PRyMordial: The first minutes of the universe, computed in seconds

Anne-Katherine Burns (she/her)
University of California, Irvine
Cosmology, Astrophysics, Theory and Collider Higgs 2024
May 2, 2024

Outline

1. ***The physics of BBN***
2. Introducing *PRyMordial*
3. Constraints on Variation of the Weak Scale from Big Bang Nucleosynthesis

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

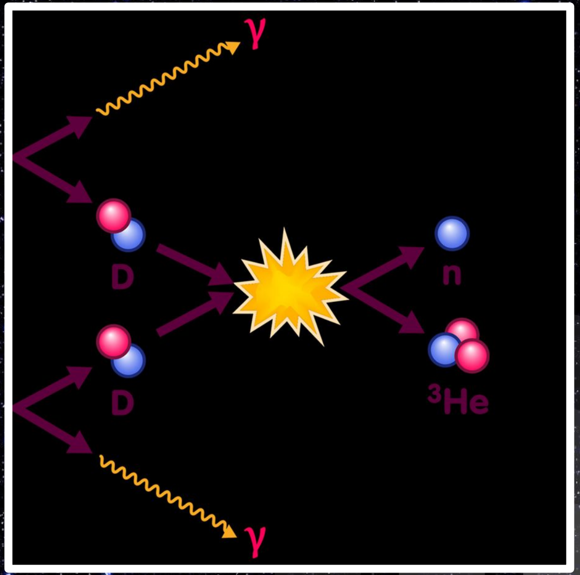
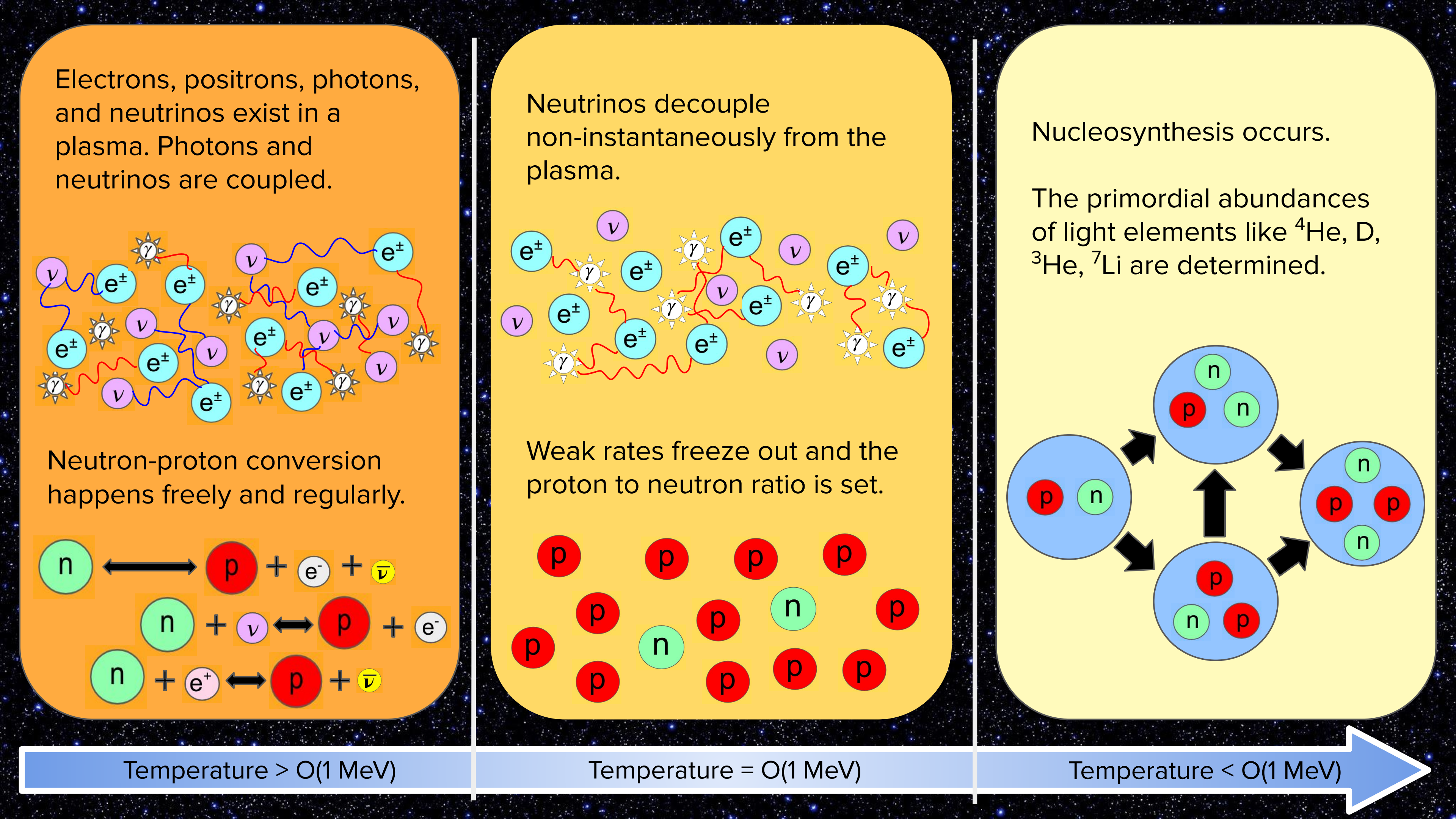
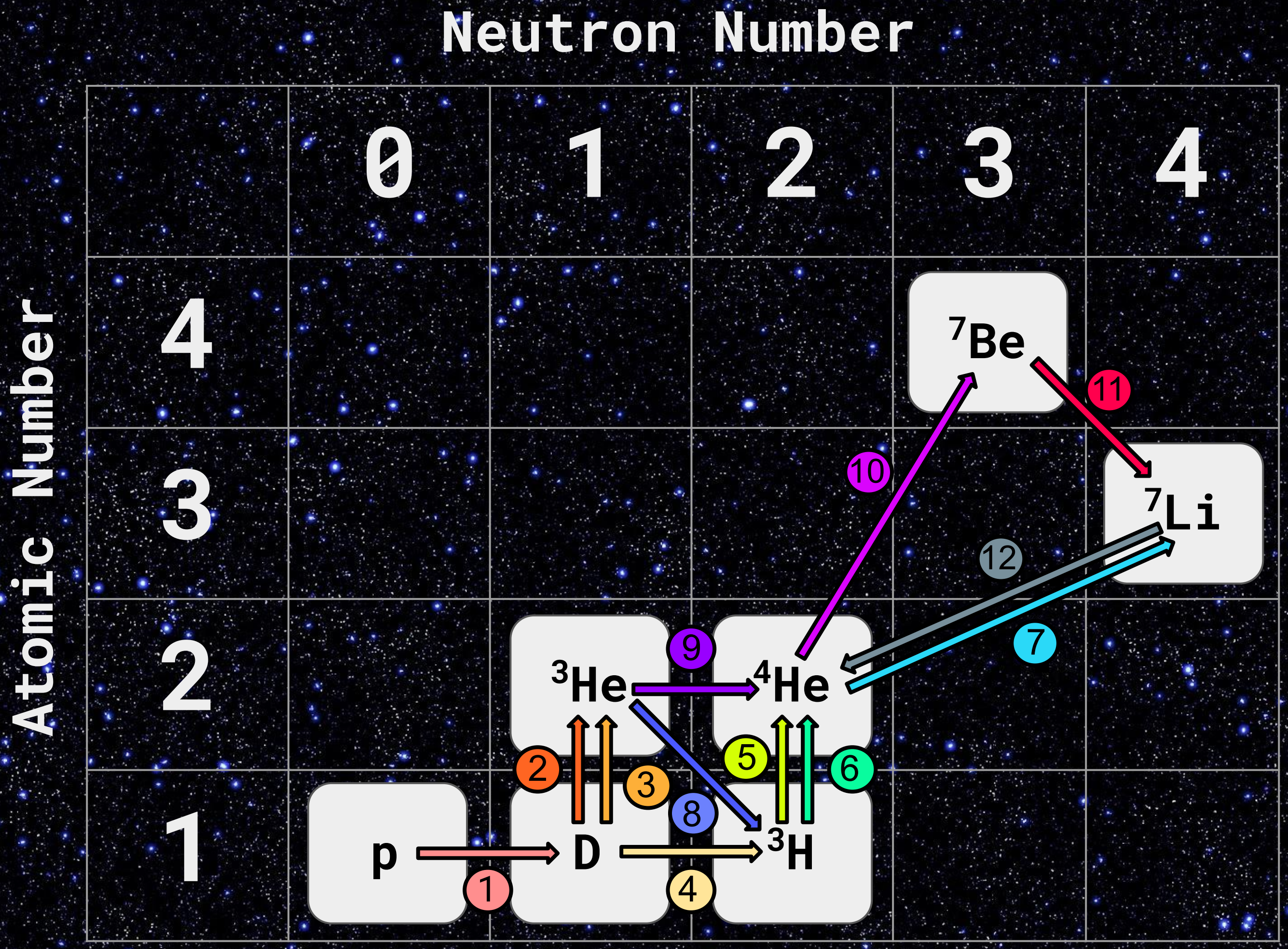


