Non-thermal Sunyaev-Zeldovich signal from radio galaxy cocoons

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ABSTRACT
Energetic electrons in the cocoons of radio galaxies make them potential sources for not only radio and X-rays but also Sunyaev-Zeldovich (SZ) distortions in the cosmic microwave background (CMB) radiation. Previous works have discussed the energetics of radio galaxy cocoons, but assuming thermal SZ effect, coming from the non-thermal electron population. We use an improved evolutionary model for radio galaxy cocoons to estimate the observed parameters such as the radio luminosities and intensity of SZ-distortions at the redshifts of observation. We, further, quantify the the effects of various relevant physical parameters of the radio galaxies, such as the jet power, the time scale over which the jet is active, the evolutionary time scale for the cocoon, etc on the observed parameters. For current SZ observations towards galaxy clusters, we find that the non-thermal SZ distortions from radio cocoons embedded in galaxy clusters can be non-negligible compared to the amount of thermal SZ distortion from the intra-cluster medium and, hence, can not be neglected. We show that small and young (and preferably residing in a cluster environment) radio galaxies offer better prospects for the detection of the non-thermal SZ signal from these sources. We further discuss the limits on different physical parameters for some sources for which SZ effect has been either detected or upper limits are available. The evolutionary models enable us to obtain limits, previously unavailable, on the low energy cut-off of electron spectrum ($p_{\text{min}} \sim 1–2$) in order to explain the recent non-thermal SZ detection (Malu et al. 2017). Finally, we discuss how future CMB experiments, which would cover higher frequency bands (>400 GHz), may provide clear signatures for non-thermal SZ effect.

Key words: Radio galaxy – CMB spectral distortions – Cosmology

1 INTRODUCTION

Studying the distortion of the cosmic microwave background radiation (CMB) through the Sunyaev-Zel’dovich effect (SZ effect) (Zeldovich & Sunyaev 1969) has become a mainstay of modern cosmology. The inverse Compton scattering of the CMB photons by energetic electrons has opened up a new window of probing the warm and hot gaseous regions of the universe (Birkinshaw 1999; Aghanim et al. 2008; Mroczkowski et al. 2019). Being complementary to the traditional X-ray observation of these ionized regions, SZ effect not only enables a robust determination of their physical properties, but also makes it possible to study them at high redshift, and consequently, study their evolution. The intensity of distortion of CMB does not dilute with increasing redshift resulting from the fact that the energy density of scattered CMB photons and the intensity of CMB photons have same functional dependence on redshift.

Besides energetic thermal electrons in hot gas, non-thermal relativistic gas can also produce SZ signal, whose distinct spectral signature makes it an interesting probe of reservoirs of such gas in the universe (Enßlin & Kaiser 2000; Majumdar 2001). One source of energetic particles can be radio galaxy cocoons where relativistic particles are supplied by the radio jet (Scheuer 1974; Begelman & Cioffi 1989; Nath 1995), which was first predicted by Felten & Rees (1969) soon after the discovery of CMB. The pressure from the energetic particles can push out the surrounding gas with the size of the cocoon growing to megaparsec length scales (Baldwin 1982; Kaiser et al. 1997). Recent detection of X-ray emission from radio lobes has been explained through inverse Compton scattering of CMB photons by non-thermal relativistic electrons that are responsible for the radio emission (Croston et al. 2005; Erlund et al. 2008; Fabian et al. 2020).

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Radio power (W Hz$^{-1}$ Str$^{-1}$) vs size of cocoon (kpc).

**Figure 1.** Comparison of radio power, at 150 MHz, obtained in this work (in thick lines) with the corresponding values in KDA1997 (thin lines) for the three cases as given in KDA1997 (their Fig. 1). The parameters for the blue (dotted), red (dashed), and black (solid) lines correspond to [Q$_j$ erg s$^{-1}$, z] = [(10$^{37}$, 2), (10$^{36}$, 0.5), and (10$^{35}$, 0.2)] respectively where Q$_j$ is the jet luminosity and z is the observed redshift of radio galaxy. The spectral index of electron energy is taken to be $\alpha = 2.15$.

2 MODEL FOR RADIO COCOONS

We start by assuming that the jet of the radio galaxy, which has a luminosity $Q_j$, injects relativistic particles throughout the jet lifetime $t_j = 10^{7.8}$ yr, after which it ceases to be active. The injected energy causes a cocoon around the jet to expand against the surrounding medium. We describe the density profile of the surrounding gas with a power law, $\rho(r) = \rho(0)(\frac{r}{a})^{-\gamma}$ with $\gamma = 2$ (Wang & Kaiser 2008). This density profile can be written as, $\rho(r) = A r^{-2}$, with $A = 10^{19}\text{g cm}^{-3}$ (Fukazawa et al. 2004; Jetha et al. 2007). The cocoon non-thermal electron energy distribution is assumed to be a power law with, $n(y_t, t) = m_0 y_t^{-\alpha} d y_t$, where $y_t$ is the Lorentz factor of electrons at time of injection $t_i$, and $\alpha$ is the spectral index. We assume the minimum $y_{\text{min}} = 1$ and the maximum, $y_{\text{max}} = 10^6$. The evolution of the radio cocoons can be described by (Reynolds & Begelman 1997),

\[ Q_j(t) = \frac{1}{\Gamma_c - 1}(V_c p_c + \Gamma_c p_c V_c), \quad \frac{dI_j}{dt} = \left(\frac{p_c}{\rho}\right)^{1/2}. \tag{1} \]

where $Q_j(t)$ is the jet luminosity which is nonzero when jet is on ($t < t_j$, where $t_j$ is the jet lifetime) and zero for $t > t_j$, $\Gamma_c = \frac{4}{3}$, $V_c$ is the volume of the cocoon, $p_c$ is the pressure in the cocoon, $L_j$ is the fiducial size of the cocoon and $\rho$ is the density of surrounding gas. We assume the axial ratio of the cylinder shaped cocoon to be $R = 2$, the average observed ratio (Leahy & Williams 1984). The volume of the cocoon is then given by,

\[ V_c = \frac{\pi}{4R^2} t_j^3. \tag{2} \]

