Probing helium reionization with kinetic Sunyaev Zel’dovich tomography

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Reionization of helium is expected to occur at redshifts \( z \sim 3 \) and have important consequences for quasar populations, galaxy formation, and the morphology of the intergalactic medium, but there is little known empirically about the process. Here we show that kinetic Sunyaev-Zeldovich (kSZ) tomography, based on the combination of CMB measurements and galaxy surveys, can be used to infer the primordial helium abundance as well as the time and duration of helium reionization. We find a high-significance detection at \( z \sim 100 \) can be expected from Vera Rubin Observatory and CMB-S4 in the near future. A more robust characterization of helium reionization will require next-generation experiments like MegaMapper (a proposed successor to DESI) and CMB-HD.

Probing helium reionization—one of the major large-scale transitions of the intergalactic medium (IGM)—has great potential significance for understanding the formation of galaxies and quasar activity at early times, and may open a new window on big bang nucleosynthesis. Since photons emitted by the first stars (sourcing the ionization of the second electron of helium as the helium reionization.

Note that throughout this work we refer to the ionization of the second electron of helium as the helium reionization.

The ionization energy of the second electron in helium is 54.4eV, while the ionization energy of hydrogen is 13.6eV.

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ing surveys such as CMB-S4 [37, 38], together with DESI, VRO or the proposed MegaMapper [39, 40].

The CMB temperature anisotropy induced by the kSZ effect from large-scale structure in a shell of width $L_{\text{shell}}$ at a redshift $z = z_*$ is

$$\Theta_{\text{kSZ}}(\mathbf{\ell}) = K(z_*) \int_0^{L_{\text{shell}}} \mathrm{d} r q_\parallel(r),$$  \hspace{1cm} (1)

where $\mathbf{r} \equiv \chi_* \hat{\mathbf{r}} + r \hat{\mathbf{r}}$, $\mathbf{\ell}$ is the angular direction on the sky, $\chi_*$ is the conformal distance to the shell, $\hat{\mathbf{r}}$ is the unit vector in the radial direction, $\Theta(\mathbf{\ell})$ is the fractional fluctuation of CMB temperature, and

$$K(z) = -\sigma_T n_{\text{H}} x_e(z) e^{-\tau(z)} (1 + z)^2,$$  \hspace{1cm} (2)

is the redshift weight function in units of $\text{Mpc}^{-1}$. Here, $\sigma_T$ is the Thomson scattering cross-section, $\tau(z)$ is the optical depth to redshift $z$, $n_{\text{H}}$ is the hydrogen number density, $x_e(z)$ is the number of free electrons per hydrogen atom, and $q_\parallel(r) = \delta_e(r) v_\parallel(r)$ is the electron-momentum field, projected onto the radial direction. The velocity field $v_\parallel(r)$ can be reconstructed at cosmological scales from its influence on the correlation between the electron-momentum field and large-scale structure. The (inverse) noise on the reconstructed velocity is given by [26]

$$\frac{1}{N_\parallel(k_L)} = \frac{K^2}{\chi_*^2} \frac{\mathrm{d}}{\mathrm{d} k} \int \frac{P_{\text{obs}}(k) C_{TT,\text{obs}}^2}{2\pi} \left|_{k = k_*} \right.$$  \hspace{1cm} (3)

where $k$ is the three-dimensional Fourier wavevector and the integral is over small-scale Fourier modes $k_S$. We represent large-scale modes with an ‘L’ subscript. Here, $C_{TT,\text{obs}}^2$ is the observed CMB spectrum including foregrounds and noise, $P_{\text{obs}}(k)$ is the observed galaxy power spectrum and $P_{\text{gg}}(k)$ is the power-spectrum of the galaxy-electron correlation.

On large scales where linear theory is valid, the reconstructed velocity fields are proportional to the cosmic growth rate. The reconstructed velocity amplitude is proportional to the free-electron density at a given redshift and satisfy

$$v_\parallel(k, z) = \left[ \bar{x}_e(z)/\bar{x}_e(z)_{\text{fid}} \right] b_\parallel(z) \mu \frac{f a H}{k} \delta_m(z, k),$$  \hspace{1cm} (4)

where $\bar{x}_e(z)/\bar{x}_e(z)_{\text{fid}}$ is equal to unity for a given fiducial cosmology with helium reionization, $b_\parallel(z)$ is the optical-depth bias due to mismodelling of the small-scale electron-galaxy cross-correlation as described in Ref. [26], $\mu$ is the linear-theory growth rate, $a$ is the scale factor and $H$ is the Hubble parameter. As a result, the reconstructed velocity fields probe the mean ionization fraction: if the helium reionization is not accounted for, the velocity amplitudes will be biased by the change of the mean ionization fraction. The combination of the

