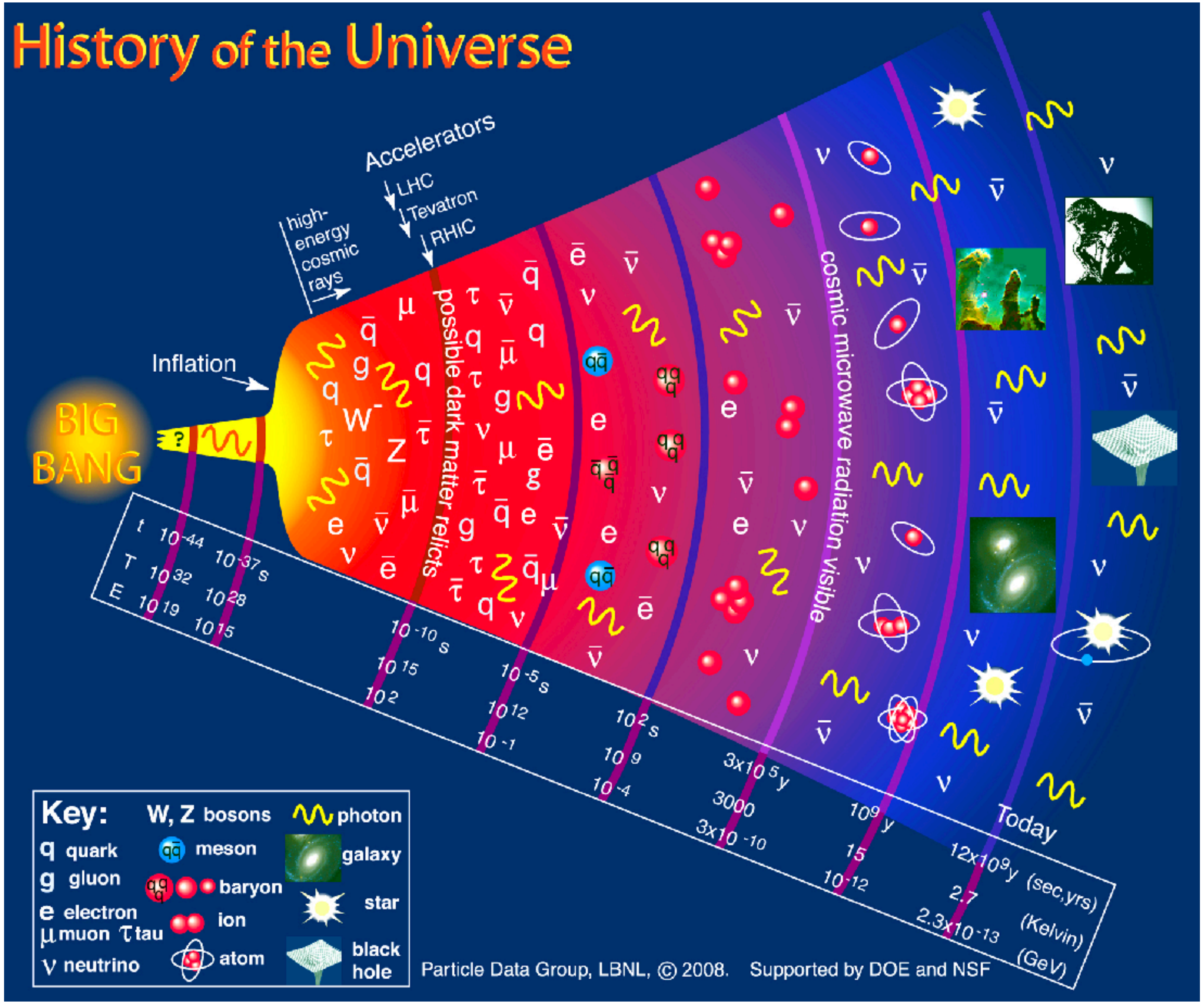
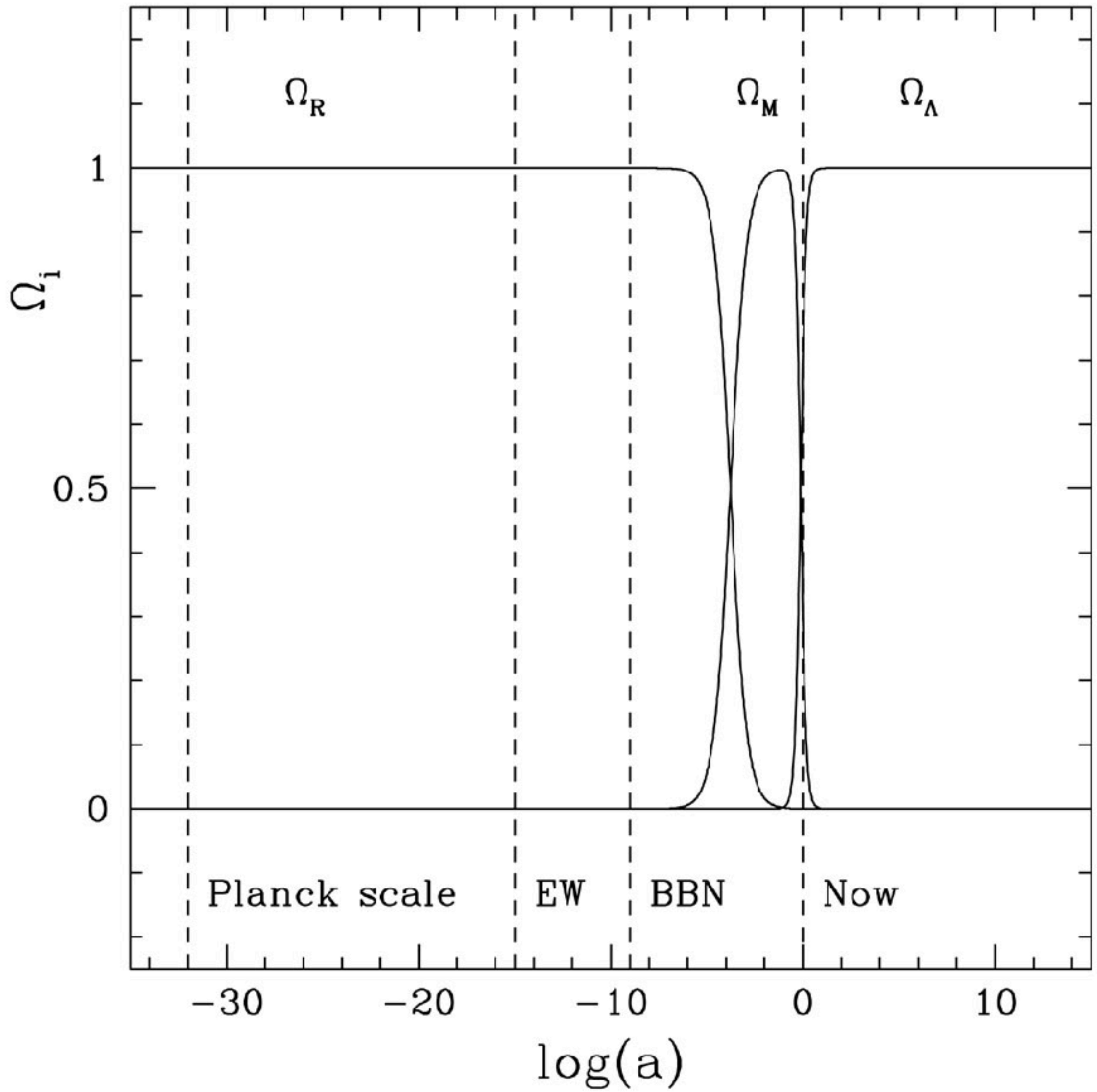
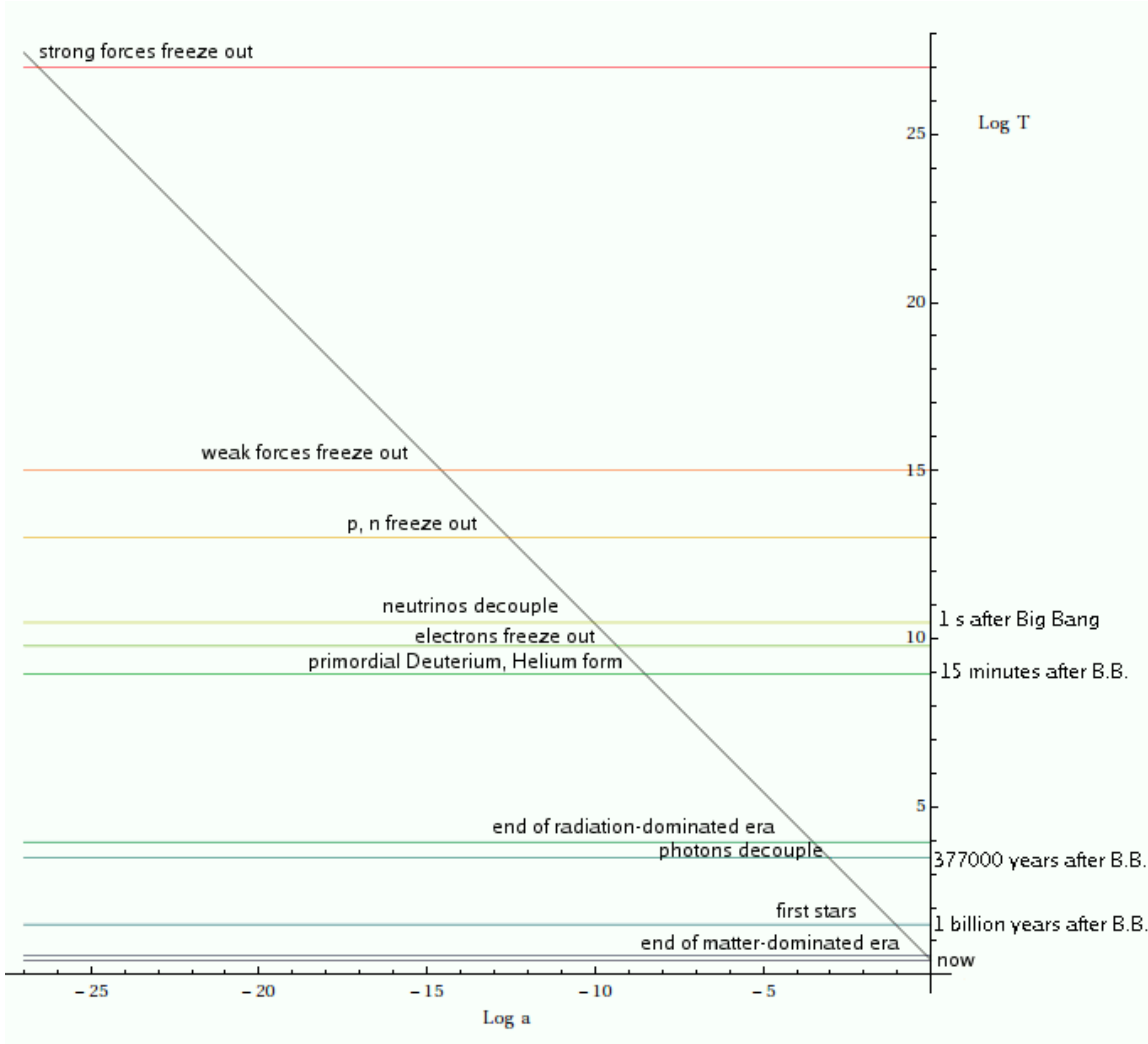
Early Universe and BBN

