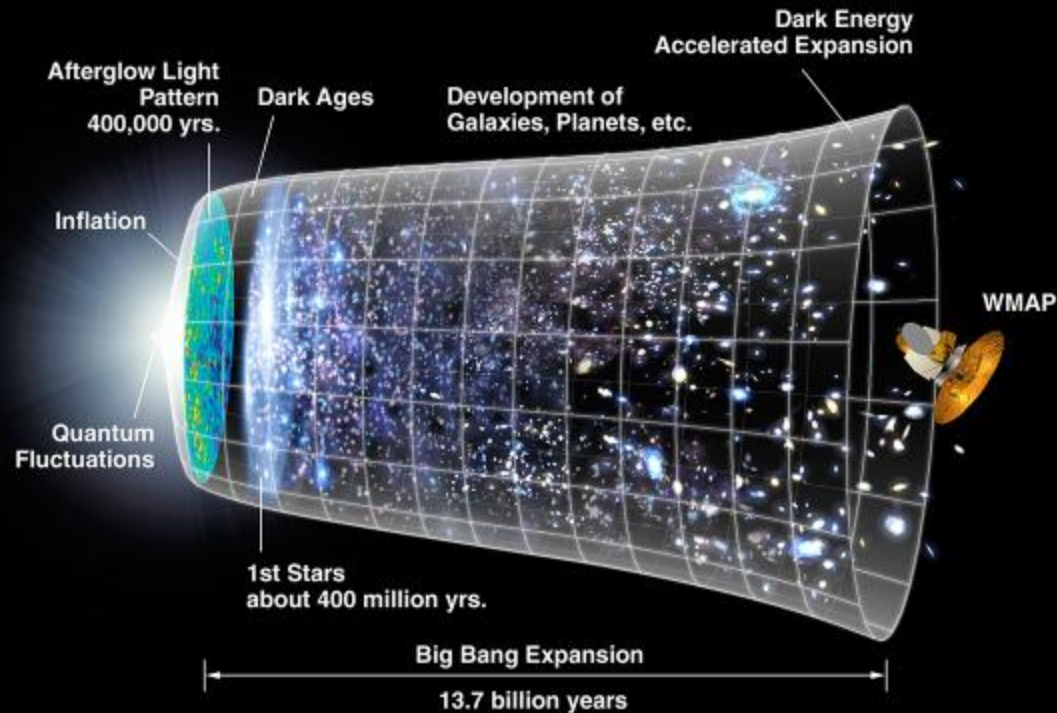


Primordial Abundances and the Conditions & Implications of Big-Bang Nucleosynthesis



Outline

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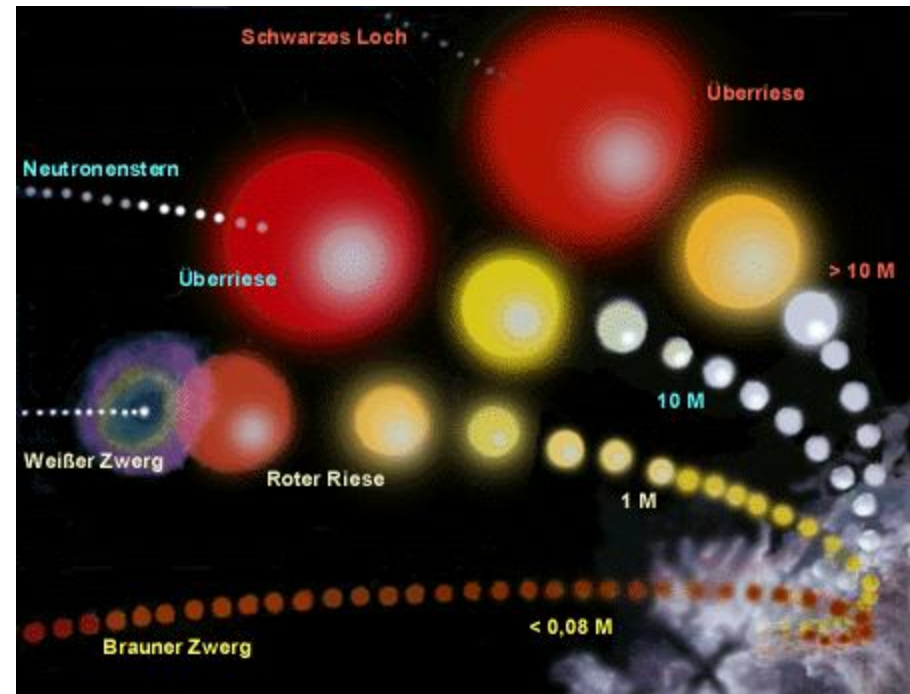
- **Introduction**
- **Big-Bang Nucleosynthesis (BBN)**
- **Reasons for Use of BBN**
- **Primordial Abundances**
 predicted by BBN vs. observed today
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- **Possible Solutions**
- **Conclusion**

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Introduction

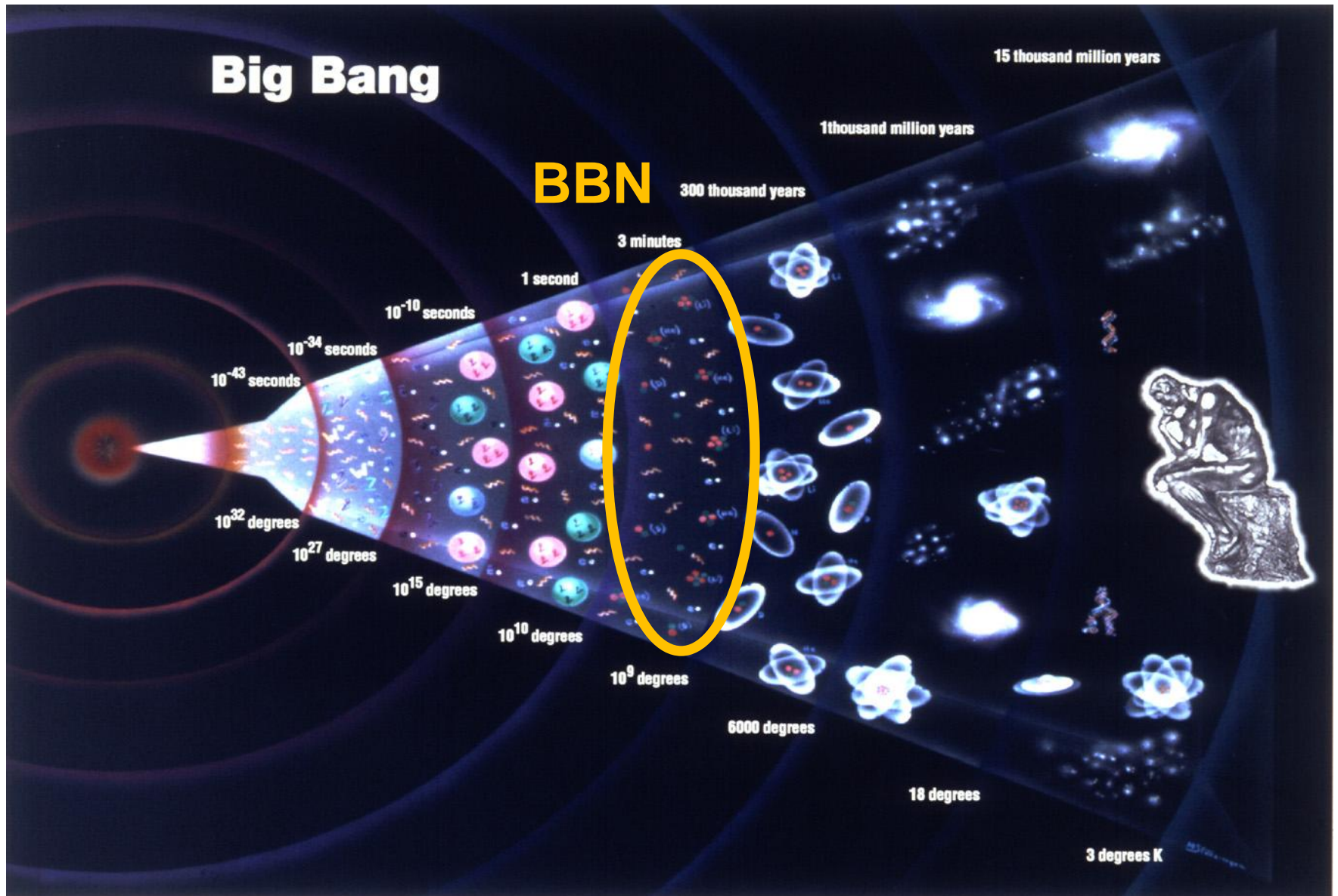
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- “Today”: Nuclear Fusion in Stars
 - He & Metals
- After Big Bang: Nuclear Fusion in the whole Universe (BBN)
 - D, He, Li, Be



