Misc

1. Second midterm is next Wednesday, usual class time (will be proctored by Dr. Brant Robertson and TAs).

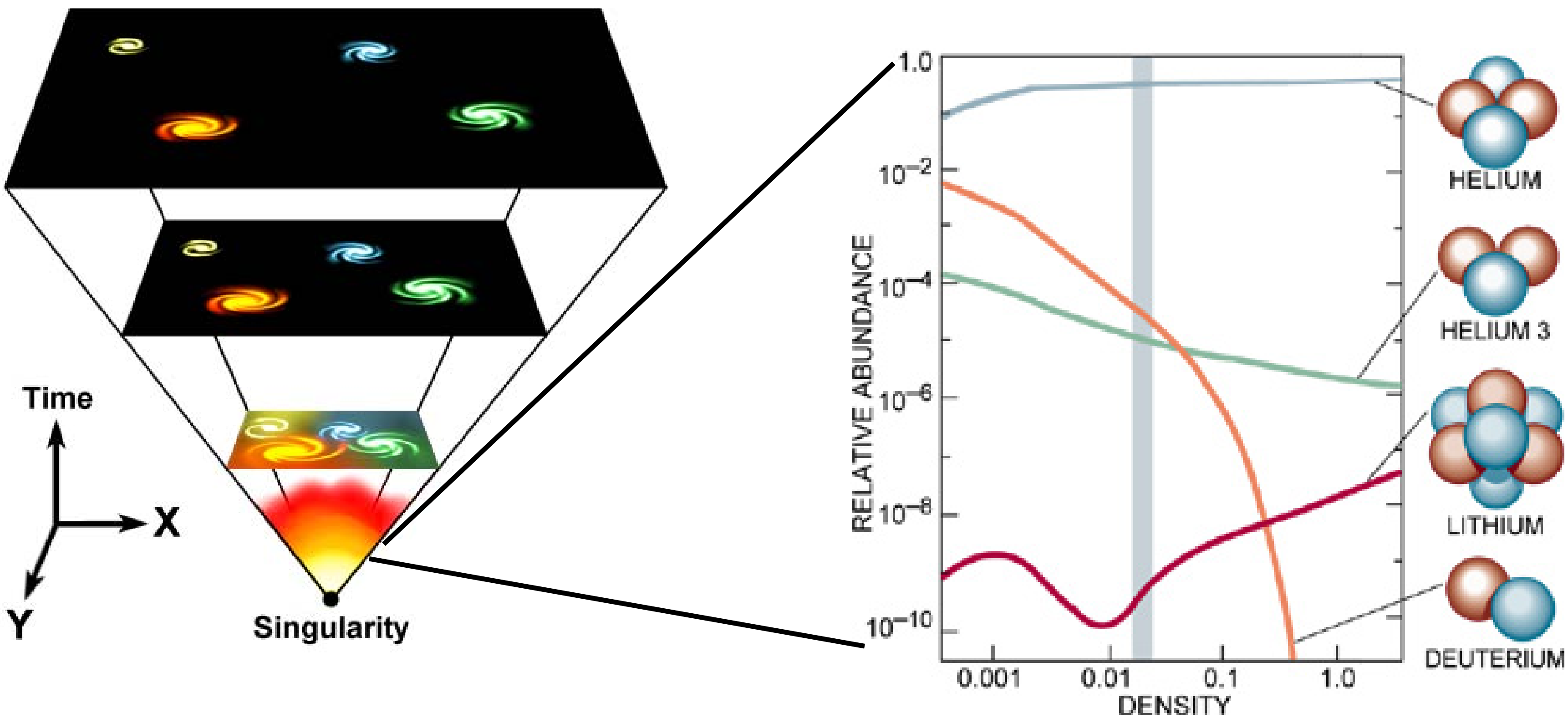
2. The midterm exam will be based on the material covered during the last two weeks and today's lecture (Ch. 25 and 26)

3. Homework 4, distributed on Friday, *is due Wednesday* in class (also available on the class web site as PDF: http://astro.uchicago.edu/~physci/120/winter-2008/)

