Big Bang Nucleosynthesis

Karsten JEDAMZIK†

† LPTA, Montpellier
Outline of Talk

I. Theory of standard BBN

II. Observational determination of primordial light elements abundances/comparison to standard BBN prediction

III. BBN as a probe of the early Universe and Physics beyond the standard model

IV. Astrophysical/nuclear physics solutions to the Lithium problem(s)

V. Beyond the standard model solutions to the lithium problem(s)
The standard BBN model at $\Omega_b h^2 \approx 0.02273$
Assumptions underlying Standard Big Bang Nucleosynthesis

- General relativity
- Equilibrium initial conditions with baryon-to-photon ratio $6.2 \times 10^{-10}$
- Vanishing lepton number chemical potentials
- Radiation energy density given only by photons, electrons/positrons, neutrinos
- No decaying or annihilating relic particles
- No inhomogeneities in baryons
- No small antimatter domains
- No impurities like cosmic strings, primordial black holes
SBBN: A one parameter model

Cyburt et al. 08

baryon density $\Omega_b h^2$

overconstrained $\rightarrow$ consistency checks possible
II. Observational determination of primordial light elements abundances/ comparison to standard BBN predictions
Helium-4 from low-metallicity extragalactic HII regions

systematic uncertainties

- atomic emissivities (changed $Y_p$ by $+0.008$ !)
- temperature variations
- ionisation corrections
- underlying stellar absorption

$Y_p = 0.2477 \pm 0.0029, 0.2516 \pm 0.0011$ Peimbert et al. 07, Izotov et al. 07

more realistic error bars: $Y_p = 0.249 \pm 0.009$ Olive & Skillman 04
Observational inferred Helium-4 with time

Year

\( ^4 \text{He mass fraction } Y_p \)


WMAP
**D/H from Quasar Absorption Systems**

![Graph showing D/H ratio for Ly-α, Ly-β, and Ly-γ lines](image)

Tytler, Fan, & Burles 96

significant dispersion → underestimated systematic errors?

Iocco et al. 09

\[ \text{D/H} = 2.98^{+0.29}_{-0.23} \times 10^{-5} \]
The $^7$Li Spite plateau

- (almost) no variation with metallicity and stellar temperature
- (almost) no measurable star-to-star scatter
- Interpretation - the Primordial $^7$Li Abundance

Spite & Spite 82, Bonifacio & Molaro 97, Ryan et al 99, Melendez Ramirez 04, Charbonnel & Primas 05, Asplund et al 06
$^{6}\text{Li}/\text{H}$ observations

A second Lithium plateau?

$^{6}\text{Li}/\text{H} \approx 6 \times 10^{-12}$ compare to standard BBN $^{6}\text{Li}/\text{H} \sim 10^{-14}$

- $^{6}\text{Li}$ and $^{7}\text{Li}$ absorption features blend together
- $^{6}\text{Li}$ from asymmetry of lines
- asymmetry of lines from convective Doppler shifts?
- non-LTE hydrodynamic simulations of two groups reach opposite conclusions
Are the $^6$Li detections real?

- only four $\sim 2\sigma$ detections
- however, distribution skewed towards positive $^6$Li/H
- a positive $^6$Li/H detection in HD84937 by four(!) groups
$^3\text{He}/D \lesssim 1.5$ for solar system Geiss & Gloeckner 07 is secure and useful in constraining non-standard BBN Sigl et al. 06
SBBN Predictions against Observations

Cyburt, Fields, & Olive 08

$^{7}$Li discrepancy $4.2 - 5.3\sigma$
## Situation Summary

<table>
<thead>
<tr>
<th>Element</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}$</td>
<td>ok/inconclusiv</td>
</tr>
<tr>
<td>$^2\text{H}$</td>
<td>good</td>
</tr>
<tr>
<td>$^3\text{He}$</td>
<td>inconclusive</td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>disagreement</td>
</tr>
<tr>
<td>$^6\text{Li}$</td>
<td>?</td>
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</tbody>
</table>
III. BBN as a probe of the early Universe and Physics beyond the standard model
The BBN early Universe Probe

- the epoch of BBN is (one) of the furthest back reaching precision probe of the early Universe

- Almost all of the theoretical work in BBN the last three decades has been done in exploring non-standard models

- changed expansion rate during BBN
- lepton chemical potentials
- neutrino oscillations, sterile neutrinos, exotic neutrino interactions
- baryon inhomogeneous models, matter-antimatter inhomogeneous models
- varying fundamental constants
- decay and annihilation of relic particles during BBN
- catalysis of BBN
BBN with decaying and annihilating particles