The magnetic and particle energy densities in the cocoon are given by,

\[ U_B = \left(\frac{A p_c(t)}{\Gamma_c - 1}(1 + A)\right), \quad U_e = \frac{p_c(t)}{\Gamma_c - 1}(1 + A). \tag{3} \]

where $A = (1 + \alpha)/4$ (Kaiser & Alexander 1997). For a comparison with result of KDA1997, we first consider the case when jet is on all the time. We then proceed to compute the radio flux at 150 MHz as a function of time or size of the cocoon. Assuming that for synchrotron radiation, an electron emits only at the frequency $\nu = \gamma^2 \nu_L$, where $\nu_L$ is the...
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Larmor frequency, we calculate the number density of electrons with Lorentz factor $\gamma_{150\text{MHz}}$ which will emit at 150 MHz as a function of time $t$. We then find the value of $\gamma_1$ which were injected at time $t_1 < t$ and which would have cooled to $\gamma_{150\text{MHz}}$ at time $t$. The equation for evolution of electron Lorentz factor $\gamma$ is given by,

$$\frac{d\gamma}{dt} = -\frac{1}{2} \frac{dV_c}{dt} - \frac{4}{3} \sigma_T \frac{\gamma^3}{m_e c^2} (U_B + U_C),$$

where $\sigma_T$ is Thomson cross-section, $m_e$ is the mass of electron, $c$ is the speed of light, $U_B$, $U_C$ are the magnetic energy density and CMB energy density, respectively. The normalisation of particle spectrum $n_0$ at time $t_1$ is given by (Kaiser et al. 1997; Nath 2010),

$$n_0(t_1) = \frac{U_c(t_1)}{m_e c^2} \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} (\gamma - 1) \gamma^{-a} d\gamma.$$

The number density of electrons with $\gamma = \gamma_{150\text{MHz}}$ at time $t$ due to expansion of cocoon, is given by,

$$n(\gamma) = n_0 \frac{\gamma_{150\text{MHz}}^2 - \gamma^2}{\gamma^2},$$

where $\frac{1}{2} \frac{dV_c}{dt} = \frac{3}{2} L_c \frac{dL_c}{dt}$ and cocoons are assumed to evolve self-similarly (as warranted by the assumption of a constant axial ratio). Any volume segment of the cocoon at time $t$ can be related to pressure at time $t_1$ as,

$$\delta V(t) = \left( \frac{\gamma_{150\text{MHz}} - 1}{\gamma_0} \right) \delta V_0 = \left( \frac{p_c(t)}{p_c(t_1)} \right)^{1/3} L_c \delta t_c,$$

where $\delta t_c$ is the time interval over which electrons were injected. Then, the power emitted at $t$ at 150 MHz is given by,

$$P_v = \int_0^t \frac{1}{3} \sigma_T U_B \frac{\gamma_{150\text{MHz}}^3}{\nu} n(\gamma_{150\text{MHz}}) \delta V,$$

where the integral is done over electron injection time $t_1$. For jet shutdown at time $t_f$, the upper limit of integral should be $\min(t, t_f)$ (Nath 2010).

In Fig. 1, we have compared our results with the result of KDA1997 with the jet on for all the time for three different cases. The differences between the solid (this work) and dashed (KDA1997) lines are due to the fact that we have used equation 1 instead of using a power-law solution ($L_j \propto \tau^{3/5-\beta}$) at all times. A higher jet luminosity increases the radio power due to a larger number of energetic particles. This also, increases the size of the cocoon due to an increase in pressure owing to these particles. The initial expansion of the cocoon is dominated by the pressure of the energetic particles and the synchrotron and inverse Compton cooling can be ignored. However, once the pressure drops due to expansion of the cocoon, the inverse Compton cooling becomes important. At higher redshifts, cooling by CMB photons become increasingly efficient as CMB energy density is proportional to $(1+z)^4$. This can be seen in the leftward shift in the break of slope of the curve at $~1000$ kpc since there are less number of energetic electrons at $\gamma_{150\text{MHz}}$ due to efficient cooling.

3 SUNYAEV-ZELDOVICH EFFECT FROM NON-THERMAL RELATIVISTIC POPULATION OF ELECTRONS

It is well known that energetic electrons can boost the CMB photons to higher energy through inverse Compton scattering creating a distortion in the CMB blackbody spectrum. If the energy distribution of the electrons is non-relativistic and thermal, then the distortion has universal $y$-distortion shape (Zeldovich & Sunyaev 1969). For relativistic electrons, with a Lorentz factor $\gamma$, a photon with energy $\epsilon$ gets boosted to $\gamma' \epsilon$. In this case, the spectral distortion shape will be a function of the electron energy distribution. The intensity of the CMB spectrum per frequency is given by,

$$I_\nu(x) = \frac{1}{\nu} \frac{\delta B T_{\text{CMB}}}{(hc)^2} \frac{x^3}{e^x - 1} = I_{\text{d}}(\nu),$$

where $I_{\text{d}}(\nu) = \frac{1}{\nu} \frac{\delta B T_{\text{CMB}}}{(hc)^2} \frac{x^3}{e^x - 1}$, $I(\nu)$ is the dimensionless intensity, $x$ is the dimensional frequency which is given by $x = \frac{\nu}{\nu_{\text{CMB}}}$, where $\nu_{\text{CMB}}$ is the energy of photon, $\delta B$ is the Boltzmann constant, $T_{\text{CMB}}$ is the CMB temperature, and other symbols have usual meanings. The intensity of distorted CMB spectrum is independent of redshift for a given population of electrons. The CMB distortion in the optically thin limit can be written as (Zeldovich & Sunyaev 1969; Birkinshaw 1999),

$$\Delta I(\tau) = \frac{1}{\nu} \frac{\delta B T_{\text{CMB}}}{(hc)^2} \frac{x^3}{e^x - 1} = I_{\text{d}}(\nu).$$

$$\Delta I(\tau) = (i(\nu) - i(\nu)) \tau,$$

where $\Delta i(\nu)$ is the spectral intensity of photons at frequency $\nu$ after being upscattered while $i(\nu)$ is the intensity of photons at frequency $\nu$ before upscattering, $\tau = \sigma_T \int n_e dl$ where $n_e$ is the electron number density and $dl$ is the line of sight width of this electron population. $i(\nu)$ is non-zero only for $0.1 <
\( x < 10 \) because only these photons are getting upscattered. Eq. 10 can be recast to include a \( \gamma \)-parameter as \( \Delta I(x) = y(x) \), where \( y = \frac{\sigma_T}{n_e c^2} \int n_e k_B T_e \, dl \) with \( k_B T_e = \frac{P_e}{n_e} \). In order to distinguish non-thermal spectral distortion shape from \( \gamma \)-type distortion (the well known thermal SZ effect), we will refer to non-thermal distortion amplitude as \( y_{NT} \), such that,

