Primordial Nucleosynthesis

The Origin of the Lightest Elements

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May 13, 2019

The Big Bang Theory in a Nutshell
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

- **geometrization** of gravity:
The Big Bang Theory in a Nutshell

- **geometrization** of gravity:

\[
R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}
\]

- \(R_{\mu\nu}\): 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)
- \(\Lambda\): cosmological constant (vacuum state \(\rightarrow\) dark energy)
- \(G\): gravitational constant
- \(c\): speed of light
The Big Bang Theory in a Nutshell

- Important parameters for an expanding universe:
  - Scale factor

\[ a \equiv a(t) \equiv \frac{d(t)}{d_0} \]

(proper (physical) distance)

(co-moving (reference) distance)

(per definition, today we have \( a = 1 \))
The Big Bang Theory in a Nutshell

- important parameters for an expanding universe:
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    \[
    a \equiv a(t) \equiv \frac{d(t)}{d_0}
    \]
    proper (physical) distance
    co-moving (reference) distance
  
    (per definition, today we have \( a = 1 \))

- **Hubble parameter**
  \[
  H \equiv H(t) \equiv \frac{\dot{a}(t)}{a(t)}
  \]
  today: \( H_0 \approx [67, 74] \ \frac{\text{km}}{\text{s} \cdot \text{Mpc}} \)
The Big Bang Theory in a Nutshell

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- normalized spatial curvature parameter
  \[ \frac{k}{a^2} = \begin{cases} +1, & \text{closed 3-sphere} \\ 0, & \text{flat universe} \\ -1, & \text{open 3-hyperboloid} \end{cases} \]
The Big Bang Theory in a Nutshell

- **critical density** for $\Lambda = k = 0$:

$$\rho_c = \frac{3H^2}{8\pi G}$$

(today roughly 5 hydrogen atoms per m$^3$)
The Big Bang Theory in a Nutshell

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- evolution of the universe:

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

\( \Omega_i \): energy densities of radiation (R), matter (M), curvature (k) and the vacuum (\( \Lambda \))
The Big Bang Theory in a Nutshell

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  primordial nucleosynthesis!
Primordial Nucleosynthesis - Overview

- also known as **Big Bang nucleosynthesis (BBN)**
Primordial Nucleosynthesis - Overview

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- explains the creation of the lightest elements (H, d, $^3$He, $^4$He, $^7$Li) **directly after the Big Bang**

- **temperature** of the universe: between $10^{11}$ K and $10^9$ K
Primordial Nucleosynthesis - Overview

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- explains the creation of the lightest elements (H, d, $^3$He, $^4$He, $^7$Li) **directly after the Big Bang**

- **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

1 billion years

10^5 K

300,000 years

10^9 K

3 minutes

10^{-10} seconds

10^{-35} seconds

10^{-43} seconds

10^{12} K

Era of Atoms

Era of Nuclei

Era of Nucleosynthesis

Time Since Big Bang

Major Events Since Big Bang

2.725 K

10^5 K

10^9 K

10^{12} K

CMB

Primordial Nucleosynthesis

- Overview

- The Origin of the Lightest Elements

- ITU, KIT

May 13, 2019

M. Krause: Primordial Nucleosynthesis – The Origin of the Lightest Elements

ITP, KIT
Primordial Nucleosynthesis - Motivations

- BBN is strongly supported by the Big Bang theory
- explanation of the origin of the lightest elements
Primordial Nucleosynthesis - Motivations

origin of the **lightest elements** (H, d, $^3$He, $^4$He, $^7$Li)
Primordial Nucleosynthesis - Motivations

origin of the **lightest elements** (H, d, $^3$He, $^4$He, $^7$Li)

<table>
<thead>
<tr>
<th>Big Bang fusion</th>
<th>Dying low-mass stars</th>
<th>Exploding massive stars</th>
<th>Human synthesis No stable isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic ray fission</td>
<td>Merging neutron stars</td>
<td>Exploding white dwarfs</td>
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### Table of Elements

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Primordial Nucleosynthesis - Motivations

- BBN is strongly supported by the Big Bang theory
- explanation of the origin of the lightest elements
- verifiable through experimental observations
Primordial Nucleosynthesis - Motivations

