Primordial Nucleosynthesis
-
The Origin of the Lightest Elements

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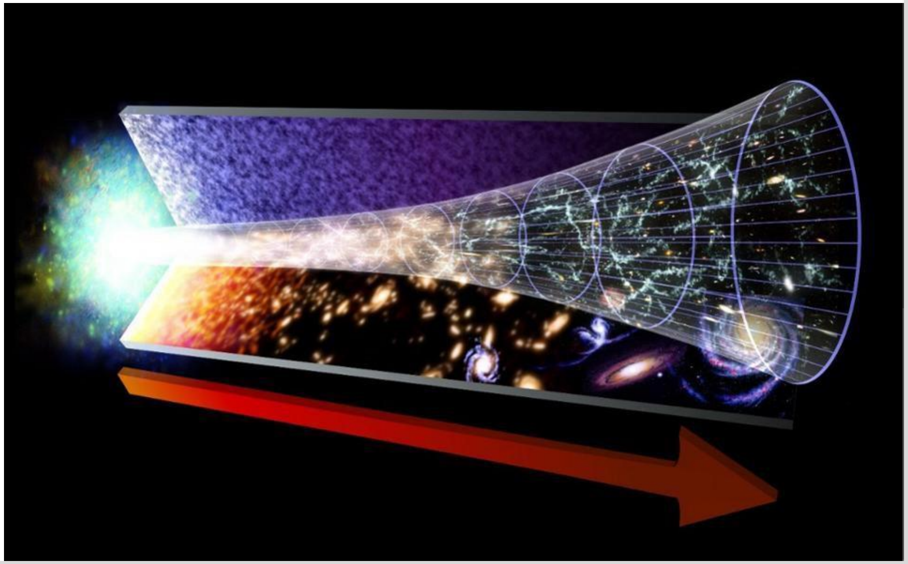
- Primordial Nucleosynthesis - Overview
- Primordial Nucleosynthesis – Processes
- Measurements of the Abundance of the Lightest Elements
- Results of the Measurements



The Big Bang Theory in a Nutshell

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The Big Bang Theory in a Nutshell

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Einstein Field Equations

$$\underbrace{R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu}}_{G_{\mu\nu}} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- $R_{\mu\nu}$: Ricci tensor (curvature of space-time)
- R : Ricci scalar (curvature of space-time)
- $g_{\mu\nu}$: metric tensor (metric of space-time)
- $G_{\mu\nu}$: Einstein tensor (manifold)
- $T_{\mu\nu}$: energy-momentum tensor ("source" of the curvature of space-time)
- Λ : cosmological constant (vacuum state → dark energy)
- G : gravitational constant
- c : speed of light

The Big Bang Theory in a Nutshell

- important parameters for an expanding universe:
  - **scale factor**

$$a \equiv a(t) \equiv \frac{d(t)}{d_0}$$

$d(t)$: proper (physical) distance

d_0: co-moving (reference) distance

(per definition, today we have $a = 1$)

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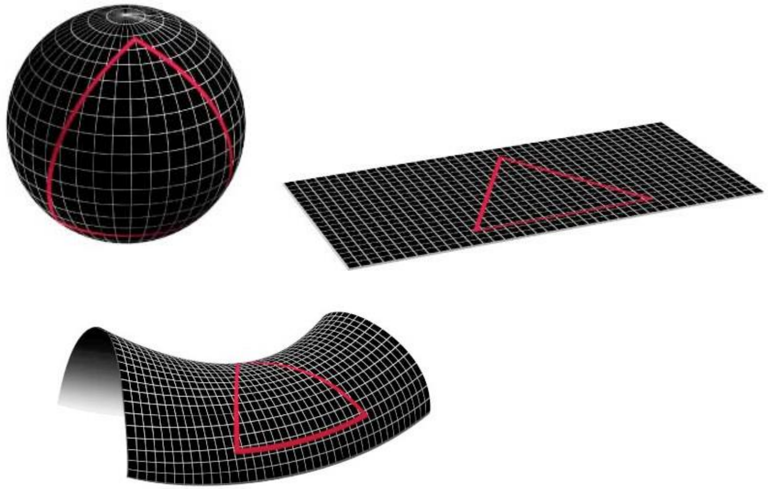
  - normalized spatial curvature parameter

$$\frac{k}{a^2} \equiv \begin{cases} +1, & \text{closed 3-sphere} \\ 0, & \text{flat universe} \\ -1, & \text{open 3-hyperboloid} \end{cases}$$



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Parametrized Friedmann Lemaître Equations

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

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primordial nucleosynthesis!

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- **temperature** of the universe: between 10^{11} K and 10^9 K
- **age of the universe**: between 0.01 s and 3 min after the Big Bang
  ⇒ famous "**first three minutes**" of the universe (cf. Weinberg etc.)

Primordial Nucleosynthesis - Overview

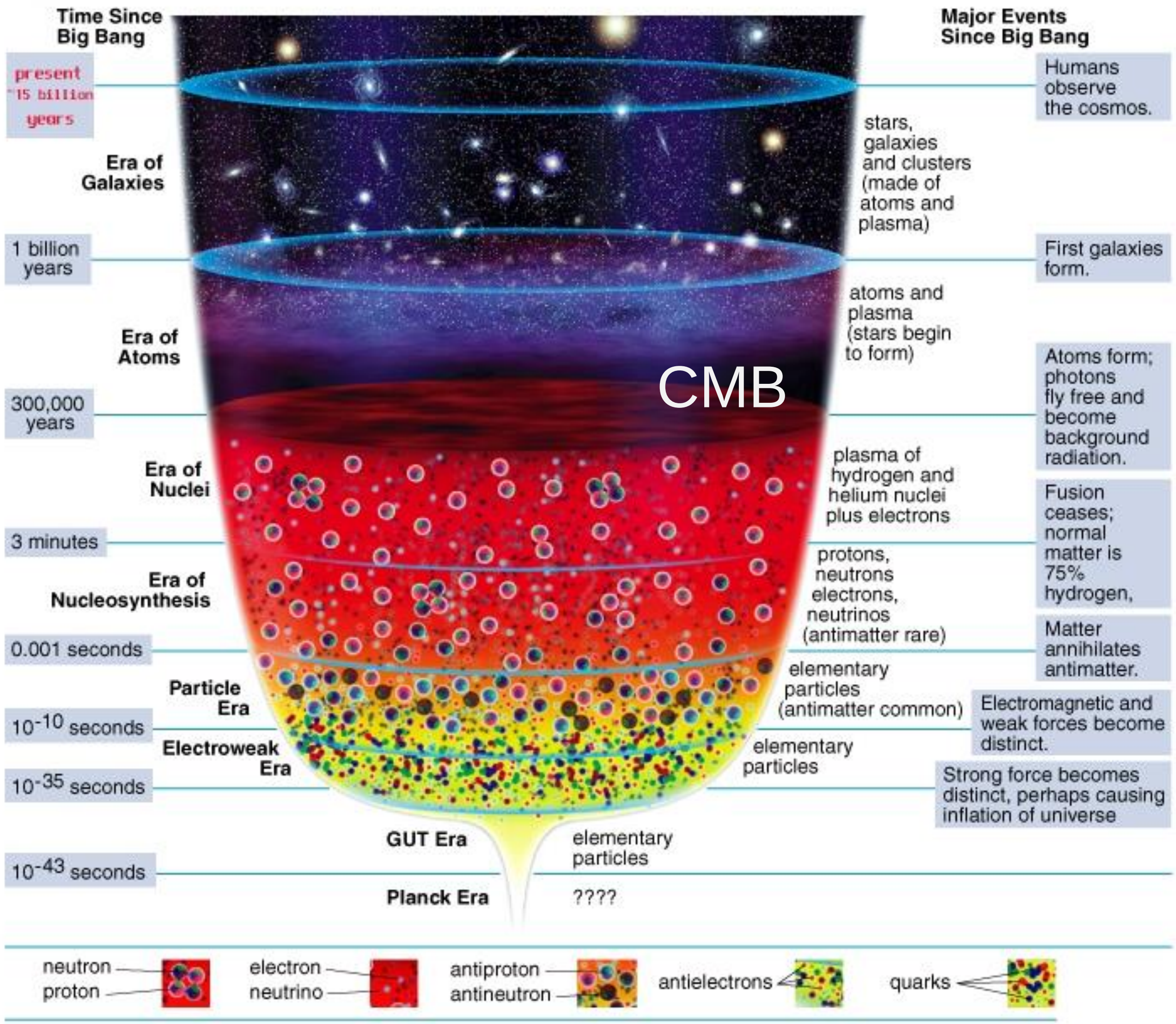
temperature

2.725 K

10^5 K

10^9 K

10^{12} K



Primordial Nucleosynthesis - Motivations

- BBN is strongly supported by the Big Bang theory
- explanation of the **origin of the lightest elements**

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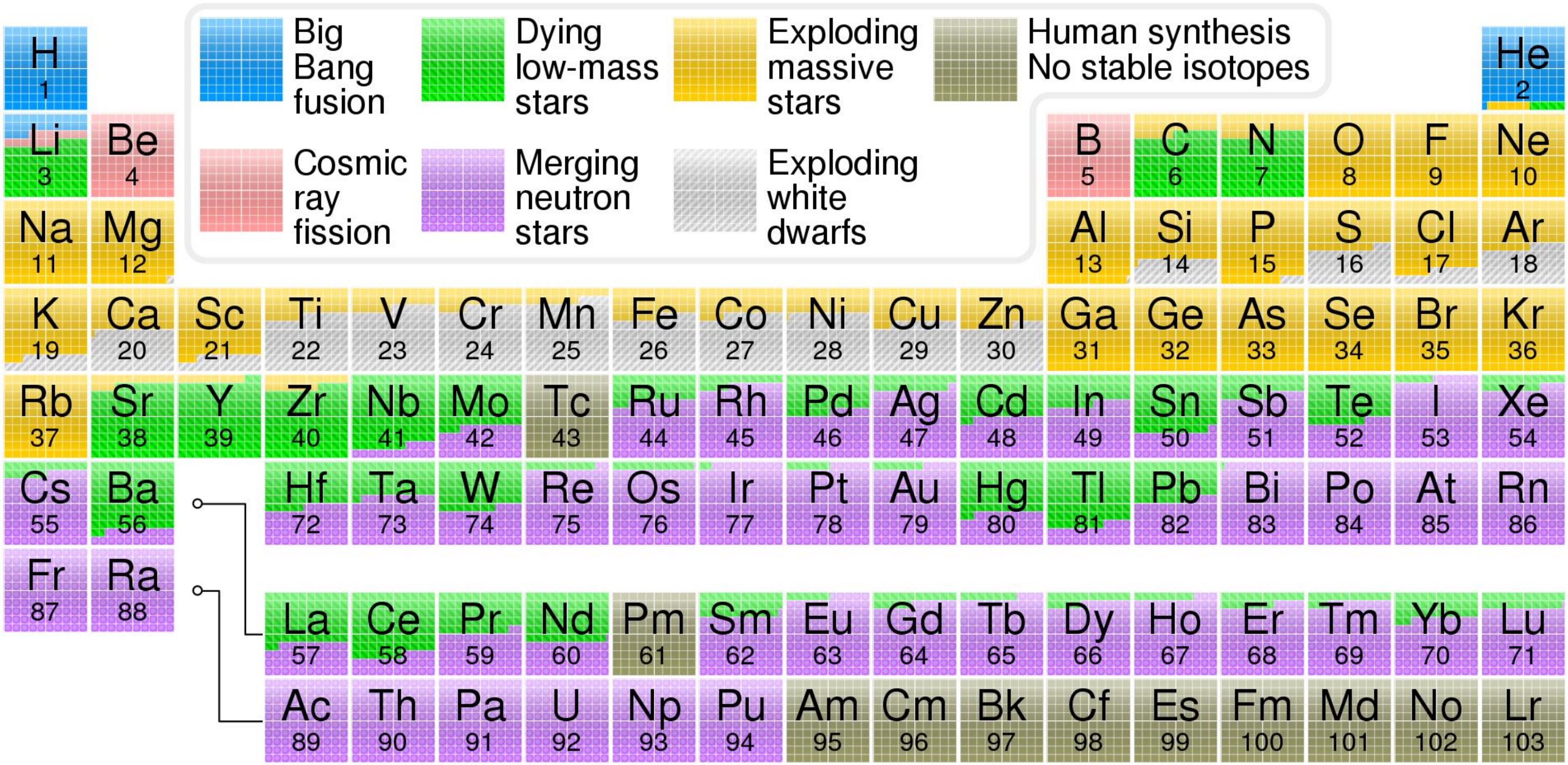

Primordial Nucleosynthesis - Motivations

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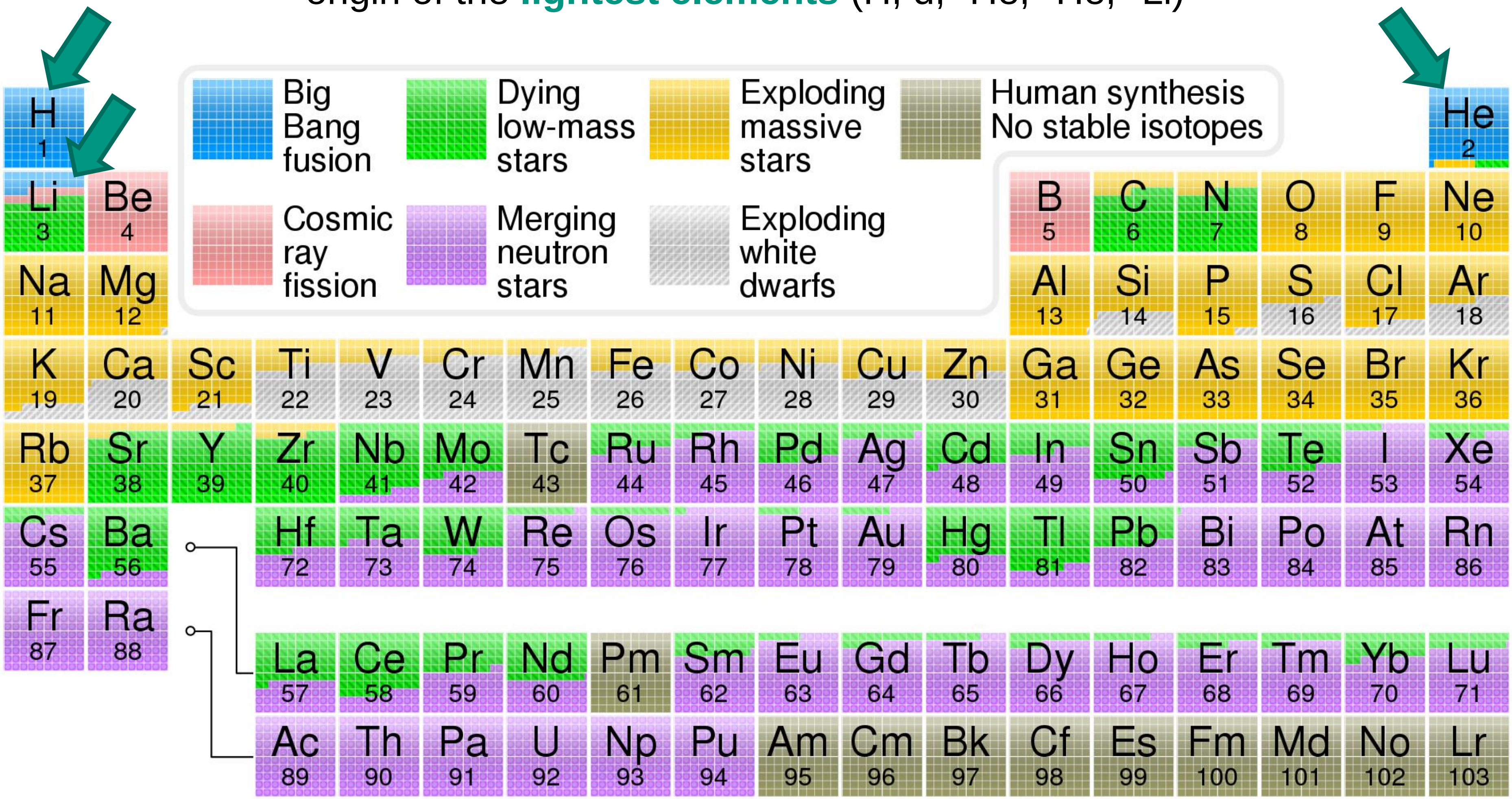

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- BBN is strongly supported by the Big Bang theory
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- **verifiable** through experimental observations
- determination of the **baryonic energy density**
- determination of the ratio of baryons and photons

Ratio of Baryons and Photons

$$\eta \equiv \frac{n_{\mathrm{baryon}}}{n_{\mathrm{photon}}} \approx \mathcal{O}(10^{-10})$$

Primordial Nucleosynthesis – Four Stages

Stage 0: Quark Gluon Plasma

$$t = 10^{-6}\,\mathrm{s}\,, \quad T = 10^{12}\,\mathrm{K}\,, \quad E = 100\,\mathrm{MeV}$$

- **quasi-free** quarks and gluons (free of confinement)
- equilibrium state
- terminates in **hadronization**

  ⇒ formation of protons and neutrons

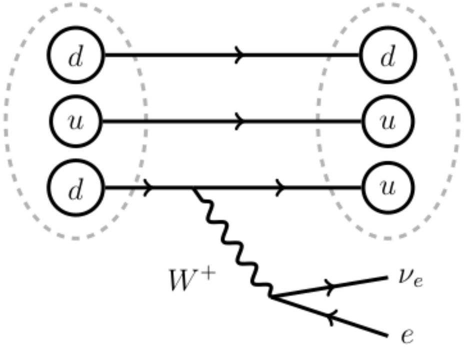
Primordial Nucleosynthesis – Four Stages

Stage I: Thermodynamic Equilibrium

$$t = 10^{-2}\,\mathrm{s}\,, \quad T = 10^{11}\,\mathrm{K}\,, \quad E = 10\,\mathrm{MeV}$$

- **dominant particles:** $p,\ n,\ \nu,\ e^{\pm}$
- equilibrium state between **protons** and **neutrons**
  ➡ continuous transformation via the weak interaction

$$\begin{aligned} p + e^- &\leftrightarrow n + \nu_e \\ p + \bar{\nu}_e &\leftrightarrow n + e^+ \\ n &\leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}$$



Primordial Nucleosynthesis – Four Stages

Stage I: Thermodynamic Equilibrium

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- $m_n > m_p$ ⇨ **difference in rest energy** $\Delta mc^2 \approx 1.293\,\mathrm{MeV}$

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- $m_n > m_p$ ➡ **difference in rest energy** $\Delta mc^2 \approx 1.293\,\mathrm{MeV}$
- proton and neutron are two states of one isospin doublet

Boltzmann Distribution in Thermal Equilibrium

$$\frac{n}{p} = \exp\left(-\frac{\Delta mc^2}{k_B T}\right) \approx \exp\left(-\frac{1.293\,\mathrm{MeV}}{k_B T}\right)$$

k_B: Boltzmann constant

- connection between neutron-proton ratio and **statistical physics**

Primordial Nucleosynthesis – Four Stages

Stage I: Thermodynamic Equilibrium

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- **reaction rate** of the weak processes:

$$\Gamma(p + e^- \leftrightarrow \nu_e + n) \approx G_F^2 T^5$$

(G_F : Fermi constant)

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- **ratio** of reaction and expansion rates:

$$\frac{\Gamma}{H} \approx \left(\frac{T}{0.8\,\mathrm{MeV}}\right)^3$$

➡ weak processes **freeze out** at roughly $T \approx 0.8\,\mathrm{MeV}$

➡ neutron-proton ratio **stabilizes** and the equilibrium is **broken**

Primordial Nucleosynthesis – Four Stages

Stage II: Freeze-Out of the Weak Processes

$$t = 1\,\mathrm{s}\,, \quad T = 10^{10}\,\mathrm{K}\,, \quad E = 1\,\mathrm{MeV}$$

- thermodynamic **equilibrium** between neutrons and protons **breaks**

$$\begin{aligned} p + e^- &\not\leftrightarrow n + \nu_e \\ p + \bar{\nu}_e &\not\leftrightarrow n + e^+ \\ n &\rightarrow p + e^- + \bar{\nu}_e \end{aligned}$$

⬅ decay of free neutrons

Neutron-Proton Ratio at the Freeze-Out Temperature

$$\frac{n}{p} = \exp\left(-\frac{\Delta m c^2}{k_B T}\right) \approx \frac{1}{6}$$

