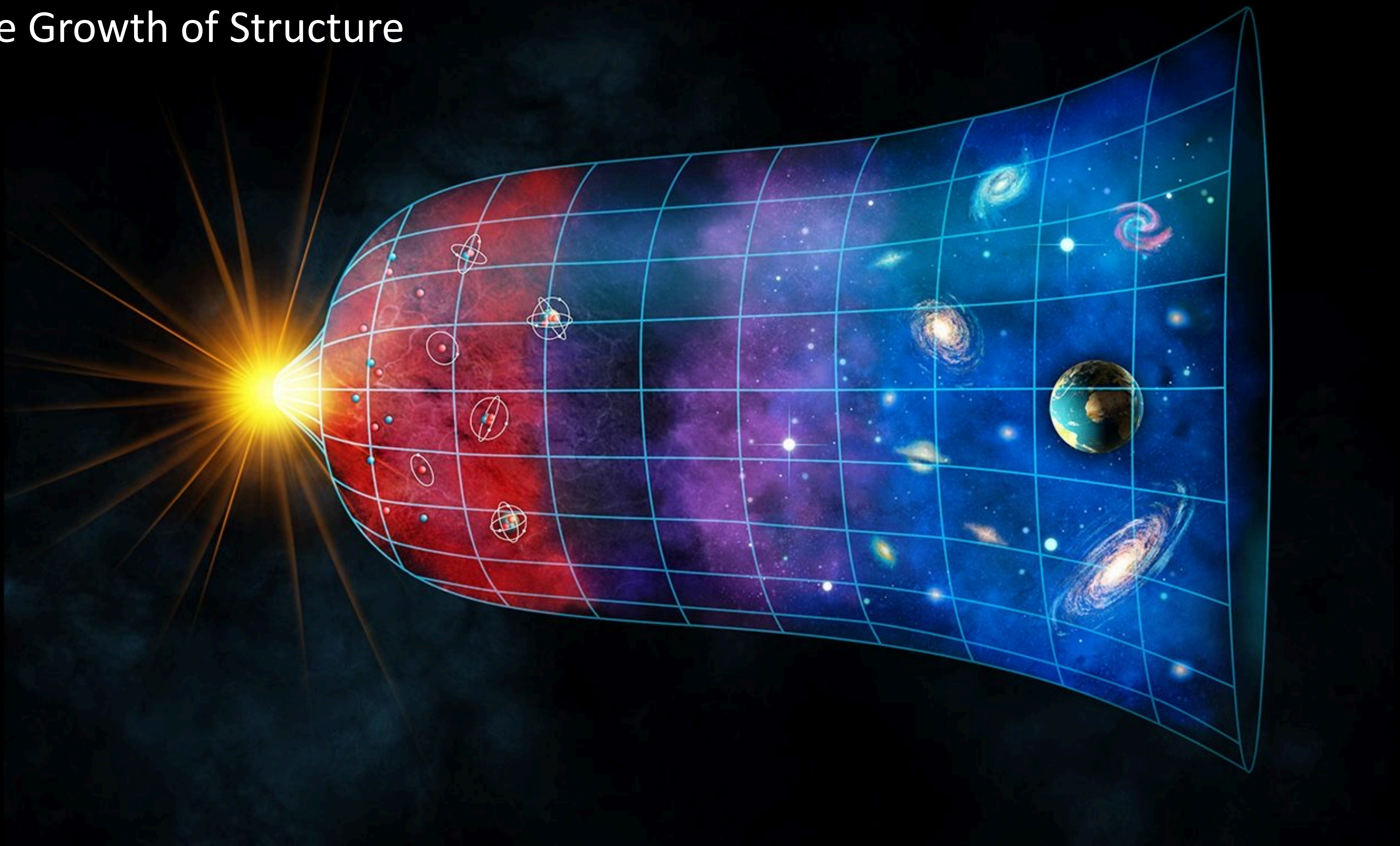
The Growth of Structure



The Early Universe: after inflation

Universe is small, dense, very hot, and filled with elementary particles. At these energies we get **pair production**: particles and antiparticles being destroyed and reforming.

For example, electrons (e^-), positrons (e^+), and gamma rays (γ):

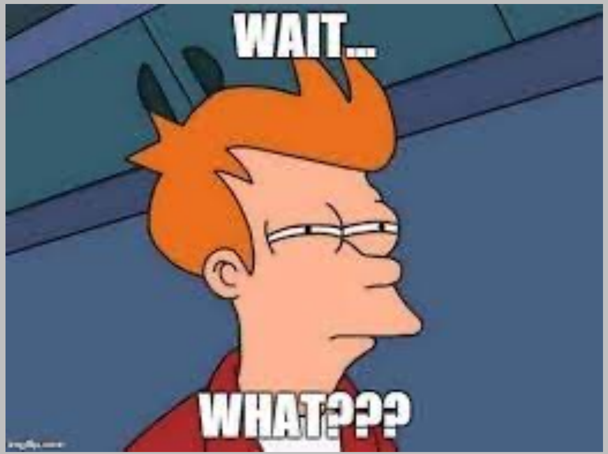
$$e^+ + e^- \Leftrightarrow \gamma + \gamma$$

annihilation ⇒

⇐ creation

and similiarly for other particles.

