An overview of the present status of Primordial Nucleosynthesis

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For reference, see Phys. Rept. 472, 1-79 (2009)

Numerical results obtained with the public available code “PArthENoPE” http://parthenope.na.infn.it/

Public Algorithm Evaluating the Nucleosynthesis of Primordial Elements
Outline

I. Brief Historical Introduction to BBN

II. The basic physical processes and predictions

Observational results I: Deuterium
(implications for cosmological concordance)

Observational results II: Helium-4
(some implications for variation of fundamental constants)

Observational results III: Lithium
(“problems”, astrophysics & new physics)

Summary & Outlook
The...\(\alpha \beta \gamma\) of Big Bang Nucleosynthesis (BBN)

- 1946 →‘50 (Gamow, \(\alpha \beta \gamma\)): nuclear reactions in the early universe might explain the abundances of elements (bold idea: abundances are not “initial conditions”!)

- 1949 Fermi and Turkevich: lack of stable nuclei with mass 5 and 8 prevents significant production of nuclei more massive than \(^7\text{Li}\).

- 1964, Peebles, Hoyle & Tayler: \(Y_p \sim 0.25\).


R.A. Alpher, H. Bethe and G. Gamow
The second stage (~‘70)

BBN (+ CMB and Hubble expansion) became a pillar of hot big bang cosmology

General agreement that in the expansion after the Big Bang, when:

\[ 1 \text{ s} \leq t \leq 3600 \text{ s} \quad (10 \text{ keV} \leq T \leq 1 \text{ MeV}) \]

the Universe, a thermal bath of \( \gamma, \nu, \nu, e^+, e^- \) (+traces of \( p, n \)…and \( X \))

behaved as a “cooling” thermo-nuclear reactor,

producing sensible amount of light nuclei,

\( \text{H, } ^2\text{H, } ^3\text{H}(\rightarrow^3\text{He}), ^3\text{He, } ^4\text{He, } ^7\text{Li, } ^7\text{Be}(\rightarrow^7\text{Li}) \)

Despite Hoyle’s opinion, Nature likes party girls...
The beginning of “astroparticle physics”

Connections with particle physics were explored:
in the minimal formulation, BBN depends on the baryon/photon ratio

Baryogenesis issue… Non-Baryonic Dark Matter…

measuring for the first time “number of light ν species”

\[ N_\nu \leq 4 \text{ is reconfirmed} \]
BBN
Astrophysics

New Physics?

CMB

ω_b, δω_b/ω_b << 1!!

Data Regression!

Physical param. G_F, G_N, α...

Systematics!

X_i

σ(E)

Cosmology

Astrophysics

BBN Flowchart

Primordial Elements Observations

Nuclear Astrophysics
Numerical approach….

\[ H \equiv \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G_N}{3}} \rho_{tot} \]

\[ \dot{T}_i = -3H(\rho_i + P_i) \left( \frac{d\rho_i}{dT} \right)^{-1} \]

\[ \frac{\dot{n}_b}{n_b} = -3 \frac{\dot{a}}{a} \]

\[ n_b \sum_i Z_i X_i = T^3 L(m_e/T, \mu_e/T) \]

\[ \dot{X}_a = \sum_{\text{react}} N_a \left[ \Gamma(k + \ldots + r \rightarrow a + \ldots + f) \frac{(X_k)^{N_k}}{N_k!} \times \ldots \times \frac{(X_r)^{N_r}}{N_r!} \right. \]

\[ \left. - \Gamma(a + \ldots + f \rightarrow k + \ldots + r) \frac{(X_a)^{N_a}}{N_a!} \times \ldots \times \frac{(X_f)^{N_f}}{N_f!} \right] \]

(Equivalent to) 2 independent Einstein Eq.s [some subtlety for \( \nu \) transfer of entropy]

(comoving) conservation of baryon number

Electrical neutrality

Nuclear (species-changing) kinetic equations

Plug in a solver for coupled, non linear, \textbf{stiff} ODE for appropriate initial conditions (and be careful!)
BBN in four steps

- T\gg 1 \text{ MeV}: initial conditions dictated by NSE & input parameters.

