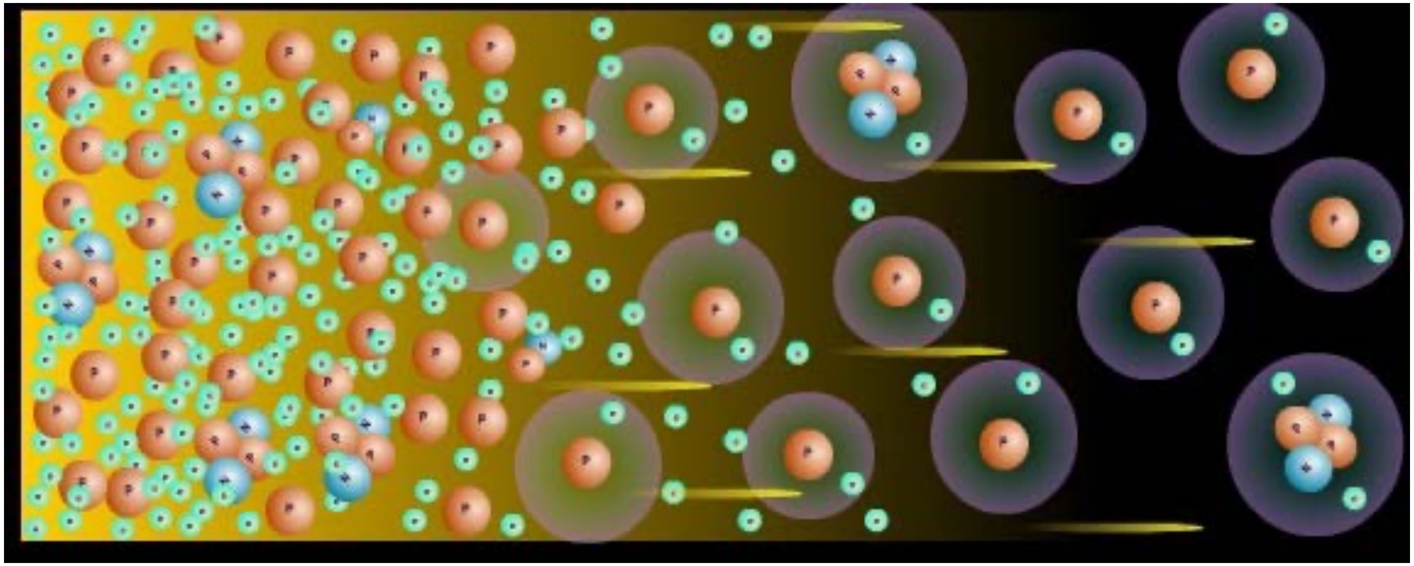
Honours Cosmology Week 4:

Big Bang Physics

In this class we will study the primeval fireball of the hot Big Bang which produced the light elements and the Cosmic Microwave Background



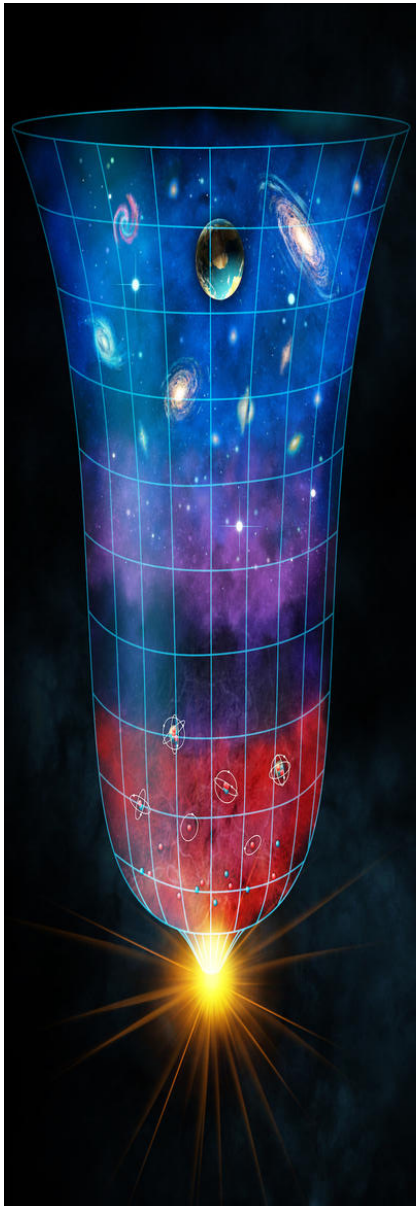
Big Bang Physics

At the end of this week you should be able to …

- … describe the **thermal history** of the early Universe
- … describe the phenomenon of **“freeze-out”**, which results in the appearance of different particle species over time
- … understand the process of **Big Bang nucleosynthesis** which forms deuterium, helium and lithium
- … understand **recombination**, which forms the CMB
- … calculate **properties of the radiation field** such as energy density, photon density and ionisation fraction

Early universe

- Let’s consider “winding back the clock” of the expanding Universe …
- … the universe is contracting …
- … energy density increases …
- … particles interact more frequently …
- … temperature increases …
- … we track back to the *primeval fireball* that is central to Big Bang physics

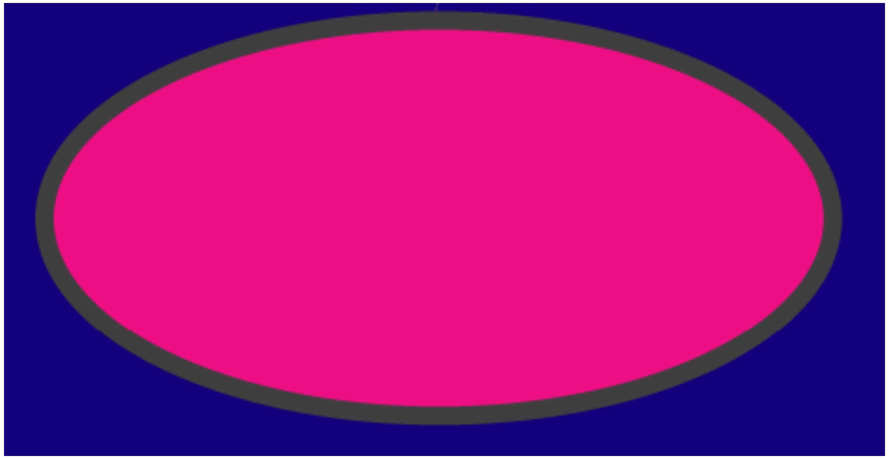


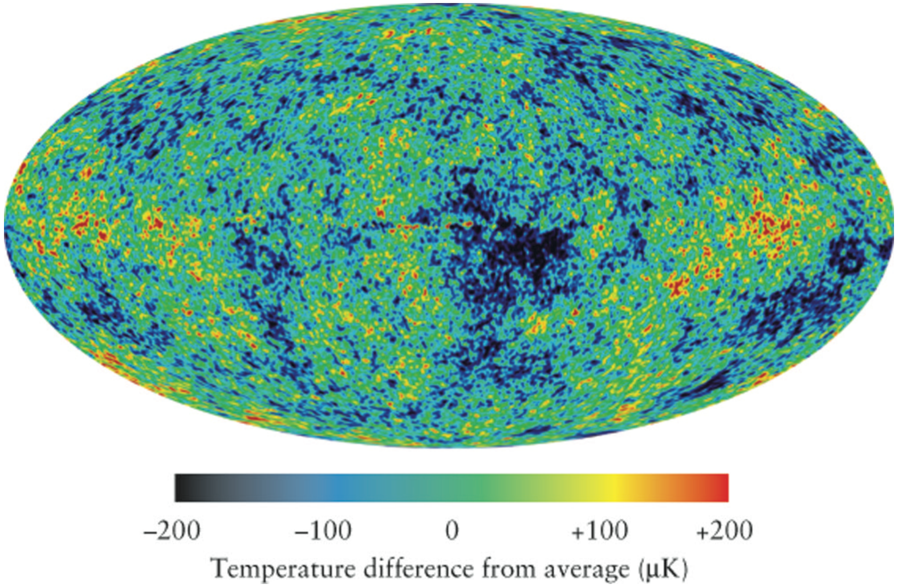
Early universe

- We can see the afterglow of that primeval fireball as the Cosmic Microwave Background radiation!