\[
\Delta I_{NT}(x) = y_{NT} \Delta N(x),
\]

where \( \Delta N(x) \) is the spectral distortion function resulting from scattering of the CMB in a non-thermal population of clusters. The pressure for a distribution of relativistic electrons is given by \( (\text{Enßlin} &\text{ Kaiser} 2000) \),

\[
P_e = n_e \int dp f_e(p) \frac{1}{2} pv(p) m_e c,
\]

where \( f_e(p) \) is the normalized electron spectrum i.e. \( \int f_e(p) \, dp = 1 \) with electron energy \( p = \sqrt{\left(\gamma^2 - 1\right)} \), \( \gamma = \beta c \), where \( \gamma \) is the Lorentz factor and \( \beta \) is the boost factor of energetic electrons. The number of CMB photons which get upscattered from energy \( x' \) to \( x \) is given by,

\[
N(x' > x) = P(t, p) \times 2 \int \frac{\left(\frac{\ln T_{\text{CMB}}}{hc} x' x^2 dx' \right)^3}{x'^4 - 1}.
\]

where \( P(t, p) \) is the kernel of the inverse Compton scattering which captures the kinematics of photon scattering with the electrons with electron energy \( p \) at \( t = \frac{t}{T} \). The number of CMB photons within energy \( x' \) and \( x' + dx' \) is \( 2 \frac{(\ln T_{\text{CMB}})^3}{hc} x'^2 dx' \) and \( \int dt P(t, p) = 1 \), which conserves the number of photons. The formula for \( P(t, p) \) is given by \( (\text{Enßlin} &\text{ Kaiser} 2000) \),

\[
P(t; p) = \frac{3}{32 p^3} \left[ 1 + (10 + 6 p^2 + 4 p^4) t + t^2 \right] + \frac{3}{8 p^5} \left[ \frac{3 + 3 p^2 + p^4}{\sqrt{1 + p^2}} - \frac{3 + 2 p^2}{2 p} \left( 2 \arcsin p - |\ln i| \right) \right].
\]

The spectral intensity of upscattered photons per frequency, in frequency bin \( x \) and \( x + \Delta x \), is given by,

\[
j(x) = \int \int f_e(p) dp P(t, p) \frac{x'^2 dx' x}{e^{x'/1} - 1}.
\]

Similar expression can be obtained for \( i(x) \).

In Fig. 2, we plot the absolute value spectral function \( g_N(x) \) for power law distribution \( (\sigma_T/p)^{\alpha} \) with power law index \( \alpha = 3.0 \). The minimum electron energy in the power law distribution is denoted by \( p_{\min} \). The value of \( g_N(x) \) at specific frequencies corresponding to frequency band of the upcoming Simons Observatory \( (\text{Ad e et al. 2019}) \) is given in Table 1.

4 NON-THERMAL SZ SIGNAL FROM RADIO COCOONS

It is clear from the previous discussion that we need to calculate the number density of relativistic electrons as a function of the energy in order to calculate the non-thermal SZ spectrum for individual radio cocoons. To proceed, we use the same strategy as used to calculate the number density of electrons which emit at 150 MHz. We divide the range in \( \gamma \) from 1 to \( 10^6 \) in 400 log spaced bins. Then, we use Eq. 4 and 6 for the whole range of electron energy (or \( \gamma \)) at each instant of time to calculate the number density \( n(\gamma) d\gamma \) at that instant of time.

In Fig. 3, we plot the number density of electrons with three different instantaneous energy with jets starting at different redshifts. The lowest energy electrons dominate the total number of relativistic particles. The cooling of electrons via inverse Compton is proportional to \( \gamma^2 U_C \). Therefore, at higher redshifts electrons cool much more efficiently via CMB photons. This can be clearly seen for \( \gamma = 20 \) curve for a jet starting at redshift 2.3, as the electron number precipitously drops after reaching \( z = 1, z = 2.5 \) respectively. The efficiency of cooling of electrons is a strong function of redshift \( (\propto (1 + z)^4) \). Therefore, the number density of electrons with the relatively higher \( \gamma = 20 \) falls immediately after jet the is shut off at higher redshift (e.g. for jet starting at \( z = 3 \)) while for jet starting at \( z = 1 \), there are energetic electrons left even after the jet is shut off.

In Fig. 4, we plot the radio power as a function of size of cocoons with different jet starting redshifts and jet luminosities keeping \( t_j = 10^8 \) yr. For a constant jet luminosity, radio power is independent of the initial redshift. Since we have assumed that the surrounding medium of cocoon has density profiles that is independent of redshift. The fall gets sharper with increasing redshift due to efficient cooling of the electrons at higher redshifts. After the jet stops, as there are no more energetic electrons that emit at 150 MHz, the power falls sharply. With increasing jet luminosity, the radio power increases as expected which is shown in Fig. 4. In Fig. 5, we show \( y_{NT} \) as a function of cocoon size and jet luminosity. The expression for \( y_{NT} \) is given by

\[
y_{NT} = \frac{\sigma_T}{m_e c^2} P_e \times 2L_j.
\]

where the symbols carry their usual meanings. The time taken for light to travel across the length of a cocoon is small compared to the light travel time to reach us. Therefore, the SZ observation of a radio cocoon gives a snapshot of the cocoon during its evolution at the observed redshift. With increase in cocoon size, the pressure inside the cocoon.
falls and, therefore, \( y_{NT} \) decreases. With increase in jet luminosity, pressure and \( y_{NT} \) increases. The curves show that in order to achieve \( y_{NT} \geq 10^{-3} \), either the cocoons have to be young (i.e. smaller in size) and the jet has to be active. In other words, it would be difficult to detect non-thermal SZ effect from ‘dead’ radio galaxies, because their distortion would be \( y_{NT} \leq 10^{-6} \). Also, giant radio galaxies with Mpc size are not favourable. For a jet luminosity of \( 10^{46} \text{erg s}^{-1} \) or higher, radio galaxies with size \( \leq 200 \text{kpc} \) are favourable for non-thermal SZ detection. We note that the cocoon size depends on the ambient density and would be smaller for a radio galaxy residing in a cluster environment (see also N2010), and may provide with good targets for non-thermal SZ detection. From Fig. 5, it is interesting to note that a small young radio cocoon of \( L_j \sim 100 - 200 \text{kpc} \) and \( Q_j = 10^{47} \text{ergs}^{-1} \) can have an \( y_{NT} \) equal in amplitude to thermal SZ from hot ICM of a galaxy cluster. Then taking into account the spectral distortion shape (see Fig. 9), the CMB distortion by a radio cocoon inside a cluster can be a significant part of the SZ distortion from the cluster ICM. Neglecting any \( y_{NT} \) would result in a source of systematic bias for the SZ measurements towards a cluster.

