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

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😊 Virtual ☹️

Weak lensing: globally optimal estimator

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

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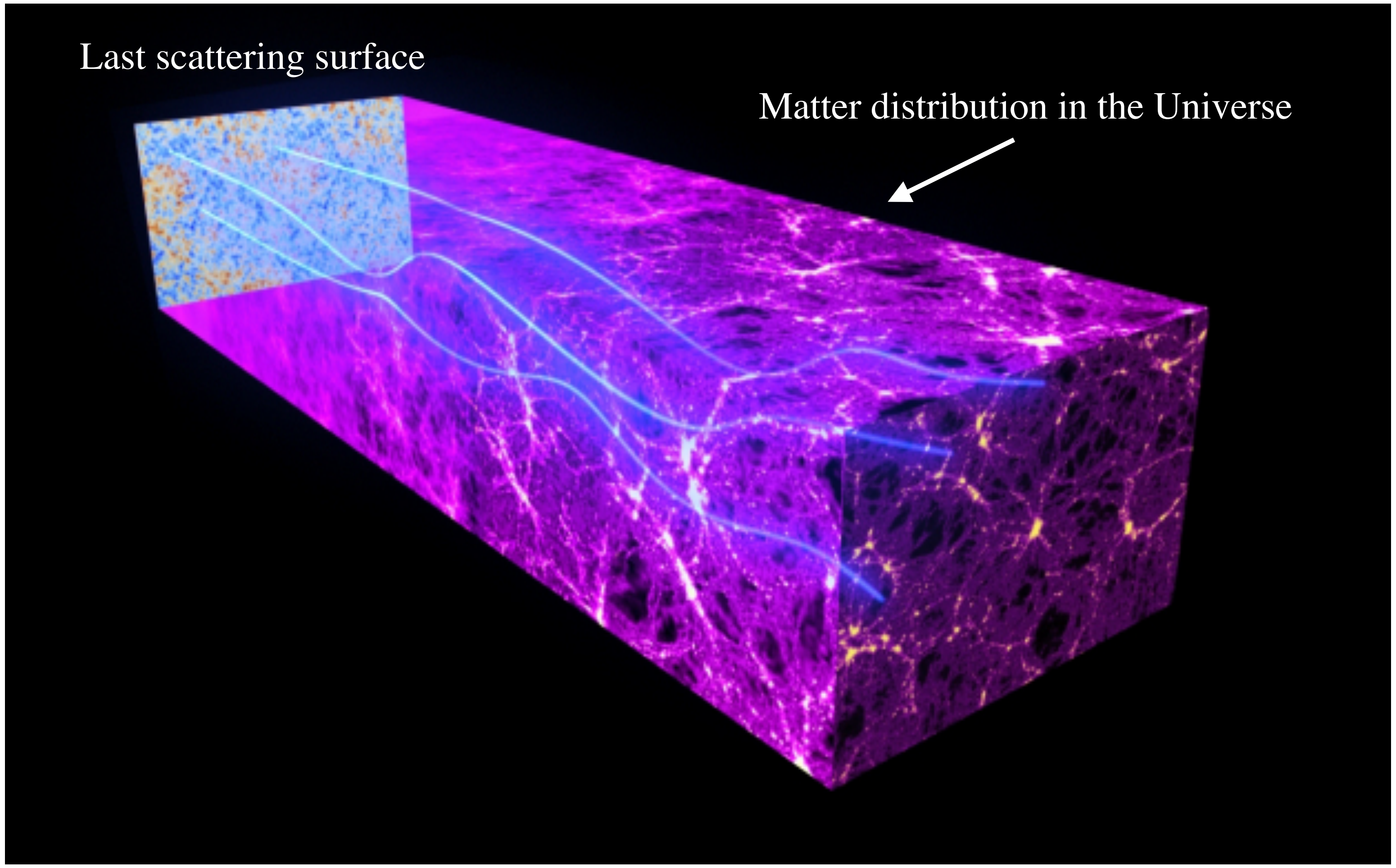
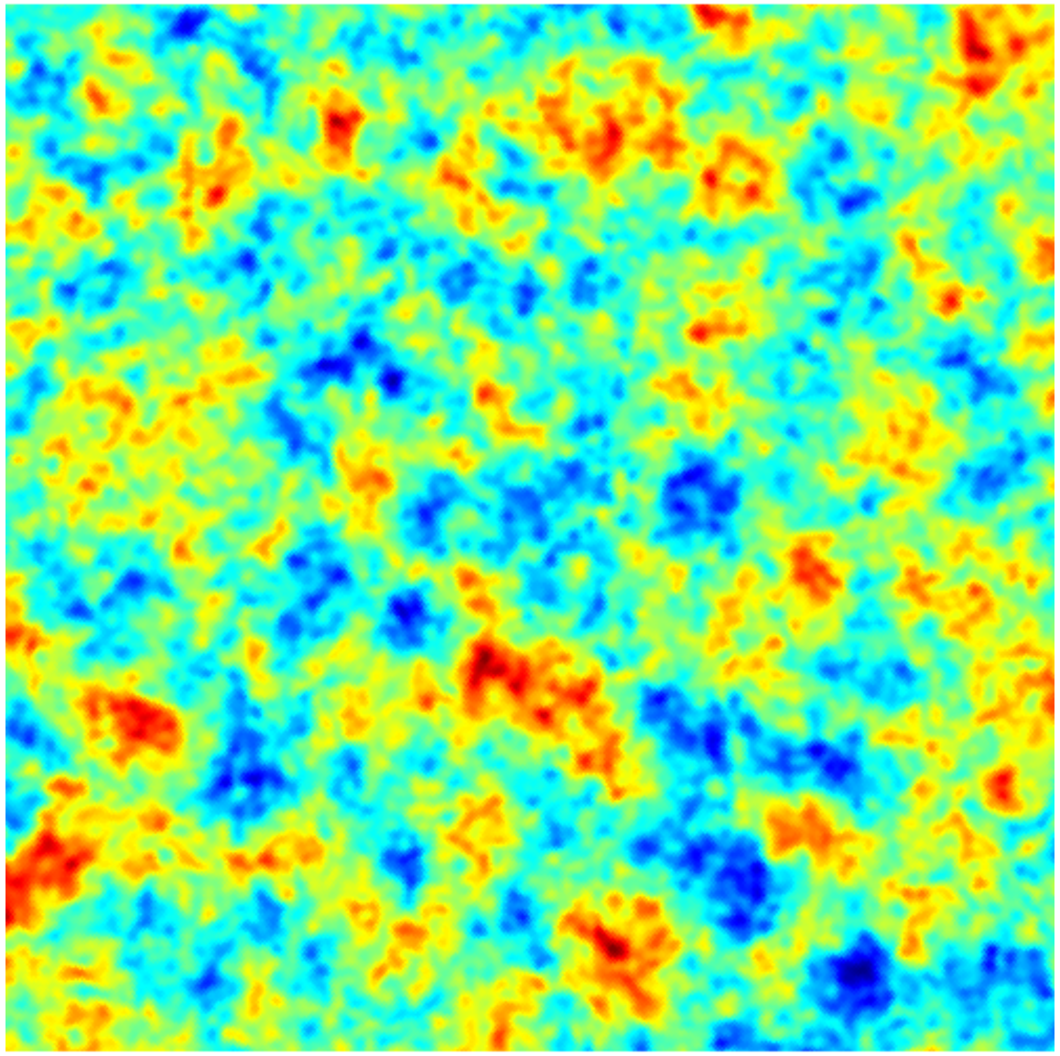
Weak lensing of the CMB

- 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

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

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

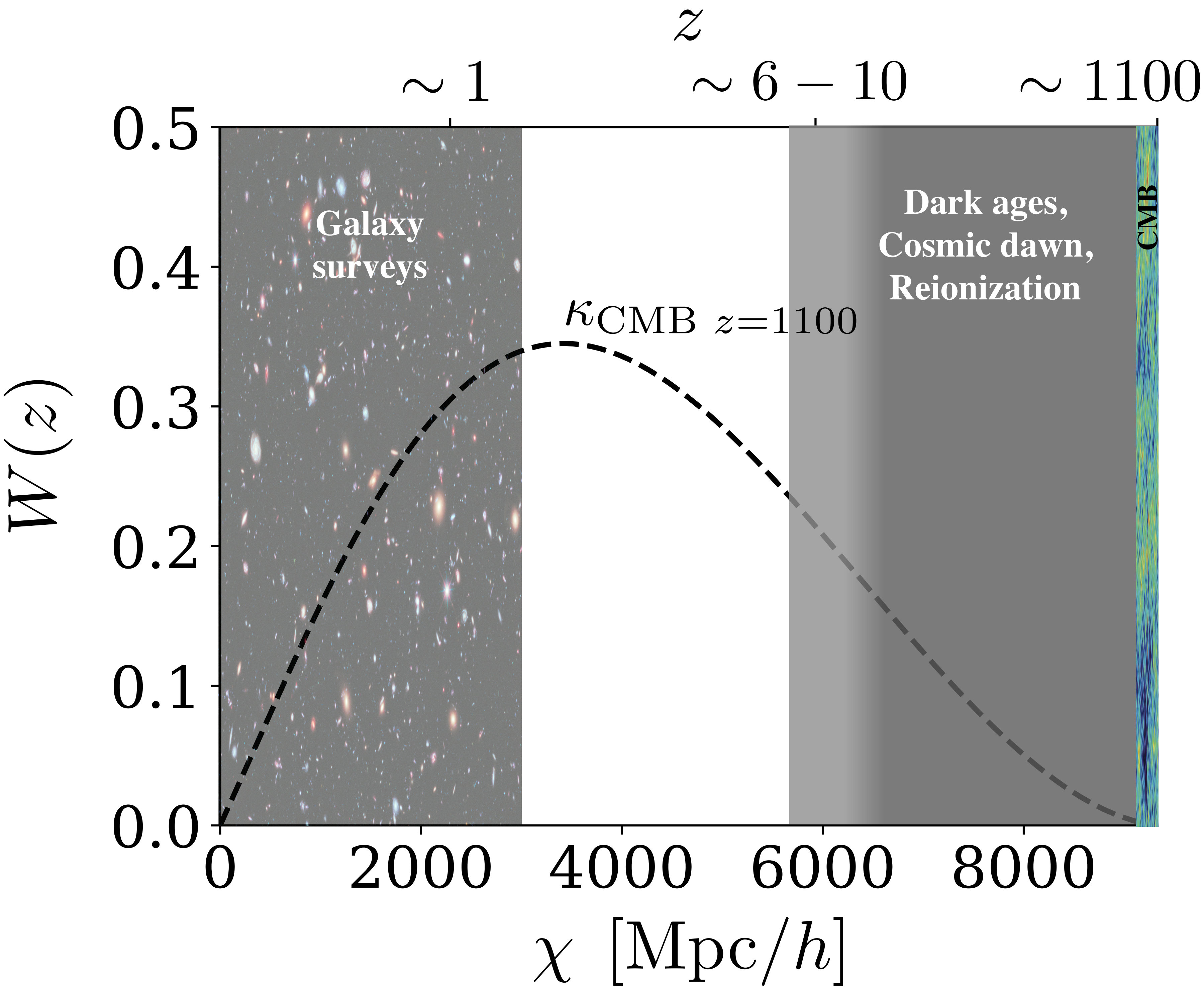
↓

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

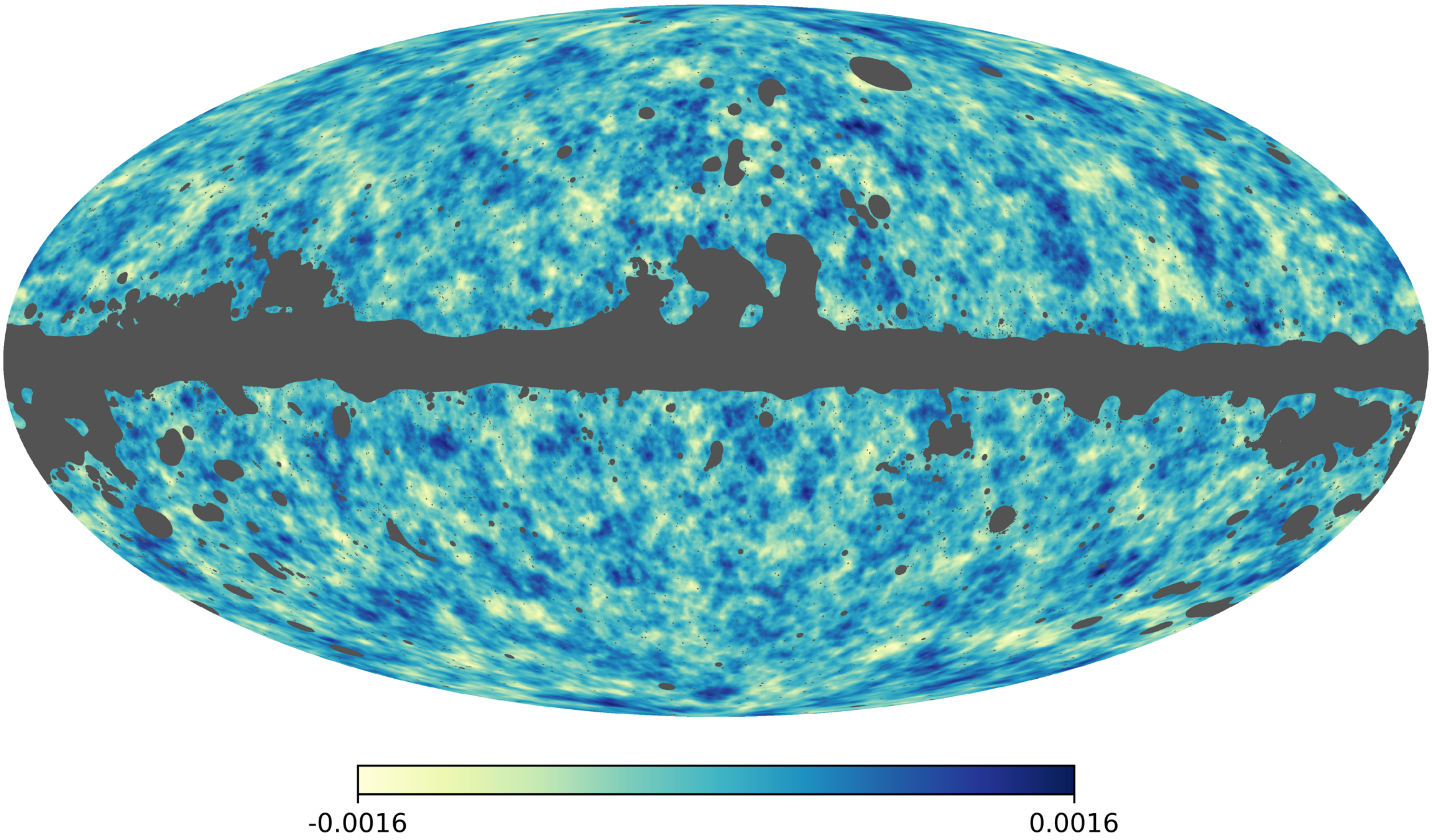
Reconstructing the density field with lensing

