Cosmology
Lecture 12

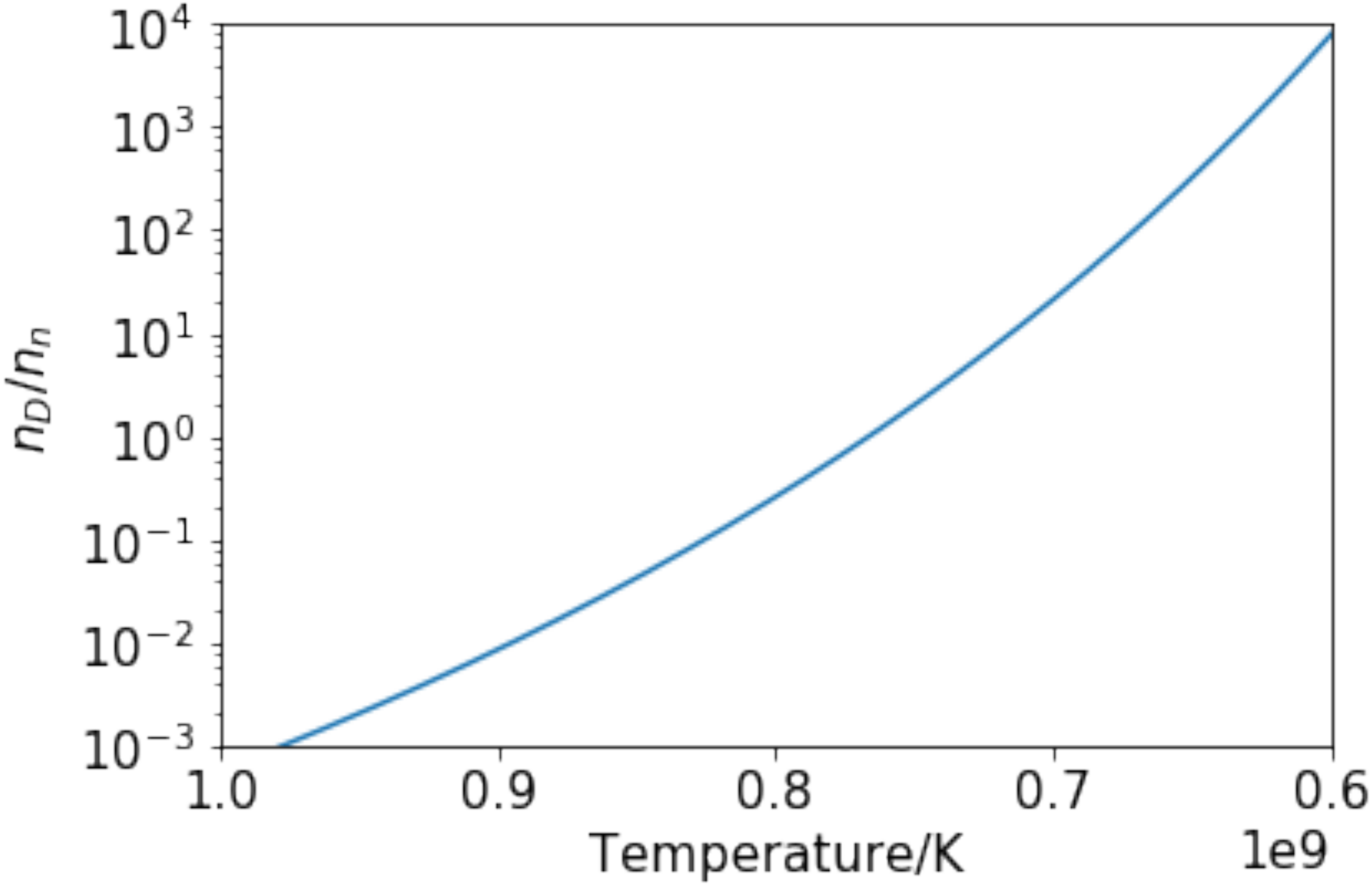
Nucleosynthesis and the first three minutes: Part 2

Learning objectives

- Know what is formed post-deuterium.
- Understand how the stability of ^4He presents a barrier to other, heavier elements forming.
- Know what came just *before* nucleosynthesis.
- Understand how a slight imbalance in the ratio of matter to antimatter produced a Universe in which normal matter dominates over anti-matter, and photons numbers dominate over Baryons.