ASTR/PHYS 4080: Intro to Cosmology
Week 9

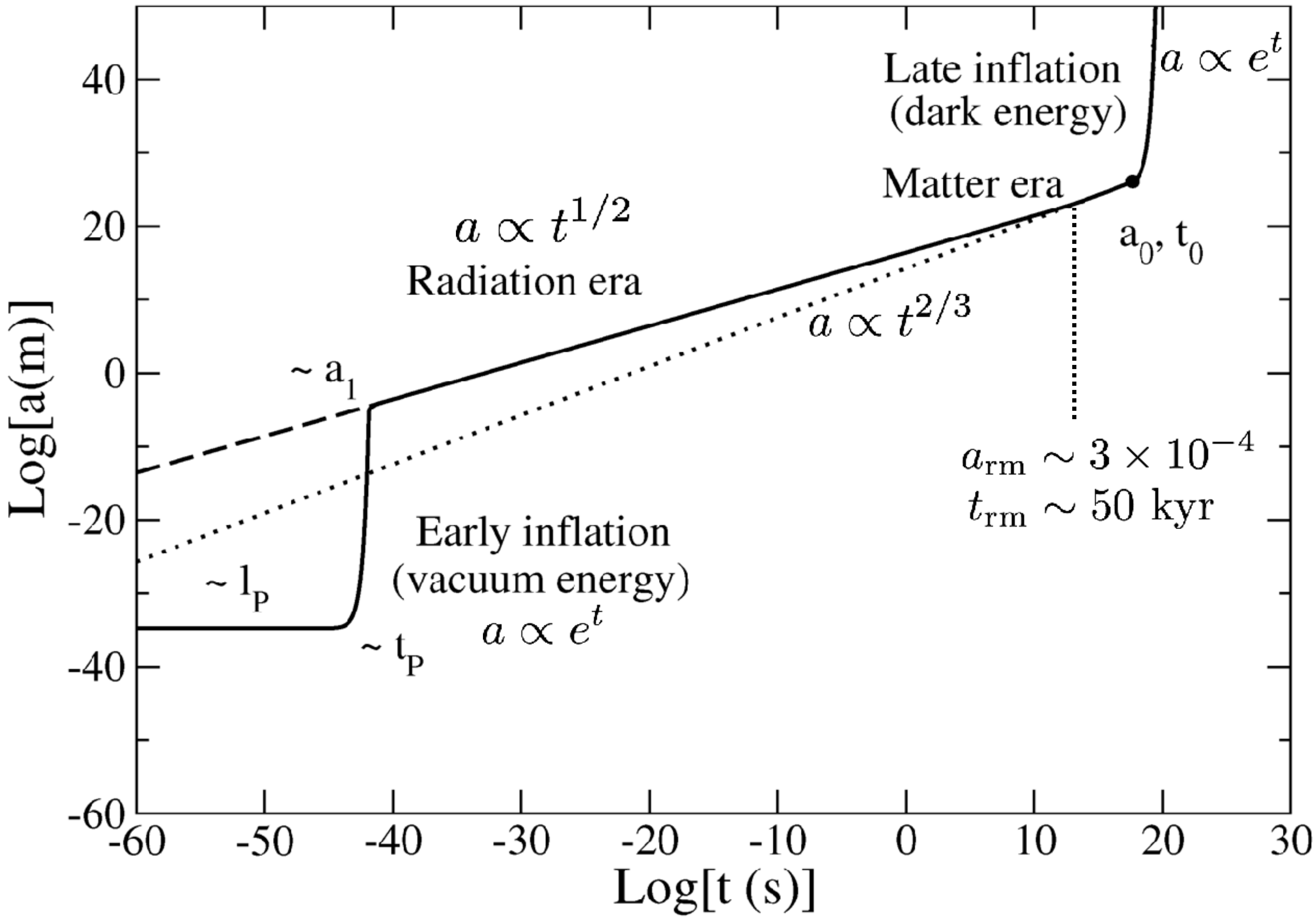


Early Universe Timescales

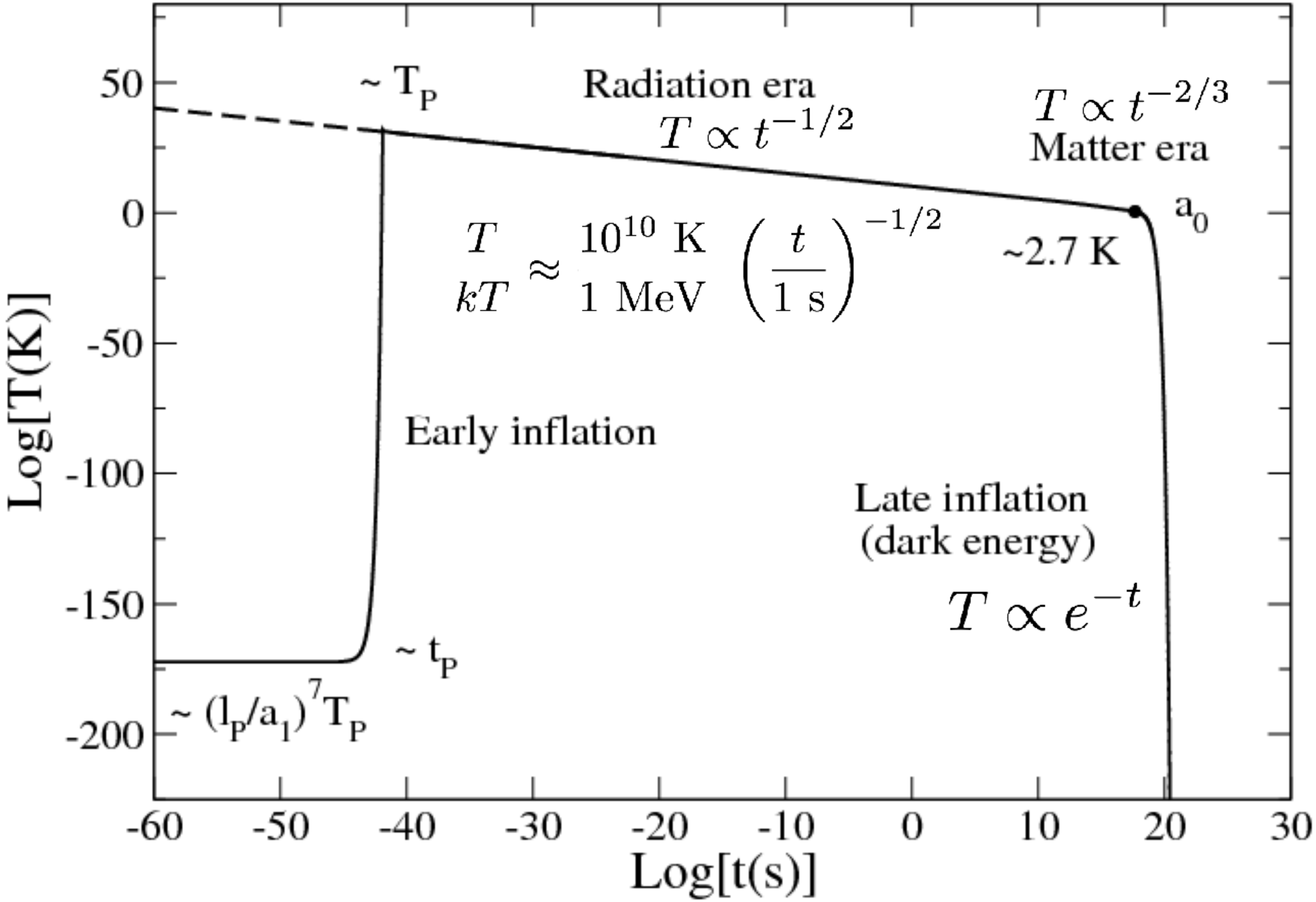




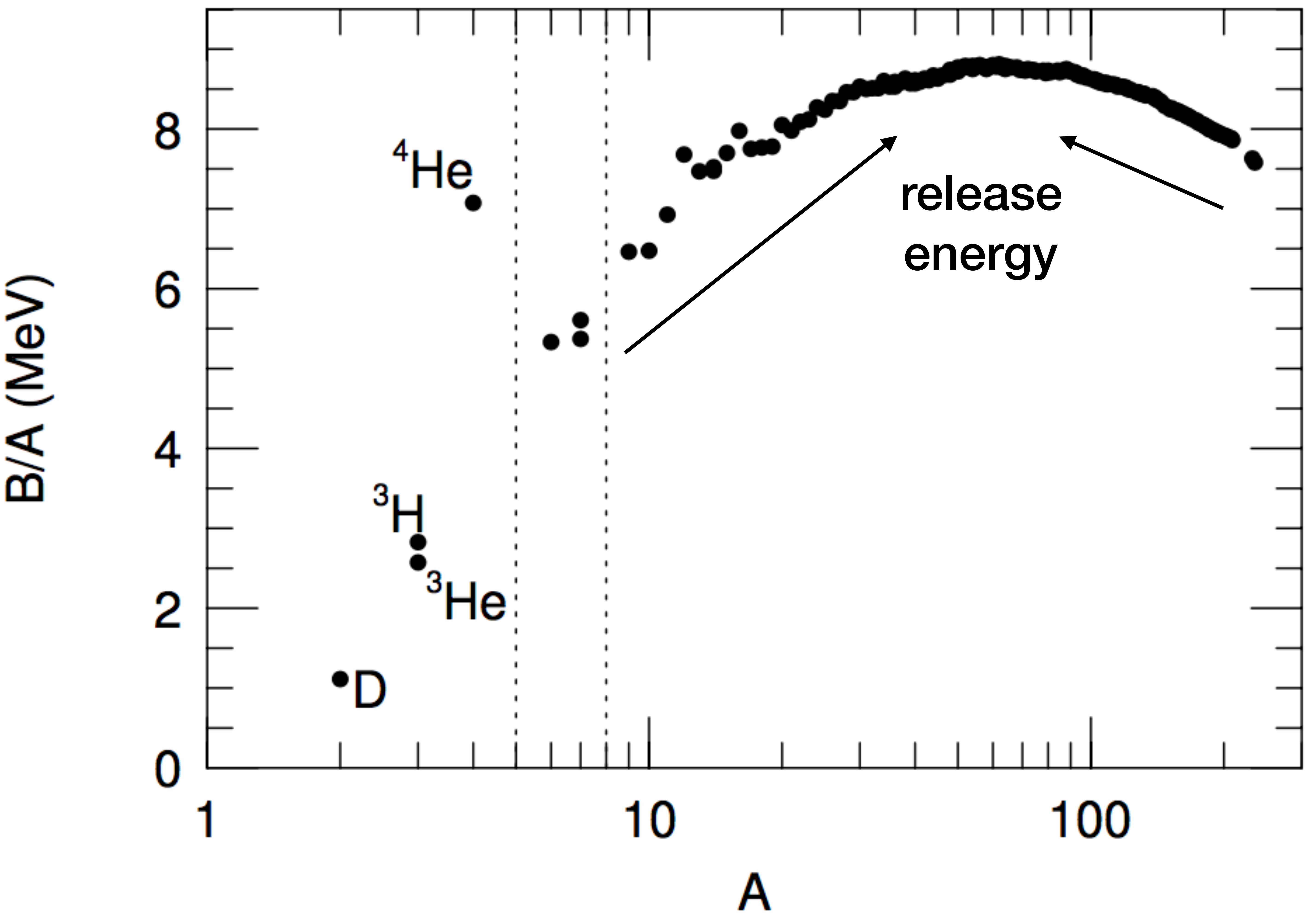
Early Universe Timescales



Early Universe Timescales



Nuclear Binding Energy



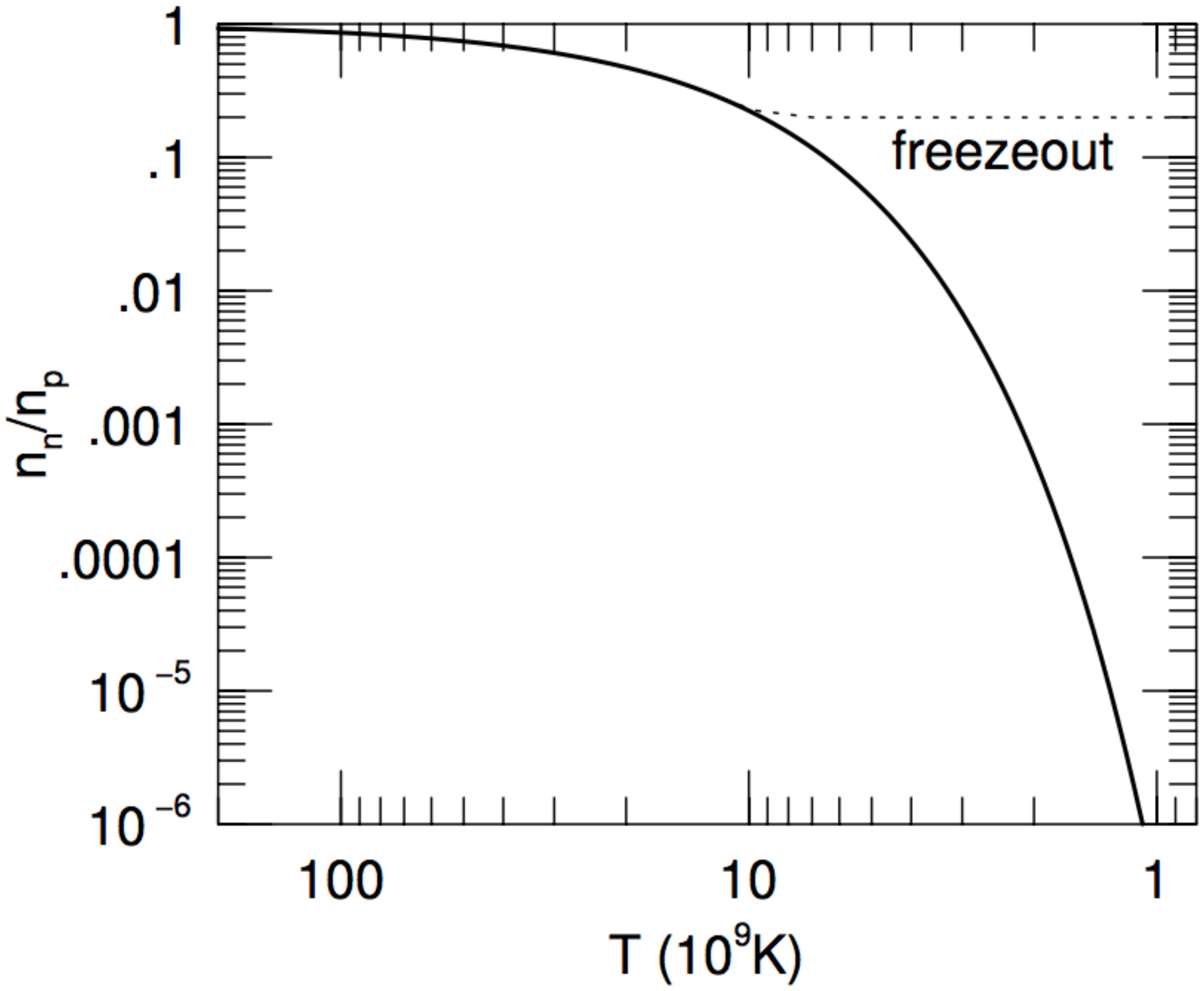
$$p + n \rightleftharpoons D + 2.22\ \mathrm{MeV}$$

expect nucleosynthesis to result in all atoms becoming iron

