The First Three Minutes
Meeting 6

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February 17, 2021

Meeting 6 – The First Three Minutes

- Announcements
- 30,000 ft
- Nuclear reactions
- Break
- Discussion of Chapter V – The First Three Minutes

Announcements

- Notes, slides, etc. on website, tinyurl.com/firstthreeminutes
- Please read Chapter VI for next week
- Questions
  - Calculation of frames in Capture V
  - Topology of the universe
  - Particle production in the early universe
  - “Friction” of expansion

30,000’ view

Galaxies are the “atoms” of the universe

When viewed on the 100 Mly scale, the universe is uniform and isotropic

Hubble’s redshift measurements showed all the galaxies are moving away from us. Their recession speed is proportional to how far away they are. H_o is the proporitonality constant.

30,000' (cont.)

The recession of the galaxies led to the idea that the space of the universe is expanding. The expansion is the same everywhere.

The numerical value of H_o implies the universe is 13.7 Gy old.

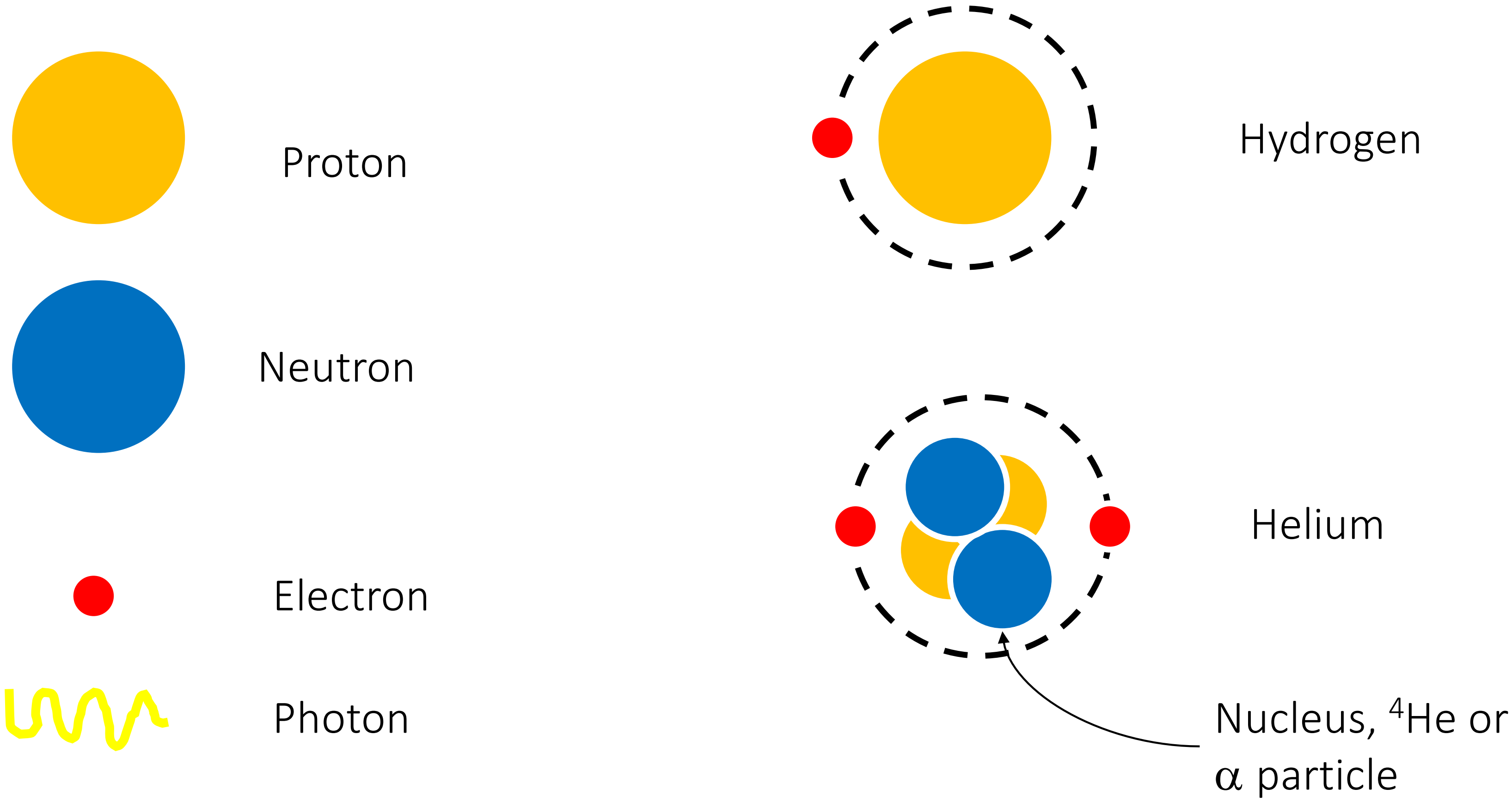
Penzias and Wilson's observation of 2.7 K radiation led to the conclusion that neutral hydrogen formed from a plasma 377,000 y after the start of the universe.

30,000’ (cont.)

At 0.01 s, the recipe for a hot universe consists of

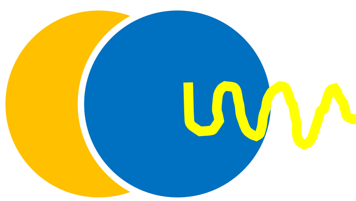
- Zero net charge
- Protons, neutrons, electrons at the 1 ppb level compared with photons (and neutrinos)
- T=100 B kelvin for black body photons
- Expansion as $t^{1/2}$

Nuclear reactions - nomenclature



Binding energy

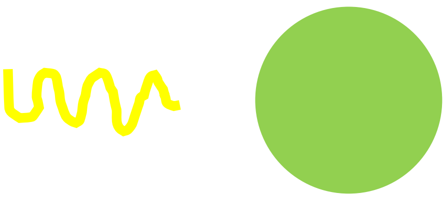
Approach with negligible speed, energy of motion (kinetic) very small. Total energy is the sum of the neutron and proton mass energies.



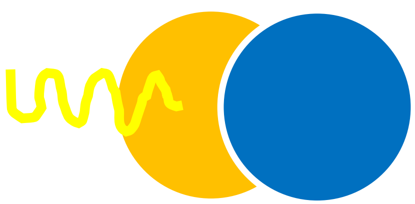
The neutron and proton merge into a bound state called a deuteron. During the merge a 2.2 MeV photon (gamma ray) is emitted.