Introduction

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- Introduction
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Big-Bang Nucleosynthesis (BBN)

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- $T > 10^{10}$ K:

γ , e^+ , e^- , ν_x , (n, p) in Thermal Equilibrium

$$N_n/N_p = \exp(-Q_{np}/k_B T) \quad Q_{np} = -1,29 \text{ MeV}$$

- $T \cong 10^9$ K:

$n + p \rightarrow D + \gamma$ faster than $D + \gamma \rightarrow n + p$

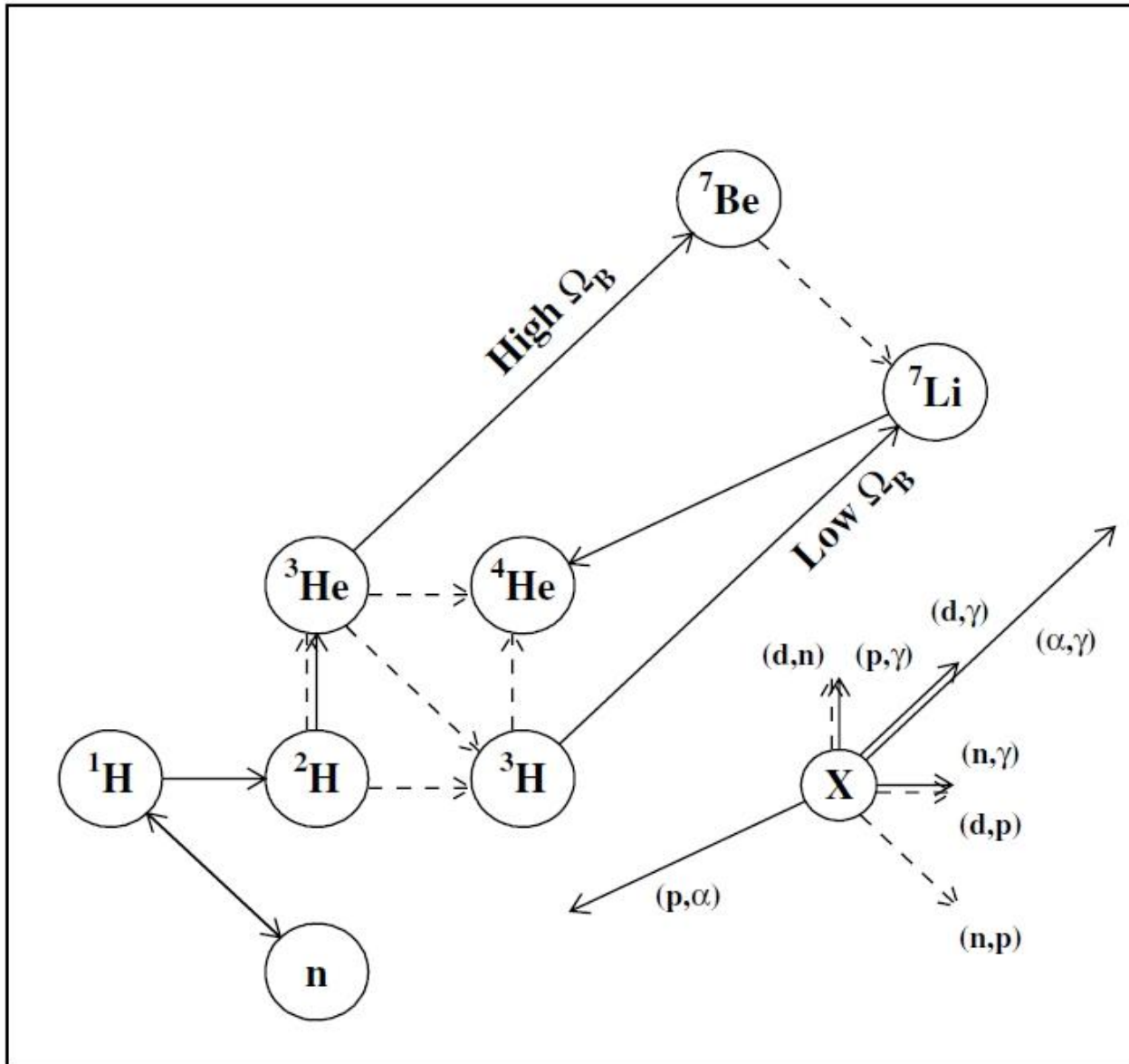
→ Production of heavier Nuclei possible!

