The Radiation Era

Radiation Energy Density

What Counts as Radiation?

Any matter that is relativistic ($p >> mc$) will red shift the same way:

- Energy is given by: $E = \sqrt{p^2c^2 + m^2c^4} \approx pc$
- Like light, it has wavelength: $\lambda = h/p$
- Like light, wavelength stretches as universe expands $\lambda/\lambda_0 = a/a_0$
- Therefore, momentum decreases with time: $E = pc \propto a^{-1}$
- Number density is also dropping: $n \propto a^{-3}$
- Therefore, its density falls as $\rho \propto u \propto a^{-4}$

What might count as radiation?

- Today: photons, gravitons
- Recent past: neutrinos
- In the distant past: everything, if hot enough

Mass Density of Radiation

We previously calculated mass density for photons:

- The factor of 2 was counting spin states = polarizations
- Can we generalize this for other things besides photons?

$$\rho = 2\frac{\pi^2}{30}\frac{(k_B T)^4}{(\hbar c)^3 c^2}$$

What are the differences?

- The other particles might have different number of spin states: $2 \rightarrow g$
- The other particles might be at a different temperature: $T \rightarrow T_i$
- The other particles might be fermions
  - You can't put more than one fermion in the same quantum state
  - This decreases the total energy by a factor of 7/8

$$\rho = \frac{\pi^2 (k_B T)^4}{30(\hbar c)^3 c^2} g_{\text{eff}}$$

$$\rho_i = \begin{cases} \dfrac{\pi^2}{30}\dfrac{(k_B T_i)^4}{(\hbar c)^3 c^2} g & \text{for bosons} \\ \dfrac{\pi^2}{30}\dfrac{(k_B T_i)^4}{(\hbar c)^3 c^2}\dfrac{7}{8} g & \text{for fermions} \end{cases}$$

$$g_{\text{eff}} = \sum_{\text{bosons}} g_b \left(\frac{T_b}{T}\right)^4 + \sum_{\text{fermions}} \tfrac{7}{8} g_f \left(\frac{T_f}{T}\right)^4$$

$$g_{\text{eff}} = g_b + \tfrac{7}{8} g_F$$

When Does Matter = Radiation?

- In homework O, we found density of all matter and electromagnetic radiation:

$$\rho_{m0} = \frac{\Omega_m H_0^2}{\frac{8}{3}\pi G} = 2.65\times 10^{-27}\ \text{kg/m}^3,$$

$$\rho_{\gamma 0} = 2\frac{\pi^2}{30}\frac{(k_B T_0)^4}{(\hbar c)^3 c^2} = 4.64\times 10^{-31}\ \text{kg/m}^3,$$

There are also some neutrinos

- Three types, plus anti-particles ($g = 6$)
- They are fermions (factor of 7/8)
- They are at a lower temperature: $T_\nu = 0.7138T$

$$g_{\text{eff}} = 2 + \tfrac{7}{8}\cdot 6\cdot (0.7138)^4$$

$$g_{\text{eff}} = 3.36$$

- This value valid back to about $k_B T = 100$ keV
- The correct radiation density is therefore
- In the past, these densities were bigger

$$\rho_{r0} = \frac{g_{eff}}{2}\rho_{\gamma 0} = 7.80\times 10^{-31}\ \text{kg/m}^3,$$

$$\rho_r = \rho_{r0}(1+z)^4$$

$$\rho_m = \rho_{m0}(1+z)^3$$

$$\frac{\rho_m}{\rho_r} = \frac{\rho_{m0}(1+z)^3}{\rho_{r0}(1+z)^4} = \frac{3400}{1+z}$$

- Radiation was more important before

$$z_{eq} \approx 3400$$

$$T_{eq} \approx 9260\ \text{K}$$

$$k_B T_{eq} \approx 0.798\ \text{eV}$$

$$t_{eq} \approx 51{,}400\ \text{yr}$$

Time-Temperature Relation

- Friedmann Equation: $$\frac{\dot{a}^2}{a^2} = \tfrac{8}{3}\pi G\rho$$

- We can relate density at any time to density at one time t_1: $\rho = \rho_1 \left(a_1/a\right)^4$
- Substitute in
- Let $x = a/a_1$, as before:

$$\frac{\dot{a}^2}{a^2} = \tfrac{8}{3}\pi G\rho_1 \frac{a_1^4}{a^4}$$

$$\frac{\dot{x}^2}{x^2} = \frac{8}{3}\pi G\rho_1 x^{-4} \qquad \left(\frac{dx}{dt}\right)^2 = \frac{\tfrac{8}{3}\pi G\rho_0}{x^2} \qquad dt = \frac{x\,dx}{\sqrt{\tfrac{8}{3}\pi G\rho_1}} \qquad t_1 = \int_0^1 \frac{x\,dx}{\sqrt{\tfrac{8}{3}\pi G\rho_1}}$$

$$t_1 = \sqrt{\frac{3}{32\pi G\rho_1}}$$

- Valid at any time during radiation era
  - Drop the subscript 1
- Substitute expression for density

$$t = \sqrt{\frac{3}{32\pi G}\frac{30c^2\left(\hbar c\right)^3}{\pi^2 g_{\text{eff}}\left(k_B T\right)^4}} = \frac{6.213\times 10^{-26}\ \text{J}^2\cdot\text{s}}{\sqrt{g_{\text{eff}}}\left(k_B T\right)^2}$$

$$t = \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}}\left(\frac{\text{MeV}}{k_B T}\right)^2$$

Which Formula Do I Use?