The CMB is a highly uniform radiation field across the sky with temperature $T = 2.73\ \mathrm{K}$ today

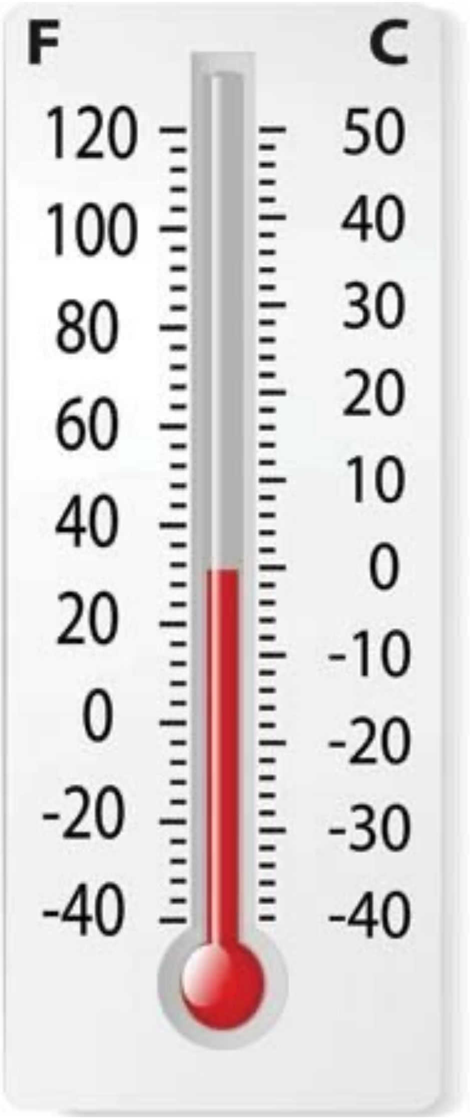
Looking closely, we can see tiny fluctuations in the CMB of size $\Delta T \sim 0.0001\ \mathrm{K}$





Early universe

- The physics of the early Universe is *governed by its temperature*, T
- Since the early Universe is radiation-dominated, density scales as $\rho \propto 1/a^4$
- For radiation, energy density $\rho \propto T^4$ (see: Stefan-Boltzmann law)
- Combining these relations, $T \propto 1/a$
- Makes sense because energy of each photon scales with wavelength $\propto 1/\lambda$, and $\lambda \propto a$

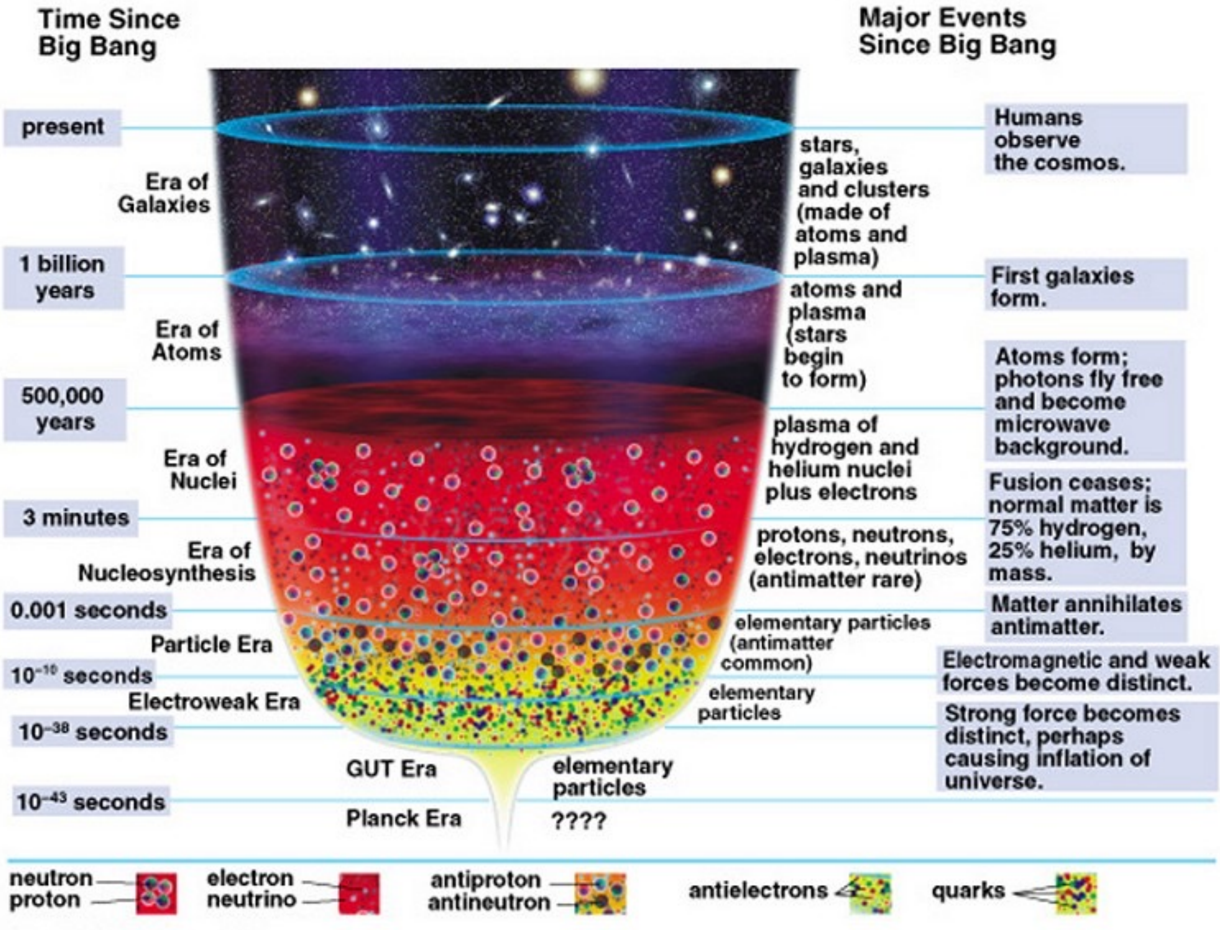


Early universe

- Since the physics is completely determined by the temperature and mix of particles, *we know the key events of the early Universe remarkably well!*
- In the first second, the quark-gluon plasma forms *protons* and *neutrons*
- In the first few minutes, protons and neutrons form the *light nuclei* *(deuterium, helium, lithium)*
- Around 300,000 years after the Big Bang, *atoms form* for the first time (and the CMB is produced)

Early universe

- Here’s a visualisation of these events!



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We’ll analyze this range of events over the next few slides!

