Creation of matter

I did a little more research on neutron stars and the situation is nowhere near clear to me. Apparently, they aren't thought to exist beyond $3 M_{sun}$, and our estimate for a limit to the radius as that of a black hole is not too far off. A lot of the work requires a more general relativistic approach to the problem and a more accurate description of a stars interior.

We did notice something interesting in the lecture last time: $\frac{\#\text{ He atoms}}{\text{total }\#\text{ atoms}} \sim 0.07$ in the sun

which gave us a ratio of $\frac{n}{p}$ of

$$\frac{0.07\,(2n)}{\underset{\text{assuming the rest is }{}^1H}{0.93\,(1p)} + 0.07\,(2p)} = \left(\frac{1}{7.6}\right)$$

The oldest rocks we're been able to find put the age of the solar system at about 5×10^9 y $\sim$ or about 1.5×10^{55} p-p interactions assuming 4×10^{26} W and 27 MeV/reaction. So if we consume 4 ${}^1_1H$ & create 1 ${}^4_2He$ with each one of these, we expect that originally

$N_n = 1.2\times10^{57}$ nucleons $= \#\,{}^1H + 4\,\#\,He = \#\,{}^1H\,(1+0.3)$ now $\#He = \left(\frac{7}{93}\right)\left(\frac{N_n}{1.30}\right)$

$\#He_{then} = 7\times10^{55} - 1.5\times10^{55} = 5.5\times10^{55}$

so that gives us

$$\frac{\# \text{ He atoms}}{\# \text{ atoms}} = \frac{5.5\times10^{55}}{1.2\times10^{57} - 4(5.5\times10^{55})} = 5.7\%$$

$$\text{\& } \frac{n}{p} = \frac{0.057(2)}{0.943 + 2(0.057)} = \frac{1}{9.3}$$

Which means that the neutrons in the sun probably came from some place else!

Suppose you created all the particles in a single huge event, what can you deduce?

$\Rightarrow$ probably took less than 10 minutes
(this is $t_{1/2}$ of a neutron)
otherwise neutrons would disappear

$\Rightarrow$ at one point it was hot enough and dense enough so that $\#n \sim \#p$
since we've seen $\#n = \#p\, e^{-1.3\,\text{MeV}/k_B T}$

type of stuff before.

So, how can we get an idea of what happened?

1) Assume we started out with a dense ball of stuff
2) Assume it expanded and cooled

tools

1) treat stuff as like any particle in a potential (even Hydrogen atom)

{ assume $E_{tot} = 0 = KE - (PE)$

$$\frac{1}{2} m \left(\frac{dr}{dt}\right)^2 = \frac{GMm}{r} \quad , \quad M = \left(\frac{4}{3}\pi r^3\right)\rho$$

$$\left(\frac{dr}{dt}\right)^2 = \left(\frac{4}{3}\pi r^3\right)\rho \frac{G}{r}$$

$$= \frac{8}{3}\pi G \rho r^2 \quad \left(- kc^2 \right)$$

and a correction

$$\left(k \begin{cases} +1 & E_{tot} < 0, \text{ bound} \\ 0 & E_{tot} = 0 \text{ no limit} \\ -1 & E_{tot} > 0 \ ??? \end{cases} \right.$$

now, if we assume M is constant

$$\rho(r) = \frac{M}{\frac{4}{3}\pi r^3}$$

and

$$\left(\frac{dr}{dt}\right)^2 = 2\frac{GM}{r}$$

$$\sqrt{r}\, dr = 2GM dt$$

$$\frac{2}{3} r^{3/2} = 2GMt$$

or $$r = (3GMt)^{2/3} \Rightarrow \left(\frac{dr}{dt}\right)^2 = \frac{2}{3}(3GM)^{2/3} t^{-\frac{1}{3}}$$

or $$\left(\frac{2}{3}\right)^2 \frac{\cancel{(3GM)^{\frac{4}{3}}}}{t^{2/3}} = \frac{8}{3}\pi G \rho \cancel{(3GM)^{\frac{4}{3}}} t^{\frac{4}{3}}$$

$$t^2 = \frac{1}{6\pi G \rho_m}$$

This says that after a long time, the universe is not too dense. (it's expanding)

When the universe was very dense and hot though, it acted more like a gas of photons. (lots of particle ~~particle~~ type anhiliations going on) & we've dealt with a gas of photons before in the homework and in the class

we found

$$\text{the } \frac{\text{number of photons}}{\text{volume}} = (2.03 \times 10^{7}/m^3K^3)\, T^3$$

$$\text{or } T \propto \frac{1}{r}$$

$$\text{while the } \frac{\text{Energy}}{\text{volume}} = \left(4.73 \times 10^{3} \frac{eV}{m^3K^4}\right) T^4$$

now, a way to deal with photons in a gravity field is to give them a "mass" E/c^2

$$\text{so we get } \rho_\gamma = \frac{E}{V}\frac{1}{c^2} = \left(4.73 \times 10^{3} \frac{eV}{m^3K^4}\right) T^4$$

$$= \left(4.73 \times 10^{3} \frac{eV}{m^3K^4}\right)\left(\frac{\#\,\text{photons}}{\frac{4\pi}{3} r^3}\right)^{\frac{4}{3}} = A/r^4$$

$$\text{so } \left(\frac{dr}{dt}\right)^2 = B\frac{1}{r^2} \qquad \left(\text{from } \frac{8}{3}\pi G \rho_\gamma r^2\right)$$

$$r\,dr = \sqrt{B}\,dt$$

$$r^2 = 2Bt, \quad r = \sqrt{2B}\, t^{1/2}, \quad \left(\frac{dr}{dt}\right)^2 = (2B)\frac{1}{4t}$$

$$\frac{8}{3}\pi G\rho_\gamma r^2 = \frac{8}{3}\pi G\rho_\gamma (2B) t = 2B\frac{1}{4t}$$

$$t^2 = \frac{3}{32\pi G\rho_\gamma}$$

or

$$t^2 = \frac{3c^2}{32\pi G\left(4.73\times10^{3}\frac{eV}{m^3K^4}\right)T^4}$$

$$T^4 = \frac{3c^2}{32\pi G\left(4.73\times10^{3}\frac{eV}{m^3K^4}\right)t^2}$$

$$T = \left(\frac{3\,(3.0\times10^{8}\,m/s)^2}{32\pi\left(6.67\times10^{-11}\frac{Nm^2}{Kg^2}\right)\left(4.73\times10^{3}\times1.6\times10^{-19}\frac{J}{m^3K^4}\right)}\right)^{\frac{1}{4}}\frac{1}{\sqrt{t}}$$

$$= \left(1.5\times10^{10}\,s^{1/2}\,K\right)/t^{1/2}$$

Temperature is important, it tells us at what times certain things happen as the universe expands.

Temperature	whats happening
$k_BT \sim E_\gamma = 2(940\ MeV)$	Threshold to create $p\bar{p}$

time $= 4.7\times10^{-7}s$

at this point, very short lived species are going to start to disapper (basically, everything with a c, s, t, or b quark is gone)

As things cool, no $p\bar{p}$ are made and the ones that are there anhiliate. There is an imbalance though & p's are left over.