Title: kSZ tomography and its applications to cosmology

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Abstract: Upcoming CMB and large-scale structure experimental data can be cross correlated to reconstruct the large-scale matter velocity field in a process called kinetic Sunyaevâ€“Zel'dovich (kSZ) tomography. Similar to CMB lensing reconstruction, kSZ tomography provides a large-scale probe from small scale observations. kSZ tomography is a powerful probe of cosmology, in particular of primordial non-Gaussianity, and I will discuss how the scientific returns from upcoming galaxy surveys can be enhanced with this method. I will also discuss a general bispectrum approach to kSZ estimation, which unifies several previously known methods.

kSZ tomography for cosmology

Cosmological Frontiers in Fundamental Physics 2019

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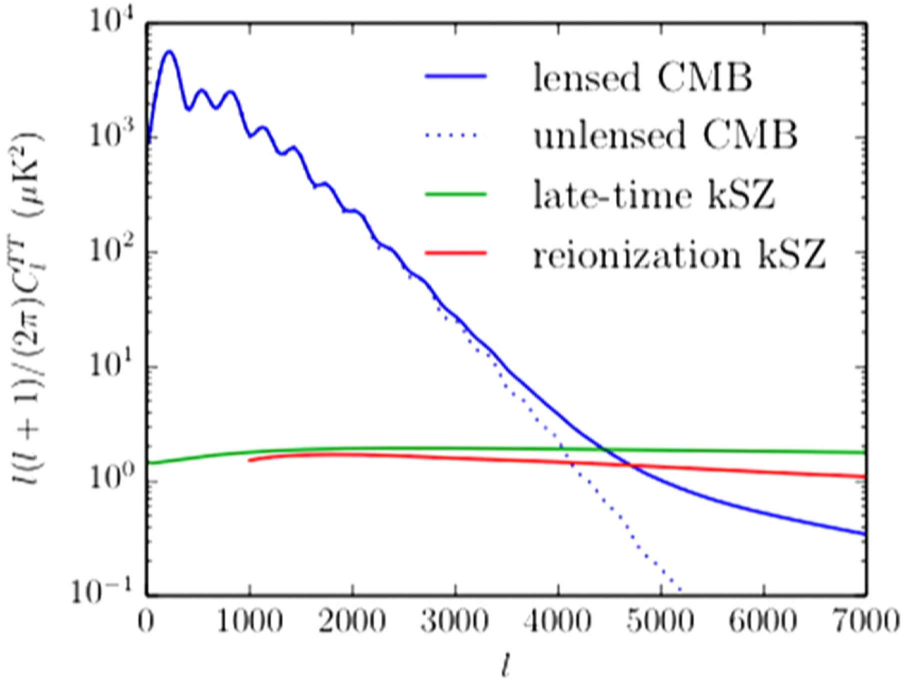
kSZ tomography

arxiv:1810.13423

CMB power spectrum

- Primary anisotropies from recombination: e.g. $\Omega_b, \Omega_c, n_s, r$
- anisotropies from lensing: e.g. m_ν, σ_8
- anisotropies from kSZ: **soon a large signal, what is it good for?**

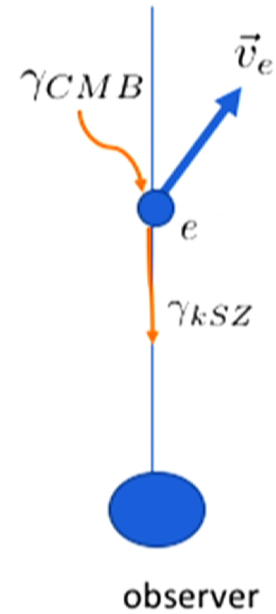


Kinetic Sunyaev-Zeldovich effect

- Thompson scattering of CMB photons on free electrons (in halos)

$$T(\theta) \sim -\int dr\, \rho_e(r,\theta) v_r(r,\theta)$$

Electron density   Radial velocity



- Doppler shift interpretation:
  - For v_r > 0 CMB photons are red shifted (cold spot)
  - For v_r < 0 CMB photons are blue shifted (hot spot)