Freeze-out

- Different types of particles appear at different times as the Universe cools and expands. When a species becomes long-lived, we say it "freezes out"

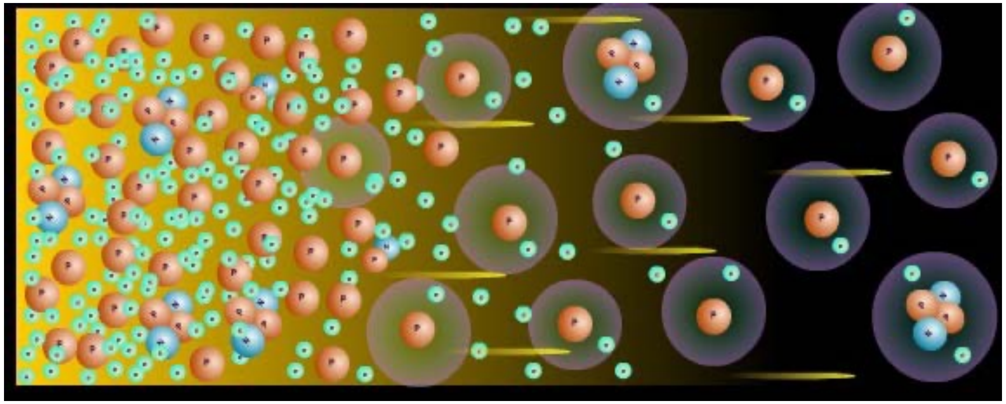
Before freeze-out a thermal equilibrium is maintained between species, and **particles are transitory**

After freeze-out the interaction rate drops owing to changing temperature or density, and **particles are long-lived**

- A good example is the freeze-out of CMB photons:

When there are plenty of electrons around, photons are in scattering equilibrium:

$$e^- + \gamma \rightarrow e^- + \gamma$$

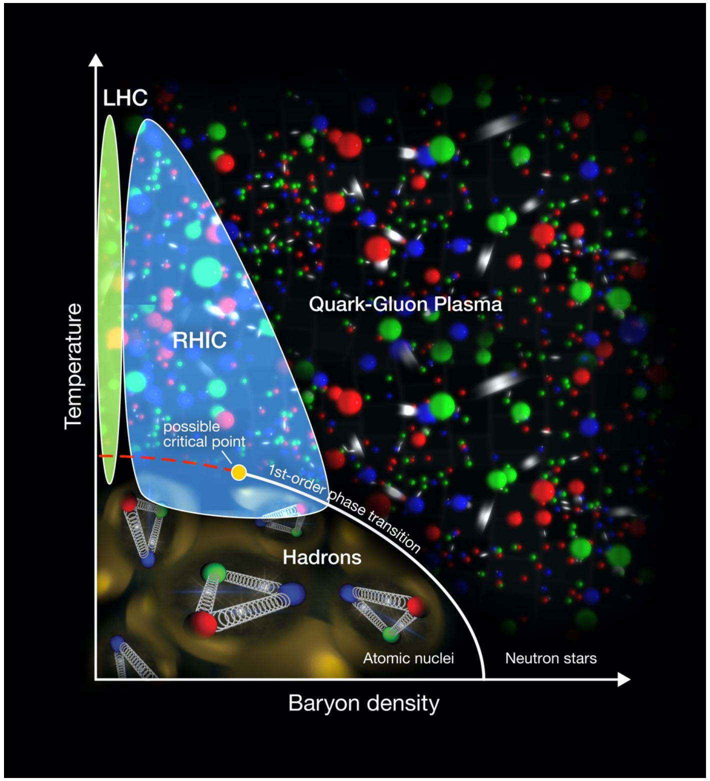


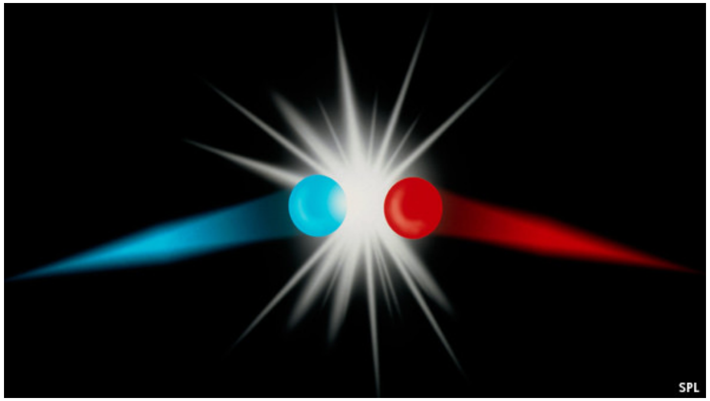
When atoms form, free electrons are no longer available, so photons become long-lived

Baryogenesis

- The first freeze-out event we'll mention is *baryogenesis* – the production of neutrons and protons from the quark-gluon plasma ($T \sim 10^{12}$ K, $t \sim 10^{-4}$ s)

- A major unsolved problem is what causes the *baryon asymmetry* that results in more matter than anti-matter!



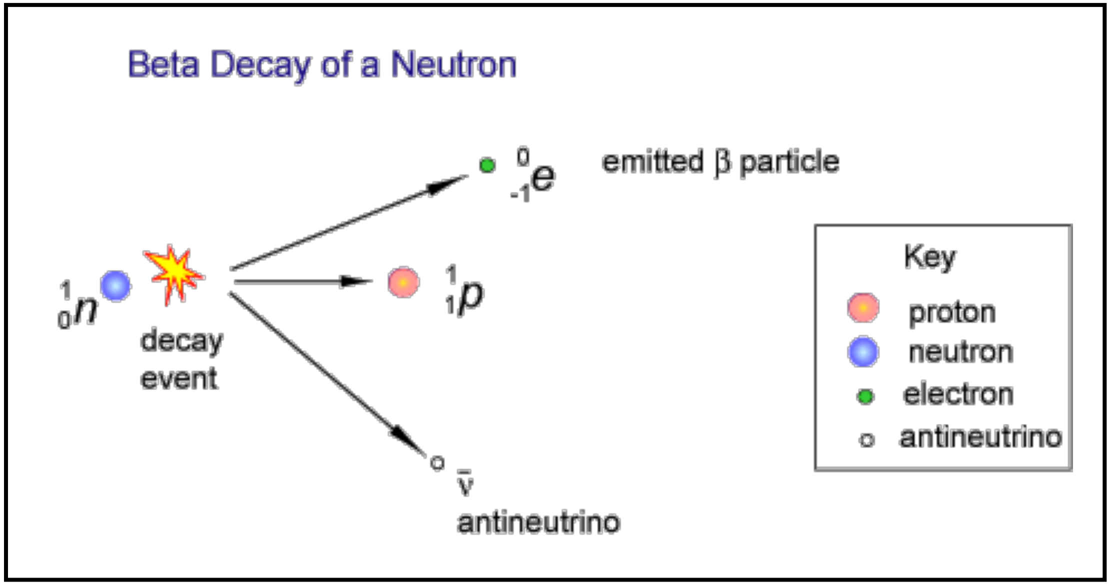


Big Bang Nucleosynthesis

- As well as hydrogen nuclei (protons), helium and lithium nuclei are produced in the early Universe, in a process called *Big Bang Nucleosynthesis (BBN)*

- When neutrons have formed, they start disappearing owing to *beta decays*

- The half-life for beta decay is $T_{1/2} \approx 10\ \mathrm{min}$, so additional nuclei composed of neutrons have to form within this time!