The mass energy of the deuteron is *less* than the sum of the mass energies of the proton and neutron by 2.2 MeV. This is called the binding energy of the deuteron.

Binding energy



Reverse reaction: a deuteron can absorb a gamma ray photon.



If the photon has at least 2.2 MeV of energy, the deuteron can break apart into a neutron and proton.

If the photon had more than 2.2 MeV of energy, the excess is shared as kinetic (motion) energy of the neutron and protons

Reactions and temperature

The reaction

$$n + p \rightarrow d + \gamma$$

can *always* occur.

The reaction

$$d + \gamma \rightarrow n + p$$

can only happen if the photon has at least 2.2 MeV of energy.

At 0.01 s, T=100 billion K, $n + p \rightarrow d + \gamma$ happens as often as $d + \gamma \rightarrow n + p$. When temperature reaches 1 billion K, very few photons have 2.2 MeV and $d + \gamma \rightarrow n + p$ stops. $n + p \rightarrow d + \gamma$ continues and more and more *d* is produced.

Reactions in the early universe

Reaction	Energy	Equivalent Temperature
$2\gamma \to 2e$	1.0 MeV	1.2×10^{10} K
$p + \nu \to e + n$	1.3 MeV	1.5×10^{10} K
$n + \nu \to p + e^-$	0	–
$n + p \to d + \gamma$	2.2 MeV	2.6×10^{10} K
$d + n \to t + \gamma$	6.3 MeV	7.3×10^{10} K
$d + p \to He3 + \gamma$	5.5 MeV	6.4×10^{10} K
$p + t \to He4 + \gamma$	20. MeV	2.3×10^{11} K

5 m Break

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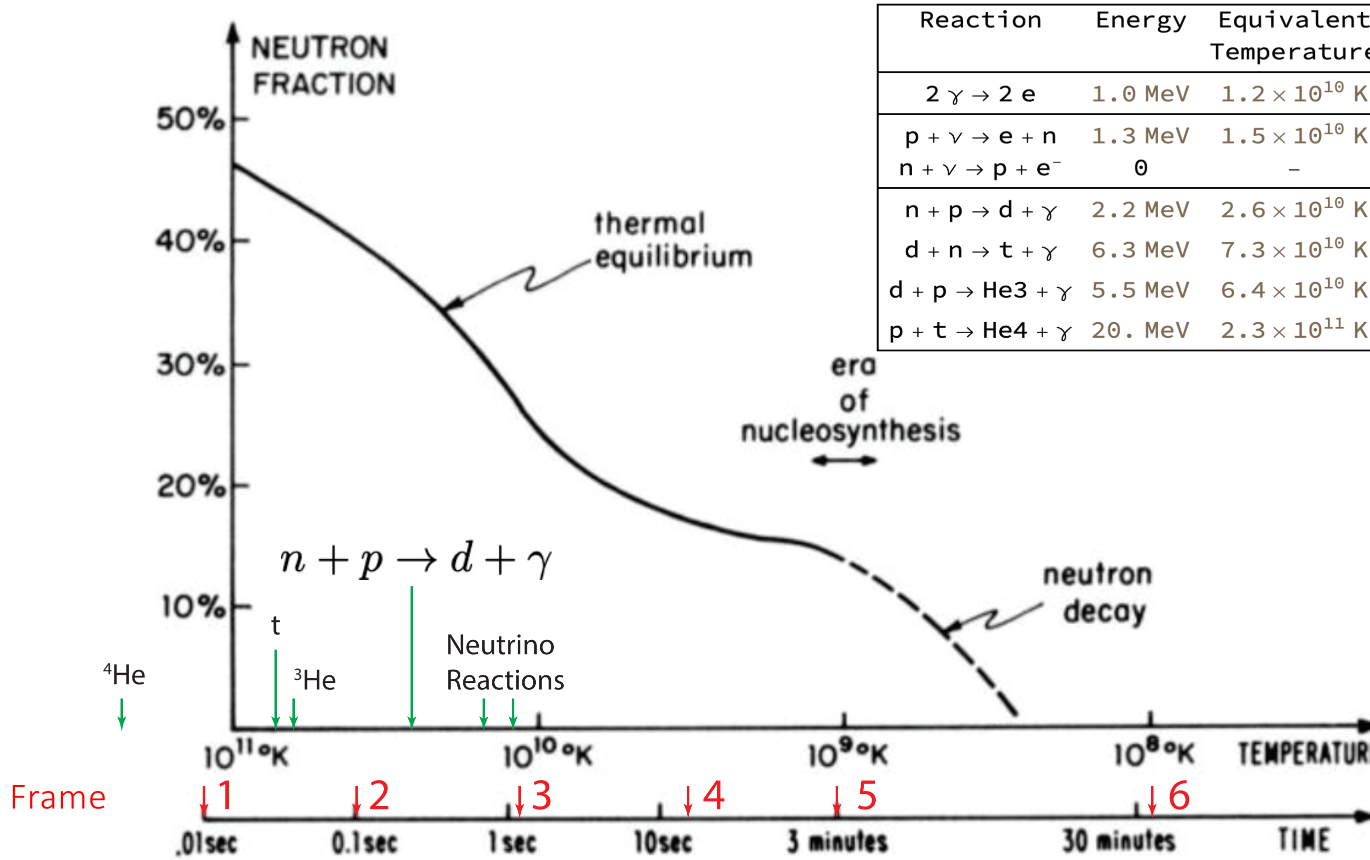
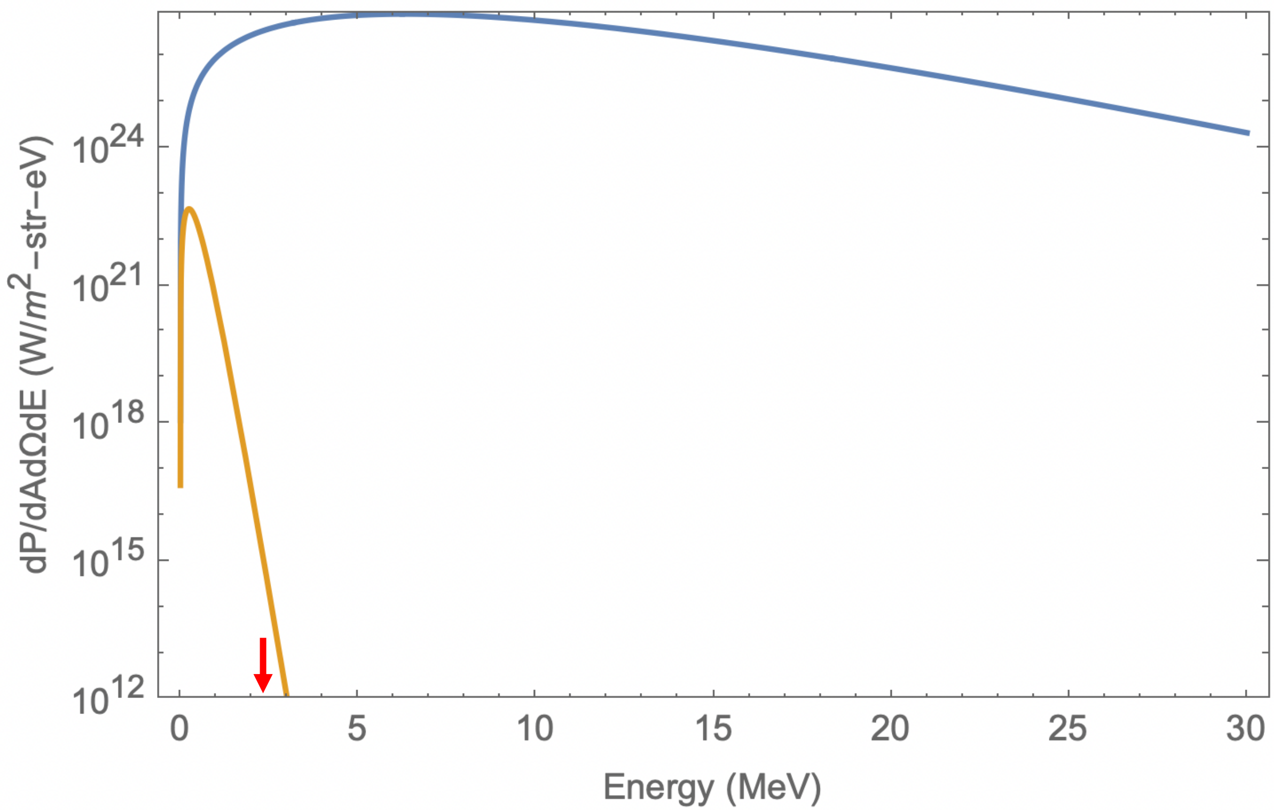


