Cosmological Impacts of Black Hole Mergers: No Relief in Sight for the Hubble Tension

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The values of the Hubble constant inferred from local measurements and the cosmic microwave background (CMB) exhibit an approximately 5σ tension. Some have suggested this tension is alleviated if matter is converted to dark radiation via dark matter decay. As it is not clear that dark matter decays, we instead examine the effects of converting matter to gravitational radiation via black hole mergers. We consider mergers of supermassive black holes (SMBHs), mergers of stellar-mass black holes, and the formation of SMBHs from mergers of smaller black holes. We find that these processes cannot alleviate the tension, as an unrealistically large merger rate, or an overproduction of SMBHs is required. We also consider whether one can use the Integrated Sachs-Wolfe effect to constrain mechanisms that form SMBHs from mergers of smaller black holes. We find that this is also too small to be viable.

I. INTRODUCTION

The Hubble constant (H_0) dictates how the redshift of galaxies increases with their distance from Earth, and is closely related to the expansion rate of the Universe, first studied in Edwin Hubble [1]. H_0 can be determined through either a local measurement or an early-time measurement, and these produce different values. The local measurement involves using Type-IA supernovae as a tool to measure distances to faraway galaxies, where the distance and the redshift can be used to obtain H_0. This method is calibrated using a distance ladder of Cepheid variables and parallax measurements for nearby Cepheids [2–4]. The early-time measurement is instead based on the power spectrum of the cosmic microwave background (CMB), where the Hubble constant is tied to the location of the first peak in the power spectrum [5]. The CMB formed at around $z = 1090$, when the Universe cooled enough for electrons and protons to combine to form atoms, allowing photons to travel freely [6]. These photons have now redshifted into the microwave band.

The CMB power spectrum implies (under the assumption of ΛCDM) a smaller value of H_0 than the locally-measured value, with the two values in a 5σ tension [4][7]. Previous studies have attempted to explain this discrepancy by assuming the conversion of matter to dark radiation via dark matter decays [8][9]. While there is a wealth of evidence to suggest that dark matter exists [10][11], it is not known that it decays in this way. It is, however, known that black hole mergers convert a fraction of the mass of the binary to gravitational radiation [12], which can be considered to be a form of dark radiation. We thus examine whether the Hubble tension can be relieved through mergers of supermassive black holes (SMBHs), stellar-mass black holes, or through forming SMBHs through mergers of smaller black holes. Others have studied the effects from conversion of matter to gravitational radiation through mergers of primordial black holes [13], though they did not consider mergers of more massive black holes, such as those that are located near the centers of galaxies [14].

We find that SMBH or stellar-mass mergers are not a viable solution for alleviating the tension, as an unreasonably large merger rate would be required. We also find that SMBH formation is not a viable pathway, as even in an extreme scenario of forming SMBHs from mergers of 10^{18} kg primordial black holes (PBHs), one would have to overproduce SMBHs by four orders of magnitude to alleviate the tension.

The formation mechanism for SMBHs is still an outstanding mystery, though two possible scenarios involve direct collapse or mergers of smaller black holes [14]. Since it is known that decaying dark matter scenarios suffer from CMB constraints due to their effect on the low multipole moment region of the CMB via the Integrated Sachs-Wolfe (ISW) effect [15], we also consider whether one could use the CMB to constrain scenarios for SMBH formation from mergers of many smaller black holes. We find that the effect on the CMB is too small for this to be viable.

II. METHODS

A. Black Hole Mergers and SMBH Formation

In studying the effects of SMBH mergers, we make the simplifying assumption that the comoving merger rate is constant after $z = 10$, and zero before that. For stellar-mass black hole mergers, we assume the comoving rate

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is zero before $z = 15$, and constant after that. A more accurate treatment would include redshift dependence, though this complication is ultimately unnecessary, given that we find black hole mergers are very far from being viable for resolving the tension.

