Sterrewacht
Leiden

Origins & Evolution of the Universe

an introduction to cosmology – Fall 2014

Did you register for the exam?

Big Bang Nucleosynthesis

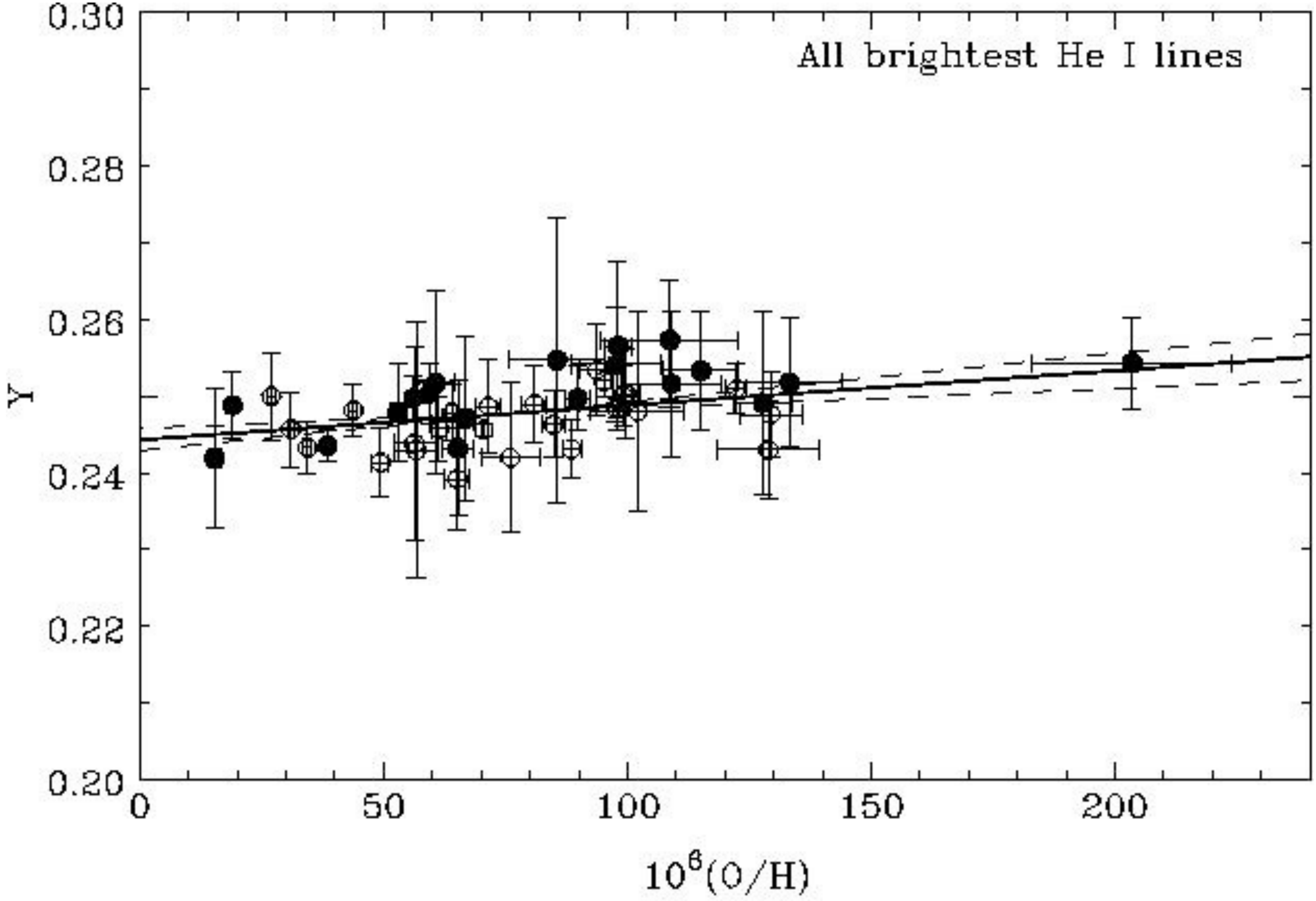
Towards the end of the lepton era nuclear physics begins to take place in the (trace) heavy particles, protons & neutrons.