→ ^4He , D, ^3H , ^3He , Li, ^7Be

Big-Bang Nucleosynthesis (BBN)

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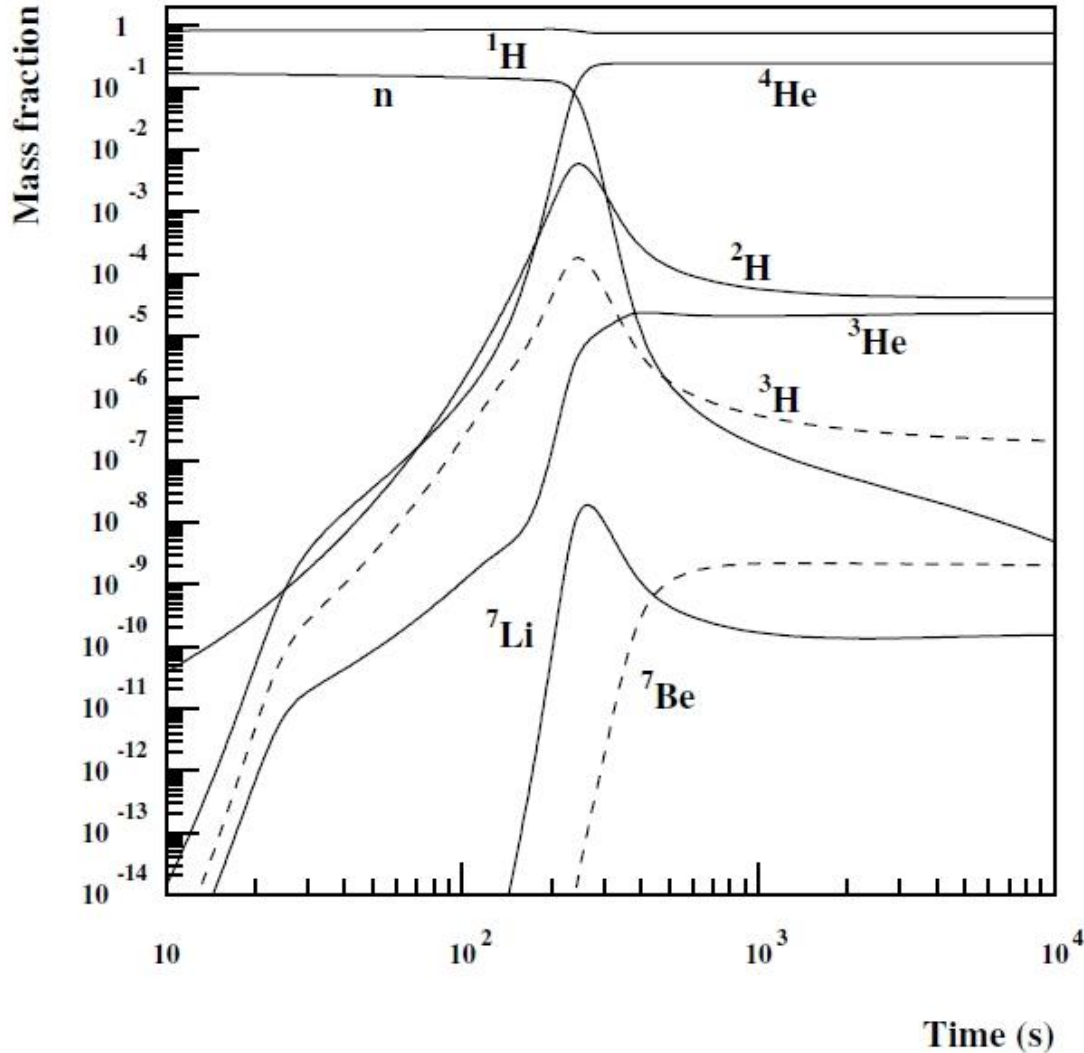
**Twelve Main
Nuclear
Reactions during
BBN.**



Big-Bang Nucleosynthesis (BBN)

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$$\Omega_B h^2 = \text{WMAP}/\Lambda\text{CMD}$$



Abundances evolving
in Time.

Big-Bang Nucleosynthesis (BBN)

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- $T \lesssim 3,5 \times 10^8$ K: End of BBN because of
 1. Coulomb Barriers / Low Temperature
 2. Absence of free Neutrons
(All incorporated in ^4He)
 3. No stable Nuclei with Mass $5u / 8u$
- From $t_{\text{Universe}} = 20\text{min.}$ until first Stars ($\sim 10^8$ yr)
no Primordial Nuclei destroyed
(Except radioactive Decay)

Big-Bang Nucleosynthesis (BBN)

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- In the past BBN dependent on

Lepton Families

→ **Standard Model of Particle Phys.**

Nuclear Reaction Rates

→ **Nuclear Physics Laboratories**

Baryonic Density / early Expansion Rate

→ **Anisotropies of CMB radiation**

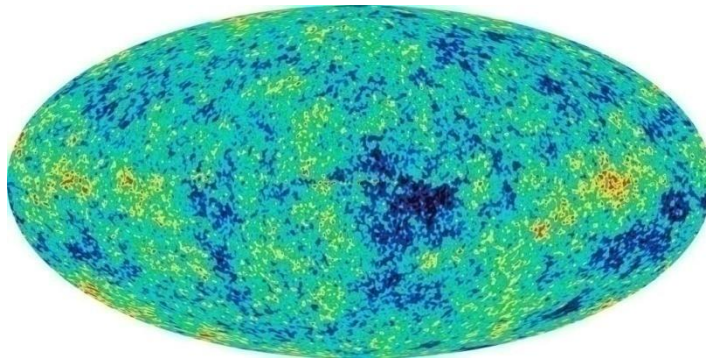
- Today (Standard-)BBN parameter-free theory

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Reasons for Use of BBN

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- **Cosmic Microwave Background (CMB) useful only up to $300 - 400 \times 10^3$ years after BB**



**CMB observed
by WMAP**

- **Understanding of the Early Universe via BBN (seconds – minutes after BB)**
- **As Consistency Check**

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Primordial Abundances: D

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- **Baryometer of Choice**
- **Only destroyed after BBN (Weak Binding
→ Burned away quickly, e.g. in Collapse
of prestellar Nebulae / in Stars)**
- **D Abundance at BBN value in Systems with
low Metallicity / high Redshift
(e.g. Absorption by neutral Gas of light
emitted in Quasi Stellar Objects)**