5 DEGENERACY BETWEEN PARAMETERS OF THE RADIO COCONO MODEL

In this section, we study the degeneracy between parameters of our radio cocoon model. Previous discussion shows that the non-thermal SZ effect depends on the jet luminosity, the starting redshift, and the observed redshift. We scan the parameter space in jet luminosity \( (Q_j) \) and starting redshift of jet \( (z_{st}) \) which will expand to a particular size at a given redshift \( z \). The parameter \( (z_{st}) \) can be translated to the time interval \( (\Delta t) \) after jet opening until the observed redshift. We consider two sources for illustrative purpose: 3C 274.1 and B2 1358+30C (Cofalofrancesco et al. 2013), observed at \( z = 0.422 \) and 0.206 respectively. The size of their major axis are 460 kpc and 1400 kpc respectively. We require that cocoon starting at \( z_{st} > z \) with some \( Q_j \) will grow to size \((2L_j) \) 460 ± 10 kpc and 1400 ± 10 kpc by \( z = 0.422 \) and 0.206 respectively. We assume initial size of cocoon to be 10 kpc which is the size of a galaxy. The degeneracy between the jet luminosity and elapsed time after jet opening formation, for two different jet lifetimes, which satisfies the constraint of getting the observed cocoon size at \( z \) is shown in Fig. 6. The luminosity is chosen to vary between \( 10^{44} \text{ergs}^{-1} \) and \( 10^{47} \text{ergs}^{-1} \) (Hardcastle & Croston 2020). The inferred jet luminosities from observed radio galaxies up to now seem to be below \( 10^{47} \text{ergs}^{-1} \). Note that for shorter jet lifetime, luminosity has to be larger so that pressure inside the cocoon is high enough to make it expand to a particular size. For \( \Delta t \) less than \( 10^7 \text{yr} \), the total energy content in the cocoon is \( Q_j \Delta t \) irrespective of jet lifetime being \( 10^7 \) or \( 10^8 \) yr and, therefore, the curves with the two different lifetimes merge.

Next, we plot the degeneracies between the estimated \( y_{NT} \) and the radio power at 150 MHz in Fig. 7 for the lifetimes \( 10^7 \text{yr} \) and \( 10^8 \text{yr} \). We take the same two sources depicted in Fig. 6. We also plot the scenario in which the radio cocoon of size 1400 kpc is observed at \( z = 0.6 \) instead \( z = 0.206 \) and show how it is almost degenerate with the other radio cocoon of size 1400 kpc, but at \( z = 0.206 \). We have assumed \( \alpha = 3 \) for the rest of the calculations as the detected radio galaxies used in this work have observed spectral index \( \sim 3 \). Compared to \( \alpha = 2.3 \), this results in a reduction of the radio power by more than an order of magnitude as electron population dies off steeply. For the range of luminosities chosen, the radio power drops drastically before the size of cocoon reaches \( \sim 1000 \text{kpc} \) for \( t_j = 10^7 \text{yr} \) as the jet dies off. Radio power is directly correlated with \( y_{NT} \) as the synchrotron and SZ signal comes from same population of high energy electrons. Higher \( y_{NT} \) corresponds to higher \( Q_j \), and consequently, higher radio power, as more number of high energy particles are emitted by the jet.

It is interesting to note that although the pressure inside a cocoon changes as the cocoon expands, for a particular cocoon size at any instant, both the radio power and \( y_{NT} \) are independent of the redshift. This may be understood from Eq. 1. Given a particular size, since we assume the density of the surrounding medium to be independent of
redshift, the pressure inside the cocoon and, therefore, \( y_{NT} \), is independent for all redshifts. Radio power is the same once the jet lifetime is held constant and the injected particles by the jet becomes constant for all cases. For a fixed radio power, \( y_{NT} \) increases with decreasing cocoon size as pressure increases with decreasing volume. For \( 10^3 \text{yr} < \Delta < 10^9 \text{yr} \), the jet with lower lifetime stops supplying particles, which then leads to reduction in emitted radio power for the jet with \( t_j = 10^9 \text{yr} \) compared to one with \( t_j = 10^5 \text{yr} \). The size of the cocoon also makes a difference. For a given jet luminosity, the cocoon can expand to \( 460 \text{ kpc} \) relatively easily compared to \( 1400 \text{ kpc} \) for \( t_j = 10^7 \text{ yr} \) while the jet is still on. Therefore, a cocoon of size \( 460 \text{ kpc} \) has significant radio power for both lifetimes, \( t_j = 10^9 \text{ and } 10^7 \text{ yr} \). In contrast, for a \( 1400 \text{ kpc} \) sized cocoon, there is practically no radio power for the lower lifetime of \( t_j = 10^7 \text{ yr} \).

We conclude that selecting cocoons of high radio power and small size (which is more likely in cluster environment, as discussed earlier) would pay off towards detection of non-thermal SZ signal.