Beyond Deuterium

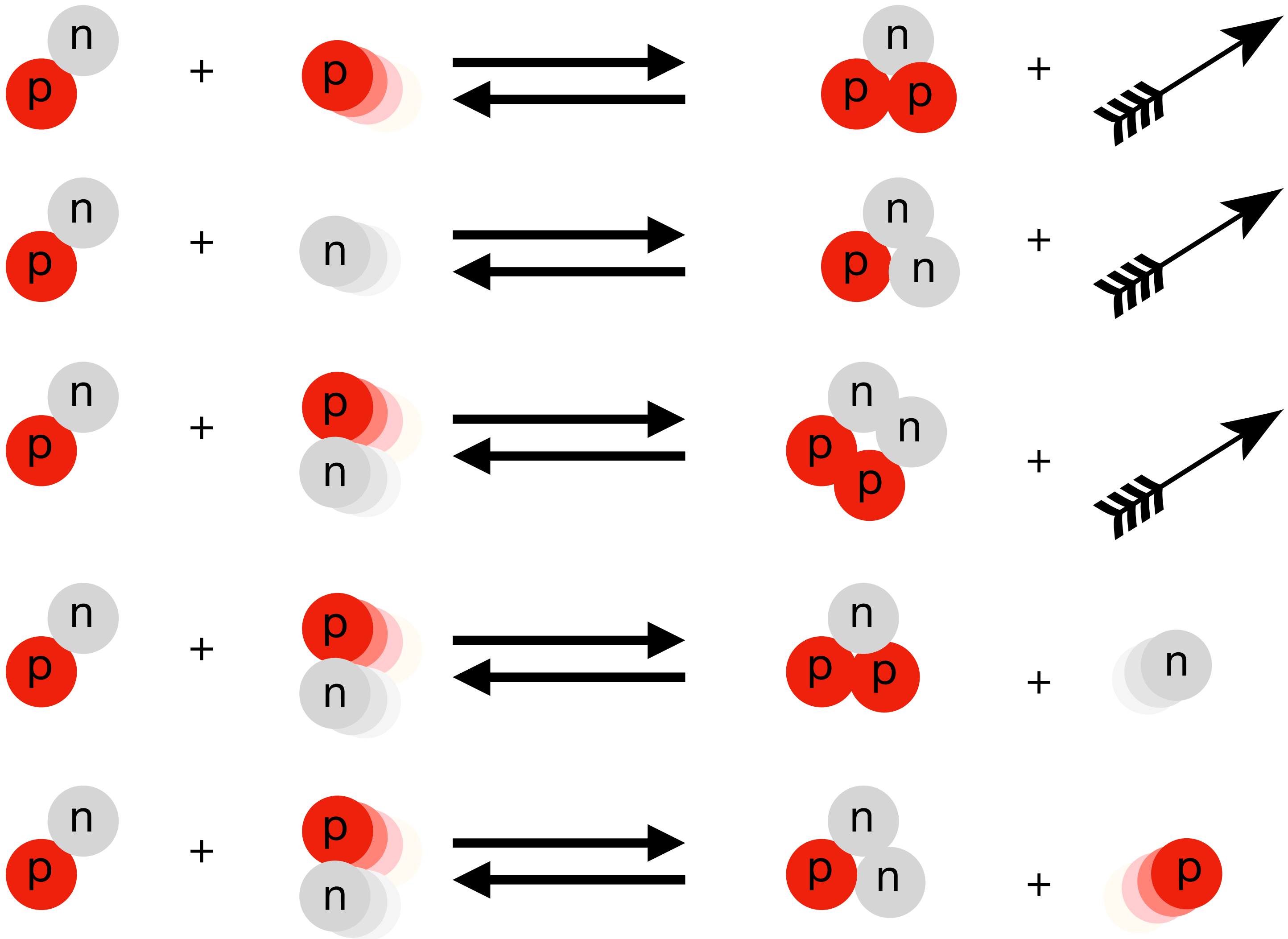
At the end of the last lecture, we left it here:



With the proportion of neutrons in Deuterium nuclei increasing inexorably upward. However, this does not continue for ever…

