Upgrading the CMB foreground and lensing analysis: improved halo models and a global minimum variance quadratic estimator

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😊 Virtual ☹️

CIB, tSZ, CIB x tSZ

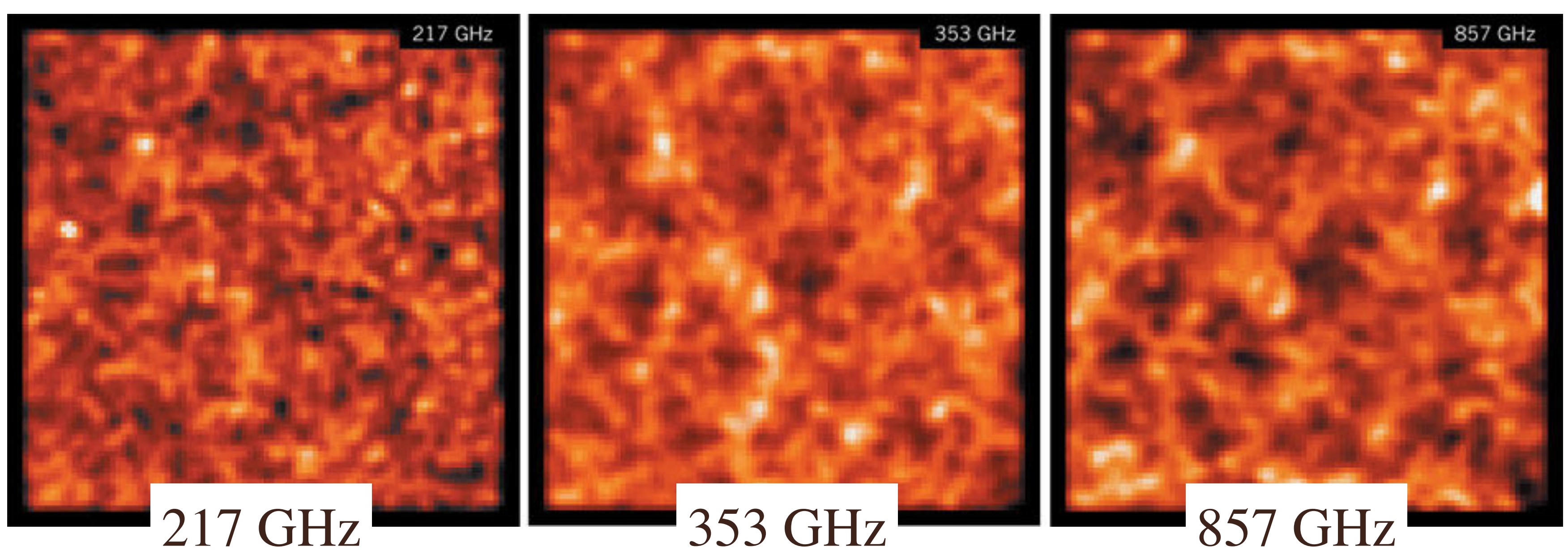
CIB Clustering on linear scales: a signal

Maniyar, Béthermin, Lagache A&A, 2018

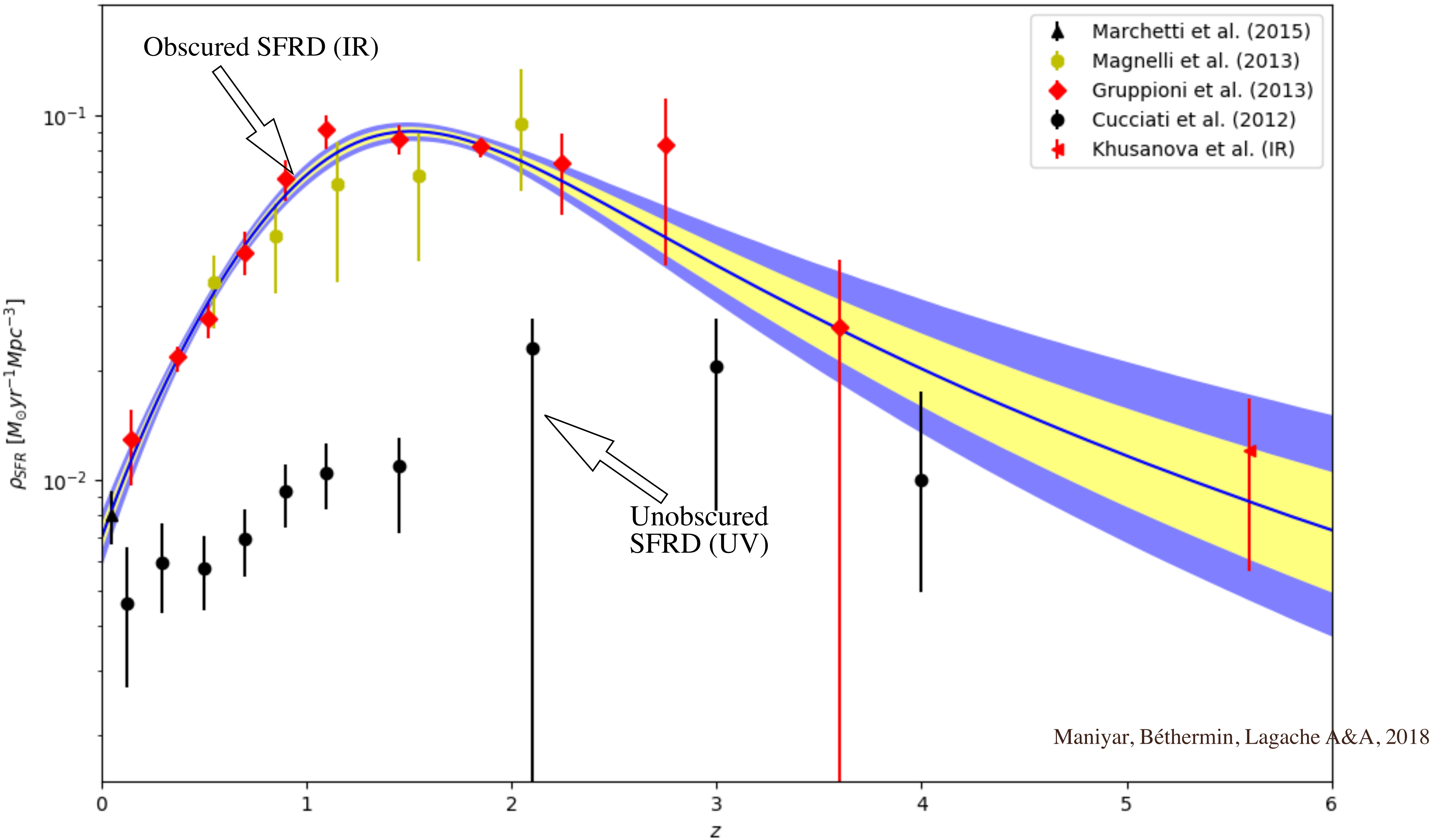
Cosmic Infrared Background (CIB)

- 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**

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

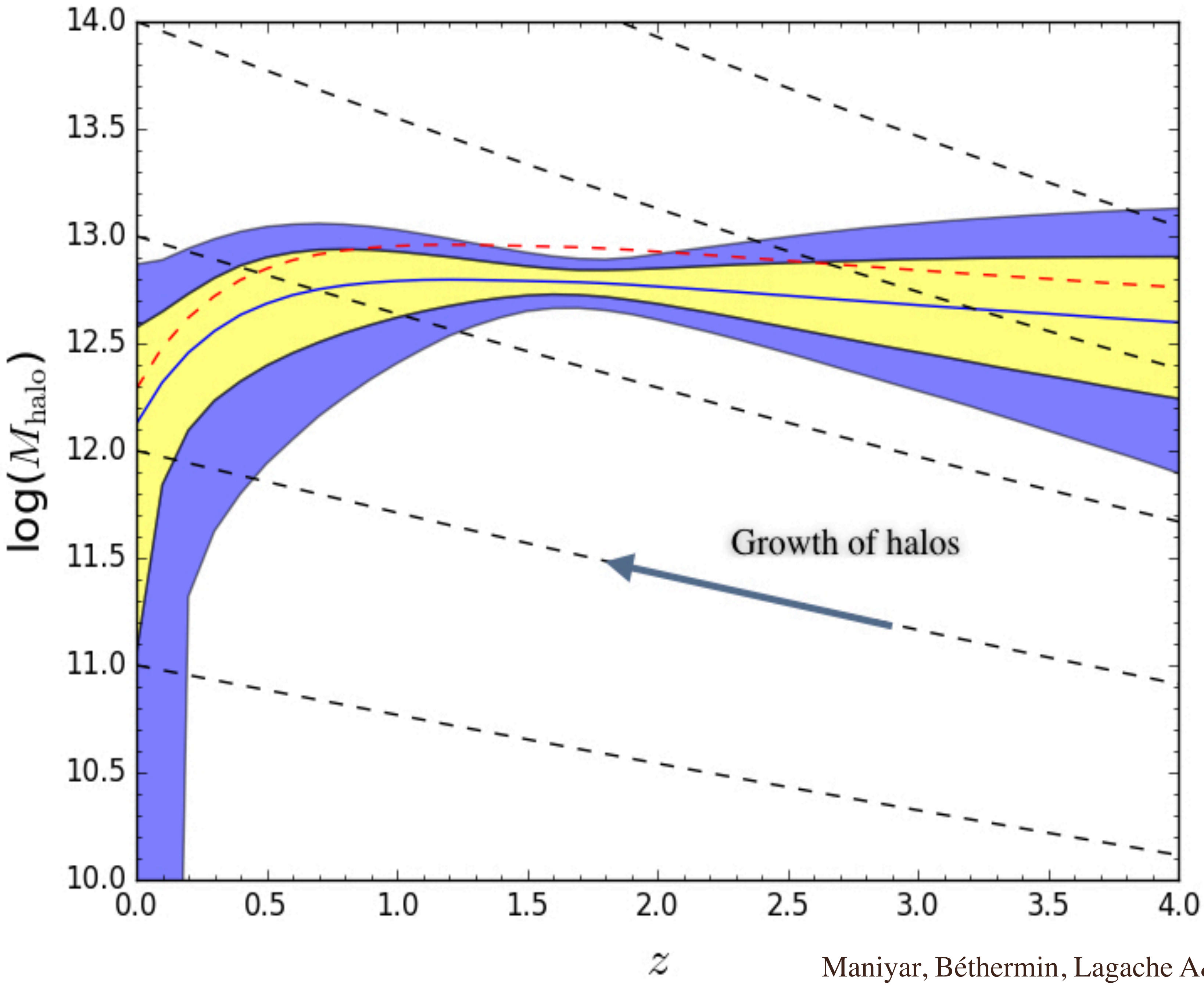


Star formation rate density history



Dark matter halo mass for the CIB emitters

$$b_{\text{eff}}(M_h, z) \Rightarrow M_h(b_{\text{eff}}, z)$$



Maniyar, Béthermin, Lagache A&A, 2018

For z > 2.5

$M_h(z=0) > 10^{13.5} M_\odot$

Progenitors of clusters

For 0.3 < z < 2.5

$10^{12.5} < M_h(z=0) < 10^{13.5} M_\odot$

Groups

For z < 0.3

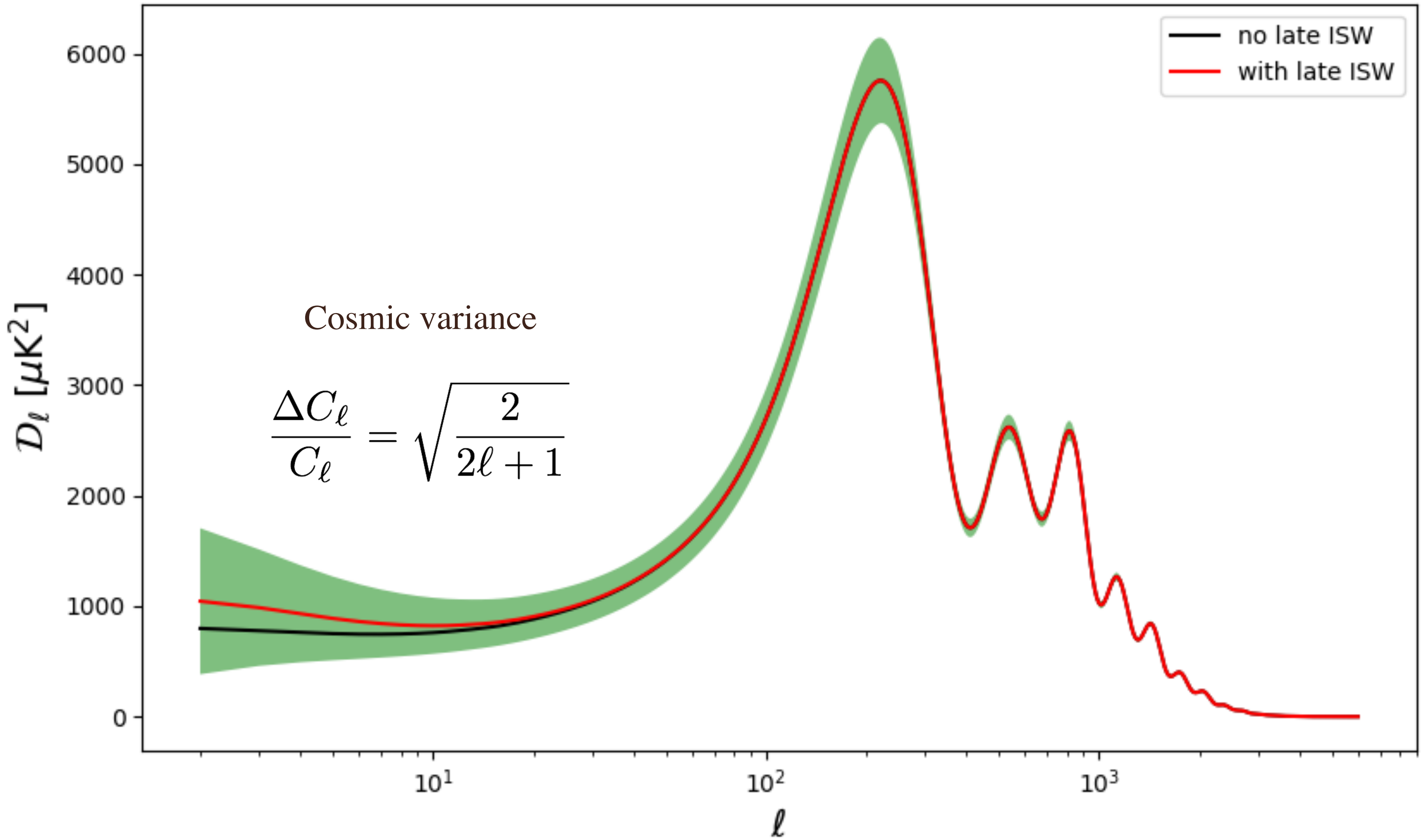
$10^{12} < M_h(z=0) < 10^{12.5} M_\odot$

Milky Way like halos

ISW (dark energy) through CIB-CMB cross-correlation

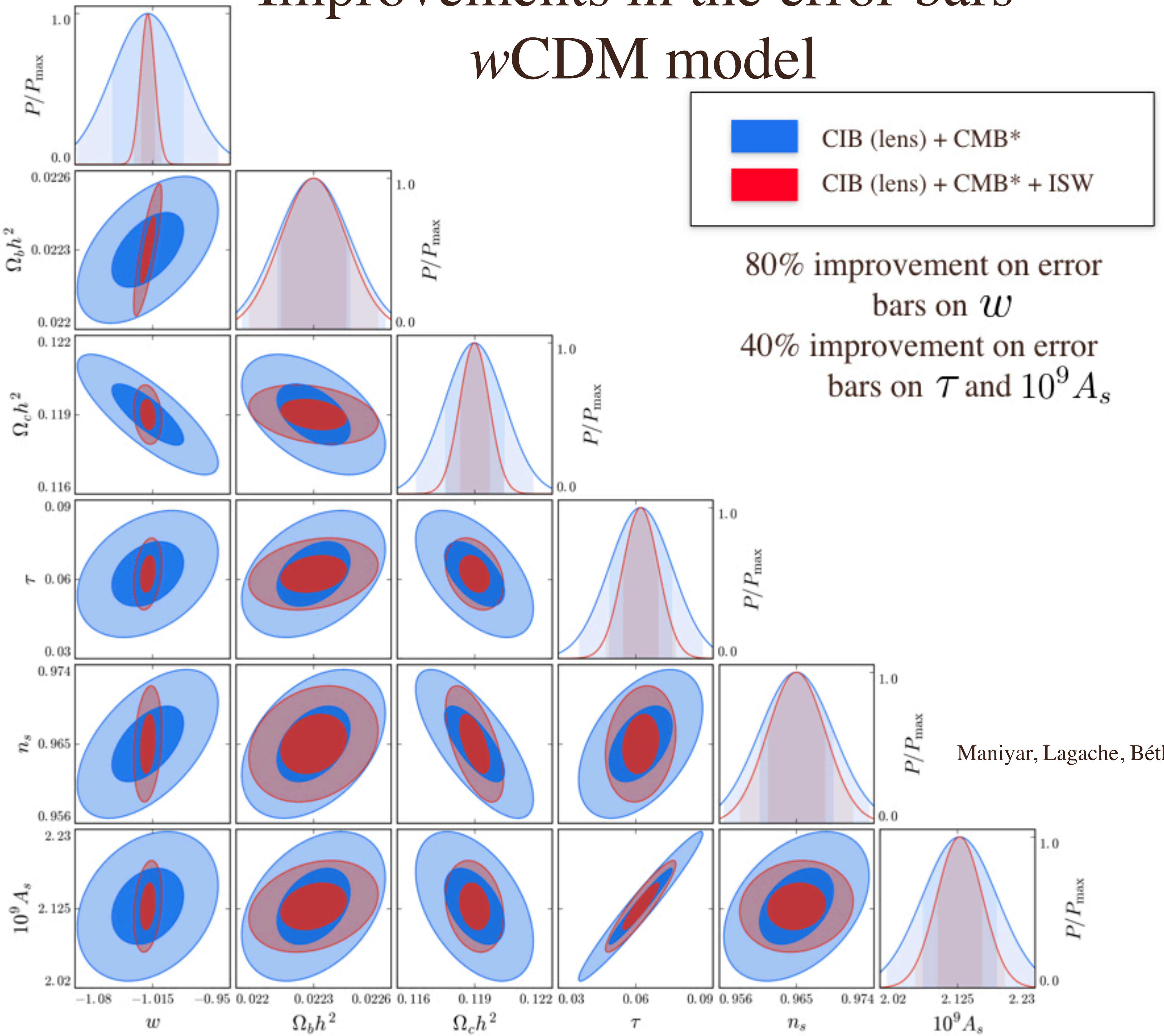
Maniyar, Lagache, Béthermin A&A, 2019

ISW in the CMB power spectrum



- Integrated Sachs-Wolfe effect Really small!
- Cross-Correlation with LSS tracers
- SNR going up to 4