Black body spectra



Deuterons are so fragile, there are still enough 2.2 MeV photons around to break it up until the universe reaches 1 billion K.

``Fragile'' means a photon hitting a deuteron is very likely to break it apart if the photon's energy is at least 2.2 MeV.

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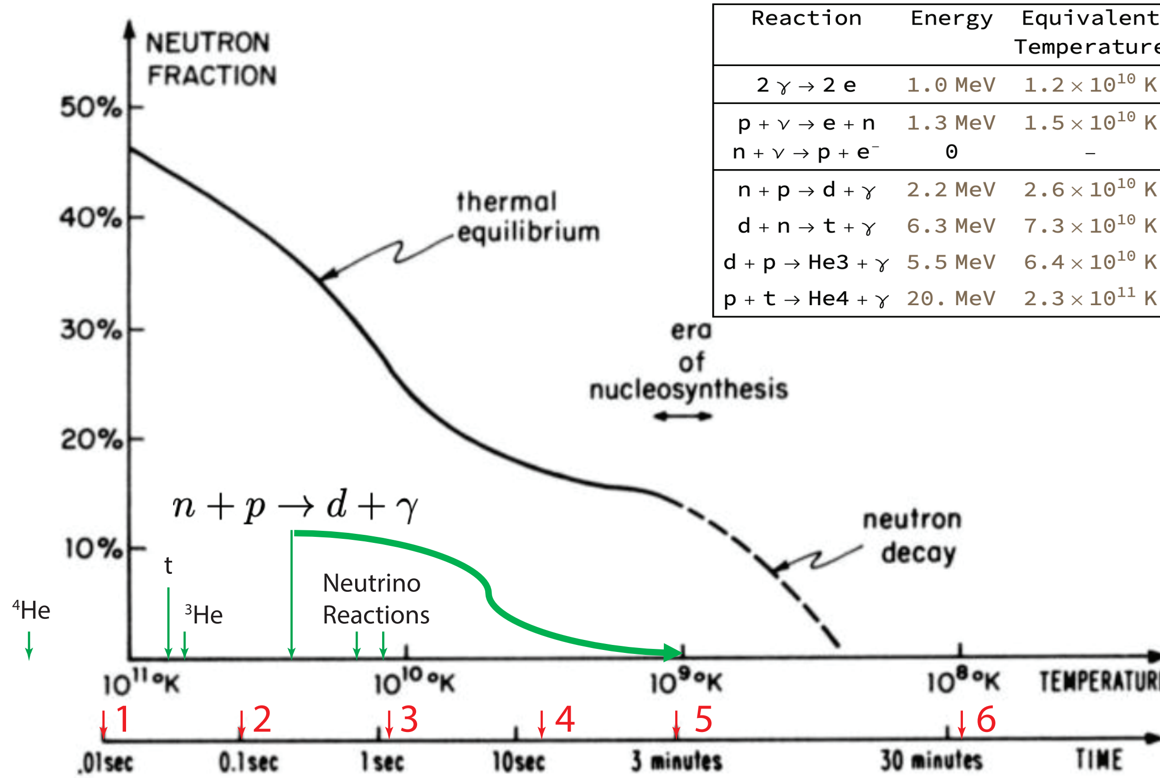
The deuteron's fragility delays creation of deuterons by 3 min, until the universe expands enough to cool to 1 B kelvin.

All the other isotopes have higher reaction thresholds, but cannot start until deuterons have been created.

The deuteron bottleneck.



