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Black holes as “time capsules”: A cosmological graviton background and the Hubble tension

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Abstract

Minuscule primordial black holes (BHs) before the end and after inflation can serve as “time capsules” bringing back energy from the past to a later epoch when they evaporate. As these BHs behave like matter, while the rest of the universe’s content behaves like radiation, the mass fraction of these BHs, which is tiny at formation, becomes significant later. If sufficiently small, these BHs will evaporate while the Universe is still radiation dominated. We revisit this process and point out that gravitons produced during evaporation behave as “dark radiation.” If the initial BHs are uniformly distributed so will the gravitons and in this case, they will be free of Silk damping and avoid current limits on “dark radiation” scenarios. Seeds for such BHs can arise during the last phases of inflation. We show here that with suitable parameters, this background graviton field can resolve the Hubble tension. We present current observational constraints on this scenario and suggest upcoming observational tests to prove or refute it. Finally, we also elaborate on the graviton background produced by particle annihilation during the Planck era or shortly after inflation.

KEYWORDS

1 | INTRODUCTION

Hawking’s (1974, 1975) dramatic discovery of black hole (BH) evaporation was the first link between general relativity and quantum theory, the two pillars of physics. In one of these papers, (Hawking 1974) predicts that primordial BHs of 10^{15} g will appear as cosmic explosions today. However, in spite of the almost 50 years that have passed, BH evaporation has evaded any observational confirmation.[1] We explore here potential cosmological consequences of BH evaporation and show that it might have had dramatic effects on the early Universe.

Minuscule BHs that form in the early universe evaporate eons later. The surrounding radiation energy density decreases like $(1+z)^4$ while the BHs’ energy density decreases like $(1+z)^3$. Thus, a tiny fraction of the early Universe mass captured in such BHs can be significant or even dominant by the time they evaporate. As such, these BHs can be considered as “time capsules”

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[1] See, however, claims of observations of Hawking radiation in analogue systems Weinfurtner et al. 2011 and Drori et al. (2019)

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that carry energy[2] from their formation time and deposit it much later.

The original idea was proposed by Hooper et al. (2019) and various aspects of this process have already been explored in detail (see e.g., Masina 2020; Arbey et al. 2021) and references therein and the review in Auffinger (2022). Here we propose an extension of this scenario in which we explore the implication of a possible *homogeneous* cosmological graviton background (CGB) to provide the means to address the Hubble tension.

This involves the possibility that minuscule BH ($m_{\rm BH} < 10^{12}$ g and typically much smaller) that form during inflation provide a source of pure "dark radiation" in the form of gravitons. This dark radiation can change the Friedman equation at recombination and thus, it can solve the Hubble tension (see e.g., Verde et al. 2019 and references therein).

It is worth mentioning that the current constraints on $\Delta N_{\rm eff}$ from the Planck satellite combined with Big Bang Nucleosynthesis (BBN) and large-scale structures Aghanim et al. (2020) limit it to be < 0.25 while a value of ≈ 0.4 is needed to fully remove the tension. However, the above constraint comes from the Silk damping and perturbation effects on the CMB high multipoles and does not apply to the Friedman equation as we will show in Section 4. Thus any background that has no perturbation and Silk damping will avoid these constraints Schöneberg et al. (2019) and (2022).

We consider first, in Section 2, the formation and the energy budget of these minuscule BHs. In Section 3 we discuss the composition of particles emitted and their thermalization and the homogeneity of this process. We address a possible solution to the Hubble tension puzzle in Section 4. We conclude in Section 5 with a brief summary and a discussion of possible observational signatures. As the formation mechanism (if any) of BHs in the early Universe is highly uncertain, our estimates are given only up to factors of order unity. In an Appendix A, we discuss aspects of graviton formation via annihilation processes during or shortly after the Planck era. While Ω_g production in this way is probably too small to resolve the Hubble tension, this is an interesting route to produce CGB whose nature could be used to explore the quantum nature of gravity.

