PROBING THE EPOCH OF PRE-REIONIZATION BY CROSS-CORRELATING COSMIC MICROWAVE AND INFRARED BACKGROUND ANISOTROPIES

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ABSTRACT

The epoch of first star formation and the state of the intergalactic medium (IGM) at that time are not directly observable with current telescopes. The radiation from those early sources is now part of the cosmic infrared background (CIB) and, as these sources ionize the gas around them, the IGM plasma would produce faint temperature anisotropies in the cosmic microwave background (CMB) via the thermal Sunyaev–Zeldovich (TSZ) effect. While these TSZ anisotropies are too faint to be detected, we show that the cross-correlation of maps of source-subtracted CIB fluctuations from Euclid, with suitably constructed microwave maps at different frequencies, can probe the physical state of the gas during reionization and test/constrain models of the early CIB sources. We identify the frequency-combined, CMB-subtracted microwave maps from space- and ground-based instruments to show that they can be cross-correlated with the forthcoming all-sky Euclid CIB maps to detect the cross-power at scales \( \sim 5' - 60' \) with signal-to-noise ratios \( (S/N)_o \) of up to \( S/N \sim 4 - 8 \) depending on the contribution to the Thomson optical depth during those pre-reionization epochs \( (\Delta \tau \sim 0.05) \) and the temperature of the IGM \( (\text{up to} \sim 10^3 \, \text{K}) \). Such a measurement would offer a new window to explore the emergence and physical properties of these first light sources.

Key words: cosmic background radiation – cosmology: observations – dark ages, reionization, first stars

Online-only material: color figure

1. INTRODUCTION

Within the framework of the standard cosmological model, it is theoretically believed that the first objects in the universe were dominated by massive stars and the first black holes that formed in minihalos of \( \sim 10^6 - 10^7 \, M_{\odot} \) (Bromm & Yoshida 2001). These objects cannot be detected individually with present-day instruments, so alternative methods are needed to probe the epochs of the first star formation.

At near-IR wavelengths (below \( \sim 5 \, \mu m \)), the cosmic infrared background (CIB) probes emission by stellar and black hole sources (Kashlinsky 2005) and its fluctuations may contain a substantial component from the first sources (Kashlinsky et al. 2004; Cooray et al. 2004). Significant CIB fluctuations have been identified in Spitzer (Kashlinsky et al. 2007a, 2012) and Akari (Matsumoto et al. 2011) data between \( \sim 2 \) and \( \sim 5 \, \mu m \) after known galaxy populations have been subtracted to deep levels. The fluctuations are too large and have the wrong spatial distribution to be explained by known galaxy populations (Kashlinsky et al. 2007a, 2012). Their origin was suggested to lie at the epoch of first stars (Kashlinsky et al. 2007a, 2007b), as implied by the slope of their spatial spectrum now measured to \( \sim 1^\circ \) (Kashlinsky et al. 2012). The high-\( z \) interpretation of the residual fluctuations is supported by the observed lack of correlation between the Spitzer CIB fluctuations and optical Hubble Space Telescope image data out to \( 0.9 \, \mu m \), where the Lyman-break at wavelength \( 0.1(1 + z) \mu m \) is expected (Kashlinsky et al. 2007c). The source-subtracted CIB fluctuations appear highly coherent with the soft \( [0.5-2] \, \text{KeV} \) unresolved cosmic X-ray background (CXB) with no detectable coherence appearing at harder X-ray energies (Cappelluti et al. 2013). The measured correlation requires a proportion of accreting black holes among the CIB sources significantly higher than in the directly observed populations (Helgason et al. 2014), further supporting the high-\( z \) origin of these sources and inconsistent with the alternative proposal for the origin of the CIB fluctuations in intrahalo light at more recent epochs (Cooray et al. 2012, see also Section 4.3 of Helgason et al. 2014 for summary of further observational difficulties of this scenario).

