Detecting patchy reionization in the CMB

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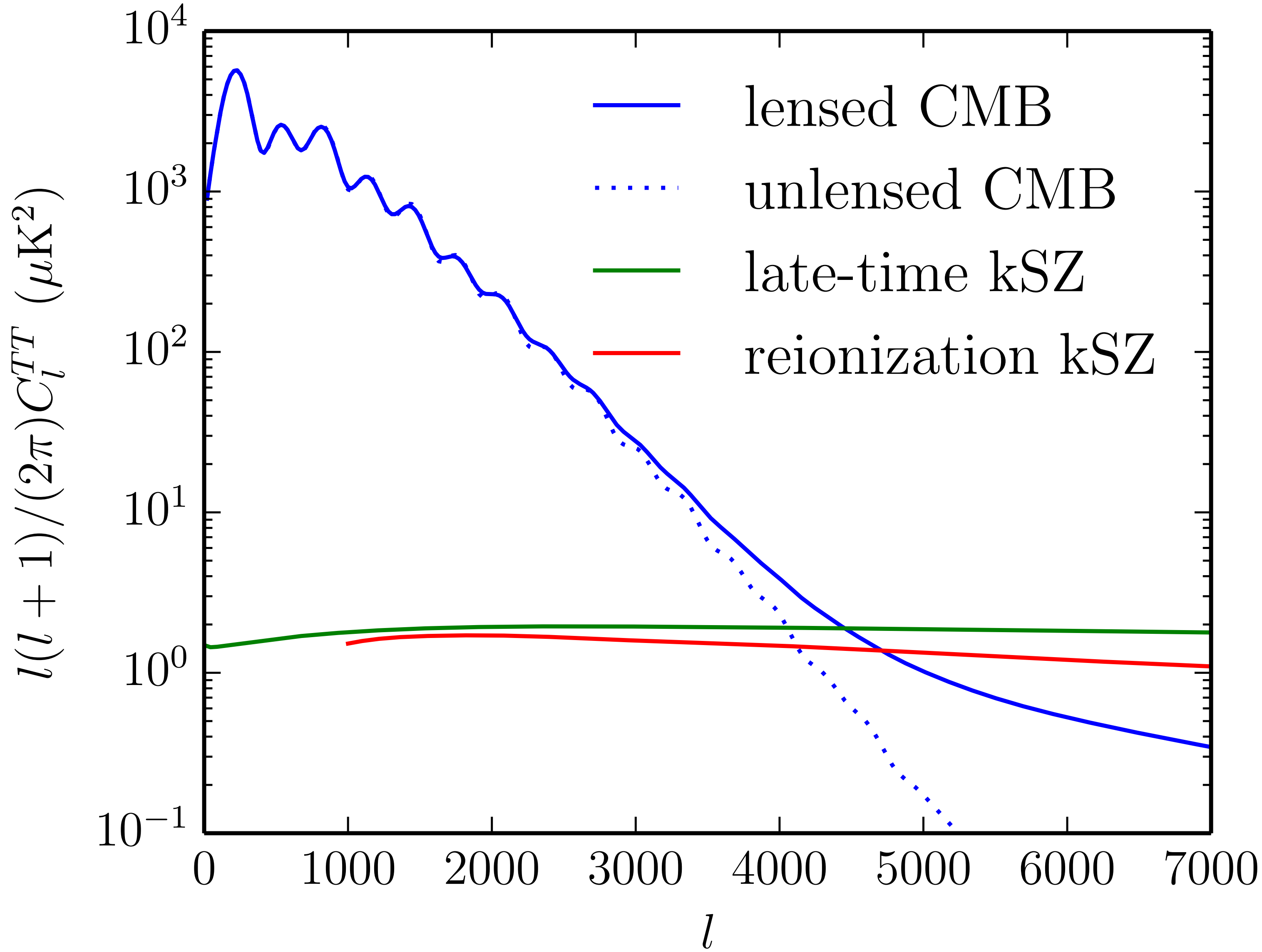
July 2016

1607.01769 with Simone Ferraro (Berkeley)

CMB power spectrum at high l

The total power spectrum can be measured to ~0.1%, but the individual contributions have large astrophysical modelling uncertainties. Hard to disentangle at power spectrum level.



CMB power spectrum at high l

The total power spectrum can be measured to ~0.1%, but the individual contributions have large astrophysical modelling uncertainties. Hard to disentangle at power spectrum level.

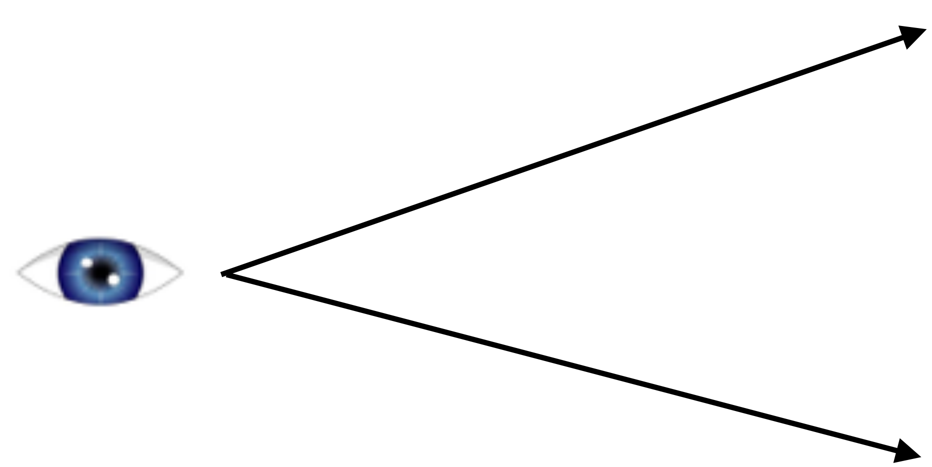
A key question:

> Are there statistics which go beyond the power spectrum which can separate these contributions?
>
> In this talk: a new proposal based on a particular limit of the 4-point correlation function.

