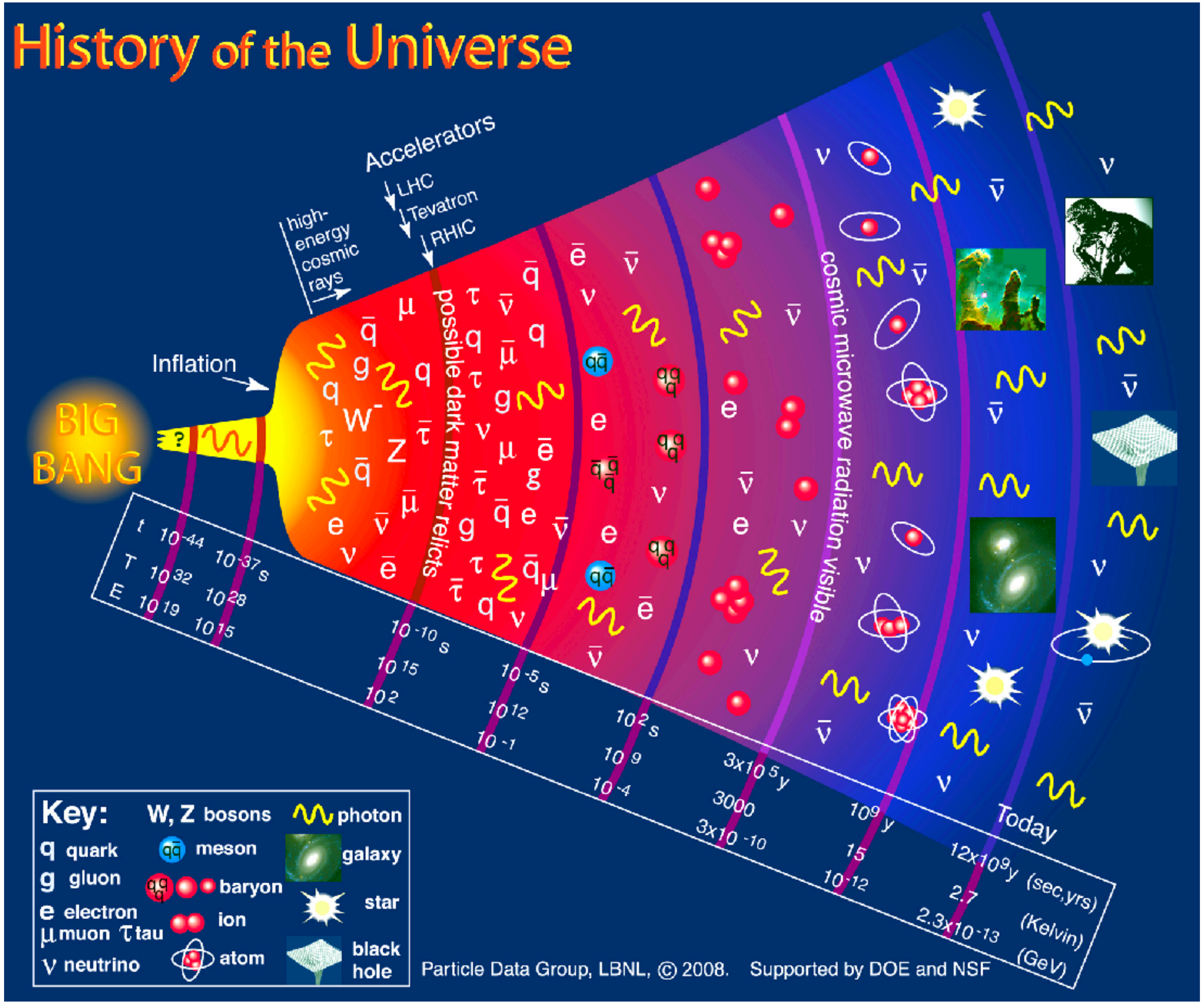
Early Universe and BBN

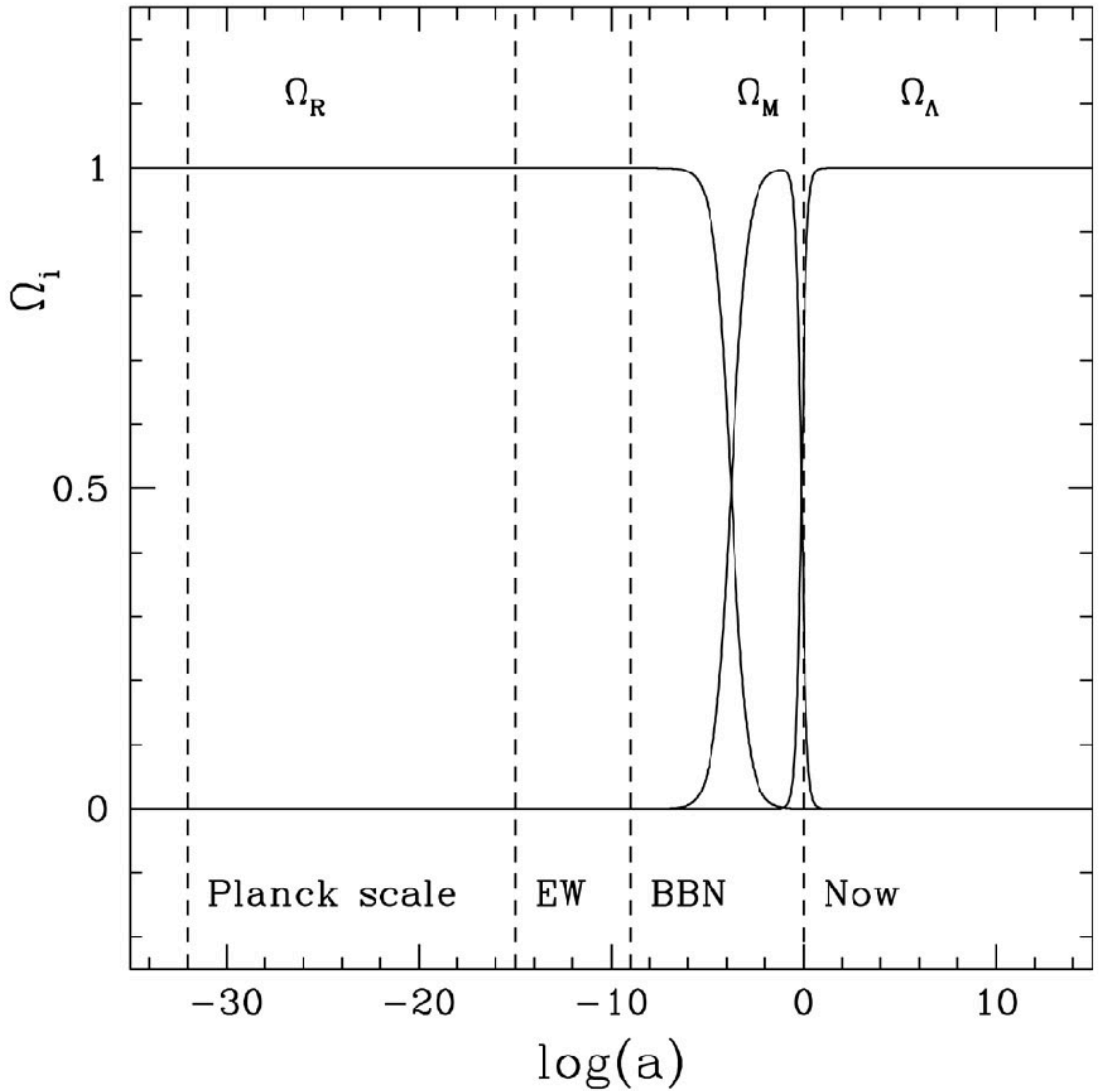
ASTR/PHYS 4080: Intro to Cosmology
Week 9