We will assume here that the sources producing these CIB fluctuations at \( (2-5) \, \mu m \) lie at early epochs, \( z \gtrsim 8 \), consistent with all the CIB-related measurements. This will be tested definitively with the Euclid data, where this team has been selected by NASA/ESA to conduct an all sky near-IR CIB program LIBRAE (Looking at Infrared Background Anisotropies with Euclid). At high-\( z \), these early sources would have ionized and heated up the surrounding gas, which, in principle, would generate secondary anisotropies in the cosmic microwave background (CMB) via the thermal Sunyaev–Zeldovich (TSZ) effect. Given that Euclid will cover \( \sim 20,000 \, \text{deg}^2 \) with sub-arcsec resolution at three near-IR channels (Laureijs et al. 2011), this weak signal may be teased out of the noise, after the suitable construction of a comparably large area, low noise, multifrequency CMB maps of \( \sim \text{arcmin} \) resolution which are expected to be available in the near future. We show here how such measurements can lead to a highly statistically significant result for plausible modes of the high-\( z \) evolution. At the same time, if the signal originates at high-\( z \), there should be no correlation between the CMB and the diffuse emission maps obtained from the Euclid VIS (visible) channel. Our goal here is not to test specific models, but rather to demonstrate how the first ionization sources very generally can produce a measurable CIB×CMB signal, whose detection or upper limit can then be used to probe...
the emergence of the universe out of the “Dark Ages.” The proposed technique offers to probe the beginning of the reionization process in a manner alternative to HI 21 cm tomographic studies (see Furlanetto et al. 2006 fora review), both methods being complementary but subject to different foregrounds and systematics.

2. CIB SOURCES AND CROSS-POWER WITH CMB

The measured CIB fluctuation spectrum appears consistent with the high-z ΛCDM clustering and is the same (within uncertainties) in different sky directions consistent with its cosmological origin (Kashlinsky et al. 2012). The source-subtracted CIB fluctuations have two components: (1) shot/white noise from the remaining (unresolved) sources dominates small angular scales and sets an upper limit on the shot noise of the new high-z populations, and (2) a fluctuation component due to clustering of new population sources is found at scales >20′. We use these measurements to normalize the TSZ anisotropy to the flux from, and the abundance of, the sources at high-z using an outline similar to Kashlinsky et al. (2007b).

Massive Population III stars of mass $m_*$ would radiate at the Eddington limit with luminosity $L_\text{edd} \propto m_*$. They would have approximately constant surface temperature $T_\text{e} \sim 10^5$ K and would have produced a large number of ionizing photons with energy $\gtrsim 13.6$ eV. These lead to a constant ratio of the ionizing photons per H-burning baryon in these objects. The results of Bromm et al. (2002); Schaerer (2002) give a number of ionizing photons $N_\text{H} \sim 10^6 m_*/M_\odot$ produced over the lifetime of these stars ($\sim 3 \times 10^8$ yr) by a halo containing $M_*$ in such sources. If $\kappa$ ionizing photons are required to ionize an H atom, around $10^6$ photons are required to ionize an H atom, around 10$^6$ K and $\tau_{\text{tsz}} \equiv \int z \Delta z P_{\text{TSZ}}(z) dz$ is the radius of the ionized cloud and $m_*$ the electron mass. Each ionized bubble would generate a CMB mean distortion over a pixel of solid angle $\omega$ subtended by the bubble would be $Y_\text{CIB} = G_{\nu} Y_{\text{C},B}(\omega/\omega_\text{TSZ})$ where $R_\text{ion}$ is the radius of the ionized cloud and $m_*$ the electron mass. Each ionized bubble would generate a CMB mean distortion over a pixel of solid angle $\omega$ subtended by the bubble would be $Y_\text{CIB} = G_{\nu} Y_{\text{C},B}(\omega/\omega_\text{TSZ})$ where $R_\text{ion}$ is the radius of the ionized cloud and $m_*$ the electron mass. Each ionized bubble would generate a CMB mean distortion over a pixel of solid angle $\omega$ subtended by the bubble would be $Y_\text{CIB} = G_{\nu} Y_{\text{C},B}(\omega/\omega_\text{TSZ})$ where $R_\text{ion}$ is the radius of the ionized cloud and $m_*$ the electron mass.