Primordial Abundances: D

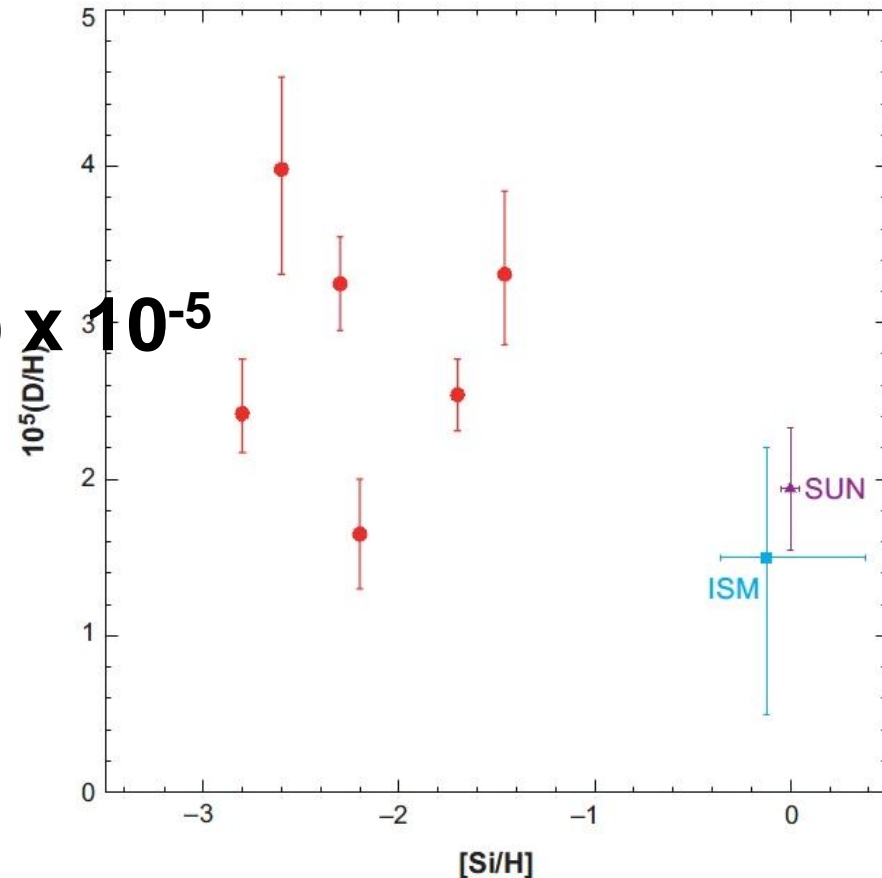
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- Difficult Measurement of D
- Few Data
- Observed Primordial

Abundance of D:

$$D/H = (2.68^{+0.27}_{-0.25}) \times 10^{-5}$$

(Steigmann, 2007)



Primordial Abundances: ^3He

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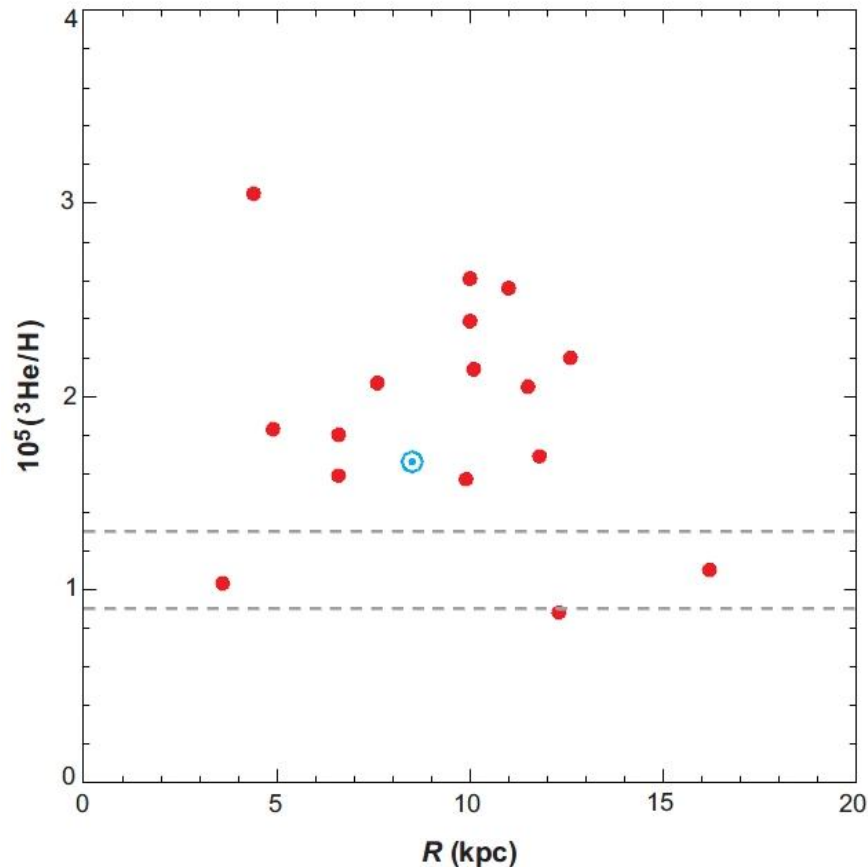
- **Production and destruction of ^3He**
- **Observation only in HII Regions in the Galaxy**
 - **limited Baryometer**
- **In Galaxy: Gradient of Metallicity with Radius**
- **If net Production / Destruction of ^3He**
 - **Abundance of ^3He dependent on Radius**
- **Observations: Possibly no Dependence**
 - **No net Production / Destruction of ^3He ?**

Primordial Abundances: ^3He

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- Observed Primordial Abundance of ^3He :

$$^3\text{He}/\text{H} = (1.1 \text{ } ^{+0.2}_{-0.2}) \times 10^{-5} \quad (\text{Steigmann, 2007})$$



Primordial Abundances: ^4He

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- **Production via Hydrogen Burning in Stars**
- **Significant Contributions to ^4He Abundance from post-BBN Production**
- **Observed Primordial Abundance of ^4He (Varying Results for Mass Fraction Y_P !)**

$$Y_P = 0,240 \pm 0,006 \quad (\text{Steigmann, 2007})$$

Primordial Abundances: ${}^7\text{Li}$

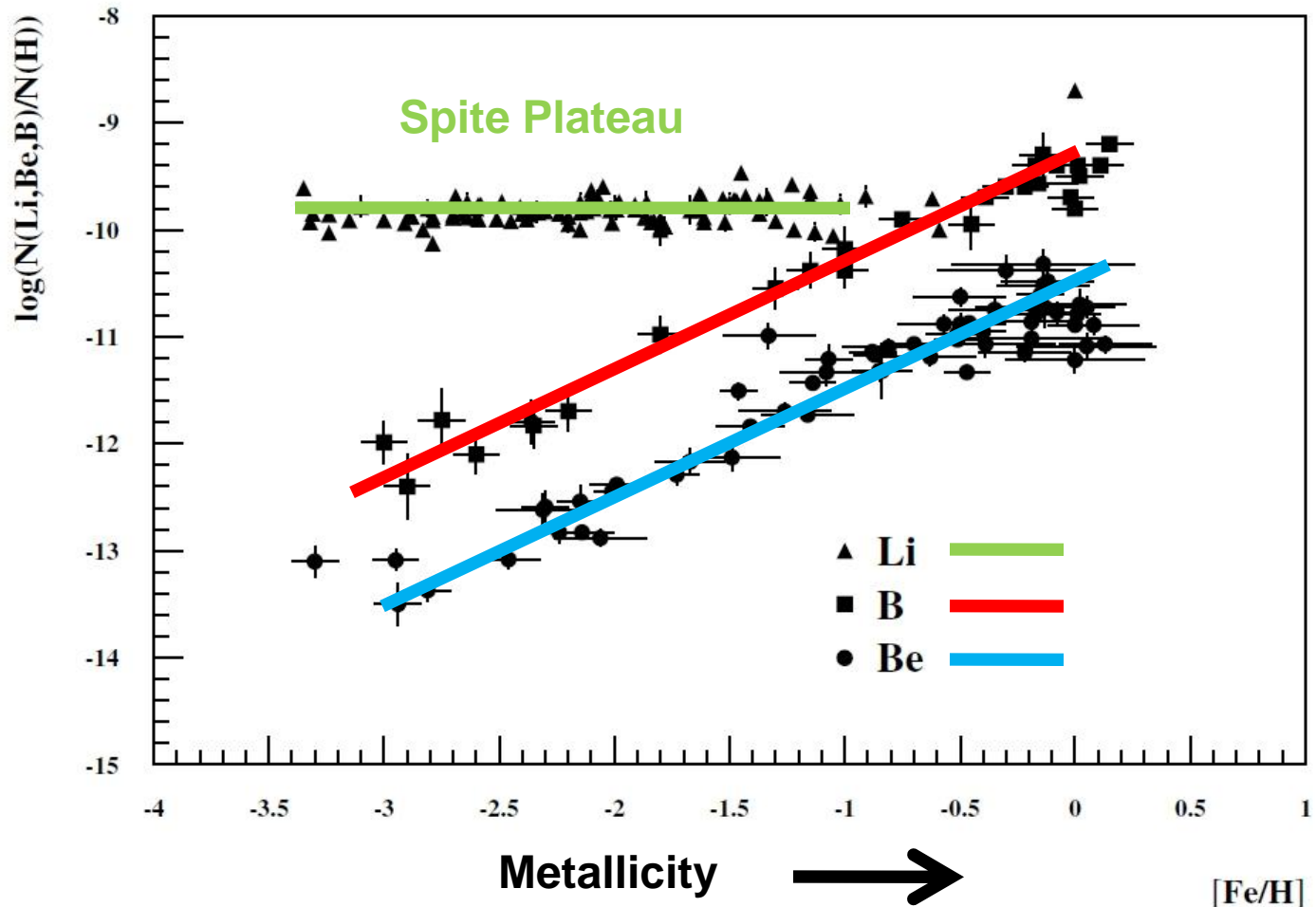
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- **Only Observation in Absorption Spectra of**
 - 1. very old / metal-poor stars in the Halo of the Galaxy**
 - 2. metal-poor Galactic Globular Cluster (GGC) Stars**
- **Potentially ideal for Probing the Primordial Abundance!**