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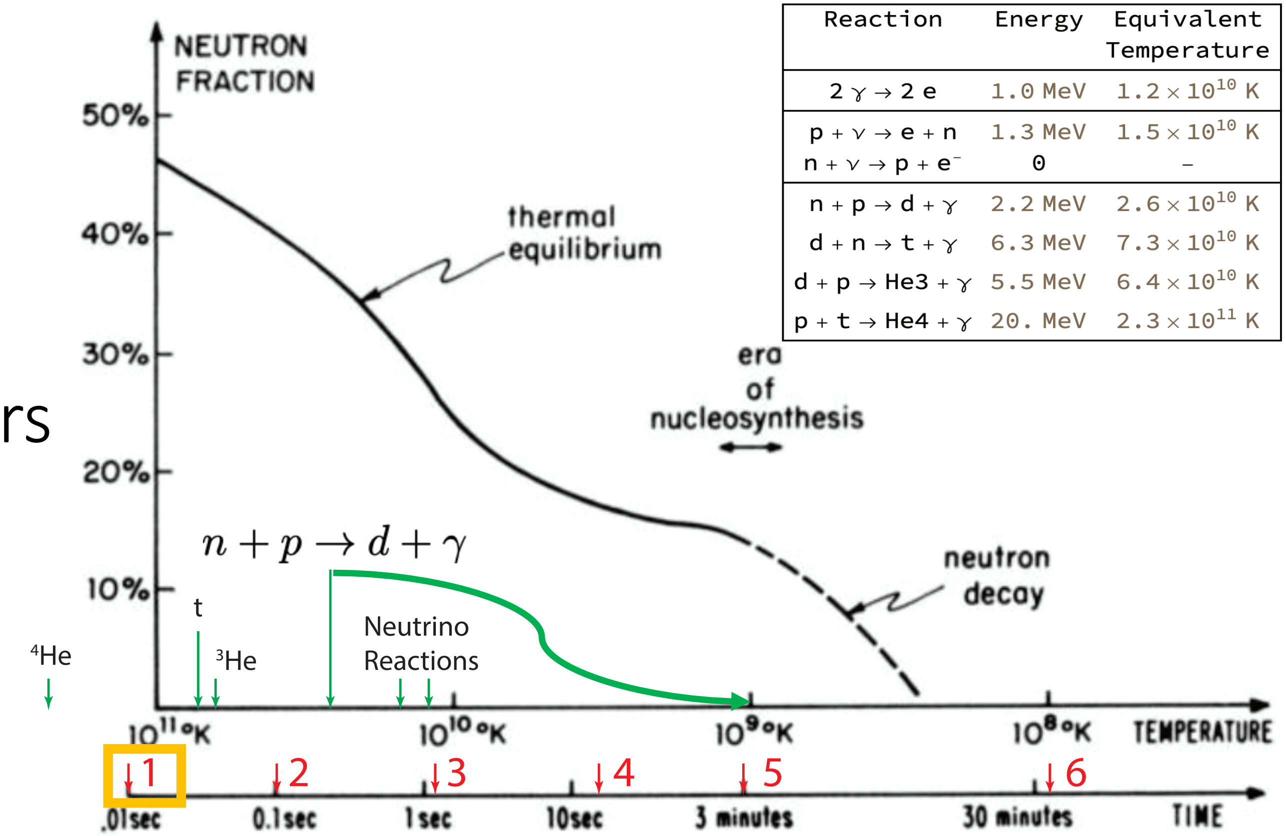
Frame 1

T=0.01 s, T=100 B

Neutrino reactions keep equal numbers of protons and neutrons



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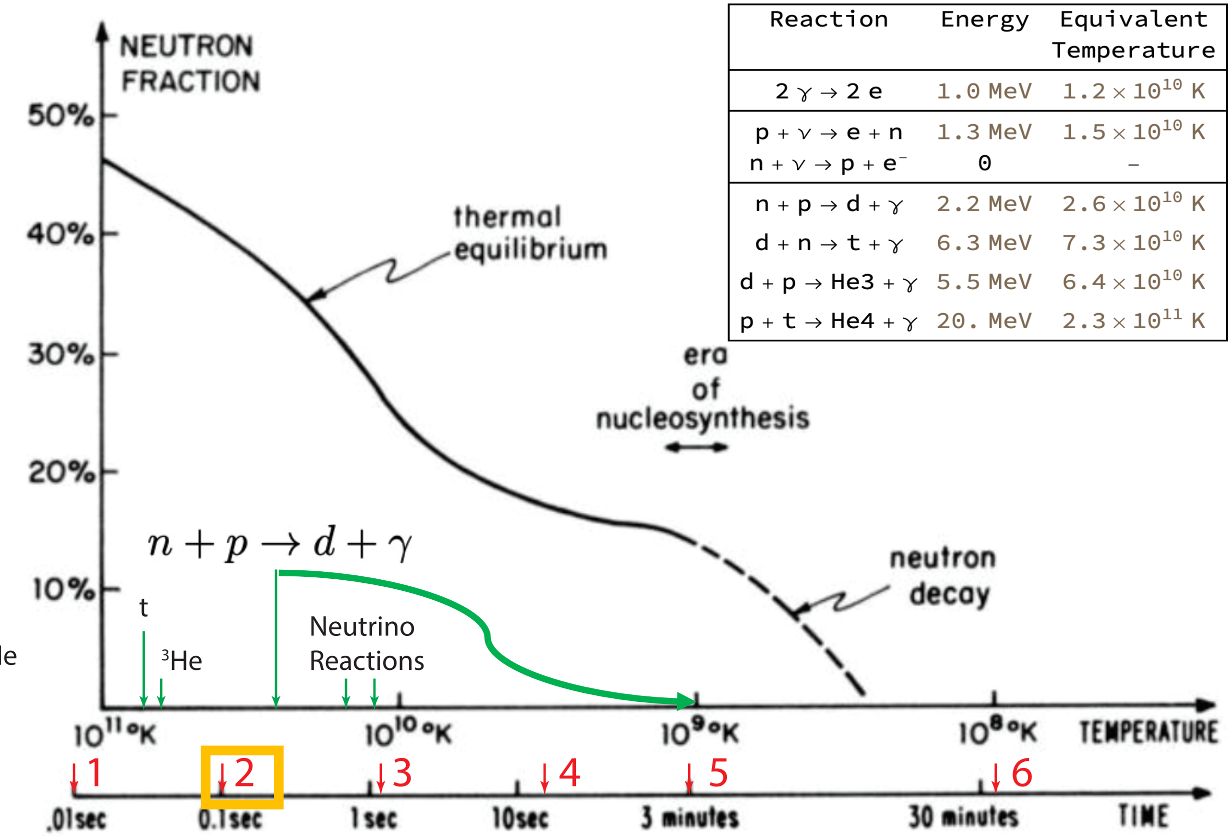
Frame 2