Strong lower limits on the projected number density of sources/bubbles can be set by the combination of the measured upper limit on the CIB shot noise power, $P_{\text{SN}}$, and the amplitude of the clustering component of the CIB fluctuations (Kashlinsky et al. 2007b). Populations at high-z, which are strongly biased and span a short period of cosmic time, are expected to produce $\Delta \sim 10^5$ relative CIB fluctuations on arcmin scales requiring a net flux of $F_{\text{CIB}} = \delta F_{\text{CIB}}/\Delta \sim 1$ nW m$^{-2}$ sr$^{-1}$ from these populations. At the same time, since $P_{\text{SN}} \sim F_{\text{CIB}}^2 / n_\text{z}$, the measured upper limit on $P_{\text{SN}} \sim 10^{-11}$ nW$^2$ m$^{-4}$ sr$^{-1}$ (Kashlinsky et al. 2007a) implies a lower limit on the two-dimensional angular sky density of these sources of $n_\text{z} \gtrsim 10^{11}$ sr$^{-1}$ with $P_{\text{SN}} \equiv P_{\text{SN},-11} 10^{-11}$ nW$^2$ m$^{-4}$ sr$^{-1}$ being the shot noise power of the high-z sources. Then,

$$T_{\text{TSZ}} \sim \frac{4}{\pi} G_{\nu} T_{\text{CMB}} \frac{k_B T_\text{e}}{m_e c^2} \frac{\sigma_T}{\mu m_\odot} \frac{M_{\text{ion}}}{P_{\text{SN}}} F_{\text{CIB}}^2$$

$$\approx 200 G_{\nu} \left( \frac{0.5 \text{ Gpc}}{d_A} \right)^2 \frac{M_*}{10^5 \kappa \mu_\odot} T_{\text{e} \text{A}} \frac{F_{\text{CIB}}^2}{P_{\text{SN},-11}} \text{nK}.$$  (1)

Here, $F_{\text{CIB}}$ is the net CIB flux from these sources in nW m$^{-2}$ sr$^{-1}$, $\mu$ is the mean gas molecular weight, and $k_B$ the Boltzmann constant. $M_*$ corresponds to a conservative choice for the mass of the ionizing sources in each early halo. In standard cosmology, $d_A = 0.5–0.9$ Gpc at $z = 20–10$. For the parameters of Equation (1), the effective Thomson optical depth due to the reionized medium is $\tau_{\text{eff}} = 0.044$, well below the measured value of $\tau = 0.097 \pm 0.038$ (Planck Collaboration 2013a).

Due to the variation on the number density of bubbles with a relative number fluctuation of $\Delta \sim 0.1$ (Kashlinsky et al. 2007b), the CMB distortion $T_{\text{TSZ}}$ would generate CMB temperature fluctuations. If we further assume that the ionized bubbles are distributed as the halos where the ionized photons originate, the TSZ temperature anisotropies would have an amplitude $\sim T_{\text{TSZ}} \Delta$ that could potentially be detected by cross-correlating the produced CMB anisotropies with CIB fluctuations. If $P_{\text{CIB}}$, $P_{\text{TSZ}}$, and $P_{\text{CIB} \times \text{TSZ}}$ are the power spectrum of the CIB flux, TSZ anisotropies, and their cross-power, respectively, and the coherence between CIB sources and bubbles is $C = P_{\text{CIB} \times \text{TSZ}} / (P_{\text{CIB}} P_{\text{TSZ}})$. For bubbles coherent with CIB sources ($C \sim 1$), the cross-power between CIB and TSZ is $P_{\text{CIB} \times \text{TSZ}} \approx \sqrt{P_{\text{CIB}} P_{\text{TSZ}}}$. To compute this cross-correlation, the sub-arcsec Euclid CIB and arcmin-resolution CMB maps will be brought to a common resolution. When measuring the cross-power from IR and microwave maps ($\mu$) of $N_{\text{TSZ}}$ CMB pixels, the error is $\sigma_{\text{CIB} \times \text{TSZ}} \approx \sqrt{\sigma_{\text{IR}} / \mu / \sqrt{N_{\text{TSZ}}}}$ (Kashlinsky et al. 2012; Cappelluti et al. 2013). At the scales of interest here ($\gtrsim 1'$), the Euclid CIB maps will have negligible noise, so $P_{\text{IR}} = P_{\text{CIB}}$. Using the Euclid Wide Survey of $A \sim 20,000$ deg$^2$, the CIB power on arcminute scales will be measurable by LIBRAE down to sub-percent statistical accuracy. If primary CMB is removed, the foreground-reduced microwave maps would be dominated by instrument noise $\sigma_{\mu}$, foreground residuals $\sigma_{\mu, \text{res}}$, and, more importantly, the TSZ of the unresolved cluster population $\sigma_{\mu, \text{cl}}$. With $N_{\text{f}}$ frequency channels, the variance of the microwave map would be $\sigma_{\mu}^2 = \sigma_{\mu}^2 / N_{\text{f}} + \sigma_{\mu, \text{res}}^2 + \sigma_{\mu, \text{cl}}^2$. The signal-to-noise ratio ($S/N$) would be $S/N \sim T_{\text{TSZ}} A \sqrt{N_{\text{TSZ}} / \mu / \sigma_{\mu}}$, which can reach $S/N \gg 1$ for some experimental configurations discussed below. Specifically,