- 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

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

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

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

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

- 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

HO02

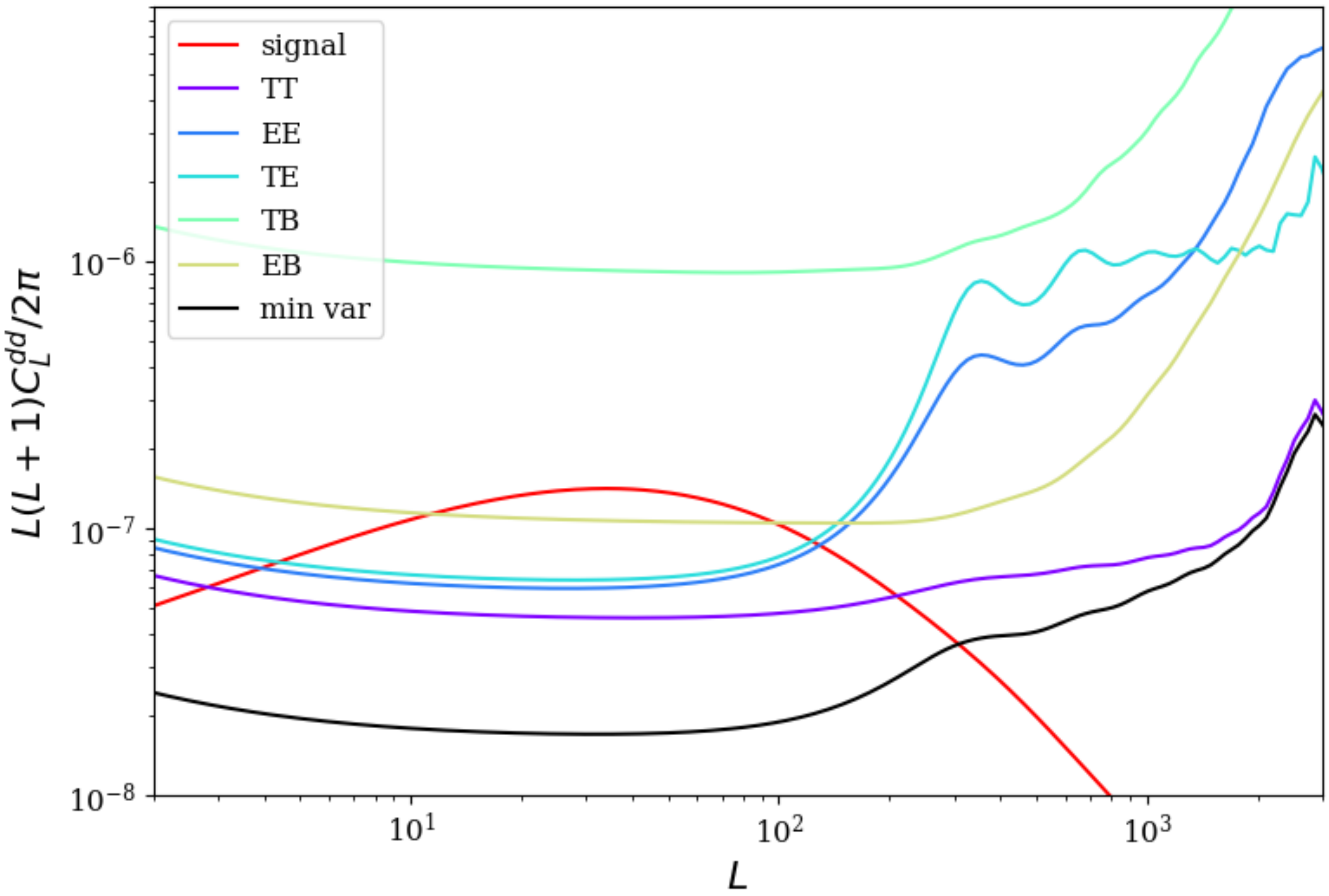
$$\hat{\phi}(\boldsymbol{L}) \propto \int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} F_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2) X(\boldsymbol{l}_1) Y(\boldsymbol{l}_2)$$

- 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

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

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

HO02: SO-like experiment



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

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!
- Previously derived, but erroneously described as equivalent to HO02 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

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

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

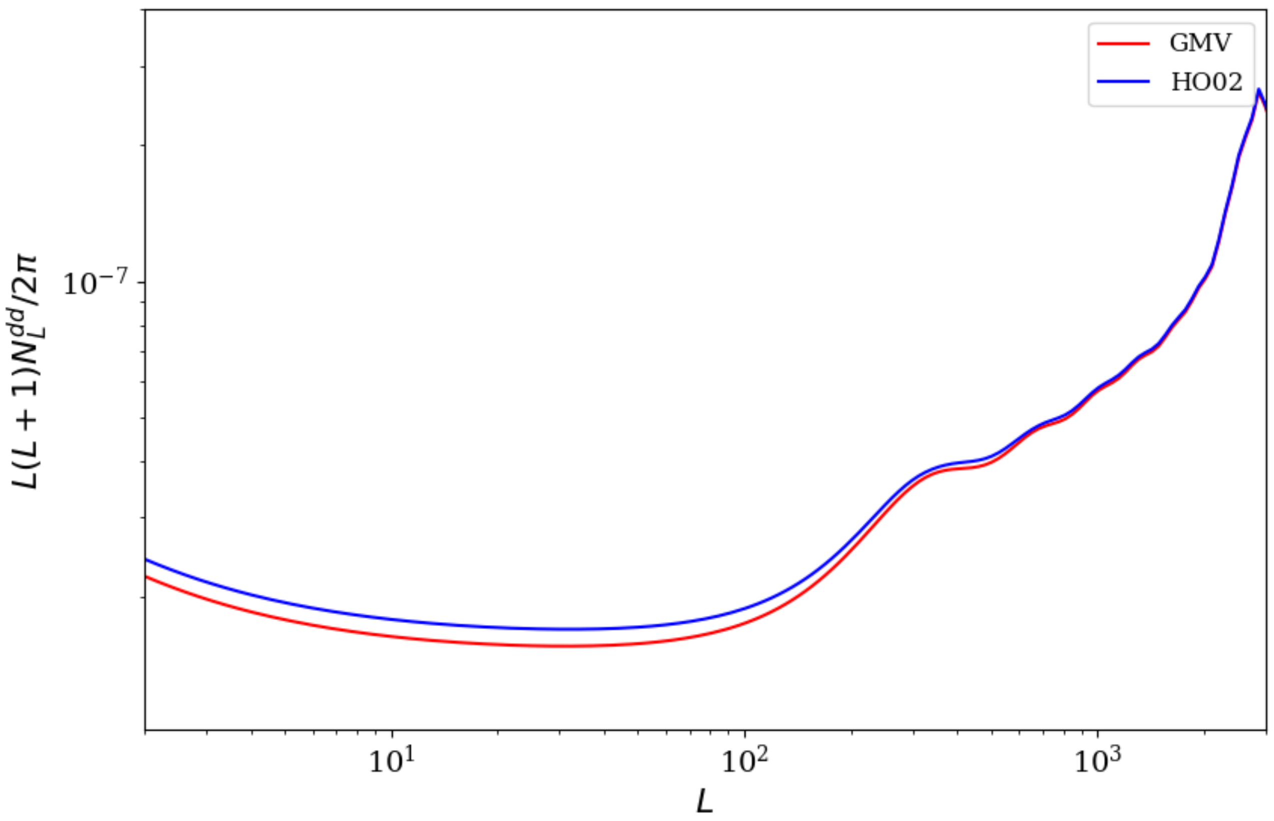
HO02

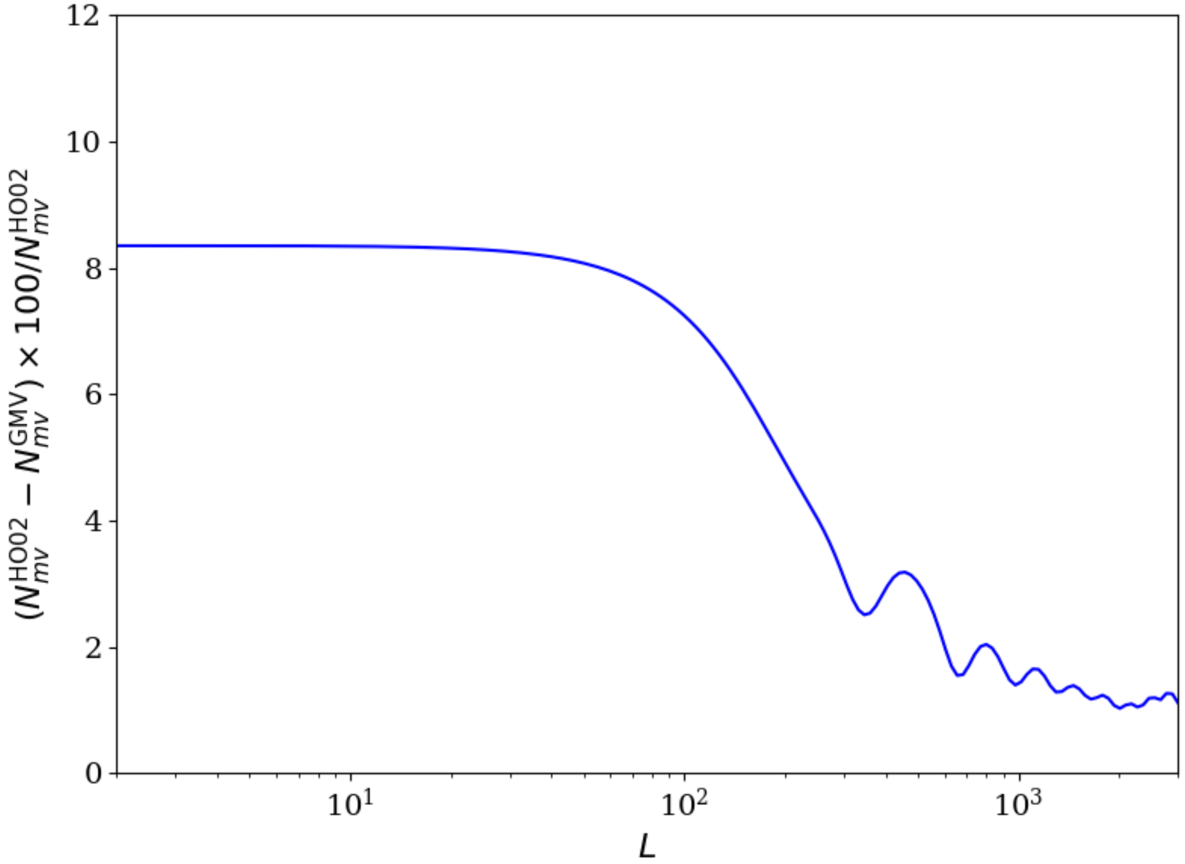
$$\int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} F_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2)X(\boldsymbol{l}_1)Y(\boldsymbol{l}_2)$$