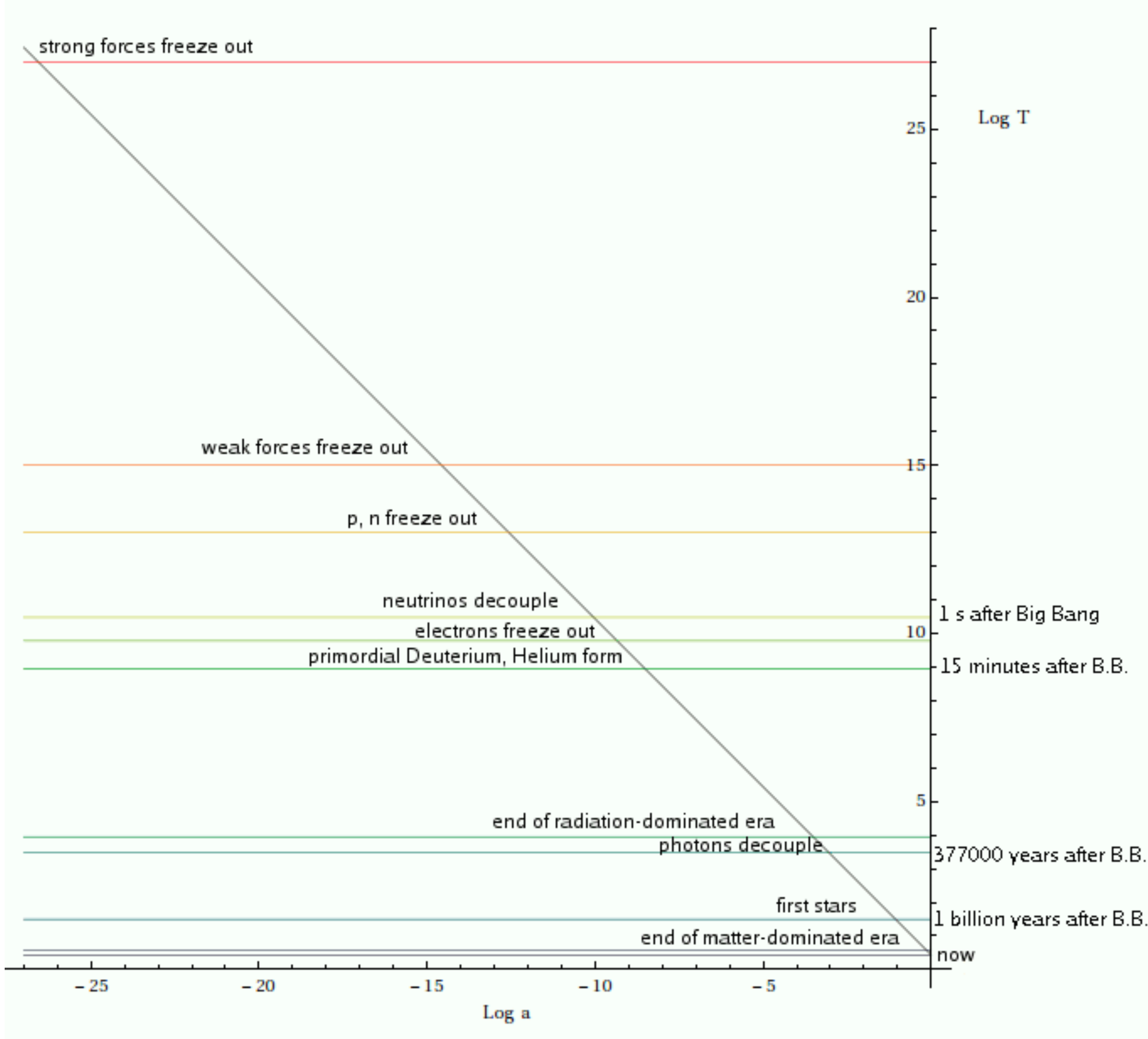
HW 6 due YESTERDAY
HW 7 due on Friday

Today:
Finish CMB (Ch. 8)
Start BB Nucleosynthesis (Ch. 9)