![FIG. 1. Fractional change in the electron fraction $x_e(z)$ during helium reionization of the three models we consider here. The error bars correspond to the measurement accuracy on the optical-depth bias $b_\parallel(z)$, representative of the error on the amplitude of the reconstructed radial velocity, as discussed in the text. Here, we include forecasts for the combination of VRO and CMB-S4, and MegaMapper and CMB-HD.](image)

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TABLE I. Assumed galaxy bias $b_g$ and number density $n_{gal}$ at each redshift bin. For VRO, we approximate the galaxy density of the “gold” sample, with $n(z) = n_{gal}(z/0.3)_0 \exp(-z/0.3)/200$ with $n_{gal} = 40$ arcmin$^{-2}$ and $z_0 = 0.3$ and take the galaxy bias as $b_g(z) = 0.95/D(z)$. Our calculation of the number density and the galaxy bias of MegaMapper, which is proposed as a follow-up to DESI that will target Lyman-break galaxies (LBGs) and Lyman-alpha emitters and use deeper VRO images, is described in Ref. [46], which follows Ref. [47], using galaxies with threshold apparent magnitude $m_{UV}^{th} = 24.5$ (matching the limiting magnitude assumed for the “idealised sample” from Ref. [47]) and using the “linear HOD model” fit of Ref. [48] at $z \simeq 3.8$.

In order to assess the prospects to detect helium reionization, we consider three LSS surveys; the ongoing measurements of quasi-stellar objects (QSOs) with DESI [49], the photometric VRO survey [36], and high-z galaxy measurements from the proposed MegaMapper [39]. We describe the survey specification of these experiments in Table I. We consider 4 redshift boxes centered at $z \in \{1.9, 2.6, 3.45, 4.45\}$. We assume a sky fraction of $f_{sky} \simeq 0.5$ which roughly gives volumes of $\{150, 200, 220, 240\} Gpc^3$ at each redshift box, respectively.

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TABLE II. Inputs to ILC noise: The beam and noise RMS parameters we assume for survey configurations roughly corresponding to Simons Observatory (SO) (baseline), CMB-S4 and CMB-HD.

| Beam FWHM | Noise RMS μK
|-----------|--------------|
| SO        | CMB-S4       | CMB-HD       |
| 39 GHz    | 5.1          | 36.3         |
| 93 GHz    | 2.2          | 15.3         |
| 145 GHz   | 1.4          | 10.0         |
| 225 GHz   | 1.0          | 6.6          |
| 280 GHz   | 0.9          | 5.4          |

TABLE III. The detection signal-to-noise (SNR) of the (reconstructed) velocity and galaxy-density cross-correlation $P_{xy}(k)$. Velocities are reconstructed from the kSZ tomography using VRO and MegaMapper surveys, together CMB measurements from Simons Observatory (SO), CMB-S4 and CMB-HD.

| kSZ SNR | $z = 1.9, 2.6, 3.45, 4.45$ |
|---------|----------------------------|
| VRO+CMB-HD | 1087, 879, 351, 51 |
| VRO+CMB-S4 | 186, 126, 48, 7 |
| VRO+CMB-SO | 87, 59, 23, 4 |
| MegaMapper+CMB-HD | 1629, 1051, 453, 129 |
| MegaMapper+CMB-S4 | 254, 154, 78, 31 |
helium reionization as the SNR on $\Delta x_{\text{He}}^\text{re}$ (or $Y_p$) after marginalising over all other parameters. We find VRO and CMB-S4 can potentially detect helium reionization at $\{4\sigma, 8\sigma, 13\sigma\}$ significance for models 1-3 respectively. For the futuristic MegaMapper and CMB-HD, the detection SNR can reach $\{39\sigma, 56\sigma, 87\sigma\}$.

