Max-Planck-Institut für Astrophysik

Cross-Correlation of kSZ with 21 cm signal and τ

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Outline:

- Basics of kSZ
- Simulations
- Results
  - Correlation of tau with kSZ
  - Correlation of 21cm with kSZ
  - Correlations of kSZ^2
- Conclusions

kinetic Sunyaev-Zel'dovich effect:

kSZ effect can be expressed as:

LOS unit vector   peculiar velocity

$$\Delta T_{\mathrm{kSZ}}(\hat{\gamma}) = -T_0 \int d\tau e^{-\tau} \frac{\hat{\gamma}\cdot\vec{v}}{c}$$

optical depth

it depends mainly on

$$\vec{q} \equiv x_e(1+\delta)\vec{v}$$

kinetic Sunyaev-Zel'dovich effect:

The contribution of $\vec{q}$ to kSZ can be separated into two parts:

1. transverse (or curl) mode:

$$\vec{q}_{\perp}(\vec{k}) = \vec{q}(\vec{k}) - \hat{k}[\vec{q}(\vec{k}) \cdot \hat{k}]$$

2. longitudinal (or gradient) mode:

$$\vec{q}_{||}(\vec{k}) = \hat{k}[\vec{q}(\vec{k}) \cdot \hat{k}]$$

kinetic Sunyaev-Zel'dovich effect :

Auto-power spectrum of mode $\vec{q}_\perp(\vec{k})$ (Park et al. 2013):

$$C_\perp(l) = \left(\frac{\sigma_T N_{b,0} T_0}{c}\right)^2 \int \frac{ds}{s^2 a^4} e^{-2\tau} \frac{P_{q_\perp}(k = l/s, s)}{2}$$

For mode $\vec{q}_{||}$ (Alvarez 2016):

$$l^2 C_{||}(l) = \int ds \psi_{||}^2 \frac{P_{\delta_0 \delta_0}(k = l/s)}{(l/s)^2}$$

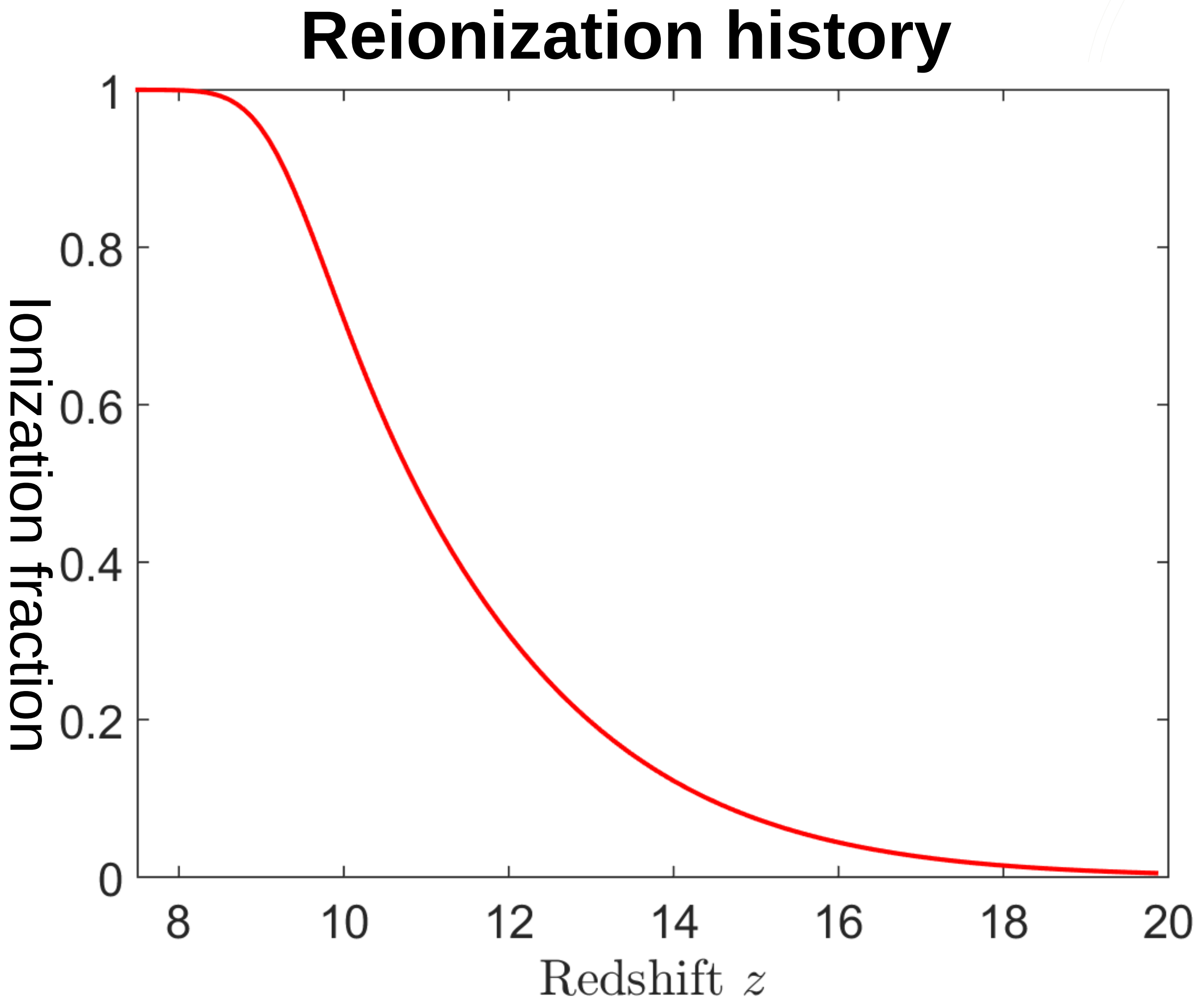
$\vec{q}_{||}$ relevant on large scales $\longrightarrow$ $\vec{q}_{||}(\vec{k}) \propto \vec{v}(k)$

$\psi_{||} \equiv \frac{T_0}{c}\frac{d}{ds}\left(\frac{d\bar{\tau}}{ds} a\dot{D}\right)$ **at high redshift** $\longrightarrow$ $\psi_{||} \propto H \frac{d}{dz}(\bar{x}_e(z) H)$

Simulations:

- Use 21CMFAST (Mesinger, Furlanetto & Cen 2011) to generate the density, ionization, velocity and 21 cm fields
- box length = 2000cMpc, grid size = 400^3, z=20-7.5
- 80 steps for ionization and 21 cm field, 400 steps for density and velocity field with step length (dz) equalling 25 cMpc or 5 cMpc along LOS.
- 60 samples totally: run the simulations 20 times, each one give 3 independent samples along different axis.

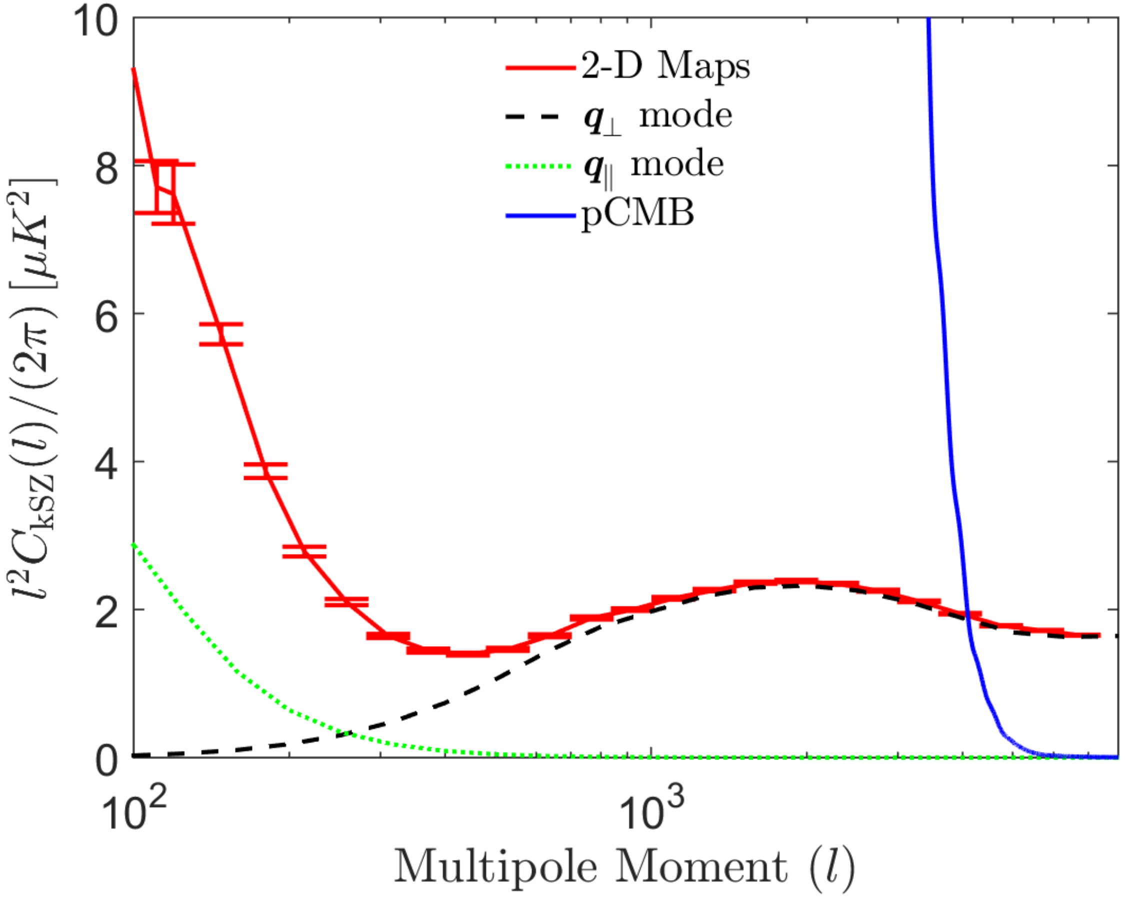
Results



The Thomson scattering optical depth is 0.1.