- T\sim 1 \text{ MeV}: p \leftrightarrow n freeze-out (weak physics… mostly affects \(^4\)He yield)
  ((departure from isospin equilibrium))

- T\sim 0.1 \text{ MeV}: Deuterium bottleneck opens

- 0.1\sim T\sim 0.01 \text{ MeV}: nuclear reactions take place.
  ((departure from NSE equilibrium))

**Interesting physics happens due to departures from equilibria!**

*Described via Boltzmann equations of the form:*

\[
\dot{f}_i(E) + 3H f_i(E) = \frac{1}{E} \int d\Xi |M|^2 \delta^{(4)}(p_{\text{in}} - p_{\text{out}}) \Pi_{\text{in}} f_{\text{in}} \Pi_{\text{out}} (1 \pm f_{\text{out}})
\]

**For quick estimates, compare:**

Rate of process of interest \( \Gamma \approx H \)

Hubble expansion rate
In its MINIMAL FORMULATION, BBN is an overconstrained theory: all the relevant observables in terms of the only unknown parameter $\eta$ ( $N_v$ and $\Gamma_k$ are fixed by “Standard Physics”)

Since CMB now provides an independent measurement of $\eta$, a single nuclide determination already provides a test of the theory!
Deuterium
Observational Strategies: Deuterium

Main problem

We cannot observe *primordial* abundances:
Stars have altered the primordial composition, in particular, destroying deuterium (fragile, easily burned)

*Observe systems with little chemical processing*

Lyman absorption lines by neutral hydrogen (HI) gas clouds placed along the line of sight of quasar systems at large red-shift ($z \sim 2 – 3$). Require:

- Right range of optical depths
- Low metallicity
- Low velocity dispersion

*still, after that, beware of interlopers or other systematics!*
After throwing away less reliable measurements and inflating error by $\sqrt{\chi^2}$ to account for residual systematics

$$10^5 (\frac{2H}{H})_{\text{obs}} = 2.87^{+0.22}_{-0.21}$$

Low Statistics
(7-9 data)

Some systematics?
($\sqrt{\chi^2}$~2)
A wonderful cosmological consistency check

\[ 10^5 \left( \frac{^2\text{H}}{\text{H}} \right)_{\text{obs}} = 2.87^{+0.22}_{-0.21} \]

Theoretical Central Value & Error slightly dependent on regression analysis for
\[ ^2\text{H}(d,p)^3\text{H}-^2\text{H}(d,n)^3\text{He}-^2\text{H}(p,\gamma)^3\text{He} \]

\( ^2\text{H} + \text{BBN} : \Omega_b h^2 = 0.021 \pm 0.002 \) (95% C.L.)

to be compared with

\( \text{WMAP5} : \Omega_b h^2 = 0.02273 \pm 0.00062 \) (95% C.L.)

Essential agreement between two completely independent determinations of \( \omega_b \) !!!

Vice versa, since the amount of deuterium left depends on a complicated number of energies and timescales entering the problem, the basic BBN mechanism seems robustly tested!
Helium-4
Observational Strategies: Helium-4

**Main problem**
We cannot observe *primordial* abundances:
Stars have altered the primordial composition.
For $^4\text{He}$, stars mostly burn H into He $\rightarrow Y > Y_p$

*Observe systems with little chemical processing*
HeII $\rightarrow$ HeI recombination lines in HII regions
(about $\sim$80 such regions known) of Blue Compact Dwarf Galaxies*

*Correct for chemical evolution*
Extrapolate *linearly* to “zero metallicity” in $Y_p$ vs O/H,N/H plots

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*small galaxies ($\sim$1/10 MW) containing large clusters of young, hot, massive stars. Among the least chemically evolved objects known.