Consider the kSZ power spectrum, written as a line-of-sight integral.

$$C_l^{\mathrm{kSZ}} = \int dz\, W(z)\, \langle v_r(z)^2 \rangle P_e\left(\frac{l}{\chi(z)}, z\right)$$

Fix a small scale l, and suppose two observers measure C_l^{kSZ} at separated sky locations n, n'. Because the two lines of sight sample different realizations of the velocity field $v_r(n,z)$, the locally measured kSZ power spectra will be different.

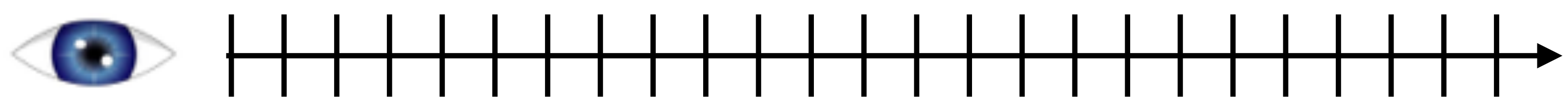


$$\int dz\, v_r(\mathbf{n}, z)^2$$

$$\int dz\, v_r(\mathbf{n}', z)^2$$

How large is this effect? (back-of-envelope version)

Divide line of sight (length ~10^4 Mpc) into segments whose size is equal to the coherence length of the velocity field (~50 Mpc).



Roughly model $v_r(z)$ as an independent Gaussian random number in each segment:

$$\int dz\, v_r(\mathbf{n}', z)^2 \sim \text{(sum of squares of N=200 Gaussians)}$$

$\Rightarrow$ Statistical fluctuations are of fractional size $\sqrt{2/N} \sim 10\%$

How large is this effect? (quantitative version)

Let's construct a statistic to measure this signal.
First, high-pass filter the CMB (in Fourier space):

$$T_S(\mathbf{l}) = W_S(l)\, T(\mathbf{l}) \qquad\qquad W_S(l) = \text{high-pass filter}$$

Then square in real space:

$$K(\mathbf{n}) = T_S(\mathbf{n})^2$$

The sky-averaged K(n) is the small-scale power spectrum

$$\bar{K} = \int \frac{d^2 l}{(2\pi)^2} W_S(l)^2 C_l$$

and the smoothed field value K(n) may be interpreted as "locally measured small scale power spectrum near n"

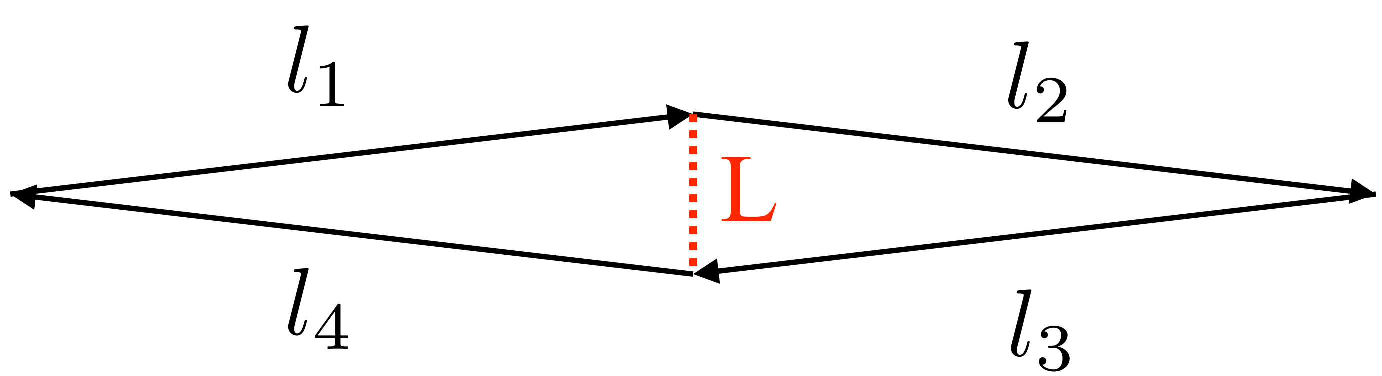
Note: the notations $\bar{K}$ (sky-averaged small-scale power) and $K(\mathbf{n})$ (local small-scale power) will be used frequently in the talk!

How large is this effect? (quantitative version)

Finally, square in Fourier space to obtain C_L^{KK} ("power spectrum of the power spectrum").

There are two scales, a small scale l where the CMB is measured and a large scale L where we look for clustering in the small-scale power spectrum.

Viewed as a 4-point estimator, C_L^{KK} sums over "collapsed" quadruples $T(l_1)\, T(l_2)\, T(l_3)\, T(l_4)$