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

- $\boldsymbol{C}_l$ 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





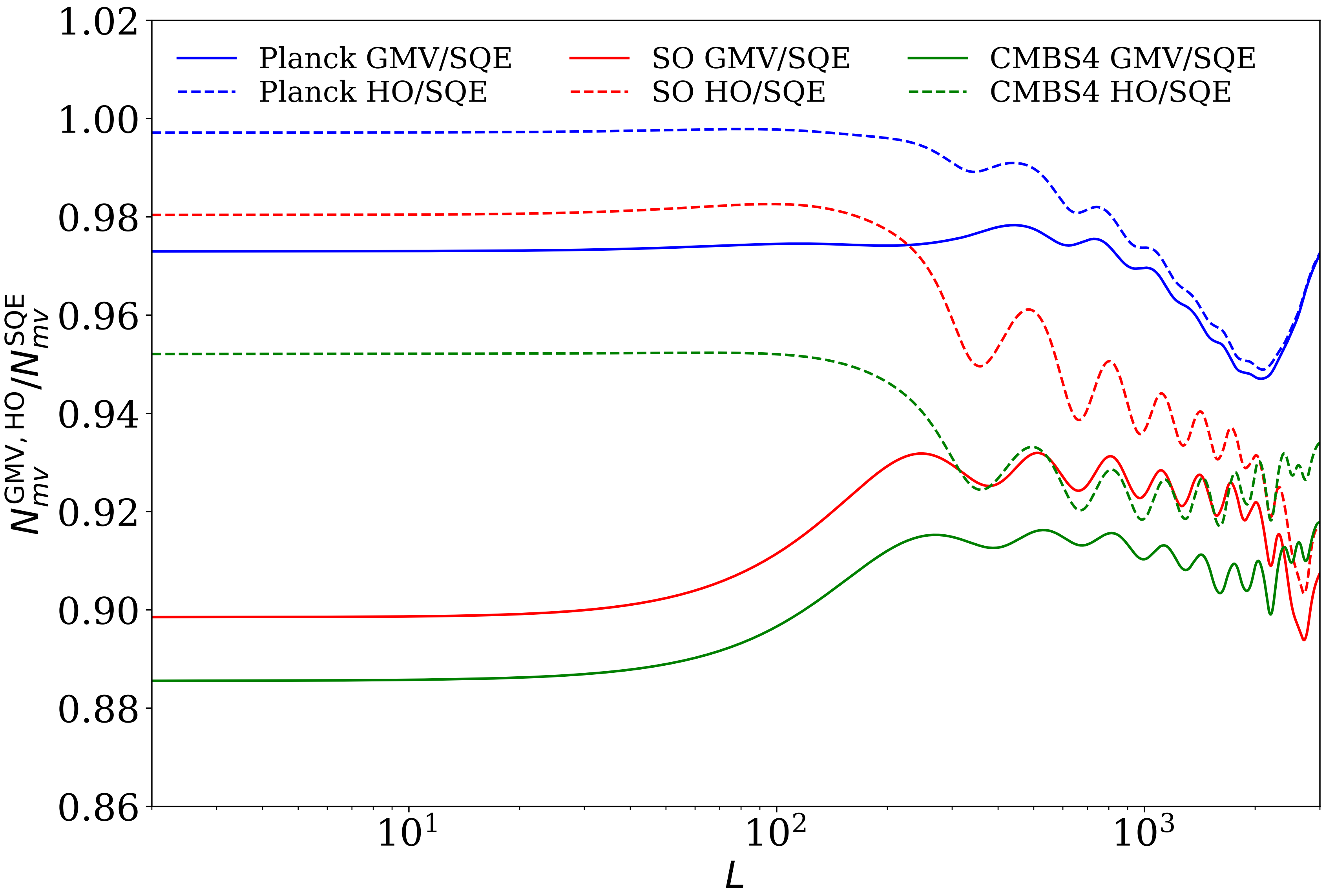
- 8-10% smaller noise than HO02 on small L
- More information out of the same maps!

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!

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 $C_l^{TE} = 0$

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

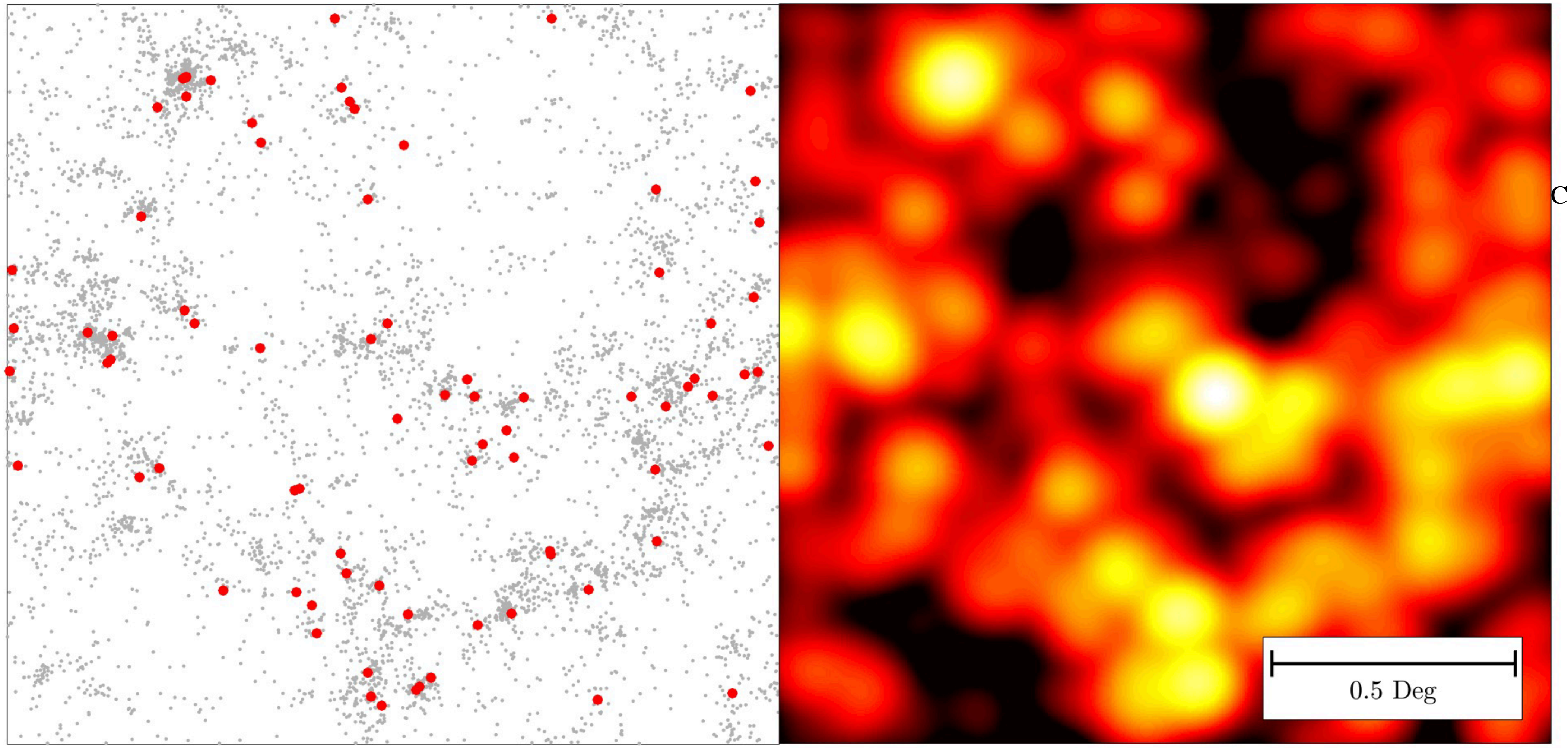
A new probe of the high-redshift Universe: nulling CMB lensing with interloper-free "LIM-pair" lensing