$$S/N = \frac{T_{\text{TSZ}} A}{200 \text{nK}} \frac{5 \mu K}{0.1} \left( \frac{N_{\text{TSZ}}}{3 \times 10^6} \right)^{1/2}$$  (2)

where $N_{\text{TSZ}} = 3 \times 10^6$ corresponds to 20,000 deg$^2$ binned into independent squares of 5° on the side, the expected sky coverage of the Euclid satellite downgraded to the native resolution of Planck.

3. CMB DATA

Equation (2) shows that CMB maps with low $\sigma_{\mu}$ covering a sufficiently large sky area are needed for a statistically significant measurement of the CIB×TSZ cross correlation.
Such maps already exist and more will be available in time for the upcoming Euclid CIB measurement with LIBRAE. Resolved sources in the Spitzer CIB analysis remove $\sim$25% of the sky (Kashlinsky et al. 2007a, 2012); this fraction is expected to be lower for the much better resolution of Euclid, which, in any event, will then be pixelated into the CMB resolution of $\gtrsim$arcmin.

To transform these CMB data into maps suitable for probing the contribution of the TSZ from the first stars era and gain insight into the epochs prior to the completion of the reionization, one needs to remove the primary CMB component of $\sigma_{\text{CMB}} \approx 80 \mu K$, which is feasible with the multi-frequency microwave maps obtained, and obtainable, with numerous instruments by, for example, subtracting a 217 GHz map, the null of the TSZ effect, from maps at other frequencies. In this process, other blackbody components, such as from the integrated Sachs–Wolfe and kinetic SZ effects, will also be removed. After the suitable CMB subtraction has been achieved, the microwave maps will be cross-correlated, via the cross-power (see Kashlinsky et al. 2012; Cappelluti et al. 2013), with the Euclid CIB maps to be produced over patches of $\sim 1^{\circ}$ on the side and covering 20,000 deg² in the Euclid Wide Survey. We now specify several instrumental configurations for such a measurement.

**Planck.** For Planck channels at frequencies $\nu = (100, 143, 217, 353)$ GHz, the beams have an effective FWHM $\theta = (9.65, 7.25, 4.99, 4.86)^{\circ}$ (Planck Collaboration 2013b). At these frequencies $G_{\nu} = (-1.51, -1.04, 0.0, 2.23)$ and a noise after the planned two years of integration is $\sigma_n = [1.3, 0.5, 0.7, 2.5] \mu K$ on pixels of $1^{\circ}$ side. Other contributions to the overall $\sigma_n$ come from sources below the threshold detection level of the instrument. The amplitude of the Poisson and clustered foreground power spectra $\Delta T = \ell (\ell + 1) C_{\ell}/2\pi$ at $\ell = 3000$ are $A = (220 \pm 53, 75 \pm 8, 60 \pm 10) \mu K^2$ and $A^{\text{CIB}} = (\sim 0, 32 \pm 8, 50 \pm 5) \mu K^2$ for 100, 143, and 217 GHz, after 1 yr of integration (Planck Collaboration 2013c). The Planck Collaboration does not provide values of these contributions at 353 GHz, so we will assume them to be negligible. These components will not cancel when subtracting the 217 GHz map from those of other frequencies. The TSZ from unresolved clusters has an amplitude $A^{\text{TSZ}} = 4G_{\nu}^2 \mu K^2$ that will also be present (Planck Collaboration 2013a). In summary, the noise in the Planck CMB difference maps $\nu - 217$ GHz is $\sigma_{\nu-217} = (9.6, 10.3, 32.0) \mu K$ for $\nu = (100, 143, 353)$ GHz on pixels corresponding to the FWHM at each frequency. Combining the three channels, taking into account the frequency dependence of the TSZ effect, the error on the Comptonization parameter would be $\sigma_{\text{Planck}} = 7.8 \mu K$ on pixels of $5^{\circ}$ after 2 yrs.

