Big Bang Nucleosynthesis: Hands on Session

Anne-Katherine Burns, PhD (she/her)
annekatherineburns@icc.ub.edu

Nuclei in the Cosmos School
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The Plan

1. ***A quick primer on the physics of BBN***
2. Introducing *PRyMordial*
3. Let’s run the code!

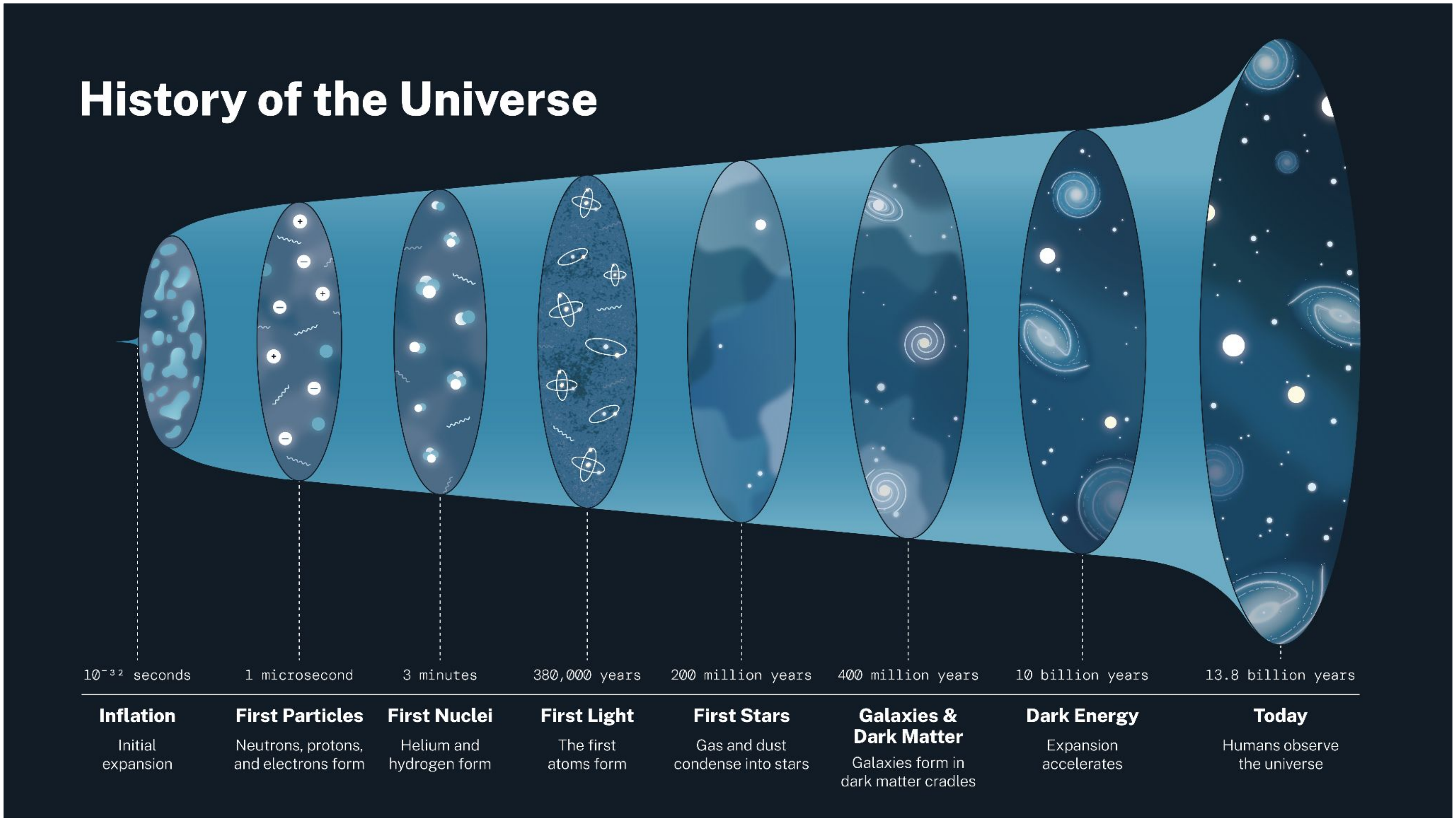

History of the Universe
10⁻³² seconds
1 microsecond
3 minutes
380,000 years
200 million years
400 million years
10 billion years
13.8 billion years
Inflation
Initial expansion
First Particles
Neutrons, protons, and electrons form
First Nuclei
Helium and hydrogen form
First Light
The first atoms form
First Stars
Gas and dust condense into stars
Galaxies & Dark Matter
Galaxies form in dark matter cradles
Dark Energy
Expansion accelerates
Today
Humans observe the universe

Image: NASA

Big Bang Nucleosynthesis