4. Homework 3 solutions and answers are posted on the class website.

5. Today, we are covering material of S 26-5 (Ch. 26) and S 27-5 (Ch. 27).

Consequences of Big Bang: primordial nucleosynthesis of light nuclei



Density of matter and radiation as a function of time

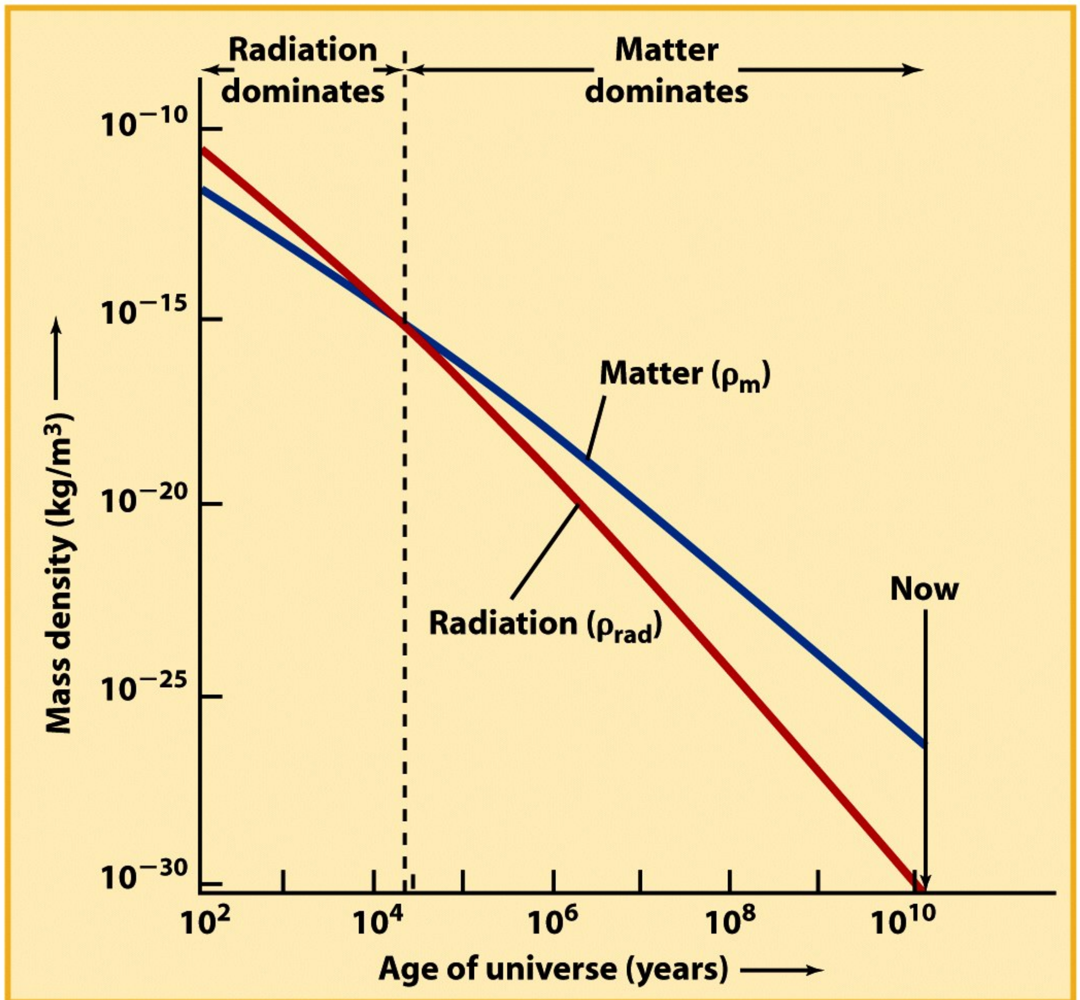


Figure 26-10
Universe, Eighth Edition

Average temperature of radiation as a function of time

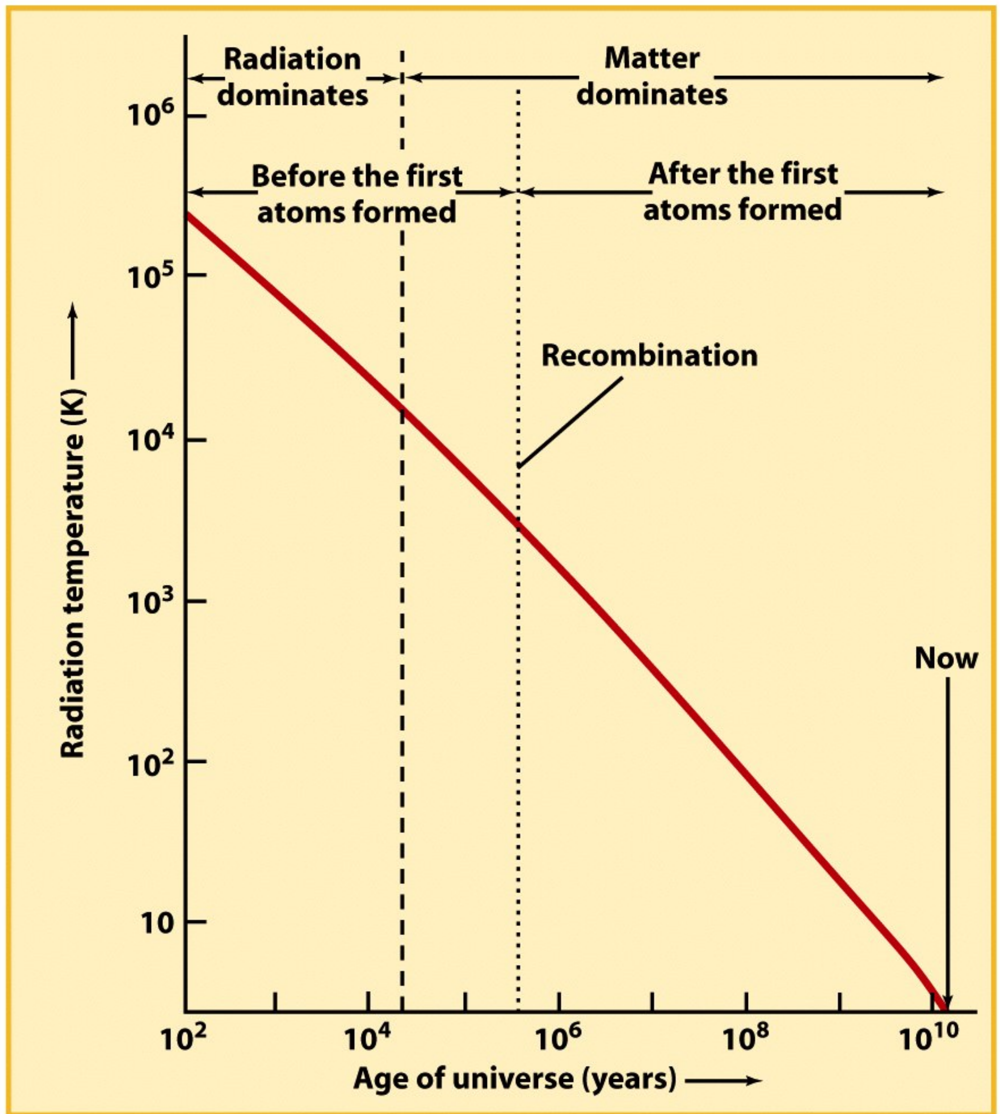
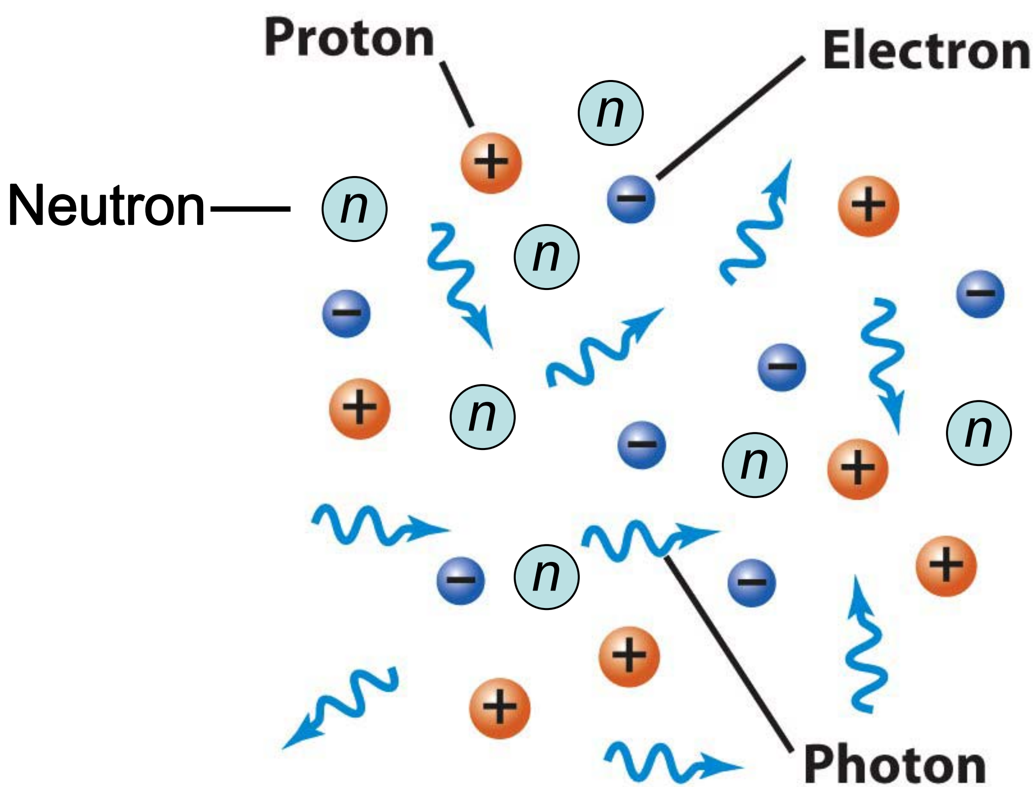