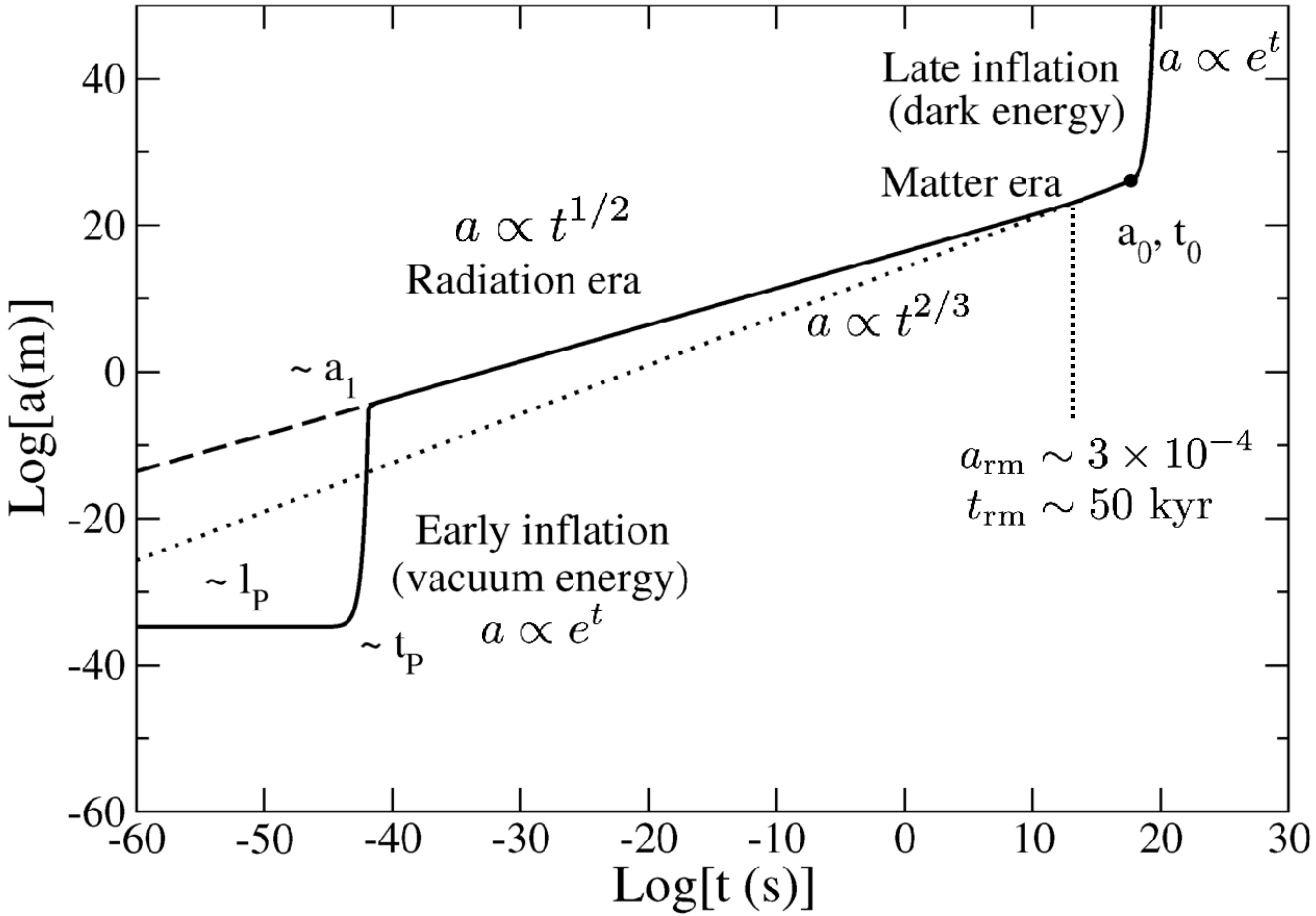


Early Universe Timescales

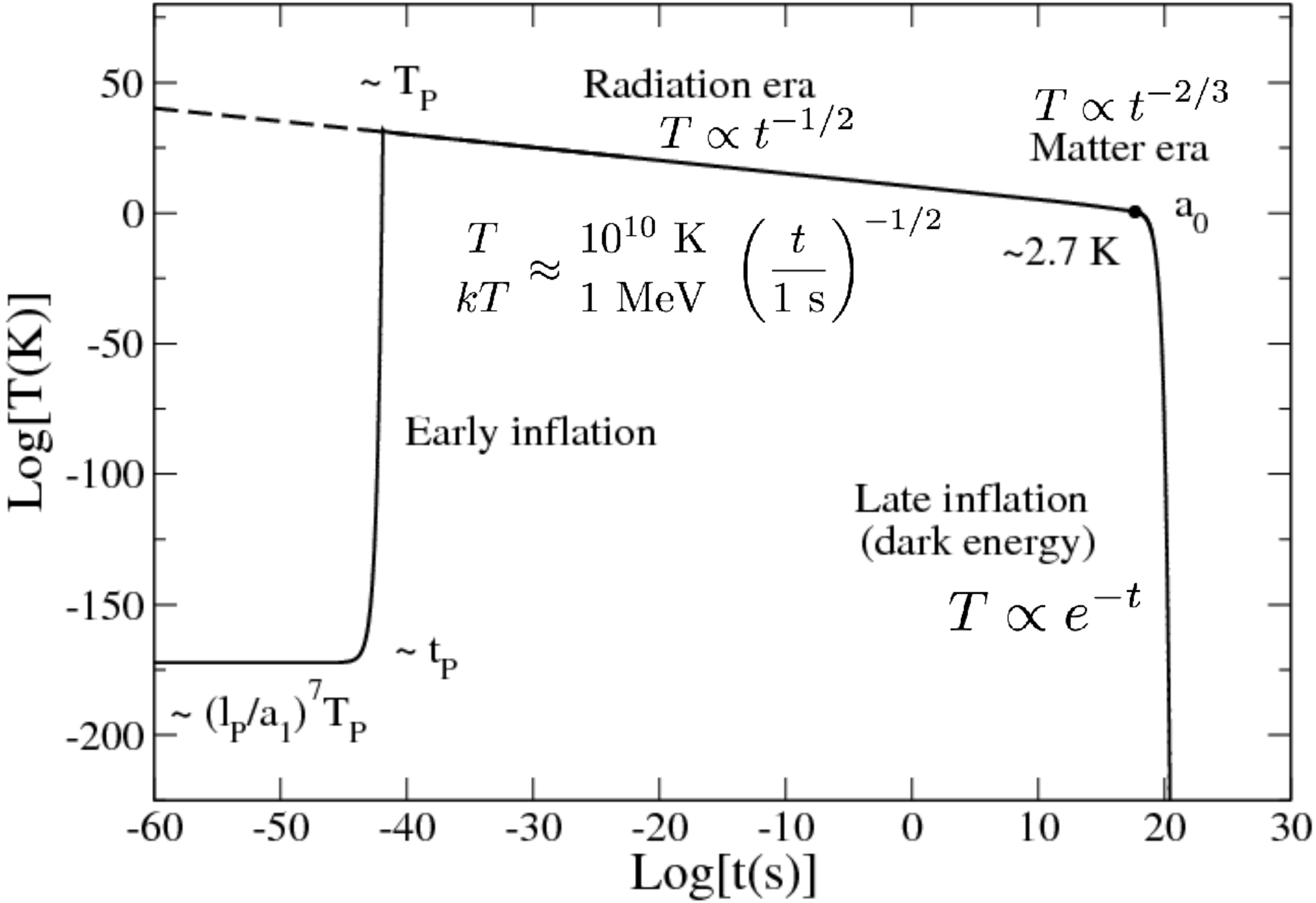




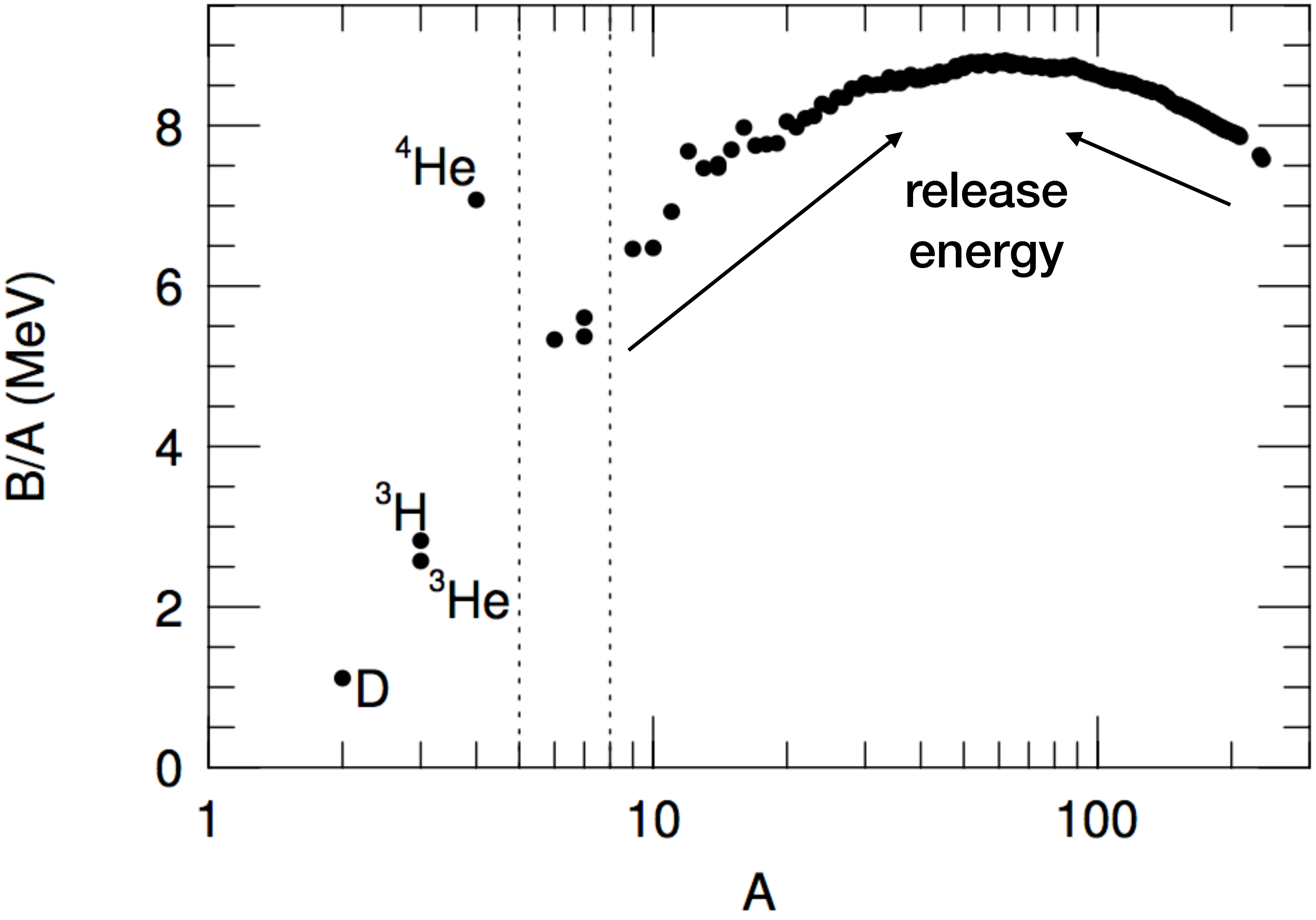
Early Universe Timescales



Early Universe Timescales



Nuclear Binding Energy



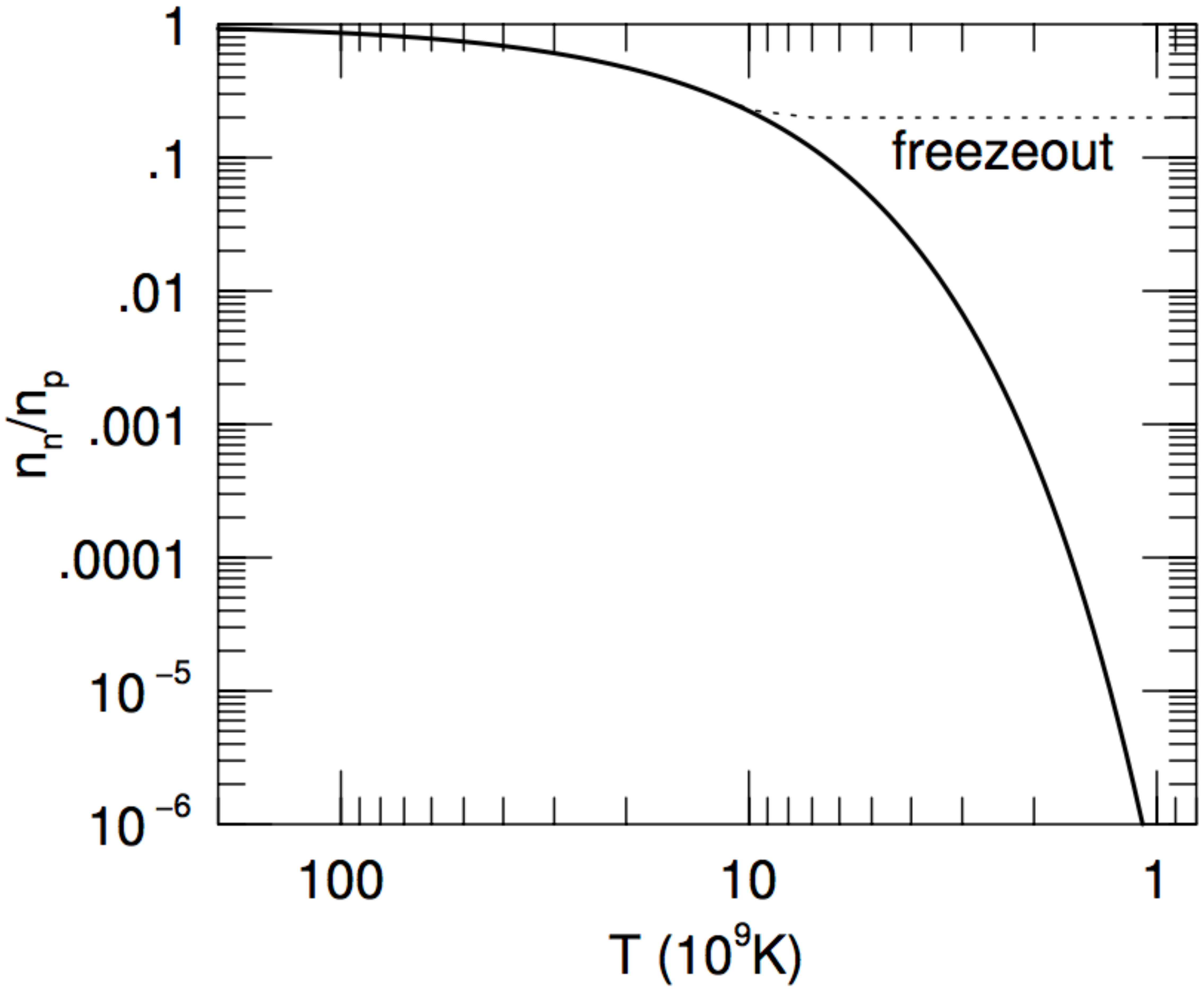
$$p + n \rightleftharpoons D + 2.22 \text{ MeV}$$

expect nucleosynthesis to result in all atoms becoming iron

does not happen - why not?