NGC 1705 from HST

![Graph showing helium mass fraction vs 10^6 times O/H ratio with data points and fit line.](image)
Observational Status, last six years

Not simple environment, systematics dominate!
Crucial to infer (consistently, if possible) the properties of the medium:
photoionization, excitations, recombinations… must be modelled and fit!

✓ Izotov et al. ‘04, $Y_p = 0.2421 \pm 0.0021$
✓ Olive et al. ‘04, $Y_p = 0.249 \pm 0.009$
sample 7/82 of IT’04, conservative uncertainties
✓ Fukugita et al. ‘06, $Y_p = 0.250 \pm 0.004$
Sample of 33/82 HII regions from IT’04
✓ Peimbert et al. ‘07, $Y_p = 0.2477 \pm 0.0029$
New atomic physics, new observations & photoion. models of HII regions
✓ Izotov et al. ‘07, $Y_p = 0.2516 \pm 0.0011$
newer HeI emissivities
✓ Olive et al. ‘10, $Y_p = 0.2561 \pm 0.0108$
Self-consistent MC… on 7 objects!

I’ll show results following from
$Y_p = 0.250 \pm 0.003_{\text{syst}}$
for illustration
(this reflects a median value from a sufficient sample with error estimate conservative but “still usable”)
Discussion

From the WMAP & $^2$H+BBN range of $\Omega_b h^2$, one infers the BBN prediction

$$Y_p = 4n_{\text{He}}/n_B \in [0.246;0.249]$$

✓ A BBN origin for the bulk of $^4$He observed is universally agreed upon
✓ Determinations consistent with Theory, but systematics prevent stringent tests

Are there other possibilities to infer the helium abundance?

→ From Globular Clusters (obs.+models): Salaris et al ‘04, $Y_p \leq Y_{GC} =0.250 \pm 0.006 \pm 0.019$
→ From solar models and observations, Asplund et al. ‘09, $Y_p < Y_{\text{proto-solar}} \sim 0.274$
→ From current CMB data $Y_p = 0.250^{+0.010}_{-0.007} (15) \pm 0.019 (17)$ @68%(95%) C.L.
Future data (Planck) can get down to ~1%, especially in combination with weak priors from stellar data! [Ichikawa et al.‘08; Komatsu et al. ‘09]

Another stringent cosmological test might come in <3 years from now!
What about theoretical errors on $Y_p$?

Once WMAP (or $^2\text{H}$) value for $\omega_b$ fixed, theoretical predictions for $Y_p$ are quite robust: controlled by weak processes, well understood theoretically!

Weak-reactions improvements in the last \(\sim15\) years:

- QED radiative corrections
- Finite nucleon mass corrections
- Plasma effects
- $\nu$ spectral distortion due to residual coupling and oscillations (last few years!)

\[
Y_p = 0.2480 \ R_1^{0.005} \ R_3^{0.006} \ R_4^{0.005} \left( \frac{\omega_b}{0.02273} \right)^{0.39} \left( \frac{\tau_n}{885.7 \text{s}} \right)^{0.72}
\]

- The above effects do contribute at the \(\sim0.1\%\) level
- Present theoretical accuracy is limited by error on $\tau_n$ (stat. \(\sim0.1\%\); syst.\(\sim0.5\%\)?)
- Nuclear reactions errors in the 1-10\% range almost irrelevant

Only room for potential worry: new physics
The embarrassing life(time) of the neutron

\[ \tau_n^{PDG} = 885.7 \pm 0.8 \text{ s} \]

Average of 7 mutually consistent measurements over last 20 years, using different methods (Penning Trap, Gravitational trap, in beam, ultra-cold neutron double bottle)

The latter, Arzumanov et al. 2000, dominates the fit.

Serebrov et al. PLB 605, 72 (2005) finds

\[ \tau_n^{S'05} = 878.5 \pm 0.7 \text{ s} \pm 0.3 \text{ s} \]

6.5 \( \sigma \) deviation from world average!