kSZ tomography

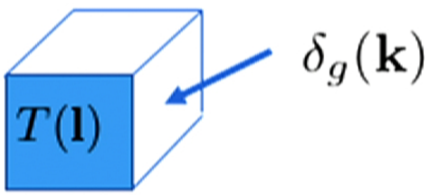
- **kSZ tomography**: Cross-correlate CMB kSZ and galaxies, to get redshift information and gain signal-to-noise.
- Direct cross correlation of CMB kSZ and galaxies vanishes:

$$\langle T(\mathbf{l})\delta_{\mathbf{g}}(\mathbf{k})\rangle = 0$$

- **kSZ tomography bispectrum** (three point function):

$$\langle \delta_g(\mathbf{k})\delta_g(\mathbf{k}')T(\mathbf{l})\rangle = B(\mathbf{k},\mathbf{k}',\mathbf{l})(2\pi)^3\delta^3\left(\mathbf{k}+\mathbf{k}'+\frac{\mathbf{l}}{\chi_*}\right)$$

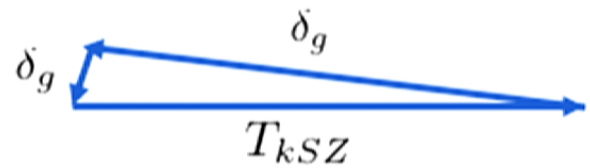
- Here we use a “box approximation”:



Properties of the kSZ tomography bispectrum

- **Squeezed limit** dominates signal-to-noise

  $k_L \ll k_S$ (typically $k_L \sim 10^{-2}$ and $k_S \sim 1\ \mathrm{Mpc}^{-1}$)



- **Interpretation**: We are sensitive to
  - Large-scale velocities.
  - Small-scale electron distribution.

	Astrophysics	**vs**	**Cosmology**
$B \propto$	$P_{ge}(k_S)$	$\times$	$P_{gv}(k_L)$

- **kSZ optical depth degeneracy**. Can trade constant factor between the two power spectra.

Bispectrum estimator

- Bispectrum estimation is very well understood in cosmology
- Use "**CMB bispectrum toolkit**" for kSZ
- Given a bispectrum

$$\langle \delta_g(\mathbf{k}_L)\delta_g(\mathbf{k}_S)T(\mathbf{l})\rangle = B(k,k',l,k_r)\,(2\pi)^3\delta^3\left(\mathbf{k}_L + \mathbf{k}_S + \frac{\mathbf{l}}{D}\right)$$

the optimal estimator is:

$$\hat{\mathcal{E}} = \int \frac{d^3\mathbf{k}}{(2\pi)^3}\frac{d^3\mathbf{k}'}{(2\pi)^3}\frac{d^2\mathbf{l}}{(2\pi)^2}\frac{B^*(k,k',l,k_r)}{P_{gg}(k)\,P_{gg}(k')\,C_l^{TT}}\Big(\delta_g(\mathbf{k})\delta_g(\mathbf{k}')T(\mathbf{l})\Big)(2\pi)^3\delta^3\left(\mathbf{k}+\mathbf{k}'+\frac{\mathbf{l}}{D}\right)$$

- We get the optimal estimator with very little effort, including systematic effects. Are other kSZ estimators optimal?

Equivalence with previous methods

- Several different estimators for kSZ-galaxy cross-correlation have been developed previously (and applied to data).
- We showed that all these estimators are special cases of our bispectrum estimator, if optimally weighted.

Example: **kSZ template method** (Ho et al 2009)

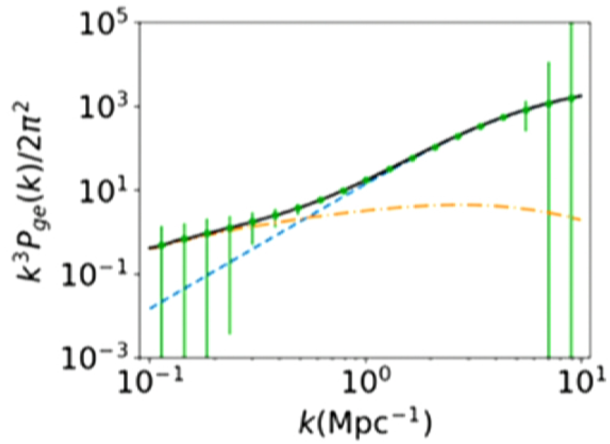
- Step 1: construct a velocity template from the galaxy survey $\delta_g \rightarrow \hat{v}$
- Step 2: construct an electron template from the galaxy survey $\delta_g \rightarrow \hat{\delta}_e$
- Step 3: from these calculate a kSZ template $\hat{T} \sim \hat{v}\ \hat{\delta}_e$
- Step 4: estimate cross-correlation of template and CMB $\left\langle \hat{T}\ T^{CMB} \right\rangle$

$$\Longrightarrow \langle \delta_g(\mathbf{k}_L)\delta_g(\mathbf{k}_S)T(\mathbf{l})\rangle$$