Primordial Nucleosynthesis – Four Stages

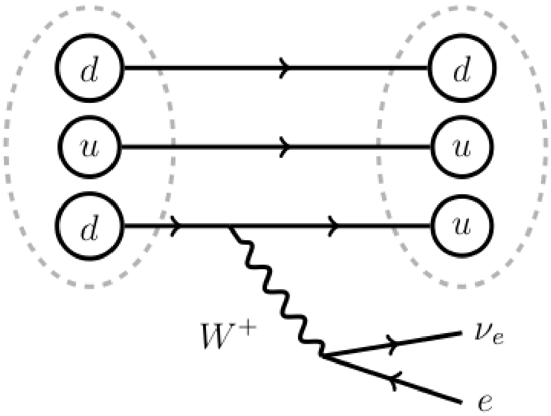
Stage III: Beta Decay of the Free Neutrons

$$t < 1\,\mathrm{min}\ , \quad T = 10^{10}\,\mathrm{K} - 10^{9}\,\mathrm{K}\ , \quad E = 1\,\mathrm{MeV} - 0.1\,\mathrm{MeV}$$

- mean lifetime of free neutrons: $\tau \approx 14.7\,\mathrm{min}$

Decay Process of Free Neutrons

$$n \;\rightarrow\; p + e^{-} + \bar{\nu}_e$$



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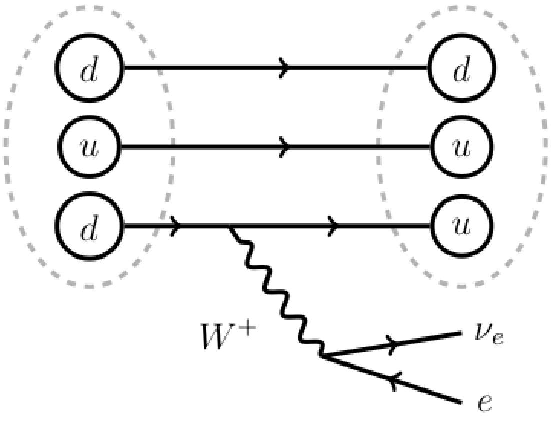
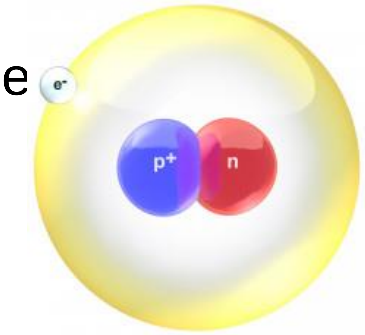


- **no light elements are produced yet**

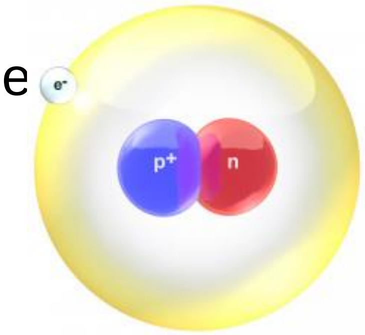
→ **why?**

Primordial Nucleosynthesis – Four Stages

- **deuterium (d)** is the next-to-lightest isotope to be produce



Primordial Nucleosynthesis – Four Stages



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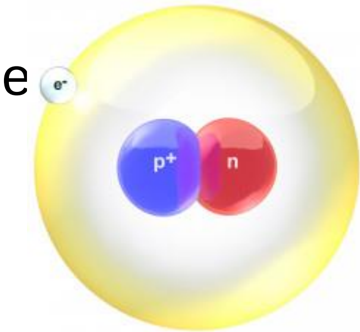
- **binding energy** of deuterium: $E_b \approx 2.2\,\mathrm{MeV}$
- ratio of **photons with the same energy** at $T \approx 0.1\,\mathrm{MeV}$ (high-end tail):

$$\frac{n_\gamma(E \geq E_b)}{n_{\gamma,\mathrm{tot}}} = \exp\left(-\frac{E_b(d)}{k_B T}\right) \approx 10^{-10}$$

Primordial Nucleosynthesis – Four Stages



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- remember: **baryon-to-photon ratio** is $\eta \approx 10^{-10}$

➡ for each produced deuteron, one high-energy photon **is present**

➡ thermal equilibrium between deuteron **production** and **spallation**

➡ neither stable deuterium nor the other light elements can be produced yet

➡ stable deuterium is needed for other elements: **"deuterium bottleneck"**

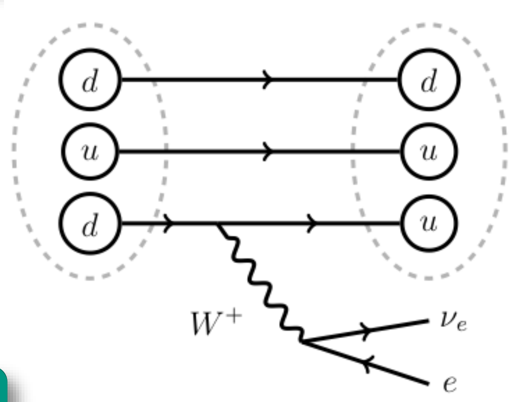
Primordial Nucleosynthesis – Four Stages

Stage IV: Primordial Nucleosynthesis

$$t \leq 3\,\mathrm{min}\ , \quad T = 10^9\,\mathrm{K}\ , \quad E = 0.1\,\mathrm{MeV}$$

- free neutrons continue to decay:

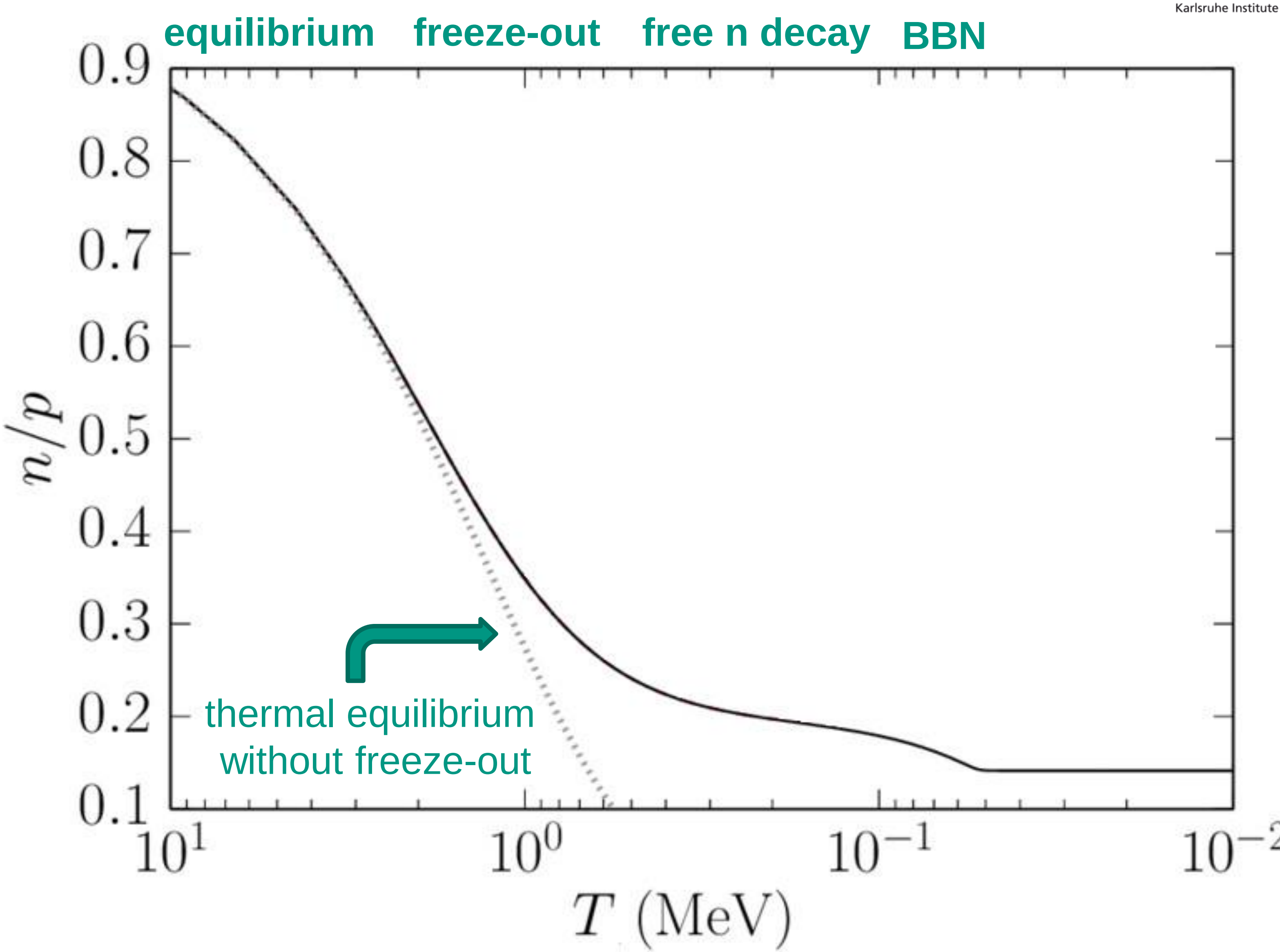
$$n \ \rightarrow \ p + e^- + \bar{\nu}_e$$



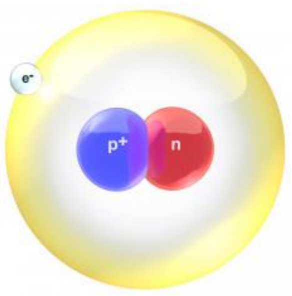
Neutron-Proton Ratio at the Beginning of BBN

$$\frac{n}{p} \approx \frac{1}{7}$$

Primordial Nucleosynthesis – Four Stages



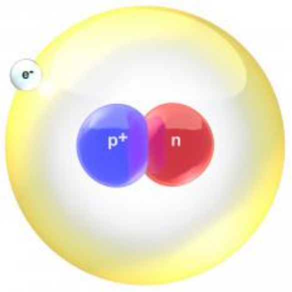
Primordial Nucleosynthesis – Processes



Production of Deuterons

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

Primordial Nucleosynthesis – Processes



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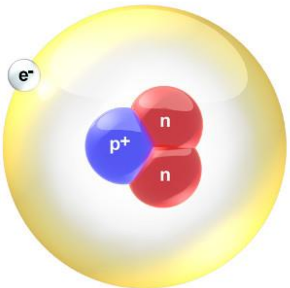
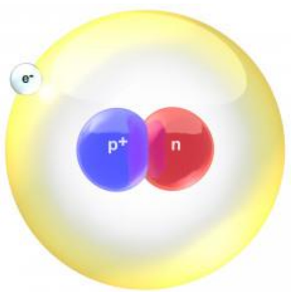


Production of Tritons

$$n + d \rightarrow t + \gamma$$

Primordial Nucleosynthesis – Processes



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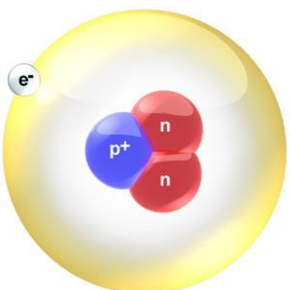

Production of Tritons

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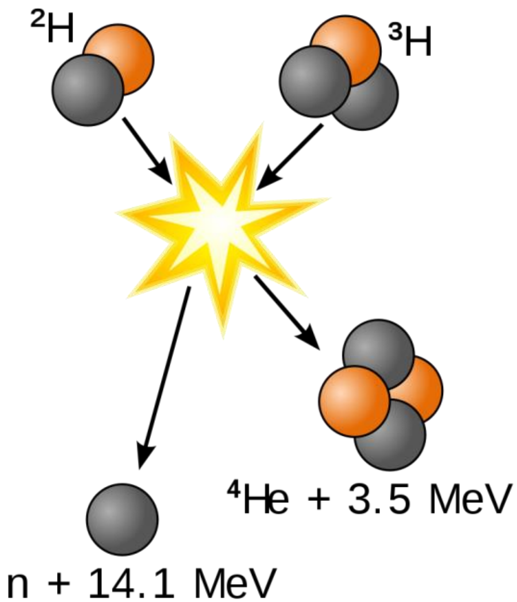
Production of Helium Isotopes

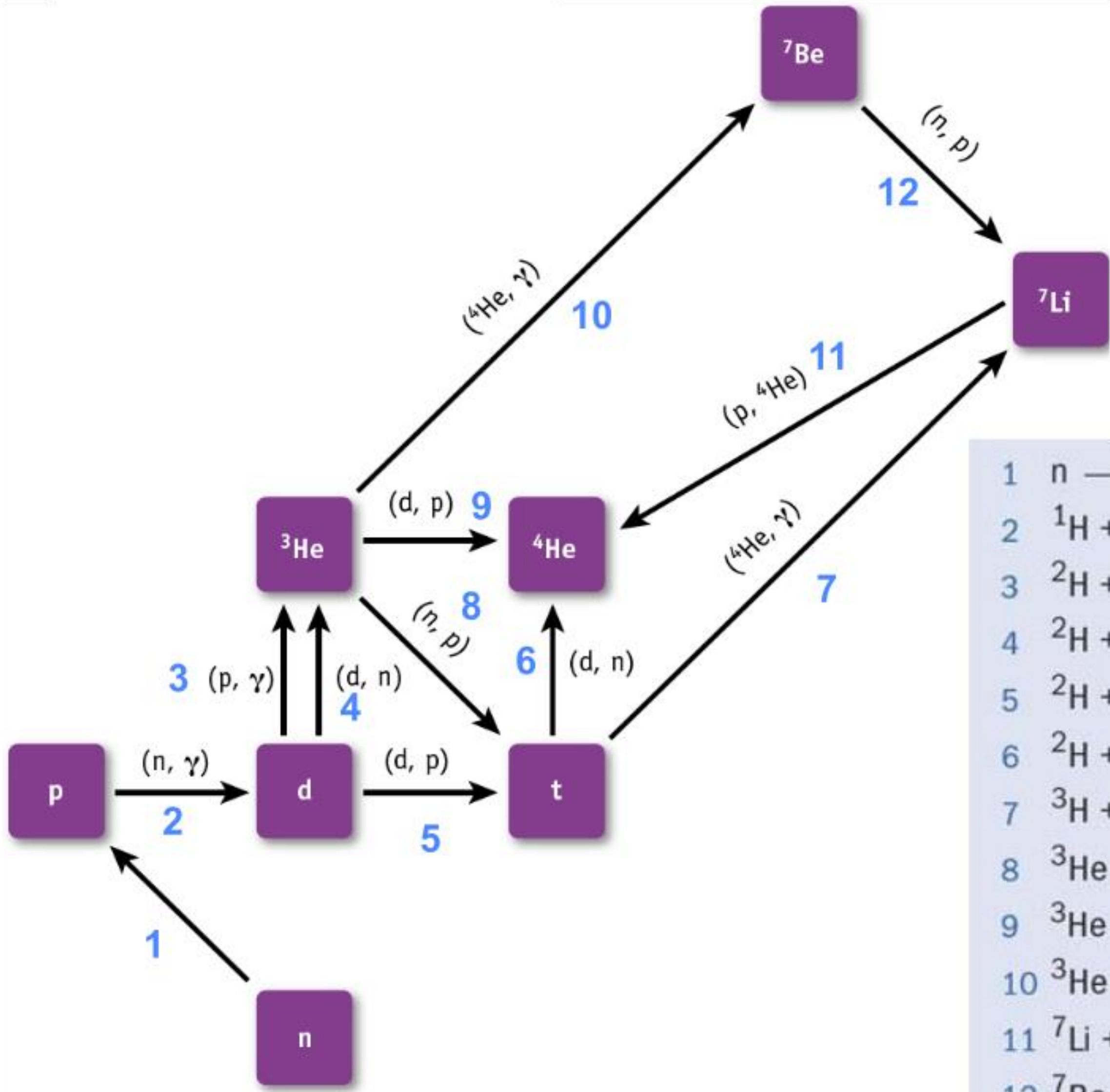
$$d + d \;\leftrightarrow\; {}^3\mathrm{He} + n$$

$$d + p \;\leftrightarrow\; {}^3\mathrm{He} + \gamma$$

$$t + d \;\leftrightarrow\; {}^4\mathrm{He} + n$$



Primordial Nucleosynthesis – Processes



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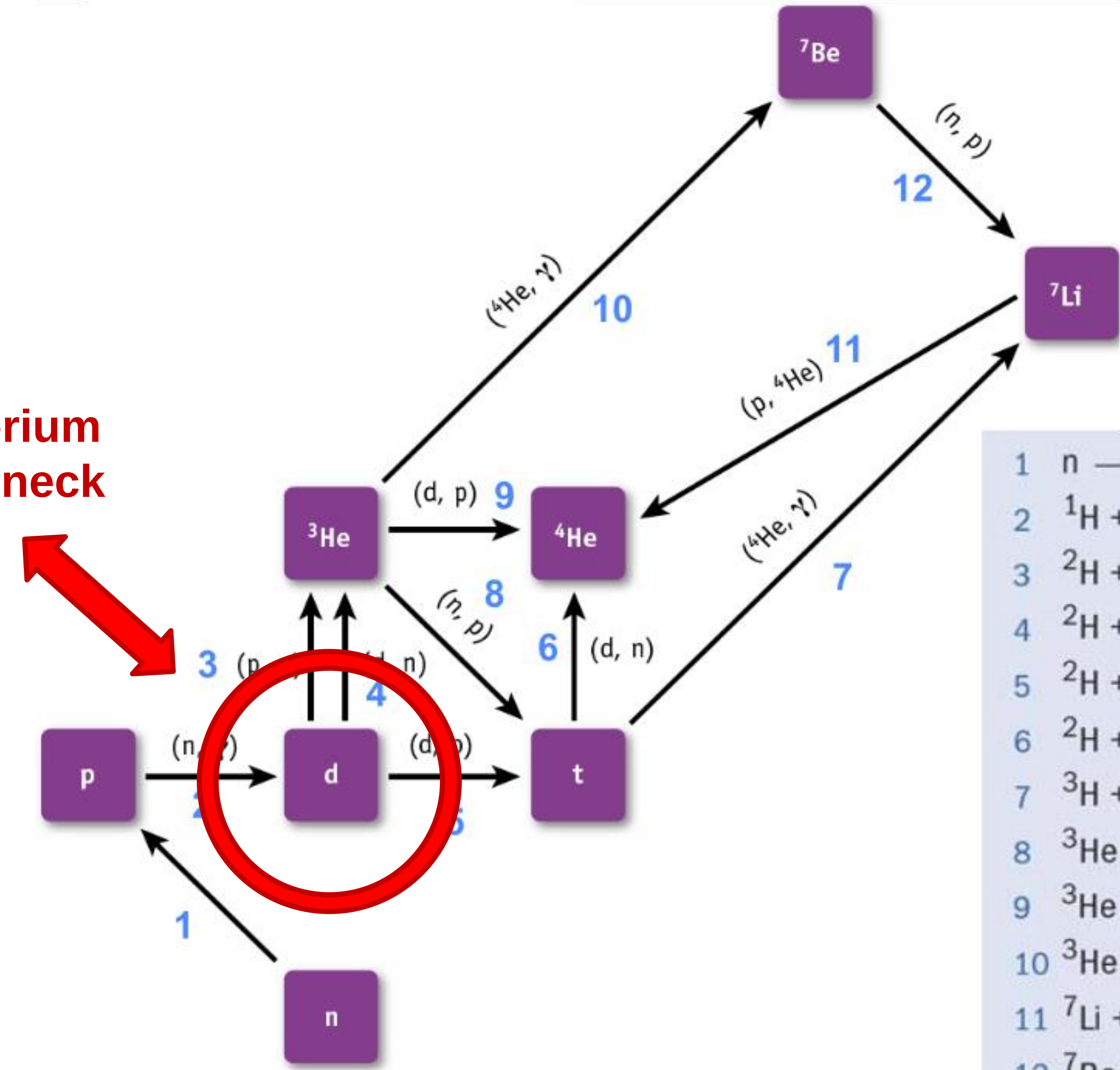
Primordial Nucleosynthesis – Processes

deuterium bottleneck



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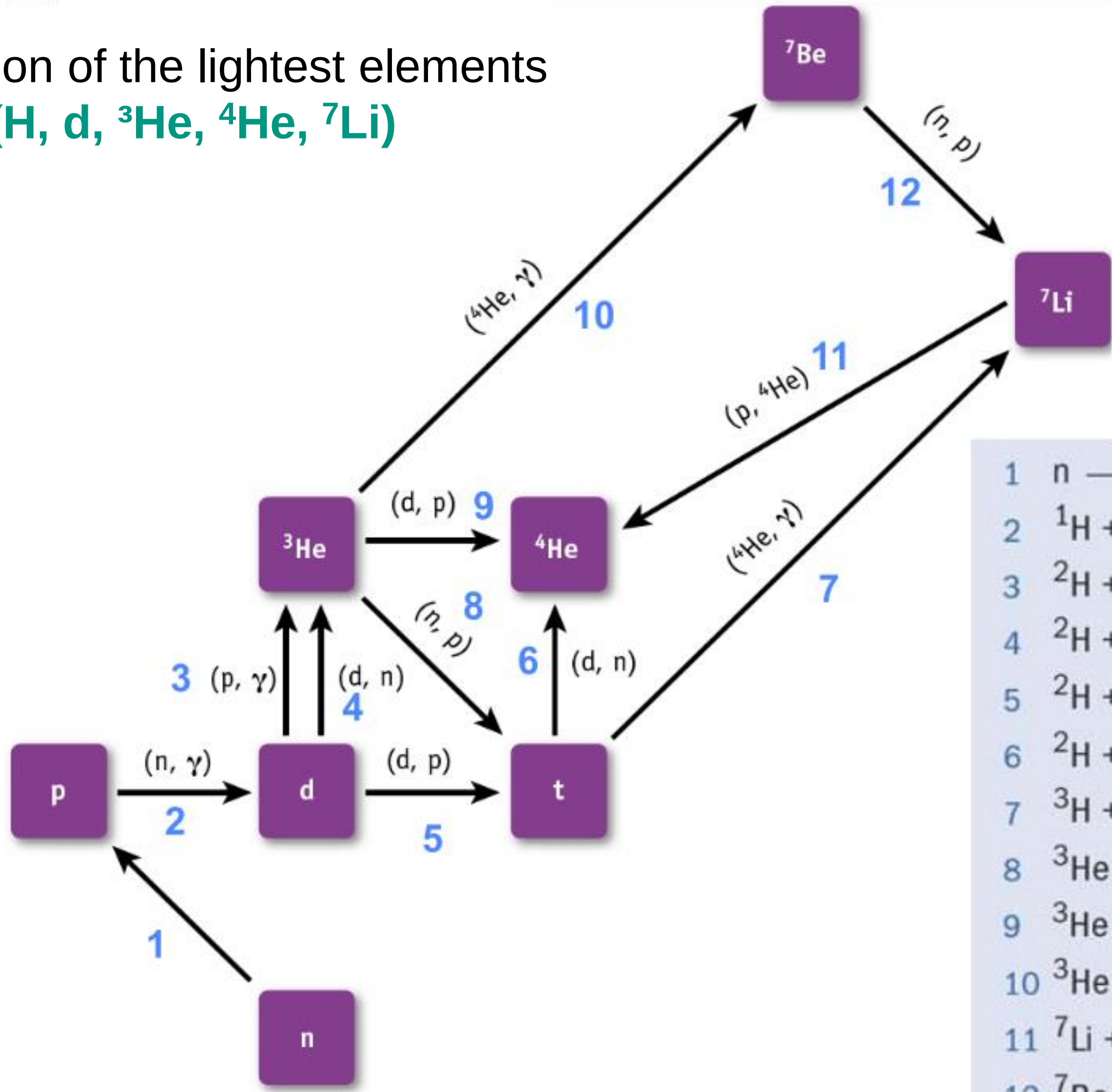
Primordial Nucleosynthesis – Processes

production of the lightest elements

(H, d, ^{3}He, ^{4}He, ^{7}Li)