Yet, gravitational trap, cold n, estrapolation to \( 1/\tau_{\text{storage}} \to 0 \); best storage time…

If this result is used in BBN, \( Y_p^{th} = 0.248 \to 0.246 \), Matthews et al. PRD 71,021302 (2005)

Experimental “solution” required! Yet, theory can tell something from EW fits…
Test of EW model can be performed with a variety of data, and the impact of the “new” $\tau_n$ determination assessed:

- Fit of data with 1 parameter ($C_A/C_V$): $\chi^2=74.08, \nu=25$ (w. S’05), 25.86, $\nu=24$ (w/o S’05)
- Fit of data with 3 free parameters: $\chi^2=82.45, \nu=47$ (w. S’05), 40.91, $\nu=46$ (w/o S’05)

EW data suggest the problem is in S’05, but experiments are required!

**Severijns et al.**

“Tests of the standard electroweak model in beta decay”,

Helium and constraints to new physics

BBN has been used to constrain new physics, e.g. scenarios lately popular as

- Extra dimensions
- Neutrino Physics (more on Friday)
- … (you name it)

Here I will limit myself to a detour on BBN & Variation of fundamental Constants

- Qualitatively expected in several theories BSM (e.g. extra-dimensions, string-inspired…)
- No unique framework for their time-dependence (model dependent), although usually the earlier time, the better (BBN is the earliest probe!)
- Only dimensionless quantities (e.g. $\alpha, m_p/m_e$…) do not suffer of system of units ambiguities
- Usually, many constants are expected to vary at the same time. In specific models, different constants vary in a correlated way (e.g. Higgs vev in $m_e$ & $G_F$)
- BBN has a complicated dependence on many of the constants. Why?
The power and limitation of BBN

The main reason is that BBN is sensitive to GR (via expansion history), to weak physics (especially neutrino sector and n-p equilibrium) to e.m. and strong interactions (nuclear processes, coulomb barrier,…)

Many studies have assumed variation of one parameter only. It is perhaps more instructive to study parametrically the Response matrix of BBN observables (nuclides $X_i$) to relative variations of fundamental parameters $\phi_i$

$$R_{ik} = \frac{\varphi_k}{X_i} \frac{\partial X_i}{\partial \varphi_k}$$

Useful to decompose

$$R = C F$$

$$C_{ij} = \frac{r_j}{X_i} \frac{\partial X_i}{\partial r_j}$$

$$F_{jk} = \frac{\varphi_k}{r_j} \frac{\partial r_j}{\partial \varphi_k}$$

$C$ robustly determined: $r_j$ are the parameters which enter directly BBN (e.g. binding energies)

$F$ requires some theoretical modelling (e.g. how does $B_D$ depends on quark masses, $\Lambda_{QCD}$)

\[ \Delta_q = m_d - m_u \quad \quad \quad \quad M_q = (m_u + m_d)/2 \]

<table>
<thead>
<tr>
<th></th>
<th>$^2\text{H}$</th>
<th>$^3\text{He}$</th>
<th>$^4\text{He}$</th>
<th>$^6\text{Li}$</th>
<th>$^7\text{Li}$</th>
</tr>
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<tbody>
<tr>
<td>$G_N$</td>
<td>0.94</td>
<td>0.33</td>
<td>0.36</td>
<td>1.4</td>
<td>-0.72</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>3.6</td>
<td>0.95</td>
<td>1.9</td>
<td>6.6</td>
<td>-11</td>
</tr>
<tr>
<td>$\nu$</td>
<td>1.6</td>
<td>0.60</td>
<td>2.9</td>
<td>5.5</td>
<td>1.7</td>
</tr>
<tr>
<td>$m_e$</td>
<td>0.46</td>
<td>0.21</td>
<td>0.40</td>
<td>0.97</td>
<td>-0.17</td>
</tr>
<tr>
<td>$\Delta_q$</td>
<td>-2.9</td>
<td>-1.1</td>
<td>-5.1</td>
<td>-9.7</td>
<td>-2.9</td>
</tr>
<tr>
<td>$M_q$</td>
<td>17</td>
<td>5.0</td>
<td>-2.7</td>
<td>-6</td>
<td>-61</td>
</tr>
<tr>
<td>$\Omega_B h^2$</td>
<td>-1.6</td>
<td>-0.57</td>
<td>0.04</td>
<td>-1.5</td>
<td>2.1</td>
</tr>
</tbody>
</table>