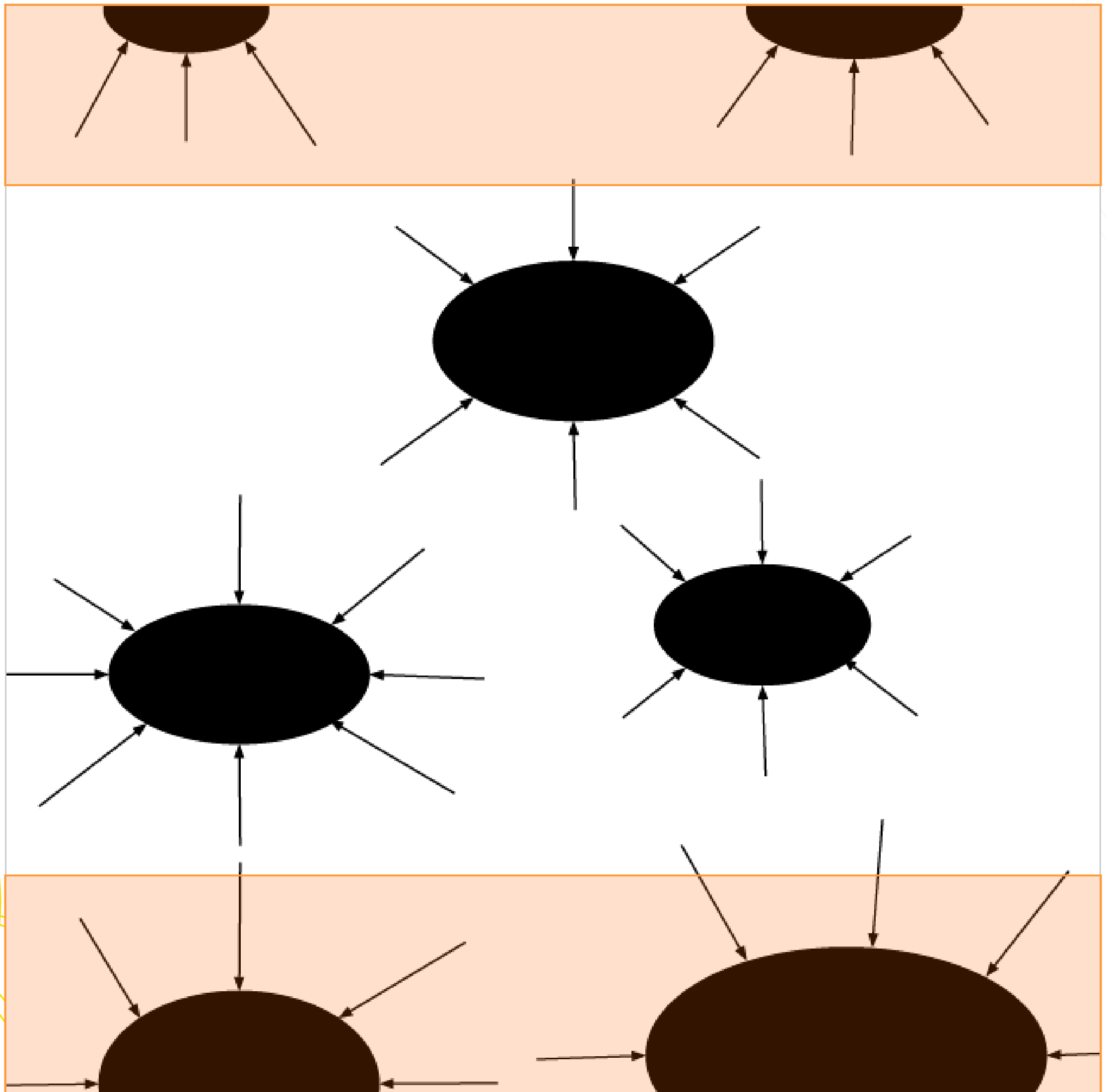
Results

Auto-power spectrum of kSZ



Result from 2-D maps is consistent with analytic calculation at small scales but not at large scales.

Problem:



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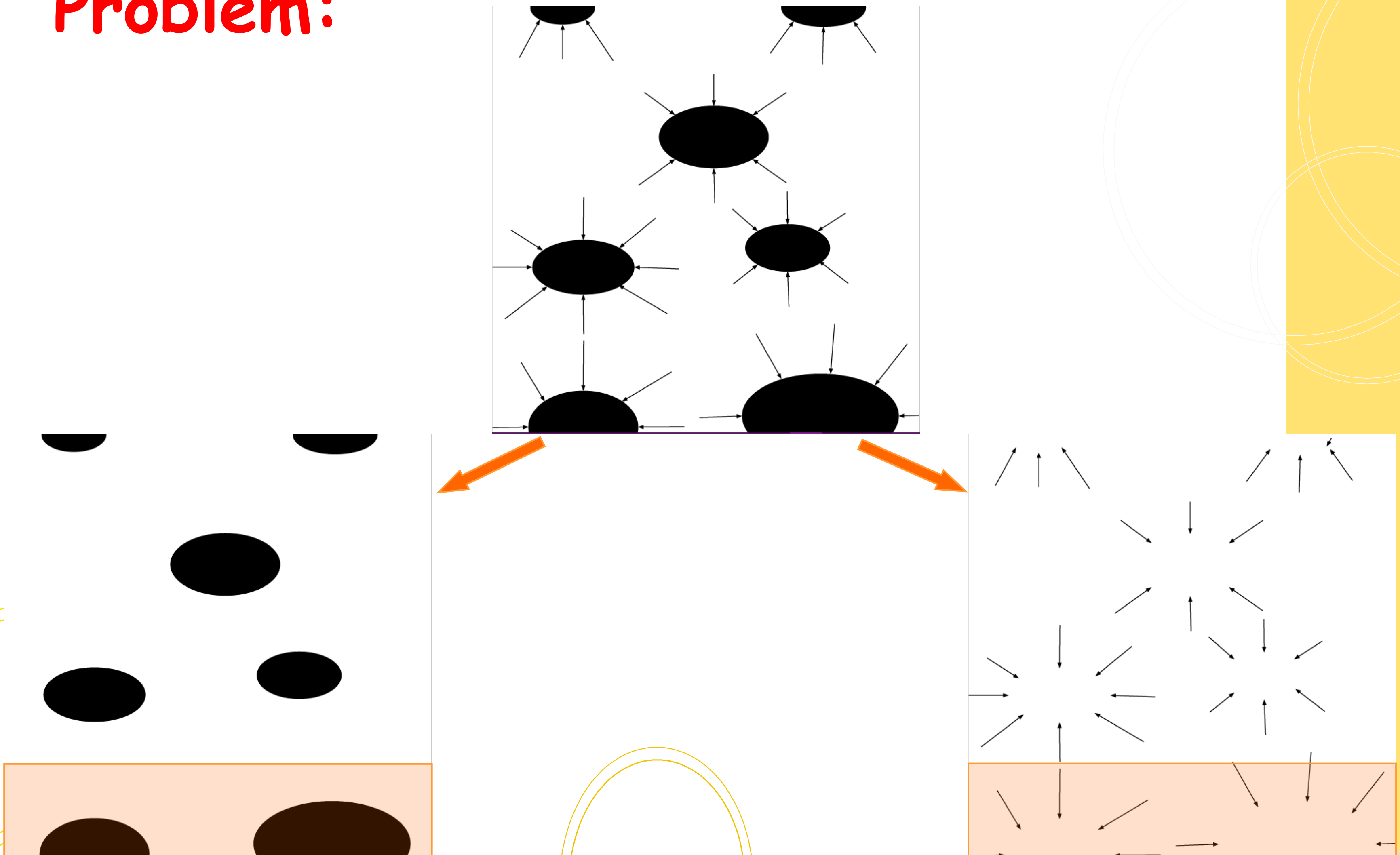


e.g. 21 cm or tau

kSZ at large scale

inconsistency is only in kSZ, not the others.