2 | FORMATION

Consider a BH that evaporates at redshift $z_{\rm ev}$. The evaporation takes place over a time scale $H^{-1}(z_{\rm ev})$, the inverse of the Hubble parameter at $z_{\rm ev}$. Equating H^{-1} to the evaporation lifetime of the BH, $5120\pi G m_{\rm BH}^3 / \left(c^3 m_{\rm pl}^2\right)$, we find $m_{\rm BH}(z_{\rm ev})$, the mass of a BH that evaporates at $z_{\rm ev}$:

$$m_{\rm BH}(z_{\rm ev}) \approx 0.02\, m_{\rm pl} \left(\frac{E_{\rm pl}}{T}\right)^{2/3} \approx 5 \cdot 10^8\ {\rm g} \left(\frac{\rm MeV}{T}\right)^{2/3}, \tag{1}$$

where $m_{\rm pl}$ and $E_{\rm pl}$ are the Planck mass and Planck energy respectively and T is the temperature of the Universe at $z_{\rm ev}$.

The horizon mass of a flat Universe is comparable to a BH mass of the same size. This determines the formation epoch $z_{\rm BH}$ of the BHs evaporating at $z_{\rm ev}$ (see Figure 1). In turn, this determines the temperature ratios and the ratio between the fraction of the BH energy densities at evaporation, $\Omega_{\rm BH}(z_{\rm ev})$, and at formation, $\Omega_{\rm BH}(z_{\rm BH})$ (see Figure 2):

$$\frac{z_{\rm BH}(z_{ev})}{z_{\rm ev}} = \frac{\Omega_{\rm BH}(z_{\rm ev})}{\Omega_{\rm BH}(z_{\rm BH})} \approx 3\left(\frac{E_{\rm pl}}{T}\right)^{2/3} \approx 1.5 \cdot 10^{15}\left(\frac{\rm MeV}{T}\right)^{2/3}. \tag{2}$$

The corresponding temperature of the Universe at the time that the BHs form, $T_{\rm BH}$, is (see Figure 1):

$$T_{\rm BH}(z_{\rm ev}) \approx 3\, E_{\rm pl}\left(\frac{T}{E_{\rm pl}}\right)^{1/3} \approx 3 \times 10^{13}\ {\rm GeV}\left(\frac{T}{\rm MeV}\right)^{1/3}. \tag{3}$$

Typical values are $z_{\rm BH} = 10^{23}$ and $m_{\rm BH} = 10^8$ g for evaporation just before nucleosynthesis. The temperature of the Universe, $T_{\rm BH}$, at the time that these BHs form is

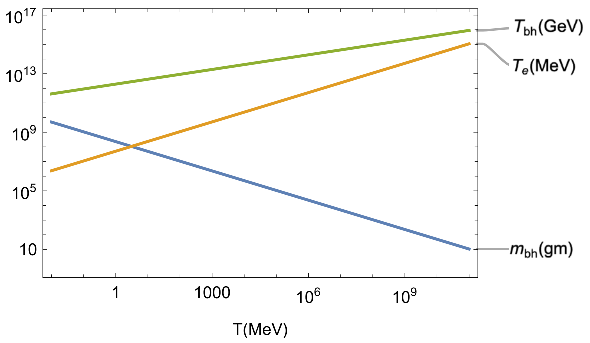

FIGURE 1 $m_{\rm BH}$, Mass of the black holes (BHs) (in grams—blue line), T_e the temperature of the evaporating BHs (in MeV—orange line), and $T_{\rm BH}$ the background temperature of the Universe (in GeV—green line) when these BHs form as a function of T, the Universe temperature at the time the BHs evaporate.

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[2] If BH evaporation releases the information captured within the BH at formation, in principle, these BHs can served as "time information capsules" as far as information as well. However, capturing the exact phases of all the radiated particles, which is essential for that, might prove very challenging as it will require a cosmic Bell-like experiment.