Primordial Abundances: ${}^7\text{Li}$

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- Plateau in ${}^7\text{Li}$ Abundance for low Metallicity



Primordial Abundances: ${}^7\text{Li}$

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- **But: Some Groups: Slope in Spite Plateau!**

- **Main Question / Task:**

Extrapolation to

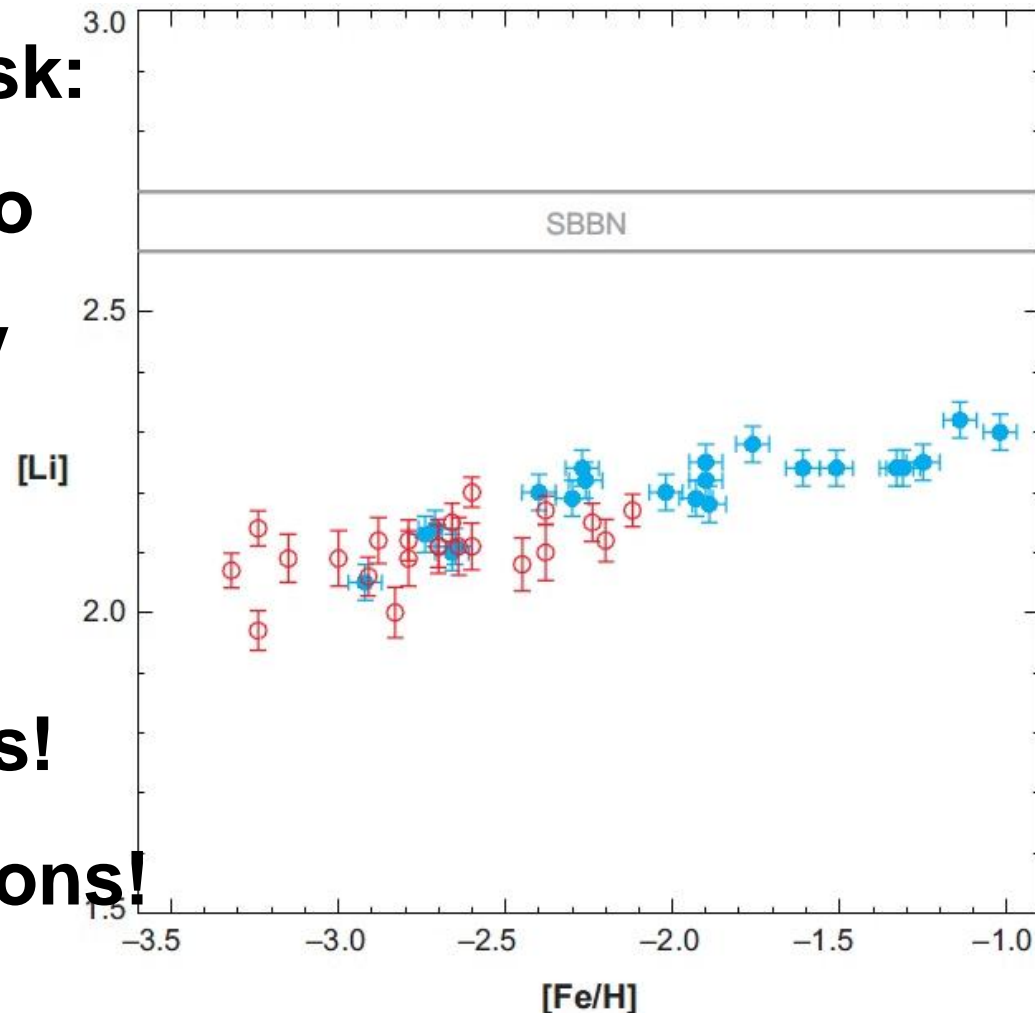
Zero Metallicity

→ Varying

Results for

different Slopes!

- **On-Going Discussions!**



Primordial Abundances: ${}^7\text{Li}$

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- **Possible sources of systematic errors:**

1. **Abundance Analysis (Dependence on T_{eff})**

- **Assumptions and poor Calibrations**

2. **Dilution & Destruction in very old Stars**

- *later*

3. **Uncertainties in Nuclear Reaction Rates**

- **Basically ruled out**

4. **Supersymmetry (Changing Reaction Rates)**

- **Theorists: “Hint for SUSY!”**

Primordial Abundances: ${}^7\text{Li}$

- **Extrapolation to zero Metallicity:**

$${}^7\text{Li}/\text{H} = (1.1 - 1.5) \times 10^{-10}$$

(Asplund et. al., 2006)