Cosmic opacity:

Anisotropies of τ can be extracted from CMB temperature and polarization (Dvorkin & Smith 2009)

With Limber approximation, the auto-spectrum is described as:

density spectrum   ionization spectrum

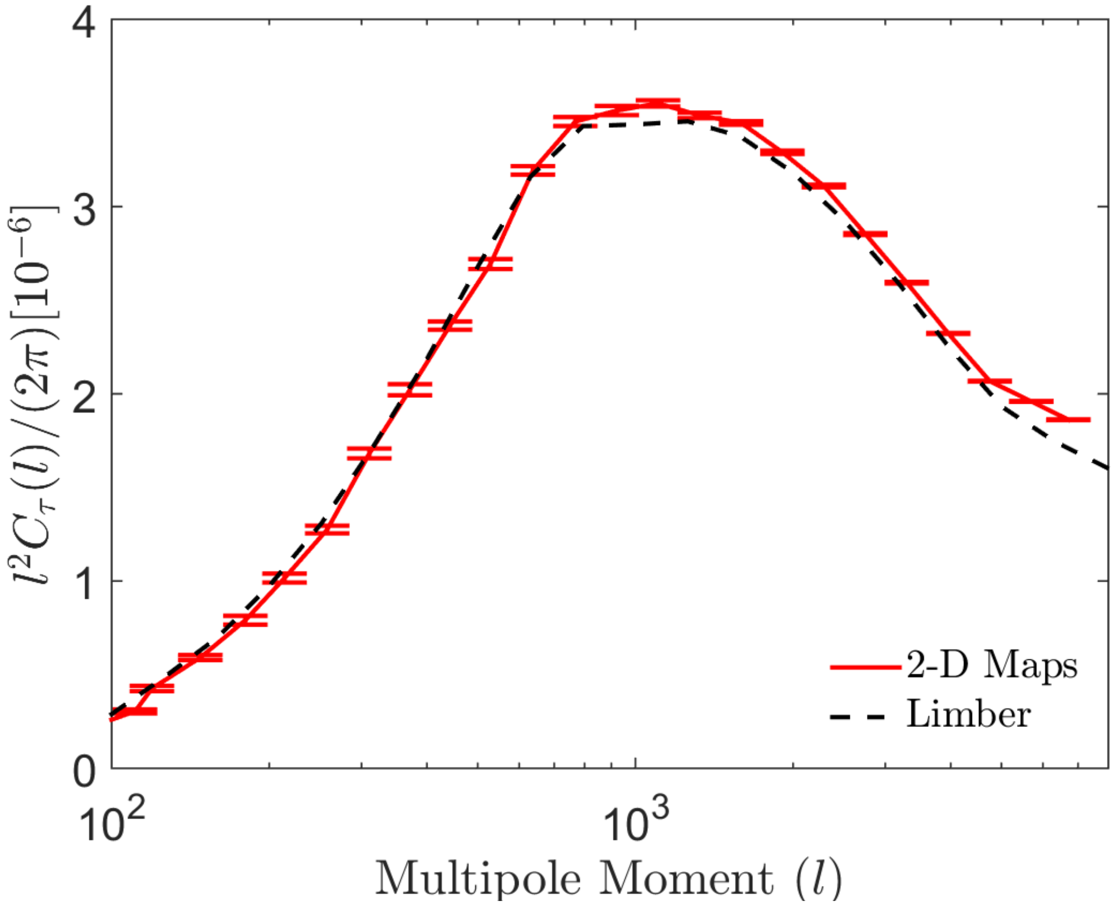
$$C_\tau(l) = \int \frac{ds}{s^2} \psi_\tau{}^2 [D^2 P_{\delta_0\delta_0}(\frac{l}{s}) + 2DP_{\delta_0\delta_x}(\frac{l}{s}) + P_{\delta_x\delta_x}(\frac{l}{s})]$$

correlation

$$\psi_\tau \equiv N_{b,0}\sigma_T \bar{x}_e (1+z)^2$$

Results

Auto-power spectrum of τ



2-D maps from simulations give consistent spectrum with Limber approximation.

Cross-correlation of kSZ with τ :

With Limber approximation, the spectrum is:

$$l^2 C_{\tau-\mathrm{kSZ}}(l) = \int ds \psi_{\parallel} \psi_{\tau} [D P_{\delta_0 \delta_0}(\frac{l}{s}) + P_{\delta_0 \delta_x}(\frac{l}{s})]$$

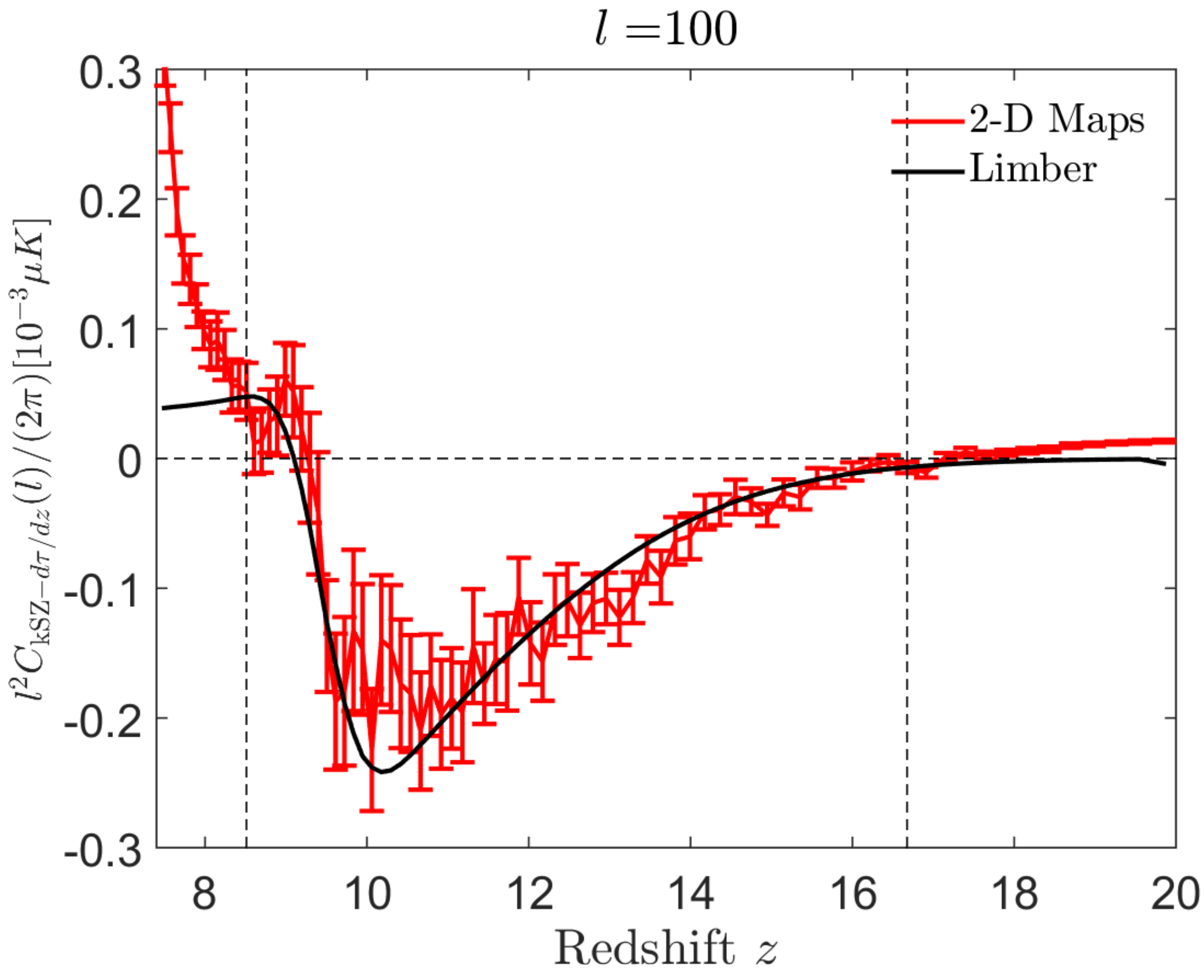
density spectrum correlation with ionization

The evolution of correlation of kSZ and $d\tau / dz$ can be described as a function of redshift:

$$l^2 C_{d\tau/dz-\mathrm{kSZ}}(l, z) = \frac{c}{H} \psi_{\parallel} \psi_{\tau} [D P_{\delta_0 \delta_0}(\frac{l}{s}) + P_{\delta_0 \delta_x}(\frac{l}{s})]$$

