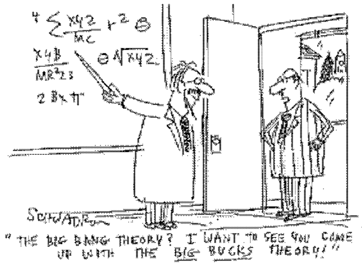
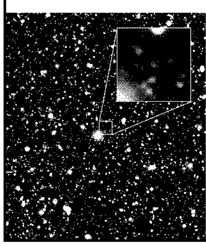
The Early Universe as a Nuclear Reactor



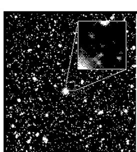
Friday, November 13

The Sun formed over 9 billion years after the Big Bang.

It contains some "recycled" material (gas that had been inside earlier stars).

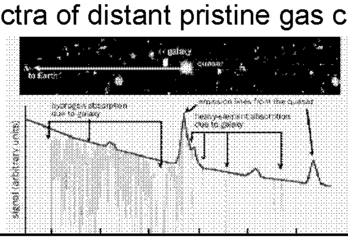


The first stars formed less than 750 million years after the Big Bang, and contained no recycled material.



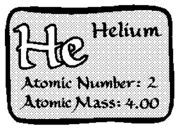
Were the first stars made of 100% pure hydrogen?

We don't have to conjecture: just look at spectra of distant pristine gas clouds.



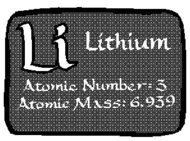
Result: none of the early gas clouds are less than **23%** helium by mass.

When the first stars formed, they formed from gas that already contained helium.



Where did this primordial helium come from?

Another result: early gas clouds invariably contain traces of lithium.



3 grams of lithium for every 10,000 tons of hydrogen.

Where did this primordial lithium come from?

The presence of helium (& a bit of lithium) in the early universe is the result of…

Big Bang Nucleosynthesis (**BBN**)
= nuclear fusion in the early universe (before the first stars)

BBN is as easy as 1 – 2 – 3

1) Hydrogen (H) has 1 proton in its nucleus

2) Helium (He) has 2 protons

3) Lithium (Li) has 3 protons

BBN is as easy as 1 – 2 – 3

1) Hydrogen-1 (^1H): 1 proton, 0 neutrons

2) Hydrogen-2 (^2H, deuterium): 1 proton, 1 neutron

3) Hydrogen-3 (^3H, tritium): 1 proton, 2 neutrons

(These are the three **isotopes** of hydrogen.)

BBN is as easy as 1 – 2 – 3

1) Helium-3 (^3He): 2 protons, 1 neutron

2) Helium-4 (^4He): 2 protons, 2 neutrons

3) Lithium-7 (^7Li): 3 protons, 4 neutrons

(These are the two isotopes of **helium**,
& the most common isotope of **lithium**.)

All atomic nuclei contain at least one proton.

All atomic nuclei heavier than Hydrogen-1 contain at least one neutron.

There are plenty of free protons in the universe today, but no free neutrons!

(Free = unbound to any other particle.)

Why are neutrons held captive within atomic nuclei?

Free neutrons are **unstable** against decay.

neutron electron

$$n \rightarrow p + e^- + \nu$$

proton neutrino

The half-life of a free neutron is 10 minutes.

Free neutrons **can** be produced by spontaneous decay of heavy elements: they just don't survive long.

When the universe was much less than 10 minutes old, free neutrons would not have had time to decay.

At t << 10 minutes, the universe had about as many neutrons as protons.

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

With both protons & neutrons present, **deuterium** (^{2}H, heavy hydrogen) formed by fusion:

$$\underset{\text{proton}}{p} + \underset{\text{neutron}}{n} \rightarrow \underset{\text{deuterium}}{{}^2H} + \underset{\text{photon}}{\gamma}$$

This is **different** from how deuterium is made in stars.

In the early universe:

$$p + n \rightarrow {}^2H + \gamma$$

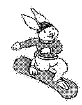
In stars:

$$p + p \rightarrow {}^2H + e^+ + \nu$$

There's more than one way to make a deuterium (^{2}H) nucleus. So what?

In stars, two positively charged protons must be brought together. This is difficult. Fusion is slow.

In the early universe, a proton must be brought together with a (neutral) neutron. This is **easy**. Fusion is **fast**.



A stumbling block to making deuterium (^2H) in the early universe:

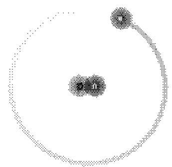
The early universe was **very** hot, and thus contained photons energetic enough to blast apart deuterium.

$$^2\mathrm{H} + \gamma \rightarrow \mathrm{p} + \mathrm{n}$$

High-energy photons broke apart deuterium as soon as it formed… until the universe was 3 minutes old.