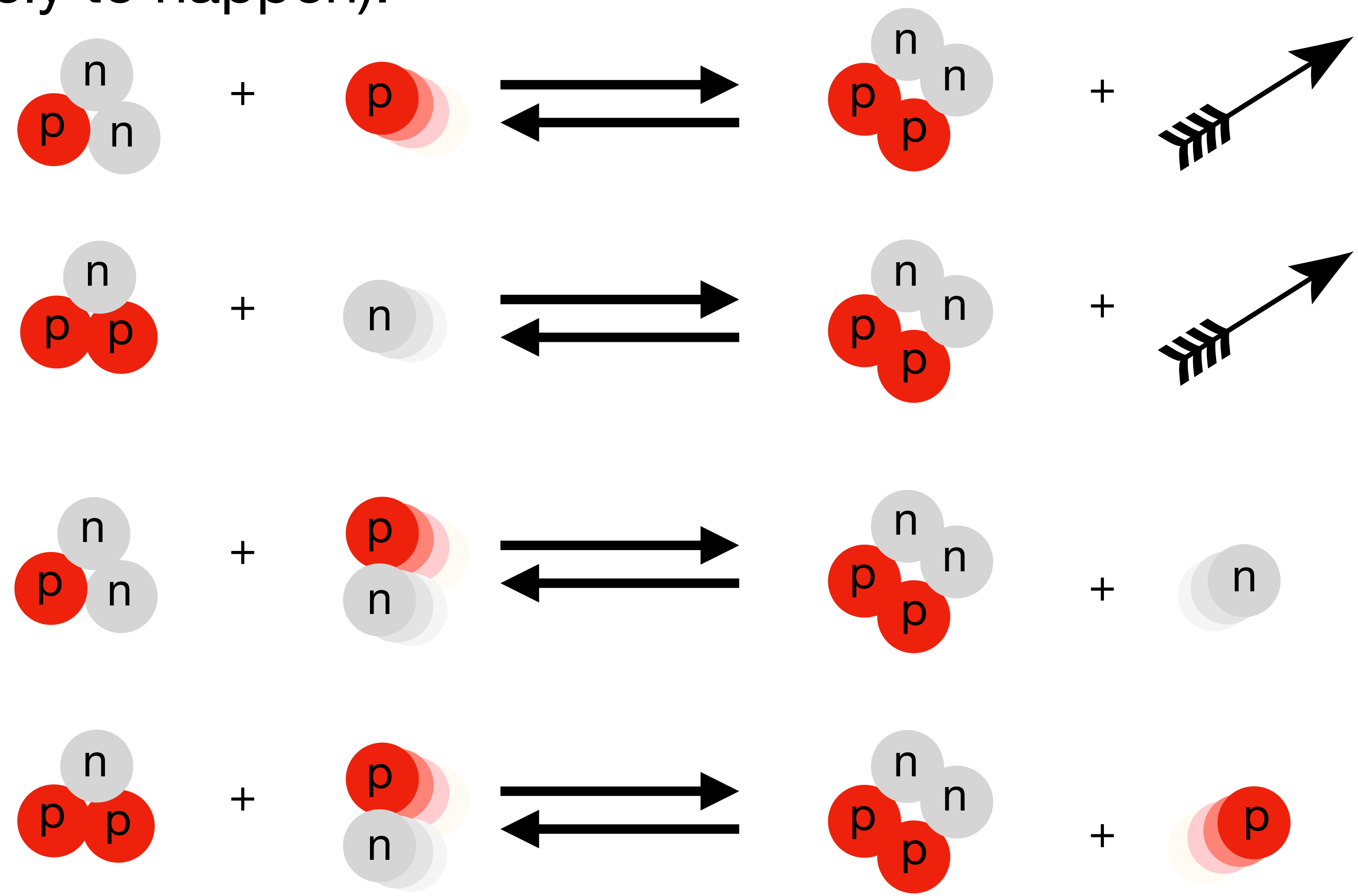
Deuterium reactions

In the high-density, high energy environment at the start of the Universe, Deuterium nuclei readily join with protons to form other, heavier nuclei:

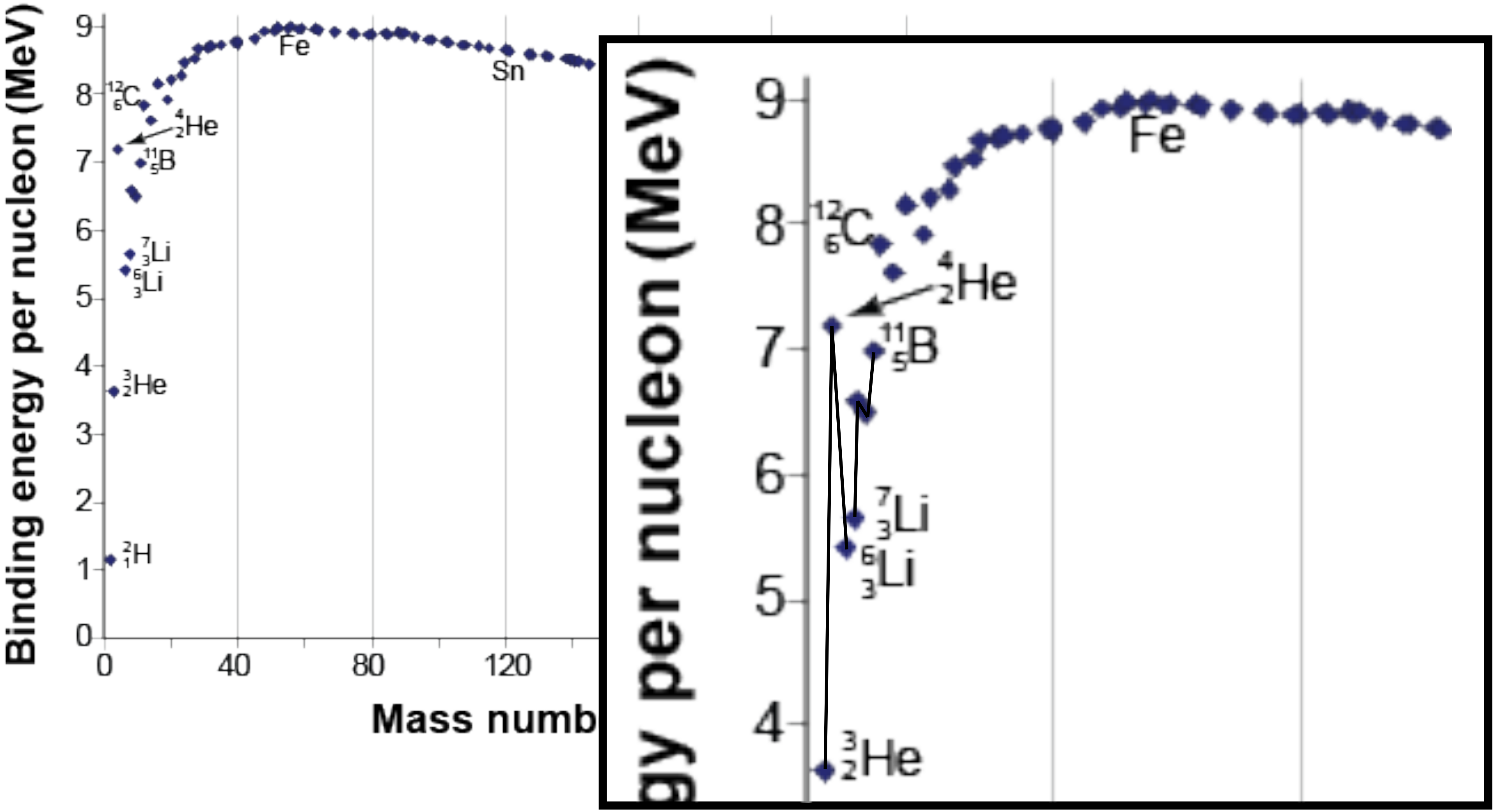


Tritium and ^{3}He reactions

Once ^{3}H and ^{3}He are formed, they quickly form ^{4}He, since the following reactions all have large cross-sections (and are thus very likely to happen):