Aside: Astrophysics with kSZ via $P_{ge}(k_S)$

- Halo model calculation of P_{ge}

$$P_{ge}^{1h}(k,z) \;=\; \int_{-\infty}^{\infty} d\ln m \; mn(m,z)\frac{m}{\rho_0}u_e(k|m,z)\frac{\langle N_c(m)\rangle + \langle N_s(m)\rangle u_g(k|m,z)}{\bar{n}_g}$$



- Depends on electron/gas profile u_e of the halo, eg. AGN feedback.
- We can measure P_{ge} to good precision (with next generation experiments) in a narrow range in k.

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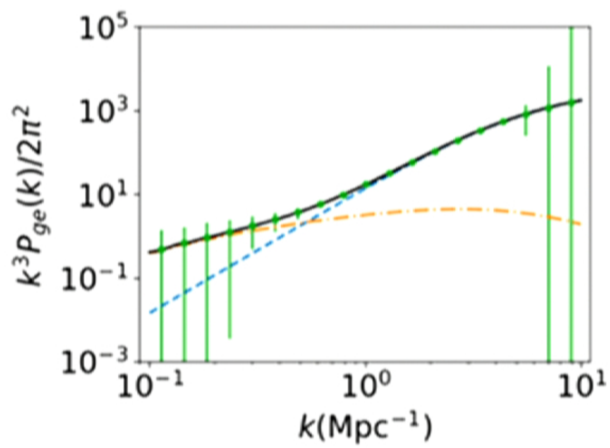

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Cosmology with kSZ: velocity reconstruction

- Another special case of kSZ bispectrum formalism, but a new idea:

$$T(\theta) \sim -\int dr\, \rho_e(r,\theta) v_r(r,\theta)$$

From CMB — From galaxies — Estimate!

- From velocities we can calculate density perturbations.

- This procedure gives the **best tracer of matter on large scales**, better than galaxy surveys. **How does this happen?**

Noise properties of the estimator

Noise power of the estimator:

$$N_{vv}^{\rm rec}(k_L,\mu) = \mu^{-2}\frac{2\pi\chi_*^2}{K_*^2}\left[\int dk_S\, k_S \left(\frac{P_{ge}(k_S)^2}{P_{gg}^{\rm tot}(k_S)C_l^{\rm tot}}\right)_{l=k_S\chi_*}\right]^{-1}$$

$\mu = \widehat{\mathbf{k}}\cdot\mathbf{n}$
Can't reconstruct transverse modes

Noise independent of k_L

Reconstruction noise depends on

- observed galaxy density
- CMB beam and noise
- But crucially: **It is constant in k**

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Relation to matter density reconstruction

- On large scales we can convert a reconstruction of $\hat{v}_r$ to a reconstruction of the matter density δ , using linear theory:

$$\delta(\mathbf{k}) = \left(\frac{k}{faH}\right)\left(\frac{k_r}{k}\right)^{-1} v_r(\mathbf{k})$$

- Thus we get a density reconstruction with noise

$$N_{\delta\delta}(\mathbf{k}_L) = \left(\frac{\mathbf{k}_{Lr}}{\mathbf{k}_L}\right)^{-2}\left(\frac{\mathbf{k}_L}{faH}\right)^{2} N_{v_r}$$

