kSZ cosmology

- Madhavacheril, Munchmeyer, Johnson, Smith, ...

$$\frac{\Delta T}{T} \simeq -\tau \, v_{los} = -\int n_e \sigma_T \, v_{los} \, dl$$

- dominant thermal anis. at $l \gtrsim 4000$

$\Rightarrow$ use kSZ to estimate $v(x)$!

Analogy: CMB lensing

$$T_{obs}(\vec\theta) = T(\vec\theta - \vec d)$$
$$= T(\vec\theta) - \vec d \cdot \vec\nabla T + \ldots$$

$d \sim$ arcmin
$T \sim$ degree

FT: $T_{obs}(\vec l) = T(\vec l) + i \int d\vec L \; \vec d(\vec L) \cdot (l - L) \, T(l-L) + \ldots$

consider $\langle T(l_1) T(l_2) \rangle$
$$\sim \vec d(l_1 - l_2) \cdot (\vec l_1 - \vec l_2) \, C_l^{TT}$$

If we know C_l^{TT} (primaries) then we get a noisy estimate of d at $L = l_1 - l_2$

etc.

Many different l_1, l_2 pairs gives same $L \Rightarrow$ combine them!

$$\hat d(L) \sim \int W(\vec L - \vec l, \vec l) \, T(\vec l) \, T(\vec L - \vec l) \, d\vec l$$

Choose weight W to make $\hat d$ estimator unbiased and minimum variance $\Rightarrow$ optimal estimator

We use lots of different triangles with same $\vec L$. Since more modes at high l, we're mainly using small-scale T to get large-scale $\vec d$.

⇒ Use exact same reasoning for kSZ.

Consider $\langle T(\ell)\, \delta_{gal}(k) \rangle$

→ has terms like $v(k - \ell/D)\, P_{ge}(k)$ $(\times\, T_{CMB}\, \sigma_T$ etc...$)$

↑ distance to LSS

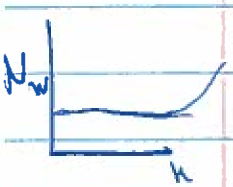
Using same reasoning as in CMB lensing, write down optimal estimator for v:

$$\hat{v}(k_\ell) \sim \int W(k_\ell, k_s)\, \delta_g(k_s)\, T((k_s - k_\ell)\cdot D)$$

Like before: choose W to give optimal $\hat{v}$

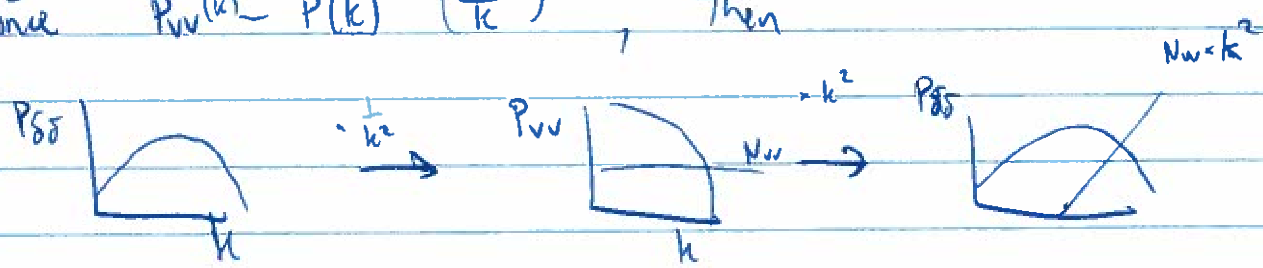
use lots of short-wavelength T and δ modes to get long-wavelength v modes.

Note: (1) since $\langle T\delta \rangle$ scales with P_{ge}, which is unknown, we have overall uncertainty in amplitude of v called "optical depth degeneracy"



(2) noise power spectrum $N_{vv}(k)$ is indep. of k at low k (ie. $k \ll \ell_{max}/D$)

Since $P_{vv}(k) \sim P(k) \left(\frac{faH}{k}\right)^2$, then



so in terms of $P_{\delta\delta}$, equiv. noise is $N_{\delta\delta} \sim N_{vv} \left(\frac{k}{faH}\right)^2$

So estimator does REALLY well at low k!
Noise is even smaller than shot noise in galaxies used in $\hat{v}$ estimator!

For CMB-S4 x DESI, crossover @ $k \approx 0.01$

- But at low k, cosmic variance is big! So who cares about high precision at low k?

$\Rightarrow$ cosmic variance cancellation!

Both $v(\vec{k})$ and $\delta(\vec{k})$ have exact same sample variance (i.e. same realization) but relation between v & δ is indep of sample variance
$\rightarrow$ measure $\boxed{faH}$ without cosmic variance.

Sounds great, but optical depth degeneracy $\rightarrow$ can't measure absolute faH, unknown normalization.

But: can measure scale dependence of f!

Fisher:

$\sigma_{m_\nu} \approx 50$ meV

$\sigma_w \sim 0.1$

What can generate $f(k)$?

- neutrinos: f changes by $O\left(\frac{\Omega_\nu}{\Omega_m}\right)$ at free-streaming scale

- dark energy: perturbations $\propto (1+w)$ for adiabatic