PROCEEDINGS OF SCIENCE

AlterBBN

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We present the code AlterBBN, a public code for the computation of the abundance of the elements from Big-Bang nucleosynthesis in the standard cosmological model as well as in non-standard scenarios.

Tools for High Energy Physics and Cosmology - TOOLS2020
2-6 November, 2020
Institut de Physique des 2 Infinis (IP2I), Lyon, France

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PoS(TOOLS2020)032

1. Introduction

Big-Bang nucleosynthesis (BBN) is the primordial era of the History of the Universe in which nucleons gathered into nuclei. This period occurred during the dark times before the emission of the Cosmic Microwave Background, and no direct observation of the Universe during BBN is possible. However, the current abundance of the elements can be observed, and in particular the observed helium and deuterium abundances can be directly compared to the abundances predicted by BBN models to set constraints on the properties of the Universe at the time of BBN.

Several public codes exist to make predictions for the abundances from BBN, such as `PRIMAT` [1], `PArthENoPE` [2, 3] and `NUC123` [4].

We present here `AlterBBN` [5, 6], which is a public code for computing the abundance of the elements in the standard cosmological models as well as in alternative scenarios.

2. The AlterBBN package

`AlterBBN` is a public code written in C (C99 standard), which does not rely on any external package. It can be downloaded from the website:

https://alterbbn.hepforge.org/

To use it, after downloading the compressed archive `alterbbn_v2.X.tgz`, it has to be uncompressed with

```
tar xzvf alterbbn_v2.X.tgz
```

and compiled with

```
cd alterbbn_v2.X
make
make program_name
```

where `program_name` is the name of one of the program files contained in the main directory:

- `stand_cosmo.c`
  Computation of the abundances in the standard cosmological model
- `alter_eta.c`
  Computation of the abundances for a given value of η, the baryon-to-photon ratio
- `alter_neutrinos.c`
  Computation of the abundances in presence of extra neutrinos and degeneracy
- `alter_etannutau.c`
  Computation of the abundances for given values of η, extra neutrino number and neutron lifetime
- `alter_standmod.c`
  Computation of the abundances in a non-standard cosmological scenario with extra dark density and dark entropy

PoS(TOOLS2020)032

- `alter_reheating.c`
  Computation of the abundances in a non-standard cosmological scenario with extra dark density and entropy injection
- `alter_phi.c`
  Computation of the abundances in a non-standard cosmological scenario with a decaying scalar field
- `alter_wimps.c`
  Computation of the abundances in presence of decaying dark matter particles

The exact parameters for each of the main programs are described in the manual [6], and they can be run with

```
./program_name.x parameters
```

In absence of `parameters`, running `./program_name.x` displays a short description of the possible parameters.

3. BBN in non-standard scenarios

The main objective of `AlterBBN` is to provide ways to constrain non-standard cosmological scenarios via the abundance of the elements. Since Big-Bang nucleosynthesis occurred during the dark era, much before the emission of the Cosmic Microwave Background, no direct observation of this epoch is possible, and there is no guarantee that the properties of the primordial plasma at the time of BBN were similar to the ones at recombination, leaving room for non-standard scenarios.

Example programs for non-standard scenarios are provided with `alter_standmod.c` and `alter_phi.c`, which involve scenarios with additional dark energy and/or entropy, and with decaying scalar field, respectively.

In presence of an additional dark energy, the expansion of the Universe is accelerated, making the duration of nuclear reactions shorter. `AlterBBN` can compute the abundance of the elements for a scenario with an additional dark density (or scalar field) parametrized by

$$\rho_d = \kappa_d\, \rho_\gamma(1\,\mathrm{MeV}) \left(\frac{a}{a_0}\right)^{-n}\,, \tag{1}$$

where κ_d is the dark density proportion to the photon density at $T = 1\,\mathrm{MeV}$, and n is the decrease exponent of the dark density. Figure 1 shows the abundance of helium and deuterium as functions of the dark density and its decrease exponent. Observations of the abundances exclude scenarios where the dark density is too large at the time of BBN and has a too small decay exponent.

For the case of a scalar field decaying into radiation, there are two effects on Big-Bang nucleosynthesis: first, the scalar field accelerates the expansion; second, the injected radiation increases the temperature of the plasma, generating a reheating which modifies the link between the expansion factor a and the temperature T.

`AlterBBN` can compute the abundances for scenarios with a scalar field decaying into radiation, with an evolution driven by