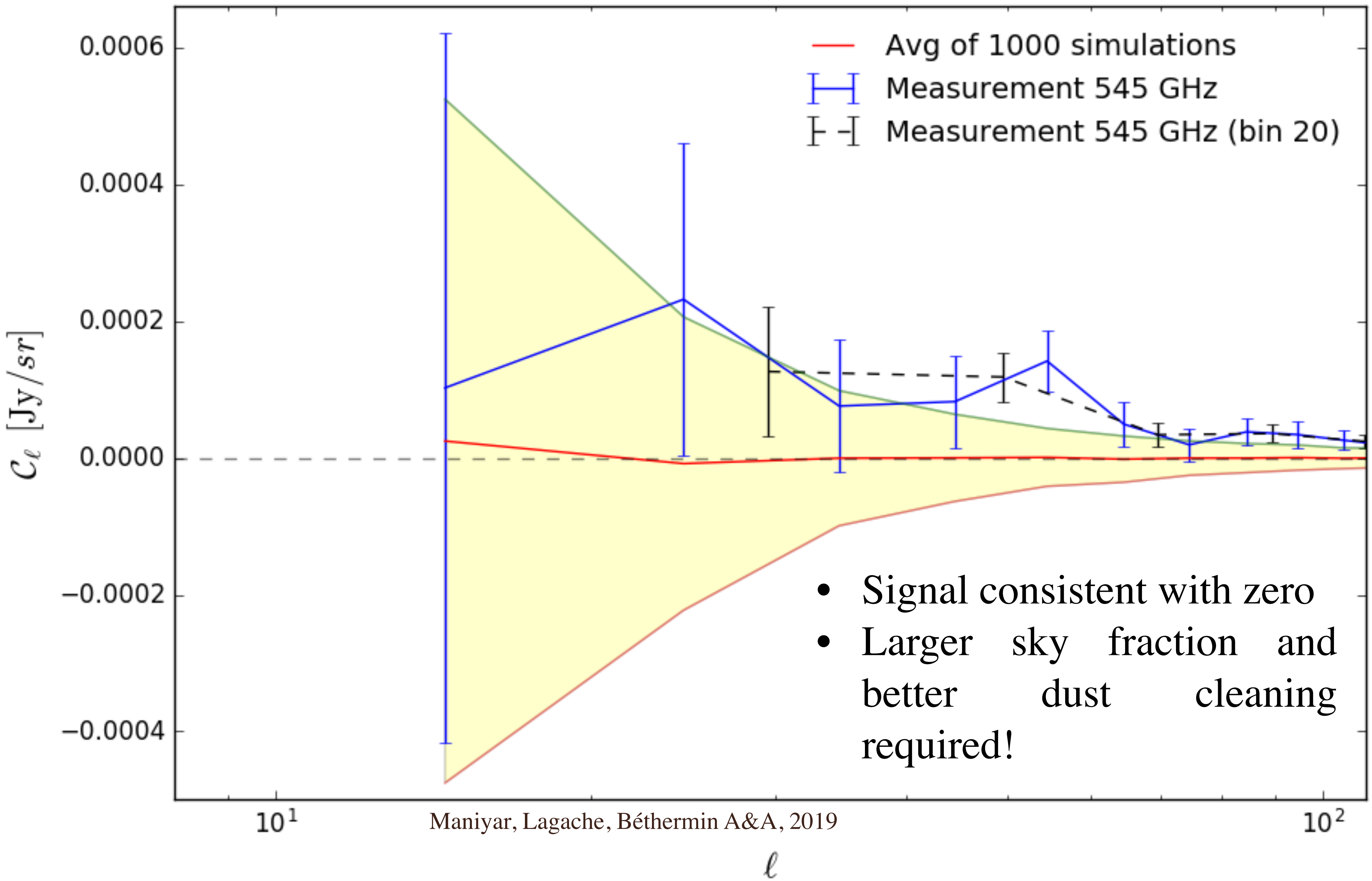
Improvements in the error bars
*w*CDM model



80% improvement on error bars on w
40% improvement on error bars on τ and $10^9 A_s$

Maniyar, Lagache, Béthermin A&A, 2019

Real CIB & CMB maps: Null test



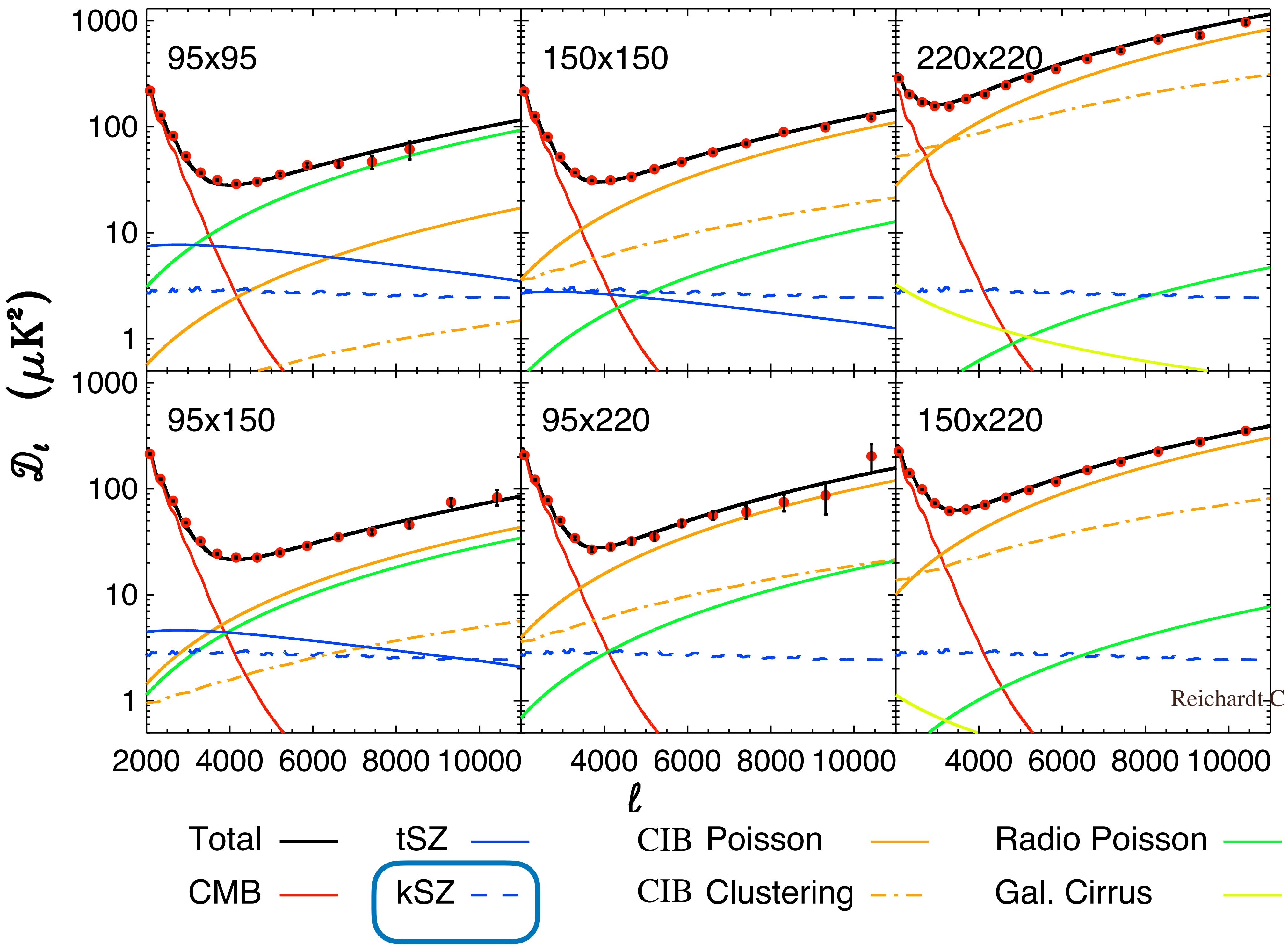
- Signal consistent with zero
- Larger sky fraction and better dust cleaning required!

Maniyar, Lagache, Béthermin A&A, 2019

On large scales, CIB and CMB combination: a cosmological signal
What about small scales?

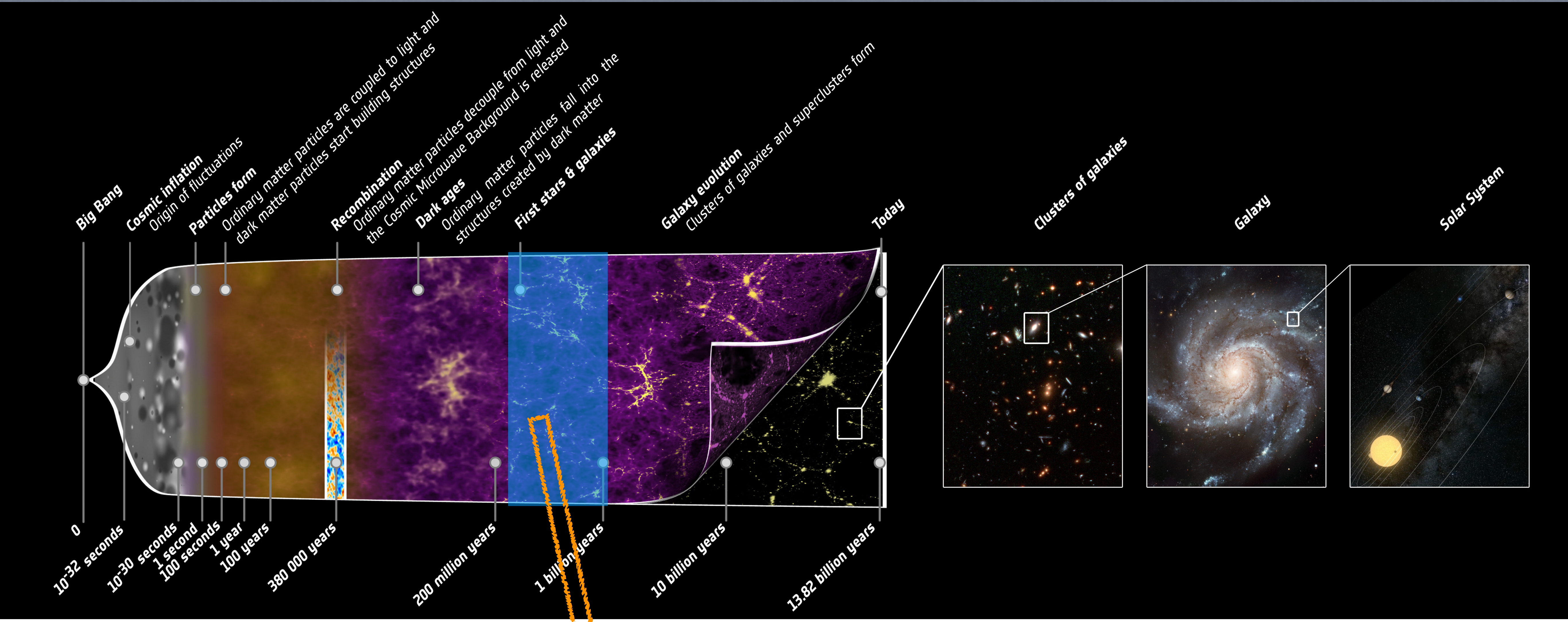
It’s complicated!

CMB power spectrum on small scales: very complicated indeed!



Reichardt C. L. et al 2021

Why kSZ? => A reionization probe!



kSZ → Homogeneous

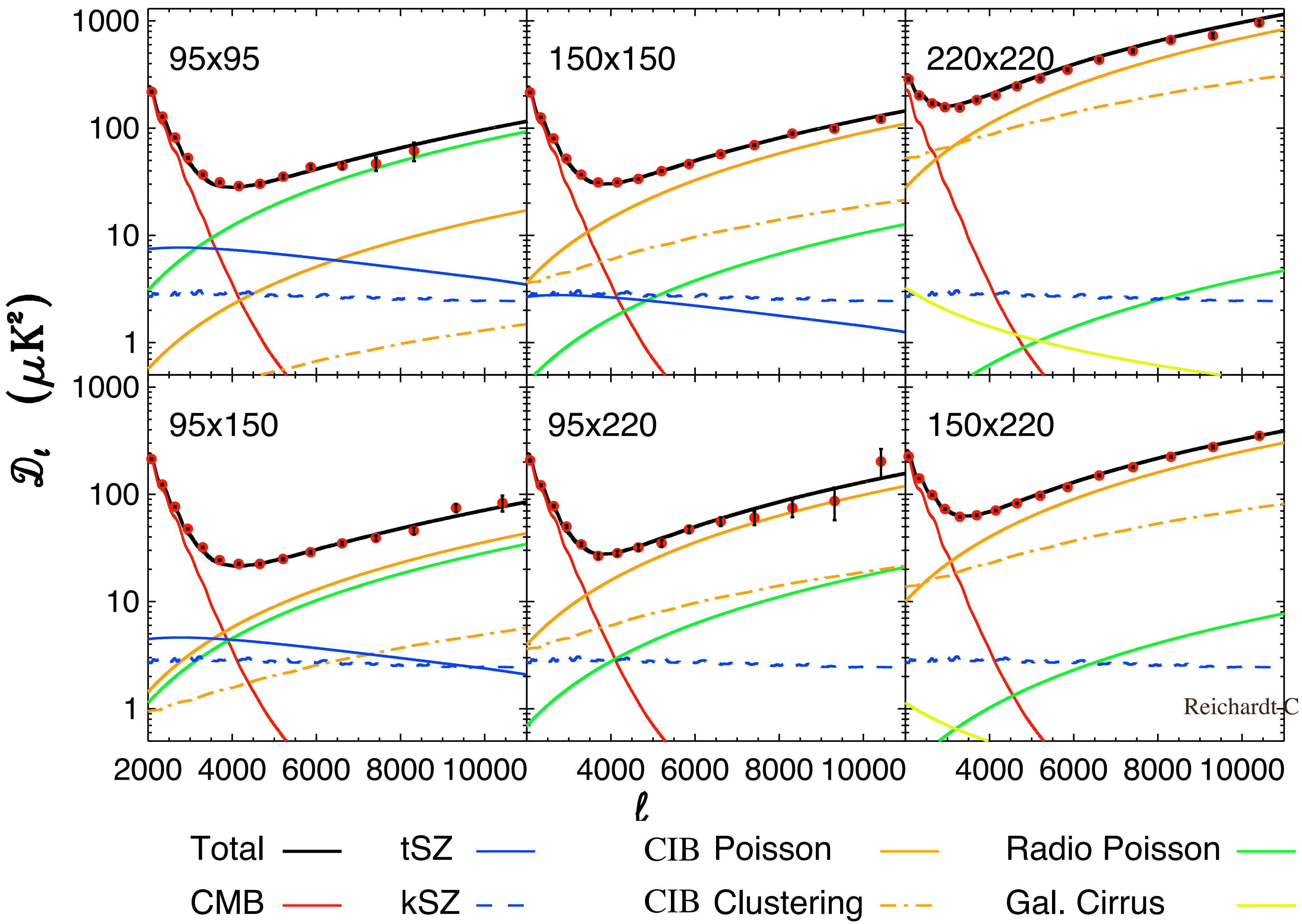
kSZ → Patchy → Reionization → Measuring the kSZ power spectrum

- When did the reionization happen?
- How long did it last?

Measuring the kSZ power spectrum from the CMB data

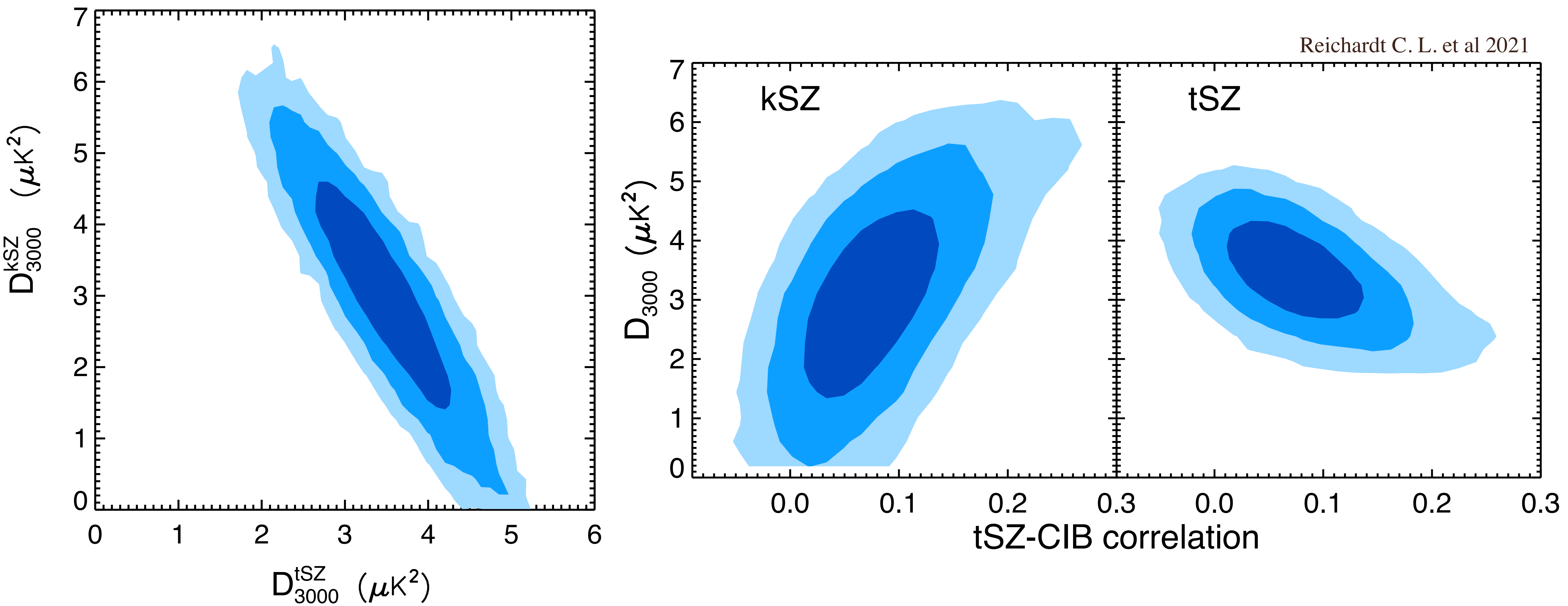
In collaboration with: Matthieu Tristram, Guilaine Lagache, Xavier Garrido

kSZ and the foregrounds in the CMB power spectrum: challenging!