It is interesting to consider the recent detection of non-thermal SZ signal from a radio galaxy by Malu et al. (2017) assuming it to be near the bullet cluster at \( z \approx 0.3 \). With this assumption, the distance of the hotspot from the radio galaxy core is estimated to be \( \approx 1 \text{ Mpc} \). The radio power at \( 5.5 \text{ GHz} \) is \( 4 \times 10^{28} \text{ W} \), over a \( 2 \text{ GHz} \) bandwidth (S. Malu, 2020, private communication). Considering the observed bandwidth, this implies radio power of \( 2 \times 10^{19} \text{ W Hz}^{-1} \). Considering the angular size of the lobe to be \( 4^\circ \times 4^\circ \approx 1.35 \times 10^{-6} \text{ sr} \), and assuming the minor axis to be half the hotspot distance, as in our model, the radio power turns out to be \( 3 \times 10^{25} \text{ W Hz}^{-1} \text{ sr}^{-1} \). Then, with a spectral index of \(-1\) (corresponding to \( \alpha = 3 \)), this implies a power at \( 150 \text{ MHz} \approx 5.5 \times 10^{26} \text{ W Hz}^{-1} \text{ sr}^{-1} \). This level of radio power is shown with 15 percent measurement uncertainty with a grey horizontal band in Fig. 8. In this figure, we also show the radio power as a function of \( y_{NT} \) for different jet lifetimes \( t_j \). The jet luminosity is varied between \( 10^{44} - 10^{48} \text{ ergs}^{-1} \). In their paper, Malu et al. (2017) reported an observed non-thermal SZ distortion with \( y = 2 \times 10^{-5} \). Note that in our calculation, the jet luminosity has to be slightly higher than \( 10^{47} \text{ ergs}^{-1} \) to explain the observed radio power for a 1 Mpc cocoon. The radio power for a 1 Mpc cocoon which can be achieved by jet luminosity \( 10^{47} \text{ ergs}^{-1} \) is shown as the black cross in Fig. 8. The required jet luminosity to explain the radio power turns out to be \( \sim 3 \times 10^{47} \text{ ergs}^{-1} \). Alternatively, the radio galaxy may be a foreground object, in which case its size is smaller, and a smaller jet luminosity is needed to explain this observation. In order to determine the requirement of energetics, we fix the jet luminosity at \( Q_j = 10^{47} \text{ ergs}^{-1} \) and vary the size of cocoon. We find that for a cocoon with size \( 200 \text{ kpc} \), the radio power can be explained by \( Q_j = 10^{47} \text{ ergs}^{-1} \) (shown with the magenta cross in the same figure). This foreground object has to be, then, located at \( z \approx 0.05 \) to have the observed angular size in the sky.

We would like to point out that Malu et al. (2017) assumed non-relativistic distortion in obtaining their value of \( y = 2 \times 10^{-5} \). However, one actually measures \( \Delta I_p \) which can be written as,

\[
\Delta I_p(x) = y_{NT}\,(\text{Malu et al. (2017)}) \\
= y_{NT} G_{NT}(x) \quad \text{(this work),}
\]

where \( y \) and \( g_{RT}(x) \) is the non-relativistic \( y \)-distortion and the spectral respectively, and similarly \( y_{NT} \) and \( G_{NT}(x) \) for non-thermal distortions. Therefore, there is a degeneracy between \( y_{NT} \) and \( G_{NT}(x) \) (or \( p_{min} \)) for a given \( \Delta I_p(x) \). This is true for the measurement of \( \Delta I_p(x) \) at a single frequency which was the case for the reported detection at 18 GHz. The magnitude of \( G_{NT}(x) \) is lower than \( g_{RT}(x) \) for all \( x \) (see Fig. 6 (of Enßlin & Kaiser 2000)) and this difference depends sensitively on the value of \( p_{min} \). At \( x = 0.35 \) (corresponding to frequency 18 GHz), the value of \( g_{RT} = 0.24 \) while \( G_{NT}(x) = 0.1 \) and 0.03 for \( p_{min} = 1 \) and 2 respectively (as seen in Fig. 2). Therefore, for \( p_{min} = 1 \) and 2, \( y_{NT} \) is higher than \( y = 2 \times 10^{-5} \) by a factor of 2.5 and 10 respectively, and can easily reach \( y_{NT} = 2 \times 10^{-4} \) for \( p_{min} = 2 \).

The degeneracy between \( y_{NT} \) and \( p_{min} \) was already noted in Malu et al. (2017) (their Fig. 2). They obtain an upper limit on \( p_{min} \) between 5 to 10 using X-ray constraints. Note, that their \( y \)-value is for non-relativistic SZ where the electron spectrum \( (p_{min}) \) does not enter. Moreover, without a radio cocoon evolution model, they could not relate \( y \)-value to the size of the cocoon. In contrast, our approach of using a detailed radio cocoon evolution model leads us to predict a value of \( y_{NT} \) for a given cocoon size and radio power. From our model, \( y_{NT} \) for 1 Mpc object turns out to be \( 6 - 7 \times 10^{-5} \) (corresponding to jet luminosity of \( \sim 3 \times 10^{47} \text{ ergs}^{-1} \)). This value of \( y_{NT} \) is consistent with the the value of \( p_{min} = 1 \). Even if we mistake the source to be a foreground object of size \( 200 \text{ kpc} \), the obtained value of \( y_{NT} \) from our evolutionary model is \( \sim 2 \times 10^{-4} \) which is consistent with \( p_{min} = 2 \). The increase in \( y_{NT} \) for 200 kpc cocoon as compared to 1 Mpc size cocoon necessarily leads to increase in \( p_{min} \) (or decrease in value of \( G_{NT}(x) \) at \( x = 0.35 \)) such that \( \Delta I_p(x) \) is unchanged as in Eq. 17. Note, that irrespective of the degeneracy between \( y_{NT} \) and \( p_{min} \), an arbitrary increase in \( y_{NT} \).
in our radio cocoon evolutionary model would result in the size of the cocoon to be unrealistically small. Therefore, the observed radio power and cocoon size (assuming the cocoon to be at $z \sim 0.3$) is consistent with $y_{NT} = 6 - 7 \times 10^{-5}$ which requires $p_{\text{min}} \sim 1$. This is the first estimate of the lower energy cutoff of non-thermal electron population in radio galaxy cocoon using SZ effect.

If we have measurements of the CMB distortions at multiple frequencies, we can directly measure the value of $p_{\text{min}}$ from the shape of distortion and break the degeneracy between $y_{NT}$ and $g_{NT}(x)$. The viability of such measurements with upcoming CMB experiments is discussed in Sec. 6.

5.1 Comparison with Colafrancesco et al.

We compare our non-thermal SZ calculation with the radio galaxies listed in Colafrancesco et al. (2013). The authors assumed a static electron distribution where the electron number density is given by,

$$N_e(p,r) = k_0 g_e(r) A(p_1, p_2, a) p^{-\alpha}.$$  \hfill (18)

The value of $k_0$ is fixed to be 2.6 cm$^{-3}$ and the average value of observed $\alpha=3$ which is obtained from fitting data to radio and X-ray observations. The electron number density is assumed to be constant, so that $g_e(r) = 1$. $A$ is a normalizing constant such that $\int_{p_1}^{p_2} A p^{-\alpha} = 1$. $p_1$ is fixed to be 1. This can be converted to cutoff in $\gamma$ as $\gamma = \sqrt{1+p_1^2}$. The size of galaxy is assumed to be ellipsoidal with major and minor axis as given in Table 1. The line of sight is assumed to be the major axis. From these informations one can calculate the optical depth for CMB photons.

