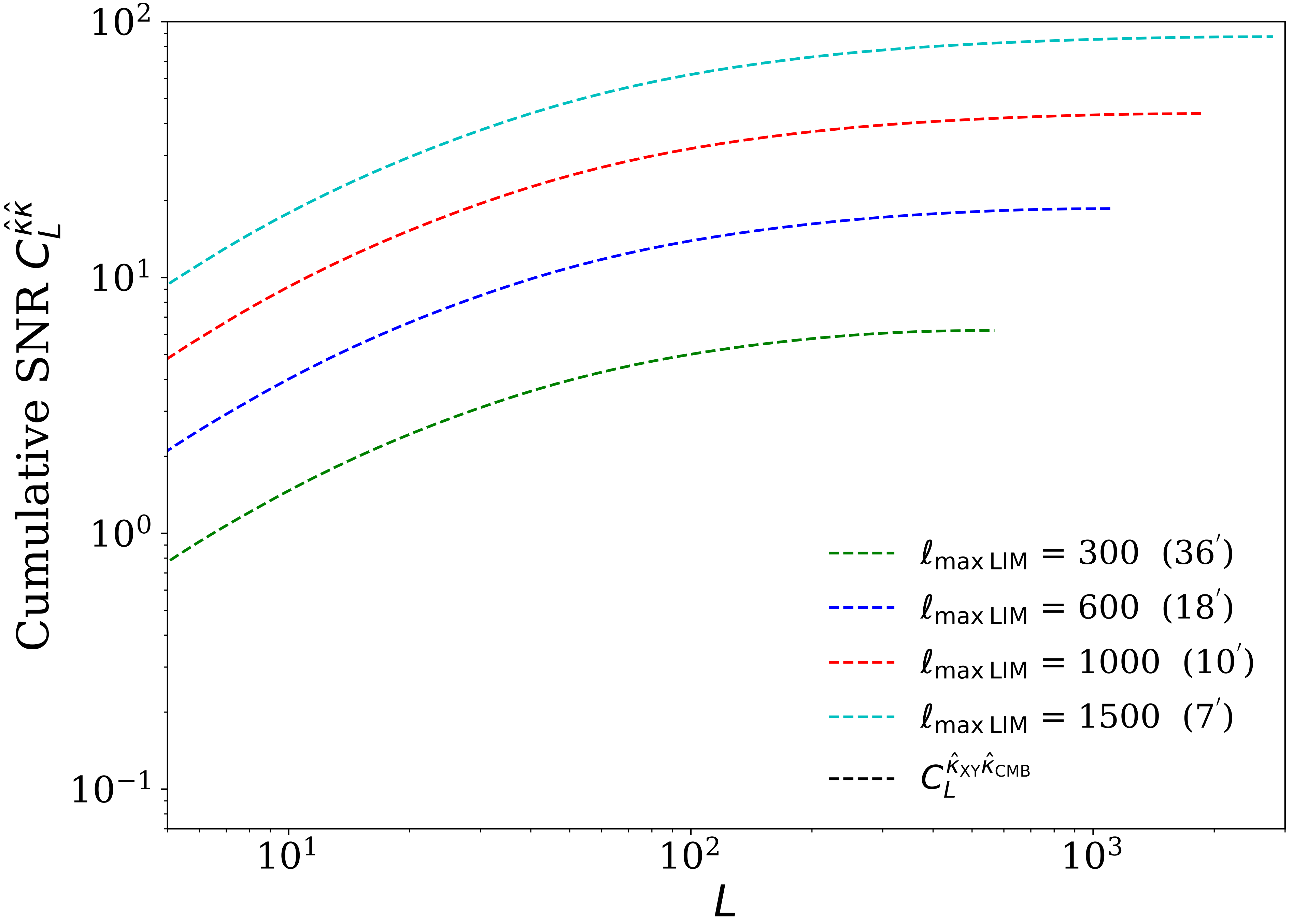
at

$z = 5$

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

