Where do all black hole remnants go?

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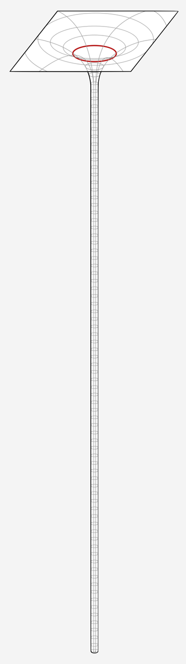
Motivation for white hole remnants

General Relativity (GR) and non-perturbative quantum gravity have revived the old idea that the end of black hole evaporation could result in a long-living Planck scale remnant.

- Classical GR provides a surprisingly natural model for Planckian remnants: white holes with a Planckian horizon but huge interior.
- Classical GR allows a spacetime where such a white hole is in the future of a parent black hole after a quantum tunnelling transition localised in space and time.
- Planck scale white holes are shielded against instability by quantum gravity.



- Non-perturbative calculations in loop quantum gravity (LQG) show that the tunnelling transition is permitted, and increasingly probable towards the end of the evaporation, with a constant probability $P \sim e^{-m^2}$ for a remnant of mass m.
- A number of objections that made the remnant idea unconvincing a few decades ago have now been shown not to apply to this scenario.

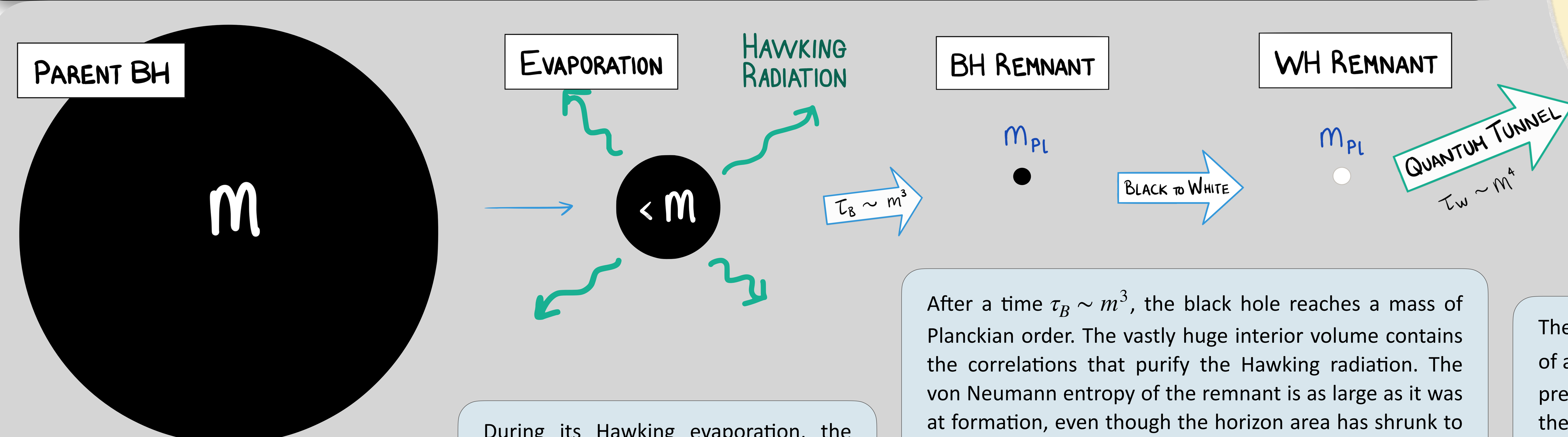
Entropy of a non-ergodic black hole

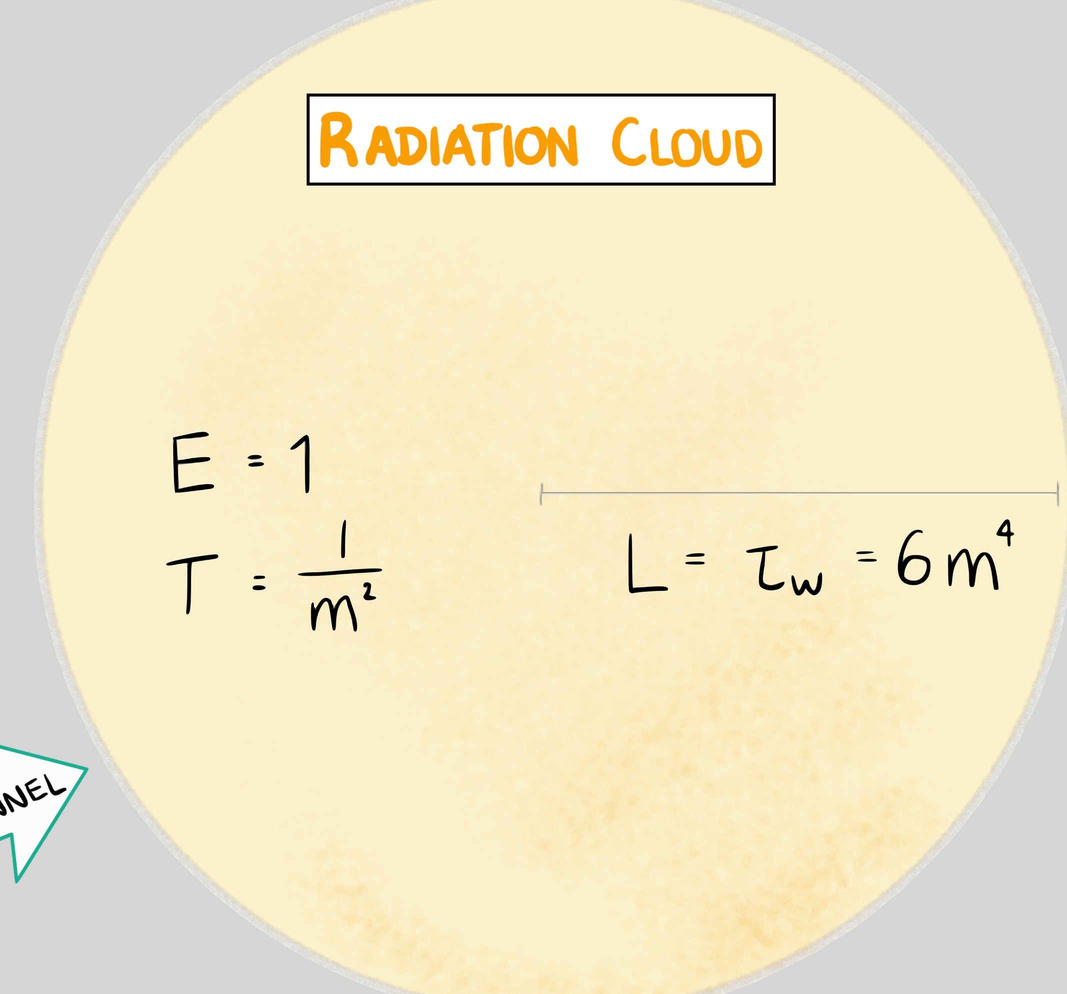
The horizon of a black hole that ends up tunnelling to a white hole is not an event horizon since its interior is causally connected to future null infinity. Thus, it does not constitute an ergodic system, so it's von Neumann entropy can be larger than it's thermodynamic entropy (unlike the holographic 'dogma' claims)

$$S_{vonNeumann} \geq S_{Thermodynamic}.$$