What is Big Bang Nucleosynthesis (BBN)?

The production of light elements in the early universe

What is the purpose of studying it?

To determine (a) the amount of radiation present at the time and (b) the primordial abundance of light elements.

Why are we interested?

By determining (a) and (b) we can put constraints on New Physics

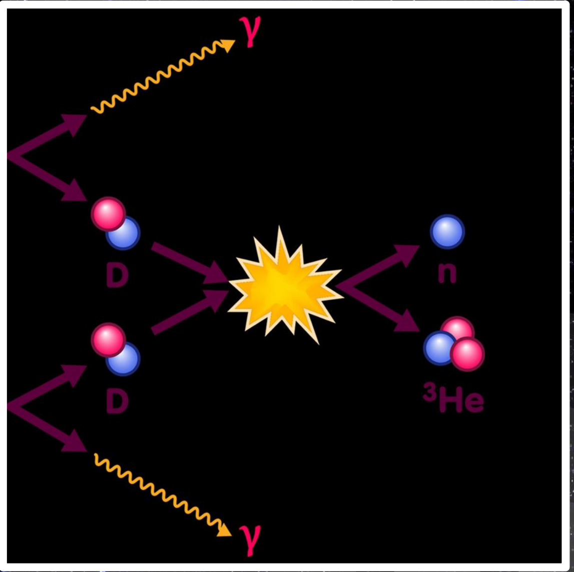
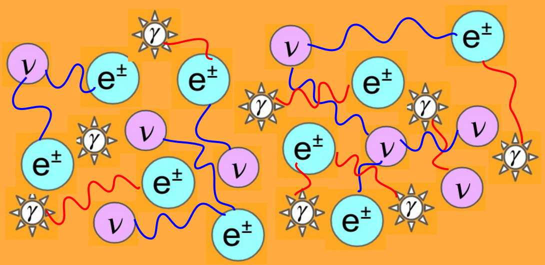


Image: Einstein Online

Electrons, positrons, photons, and neutrinos exist in a plasma. Photons and neutrinos are coupled.



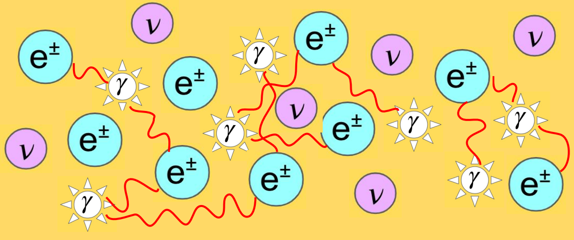
Neutron-proton conversion happens freely and regularly.

$$n \leftrightarrow p + e^- + \bar{\nu}$$

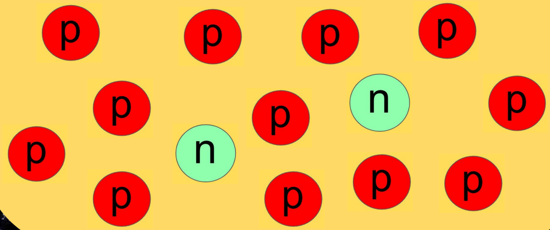
$$n + \nu \leftrightarrow p + e^-$$

$$n + e^+ \leftrightarrow p + \bar{\nu}$$

Neutrinos decouple non-instantaneously from the plasma.