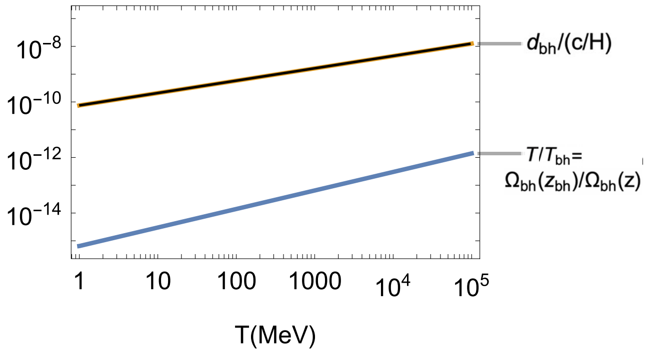

FIGURE 2 The ratio, $d_{\mathrm{BH}}/(c/H)$, of the distance between the evaporation black holes (BHs) to the horizon (black) and the ratio, T/T_{BH}, of the temperature at BH evaporation, T, to the temperature at formation, T_{BH} (blue), as a function of T. The latter ratio also equals (see Equation 2) the ratio $\Omega_{\mathrm{BH}}\left(z_{\mathrm{BH}}\right)/\Omega_{\mathrm{BH}}\left(z_{\mathrm{ev}}\right)$, demonstrating that a minute fraction of the energy density of the Universe in BHs in the early Universe can be very significant and even dominant later.

$\approx 10^{12}$ GeV, just a few orders of magnitude below the canonical scale of exit from inflation. This suggests that their formation may be associated with the end of inflation. Specifically, it is possible that exit from inflation is not smooth and the fluctuations that led to the formation of minuscule BHs arose at this stage, or that BH formation is a generic feature at small scales Gomez & Jimenez (2022).

After formation, BHs will accrete some of the surrounding matter. With $\dot{M}=\pi G^2 m_{\mathrm{BH}}^2 \rho/c_s^3$, where $\rho, c_s = c/\sqrt{3}$ are the surrounding density and speed of sound, this accretion is significant only right after BH formation when the surrounding density is largest. At this stage, the BHs grow by a factor of ~2 compared to their initial mass. This order of unity effect can be ignored.

3 | EVAPORATION

3.1 | The composition of the evaporating particles

The evaporation temperature, T_e:

$$T_e \approx 2\left(\frac{m_{\mathrm{pl}}}{T}\right)^{1/3} T \approx 10^7 \mathrm{GeV}\left(\frac{T}{\mathrm{MeV}}\right)^{2/3}, \tag{4}$$

determines the composition of the particles that are produced according to their rest mass and spin Page (1976a). *Photons, neutrinos*, and *gravitons*, which are massless,[3] are produced at any temperature. Their energy density ratio depends strongly on the evaporating BH spin. Gravitons dominate for high-spin BHs and neutrinos for low-spin ones Page (1976a). In the following, we assume, lacking information on these primordial BHs, that their spin distribution results in roughly equal amounts of different massless particles.

At higher evaporation temperatures, massive particles form. Within most of the relevant regimes, evaporation temperatures are above the QED and QCD phase transitions and the composition of the evaporating matter resembles the early Universe composition with one significant difference, the production of thermal gravitons. At these temperatures g_* that measures the effective number of degrees of freedom[4] (see e.g., Figure 1 in Borsanyi et al. (2016)), is ≈ 100, and at first glance, it seems that f_g, the fraction of the BH energy deposited in gravitons, is small ($f_g \sim 1\%$) Page (1976a). However, this fraction increases if the BHs are rotating rapidly Page (1976b). f_g can be as high as 10% for $a > 0.95$ and seems to plateau at that value even for $a \sim 0.9999$ (Arbey et al. 2021).