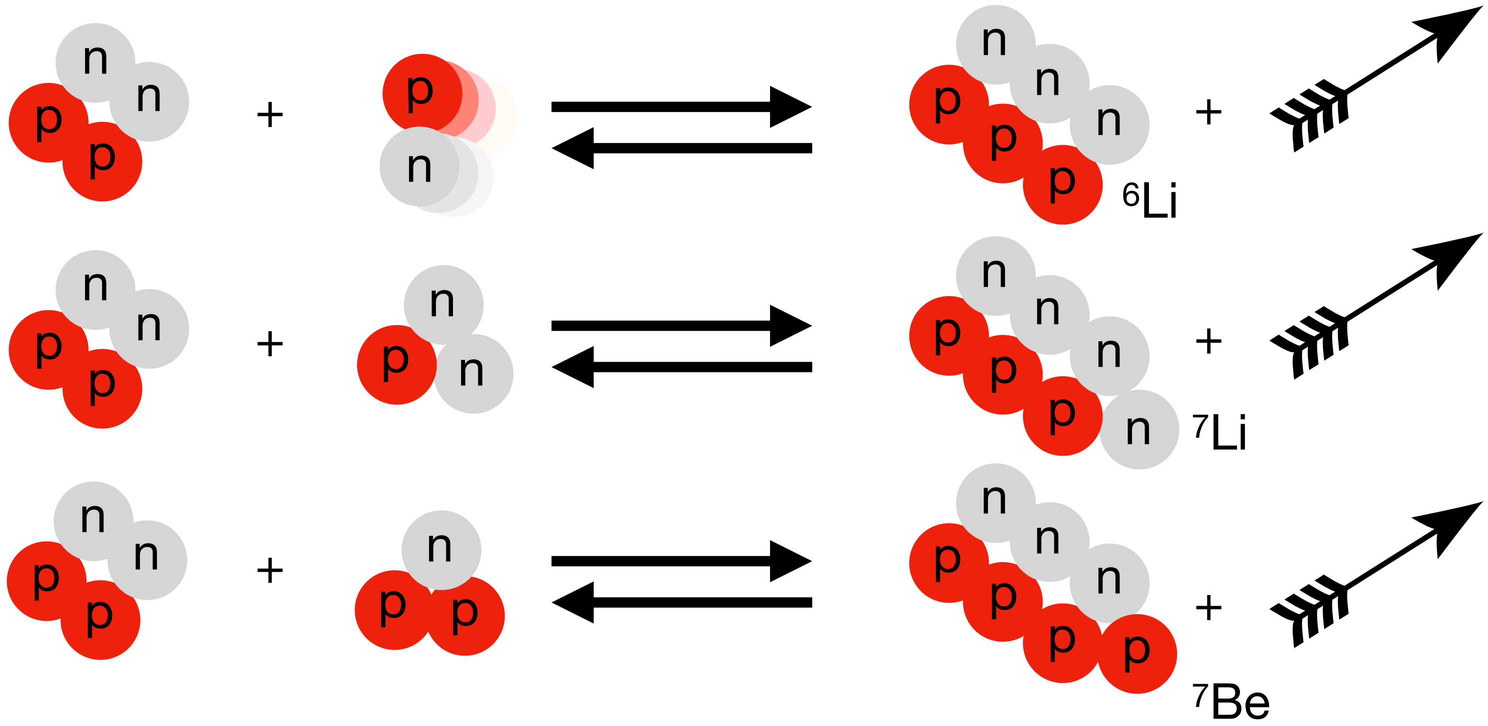
Beyond Helium-4



^{4}He is a fantastically stable nucleus, whereas there are no stable nuclei with a mass-number of 5. ^{4}He is therefore resistant to reactions with protons or neutrons.