Reichardt C. L. et al 2021

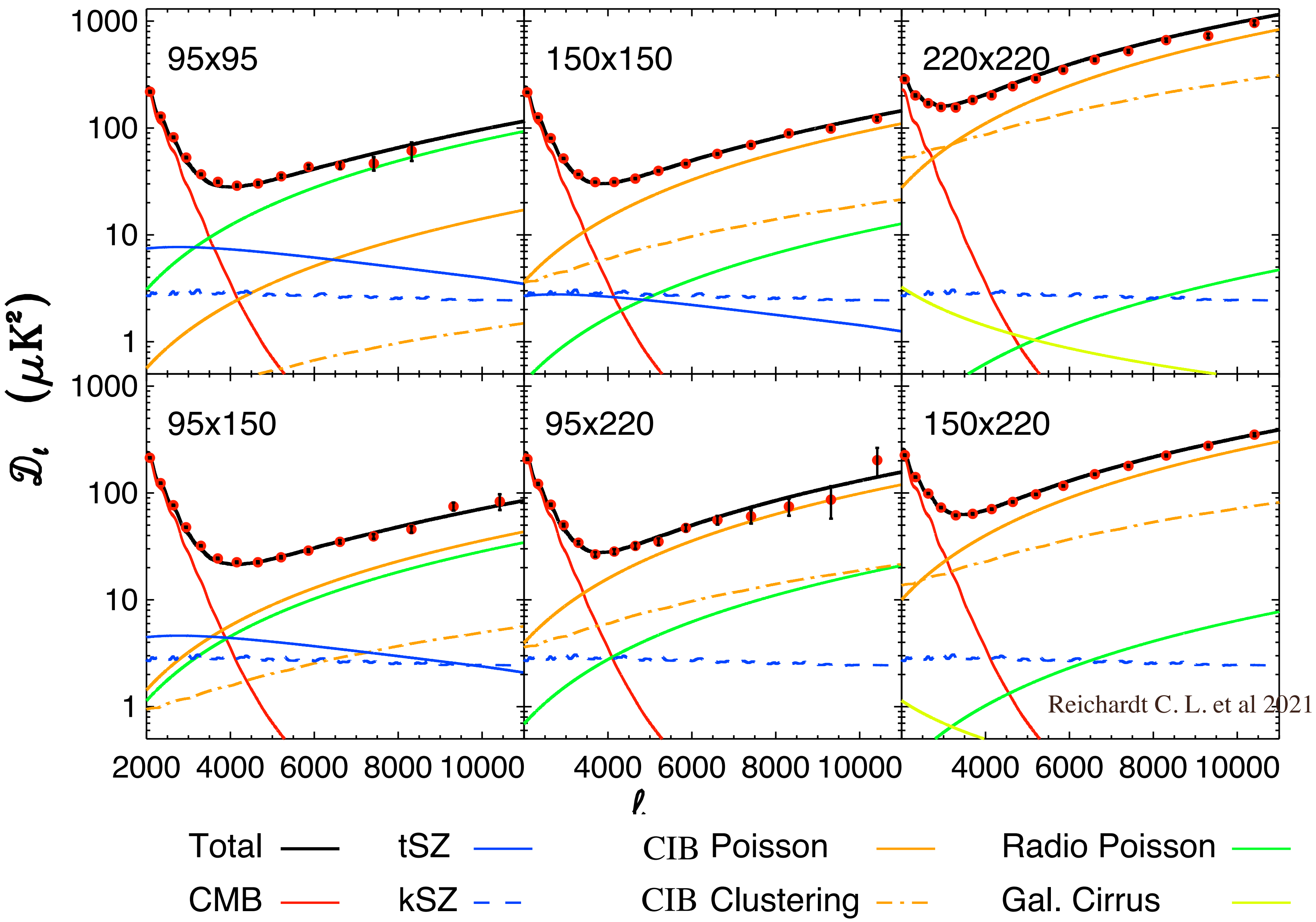
kSZ and the foregrounds correlations



Data quality getting better and better (SO, CMB Stage-4)!

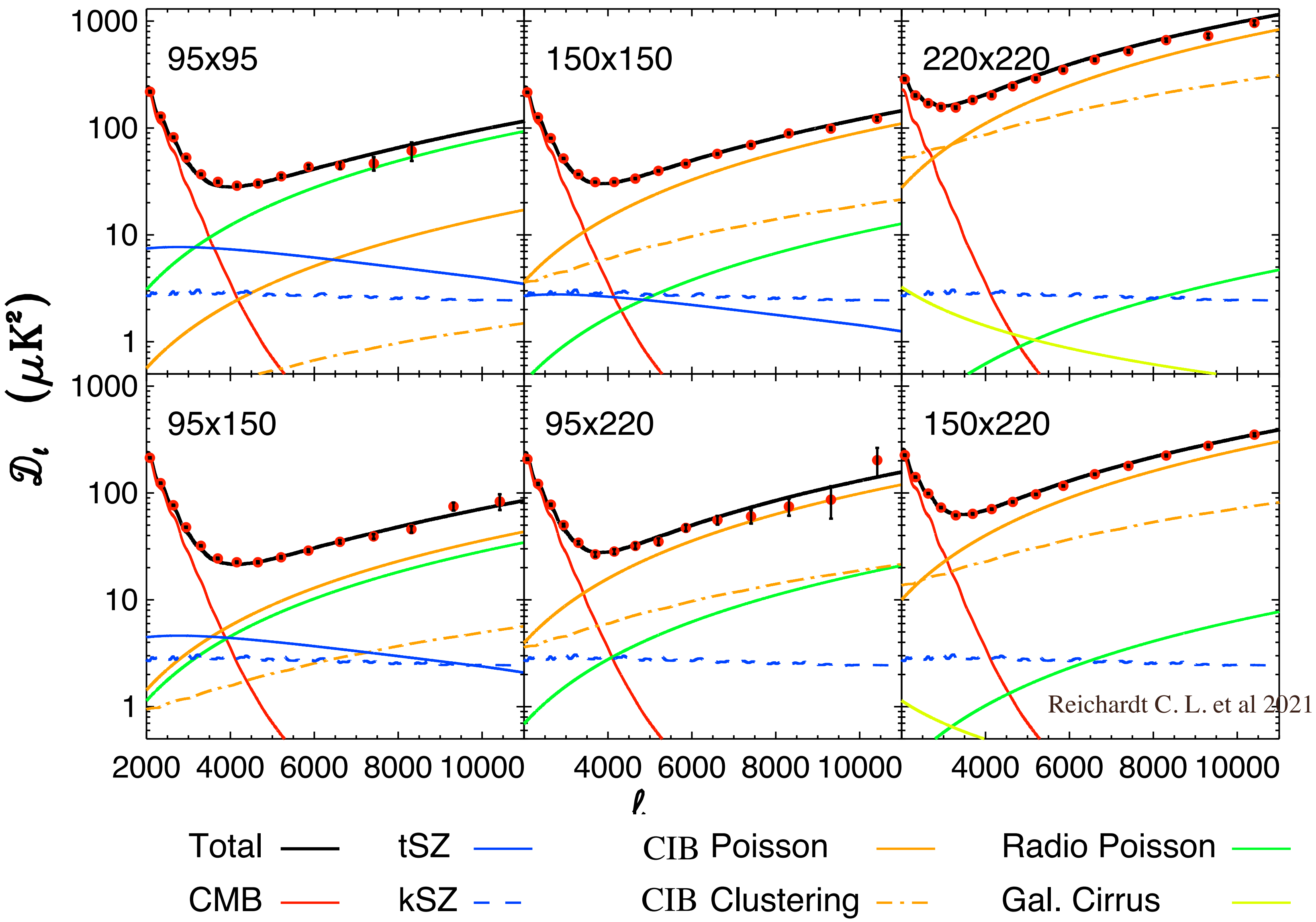
=> Need precise and reliable models!

Current approach and limitations



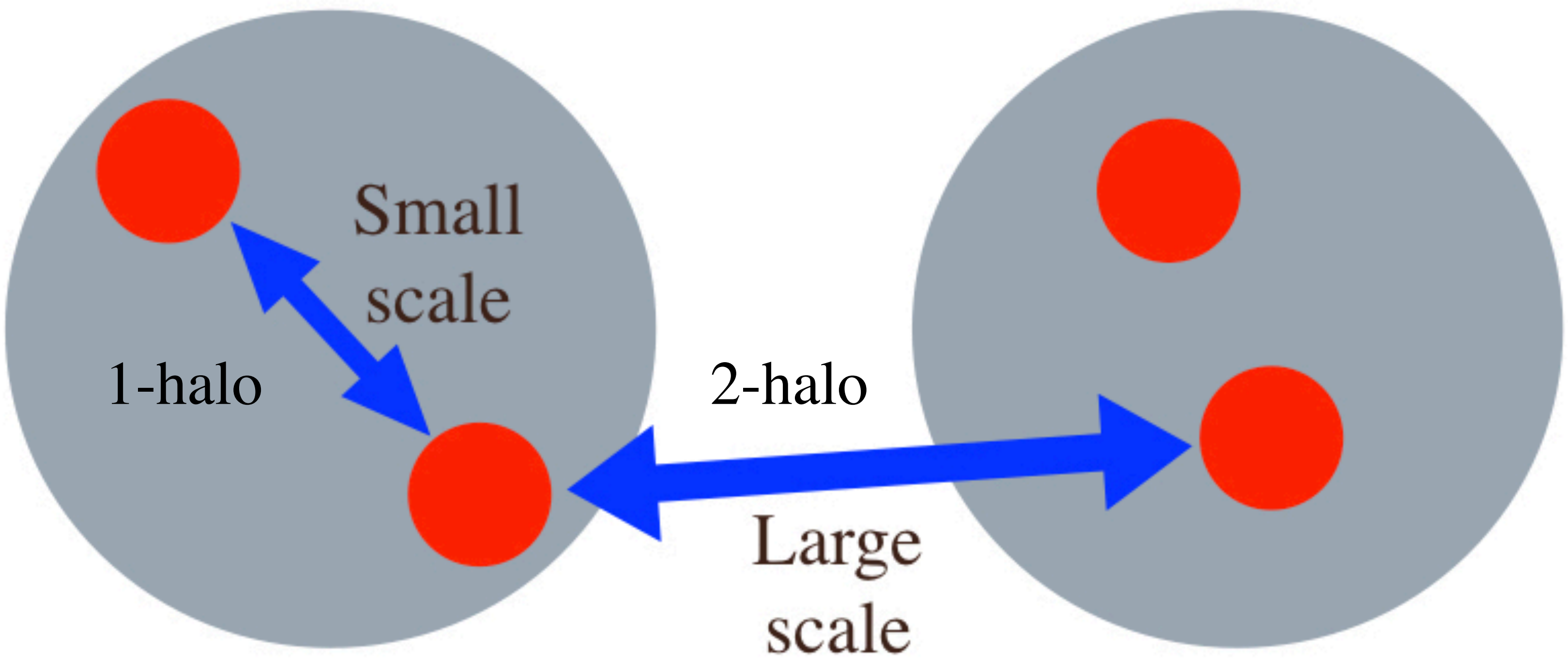
- Power law/best fit templates for the CIB, tSZ, and CIB x tSZ
- Different frequency channels assumed to be perfectly correlated for the CIB
- Inconsistencies between the CIB, tSZ and CIB x tSZ templates
- Cosmology dependance

What we need



- Physically motivated halo model for the CIB and tSZ
- Consistent halo model for CIB-tSZ correlation
- Cosmology dependance explicitly considered
- Combining different frequency data (Planck, SPT, and ACT; Herschel, Planck HFI)

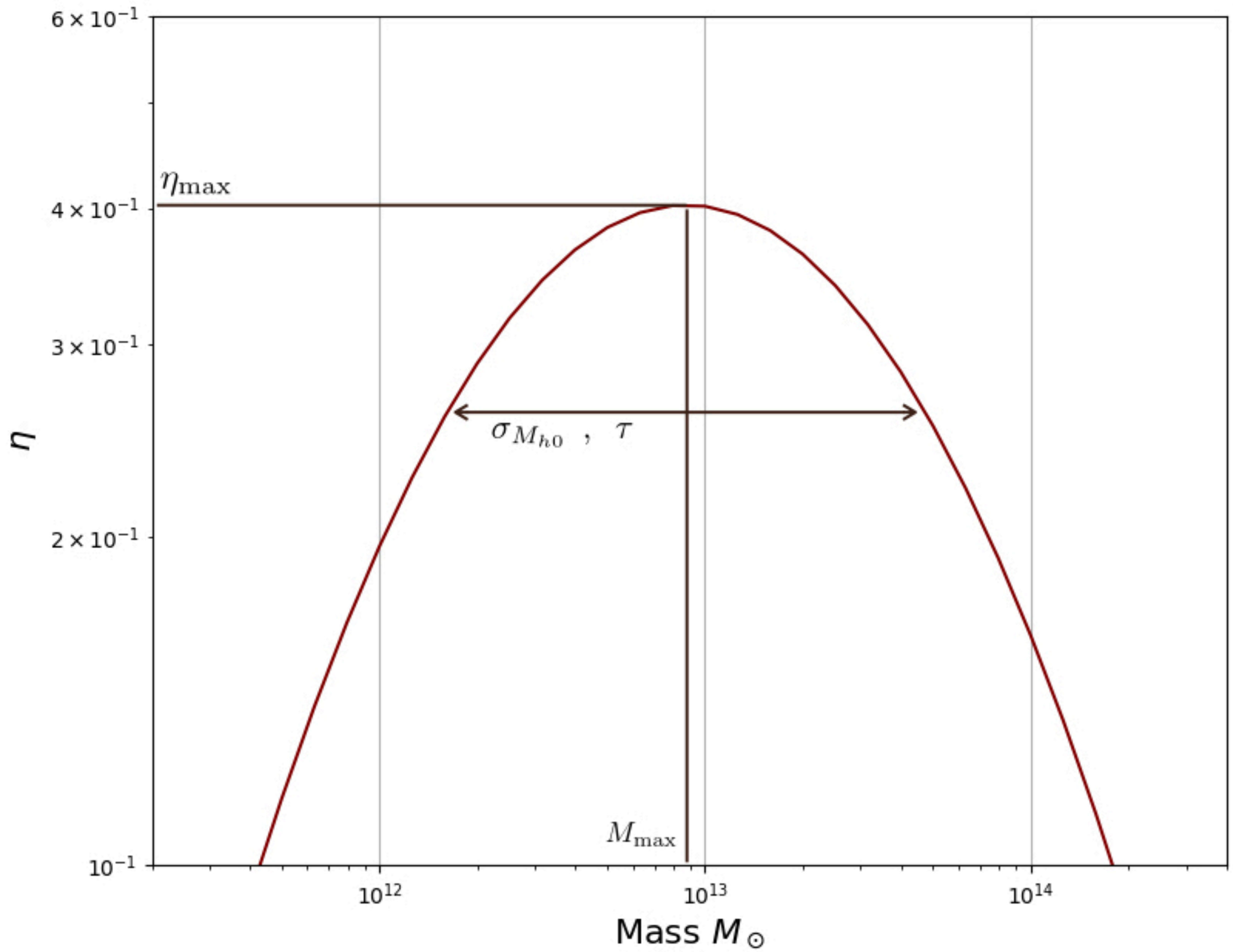
Halo model required



Previous halo models

- L-M relation (Shang et al 2012)
- High number of parameters
- Results not consistent with data => SFRD

Accretion on the dark matter halos to SFR



Baryonic Accretion Rate

$$\mathrm{BAR}(M,z) = \langle \dot{M}_h(M,z)\rangle \times \Omega_b(z)/\Omega_m(z)$$

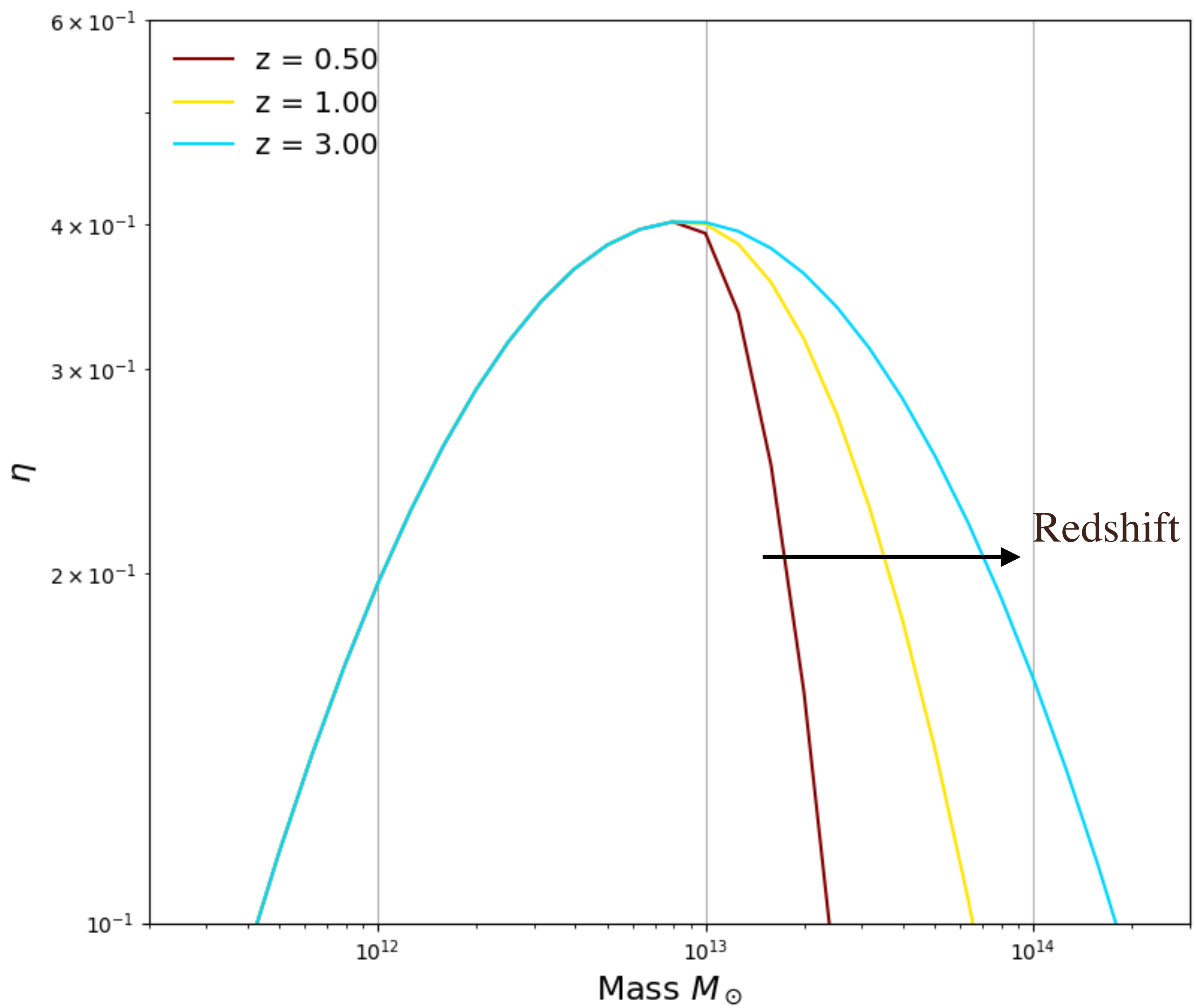
Efficiency to convert accreted baryons into stars

$$\frac{\mathrm{SFR}}{\mathrm{BAR}} = \eta = \eta_{\max}\, e^{-\frac{(\log M_h - \log M_{\max})^2}{2\sigma^2_{M_h}}}$$