- Recent Past: ($z < 3000$, $k_B T < 0.5$ eV)

$$t = \frac{17.3\ \text{Gyr}}{(1+z)^{3/2}}$$

$$t = \frac{64.0\ \text{kyr}}{(k_B T/\text{eV})^{1.5}}$$

- Distant Past: ($z > 3000$, $k_B T > 0.5$ eV)

$$t = \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}}\left(\frac{\text{MeV}}{k_B T}\right)^2$$

$$g_{\text{eff}} = 3.36 \quad \text{if } k_B T < 0.1\ \text{MeV}$$

Number Density of Particles:

- We sometimes want to know about how many particles are present
- We need to do an integral similar to the one we did for energy density
- The main difference is that the integral doesn't contain a factor of *E*, the energy
- When you work it all out, you get
- The average energy is the ratio of the energy to the number density $\bar{E} = \frac{u}{n}$
- It works out to about $\boxed{\bar{E} \approx 3k_B T}$

$$u_i = \begin{cases} \frac{\pi^2}{30} \frac{(k_B T_i)^4}{(\hbar c)^3} g & \text{for bosons} \\ \frac{\pi^2}{30} \frac{(k_B T_i)^4}{(\hbar c)^3} \frac{7}{8} g & \text{for fermions} \end{cases}$$

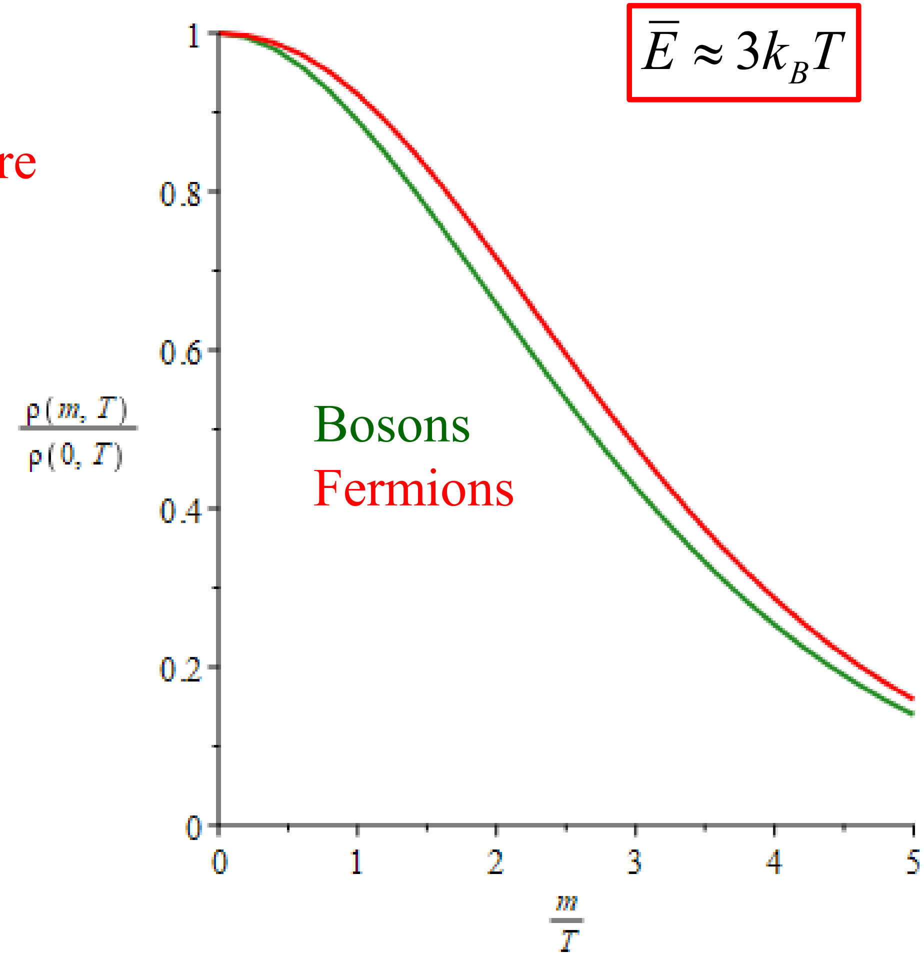
$$n_i = \begin{cases} \frac{\zeta(3)}{\pi^2} \left(\frac{k_B T_i}{\hbar c} \right)^3 g & \text{for bosons} \\ \frac{\zeta(3)}{\pi^2} \left(\frac{k_B T_i}{\hbar c} \right)^3 \frac{3}{4} g & \text{for fermions} \end{cases}$$

$$\zeta(3) \equiv \sum_{n=1}^{\infty} \frac{1}{n^3} = 1.202$$

When Do Particles Disappear?

- Assume we have a means for eliminating particles
- At high temperature ($3k_BT >> mc^2$), the particles are effectively massless
  - Treat as massless
- At low temperature ($3k_BT << mc^2$), the particles are supermassive
  - Probability of each state being occupied is very small
  - Treat as if particle doesn't exist
- For example, density as a function of mass:

$$\bar{E} \approx 3k_BT$$



Include particles with mass $mc^2 < 3k_BT$
Exclude particles with mass $mc^2 > 3k_BT$

Outline of History of Universe

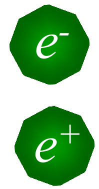
Time	T or $k_B T$	Events
10^{-43} s	10^{18} GeV	Planck Era; time becomes meaningless?
10^{-39} s	10^{16} GeV	Inflation begins; forces unified
10^{-35} s	10^{15} GeV	Inflation ends; reheating; forces separate; baryosynthesis (?)
10^{-13} s	1500 GeV	Supersymmetry breaking, LSP (dark matter)
10^{-11} s	160 GeV	Electroweak symmetry breaking
14 μs	150 MeV	Quark Confinement
0.4 s	1.5 MeV	Neutrino Decoupling
1.5 s	0.7 MeV	Neutron/Proton freezeout
20 s	170 keV	Electron/Positron annihilation
200 s	80 keV	Nucleosynthesis
57 ky	0.76 eV	Matter-Radiation equality
370 ky	0.26 eV	Recombination
600 My	30 K	First Structure/First Stars
13.8 Gy	2.725 K	Today