Results

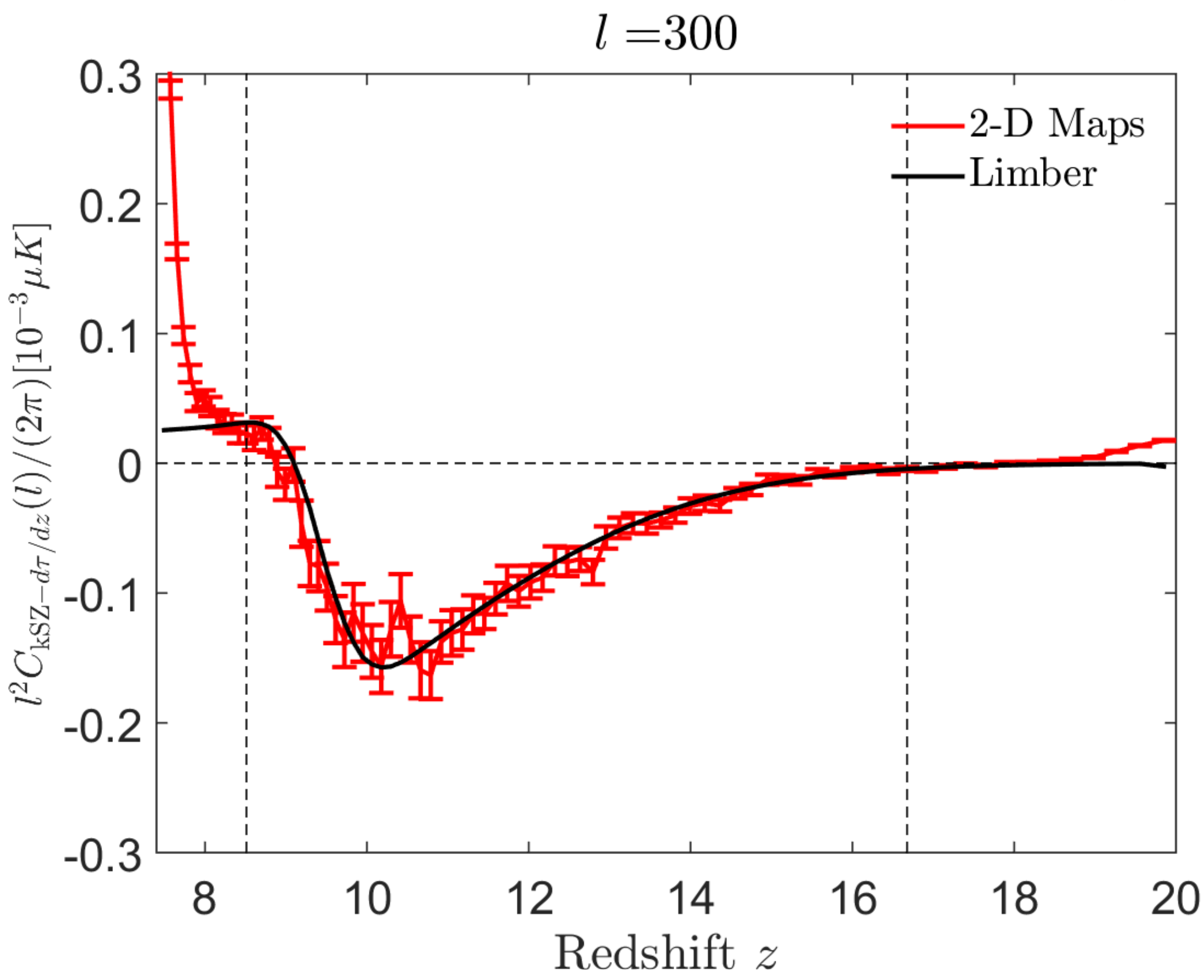
Correlation of kSZ with $d\tau / dz$:



The spectrum from 2-D Maps is much larger than Limber approximation at two ends of redshift range.

Results

Correlation of kSZ with $d\tau / dz$:



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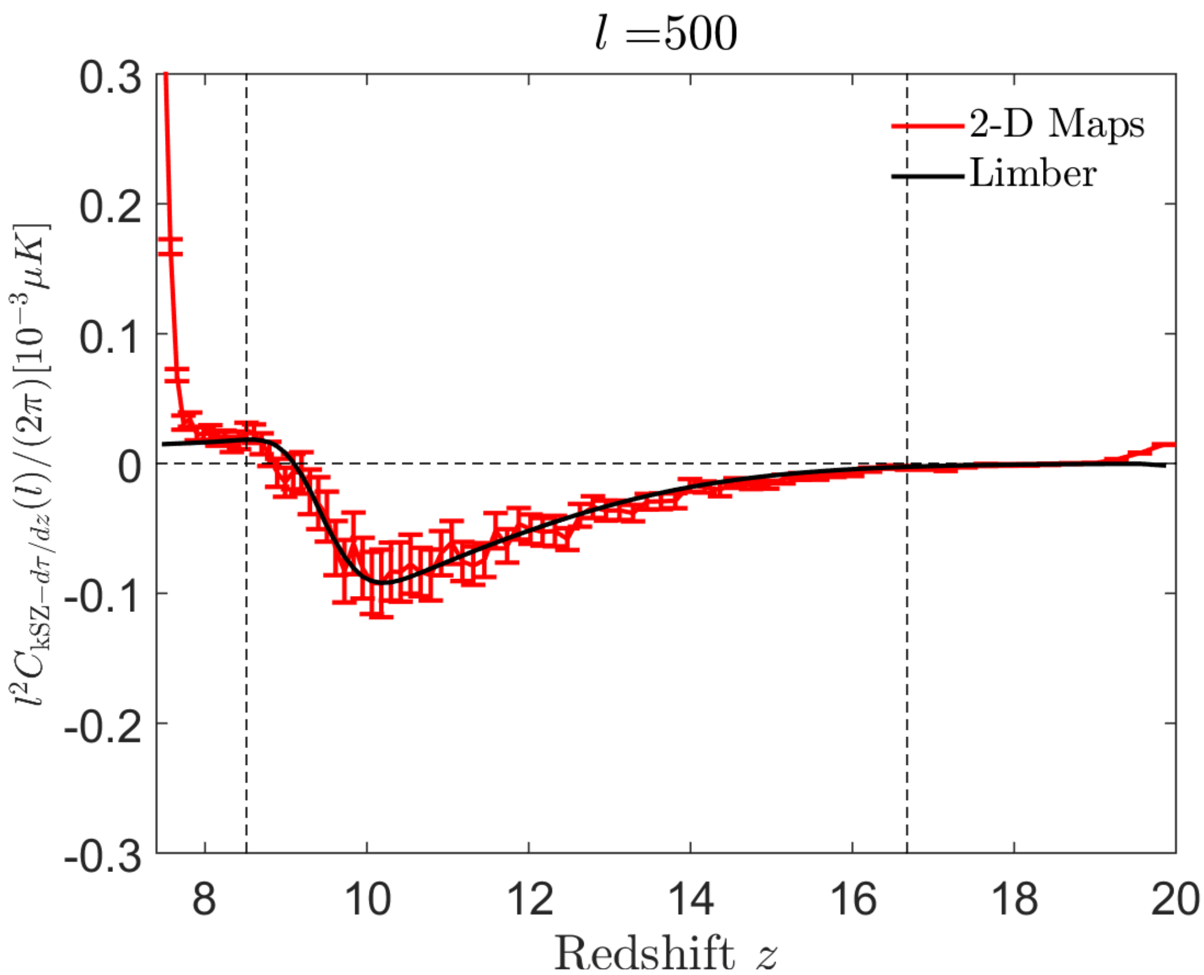
Correlation of kSZ with $d\tau / dz$:



The spectrum from 2-D Maps is much larger than Limber approximation at two ends of redshift range.

Solution:

$$L = \frac{2\pi}{k} = \frac{2\pi s}{l}$$

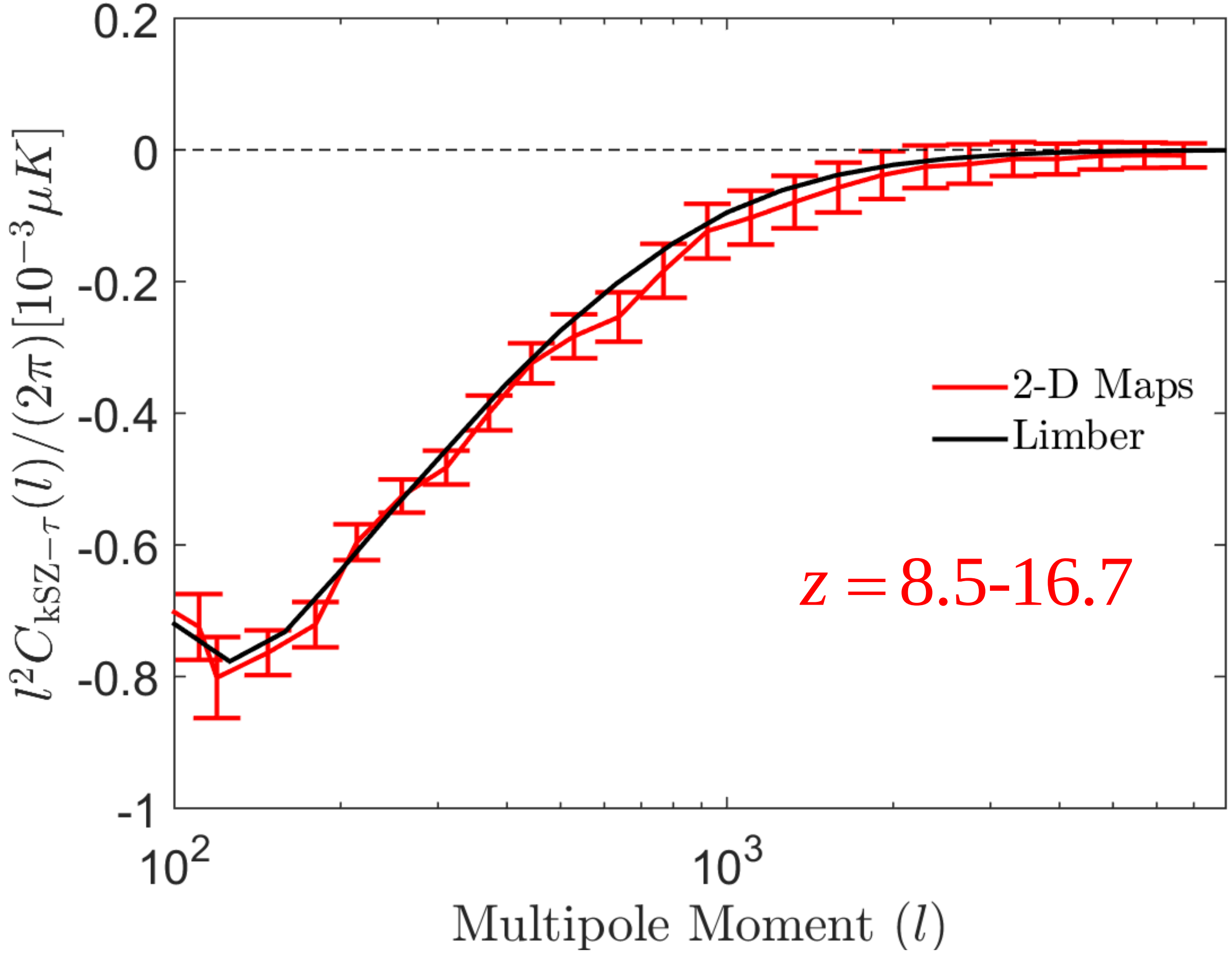
for l=100 at z=10, L≈600cMpc.

Solution: cut off 300Mpc at two ends of box

The new redshift range covered is 8.5-16.7.

Results

Correlation of kSZ with τ:



Only kSZ longitudinal mode correlates with cosmic τ .

21 cm signal:

21 cm signal can be described as:

$$T_{21cm} = \psi_{21cm} x_{\mathrm{HI}} (1+\delta)\left(\frac{H}{dv_s/ds + H}\right)\left(1 - \frac{T_{\mathrm{CMB}}(z)}{T_{\mathrm{S}}}\right)$$

$$t \equiv 1 - \frac{T_{\mathrm{CMB}}(z)}{T_{\mathrm{S}}}$$

$$\psi_{21cm}(z) \equiv 23\mathrm{mK}\left(\frac{\Omega_b h^2}{0.02}\right)\left[\left(\frac{0.15}{\Omega_m h^2}\right)\left(\frac{1+z}{10}\right)\right]^{0.5}$$

The cross-spectrum of 21 cm and kSZ is (Alvarez et al. 2006) :

correlation with ionization

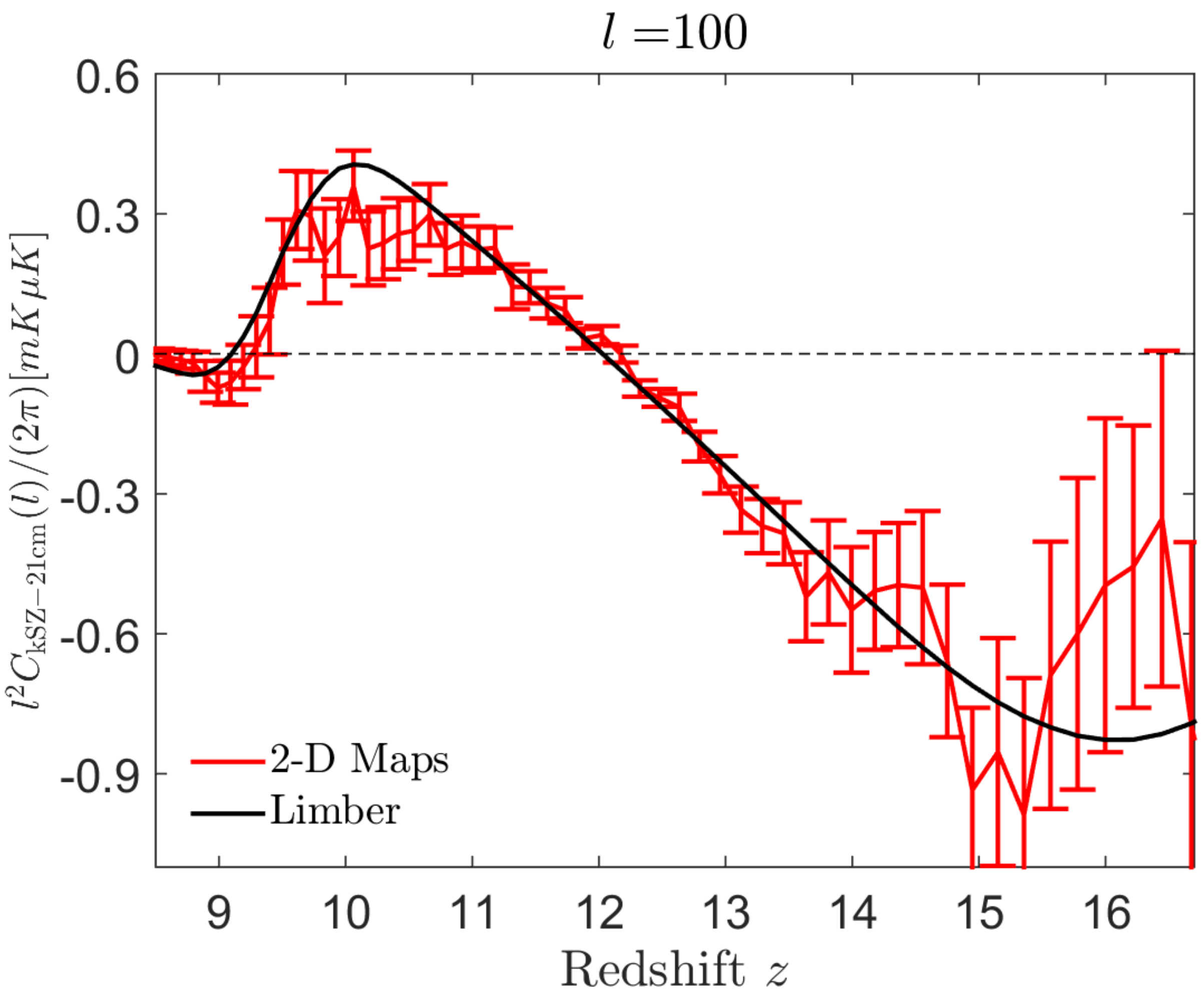
$$l^2 C_{\text{21cm-kSZ}}(l,z) = \psi_{\parallel}\psi_{\text{21cm}}\bar{t}\left[\bar{x}_{\mathrm{HI}} D P_{\delta_0\delta_0}\left(\frac{l}{s}\right) - \bar{x}_e P_{\delta_0\delta_x}\left(\frac{l}{s}\right) + \bar{x}_{\mathrm{HI}} P_{\delta_0\delta_t}\left(\frac{l}{s}\right)\right]$$