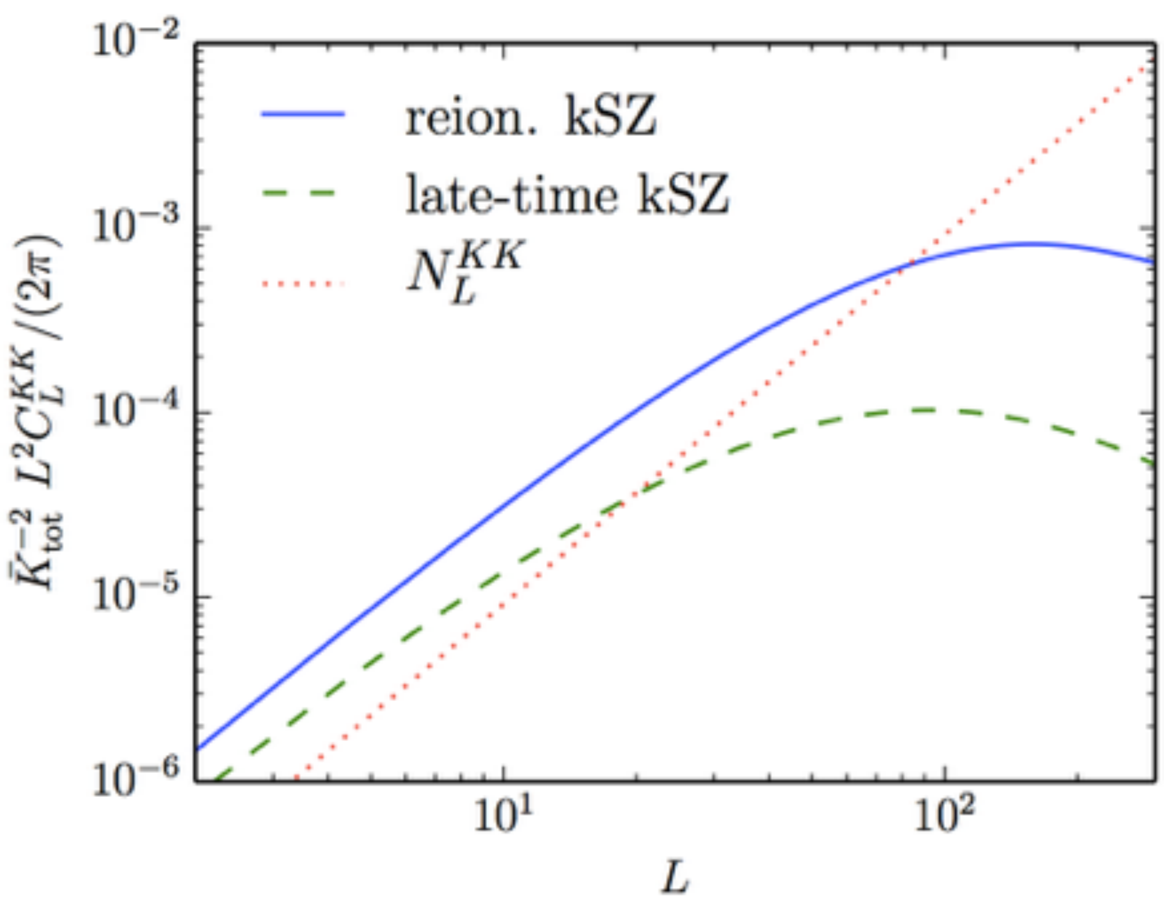


Very similar to CMB lensing!

How large is this effect? (quantitative version)

Continuing the analogy with CMB lensing, define the "reconstruction noise" N_L^{KK} to be the value of C_L^{KK} that would be obtained for a Gaussian field

The signal C_L^{KK} and noise N_L^{KK} compare roughly as follows. There is a huge signal!



Modelling the signal

The signal C_L^{KK} was calculated using the following minimal model (the "η -model"). Write the sky-averaged small-scale power spectrum as an integral

$$\bar{K} = \int dz \, \frac{d\bar{K}}{dz}$$

Now model

$$K(\mathbf{n}) = \int dz \, \frac{d\bar{K}}{dz} \eta(\mathbf{n}, z) \qquad \text{where} \quad \eta(\mathbf{n}, z) = \frac{v_r(\mathbf{n}, z)}{\langle v_r^2(z) \rangle}$$

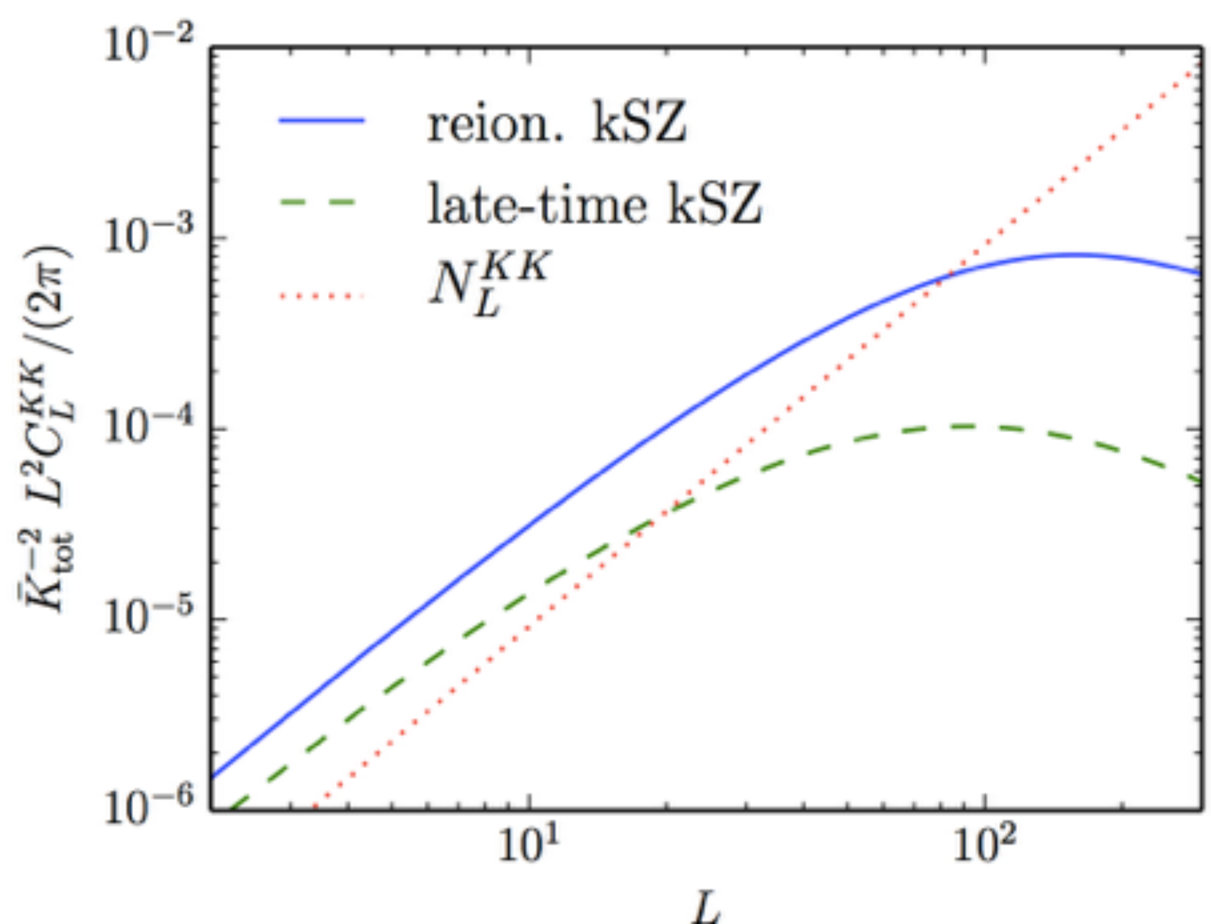
$$C_L^{KK} = \int dz \frac{H(z)}{\chi(z)^2} \left(\frac{d\bar{K}}{dz} \right)^2 P_\eta\left(\frac{L}{\chi(z)}, z \right) \qquad \text{[Limber]}$$