$$Y_p \equiv \frac{\rho(^4\text{He})}{\rho_{\text{bary}}}$$

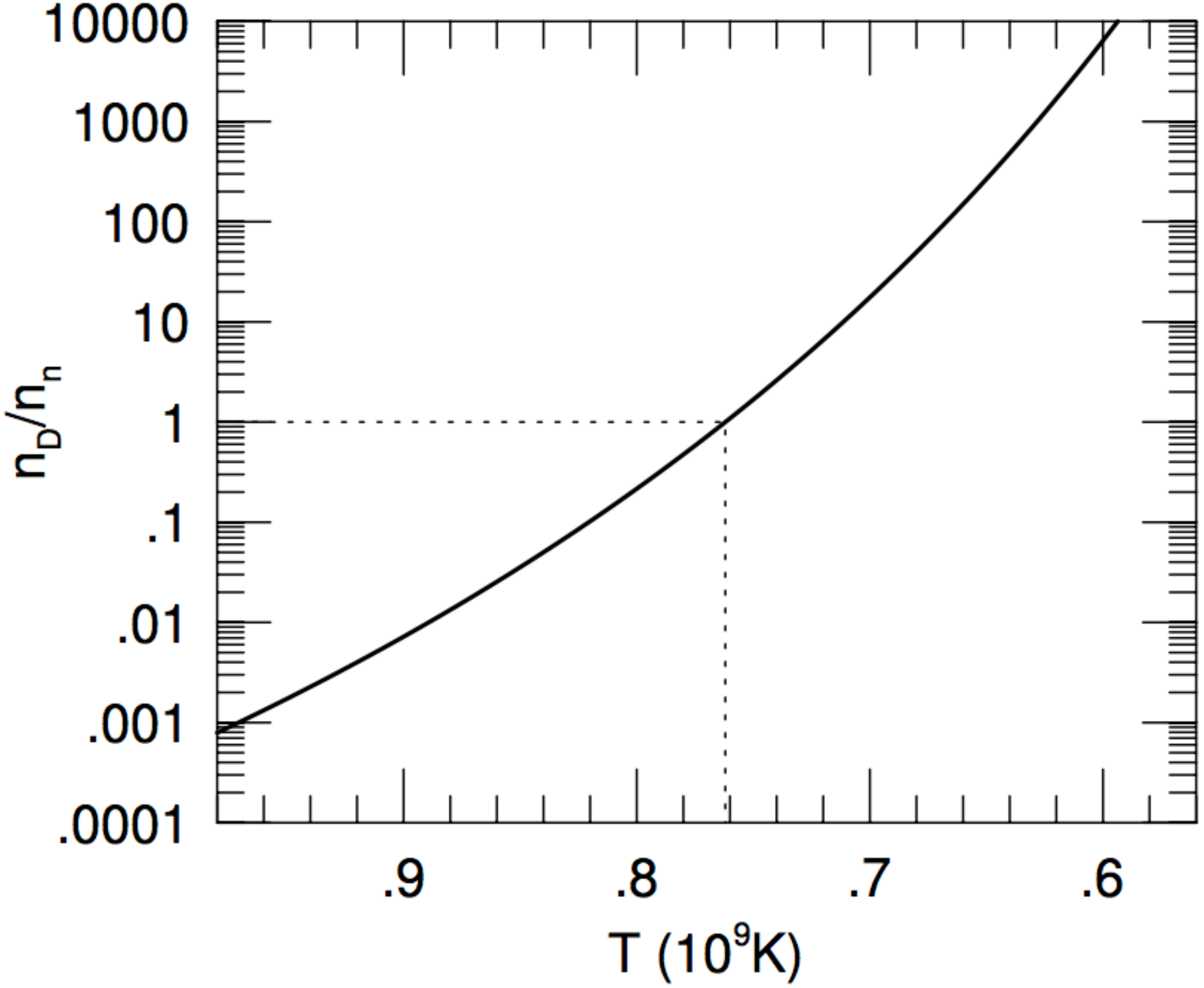
neutron-proton ratio



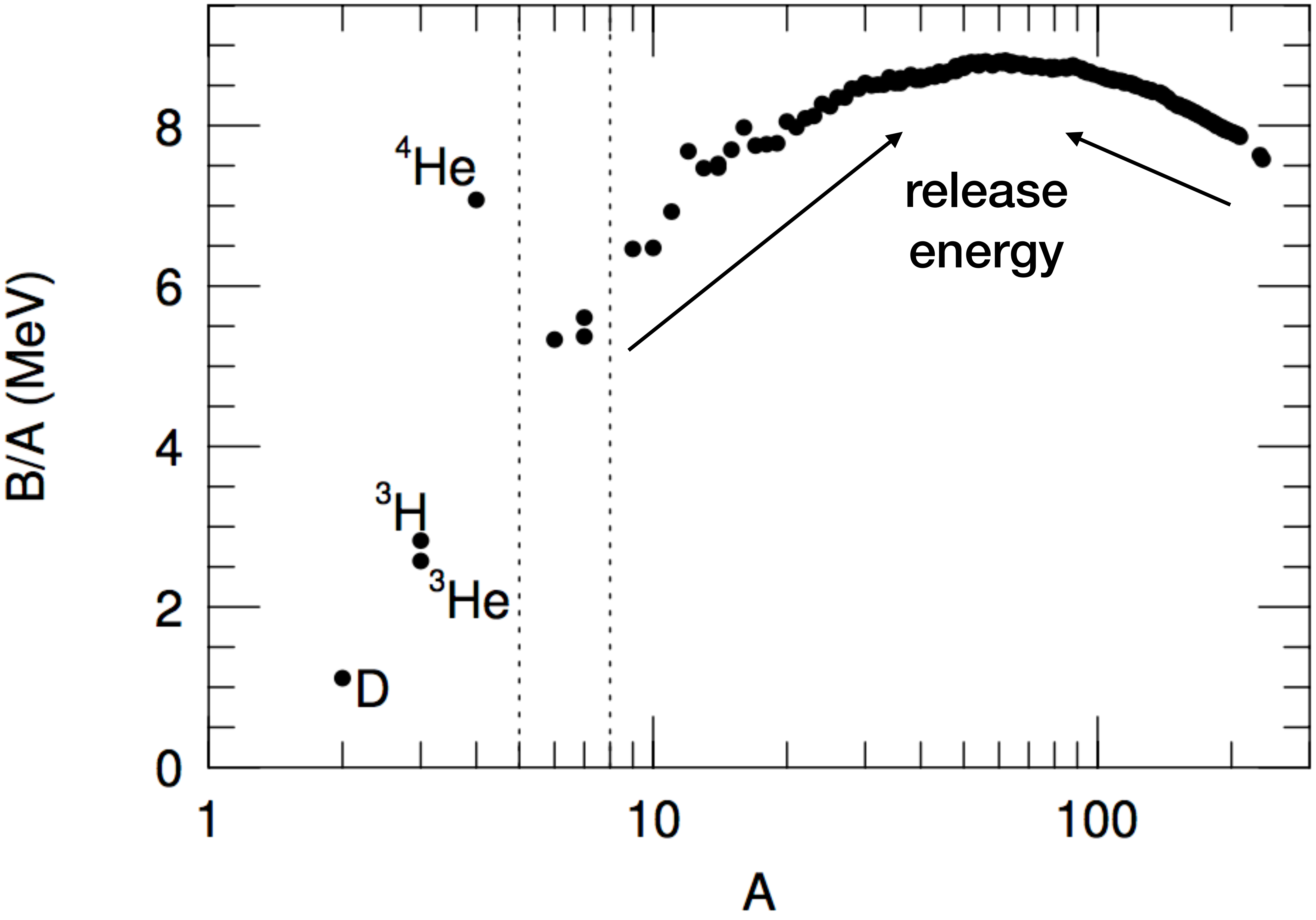
$$n_x = g_x \left(\frac{m_x kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{-m_x c^2 + \mu_x}{kT}\right)$$

$$\frac{n_n}{n_p} = \exp\left(-\frac{(m_n - m_p)c^2}{kT}\right)$$

Deuterium Synthesis



Making He



after 200s, all non-decayed neutrons could end up in a D nucleus, BUT D reactions can also occur:

$$D + p \rightleftharpoons {}^3\mathrm{He} + \gamma$$

$$D + p \rightleftharpoons {}^3\mathrm{H} + \gamma$$

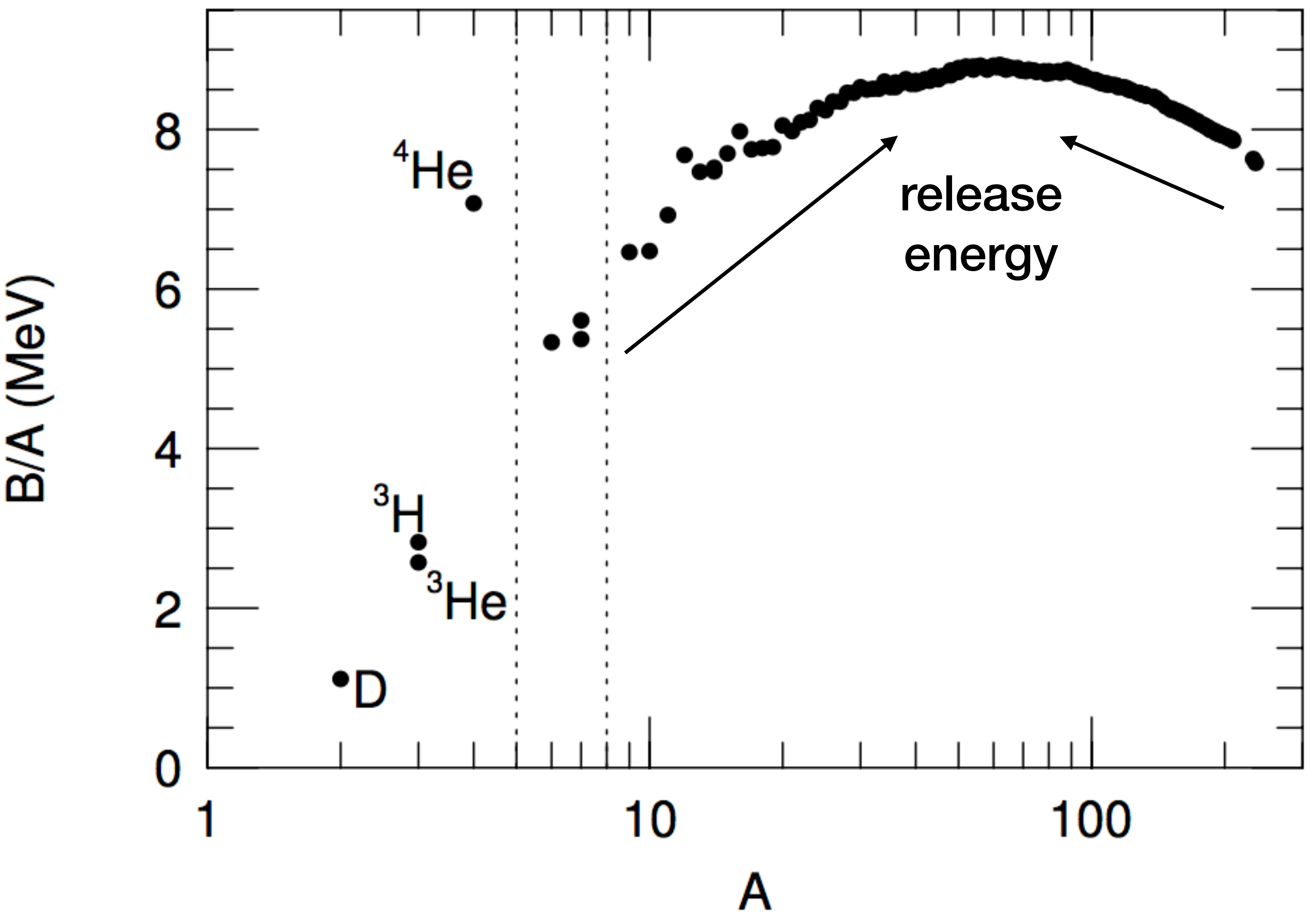
$$D + D \rightleftharpoons {}^4\mathrm{He} + \gamma$$