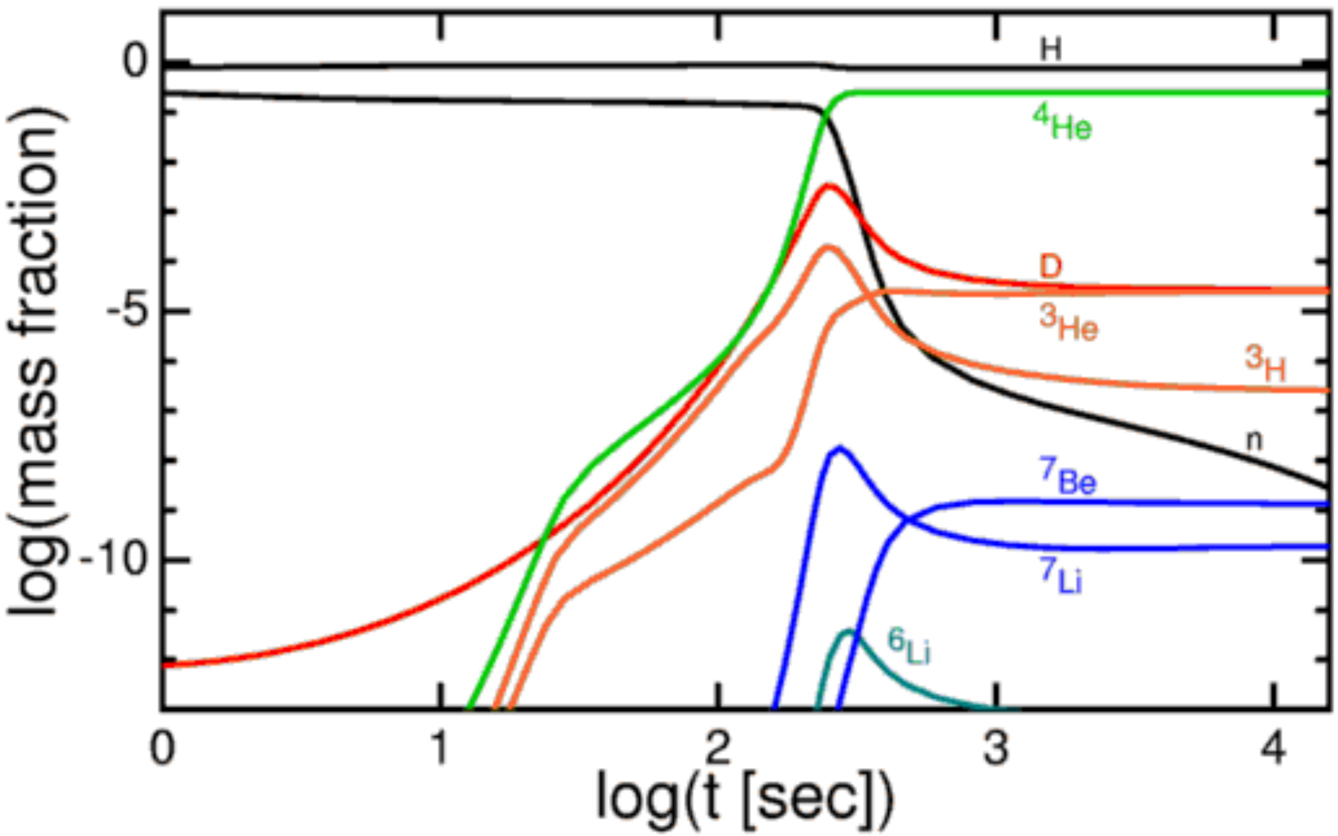
Heavier than ^{4}He

He is able to fuse with higher mass nuclei to form heavier, stable nuclei:



However, these reactions occur much less frequently, so nuclei heavier than ^{4}He are much less abundant.

Timeline of elemental abundances



- At t < 1 s after the Big Bang, the number of neutrons and protons are roughly equal.
- But, because neutrons are more massive, protons are preferred as the Universe cools.
- Eventually, at t ~ 1 s, p/n freeze-out occurs, freezing the n-to-p ratio at 1:5.
- As the Universe cools further, Deuterium starts to form, and by 180 s roughly half of all neutrons are within Deuterium nuclei.
- Deuterium quickly bonds with n or p, eventually forming stable ^{4}He, and a few other trace elements.
- By 1000 s, all reactions are complete and any remaining free n decay to p.

Timeline of elemental abundances

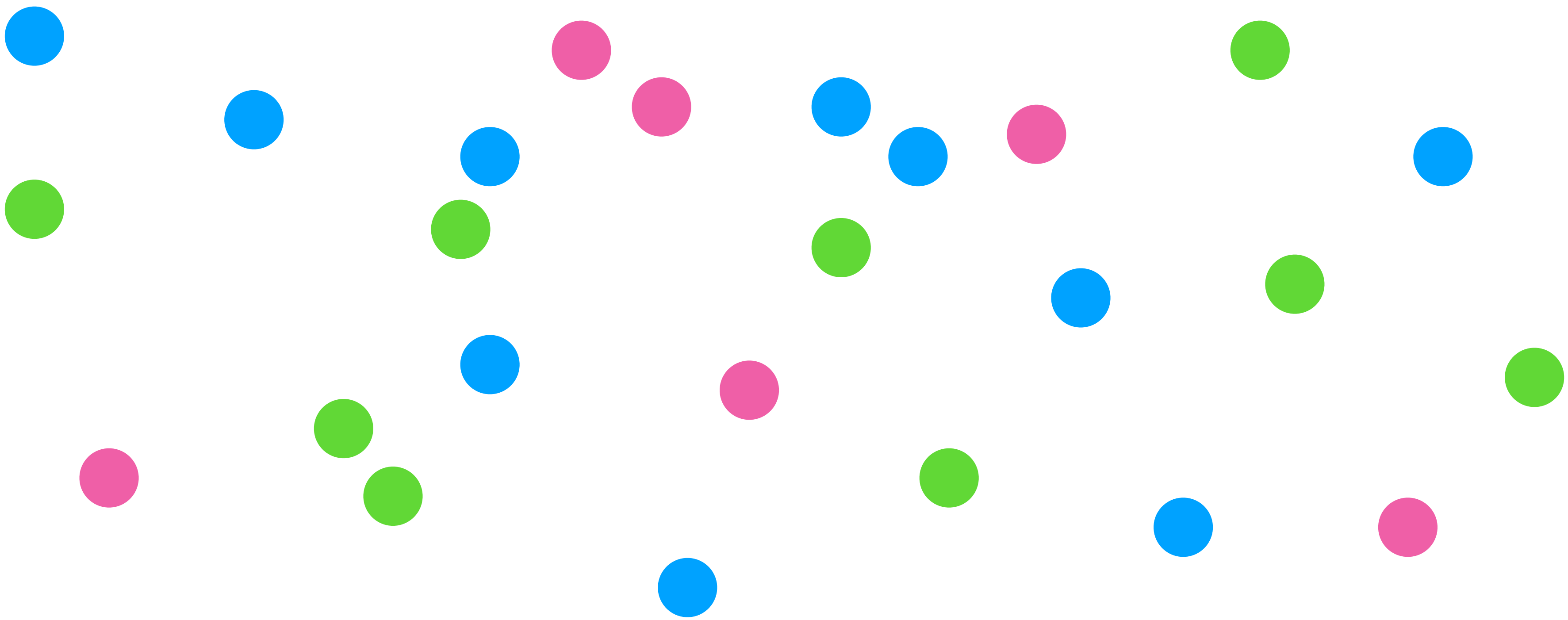
These elemental abundances remained the same through the epoch of recombination until the first stars formed, likely sometime between 50 and 200 Myr after the Big Bang.