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

\[ \eta \equiv \frac{n_{\text{baryon}}}{n_{\text{photon}}} \approx \mathcal{O}(10^{-10}) \]
Primordial Nucleosynthesis – Four Stages

Stage 0: Quark Gluon Plasma

\[ t = 10^{-6} \text{ s} , \quad T = 10^{12} \text{ K} , \quad E = 100 \text{ MeV} \]

- **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

\[ t = 10^{-2} \text{s} \quad , \quad T = 10^{11} \text{ K} \quad , \quad E = 10 \text{ MeV} \]

- **dominant particles**: \( p, n, \nu, e^\pm \)

- equilibrium state between **protons** and **neutrons**
  - continuous transformation via the weak interaction

\[
\begin{align*}
p + e^- & \leftrightarrow n + \nu_e \\
p + \bar{\nu}_e & \leftrightarrow n + e^+ \\
n & \leftrightarrow p + e^- + \bar{\nu}_e
\end{align*}
\]
Primordial Nucleosynthesis – Four Stages

Stage I: Thermodynamic Equilibrium

\[ t = 10^{-2} \text{s} \,, \quad T = 10^{11} \text{K} \,, \quad E = 10 \text{MeV} \]

- \( m_n > m_p \)  \( \longrightarrow \) difference in rest energy  \( \Delta mc^2 \approx 1.293 \text{MeV} \)
Primordial Nucleosynthesis – Four Stages

Stage I: Thermodynamic Equilibrium

\[ t = 10^{-2} \text{s}, \quad T = 10^{11} \text{K}, \quad E = 10 \text{MeV} \]

- \( m_n > m_p \) \quad \text{difference in rest energy} \quad \Delta mc^2 \approx 1.293 \text{MeV}
- proton and neutron are two states of one isospin doublet

Boltzmann Distribution in Thermal Equilibrium

\[ \frac{n}{p} = \exp \left( - \frac{\Delta mc^2}{k_B T} \right) \approx \exp \left( - \frac{1.293 \text{MeV}}{k_B T} \right) \]

- connection between neutron-proton ratio and statistical physics
Primordial Nucleosynthesis – Four Stages

Stage I: Thermodynamic Equilibrium

\[ t = 10^{-2} \text{ s} \, , \, \quad T = 10^{11} \text{ K} \, , \, \quad E = 10 \text{ MeV} \]

- reaction rate of the weak processes:

\[ \Gamma(p + e^- \leftrightarrow \nu_e + n) \approx G_F^2 T^5 \]
\[ (G_F : \text{Fermi constant}) \]
Primordial Nucleosynthesis – Four Stages

Stage I: Thermodynamic Equilibrium

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- **expansion rate** of the universe:
  \[ H \propto T^2 \]
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

- **expansion rate** of the universe:
  \[ H \propto T^2 \]

- **ratio** of reaction and expansion rates:
  \[ \frac{\Gamma}{H} \approx \left( \frac{T}{0.8 \text{ MeV}} \right)^3 \]

  - weak processes **freeze out** at roughly \( T \approx 0.8 \text{ MeV} \)
  - neutron-proton ratio **stabilizes** and the equilibrium is **broken**
Primordial Nucleosynthesis – Four Stages

Stage II: Freeze-Out of the Weak Processes

\[ t = 1 \, \text{s}, \quad T = 10^{10} \, \text{K}, \quad E = 1 \, \text{MeV} \]

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

\[
p + e^- \not\leftrightarrow n + \nu_e \\
p + \bar{\nu}_e \not\leftrightarrow n + e^+ \\
n \rightarrow p + e^- + \bar{\nu}_e \quad \text{decay of free neutrons}
\]

Neutron-Proton Ratio at the Freeze-Out Temperature

\[
\frac{n}{p} = \exp \left( -\frac{\Delta m c^2}{k_B T} \right) \approx \frac{1}{6}
\]
Stage III: Beta Decay of the Free Neutrons

\[ t < 1 \text{ min} \, , \quad T = 10^{10} \text{ K} - 10^9 \text{ K} \, , \quad E = 1 \text{ MeV} - 0.1 \text{ MeV} \]

- mean lifetime of free neutrons: \( \tau \approx 14.7 \text{ min} \)