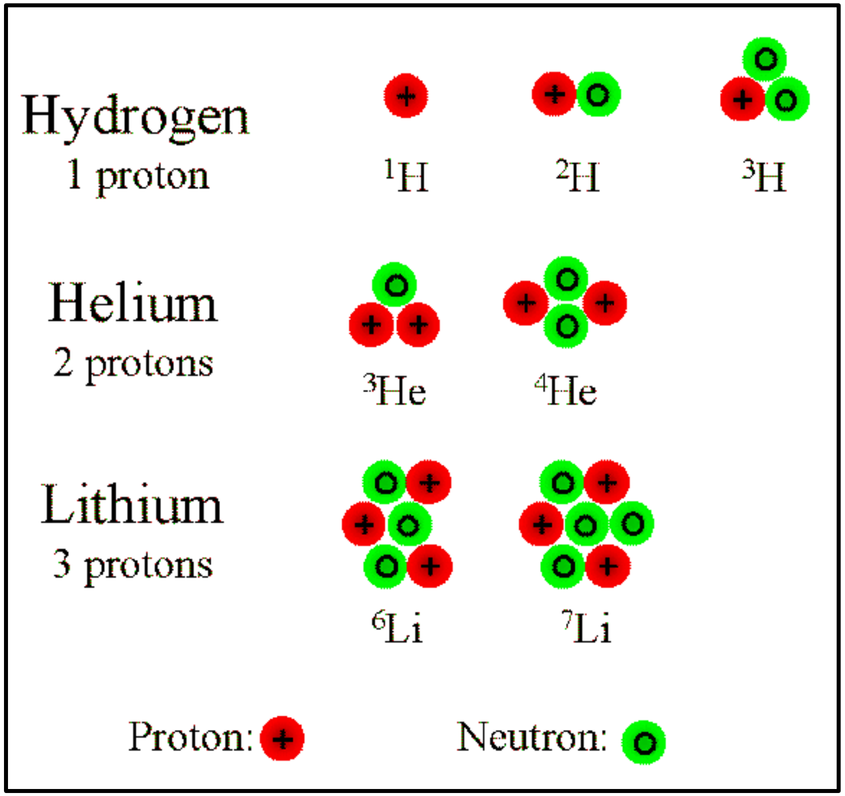


Big Bang Nucleosynthesis

- *Helium* cannot form immediately, since the lightest isotope is helium-3, which would require a very unlikely three-particle interaction to be produced by protons and neutrons

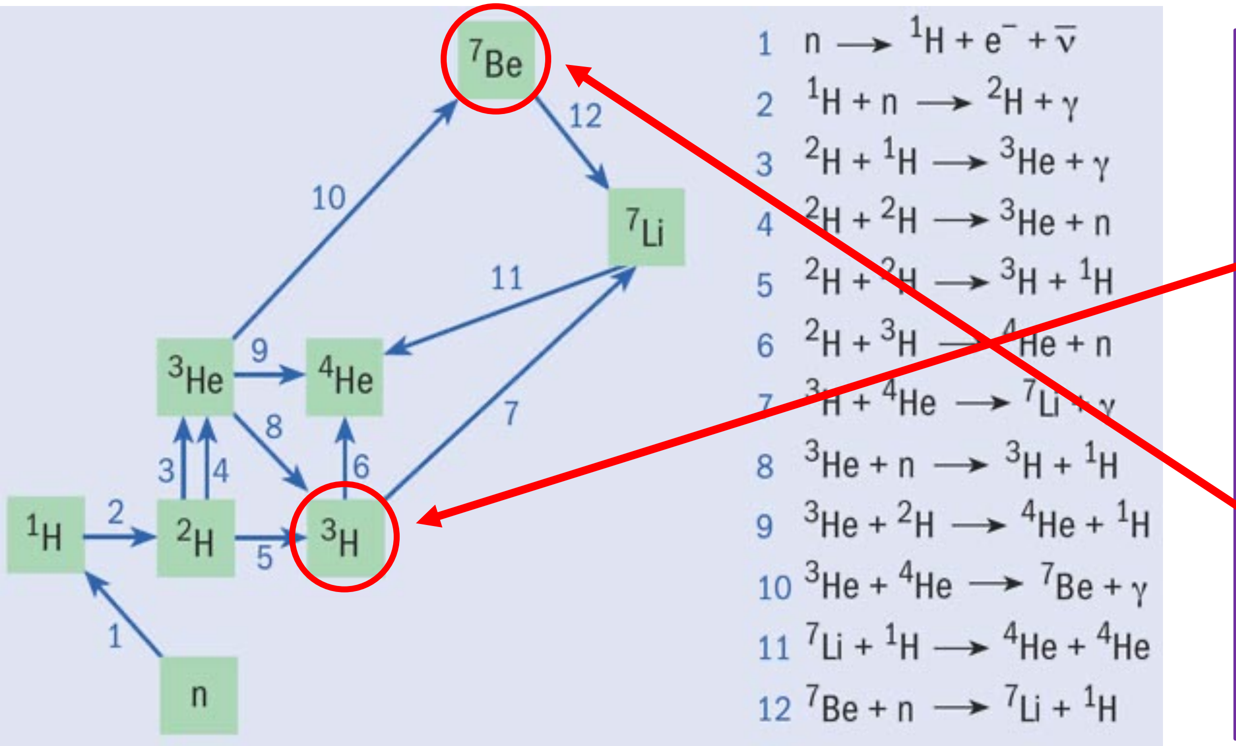
- Therefore, *deuterium* (^2H) forms first, and *helium forms from deuterium*

- It takes 6 minutes after the Big Bang for the Universe to cool sufficiently for deuterium to be stable, so the neutrons are running out!



Big Bang Nucleosynthesis

- The chain of reactions also produces some residual lithium before nucleosynthesis ends due to the falling temperature



