1. The picture shows a sample of the universe 0.001 s after the big bang, when the expansion parameter was $6 \times 10^{-12}$. (Recall that the expansion parameter is distance/(present distance). The box was a cube $2 \times 10^{-11}$ m on a side. There are 8 neutrons, 8 protons, and lots of light in the box.

   a. (5 pts.) The box expands with the universe. Draw its contents just before helium formed (at 3 minutes, when the expansion parameter is $2.3 \times 10^{-9}$). The number must be precise to 10%; for example, drawing 15 protons is OK if the actual number of protons is 16.

   Key idea: Just before helium formed, the neutrons were free, and the ratio of the number of neutrons to the number of protons was the same as it is now, 1:7.

   There are 2 neutrons and 14 protons in the box.

   b. (3 pts.) What is the temperature of the radiation in the box when helium formed?

   Key idea: The temperature of the radiation changes as $a^{-1}$, where $a$ is the expansion parameter.

   The present temperature is 2.7K, and the expansion parameter is 1. When helium formed, the temperature is $2.7K / 2.3 \times 10^{-9} = 1.2 \times 10^9$ K.

   c. The box expands with the universe. (3 pts.) Draw its contents at the present time.

   Key idea: When helium formed at 3 min, the neutrons became locked up in $^4$He, which means the number of neutrons does not change.

   With 2 neutrons, one $^4$He nucleus forms. There are 12 protons left. Inside the box is one $^4$He and 12 H.

   d. (3 pts.) How big is the box now?

   No key ideas; this asks the definition of the expansion parameter.

   $$(\text{Width of box at 0.001 s})/(\text{Current width of box}) = (a \text{ at 0.001 s})/(\text{Current a})$$

   $$2 \times 10^{11} \text{ m}/(\text{Current width of box}) = 6 \times 10^{12} / 1$$

   Current width of box = 3.3 m