In Table 2, we list the sources, their size, radio power at 150 GHz which were considered in Colafrancesco et al. (2013). We then predict the $y_{NT}$, an estimate of $t_j$ and flux for Simons Observatory at two frequencies, which are allowed by our model and satisfy the size and radio flux as given. The beam and instrument noise for Simons Observatory are listed in Table 1 of Ade et al. (2019). We use the best case scenario with specifications for LAT ($f_{sky} = 0.4$) with FWHM as the beam. The expected noise are 6.3 and 37 $\mu$K-arcmin for the two frequencies in Table 2. The $t_j$ values listed in Table 2 should be considered as a lower limit of jet lifetime that satisfies the constraints. We see that for most of the sources, the required jet luminosity needs to be higher than $10^{47}$ erg s$^{-1}$. Therefore, we have allowed the jet luminosity to vary between $10^{44}$ and $10^{48}$ erg s$^{-1}$. For a given radio galaxy size, there is a three-way degeneracy between the jet luminosity, the lifetime of jet and the starting redshift of jet ($z_{\text{start}}$) or the time-interval between jet starting redshift and observed redshift ($\Delta t$) (Fig. 6). For a given jet lifetime and size, we can increase $\Delta t$ by reducing jet luminosity or vice versa. Therefore, a bound on jet luminosity gives a bound on $\Delta t$. The radio power from a galaxy drops sharply once jet is off i.e. we should not observe radio flux if $\Delta t > t_j$. This criteria and prior condition on jet luminosity gives a lower bound on $t_j$. However, radio observation does not give an upper bound on $t_j$ since the radio cocoons becomes invisible in radio as it grows too big and faint. In contrast, the radio galaxy should be observable in SZ even after jet goes off. Therefore, SZ observations can put an upper bound on jet lifetimes of these radio galaxies.

6 DETECTION PROSPECTS OF NON-TERMAL SZ WITH FUTURE CMB EXPERIMENTS

In this section, we study the feasibility of detecting non-thermal SZ with future CMB experiments. The distortion in
Table 2. We list the redshifts of the sources, size (major axis), radio flux at 150 GHz given in Table 1 and 2 of (Colafrancesco et al. 2013). We predict the corresponding $\nu_{NT}$, $\nu$ and flux for the source with Simons Observatory (Ade et al. 2019) or CMB-S4 (Abazajian et al. 2019) type experiment to match the observation of size and radio power, allowed by our model for radio galaxy. We have used the best case noise limit (LAT, $f_{kk} = 0.4$) of Simons Observatory to derive the significance of the detection. For non-thermal spectrum, we choose $p_{\text{min}} = 1$. We have abbreviated a couple of source names to make space. Please note that for radio galaxy RG01, the flux is given at 5.5 GHz. We also assume the source to be at $z=0.3$ (at the location of bullet cluster). If the source is a foreground object, then the physical properties of the galaxy will be different (see text).

| Source     | $z$  | Size (arcsec, major axis) | Flux (mJy) | $\nu_{NT}$ | $\nu$ | Flux (\(\mu\)K-arcmin) (150 GHz) | Flux (\(\mu\)K-arcmin) (280 GHz) |
|------------|-----|--------------------------|------------|------------|-----|----------------------------------|----------------------------------|
| CGCG 186-048 | 0.063 | 388                       | 485        | 1          | $2 \times 10^{-4}$ | 3 x $10^{-10}$ | 399 (63\(\sigma\)) | 6.1 (1.6\(\sigma\)) |
| B2 1158+35 | 0.55  | 70                        | 462        | $2 \times 10^{-3}$ | 5 x $10^{-10}$ | 130 (21\(\sigma\)) | 20 (0.5\(\sigma\)) |
| 3C 270      | 0.0075 | 577                       | 93         | 1.5        | $10^{-1}$       | $10^{-5}$       | 441 (70\(\sigma\)) | 68 (1.8\(\sigma\)) |
| 87GB 121815.5... | 0.2  | 924                       | 3141       | $10^{-5}$  | $10^{8}$       | 1131 (180\(\sigma\)) | 174 (4.7\(\sigma\)) |
| 3C 274.1    | 0.422 | 89                        | 508        | 30         | $10^{5}$       | $10^{7}$       | 630 (100\(\sigma\)) | 174 (2.6\(\sigma\)) |
| 4C +69.15   | 0.106 | 822                       | 1646       | 26         | $10^{5}$       | $10^{7}$       | 8956 (1421\(\sigma\)) | 1378 (37\(\sigma\)) |
| 3C 292      | 0.71  | 64                        | 473        | 16         | $10^{5}$       | $10^{7}$       | 434 (69\(\sigma\)) | 67 (1.8\(\sigma\)) |
| B2 1358+30C | 0.206 | 408                       | 1421       | 0.28       | $10^{5}$       | $10^{7}$       | 441 (70\(\sigma\)) | 68 (1.8\(\sigma\)) |
| 3C 294      | 1.779 | 29                        | 233         | 2         | $10^{5}$       | $10^{7}$       | 45 (7\(\sigma\)) | 7 (0.2\(\sigma\)) |
| PKS 1514+00 | 0.052 | 519                       | 543        | 480        | $10^{5}$       | $10^{7}$       | 17851 (2833\(\sigma\)) | 2746 (74\(\sigma\)) |
| GB1 1519+512 | 0.37  | 312                       | 1646       | 22         | $10^{5}$       | $10^{7}$       | 3871 (614\(\sigma\)) | 595 (16\(\sigma\)) |
| 3C 326      | 0.0895 | 684                       | 1177       | $10^{-4}$  | $10^{8}$       | $10^{7}$       | 6201 (984\(\sigma\)) | 954 (26\(\sigma\)) |
| 7C 1602+3739 | 0.814 | 100                       | 778        | $10^{-3}$  | $10^{8}$       | $10^{8}$       | 132 (21\(\sigma\)) | 20 (0.5\(\sigma\)) |
| MRK 1498    | 0.0547 | 583                       | 639        | 15         | $10^{5}$       | $10^{7}$       | 9010 (1430\(\sigma\)) | 1386 (37\(\sigma\)) |
| B3 1636+418 | 0.867 | 57                        | 452        | 16         | $10^{5}$       | $10^{7}$       | 43 (6.8\(\sigma\)) | 7 (0.2\(\sigma\)) |
| Hercules A  | 0.154 | 200                       | 551        | 23         | $10^{5}$       | $10^{7}$       | 4772 (750\(\sigma\)) | 734 (20\(\sigma\)) |
| B3 1701+423 | 0.476 | 120                       | 735        | 15         | $10^{5}$       | $10^{7}$       | 191 (30\(\sigma\)) | 29 (0.8\(\sigma\)) |
| 4C 34.47    | 0.206 | 92                        | 320        | 9.5        | $10^{5}$       | $10^{7}$       | 337 (53\(\sigma\)) | 52 (1.5\(\sigma\)) |
| 87GB 183438.3... | 0.5194 | 69                       | 443        | 3.9        | $10^{5}$       | $10^{7}$       | 190 (30\(\sigma\)) | 29 (0.8\(\sigma\)) |
| 4C +74.26   | 0.104 | 775                       | 1522       | 94         | $10^{-3}$      | $10^{-5}$      | 23760 (3771\(\sigma\)) | 3655 (99\(\sigma\)) |
| RG01 (Malu et al. 2017) | 0.3  | 240                       | 11200      | 7 $x 10^{-5}$ | $10^{-3}$      | $10^{8}$       | 534 (85\(\sigma\)) | 82.2 (2.2\(\sigma\)) |