- injection of energetic nucleons and mesons
  - charge exchange reactions
    \[ \pi^- + p \rightarrow \pi^0 + n \]
  - elastic- and inelastic scatterings
    \[ p + p \rightarrow p(n) + (p)n + \pi's \]
  - spallation reactions
    \[ p(n) + ^4\text{He} \rightarrow ^3\text{H}, ^3\text{He}, ^2\text{H} + \ldots \]
  - Coulomb stopping of charged nuclei
    \[ ^3\text{H} + e^\pm \rightarrow ^3\text{H}' + e^\pm \]
- injection of energetic photons and electrons/positrons
  - pair production on CMBR
    \[ \gamma + \gamma_{\text{CMBR}} \rightarrow e^- + e^+ \]
  - inverse Compton scattering
    \[ e^\pm + \gamma_{\text{CMBR}} \rightarrow e^\pm + \gamma \]
  - Bethe-Heitler scattering
    \[ \gamma + p \rightarrow p + e^- + e^+ \]
  - photodisintegration
    \[ \gamma + ^4\text{He} \rightarrow ^3\text{H} + p \]
Example: Supersymmetry, BBN, and $T_{rh}$

gravitino not LSP $\rightarrow T_{rh}$ must be low to avoid too many decays of thermally produced gravitinos during BBN

gravitino LSP $\rightarrow$ NLSP decays dangerous unless $\tau \lesssim 5 \times 10^3$ sec $\rightarrow$ gravitino LSP somewhat lighter than weak scale $\rightarrow$ reheat temperature must be low

$\rightarrow$ supergravity and leptogenesis (in most cases) incompatible
IV. Astrophysical/nuclear physics solutions to the lithium problem(s)
Nuclear reactions/stellar atmospheres?

- stellar temperature $\Delta T \sim 900$ K underestimated seems impossible

- narrow nuclear resonance in
  $^7\text{Be} + ^2\text{H} \rightarrow ^9\text{B}^{*}_{5/2+} \rightarrow ^4\text{He} + p$

Cyburt & Pospelov 09, Angulo et al. 05

seems unlikely but not ruled out $\rightarrow$ need further measurement
Depletion of Lithium in PopII stars?

$^7\text{Li}$ is observed in the atmospheres of PopII stars. It may be destroyed via $^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$ in the interior of the star. Atmospheric material transported into the star and $^7\text{Li}$-depleted gas returned to the atmosphere.

Spite plateau not primordial?

Depletion of $^7\text{Li}$ by factor 2 – 4 in halo stars is not understood and may currently only be explained with fine-tuned stellar conditions.

Dispersion?
$^7$Li depletion by atomic diffusion in PopII stars?

Korn et al., Richards et al.

- atomic diffusion
- turbulent mixing

Fine-tuned turbulent diffusion coefficient $D_T = 400 D_{^{4}He}^{^{2}H}(\frac{\rho}{\rho(T_0)})^{-3}$ at $\log(T_0) = 6.0 \pm 0.1 \rightarrow \pm 25\%$

→ factor 1.8 $^7$Li depletion

but stellar models ad hoc and tuned

SBBN + WMAP predicted $\text{Li/H}$ (2−$\sigma$-error bars) → factor 1.8 $^7$Li depletion

observed $\text{Li/H}$ by different groups


\( ^6\text{Li} \) production by early cosmic rays: Energetics?

\( ^6\text{Li} \) originates in galactic cosmic ray nucleosynthesis (along, with \(^9\text{Be}, \) and \( \text{B} \))

- via \( p, \alpha + \text{CNO} \rightarrow \text{LiBeB} \)
- and some \( \alpha + \alpha \rightarrow \text{Li} \)

need 100 eV/nucleon to synthesize \( ^6\text{Li}/H \sim 5 \times 10^{-12} \)

standard cosmic rays may provide 5 eV/nucleon (up to \([Z] \sim -2.7 \))

only very efficient accretion on central black hole, or large fraction of baryons in supermassive \( \sim 100M_\odot \) stars may provide the required cosmic rays

Suzuki & Inoue 00 Rollinde et al. 05, Prantzos et al. 05 Nath et al. 05
V. Beyond the standard model solutions to the lithium problem(s)
Destruction of $^7\text{Li}$ during BBN due to injection of neutrons

K.J. 04

$^7\text{Li}$ destruction: $^7\text{Be} + n \rightarrow ^7\text{Li} + p$; $^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$

at $T \approx 30$ keV

need only $10^{-5}$ extra neutrons per baryon

some extra $^2\text{H}$ will be also synthesized

→ possible by decay/annihilation or relic particles, evaporation of defects
Production of $^6\text{Li}$ in cascade nucleosynthesis

$^6\text{Li}$ is very easily produced by small "perturbations" of the standard model Dimopoulos et al. 88, K.J. 00

Electromagnetic:
$$\gamma + ^4\text{He} \rightarrow ^3\text{H} + p$$
$$^3\text{H} + ^4\text{He} \rightarrow ^6\text{Li} + n$$
\text{at } T \lesssim 0.1 \text{ keV}

Hadronic:
$$n + ^4\text{He} \rightarrow ^3\text{H} + p + n$$
$$^3\text{H} + ^4\text{He} \rightarrow ^6\text{Li} + n$$
\text{at } T \lesssim 10 \text{ keV}
charged relic - nuclei bound states during/after BBN