1 $n \longrightarrow {}^{1}H + e^{-} + \bar{\nu}$

2 ${}^{1}H + n \longrightarrow {}^{2}H + \gamma$

3 ${}^{2}H + {}^{1}H \longrightarrow {}^{3}He + \gamma$

4 ${}^{2}H + {}^{2}H \longrightarrow {}^{3}He + n$

5 ${}^{2}H + {}^{2}H \longrightarrow {}^{3}H + {}^{1}H$

6 ${}^{2}H + {}^{3}H \longrightarrow {}^{4}He + n$

7 ${}^{3}H + {}^{4}He \longrightarrow {}^{7}Li + \gamma$

8 ${}^{3}He + n \longrightarrow {}^{3}H + {}^{1}H$

9 ${}^{3}He + {}^{2}H \longrightarrow {}^{4}He + {}^{1}H$

10 ${}^{3}He + {}^{4}He \longrightarrow {}^{7}Be + \gamma$

11 ${}^{7}Li + {}^{1}H \longrightarrow {}^{4}He + {}^{4}He$

12 ${}^{7}Be + n \longrightarrow {}^{7}Li + {}^{1}H$

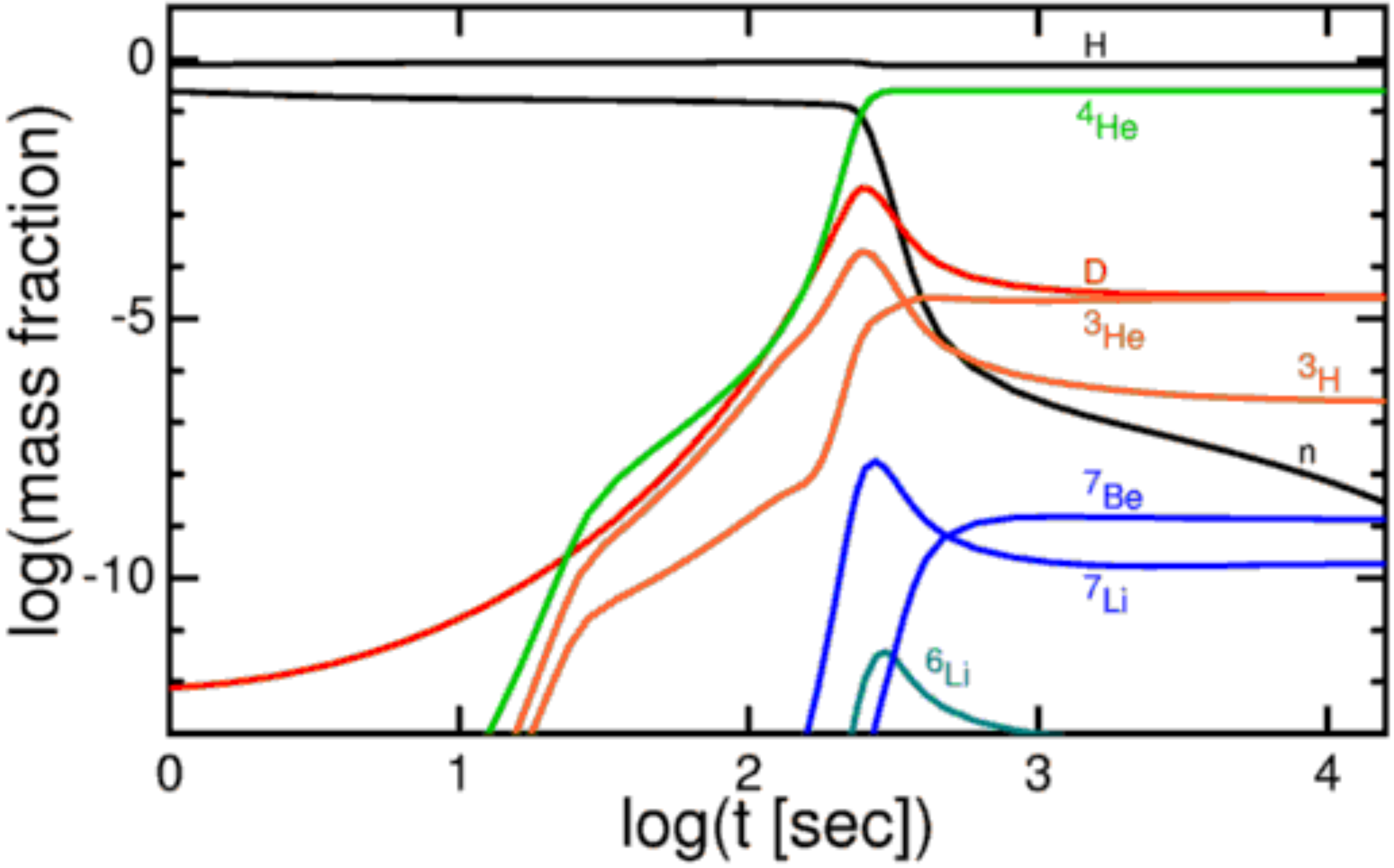
Note that …

- Tritium (^{3}H) decays into ^{3}He (half-life = 12 yr)
- Beryllium (^{7}Be) decays into ^{7}Li (half-life = 53 days)

… so they do not survive

Big Bang Nucleosynthesis

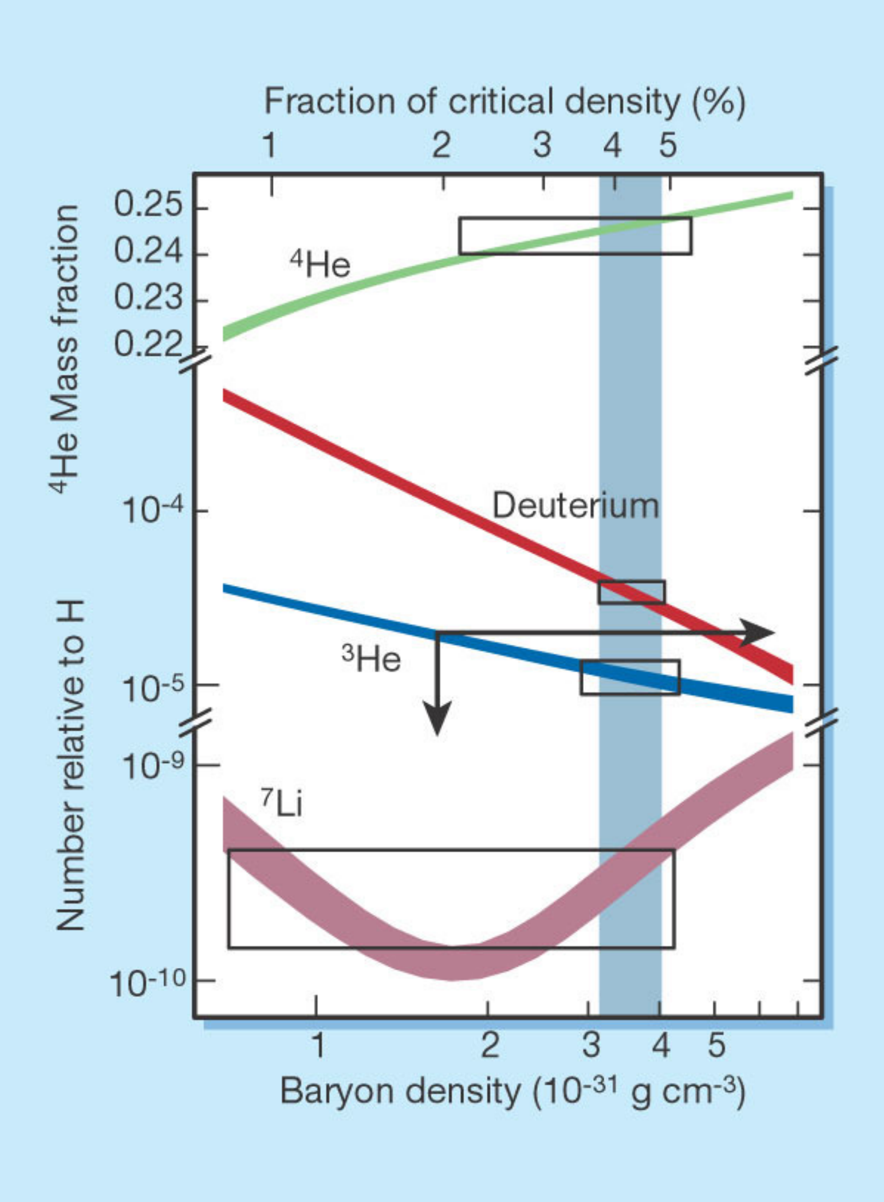
- The following chart shows the mix of nuclei with time …



Big Bang Nucleosynthesis

- Through modelling these reaction rates, we can describe how the *abundance* of each element formed by BBN depends on the baryon density

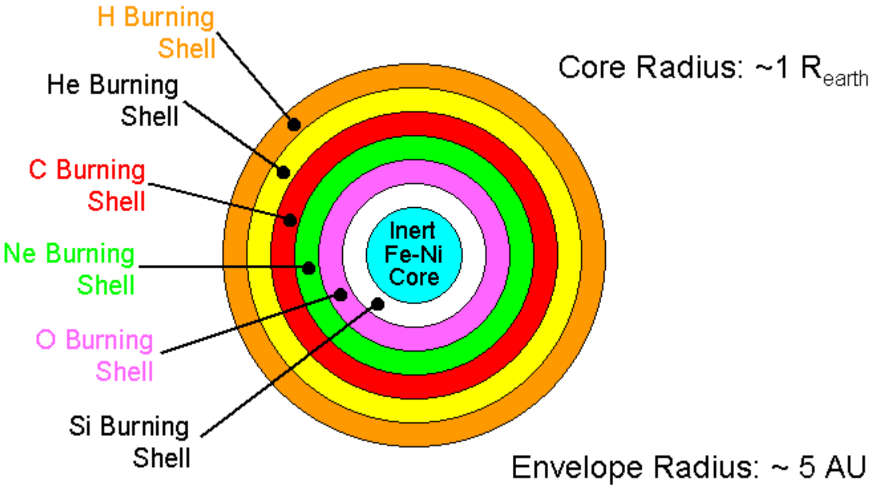
- Measuring these abundances in today's Universe allows us to *determine the baryon density*, $\Omega_b \approx 0.05$



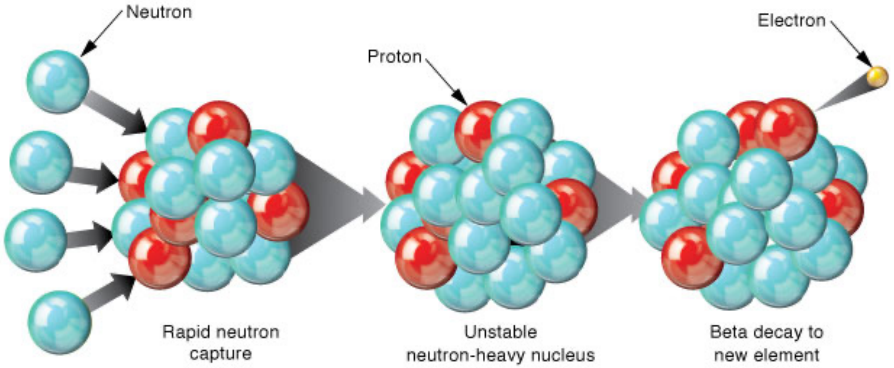
The rest of the periodic table!