Calculating SFR

$$\mathrm{SFR}(M_h,z) = \eta(M_h,z) \times \mathrm{BAR}(M_h,z)$$

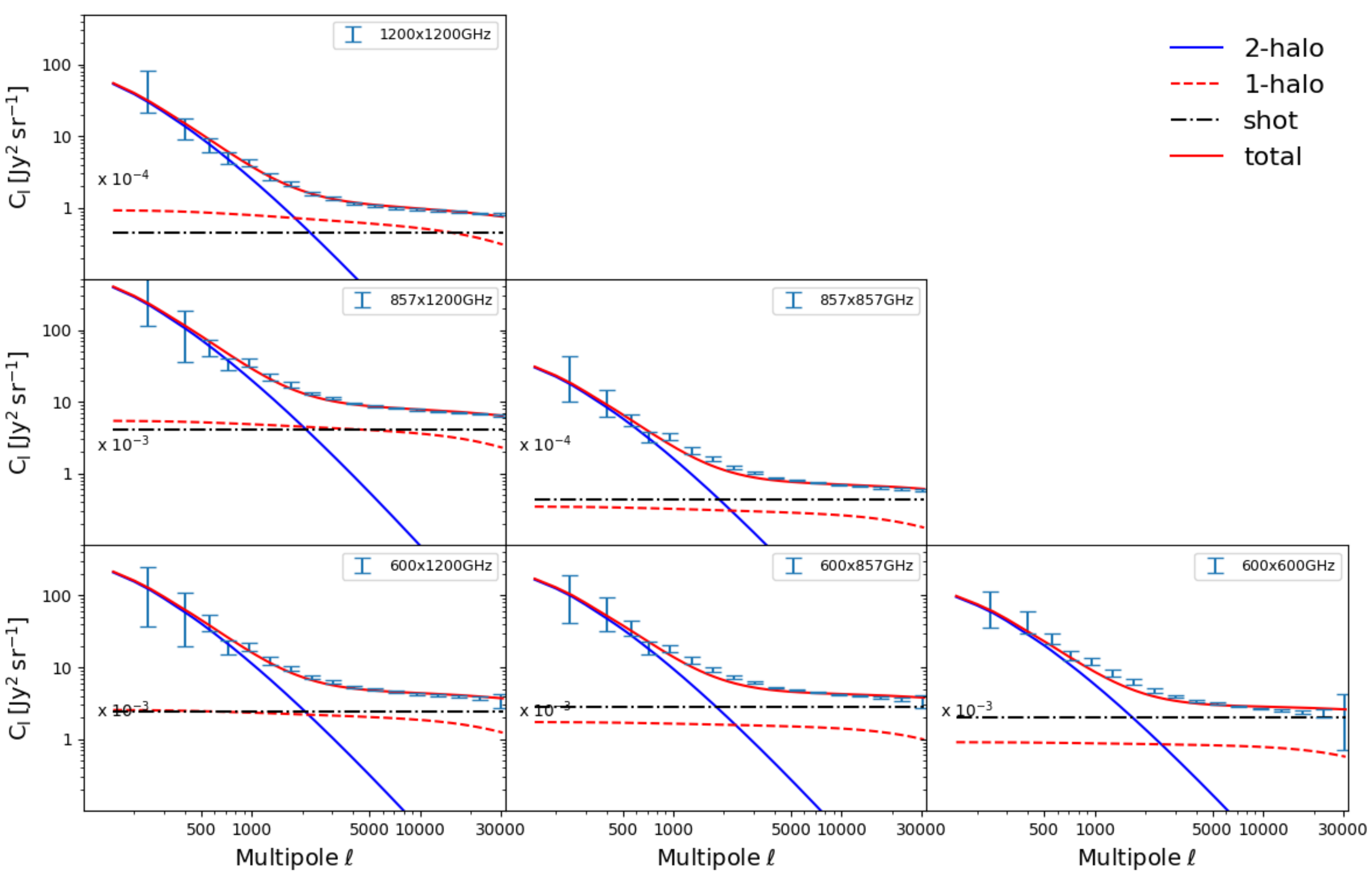
Accretion on the dark matter halos to SFR

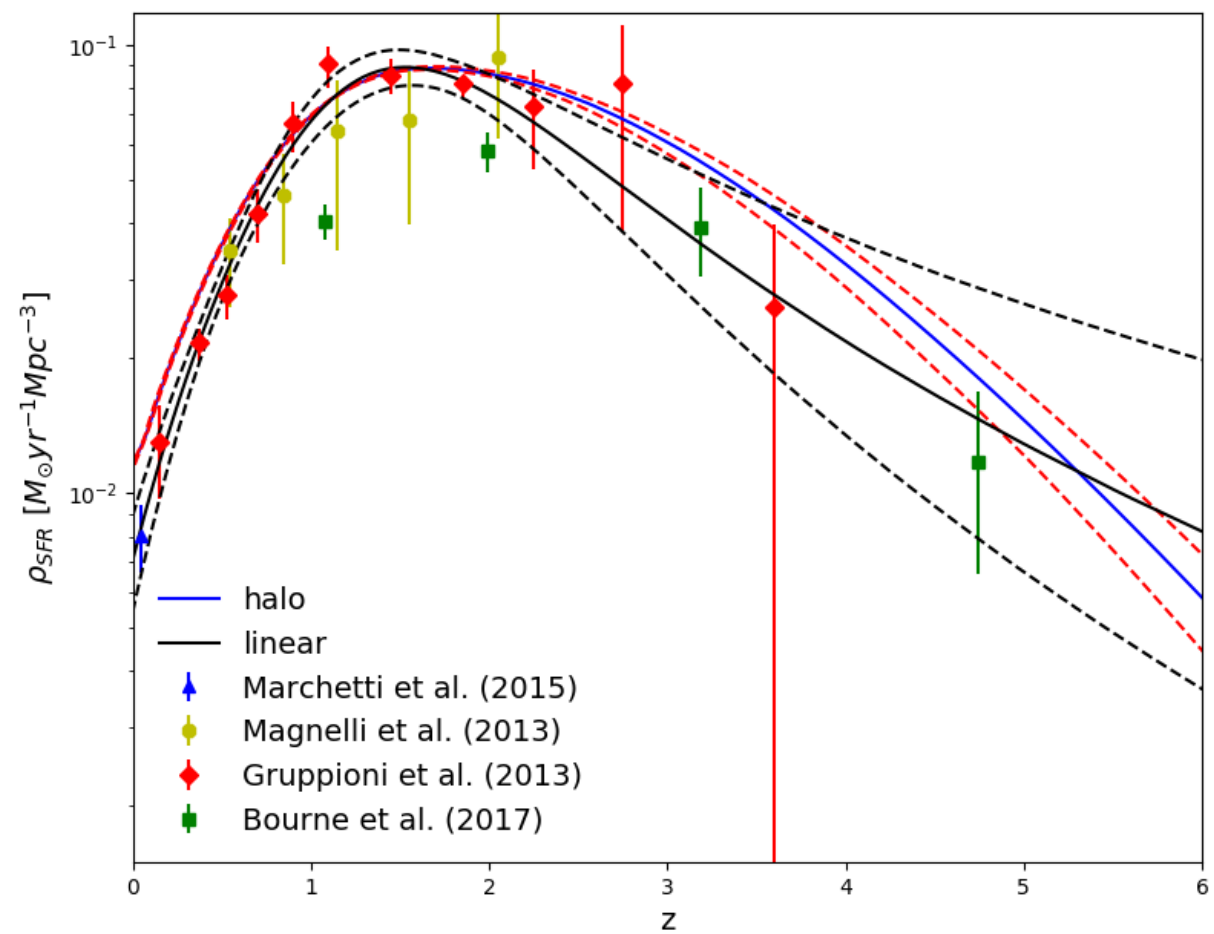


SFR => $\frac{dj_\nu}{d\log M}(M,z)$ => $C_\ell^{\nu,\nu'}$

- Evolution in width of the lognormal up to a redshift
- Massive halos at lower redshift inefficient star formation (e.g. Popesso et al. 2015)
- Massive halos at high redshift can have efficient star formation (e.g. Miller et al. 2018)

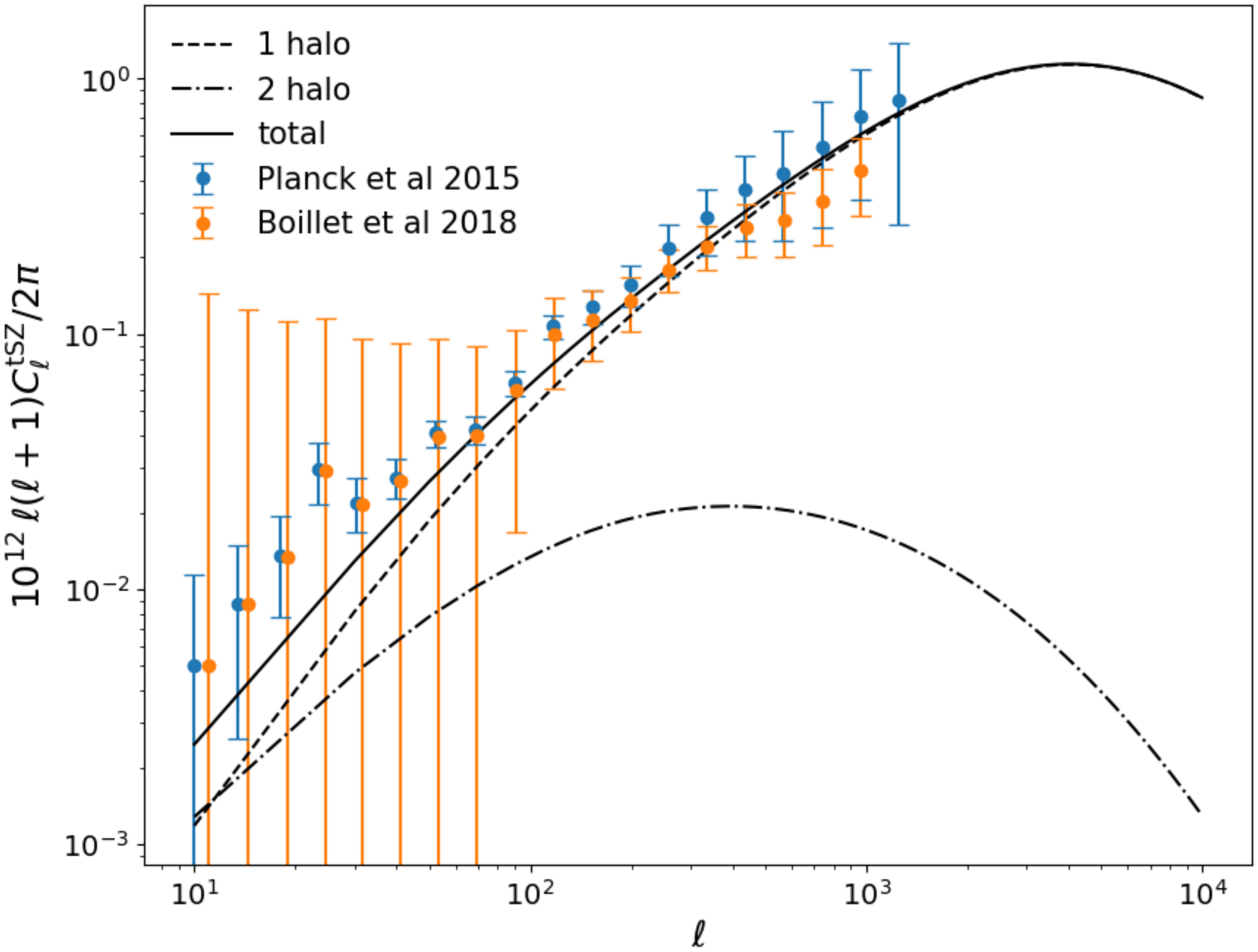
Fitting both Planck and Herschel data & consistent with data for SFRD





Maniyar, Lagache, Béthermin, A&A, 2021

tSZ halo model (both 1-halo and 2-halo terms)



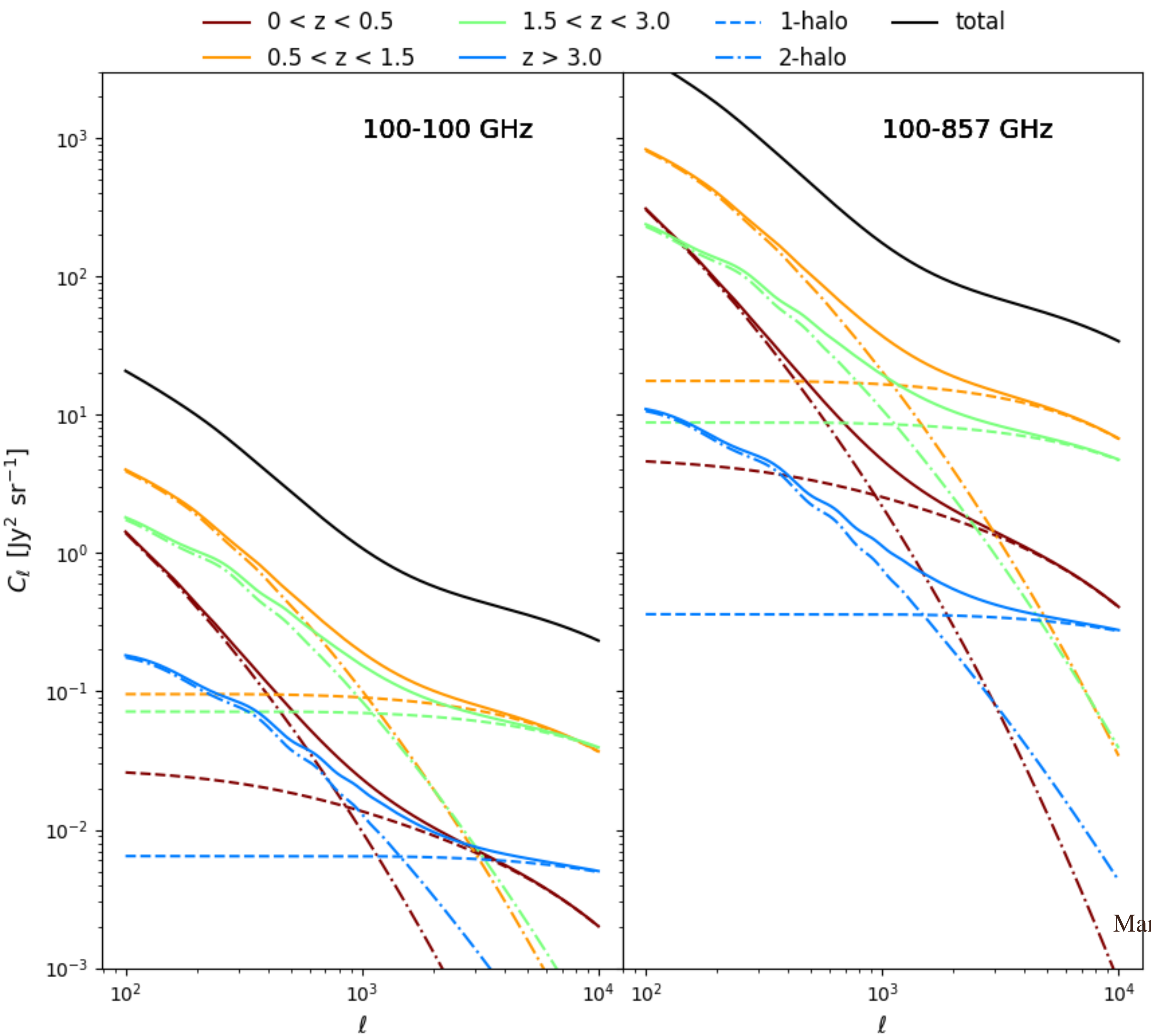
$$\tilde{M}_{500_c} = M_{500_c}/B$$

Mass bias parameter

CIB x tSZ correlation

- CIB => tracing the large scale structure
- tSZ => hot electrons in the galaxy clusters => large scale structure
- CIB galaxies residing in the clusters contributing to the tSZ => one halo term
- Overlap in the redshift distribution of the CIB and the tSZ => two halo term

Redshift distribution: CIB x tSZ power spectra



- tSZ: low redshift
- CIB: low frequency => high redshift => contribution from lowest and highest redshift bin almost similar
- CIB-tSZ: 2-halo non-negligible

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Our approach

- ✓ Physically motivated halo model for the CIB and tSZ
- ✓ Consistent halo model for CIB-tSZ correlation
- ✓ High-*l* Likelihood on Polarized Power spectra (HiLLiPOP) likelihood
- ✓ Combining different frequency data (Planck, SPT, and ACT for the CMB; Herschel/Spire, Planck/HFI for the CIB)
- ✓ COBAYA toolbox for MCMC
    - ✓ Replacing old templates for foregrounds with halo models
    - ✓ Cosmology dependance of all the foregrounds explicitly considered at every step
    - ◉ Integrating SPT likelihood