The unique spectral shapes of the different SZ distortions can be used to separate them, hence isolating the non-thermal SZ from other dominant CMB fluctuations, at relevant angular scales. In Fig. 9, we plot the intensity of different distortions as discussed above. The spectral shapes of these distortions are different from each other. Therefore, with a multifrequency study, we can distinguish non-thermal distortion from other forms of distortions. To check if non-thermal distortion can be mimicked by combination of other
In post recombination universe, the hotter electrons in the $y$ give rise to positive distortion from decay or annihilation of unstable particles etc. While acoustic damping and injection of energy can be expected, two points can be fit with 4 parameters written as a linear combination of other forms of distortions. We design a hypothetical experiment with all the constraints that $y$ and $rSZ$ distortion from future CMB experiments. However, as can be seen from Fig. 9, the intensity of $kSZ$ and $rSZ$ distortions is roughly similar to non-thermal distortion for frequency $\lesssim 300$ GHz. Once, we ignore $kSZ$ with the positivity condition on $y$ and $rSZ$, we are able to distinguish non-thermal SZ signal as there are non-zero residual at some frequencies (Fig. 13). For an order of magnitude estimate of temperature shift due to $kSZ$, we consider the source Hercules A from Table 2 with highest $y$ parameter ($y_{NT} = 9 \times 10^{-6}$). The optical depth of this source turns out to be $\sim 10^{-4}$. With $\nu/c \sim 10^{-3}$, we see that the distortion due to $kSZ$ are of the order $\frac{\Delta T}{T} \sim 10^{-7} - 10^{-8}$. Therefore, we can safely ignore the $kSZ$ temperature shift and consequently will be able to differentiate non-thermal $kSZ$ from other distortions, for this source.

For a completely unambiguous detection without any assumption on the $y$, $kSZ$ and $rSZ$ distortions, it is clear from the above discussion that the location of the null point of the total distortion may not be a reliable signature of non-thermal SZ from future CMB experiments. However, as can be seen from Fig. 9, the intensity of $y$, $kSZ$ and $rSZ$ distortions after 400 GHz starts to decrease in magnitude and approach zero while for non-thermal SZ, the spectrum is relatively flat. Therefore, high frequency channels (>400GHz) would be able to differentiate non-thermal distortion from others. We design a hypothetical experiment with all the frequency band of Simons Observatory and add three more frequency channel at 350 GHz, 500 GHz and 600 GHz. In this setup, we are able to distinguish non-thermal distortion from others without putting any constraints on best fit parameters of $y$, $kSZ$ temperature shift due to $kSZ$ and $rSZ$ distortions as can be clearly seen in Fig. 12 and Fig. 13.
be larger. Note, that for particular radio galaxies considered in this work (refer to Table 2), the estimates of radio power and $y_{NT}$ will not differ significantly from those presented here.

The SZ effect from galaxy clusters can be used as cluster mass proxy in SZ surveys which aims at using cluster number counts and their spatial correlations to constrain cosmological parameters. However, this is crucially dependent on establishing an unbiased SZ distortion - cluster mass scaling. The thermal SZ effect $y$-distortion is the dominant distortion for large clusters ($y \sim 10^{-5} - 10^{-4}$ for clusters of virial mass ~ $10^{14} M_\odot - 10^{15} M_\odot$). The non-thermal SZ signal from radio cocoons inside the clusters can easily be a significant fraction of the thermal SZ from the cluster gas and cannot not be ignored. In the absence of observations at many different frequencies, one needs to model the non-thermal SZ (as in Table 2) and subtract it out from the total SZ distortion so as to have an unbiased estimate of the SZ from the cluster gas. However, if there are many observable frequencies, then the separation of the different components can be done by utilising their unique spectral shapes as demonstrated in the previous section. Additionally, neglecting SZ distortions from radio cocoons (inside clusters) would be bias the estimate of the Hubble Constant $H_0$ using a combination of SZ and XRay observations towards galaxy clusters. It is interesting to note that subtracting a contribution from radio cocoons lowers the estimate of the net SZ distortion from the cluster gas, and pushes the the value of $H_0$ up, in the right direction.