- The other atomic elements are **not** formed during Big Bang Nucleosynthesis, but inside stars

Nuclear fusion processes transform light nuclei into heavier nuclei, releasing energy within stars

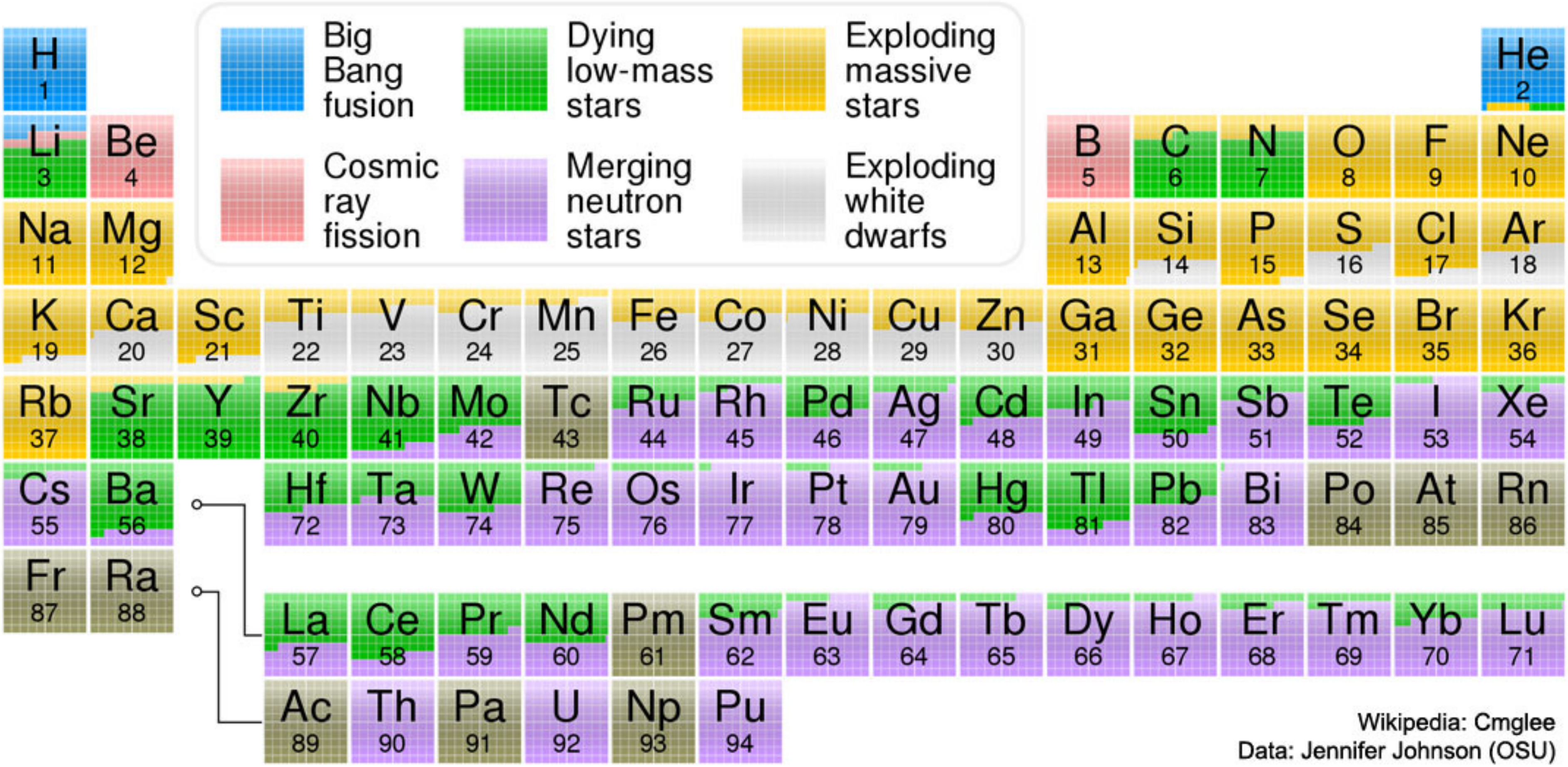


Other heavy nuclei are formed by neutron capture during supernova explosions (see: r-process, s-process)



The rest of the periodic table!

- Here is a nice summary figure:



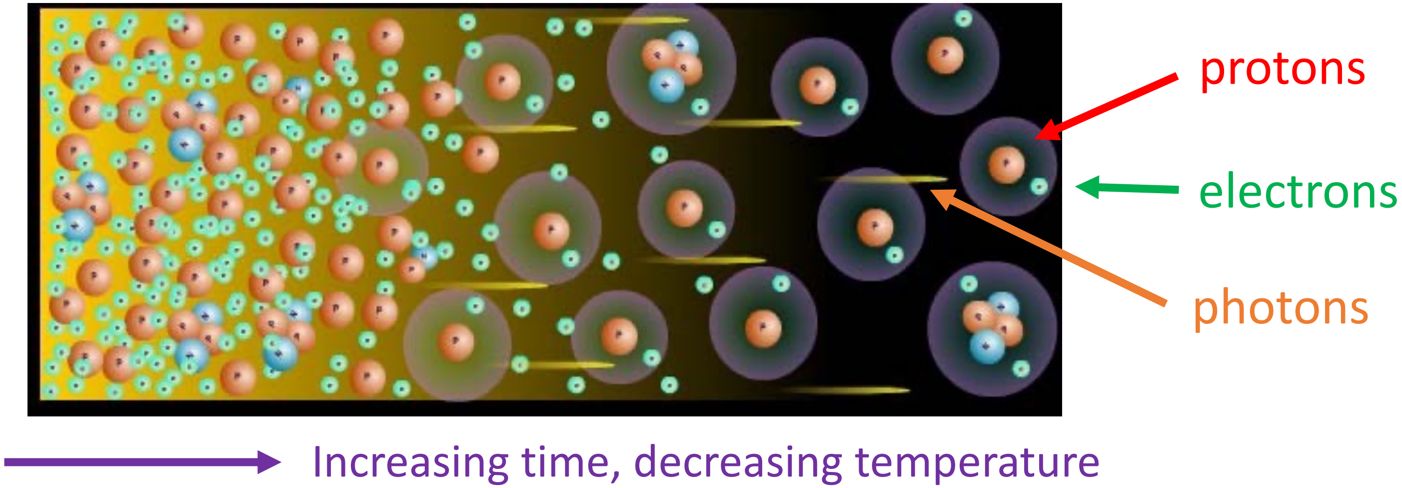
Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

Recombination

- As the Universe cools further, electrons and protons are able to combine into *hydrogen atoms*:

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

- This process is called *recombination* (should be called "combination", but too late to do anything about it now!)