Nuclear Interactions

Electron-Positron Annnihilation

Particles and Anti-Particles

- For every particle there is an anti-particle
  - Same mass, same spin opposite charge



- Consider the electron, denoted e^- (m = 511 keV/c^2, spin ½, charge $-e$)
- The anti-electron e^+ (m = 511 keV/c^2, spin ½, charge $+e$)
  - Anti-electron is also known as positron
- Sometimes, particles are their own anti-particles
  - The photon, for instance
- There are always processes that cause particles and anti-particles to be created and destroyed
  - Example: electrons and positrons

$$e^- + e^+ \leftrightarrow \gamma + \gamma$$

Thermal Equilibrium for Electrons & Positrons

$$e^- + e^+ \leftrightarrow \gamma + \gamma$$

- This process has a cross-section comparable to Thomson cross section
  - *Easily* keeps things in thermal equilibrium at early times

- Electrons, positrons and photons all in thermal equilibrium

- At high temperatures ($k_B T >> m_e c^2$), the electrons are effectively massless

- They will contribute to energy density proportional to the spin states
  - Two spin states for electron
  - Two more for the positron

$$g_e = 4$$

- The total energy in photons, electrons, and positrons at early times is

$$\rho = \frac{\pi^2 (k_B T)^4}{30(\hbar c)^3 c^2} g_{\text{eff}}$$

$$g_{\text{eff}} = g_b + \tfrac{7}{8} g_F = 2 + \tfrac{7}{8} \cdot 4 = 5.5$$

When Do the Electrons & Positrons Annihilate?

$$e^- + e^+ \leftrightarrow \gamma + \gamma$$

- Recall: energy for massless particles (like photons) are typically $3k_BT$
- To make a positron/electron pair, we need two photons to have energy $2m_ec^2$

- In round numbers, we can make process go to the left if and only if:

$$3k_BT > m_ec^2$$

- Since $m_ec^2 = 511$ keV, this means we need $k_BT > 170$ keV

- Electrons and Positrons annihilate at about 170 keV
- This is at $t \approx 20$ s

Time	T or k_BT	Events
20 s	170 keV	Electron/Positron annihilation

- However, there are still some electrons (not positrons) around today
  - About 10^{-10} compared to the number that were there then

- This implies there was a tiny surplus of electrons over positrons beforehand
  - Related to baryon asymmetry
  - To be described later

Annihilation "Reheating" of Photons

$$e^- + e^+ \leftrightarrow \gamma + \gamma$$

- As temperature drops, due to expansion of universe, electrons and positrons annihilate to make photons
- This causes "reheating" of photons
  - A misnomer, actually what happens is photons cool more slowly

- We normally say that temperature drops inversely proportional to scale factor

$$a_{\text{after}} T_{\text{after}} = a_{\text{before}} T_{\text{before}}$$

- However, the energy in electrons + positrons + photons gets rechanneled into just photons

$$g_{\text{eff,before}} = 5.5, \quad g_{\text{eff,after}} = 2$$

- Can show this causes photons to be hotter than expected:

$$a_{\text{after}} T_{\text{after}} = (5.5/2)^{1/3} a_{\text{before}} T_{\text{before}} = 1.401 a_{\text{before}} T_{\text{before}}$$

Neutrino Decoupling

Neutrinos

- Some important particles for our discussion are the neutrinos

- There are three types of neutrinos labeled ν_1, ν_2, and ν_3 *
- They have very small masses, $m_i < 2 \text{ eV}/c^2$
  - At these early times, treat them as massless
- They are spin ½ and are their own anti-particles**

- At low energies, their interactions are very weak
  - In fact, the interactions they have are called *weak interactions*
- Weak Interactions typically have cross-sections of order
- G_F is a new constant called *Fermi's constant*
- E_1 and E_2 are the energies of the two colliding particles

$$\sigma \approx \frac{G_F^2}{(\hbar c)^4} E_1 E_2$$

$$\frac{G_F}{(\hbar c)^3} = 1.166 \times 10^{-5} \text{ GeV}^{-2}$$

*Often, the three neutrinos are listed as ν_e, ν_μ, and ν_τ. For technical reasons that don't concern us, this is now known to be more or less wrong

**This may be wrong, but if so, the errors introduced by this assumption cancel out

What Keeps Neutrinos in Equilibrium?

- Are neutrinos, or were they ever, in equilibrium?
- One process that creates and eliminates neutrinos is $e^- + e^+ \leftrightarrow \nu + \nu$

- How fast does this happen?
- Typical cross-section is about

$$\sigma \approx \frac{G_F^2}{(\hbar c)^4} E_1 E_2$$

- Typical energies around $3k_B T$
- Density of electrons around $n \approx \frac{g}{\pi^2}\left(\frac{k_B T}{\hbar c}\right)^3$
- Relative velocity around c
- Total rate about $\Gamma = n\sigma(\Delta v) \approx \frac{G_F^2 c}{(\hbar c)^7}(k_B T)^5$

When Did Neutrinos Decouple?

$$\Gamma \approx \frac{G_F^2 c}{(\hbar c)^7}(k_B T)^5$$

- We generally consider something in equilibrium as long as $\Gamma t >> 1$
- Age in the radiation dominated era is

$$t = \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}}\left(\frac{\text{MeV}}{k_B T}\right)^2$$