density spectrum

correlation with t

Results

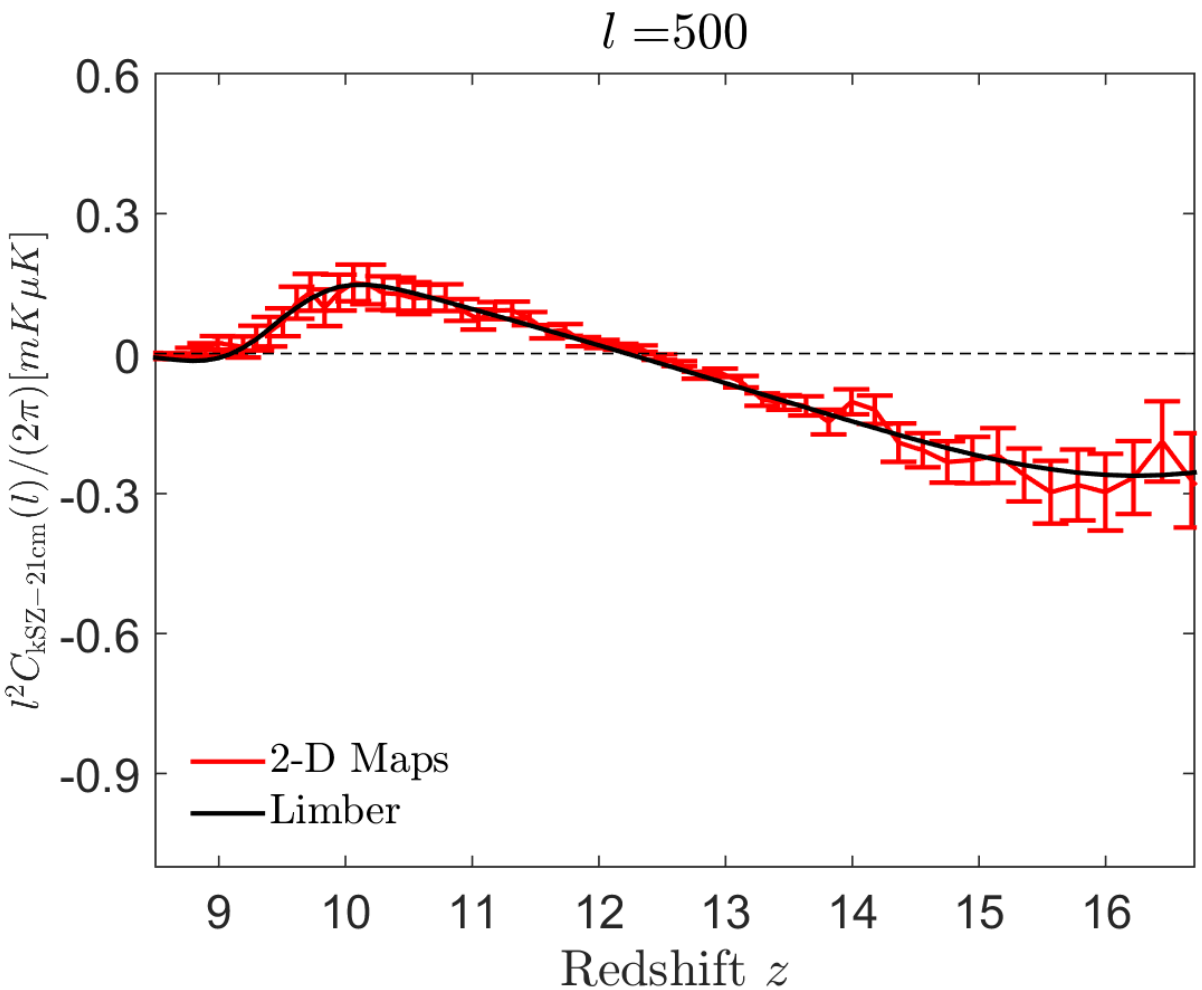
Correlation of kSZ with 21 cm:



The signal is positive ar z<12 but negative at z>12.

Results

Correlation of kSZ with 21 cm:



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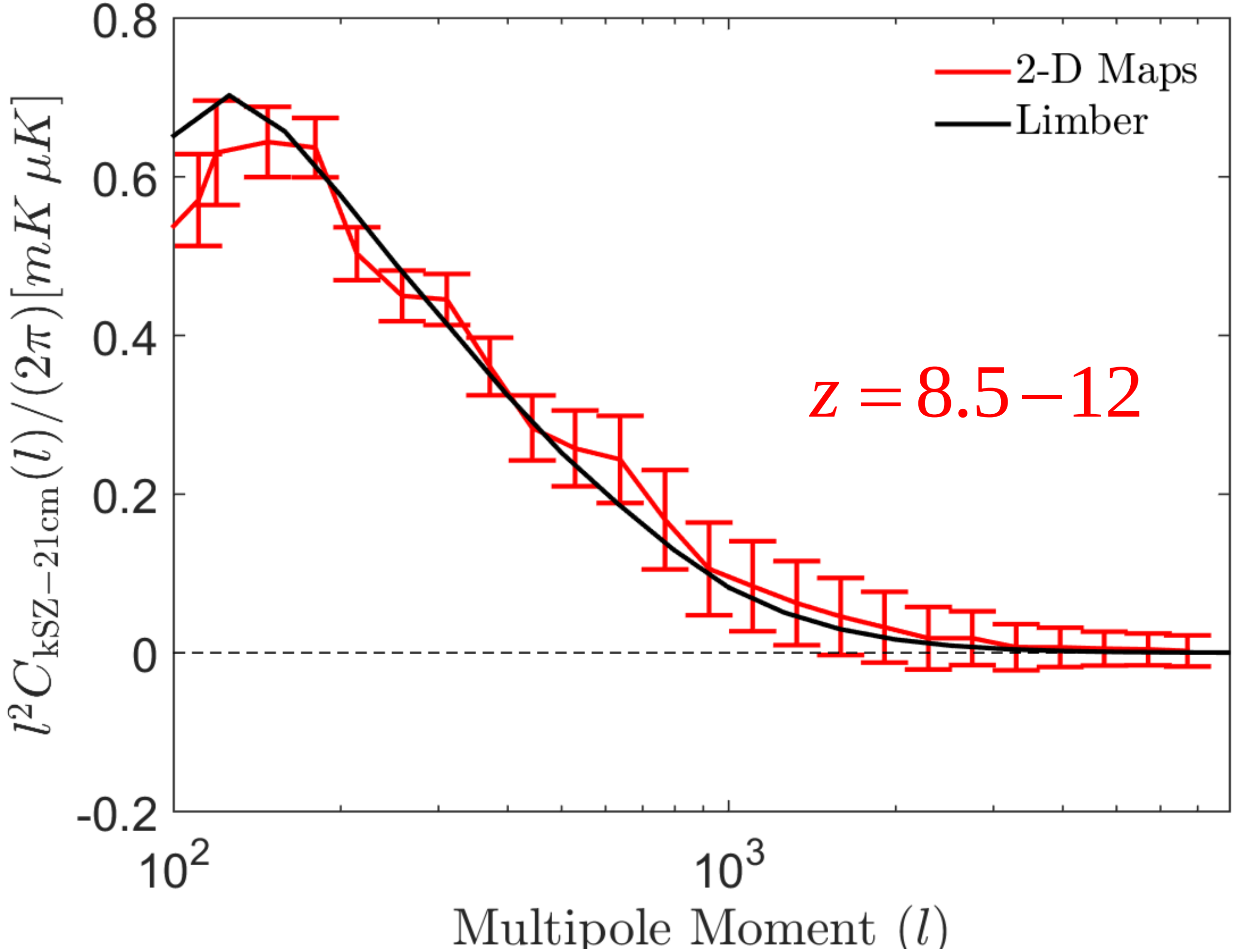
Results

Correlation of kSZ with 21cm:



The integration would increase the signal to noise ratio.

Cross-correlation of kSZ^2 and others:

Three-point statistic may be non-vanishing at small scale: two kSZ points (even of the velocity) and one others (Dore et al 2004).

$$C_{X-\mathrm{kSZ}^2}(l) = \int \frac{ds}{s^2} \psi_X \psi^2_{\mathrm{kSZ}} \Phi(k = \frac{l}{s})$$

$$\Phi(k, z) \equiv \int \frac{d^2\vec{k}'}{(2\pi)^2} B_{\delta\vec{p}\vec{p}}(\vec{k}, \vec{k}', -\vec{k} - \vec{k}')$$

The correlation with 21 cm signal has been studied in N-body simulations with radiative transfer (Jelic et al. 2010).

Cross-correlation of kSZ² and others:

The detection of the kSZ and 21 cm signal correlation may be possible (Tashiro et al 2010).