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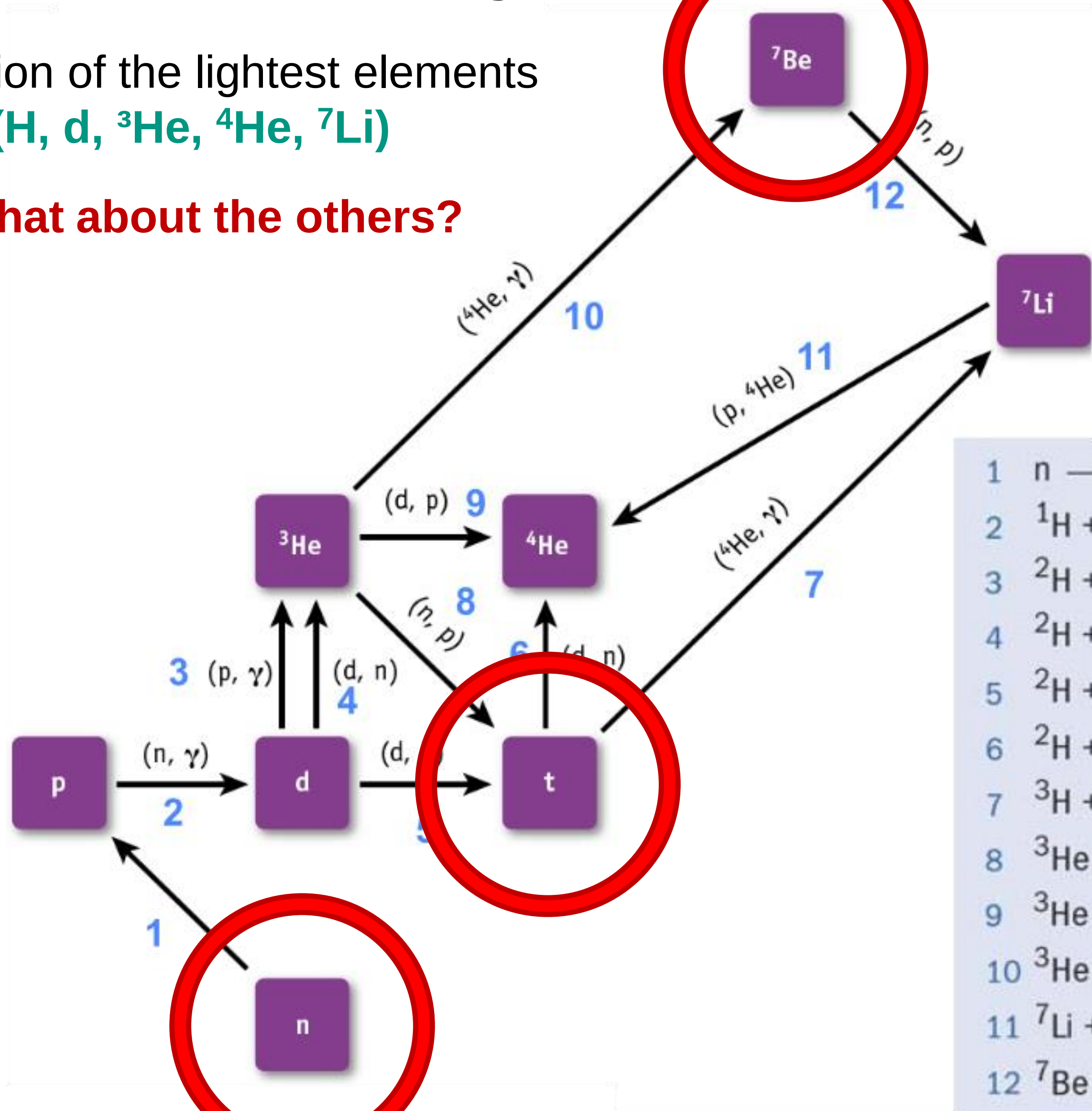
Primordial Nucleosynthesis – Processes

production of the lightest elements
(H, d, ^{3}He, ^{4}He, ^{7}Li)

➡ **what about the others?**



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Primordial Nucleosynthesis – Processes

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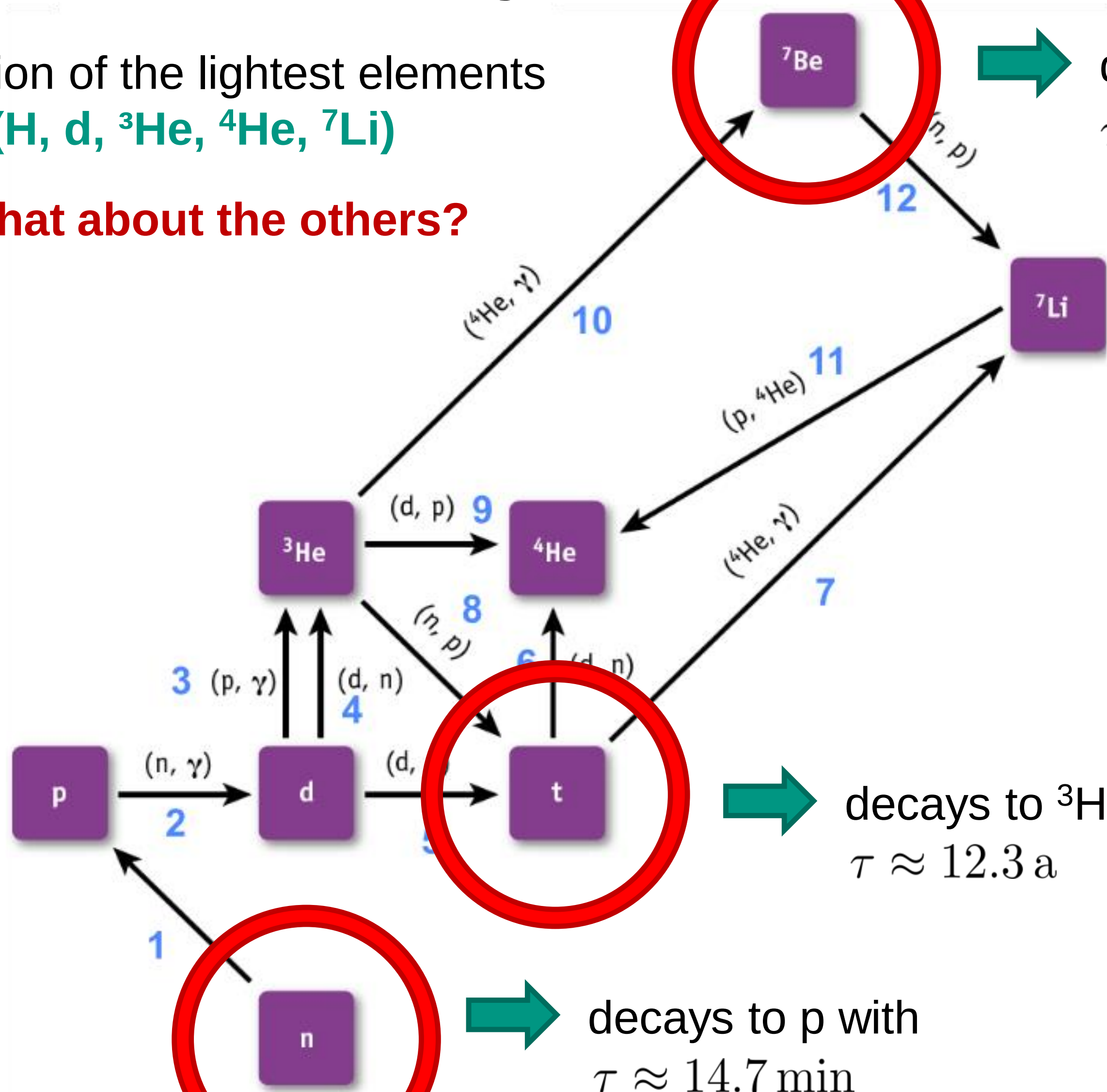

➡ decays to ^{7}Li with
$\tau \approx 53.1\,\mathrm{d}$

➡ decays to ^{3}He with
$\tau \approx 12.3\,\mathrm{a}$

➡ decays to p with
$\tau \approx 14.7\,\mathrm{min}$

Primordial Nucleosynthesis – Processes

- **all dominant** processes terminate in ^{4}**He**

  ⇒ **second most common atom** in the universe

Primordial Nucleosynthesis – Processes

- **all dominant** processes terminate in **^{4}He**
  - ⇨ **second most common atom** in the universe
- we had $\frac{n}{p} \approx \frac{1}{7}$

Estimate of the Helium Abundance After the BBN

$$Y \equiv \frac{2\,\frac{n}{p}}{\frac{n}{p}+1} \approx 0.25$$

Primordial Nucleosynthesis – Processes

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Estimate of the Helium Abundance After the BBN

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- approximate abundance of the two lightest stable elements:

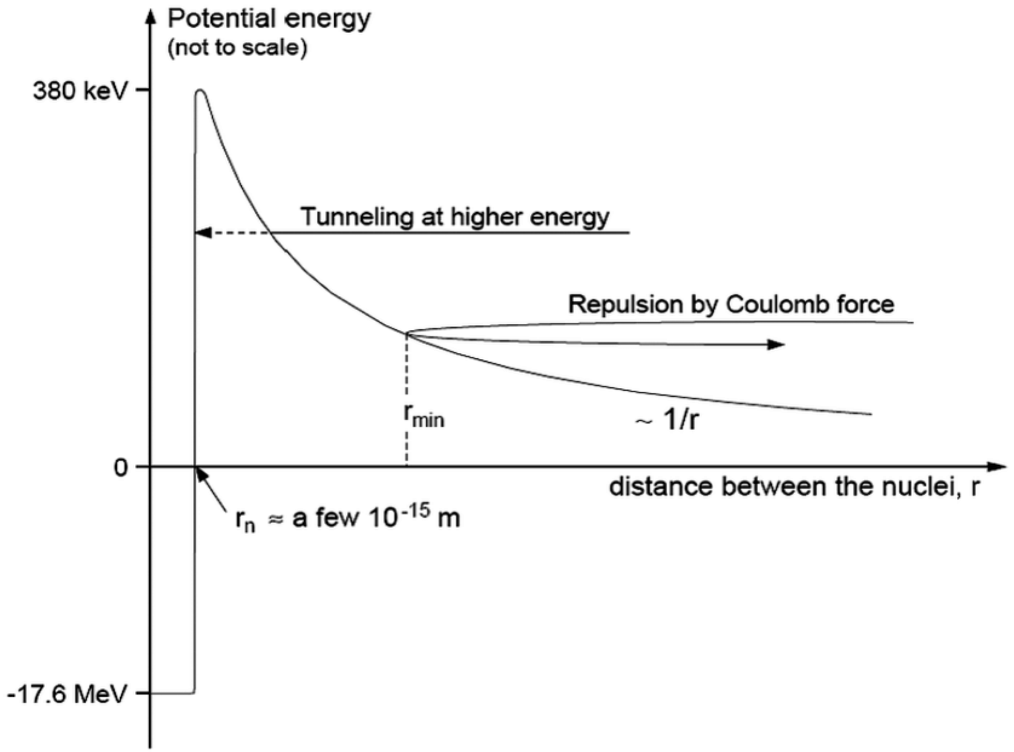
75% H, 25% ^{4}He

Primordial Nucleosynthesis – Processes

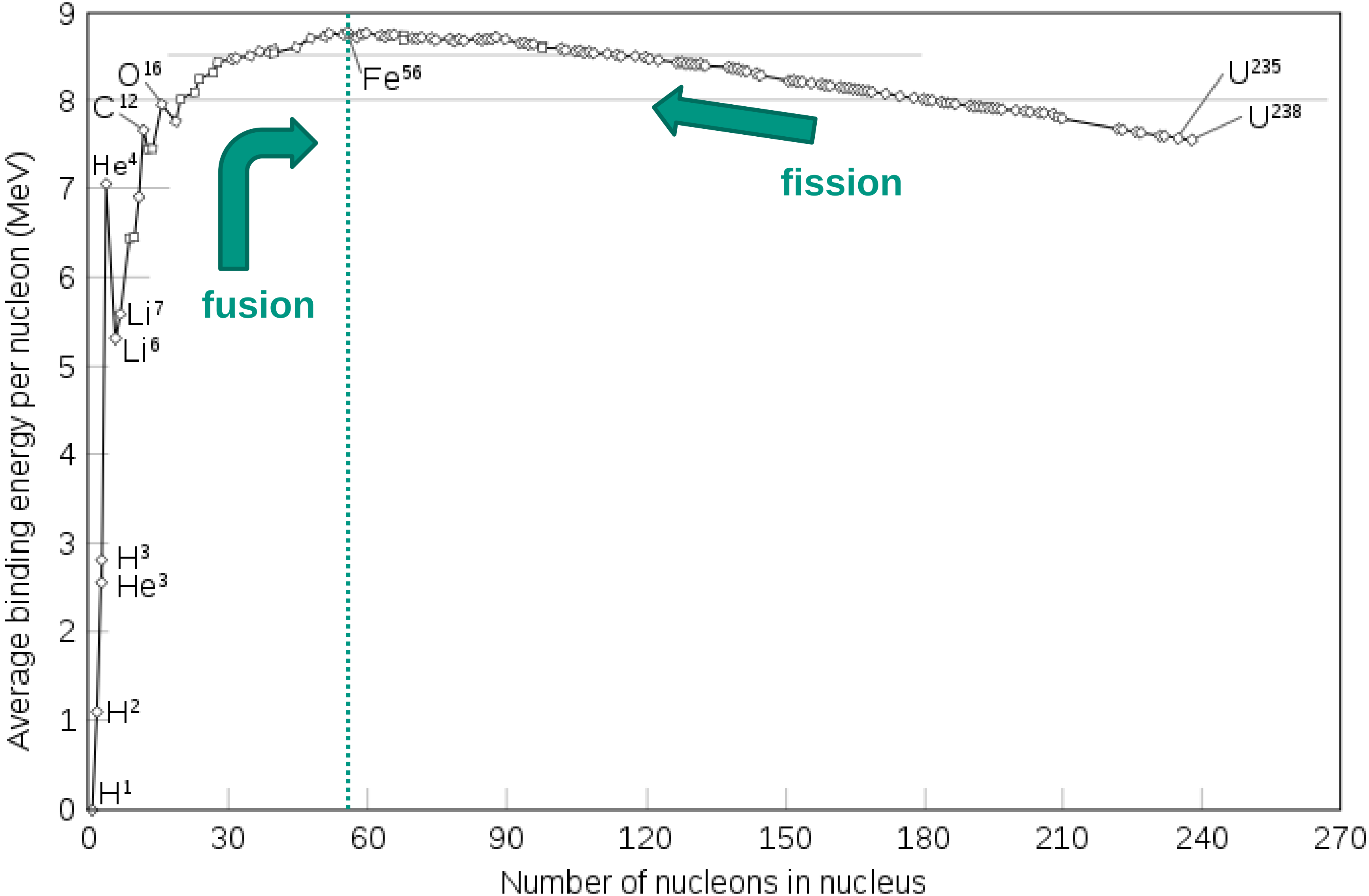
- what about **heavier elements?**

Primordial Nucleosynthesis – Processes

- what about **heavier elements?**
- production **very unlikely**:
  - no **stable** elements with mass numbers 5 or 8
  - Coulomb wall increases drastically with increasing mass number