Figure 26-11

The first 3 minutes

In the first three minutes the temperature of primordial plasma was hotter than the temperature in the center of the Sun, and conditions existed for hydrogen fusion similar to the thermonuclear fusion in the centers of stars.



The Big Bang nucleosynthesis (BBN)

In 1948, Alpher, Bethe, and Gamow published a paper exploring consequences of the hot big bang on nuncleosynthesis – production of light elements.

Ralph Alpher

Hans Bethe

George Gamow

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. BETHE
Cornell University, Ithaca, New York

AND

G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

“The results of these calculations were first announced in a letter to *The Physical Review*, April 1, 1948. This was signed Alpher, Bethe, and Gamow, and is often referred to as the 'alphabetical article.‘

It seemed unfair to the Greek alphabet to have the article signed by Alpher and Gamow only, and so the name of Dr. Hans A. Bethe (*in absentia*) was inserted in preparing the manuscript for print. Dr. Bethe, who received a copy of the manuscript, did not object, and, as a matter of fact, was quite helpful in subsequent discussions. There was, however, a rumor that later, when the alpha, beta, gamma theory went temporarily on the rocks, Dr. Bethe seriously considered changing his name to Zacharias.

The close fit of the calculated curve and the observed abundances is shown in Fig. 15, which represents the results of later calculations carried out on the electronic computer of the National Bureau of Standards by Ralph Alpher and R. C. Herman (*who stubbornly refuses to change his name to Delter*.)”

- *George Gamow, in “Creation of the Universe”, 1952*

The Alpher-Gamow BBN:

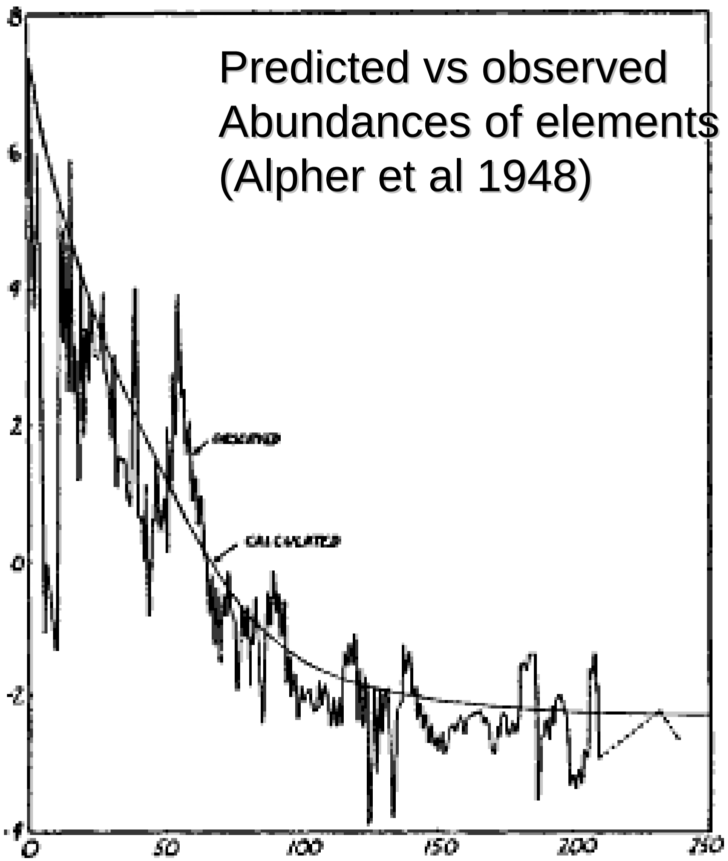


FIG. 1.