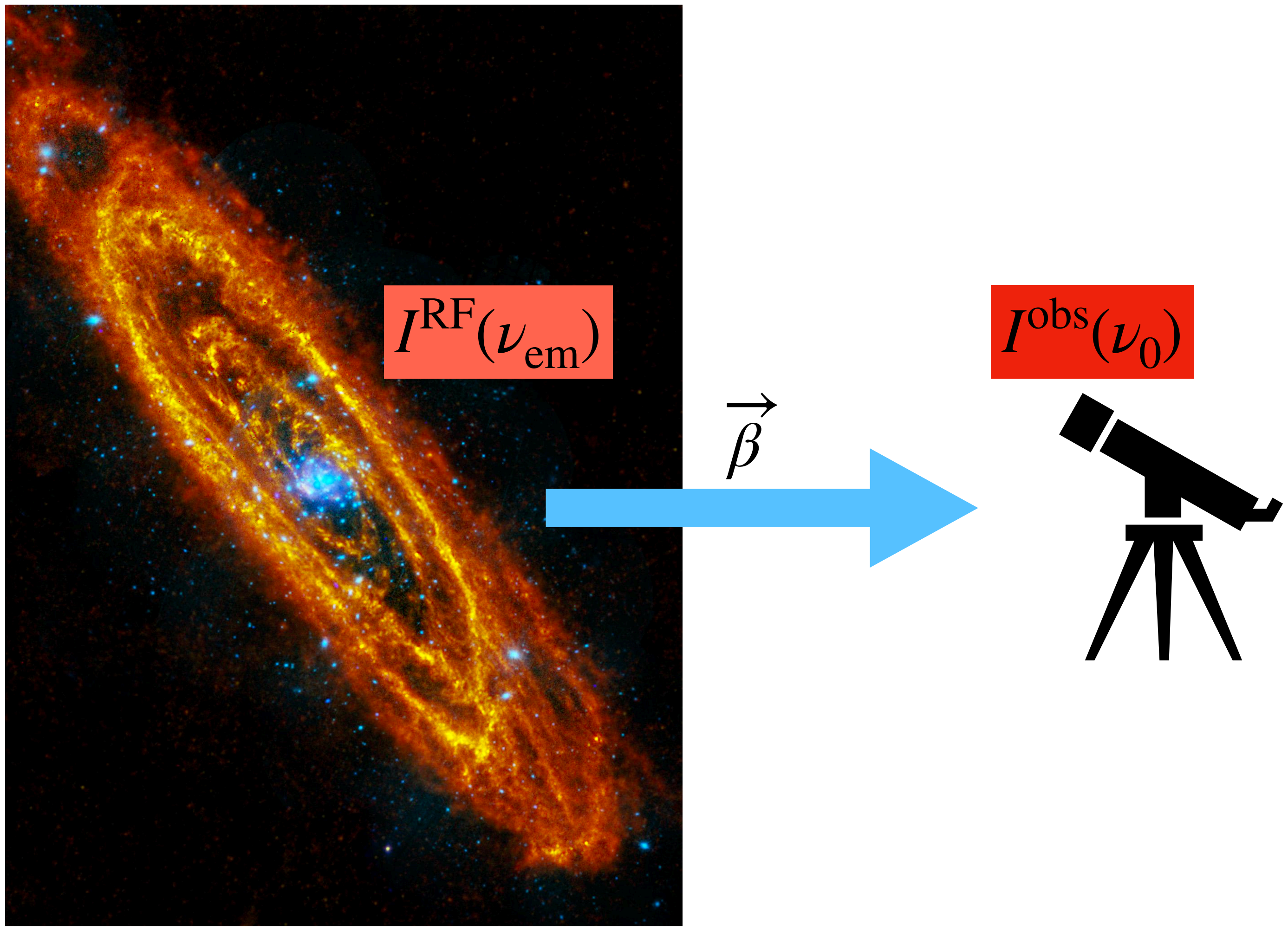
Next steps

- Combined MCMC with Planck, ACT, SPT, Herschel data
- kSZ power spectrum
- Reionisation constraints

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

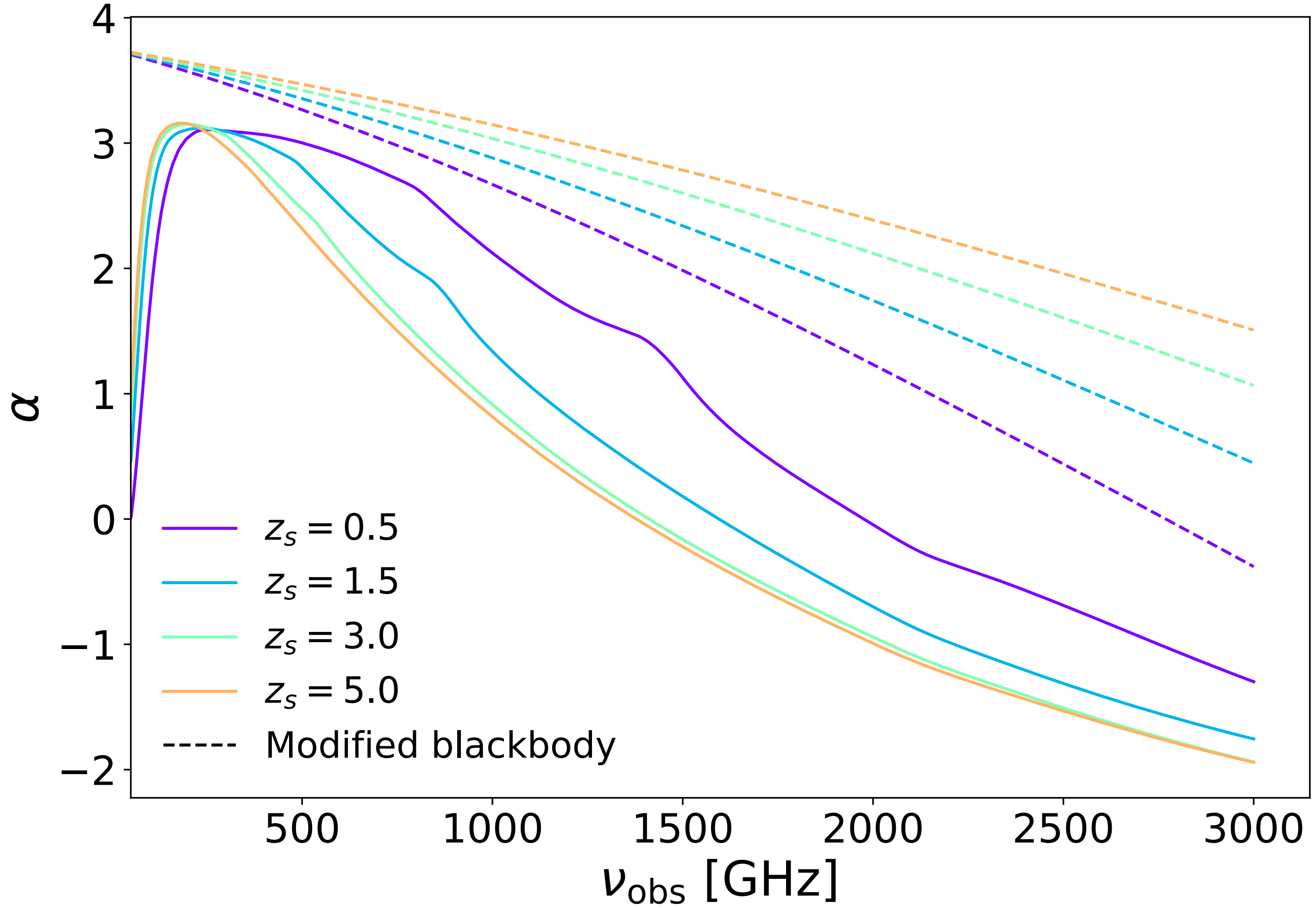
In collaboration with: Emmanuel Schaan & Simone Ferraro

Analogous to kSZ



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

Preliminary results!



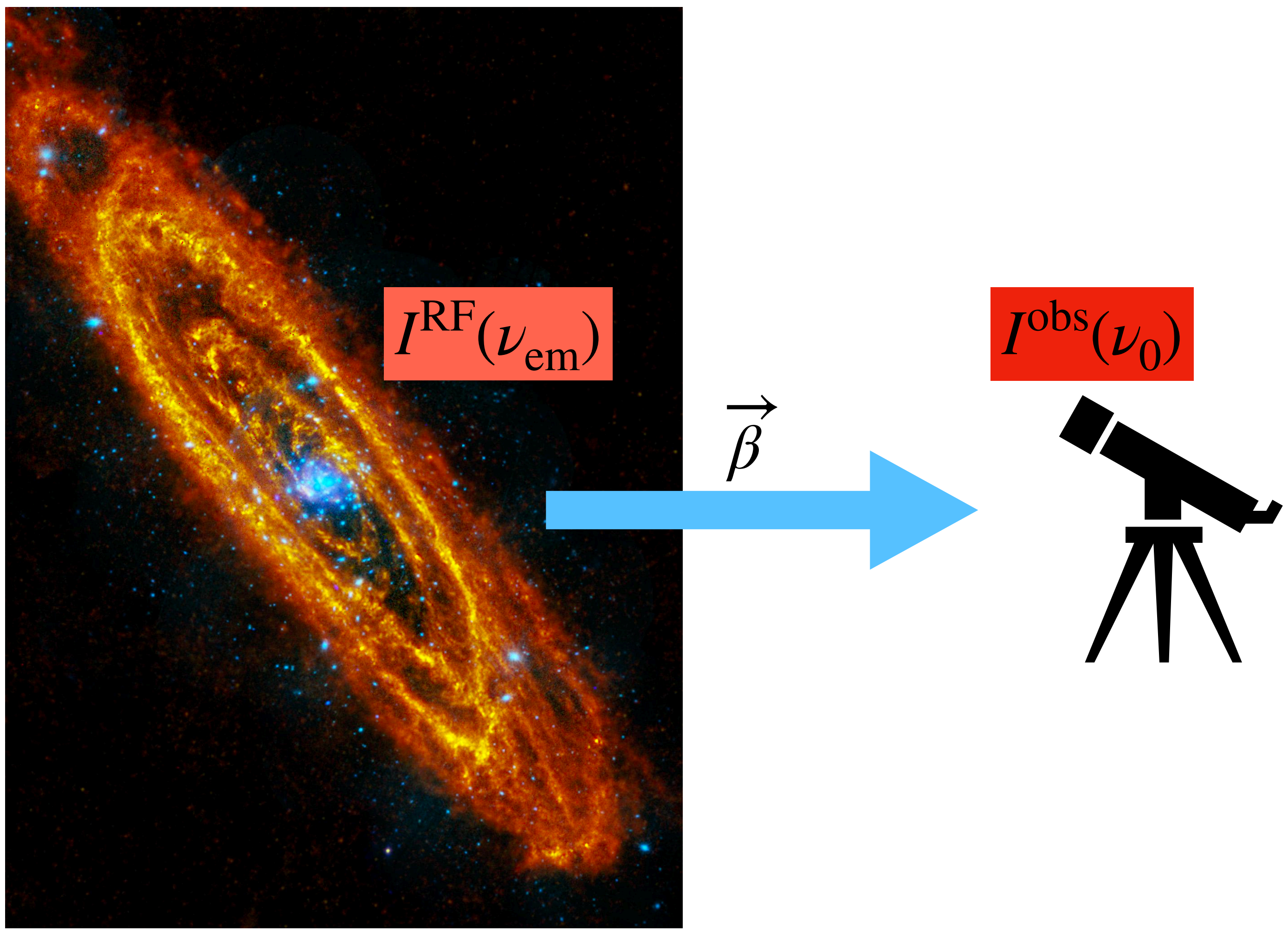
CIB exp	Galaxy exp	SNR
Planck 545 (857) GHz	CMASS	0.05 (0.19)
	DESI-ELG	0.70 (1.78)
	DESI-LRG	0.35 (0.99)
CCAT-Prime 545 (857) GHz	CMASS	1.87 (6.48)
	DESI-ELG	23 (52)
	DESI-LRG	12 (31)

SNR on $C_\ell^{\Delta I_{\nu_0} q_\gamma}$ → Velocity weighted density field

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

→ α

Signal & foreground!



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

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

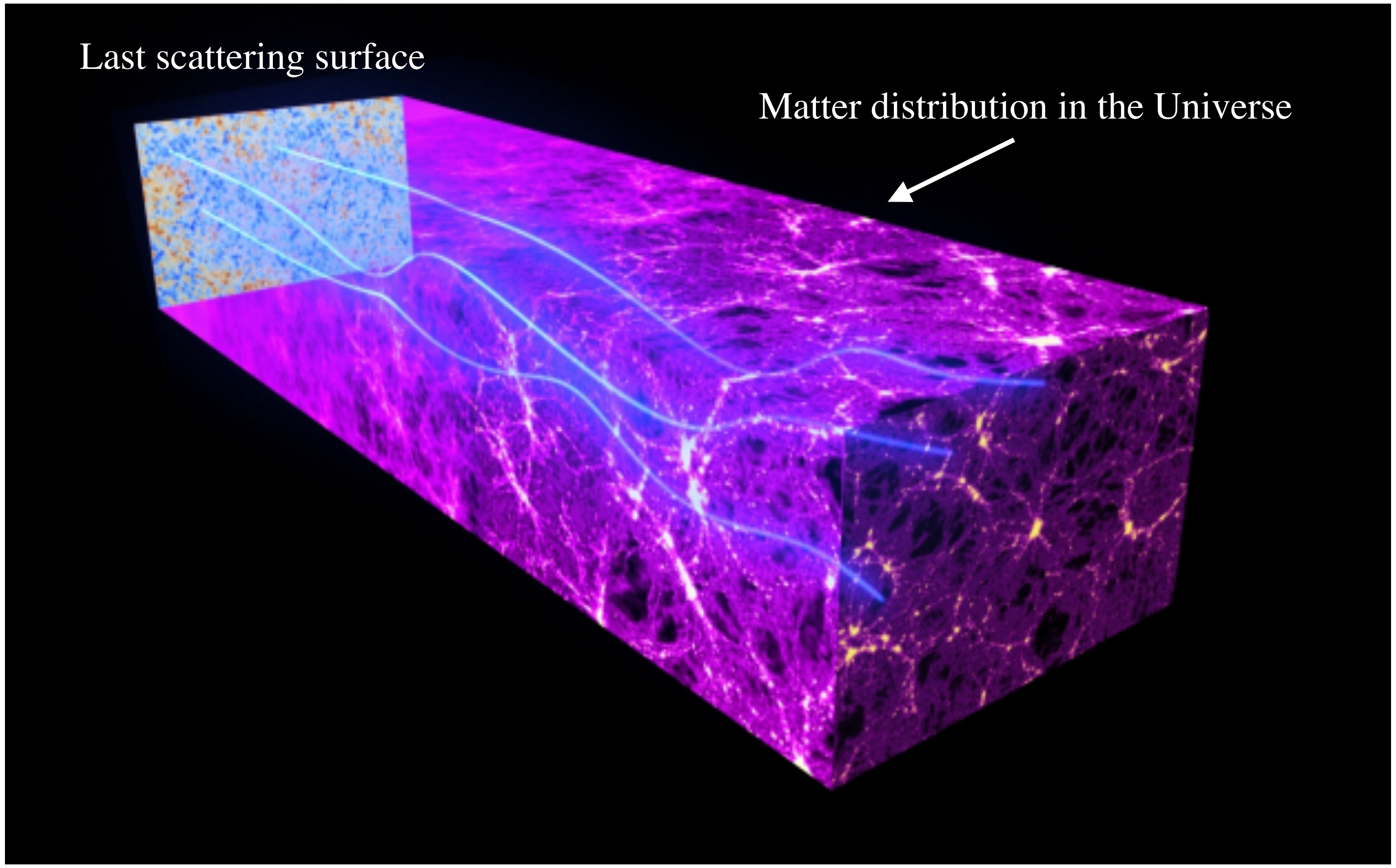
Weak lensing of the CMB: a global minimum variance quadratic estimator

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

Phys. Rev. D103, 083524 (2021)

Weak lensing of the CMB

- Distribution of the foreground matter fluctuations deflects CMB photons
- What we see is a distorted CMB map
- Reconstructing lensing potential: projected matter field



Quadratic estimators

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

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

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

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

- 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

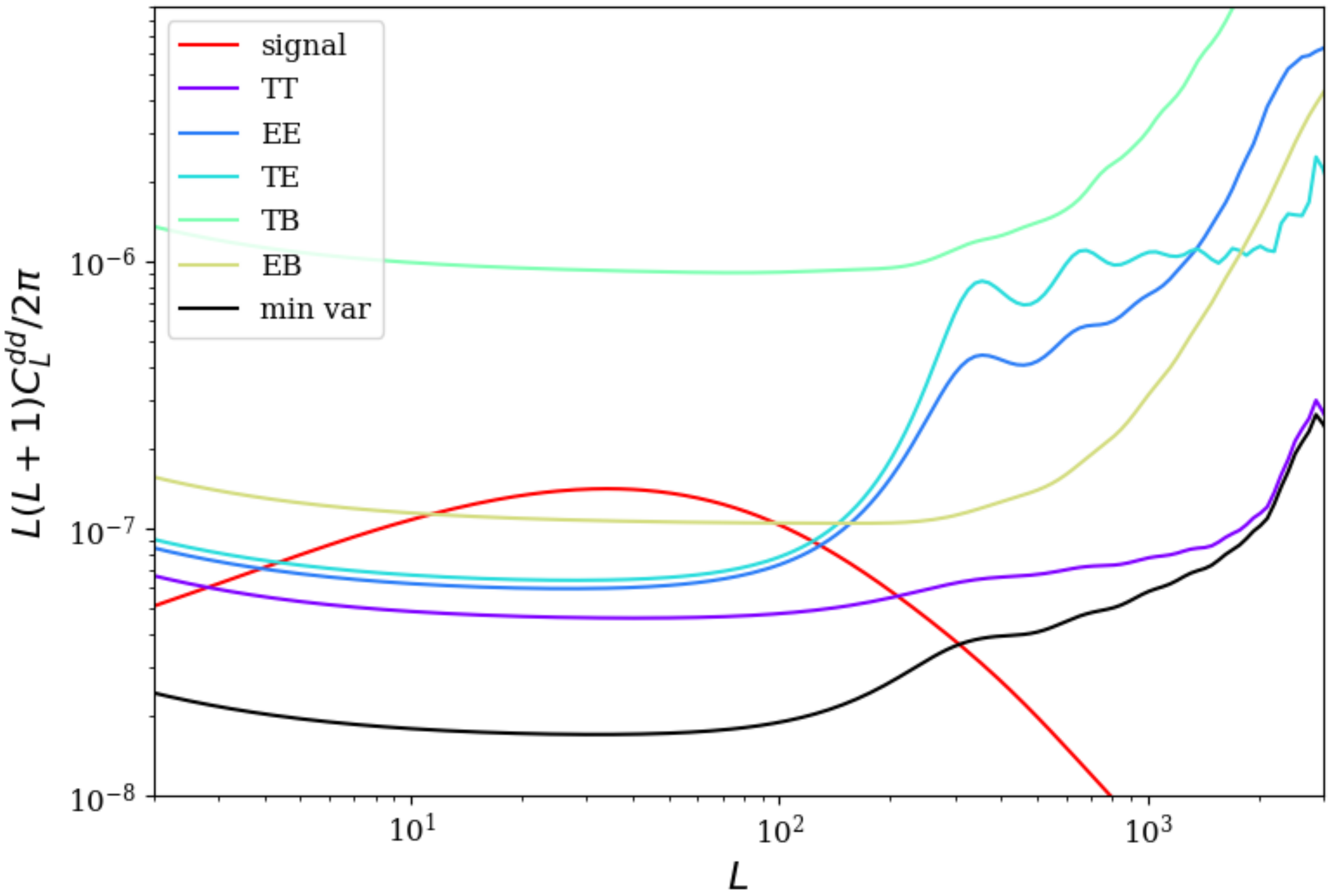
HO02

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

- 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

$$\hat{\phi}_{\rm HO02} = w_{TT}\hat{\phi}_{TT} + w_{EE}\hat{\phi}_{EE} + w_{TE}\hat{\phi}_{TE} + w_{TB}\hat{\phi}_{TB} + w_{EB}\hat{\phi}_{EB}$$
$$w_{TT} + w_{EE} + w_{TE} + w_{TB} + w_{EB} = 1$$

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!