Pospelov 06,07, Kohri & Takayama 06, Kaplinghat & Rajaraman 06, Cyburt et al 06, Pradler & Steffen 06, Hamaguchi et al. 07, Bird, Koopmans, & Pospelov 07, Kawasaki et al. 07, Takayama 07, Jittoh et al. 07, Jedamzik 07,08

binding energy between nuclei and electrically charged weak mass scale relics appreciable:

\[ {^7}\text{Be} + \tilde{\tau} \rightarrow ( {^7}\text{Be}\tilde{\tau}) + \gamma, \quad {^4}\text{He} + \tilde{\tau} \rightarrow ( {^7}\text{He}\tilde{\tau}) + \gamma, \quad \text{etc.} \]

Bohr radius of bound nuclei between 2 − 4 Fermis

→ formation of bound states towards the end of BBN
Fraction of nuclei bound to $X^-$

Oh$^2 = 0.41$, $M_x = 1$ TeV

Karsten Jedamzik, Brussels, December 3$^{rd}$ '09 – p. 29
Production of $^6\text{Li}$ in catalytic nucleosynthesis

negatively charged weak mass scale particles $X^-$ during BBN →

formation of bound states with nuclei

$^7\text{Be} + X^- \rightarrow (^7\text{Be}X^-) + \gamma$ at $\approx 30\text{ keV}$

$^4\text{He} + X^- \rightarrow (^4\text{He}X^-) + \gamma$, at $\approx 10\text{ keV}$

$X^-$ acts as catalysator for reactions

$(^4\text{He}X^-) + D \rightarrow ^6\text{Li} + X^-$

$^4\text{He}X^- + ^4\text{He} \rightarrow (^8\text{Be}X^-) + \gamma$;

$^8\text{Be}X^- + n \rightarrow ^9\text{Be} + X^-$

important when $B_h \lesssim 10^{-2}$ as with supersymmetric stau!
Catalysis and $^6$Li, $^7$Li, and $^7$Be

Catalysis:

- main production mechanism for $^6$Li if $B_h \lesssim 10^{-2}$
- may not solve the $^7$Li problem, unless $B_h \lesssim 10^{-5}$ rather small and $\Omega X \gtrsim 10$ rather large
- not clear if may lead to some $^9$Be production
The lithium friendly parameter space in cascade nucleosynthesis

K.J. 04

D/H
3e-05

7Li/H
1e-10

6Li/7Li 1
0.1
1e-02

10
10^2 10^3 10^4 10^5 10^6
τ (sec)

Bailly, K.J., Moultaka 08

Ω X h^2 B_h

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2 10^3 10^4 10^5
τ (sec)

Y_p > 0.258
D/H > 4x10^{-5}

Karsten Jedamzik, Brussels, December 3rd, 09 – p. 32
Signatures at the LHC!

A metastable particle $X$ with life time between $100 - 1000$ sec, if not too massive, could be potentially produced at the LHC (since having at least some hadronic interactions), and ...., if electromagnetically or strongly interacting stopped in the detector $\rightarrow$ smoking gun for non-standard BBN $\rightarrow$ possible connection to the dark matter

Examples:
Gluino in split supersymmetry
supersymmetric stau Next-to-LSP with gravitino LSP
Example: Gravitino dark matter in the CMSSM

K.J., Choi, Roszkowski, Ruiz de Austri 06
Solving the $^6\text{Li}$ and $^7\text{Li}$ problems by neutralino annihilation?
Varying fundamental constants and $^7\text{Li}$

Dmitriev, Flambaum, & Webb 04, Dent, Stern, & Wetterich 07, Berengut, Flambaum, & Dmitriev 09

$^7\text{Li}$ depends strongly on $B_d$ and $B_{^7\text{Be}}$

$\Delta B_d/B_d \approx -0.019 \pm 0.005 \rightarrow$ reduce $^7\text{Li}$ (and $^4\text{He}$)

$\Delta m_q/m_q \approx 0.013 \pm 0.002 \rightarrow$ reduce $^7\text{Li}$
Conclusions

- The by standard BBN at $\eta_{\mathrm{WMAP}}$ predicted D (and $^4\mathrm{He}$) are in good agreement with those observed.

- In contrast, there is a factor 3-4 discrepancy between SBBN predicted and observationally inferred $^7\mathrm{Li}$.

- This discrepancy could possibly be removed if $^7\mathrm{Li}$ is destroyed in Pop II stars, though how this is done exactly is not understood.

- Alternatively BBN could have been non-standard, e.g. including the decay of a relic particle $\rightarrow$ potentially testable at the LHC.

- Observations of the existence of a $^6\mathrm{Li}$ plateau (similar to the $^7\mathrm{Li}$ Spite plateau) are currently controversial.

- BBN continues to be a powerful probe of the early Universe and physics beyond the standard model.