Recombination

- Recombination is a *continuous equilibrium process* as the Universe cools, and the ionisation fraction at any point is determined by temperature using the *Saha equation*:

n_b = baryon density

h = Planck's constant

$$\frac{1-x}{x^2} = \frac{n_b\, h^3}{(2\pi m_e k_B T)^{3/2}}\, e^{E_{\text{bind}}/k_B T}$$

k_B = Boltzmann's constant

x = fraction of electrons that are free

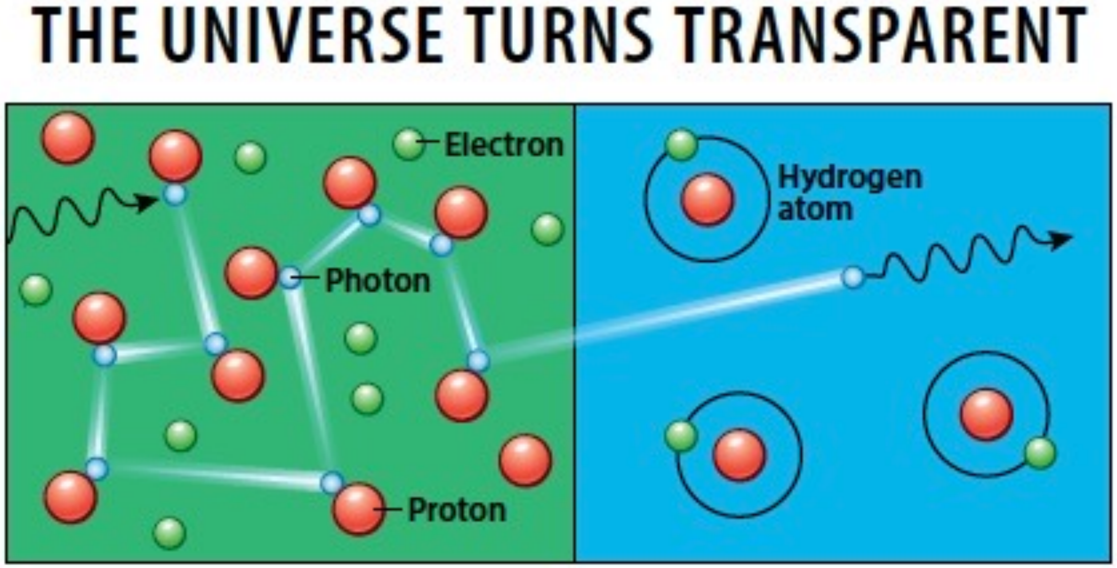
m_e = mass of electron

$E_{\text{bind}} = 13.6\ \text{eV}$: binding energy of hydrogen

- Solving this equation, we find that when $x = 0.1$ (90% of electrons are in atoms), $k_B T = 0.3\ \text{eV}$, or $T = 3600\ \text{K}$. This happens at around $t \approx 300{,}000\ \text{yrs}$

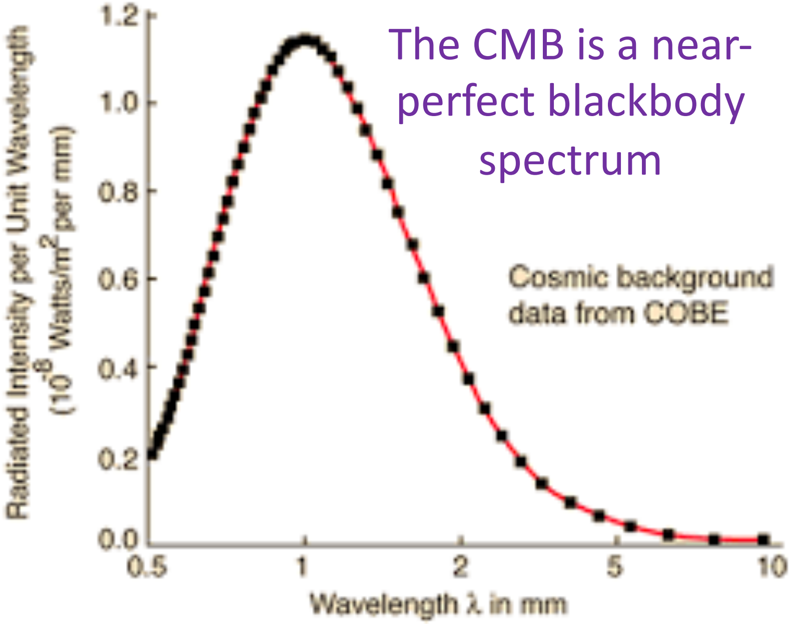
Recombination

- Since photons interact with electrons ("Thomson scattering"), the consequence of recombination is that *photons are now free to propagate* through the Universe
- Hence, recombination is also referred to as *last scattering* (of photons from electrons), and *this produces the CMB light*



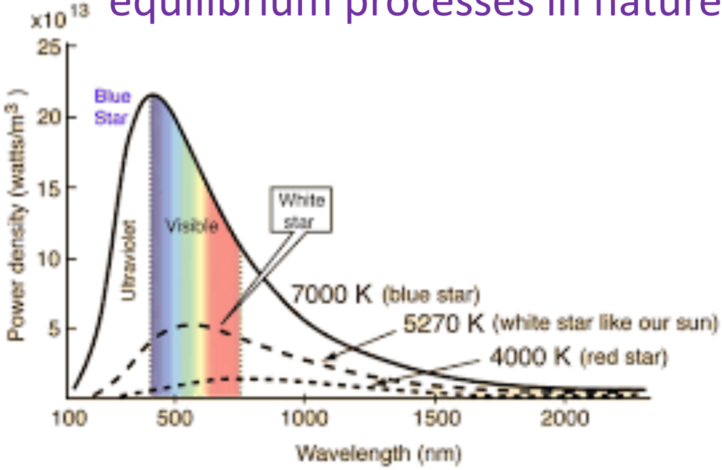
Cosmic Microwave Background

- The energy spectrum of the CMB is a *“blackbody spectrum”*, which is produced when radiation is in thermal equilibrium at a given temperature
- Today, that temperature is $T = 2.73\ \mathrm{K}$



The CMB is a near-perfect blackbody spectrum

Blackbody spectra are characteristic of all thermal equilibrium processes in nature



Cosmic Microwave Background

- Using statistical mechanics distributions, we can determine the energy density and number density of blackbody photons:
- *Energy density* $U_\gamma = \frac{4\sigma}{c} T^4 = \frac{\pi^2}{15\hbar^3 c^3}(k_B T)^4 \approx 4.2\times10^{-14}\ \mathrm{kg\ m^{-1}\ s^{-2}}$
- More usefully: $\Omega_\gamma = \frac{\rho_\gamma}{\rho_\mathrm{crit}} \approx 5.1\times10^{-5}$ – the CMB constitutes a small fraction of the Universe’s energy today, but still dwarfing starlight!
- *Number density* $n_\gamma = \frac{2.4}{\pi^2\hbar^3 c^3}(k_B T)^3 \approx 4.1\times10^{8}\ \mathrm{m^{-3}}$
- It’s interesting to compare this to the number density of baryons today, which we may deduce from $\Omega_b \approx 0.05$, obtaining $n_b \approx 0.28\ \mathrm{m^{-3}}$
- There are $\approx 10^9$ CMB photons for every baryon in the Universe!! – photons are the most abundant particle in the Universe

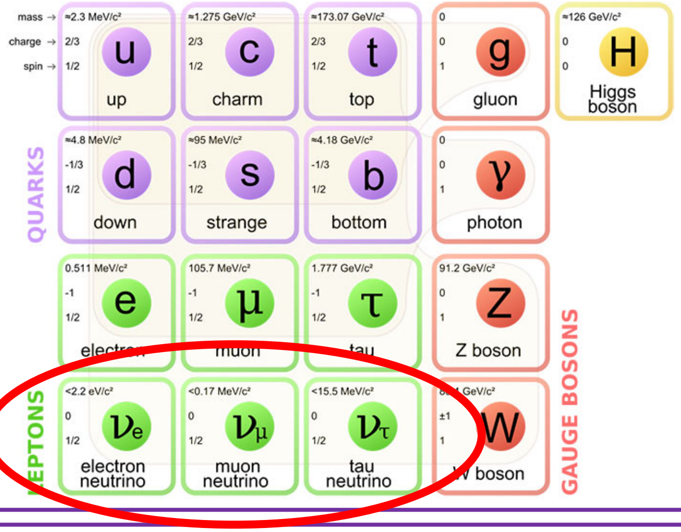
Neutrinos

- Photons are not the only relativistic particles in the Universe – there are also *neutrinos*!