Not a complete calculation of the kSZ 4-point function, but rather a term which must be present on large scales, regardless of the details of the small-scale physics

A very important property of this model!

$$C_L^{KK} = \int dz \frac{H(z)}{\chi(z)^2} \left(\frac{d\bar{K}}{dz}\right)^2 P_\eta\left(\frac{L}{\chi(z)}, z\right)$$

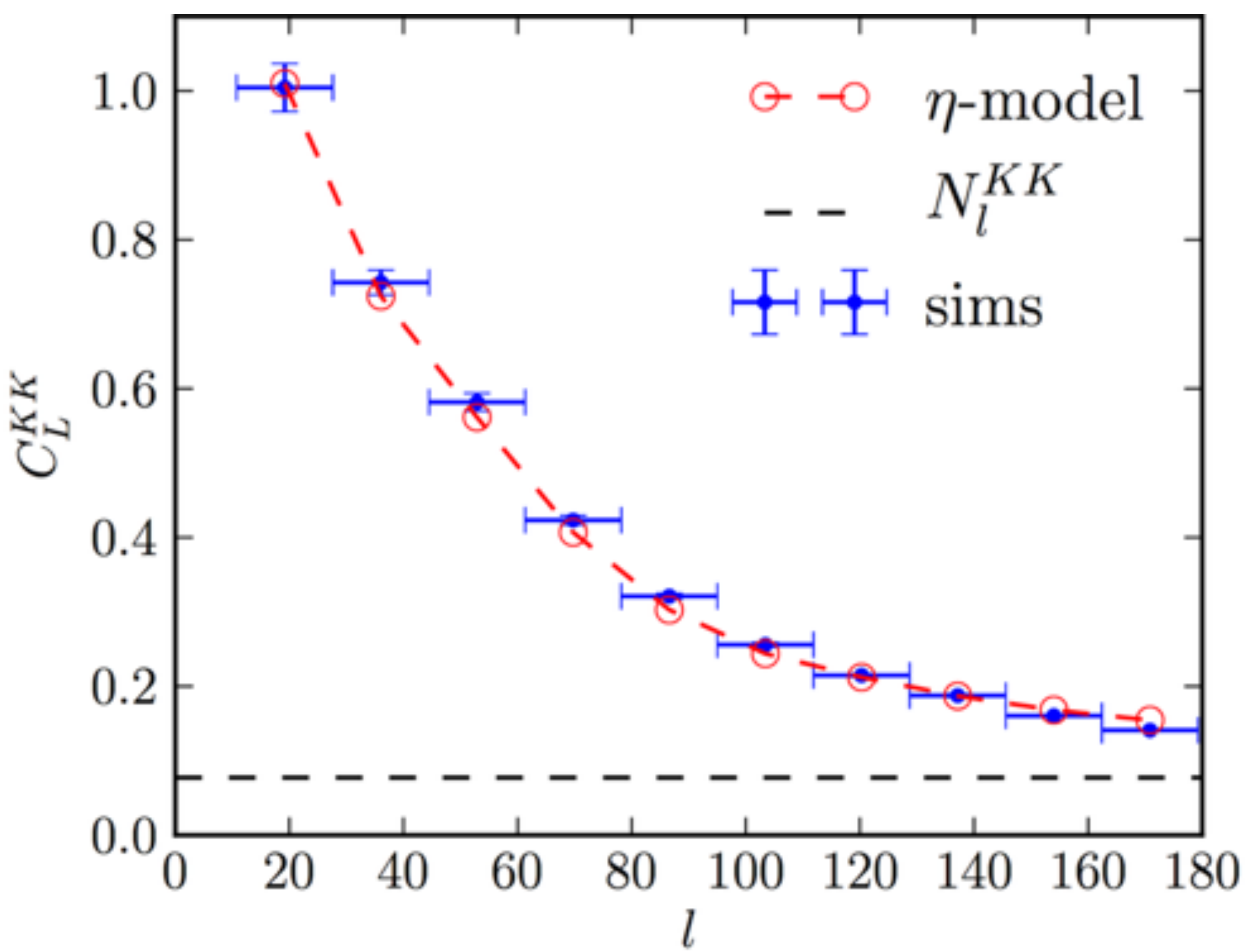
Consider the contribution to C_L^{KK} from a narrow redshift bin. The amplitude depends on small scale physics (via dK/dz) but the "shape" in L is predicted by linear perturbation theory and depends only on the source redshift z.



This independence of small-scale physics means that we can test the model using simplified simulations:

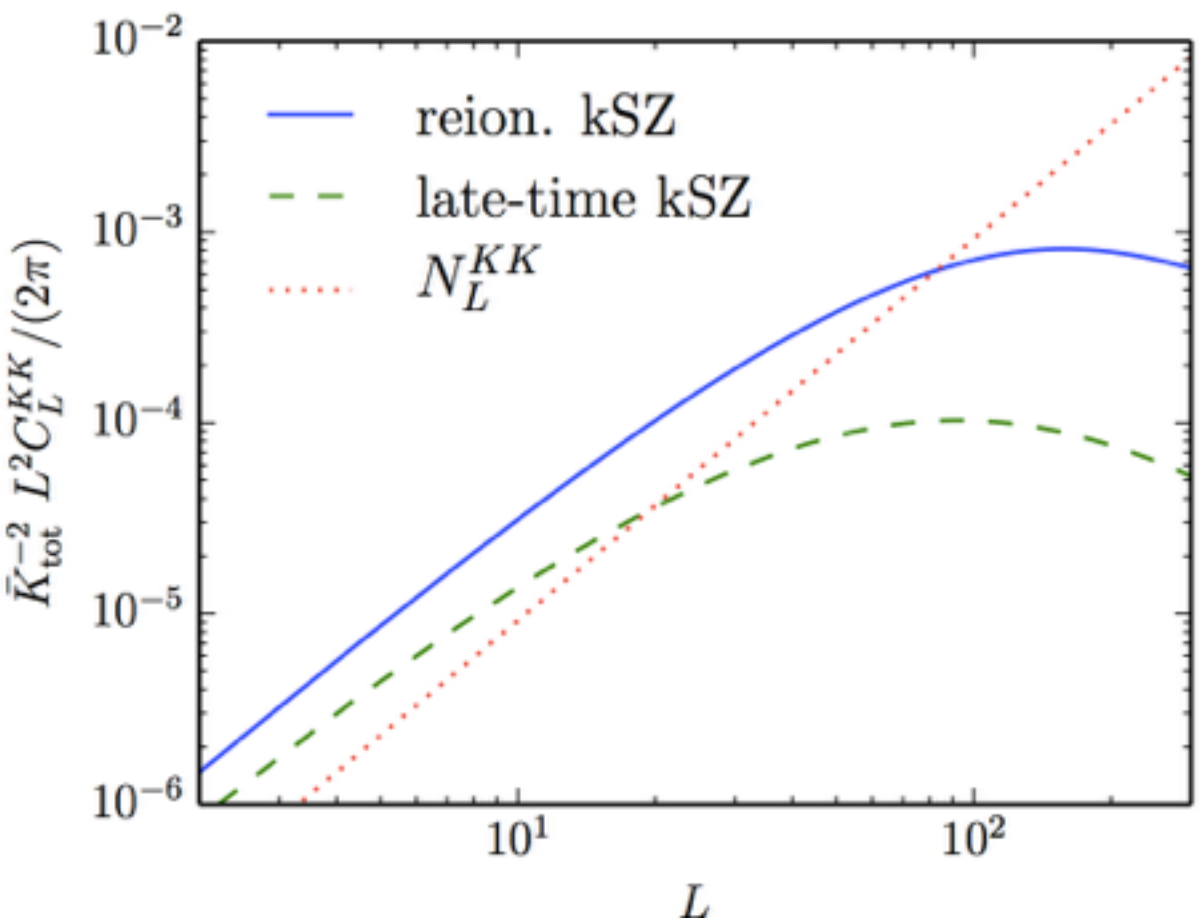
- Electrons = dark matter particles
- 2LPT approximation to N-body
- Cubic (not lightcone) geometry

Agreement is excellent (after adding a constant to the model C_L^{KK}, for reasons I'll explain shortly)



Since different source redshifts produce different shapes in L, we can do redshift tomography: by fitting C_L^{KK} as a sum of contributions from different redshift bins, we can try to determine the source redshift distribution of the kSZ.

In particular, it may be possible to separate the late-time and reionization kSZ signal using this approach.



Before presenting signal-to-noise forecasts, let's consider a crucial issue: the other secondary anisotropies (lensing etc.)

So far we've considered contributions to C_L^{KK} from kSZ and counting modes of a Gaussian field (the noise N_L^{KK}).

But since the other secondaries are non-Gaussian, they will also contribute to C_L^{KK} at some level. How do we know our approach is robust? (Indeed, the whole idea was to construct something more robust than the power spectrum C_l^{TT}!)

In the next few slides we will argue that C_L^{KK} is kSZ-dominated on large scales. We'll examine other contributions one at a time.

Some secondaries do not cluster on large scales ($L \lesssim 300$).
E.g. residual SZ is 1-halo dominated, can be modelled as Poisson distributed sources with angular profile $W_l(M, z)$

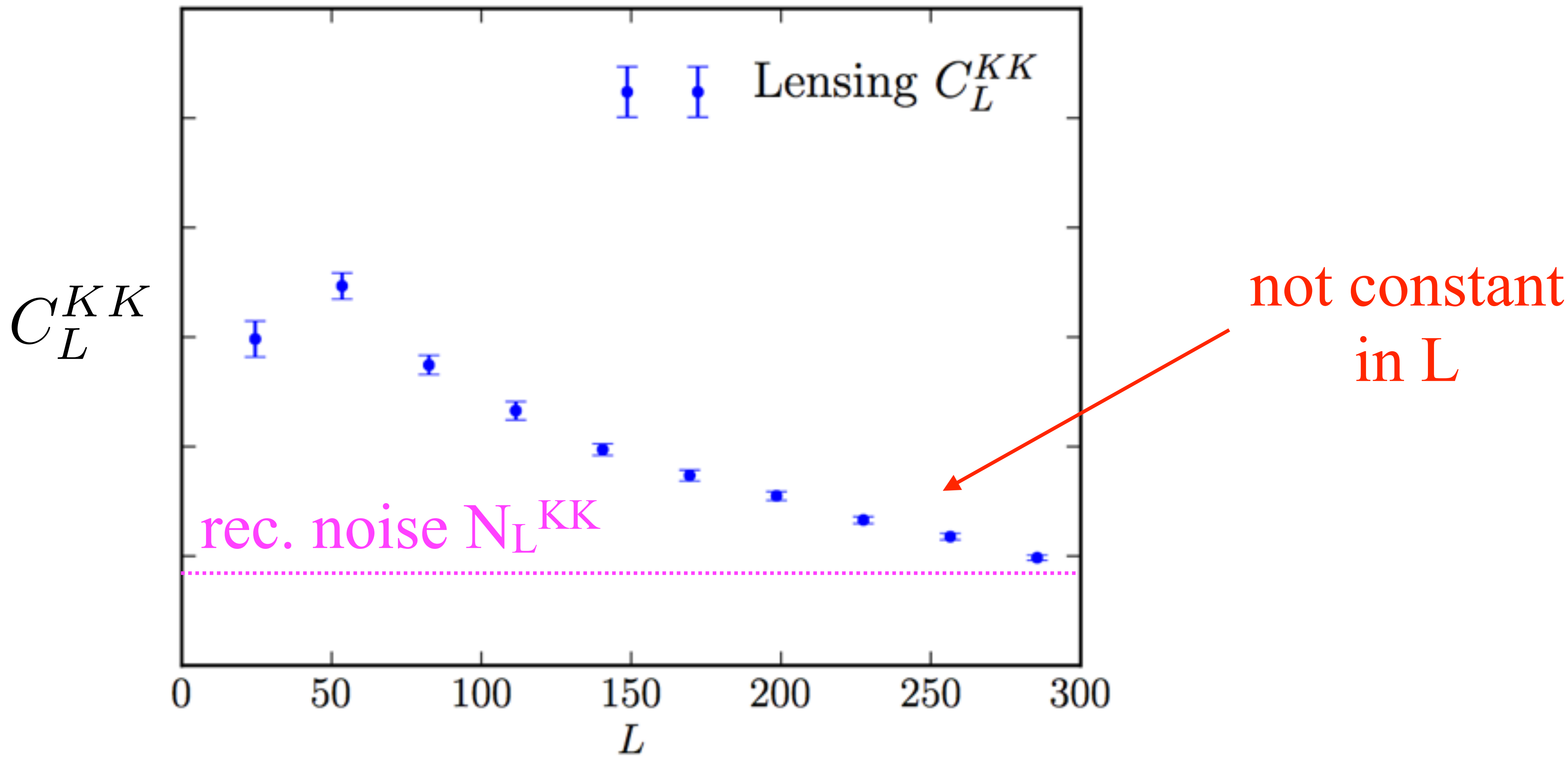
A short calculation shows that C_L^{KK} is constant on scales