does not happen - why not?

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

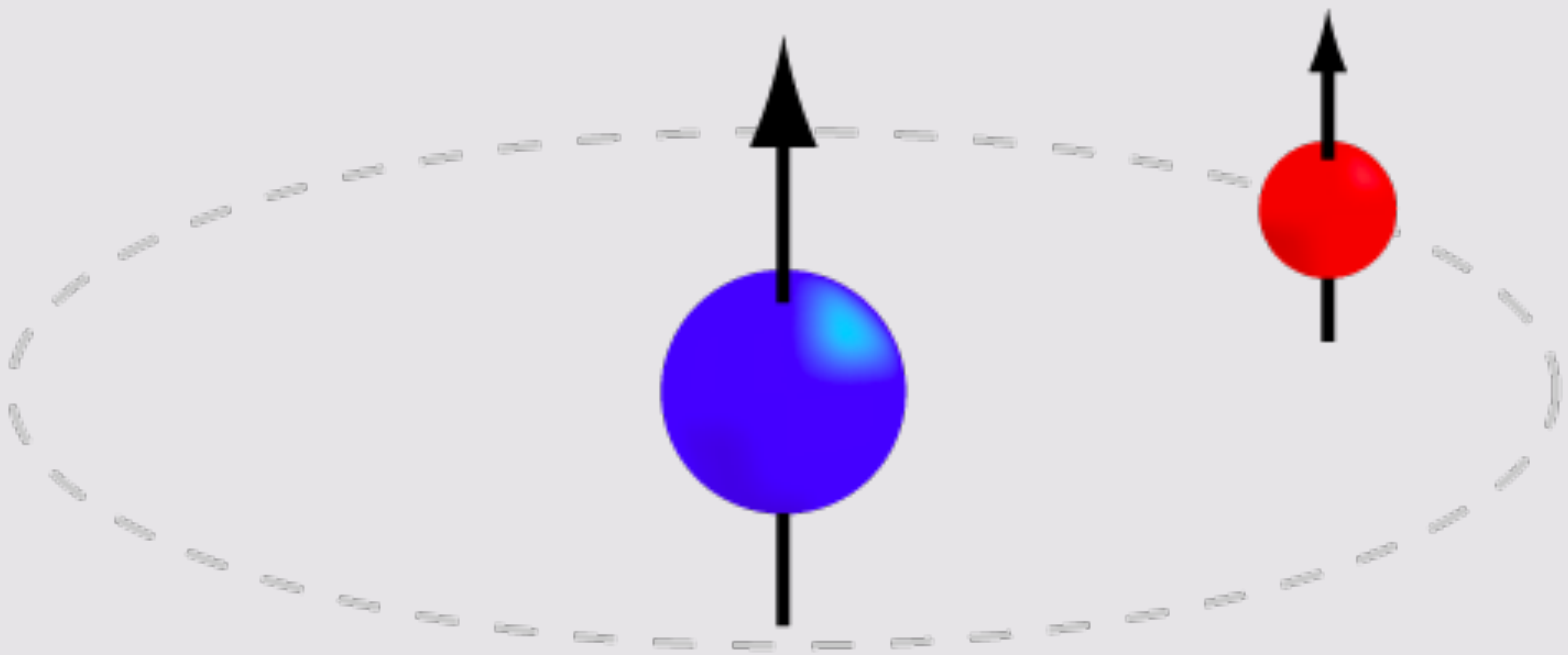
neutron-proton ratio



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

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

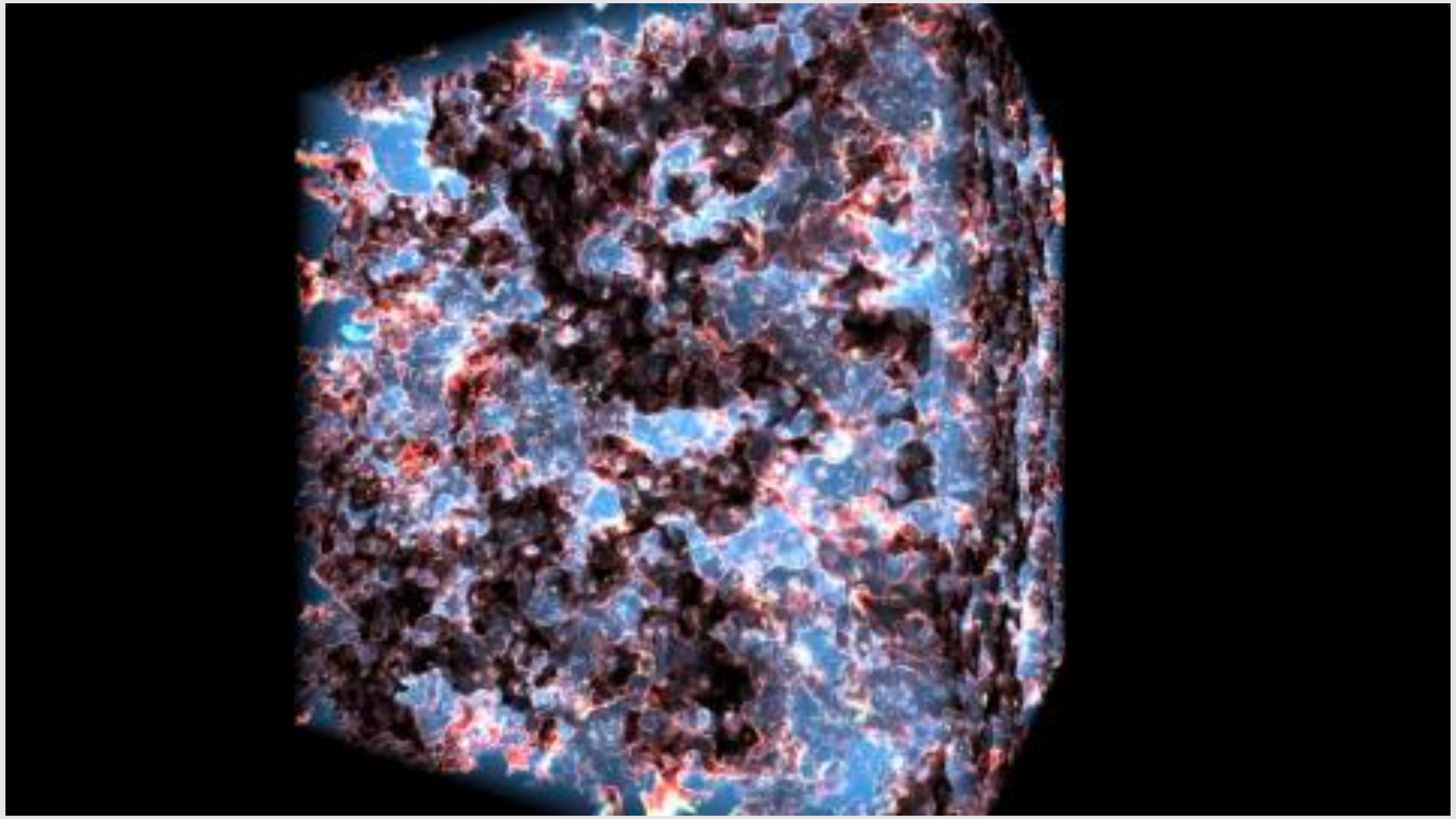
ASIDE: Reionization Signature



hydrogen hyperfine transition
(electron spin flips)