Log of relative abundance

Atomic weight

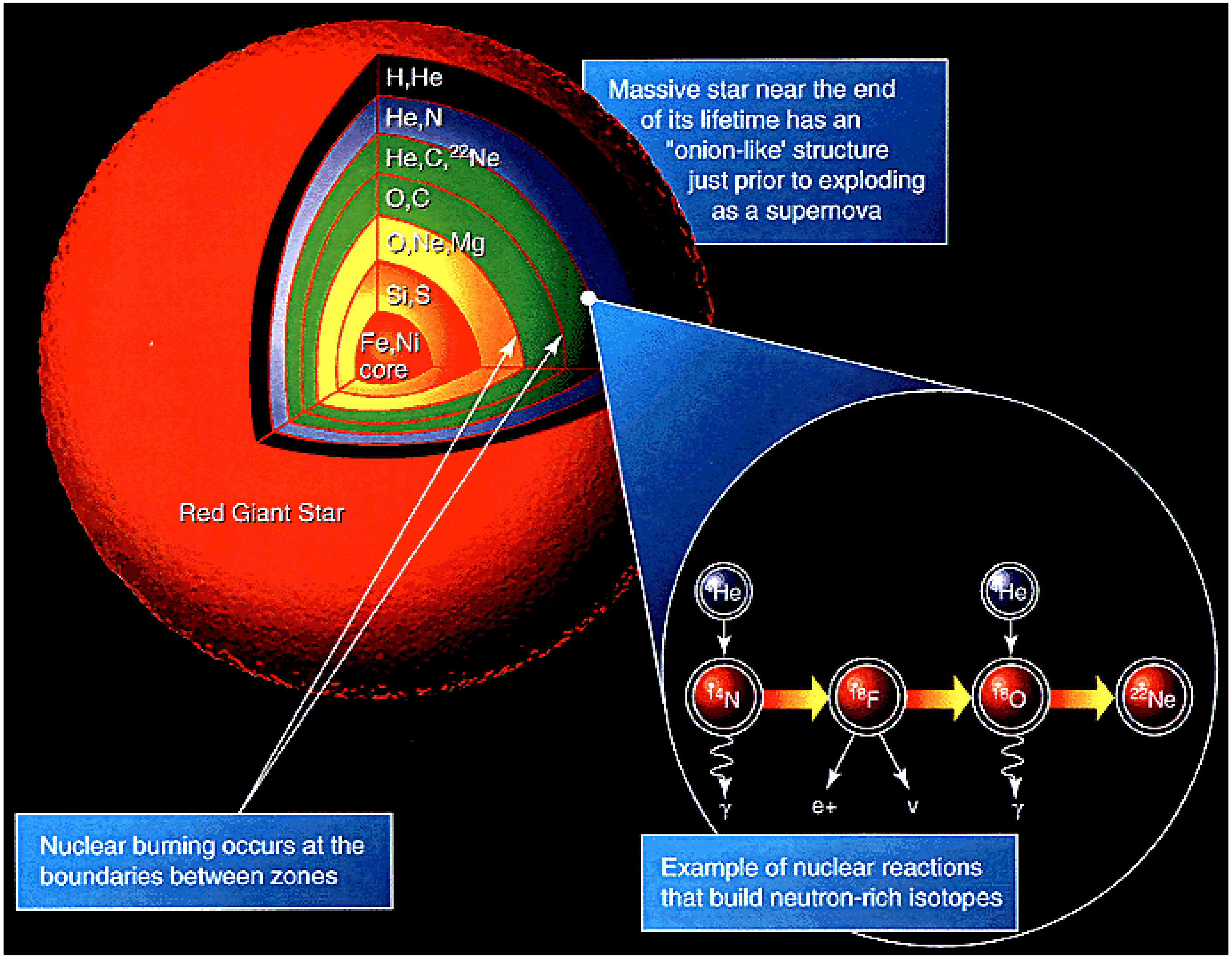
Start with neutrons only -> some neutrons decay into protons and electrons -> heavier nuclei are formed by successive neutron captures and beta-decays

They actually sought to explain creation of *<u>all</u>* elements in the Universe, but they did not realize existence of “stability gaps,” which make it difficult to create certain elements. For example fusion of two He nuclei produces unstable Berillium8 which decays back to two He nuclei, so it was not clear how Carbon can be created.