- Therefore:

$$\Gamma t \propto (k_B T)^3$$

- Equilibrium well-maintained at high T, poorly at low T
- Neutrinos decouple at about 1.5 MeV
- Corresponding time is about 0.4 s

Time	T or $k_B T$	Events
0.4 s	1.5 MeV	Neutrino Decoupling
20 s	170 keV	Electron/Positron annihilation

Background Neutrino Temperature

- As $k_B T$ drops below 1.5 MeV, neutrinos cease to be in thermal equilibrium with everything else
- However, as long as they are massless, a thermal distribution remains thermal

- The photons were reheated by electron-positron annihilation

$$a_{\text{after}} T_{\text{after},\gamma} = \left(\frac{5.5}{2}\right)^{1/3} a_{\text{before}} T_{\text{before}}$$

- In contrast, for neutrinos

- Combining these, $a_{\text{after}} T_{\text{after},\nu} = a_{\text{before}} T_{\text{before}}$

$$a_{\text{after}} T_{\text{after},\gamma} = \left(\frac{5.5}{2}\right)^{1/3} a_{\text{after}} T_{\text{after},\nu} \qquad T_\nu = \left(\frac{2}{5.5}\right)^{1/3} T_\gamma = 0.714 T_\gamma$$

- So, after electron/positron annihilation

$$\boxed{T_{\nu 0} = 1.945\ \text{K}}$$

- Assuming we can treat neutrinos as massless, this even applies today
- And we can even calculate the number density of neutrinos

$$n_{\nu i} = \frac{\zeta(3)}{\pi^2}\left(\frac{k_B T_\nu}{\hbar c}\right)^3 \frac{3}{4} \cdot 2 = 1.12 \times 10^8\ \text{m}^{-3}$$

- Even if the mass becomes relevant, this number density is still correct

Proton/Neutron Freezeout

Baryons

- Most of the ordinary mass of the current universe is in the form of protons or neutrons
- These two particles are part of a class of particles called *baryons*

- According to our current theory of particle physics, baryons are conserved*
- The total number of baryons is tiny ($\sim 10^{-9}$) compared to, say, photons
  - This needs to be explained
  - Comes much later

- Weak interactions can convert protons ←→ neutrons

- We would like to understand what determined the ratio of these to each other
  - Proton/neutron freezeout

- And how they got bound together into nuclei
  - Primordial Nucleosyntheis

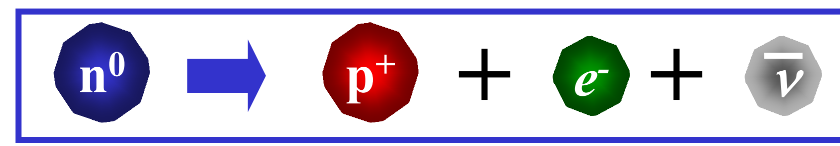
*Later we will discuss the possibility that they are not conserved

Neutron Decay and Interconversion

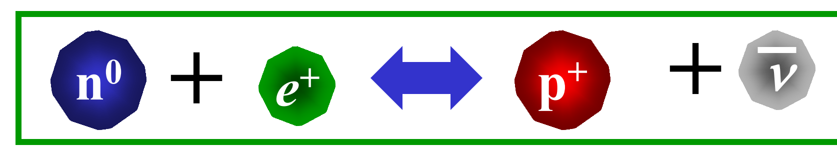
Particle processes are a lot like equations

- You can turn them around and they still work
- You can move particles to the other side by "subtracting them"
  - This means replacing them with anti-particles

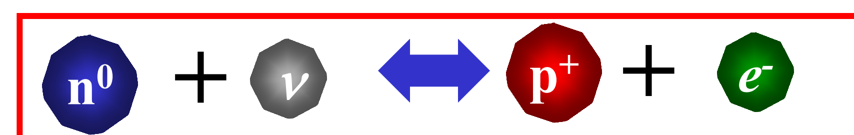
- The neutron (in isolation) is an unstable particle
  - Decays to proton + electron + anti-neutrino
  - Mean lifetime: 882 seconds



- Put the electron on the other side



- Put the neutrino on the other side



- All thee processes convert neutrons to protons and vice versa

Neutron/Proton Interconversion Rates

$$n^0 \rightarrow p^+ + e^- + \bar{\nu}$$

$$n^0 + e^+ \leftrightarrow p^+ + \bar{\nu}$$

$$n^0 + \nu \leftrightarrow p^+ + e^-$$

- At early times ($t \sim 1$ s) the first process is too slow
- The other two processes are governed by weak interactions, with cross sections like

$$\sigma \approx \frac{G_F^2}{(\hbar c)^4} E_1 E_2$$

- E_1 is energy of electron or neutrino, at neutrino freezeout $3k_B T \sim 5$ MeV
- But the other energy, E_2 is the much larger proton or neutron rest mass ~ 900 MeV

- Compared to neutrino freezeout ($k_B T = 1.5$ MeV), this cross-section is bigger
- It allows this process to stay in equilibrium a bit longer
- So this neutron/proton freezeout occurs around $k_B T = 0.71$ MeV

$$t = \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}} \left(\frac{\text{MeV}}{k_B T} \right)^2$$

$$= \frac{2.42\ \text{s}}{\sqrt{10.75}} \left(\frac{\text{MeV}}{0.71\ \text{MeV}} \right)^2 = 1.5\ \text{s}$$

Time	T or $k_B T$	Events
0.4 s	1.5 MeV	Neutrino Decoupling
1.5 s	0.71 MeV	Neutron/Proton freezeout
20 s	0.2 MeV	Electron/Positron annihilation