Primordial Nucleosynthesis – Processes



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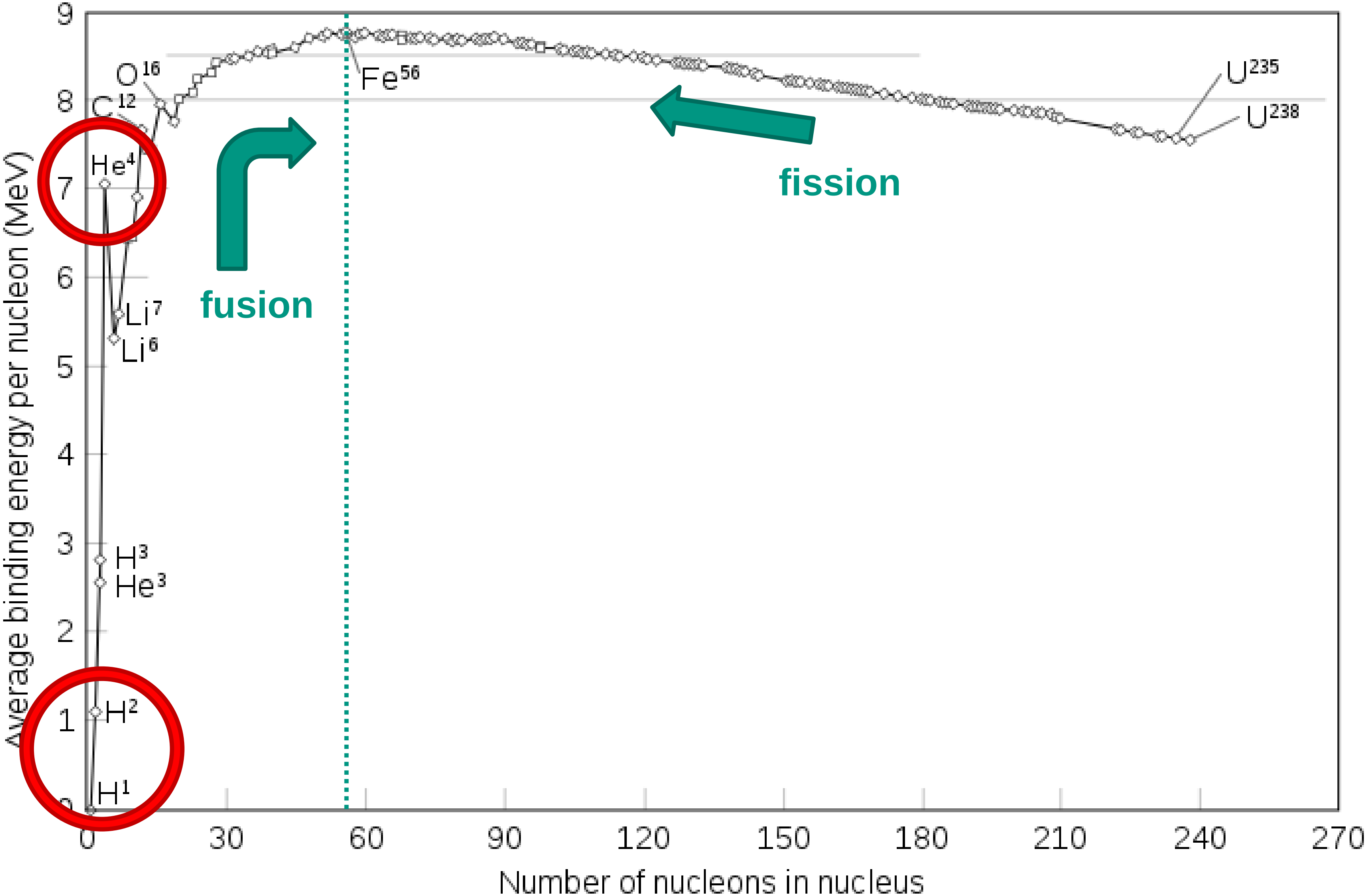
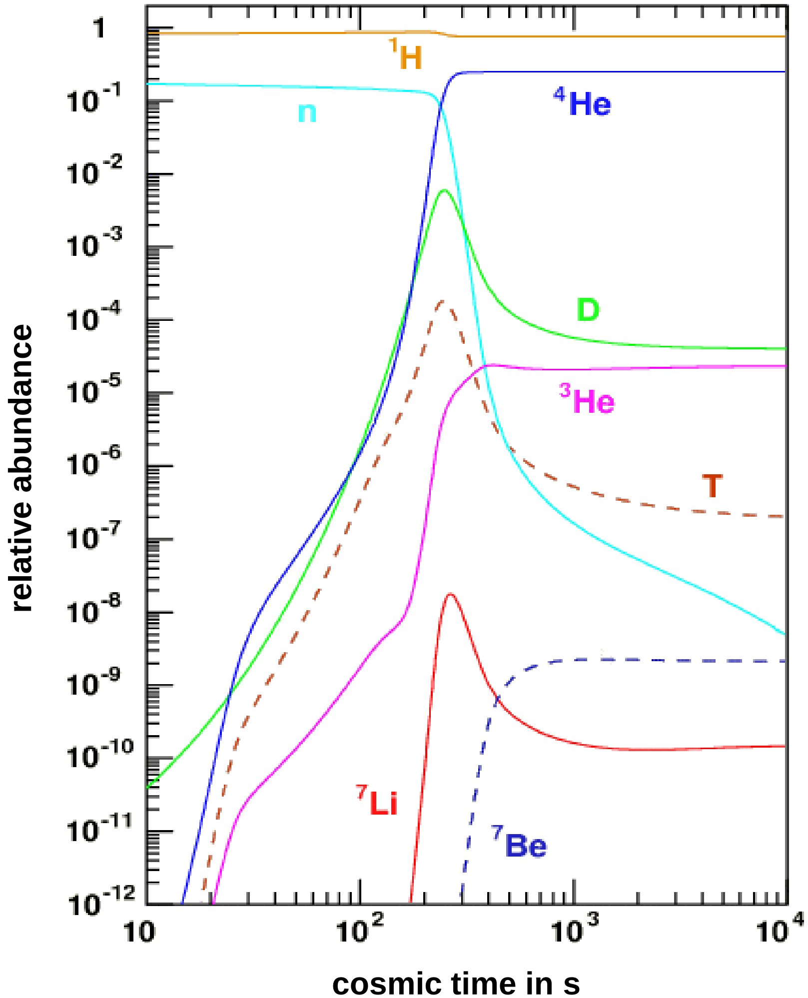


Primordial Nucleosynthesis – Processes

Karlsruhe Institute of Technology

- **prediction** of abundance of all light elements during/after the BBN



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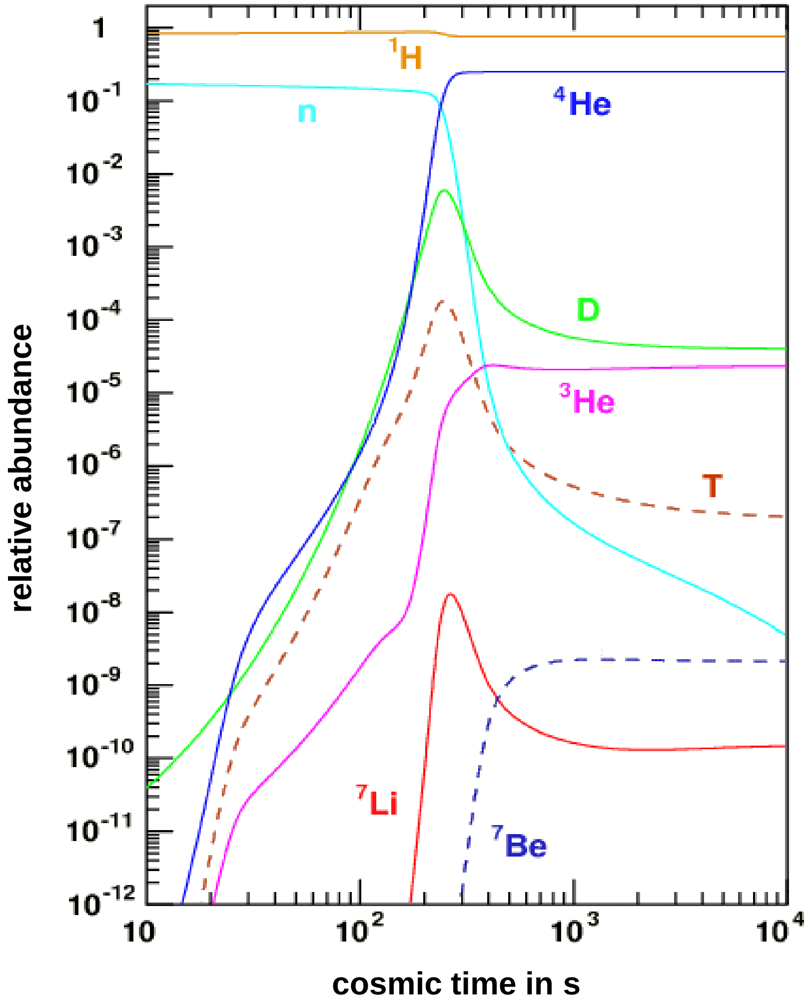
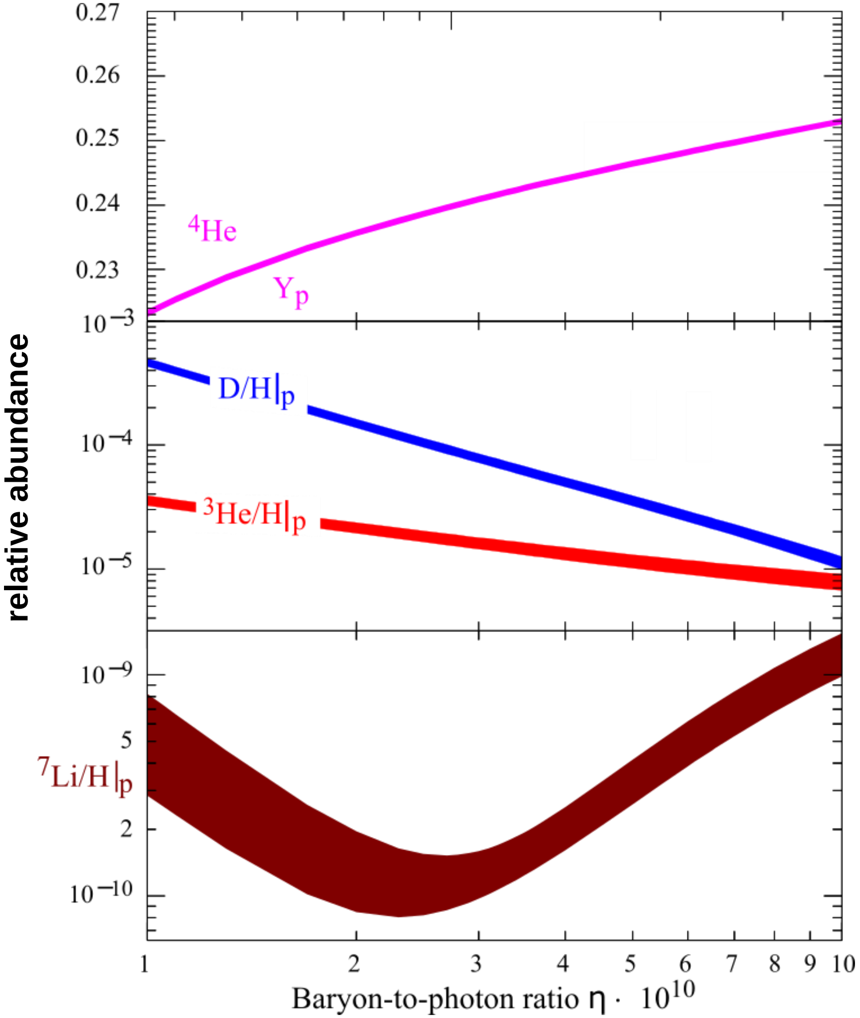


- roughly 75% H
- roughly 25% ^{4}He
- $d/H \approx 10^{-5}$
- $^3He/H \approx 10^{-6}$
- $^7Li/H \approx 10^{-10}$

➡ valid for **one chosen** η

Primordial Nucleosynthesis – Processes

- **variation** of the baryon-photon ratio η



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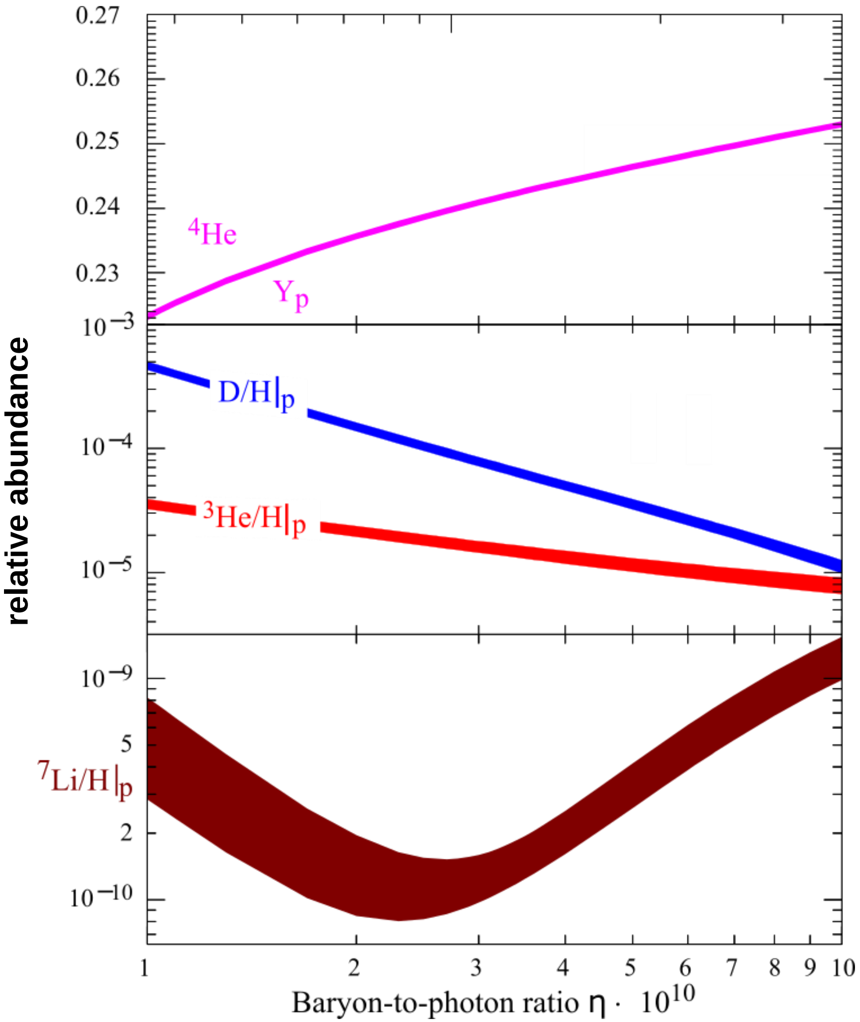

Effect on ^{4}He Production

higher η: higher n/p ratio

➡ earlier production due to more n

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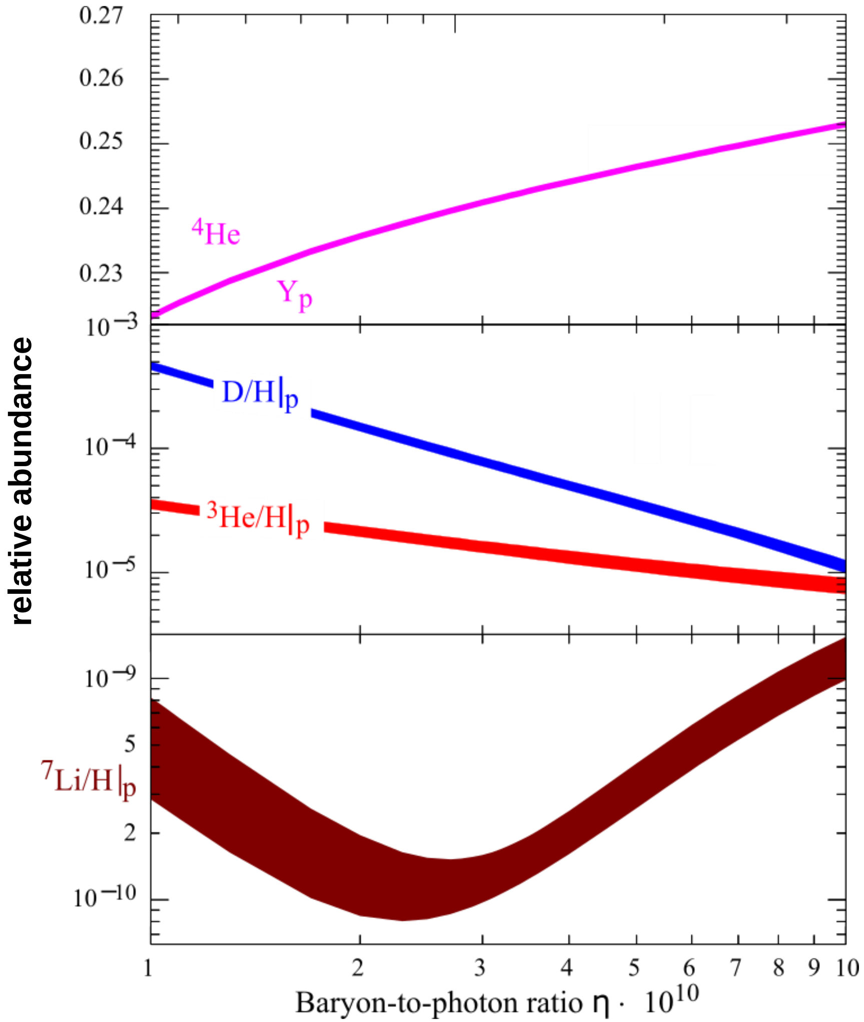

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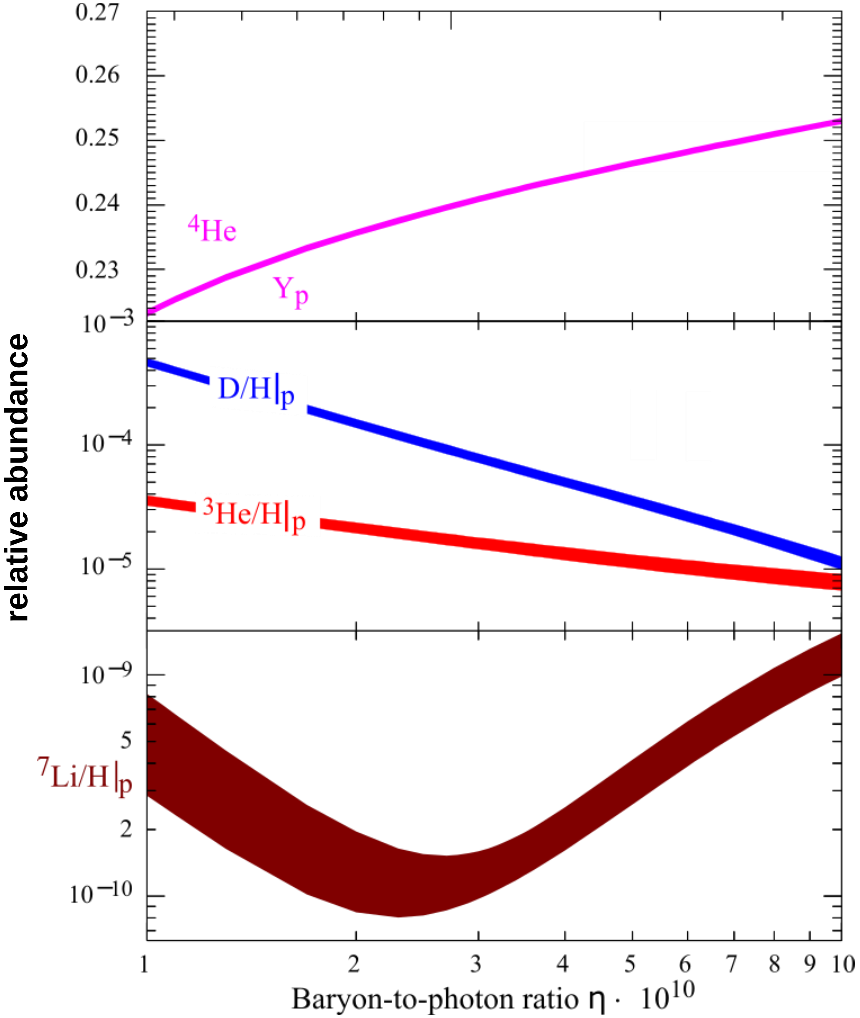

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Effect on d Production

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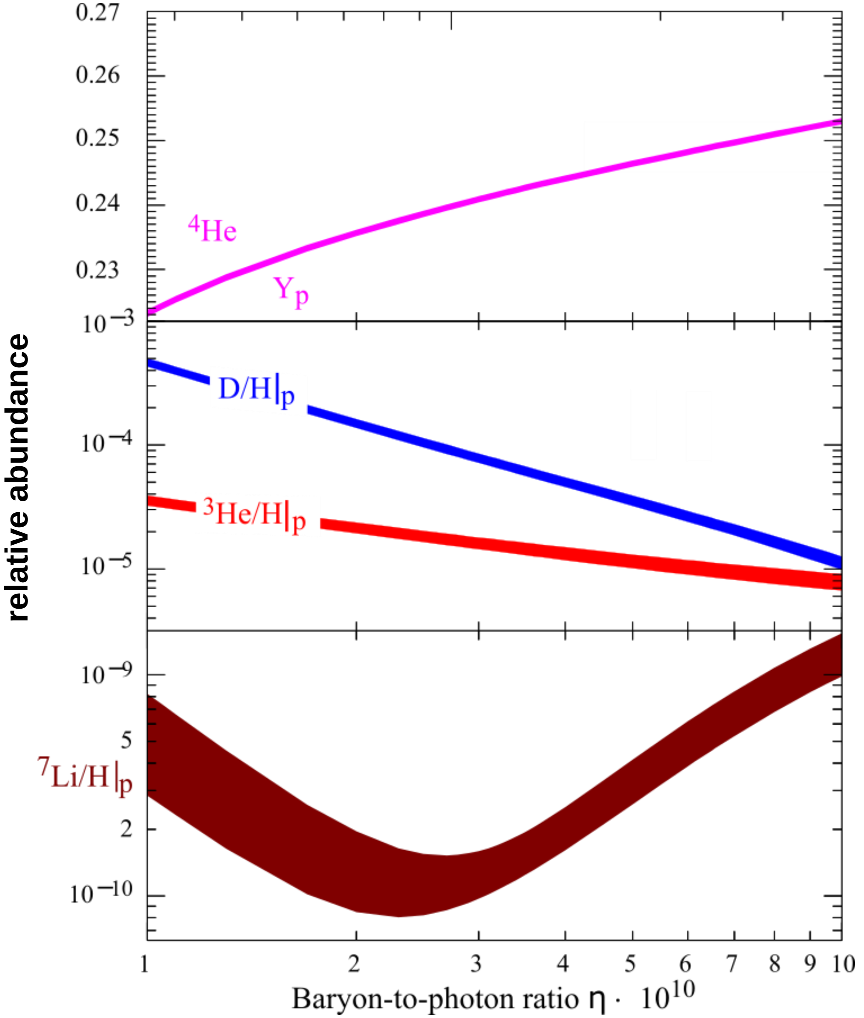
Effect on ^{7}Li Production

lower η: more frequent decay to ^{4}He

higher η: earlier synthesis

Primordial Nucleosynthesis – Processes

- **measuring** the abundance of the elements fixes η



Motivations:

- confirms the **Big Bang theory**
- determines η and Ω_B
- indicates consistency of the BBN over **ten orders of magnitude**

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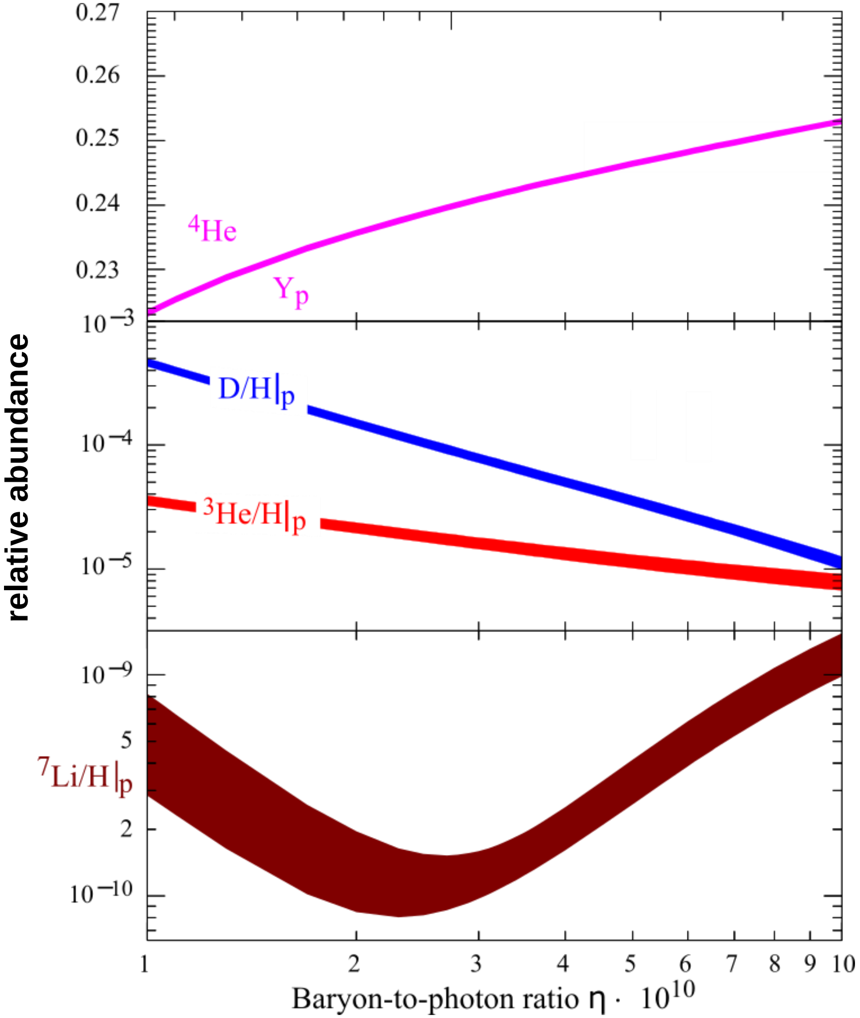

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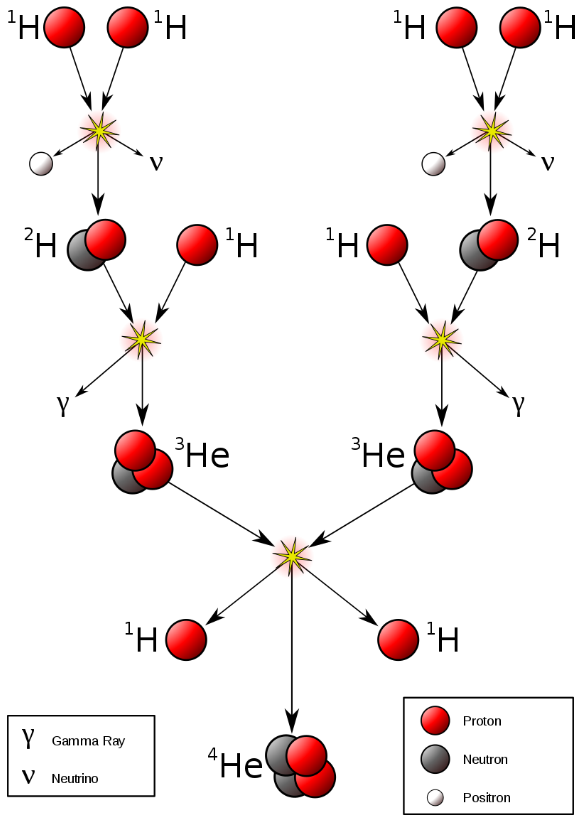
Methodology:

- measurements yield the **horizontals** in the plots
- **point(s) of intersection** indicate the measured value of η

Measurements of ^{4}He

- **stellar nucleosynthesis**: amount of ^{4}He increases compared to the abundance after the BBN

  ⇨ entanglement of primordial and stellar ^{4}He production



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Definition of Metallicity

$$\text{metallicity} \equiv \frac{O}{H} \equiv \frac{\text{amount of oxygen}}{\text{amount of hydrogen}}$$

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(low metallicity, gas-rich, H-II region)

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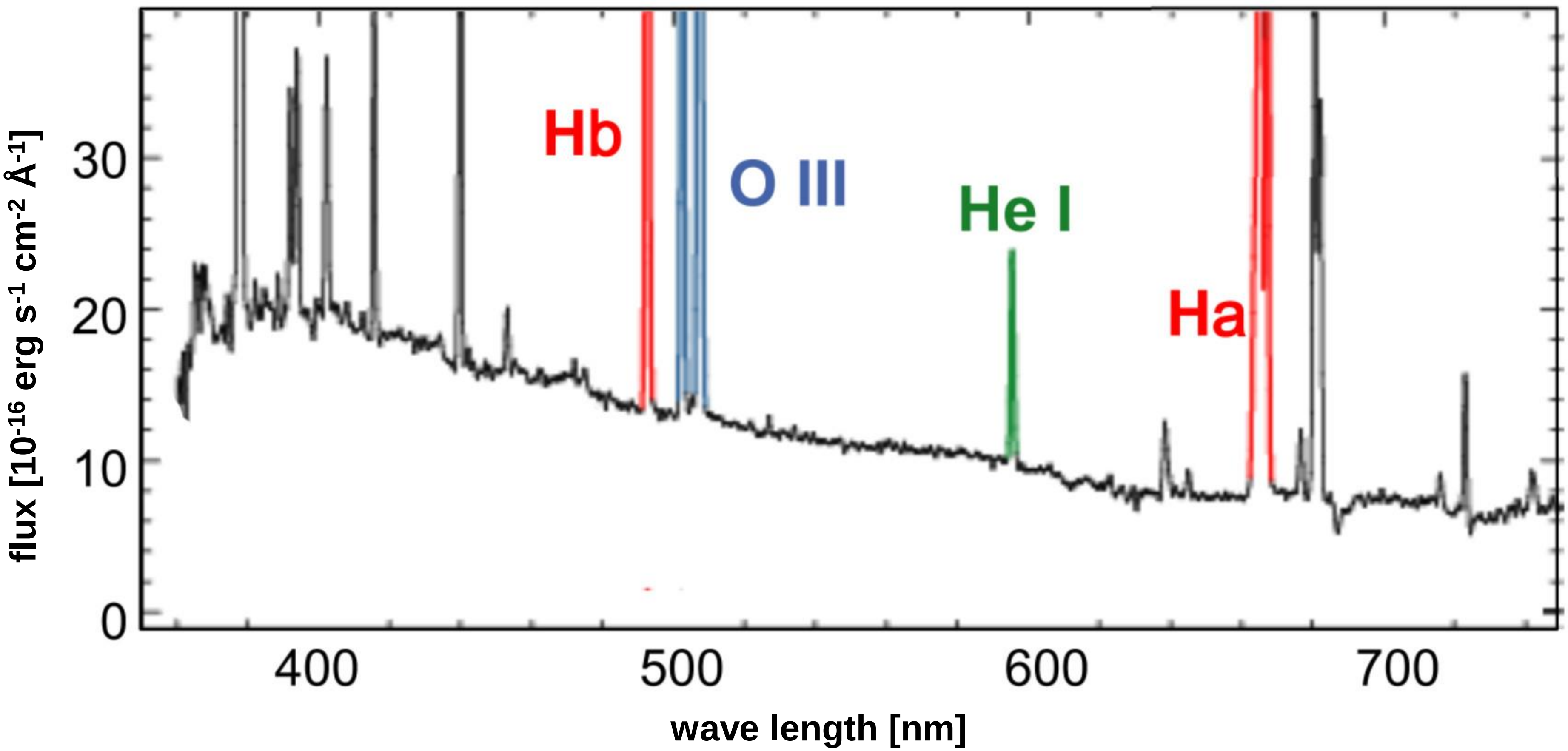
Measurements of ^{4}He



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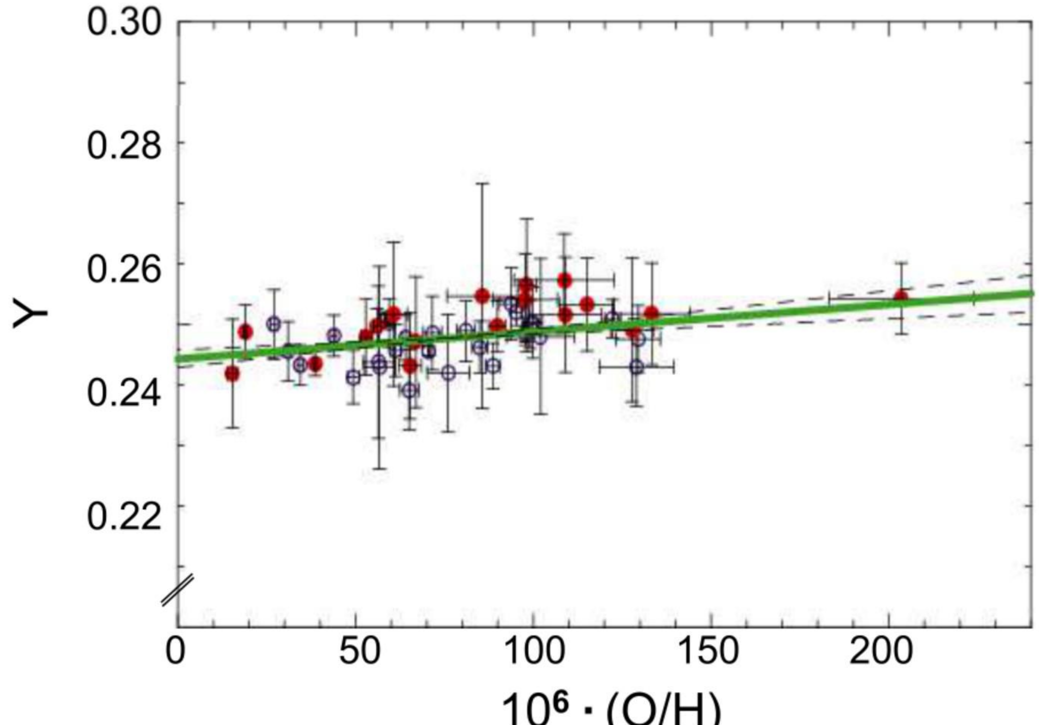

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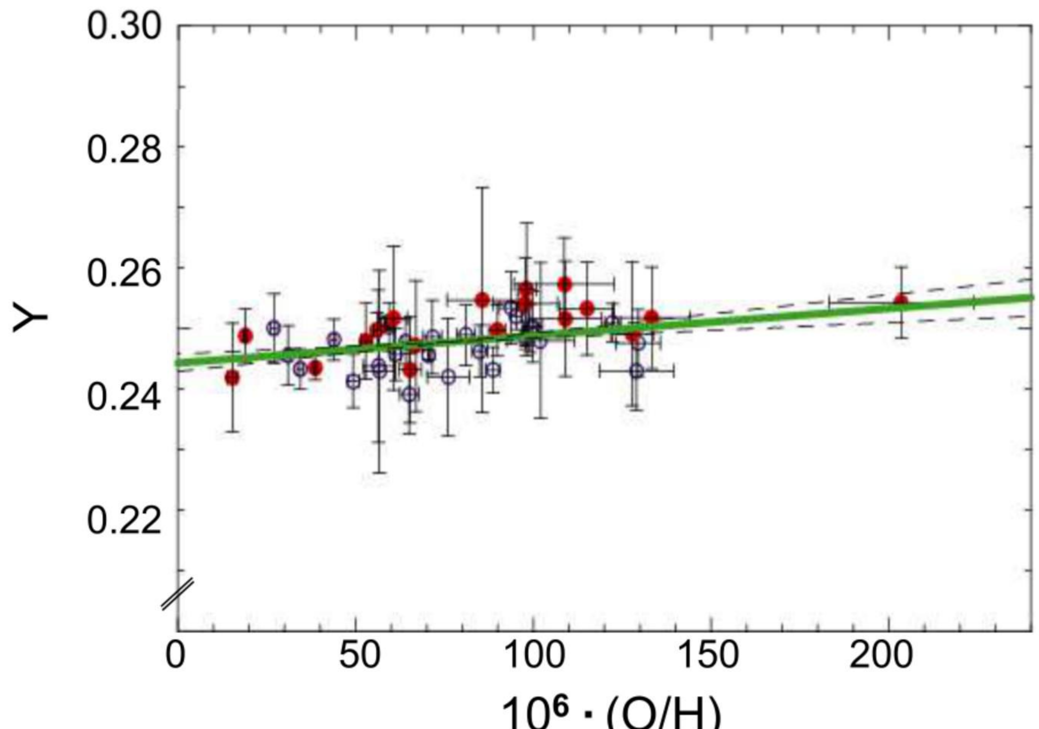
➡ extrapolation to zero metallicity

➡ **primordial amount** of ^{4}He



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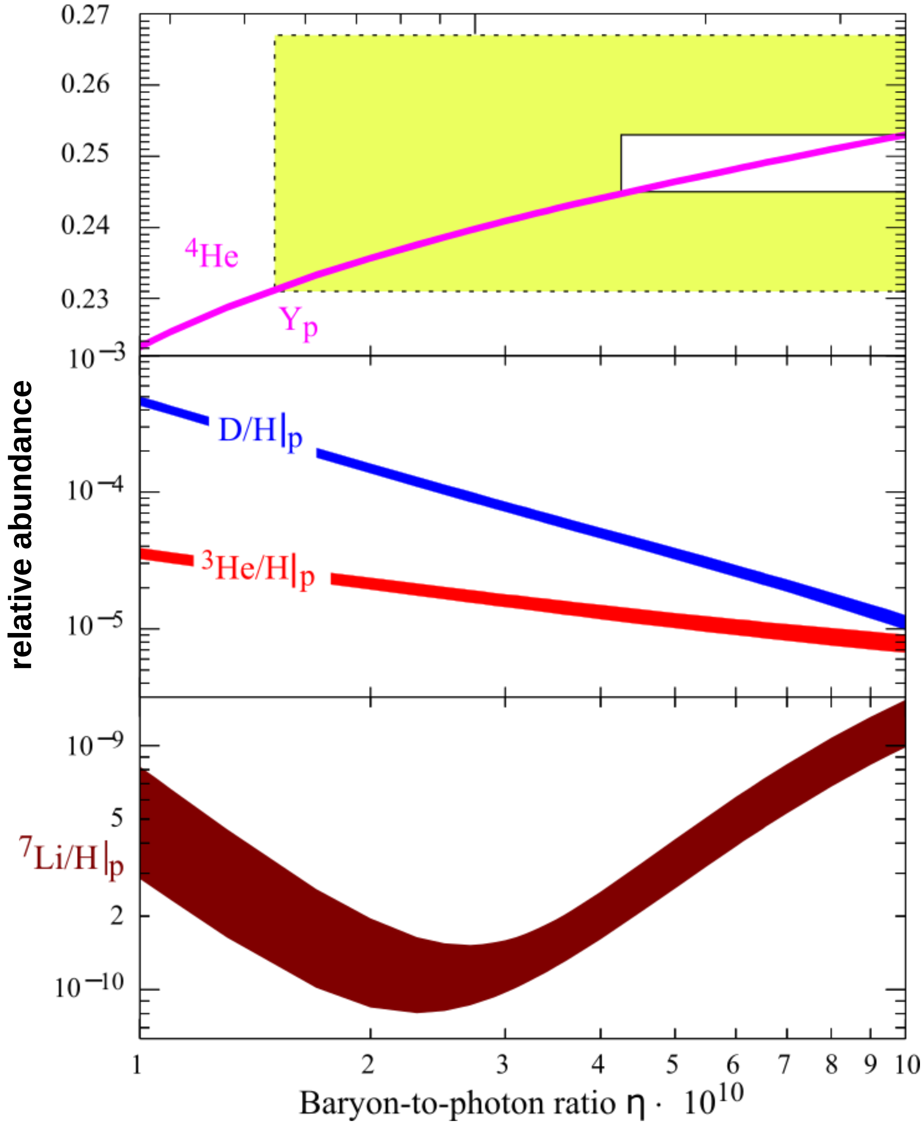

- theoretical estimate:

$$Y_{\mathrm{theor}} \approx 0.25$$

- experimental value (PDG):

$$Y_{\mathrm{exp}} \approx 0.245 \pm 0.003$$

Measurements of d

- **no significant** deuterium **production** after the BBN

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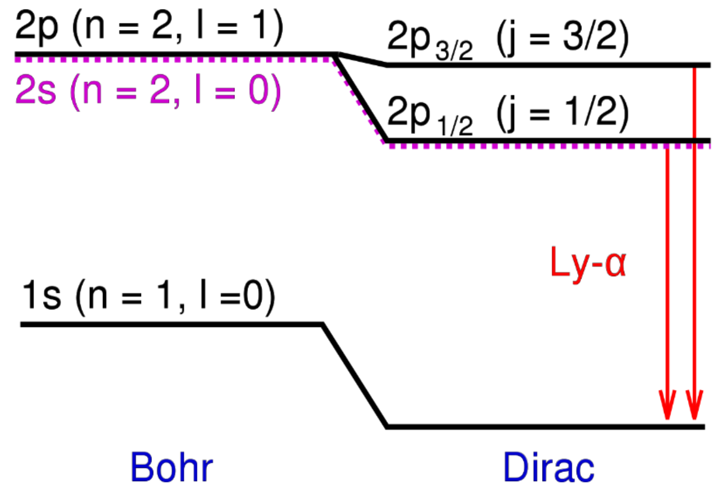

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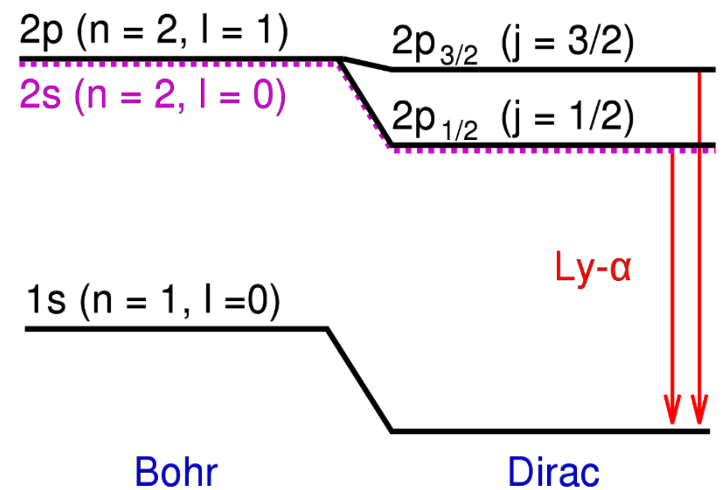

➡ Ly-α line at $\lambda_{\text{Ly-}\alpha} \approx 121.5\,\mathrm{nm}$ (**UV regime**)