We assume that each merger converts a fraction $\epsilon = 0.08$ of the total mass ($\mathrm{M_{BINARY}} = 2 \times 10^7 \mathrm{M_\odot}$ for SMBH binaries, or $\mathrm{M_{BINARY}} = 60\mathrm{M_\odot}$ for stellar-mass binaries) to gravitational radiation. This yields the following equations (derived from the perfect fluid equation), where R is a comoving merger rate.

$$\frac{d\rho_m}{dz} = \frac{1}{(1+z)H}(3H\rho_m + R(1+z)^3\epsilon M_{\mathrm{BINARY}}) \quad (1)$$

$$\frac{d\rho_r}{dz} = \frac{1}{(1+z)H}(4H\rho_m - R(1+z)^3\epsilon M_{\mathrm{BINARY}}) \quad (2)$$

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_r + \rho_\Lambda) \quad (3)$$

We integrate this system from $z_{REC} = 1090$ to $z = 0$, where we set initial conditions by setting a value for h, as shown below. (Note that this is not the same as h found from evolving the system to $z = 0$.) This is very similar to what was done in past studies that looked at decaying dark matter [8, 15]. Also note that $\mathrm{H_{0SI}}$ is $100\frac{\mathrm{km}}{\mathrm{secMpc}}\mathrm{h}$ converted to units of sec^{-1}. The radiation component is governed by the equation below [16].

$$\Omega_r = 4.15 \times 10^{-5}/h^2 \quad (4)$$

The matter component is governed by the equation below [7]. The following equations then provide the densities.

$$\Omega_m = 0.14241/h^2 \quad (5)$$

$$\rho_{CRIT_0} = \mathrm{H}^2_{0\mathrm{SI}}/8\pi\mathrm{G} \quad (6)$$

$$\Omega_\Lambda = 1.0 - \Omega_m - \Omega_r \quad (7)$$

$$\rho_{m_{initial}} = \Omega_m \rho_{CRIT_0}(1 + z_{REC})^3 \quad (8)$$

$$\rho_{r_{initial}} = \Omega_r \rho_{CRIT_0}(1 + z_{REC})^4 \quad (9)$$

$$\rho_{\Lambda_{initial}} = \Omega_\Lambda \rho_{CRIT_0} \quad (10)$$

We then vary h and the comoving merger rate to fit to data for late-time H(z) [4, 17–20]. These were the same values for H(z) used in [8]. We use the L-BFGS-B algorithm packaged within SciPy to minimize χ^2 [21]. To produce the initial guesses for the minimizer, we first conduct a brute-force grid search over the parameter space to find the parameter combination with the smallest χ^2. This approach is viable here because we only have two free parameters. For the grid search, we try 20 linearly spaced values for h between 0.5 and 1. For SMBH mergers, we try 100 linearly spaced values between 0 and 1×10^4 $\mathrm{Gpc^{-3}yr^{-1}}$ for R. For stellar-mass mergers, we try 100 linearly spaced values between 0 and 3.33×10^9 $\mathrm{Gpc^{-3}yr^{-1}}$ for R. (This is the same range as for SMBH mergers, scaled by $\frac{10^7}{30}$.) For SMBH formation from PBHs, we are interested in the constant in the numerator of the formation rate function (see below). We try 100 linearly spaced values between 0 and 100 for the grid search.

When considering SMBH formation from PBHs, we follow a similar process, though instead of a comoving merger rate, we consider a comoving SMBH formation rate of the following form, plotted in Figure 1.

$$\mathrm{Rate} = \frac{\mathrm{Const}}{1 + (\mathrm{z} - 15)^2} \quad (11)$$

We then say that 100 times the mass of the SMBH is converted to radiation, for every SMBH that forms. This approximation is roughly consistent with forming SMBHs from pairwise mergers of black holes, starting with 10^{18} kg PBHs, though the factor depends on the exact fraction of each merger that goes to radiation.