T=0.1 s, T=30 B

Neutrino reactions favor protons, 38% n, 62% p

Below threshold for helium production



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Frame 3

T=1.1 s, T=10 B

Neutrino reactions favor protons, 24% n, 76% p

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

threshold crossed

Below threshold for helium production

Reaction	Energy	Equivalent Temperature
$2\gamma \rightarrow 2e$	1.0 MeV	1.2×10^{10} K
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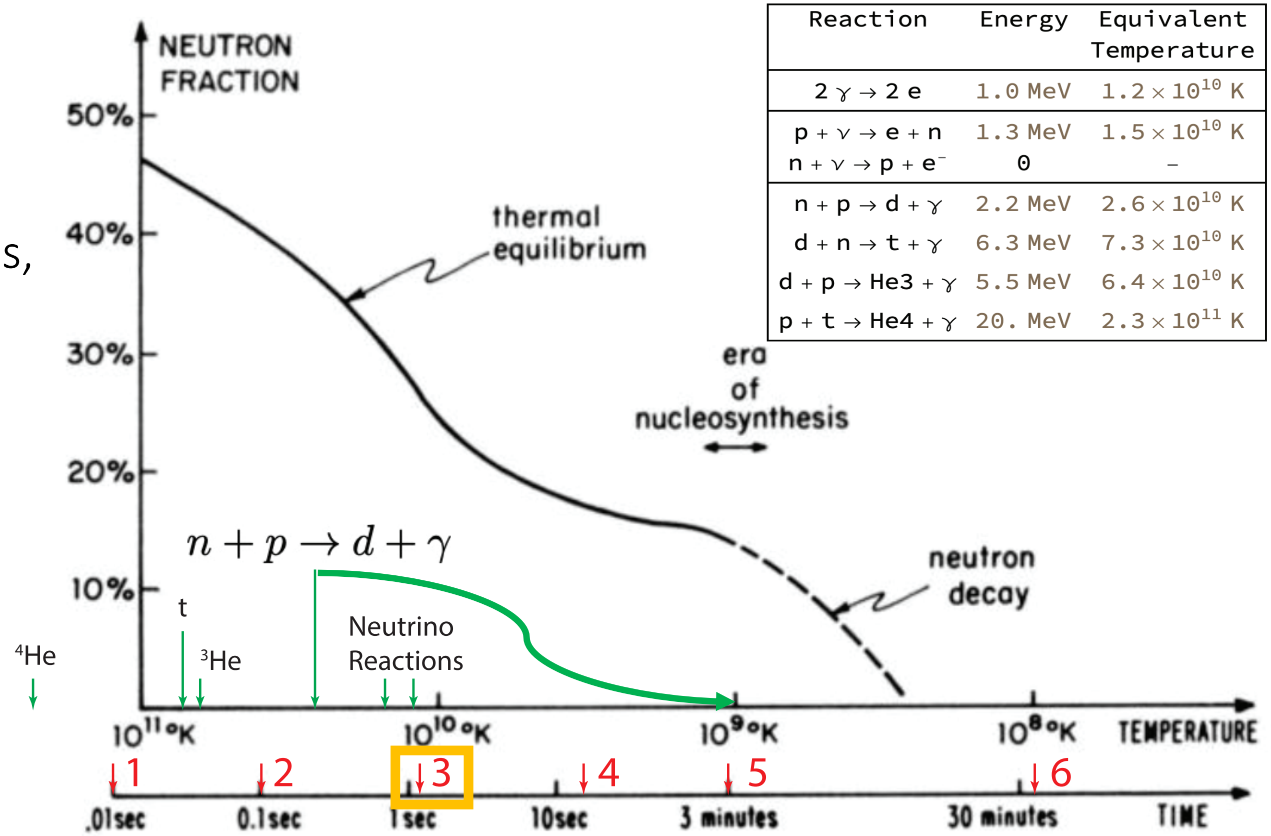
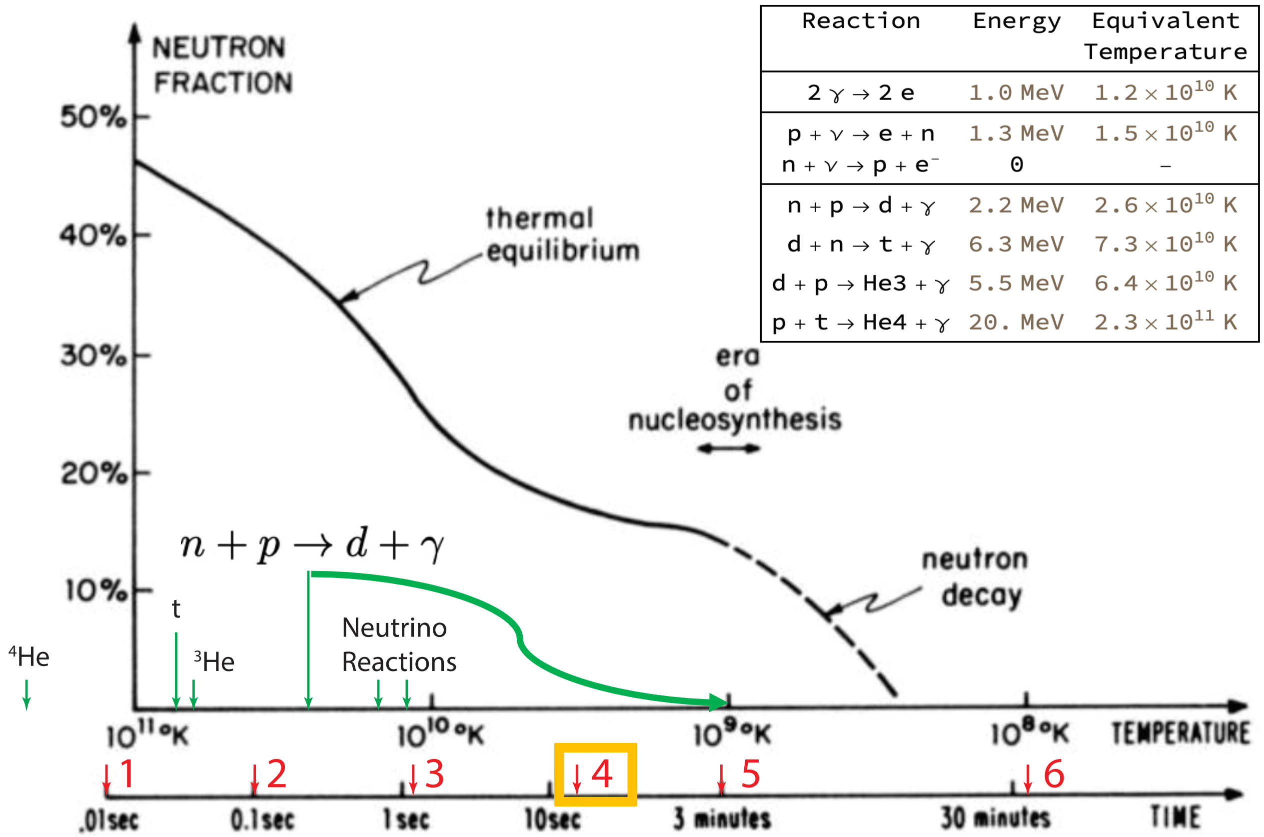