As the Universe expands, gamma rays are being redshifted and losing energy, and after a few micro-seconds, they don't have enough energy to create particles. But particles can still be destroyed by annihilating with their anti-particles, so in a flash we lose all our matter, converting it via annihilations into high energy radiation (destined to be redshifted to form the CMB).



OK, we don't lose all the matter, some must have survived. To match the total matter the amount of mass in the Universe today with the number of CMB photons we see, for every 10^9 anti-particles there must have been 10^9+1 particles: the ***matter-antimatter asymmetry***.

For every 10^9 annihilations, one unpaired particle survives. Ask the physicists about that!

Big Bang Nucleosynthesis: Cooking up elements

Now we have the building blocks for the elements: protons (p), neutrons (n), electrons (e^-). The temperature and density is high, but dropping fast as the Universe expands. If we act quick, we might be able to drive nuclear fusion.

Step 1: Assemble your ingredients

At high energies ($t < 1$ second), interactions are transforming particles back and forth:

neutrino

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

The particles are in thermal equilibrium, so that the proton-neutron ratio is given by the **Boltzmann equation**:

$$\frac{N_n}{N_p} = e^{-\Delta E/kT} = e^{-(m_p - m_n)c^2/kT}$$

at $t \approx 1$ second, $\mathrm{T} \approx 10^{10}$ K, so the ratio is $N_n/N_p = 0.223$. Below that temperature, those reactions stop and the ratio is frozen in.

But it is too hot for sustained fusion, so that ratio is maintained: for every 1000 protons, there are 223 neutrons.

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Step 2: Make a mess and spill your ingredients (1000 protons, 223 neutrons).

So for every 1000 protons, there are 223 neutrons, but we are waiting for things to cool.

But free neutrons are unstable and undergo beta decay:

$$n \Rightarrow p + e^- + \overline{\nu_e}$$

with a half-life of about 10 minutes. So for every 10 minutes you wait, you lose half of the neutrons you had, converting them to protons.

To begin fusion, you need the temperature to drop from $\mathrm{T} \approx 10^{10}$ K to $\mathrm{T} \approx 10^{9}$ K, and that takes about 4 minutes, at which point the neutron-to-proton ratio has dropped from $N_n/N_p = 0.223$ to $N_n/N_p = 0.164$.

So by the time you start fusion, your original mix has turned into 1051 protons, there are now 172 neutrons.

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Step 3: Start cooking – nuclear fusion! (1051 protons, 172 neutrons)

At 10^9 K, the oven is ready, and we begin fusion.

1. Protons and neutrons fuse to form deuterium and release a gamma ray:

$$p + n \Leftrightarrow {}^2_1H + \gamma$$

2. Deuterium fuses to form tritium and a proton:

$${}^2_1H + {}^2_1H \Leftrightarrow {}^3_1H + p$$

3. Tritium and deuterium fuse to form helium and a proton:

$${}^3_1H + {}^2_1H \Leftrightarrow {}^4_2He + p$$

Net result: convert 4 protons into 1 helium nucleus.

(But note: the reaction chain is different from how the Sun and stars do it!)

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Step 4: Taste the dish – how did it turn out?

If the fusion process is 100% efficient, at the end of this process we have made all the Helium we possibly could have. How much Helium is that?

We started fusion with 1051 protons and 172 neutrons. Since a Helium nucleus has 2 protons and 2 neutrons, we can make a total of 172/2 = 86 Helium nuclei. They would use up 172 protons as well, leaving you with 1051 − 172 = 879 protons.

This means the fraction of Helium by mass is given by:

$$Y = \frac{4\times 86}{(1\times 879 + 4\times 86)} = 0.28$$

Which is pretty close to the primordial helium abundance (measured in low metallicity stars) of $Y \approx 0.23 - 0.24$.

⇒ Most of the Helium in the Universe was made during the Big Bang, and not inside stars!

BBN constraints on baryonic matter density ($\Omega_\mathbf{b}$).

The efficiency of BBN depends on the density of baryonic (normal) matter in the Universe:

Higher density ⇒ more collisions ⇒ more efficient fusion
⇒ *More helium, fewer leftovers* (e.g., deuterium).

Lower density ⇒ fewer collisions ⇒ less efficient fusion
⇒ *Less helium, more leftovers*.

The primordial abundances of helium, deuterium, and a few other of the "light elements" depend on the baryon density of the universe

Comparing to observed values shows that

$$\Omega_b \approx 0.04$$

And since $\Omega_m \approx 0.25 - 0.3 \gg \Omega_b$, **dark matter cannot be made of normal baryonic matter.**