Other than radio cocoons residing within clusters, radio galaxies having cocoons are ubiquitous in our Universe. In the previous sections, we have calculated the magnitude of distortion of the CMB spectrum from individual radio galaxy cocoons. As a next step, we can consider an ensemble of radio cocoons populating the universe and calculate the global averaged CMB distortions. A first calculation of the average $y$-distortion has been done in Yamada et al. (1999) and Majumdar (2001) assuming that the radio cocoons reside inside the dark matter halos with one percent halo occupational efficiency. The jet luminosity was assumed to be equal to the Eddington luminosity of central black hole mass $M_{BH}$ with $M_{BH} = 0.002 M_\odot$. Moreover, Majumdar (2001) calculated the angular power spectrum, $C_\ell$, of CMB distortions from unresolved radio galaxy cocoons. However, these initial efforts assumed the distortion to be non-relativistic $y$-distortion and concluded that a cosmological distribution of cocoons with $t_j = 10^7$ yr to be severely constrained due to the COBE CMB spectral distortion limit (Fixsen et al. 1996). Our calculations suggest that in a $\Lambda$CDM universe with the current cosmological parameters, the global averaged $\langle y \rangle \sim 10^{-6}$ for $t_j = 10^7$ yr. Several improvements are in order to make progress - for example, the assumed jet luminosity of their model may be too high compared to the jet luminosity inferred from individual radio galaxies (Hardcastle & Croston 2020). Also, the efficiency factor will not be a constant but a function of dark matter halo mass. Our preliminary work on calculating the two point correlation functions of SZ fluctuations imply that the contribution from radio galaxies can be ~ 10 percent of contribution from galaxy clusters. We will present the results for $\langle y \rangle$ and $C_\ell$ for a cosmological distribution of radio cocoons in a followup work.

7 DISCUSSION

For the sake of simplicity, we have assumed a constant value of the ambient density in our radio galaxy evolutionary model. Realistically, the density increases with redshift, since it should scale with the critical density, thus implying smaller sized of radio cocoons and higher radio power at larger redshifts, but also with rapid decline in radio power once the jet switches off. The net non-thermal SZ signal will

![Figure 12](image1.png)

**Figure 12.** Same as Fig. 10, but for a hypothetical experiment with the six frequencies of Simons observatory and additional frequency bands at 350 GHz, 500 GHz and 600 GHz. A linear combination of $y$, $\mu$, $kSZ$ and $rSZ$ distortions can no more pass through all the observed points.

![Figure 13](image2.png)

**Figure 13.** Residual after subtracting best fit linear combination of $y$, $\mu$, $kSZ$ and $rSZ$ distortions from non-thermal distortions corresponding to Figs. 11 & 12.

Some of the sources listed in Table 2 can be very good candidates for Simons Observatory or CMB-S4 experiments due to high signal to noise ratio at 150 and 280 GHz frequency bands. However, for unambiguous detection, we will need higher frequency bands. Experiments like Probe of Inflation and Cosmic Origins (PICO) (Hanausy et al. 2019) with many more frequency bands with noise ~ $\mathcal{O}(1)$ $\mu$K-arcmin upto 500 GHz will be extremely useful for such detections.
8 CONCLUSIONS

We perform a detailed quantitative study of the non-thermal hot electrons in radio galaxy cocoons, both during the lifetime of the radio jets and after the jets stop, as a potential source of non-thermal SZ distortion to CMB black body spectrum. Since the energetic particles inside the cocoons cool via both synchrotron radiation and inverse Compton scattering, there is a correlation between emitted radio power and expected intensity of CMB distortion at any instant. Combining radio galaxy evolution models of Kaiser et al. (1997) with suitable modification for jet stopping as in Nath (2010), we are able to estimate the physical properties of the radio cocoons at any instant of time.

We predict the value of $y_{NT}$, given the observed size and radio power of a cocoon, from our evolutionary model by taking into account the cooling of electrons of all energy. This is in contrast to previous works, for example Colafrancesco et al. (2013), in which the authors inferred the value of number density of electrons from radio and X-ray observations. Radio and X-ray observation constrain the spectrum of electrons at $γ > 10^5$. The authors extrapolate the spectrum of electrons to lower energy electrons which are responsible for the SZ signal. We do no such extrapolation. Further, we use the non-thermal spectrum of these relativistic particles to calculate the distortion on the CMB for a given size and radio power of the radio galaxy cocoons. A summary of our predictions for 21 radio cocoons is tabulated in Table 2. The key points of this work are summarized below:

- Although the pressure inside a cocoon changes as the cocoon expands, for a particular cocoon size at any instant, both the radio power and $y_{NT}$ is independent of redshift. This is a consequence of assuming the density of the surrounding medium to be independent of the redshift. As long as the jet is on, radio power is just a function of the jet luminosity and not the jet lifetime i.e. the radio power from two sources with $t_j = 10^7$ and $10^8$ yr are the same when both sources are relatively young.
- The injected electrons, when the jet is on, cool efficiently via inverse Compton scattering especially at higher redshifts. After the jet shuts off, there is no more supply of energetic electrons. Therefore, as soon as the jet turns off, there is a steep fall of radio power as the energetic electrons which are responsible for radio emission have all cooled down.
- For a fixed radio power, $y_{NT}$ increases with decreasing cocoon size as pressure is larger for smaller volume (which leads to the expansion of the cocoon). The prospect of detecting non-thermal SZ from cocoons increases if the cocoons are young (or smaller in size) and/or jet the is active.
- A direct consequence of the above points is that radio galaxy cocoons residing in cluster environments would be better potential targets for non-thermal SZ detection. Similarly, dead field radio galaxies, with large cocoon sizes, are not favourable sources for non-thermal SZ detection.
- The analysis presented in this paper can successfully model the recent first detection of non-thermal SZ effect from the radio galaxy RG01 (Malu et al. 2017). This gives us the confidence in predicting the non-thermal SZ distortion for a further sample of 20 radio galaxy sources (in Table 2) which can be targeted by upcoming ground based SZ searches.

- For a given intensity of distortion on the CMB, there is a degeneracy between $y_{NT}$ and $g_{NT}(x)$. In contrast to previous studies, we can predict $y_{NT}$ from our galaxy evolution model which can then constrain the value of spectral function $g_{NT}(x)$.
- Radio and SZ detection of radio cocoons can help determine the physical properties of energetic electrons inside the cocoons. For the non-thermal SZ detection from RG01, we are able to constrain the value of $p_{min}$ (the lowest energy threshold of the electron spectrum) using SZ effect for the very first time. We find $p_{min} = 1 - 2$ is needed to explain the observations.
- We demonstrate that future CMB experiments, with higher frequency bands ($\gtrsim 300$ GHz), are needed for differentiating non-thermal SZ from radio cocoons from other SZ distortions (for example, kSZ distortions from clusters of galaxies). In this respect CMB S4 (Abazajian et al. 2016), PICO (Hanany et al. 2019), CMB Bharat (CMB Bharat Consortium 2018) would be most promising.

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