Atmospheres of main-sequence stars consist of ≈25% ^{4}He by mass (or 6% by number). We observe only a small trend with age and metallicity: must be close to the primordial abundance.

Abundance of ^{4}He: $Y \approx 0.25$; $^3\text{He} \approx 10^{-3} Y$; $^2\text{H} = \text{D} \approx 0.02 Y$

Observational challenge: the observed abundances are affected by late-time affects: pollution due to stellar nuclear reactions, but also cosmic-ray bombardments).

Big Bang Nucleosynthesis



Big Bang Nucleosynthesis

The mass difference m_n - m_p =1.29 MeV means there will be more protons than neutrons.

As long as the neutrinos are coupled, the nuclei are in thermal equilibrium with a ratio

$$e^{-\Delta mc^2/k_B T}$$

At t≈2s, the cross section for weak interactions is too small to maintain equilibrium and the ratio freezes our at a ratio $n_n/n_p \approx 0.2$.

If all neutrons are captured then $Y_{max}=0.33$

Formation of Deuterium

At $T>10^9$K the baryons are in the form of free protons and neutrons.

As the temperature drops the neutron are being captured to form deuterium

Once there is sufficient deuterium ^{3}He and ^{3}H is formed which is then mostly fused into ^{4}He.

The yields depend on η, which determines when nucleosynthesis starts.

