Title: kSZ tomography and its applications to cosmology

Speakers: Moritz Munchmeyer

Collection: Cosmological Frontiers in Fundamental Physics 2019

Date: September 06, 2019 - 11:30 AM

URL: http://pirsa.org/19090018

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
Moritz Münchmeyer, Perimeter Institute
Work with:

Simone Ferraro  Utkarsh Giri  Matt Johnson  Mathew Madhavacheril  Kendrick Smith
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. $m_\nu$, $\sigma_8$
- 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:
  \[ \langle T(1)\delta_g(k) \rangle = 0 \]
- **kSZ tomography bispectrum** (three point function):
  \[ \langle \delta_g(k)\delta_g(k')T(1) \rangle = B(k, k', l)(2\pi)^3\delta^3 \left( k + k' + \frac{1}{\chi_*} \right) \]
- Here we use a “box approximation”:
Properties of the kSZ tomography bispectrum

- **Squeezed limit** dominates signal-to-noise
  \[ k_L \ll k_S \text{ (typically } k_L \sim 10^{-2} \text{ and } k_S \sim 1 \text{ Mpc}^{-1} ) \]

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

\[ T_{kSZ} = \delta_g \]

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

\[ B \propto P_{ge}(k_S) \times P_{gv}(k_L) \]
Bispectrum estimator

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

\[ \langle \delta_g(k_L)\delta_g(k_S)T(l) \rangle = B(k, k', l, k_r) (2\pi)^3 \delta^3 \left( k_L + k_S + \frac{1}{D} \right) \]

the optimal estimator is:

\[ \hat{\epsilon} = \int \frac{d^3k}{(2\pi)^3} \frac{d^3k'}{(2\pi)^3} \frac{d^2l}{(2\pi)^2} \frac{B^*(k, k', l, k_r)}{P_{gg}(k) P_{gg}(k')} C_l^{TT} \left( \delta_g(k)\delta_g(k')T(l) \right) (2\pi)^3 \delta^3 \left( k + k' + \frac{1}{D} \right) \]

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

\[ \left\langle \delta_g(k_L) \delta_g(k_S) T(1) \right\rangle \]
Aside: Astrophysics with kSZ via $P_{ge}(k_S)$

- Halo model calculation of $P_{ge}$

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

- 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 $k$. 
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 $k$. 
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:

\[ N_{vv}^{\text{rec}}(k_L, \mu) = \mu^{-2} \frac{2 \pi X_s^2}{K_s^2} \left[ \int dk_S k_S \left( \frac{P_{ge}(k_S)^2}{P_{tot}(k_S)C_{l,tot}} \right)_{l=k_S x_s} \right]^{-1} \]

\[ \mu = \hat{k} \cdot n \]

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** \( k \)
Noise properties of the estimator

Noise power of the estimator:

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

\[ \mu = \hat{k} \cdot n \]

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 \( k \)
Relation to matter density reconstruction

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

$$\delta(k) = \left( \frac{k}{f\alpha H} \right) \left( \frac{k_r}{k} \right)^{-1} \nu_r(k)$$

• Thus we get a density reconstruction with noise

$$N_{\delta\delta}(k_L) = \left( \frac{k_{Lr}}{k_L} \right)^{-2} \left( \frac{k_L}{f\alpha H} \right)^2 N_{\nu r}$$

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):
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):

![Graph showing comparison of DESI + SO kSZ and DESI galaxy shot noise](image)

Region of improvement
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):

![Galaxy power spectrum](image)

- 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: \((v_k, \delta^g_k)\)
  
  From kSZ+galaxies  From galaxies

- Power spectra

\[
P_{gg}(k, z, \mu) = \left( b_g + f_{NL} \frac{\beta_f}{\alpha(k, z)} + f\mu^2 \right)^2 P_{mm}(k, z)
\]

\[
P_{vg}(k, z, \mu) = \left( \frac{b_v f a H}{k} \right) \left( b_g + f_{NL} \frac{\beta_f}{\alpha(k, z)} + f\mu^2 \right) P_{mm}(k, z)
\]

\[
P_{vv}(k, z) = \left( \frac{b_v f a H}{k} \right)^2 P_{mm}(k, z),
\]

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

- Scaling with galaxy density

![Graph showing scaling with galaxy density]

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