Primordial Black Holes

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Immediately after the Big Bang, the universe was extremely hot and dense, though, it cooled as it expanded. Any slight overdensities in the mass/energy in the early universe would cause the particles in the surrounding volumes to begin to coalesce, forming continually increasingly dense pockets. These overdense pockets are the basis for the formation of structures such as galaxies and the first stars. It is possible that these regions could have even been dense enough to form black holes. Black holes that formed early in the universe -- before the epoch of recombination (when the cosmic background radiation last interacted with matter) -- are referred to as primordial black holes.

The concept of primordial black holes was first proposed by Bernard Carr and Stephen Hawking in the 1970s. More research has been done over the past 50 years to see if primordial black holes can be used to explain numerous astronomical phenomena such as seed black holes for galaxy formation, quasars and their possible existence early in the universe, dark matter, and observed gamma ray bursts. Through a mathematical derivation, I found that the likelihood of a black hole forming from a slight overdensity in the radiation dominated universe is very high. An abbreviated derivation is shown on slide 2.

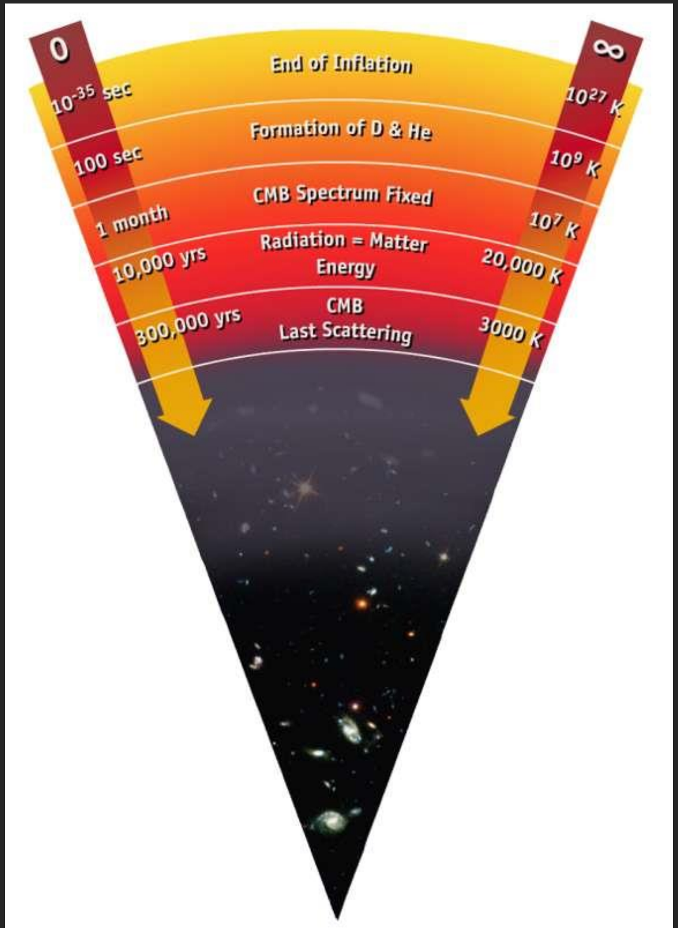

Figure 1. A simple timeline of the early universe with associated temperatures at the right.
From: http://www.astro.ucla.edu/wright/BBhistory.html

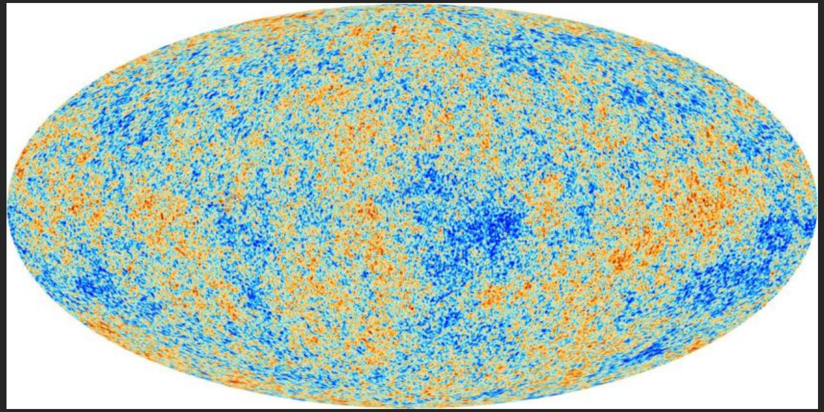

Figure 2. The Planck satellite image of the cosmic microwave background showing density fluctuations in the early universe

A black hole, by definition, must have an escape speed greater than the speed of light. This requirement can be expressed as a minimum mass-to-radius ratio given by:

$$\frac{M}{R} \geq \frac{c^2}{2G}.$$

We can then define mass as mass density times volume. Dividing both sides of the equation by radius gives another equation for mass-to-radius ratio. This is:

$$\frac{M}{r} = \rho \frac{4}{3} \pi r^2.$$

By equating these two equations, we construct the condition for the formation of a black hole.

We insert the expression for the mass density of the primordial universe (when it was radiation dominated) which is given by

$$\rho = \frac{43}{8} \frac{aT^4}{c^2}.$$

From these equations, we obtain the condition for black hole formation early in the universe, which looks like:

$$\frac{c^2}{2G} = \frac{43}{8} \frac{aT^4}{c^2} \frac{4}{3} \pi r^2.$$

Solving for radius will give us an expression that we can compare to the horizon size of the universe. Horizon size during this time in the universe is defined as:

$$d_H = 2ct$$

Using the fact that the temperature at 1 second after the Big Bang is equal to 10^{10} Kelvin, we can write the radius expression as:

$$r^2 = \frac{3c^4}{43 * 10^{40} \pi G a} t^2.$$

So, the radius that comes out of this equation must be less than or equal to the horizon size for black holes to be able to form in the early universe. We can therefore construct this inequality:

$$\frac{3c^4}{43 * 10^{40} \pi G a} t^2 \leq (2ct)^2$$

Performing this calculation gives us the following result:

$$\frac{3c^2}{43 * 10^{40} \pi G a} \approx 3.96 \leq 4$$

Thus, any region of space in the universe is right on the brink of forming a black hole and it must have been very easy for primordial black holes to form.

I also calculated the horizon mass inside this horizon size and concluded that a black hole formed at 1 second after the Big Bang would be a supermassive black hole. Supermassive black holes are most often found at the centers of galaxies and are the engines for quasars.

Altogether, it seems that primordial black holes offer a good explanation for the distant quasars we observe and may have accreted matter early in the universe to form galaxies.