Primary CMB

kSZ

e.g. 21 cm

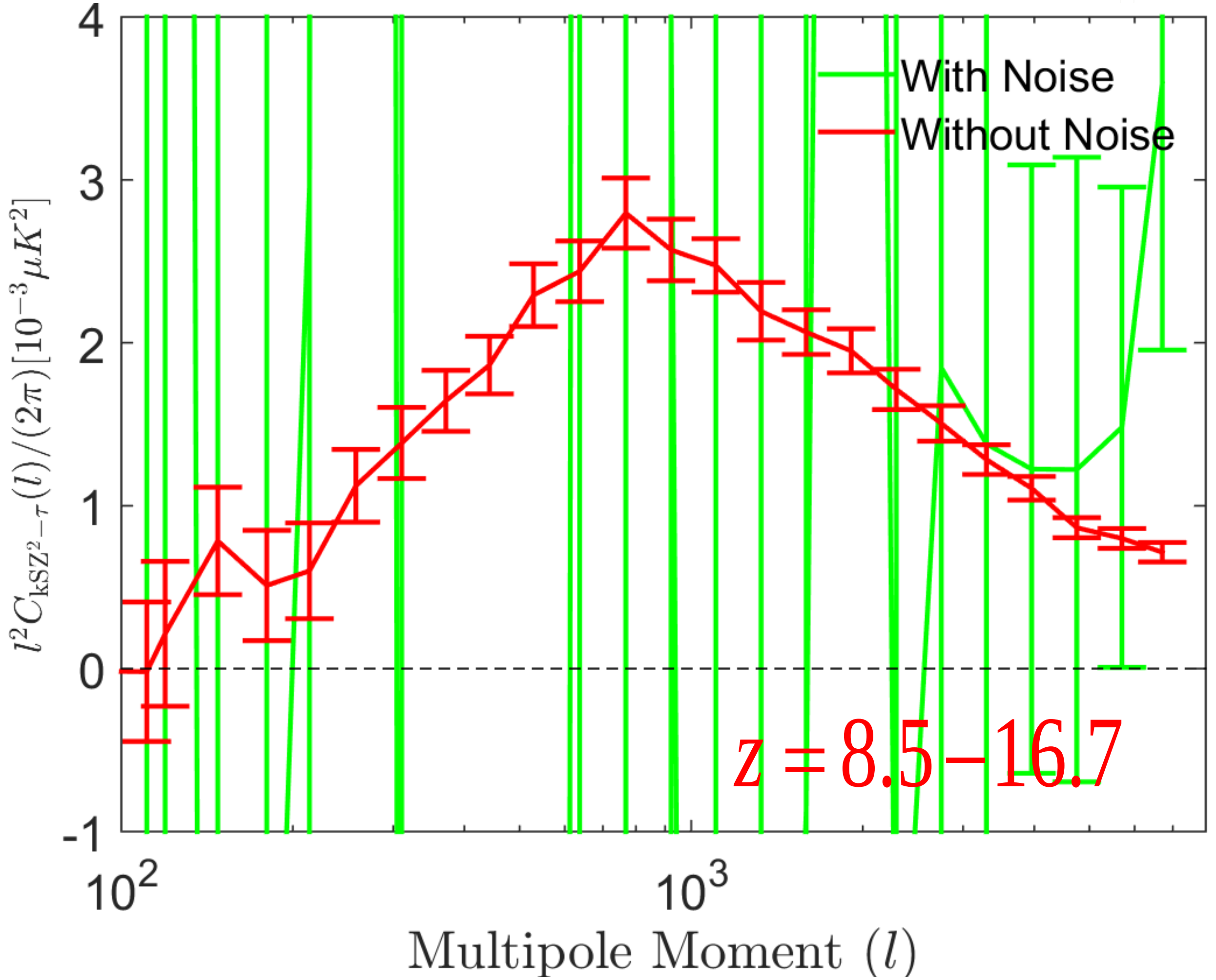
$$(A+B)^2 \otimes C = A^2 \otimes C + B^2 \otimes C + (2A^*B) \otimes C$$

For the correlations of kSZ², the CMB noise can be removed with Wiener Filtering (Doré et al. 2004; Hill et al. 2016) :

$$g(l) = \frac{C_{kSZ}(l)}{C_{kSZ}(l) + C_N(l)}$$

Results

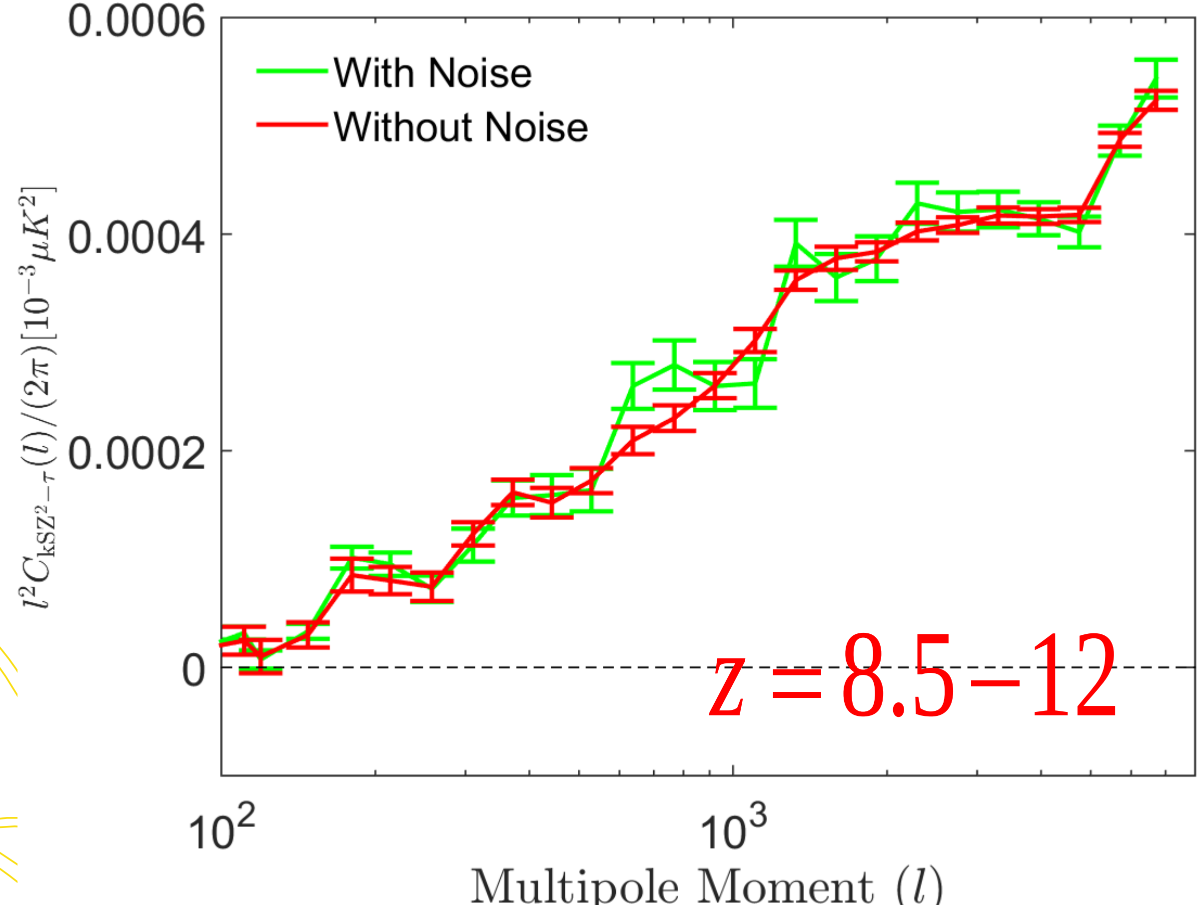
Correlation of kSZ^2 with τ:



The correlation is positive and peaks around l=1000.

Results

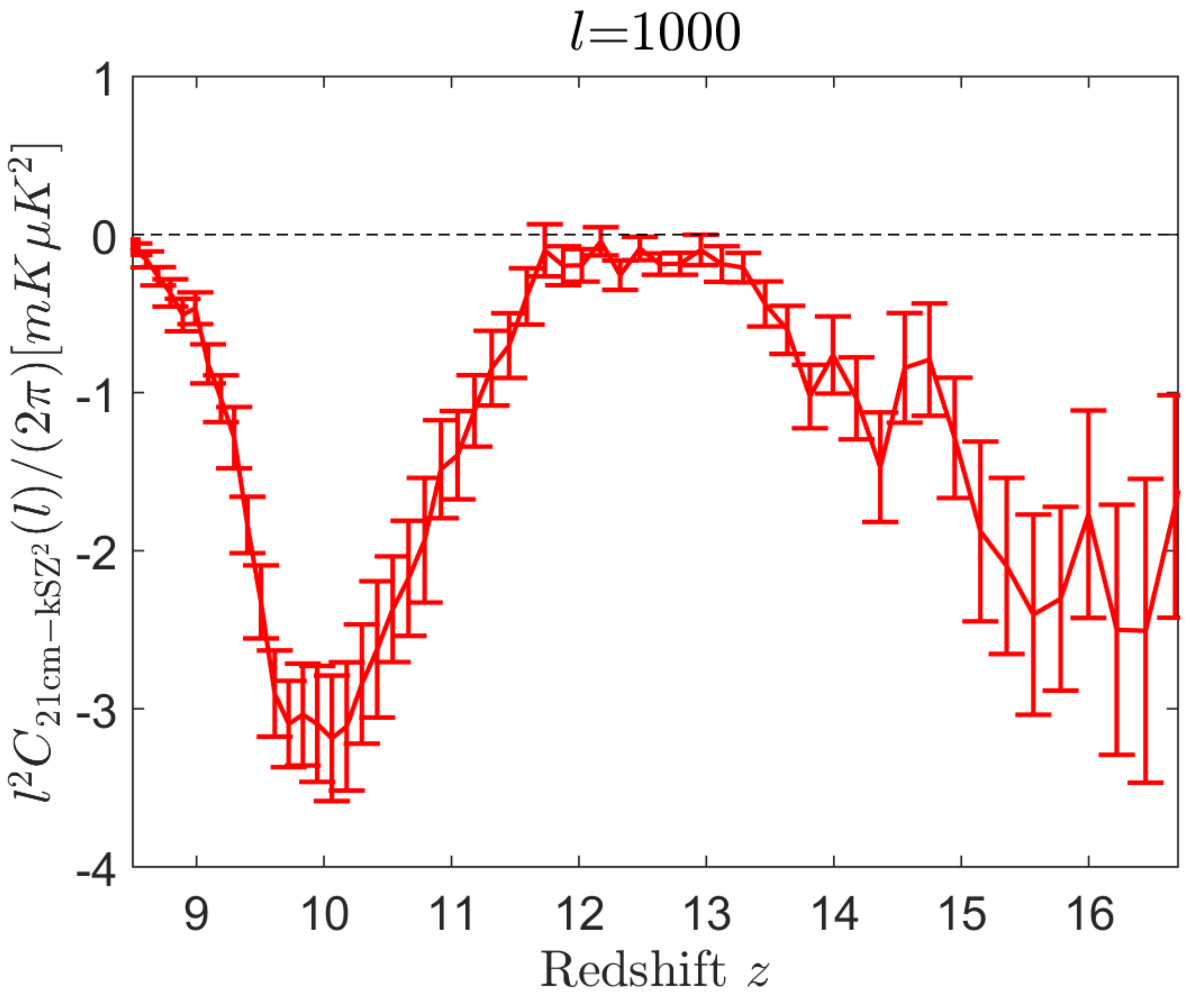
Correlation of kSZ² with τ:



After Wiener Filtering the spectrum becomes very small but the S/N ratio increased.