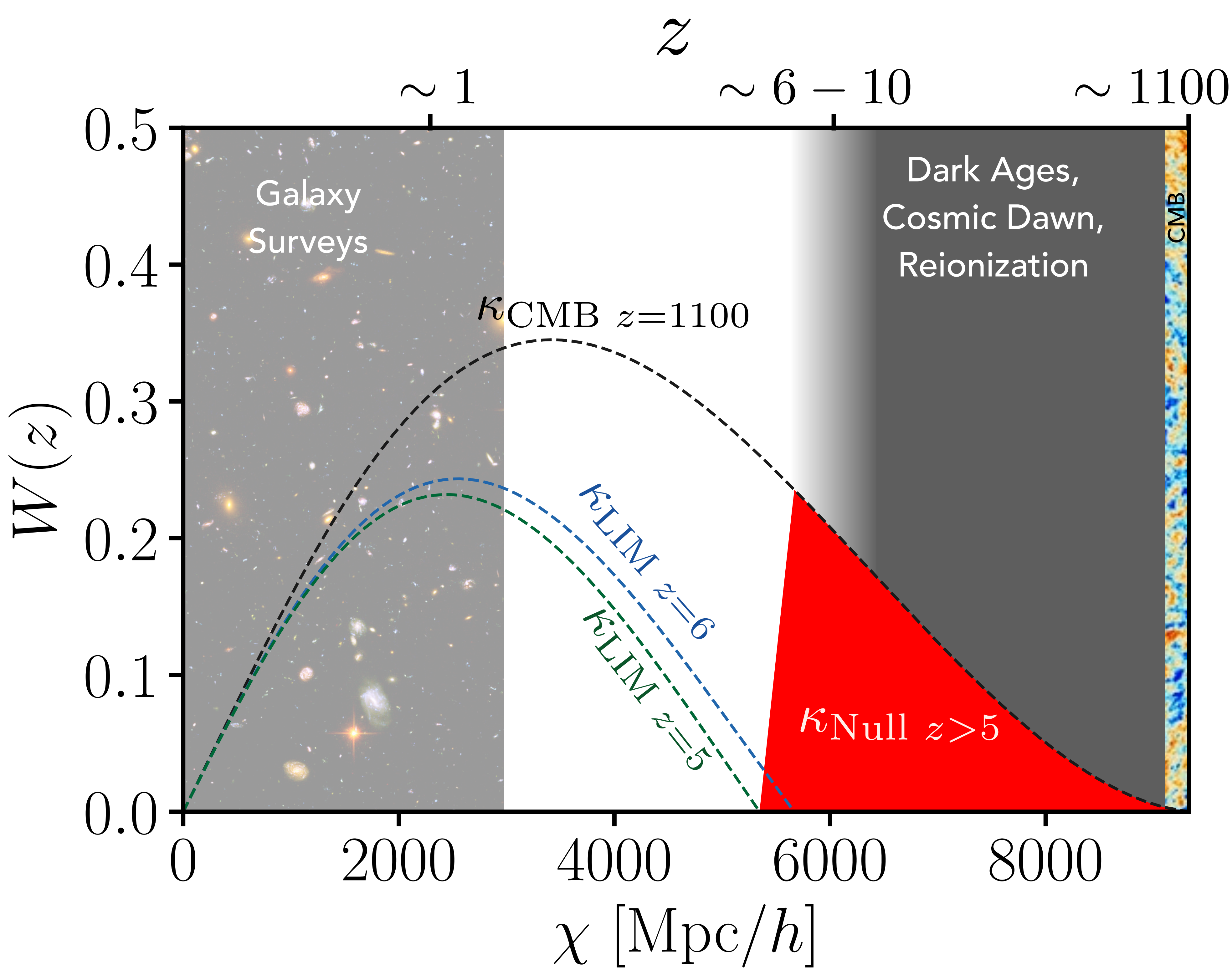
Zero non-Gaussian bias!