$L \ll l_*$ (= characteristic profile size)

To remove this type of contribution, we always marginalize a constant contribution to C_L^{KK}

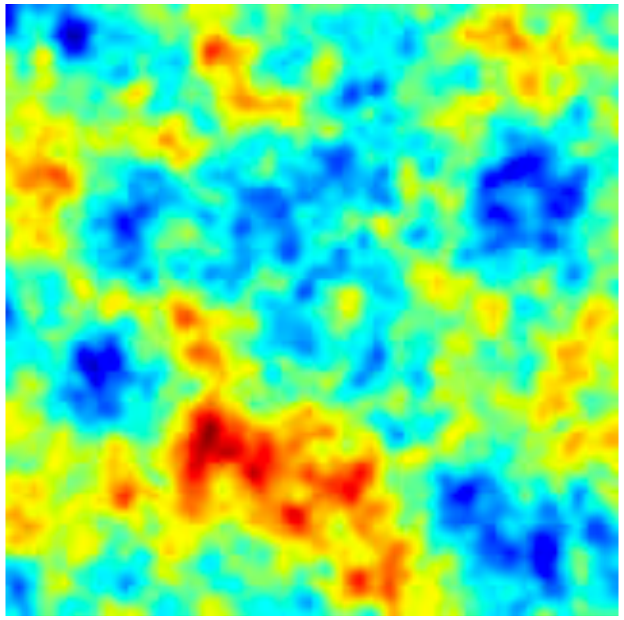
Gravitational lensing is an exception, since there are sources of clustering on large scales. For example, lensing involves $\nabla T_{\rm CMB}$ which has degree scale power.

From Monte Carlo lensed CMB simulations:

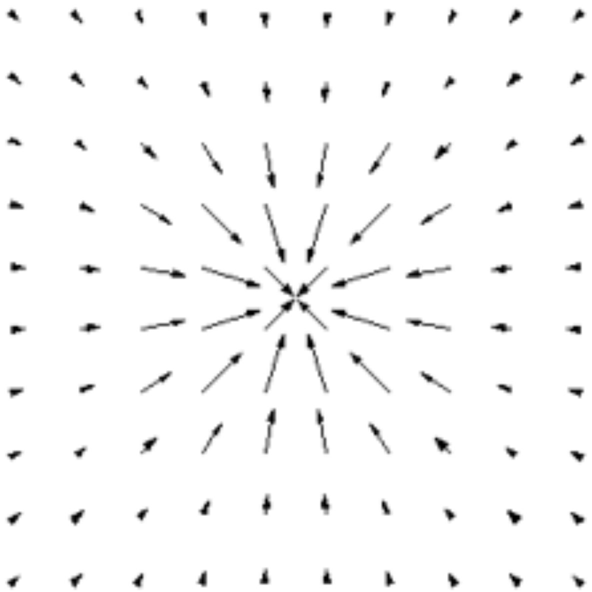


At cartoon level, one might reason as follows.

What are the possible sources of large-scale clustering in K(n), i.e. what determines the locally measured small-scale power in a degree sized patch?