In collaboration with: Emmanuel Schaan & Anthony Pullen

arXiv:2106.09005

Line intensity mapping

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



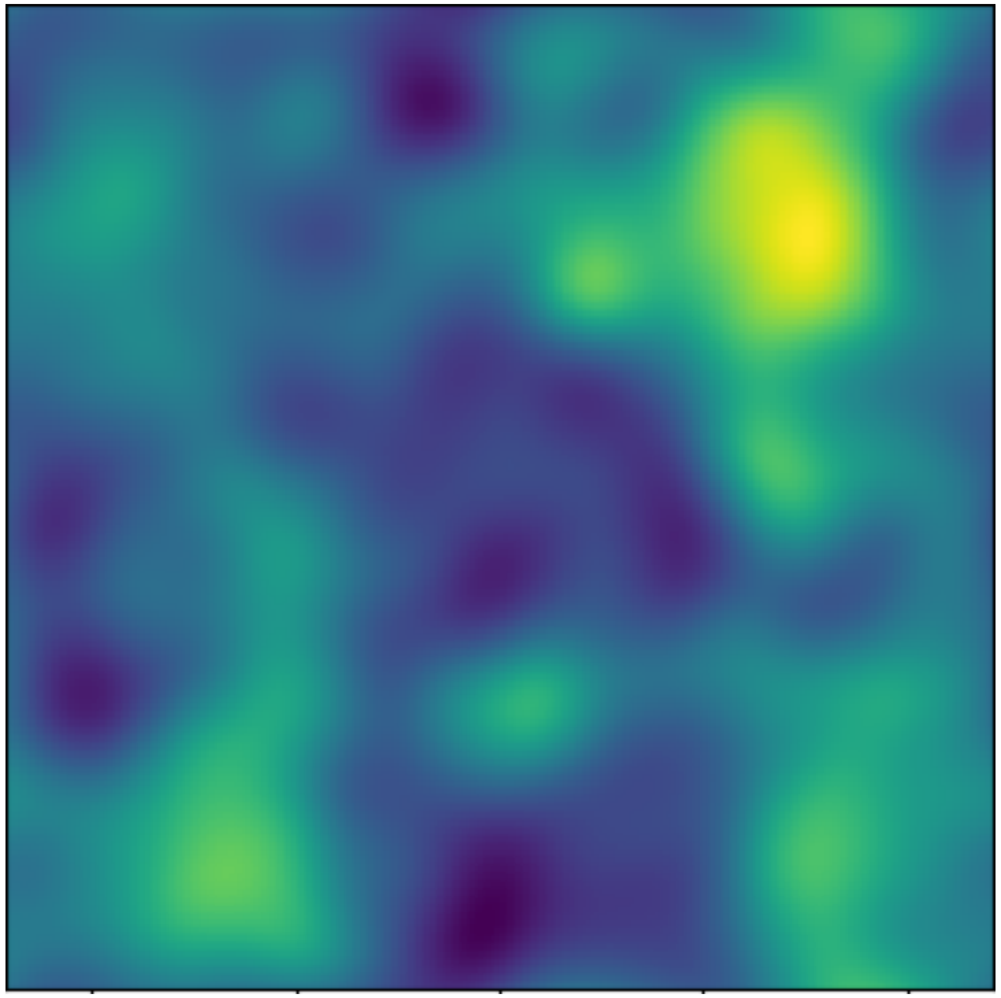
Credit: Patrick Breysse

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



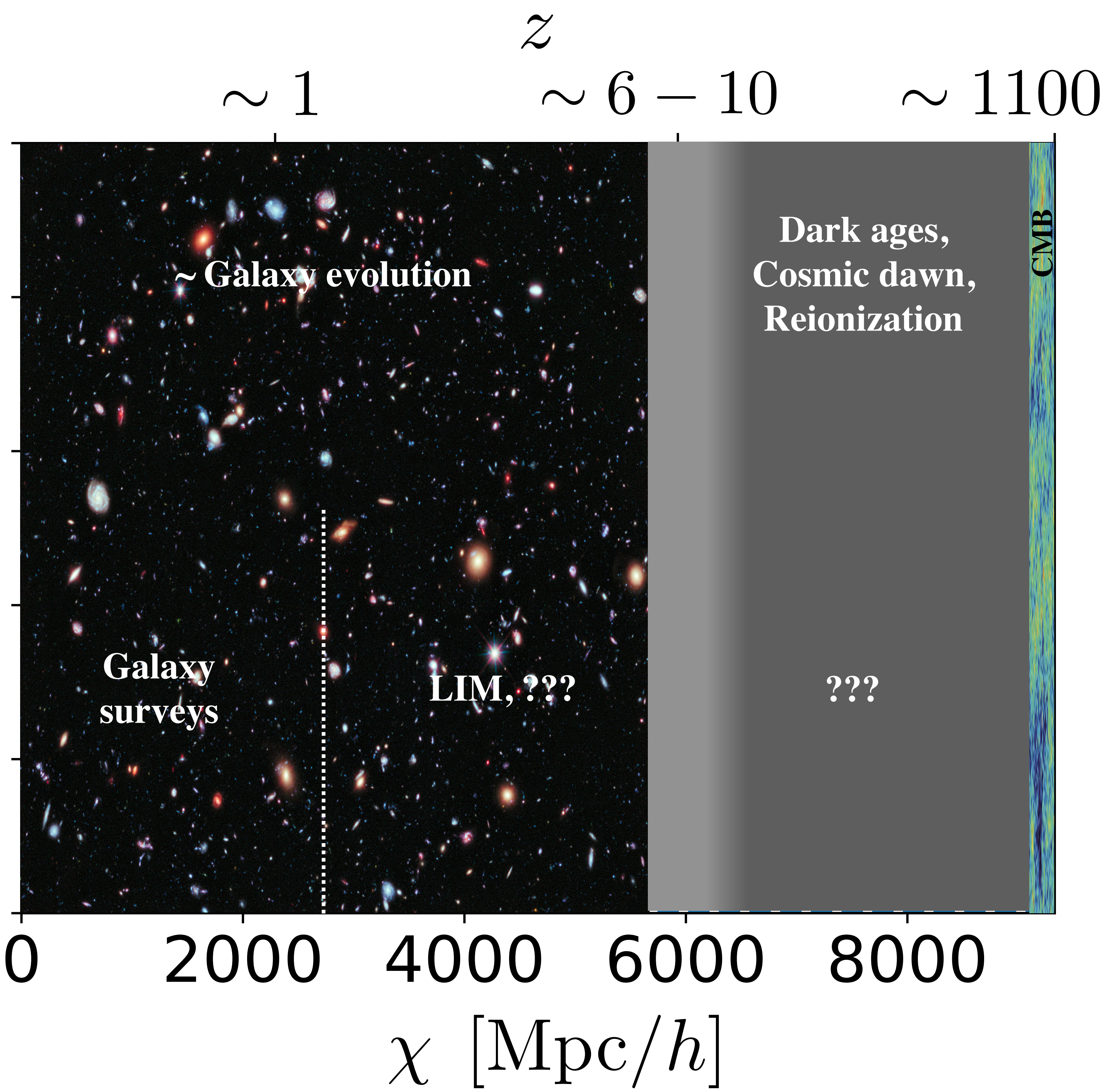
500 GHz

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

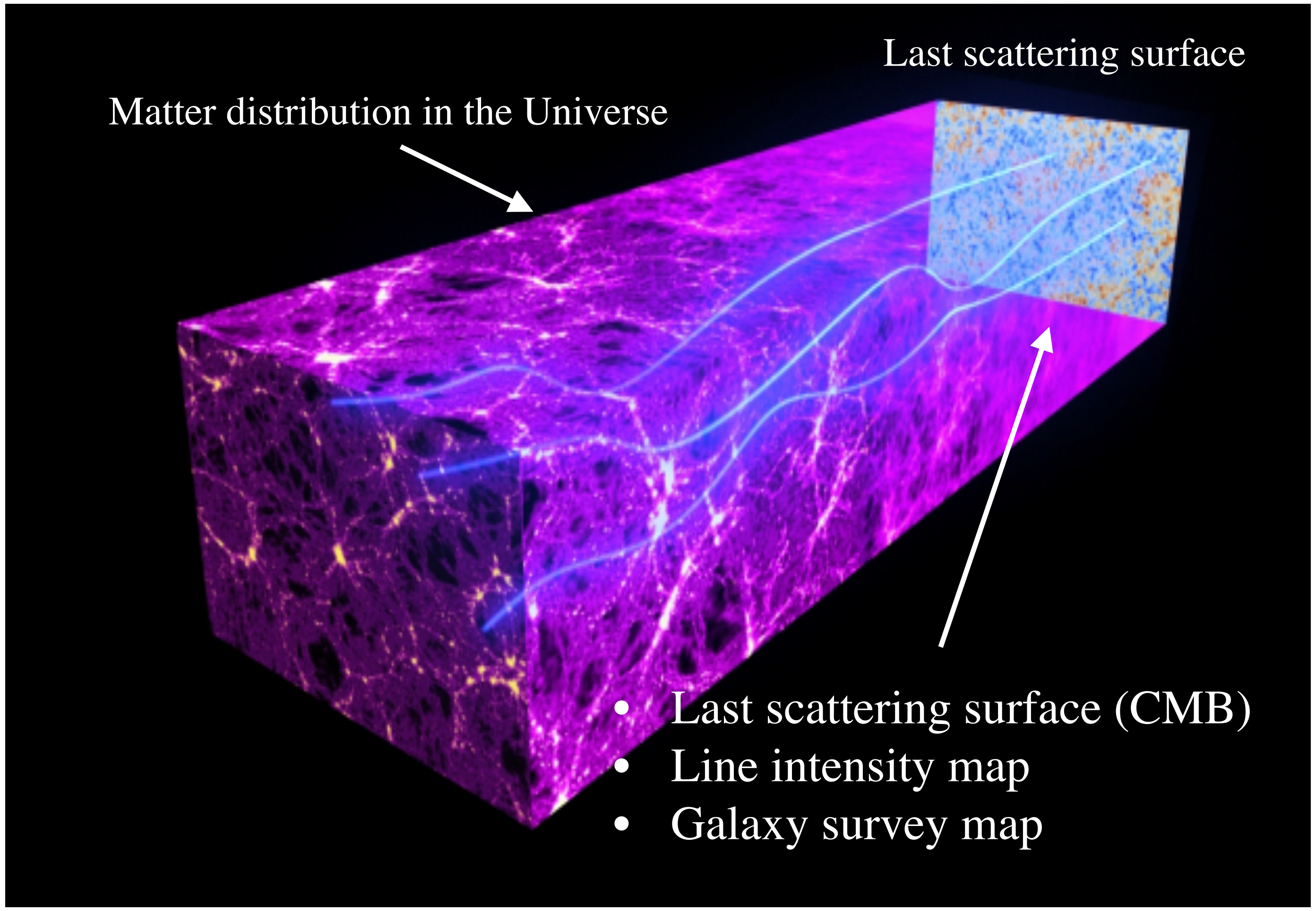
Also continuum emission: Cosmic Infrared Background, Milky Way!

High redshift universe

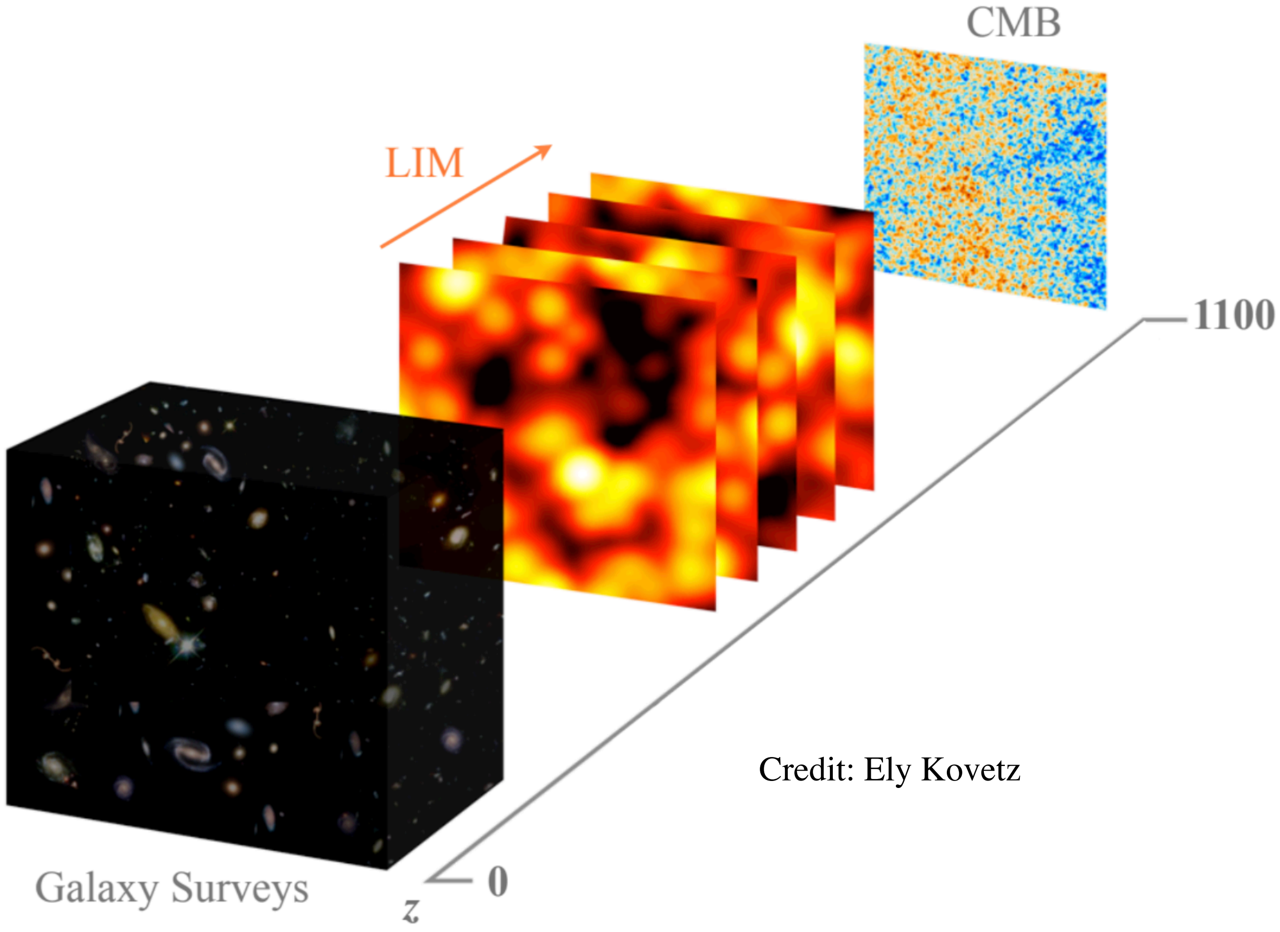
- Galaxy surveys: matter density field at z < ~1.5
- LIM at high redshifts?
  - Continuum foregrounds render modes perpendicular to LOS $k_{\parallel} \simeq 0$ unusable for cosmology
- Constructing matter density field at z > ~1.5 quite difficult
- Cosmic dawn, dark ages even more difficult
- Some new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



Weak lensing of the CMB/LIM/Galaxies



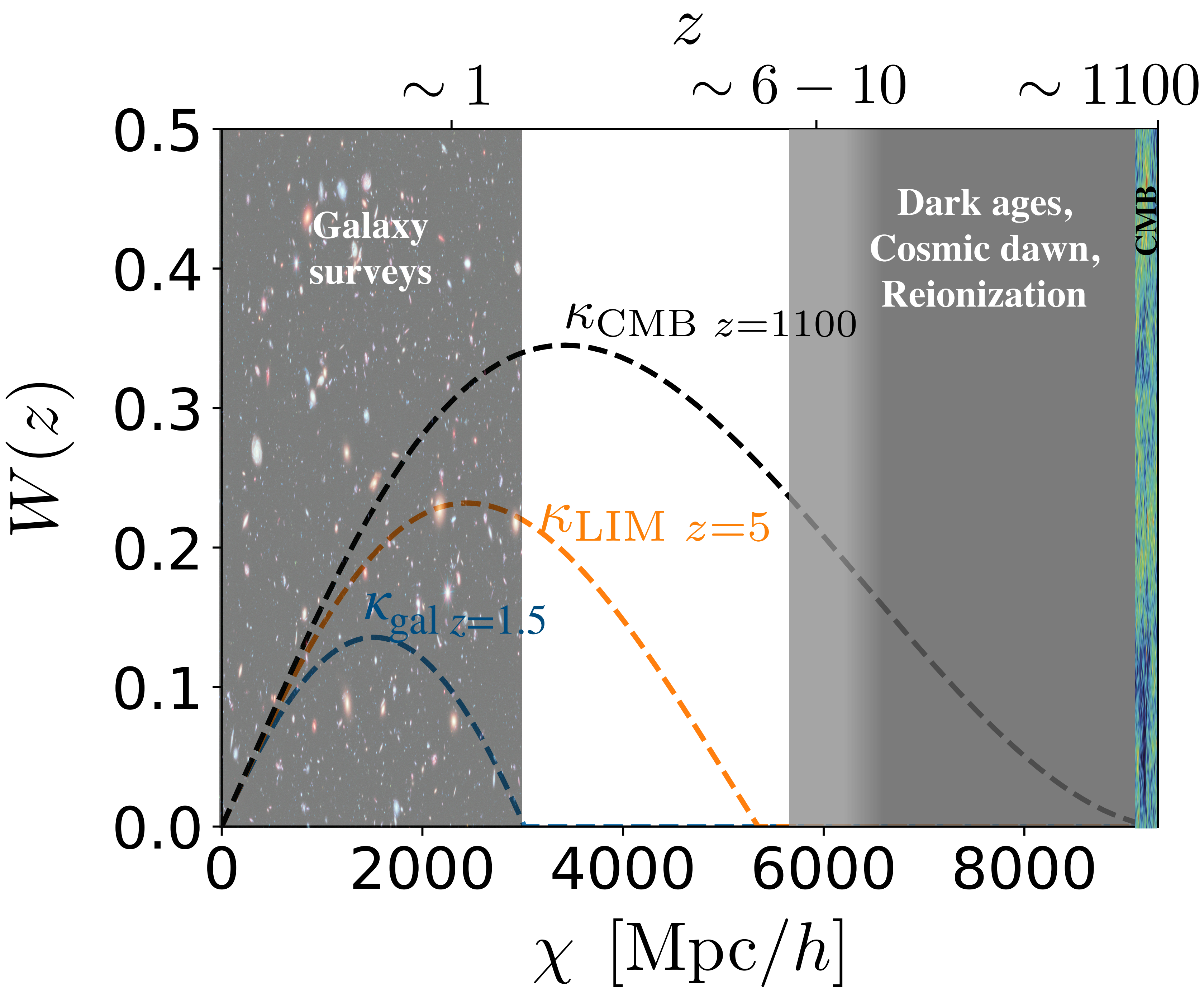
- Last scattering surface (CMB)
- Line intensity map
- Galaxy survey map



Credit: Ely Kovetz

Reconstructing the density field with lensing

- κ probes projected mass density



But..