The density in gravitons with respect to the whole radiation one is[5]

$$\frac{\rho_G\left(T_{\mathrm{eq}}\right)}{\rho_R\left(T_{\mathrm{eq}}\right)} = f_g\left(\frac{g_s\left(T_{\mathrm{eq}}\right)}{g_s\left(T_{\mathrm{ev}}\right)}\right)^{1/3} \tag{5}$$

3.2 | Thermalization

The fate of the produced particles depends on their interaction with the surrounding matter. Within the relevant temperature range that we consider here, ($T \gtrsim 1$ MeV) all electromagnetically or strongly and even weakly interacting particles are strongly coupled and they thermalize quickly, depositing their energy to the rest of the energy reservoir at that time. However, Gravitons remain decoupled at all temperatures. As gravitons propagate freely they form a background radiation field whose typical energy today is T_e/z_{ev} (see Figure 1):

$$h\nu_g \approx \left(\frac{m_{\mathrm{pl}}}{T}\right)^{1/3} T_0 \approx 10\ \mathrm{keV}\left(\frac{\mathrm{MeV}}{T}\right)^{1/3}, \tag{6}$$

where T_0 is the current CMB temperature. These energies correspond to frequencies of $\approx 10^{18}$ Hz. These are

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[3] Neutrinos are effectively massless at the relevant temperatures discussed

[4] Considering only the degrees of freedom of the standard model of particle physics at those energies.

[5] At high temperatures (corresponding to larger than matter-radiation equality) the entropy degrees of freedom are equal to the particle ones.

comparable to the energies of gravitons produced by gravitational bremsstrahlung at the Sun Weinberg (1965). This prediction can, at least in principle, be tested observationally.

3.2.1 | Massive relics

Over most of the relevant range of T the evaporation energy, T_e, is much larger than the QCD and QED transition energies. The mean free path of the vast majority of these particles will be much smaller than the horizon size and they quickly thermalize. An interesting exception is a case in which a particle, denoted X, has the lowest mass with a specific charge. At $T < m_X$ particle X can only annihilate with its anti-particle, $\overline{X}$. Depending on the details of the evaporation and on $\sigma_{X\overline{X}}$, Ω_X might be significant. Importantly, Ω_X will not satisfy, in such a case the common relation (the so-called WIMP miracle) between m_X and $\sigma_{X\overline{X}}$ that holds for a regular freeze-out. This leaves room for the formation of a WIMP type of dark matter that does not satisfy this condition, a possibility that has been explored further elsewhere Hooper et al. (2019), Masina (2020), Arbey et al. (2021), and Morrison et al. (2019).

3.3 | Black hole scale homogeneity

The evaporating BHs masses are extremely small compared to $M_{\rm H}\,(z_{\rm ev})$, the horizon mass at evaporation:

$$\frac{m_{\rm BH}\,(z_{\rm ev})}{M_{\rm H}\,(z_{\rm ev})} \approx 0.01 \left(\frac{T}{E_{\rm pl}}\right)^{4/3} \approx 4 \cdot 10^{-31} \left(\frac{T}{\rm MeV}\right)^{4/3}. \quad (7)$$

The corresponding ratio between the distance between evaporating BHs, $d_{\rm BH}$ and the horizon c/H, determine the inhomogeneity (or lack of) induced by the evaporation:

$$\frac{d_{\rm BH}}{c/H\,(z_{\rm ev})} \approx 0.1 \left(\frac{T}{E_{\rm pl}}\right)^{4/9} \approx 10^{-9} \left(\frac{T}{\rm MeV}\right)^{4/9}. \quad (8)$$

As this ratio is extremely small (see Figure 2), the inhomogeneity that it introduces is erased on a time scale much shorter than the horizon crossing time and the evaporation does not affect the homogeneity of the Universe.