Neutron/Proton Freezeout

- At $k_B T = 0.71$ MeV, the process stops

$$P(E) \propto \exp\left(-\frac{E}{k_B T}\right)$$

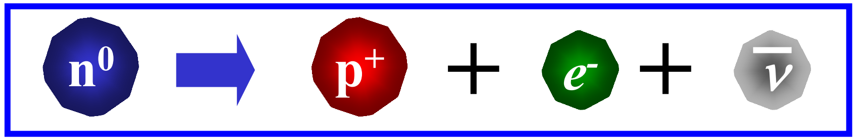
- What is ratio of protons to neutrons at this temperature?
- Non-relativistic, $E = mc^2$.
- Ratio is:

$$P_n \propto \exp\left(-\frac{m_n c^2}{k_B T}\right), \quad P_p \propto \exp\left(-\frac{m_p c^2}{k_B T}\right)$$

$$\frac{n_n}{n_p} = \frac{P_n}{P_p} = \frac{\exp\left(-\frac{m_n c^2}{k_B T}\right)}{\exp\left(-\frac{m_p c^2}{k_B T}\right)} = \exp\left(-\frac{(\Delta m) c^2}{k_B T}\right) = \exp\left(-\frac{1.294 \text{ MeV}}{0.71 \text{ MeV}}\right) = 0.162$$

$$\frac{n_n}{n_B} = \frac{n_n}{n_n + n_p} = \frac{0.162}{1.162} = 0.139$$

- Neutron/proton ratio at this point freezes
- *But* the neutrons continue decaying through the process we've been ignoring



Outline of History of Universe

Time	T or $k_B T$	Events
10^{-43} s	10^{18} GeV	Planck Era; time becomes meaningless?
10^{-39} s	10^{16} GeV	Inflation begins; forces unified
10^{-35} s	10^{15} GeV	Inflation ends; reheating; forces separate; baryosynthesis (?)
10^{-13} s	1500 GeV	Supersymmetry breaking, LSP (dark matter)
10^{-11} s	160 GeV	Electroweak symmetry breaking
14 μs	150 MeV	Quark Confinement
0.4 s	1.5 MeV	Neutrino Decoupling
1.5 s	0.7 MeV	Neutron/Proton freezeout
20 s	170 keV	Electron/Positron annihilation
200 s	80 keV	Nucleosynthesis
57 ky	0.76 eV	Matter-Radiation equality
370 ky	0.26 eV	Recombination
600 My	30 K	First Structure/First Stars
13.8 Gy	2.725 K	Today

Primordial Nucleosynthesis

Stellar Versus Primordial Nucleosynthesis

- Protons and neutrons have lower energy when they bind into more complex nuclei
- Just as in stars, the first step is to make deuterium, ^2H
- However, many aspects of stellar and primordial nucleosynthesis are different

<u>Stellar Nucleosynthesis</u>

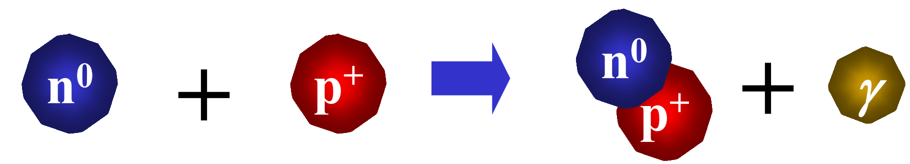
- Starts with just protons
  - First step is partly weak interaction
- Occurs at high density
  - Denser than lead (for the Sun)
- Must have sufficiently high temperature
- Takes billions of years to complete

<u>Primordial Nucleosynthesis</u>

- Starts with protons and neutrons
  - First step is mostly strong interaction
- Occurs at low density
  - Less dense than air
- Must have sufficiently low temperatures
- Must finish in a few minutes

The Deuterium Bottleneck

- The first step in making more complex elements is to make ^{2}H, deuterium:



- This releases about E_b = 2.24 MeV of energy
- This process is very similar to recombination
  - With the neutrons playing the role of electrons getting bound to protons
- We get a similar Saha-type equation describing the abundance of n^0, p^+, and ^2H:

$$\frac{n_D}{n_n} = \frac{3}{4} n_p \left(\frac{k_B T m_n m_p}{2\pi\hbar^2 m_D} \right)^{-3/2} \exp\left(\frac{E_b}{k_B T} \right)$$

- The most important factor here is the exponential
  - Strongly favors deuterium once $k_B T < 2.24$ MeV
- However, because the density of hydrogen is so low, the exponential has to beat a tiny factor
- At around $k_B T = 0.1$ MeV, neutrons will suddenly be incorporated into deuterium

Time	T or $k_B T$	Events
0.4 s	1.5 MeV	Neutrino Decoupling
1.5 s	0.71 MeV	Neutron/Proton freezeout
20 s	0.2 MeV	Electron/Positron annihilation
200 s	80 keV	Primordial nucelosynthesis

What is the Neutron/Proton Ratio?