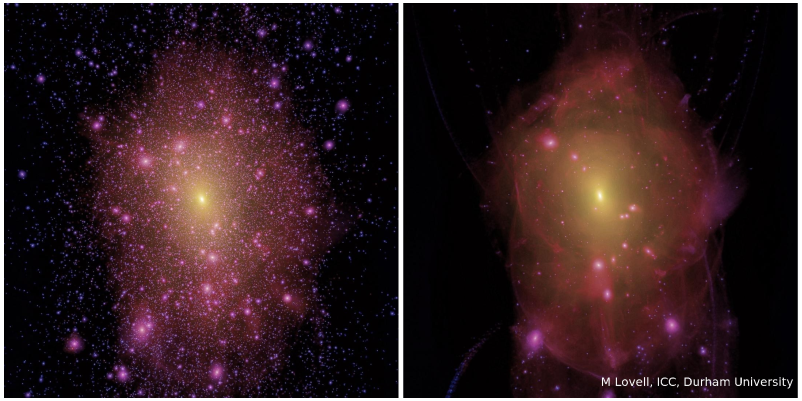
- Neutrinos are weakly-interacting particles which are produced in the early Universe and freeze-out at $t \approx 1$ s and $T \approx 10^{10}$ K

- Neutrinos contribute $\Omega_\nu \approx 3.4{\times}10^{-5}$ to today's energy density, and count as radiation in the early Universe

Neutrinos are elementary particles in the standard model



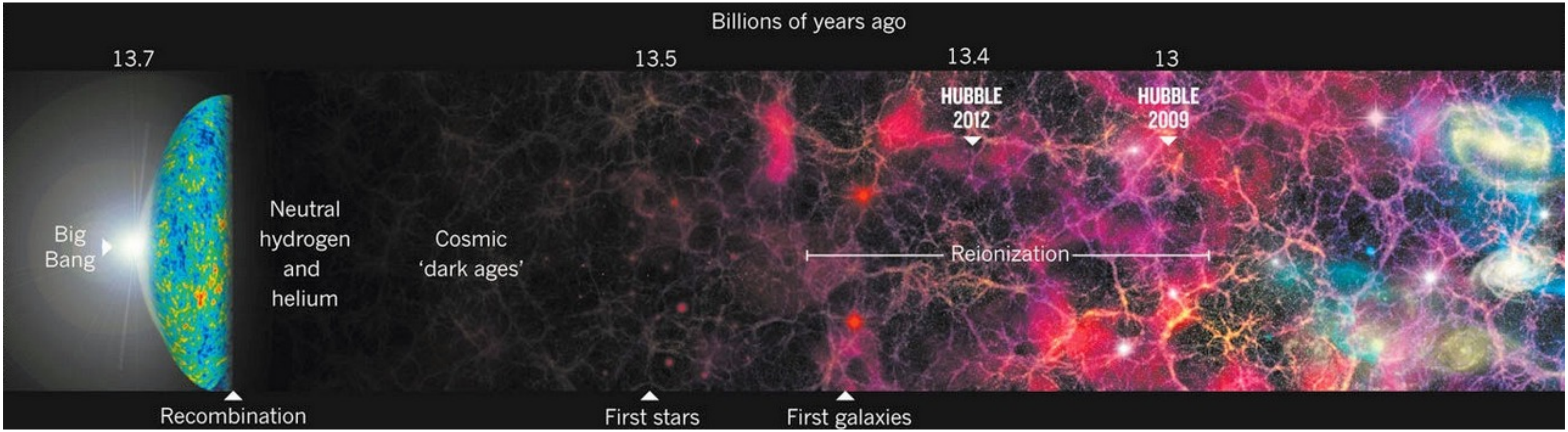
They act as a "hot dark matter", smoothing out cosmic structure



M Lovell, ICC, Durham University

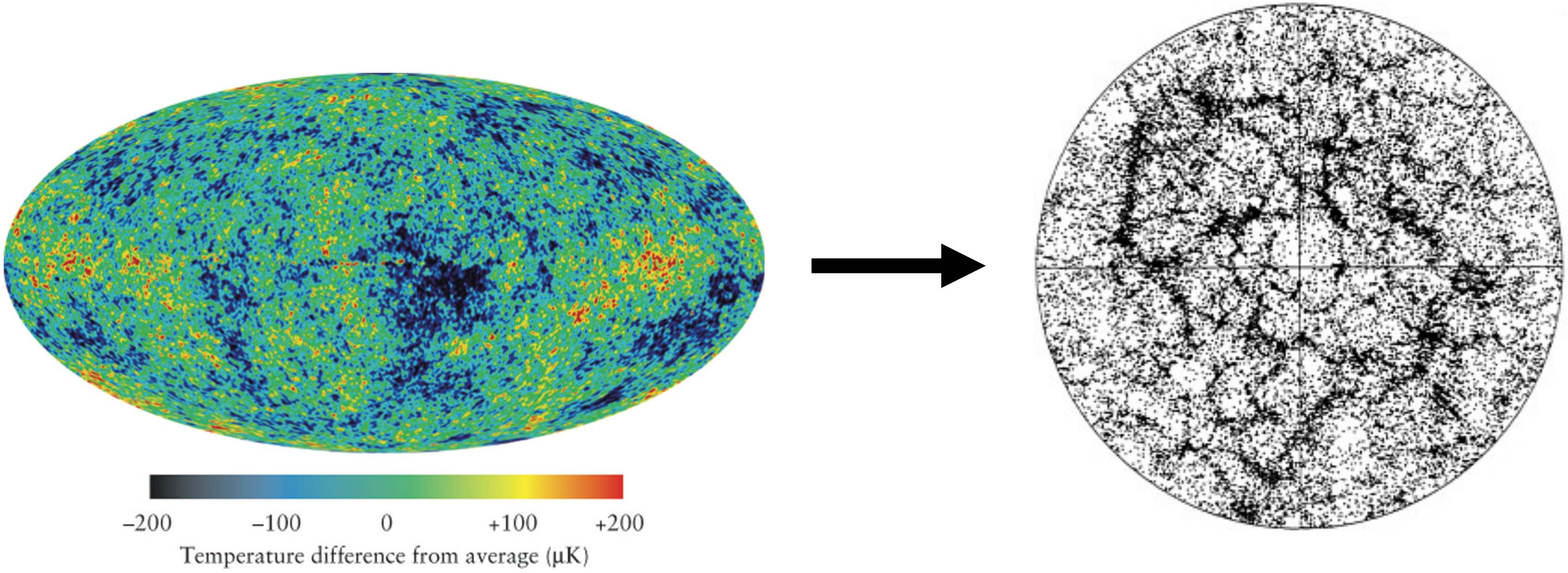
Reionisation

- 100 million years after the Big Bang, the *first stars and galaxies* start forming
- These stars produce radiation, which *re-ionises* the neutral gas left-over from the early Universe, and allows the Universe to be observed again!



Formation of today’s Universe

- The small fluctuations traced by the CMB radiation are *amplified by gravity* to produce galaxies and larger-scale structures – we’ll study this next week!



Key take-aways

- The physics of the early Universe is governed by its **temperature**, which drops as the Universe expands
- As temperature falls, different species of fundamental particles **“freeze-out”** from the hot plasma
- In **Big Bang Nucleosynthesis**, protons and neutrons combine, via deuterium, to produce helium and lithium
- As the Universe cools, protons and electrons undergo **recombination** into atoms, leaving the Universe transparent to radiation and forming the **Cosmic Microwave Background**
- Using the CMB temperature we can estimate that there are about a **billion photons for every baryon**!