Decay Process of Free Neutrons

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
Primordial Nucleosynthesis – Four Stages

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- Mean lifetime of free neutrons: $\tau \approx 14.7 \text{ min}$

Decay Process of Free Neutrons

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

- No light elements are produced yet

why?
Primordial Nucleosynthesis – Four Stages

- **deuterium (d)** is the next-to-lightest isotope to be produced.
Primordial Nucleosynthesis – Four Stages

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

- **binding energy** of deuterium: \( E_b \approx 2.2 \text{ MeV} \)

- **ratio of photons with the same energy** at \( T \approx 0.1 \text{ MeV} \) (high-end tail):

\[
\frac{n_\gamma(E \geq E_b)}{n_\gamma,\text{tot}} = \exp\left(-\frac{E_b(d)}{k_BT}\right) \approx 10^{-10}
\]
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**”
Stage IV: Primordial Nucleosynthesis

\( t \leq 3 \text{ min} , \quad T = 10^9 \text{ K} , \quad E = 0.1 \text{ MeV} \)

- 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

- thermal equilibrium
- without freeze-out
- free n decay
- BBN
Primordial Nucleosynthesis – Processes

Production of Deuterons

\[ n + p \rightarrow d + \gamma \]
Primordial Nucleosynthesis – Processes

Production of Deuterons
\[ n + p \rightarrow d + \gamma \]

Production of Tritons
\[ n + d \rightarrow t + \gamma \]
**Primordial Nucleosynthesis – Processes**

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<thead>
<tr>
<th>Production of Deuterons</th>
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<td>( d + p \leftrightarrow ^3\text{He} + \gamma )</td>
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<td>( t + d \leftrightarrow ^4\text{He} + n )</td>
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\[ ^2\text{H} \rightarrow ^3\text{H} \]

\[ ^2\text{H} \rightarrow ^3\text{H} \]

\[ n + 14.1 \text{ MeV} \]

\[ ^4\text{He} + 3.5 \text{ MeV} \]
Primordial Nucleosynthesis – Processes

1. $n \rightarrow 1H + e^- + \bar{\nu}$
2. $1H + n \rightarrow 2H + \gamma$
3. $2H + 1H \rightarrow 3He + \gamma$
4. $2H + 2H \rightarrow 3He + n$
5. $2H + 2H \rightarrow 3H + 1H$
6. $2H + 3H \rightarrow 4He + n$
7. $3H + 4He \rightarrow 7Li + \gamma$
8. $3He + n \rightarrow 3H + 1H$
9. $3He + 2H \rightarrow 4He + 1H$
10. $3He + 4He \rightarrow 7Be + \gamma$
11. $7Li + 1H \rightarrow 4He + 4He$
12. $7Be + n \rightarrow 7Li + 1H$
Primordial Nucleosynthesis – Processes

deuterium bottleneck

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Primordial Nucleosynthesis – Processes

production of the lightest elements

\((H, d, ^3\text{He}, ^4\text{He}, ^7\text{Li})\)
Primordial Nucleosynthesis – Processes

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

what about the others?
Primordial Nucleosynthesis – Processes

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

- \(^7\)Be decays to \(^7\)Li with \(\tau \approx 53.1\) d
- \(^3\)He decays to p with \(\tau \approx 14.7\) min

what about the others?
Primordial Nucleosynthesis – Processes

- all dominant processes terminate in $^4\text{He}$
- second most common atom in the universe
Primordial Nucleosynthesis – Processes

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

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

- approximate abundance of the two lightest stable elements:

$$75\% \text{ H, } 25\% \ ^4\text{He}$$
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

![Graph showing potential energy versus distance between nuclei](image)
Primordial Nucleosynthesis – Processes

- Fusion
- Fission

Graph showing the average binding energy per nucleon for different elements as a function of the number of nucleons in the nucleus. Elements like H, Li, C, O, Ne, and Fe are plotted, with arrows indicating the processes of fusion and fission.
Primordial Nucleosynthesis – Processes

Average binding energy per nucleon (MeV) vs. Number of nucleons in nucleus

- Fusion
- Fission

M. Krause: Primordial Nucleosynthesis – The Origin of the Lightest Elements

May 13, 2019 ITP, KIT
prediction of abundance of all light elements during/after the BBN
Primordial Nucleosynthesis – Processes

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

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

valid for **one chosen** $\eta$
variation of the baryon-photon ratio $\eta$
**Primordial Nucleosynthesis – Processes**

- **variation** of the baryon-photon ratio $\eta$

Effect on $^4$He Production

- higher $\eta$: higher n/p ratio
- earlier production due to more n
Primordial Nucleosynthesis – Processes

- **variation** of the baryon-photon ratio $\eta$

![Graph showing relative abundance of different elements vs. baryon-to-photon ratio $\eta$.]