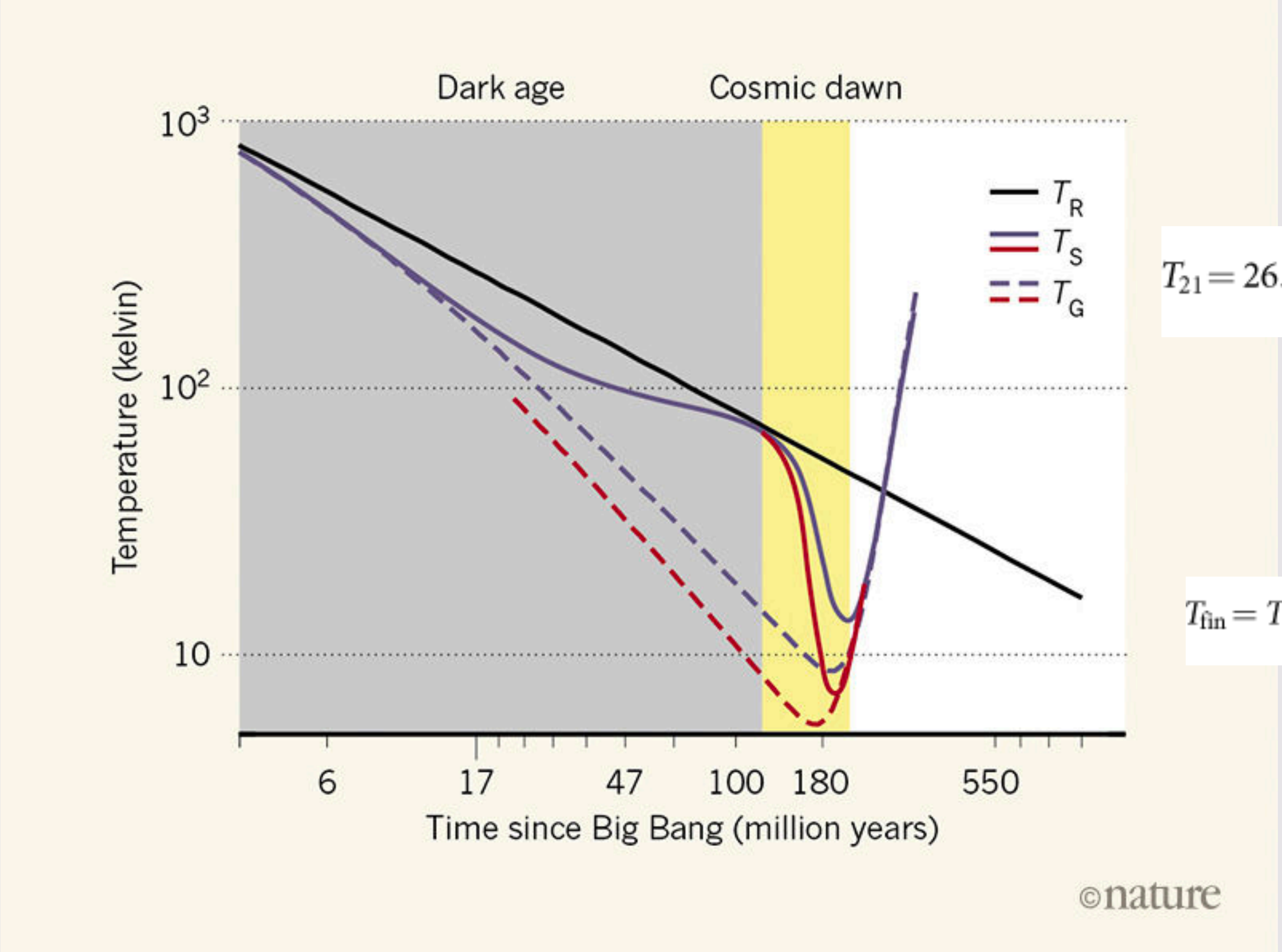
emits photon at 21cm (1.4 GHz)

can observe at high (z~10) redshifts and see the first stars ionizing the neutral gas formed at recombination



https://youtu.be/kifF3RYcfn0

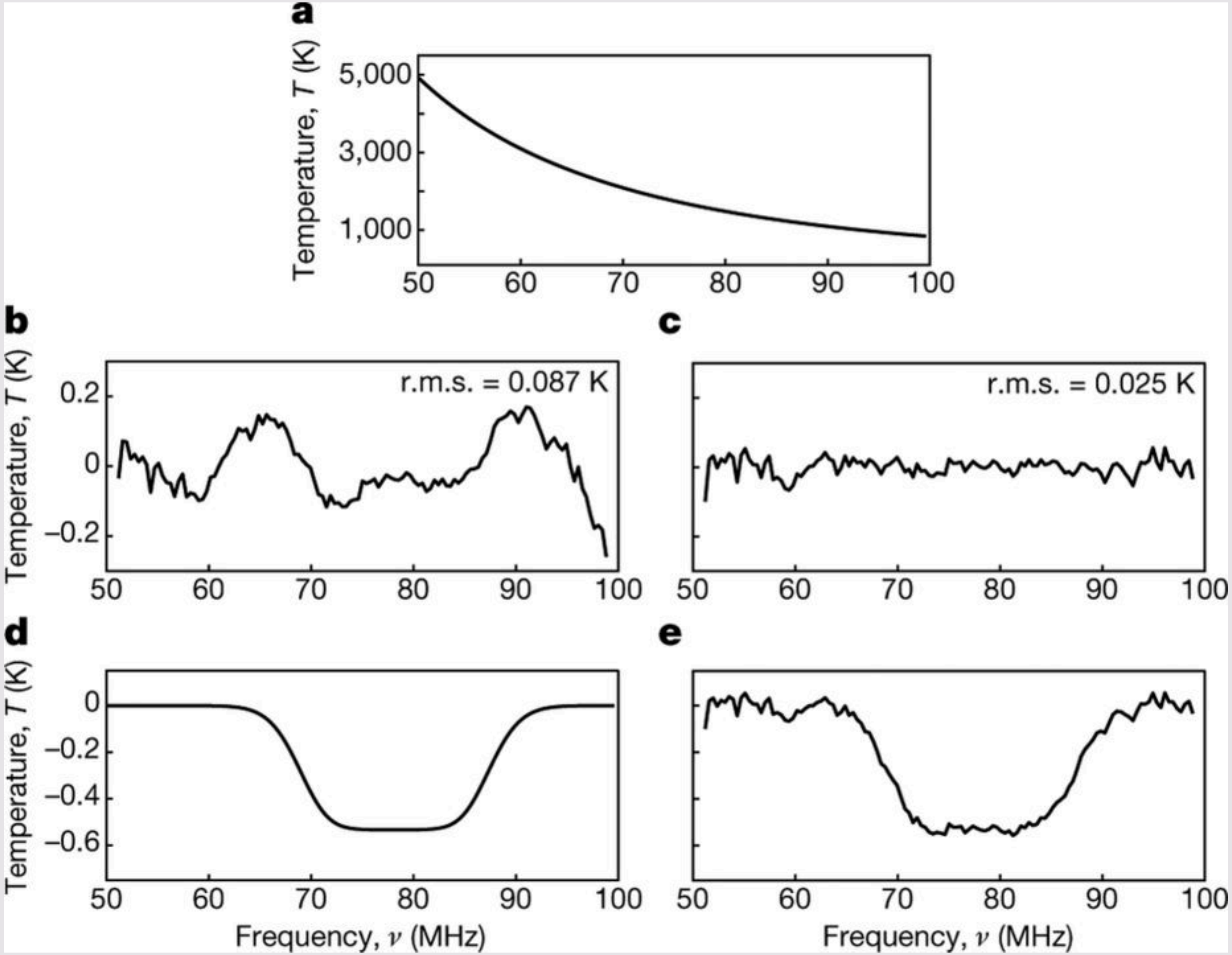
ASIDE: Reionization Signature



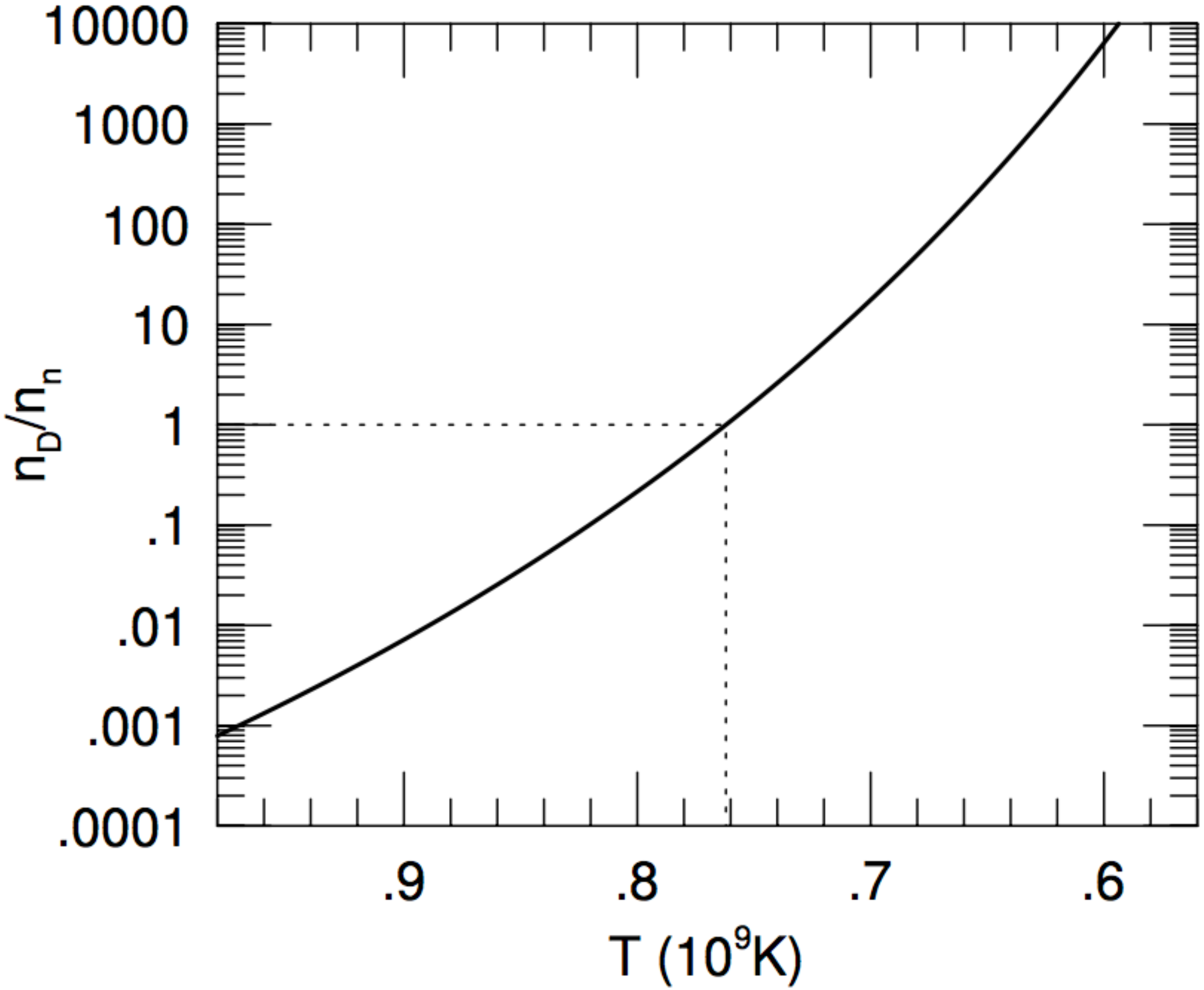
$$T_{21} = 26.8 x_{\mathrm{HI}} \frac{\rho_g}{\bar{\rho}_g} \left(\frac{\Omega_b h}{0.0327}\right) \left(\frac{\Omega_m}{0.307}\right)^{-1/2} \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_S - T_{CMB}}{T_S}\right)$$

$$T_{\mathrm{fin}} = T_{\mathrm{gas}} \frac{n_b}{n_b + n_\chi} = \frac{T_{\mathrm{gas}}}{1 + (\rho_\chi/\rho_b)(\mu_b/m_\chi)} \approx \frac{T_{\mathrm{gas}}}{1 + (6\ \mathrm{GeV})/m_\chi}$$