4 | THE HUBBLE TENSION

The recently realized "Hubble tension" between early and late Universe observations may indicate or point to the need for new physics to describe the Universe (see e.g., the review in Verde et al. (2019) and references therein). This tension consists of a mismatch between the model-dependent inferred value of H_0 from the cosmic microwave background (CMB) temperature and polarization data Aghanim et al. (2020) and direct measurements using parallaxes and different standardizable candles in the local Universe ($z < 0.1$), which are cosmology independent. The disagreement is at the $4-5\sigma$ level of Verde et al. (2019) and translates into the local value of H_0 being about 10% larger than the CMB inferred one. It is worth taking it seriously given the exhaustive tests for systematic uncertainties that both measurements have endured, finding no obvious source for such an effect.

There is already a myriad of theoretical solutions proposed (see Schöneberg et al. 2021 for a fairly exhaustive description of possible solutions) to alleviate and resolve this tension. All boil down to the need to change the anchors (either at the early Universe or the late one) as the evolution since the high-z Universe ($H(z)$ for $z < 2$ as given by SN, BAO, and cosmic chronometers) to the local one is well described by the current LCDM paradigm Heavens et al. (2014) and Verde et al. (2017). For the early Universe, this translates into changing the length of the standard ruler.

It is straightforward to see that a change in the energy densities will lead to a change in the inferred H_0 value from the CMB. To establish the value of H_0, we use the CMB to infer angles and the sound horizon scale, r_s:

$$r_s = \int_{z_s}^{\infty} \frac{c_s dz}{H(z)}. \quad (9)$$

This equation is fully model dependent as it relies on the assumed value for the sound speed c_s, the recombination redshift z_s and the Hubble parameter $H(z)$ A change in the Hubble parameter up to the recombination redshift will change the value of r_s. In particular, an increase of $H(z)$ by some additional radiation field will decrease r_s, so the true value of H_0 would have to be higher in order to compensate for this change in length. This solution is generally referred to as "dark radiation."

Usually "dark radiation" is discarded as a solution to the Hubble tension because in these models Silk damping of this dark radiation field puts a strong limit on the amount of dark radiation due to CMB constraints Aghanim et al. (2020). This limit is expressed using $N_{\rm eff}$, the extra relativistic degrees of freedom that affect the thermal budget of the Universe according to the well-known equation (see e.g., Kolb & Turner 1990)

$$\Delta N_{\rm eff} = \frac{4}{7} g_{Y,*} \left(\frac{43}{4 g_* \,(T_F)}\right)^{4/3} \quad (10)$$

where g_* is the effective number of degrees of freedom of the dark radiation particle Y and $g_*(T_F)$ is the effective number of relativistic degrees of freedom in thermal equilibrium at the temperature T_F at which Y decouples from the plasma. To resolve the tension we need to increase H_0 to change the sound horizon scale as can be trivially seen in (9). Within "dark radiation" solutions, this corresponds to increasing $N_{\rm eff}$ by ≈ 0.4.

The problem is that the value of $\Delta N_{\rm eff}$ needed to fix the tension (≈ 0.4 Verde et al. (2019)) is already ruled out by observations. Silk damping limit $\Delta N_{\rm eff} < 0.25$ (e.g., Schöneberg et al. 2021). A second, weaker limit on $\Delta N_{\rm eff}$ arises from BBN constraints, as the combination of deuterium and helium, limits the value of $N_{\rm eff}$ in a near cosmology model-independent way. Using fig. 8 of Schöneberg et al. (2022), the right panel shows that indeed, it is possible to have $\Delta N_{\rm eff} \lesssim 0.5$. With this upper limit, we obtain values of H_0 as high as $73\ {\rm km\ s^{-1}\ Mpc^{-1}}$ within the current constraints of BBN at the 95% confidence level. This will remove the tension.