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

GMV

GMV

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

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

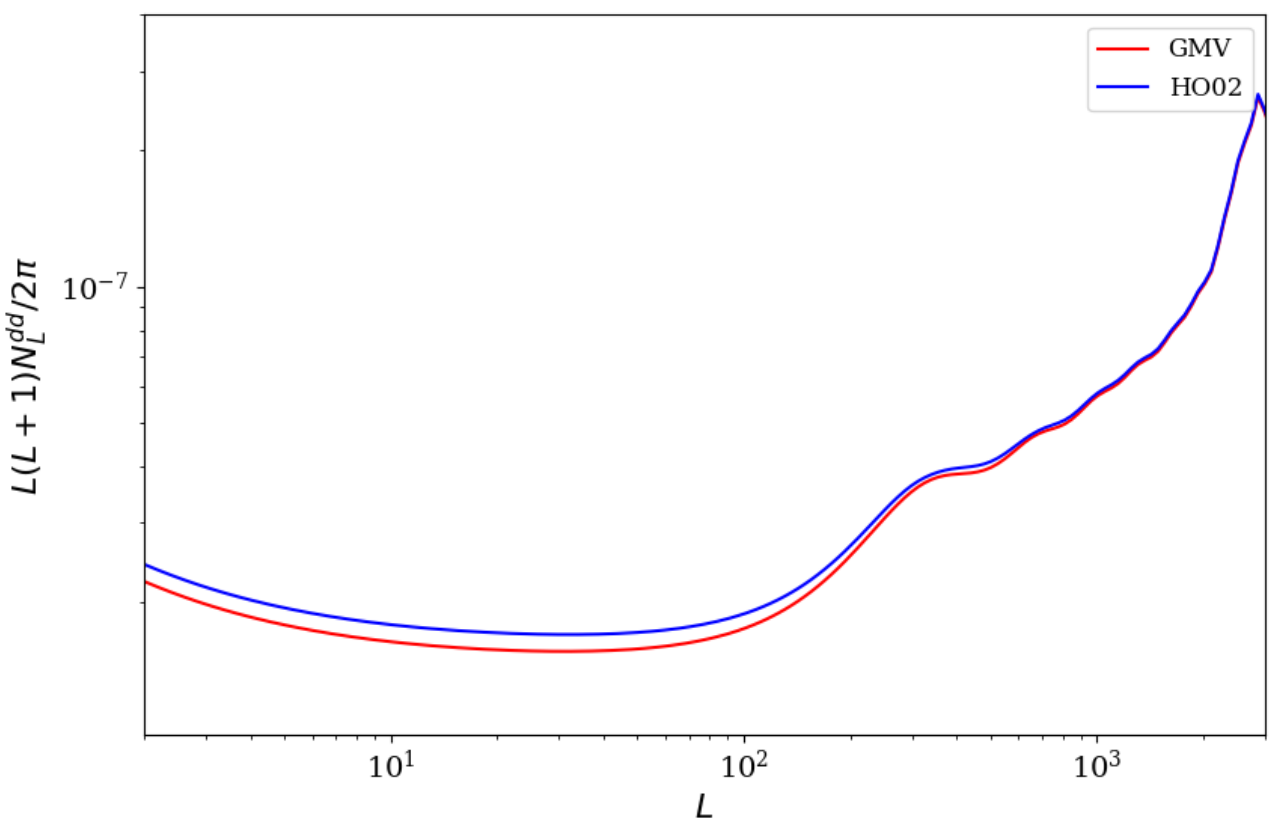
HO02

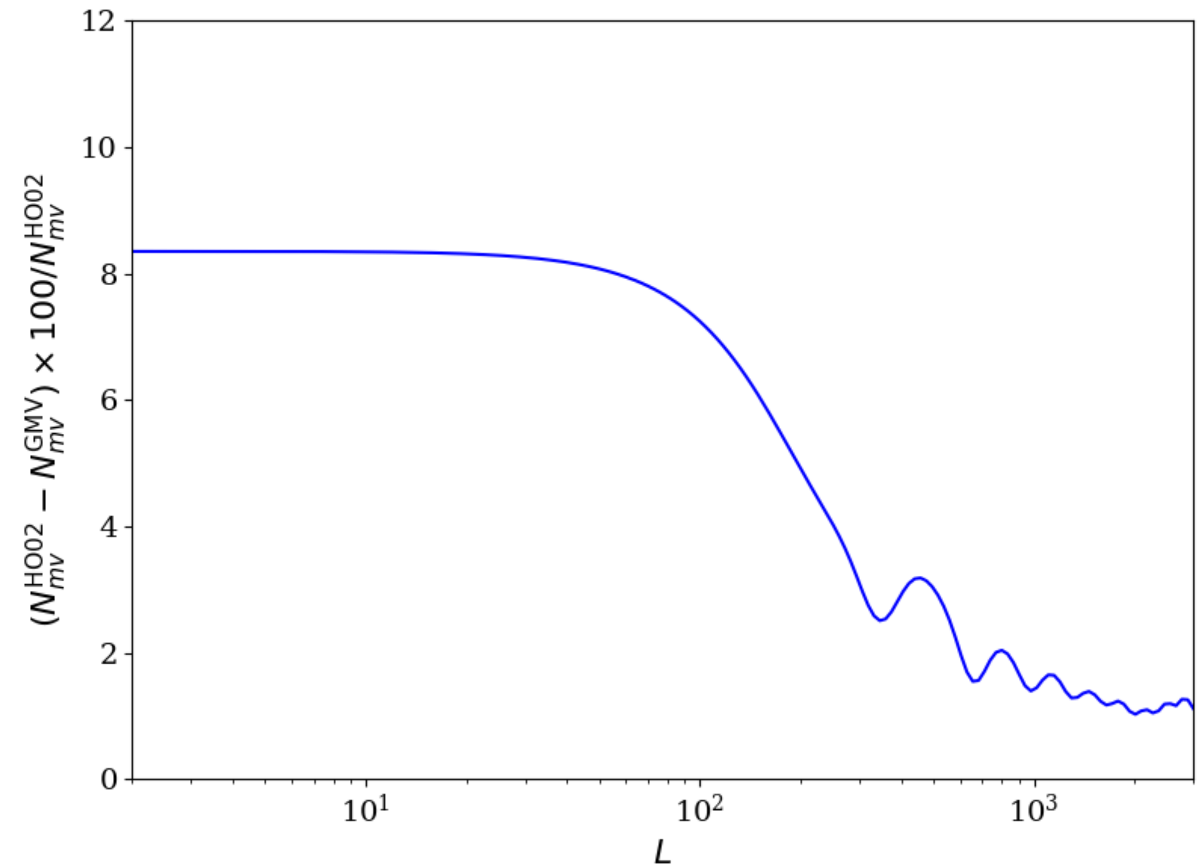
$$\int_{\boldsymbol{l}_1 \neq \boldsymbol{l}_2} F_{XY}(\boldsymbol{l}_1, \boldsymbol{l}_2) X(\boldsymbol{l}_1) Y(\boldsymbol{l}_2)$$

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

- $\boldsymbol{C}_l$ 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





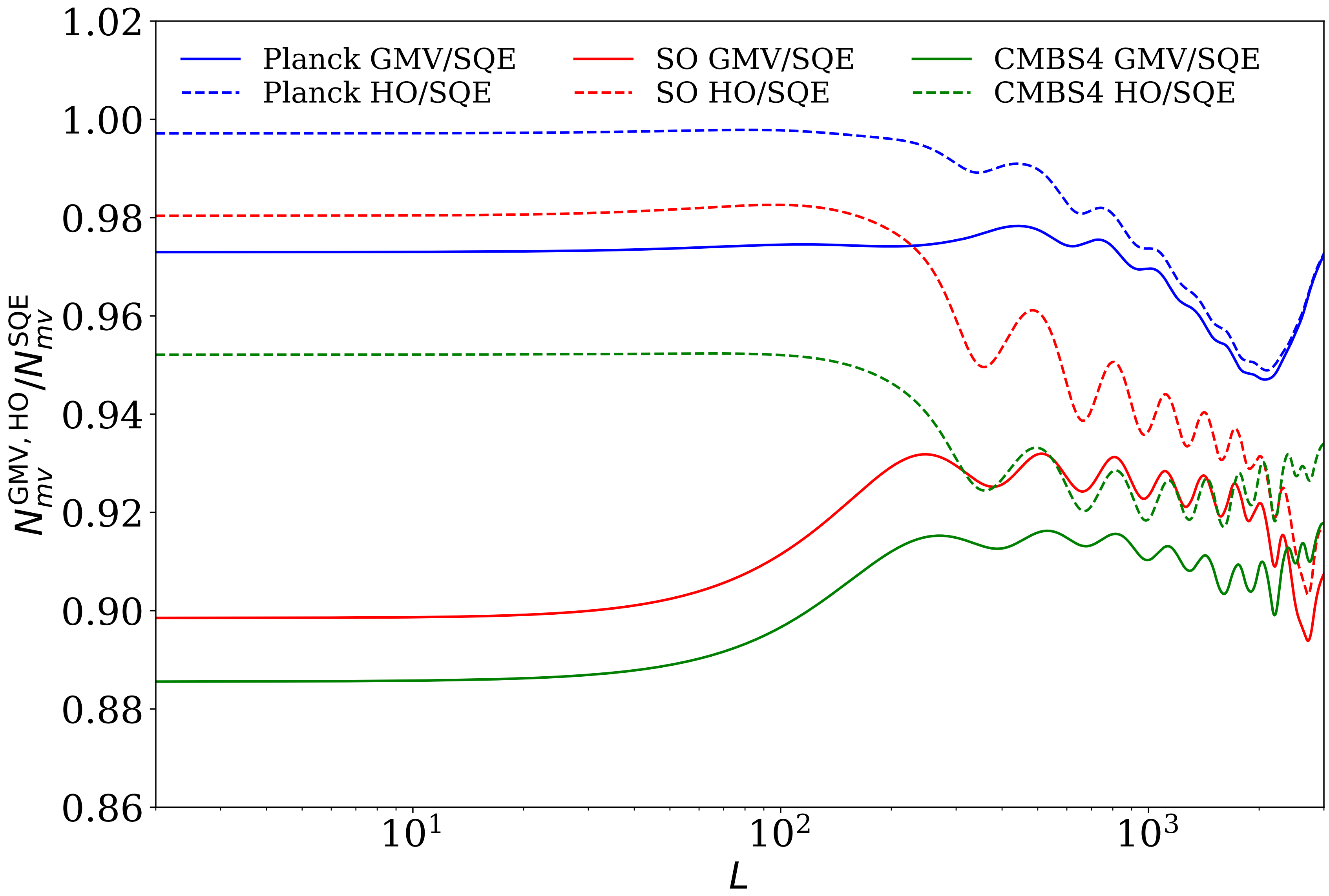
- 8-10% smaller noise than HO02 on small L
- More information out of the same maps!

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



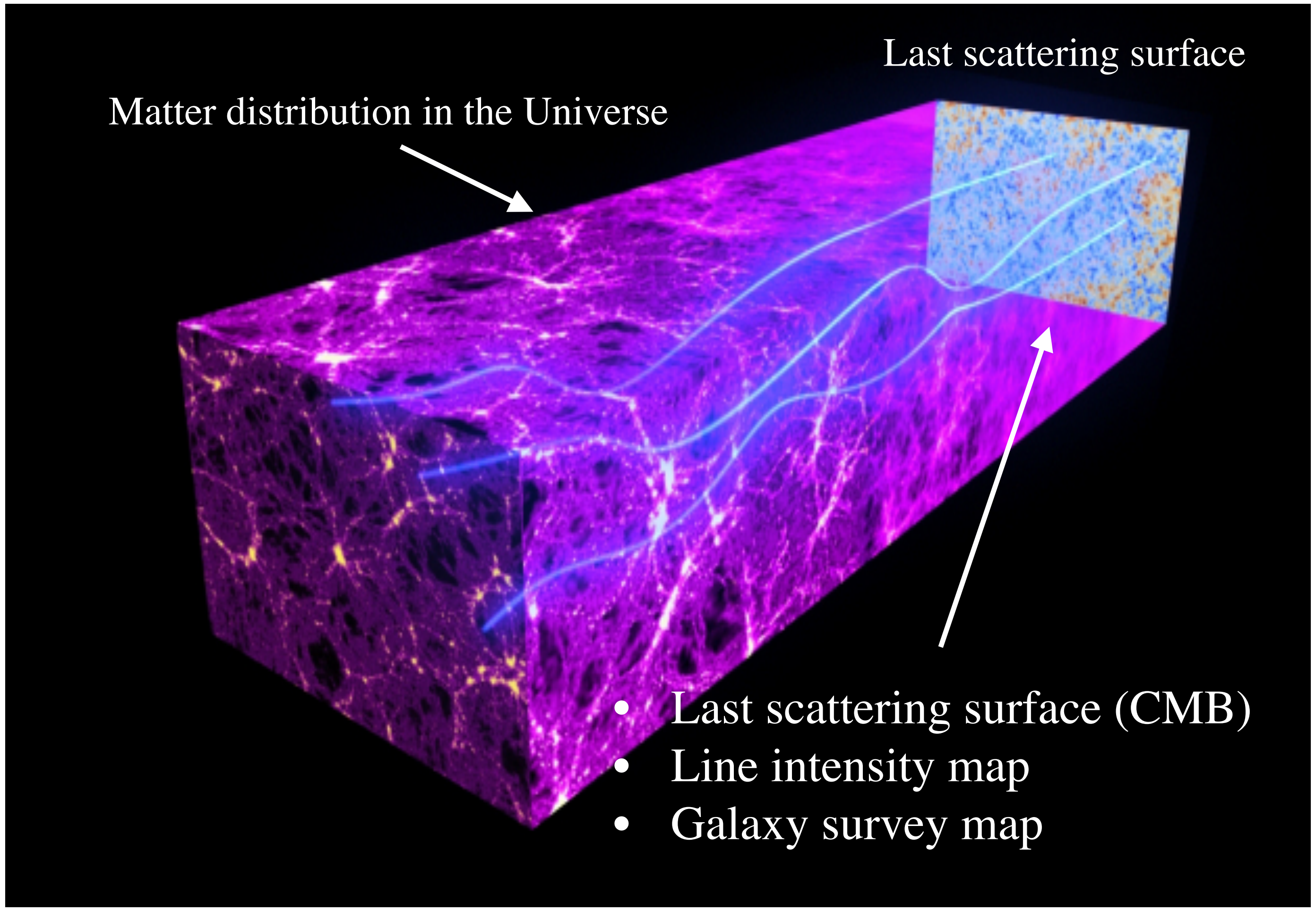
- SQE to GMV difference:
  - 3-6% for Planck-like experiments
  - 11-12% for SO-like experiments
- Should motivate use of full covariance matrix rather than setting $C_l^{TE} = 0$

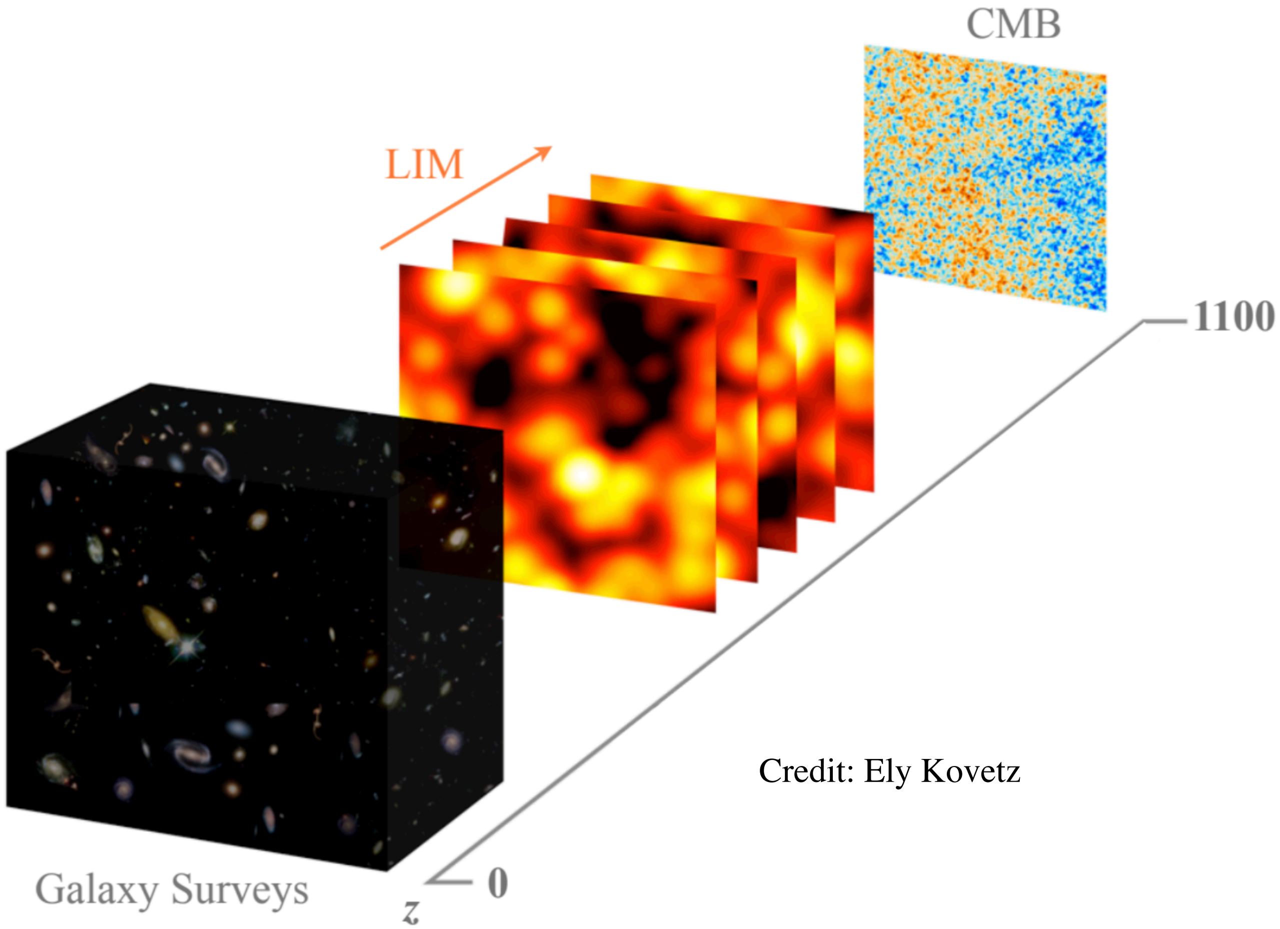
Application to LIM: interloper-free "LIM-pair" lensing

