Reconstructing Cosmic velocities with the kinetic Sunyaev-Zeldovich effect

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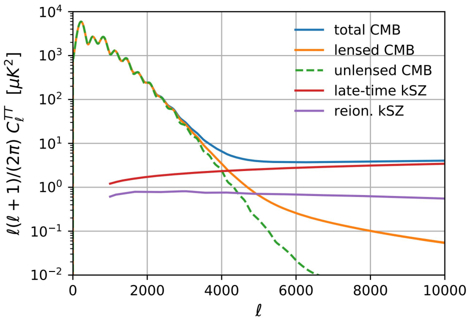
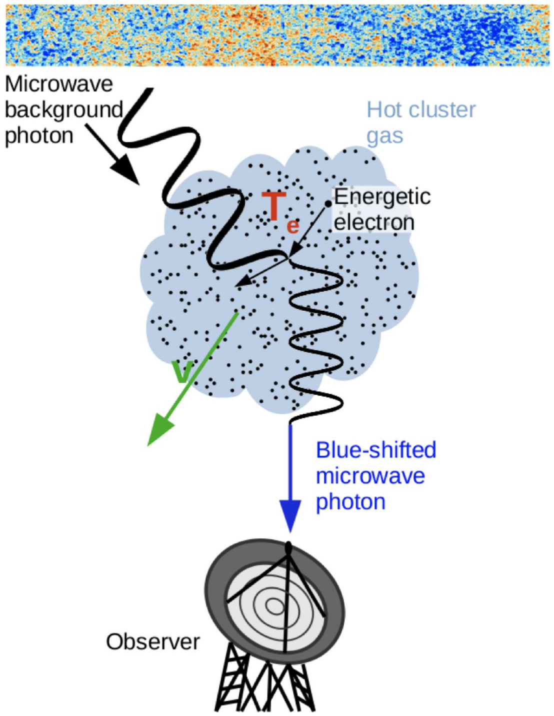
Kinetic Sunyaev-Zeldovich (kSZ)

- Sourced by scattering of CMB off free electron clouds with bulk radial velocity

$$T(\theta) \propto \underbrace{v_r}_{\text{large-scale velocity}} \; \underbrace{n_e}_{\text{Small-scale electron fluctuation}}$$

- Dominant component at arc-min scales





- **SNR:** CMB-S4 + (DESI, LSST-Y1, LSST-Y10) = (653, 333, 366)

kSZ velocity reconstruction

A fixed realization of v_r produces non-vanishing correlation between δ_g and T

A Quadratic Estimator (QE) can utilize this to reconstruct v_r

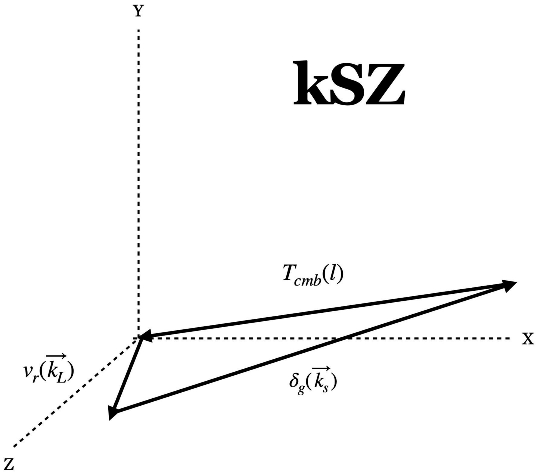
$$\hat{v}_r\big|_{fix\ k_L} \sim \delta_g(k_s)T(l) \sim \langle\delta_g(k_s)\delta_e(k_s)\rangle v_r(k_L)$$

More precisely,

$$\hat{v}_r(k_L) = N_{\hat{v}_r}(k_L)\int \frac{P_{ge}(k_s)}{P_{gg}(k_s)C_l}\delta_g(k_s)T(l)_{l=k_s\chi_*}$$

Reconstruction noise @ leading order is white

$$N_{\hat{v}_r}(k_L) \propto \left[\int \frac{P_{ge}(k_s)^2}{P_{gg}(k_s)C_l}\right]^{-1}_{l=k_s\chi_*} \quad (\text{independent of } \mathrm{k_L})$$



$$\boxed{P_{g\hat{v}_r} \propto B(k_L, k_s, l, k_{L_r})}$$

kSZ velocity Reconstruction

$\hat{v}_r$ gives the best probe of cosmological modes on large-scales!!