Frame 4

T=14 s, T=3 B



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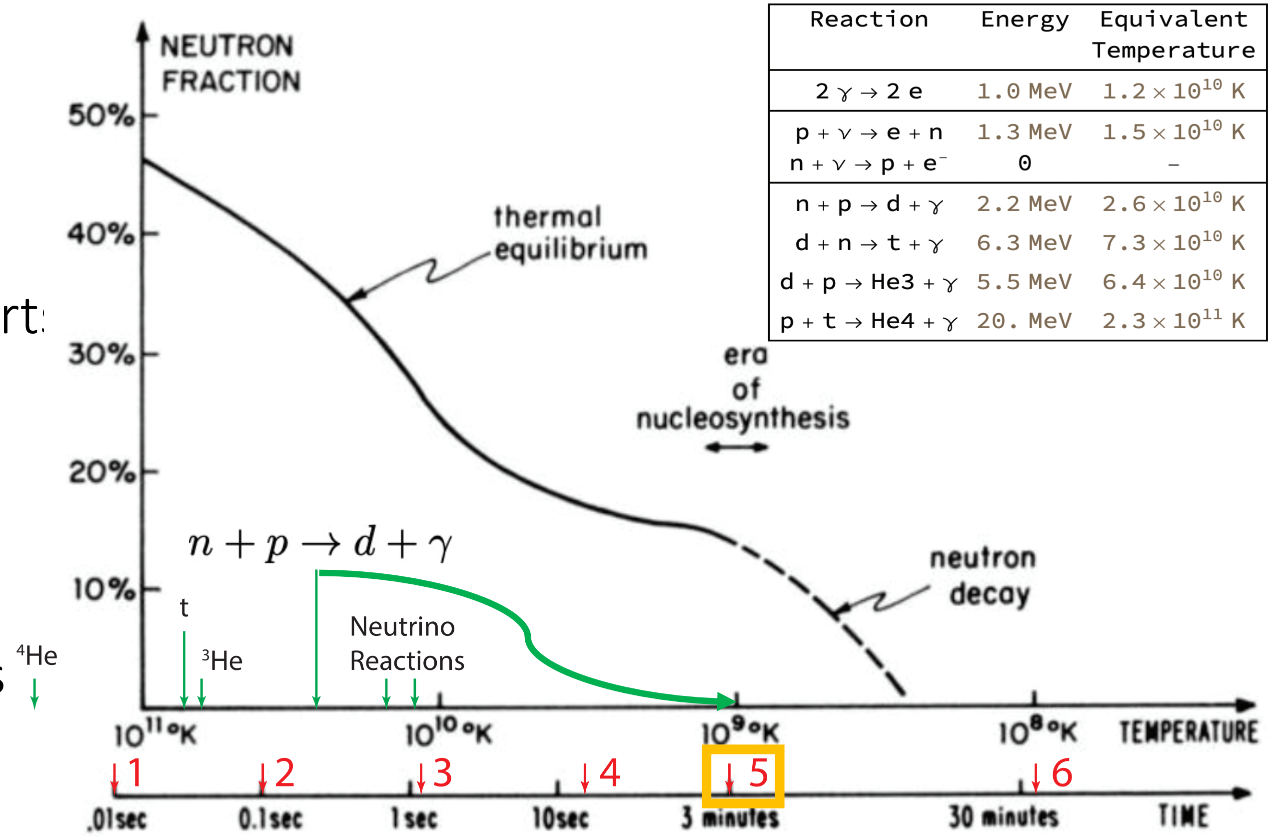
Frame 5

t=3 m, T=1 B

Deuteron production starts

20% of neutrons have decayed.

Helium production starts



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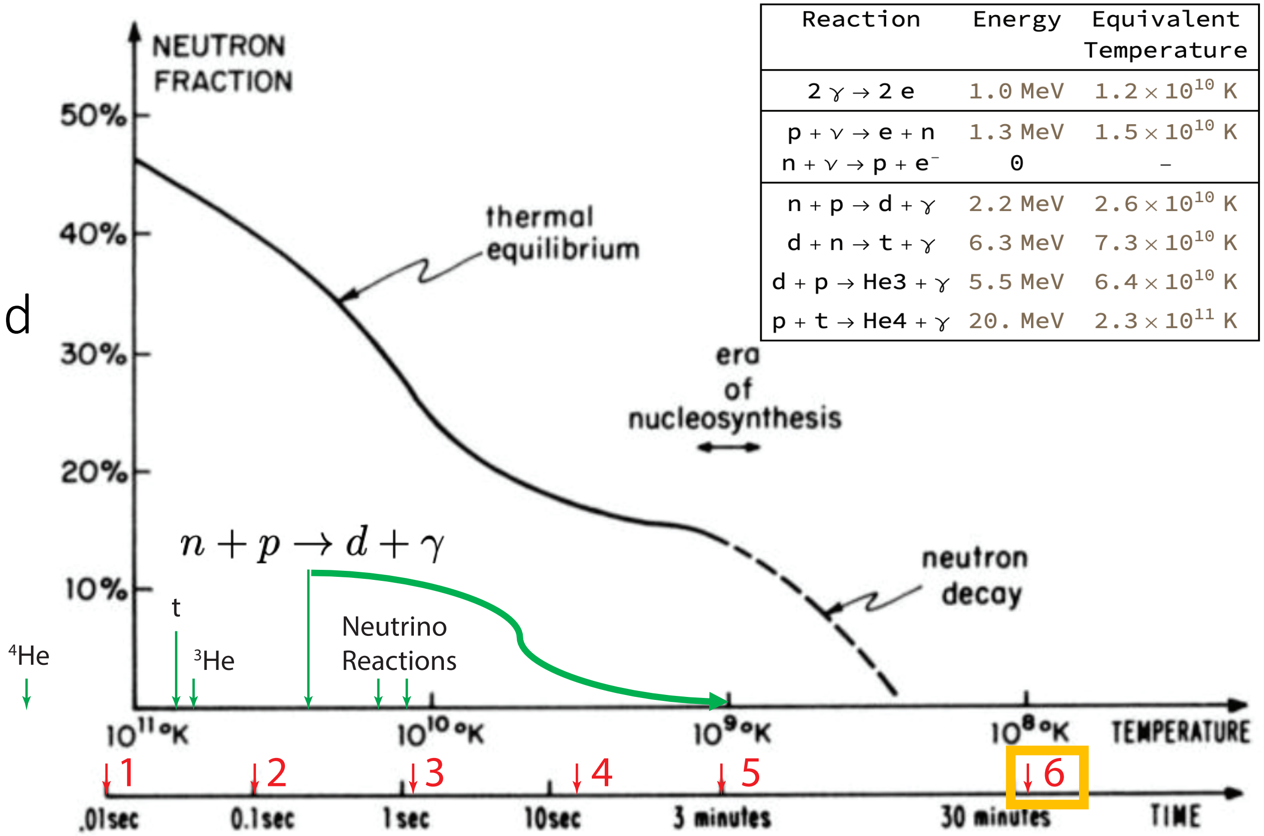
Frame 6