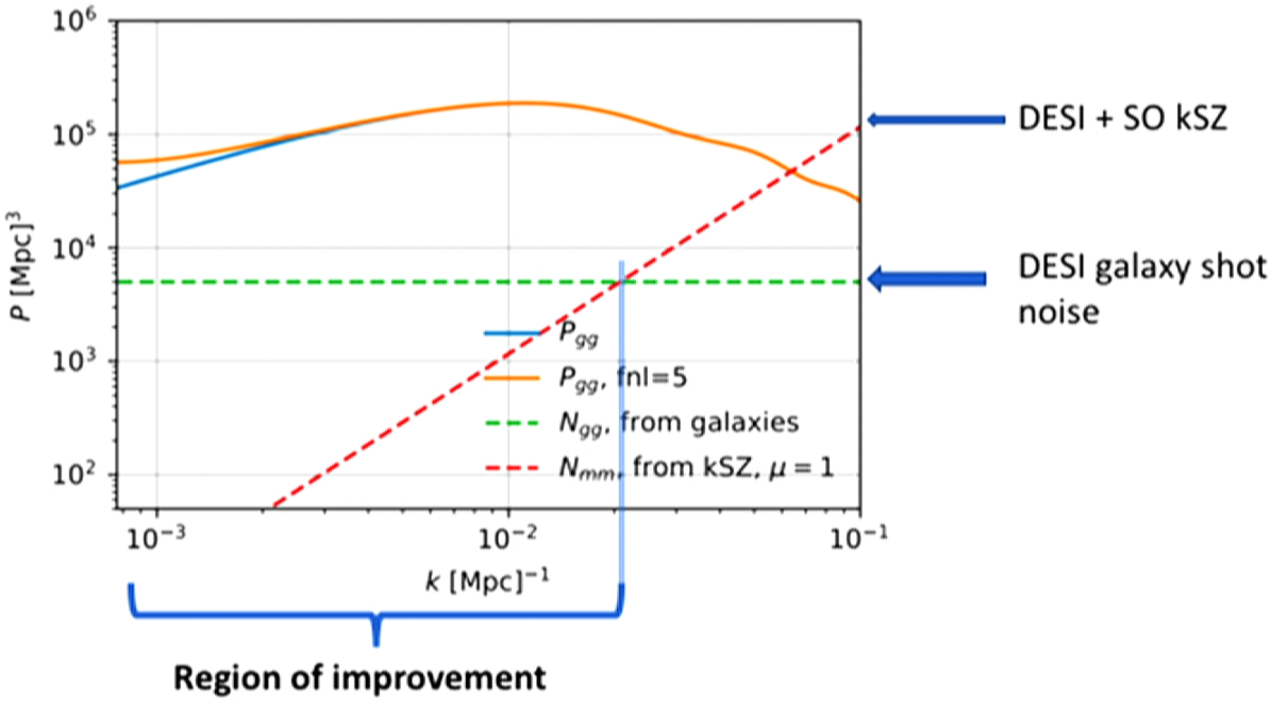
i.e. the noise is **proportional to k^2.**

- This is different from constant galaxy shot noise $N_\delta = \frac{1}{n_g}$

➡ On large scales kSZ velocities will win!

Extremely low noise on large scales

- On large scales, and for **radial modes**, we beat the shot noise of the galaxy catalogue. Example (SO+DESI):