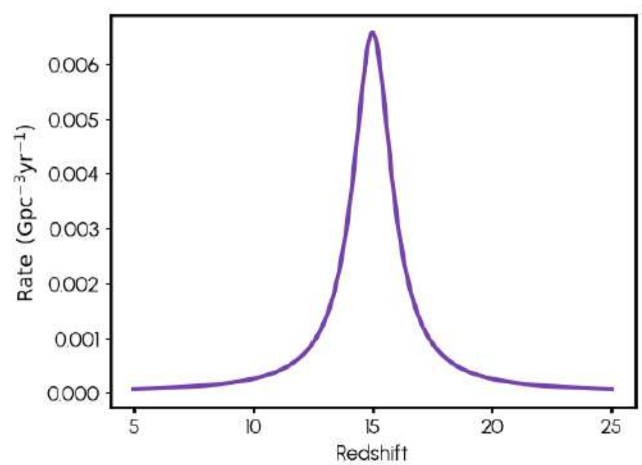

FIG. 1. Here we plot the comoving SMBH formation rate in units of $\mathrm{Gpc^{-3}yr^{-1}}$, that results in a number density of 10^6 SMBHs per Gpc^3 at $z = 0$.

B. Estimating the ISW Effect

When black holes merge, they convert some of the mass of the binary to radiation. Similarly to decaying dark matter, if enough matter is converted to radiation, dark energy will dominate sooner, and the CMB will be boosted at low multipole moment via the ISW effect. This is known to constrain models of decaying dark matter [15], so we seek to determine whether this effect can be used to constrain scenarios for SMBH formation from mergers of smaller black holes. When we constrain the comoving SMBH formation rate so that SMBHs are not overproduced, we find that a very small fraction of the matter in the Universe is converted to radiation, even when SMBHs are produced from PBHs. The conversion of matter to radiation then has a negligible effect on H(z) when SMBHs are not overproduced, so any effect on H(z) is due to the adjustment to the initial conditions by setting h when fitting to experimentally measured H(z). We can then approximate the effect on the CMB without modifying the CLASS package [22], where we simply adjust h. The effect on the CMB is so small that an approximate result is sufficient.

III. RESULTS AND DISCUSSION

A. SMBH Mergers

We find that the data favors a comoving merger rate of approximately 2400 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$, with initial conditions following from $h = 0.782$. This yields $\mathrm{H}_0 \approx 73.2$ km $\mathrm{sec}^{-1}\mathrm{Mpc}^{-1}$ at $z = 0$. While SMBH merger rates are not known for certain, this is at least a few orders of magnitude larger than the expected rate [23], which suggests that SMBH mergers are not the solution to the Hubble tension. We show the effect on H(z) in Figure 2 and Figure 3.

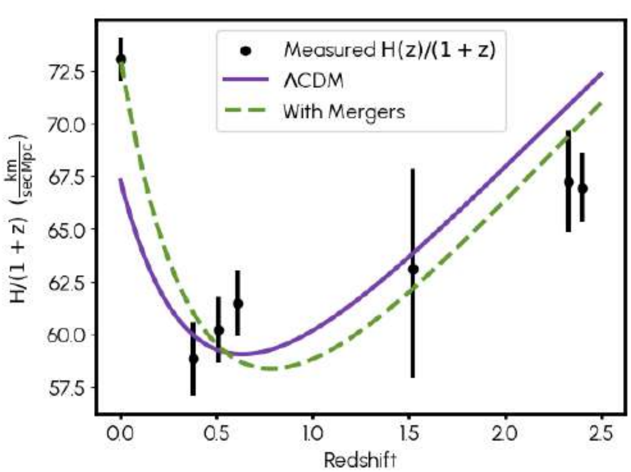

FIG. 2. Here we show the evolution of the Hubble parameter with redshift, with and without SMBH mergers, with the best-fit comoving merger rate of around 2400 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$. This is unreasonably large, making this mechanism for alleviating the tension non-viable.