Previous estimates of the possible role of massless particles produced by evaporation primordial BHs Hooper et al. (2019) focused on Silk damping and concluded that, since such particles can contribute at most $\Delta N_{\rm eff} \approx 0.2$ they cannot resolve the tension. However, this limit can be avoided if the "dark radiation" does not suffer from Silk damping. This can happen for gravitons produced by evaporating minuscule BHs if the BHs are distributed uniformly. As the gravitons do not interact with the rest of the matter, they will remain uniform. In this case, the only limit on "dark radiation" will be the BBN limit which allows a solution of the Hubble tension.

The question is whether enough gravitons are produced so that their energy density, $\Omega_{\rm gr}$, (corresponding to $\Delta N_{\rm eff} \sim 0.4$) is 10% of the CMB energy. Using eq. 32 in Hooper et al. (2020):

$$\Delta N_{\rm eff,g} \sim 0.013 \left(\frac{f_g}{0.0047}\right) \left(\frac{106}{g_*}\right)^{0.33} \Omega_{\rm BH}(z_{\rm ev}), \qquad (11)$$

If evaporation is before BBN,[6] then $g \sim 100$. If the BHs are fast rotating then $f_g = 0.1$ and $\Delta N_{\rm eff,G} \Omega_{\rm BH}(z_{\rm ev}) \sim 0.3 \Omega_{\rm BH}(z_{\rm ev})$, which is consistent, although an underestimate, with the values found in the detailed numerical analysis by Masina (2020) and Arbey et al. (2021). Thus, to produce sufficient gravitons, the BHs must be rapidly rotating and $\Omega_{\rm BH}(z_{\rm ev})$ must be of order unity.

The above considerations put somewhat opposing limits on the conditions needed to resolve the Hubble tension. On one hand, $\Omega_{\rm BH}$ must be of order unity. On the other hand, these uniformly distributed BHs produce other particles as well. Hence, they should not be too abundant as otherwise, their products would dominate the Universe resulting in a uniform Universe. These two opposing conditions suggest a small window of $\Omega_{\rm BH} \sim 0.8 - 0.9$ at the time of evaporation. Within this, enough gravitons are produced. The other products of the evaporating BHs dominate, but there is enough room for relic material to produce the needed structure. Because of the dilution factor due to the evaporation product, this relic must have higher fluctuations than what is observed today.

Let us summarize the conditions needed for gravitons produced by evaporating BHs to provide a solution to the Hubble tension:

1. BHs must form uniformly.[7] Within the context of inflationary models, this could happen if the BHs for during the last epochs of inflation or right after it during the re-heating phase. Recall that only a minute fraction of the Universe is initially in these BHs.
2. BHs must be rotating with spins > 0.9 to provide a sizable amount of gravitons.
3. $\Omega_{\rm BH}$ must be close to unity but somewhat smaller to avoid all energy content in the universe being homogeneous. This means that most of the matter in the Universe, but not all, has been "recycled" through black holes. The condition $\Omega_{\rm BH}(z_{\rm ev}) \approx 0.8 - 0.9$ can be seen as a fine-tuning requirement in our model.
4. Evaporation must take place before BBN so as to not alter the successful agreement of current BBN estimates with observations. This constrains the maximal mass of the BHs to $< 10^9$ g.

5 | CONCLUSIONS AND OBSERVATIONAL SIGNATURES

Light ($M_{\rm BH} < 10^{12}$ g) primordial BHs will evaporate during the radiation-dominated era and those with $M_{\rm BH} < 10^9$ g before BBN. Most of the evaporating particles, apart from gravitons and possibly some unknown weakly interacting particles that may contribute to the dark matter, thermalize rapidly. A background field of $\sim 10^{18}$ Hz gravitons is the natural remnant of these BHs. With suitable parameters, the resulting graviton radiation field can resolve the so-called Hubble tension. This can happen if the BHs are (i) rapidly rotating, (ii) uniformly distributed, and (iii) at the time of evaporation they compose a dominant fraction, $\sim 0.8 - 0.9$, of the energy density of the Universe.

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[6] The high energy photons arising from evaporation after BBN may destroy the BBN products.