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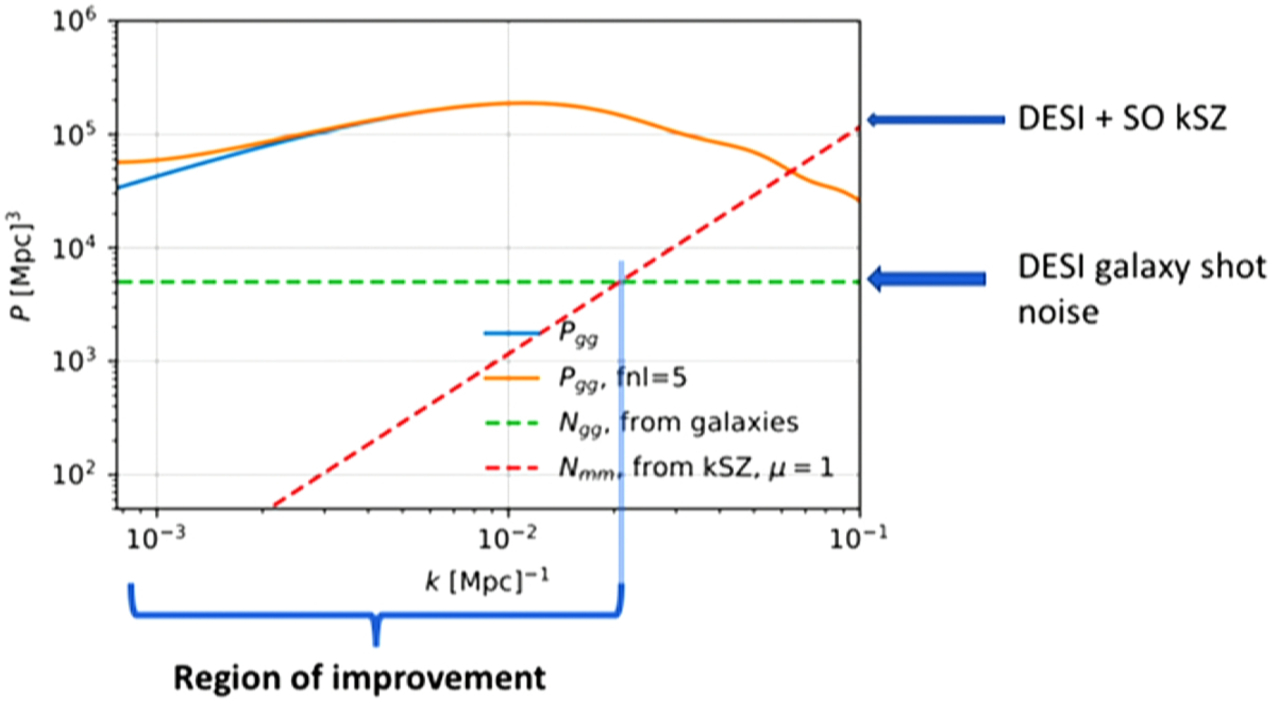
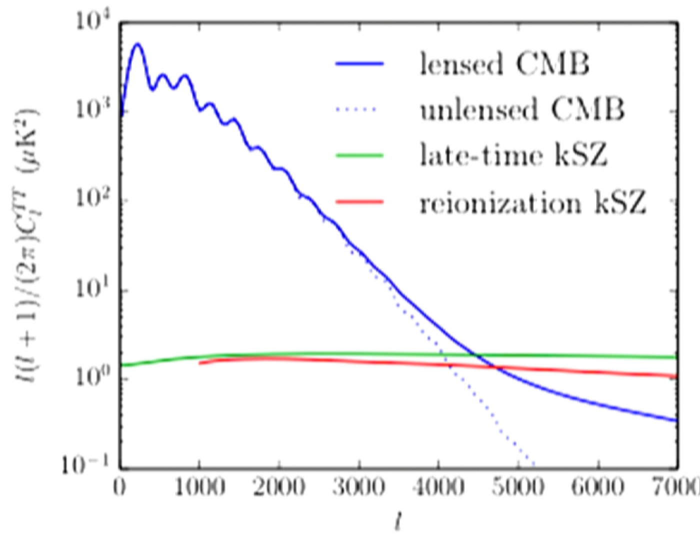


Complementary to CMB lensing

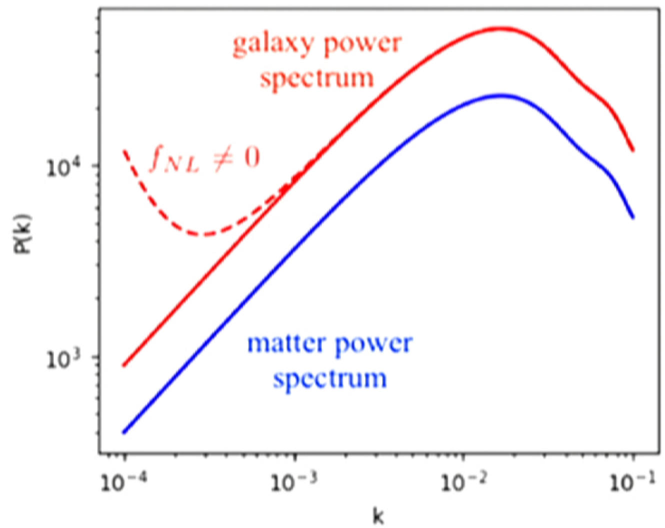
- kSZ velocity reconstruction is a new large scale probe from small scale CMB data.
- Complementary to CMB lensing, which is also a large scale probe from small scale CMB.
- Interestingly kSZ probes radial modes, while lensing probes transverse modes.
- Applications in principle similar to CMB lensing, but much less studied!