The sensitivities on the parameters describing the helium reionization—given our fiducial model labelled 1—are shown in Fig. 2. The blue (orange) contours correspond to combination of VRO and CMB-S4 (MegaMapper and CMB-HD). In both cases we assume no prior information on the optical-depth and galaxy biases.\textsuperscript{4} The innermost lighter-coloured contours assume 0.005 prior on the $Y_p$ parameter, which can be provided from helium emission line measurements \cite{52} as well as potentially the CMB \cite{53, 54}. We find assuming priors on $Y_p$ improves the measurement accuracy on the other helium reionization parameters, most notably for VRO and CMB-S4. We show our forecasted sensitivities ($1\sigma$ errors) on a table inside the caption of Fig. 2. We find the combination of VRO and CMB-S4 can measure the time of helium reionization at a precision that would allow distinguishing between models 1 and 3 and put potentially informative lower limits on duration of helium reionization. With MegaMapper and CMB-HD, we find kSZ tomography can measure the redshift and the duration of reionization at much higher significance, potentially allowing distinguishing between models of similar.

Interestingly, as demonstrated in Fig. 2, we find the combination of MegaMapper and CMB-HD may have a sensitivity to $Y_p$ comparable to the accuracy of CMB and helium emission-line measurements. In order to assess further, we perform CMB forecasts on $Y_p$ using FisherLens, a publicly available\textsuperscript{5} forecasting software \cite{55}. We take experimental specifications matching CMB-HD and with cosmological model parameters including the six standard $\Lambda$CDM parameters in addition to $N_{\text{eff}}$, and $Y_p$. We observe a CMB-HD-like experiment including the both temperature and polarization information can be expected to achieve $\sigma(Y_p) \approx 0.004$ sensitivity, and that adding $\sigma(Y_p) \approx 0.006$ measurement from kSZ tomography from helium reionization can improve the error on $Y_p$ by $\sim 15\%$. We find that this improvement leads to a $\sim 10\%$ reduction in $N_{\text{eff}}$ error, due to the partial breaking of the degeneracy suffered between the two parameters, suggesting kSZ measurements of helium reionization can potentially improve our understanding of relativistic species.

We have omitted the potential effect of helium reionization on the selection function of high-z quasars and galaxies. Across helium reionization, the ionizing processes can modulate the ultra-violet background fluctuations, the star formation and the absorption lines used for inferring the redshift with spectroscopic imaging surveys such as DESI and MegaMapper. Such effects can potentially cause significant changes that need to be taken into account in the selection function of these surveys, and likely need to be modelled for an unambiguous characterisation of helium reionization, as well as using more accurate inputs (such as the galaxy bias and number density) when performing forecasts in the future.

Throughout this paper, we used the so-called ‘box’ formalism introduced in Ref. \cite{26}. The benefit of this formalism is its simplicity; while using redshift bins on the light cone is likely a more accurate representation of kSZ tomography in practice, as discussed in Refs. \cite{25, 56, 57}, for example.\textsuperscript{6} Here, our goal was to produce easy-to-reproduce forecasts that access and high-

\begin{table}[h]
\begin{tabular}{|c|c|c|}
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Surveys & $\sigma(x_{\text{He}}^\text{re})$ & $\sigma(\Delta x_{\text{He}}^\text{re})$ \\
\hline
VRO+CMB-S4 & 0.90 (0.71) & 0.80 (0.41) \\
MegaMapper+CMB-HD & 0.056 (0.057) & 0.057 (0.042) \\
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\end{tabular}
\end{table}

\textsuperscript{4} Note that better sensitivity on optical-depth or the galaxy biases only marginally improve the sensitivity of these experiments to helium reionization parameters, since the degeneracy between them and the bias parameters at each redshift is broken by the distinct redshift dependence of the models we consider.

\textsuperscript{5} https://github.com/ctrendafilova/FisherLens

\textsuperscript{6} In addition, formalising kSZ tomography on the light cone has the benefit of better capturing the redshift dependence of the signal, particularly in the case of spectroscopic surveys where one can separate the redshift range in many bins, as well as better capturing the degrading effect of CMB foregrounds, for example. In our upcoming studies on this topic, we will focus on the light-cone formalism.
light the prospects of detecting and characterising helium reionization.

The epoch of helium reionization carries a large amount of information about astrophysics and cosmology that can potentially be accessed in the foreseeable future. As it occurs at lower redshifts, it allows the utilisation of the significant statistical power afforded by the LSS and CMB cross-correlation program—a quality likely not shared with hydrogen reionization.

Reconstructing velocities at high SNR with future surveys will provide precise tests of fundamental physics. We have shown here that this also provides a new path to detecting and characterising helium reionization. These measurements will not require new experiments other than those being built or proposed, offering new opportunities and avenues for exploration for both cosmology and astrophysics.

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