more likely:

$$D + D \rightleftharpoons {}^3\mathrm{H} + p$$

$$D + D \rightleftharpoons {}^3\mathrm{He} + n$$

Making He

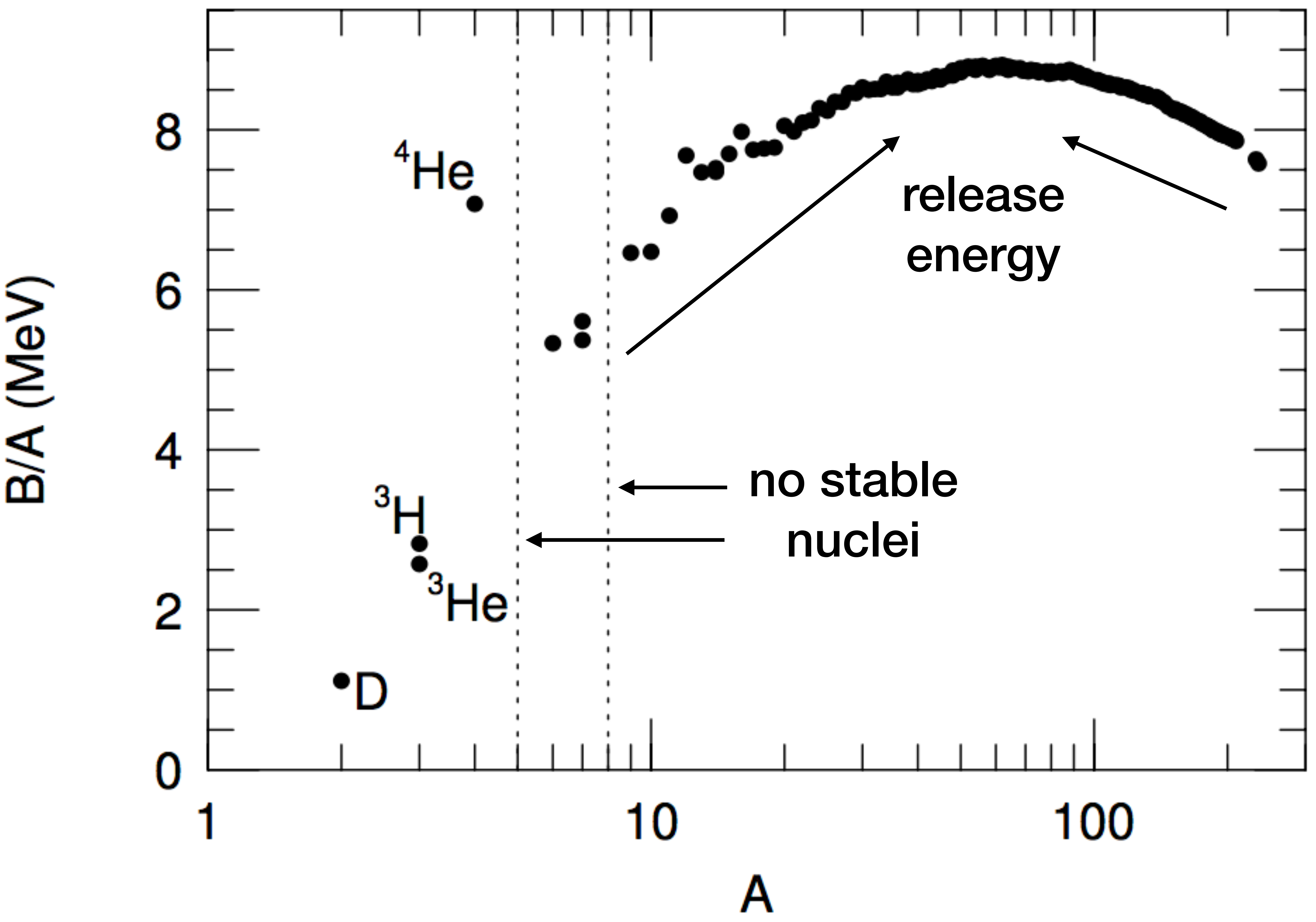


Tritium and He-3 quickly interact with other particles to form He-4:

$$^3\mathrm{H} + p \rightleftharpoons {}^4\mathrm{He} + \gamma$$
$$^3\mathrm{He} + n \rightleftharpoons {}^4\mathrm{He} + \gamma$$
$$^3\mathrm{H} + D \rightleftharpoons {}^4\mathrm{He} + n$$
$$^3\mathrm{He} + D \rightleftharpoons {}^4\mathrm{He} + p$$

Strong force reactions: large cross-sections and fast rates
End up with mostly He-4, since it's so tightly bound

Making He



Can't add p or n to He-4 to make a new atom, so have to use later products to form Li/Be nuclei

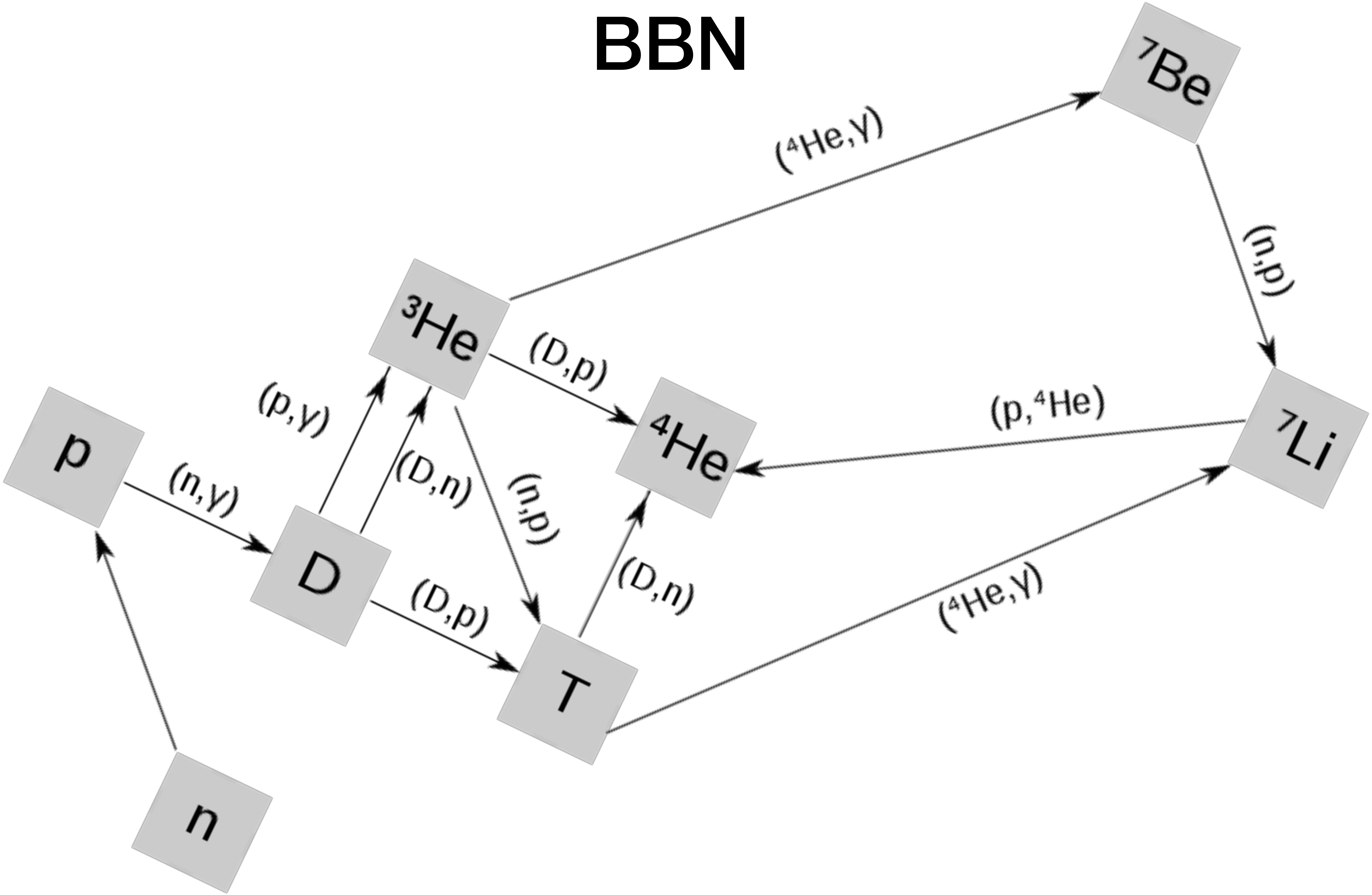
$$^4\mathrm{He} + D \rightleftharpoons {}^6\mathrm{Li} + \gamma$$