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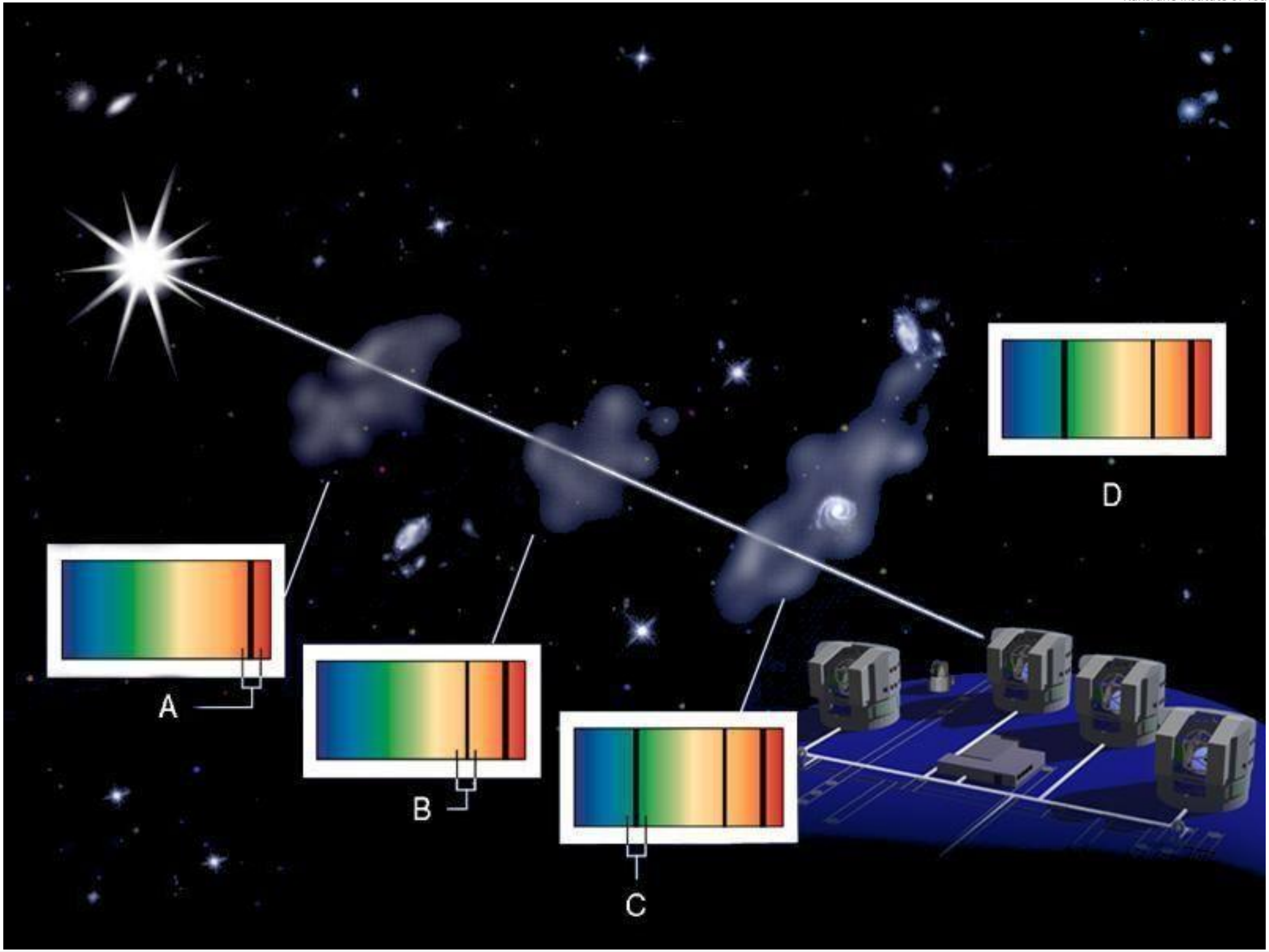
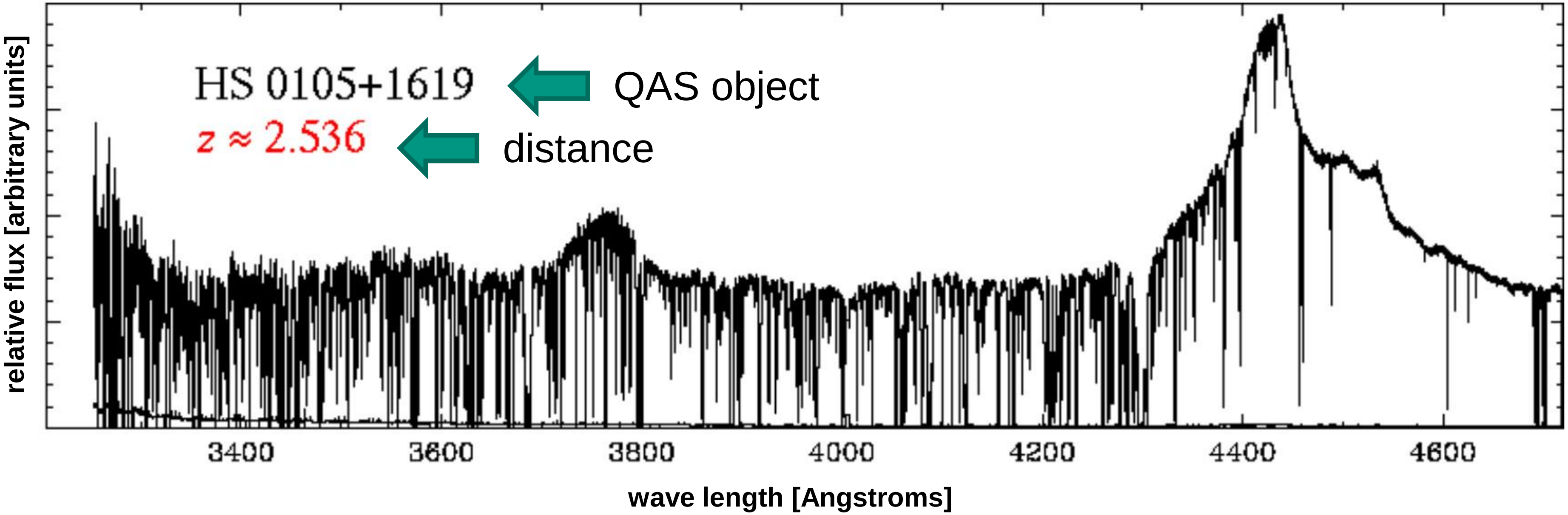
- the spectrum shows **different Ly-α lines** due to **different redshifts *z***
- the **redshift is necessary** since optical instruments are not sensitive enough in the UV regime

Measurements of d



Measurements of d

- actual spectral analysis shows the **Lyman-α forest**



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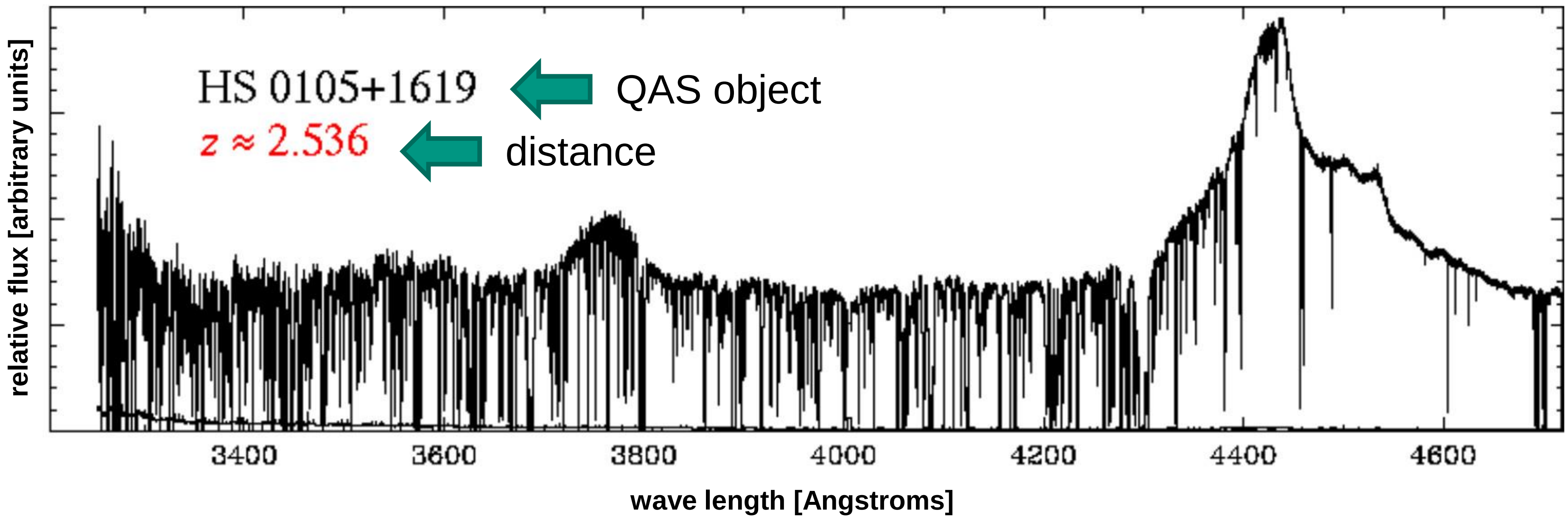

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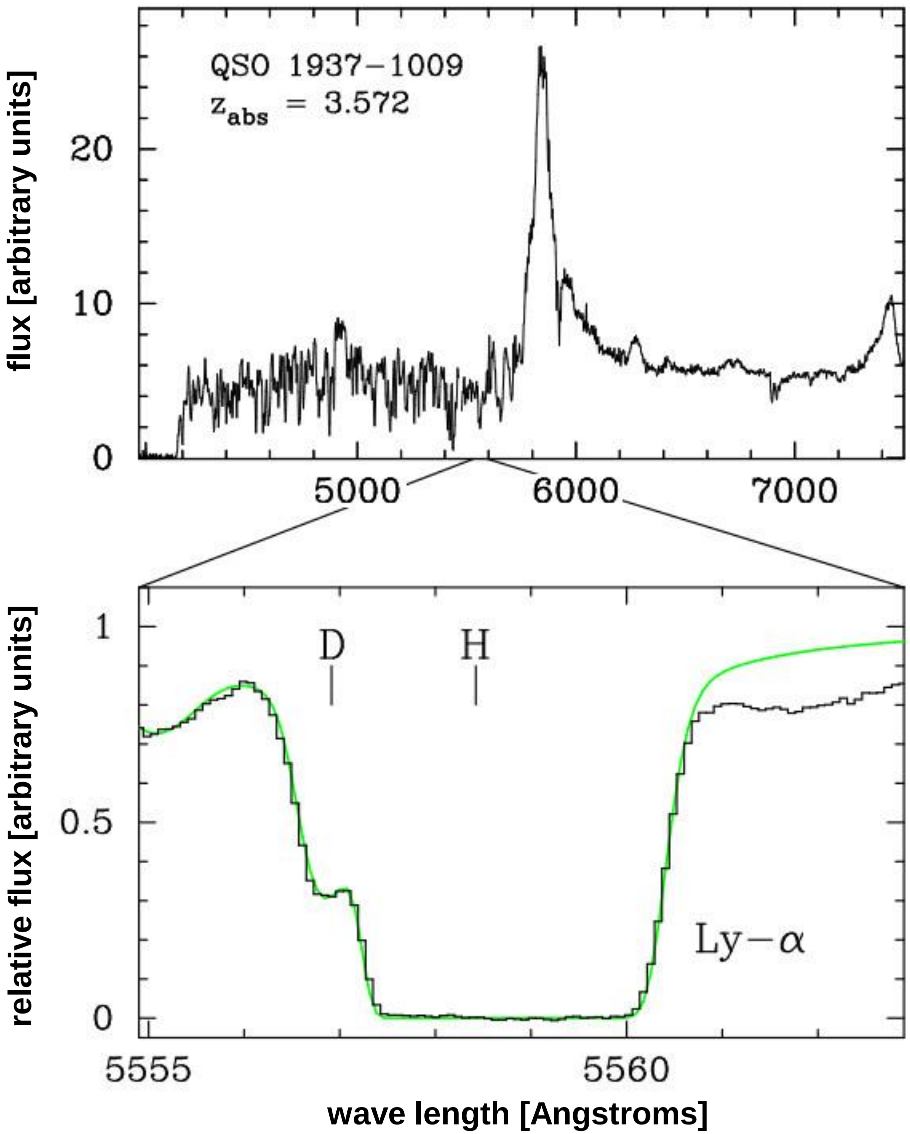
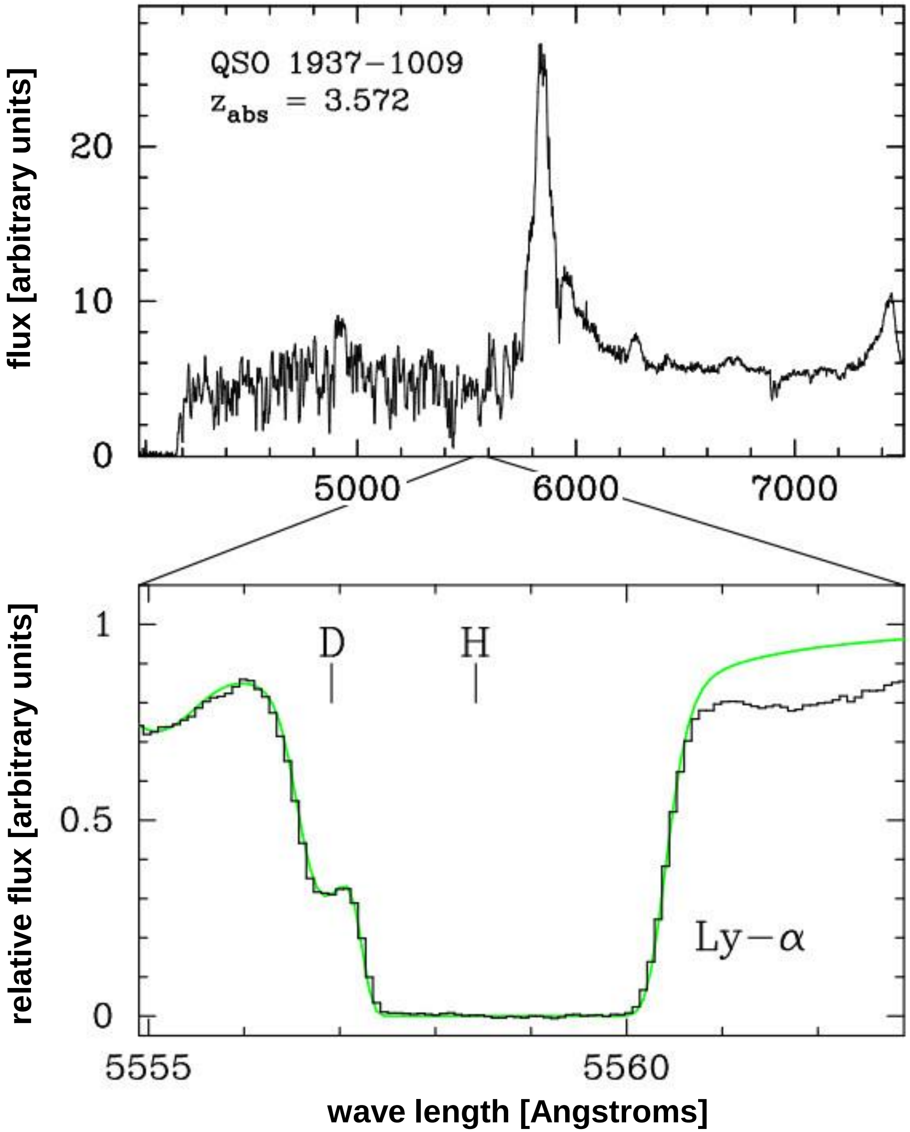


- consider a **single** absorption line

Measurements of d



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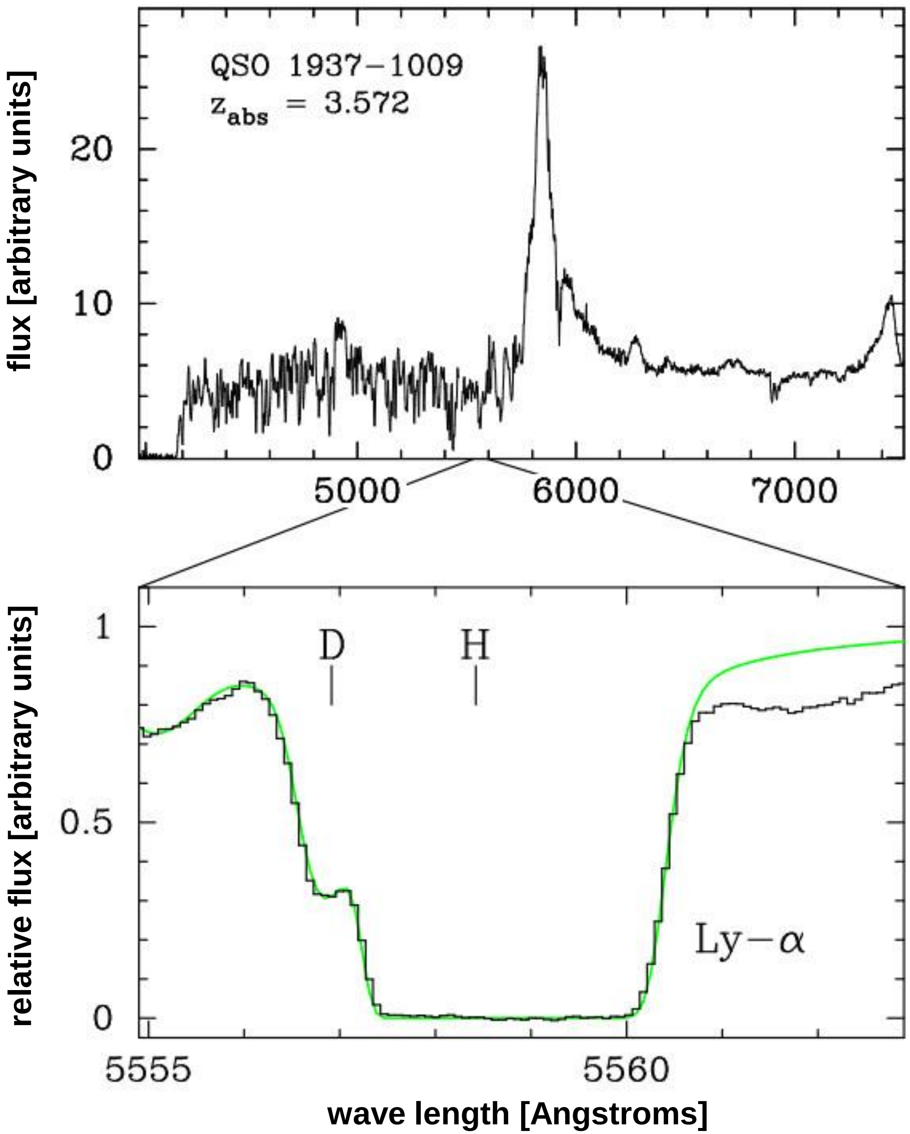

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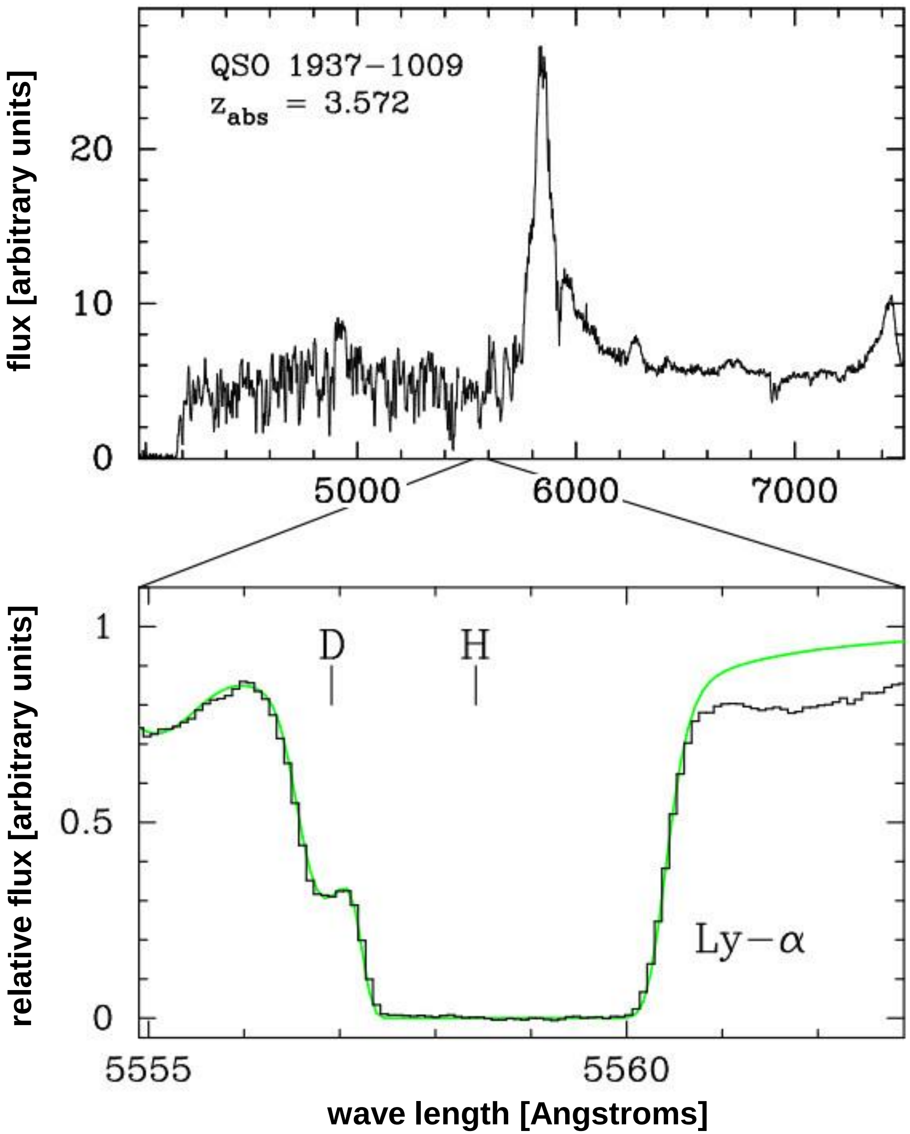