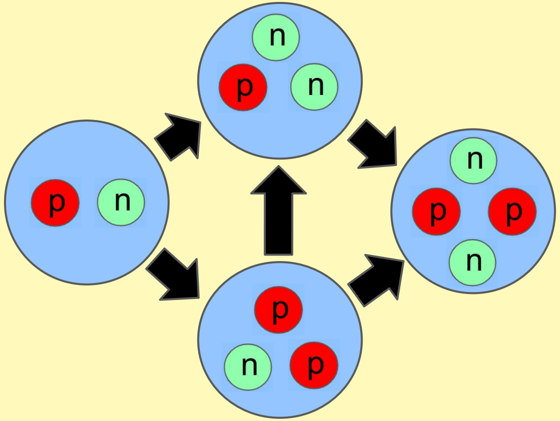


Weak rates freeze out and the proton to neutron ratio is set.



Nucleosynthesis occurs.

The primordial abundances of light elements like ^{4}He, D, ^{3}He, ^{7}Li are determined.



Temperature > O(1 MeV) | Temperature = O(1 MeV) | Temperature < O(1 MeV)

Neutron - Proton Conversion & Freeze Out

QCD Phase Transition

Neutron to proton conversion happens freely and regularly:

$n \leftrightarrow p + e^- + \bar{\nu}$

$n + \nu \leftrightarrow p + e^-$

$n + e^+ \leftrightarrow p + \bar{\nu}$

Neutron to proton conversion freezes out, n:p $\simeq$ 1/6

Deuterium Bottleneck:

$p + n \leftrightarrow D + \gamma$

Average photon energy is above deuterium binding energy → deuterium photo-dissociates quickly. Neutrons decay via beta decay during this time. n:p decreases to ~ 1/7.

Deuterium becomes stable and BBN proceeds. The majority of neutrons end up in ^{4}He.