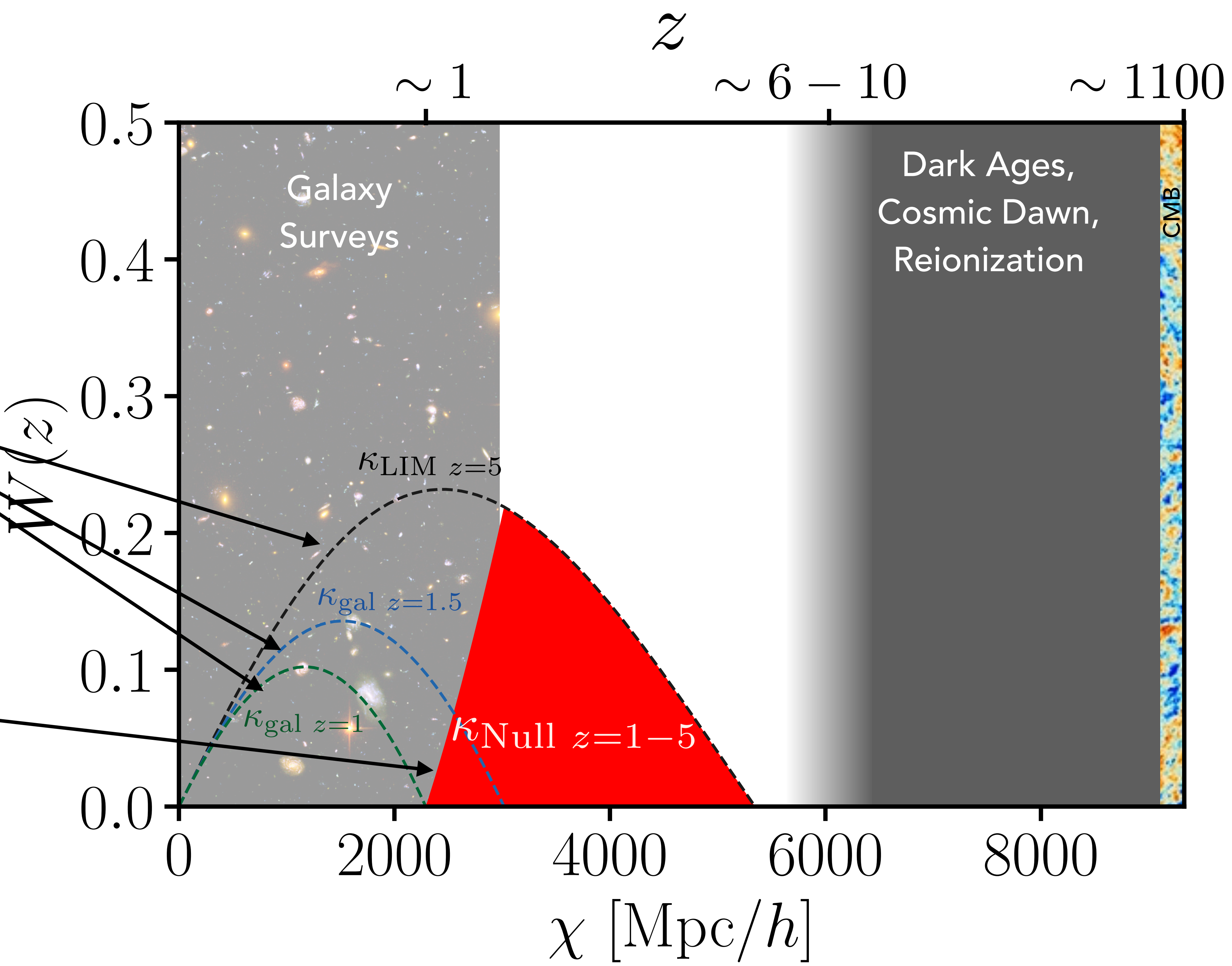
- How can we access the density field only for e.g. $1 < z < 5$?
- How can we access the density field only for e.g. $z > 5$?
- Galaxy surveys too expensive and limited at high redshifts

Nulling!

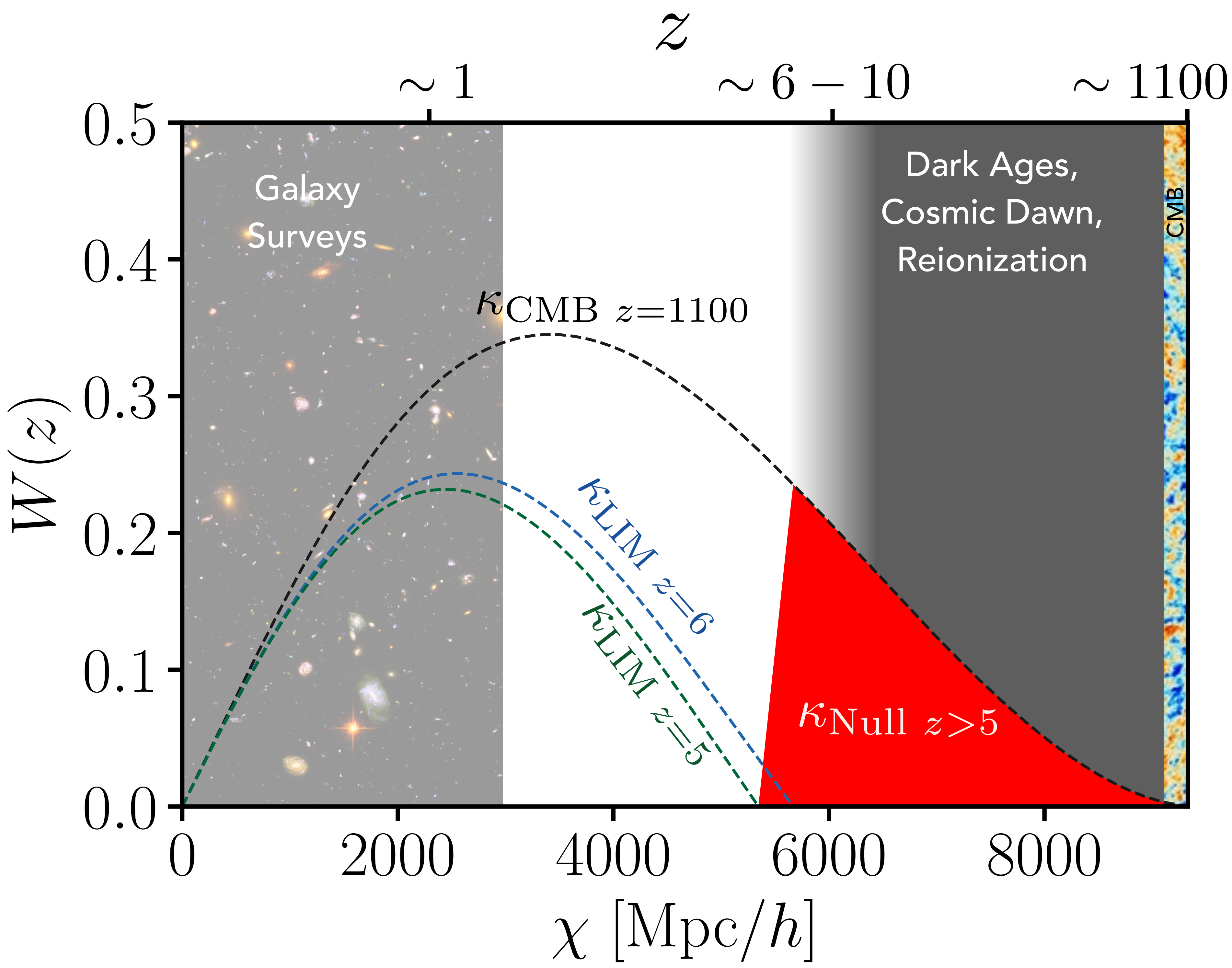
Can not just subtract curves…

2nd order polynomial in χ

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



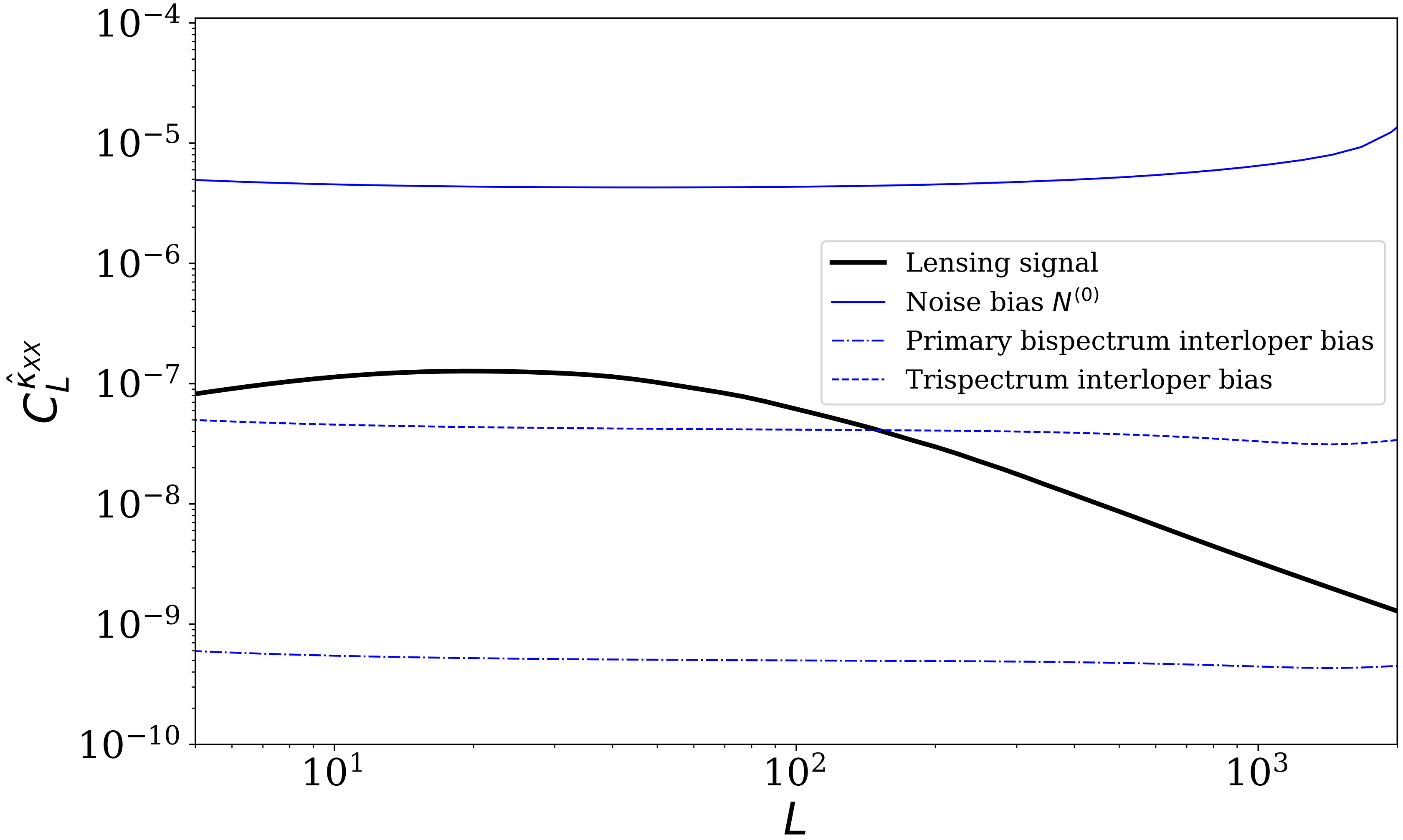
Nulling!


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 → $C_L^{\kappa\kappa}$

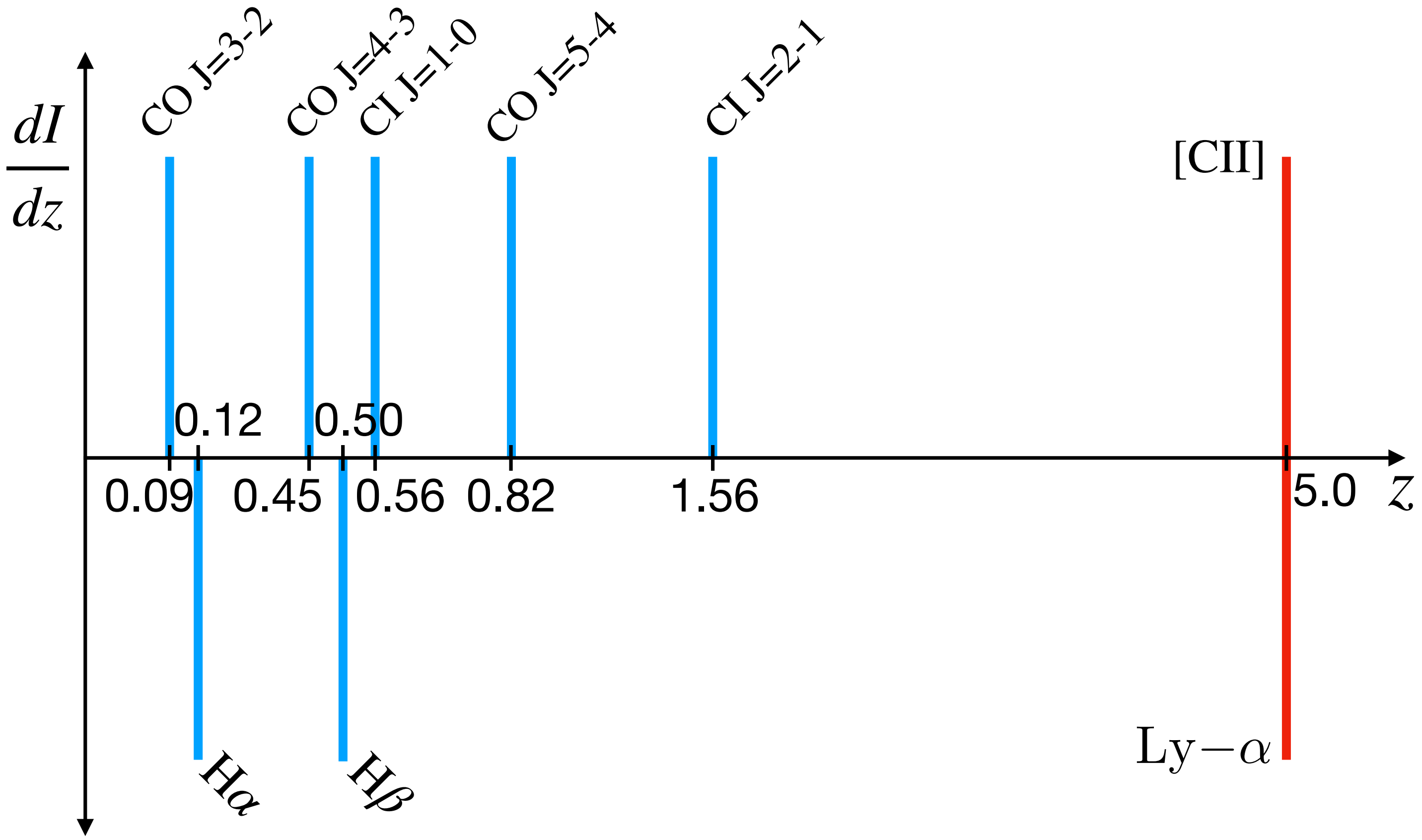
LIM Lensing



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!