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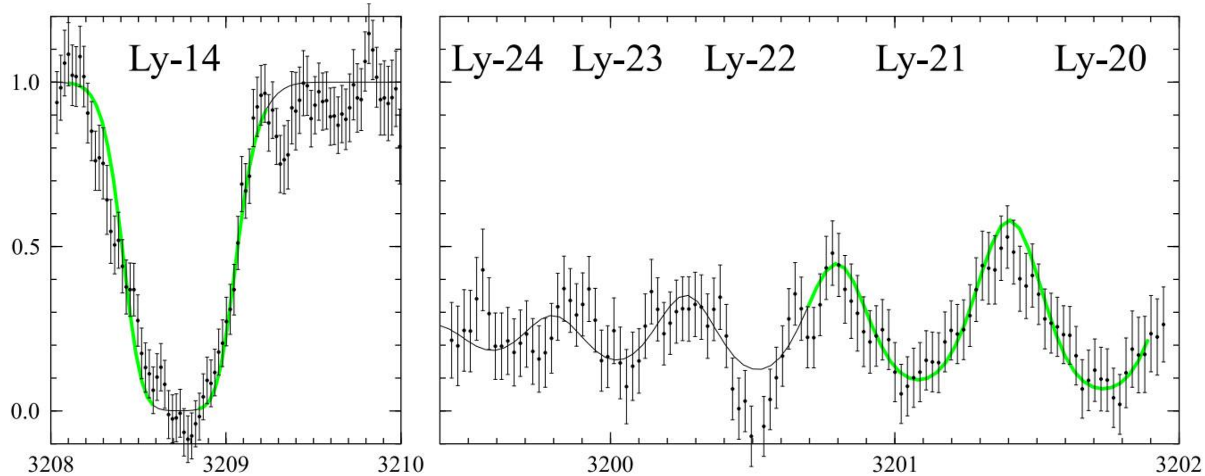

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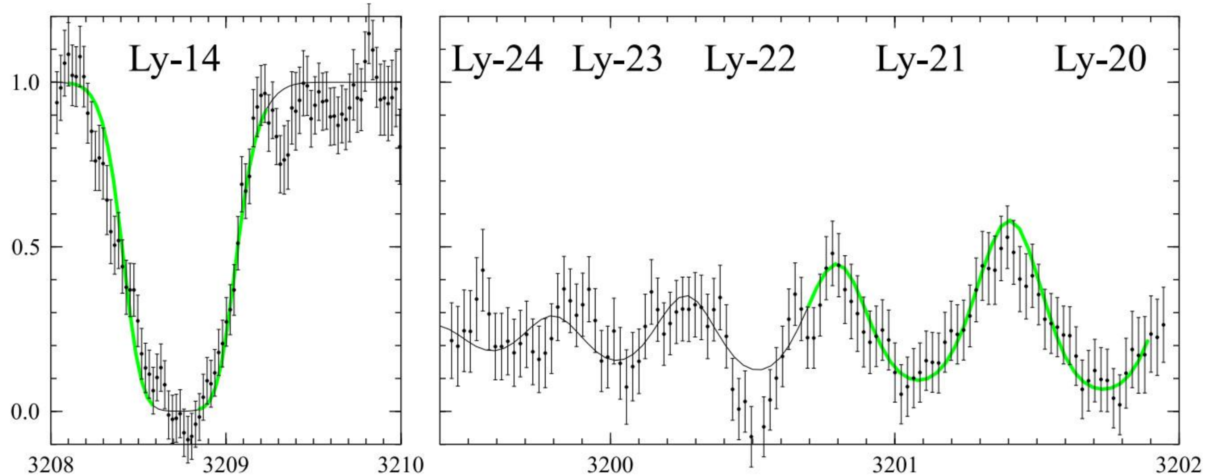
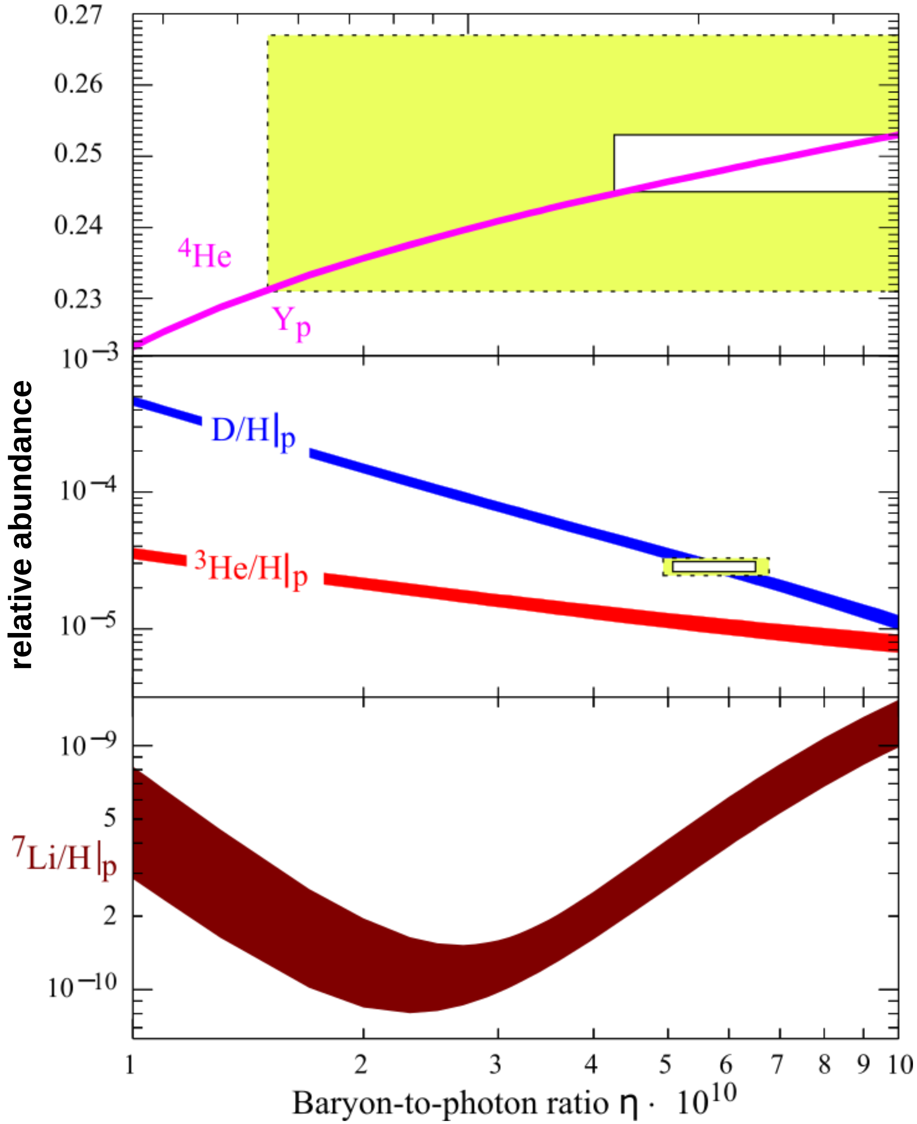


- more **caveats** for the measurements:
  - the Ly-α lines for d and H are **close to each other**: $\Delta\lambda_{\text{Ly-}\alpha} \approx 34\,\text{pm}$
  - **Doppler shift** of the Ly-α lines through rotation of the clouds reduces the **resolution** of the Ly-α forest
  - quasars are required to be at a suitable distance in order to avoid **overlaps** of red-shifted Ly-α lines from d and H
  - many quasars yield results with **huge standard deviations**

Measurements of d



- many quasars yield results with **huge standard deviations**

➡ only **10** measurements are suitable for the current best-fit analysis

- experimental value (PDG):

$$\frac{d}{\mathrm{H}}\Big|_{\mathrm{exp}} \approx (2.569 \pm 0.027) \cdot 10^{-5}$$

Measurements of ^{3}He

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- distinguishing ^{3}He and ^{4}He is technically **very difficult**

  ➡ abundance of ^{3}He is **not considered a suitable observable** for the analysis of the BBN

Measurements of ^{7}Li

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  population II stars (very old, low metallicity, thin convection layer)

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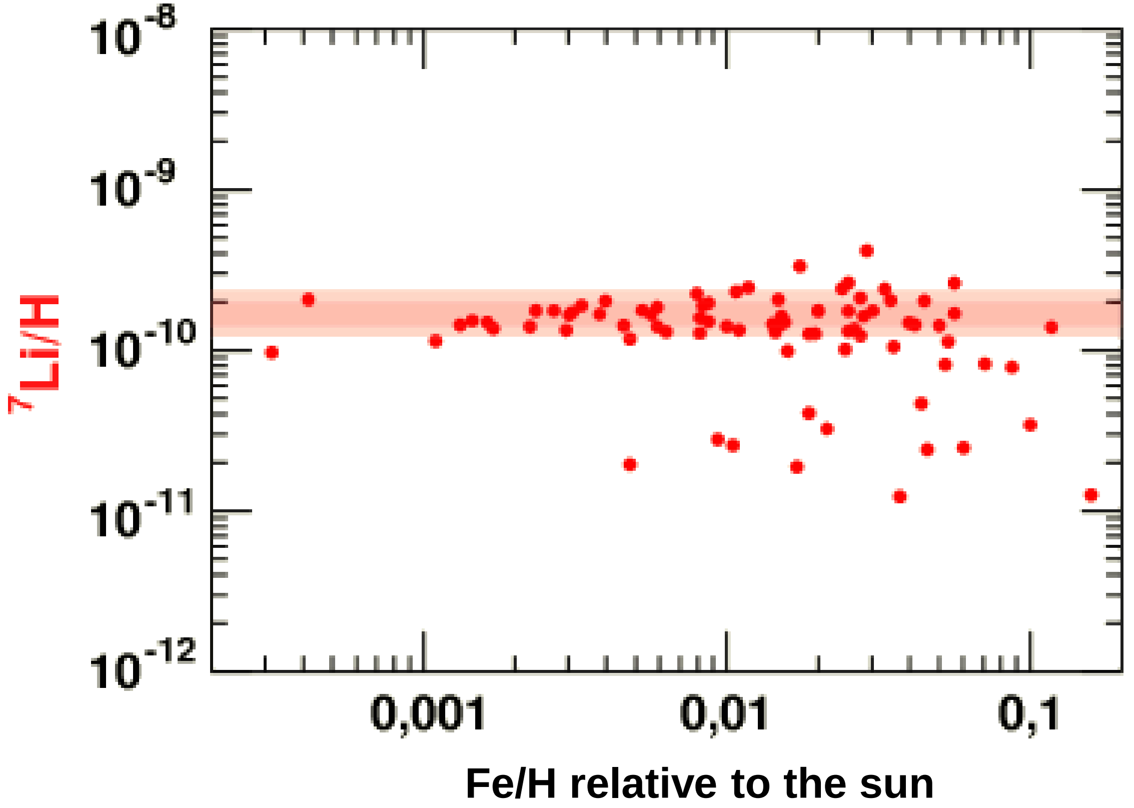
- **spectroscopy** of the **stellar atmosphere**:
  ^{7}Li resonance doublets at $\lambda \approx 670.7\,\mathrm{nm}$

- observation: "**linear" dependence** between ^{7}Li and **Fe** abundance

  ➡ extrapolation yields the primordial ^{7}Li abundance

Measurements of ^7Li



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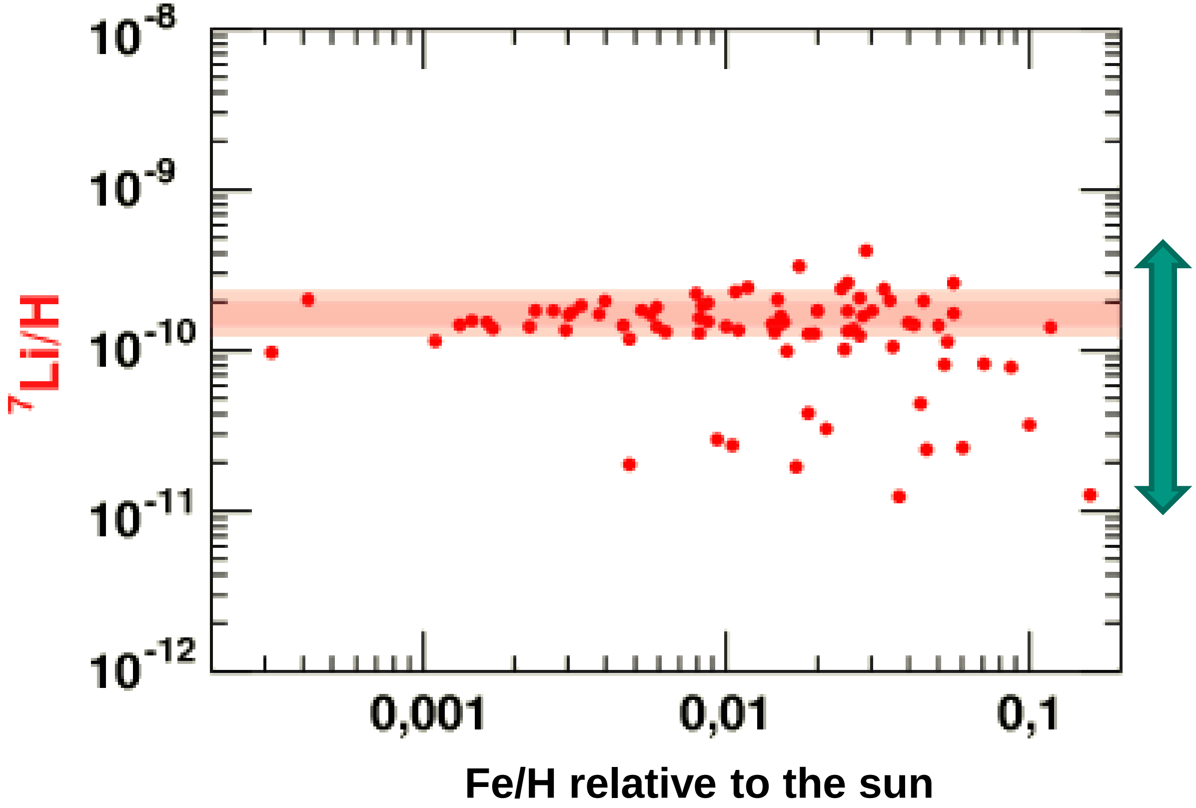

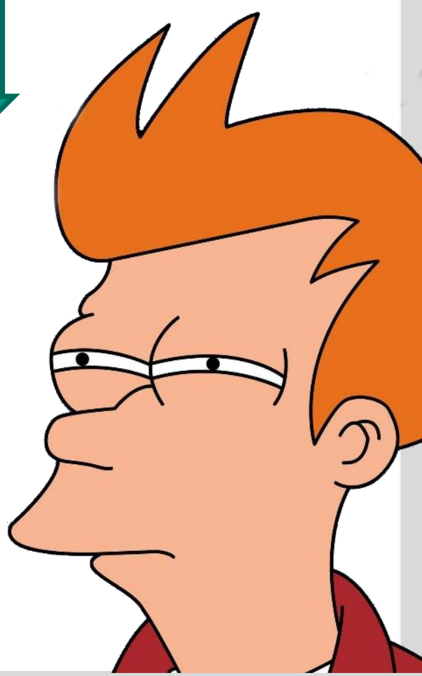

Measurements of ^{7}Li

- **caveat** for the measurements: ^{7}Li is converted for $T \geq 2.5 \cdot 10^6\,\mathrm{K}$

Lithium Burning

$$\begin{aligned} {}^1\mathrm{H} + {}^7\mathrm{Li} &\rightarrow {}^8\mathrm{Be} \\ {}^8\mathrm{Be} &\rightarrow {}^4\mathrm{He} + {}^4\mathrm{He} \end{aligned}$$

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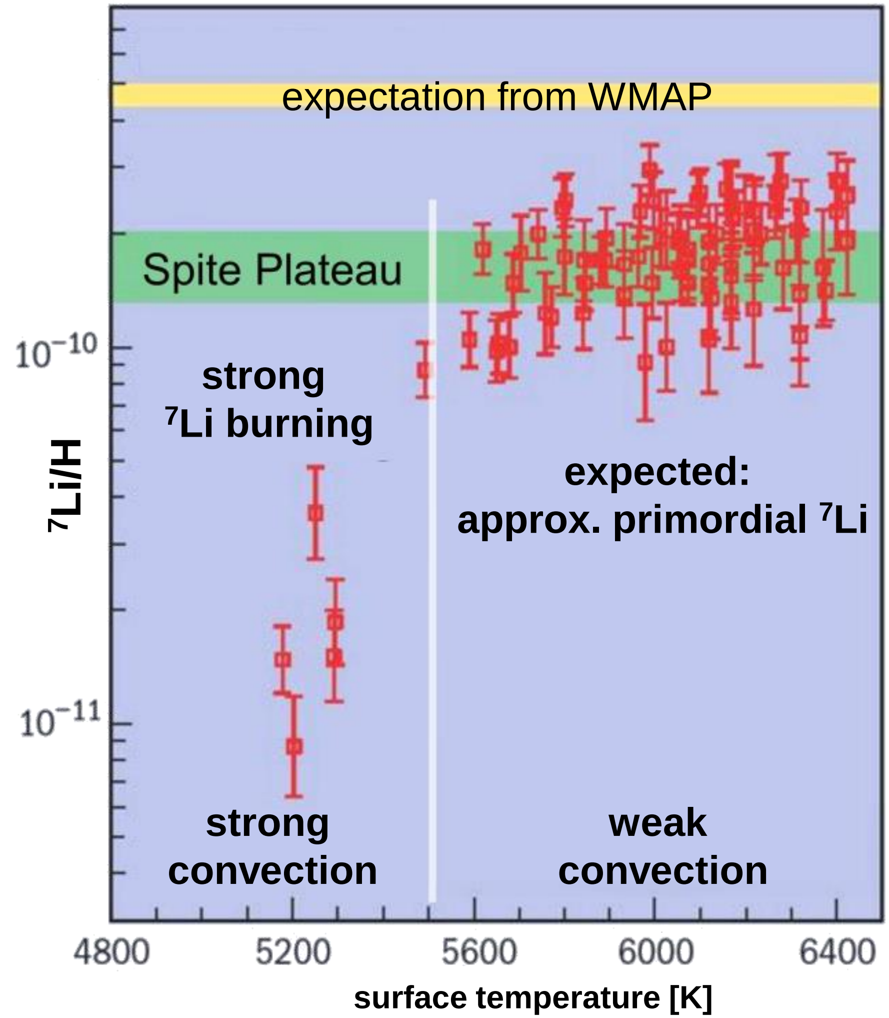