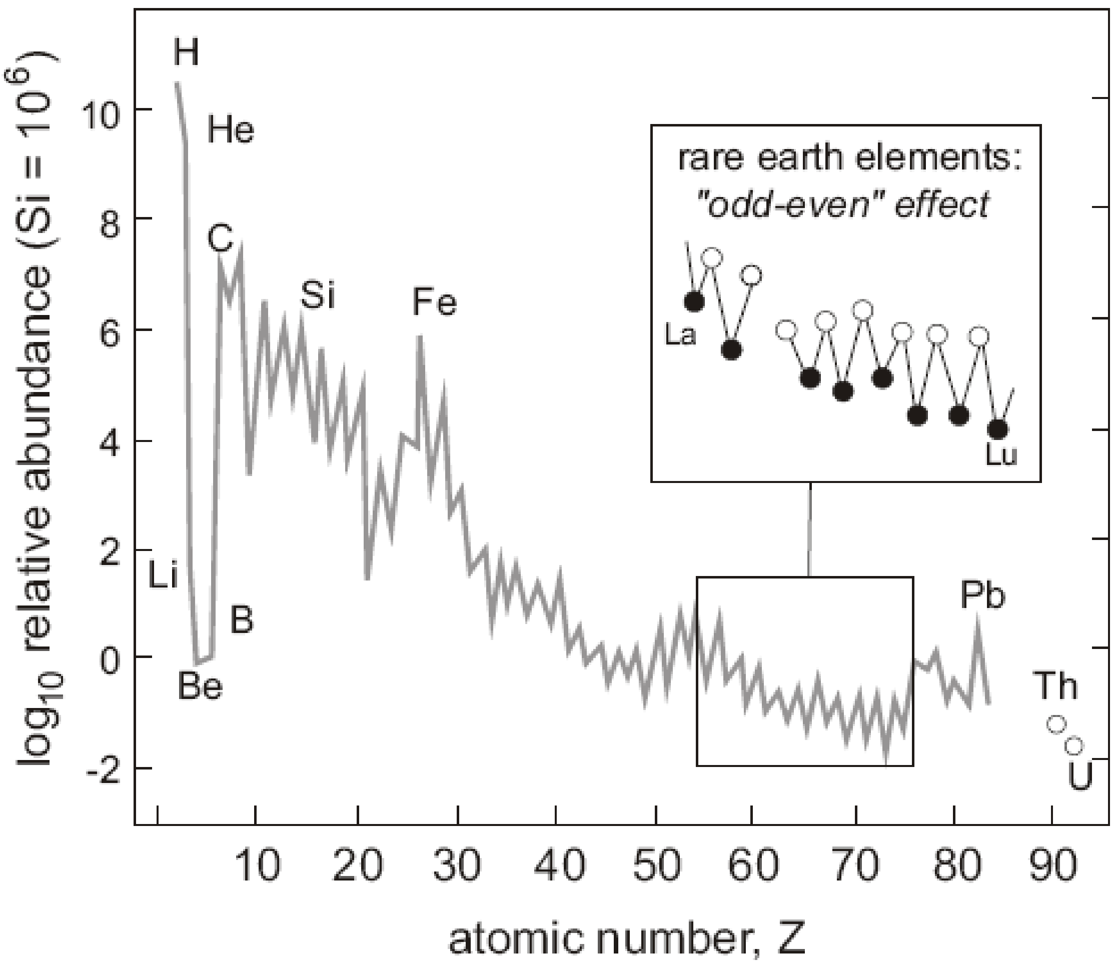
The BBN thus explains creation of light elements – Deuterium, Helium, and Lithium.

Heavier elements are synthesized in stars and by the processes in interstellar medium

Nucleosynthesis of heavy elements in stars



COSMIC ABUNDANCES of the elements



Synthesized in stars

Synthesized in the early Universe

Big Bang Nucleosynthesis: details

Less than 1 second after the Big Bang, the reactions shown at right maintain the neutron to proton ratio in thermal equilibrium. About 1 second after the Big Bang, these weak reactions become slower than the expansion rate of the Universe, and the neutron:proton ratio freezes out at about 1:6.

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

$$n + e^+ \longleftrightarrow p + \bar{\nu}$$

After 1 second, the only reaction that appreciably changes the number of neutrons is neutron decay, shown at right. The half-life of the neutron is 615 seconds. Without further reactions to preserve neutrons within stable nuclei, the Universe would be pure hydrogen.

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

The reaction that preserves the neutrons is ***deuteron*** *formation.* ***The deuteron is the nucleus of deuterium, which is the heavy form of hydrogen*** *(H^2). The deuteron, however, is easily destroyed by the energetic photons until the Universe has cooled to 1 billion K, about 2-3 minutes after the Big Bang. At this time, the neutron:proton ratio is about 1:7 (87% protons and 13% neutrons).*

$$p + n \longleftrightarrow d + \gamma$$

Adopted from Ned Wrights cosmology tutorial: http://www.astro.ucla.edu/~wright/BBNS.html

Big Bang Nucleosynthesis: details

Once deuteron formation has occurred, further reactions proceed to make helium nuclei.

$$d + n \longrightarrow H^3 + \gamma$$
$$H^3 + p \longrightarrow He^4 + \gamma$$
$$d + p \longrightarrow He^3 + \gamma$$
$$He^3 + n \longrightarrow He^4 + \gamma$$

