Solving the cosmological « lithium problem » with a sterile neutrino

A loophole to the standard theory of electromagnetic cascade

Vivian Poulin
LAPTh and RWTH Aachen University

Talk based on

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In collaboration with

Pasquale D. Serpico (LAPTh)

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Big Bang Nucleosynthesis in a nutshell

- Happened 10 - 200 s after the BB when the Universe had $T = [30, 70]$ keV
- Main nucleus form $^4\text{He}$: $Y_p = 4n_{^4\text{He}}/n_B \approx 0.25$, others $\mathcal{O}(10^{-5} - 10^{-10})$

A typical reaction network, © Achim Weiss

Only one free parameter: 

The photon-to-baryon ratio

$$\eta \equiv \frac{n_b}{n_\gamma} \sim 6 \times 10^{-10}$$

=> All abundances can be computed using numerical algorithm such as PArthENoPE

A. BBN and sterile neutrino

I. BBN and sterile neutrino
Main results

- Sterile neutrino and the lithium problem

I. BBN and sterile neutrino

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Main results

For 3 nuclei:

Strong observational constraints

\[ Y_P > 0.2368 \]
\[ 2.56 \times 10^{-5} < ^2H/H < 3.48 \times 10^{-5} \]
\[ ^3He/H < 1.5 \times 10^{-5} \]

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The Lithium problem:

Overprediction of the $^7\text{Li}$ abundance

$$Y_{\text{Li}}^{\text{theo}} \approx 3 \times Y_{\text{Li}}^{\text{obs}}$$

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The Lithium problem:

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$Y_{p} > 0.2368$

$2.56 \times 10^{-5} < ^2\text{H}/H < 3.48 \times 10^{-5}$

$^3\text{He}/H < 1.5 \times 10^{-5}$

For 3 nuclei:

Strong observational constraints

$Y_{\text{Li}}^\text{theo} \simeq 3 \times Y_{\text{Li}}^\text{obs}$

Lithium is indirectly produced!

$^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$

followed by

$^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e, \tau_{\text{Be}} \sim 53\text{d}$

One has to destroy the Beryllium!
Sterile Neutrino and the BBN

- Modification of $N_{\text{eff}}$ affects the expansion rate and the BBN outcome;
- If coupling $\nu_s \leftrightarrow \nu_e$, modification of the weak rates affects the n-p equilibrium which (mostly) sets the $^4\text{He}$ abundance;
- Eventually, creation of a lepton asymmetry influencing BBN;
- Decay products directly interacting with nuclei can modify BBN yields.
An « old » problem:

Jedamzik, Phys. Rev. D74 103509, 2006;
arXiv:0809.0631; arXiv:1403.5995...

- Big constraints from other nuclei
- Big constraints from entropy production and spectral distortions
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- Big constraints from other nuclei
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\[ 7\text{Be} + \gamma \rightarrow 4\text{He} + 3\text{He} \]

\[ E_{\text{threshold}}(\text{Be}) = 1.58 \text{ MeV} \]
\[ E_{\text{threshold}}(\text{De}) = 2.2 \text{ MeV} \]

One « trick »: if \(1.6 < E_0 < 2.2 \text{ MeV}\) it is possible to avoid all BBN constraints!
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However, this was known to fail, why would it work now?
Electromagnetic Cascade in a nutshell

We want to describe electromagnetic energy injection in a plasma of photons (very few e+e-, nuclei):
what is the resulting metastable distribution of photons?

Basic processes are (at high energies)

Particle multiplication and energy redistribution
Electromagnetic Cascade in a nutshell

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Basic processes are (at high energies)

\[ \gamma \gamma_{th} \rightarrow e^+ e^- \]
\[ e \gamma_{th} \rightarrow e \gamma \]

Particle multiplication and energy redistribution

The first process has a threshold, below it

\[ \gamma \gamma_{th} \rightarrow \gamma \gamma \]

and eventually (very low rates)

\[ \gamma N \rightarrow e N \]
\[ \gamma e_{th} \rightarrow \gamma e \]
This has been shown to lead to a **universal spectrum**

- Shape independent of the energy / temperature of the bath:
  - Only dictates the **overall normalisation**;
- Threshold due to pair production.

---

Typically, after the end of standard BBN (5 keV):

\[ E_{\text{cutoff}}(1 \text{ keV}) \sim 12 \text{ MeV} \quad E_{\text{cutoff}}(10 \text{ eV}) \sim 1.2 \text{ GeV} \]

All cases simulated inject energy such that \( E_{\gamma} \gg E_{\text{cutoff}} \)

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**What if** \( E_{\text{Injected}} < E_{\text{cutoff}} \), i.e. pair production is not operational?
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Standard theory of electromagnetic cascade cannot be applied!