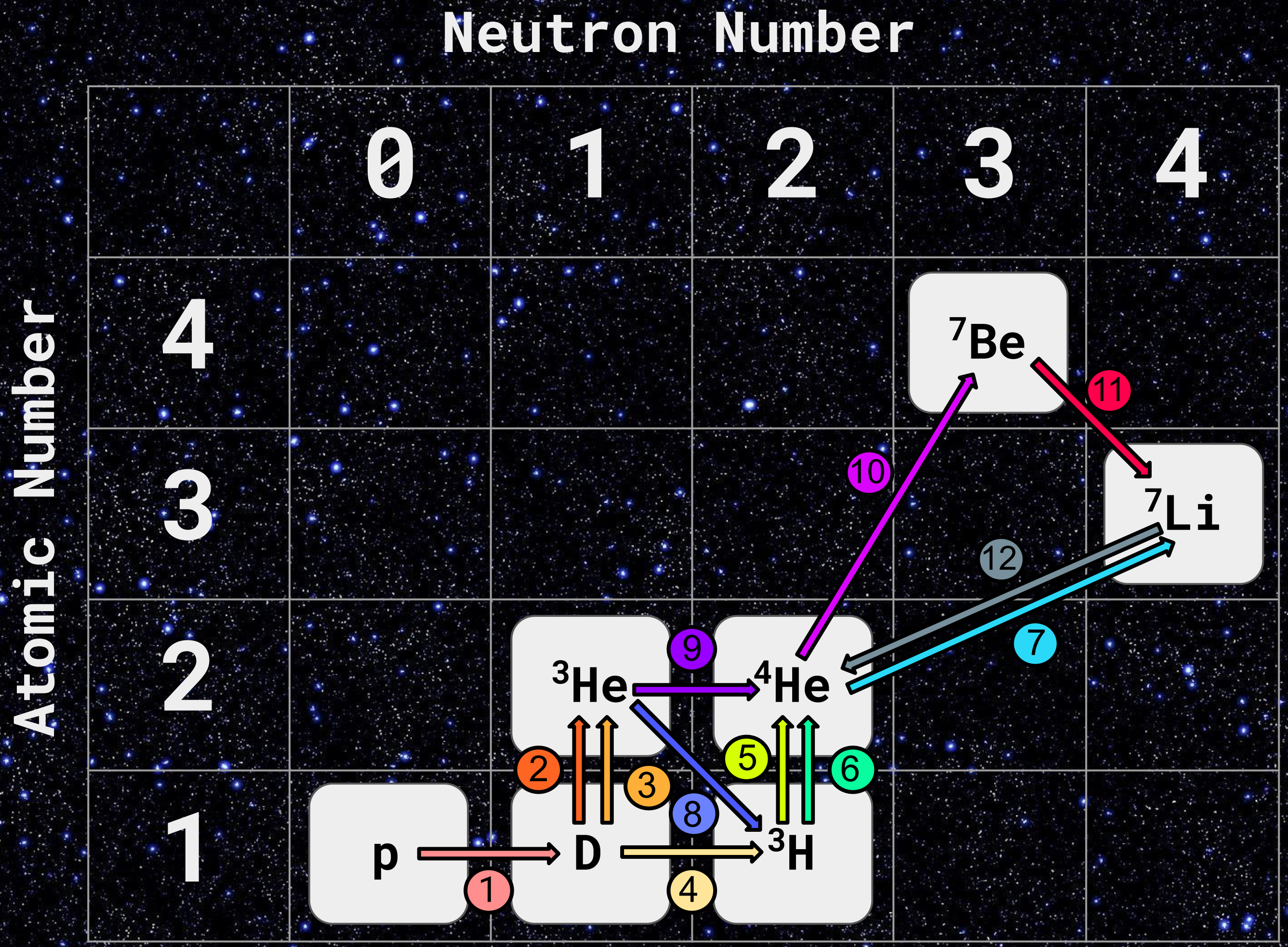
~ 10μs

1s

~ 10s

Essential Nuclear Reactions

0. $n \rightarrow p$
1. $n + p \rightarrow D + \gamma$
2. $D + p \rightarrow {}^{3}He + \gamma$
3. $D + D \rightarrow {}^{3}He + n$
4. $D + D \rightarrow {}^{3}H + p$
5. ${}^{3}H + p \rightarrow {}^{4}He + \gamma$
6. ${}^{3}H + D \rightarrow {}^{4}He + n$
7. ${}^{3}H + {}^{4}He \rightarrow {}^{7}Li + \gamma$
8. ${}^{3}He + n \rightarrow {}^{3}H + p$
9. ${}^{3}He + D \rightarrow {}^{4}He + p$
10. ${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
11. ${}^{7}Be + n \rightarrow {}^{7}Li + p$
12. ${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$



Element	Observation Method
^{4}He ~24.7%	Observed in “metal poor” galaxies. Primordial interstellar gas is ionised by photons emitted from young stars. The gas then cools via a number of strong emission lines.
D ~0.01%	Observations of Hydrogen in distant gas clouds back lit by Quasi Stellar Objects provides a probe of extremely low metallicity environments. D is observed as a weak absorption doublet of Hydrogen with a characteristic velocity offset.
^{7}Li ~10^{-10} %	Observed in stellar atmospheres. Accurate estimation of primordial abundances requires low metallicity stars and a good understanding of element production and distribution rates in stellar interiors.