Results

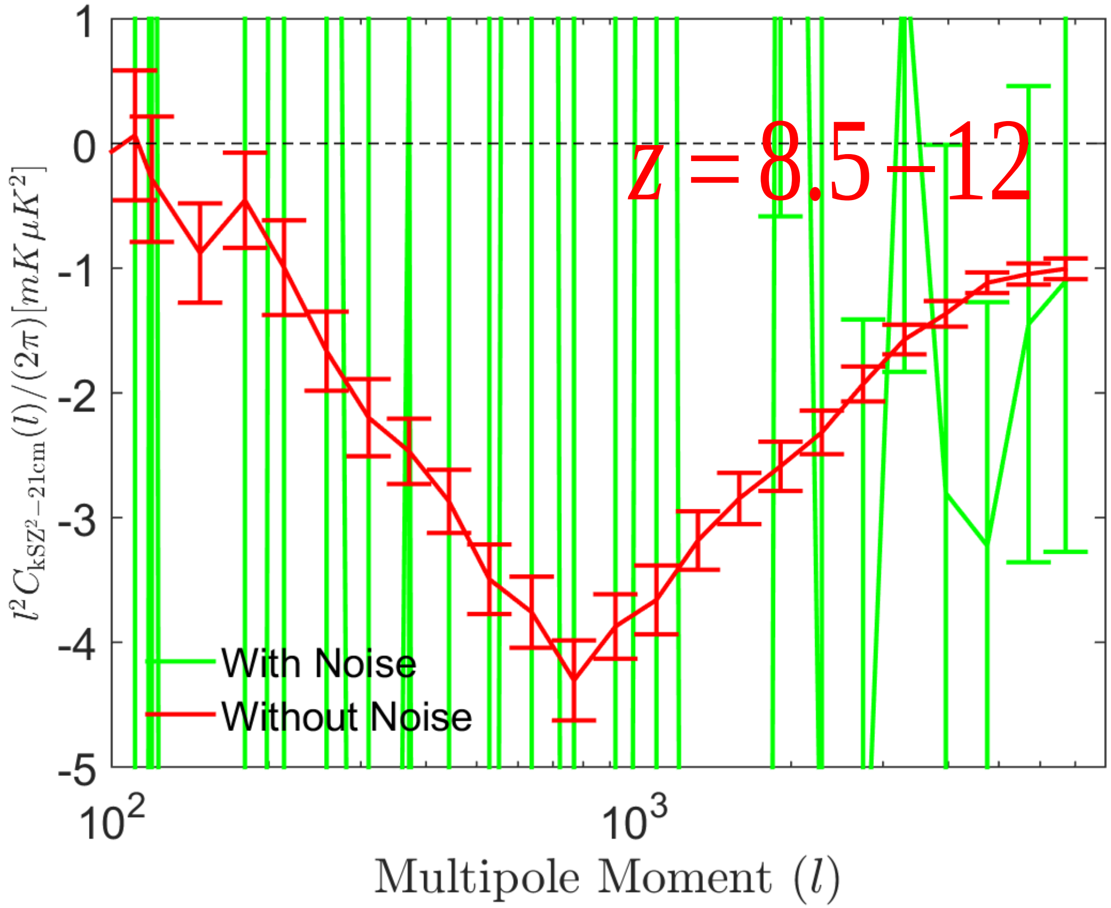
Correlation of kSZ^2 with 21 cm:



The correlation is always negative at z<12.

Results

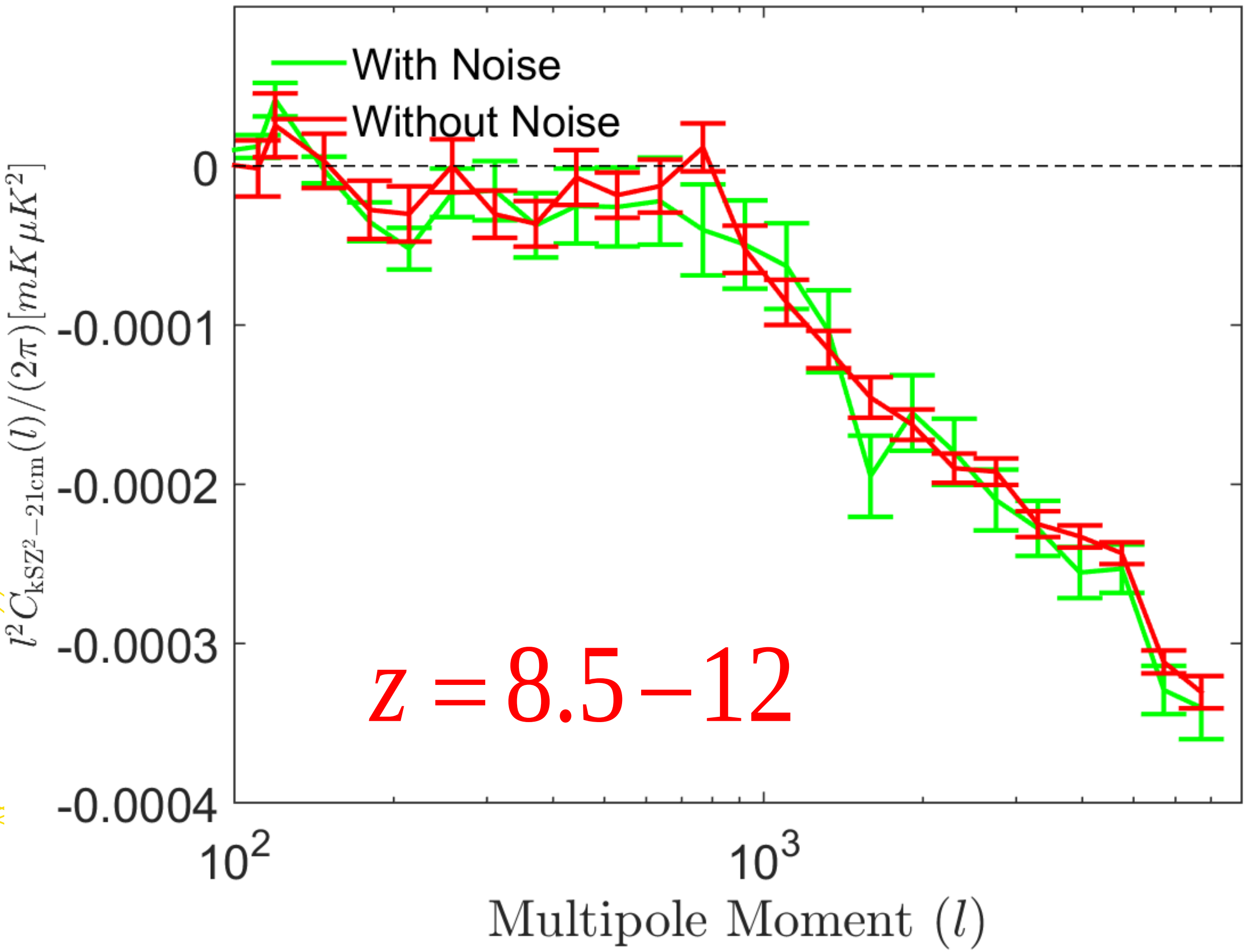
Correlation of kSZ^2 with 21 cm:



The direct result from observations would be dominated by the noise.

Results

Correlation of kSZ^2 with 21 cm:



The S/N ratio would be increased with Wiener Filtering.

Conclusions:

- ✓ The simulations can mimic kSZ effect very well, especially the correlations with other observables.
- ✓ 21 cm signal and cosmic opacity only correlate with kSZ at large scale, and the signal is sensitive to the reionization history.
- ✓ kSZ^2 has correlation with cosmic opacity or 21 cm signal, the signal peaks around l=1000.
- ✓ Wiener Filtering would be helpful to remove the CMB noise for the kSZ^2 correlations.

Thank you