We assume the information contained in the remnant must be emitted. Let τ_W be the average lifetime of a white hole remnant since it forms until it finally dissipates. Any radiation it emits will be contained within a sphere of radius $L = \tau_W$ by causality. The radiation is emitted radially, so we model it as a uniform, 1-dimensional gas of photons in equilibrium. At the end of the diffuse emission, the total energy of the radiation is, of the order of the Planckian energy.

From black to white to radiation





A spherically symmetric black hole forms with initial mass m and horizon area

$$A_{formation} = 16\pi m^2.$$

During its Hawking evaporation, the mass of the black hole decreases, and so does its horizon area. However, the correlations needed to purify the mixed state of Hawking radiation can remain inside the hole's huge interior. This information must be let out later by unitarity.

After a time $\tau_B \sim m^3$, the black hole reaches a mass of Planckian order. The vastly huge interior volume contains the correlations that purify the Hawking radiation. The von Neumann entropy of the remnant is as large as it was at formation, even though the horizon area has shrunk to Planckian order at this stage:

$$S_{vonNeumann} = \frac{A_{formation}}{4} = 4\pi m^2.$$

The probability of such remnant quantum-tunnelling to a white hole remnant reaches order unity

$$P \sim e^{-m_{Pl}^2} \sim O(1).$$

The radius of the radiation cloud, and therefore also the lifetime of a white hole, is found to be $L = \tau_W = 6m^4$, in agreement with previous estimates. The temperature and and peak frequency of the cloud in equilibrium are found to be

$$T = \frac{1}{m^2} \quad \text{and} \quad \nu_{peak} = \alpha T = \frac{\alpha}{m^2} \quad \text{where } \alpha = 2.82.$$

The model corrects the infinite explosion predicted by Hawking at the end of the black hole evaporation.