- **Effect on $^4$He Production**
  - higher $\eta$: higher n/p ratio
  - earlier production due to more n

- **Effect on $^3$H Production**
  - higher $\eta$: fewer high-energy photons
  - earlier synthesis but dense universe
Variation of the baryon-photon ratio $\eta$

**Effect on $^4$He Production**
- Higher $\eta$: higher n/p ratio
- Earlier production due to more n

**Effect on d Production**
- Higher $\eta$: fewer high-energy photons
- Earlier synthesis but dense universe

**Effect on $^7$Li Production**
- Lower $\eta$: more frequent decay to $^4$He
- Higher $\eta$: earlier synthesis
Primordial Nucleosynthesis – Processes

- measuring the abundance of the elements fixes $\eta$

Motivations:
- confirms the Big Bang theory
- determines $\eta$ and $\Omega_B$
- indicates consistency of the BBN over ten orders of magnitude
measuring the abundance of the elements fixes $\eta$
Measurements of $^4\text{He}$

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

  entanglement of primordial and stellar $^4\text{He}$ production

$$\text{He}^3 + p \rightarrow \text{He}^4$$
Measurements of $^4\text{He}$

- **stellar nucleosynthesis**: amount of $^4\text{He}$ increases compared to the abundance after the BBN
  - entanglement of primordial and stellar $^4\text{He}$ production

- idea: search for stars with **very low metallicity**

**Definition of Metallicity**

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

- prime candidate: “Blue Compact Dwarf Galaxies”
  - (low metallicity, gas-rich, H-II region)
Measurements of $^4\text{He}$

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  \]

  - prime candidate: “Blue Compact Dwarf Galaxies”
    (low metallicity, gas-rich, H-II region)

- spectral analysis of the H-II regions reveals the approximate primordial amount of $^4\text{He}$
Measurements of $^4$He

![Graph showing measurements of $^4$He flux against wavelength. Peaks labeled Hb, O III, He I, and Ha are visible in the spectrum.]
Measurements of $^4\text{He}$

- relative amount $Y$ of $^4\text{He}$ is **higher** in stars with higher metallicity
Measurements of $^4$He

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- measure the **He-I recombination line** at $\lambda = 587.6 \text{ nm}$
- spectral analysis yields **$Y$ over metallicity $O/H$**
Measurements of $^4$He

- Relative amount $Y$ of $^4$He is higher in stars with higher metallicity.
- Measure the He-I recombination line at $\lambda = 587.6$ nm.
- Spectral analysis yields $Y$ over metallicity $O/H$.
- Extrapolation to zero metallicity.
- Primordial amount of $^4$He.
Measurements of $^4\text{He}$

- theoretical estimate: $Y_{\text{theor}} \approx 0.25$
- experimental value (PDG): $Y_{\text{exp}} \approx 0.245 \pm 0.003$
Measurements of $d$

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

  - BBN is the *main source* of deuterium
Measurements of $d$

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  - BBN is the **main source** of deuterium

- deuterium is **converted** in stellar nucleosynthesis processes:
  \[ p + d \rightarrow ^3\text{He} + \gamma \]
Measurements of d

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- measure the primordial d abundance through **Lyman-\(\alpha\) absorption lines**

```
2p (n = 2, l = 1)
2s (n = 2, l = 0)
1s (n = 1, l = 0)
2p_{3/2} (j = 3/2)
2p_{1/2} (j = 1/2)
```

Discrete energy levels of deuterium
Measurements of d

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  - BBN is the **main source** of deuterium

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- measure the primordial d abundance through **Lyman-\(\alpha\) absorption lines**