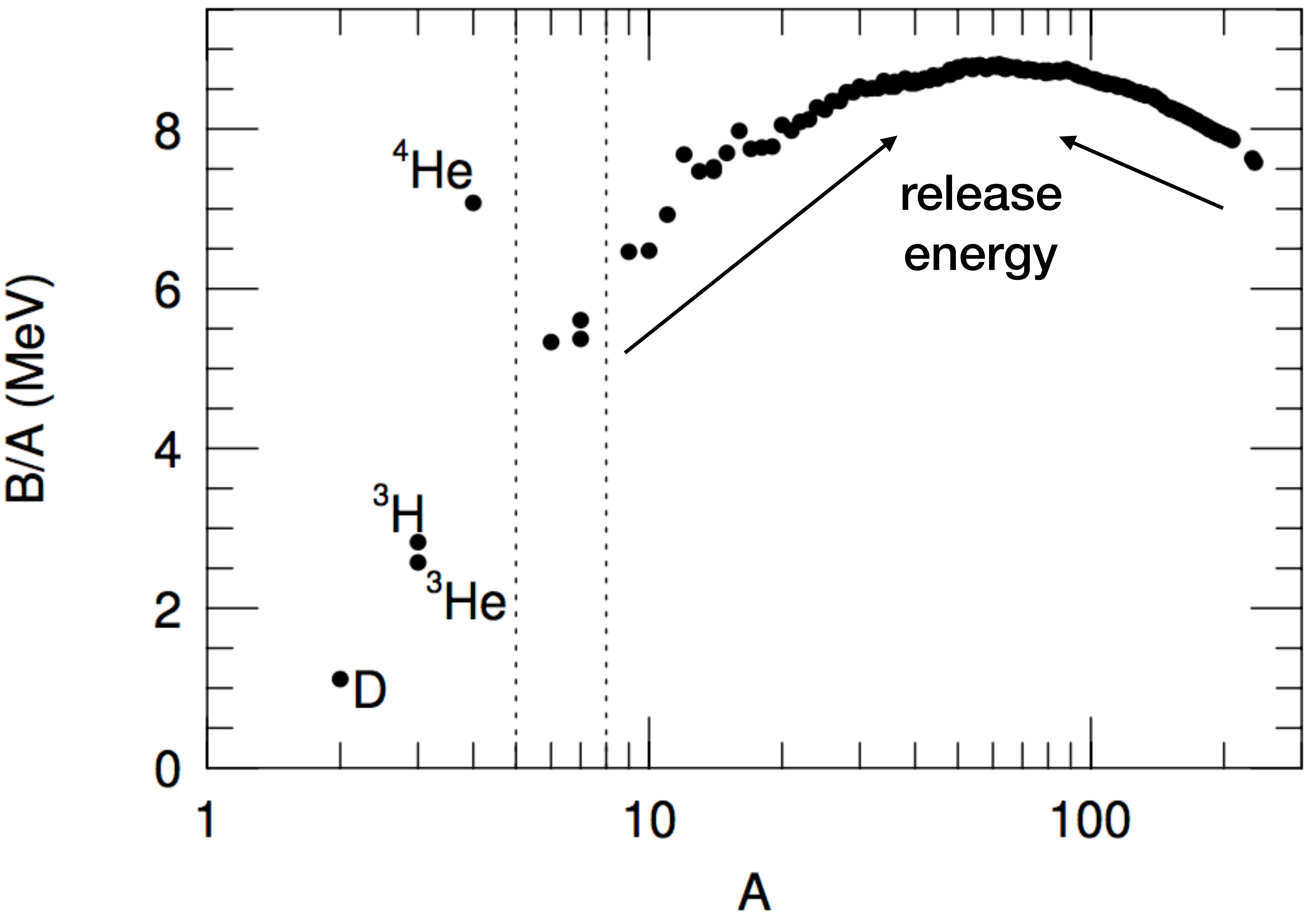
ASIDE: Reionization Signature



Deuterium Synthesis



Making He



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

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

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

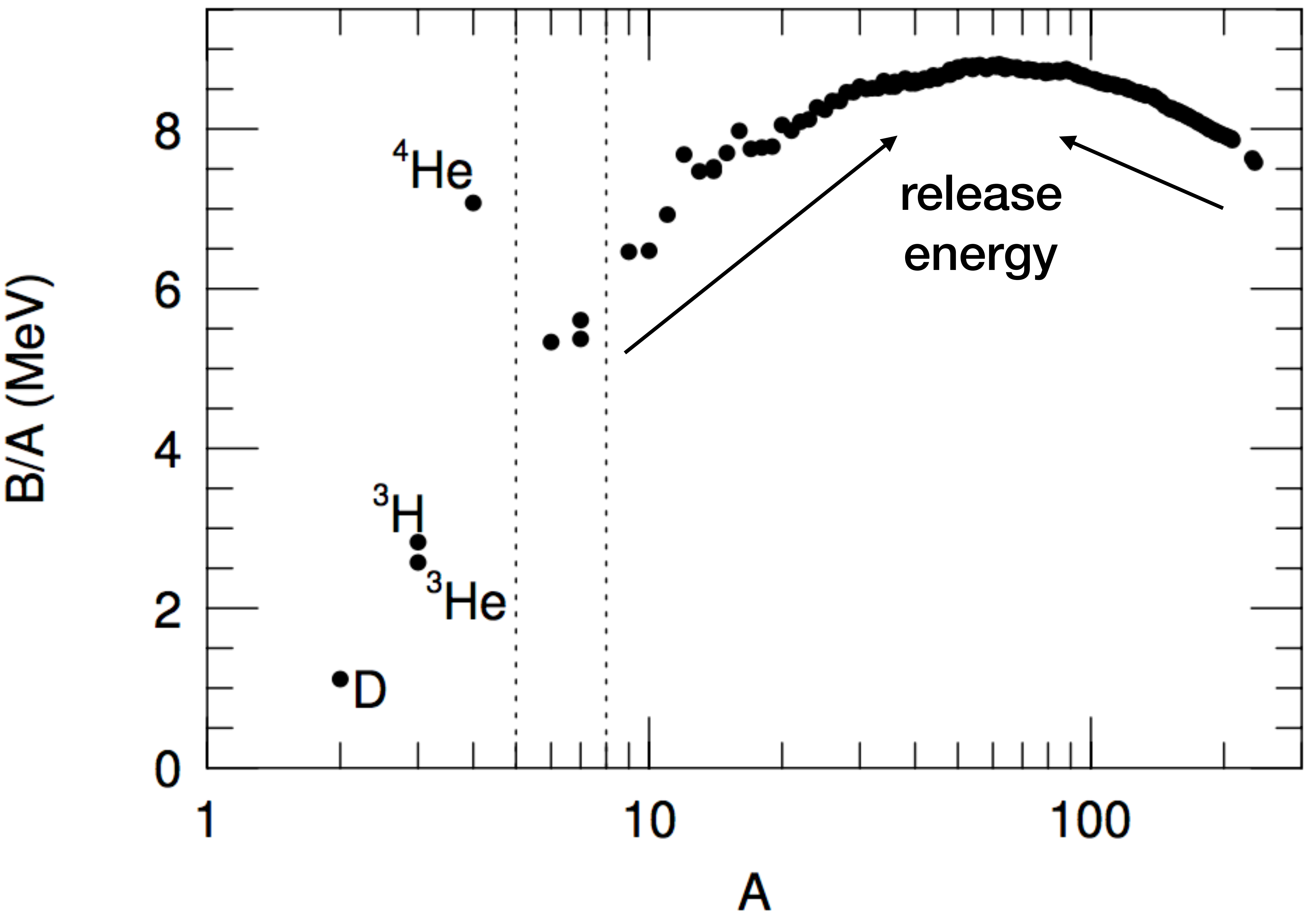
$$D + D \rightleftharpoons {}^4\mathrm{He} + \gamma$$

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:

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

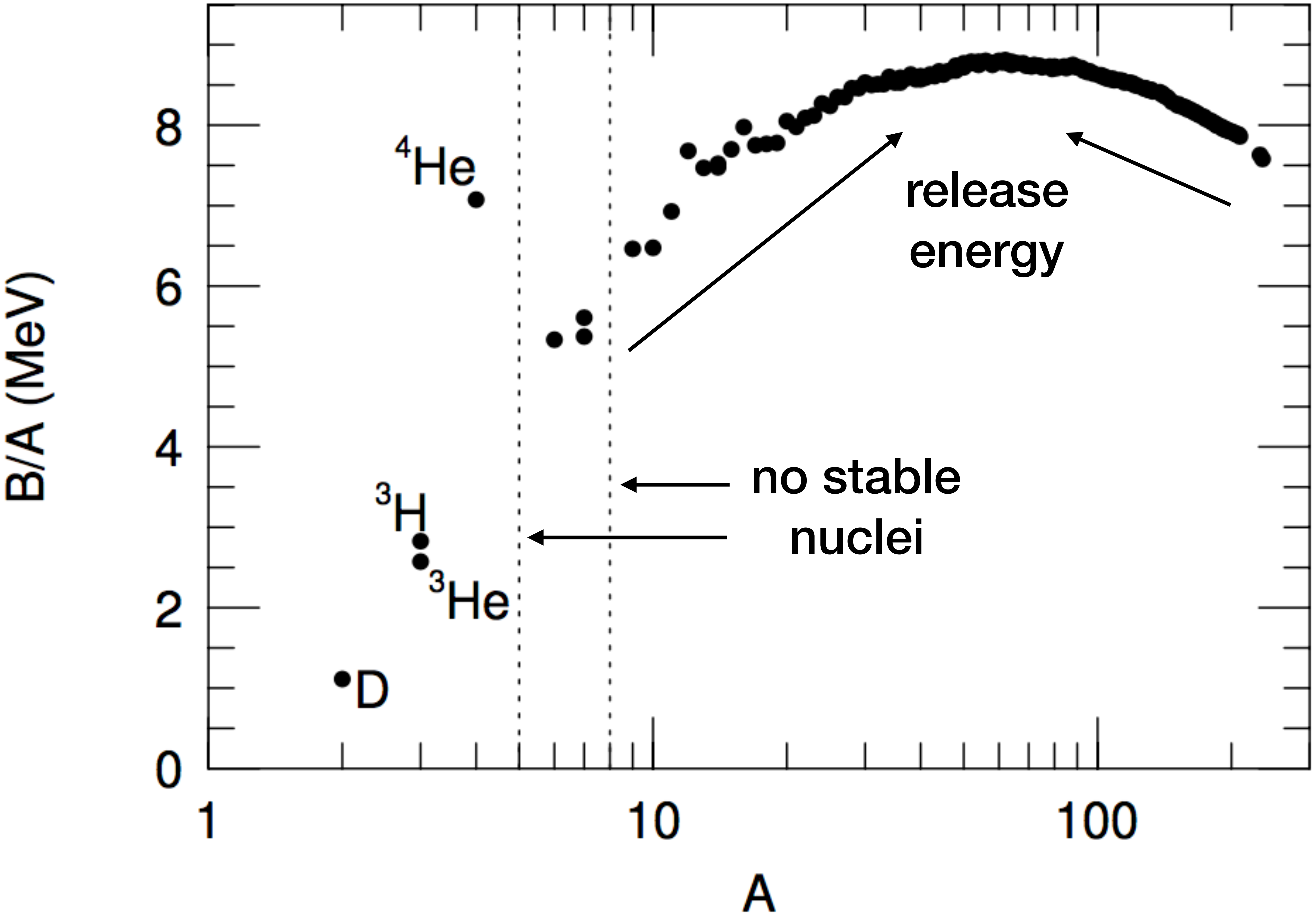
$$^3\mathrm{He} + n \rightleftharpoons {}^4\mathrm{He} + \gamma$$

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

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

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

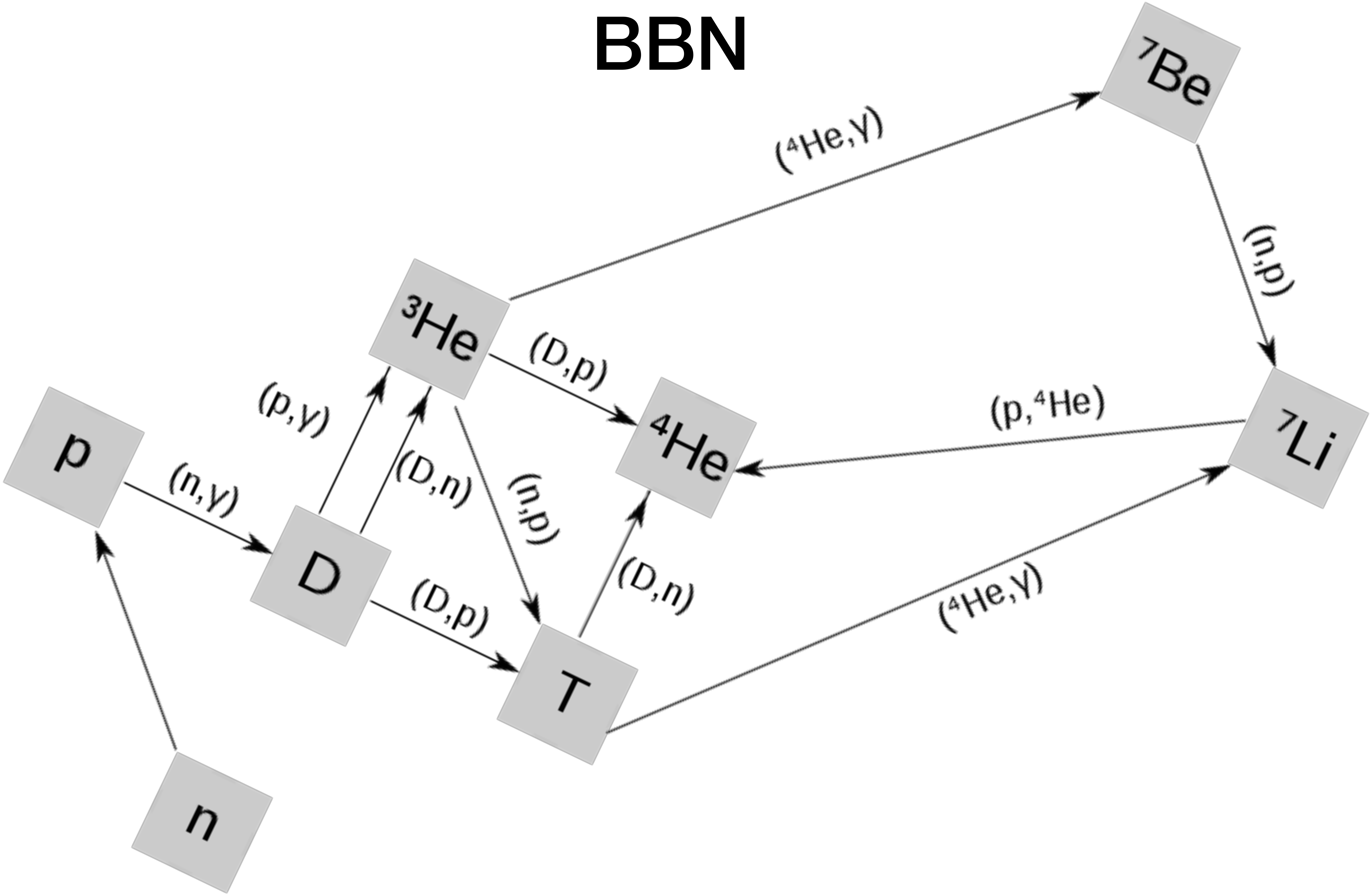
$$^4\mathrm{He} + D \rightleftharpoons {}^6\mathrm{Li} + \gamma$$

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

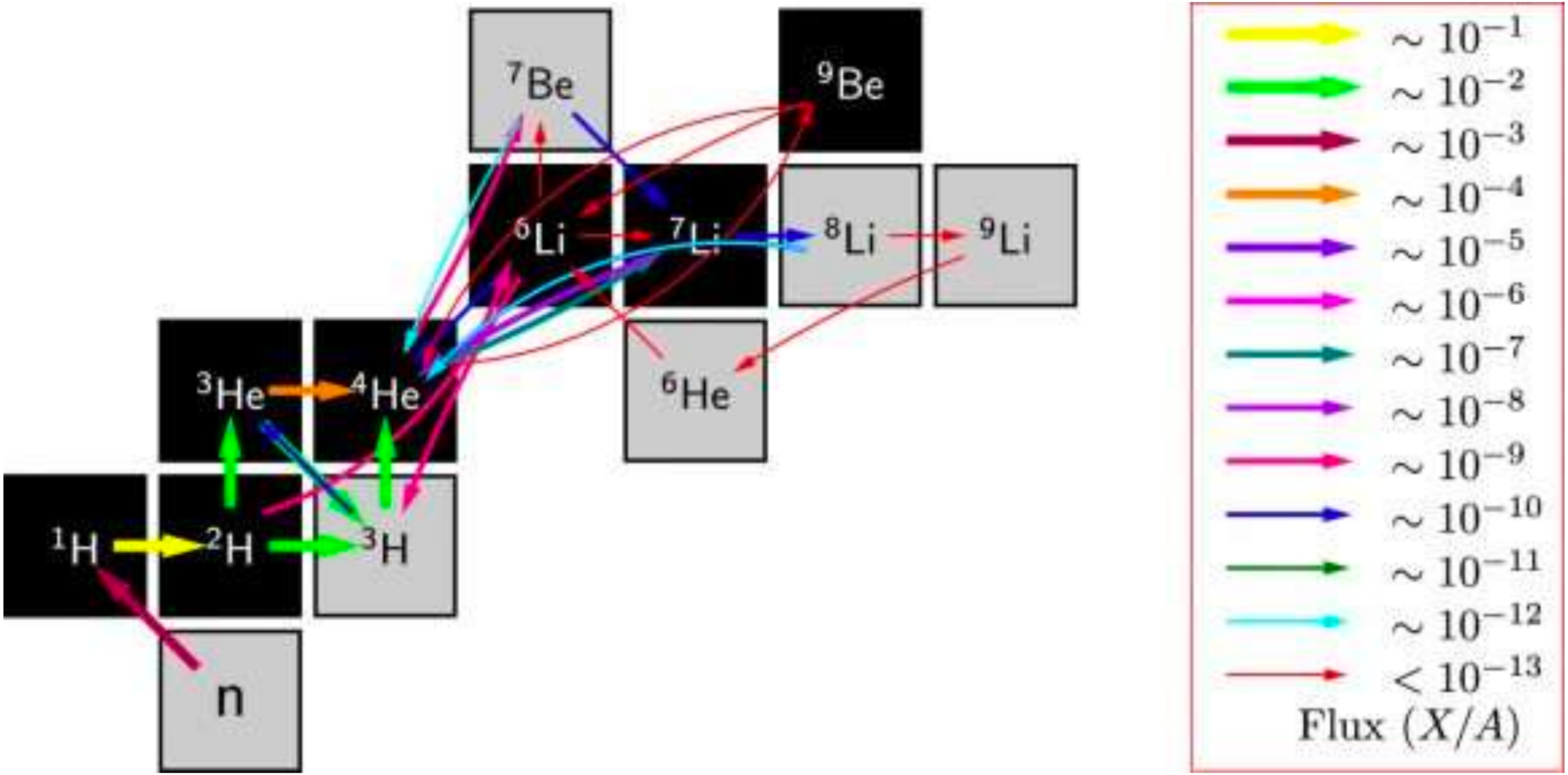
$$^4\mathrm{He} + {}^3\mathrm{He} \rightleftharpoons {}^7\mathrm{Be} + \gamma$$