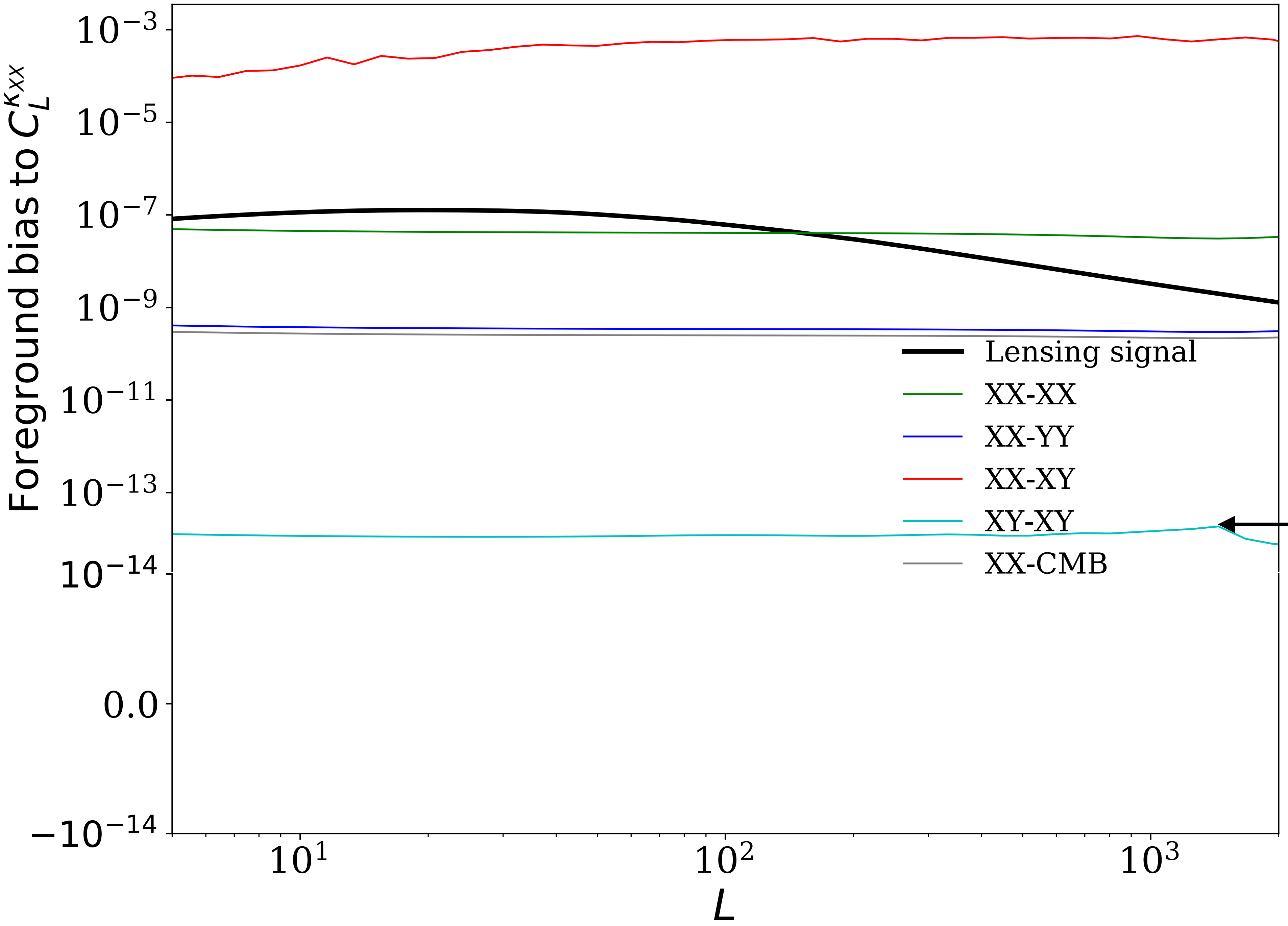
“LIM-pair” lensing!



- 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 = $\mathrm{Ly}-\alpha$

&

$Y = [\mathrm{CII}]$ or CMB

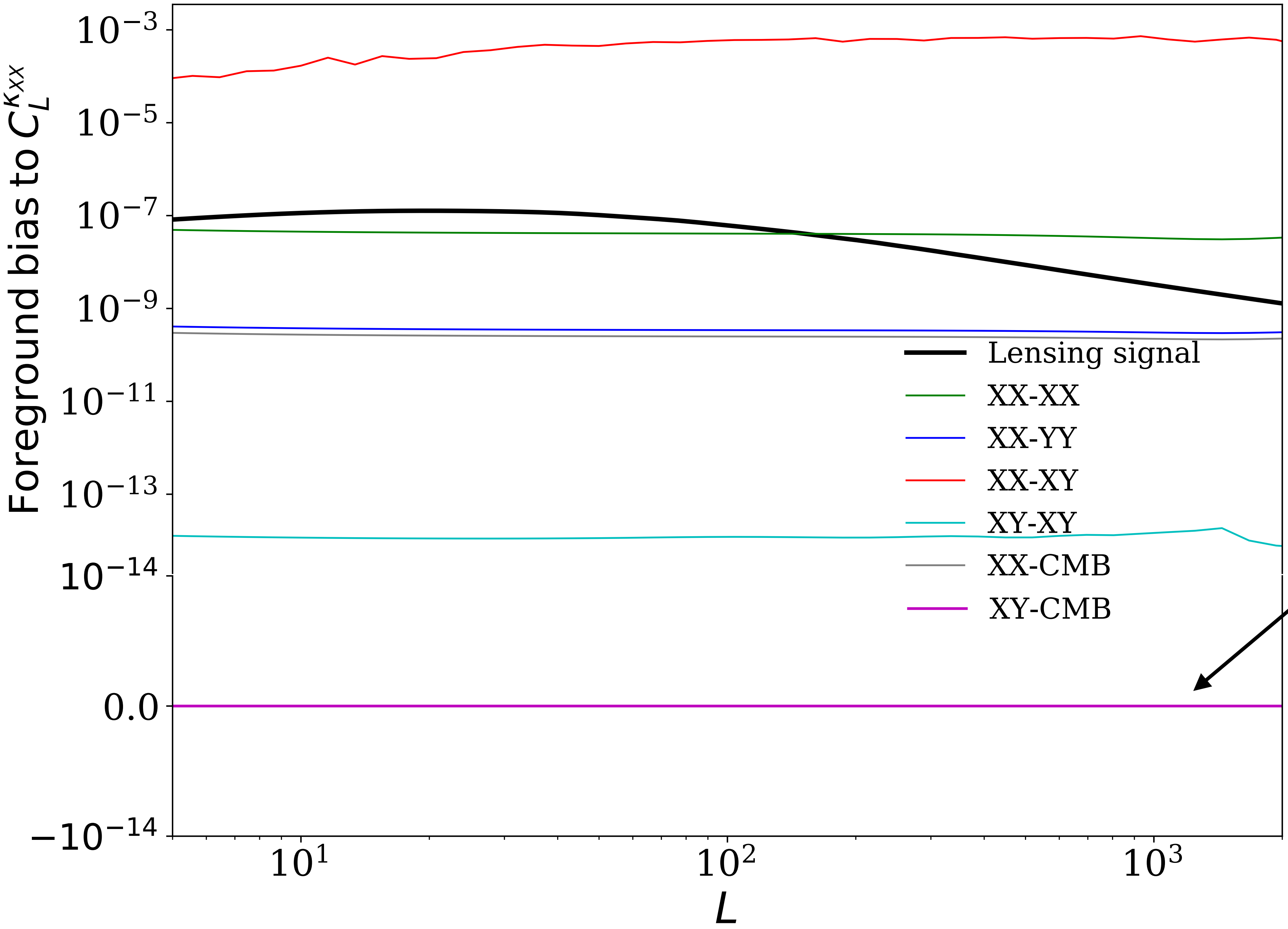
at

$z = 5$

XY is biased as well!

Secondary bispectrum bias

“LIM-pair” lensing!