- At around $k_B T = 0.1$ MeV, neutrons will suddenly be incorporated into deuterium

$$\frac{n_D}{n_n} = \frac{3}{4} n_H \left(\frac{k_B T m_n m_H}{2\pi\hbar^2 m_D} \right)^{-3/2} \exp\left(\frac{E_b}{k_B T} \right)$$

- The time at this point will be

$$t = \frac{2.42\ \text{s}}{\sqrt{g_{\text{eff}}}} \left(\frac{\text{MeV}}{k_B T} \right)^2 = \frac{2.42\ \text{s}}{\sqrt{3.36}} \left(\frac{\text{MeV}}{0.1\ \text{MeV}} \right)^2 = 132\ \text{s}$$

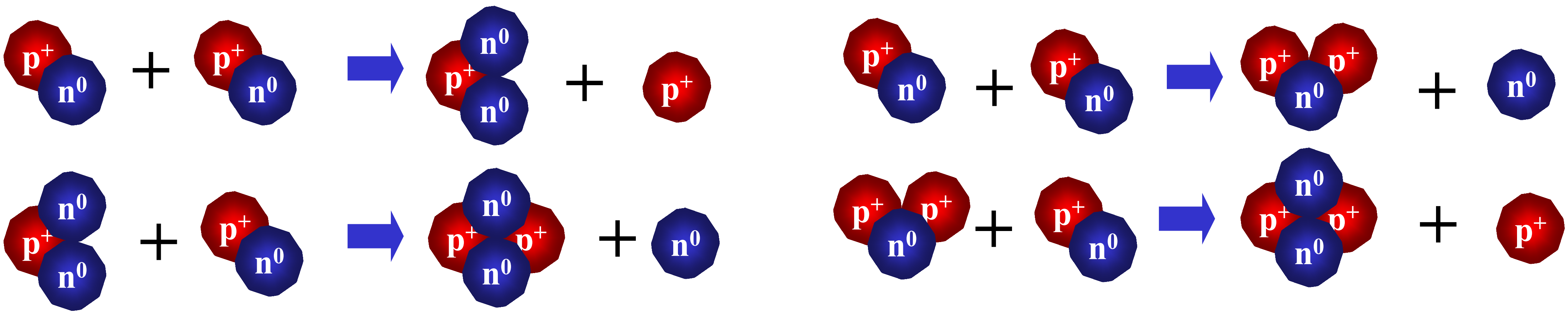
- During this time, neutrons have been decaying steadily, so the neutron fraction will be reduced
- About 1/8 of the baryons are currently neutrons

$$\left(\frac{n_n}{n_B} \right)_{132\ \text{s}} = \left(\frac{n_n}{n_B} \right)_{1.5\ \text{s}} \exp\left(-\frac{130\ \text{s}}{882\ \text{s}} \right) = 0.120$$

- A comparable number of protons get incorporated into deuterons
  - So ¼ of the baryons are in deuterons
- The *exact* time this happens will depend weakly on density of baryons
  - The more baryons, the earlier it happens
- And therefore, the *exact* fraction that becomes deuterons will depend on density
  - The more baryons, the larger the fraction

Making Helium

- Once we make deuterium, we continue quickly to continue to ^{4}He:



- For every two neutrons, there will be two protons that combine to make ^{4}He
  - Mass fraction of ^{4}He is twice that of neutron fraction

$$Y_P = \frac{\rho\left({}^4\text{He}\right)}{\rho\left(\text{total}\right)} = \frac{2n_n}{n_B} = 2\times 0.12 = 0.24$$

- ^{4}He is extremely stable – once formed it won't go back
- The more baryons there are, the larger the neutron fraction

$$\eta \equiv \frac{n_B}{n_\gamma}$$

- Define η as the current ratio of baryons to photons
- As η increases, Y_P increases weakly:

$$Y_P = 0.248 + 0.011\ln\left(\frac{\eta}{6\times 10^{-10}}\right)$$

Making Other Elements

- As that last of the deuterium and neutrons are used up, other processes become important

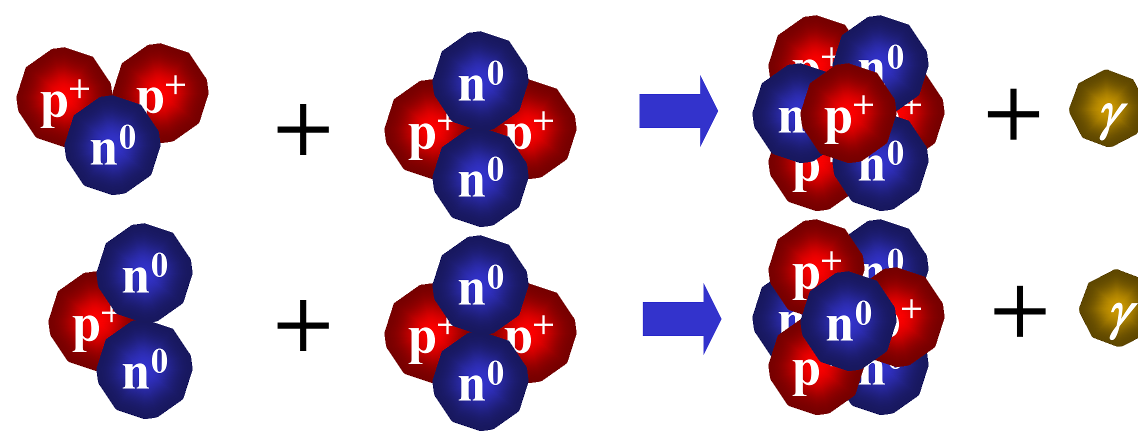
- The last few ^{2}H, ^{3}He, and ^{3}H nuclei will have trouble finding partners
  - There will be small amount of each of these isotopes left

- The more baryons there are, the easier it is to find a partner
  - As η increases, ^{2}H, ^{3}He, and ^{3}H all decrease

- There are other rare processes that produce a couple of other isotopes:

- ^{7}Li and ^{7}Be are produced
  - Not sure how they depend on η

- Within a few hundred seconds, the baryons are all in n^0, ^{1}H, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Be and ^{7}Li