Image: Einstein Online


Electrons, positrons, photons, and neutrinos exist in a plasma. Photons and neutrinos are coupled.
Neutron-proton conversion happens freely and regularly.
n ⟷ p + e⁻ + ν̄
n + ν ⟷ p + e⁻
n + e⁺ ⟷ p + ν̄
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)

Essential Nuclear Reactions

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

Outline

1. The physics of BBN
2. ***Introducing PRyMordial***
3. Constraints on Variation of the Weak Scale from Big Bang Nucleosynthesis

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.

Why PRyMordial?

PRyMoridal is different from other publicly available BBN codes in four key ways. It is crafted to:

1. Enable rapid, accurate assessment of the thermal bath physics
2. Establish a direct connection between a first-principle thermal background calculation and precise neutron-to-proton conversion
3. Facilitate exploration of BBN-era input parameters and rate uncertainties
4. Utilize Python 3 for efficient numerical computation with an option to use Julia for enhanced efficiency

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.

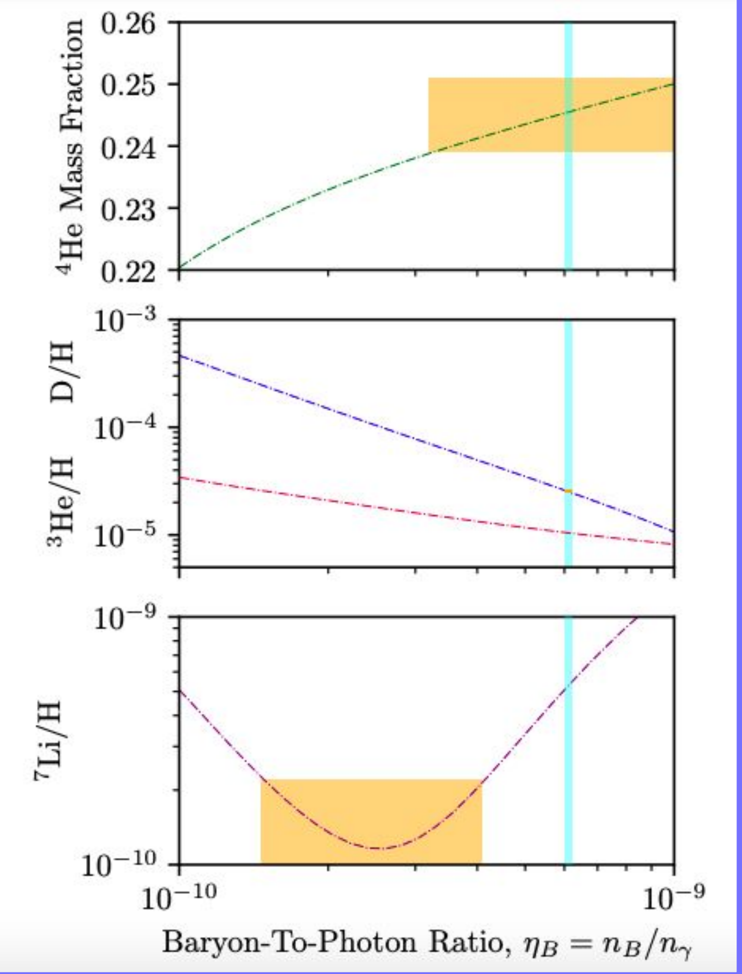
Two approaches for computation of key reaction rates, $\Gamma_{j1\ldots jq \Rightarrow i1\ldots iq}$

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.

PRyMordial: Results

- 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

```
# 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]
```



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 λQCD
- A change in SM Yukawa interactions
- And many more - the universe is your oyster!