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

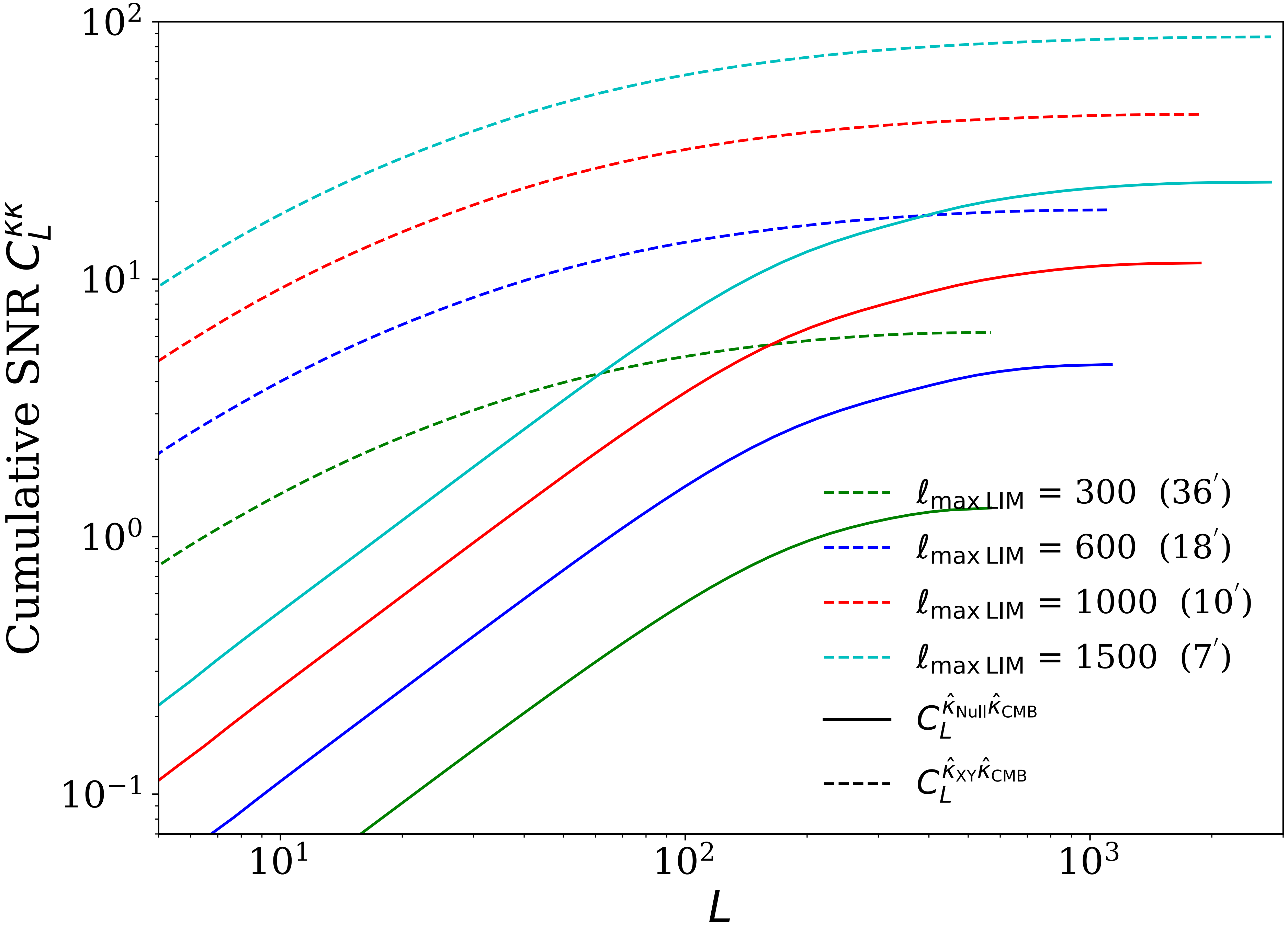


- f_sky = 40%
- Can be detected with very high SNR!

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



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



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

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!

Thank you!