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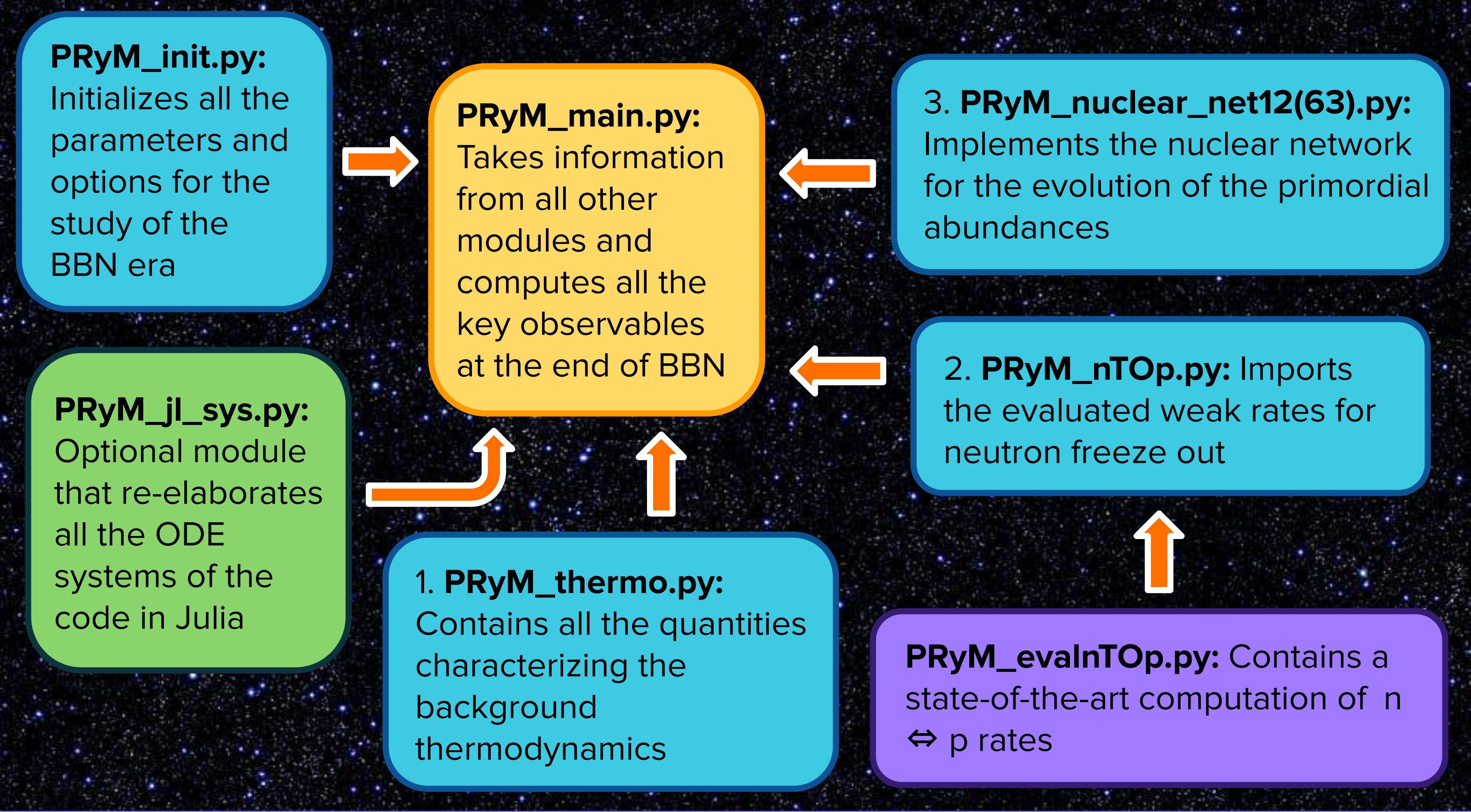
Introducing PRyMordial

Purpose: to simulate the evolution of light nuclei production in the first few minutes after the big bang

⇨ $T = 10^{11}$ K - $O(10^7)$ K

Quantities calculated: N_{eff} and the abundances of ^{4}He, deuterium, ^{3}He, tritium, and ^{7}Li

Corrections Included: QED plasma effects, corrections to the neutron lifetime, and incomplete neutrino decoupling.