- **Discrepancies between Observation
and Theory!**

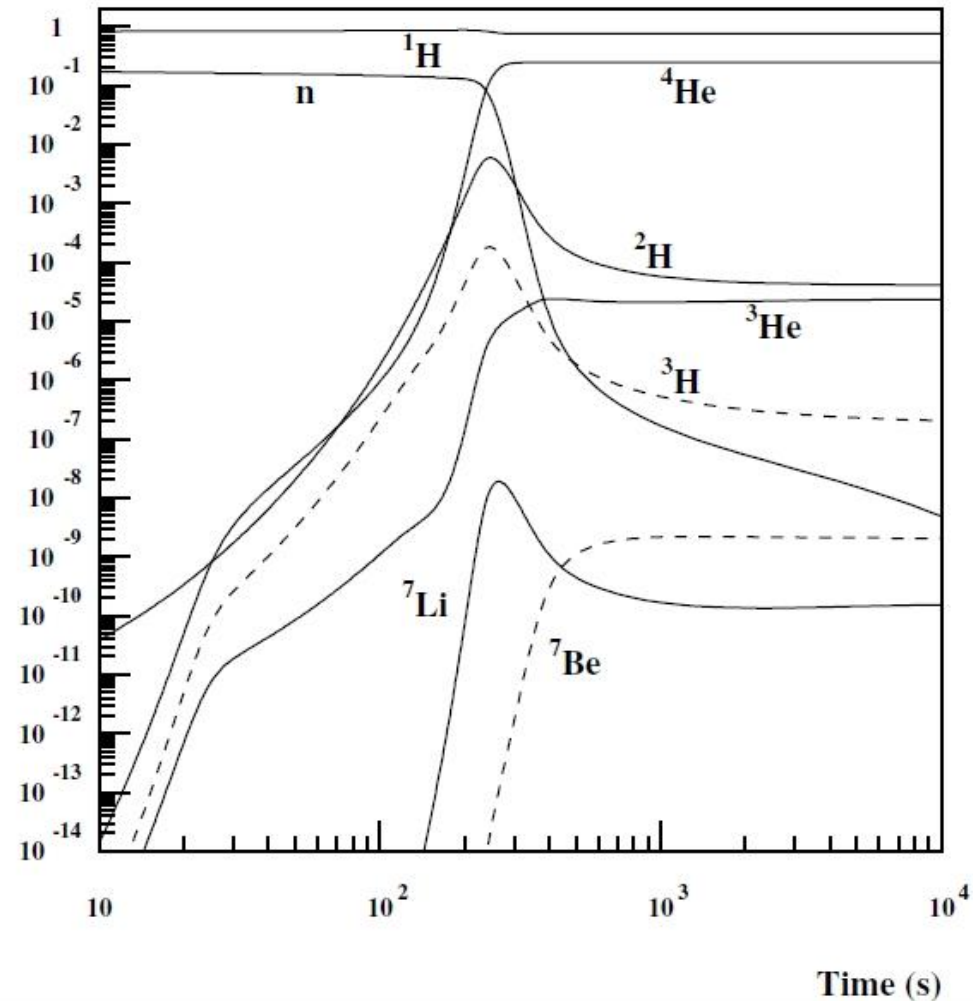
$$\rightarrow \text{Theory}/\text{Observation} \approx 2 \dots 5$$

Primordial Abundances: Predicted vs. Observed

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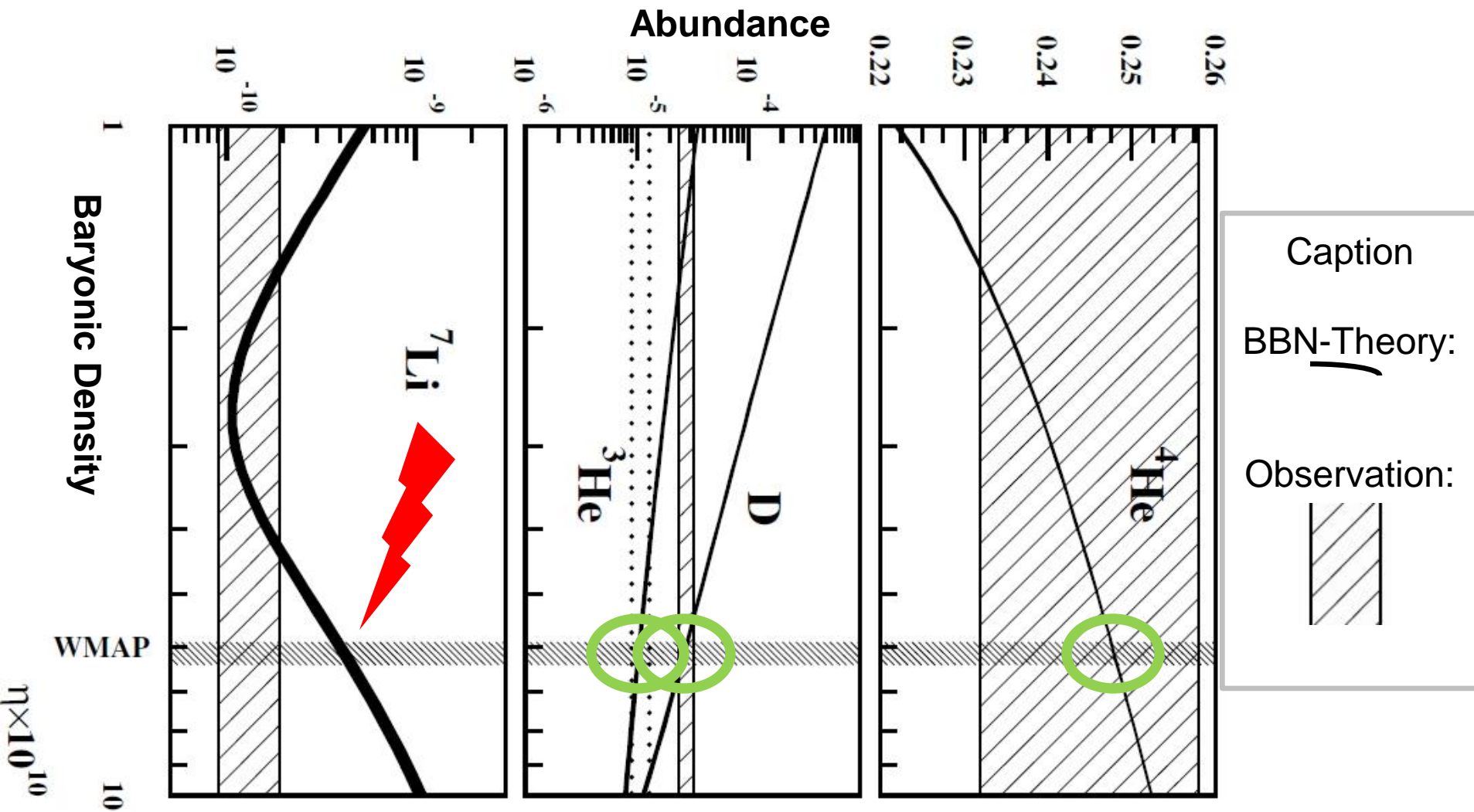
$$\Omega_B h^2 = \text{WMAP}/\Lambda\text{CDM}$$