$$^4\mathrm{He} + {}^3\mathrm{H} \rightleftharpoons {}^7\mathrm{Li} + \gamma$$

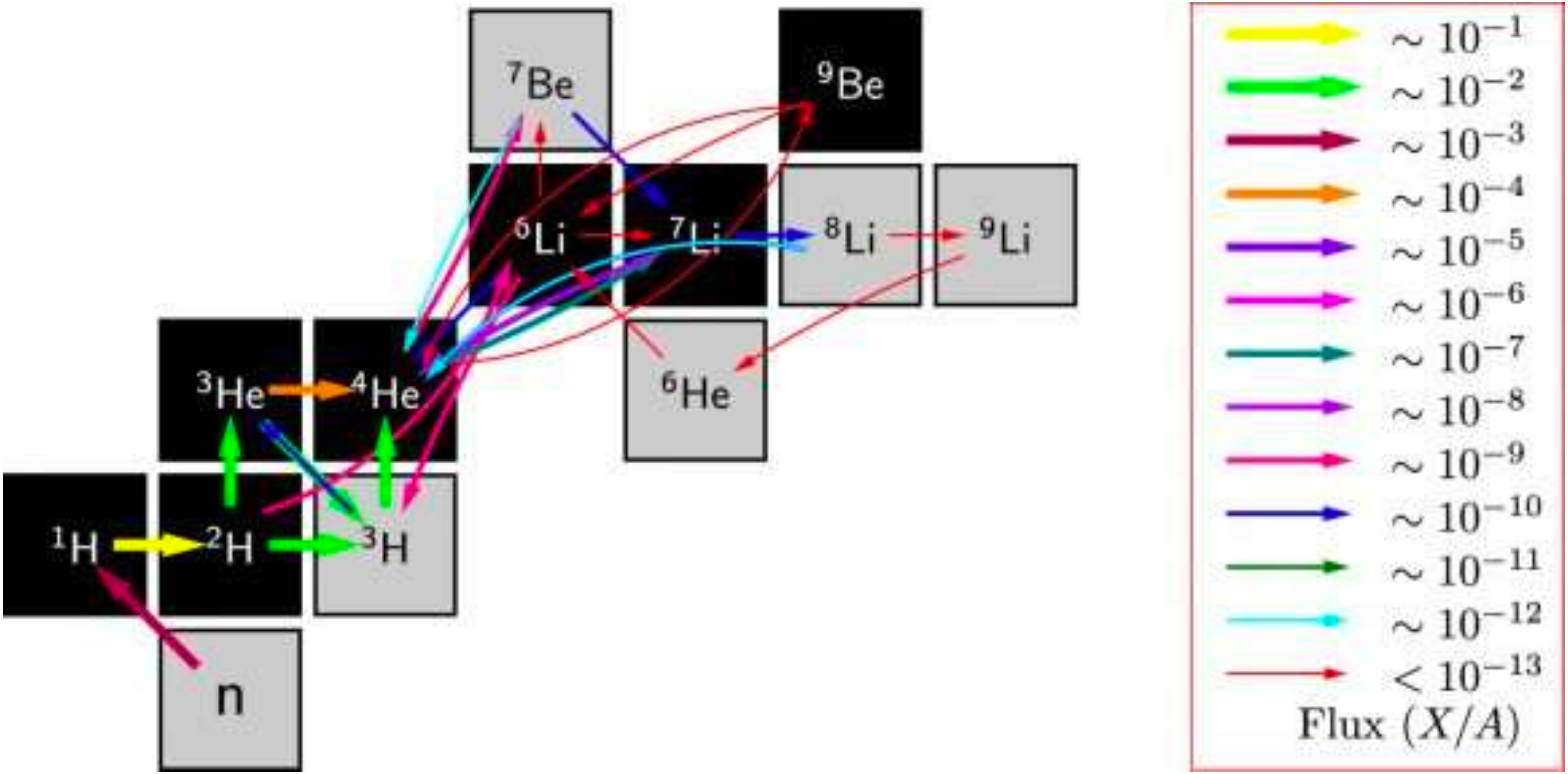
$$^4\mathrm{He} + {}^3\mathrm{He} \rightleftharpoons {}^7\mathrm{Be} + \gamma$$

Stable He-4 is made quickly, but harder to form higher A elements so their creation is slower

BBN

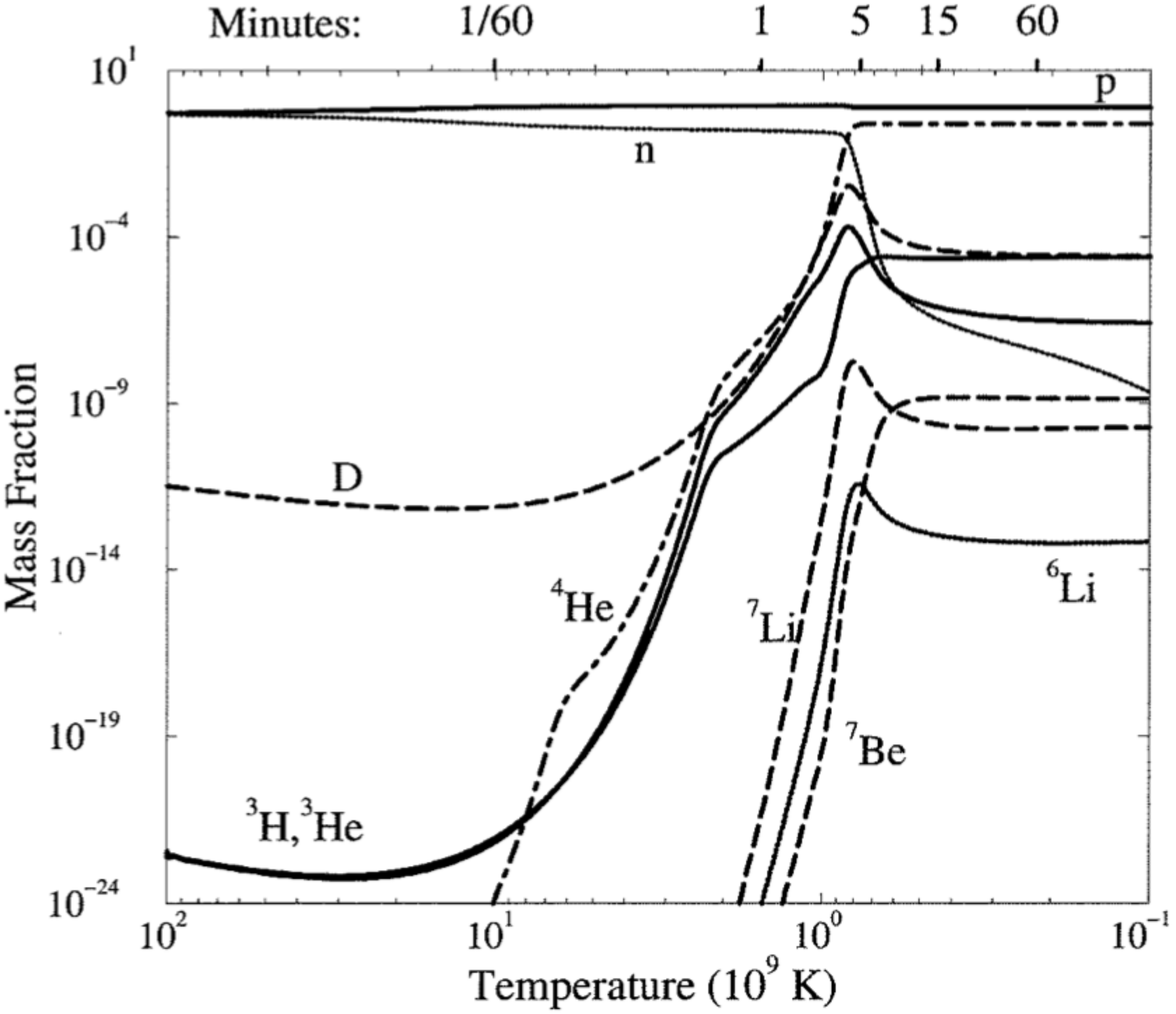


BBN



^{7}Be
^{9}Be
^{6}Li
^{7}Li
^{8}Li
^{9}Li
^{3}He
^{4}He
^{6}He
^{1}H
^{2}H
^{3}H
n
$\sim 10^{-1}$
$\sim 10^{-2}$
$\sim 10^{-3}$
$\sim 10^{-4}$
$\sim 10^{-5}$
$\sim 10^{-6}$
$\sim 10^{-7}$
$\sim 10^{-8}$
$\sim 10^{-9}$
$\sim 10^{-10}$
$\sim 10^{-11}$
$\sim 10^{-12}$
$< 10^{-13}$
Flux (X/A)