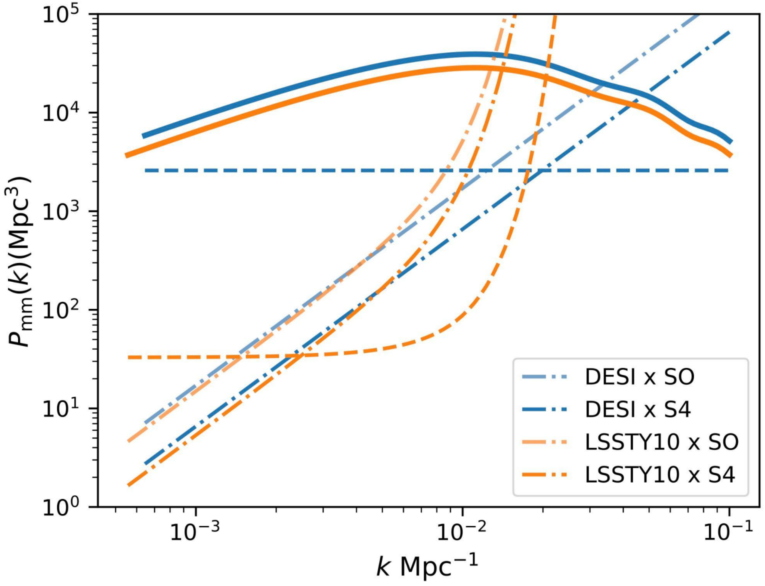
How?

On large-scales fields are linearly related

Using continuity relation for large-scales

$$N_{\delta_m}(k_L) = \left[\frac{k_L}{\mu f a H}\right]^2 N_{\hat{v}_r}(k_L)$$

$$N_{\delta_m} < N_{shot} \text{ for } \mathrm{k_L} \simeq 0.01 \, \mathrm{Mpc}^{-1}$$



Application:

Constraining local non-gaussianity using sample variance cancellation

$$\delta_g(k_L) = b_g \delta_m(k_L)$$

$$f_{NL} \neq 0 \Rightarrow b_g \to b_g + \Delta b(k, f_{NL})$$

$\sigma(f_{NL}|\delta_g)$ limited by sample variance but $\sigma(f_{NL}|\delta_g, \delta_2)$ is not! Need additional tracer!

Using $\hat{v}_r$ as the additional tracer

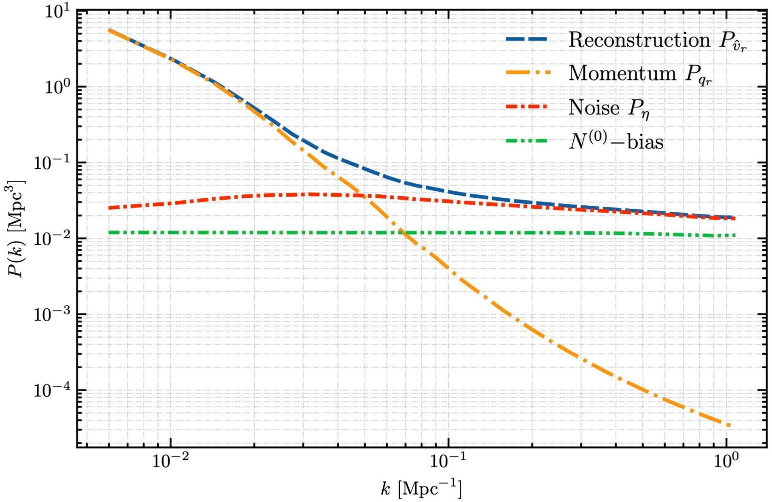
$$\sigma_{f_{NL}} = \begin{cases} 1\text{-}2 & \text{LSST} \\ 1.0 & \text{LSST + SO [Munchmeyer et al. 18]} \\ 0.7 & \text{LSST + CMB-S4 [Munchmeyer et al. 18]} \end{cases}$$

Forecast rely on leading order noise model! Non-linearity can ruin this picture!