weak n-p reactions, mostly

*Binding energy (note lithium-7!)*
Typically constrained at the 10% level. Most correlations understood as degeneracies with weak rates (n-p freezeout)
Lithium
Main problem
We cannot observe *primordial* abundances:
Stars easily burn Li, but other processes pre-galactic or galactic
(CR Spallation, $\nu$ process in Snae, novae…) could have increased it

Observe systems with little chemical processing
Warm ($5700 \,\text{K} < T < 6500 \,\text{K}$) metal poor dwarf
stars in the halo

Correct for chemical evolution?
“metallicity plateau” found, means
it’s primordial? *Spite & Spite ’82*

A factor~4 problem?

Caveat...

[Spite & Spite ‘10]
What about theoretical errors on Lithium?

Given the WMAP (or deuterium) result, the road to $^7$Li is clarified:

After a first $^7$Li bump @ T~70 keV via $^4$He($^3$H,$\gamma$) $^7$Li, a small plateau reached because of competition of $^7$Li(p,$\alpha$) $^4$He. Finally Indirect $^7$Li production via $^4$He($^3$He,$\gamma$) $^7$Be & late EC decays to $^7$Li (the latter dominates for preferred $\omega_b$)

$$10^{10}(\frac{^7\text{Li}}{\text{H}})_{\text{th}} = 4.8 \pm 0.4 \pm 0.4$$

Due to $\delta \omega_b = 0.001$

Due to nuclear uncertainties

Wrong cross sections for the important rates disfavoured/excluded by both solar $\nu$ data [Cyburt et al., PRD 69 (2004)] and measurements, [C. Angulo @ NIC VIII]

<table>
<thead>
<tr>
<th>rate</th>
<th>$\Delta \sigma_{\text{Li}}^2 / \sigma_{\text{Li}}^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7$Be(n,$^4$He)$^4$He</td>
<td>40.9</td>
</tr>
<tr>
<td>$^4$He($^3$He,$\gamma$)$^7$Be</td>
<td>25.1</td>
</tr>
<tr>
<td>$^7$Be(d,p)$^4$He$^4$He</td>
<td>16.2</td>
</tr>
<tr>
<td>$^3$He(d,p)$^4$He</td>
<td>8.6</td>
</tr>
<tr>
<td>$^2$H(p,$\gamma$)$^3$He</td>
<td>4</td>
</tr>
<tr>
<td>others</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Propaganda: we did not limit to reanalyze the ~O(10) reactions believed to be dominant. We revised and update the whole network (O(~100)), improved the analysis or looked for new important reactions (including partition functions for excited states, some 3-body), and checked again the relative weights of the different channels. Almost two years of work...
Nowadays, anomalous dispersion around the average & trend with metallicity established without doubt!!

*Sbordone et al. arXiv:1003.4510*

**Observational evidence for a broken Li Spite plateau and mass-dependent Li depletion**

*Melendez et al., arXiv:1005.2944*

Our results imply that the Li abundances observed in Li plateau stars have been depleted from their original values and therefore do not represent the primordial Li abundance. It appears that the observed Li abundances in metal-poor stars can be reasonably well reconciled with the predictions from standard Big Bang nucleosynthesis by means of stellar evolution models that include Li depletion through diffusion and turbulent mixing.
So, why the (old, quasi-)‘plateau’?

Astration: incomplete “chemical” mixing of the gas forming the Milky Way (troubles with $\omega$ Cen, from captured dwarf?)