It took until the first stars formed before heavier elements could be generated in their nuclei and, ultimately, when they explode as SN.

Before protons and neutrons

Protons and neutrons are made of quarks:
- Proton: 2 x up quarks, 1 x down quark;
- Neutron: 1 x up quark, 2 x down quarks.

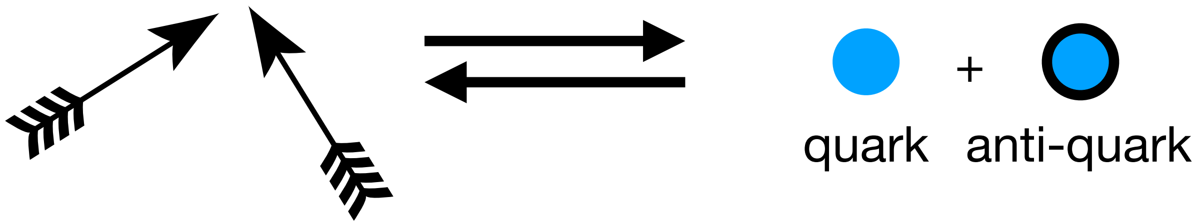
Prior to nucleosynthesis, when the temperature of the Universe was $kT > 150$ MeV, it was hot enough for quarks to remain unbound.



Where did all these quarks come from?

The epoch of quark formation

In the first few microseconds of the Universe, quarks were created from high-energy photons via pair-production:



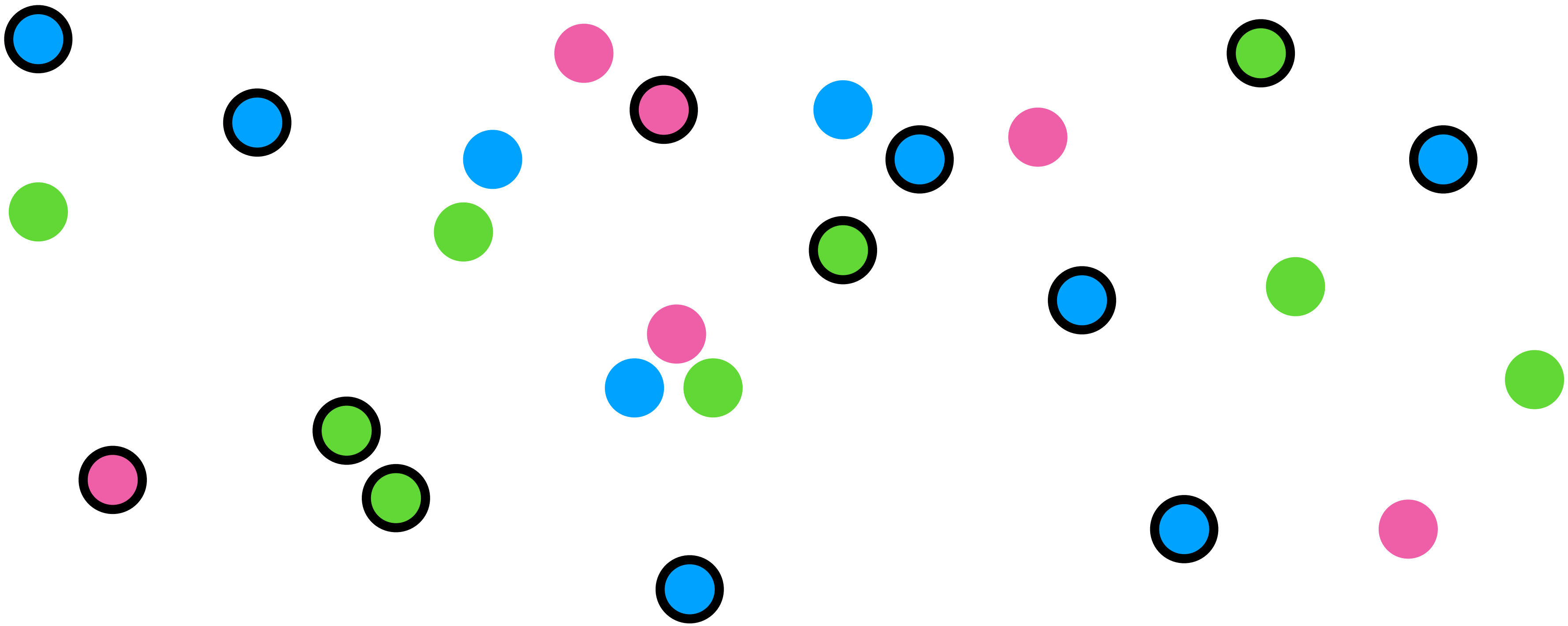
At the time, there *should* have been the same numbers of quarks being produced as anti-quarks.