**The Atacama Cosmology Telescope.** (ACT) has already mapped CMB over 600 deg² at 148, 218, and 277 GHz with a resolution of $(1.4, 1.0, 0.9)^{\circ}$ (Gralla et al. 2014). The currently observed area is small for the purposes of the present discussion and adds little to the S/N of the measurement, but an expanded area could eventually provide useful data.

**South Pole Telescope.** (SPT) has already mapped 2540 deg² at (95, 150, 220) GHz, with a resolution of $(1.7, 1.2, 1.0)^{\circ}$. The noise levels are 18 $\mu K$ at 150 GHz and $\sim \sqrt{2}$ larger for the other two channels (George et al. 2014). The CMB-subtracted maps have a residual noise of $\sigma_{\nu-220} \approx (36, 32) \mu K$ with a similar number of pixels as Planck ($N_{\text{pix}} > 3 \times 10^9$) for the lowest-resolution channel. Combining the two frequencies, the noise on the Comptonization parameter scaled to $5^{\circ}$ pixels is $\sigma_{\text{SPT}} = 4.74 \mu K$, smaller than that of Planck but over one-eighth the area covered by Euclid. It would provide competitive results with those of Euclid and Planck. In addition, due to its location, the SPT data should be useful for a similar analysis with WFIRST (Spergel et al. 2013).

**Future Experiments.** Like Advanced ACTPol (Calabrese et al. 2014) and CMB-Stage 4 (Abazajian et al. 2014) would aim to map one-half to two-thirds of the sky with a sensitivity of $\sim 10 \mu K$ arcmin$^{-1}$ and $\sim 1 \mu K$ arcmin$^{-1}$ at a wide range of frequencies, 30–300 GHz and 40–240 GHz, respectively. In these future instruments, the limiting factor will not be instrumental noise, but confusion from foreground sources and TSZ contributions from unresolved clusters. These foregrounds would contribute $\sigma_q = 3−10 \mu K$ in the frequency range 100–217 GHz. These low noise levels, in combination with Euclid and potentially also WFIRST-based, CIB maps, offer the exciting possibility of probing how CIB sources affected the physical properties of the intergalactic medium (IGM) prior to reionization.

### 4. The CIB–CMB Cross-Power Spectrum

We can refine the previous estimate (Equation (2)) by a specific model computation of the cross-power of TSZ anisotropies and CIB fluctuations. We compute the TSZ–CIB cross-power on an angular scale $\theta = 2\pi/q$ via the relativistic Limber equation

$$P_{CIB\times TSZ}(q) = \int d\ell(z) \left( \frac{dF_{CIB}}{dr} \right) \left( \frac{dY_C}{dr} \right) \frac{P_3(q/r, z)}{r^2},$$

and normalize it to the measured CIB auto-power as discussed in (A. Kashlinsky et al. 2014, in preparation). In the above, $q = 2\pi/\theta$, $P_3$ is the three-dimensional biased power spectrum of the sources, and $r = d_A(1+z) = d_L/(1+z)$ is the comoving distance.

As in Kashlinsky et al. (2004), we assume that the sources radiate at the Eddington limit, form proportionally to their collapse rate, and, in addition, are designed to reproduce the measured integrated CIB fluctuations over 2–5 $\mu$m, verifying that their relative fluctuation $\Delta \approx 0.1$ at $2\pi/q = 5$ ($A$. Kashlinsky et al. 2014, in preparation). As the ionized bubbles appear around the CIB sources, they will start generating the optical depth due to Thomson scattering, $\tau = \rho_b n_b / (\rho_m c) x_e(x_e - 1 \pm 1)^{-1}$, where $x_e$ is the ionization fraction, as well as contribute to the Comptonization, $dY_C/dr = (k_b T_e / m_e c^2) d\tau/dr$. Because the ionized bubbles surround the first sources, we assume the same biasing for both TSZ and CIB and use the methodology of Kashlinsky et al. (2004) and Cooray et al. (2004) to relate it to the underlying standard LCDM power spectrum.