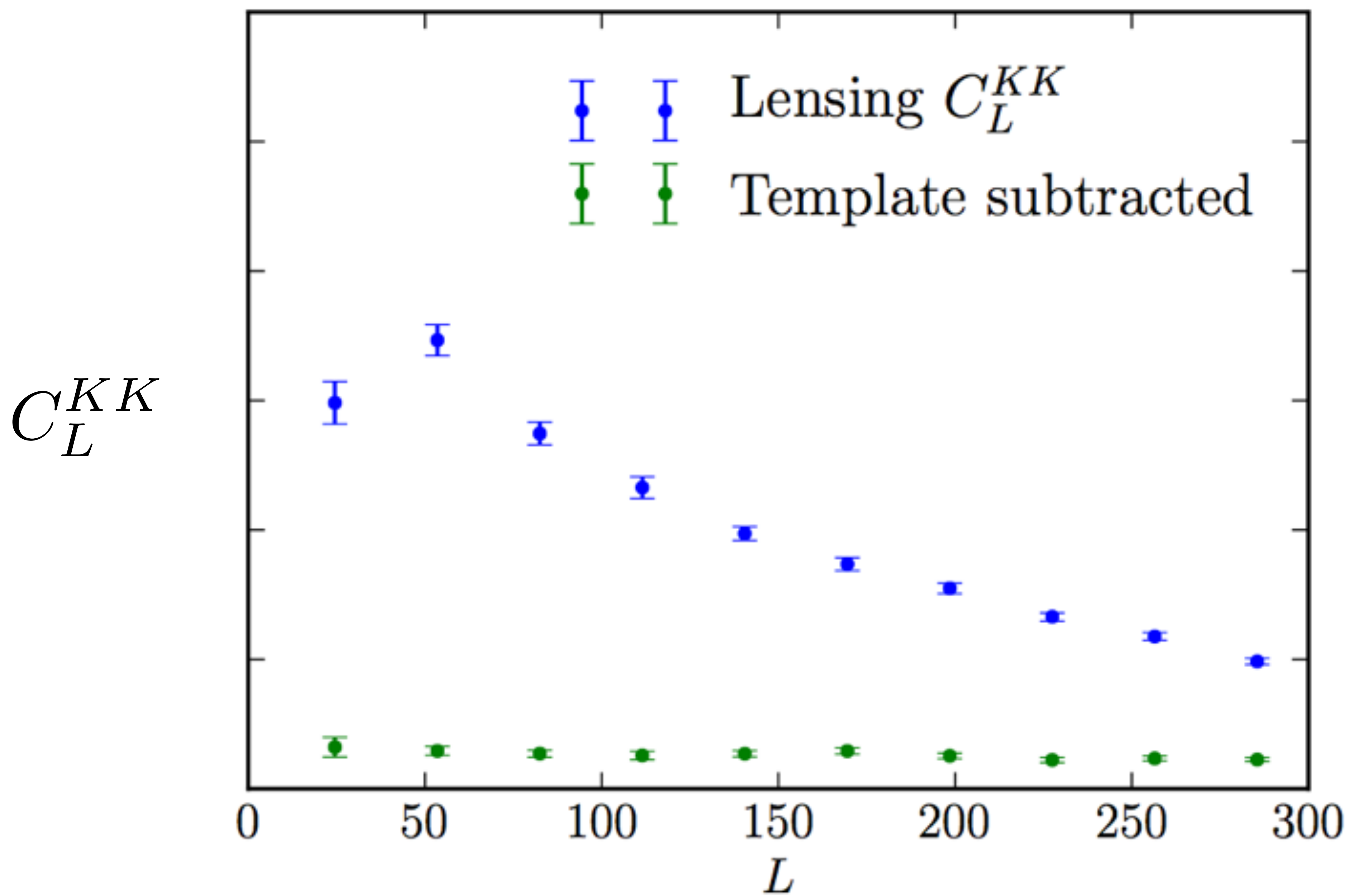
The local gradient of T: since small-scale lensed CMB modes are proportional to ∇T, suggesting a term $K \supset (\nabla T)^2$



Lensing convergence κ: degree-scale magnification shifts small-scale power, suggesting a term $K \supset \kappa$

We tried lens-cleaning K(n) on large scales by template subtraction: treat κ and $(\nabla T)^2$ as template maps, and subtract best-fit multiples.

This works beautifully: almost all power is removed, and what remains is nearly constant in L.

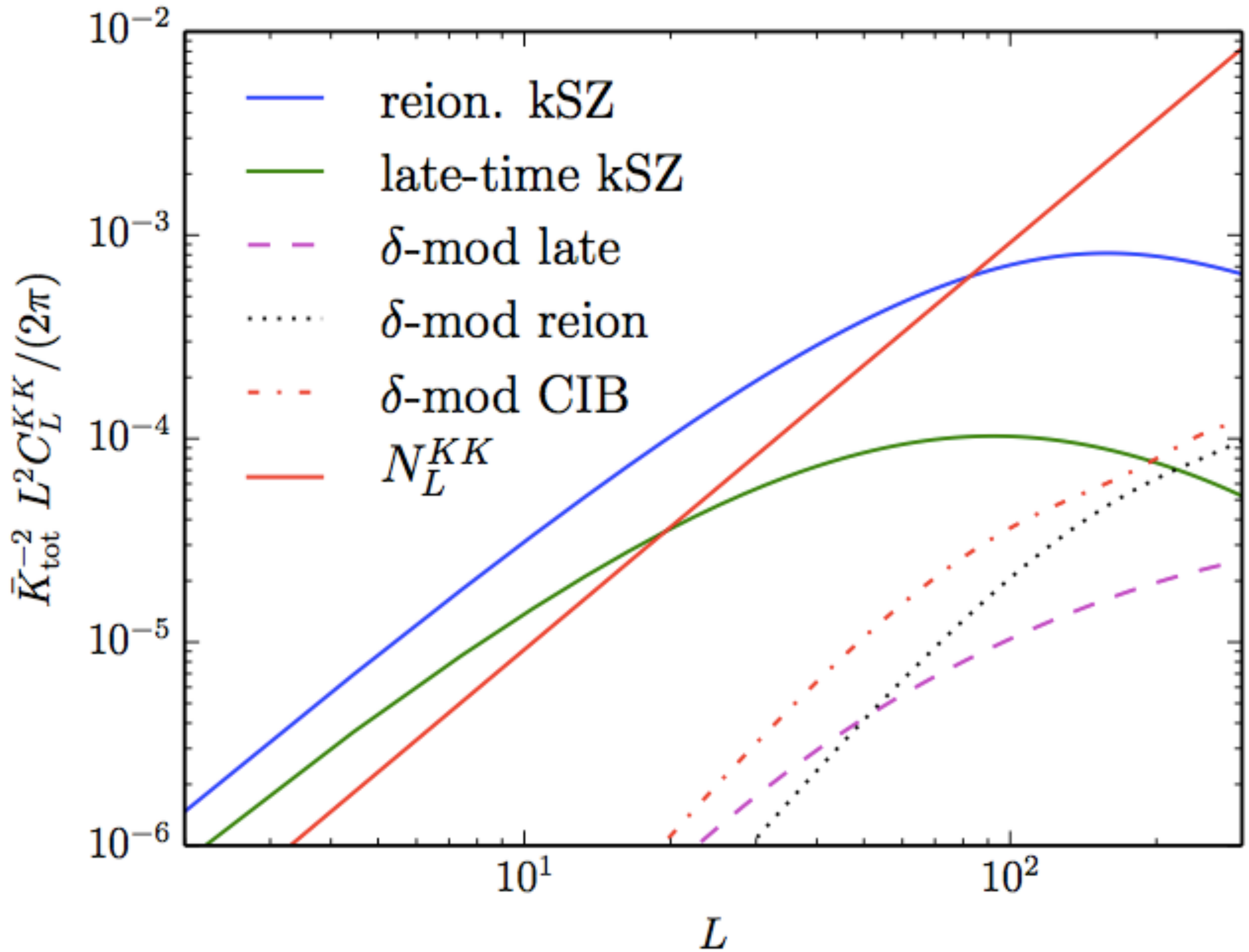


Another type of contribution: large-scale clustering secondaries which trace the matter distribution.