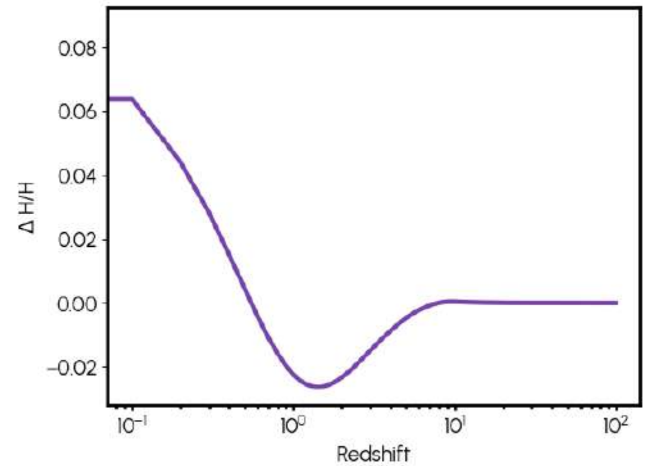

FIG. 3. Here we show the fractional change of the Hubble parameter with SMBH mergers as compared to the case without mergers. This is using the best-fit comoving merger rate of around 2400 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$. One can readily see that the case with mergers has a larger Hubble parameter at late times.

B. SMBH Formation from PBHs

SMBH Formation from PBHs is an extreme scenario, though it is useful for illustrating that even such a case is unlikely to alleviate the Hubble tension, or be constrained via the ISW effect. We find that in order to alleviate the Hubble tension, one would need to overproduce SMBHs by a factor of around 10^4, so far too little matter would be converted to radiation, if SMBHs are not overproduced. We find a best-fit value of around 74.7 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ for the constant in the numerator of the comoving formation rate function. We show the impacts on H(z) in Figure 4 and Figure 5.

We also consider the effect on the CMB via the ISW effect where the SMBH formation rate is constrained so that SMBHs are not overproduced. We find that the boost to the CMB power spectrum at low multipole moment is around five percent, which suggests that the effect is well within the error bars on the CMB. This implies that the ISW effect likely cannot be used to constrain realistic SMBH formation channels, as even the extreme case does not convert enough matter to radiation to be excluded.

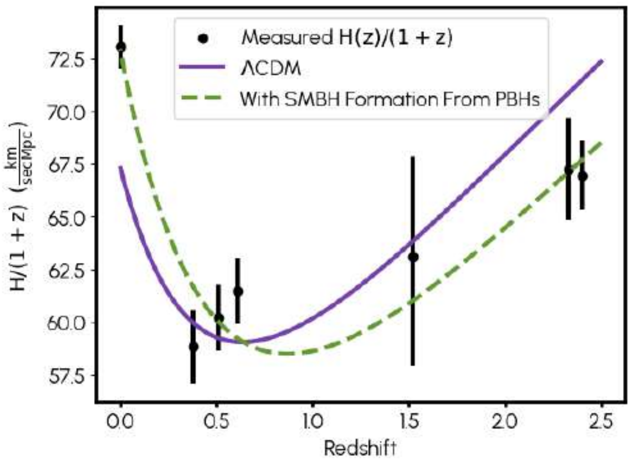

FIG. 4. Here we show the evolution of the Hubble parameter with redshift, with and without SMBH formation from PBHs, with the best-fit comoving formation rate. This best-fit rate can alleviate the Hubble tension, but overproduces SMBH by four orders of magnitude.

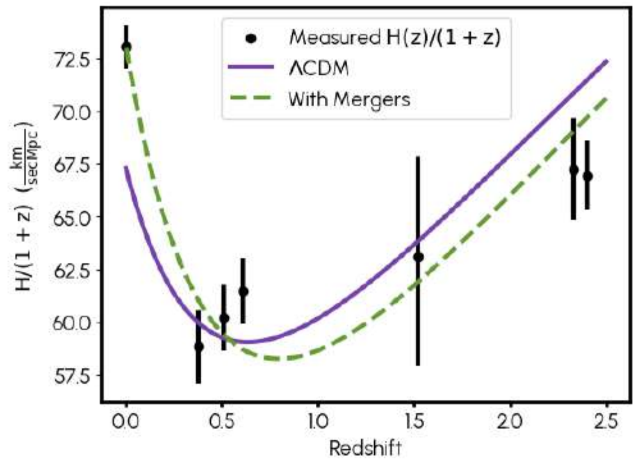

FIG. 6. Here we show the evolution of the Hubble parameter with redshift, with and without mergers of stellar-mass black holes (30 $M_{\odot}$), with the best-fit comoving merger rate. This best-fit rate can alleviate the Hubble tension, but requires an unphysically large merger rate.