$$\frac{d\rho_\phi}{dt} = -nH\rho_\phi - \Gamma_\phi \rho_\phi\,, \tag{2}$$

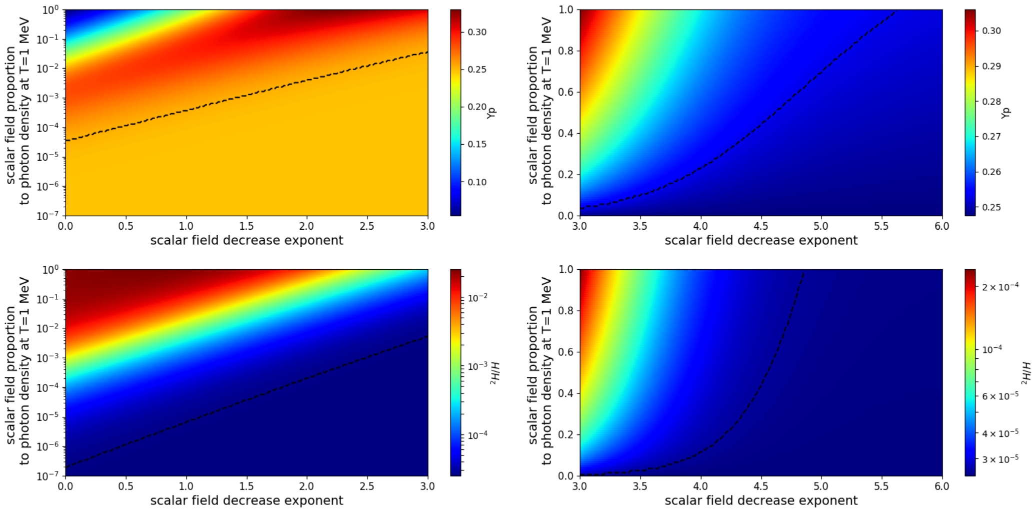

Figure 1: Helium (top) and Deuterium (bottom) abundances in the dark density proportion to the photon density at $T = 1\,\text{MeV}$ vs. the decrease exponent parameter plane, for decrease exponent below 3 (left) and above 3 (right). The dashed lines denote the observational limit, which exclude regions with too large abundances (from [7]).

where n is the original decrease exponent of the scalar field before its decay, and Γ_ϕ is the decay width of the scalar field, which can be related to the reheating temperature as:

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_{\rm eff}(T_{\rm RH})}{45}}\,\frac{T_{\rm RH}^2}{M_P}\,, \tag{3}$$

where $g_{\rm eff}$ is the number of effective energy degrees of freedom of radiation. The scalar field has 3 parameters: the decrease exponent n, the reheating temperature $T_{\rm RH}$ and the initial scalar field density. In Figure 2, we show the abundances of helium and deuterium in presence of a decaying scalar field with initial decrease exponents of 6 and 0, as functions of the initial scalar field density and of the reheating temperature, together with the observational limits, which exclude too low abundances.

These scenarios can also affect the abundance of dark matter relic particles [8–10], and it is therefore important to be able to set limits using the BBN constraints. For this purpose, `AlterBBN` has been interfaced into `SuperIso Relic` [11–13], which aims in particular at computing the relic density of supersymmetric particles in the standard cosmological model and in less standard scenarios. `AlterBBN` also contains models of weakly-interacting massive particles (WIMPs) decaying at the time of BBN, as exemplified by the `alter_wimps.c` program, which can affect the abundance of the elements.

A special feature of `AlterBBN` is the possibility to use larger nuclear networks and heavier elements via an interface with the JINA REACLIB database [14], which is usually used for thermonuclear modelling of supernovae. In `AlterBBN`, the user can choose the heaviest elements to be considered for the calculation of the primordial abundances. This is particularly useful in the context of inhomogeneous BBN [15], where local baryon densities at BBN time can be much larger than in standard BBN.

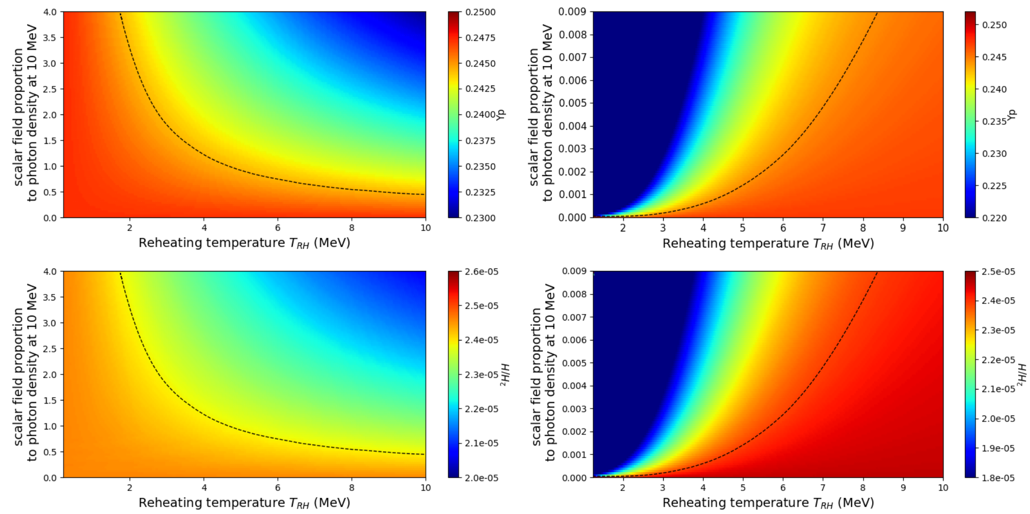

Figure 2: Helium (top) and Deuterium (bottom) abundances in the scalar field density proportion to the photon density at $T = 10\,\text{MeV}$ vs. reheating temperature parameter plane, for decrease exponent of 6 (left) and of 0 (right). The dashed lines denote the observational limits, which exclude regions with too low abundances (from [7]).

4. Conclusion and perspectives

`AlterBBN` is a public tool for computing the abundance of the elements from Big-Bang nucleosynthesis. It is flexible, easy to use and to modify, and features different cosmological scenarios which can be constrained using observations. For the near future, updates of the nuclear network are planned, together with the implementation of more cosmological scenarios, with in particular the possibility to directly input the scale factor and temperature evolution as a function of time, and the implementation of a scenario in which primordial black holes inject radiation at BBN time, via an interface with the `BlackHawk` code [16].

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