X = Ly$-\alpha$

&

Y = [CII] or CMB

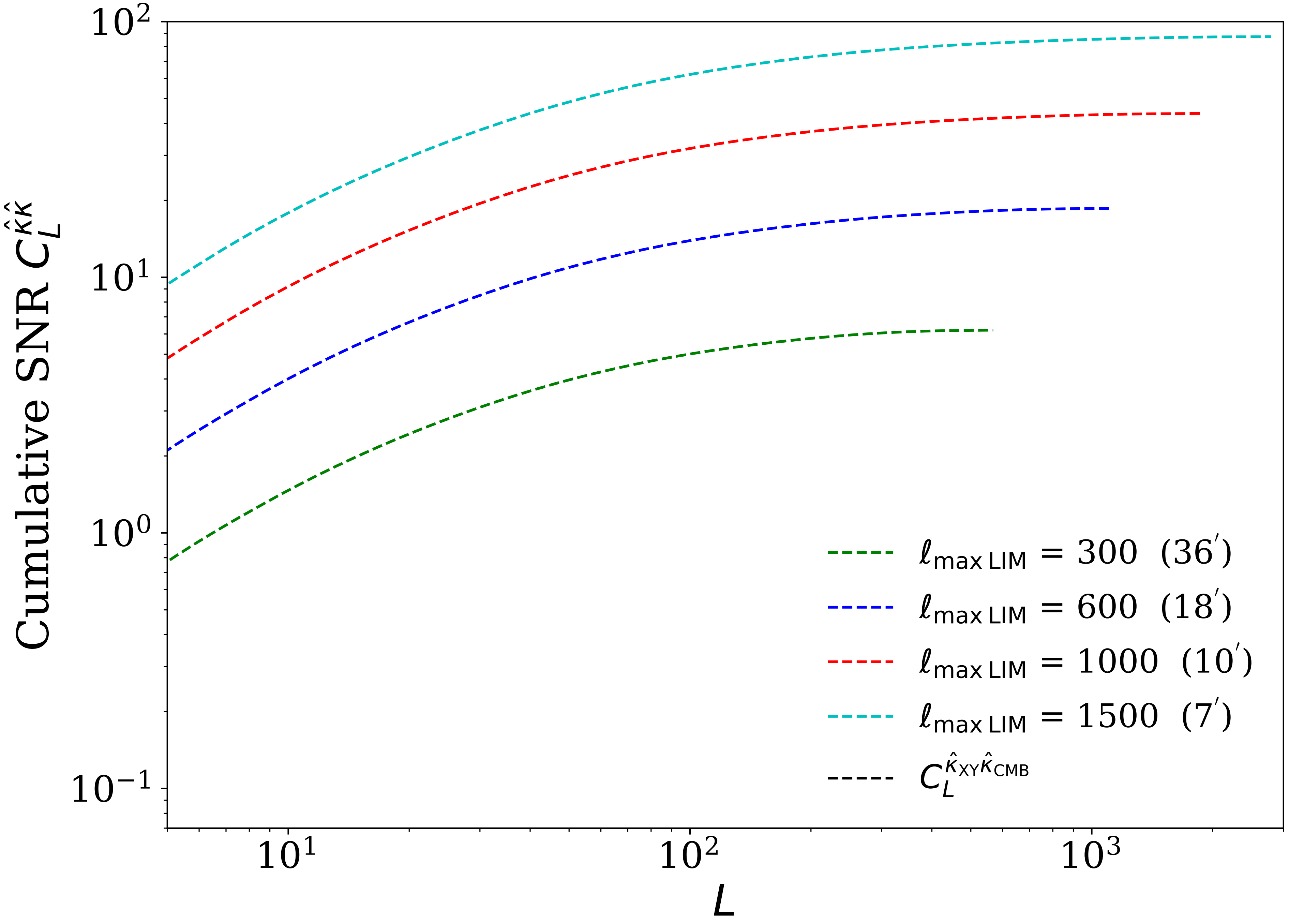
at

$z = 5$

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

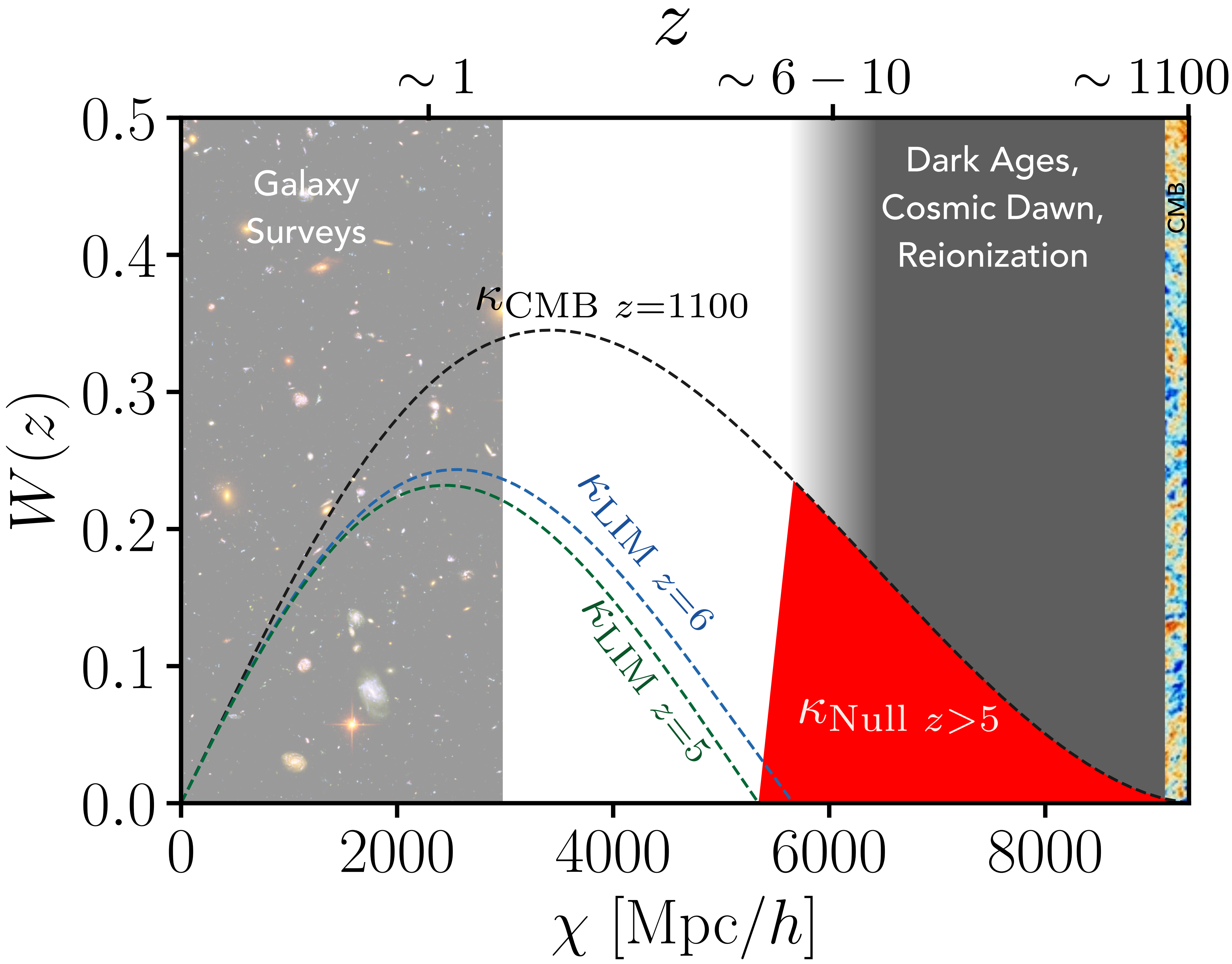
Zero non-Gaussian bias!

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

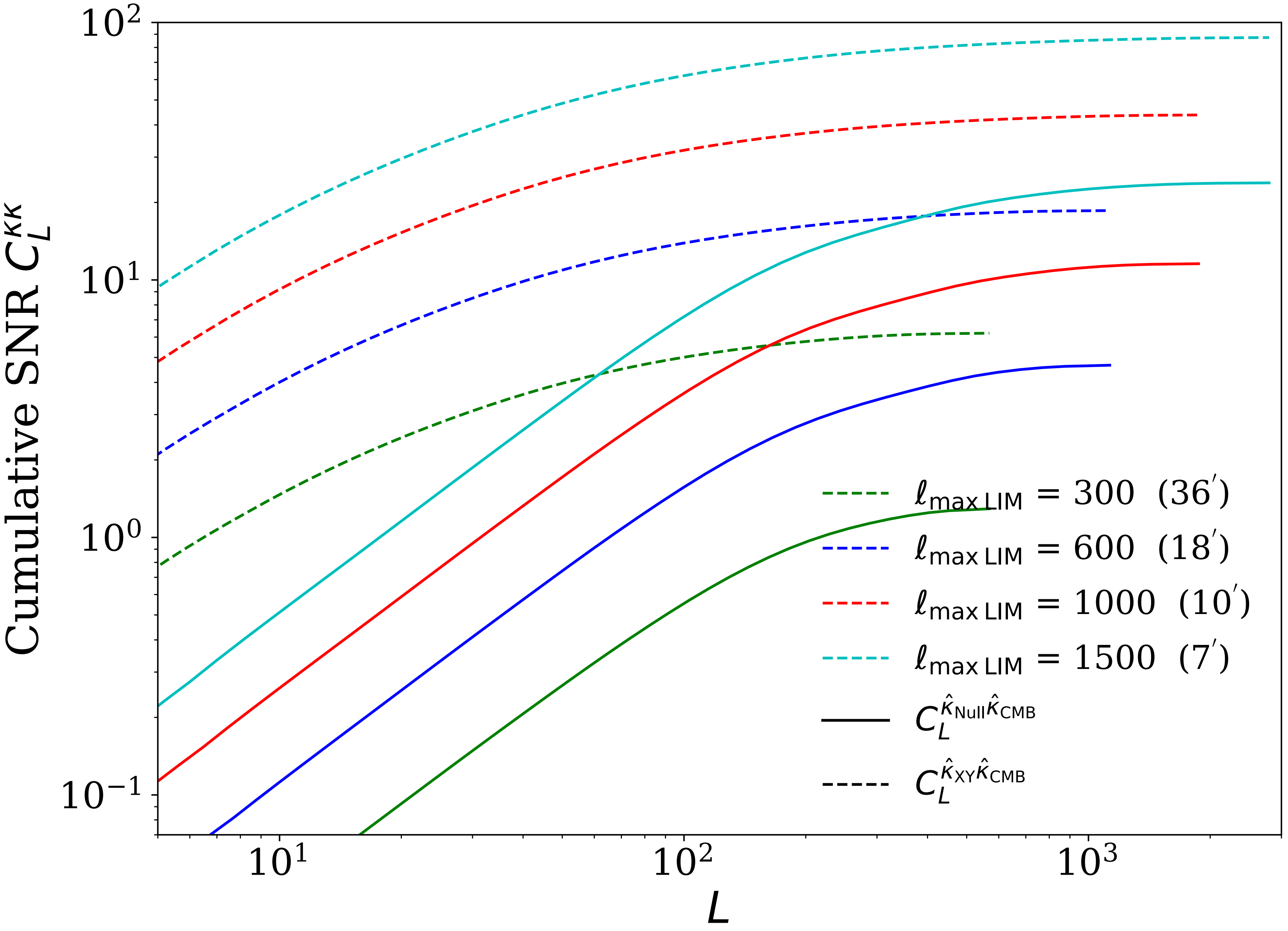


- f_sky = 40%
- Can be detected with very high SNR!

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!

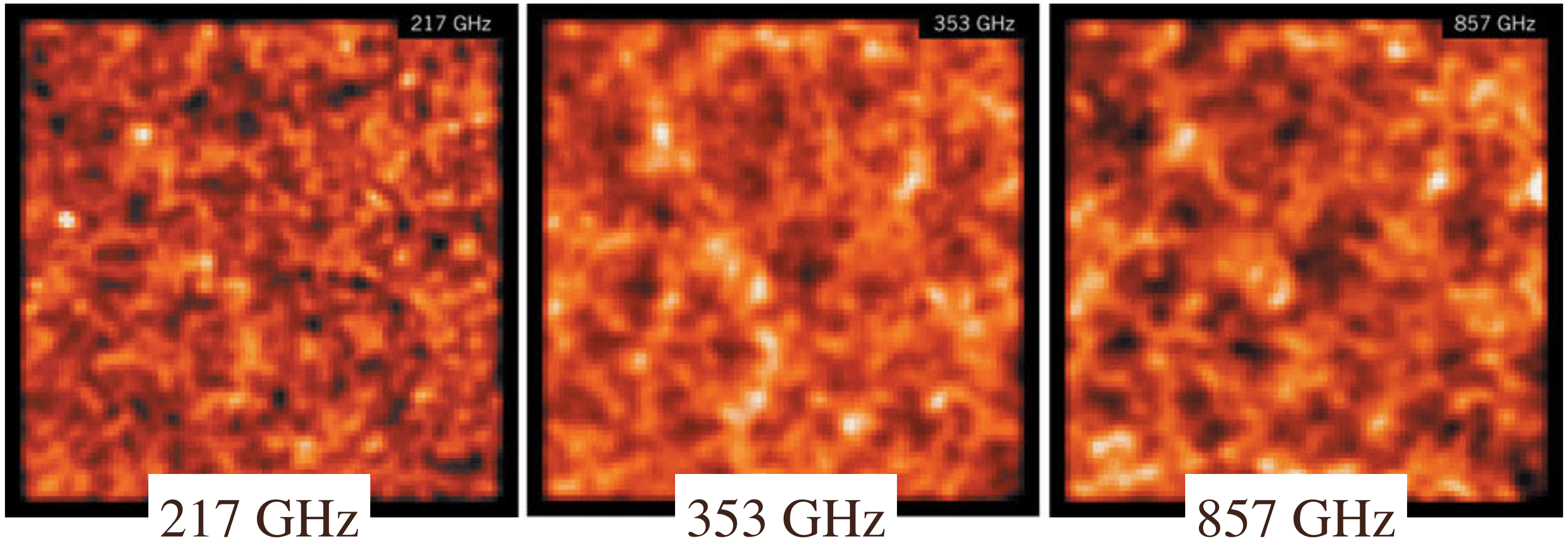
Doppler boosted emission from the CIB galaxies: A signal and a foreground

In collaboration with: Emmanuel Schaan & Simone Ferraro

Cosmic Infrared Background (CIB)

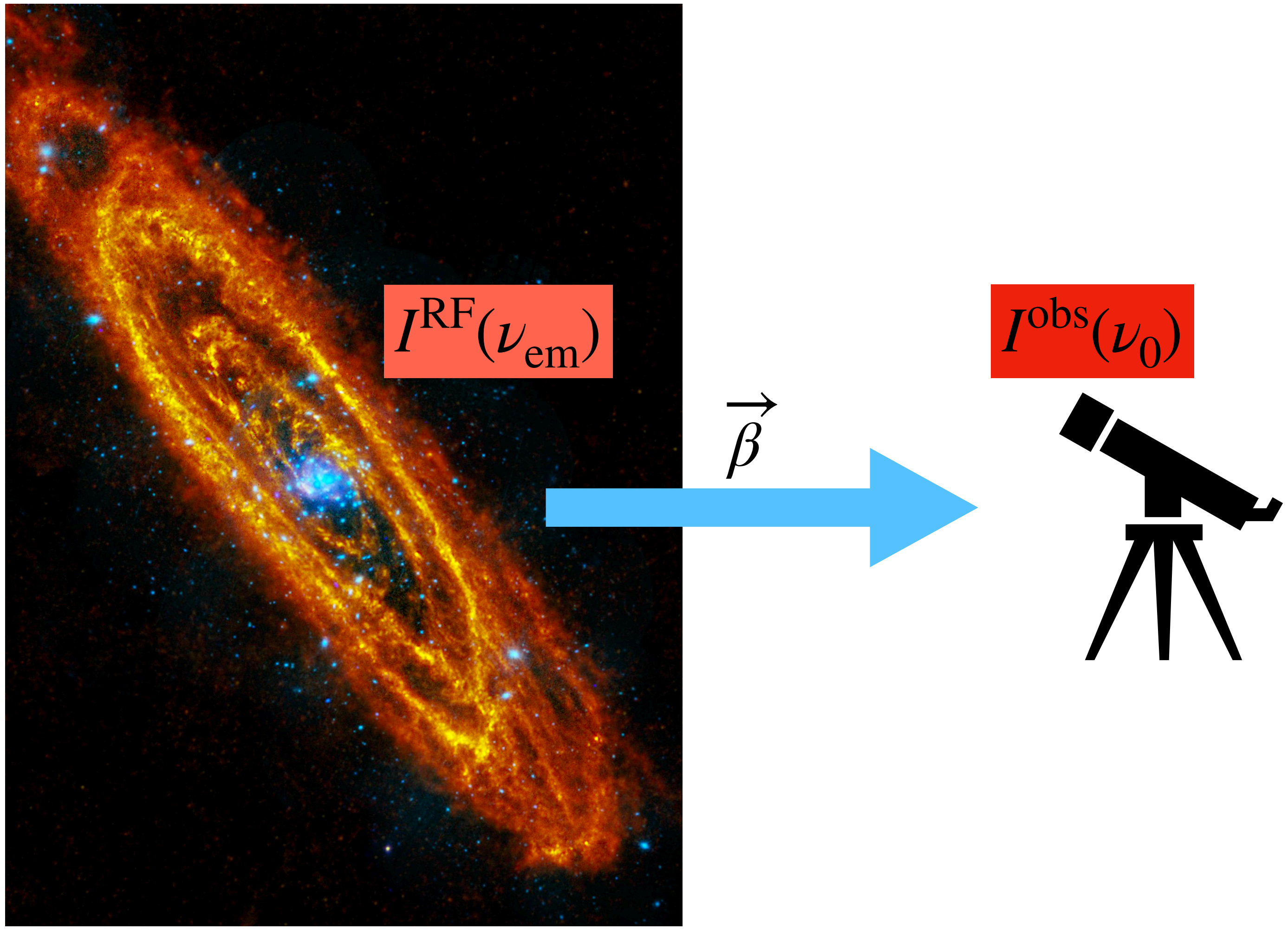
- Cumulative IR emission from dusty star forming galaxies throughout the cosmic history
- CIB galaxies clustered in the host dark matter halos
  - ✦ Anisotropies in the CIB
- CIB anisotropies => **Trace the large scale distribution** of dusty star forming galaxies => **underlying dark matter distribution**