Big Bang Nucleosynthesis

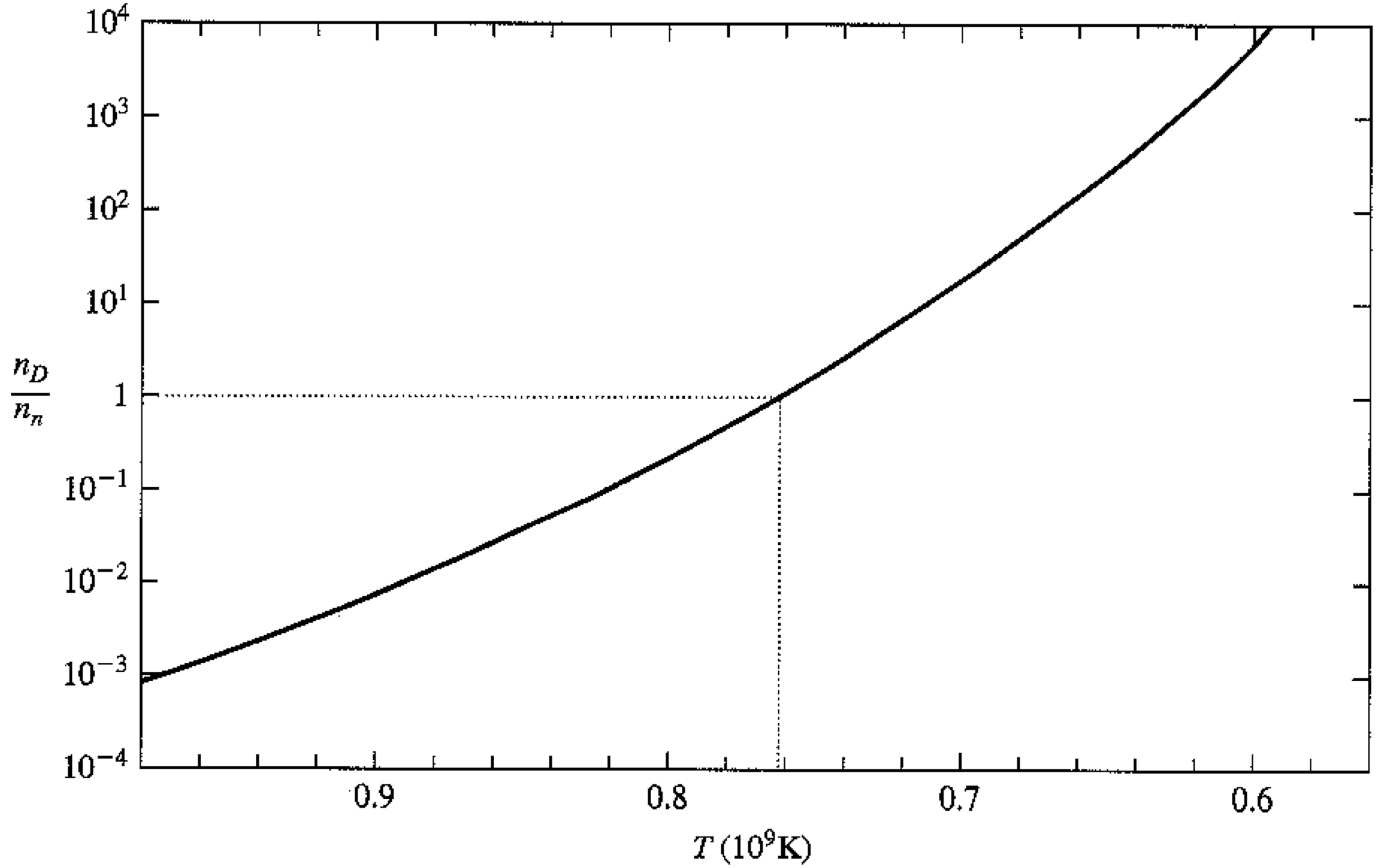
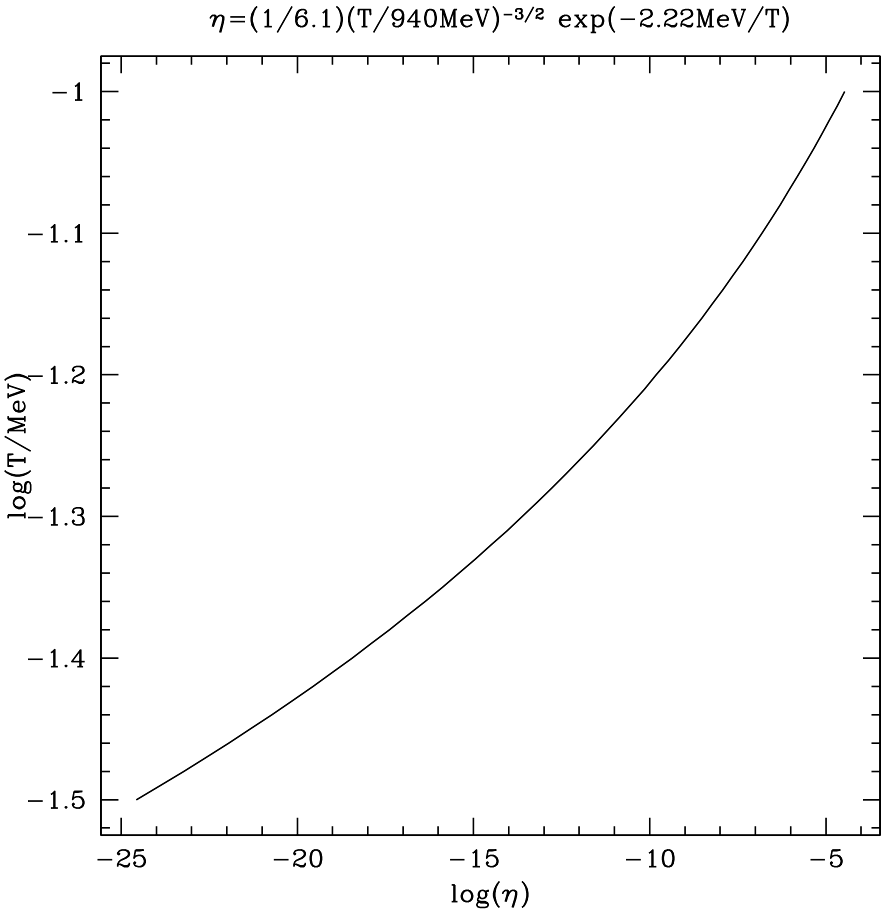


FIGURE 10.3 The deuterium-to-neutron ratio during the epoch of deuterium synthesis. The

Big Bang Nucleosynthesis



Note onset of deuterium formation is strong function of baryon-to-photon ratio η (and hence of GUT-scale baryon asymmetry!)