→ kSZ velocities are a powerful new cosmology observable

Scale-dependent bias and non-Gaussianity

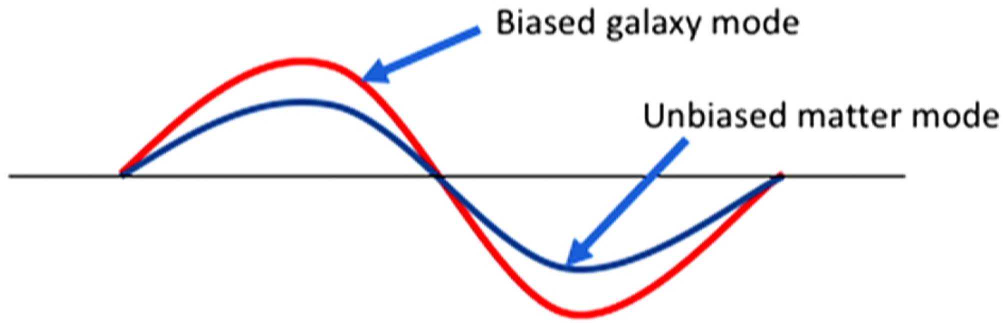
- Local non-Gaussianities are visible in the **galaxy bias b_g** on large scales (Dalal et. al. 2008):



- In the future galaxies will be a better probe than CMB, but $f_{NL}<1$ will remain challenging.
- kSZ velocities are a tracer of the matter power, i.e. unbiased. **So how can they help?**

Sample variance cancellation with kSZ velocities

- Idea of sample variance cancellation (Seljak et al 2008):



- Each mode by itself is stochastic, but the ratio is not. Schematically:

$$\frac{\delta_g}{\delta_m} = \left(b_g + \frac{f_{NL}}{k^2} \alpha \right)$$

- Here our unbiased modes comes from kSZ tomography v_r. The low noise means that we can "cancel sample variance" effectively.

Fisher forecast for f_NL

- Input data: $(v_{\mathbf{k}}, \delta^g_{\mathbf{k}})$

From kSZ+galaxies — From galaxies

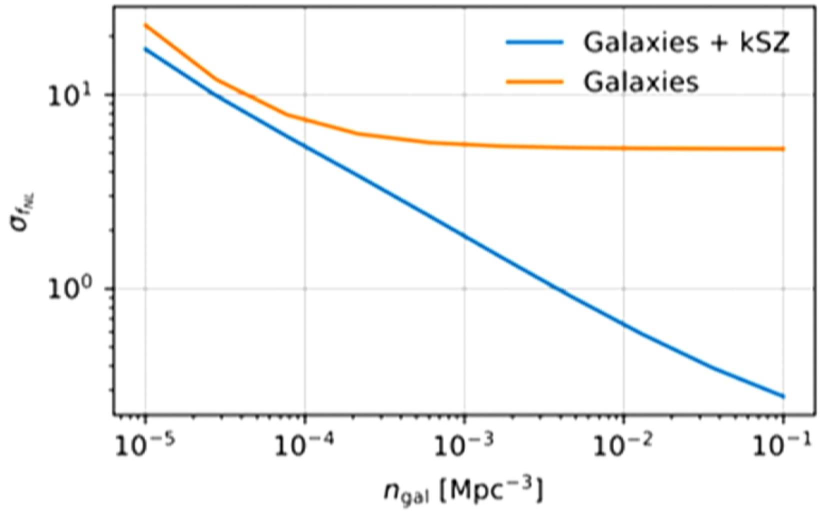
- Power spectra

$$
\begin{aligned}
P_{gg}(k,z,\mu) &= \left(b_g + f_{NL}\frac{\beta_f}{\alpha(k,z)} + f\mu^2\right)^2 P_{mm}(k,z) \\
P_{vg}(k,z,\mu) &= \left(\frac{b_v f a H}{k}\right)\left(b_g + f_{NL}\frac{\beta_f}{\alpha(k,z)} + f\mu^2\right) P_{mm}(k,z) \\
P_{vv}(k,z) &= \left(\frac{b_v f a H}{k}\right)^2 P_{mm}(k,z),
\end{aligned}
$$

- Marginalize over galaxy bias an kSZ optical depth degeneracy.
- Include RSD and photo-z errors.

Sample variance cancellation again

- Scaling with galaxy density



- There are much more galaxies, even beyond LSST. Constraint is far from saturated.