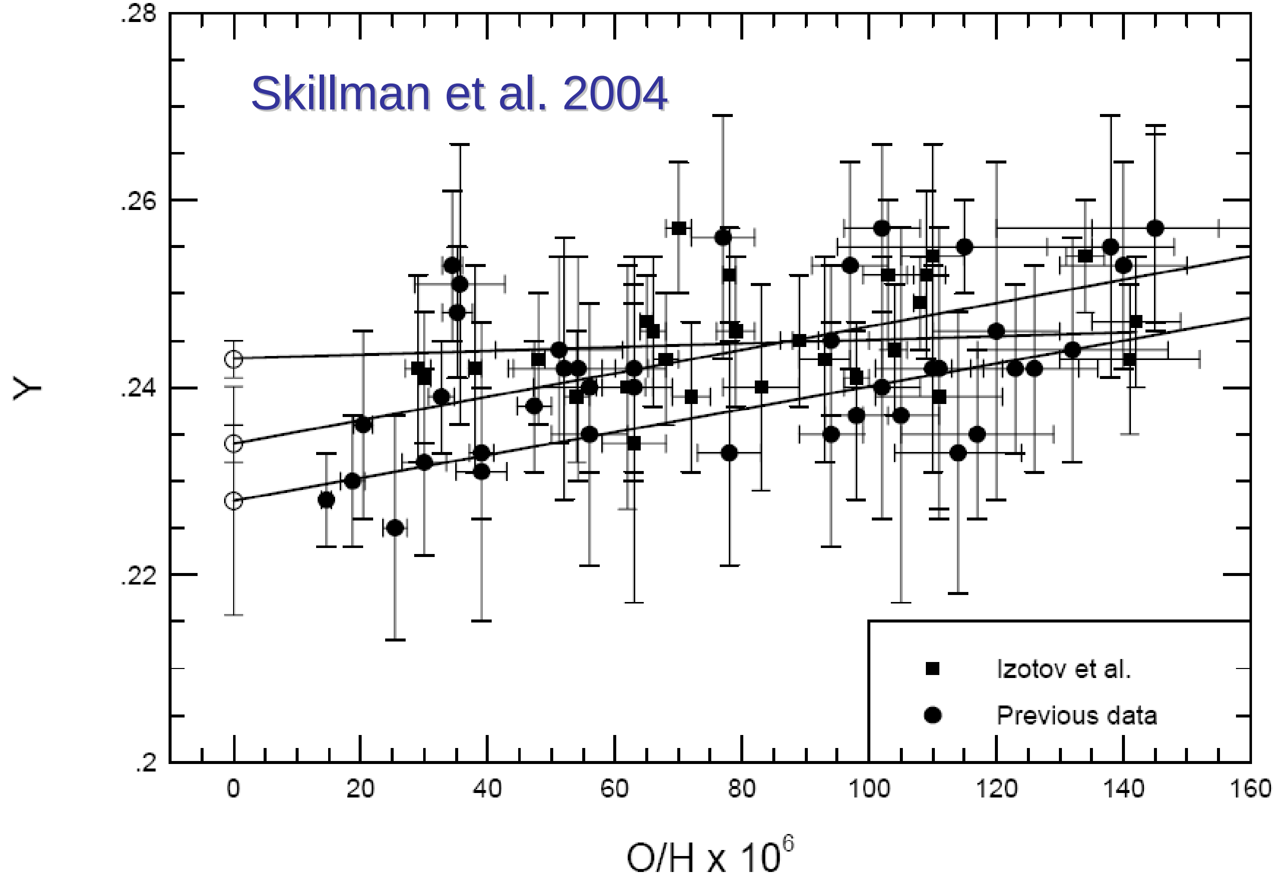
$$d + d \longrightarrow He^3 + n$$
$$d + d \longrightarrow H^3 + p$$
$$H^3 + d \longrightarrow He^4 + n$$
$$He^3 + d \longrightarrow He^4 + p$$

The net effect is shown at right. Eventually the temperature gets so low that the electrostatic repulsion of the deuterons causes the reaction to stop. Almost all the neutrons in the Universe end up in normal helium nuclei. For a neutron:proton ratio of 1:7 at the time of deuteron formation, 25% of the mass ends up in helium.

$$d + d \longrightarrow He^4 + \gamma$$

Adopted from Ned Wrights cosmology tutorial: http://www.astro.ucla.edu/~wright/BBNS.html