Abundances from Nucleosynthesis

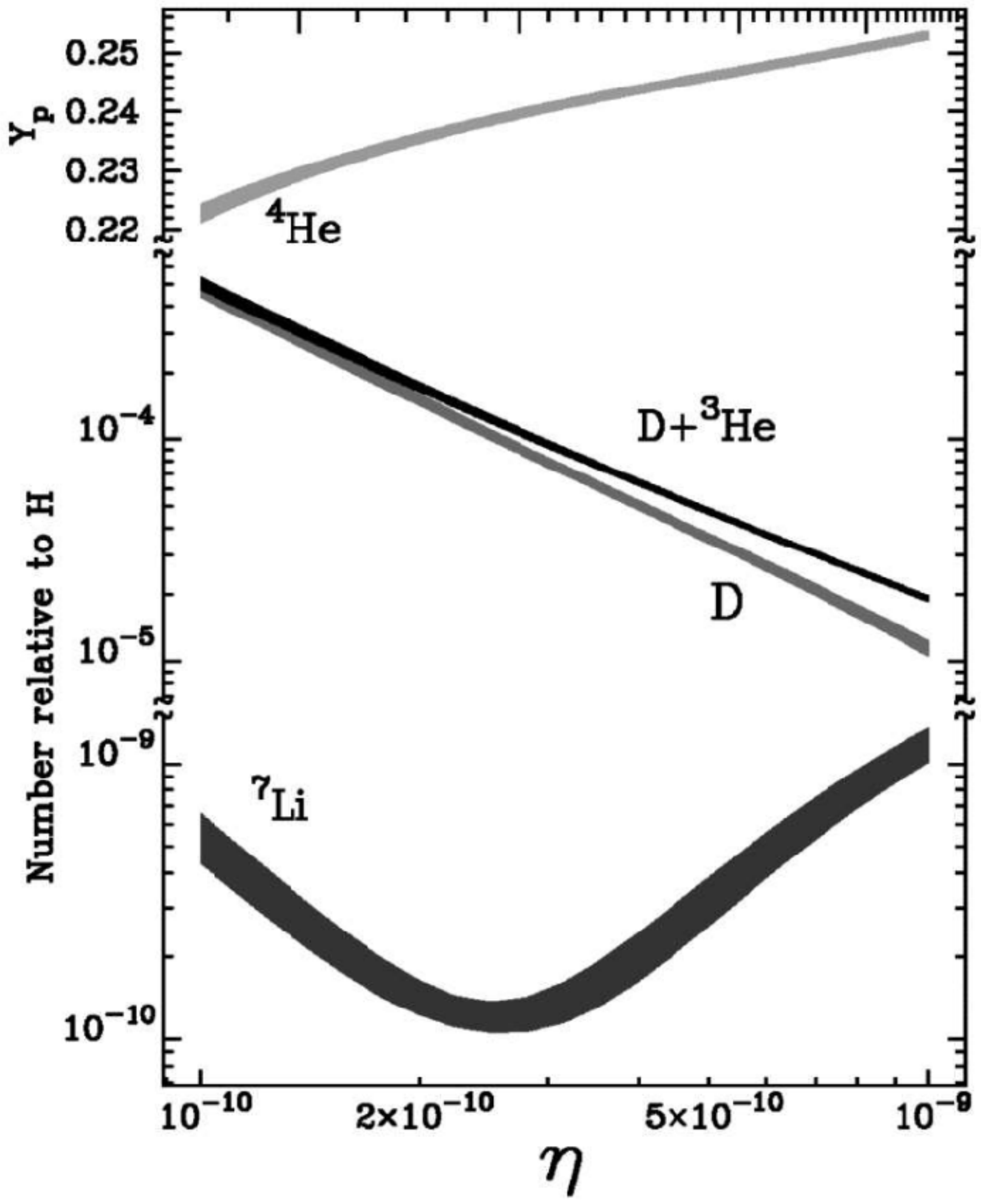


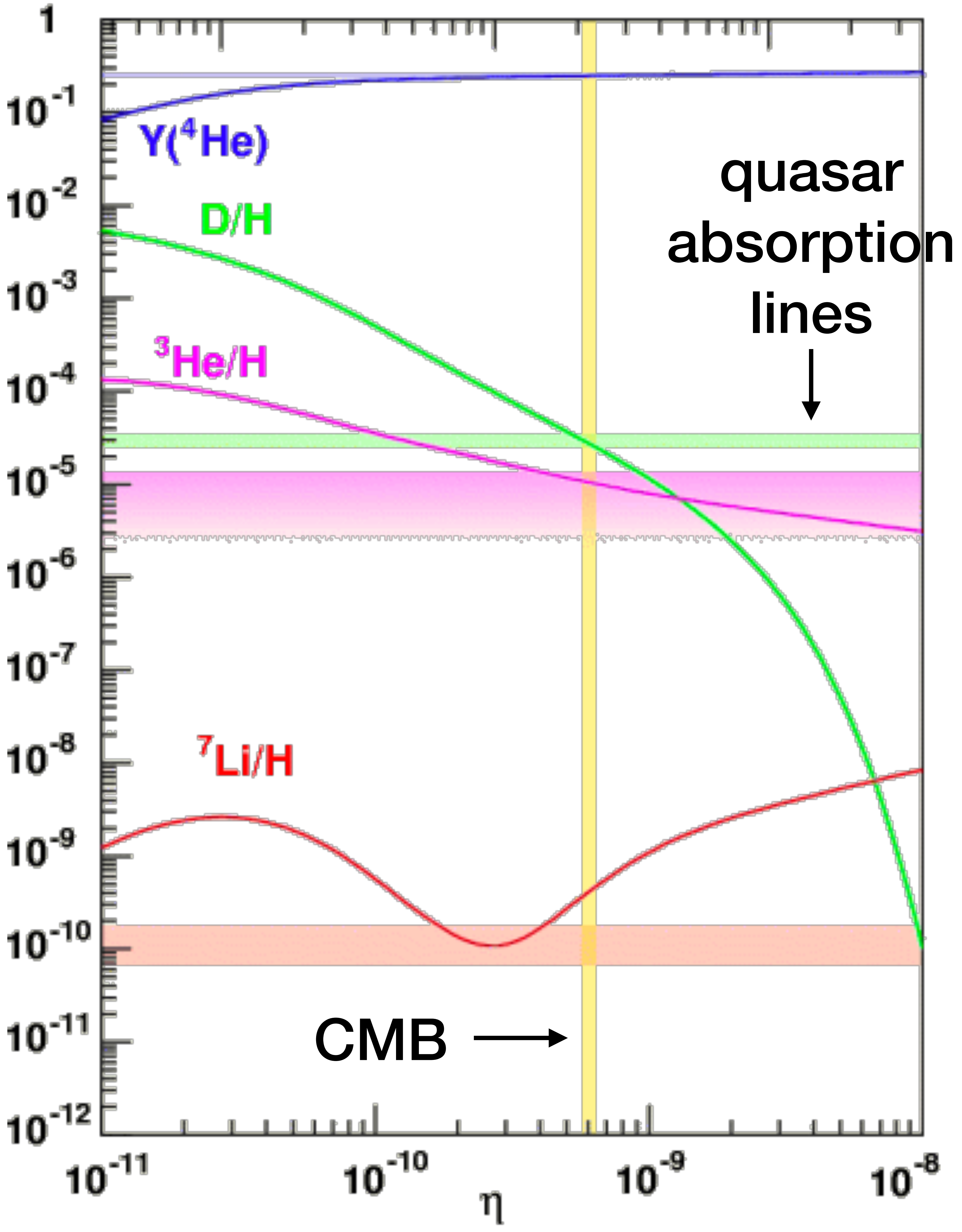
Creation process depends on relative abundances at any given time, so have to calculate computationally

Nucleosynthesis doesn't run to completion like in stars — rapidly dropping temperature cuts it off and "freezes" abundance pattern

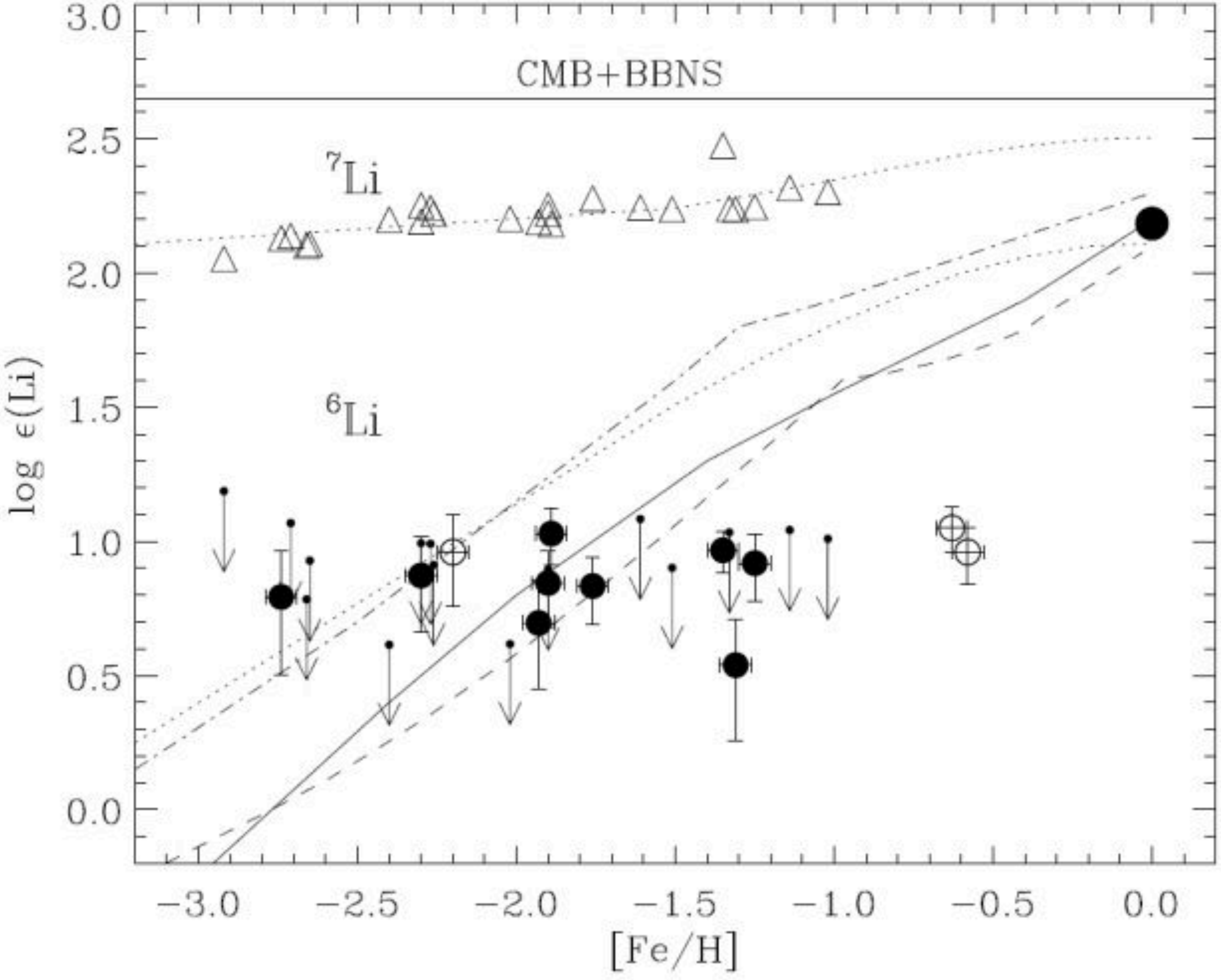
Exact yields depend most on baryon-to-photon ratio: η
(determines temperature of nucleosynthesis)