E.g. residual CIB: the number of dusty galaxies in a given region of sky depends on the long-wavelength density field in that region, giving rise to large-scale clustering.

Intuitively, we expect this type of contribution to be subdominant to kSZ on large scales (low L) since there is an extra power of k in the density field, relative to the velocity field. (This is an important technical point which makes the C_L^{KK} idea work!)

Some forecasts for this type of contribution using the halo model:



The non-kSZ contributions appear to be subdominant on large scales, and have different shapes in L so there is not much degeneracy.

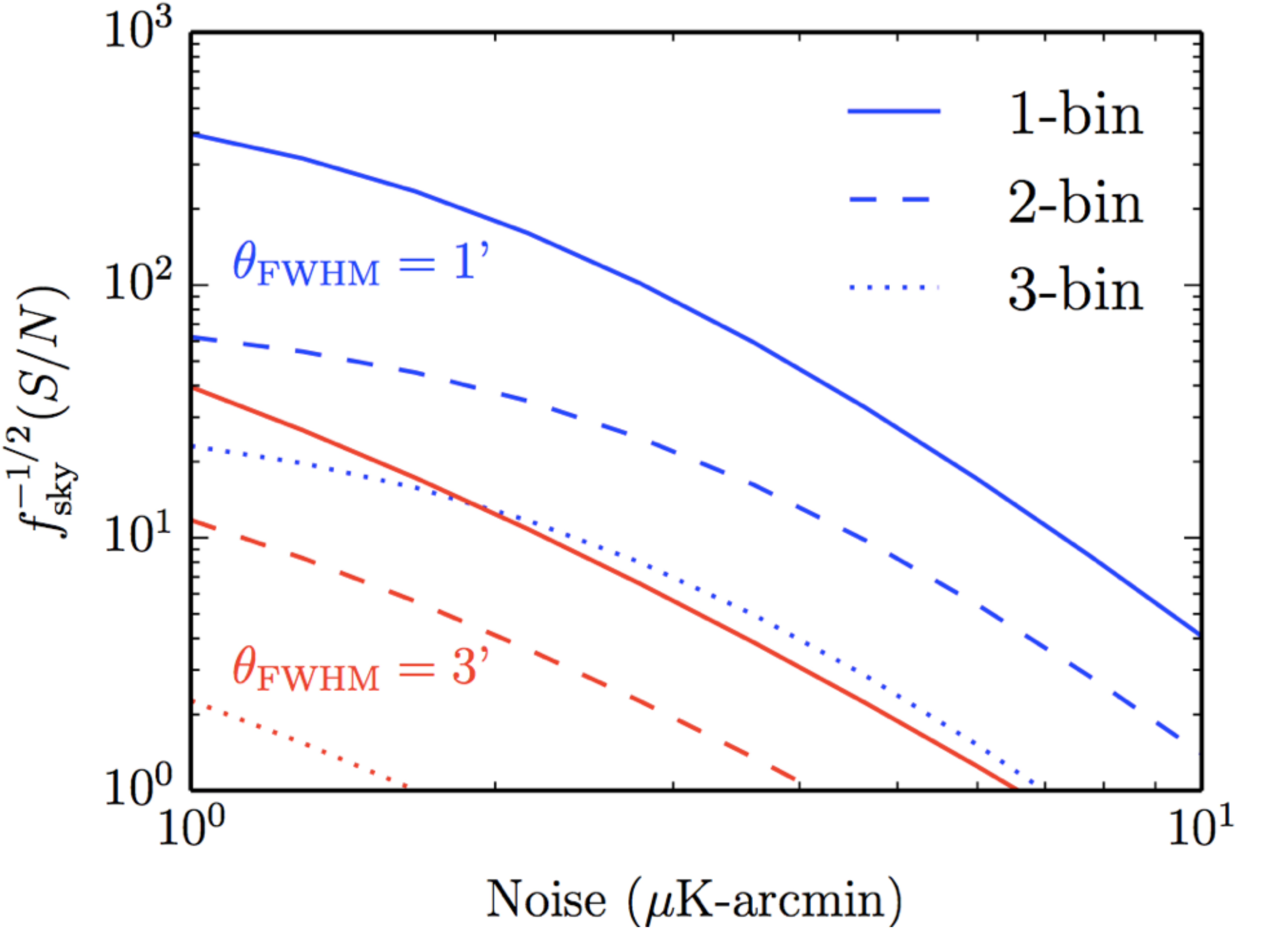
"Bottom-line" signal-to-noise forecasts

We will show forecasts for:

- "One-bin detection": total significance of C_L^{KK}, summed over all source redshifts (single z-bin). Since ~85% of the signal-to-noise is predicted to come from reionization, this would be fairly strong evidence for patchy reionization.

- "Two-bin detection": detection significance of a high-z contribution ($z > 4$), marginalized over amplitude of a low-z contribution. Would be a detection of patchy reionization with no assumptions on the low-z amplitude.

- "Three-bin detection": detection significance of a high-z contribution, marginalized over low-z and intermediate z. Would establish the bimodal redshift dependence of kSZ.



10^3
10^2
10^1
10^0
10^0
10^1
$f_{\rm sky}^{-1/2}(S/N)$
Noise (μK-arcmin)
1-bin
2-bin
3-bin
$\theta_{\rm FWHM} = 1'$
$\theta_{\rm FWHM} = 3'$

- A “third generation” experiment (Adv ACT / SPT-3G) which includes a deep small-field survey (few hundred deg^2) can make a high-significance 1-bin detection of kSZ, and also probe the 2-bin/3-bin regime at some level.

- For a futuristic CMB-S4 type configuration we get 279σ, 44σ, 16σ for $\{1,2,3\}$-bin detections.

- A “clean” probe: other secondaries can be statistically separated.

- Requires low noise and small beam, but can potentially open a powerful and qualitatively new window on patchy reionization from the CMB.

Thanks!