In collaboration with: Emmanuel Schaan & Anthony Pullen

arXiv:2106.09005

Weak lensing of the CMB/LIM/Galaxies



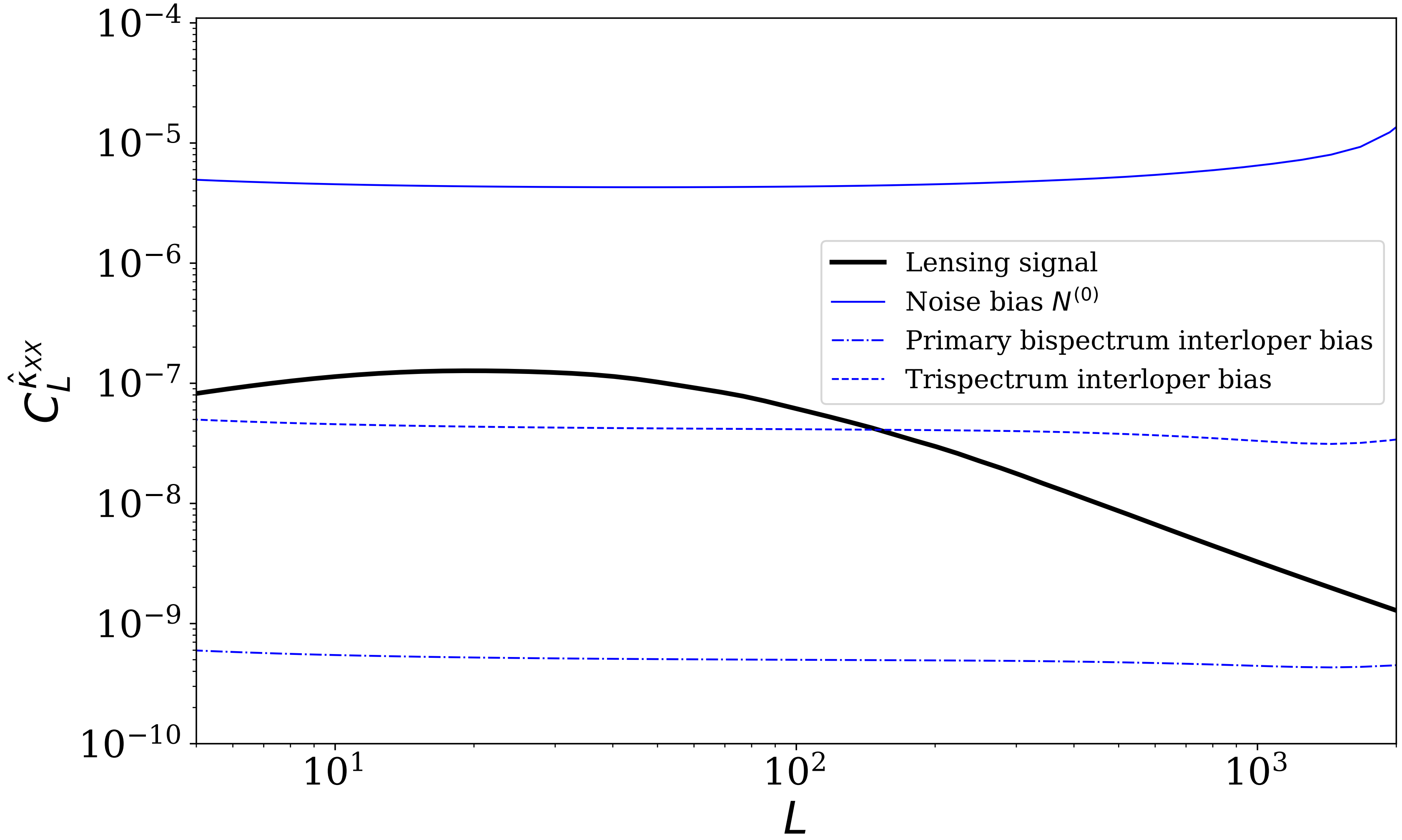


Credit: Ely Kovetz

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 → $C_L^{\kappa\kappa}$

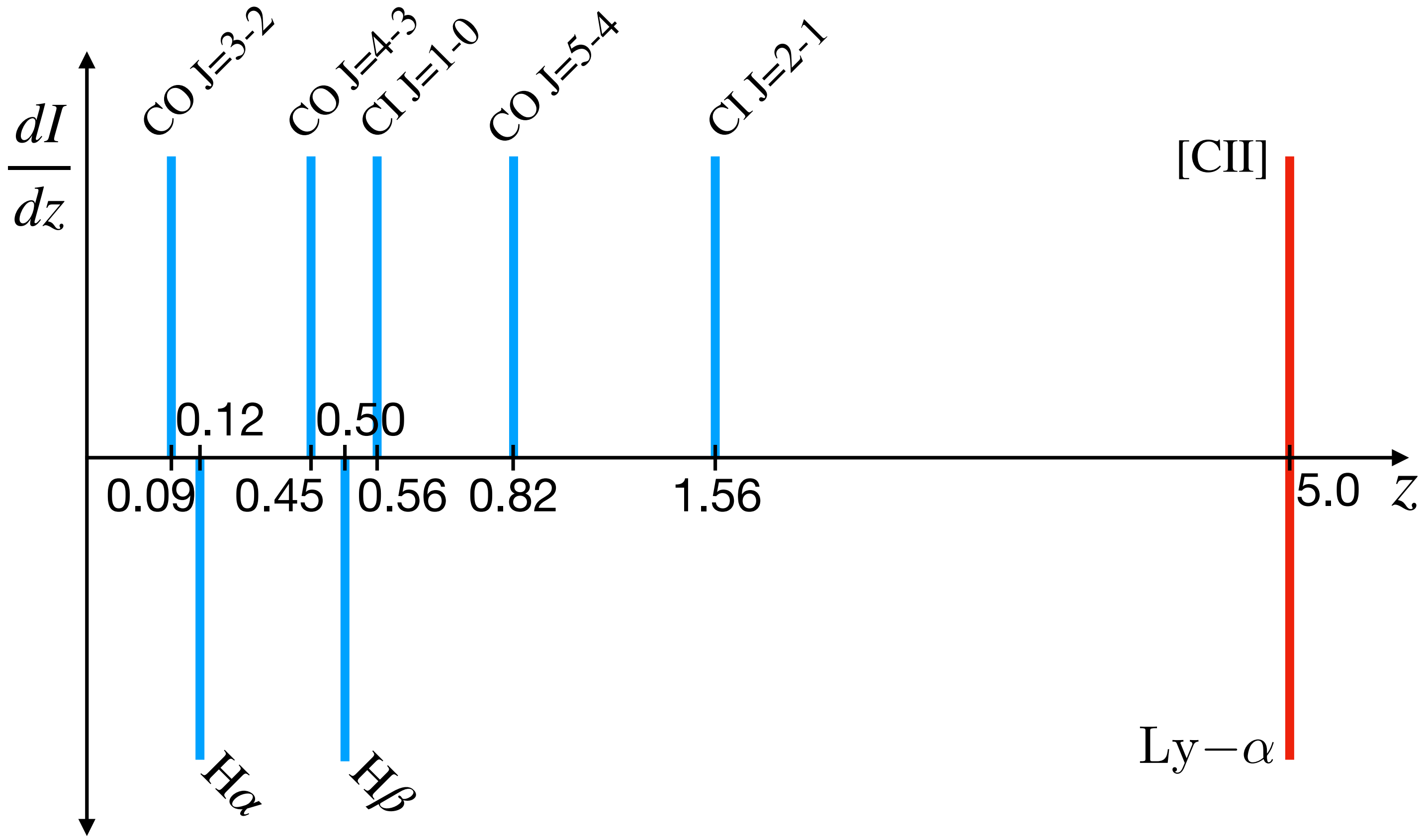
LIM Lensing



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!

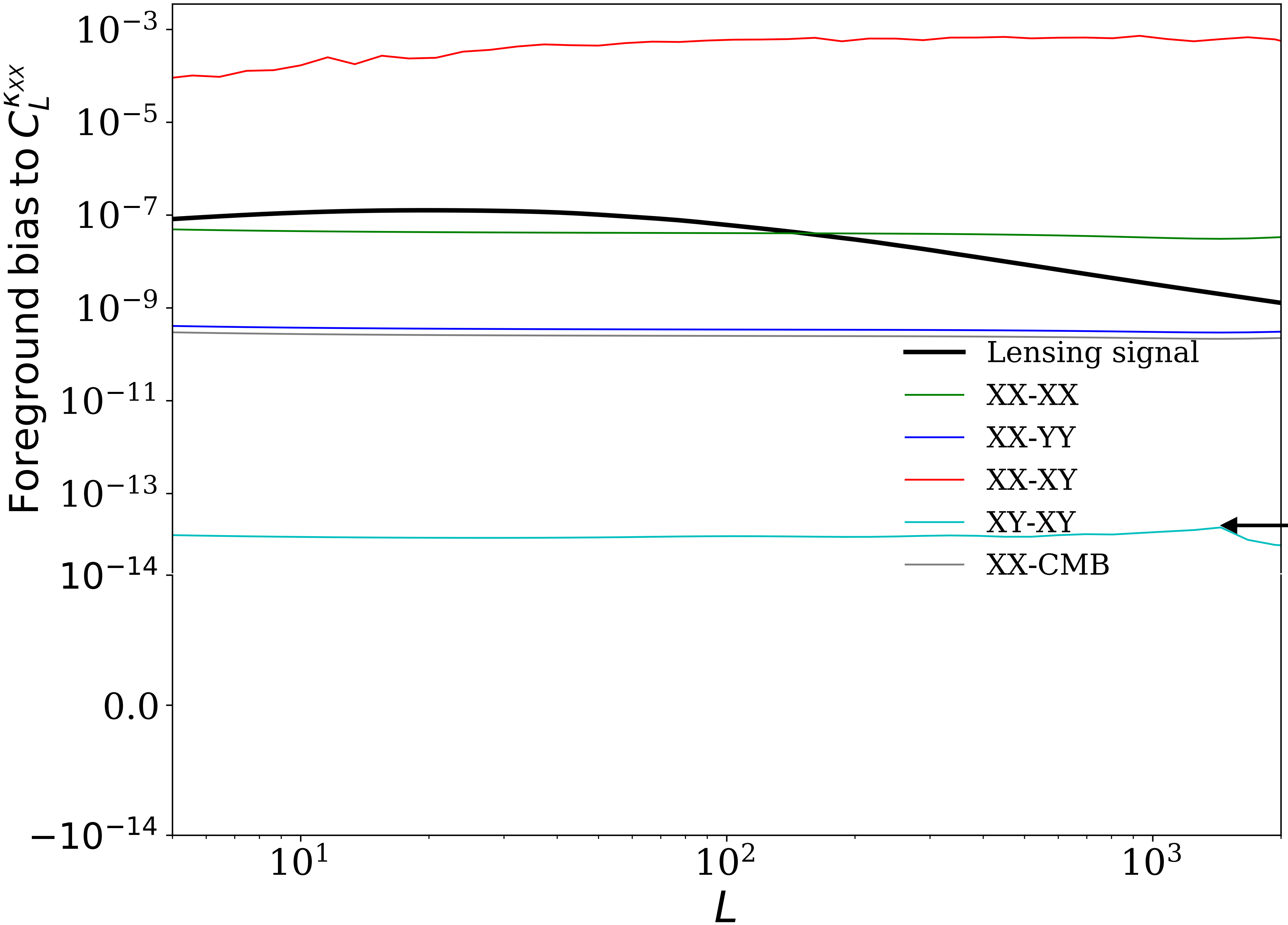
"LIM-pair" lensing!



- 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

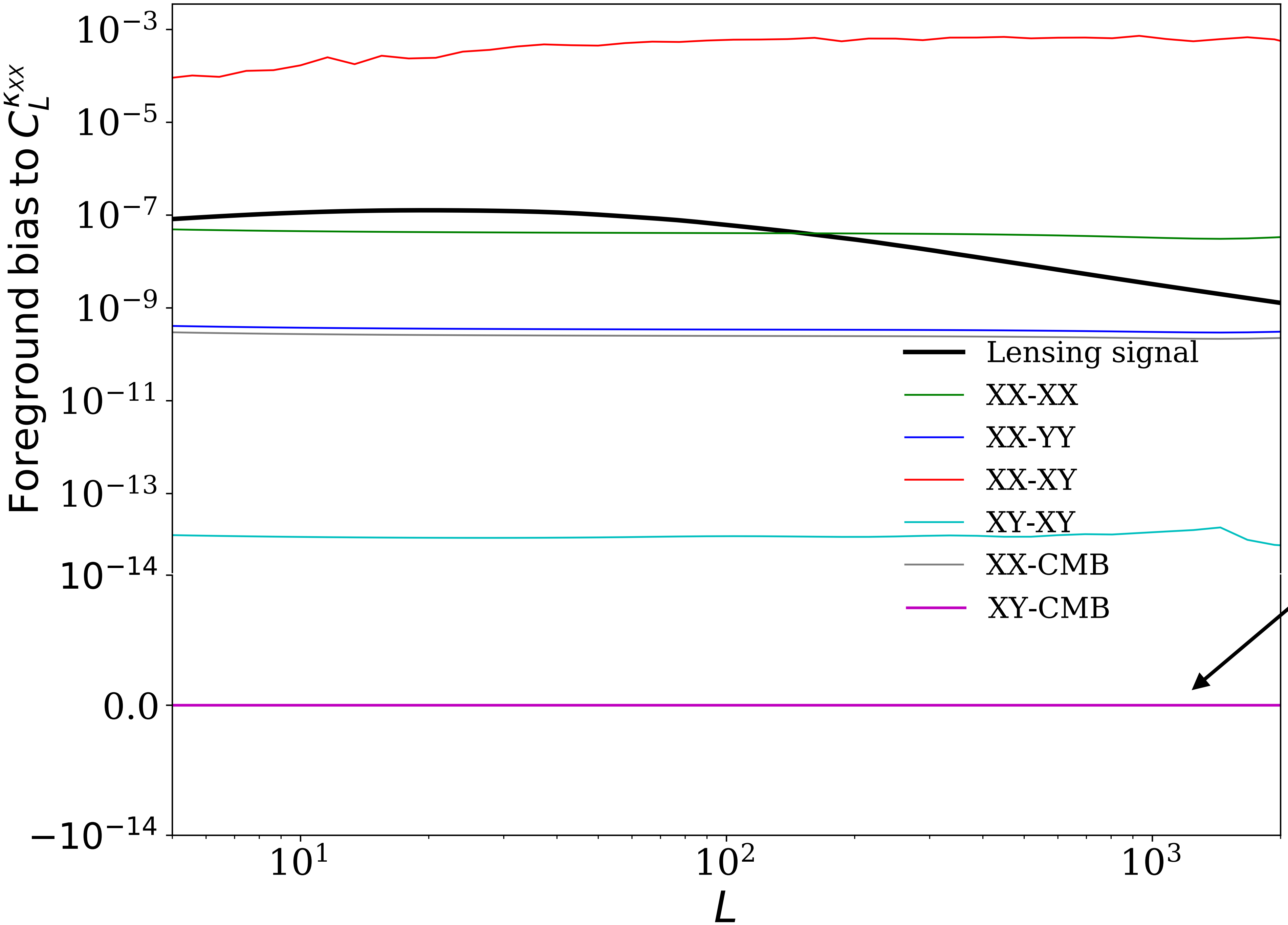
at

$z = 5$

XY is biased as well!

Secondary bispectrum bias

"LIM-pair" lensing!