[7] With these conditions dark matter cannot be formed from the evaporating BHs as it must be non-uniform.

In our scenario seeds for primordial black holes are formed during inflation and inflation homogenizes their distribution. Our main assumption is that these BHs rotate rapidly in order to produce gravitons. Although even almost non-rotating BHs do produce some gravitons, so in this case their abundance will need to be higher by a factor $\sim 10 - 100$. One important point is that the required initial energy density in these BHs is so tiny $< 10^{-10}$ or less, that even if their seeds are produced during the late phases of inflation and hence are diluted by expansion they will have a noticeable effect.

The observational predictions of these scenarios are very clear: First, gravitational wave experiments in the 10^{18} Hz range should see a stochastic background. If this is indeed the solution of the Hubble tension, then the energy density of this background is a significant fraction (a few percent) of the CMB energy density. Exploring this window (see e.g., Berlin et al. 2022 and references therein) could therefore also unveil the presence in the early Universe of evaporating BHs and indirectly probe the quantum nature of gravity.

While detecting these gravitons is an experimental challenge for the future, the above estimates provide an avenue to test our scenario rather soon. Improvements in theoretical reactions rates relevant to BBN calculations by the LUNA[8] project, as well as further analysis from a large-scale structure by the ShapeFit team Brieden et al. (2022), will provide much tighter constrain on the allowed value of $\Delta N_{\rm eff}$ during BBN. This can either refute our scenario or support it. Strong upper limits on $\Delta N_{\rm eff}(BBN)$ would put very tight constraints on primordial BH production with $M_{\rm BH} \lesssim 10^9$ g/cm^3.

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APPENDIX A. COSMOLOGICAL GRAVITON PRODUCTION VIA ANNIHILATION

One of the firm predictions of quantum gravity is that quanta known as gravitons should exist. Gravitons are quantum whereas the detected gravitational waves by LIGO are classical. To verify that gravitons exist we must detect single gravitons, for example by observing gravito-ioninization atomic transitions due to absorption of a graviton—or an equivalent type of quantum experiment.

In the main body of this paper, we have explored graviton production via the super-radiance process in Hawking evaporation. There is, however, a much less explored process that can lead to a measurable signature of the quantum nature of gravity. This process is the production of gravitons via annihilation. The annihilation process is quantized producing two gravitons in each event. Even indirect evidence for the existence of this particular CGB would verify that gravitons do exist as quantum objects, and we consider the detection prospects.

In this appendix, we explore a different route to produce a uniform cosmological gravitation background. This is by the process

$$X\overline{X} \rightarrow 2\,g, \tag{A1}$$

where X is an arbitrary particle. The annihilation cross-section to gravitons (denoted hereafter g) is extremely small but non-vanishing. Detailed calculations (Vladimirov (1963), see Papini & Valluri (1977) for a review), as well as dimensional analysis, suggest that it behaves like,

$$\sigma_{x\bar{x}\leftrightarrow gg} \approx \left(GE/c^4\right)^2 = r_g^2(E), \tag{A2}$$

the square of the gravitational radius of a particle with total energy E. Thus, two particles with energy E can annihilate and produce two gravitons of the same energy. As the cross-section is proportional to the square of the gravitational radius of the particles, this process is significant only when the typical energy of the particles is of the order of the Planck energy. Similarly, the inverse process of annihilation of two gravitons to a particle-antiparticle pair will be significant only in the Planck era. Namely, it is only at this energy that gravitons can be in thermal equilibrium with other particles.