PRyM_init.py: Initializes all the parameters and options for the study of the BBN era
PRyM_main.py: Takes information from all other modules and computes all the key observables at the end of BBN
3. **PRyM_nuclear_net12(63).py:** Implements the nuclear network for the evolution of the primordial abundances
PRyM_jl_sys.py: Optional module that re-elaborates all the ODE systems of the code in Julia
2. **PRyM_nTOp.py:** Imports the evaluated weak rates for neutron freeze out
1. **PRyM_thermo.py:** Contains all the quantities characterizing the background thermodynamics
PRyM_evalnTOp.py: Contains a state-of-the-art computation of n ⇔ p rates

A quick aside: Thermonuclear Rates

$$\dot{Y}_{i_1} = \sum_{i_2 \ldots i_p, j_1 \ldots j_q} N_{i_1} \left(\Gamma_{j_1 \ldots j_q \to i_1 \ldots i_p} \frac{Y_{j_1}^{N_{j_1}} \ldots Y_{j_q}^{N_{j_q}}}{N_{j_1}! \ldots N_{j_q}!} - \Gamma_{i_1 \ldots i_p \to j_1 \ldots j_q} \frac{Y_{i_1}^{N_{i_1}} \ldots Y_{i_p}^{N_{i_p}}}{N_{i_1}! \ldots N_{i_p}!} \right)$$

PRIMAT driven: Nuclear rates are implemented according to the statistical determination of various groups. Follows theoretical energy modeling tuned to datasets.

Two approaches for computation of key reaction rates, $\Gamma_{j1 \ldots jq \Rightarrow i1 \ldots iq}$

NACRE II driven: Nuclear rates are interpolated from the updated NACRE compilation [1310.7099], comprising charged-particle-induced reactions. For $D + p \rightarrow \gamma + {}^3He$ we use the LUNA result; for ${}^7Be + n \rightarrow p + {}^7Li$ we adopt the baseline of 1912.01132.

What can PRyMordial be used for?

This code can be used to compute **SM abundances** of primordial elements as well as abundances modified by some of the following ***new physics scenarios***:

- New light degrees of freedom
- Changed interaction strengths at early times
- The scaling of nuclear rates with λ_{QCD}
- A change in SM Yukawa interactions
- And many more - the universe is your oyster!

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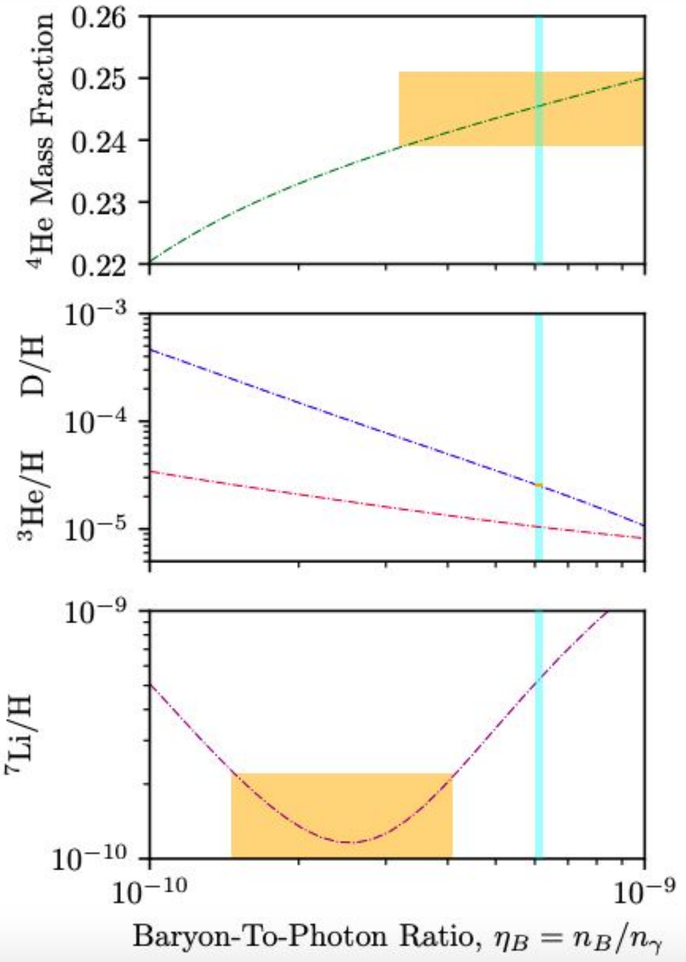
Let's run the code:

- We can reproduce the famous PDG BBN plot using PRyMordial!
- Yellow boxes correspond to measured values
- Blue line is the CMB constraint on the baryon-to-photon ratio

```python
# PDG plot
npoints = 50
import numpy as np
etabvec = np.logspace(-10,-9,npoints)
# Initialization of array of observables
YP_vec, DoH_vec, He3oH_vec, Li7oH_vec = np.zeros((4,npoints))
for i in range(npoints):
    # Update value of baryon-to-photon ratio and store new obs
    PRyMini.eta0b = etabvec[i]
    YP_vec[i], DoH_vec[i], He3oH_vec[i], Li7oH_vec[i] =
    PRyMmain.PRyMclass().PRyMresults()[4:8]
```



```
python3 -m venv BBN_venv
source BBN_venv/bin/activate
pip install numba
```

```python
import numpy as np
import matplotlib.pyplot as plt

# Example input
npoints = 10
etabvec = np.logspace(-10, -9, npoints)
YP_vec, DoH_vec, He3oH_vec, Li7oH_vec = np.zeros((4, npoints))

# --- Loop to fill observable arrays ---
for i in range(npoints):
    PRyMini.eta0b = etabvec[i]
    results = PRyMmain.PRyMclass().PRyMresults()
    YP_vec[i], DoH_vec[i], He3oH_vec[i], Li7oH_vec[i] = results[4:8]
```

```
# --- Observational bounds (example values; update as
needed) ---
eta_planck = 6.04e-10
eta_err = 0.12e-10
YP_obs = 0.245
YP_err = 0.003
D_obs = 2.547
D_err = 0.029
Li7_obs = 1.6
Li7_err = 0.3
```

```python
# --- Plot ---
fig, axs = plt.subplots(3, 1, figsize=(6, 8), sharex=True, constrained_layout=True)

# Top: Y_P
axs[0].plot(etabvec, YP_vec, 'g-.', label=r'$^4$He')
axs[0].fill_between(etabvec, YP_obs - YP_err, YP_obs + YP_err, color='orange', alpha=0.5)
axs[0].axvspan(eta_planck - eta_err, eta_planck + eta_err, color='cyan', alpha=0.5)
axs[0].set_ylabel(r'$^4$He Mass Fraction')
axs[0].set_ylim(0.22, 0.26)

# Middle: D/H and He3/H
axs[1].loglog(etabvec, DoH_vec, 'b-.', label='D/H')
axs[1].fill_between(etabvec, D_obs - D_err, D_obs + D_err, color='orange', alpha=0.5)
axs[1].loglog(etabvec, He3oH_vec, 'r-.', label=r'$^3$He/H')
axs[1].axvspan(eta_planck - eta_err, eta_planck + eta_err, color='cyan', alpha=0.5)
axs[1].set_ylabel(r'D/H*10^5, $^3$He/H*10^5')
axs[1].legend()

# Bottom: Li7/H
axs[2].loglog(etabvec, Li7oH_vec, 'purple', linestyle='-.', label=r'$^7$Li/H*10^10')
axs[2].fill_between(etabvec, Li7_obs - Li7_err, Li7_obs + Li7_err, color='orange', alpha=0.5)
axs[2].axvspan(eta_planck - eta_err, eta_planck + eta_err, color='cyan', alpha=0.5)
axs[2].set_ylabel(r'$^7$Li/H')
axs[2].set_xlabel(r'Baryon-To-Photon Ratio, $\eta_B = n_B/n_\gamma$')

plt.show()
```