  - Ly-\(\alpha\) line at \(\lambda_{\text{Ly-}\alpha} \approx 121.5\) nm
    - (UV regime)
    - discrete energy levels of deuterium
Measurements of $d$  

- measure the primordial $d$ abundance through Lyman-$\alpha$ absorption lines  
- prime candidates: Quasar Absorption Systems (QAS)
Measurements of $d$

- measure the primordial $d$ abundance through **Lyman-α absorption lines**
  - prime candidates: Quasar Absorption Systems (QAS)

- radiation emitted from quasars travels through **interstellar clouds**

- increasing **redshift $z$** with increasing distance from the quasar:
  \[
  \lambda_{\text{Ly-α}} \approx 121.5 \ (1 + z) \ \text{nm}
  \]
Measurements of $d$

- measure the primordial $d$ abundance through **Lyman-α absorption lines**
  - prime candidates: *Quasar Absorption Systems (QAS)*

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- increasing **redshift $z$** with increasing distance from the quasar:
  \[ \lambda_{\text{Ly-α}} \approx 121.5 \left( 1 + z \right) \text{ nm} \]

- 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

![Graph showing Lyman-α forest](image)

**HS 0105+1619**  
**QAS object**  
**z ≈ 2.536**  
**distance**
Measurements of d actual spectral analysis shows the Lyman-α forest.
Measurements of $d$

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

![Graph showing the Lyman-α forest with spectral analysis](image)

- HS 0105+1619 is a QAS object with a redshift $z \approx 2.536$.
Measurements of d

consider a single absorption line
Measurements of d

- consider a **single** absorption line
- **split the flux** into the normalized flux of d and H
- **ratio** yields the relative abundance of d compared to H
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**caveats:**
- due to the dominance of H, the **difference in intensities** is huge
- the flux at the absorption line of H is **practically vanishing**
Measurements of d

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consider a lot of different Ly-α lines from different sources
Measurements of $d$

- consider a lot of different Ly-\(\alpha\) lines from different sources
Measurements of d

- consider a lot of different Ly-α lines from **different sources**

![Graph showing Ly-α lines from different sources]

- more **caveats** for the measurements:
  - the Ly-α lines for d and H are **close to each other**: \( \Delta \lambda_{\text{Ly-α}} \approx 34 \text{ pm} \)
  - **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):
  \[
  \left. \frac{d}{H} \right|_{\text{exp}} \approx (2.569 \pm 0.027) \cdot 10^{-5}
  \]
Measurements of $^3$He

$^3$He is *constantly produced and converted* in stellar nucleosynthesis processes.
Measurements of $^3$He

- $^3$He is **constantly produced and converted** in stellar nucleosynthesis processes

- The only available measurements of the $^3$He abundance stem from
  - regions **within the solar system**
  - regions with **very high metallicity**

  - not suitable for determining the **primordial** abundance of $^3$He
Measurements of $^3$He

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- the only available measurements of the $^3$He abundance stem from
  - regions **within the solar system**
  - regions with **very high metallicity**
    - not suitable for determining the **primordial** abundance of $^3$He

- 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 $^7\text{Li}$

- most suitable objects for measuring $^7\text{Li}$:
  - population II stars (very old, low metallicity, thin convection layer)
Measurements of $^7\text{Li}$

- most suitable objects for measuring $^7\text{Li}$: population II stars (very old, low metallicity, thin convection layer)

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

- observation: “linear” dependence between $^7\text{Li}$ and $\text{Fe}$ abundance
  - extrapolation yields the primordial $^7\text{Li}$ abundance
Measurements of $^7\text{Li}$

![Graph showing measurements of $^7\text{Li}$ versus Fe/H relative to the sun.](image)
Measurements of $^7\text{Li}$

$^7\text{Li}/H$ relative to the sun

Fe/H relative to the sun
caveat for the measurements: $^7$Li is converted for $T \geq 2.5 \cdot 10^6$ K

**Lithium Burning**

$^1$H + $^7$Li → $^8$Be

$^8$Be → $^4$He + $^4$He
Measurements of $^7\text{Li}$

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

**Lithium Burning**

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\[ ^8\text{Be} \rightarrow ^4\text{He} + ^4\text{He} \]
Measurements of $^7\text{Li}$

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**Lithium Burning**

\[ ^1\text{H} + ^7\text{Li} \rightarrow ^8\text{Be} \]

\[ ^8\text{Be} \rightarrow ^4\text{He} + ^4\text{He} \]

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

consider population II stars with weak surface convection
Measurements of $^7$Li

- **Experimental value (PDG):**
  \[ \frac{^7\text{Li}}{\text{H}} \bigg|_{\text{exp}} \approx (1.6 \pm 0.3) \times 10^{-10} \]

- **Uncertainties** in the measurements are very high.