But…suppose there wasn't. Suppose our theories of quark pair-production aren't quite correct, and that there was a slight preference for quarks over anti-quarks:

$$\delta_q = \frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} = \frac{3}{1.6 \times 10^9} \approx 2 \times 10^{-9}$$

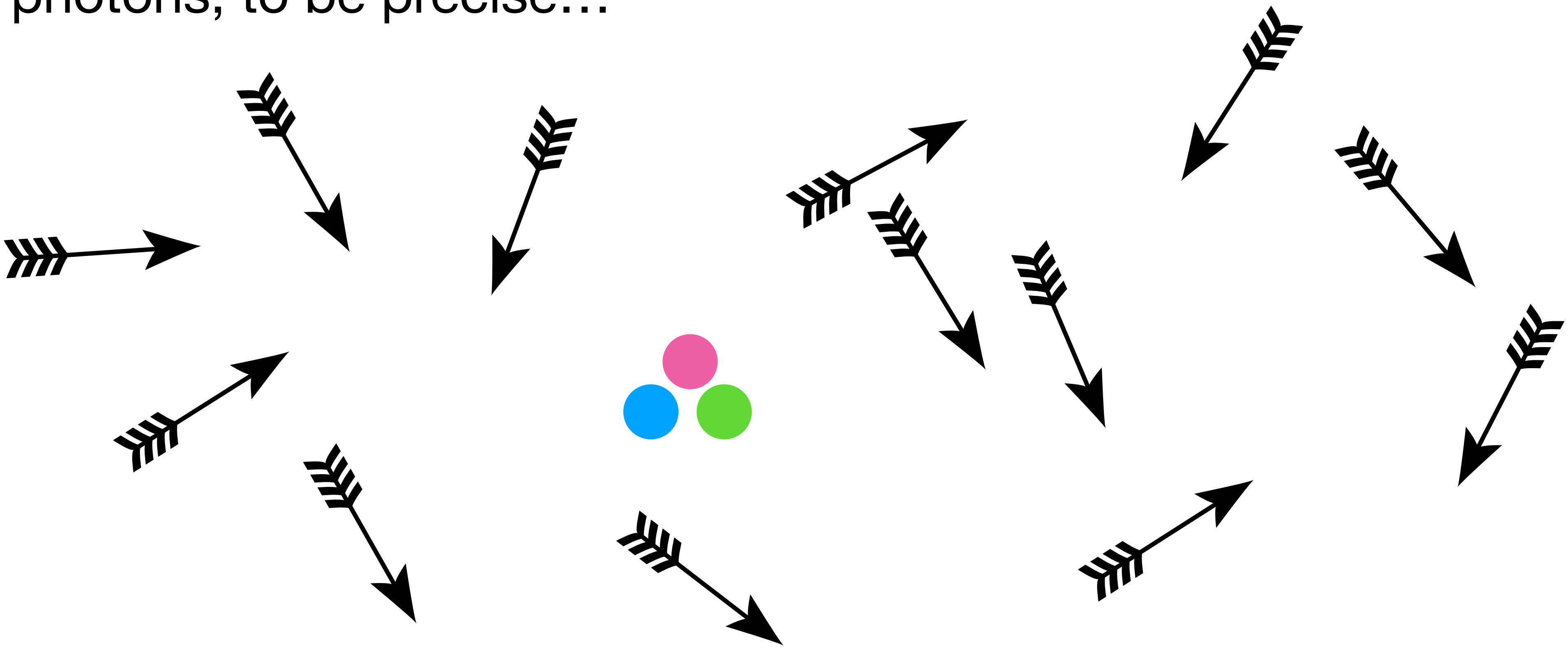
The remaining quarks

Almost all the quarks and antiquarks would annihilate to form photons. 1.6 billion photons, to be precise…



The remaining quarks

Almost all the quarks and antiquarks would annihilate to form photons, leaving three quarks for every 1.6 billion photons, to be precise…