Early or pre-galactic synthesis (pop-III, flares, etc.): Why not other element ‘anomalies’? Missing processes (like $^3$He rich flares)?

Depletion (via diffusion/turbulence): it appears likely (see CS 22876 binary) but in most cases one has to fine tune the parameters to get a “quasi-plateau”

- Only safe conclusion is that most likely what we see is not primordial, although it is qualitatively consistent with a depletion of the primordial yield (which correctly predicts the order of magnitude, at least!)

- However there is no compelling explanation of what observed. A non-standard primordial lithium abundance is certainly possible (not required, neither “constrainable” at the present level of uncertainty)
Issues with Lithium-6?

Even more loosely bound, not produced in BBN ($^{6}\text{Li}/^{7}\text{Li}<10^{-4}$). Still, claimed $O(10)$ 2-3 $\sigma$ observations of $^{6}\text{Li}/^{7}\text{Li}$~0.05, consistent perhaps with a plateau.

- Might be just an instrumental effect (errors slightly underestimated).
- If true, indicates further synthesis channel of Lithium isotopes (pre-galactic?)

Then, since mixing/depletion is at work & depends on several free parameters, inferring primordial abundances is a nightmare!
Lithium as a window to new physics?

✓ The “least abundant” primordial element: it would be natural that subleading departures from standard BBN show out there, if anywhere.

✓ The absence of $^6\text{Li}$ in SBBN could offer an “appearence channel”.

✓ It’s easy to dissociate, but also easy to produce via non-thermal nucleosynthesis alterations

✓ Decaying (or annihilating) WIMPs may produce electromagnetic and/or hadronic cascades inducing such a process

✓ Recent interest for “cathalytic” processes induced e.g. by charged NLSP.

Caveat (personal opinion):

➢ Although subjects worth investigating, a proper quantitative understanding is anyway prevented by the uncertainties in the post-primordial history of these isotopes
Electromagnetic cascades

- Develops rapidly: results depend mostly on injection time $\tau_X$ (large enough for $\gamma$’s with $E_\gamma > \gamma_H$). Binding to avoid damping via $\gamma\gamma_{\text{CMB}} \rightarrow e^\pm$) & overall injected energy, e.g. via $\zeta = m_X n_X / n_\gamma$.

- At small $\tau_X$ Li not formed yet, constraints from D. At large $\tau_X$ large $\zeta$ yields also too much depletion of the fragile $^7\text{Li}$; but even small $\zeta$ sufficient to overproduce $^6\text{Li}$ (thanks to late injection of energetic $^3\text{He}$ & $^3\text{H}$ from tiny fraction of $^4\text{He}$ dissociation).

- If DM is produced from X in the process, $\zeta > 2 \times 10^{-9}$ GeV $\Rightarrow \tau_X < 3 \times 10^5$ s

Cyburt et al.
Hadronic Cascades

- Much more complicated process, since “factorization”
  Standard BBN $\rightarrow$ non-thermal Nucleos. is not possible at early times. Many secondary processes are induced!

- Depends on many particle physics parameters, e.g. b.r.’s. More model dependent!

- At late $\tau_X$ e.m. effects dominate.

- At early times, the n/p ratio can be directly altered by the presence of antinucleons and mesons.

- At intermediate times, novelty is introduced via the possibility of $^4$He dissociation by (anti)nucleons.

**Studied via MC, e.g. PITHYA based**
1 TeV particle,
Hadronic B.r.=3.3%
(relic abundance it would have today…)

note that if this is responsible for DM,
$\tau_\chi > 2 \times 10^2$ is excluded.

In the vanishing $B_h$ limit,
one recovers e.m. constraints
for the convolution of the bounds
For example, decay or annihilation of WIMPs consistent with other abundances can be found (modulo O(few) factors…)

e.g. K. Jedamzik, PRD 70 (2004)
Negatively charged, long lived particles $X^-$ with mass $m_X >> m_p$ form bound-states with nuclei, altering the network of reactions leading to the synthesis of light elements.