Beyond Deuterium

D formation is the onset of nucleosynthesis, but not the end: D is very reactive at these temperatures

Many more reactions possible

- proton capture $D + p \leftrightarrow {}^3He + \gamma$
- neutron capture $D + n \leftrightarrow {}^3H + \gamma$
- formation of α particle (rare) $D + D \leftrightarrow {}^4He + \gamma$
- Tritium formation $D + D \leftrightarrow {}^3H + p$
- ^{3}He formation $D + D \leftrightarrow {}^3He + n$

Note Tritium (^{3}H) has half-life of 18 years: infinity!

The bottleneck

Helium-3 and Tritium quickly convert to Helium-4

- many pathways
- strong interactions, fast

$$
\begin{aligned}
{}^3H + p &\leftrightarrow {}^4He + \gamma \\
{}^3He + n &\leftrightarrow {}^4He + \gamma \\
{}^3H + D &\leftrightarrow {}^4He + n \\
{}^3He + D &\leftrightarrow {}^4He + p
\end{aligned}
$$

Then hit the 'helium gap'.

- hard to form elements larger than ^{4}He

The bottleneck

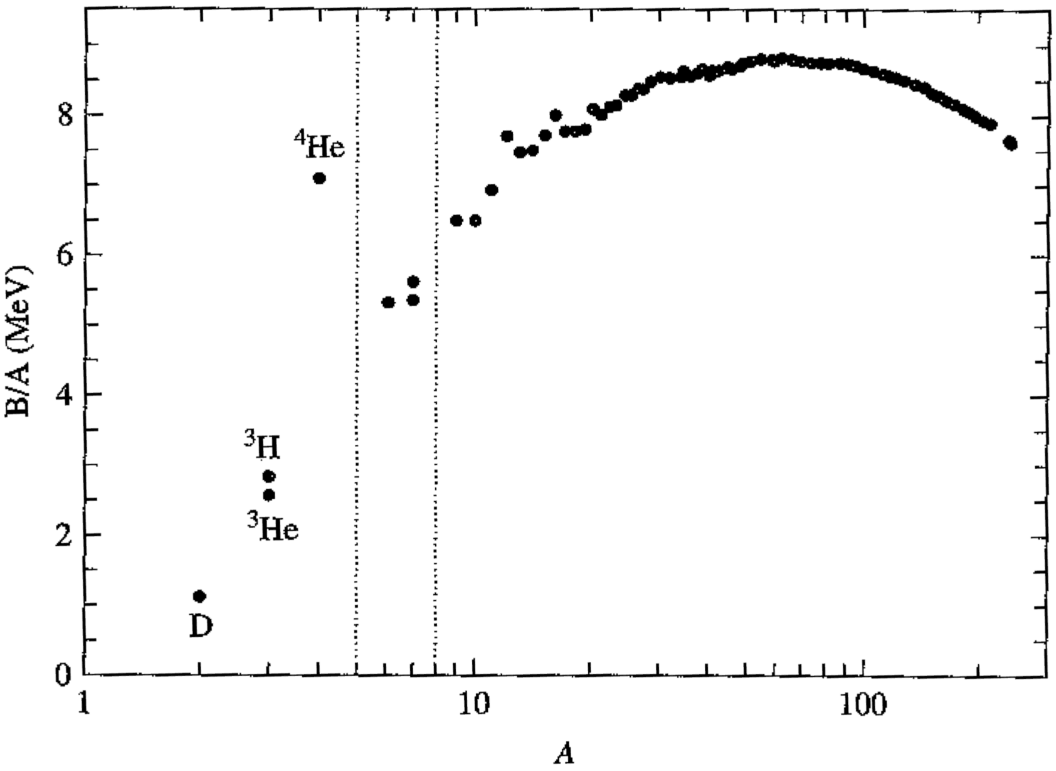
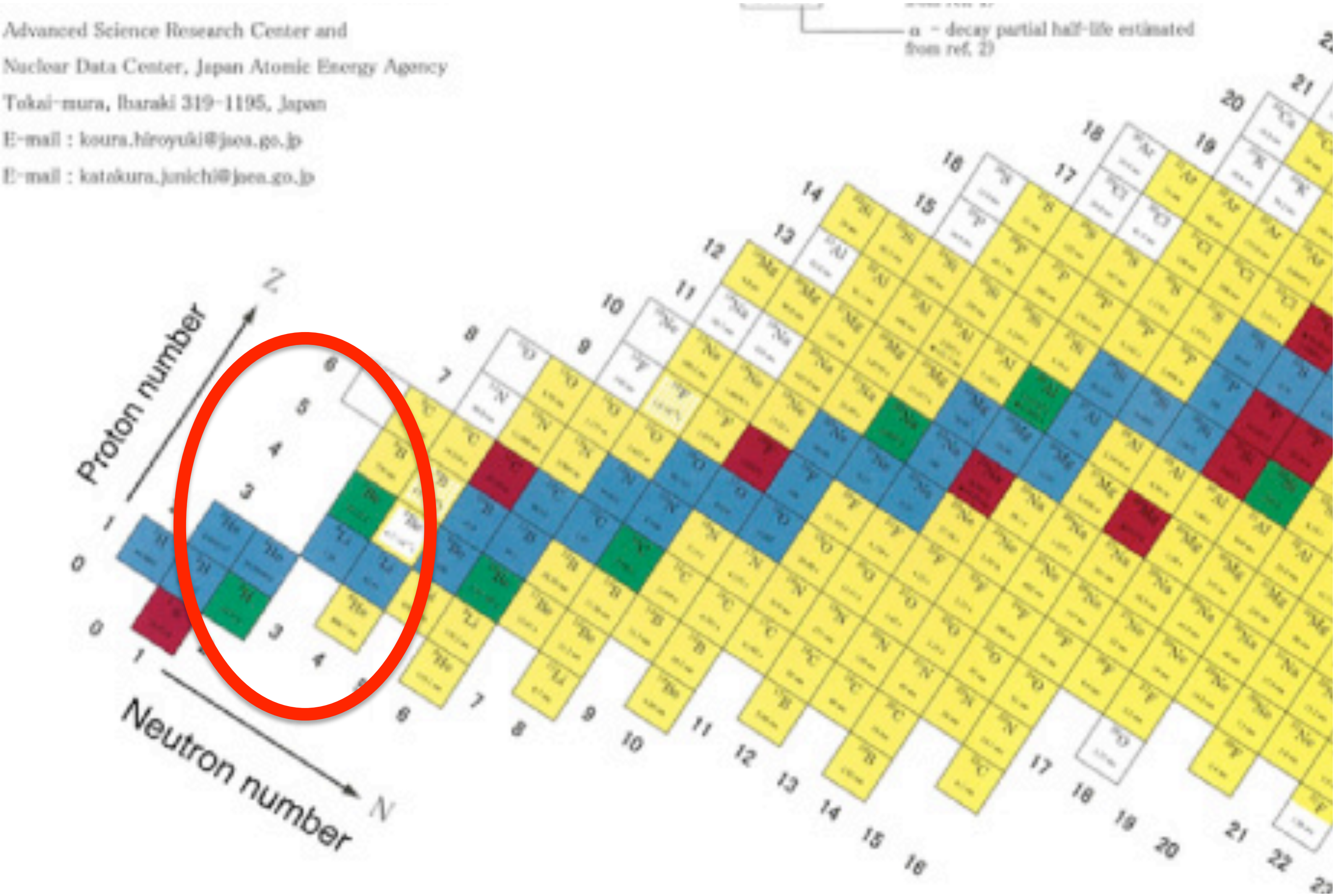


FIGURE 10.1 The binding energy per nucleon (B/A) as a function of the number of nucleons (protons and neutrons) in an atomic nucleus. Note the absence of nuclei at $A = 5$ and $A = 8$.