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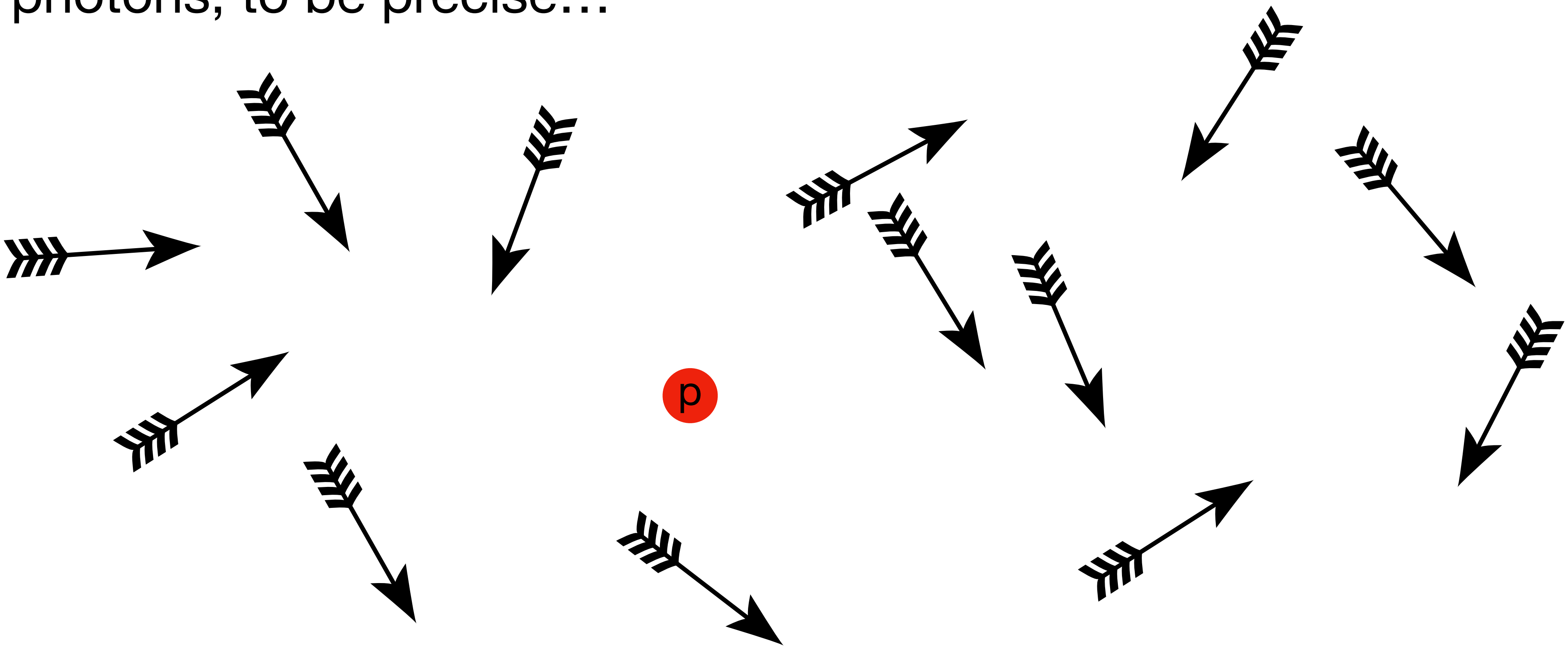
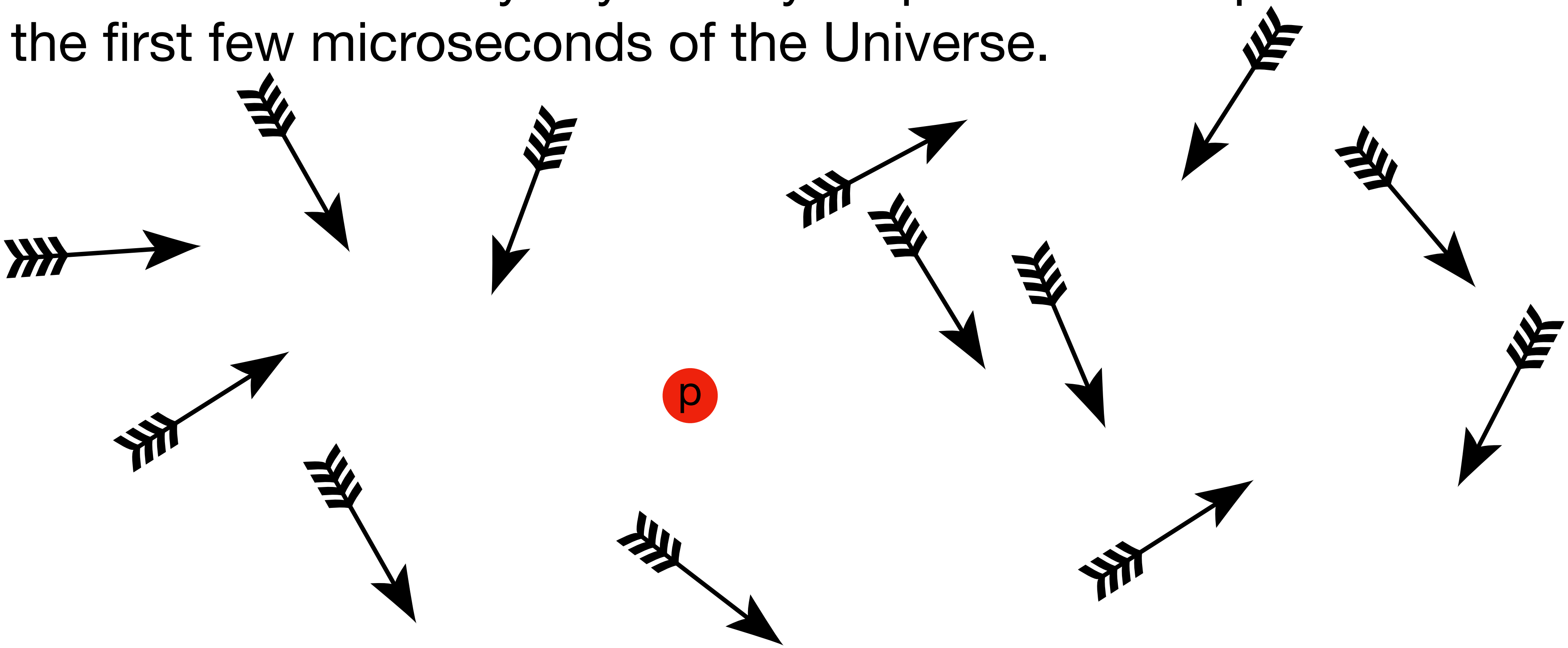


…and these three would form a Baryon.

The remaining quarks

The lack of anti-particles in today's Universe and the massive over-abundance of photons to baryons (1.6 billion to one) is consistent with a tiny asymmetry in quarks to antiquarks within the first few microseconds of the Universe.



We just don't know what would cause such an asymmetry.

Getting the feel for it…

- Once the Universe has cooled sufficiently for Deuterium to form, it fuses readily with protons, neutrons, or other Deuterium nuclei to form 3He, 3H, or ^{4}He.

- The stability of ^{4}He, however, makes producing heavier elements much more difficult, resulting in only trace amounts of Li and Be.

- This situation remains until the first stars.

- Prior to proton and neutron synthesis, the Universe was filled with quarks and antiquarks.

- Just a tiny difference (~3 parts in a billion) would have resulted in the photon-dominated, no-anti-matter Universe we live in today.