t=34 m, T=100 M

All reactions have stopped

75% H, 25% He

90% of neutrons have decayed



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After the first three minutes

The universe is now very quiet: expansion continues and the photons cool.

Deuterons are 25.47 ± 0.25 ppm of hydrogen

$^{3}\mathrm{He}$ is 11 ± 1 ppm of hydrogen

The fraction of protons and neutrons in helium is $24.5 \pm 0.3\%$

There are 1.5-1.7 billion photons for every baryon.

Nothing happens for 47,000 years, when the radiation dominated era ends.

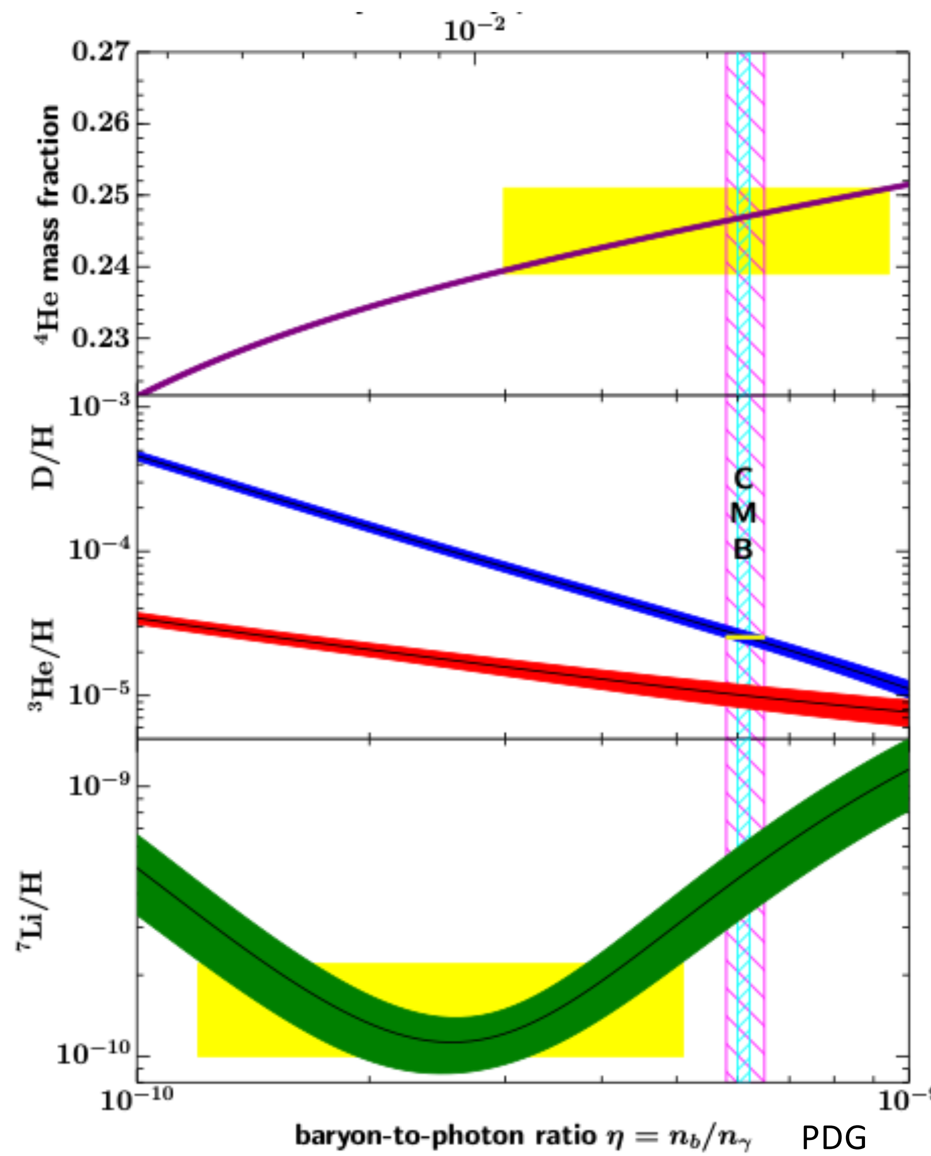
The CMB measures the temperature of the photons at any time (know expansion).

This gives the photon density at any time (black body).