Outline

1. The physics of BBN
2. Introducing *PRyMordial*
3. ***Constraints on Variation of the Weak Scale from Big Bang Nucleosynthesis***

Discovery of a *Helium Anomaly*

- The Helium-4 abundance, Y_P has been determined by the Subaru Survey collaboration via the observation of **10 extremely metal-poor galaxies** (EMPGs)
- EMPG host gas of nebulae → very clean environment for extrapolating Y_P to zero metallicity
- Combined [new data from 10 EMPGs + existing data from 3 EMPGs + existing data from 51 MPGs + measurements of the He λ10830 infrared emission line] [2203.09617]

$$Y_{P,\,obs\,[Subaru]} = 0.2379^{+0.0031}_{-0.0030}$$

$$Y_{P,\,obs\,[PDG]} = 0.245 \pm 0.003$$

$$Y_{P,\,SM}^{*} = 0.24709 \pm 0.00018$$

From Pitrou, et. al. 2018 [1801.08023]

→ 3σ tension with SM

Status of the Deuterium Measurement and Prediction

- Astrophysicists use quasar absorption spectra to determine the primordial deuterium abundance to 1% precision

$(D/H \times 10^5)_{obs\ [PDG]} = 2.547 \pm 0.025$

$(D/H \times 10^5)_{SM}{}^* = 2.460 \pm 0.046$

→ 2σ tension with SM?

- This tension is heavily debated (2011.11537, 2011.13874) due to lack of understanding of the uncertainties in key nuclear reactions involved in deuterium production
- The LUNA collaboration recently measured $D(p, \gamma)^3He$ - important for BBN constraints on New Physics**

*From Pitrou, et. al. 2018 (1801.08023)

**V. Mossa et al., Nature 587, 210 (2020)

Constraints on Variation of the Weak Scale from Big Bang Nucleosynthesis

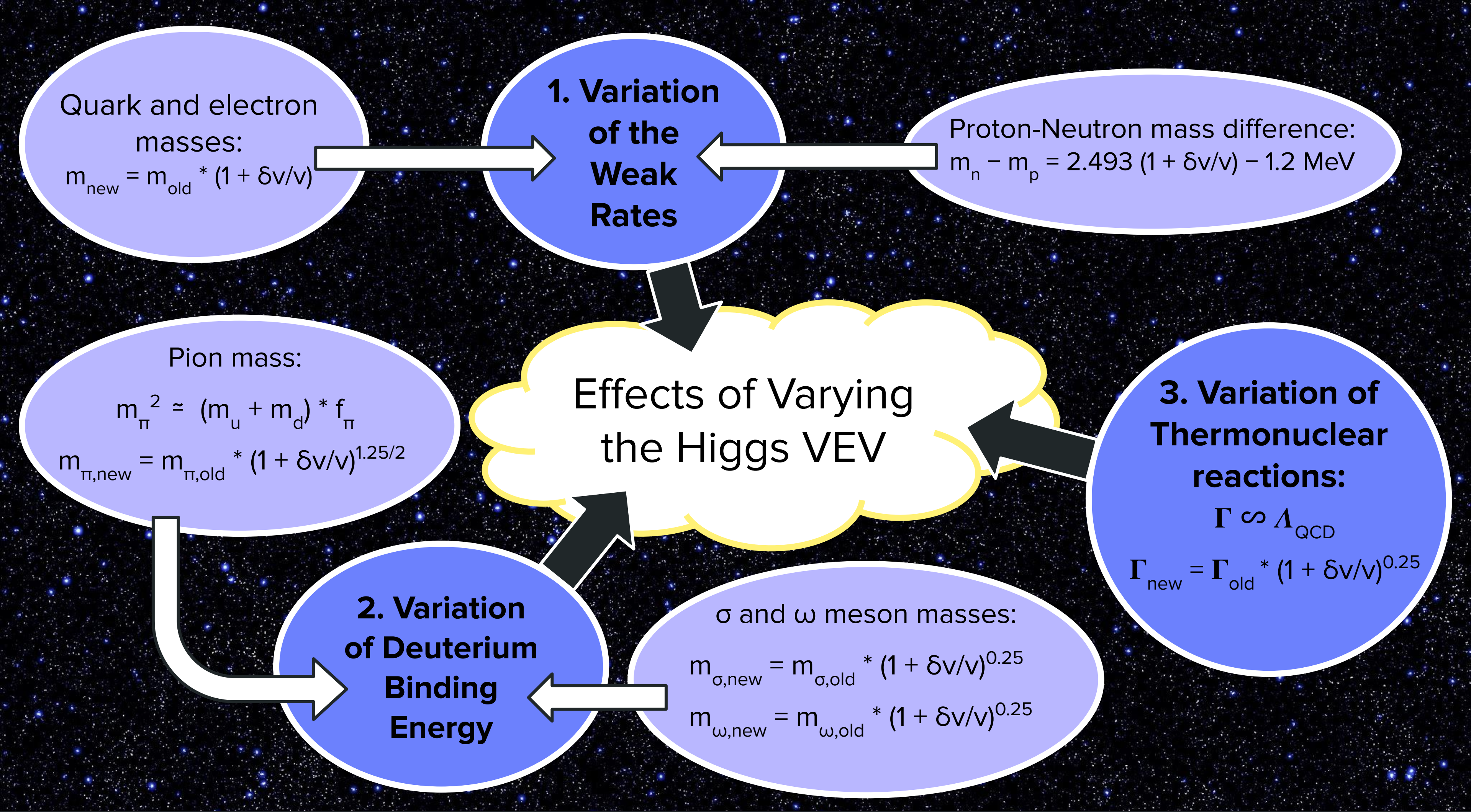
- One tactic for resolving ***Helium anomaly***