That's when the photons of the Cosmic Background dropped too low in energy to bust up deuterium.

Three minutes after the Big Bang, the universe was made safe for deuterium.

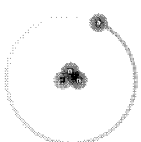


However, there's **not** a lot of deuterium today. (Heavy water – deuterium oxide – costs $2000 per gallon at retail.)

Why the scarcity of deuterium?
Because nucleosynthesis continued…

deuterium, tritium, neutron, photon

$$^{2}\mathrm{H} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + \gamma$$

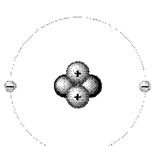


However, tritium is even scarcer than deuterium today.

Why the scarcity of **tritium**?
Because nucleosynthesis continued…

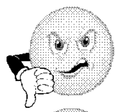
tritium, helium, proton, photon

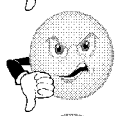
$$^{3}\mathrm{H} + \mathrm{p} \rightarrow {}^{4}\mathrm{He} + \gamma$$

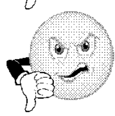


Helium is common today.

Why the abundance of **helium**?
Because nucleosynthesis didn't go much beyond helium.

$^{4}He + p \rightarrow {}^{5}Li$  not a stable element

$^{4}He + n \rightarrow {}^{5}He$  not a stable element

$^{4}He + {}^{4}He \rightarrow {}^{8}Be$  not a stable element

Small amounts of stable lithium were made.

$$\underset{\text{tritium}}{^{3}H} + \underset{\text{helium}}{^{4}He} \rightarrow \underset{\text{lithium}}{^{7}Li} + \underset{\text{photon}}{\gamma}$$

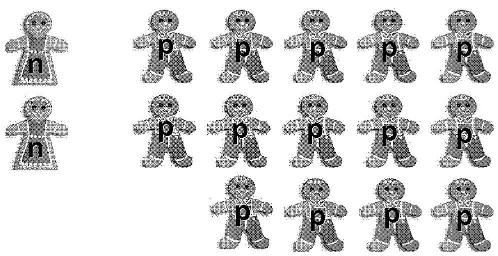
However, by this time ($t \approx 15$ minutes) the temperature dropped low enough that fusion ceased.

Big Bang Nucleosynthesis worked efficiently up to helium-4, but not beyond.

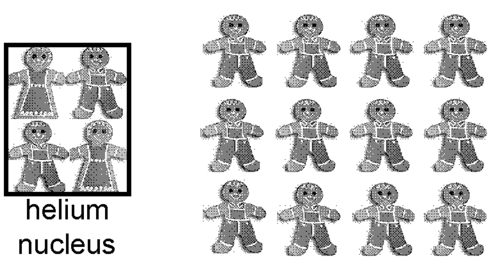
(Elements heavier than helium were mostly made in stars and supernovas.)

How much helium-4 do we expect from Big Bang Nucleosynthesis?

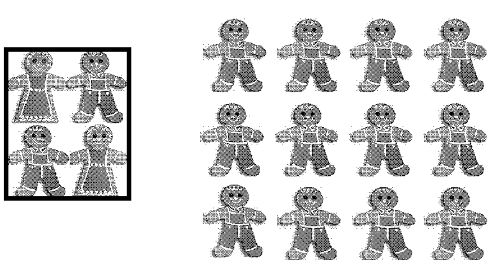
Before BBN, there were about 2 neutrons for every 14 protons. (Some neutrons had already decayed.)



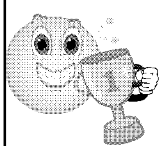
2 neutrons combine with 2 protons to form 1 stable helium nucleus, with 12 lonely protons (hydrogen nuclei) left over.



About 25% of the initial protons & neutrons (hence 25% of their mass) will be in helium: the rest will be hydrogen.

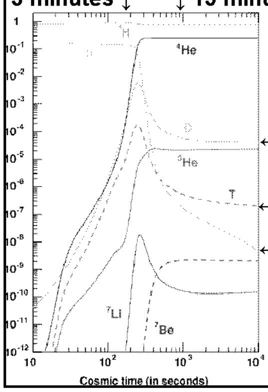


Early gas clouds are indeed about 25% helium by mass, and about 75% hydrogen.



TRIUMPH FOR BIG BANG NUCLEOSYNTHESIS!
There's just the amount of H & He that was predicted.

3 minutes ↓ ↓ 15 minutes



← D = deuterium

← T = tritium

← n = neutron

Monday's Lecture:

The Hot Big Bang

Reading:

Chapter 10