Measuring deuterium abundance in the interstellar medium of nearby galaxies



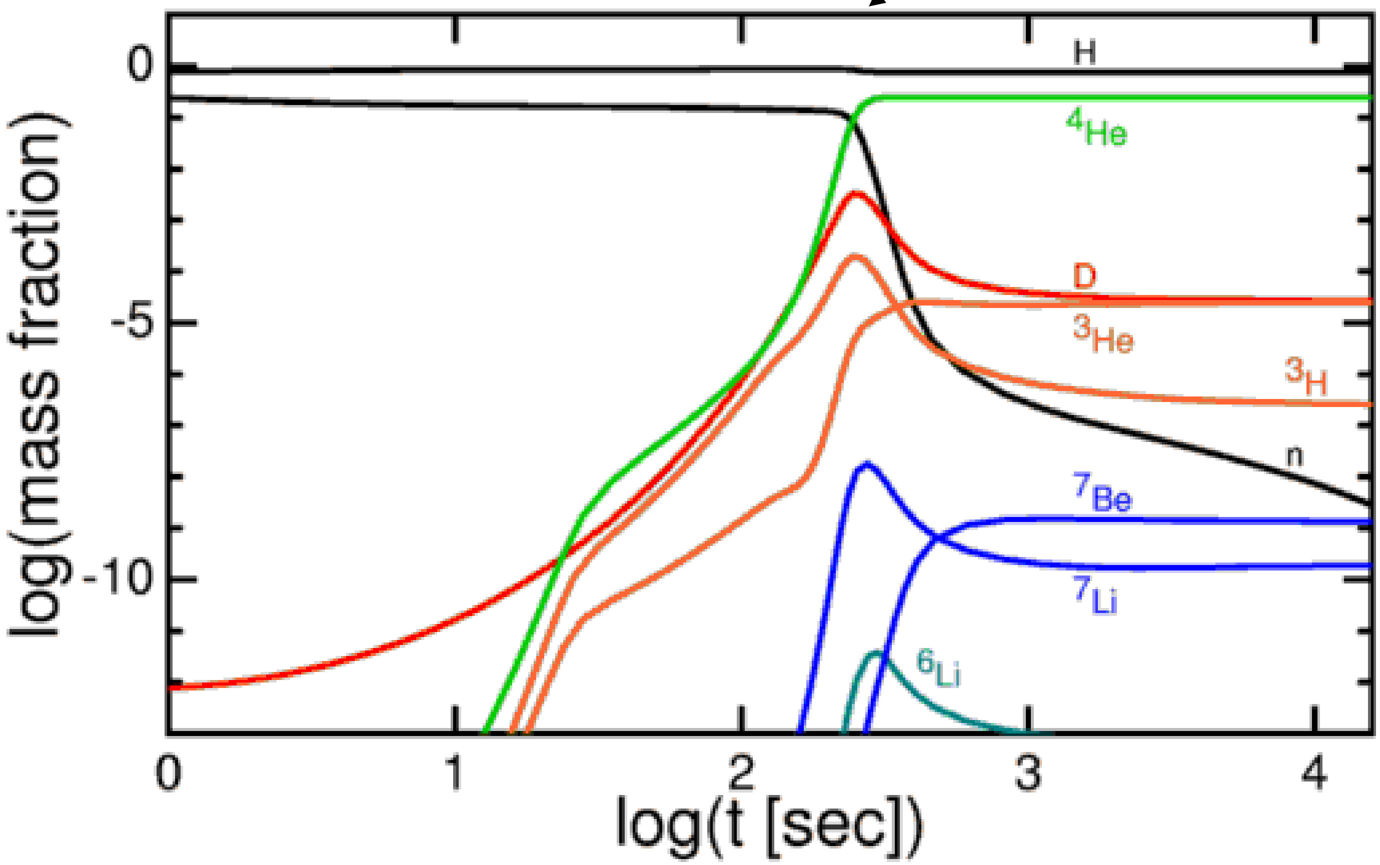
Helium fraction by mass

Oxygen abundance with respect to hydrogen

Abundance of light elements as a function of time

Prediction based on theoretical calculation assuming a certain density of protons and neutrons in the Universe

3 minutes after the Big Bang



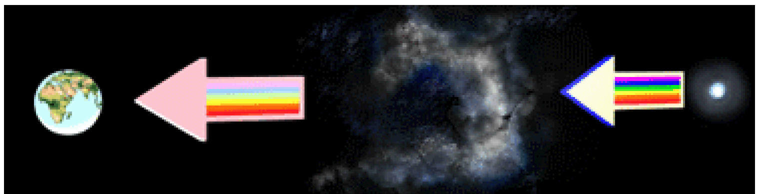
Adopted from Ned Wrights cosmology tutorial: http://www.astro.ucla.edu/~wright/BBNS.html