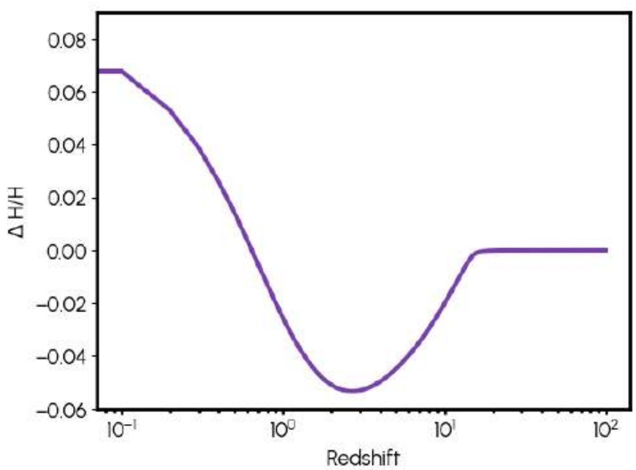

FIG. 5. Here we show the fractional change of the Hubble parameter with redshift, with and without SMBH formation from PBHs, with the best-fit comoving formation rate. This best-fit rate can alleviate the Hubble tension, but overproduces SMBH by four orders of magnitude.

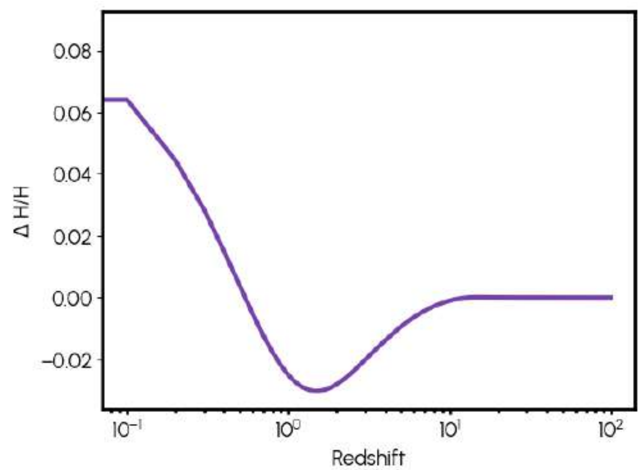

FIG. 7. Here we show the fractional change of the Hubble parameter with redshift, with and without mergers of stellar-mass black holes (30 $M_{\odot}$), with the best-fit comoving merger rate. This best-fit rate can alleviate the Hubble tension, but requires an unphysically large merger rate.

C. Mergers of Stellar-Mass Black Holes

We also considered mergers of stellar-mass black holes, with masses of 30 $M_{\odot}$. This is roughly in line with the masses commonly seen in LIGO events. Much like the case of SMBH mergers, we find that the necessary merger rate for alleviating the Hubble tension (approx. 7.5×10^8 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$) is many orders of magnitude larger than the rate inferred from LIGO events (approx. 24 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$) [24]. We show the impacts on H(z) in Figure 6 and Figure 7.

IV. CONCLUSION

We find that neither SMBH mergers nor stellar-mass black hole mergers can alleviate the Hubble tension, as the required merger rates are unreasonably large. We find that formation of SMBHs from mergers of smaller black holes also cannot alleviate the tension, as one would need to overproduce SMBHs. We also see that SMBH formation channels via mergers cannot be easily constrained using the ISW effect, as too little matter is converted to radiation. This perhaps further suggests that the Hubble tension could be a sign of new physics.

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