WMAP (Λ CDM):
Baryonic Density
+
BBN-Theory
=
Abundances in Time

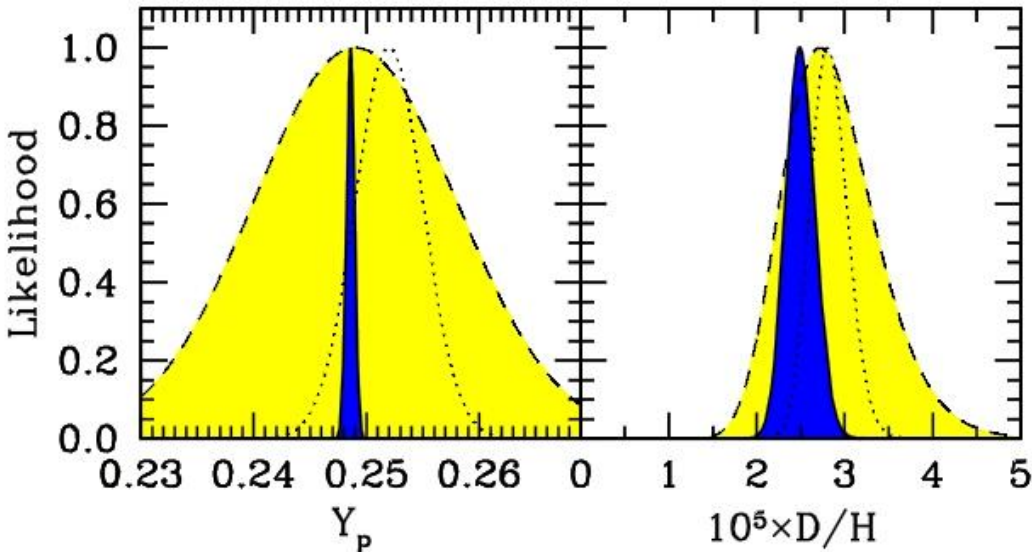


Primordial Abundances: Predicted vs. Observed

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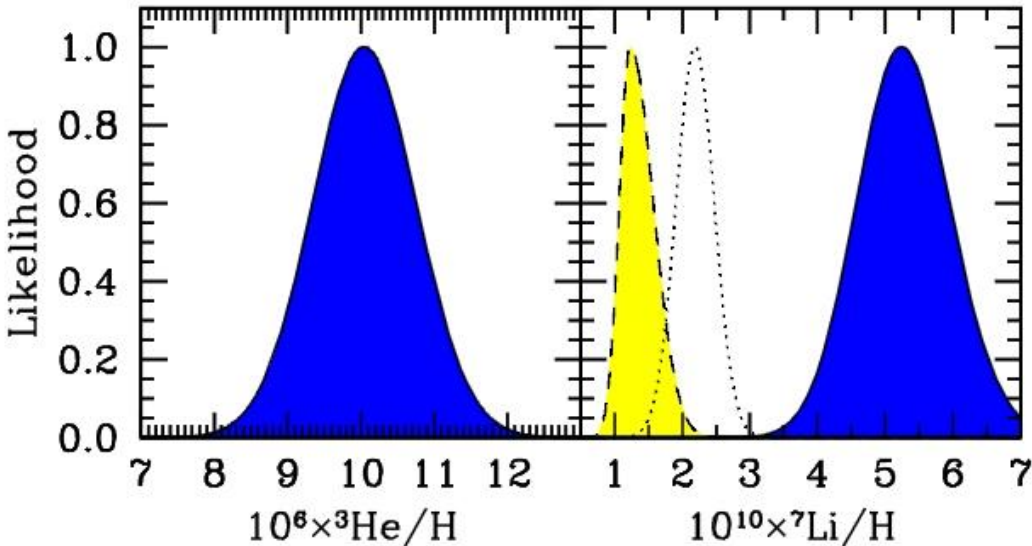
Primordial Abundances: Predicted vs. Observed



**BBN-Theory at
Baryonic Density from
WMAP (CMB)**

**Observational
Likelihood I**

**Observational
Likelihood II**



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Summary and Problems

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- **BBN ~ 1000 Seconds**
- **BBN parameter-free by means of Experiments
in Laboratories, Observations of CMB
(e.g. WMAP) and Standard Model of
Particle Physics**
- **Necessity of Measuring Abundances in old,
metal-poor Objects**

Summary and Problems

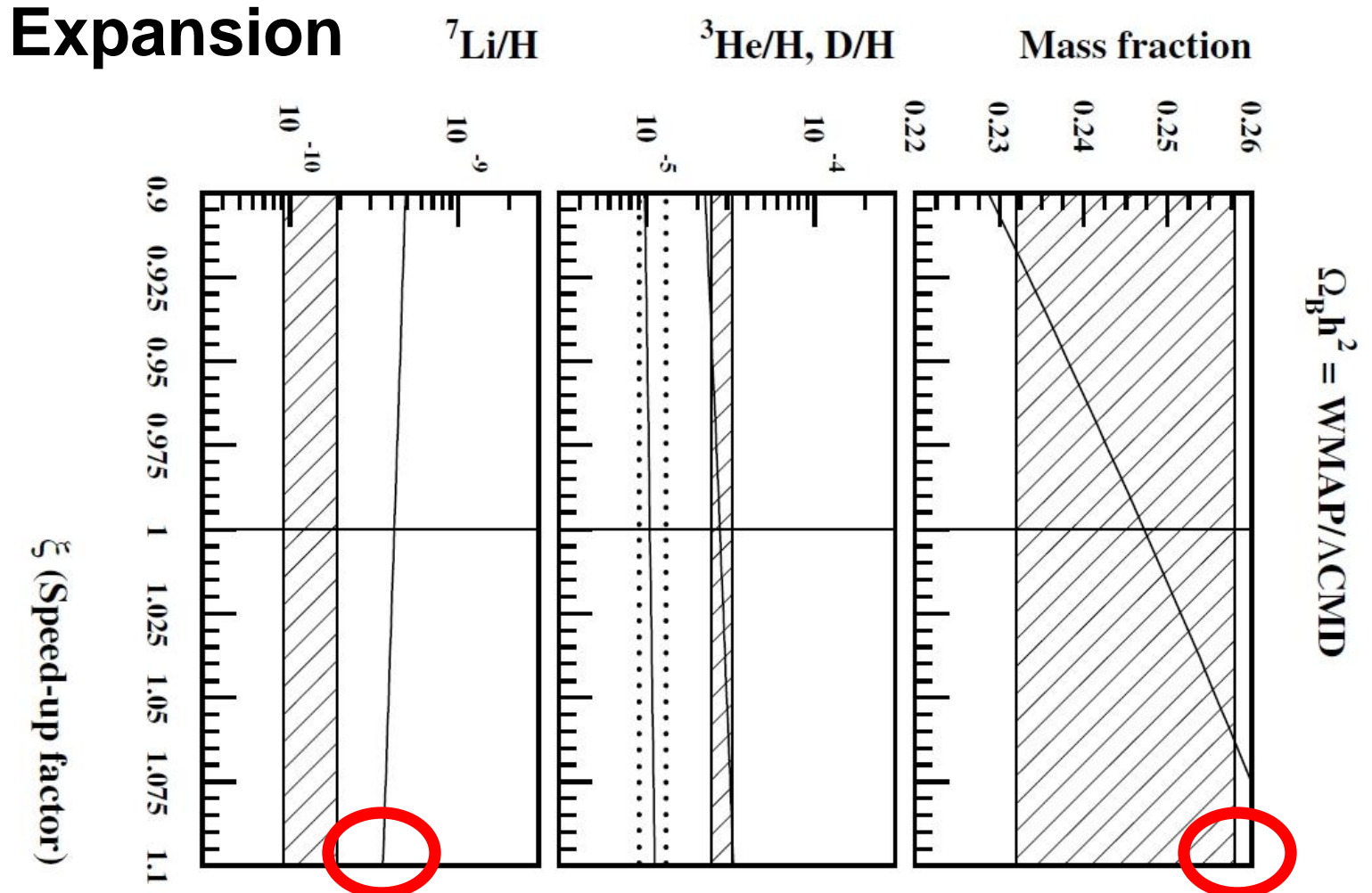
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- **Good Agreement between BBN+CMB predicted Theory and present Observations for D, ³He, ⁴He.**
- **Heavy Disagreement for ⁷Li (Factor ~ 3) and ⁶Li (Orders of Magnitude)**
→ “Lithium Problem”