Binding energy per nucleon = $(m_{nucl} - Zm_p - Nm_n)c^2/A$

^{56}Fe, ^{62}Ni most stable nuclei - ^{4}He also stands out

The bottleneck



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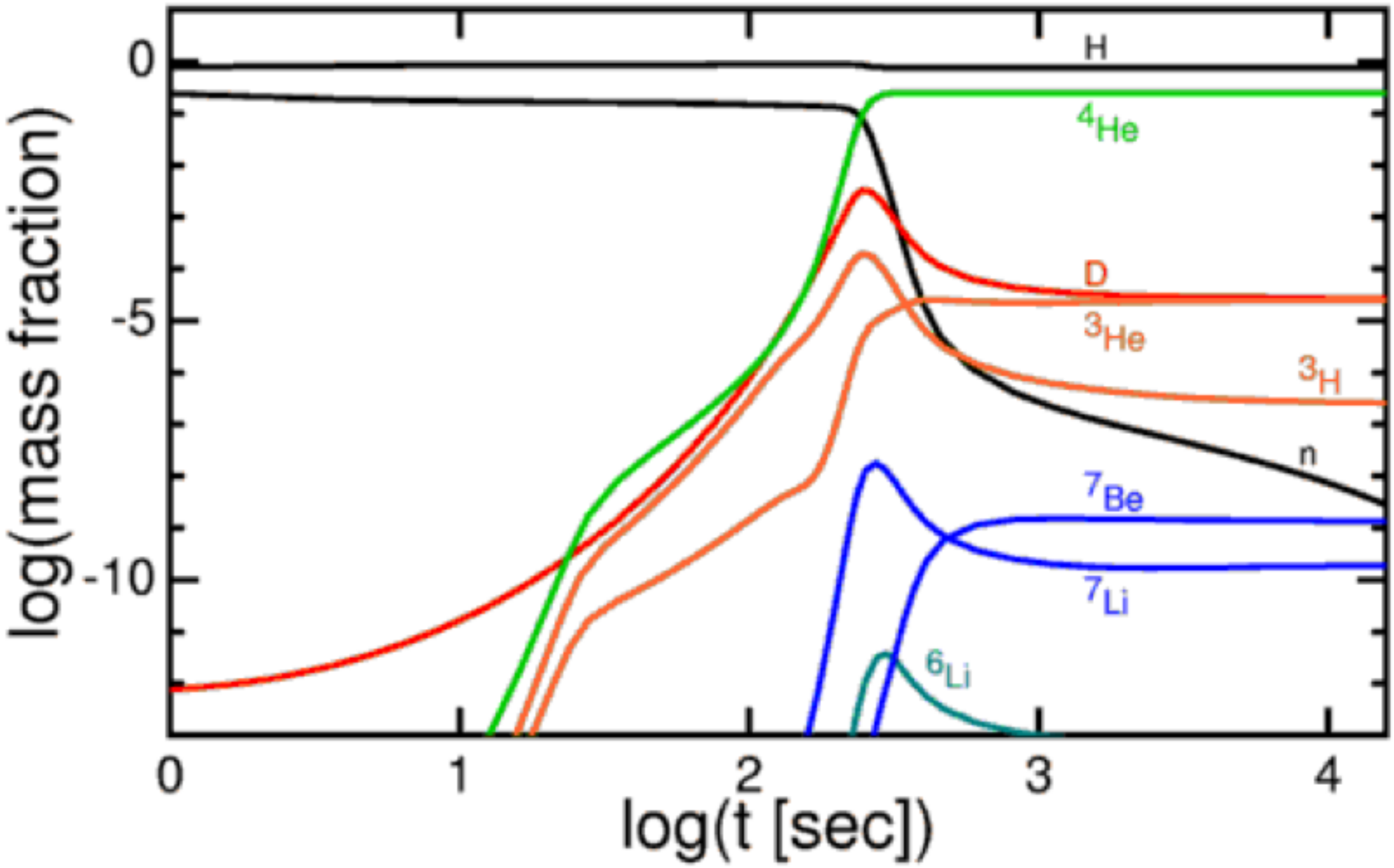
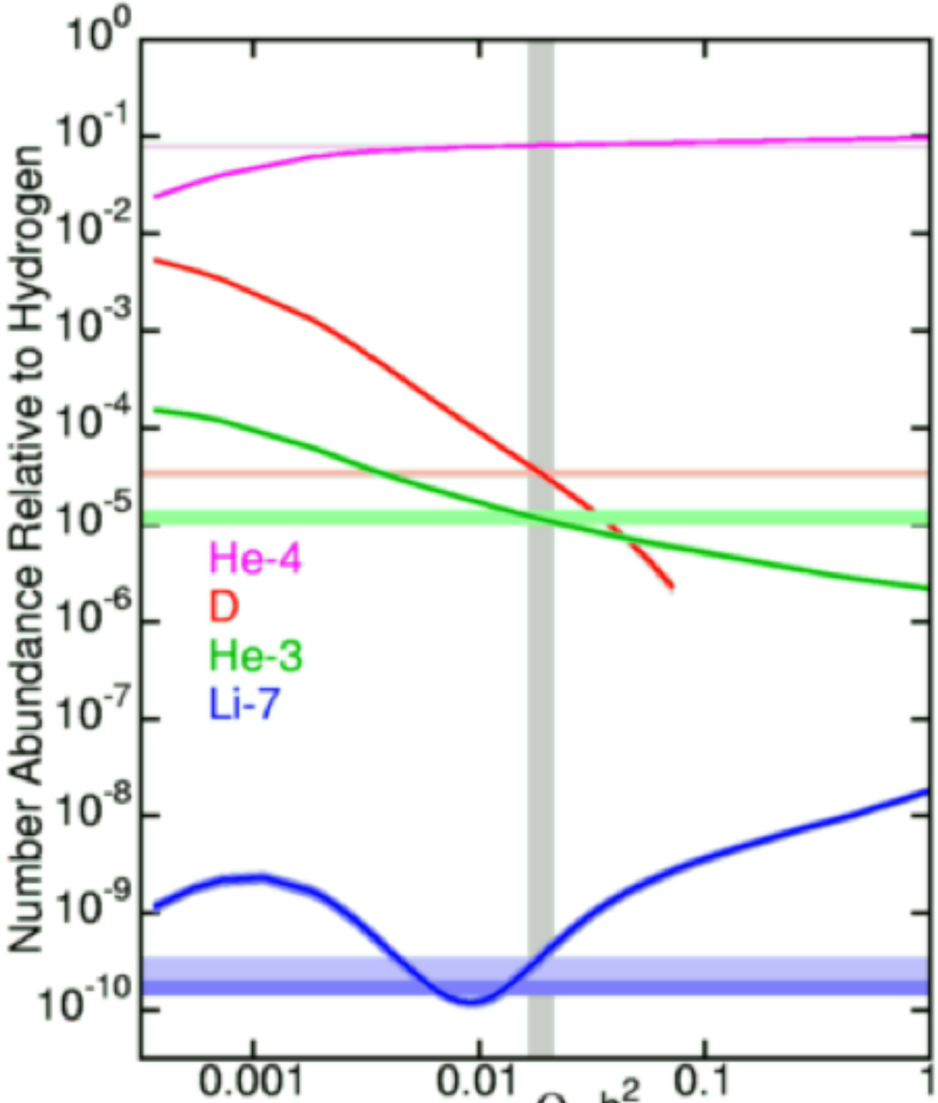
BBN calculations



Consistency with observations!



What do we learn from BBN?

- ^{4}He: extrapolating abundance in old, low-metallicity stars to zero metallicity gives Y=23.4%.
- D: affected by stellar processes and hard to measure (isotopic Lyα line in QSO absorption spectra)
- ^{3}He: destroyed in stars at higher temp than D, but created in destruction of D. So ^{3}He+D together is more useful measurement.
- ^{7}Li: created (cosmic ray spallation) and destroyed in stars. So difficult to interpret.

Consistent picture for $\eta=3.10^{-10}$. This yields $\Omega_b h^2=0.02$. Therefore dark matter is non-baryonic!