- Experimental results are **at odds** with predictions from BBN.

  „**Cosmological lithium problem**“
Measurements of $^7$Li

- the cosmological lithium problem is unsolved as of today
Measurements of $^7\text{Li}$

- the cosmological lithium problem is **unsolved** as of today

- possible explanations for the “lithium gap” **within the Standard Model** (SM) are **inconclusive**  

  portal for beyond the SM (BSM) physics
the cosmological lithium problem is **unsolved** as of today

possible explanations for the “lithium gap” within the **Standard Model** (SM) are **inconclusive**  

portal for beyond the SM (BSM) physics

**BSM** explanations for the lithium gap are also **inconclusive**  
[C. A. Bertulani *et al* EPJ Web of Conferences 184, 01002 (2018), arXiv:1802.03469 (nucl-th)]

remains an **open problem** to be solved
Combination of the Results

- experimental best fit (PDG):
  \[ 5.8 \times 10^{-10} \leq \eta_{\text{exp}} \leq 6.6 \times 10^{-10} \]
  (95% CL)
- with \( \eta \), also the baryonic energy density \( \Omega_B \) is determined
Determination of $\Omega_B$ – Method 1 via BBN

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

$$\rho_\gamma \approx 4.11 \cdot 10^8\, m^{-3}$$
Determination of $\Omega_B$ – Method 1 via BBN

- photon density at $T = 2.725 \, \text{K}$ from black body radiation:
  \[ \rho_\gamma \approx 4.11 \cdot 10^8 \, \text{m}^{-3} \]

- the baryonic energy density can now be calculated:
  \[
  \Omega_B h^2 = \frac{m_p c^2 \eta_{\text{exp}} \rho_\gamma h^2}{\rho_c} \approx 0.02
  \]
  reduced Hubble constant:
  \[
  h \equiv \frac{H_0}{100 \, \text{km s}^{-1} \, \text{Mpc}^{-1}}
  \]
Determination of $\Omega_B$ – Method 1 via BBN

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- the baryonic energy density can now be **calculated**:
  \[
  \Omega_B h^2 = \frac{m_p c^2 \eta_{\exp} \rho_\gamma h^2}{\rho_c} \approx 0.02
  \]

- **current best-fit value** (PDG) at 95% CL:
  \[
  0.021 \leq \Omega_B h^2 \leq 0.0245
  \]

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

- reduced Hubble constant:
  \[
  h \equiv \frac{H_0}{100 \, \text{km s}^{-1} \, \text{Mpc}^{-1}}
  \]
Determination of $\Omega_B$ – Method 2 via CMB

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

$$\Omega_B h^2 = 0.0223 \pm 0.0002$$
Determination of $\Omega_B$ – Method 2 via CMB

- Measurements of the Cosmic Microwave Background (CMB) through Planck 2015 data directly yield:
  \[ \Omega_B h^2 = 0.0223 \pm 0.0002 \]

- From this, the baryon-photon ratio is calculated:
  \[ \eta_{\text{CMB}} = (6.09 \pm 0.06) \cdot 10^{-10} \]

  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

- Dark Matter: 24%
- Atoms: 4.6%
- Dark Energy: 71.4%

TODAY
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!
May 13, 2019

M. Krause: Primordial Nucleosynthesis – The Origin of the Lightest Elements
Figure References

- https://cdn-images-1.medium.com/max/1000/1*0Rh6Fxy_B4rHxdjpblwFFw.jpeg
- https://web.njit.edu/~gary/202/assets/fig2202.jpg
- https://www.researchgate.net/figure/Atomic-particles-can-overcome-the-Coulomb-barrier-electrostatic-repulsion-at-much_fig1_282394950
- 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