What can we learn about reionization from the kSZ

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IGM effect on CMB primary temperature anisotropies

ionized IGM damps
CMB temperature anisotropies
through Thomson scattering

end of reionization
\( z \geq 5 \)

recombination
\( z \approx 1100 \)
Velocity field modulates anisotropies

\[
\frac{\Delta T}{T}(\hat{u}) = \sigma_T \int dz \ c \ (dt/dz) \ e^{-\tau_e(z)} n_e \hat{u} \cdot \mathbf{v}
\]

CMB secondary temperature anisotropies:

kSZ post-reionization (~OV signal)
CMB secondary temperature anisotropies: kSZ patchy reionization

$\Delta T/T(\hat{u}) = \sigma_T \int dz \frac{c}{dt/dz} e^{-\tau_e(z)} n_e \hat{u} \cdot \mathbf{v}$

Velocity field + HII morphology modulates anisotropies
In this section, we assess the observability of patchy reionization.

Upcoming experiments such as ACT and SPT will observe the CMB from this epoch is shown by solid curves. At later times, the universe is homogeneously reionized, and the dashed curve shows the $kSZ$ effect for this period.

From these specifications and a template for the power spectral constraints from ACT and SPT, we can calculate the accuracy of the $kSZ$ effect. Given that the plateau of the extended patchy model ($\frac{1}{2} < l < 4000$), the primordial anisotropies are of a magnitude similar to that of the Doppler effect induced by thermal SZ, the two will degrade our ability to detect the $kSZ$ effect (Huffenberger & Seljak 2005; we included their estimate for the IR source power spectrum and angular clustering. In our analysis, we understood its frequency dependence well). To compare the experimental constraints with the power spectra extracted from our simulations on degree patches on the sky, we bin the errors into bands of width $\frac{1}{219}$, $\frac{1}{274}$, and $\frac{1}{345}$ GHz. The $\frac{1}{219}$ GHz channel will have an angular resolution of $0.03\,\text{FWHM}$, $0.05\,\text{FWHM}$, and $0.07\,\text{FWHM}$ for $\frac{1}{219}$, $\frac{1}{274}$, and $\frac{1}{345}$ GHz, respectively. We use the assumption of perfect cleaning of the thermal SZ effect is safer because we understand its frequency dependence well. See http://www.eso.org/projects/alma/science/alma-science.pdf.

$\frac{1}{219}, 274, 345$ GHz. The $\frac{1}{219}$ GHz channel will have an angular resolution of $0.03\,\text{FWHM}$, $0.05\,\text{FWHM}$, and $0.07\,\text{FWHM}$ for $\frac{1}{219}, 274, 345$ GHz, respectively. We use the assumption of perfect cleaning of the thermal SZ effect is safer because we understand its frequency dependence well.

Zahn+2005
Extract out OV component of kSZ

<table>
<thead>
<tr>
<th>Paper</th>
<th>$D_{3000}$ [µK$^2$]</th>
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<tr>
<td></td>
<td>Unnorm.</td>
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<tr>
<td>WHS02</td>
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<td>H09</td>
<td>7.40</td>
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<tr>
<td>B10, NR</td>
<td>2.50</td>
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<tr>
<td>B10, AGN</td>
<td>1.50</td>
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<tr>
<td>TBO11, adiabatic</td>
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<tr>
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<td>This work, NR</td>
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<td>This work, CSF</td>
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**Note.** — The amplitude of the kSZ power predicted by hydrodynamical simulations in previous work. We show the results from the SPH simulations of White et al. (2002, WHS02), the ENZO simulations of Hallman et al. (2009, H09), both the non-radiative (NR) simulations and those including cooling, star-formation and AGN feedback from Battaglia et al. (2010, B10) and the ‘adiabatic’ and ‘standard’ models from the N-body plus semi-analytic approach of Trac et al. (2011, TBO11).

$P_{kSZ}^{OV} \sim 2-3\,\mu K^2$
Large diameter (fine resolution) telescopes:
• Atacama Cosmology Telescope (ACT)
• South Pole Telescope (STP)

**Constraints on reionization kSZ power at l~3000 from SPT** (Reichardt + 2012):
• \( P_{kSZ}^{\text{patchy}} \lesssim 1 \, \mu K^2 \) (95% CL) assuming no tSZ-CIB correlation
• \( P_{kSZ}^{\text{patchy}} \lesssim 4 \, \mu K^2 \) (95% CL) allowing tSZ-CIB correlation

A *(marginal) detection* (Crawford+2013):
• \( P_{kSZ}^{\text{patchy}} = 0.9 \pm 1.5 \, \mu K^2 \)