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

BBN

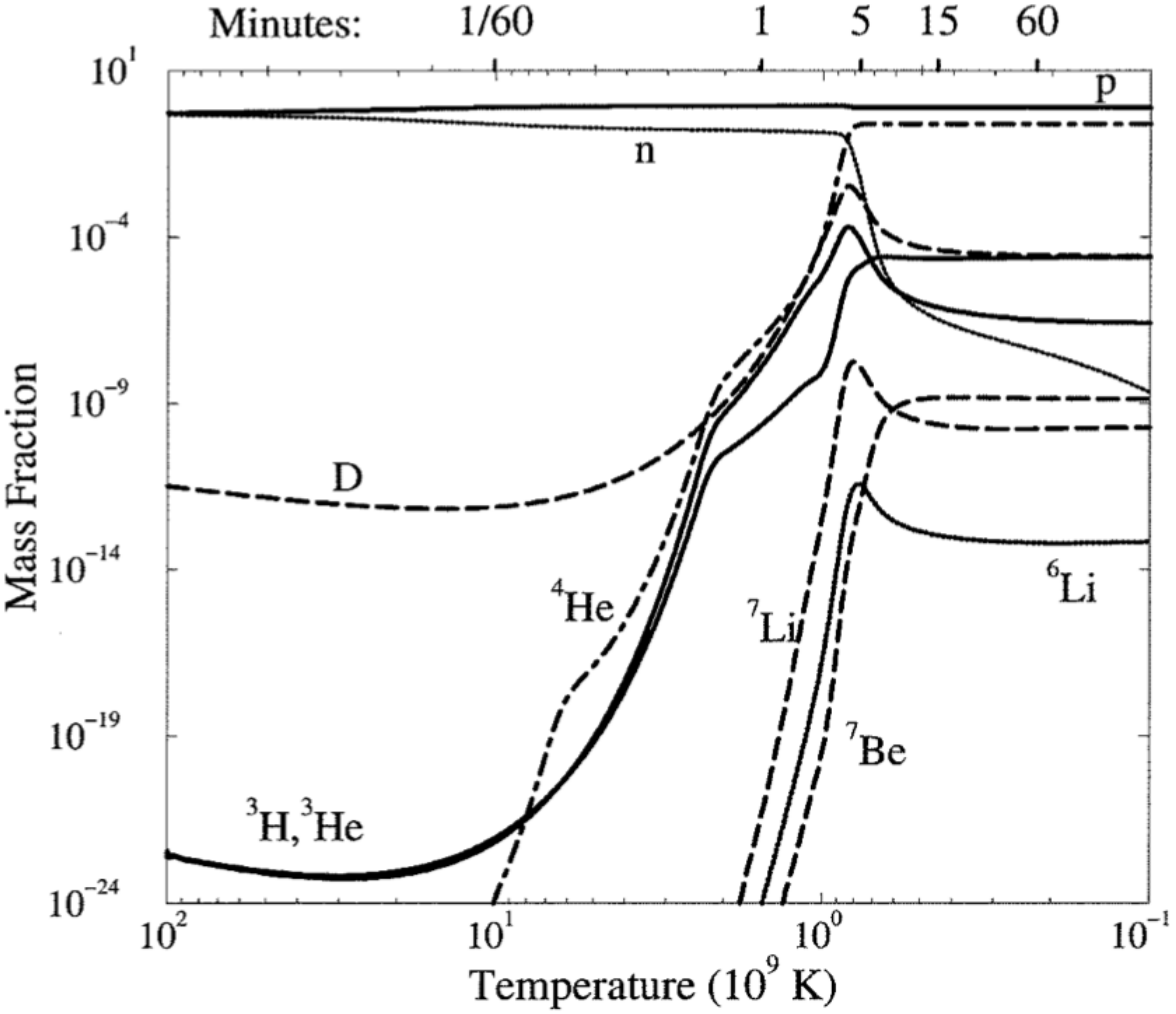


BBN



⁷Be
⁹Be
⁶Li
⁷Li
⁸Li
⁹Li
³He
⁴He
⁶He
¹H
²H
³H
n
~ 10⁻¹
~ 10⁻²
~ 10⁻³
~ 10⁻⁴
~ 10⁻⁵
~ 10⁻⁶
~ 10⁻⁷
~ 10⁻⁸
~ 10⁻⁹
~ 10⁻¹⁰
~ 10⁻¹¹
~ 10⁻¹²
< 10⁻¹³
Flux (X/A)

Abundances from Nucleosynthesis

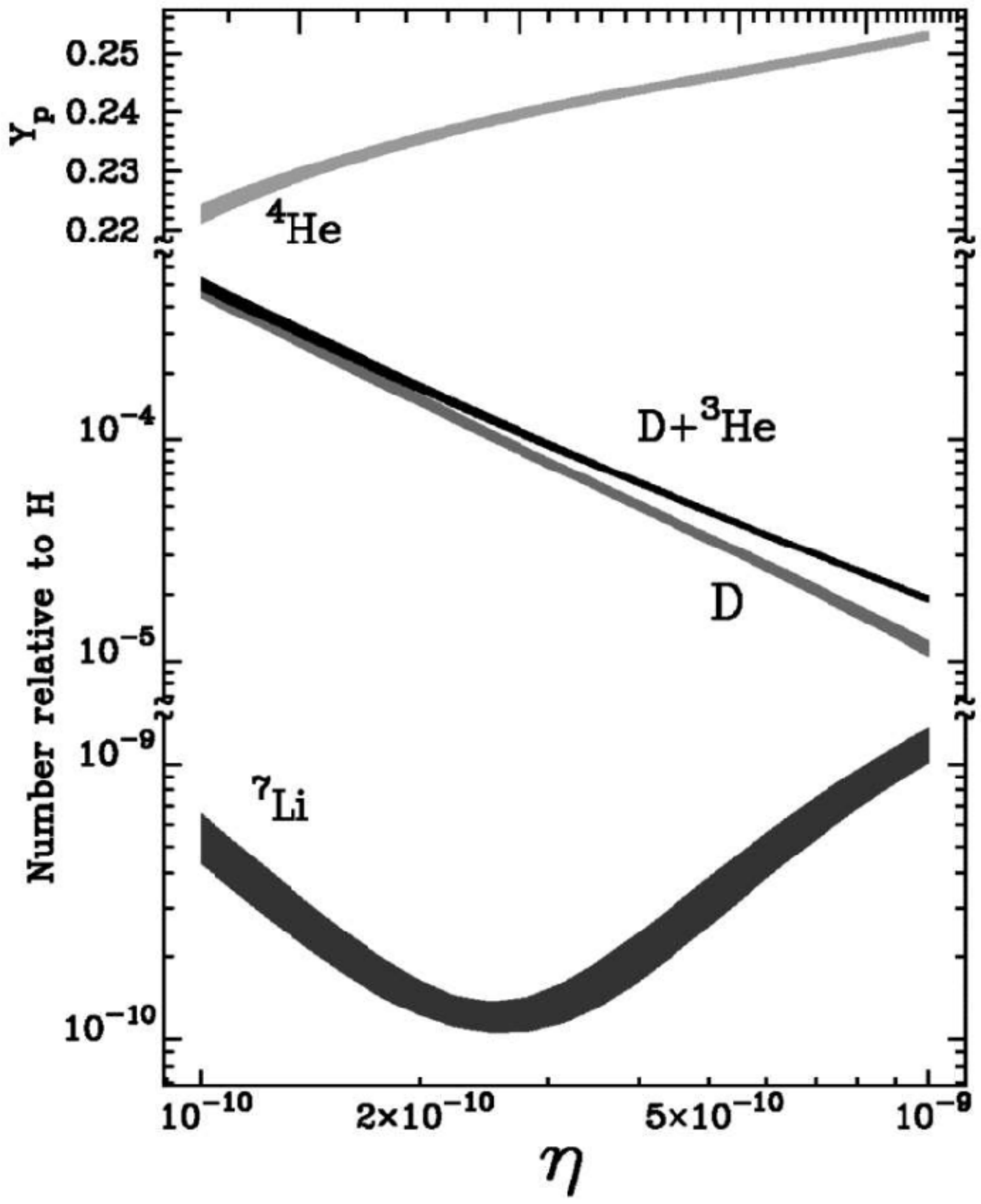


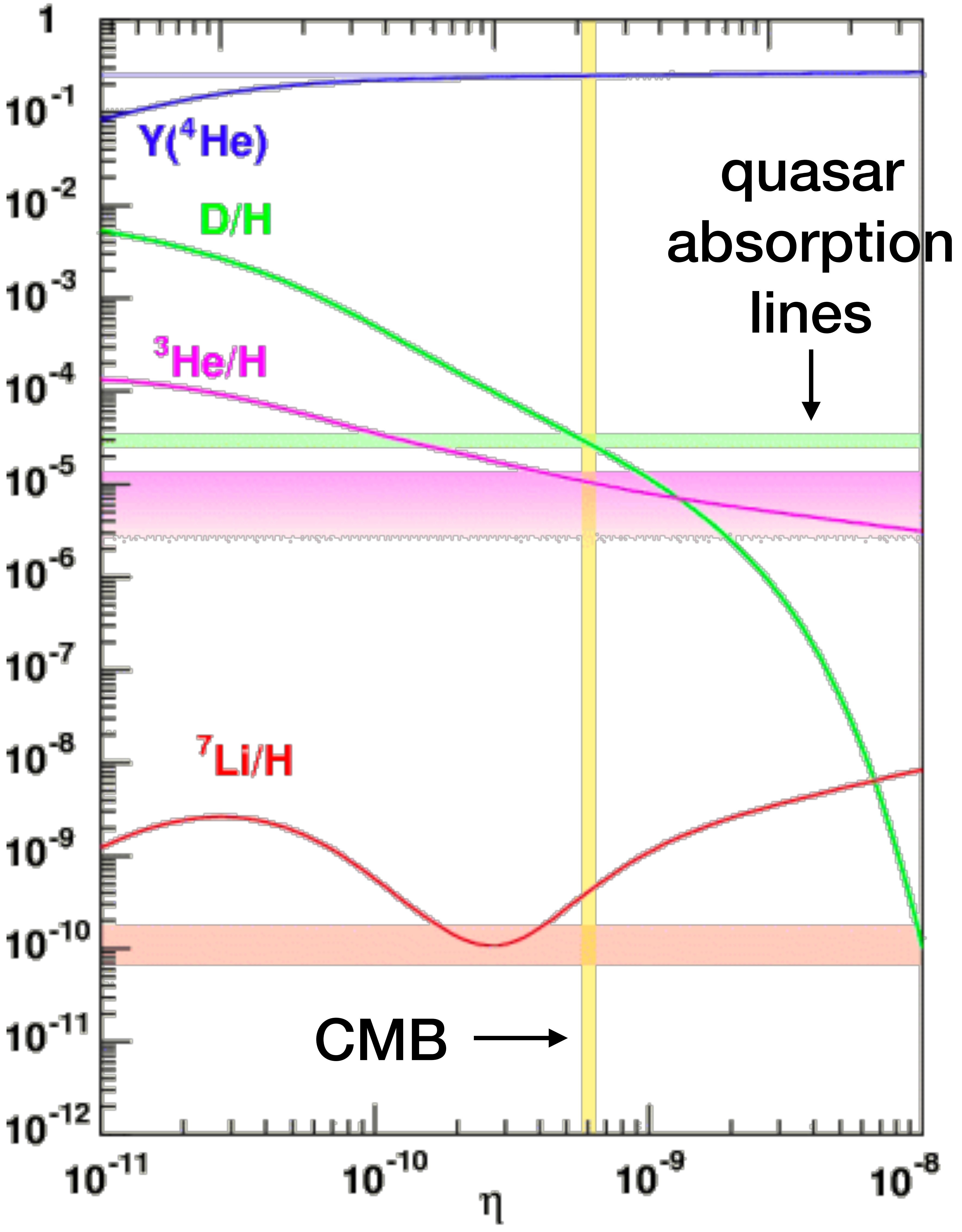
Creation process depends on relative abundances at any given time, so have to calculate computationally