Subsequent Decay and Observations

- Three of these are unstable:

$$n^0 \to p^+ + e^- + \bar{\nu}_e$$

$$^3\text{H} \to {}^3\text{He} + e^+ + \nu_e$$

$$^7\text{Be} + e^- \to {}^7\text{Li} + \nu_e$$

- Add n^0 to ^{1}H, ^{3}H to ^{3}He, and ^{7}Be to ^{7}Li
- The process whereby stars make heavier elements do *not* work in the early universe
- Density is too low for unstable ^{8}Be to find another ^{4}He to react with

$$^4\text{He} + {}^4\text{He} \to {}^8\text{Be}^*$$

$$^8\text{Be}^* + {}^4\text{He} \to {}^{12}\text{C}$$

- In the end, we should be able to predict abundance (compared to hydrogen) of

  ^{2}H, ^{3}He, ^{4}He, ^{7}Li

- We now wish to compare to observations

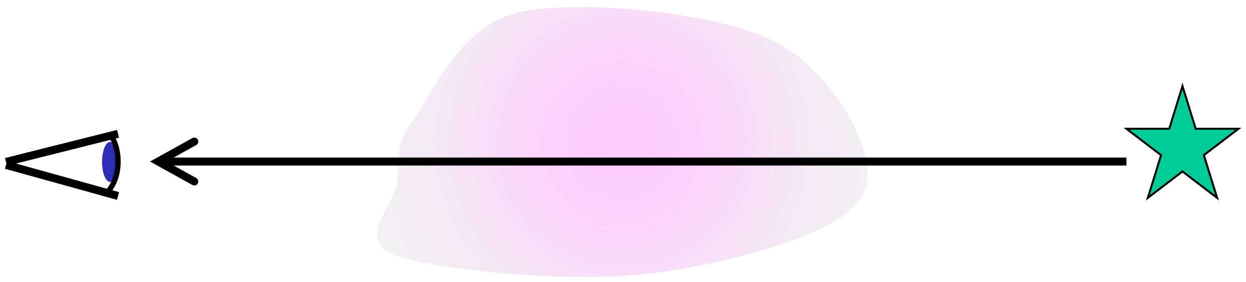
Observations of Primordial Densities

- At the end of Primordial Nucleosynthesis (and subsequent decay), we have a prediction of the following isotope fractions compared to hydrogen: ^{2}H, ^{3}He, ^{4}He, ^{7}Li

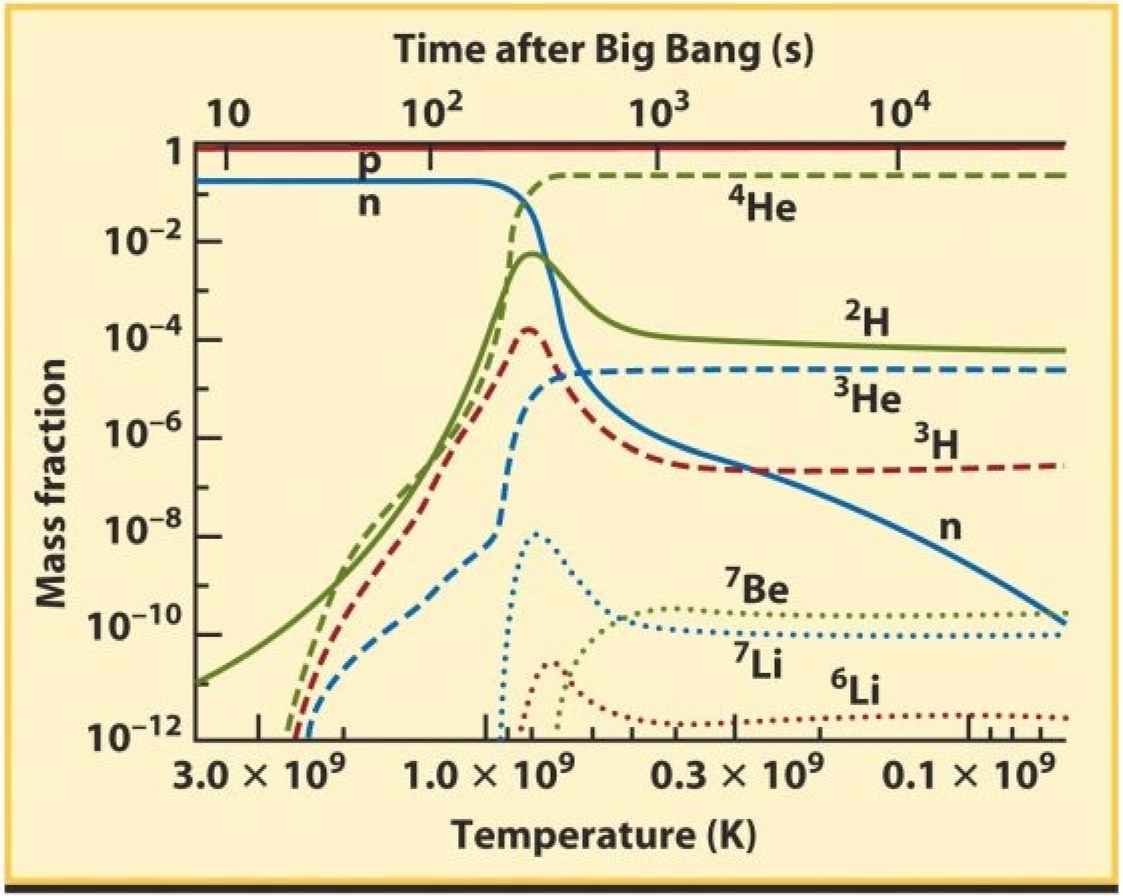
- These are *primordial* values
  - They will get subsequently modified by whatever happens in the later universe