The total number of photons emitted per remnant is $N_\gamma = \frac{m^2}{\alpha}$.

Diffuse emission by remnant population

Quantum emission

A key result from LQG is the quantization of physical area, with a minimum non-zero eigenvalue of Planckian order, namely, the "area gap". Since the area of a Planckian remnant cannot decrease steadily below the Planckian value, neither can its mass decrease below the minimum value μ_{min}. The full remnant emission must be a single quantum transition to a state where the remnant has completely dissipated into a cloud of radiation, hypothesised to be just photons.

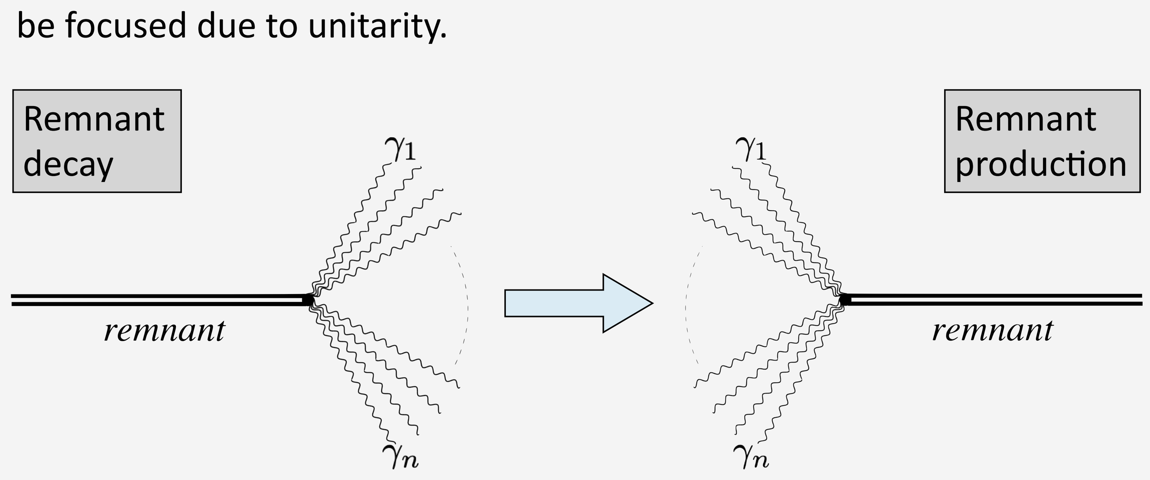
From a QFT perspective, the only allowed transition to 1st order perturbation theory is

$$|\mu_{min}, x_i\rangle \to |\gamma_1, \dots, \gamma_n\rangle$$

Quantum numbers capturing internal degrees of freedom, $i \sim e^S \sim e^{m^2}$.

State with n photons

Since the entropy cannot decrease throughout this process, $n = N_\gamma \sim m^2$, which is a huge number of emitted photons. Vice-versa, for a stable, long-lived remnant to be produced in an experiment, a tremendous (and unfeasible?) number of correlated photons have to be focused due to unitarity.



As an example, to form a stable remnant with a lifetime corresponding to originating from a 10^{15}g primordial black hole's evaporation, a whopping 10^{48} correlated photons are required to converge in a lab!

Ensemble behaviour

A single decay into many photons and a probability of transition which is constant in time resembles radioactive decay. The total energy density of a population of remnants decays exponentially like:

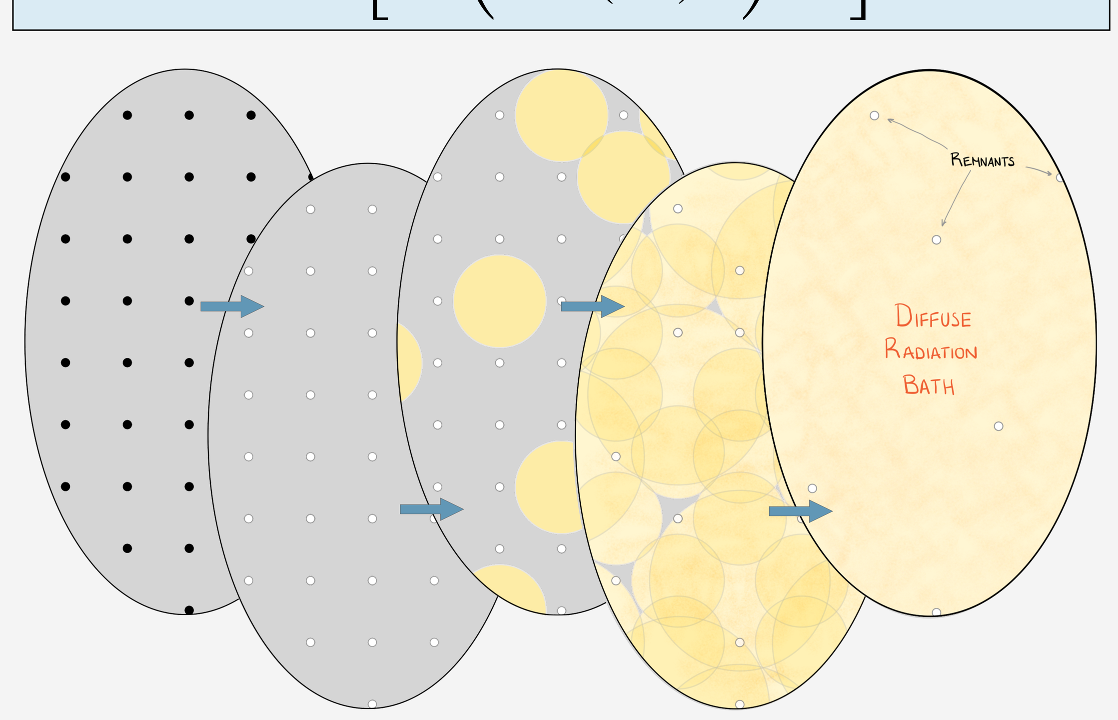
$$\rho_{rem}(t) = \Omega e^{-\lambda(t-\tau_B)}$$

with $\lambda \sim (\tau_W - \tau_B)^{-1}$ by Bohr's correspondence principle. Consequently, the energy density of the emitted diffuse radiation is 0 before the formation of remnants at $t = \tau_B = m^3$ and

$$\rho_{rad}(t,m) = \rho_{rem}(t)\left[\exp\left(\frac{1-tm^{-3}}{1-6m}\right)-1\right] \quad \text{for } t > m^3,$$

or equivalently expressed in terms of the peak frequency

$$\rho_{rad}(t,\nu) = \rho_{rem}(t)\left[\exp\left(\frac{1-t(\nu/\alpha)^{3/2}}{1-6(\alpha/\nu)^{1/2}}\right)-1\right] \quad \text{for } t > m^3$$



This is what the evolution of an ensemble of black holes becoming Planckian remnants and finally creating a bath of diffuse radiation on cosmological scales would look like.

Component of dark matter

An observation of a diffuse radiation bath with energy density ρ_{rad} peaked at frequency ν can be explained by the presence of a population of white hole remnants with energy density ρ_{rem} as related above formed a time t in the past with mass $m = \sqrt{\alpha/\nu}$. If $\rho_{rem} \sim \rho_{DM}$, a population of remnants could account for the dark matter (DM) content of the universe.

Standard big-bang cosmology

A population of primordial black holes forms at reheating after inflation, roughly a Hubble time $t_H = 10^{61} t_{Pl}$ in the past. If their formation mass was roughly within the range

$$10^{15} m_{Pl} < m < 10^{20} m_{Pl},$$

we would currently be in the emission stage of the model, and we would be able to observe the diffuse radiation bath. The corresponding energy density of the remnant dark matter would be

$$\rho_{rem}(x) = \rho_{rad}\left[\exp\left(\frac{1-10^{61-3x}}{1-6\cdot 10^{x}}\right)-1\right]$$

where

$$x = -\frac{1}{2}\log_{10}\left(\frac{\nu}{\alpha\nu_{Pl}}\right).$$

Bouncing cosmology

A black hole population could have formed in a previous era before a cosmological bounce, a longer time ago than constrained by the big-bang scenario. They could form with a much larger mass, become remnants which are yet longer-living, and traverse the bounce into the current expanding era. Constituting dark matter in our universe is more plausible in this scenario. Furthermore, quantum gravity effects sourced from remnants could favour the universe bouncing with a energy density a few orders of magnitude below Planckian.