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

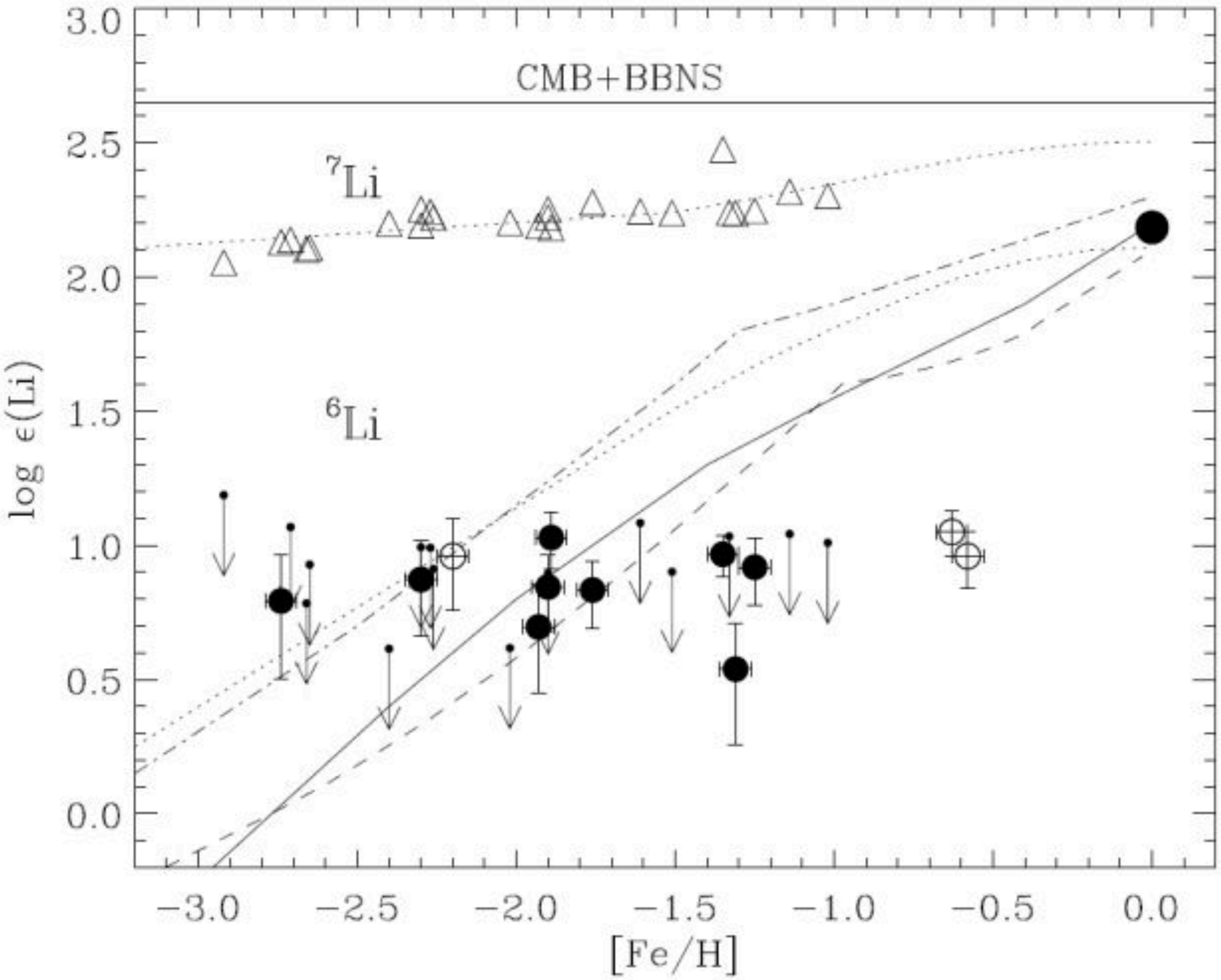
Exact yields depend most on baryon-to-photon ratio: η
(determines temperature of nucleosynthesis)

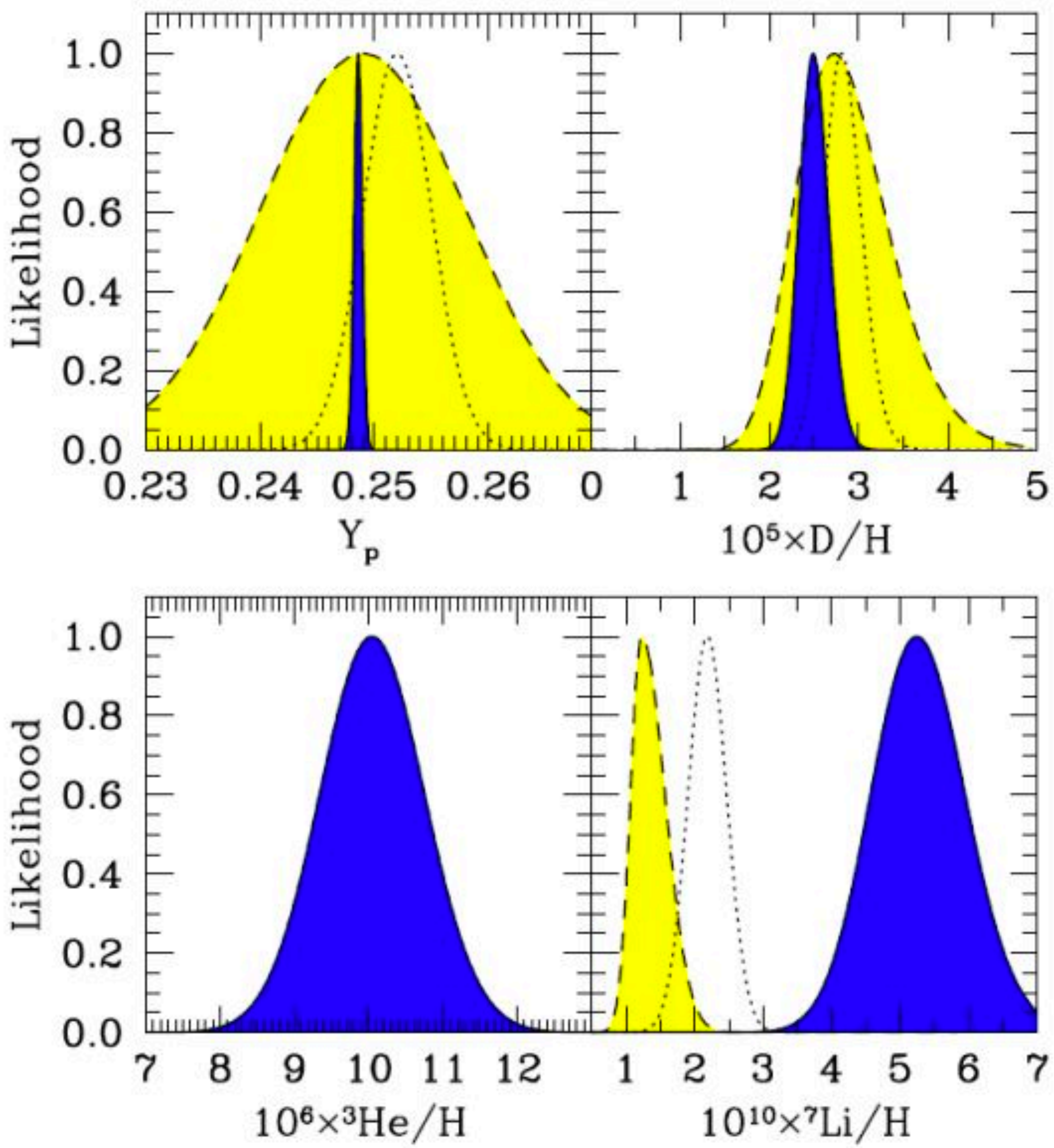
Measuring BBN



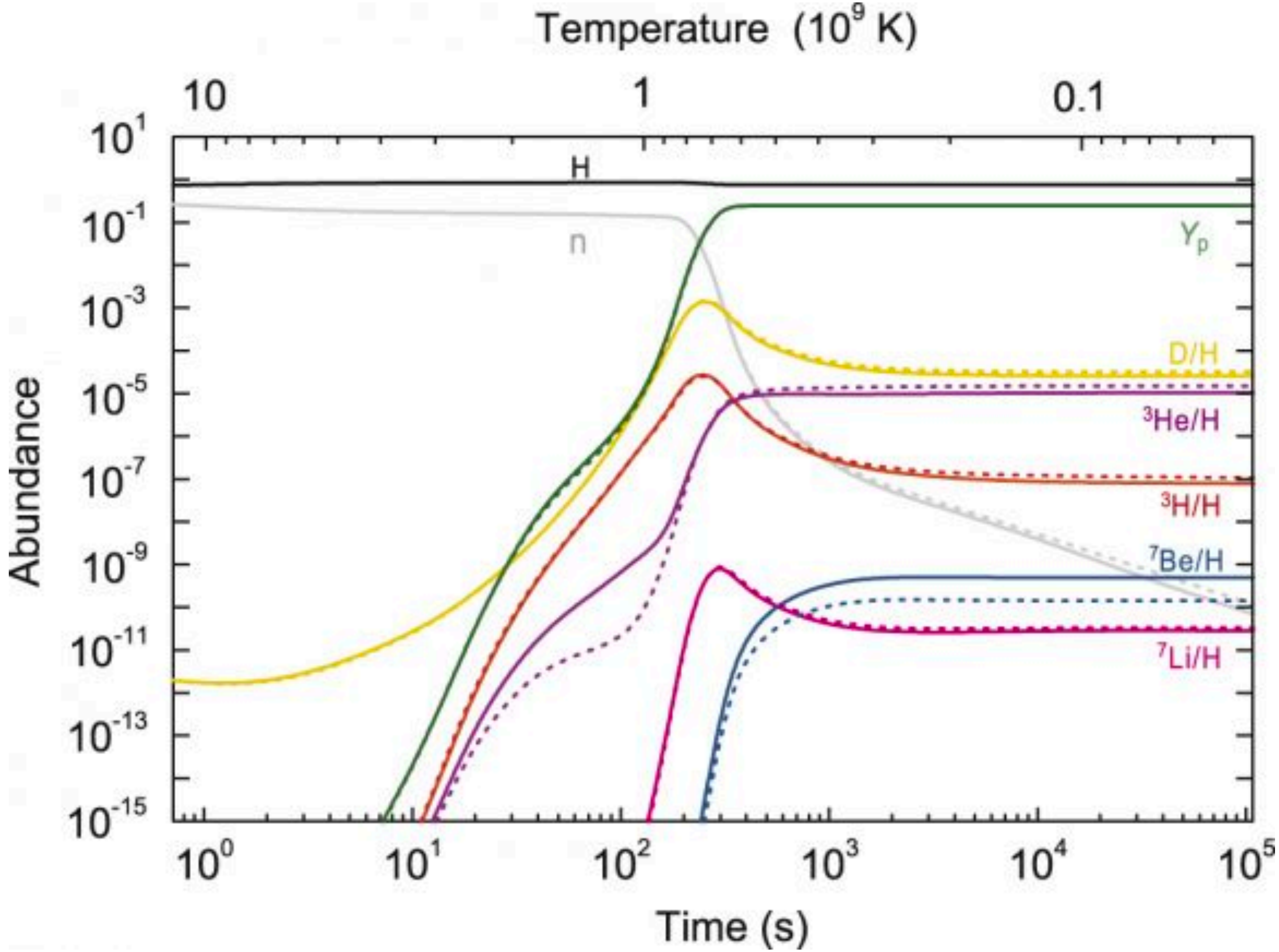


Lithium Problem





Solution?



Temperature (10^9 K)
10
1
0.1
Abundance
H
n
Y_p
D/H
³He/H
³H/H
⁷Be/H
⁷Li/H
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!

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