Limits include a conservatively small contribution from OV of \( 2 \, \mu K^2 \)

**Caution:** constraints are sensitive to the choice of prior
Interpreting the patchy reionization signal

Challenges:
- Large-dynamic range: need to capture small ionization structure (~Mpc) and go out to large scales to capture the velocity field (~Gpc)
- Very little is known about reionization -> large parameter space to explore

Can construct empirical models (e.g. Zahn+2012, Battaglia+2013)
- fast, adaptable to MCMC
- however unclear physical insight
- must be careful not to over-interpret results from unphysical models
Interpreting the patchy reionization signal

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Or: use 21cmFAST (Mesinger & Furlanetto 2007; Mesinger+2011) to do astrophysical parameter exploration

• Combination of Lagrangian perturbation theory and excursion-set formalism
• Generates realizations of reionization in minutes, allowing true parameter space studies of physical models
• Tested extensively against cosmo sims
• Publicly available
Interpreting the patchy reionization signal

(Mesinger, McQuinn, Spergel 2012)

3 free parameters:

• $\zeta$ - ionizing efficiency of high-redshift galaxies. For example: $\zeta = f_{\text{esc}} f_\star N_\gamma/(1+n_{\text{rec}})$

• $T_{\text{vir}}$ – minimum virial temperature of halos which can host stars

• $R_{\text{mfp}}$ – mean free path of ionizing photons inside ionized IGM (set, e.g. by LLSs). $R_{\text{mfp}} \sim 30-50\text{Mpc}$ at $z \sim 6$
Modeling reionization (\(\sim 100\) realizations)
Spectra as one varies parameters

Mesinger, McQuinn, Spergel (2012)
Easiest to detect or rule out (i.e. largest signal): models driven by small galaxies which form early, evolve slowly, and where ionization is retarded by abundant absorption systems
Including constraints from WMAP and QSOs
Mfp slices

R_{mfp} = 60 cMpc

R_{mfp} = 3 cMpc
Zeta slices
Tvir slices
Empirical parameters, $\Delta z_{re}$ and $z_{re}$

$z_{re}$ – redshift when $\langle x_{HI} \rangle = 0.5$

$\Delta z_{re}$ – redshift duration from $\langle x_{HI} \rangle = 0.75$ to $\langle x_{HI} \rangle = 0.25$

caution: the kSZ power is not a singly defined function of $\Delta z_{re}$ and $z_{re}$
What is sourcing the signal?

• Early to mid stages source the bulk of the $l \sim 3000$ power.

![](image)

• A “fiducial” model has half of patchy power imprinted already when $x_{HI} > 0.75$.

• By $x_{HI} > 0.5$, 85% of the kSZ power is in place

cautions: the end of reionization cannot be directly constrained by kSZ (e.g. Zahn+2012)
What about X-ray reionization?

- Due to their long mean free paths, X-rays can have a dramatic impact on reionization morphology:

\[ \lambda_x \approx 20 \bar{x}_{HI}^{-1} \left( \frac{E_x}{300\text{eV}} \right)^{2.6} \left( \frac{1+z}{10} \right)^{-2} \text{cMpc} \]

no fiducial “swiss cheese” morphology?

Cream cheese morphology?
X-ray reionization

“fiducial” model (UV driven reionization) vs “extreme” model (X-ray driven reionization)

Mesinger, Ferrara, Spiegel (2013)
Reasonable X-ray models have only a mild impact on kSZ

Crawford+2013, 2σ

Crawford+2013, 1σ

Crawford+2013

0.5μK² decrease by ~50% contribution

\[ kSZ_0.5 \mu K^2 \text{ decrease by } \sim 50\% \text{ contribution} \]
Conclusions

• Despite wide parameter space exploration, the patchy kSZ signal at \( l=3000 \) only ranges from \( 1.5 - 3.5 \, \mu K^2 \) (when including WMAP and QSO constraints)

• Observed SPT limits (2 \( \sigma \)) are just at this border, under conservative assumptions

• Largest power (first to be ruled out) comes from early/extended reionization scenarios (minihalos + abundant sinks)

• Bulk of the signal is sourced from early to mid stages of reionization \( \rightarrow \) kSZ does not tell us about the end of reionization

• X-rays can decrease the kSZ power by \(<~0.5 \, \mu K^2\)

• Slope is useful in breaking the degeneracy between different ionization morphologies with the same \( l\sim3000 \) kSZ power

• kSZ might be the only near-term indirect probe of \( z >~10 \)