$5^\circ \times 5^\circ$



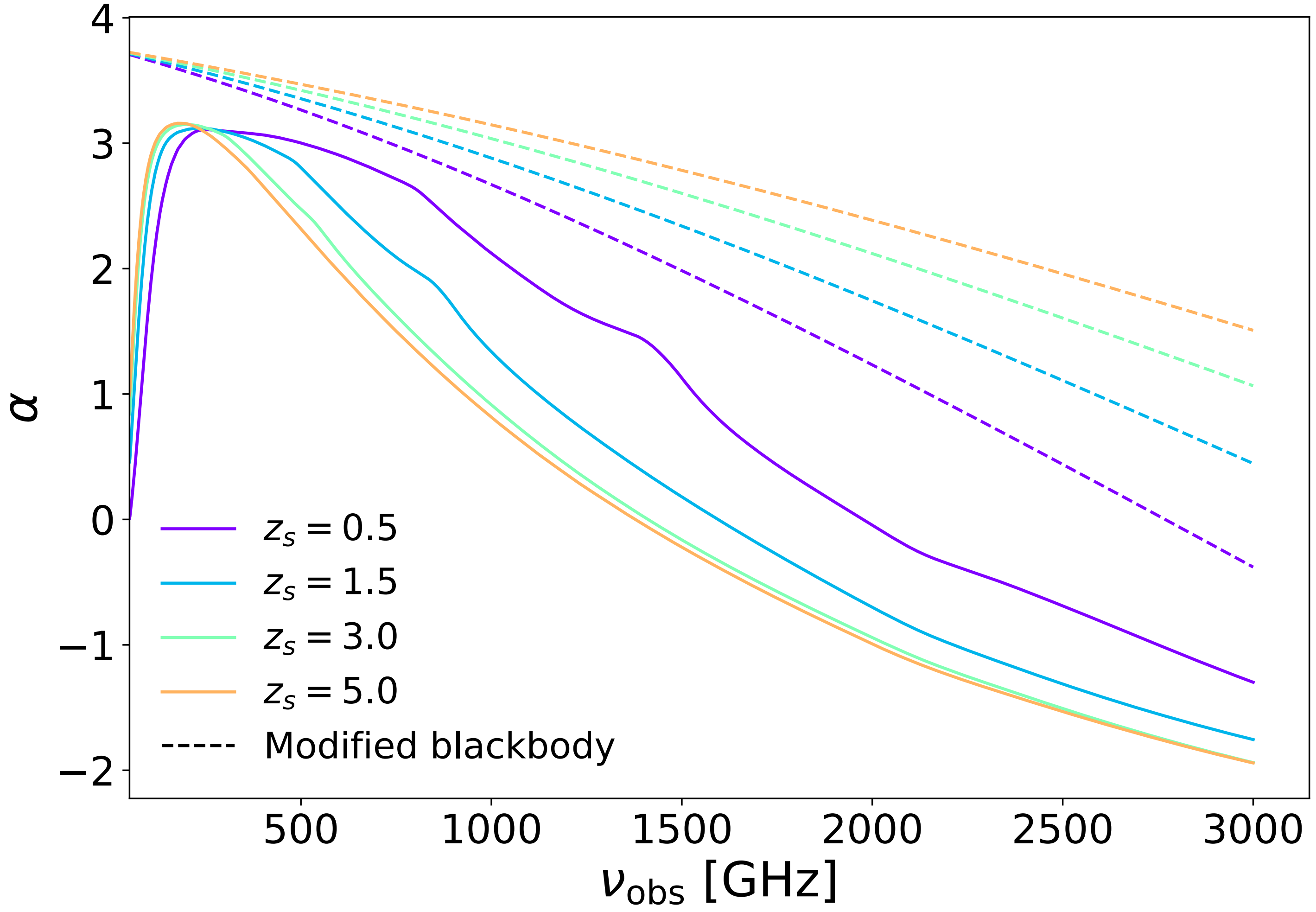
217 GHz 353 GHz 857 GHz

Analogous to kSZ



$$\frac{\Delta I(\nu_0)}{I(\nu_0)} \equiv \frac{I^{\mathrm{obs}}(\nu_0) - I^{\mathrm{obs}}(\nu_0)\,|_{\beta=0}}{I^{\mathrm{obs}}(\nu_0)\,|_{\beta=0}} = \beta\left(3 - \frac{d\ln I^{\mathrm{obs}}(\nu_0)}{d\ln\nu_0}\right) \longrightarrow \alpha$$

Preliminary results!



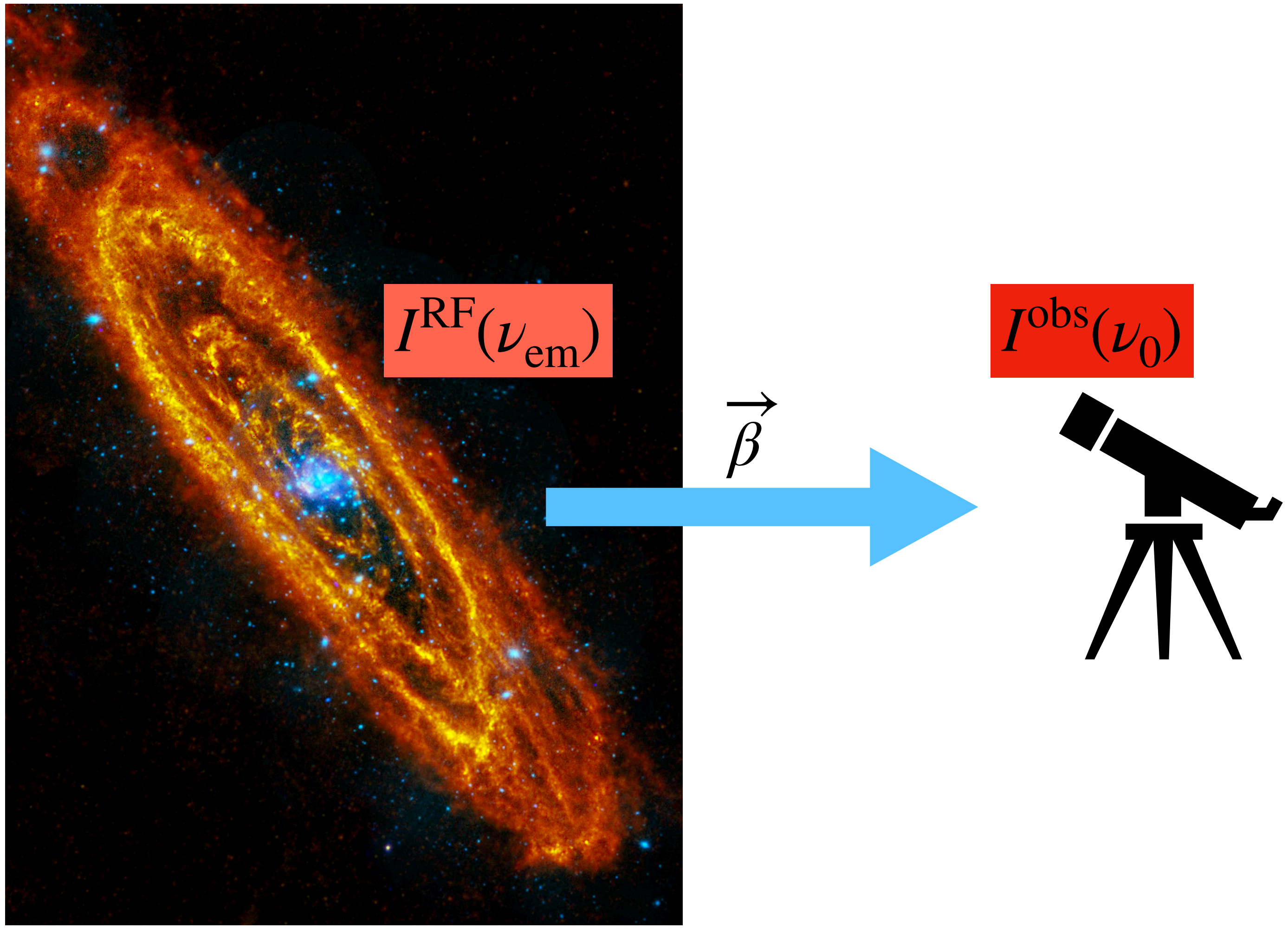
CIB exp	Galaxy exp	SNR
Planck 545 (857) GHz	CMASS	0.05 (0.19)
	DESI-ELG	0.70 (1.78)
	DESI-LRG	0.35 (0.99)
CCAT-Prime 545 (857) GHz	CMASS	1.87 (6.48)
	DESI-ELG	23 (52)
	DESI-LRG	12 (31)

SNR on $C_\ell^{\Delta I_{\nu_0} q_\gamma} \swarrow$

Velocity weighted density field

$$\frac{\Delta I(\nu_0)}{I(\nu_0)} \equiv \frac{I^{\rm obs}(\nu_0) - I^{\rm obs}(\nu_0)\,|_{\beta=0}}{I^{\rm obs}(\nu_0)\,|_{\beta=0}} = \beta\left(3 - \underbrace{\frac{d\ln I^{\rm obs}(\nu_0)}{d\ln \nu_0}}\right) \rightarrow \alpha$$

Signal & foreground!



- Signal:
  - Can estimate β
  - Potential to constrain f_{NL}!
  - kSZ: $\frac{\Delta T}{T} = \alpha\tau\beta$
  - Here: $I(\nu_0)$ calibratable
- As foreground: contaminant to kSZ!

$$\frac{\Delta I(\nu_0)}{I(\nu_0)} \equiv \frac{I^{\rm obs}(\nu_0) - I^{\rm obs}(\nu_0)\,|_{\beta=0}}{I^{\rm obs}(\nu_0)\,|_{\beta=0}} = \beta\left(3 - \frac{d\ln I^{\rm obs}(\nu_0)}{d\ln\nu_0}\right) \longrightarrow \alpha$$

Thank you!

Non-Gaussian biases

$$\langle\hat{\kappa}_{XX}(\boldsymbol{L})\hat{\kappa}_{XX}(\boldsymbol{L}')\rangle = C_L^{\hat{\kappa}_{XX}} + N_L^{\hat{\kappa}_{XX}} \qquad X = [\mathrm{CII}], \mathrm{Ly}{-}\alpha, ...$$

$$\langle X(\boldsymbol{l}_1)X(\boldsymbol{l}_2)X(\boldsymbol{l}_3)X(\boldsymbol{l}_4)\rangle \longrightarrow X(\boldsymbol{l}_1) = t(\boldsymbol{l}_1) + g(\boldsymbol{l}_1)$$

Non-Gaussian Biases!

Target line

Interlopers

Target signal $\langle\kappa\kappa\rangle$	$\big\langle\big(t(\boldsymbol{l}_1)t(\boldsymbol{l}_2)\big)\big(t(\boldsymbol{l}_3)t(\boldsymbol{l}_4)\big)\big\rangle_c$
Primary bispectrum $\mathcal{B}^{\kappa gg}$	$\big\langle\big(t(\boldsymbol{l}_1)t(\boldsymbol{l}_2)\big)\big(g(\boldsymbol{l}_3)g(\boldsymbol{l}_4)\big)\big\rangle_c + \big\langle\big(g(\boldsymbol{l}_1)g(\boldsymbol{l}_2)\big)\big(t(\boldsymbol{l}_3)t(\boldsymbol{l}_4)\big)\big\rangle_c$
Secondary bispectrum $\mathcal{B}^{\kappa gg}$	$\big\langle\big(t(\boldsymbol{l}_1)g(\boldsymbol{l}_2)\big)\big(t(\boldsymbol{l}_3)g(\boldsymbol{l}_4)\big)\big\rangle_c$ + 3 permutations
Trispectrum $\mathcal{T}^{gggg}$	$\big\langle\big(g(\boldsymbol{l}_1)g(\boldsymbol{l}_2)\big)\big(g(\boldsymbol{l}_3)g(\boldsymbol{l}_4)\big)\big\rangle_c$

Nulling!

$$W_\kappa(\chi,\chi_S) = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \frac{\Omega_m^0}{a}\,\chi\left(1-\frac{\chi}{\chi_S}\right) \longrightarrow$$ 2nd order polynomial in χ

$$W_\kappa(\chi,\chi_3)+\alpha W_\kappa(\chi,\chi_2)-(1+\alpha)W_\kappa(\chi,\chi_1) \rightarrow \alpha = \frac{1/\chi_3 - 1/\chi_1}{1/\chi_1 - 1/\chi_2} \rightarrow \chi_1 < \chi_2 < \chi_3$$

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