PRIMORDIAL BLACK HOLES

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Primordial Universe

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INTRODUCTION

- Primordial black holes were first theorized in 1966 $M_H \approx \frac{c^2 t}{G} \approx 10^{15} \left(\frac{t}{10^{-23}}\right) g$
- In 1974 Hawking realized that black holes could evaporate, emitting particles like a blackbody with a temperature:

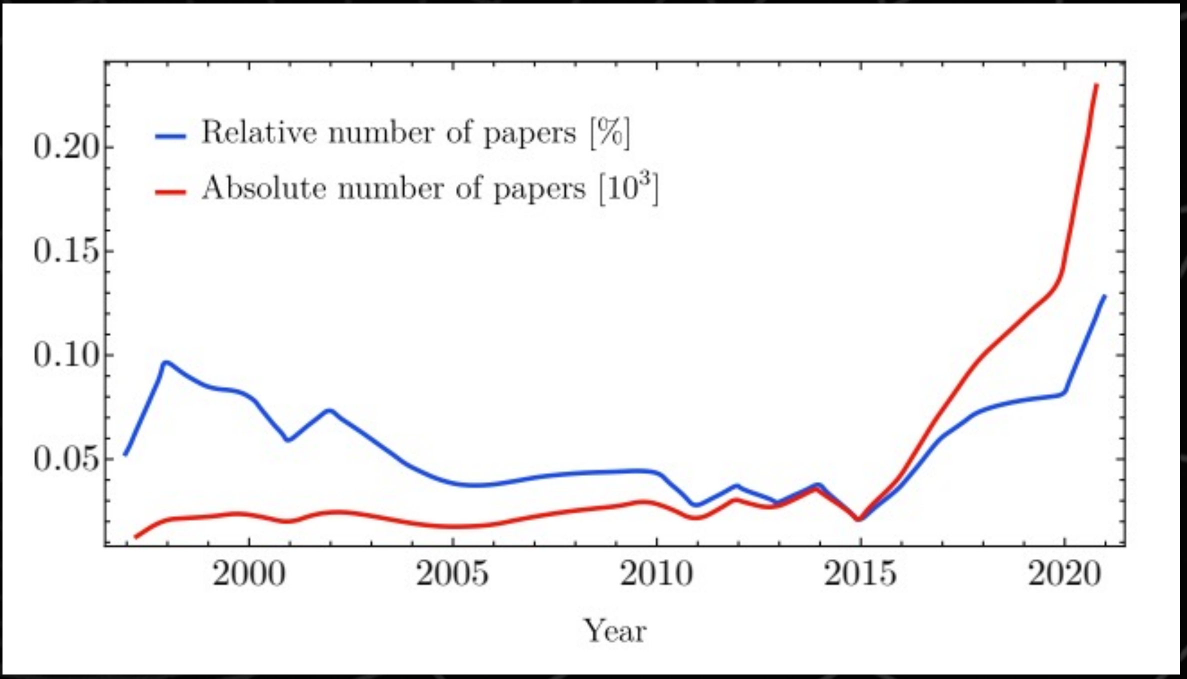
$$T = \frac{\hbar c^3}{8\,\pi\, GMk} \approx 10^{-7} \left(\frac{M}{M_\odot}\right)^3$$

- and evaporate with a timescale:

$$\tau(M) \approx \frac{\hbar c^4}{G^2 M^3} \approx 10^{64} \left(\frac{M}{M_\odot}\right)^3$$

A RENEWED INTEREST IN PBHs

- PBHs have been studied for three main proposes:
  - To explain dark matter
  - To generate observed LIGO/Virgo coalescences
  - To provide seeds for supermassive black holes in the galactic nuclei



FORMATION OF PRIMORDIAL BLACK HOLES

- For a primordial black hole to be formed, a large overdensity is needed;
- The fraction of regions that will collapse to form a black hole is epoch-dependent;
- We will review three formation mechanisms: large density fluctuations, cosmic string loops and bubble collisions;