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Possible Solutions

- Modifying BBN using Speed-Up Factor ξ for

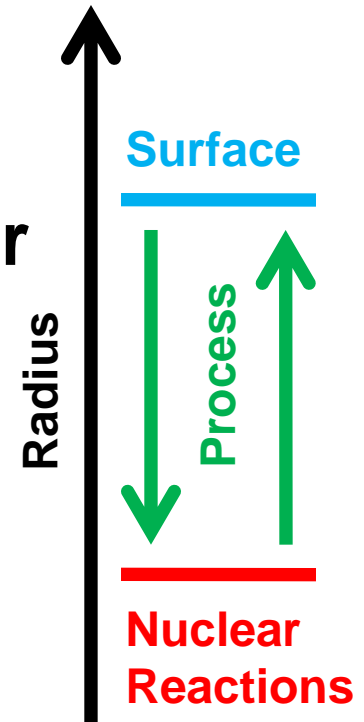


Possible Solutions

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- **Modifying Models of Stars:**
 - Transport of ${}^7\text{Li}$ to hotter Interior
 - Nuclear Fusion possible
 - Transport to Surface Again

➔ **Reduced Abundance of ${}^7\text{Li}$**



- **Discussed Processes fulfilling Requirements:**
 1. **Rotationally induced Mixing**
 2. **Diffusion + Turbulent Mixing**

Possible Solutions

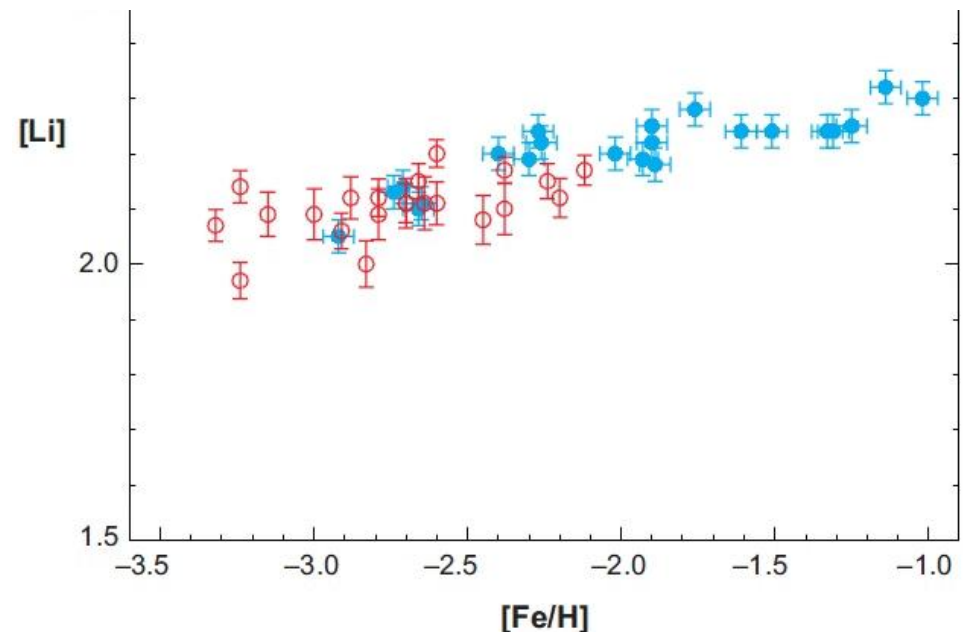
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- **Rotationally induced Mixing:**

All observed Stars with too low ${}^7\text{Li}$

→ Constant Effect largely independent of Stars' Properties: Angular Momentum!

→ Possible??



Possible Solutions

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- **Diffusion + Turbulent Mixing:**

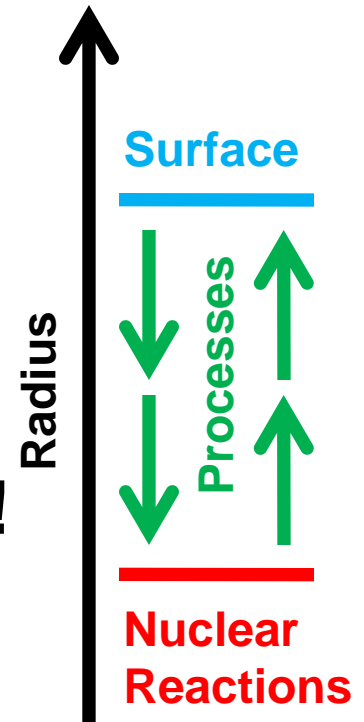
Diffusion not sufficient:

Not deep enough!

➔ **“Turbulent Mixing” necessary!**

➔ **Presently no Explanation!**

➔ **Poor Understanding of Stars’ Interior??**



Possible Solutions

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Further Possibilities:

- **Non-Standard Big Bang Nucleosynthesis /
Physics beyond the Standard Model
(e.g. Hadronic Decays of Exotic Particles)**
- **Systematic Errors in Observations / Abundance
Analysis (e.g. concerning Halo Stars)**
- **Erroneous Nuclear Reaction Rates**
- **Modified Gravity and varying Constants, e.g. α**

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Conclusion

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- **Great Progress in Understanding the Early Universe and Determining its Physics**
- **Still Disagreement between different Theories / Experiments concerning BBN**
- **On-Going Research necessary!**

Thank You!

Sources:

- A. Coc: An Introduction to Primordial Nucleosynthesis. 2008
- R. Cyburt et al.: An Update on the Big Bang Nucleosynthesis prediction for ${}^7\text{Li}$: The Problem worsens. 2008
- G. Steigman: Primordial Nucleosynthesis in the Precision Cosmology Era. 2007
- M. Asplund et al.: Lithium Isotopic Abundances in metal-poor Halo Stars. 2006