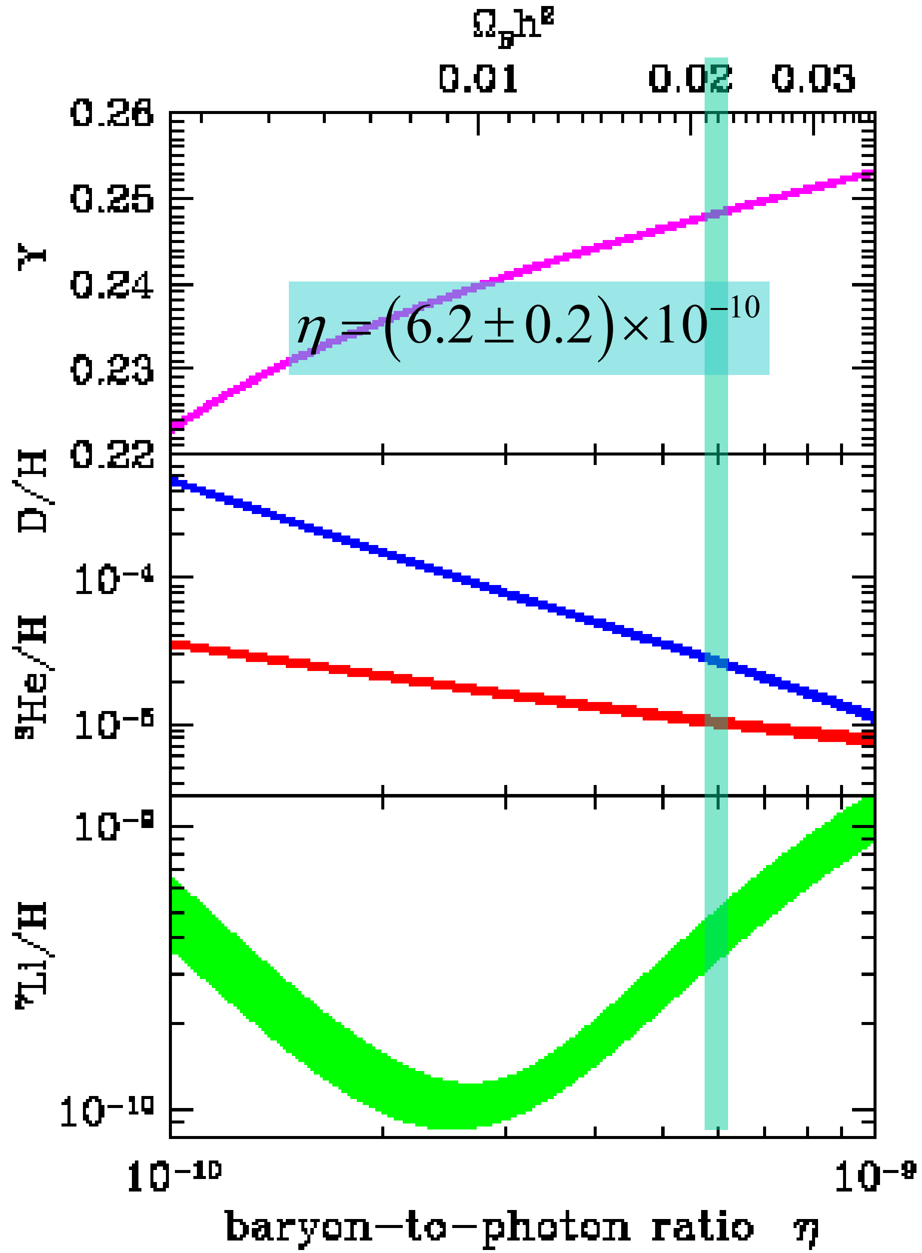
- ^{4}He tends to be created in stars
- We can estimate ^{4}He by looking at very early stars (Z low) that have not produced any *surface* helium
  - Requires extrapolation to $Z = 0$
- We can estimate ^{7}Li in a similar way by looking at old stars

- For ^{3}He and ^{2}H, they tend to get quickly destroyed in stars
- We can study absorption lines of gas that we think probably has not yet been made into stars at all
- We need bright sources at very high red shift
  - Quasars



The Results





- Predictions for ^{4}He, ^{2}H and ^{3}He all work very well
- Prediction for ^{7}Li seems to be off
  - The Lithium problem
- Overall, success for the model

Outline of History of Universe

Time	T or $k_B T$	Events
10^{-43} s	10^{18} GeV	Planck Era; time becomes meaningless?
10^{-39} s	10^{16} GeV	Inflation begins; forces unified
10^{-35} s	10^{15} GeV	Inflation ends; reheating; forces separate; baryosynthesis (?)
10^{-13} s	1500 GeV	Supersymmetry breaking, LSP (dark matter)
10^{-11} s	160 GeV	Electroweak symmetry breaking
14 μs	150 MeV	Quark Confinement
0.4 s	1.5 MeV	Neutrino Decoupling
1.5 s	0.7 MeV	Neutron/Proton freezeout
20 s	170 keV	Electron/Positron annihilation
200 s	80 keV	Nucleosynthesis
57 ky	0.76 eV	Matter-Radiation equality
370 ky	0.26 eV	Recombination
600 My	30 K	First Structure/First Stars
13.8 Gy	2.725 K	Today

Particle Physics and Early Events

- As we get to higher and higher temperatures, new particles appear
  - This happens roughly when $3k_BT = mc^2$
- Muons, mass 105.7 MeV/c^2, at about $k_BT = 35$ MeV ($g = 4$ fermions)
- Pions, mass 135-139 MeV/c^2, at about $k_BT = 45$ MeV ($g = 3$ bosons)
- At a temperature of about $k_BT = 150$ MeV, we have quark deconfinement
- As we get to still higher temperatures, we get to the electroweak phase transition
- And beyond that, we get into the realm of unknown physics
- To understand what we do and don't understand, we need to learn some particle physics