LARGE DENSITY FLUCTUATIONS

- During the radiation dominated era, if a density fluctuation is large enough, gravity will overcome the pressure forces and the fluctuation will collapse to form a PBH, shortly after entering the horizon;
- For the collapse to happen, the region must be larger than the Jeans length;
- For a region to collapse to a PBH, an overdensity at the horizon epoch δ to be higher than ω is required, which means that:

$$\delta \geq \delta_c \approx \omega = \frac{1}{3}$$ for a radiation dominated era

LARGE DENSITY FLUCTUATIONS

- If we consider the fluctuations to have a Gaussian distribution and to be spherically symmetric:

$$\beta \approx \mathrm{Erfc}\left[\frac{\delta_c}{\sqrt{2}\,\sigma}\right]$$

- If we consider the fluctuations to be scale invariant, the PBHs will gave an extended mass spectrum

$$\frac{dn}{dM} = (\alpha - 2)\left(\frac{M}{M_*}\right)^{-\alpha} M_*^{-2}\Omega_{PBH}\rho_c \qquad \text{where} \qquad \alpha = \frac{2(1+2\omega)}{1+\omega}$$

REFINEMENTS

- In more recent simulations, using peaks theory, it was concluded that the collapse threshold should be: $\delta_C \approx 0.45$

- **Critical collapse**. The mass of a PBH will depend on the size of the fluctuations from which it was formed:

$$M = K(\delta - \delta_c)^\eta$$

- **Critical collapse**. We will have the following mass function:

$$\frac{dn}{dM} \propto \left(\frac{M}{\xi M_f}\right)^{1/\eta - 1} \exp\left[-(1-\eta)\left(\frac{M}{\eta M_f}\right)^{1/\eta}\right] \quad \text{with} \quad \xi \equiv (1 - \eta/s)^\eta \qquad s = \delta_c/\sigma$$

COLLAPSE IN A MATTER-DOMINATED ERA

- It has been argued that PBHs might form more easily if the Universe is pressureless, which happens in a matter dominated era;
- In this case, the Jeans length is much smaller than the particle horizon so the pressure will not be the main force stopping the collapse;

$$\beta(M) = 0{,}02\delta_H(M)^5 \qquad \frac{dn}{dM} \propto M^{-2}\delta_H(M)^5$$

$$M_{\min} \sim M_H(t_1) < M < M_{\max} \sim M_H(t_2)\delta_H(M_{\max})^{3/2}$$

COLLAPASE FROM INFLATIONARY FLUCTUATIONS

- If fluctuations caused by inflation decrease with increasing scale (have a blue spectrum) and the PBHs form from the high-σ tail of the fluctuation distribution it can be argued that when inflation ends, the PBH mass function should have an exponential upper cut-off at the horizon mass.
- The mass function will be:

$$\frac{dn}{dM} \alpha \frac{1}{M^2} \exp\left[-\frac{(\log M - \log H_C)^2}{2\sigma^2}\right]$$

COSMIC STRING LOOPS

- Cosmic strings are one-dimensional topological defects that could form during phase transitions in the very early Universe.
- Usually, these loops would be larger than its Schwarzschild radius by the factor $(G\mu)^{-1}$ where μ would be the string mass per unit length
- There is, however, a small probability that an oscillating cosmic string loop will get in a configuration where all of its dimensions are less than its Schwarzschild radius and so it would collapse to form a PBH.

$$\beta \sim (G\mu)^{2x-4}$$

$x \equiv L/s$ $\quad\quad$ $G\mu < 10^{-7}$

BUBBLE COLLISIONS

- During a first order phase transition, bubbles of the new phase will be formed. These bubbles will expand and eventually collide;
- In this collision there could be the formation of PBHs with mass of order the horizon mass;
- If a PBH were to be formed at the grand unification epoch, they would have a mass of around 10^3g;

THANK YOU FOR LISTENING !

Any questions?