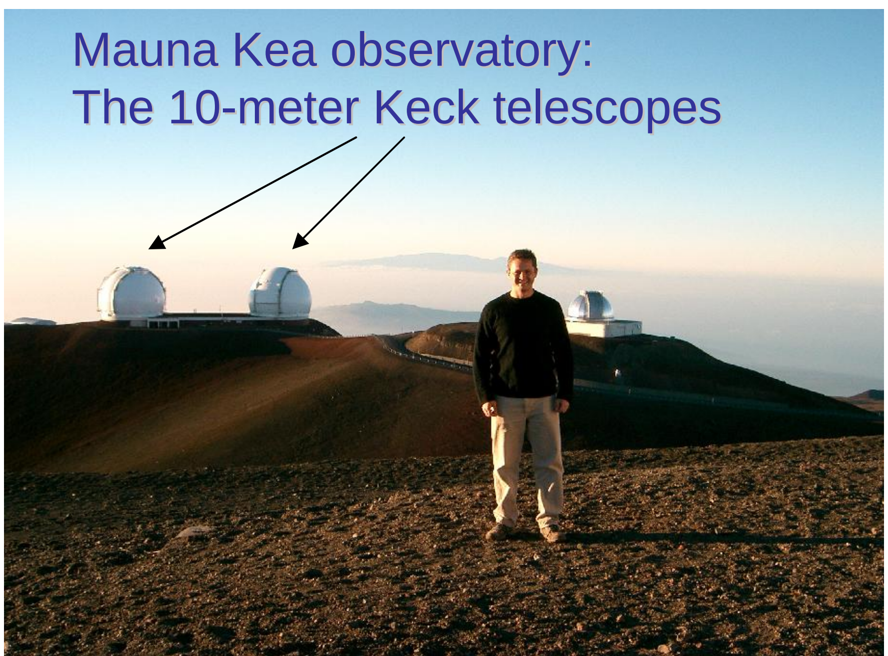
Measuring deuterium abundance

observer

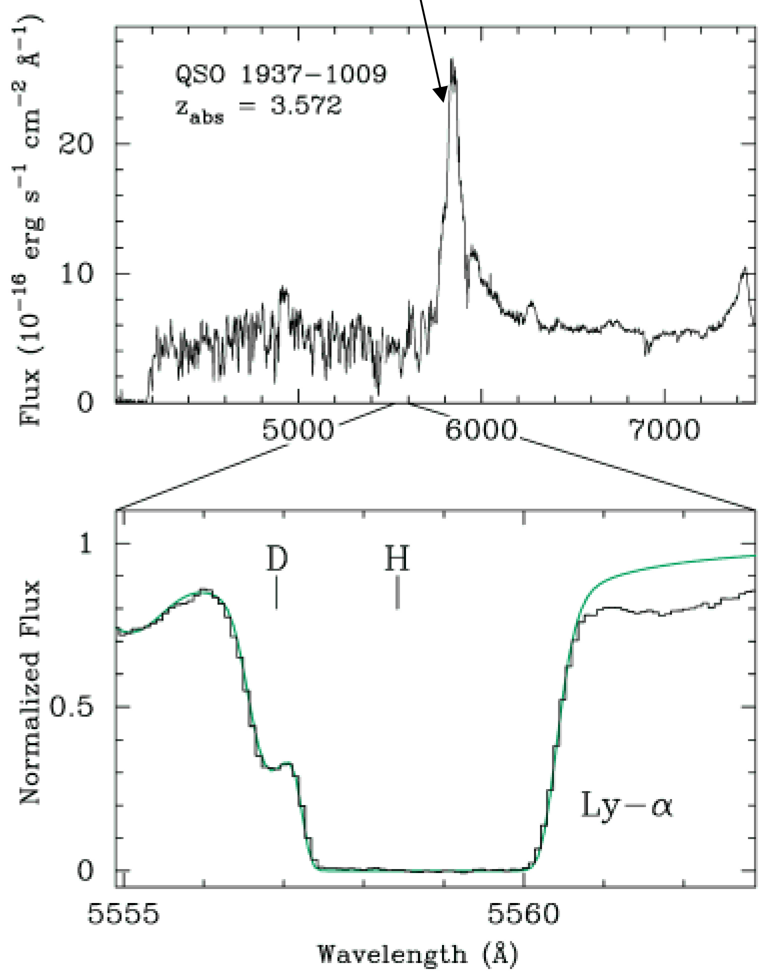
intervening gas cloud

bright QSO

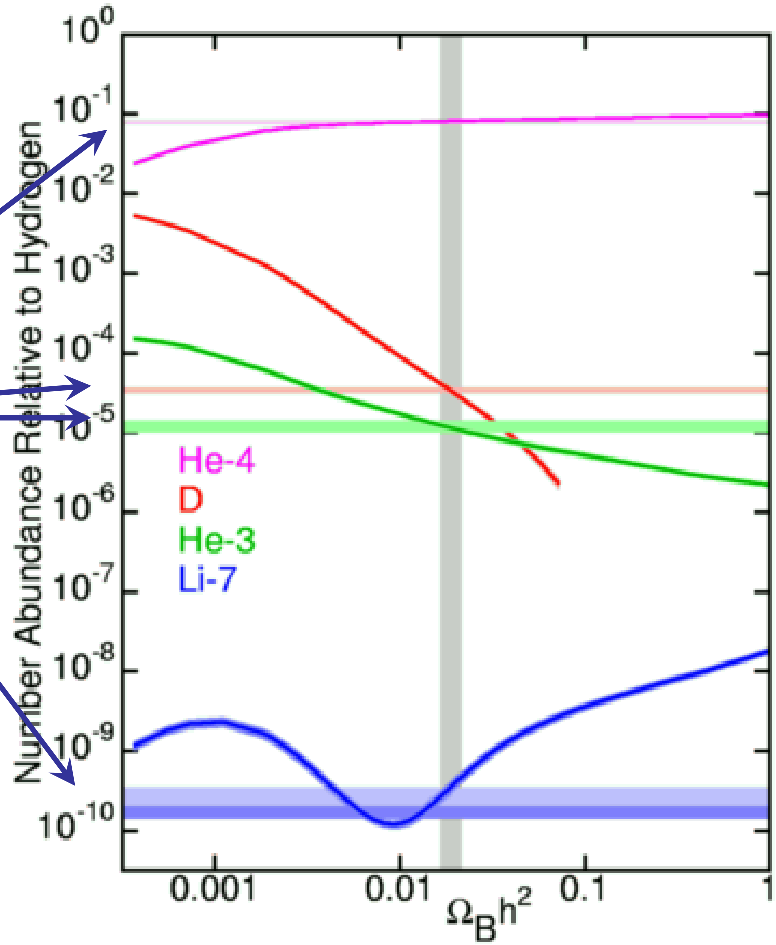




Quasar spectrum



Abundance of light elements as a function of baryon density



Horizonthal bands = observations

Color lines are model predictions

Comparing model predictions to observations of He, D, Li abundance provides a measure of the cosmic density of baryons:

$\Omega_B h^2 = 0.0224$
+/- 0.001

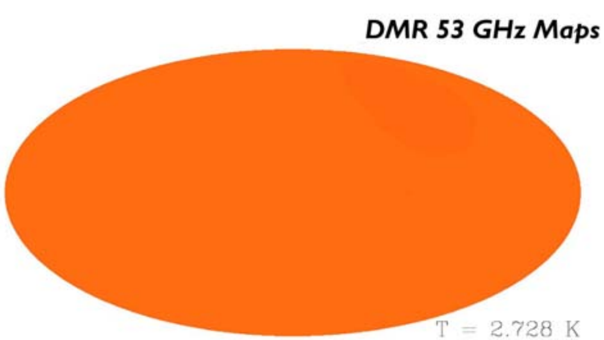
Adopted from Ned Wrights cosmology tutorial: http://www.astro.ucla.edu/~wright/BBNS.html

Primordial nucleosynthesis of light elements is one of the main "pillars" of the Big Bang theory

Explanation of the observed cosmic abundances of H, D, He, and Li is one of the main successes of the hot Big Bang theory

In fact, there is no alternative model that can do this…

BBN calculations resulted in the first predictions of the CMB



Gamow, Alpher and Herman have also explored implications of the Hot Big Bang Nucleosynthesis.

The fact that the Universe is supposed to be hot implies existence of many high-energy photons per each nucleus.

Gamow realized that these should escape at some point and remain as a relic radiation which cools off as the Universe expands.

Alpher and Gamow calculated the temperature to be ~10 K. This calculation was later (1951-52) improved by Alpher and Herman who got the temperature of 5 K – very close to the true temperature of 2.7 K

For some reason, unlike their work on the BBN, this work was not appreciated by the physics community and the result was not widely known…