Calculation relates the D/H ratio to the n_b/n_γ ratio

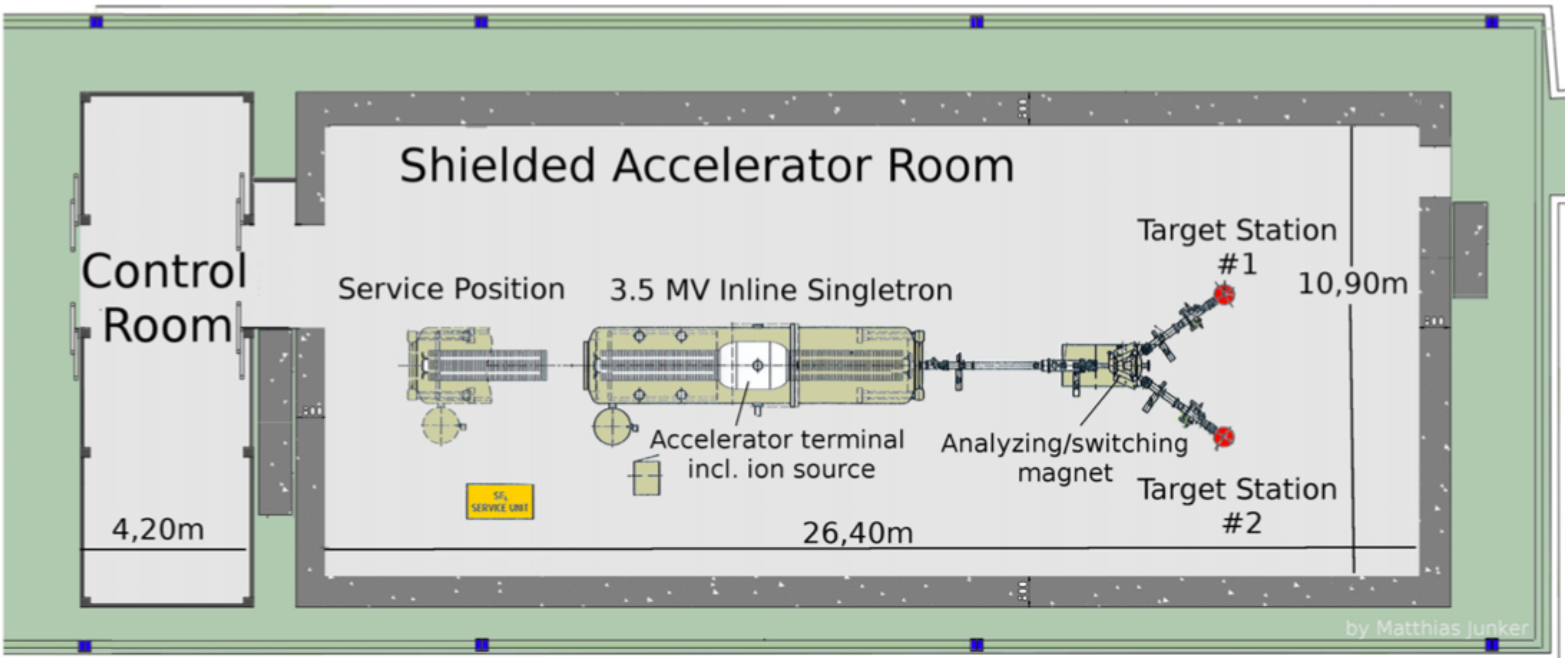
Weinberg, p. 114

Photons/nuclear particle	Deuterium abundance (parts per million)
100 million	0.00008
1,000 million	16
10,000 million	600



PDG

Laboratory for Underground Astrophysics (LUNA)



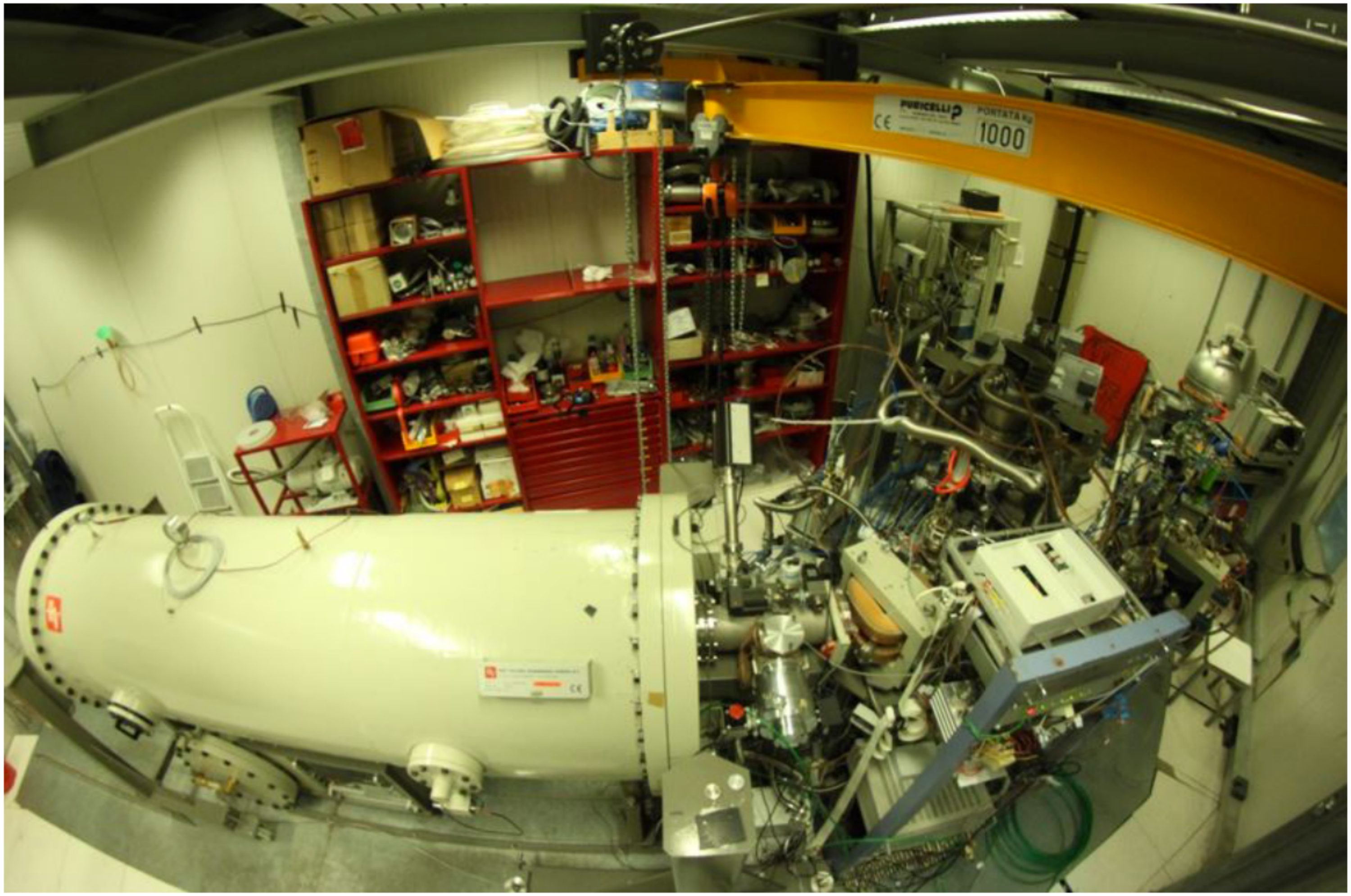


Figure 1. The LUNA400 facility in operation in the underground laboratory of Gran Sasso, Italy

THE A, B AND C OF GRAN SASSO

Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.