X = Ly$-\alpha$

&

Y = [CII] or CMB

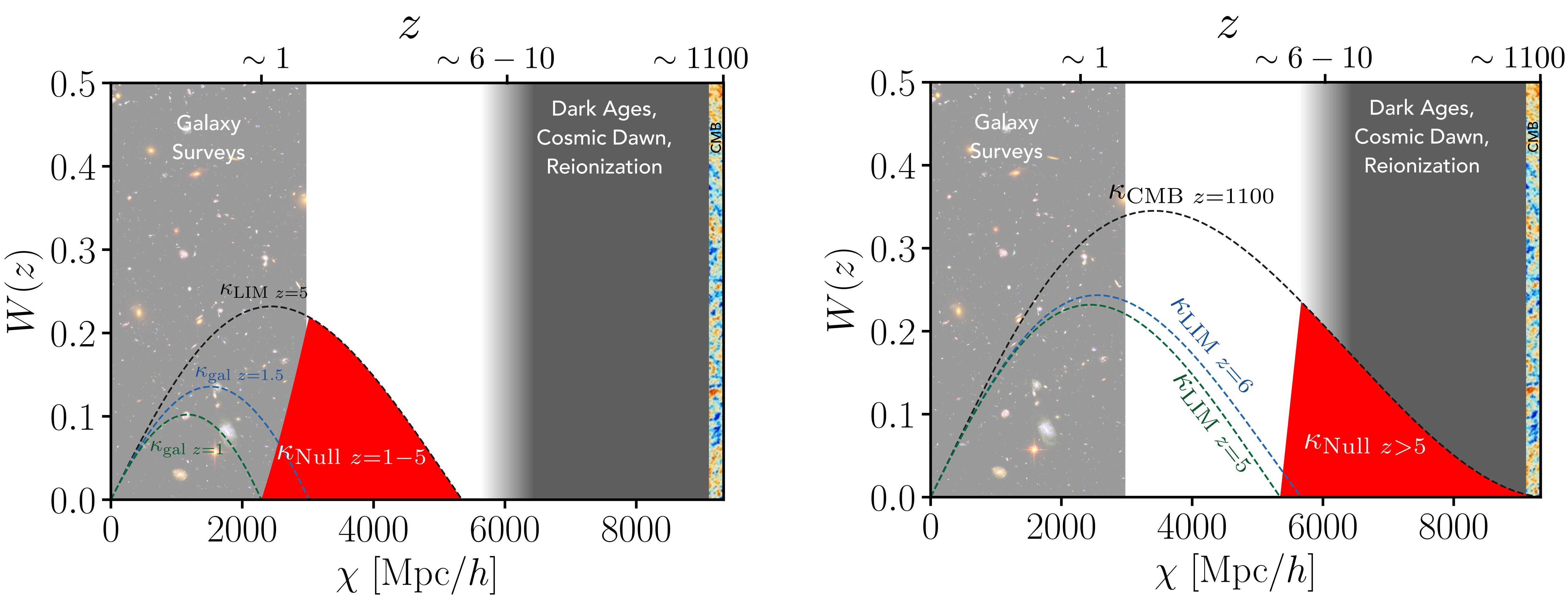
at

$z = 5$

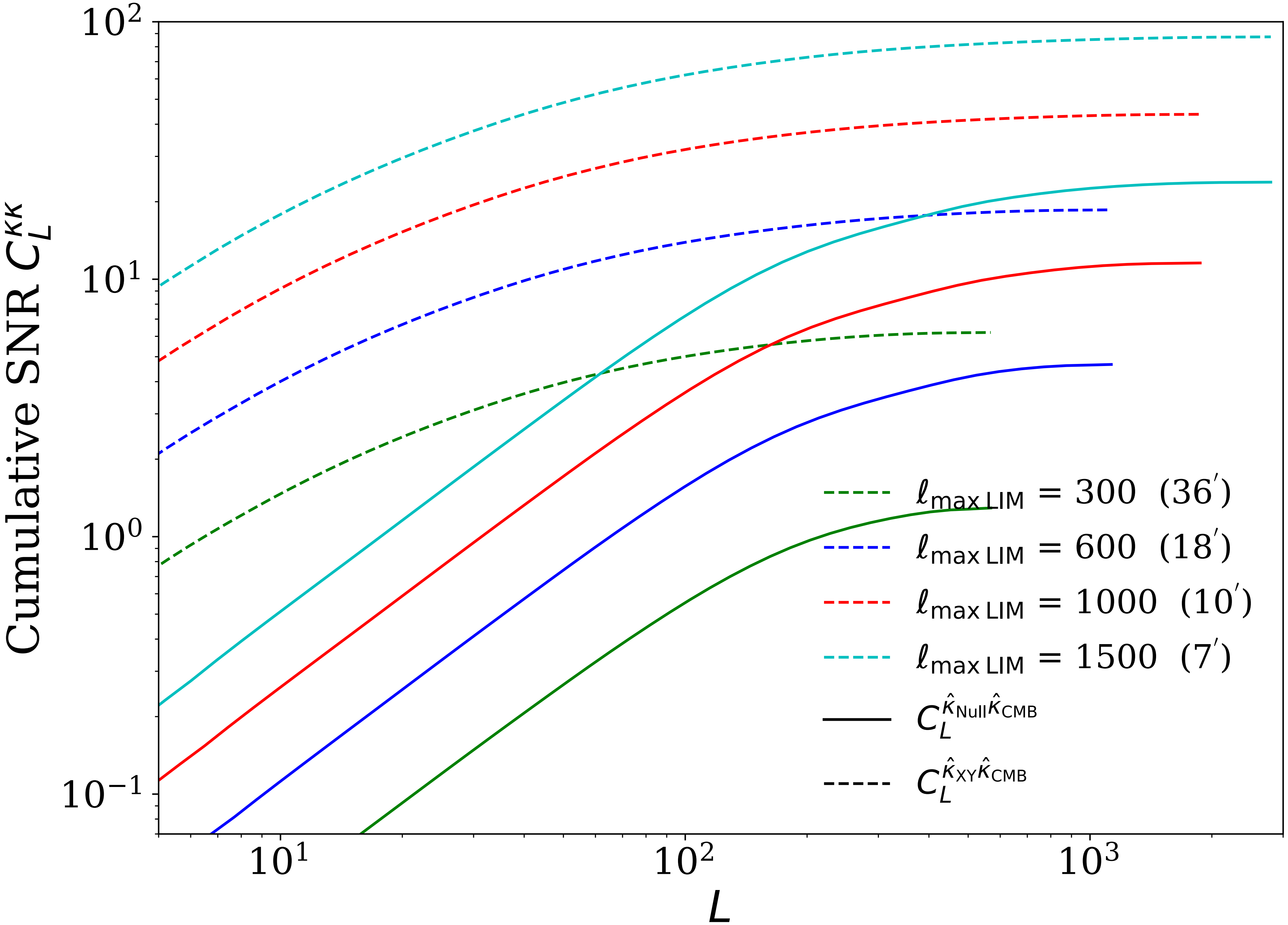
$\langle \hat{\kappa}_{XY} \hat{\kappa}_{\rm CMB} \rangle$

Zero non-Gaussian bias!

“LIM-pair” lensing: probing high redshift Universe with nulling technique



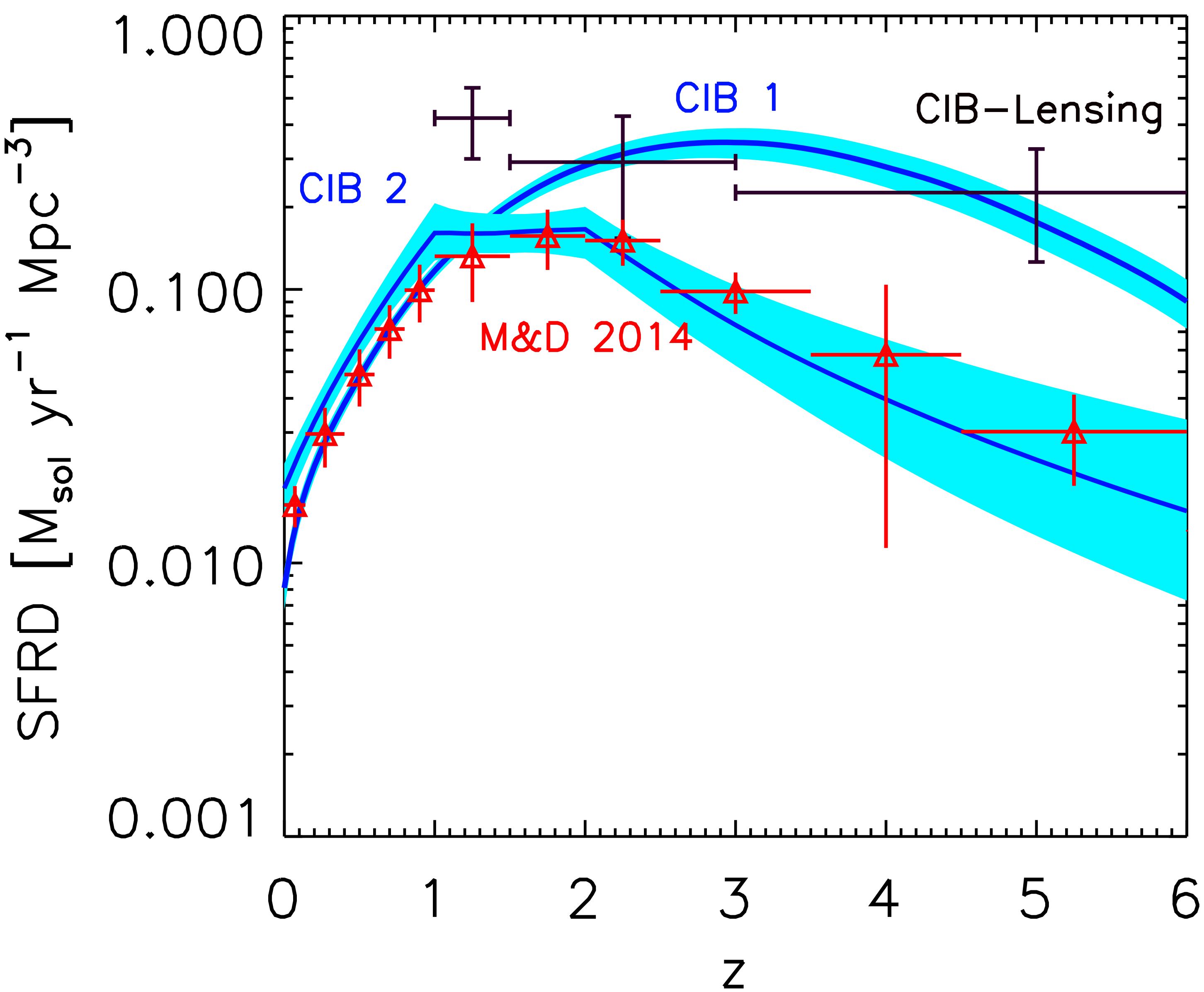
Can we detect this? $C_L^{\hat{\kappa}_{\rm null}\hat{\kappa}_{\rm CMB}}$: Yes! (Futuristic!)



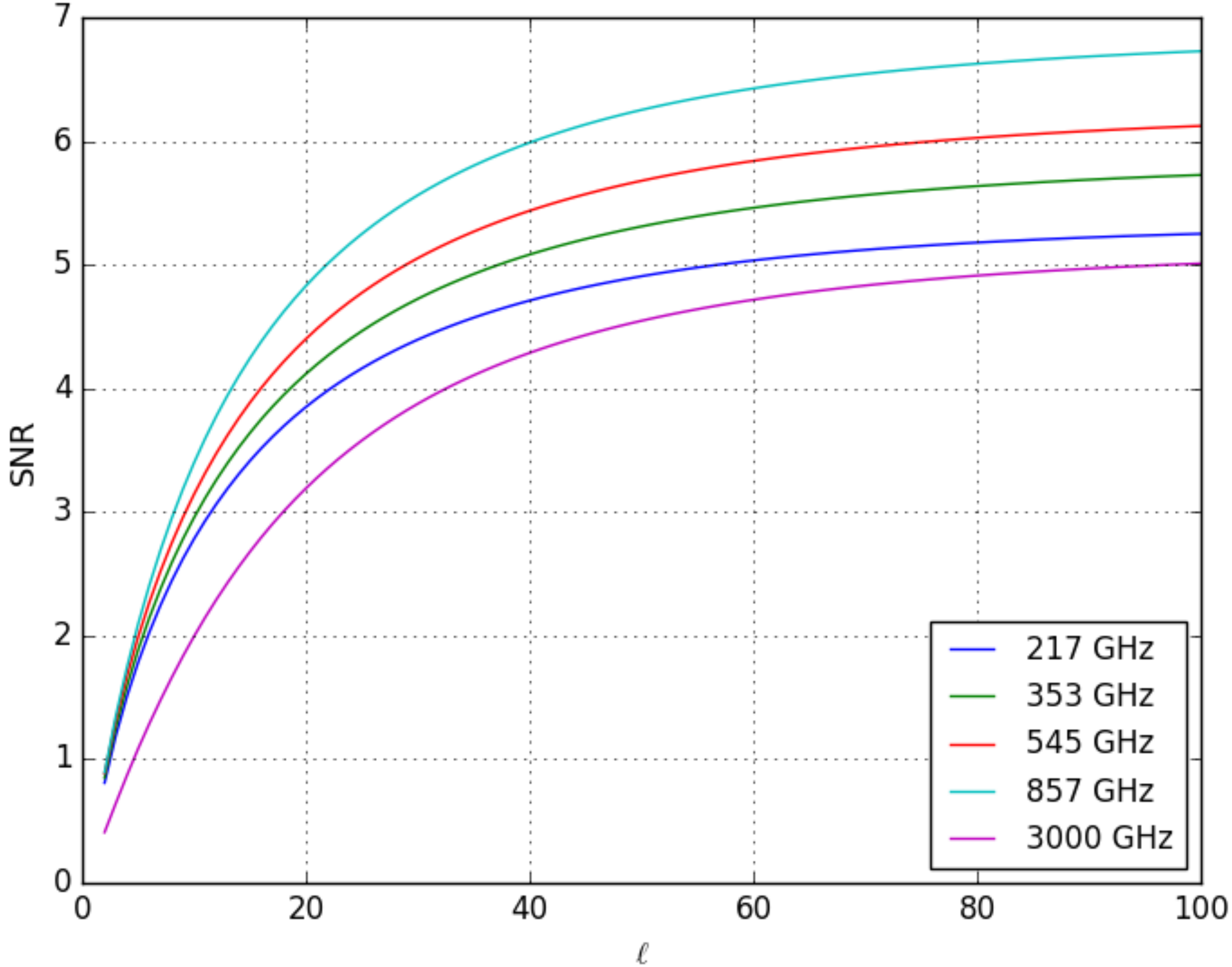
- f_sky = 40%
- Would be possible to detect this signal
- Angular resolution should not be an issue

Thank you!

SFRD from different models/measurements

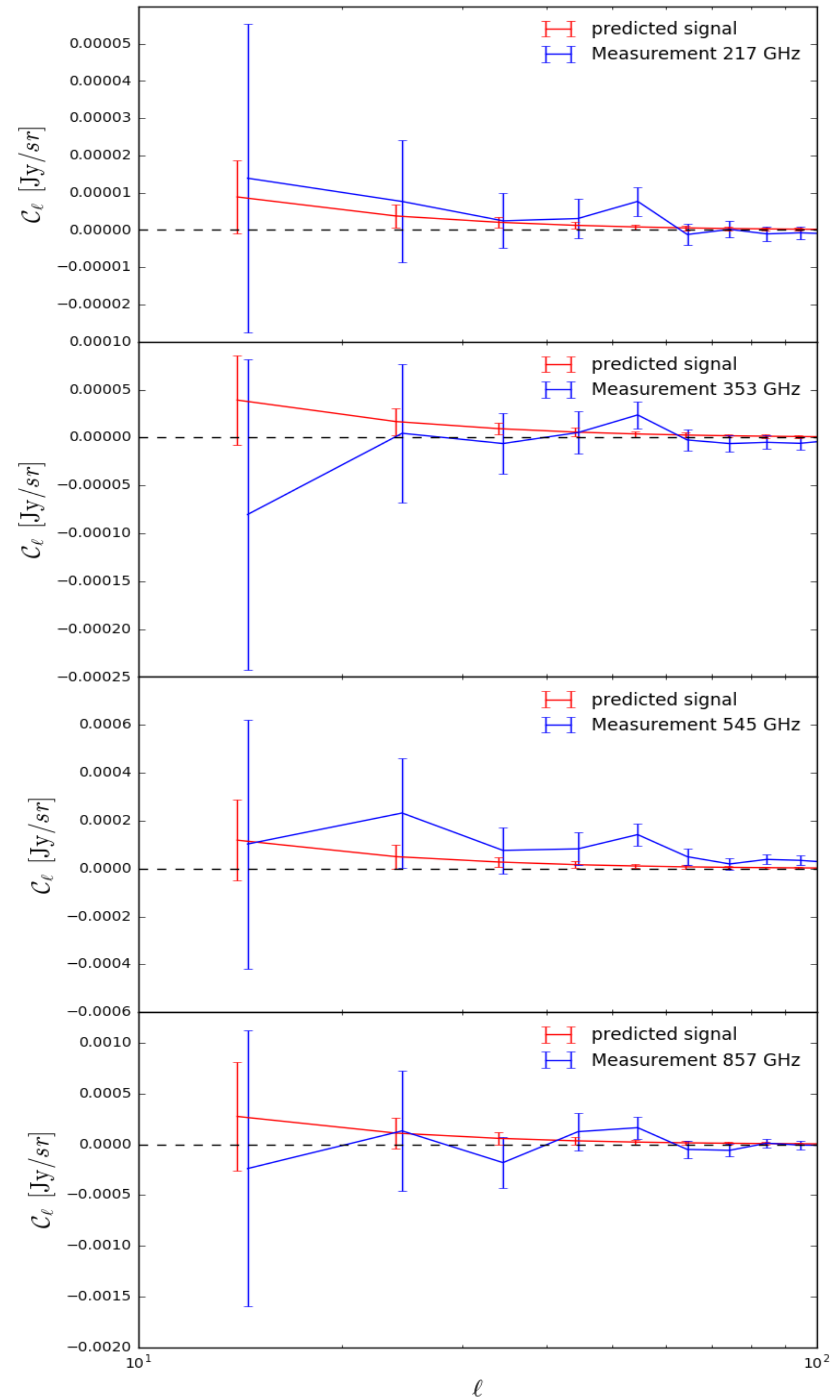


Optimistic: ISW SNR (100% sky, no dust) forecast



ISW SNR (10% dust residuals)

Freq. (GHz)	217	353	545	857	3000
SNR 20% f_{sky}	1.46	1.51	1.41	1.14	0.52
SNR 40% f_{sky}	1.16	1.16	0.99	0.69	0.27
SNR 60% f_{sky}	0.92	0.90	0.74	0.49	0.18
SNR 70% f_{sky}	0.80	0.78	0.63	0.42	0.16
SNR 80% f_{sky}	0.59	0.57	0.45	0.30	0.11



predicted signal
Measurement 217 GHz
predicted signal
Measurement 353 GHz
predicted signal
Measurement 545 GHz
predicted signal
Measurement 857 GHz
C_ℓ [Jy/sr]
ℓ

Experimental specs

Experiment	$\ell_{\max}$	Δ_T μK-arcmin	Δ_P μK-arcmin	σ arcmin
Planck	3000	35.0	60.0	5.0
SO	3000	8.0	$8.0\sqrt{2}$	1.4
CMBS4	3000	1.0	$1.0\sqrt{2}$	1.0

TABLE II: Experimental specifications used in this work.

$$\ell_{\max}^{T} = \ell_{\max}^{P}$$