Once formed, the graviton's energy decreases like the expansion factor a^{-1}. As the energy of the gravitons decreases, their cross-section for annihilation decreases rapidly. Thus, apart from a brief phase in the Planck era gravitons can never be in thermal equilibrium with other matter fields Zel'dovich (1967); Smolin (1985). For this reason, Zel'dovich (1967) remarked that the graviton background is determined just by the initial conditions of the Universe. This is in contrast with thermal equilibrium at lower temperatures, assumed by Matzner (1968) and subsequent work, that have led to an overestimated Ω_g. Once gravitons form, their chance to annihilate back to other forms of matter is negligible. The CGB is an energy sink that hides a fraction of the total energy as dark radiation. Namely, it has no interaction apart from gravity and will only contribute to the radiation energy density of the Universe.

The graviton energy production rate per volume element in a thermal bath with a temperature T and a density $n \approx (kT/\hbar c)^3$ is:

$$\dot{e}_{\rm gr} \approx cn^2 r_g^2(E)E = \frac{G^2}{c^7}n^2E^3, \tag{A3}$$

where $E = kT$. In Hubble time, $H^{-1} \sim \left(Ge/c^2\right)^{-1/2}$, energy $\dot{e}_{\rm gr}H^{-1}$ is converted per comoving volume to gravitons. Its ratio to the total energy density is:

$$\Omega_g = \frac{\dot{e}_{\rm gr}H^{-1}}{e} \approx \left(\frac{E}{E_{\rm pl}}\right)^3 = \left(\frac{T}{T_{\rm pl}}\right)^3, \tag{A4}$$

where $E_{\rm pl}$ is the Planck energy. This last relation can be cast into the form

$$\Omega_g \approx \left(\frac{E_{\rm gr}}{E_{\rm pl}}\right)^3 \Omega_{\rm CMB}, \tag{A5}$$

where $E_{\rm gr}$ is the energy scale when most gravitons formed and $\Omega_{\rm CGB;CMB}$ are the cosmological energy fractions. This ratio is of order unity for the Planck era but it decreases rapidly as the temperature decreases.

We have to consider two different scenarios distinguished by the question of whether inflation took place or not.

A.1. Annihilation CGB with Inflation

Inflation that took place sometime after the Planck era, diluted and erased the CGB that formed during the Planck era. As inflation ends, a thermal phase is restored at temperature $T_{\rm inf}$. A minuscule fraction of the particle will annihilate to gravitons, forming a new CGB, whose fraction of the total energy is $\approx \left(T_{\rm inf}/T_{\rm pl}\right)^3$. The initial energy of these gravitons will be $T_{\rm inf}$, but of course, they will not be in thermal equilibrium with the rest of the universe and their density will be much lower than the thermal density of massless particles at this temperature.

Today the energy of these gravitons will be comparable, but slightly smaller than the energy of a CMB photon.[9] Namely, it will be of order $\sim 10^{-4}$ eV with a corresponding frequency of $\sim$10 GHz.

If inflation wasn't too far from the Planck era we might be able to detect the CGB by measuring its $\Delta N_{\rm eff,g}$, contribution to the light particles' cosmic background. Otherwise, the argument can be reversed to set a new model-independent limit on the epoch of inflation. An upper limit on $\Delta N_{\rm eff,g}$ (where here we consider just the contribution of these specific gravitons that are formed via annihilation and are today at $\sim$10 GHz) implies a lower limit on the energy scale in which inflation took place.

A.2. Annihilation CGB with no inflation

The situation is much more interesting if inflation did not take place. In this case, the relic gravitons will have a non-negligible Ω_g. The above estimate, which ignores gravitons annihilating back to regular particles, suggests that when this is also taken into account the gravitons are in thermal equilibrium with the rest of the universe. In such case we expect

$$\Omega_g \lesssim \frac{\Omega_{\rm CMB}}{g_{\rm pl}} , \tag{A6}$$

where $g_{\rm pl}$ is the unknown number of degrees of freedom (particle species multiplied by the spin factor) at the Planck time. $g_{\rm pl}$ is most likely large and hence $\Omega_{\rm g}$ is too small to resolve the Hubble tension.

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[9] The photons that have been until then in thermal equilibrium in the early universe will have their energy boosted by subsequent annihilation of other species.