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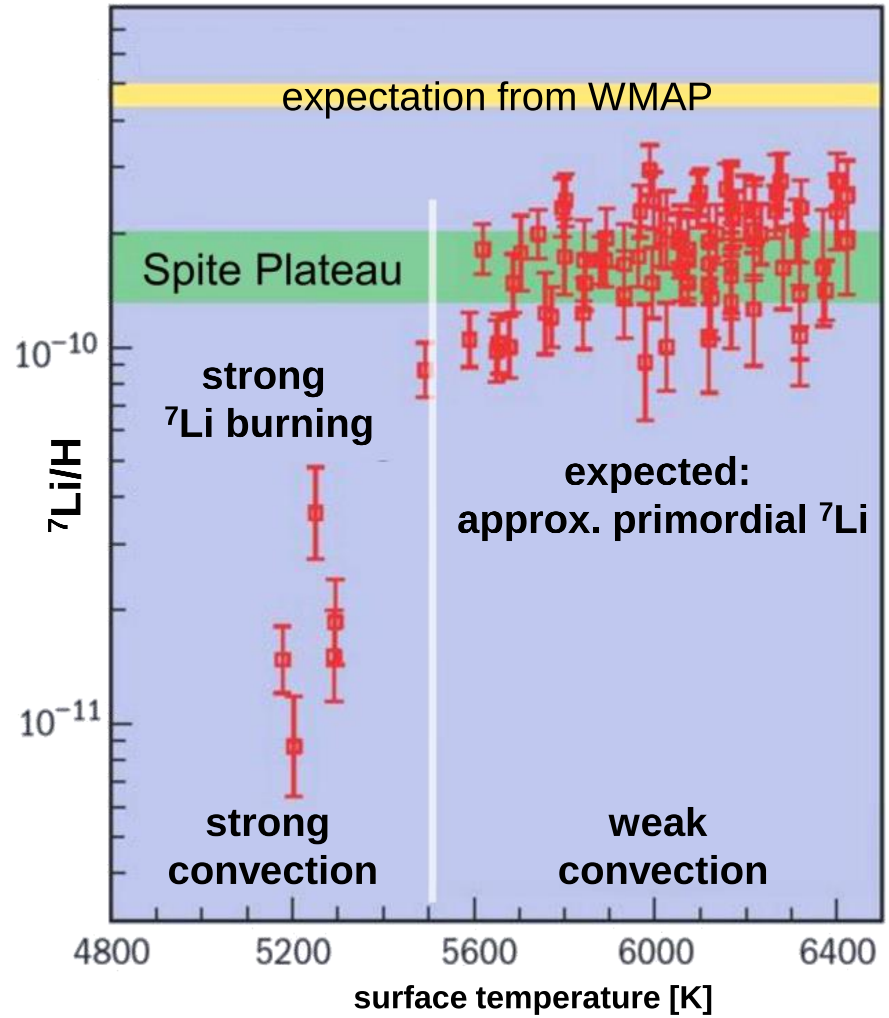
- conversion dominantly happens in the **convection layer** of the star

→ consider population II stars with weak surface convection



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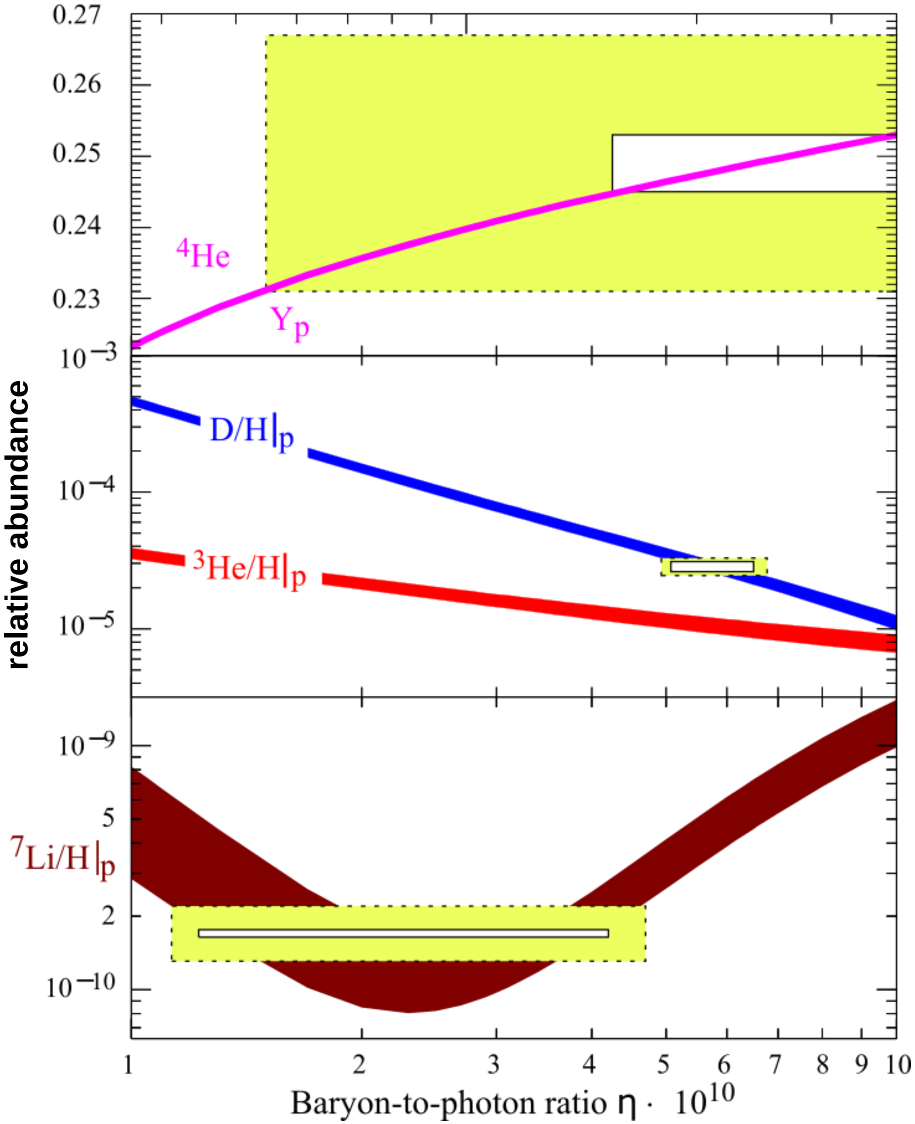

- experimental value (PDG):

$$\left.\frac{^7\mathrm{Li}}{\mathrm{H}}\right|_{\mathrm{exp}} \approx (1.6 \pm 0.3) \cdot 10^{-10}$$

- **uncertainties** in the measurements are very high
- experimental results are **at odds** with predictions from BBN

„cosmological lithium problem“

Measurements of ^{7}Li

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- possible explanations for the “lithium gap” **within the Standard Model** (SM) are **inconclusive** [A. Coc *et al* JCAP10(2014)050, arXiv:1403.6694 (astro-ph.CO)]

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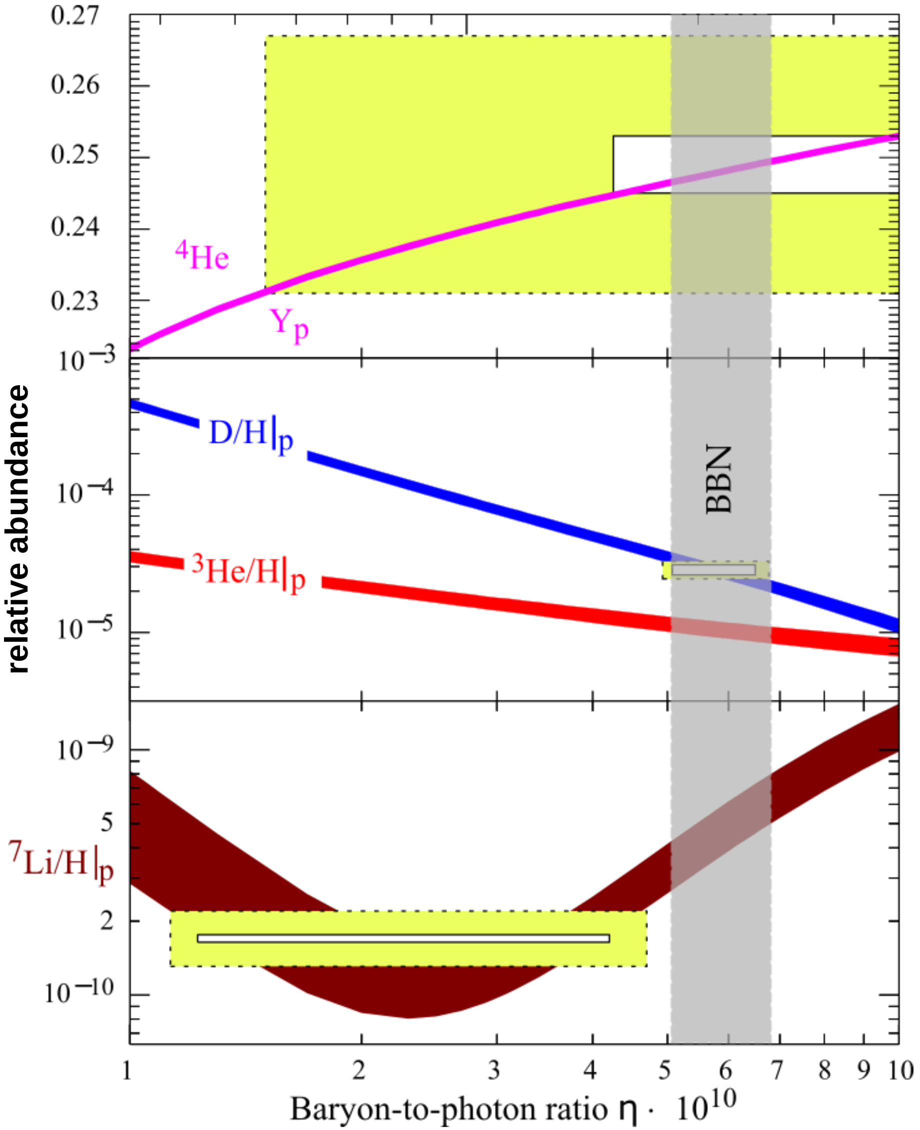
- **BSM** explanations for the lithium gap are also **inconclusive**

  [C. A. Bertulani *et al* EPJ Web of Conferences **184**, 01002 (2018), arXiv:1802.03469 (nulc-th)]

  ⇒ remains an **open problem** to be solved

Combination of the Results



- experimental best fit (PDG):

$$5.8 \cdot 10^{-10} \le \eta_{\rm exp} \le 6.6 \cdot 10^{-10}$$

(95% CL)

- with η, also the **baryonic energy density** Ω_B is determined

Determination of Ω_B – Method 1 via BBN

- **photon density** at $T = 2.725\,\mathrm{K}$ from **black body radiation**:

$$\rho_\gamma \approx 4.11 \cdot 10^8\, m^{-3}$$

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- the baryonic energy density can now be **calculated**:

$$\Omega_B h^2 = \frac{m_p c^2 \eta_{\mathrm{exp}} \rho_\gamma h^2}{\rho_c} \approx 0.02$$

reduced Hubble constant:

$$h \equiv \frac{H_0}{100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}$$

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- **current best-fit value** (PDG) at 95% CL:

$$0.021 \le \Omega_B h^2 \le 0.0245$$

➡ baryons account for roughly **4% to 5%** of the **total energy density** of the universe

Determination of Ω_B – Method 2 via CMB

- measurements of the **Cosmic Microwave Background (CMB)** through **Planck 2015 data** directly yield:

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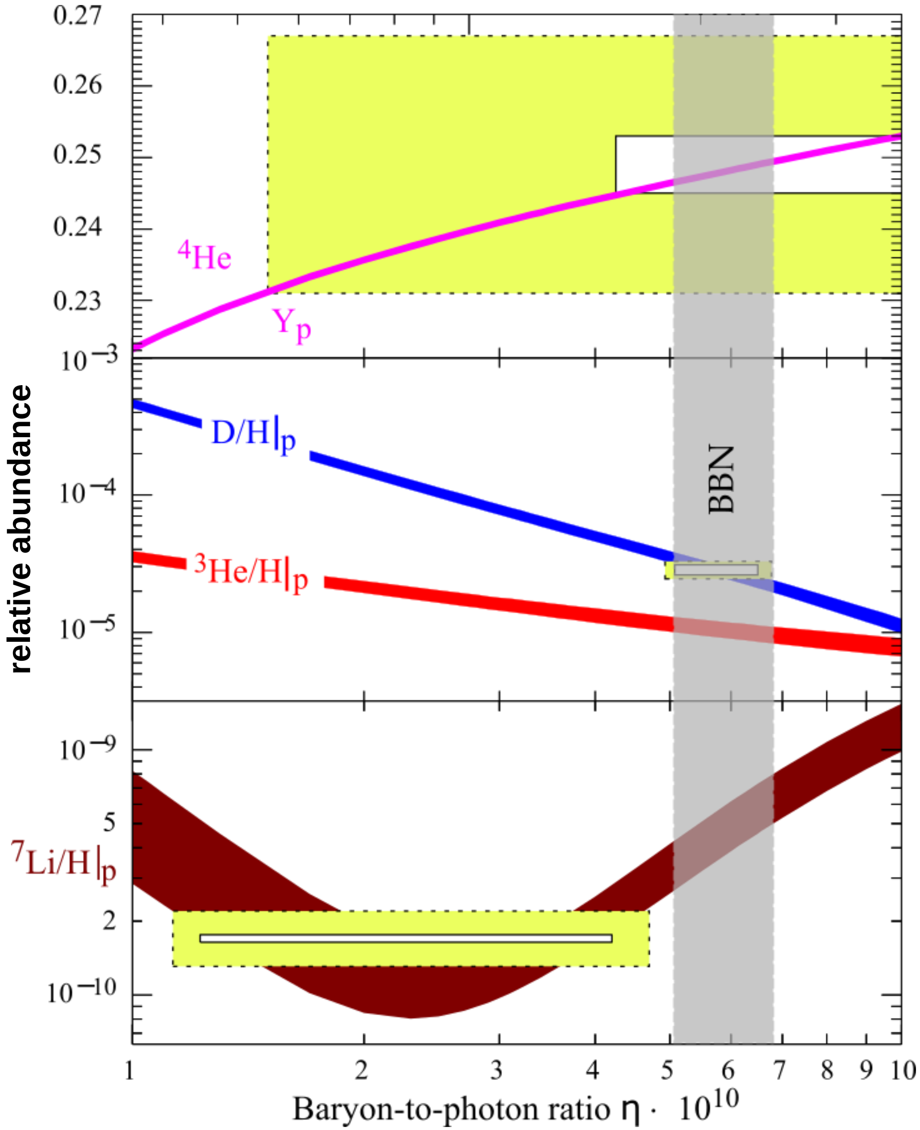
- from this, the **baryon-photon ratio** is calculated:

$$\eta_{\mathrm{CMB}} = (6.09 \pm 0.06) \cdot 10^{-10}$$

➡ the CMB yields an **independent cross-check** of the results gained by analyzing the BBN

➡ **good agreement** between the BBN and the CMB results

Combination of the Results



- experimental value through BBN:

$$0.021 \leq \Omega_B h^2 \leq 0.0245$$

- experimental value through CMB:

$$\Omega_B h^2 = 0.0223 \pm 0.0002$$

→ **good agreement** between BBN and CMB results

Hints of Dark Matter

- measurements through **BBN** yield:

$$0.021 \leq \Omega_B h^2 \leq 0.0245$$

- measurements through **CMB** yield: **independent** measurements

$$\Omega_B h^2 = 0.0223 \pm 0.0002$$

Hints of Dark Matter

- measurements through **BBN** yield:

$$0.021 \leq \Omega_B h^2 \leq 0.0245$$

- measurements through **CMB** yield: **independent** measurements

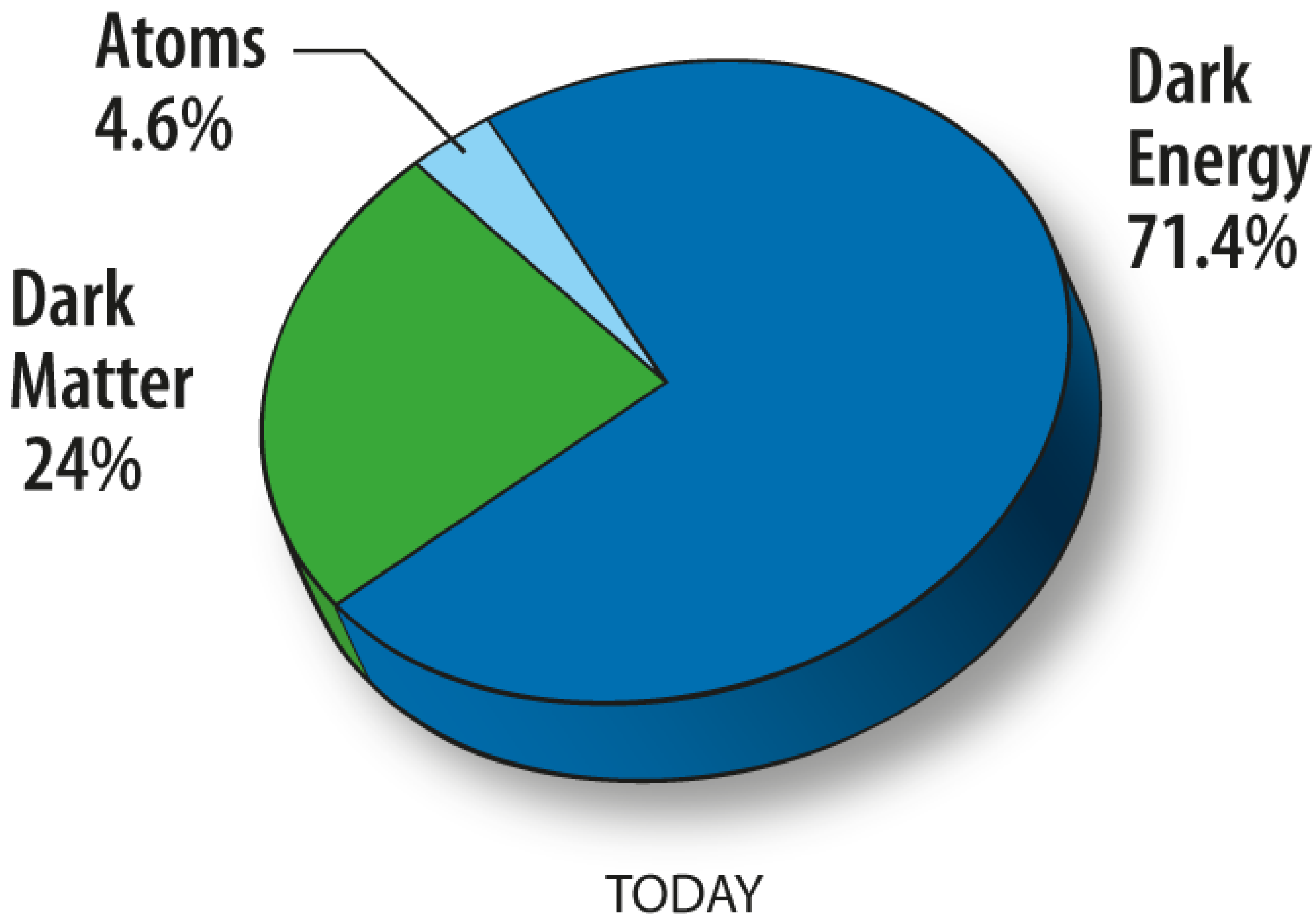
$$\Omega_B h^2 = 0.0223 \pm 0.0002$$

- on the other hand, measuring the **full matter density** yields:

$$\Omega_M h^2 \approx 0.14$$

⇒ most of the matter content of the universe is **non-baryonic "dark" matter**

Hints of Dark Matter



Conclusion

- the BBN describes the **first three minutes** of the universe
- the relative abundance of the lightest elements is not arbitrary but **can be calculated**
- theoretical predictions gained by the BBN are **consistent** over **ten orders of magnitude**
- through **spectral observations**, the baryonic matter density can be **measured** in the framework of the BBN
- independent measurements through the CMB provide a **cross-check** of the results gained by the BBN → **excellent agreement**
- the measured baryonic matter density is a hint towards **dark matter**
- open questions with respect to the **cosmological lithium problem** (portal to **BSM** physics?)

Thanks!

Figure References

- https://cdn-images-1.medium.com/max/1000/1*0Rh6Fxy_B4rHxdjpbIwFFw.jpeg
- https://upload.wikimedia.org/wikipedia/commons/9/98/End_of_universe.jpg
- https://web.njit.edu/~gary/202/assets/fig2202.jpg
- https://en.wikipedia.org/wiki/Big_Bang_nucleosynthesis#/media/File:Nucleosynthesis_periodic_table.svg
- https://simple.wikipedia.org/wiki/Isotope#/media/File:Blausen_0530_HydrogenIsotopes.png
- https://www.researchgate.net/figure/The-n-p-ratio-as-a-function-of-comoving-temperature-parameter-Tcm-in-the-third-scenario_fig3_305186106
- https://de.wikipedia.org/wiki/Kernfusion#/media/File:Deuterium-tritium_fusion.svg
- https://www.researchgate.net/figure/Atomic-particles-can-overcome-the-Coulomb-barrier-electrostatic-repulsion-at-much_fig1_282394950
- https://en.wikipedia.org/wiki/Stellar_nucleosynthesis#/media/File:FusionintheSun.svg
- https://wmap.gsfc.nasa.gov/media/121236/121236_NewPieCharts720.png
- https://i0.wp.com/thecuriousjalebi.com/wp-content/uploads/2018/10/5dc15a58073122dfbb1db83934e49fdc.jpg?ssl=1

Back-up slides