After « standard » BBN:

\[ E_{\text{threshold}}(\text{Be}) = 1.58 \text{ MeV} < E_{\text{cutoff}} \]

If \( E_{\text{threshold}} < E_0 < E_{\text{cutoff}} \)
results in the literature are wrong!
Consider a photon injection and start by neglecting diffused electrons. Remaining processes are:

\[ \gamma \gamma_{th} \rightarrow \gamma \gamma, \ \gamma e_{th}^{\pm} \rightarrow \gamma e^{\pm}, \ \gamma N \rightarrow Ne^{\pm} \]
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Relevant Boltzmann equation writes:

\[
\frac{\partial f_\gamma(E_\gamma)}{\partial t} = -\Gamma_\gamma(E_\gamma, T(t)) f_\gamma(E_\gamma, T(t)) + S(E_\gamma, t)
\]

whose stationary solution is

\[
f_\gamma^S(E_\gamma) = \frac{S(E_\gamma, t)}{\Gamma_\gamma(E_\gamma, t)}
\]

where for a decaying particle

\[
S(E_\gamma, t) = \frac{n_\gamma^0 \zeta_X (1 + z(t))^3 e^{-t/\tau_X}}{E_0 \tau_X} p_\gamma(E_\gamma, t)
\]

Hubble rate much smaller than all particle physics interaction rate, thus neglected.
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Hubble rate much smaller than all particle physics interaction rate, thus neglected.
Starting from two body decay

$$p_\gamma(E_\gamma) = \delta(E_\gamma - E_0) \text{ with } E_0 = \frac{m_X}{2}$$

exact at the end-point, then iterate

$$S(E_\gamma, t) \to S(E_\gamma, t) + \int_{E_\gamma}^\infty dx K_\gamma(E_\gamma, x, t) f_\gamma(x, t)$$
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Finally compute nuclei abundances:

\[ \frac{dY_A}{dt} = \sum_T Y_T \int_{0}^{\infty} dE_\gamma f_\gamma(E_\gamma, t) \sigma_{\gamma + T \rightarrow A}(E_\gamma) - Y_A \sum_P \int_{0}^{\infty} dE_\gamma f_\gamma(E_\gamma, t) \sigma_{\gamma + A \rightarrow P}(E_\gamma) \]

\[ Y_A \equiv \frac{n_A}{n_b} \]
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Production from photodissociation of heavier nuclei

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Production from photodissociation of heavier nuclei

$$Y_A \sum_P \int_0^\infty dE_\gamma f_\gamma(E_\gamma, t) \sigma_{\gamma + A \to P}(E_\gamma)$$

Destruction from its photodissociation

$$Y_A \equiv \frac{n_A}{n_b}$$
Typical results for a given energy and a given temperature of the thermal bath.

Here injected monochromatic photon $E_0 = 70\,\text{MeV}$ at $T = 100\,\text{eV}$.
Proof of principle solution: monochromatic photon injection

In our case, it is possible to solve the lithium problem, while fulfilling other constraints.

Note that this was not obvious at all!!
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Solution with « wrong » spectrum: all regions are killed
**Proof of principle solution:**
monochromatic photon injection

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Note that this was not obvious at all!!
Try with a « real » model that was known to fail when using universal spectrum: the Sterile (majorana) Neutrino

H. Ishida, M. Kusakabe and H. Okada,
PRD 90, 8, 083519 (2014)
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Convert the variables

\[ \tau \rightarrow \Theta \quad \text{mixing angle} \]

\[ \zeta \rightarrow \frac{n_s^0}{n_\nu^0} \quad \text{normalise to active neutrino density} \]

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To avoid constraints from cosmology and labs mixing required to be mostly \( \nu_\mu \) or \( \nu_\tau \)

Typical branching ratio

\[ 1 : 0.1 : 0.01 \] in \( 3
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Bounds from entropy is stronger and there’s a new constraint: variation of \( N_{\text{eff}} \) (planck sensitivity)

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It works!
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More details:


It works!
In a nutshell:
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- We have addressed an unexplored corner of the parameter space, below the pair production threshold.
- We have shown that the *universality hypothesis breaks down.*
  The resulting spectrum can be *very different from the universal one.*
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- We have addressed an unexplored corner of the parameter space, below the pair production threshold.

- We have shown that the universality hypothesis breaks down. The resulting spectrum can be very different from the universal one.

- We have shown how it might ease particle physics (electromagnetic) solution to the lithium problem, as illustrated with the sterile neutrino model.

- The same phenomenon also has important consequences for BBN bounds: they are more stringent and non-universal.
Thanks for your attention!