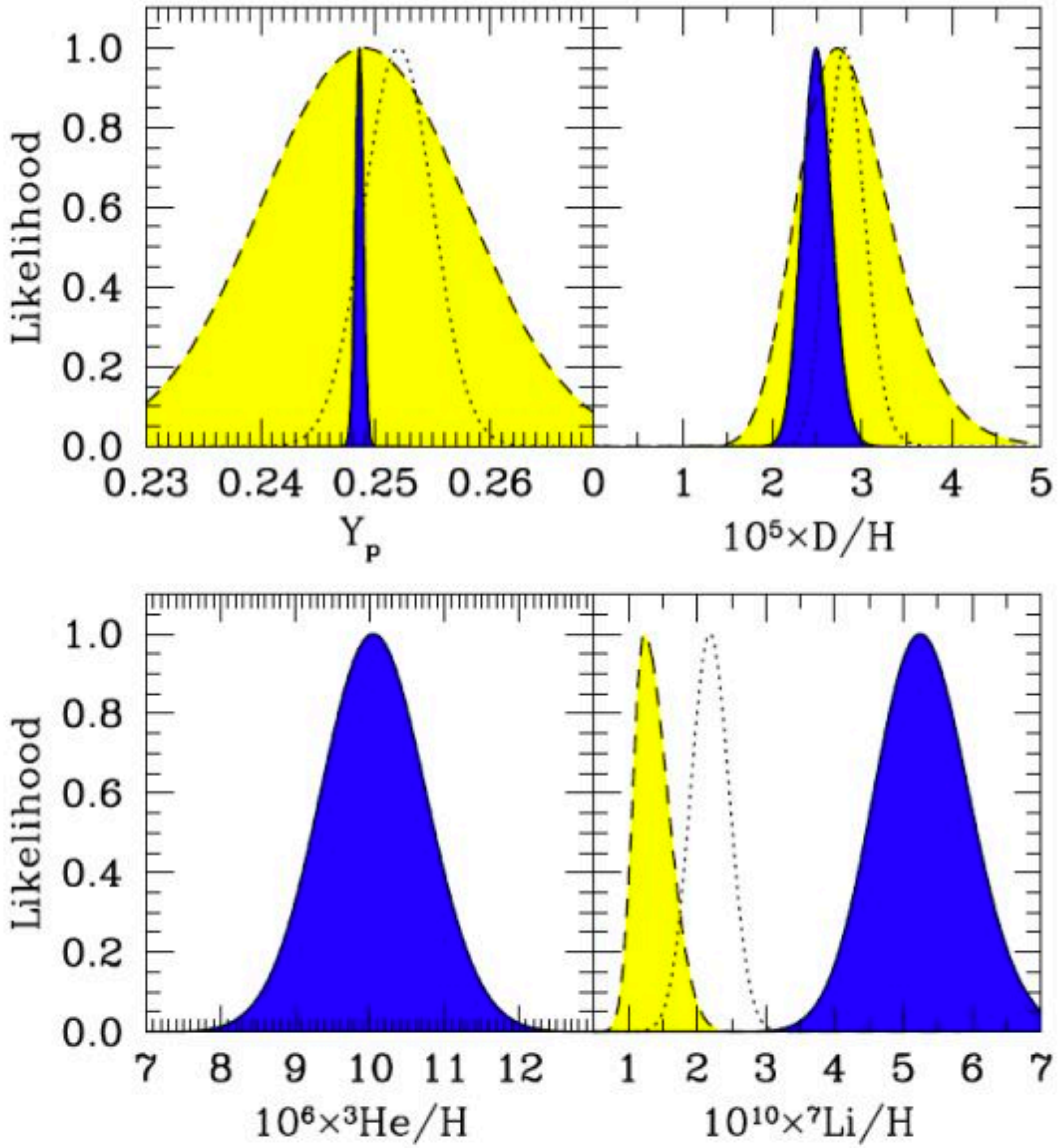
Measuring BBN



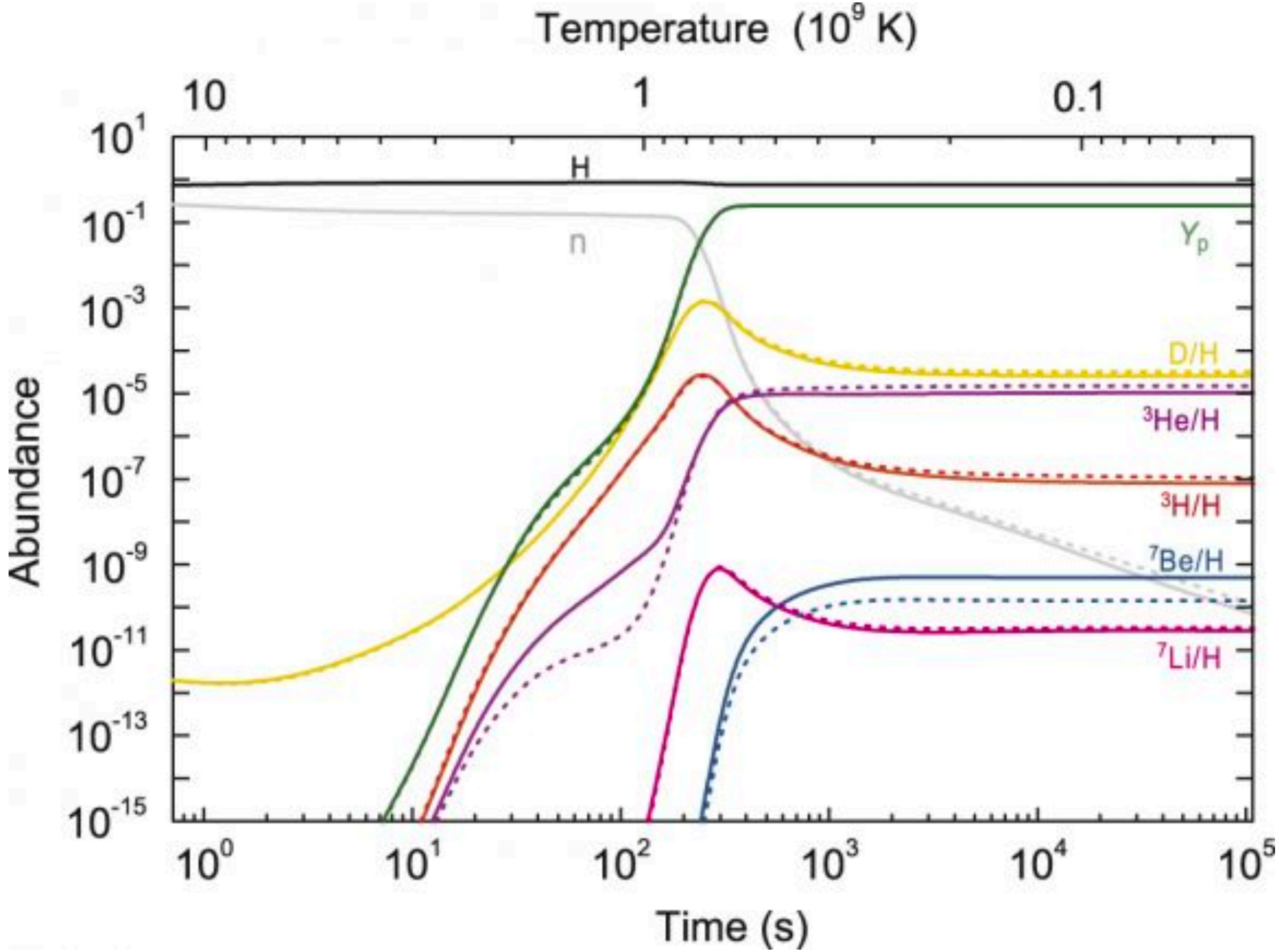


Lithium Problem





Solution?



Temperature (10^9 K)
10
1
0.1
H
n
Y_p
D/H
^{3}He/H
^{3}H/H
^{7}Be/H
^{7}Li/H
Abundance
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Time (s)

Baryon-Antibaryon Asymmetry

no leftover antimatter from the early universe: Standard Model predicts existence of antimatter equally likely

$$\gamma + \gamma \rightleftharpoons q + \bar{q}$$

should be 1 quark-antiquark pair for every 2 photons in the early universe
when temperature drops, quarks annihilate but are no longer produced
—> universe should be entirely photons!

$$\delta_q \equiv \frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \ll 1$$

must be a small asymmetry!

$$\frac{n_q}{n_\gamma} = 3\eta \sim \delta_q$$