Compared with a generic nucleus $A$ of charge $Z$ and mass $m_A$, its corresponding bound state $AX$ has a mass higher by $m_X$, a charge $Z-1$, and it is characterized by a $X$-$A$ binding energy $Z^2 \alpha m_A/2$ in the limit $m_A << m_X$.

The most important consequence is the much easier production of $^6$Li

**SBBN:** $^4$He$^+$ $^2$H $\rightarrow \gamma^+ ~^6$Li

E2 (quadrupole) transition, due to similar $A/Z$ of $^2$H & $^4$He $\Rightarrow ^6$Li/ $^7$Li $<< 1$

**CBBN:** $^4$He$X^+$ $^2$H $\rightarrow X^+ ^6$Li

Unsuppressed, enhancement by several orders of magnitude!

Constraints do change especially for intermediate lifetimes, $3 \times 10^2 \text{ s} < \tau_X < 5 \times 10^5 \text{ s}$; detailed implications still being developed: a whole new “nuclear physics” industry, far from trivial
Who ordered these particles decaying \text{ @ BBN}? 

- One possibility is to play with phase-space and/or gravitationally suppressed interactions

Alternatively,

- The long lifetime of particles in the “dark sector” might be due to very tiny breaking of some symmetry, just like the proton is stable due to “accidental” baryon number conservation.

What if same GUT operators mediating “rare” p-decays are involved in the decays of dark sector particles? Naïve estimate for the lifetime:

\[
\tau_{DM} \approx 8\pi \frac{M_{GUT}^2}{m_{DM}^3} \approx 7 \times 10^7 \text{s} \left( \frac{\text{TeV}}{m_{DM}} \right)^3 \left( \frac{M_{GUT}}{2 \times 10^{16} \text{GeV}} \right)^2
\]

From Dim 5 Operator
Related to metastable particles decaying at BBN epoch & solution to “Lithium problems”?

\[
\tau_{DM} \approx 8\pi \frac{M_{GUT}^4}{m_{DM}^5} \approx 3 \times 10^{27} \text{s} \left( \frac{\text{TeV}}{m_{DM}} \right)^5 \left( \frac{M_{GUT}}{2 \times 10^{16} \text{GeV}} \right)^4
\]

From Dim 6 Operator
Observable consequences in cosmic rays in the halo?

For further considerations along these lines: \textit{Arvanitaki, Dimopoulos, Dubovsky, et al. arXiv:0812.2075}

Caveat: be careful in drawing strong conclusions when strong dependences on the parameters are present!
Historically, BBN provided one robust indication in favour of the Hot big bang scenario, and later insights on the baryogenesis problem and the non-baryonic nature of Dark Matter.

Deuterium observations permit nowadays a crucial quantitative test of self-consistency for the standard cosmological scenario.

$^4\text{He}$ predictions and observations are ok at the ~3-5% level, but more refined comparisons are plagued by systematics. In the future years, situations should improve thanks to synergy BBN+Planck (e.g. breaking $Y_p$ degeneracies).

$^7\text{Li}$ observations only show an order of magnitude agreement with predictions. Recently, evidence that what observed is not primordial (but how close to it is unclear!)

$^6\text{Li}$ claimed observations, if confirmed, imply some further nucleosynthetic process (not produced in SBBN for nuclear physics reasons!)
Despite uncertainties, interesting considerations can and have been drawn for particle physics models using BBN, e.g. in $\nu$ physics or WIMP models.

My opinion is that it is ok to derive such constraints when collider constraints are not available, provided that caveats are made clear. However, claiming hints for new physics or even “discoveries” is at present out of question.

**Take home two messages**

A BBN lesson for new frontiers in Cosmology (think of 21 cm):

*Precision cosmology* with astrophysical environments is a messy business!

Should new physics be discovered at LHC, consequences for astrophysics/cosmology other than “Dark Matter” can be envisioned. BBN is one!