In principle, the ionization fraction $x_e(z)$ can be related to the fraction of baryons in stars as: $x_e = n_1 f_s$, where $n_1$ is the number of ionized atoms per baryon in CIB sources and $f_s(z)$ is the fraction locked in CIB sources up to $z$. To simplify our treatment, we parameterize $f_s(z) \propto \text{erfc}((z - z_0)/\Delta z)$, where $z_0$ is the redshift at which half of $f_s$ have been locked up in CIB sources, and $\Delta z$ determines how fast baryons collapse to form CIB sources. We normalize below the overall optical depth produced by these sources to $\Delta r = 0.05$ and take the temperature of the gas in the bubbles to be $T_e = 10^5 K$, where atomic cooling becomes inefficient in the absence of $H_2$. In the presence of heating by accreting black holes or X-ray binaries, $T_e$ can rise somewhat above $10^5 K$ (Mirabel et al. 2011; Jeon et al. 2014).

We assumed in computations that $z_0 = [13, 20]$ and $\Delta z = [0.3, 1.3]$, fixing the final ionization fraction to reproduce $\Delta r = 0.05$; this corresponds to $0.3 < x_e < 1$ at the end...
of that period. We verify that the coherence of these models varies between $0.8 < \sqrt{C_{\text{TSZ}} \times C_{\text{CIB}}} < 0.95$ to compare with the discussion in Section 2. In Figure 1(a), we show how the optical depth reaches $\Delta \tau = 0.05$ for these models. Figure 1(b) shows the $S/N$ with which the experiments discussed in Section 3 can probe the $C_{\text{CIB}} \times C_{\text{TSZ}}$ cross-correlation at different angular scales. We always assume that the experiment has at least two frequencies with overlapping resolution so the primary CMB and the kinetic SZ component can be removed from the maps. The band width encloses the minimum/maximum values of all our models. Note that the final $S/N$ is weakly dependent on when reionization occurs (parameterized by $z_0$) and the width of this period ($\Delta z$). This is a consequence of normalizing all models to the measured CIB flux and to the same electron optical depth. The blue band corresponds to an experiment with the instrumental noise and the foreground residuals of $\sigma_{\text{noise}} = 5 \mu K$ on pixels of 5' side covering the area of the Euclid wide field survey. The red band corresponds to the $S/N$ using Euclid and the HFI Planck data at the end of the nominal 2 yr mission. The $S/N$ is $\sim 2$ when using the 353 GHz and 217 GHz channels and increases to $\sim 5$ when the 143 and 100 GHz channels are added. Adding SPT data (George et al. 2014) increases the $S/N$ to $\sim 6$ at 13'.

The results of Figure 1 scale as $(S/N) \propto \Delta \tau \cdot T_e$, leading to higher significance for $T_{e, A} > 1$ as reached in the modeling of, e.g., Jeon et al. (2014). The $S/N$ can be increased by computing the cross-power over wider angular bins, allowing us to probe much lower parameters as done in Cappelluti et al. (2013). In addition, in experiments such as Planck, observing at frequencies above and below the TSZ null frequency, the CIB–TSZ correlation will change sign, offering a potential test to eliminate spurious contributions.

5. DISCUSSION

We have demonstrated that the cross-correlation of the future CIB Euclid maps with the CMB data expected by that time can probe or constrain the pre-reionization epochs as the universe emerges out of the “Dark Ages.” If (1) these sources contributed about half of the measured optical depth to the last scattering surface and (2) the ionized blobs contained gas at $T_e = 10^4$ K, the measurement would be at $S/N > 6$ using the CMB map differencing method discussed here. The cross-power measurement can be further improved by computing the latter in wider angular bins. The overall $S/N$ demonstrated here is large enough for the detection to remain significant even if parts of the Euclid CIB maps are polluted by Galactic cirrus, which would not correlate with the TSZ component.

At fixed angular resolution the significance scales with the area of CIB–CMB overlap, $A$, as $S/N \propto \sqrt{A}$. Additionally, WFIRST, the Dark Energy mission currently considered by NASA, could likewise provide significant results with its coverage of four near-IR channels currently planned to cover $\sim 2000 \text{ deg}^2$ (Spergel et al. 2013) combined with the proposed CMB-Stage 4 arcmin-resolution instrument (Abazajian et al. 2014). The planned absence of the visible channel on board WFIRST in testing the high-$z$ origin of the cross-power can be compensated with the Euclid VIS data.

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