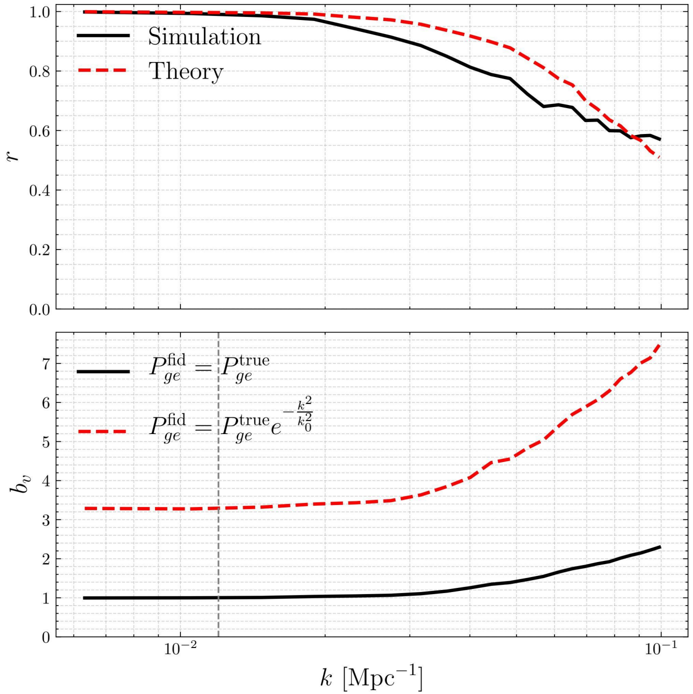
Reconstruction with simulations

- We use suite of 100 N-body simulations.
- ~ DESI X CMB-S4 configuration

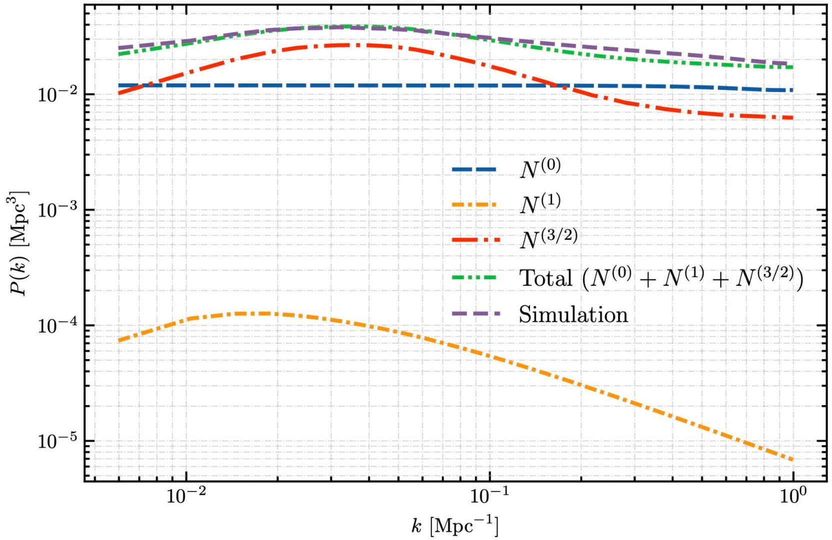
Reconstruction Noise: 2-3 X $N_{\hat{v}_r}$



Map level expectations hold!



Revisiting Noise



Under reasonable simplification

$$\hat{v}_r \sim \delta_g T \sim \delta_g \delta_e v_r + \delta_g T_{non-kSZ}$$

$$P_{\hat{v}_r \hat{v}_r} = P_{v_r v_r} + N^0 + N^1 + N^{3/2}$$

$$P_{\hat{v}_r \hat{v}_r} \longrightarrow (\delta_g v_r \delta_e)(\delta_g v_r g \delta_e)$$

$$N^0 \longrightarrow \langle \delta_g \delta_g \rangle \langle T_{\text{other}} T_{\text{other}} \rangle + (\delta_g v_r \delta_e)(\delta_g v_r \delta_e)$$

$$N^1 \longrightarrow (\delta_g v_r \delta_e)(\delta_g v_r \delta_e)$$

Gaussian, subdominant contribution

$$N^{3/2} \longrightarrow \langle (\delta_g v_r \delta_e)(\delta_g v_r \delta_e) \rangle_{ng}$$

Non-gaussian, 6-point contribution

Together they accurately account for the reconstruction noise in simulations!

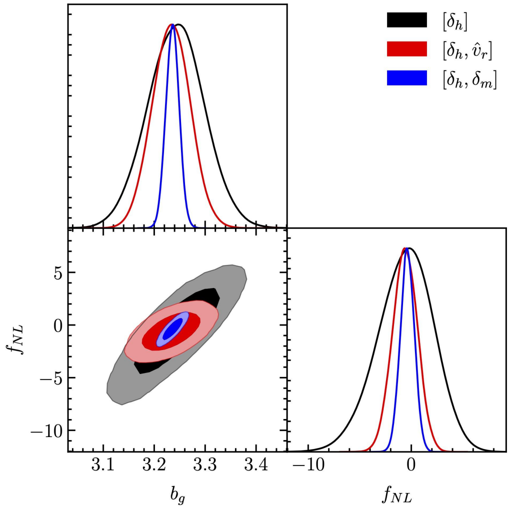
Constraining f_{NL}

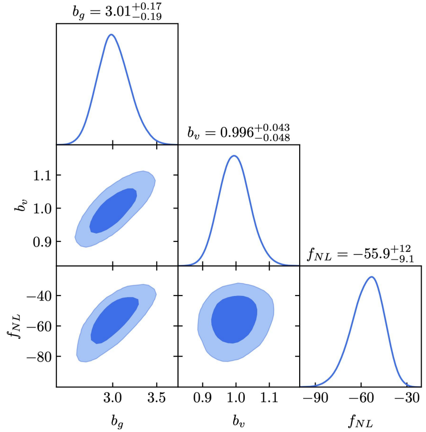
- Defined a mode based likelihood model

$$L(b_g, b_v, f_{NL}) \propto \exp\left(-\frac{D^T C^{-1} D}{2}\right)$$

$$D = [\delta_g, \hat{v}_r] \qquad C = \begin{pmatrix} P_{gg} + \frac{1}{n_g} & P_{gv} \\ P_{gv} & P_{vv} + N^{(0)} \end{pmatrix}$$

- We recover unbiased estimates of f_{NL}
- SVC works: error-bars reduce by $\boxed{\sim 2.5 \text{ times}}$ compared to galaxy-only case





Thanks!