$$Y_{P,\ obs\ [Subaru]} = 0.2379{+}0.0031$$

$$Y_{P,\ obs\ [PDG]} = 0.245 \pm 0.003$$

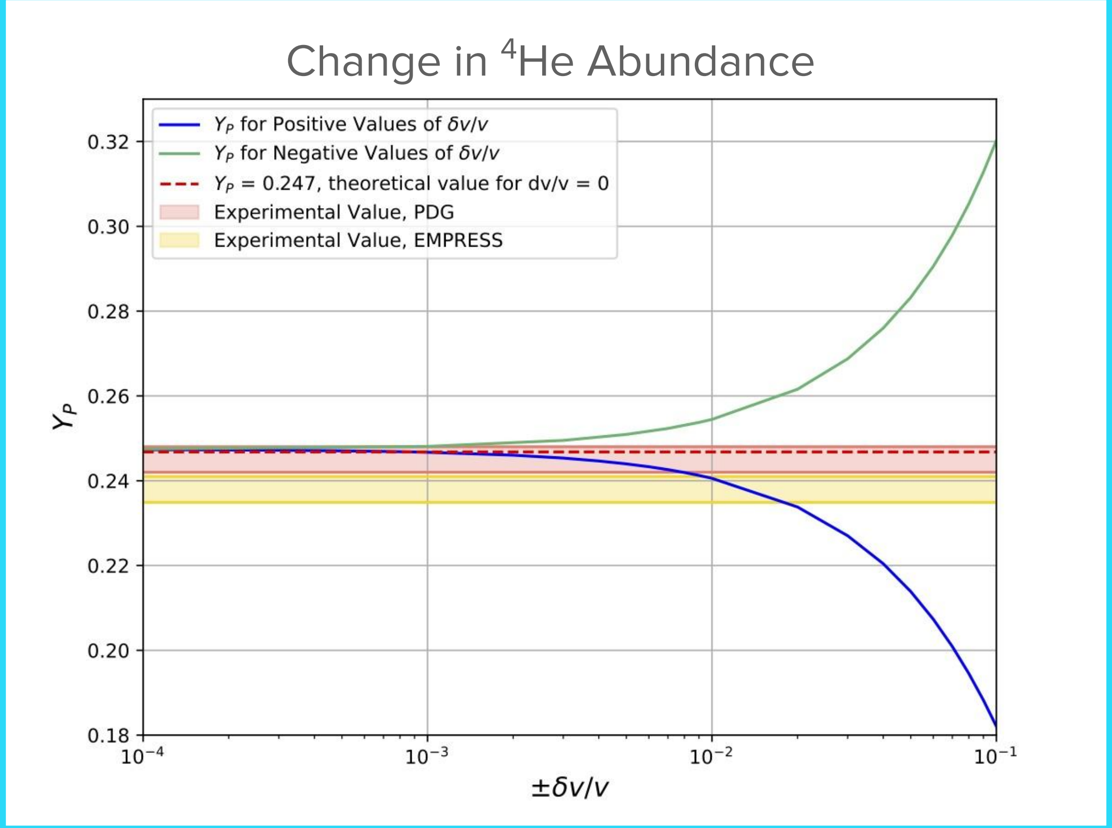
$$Y_{P,\ SM} = 0.24709 \pm 0.00018$$

- Varied the Higgs VEV: the only dimensionful parameter in the Standard Model
- VEV is cosmologically dynamical: varied during EWPT



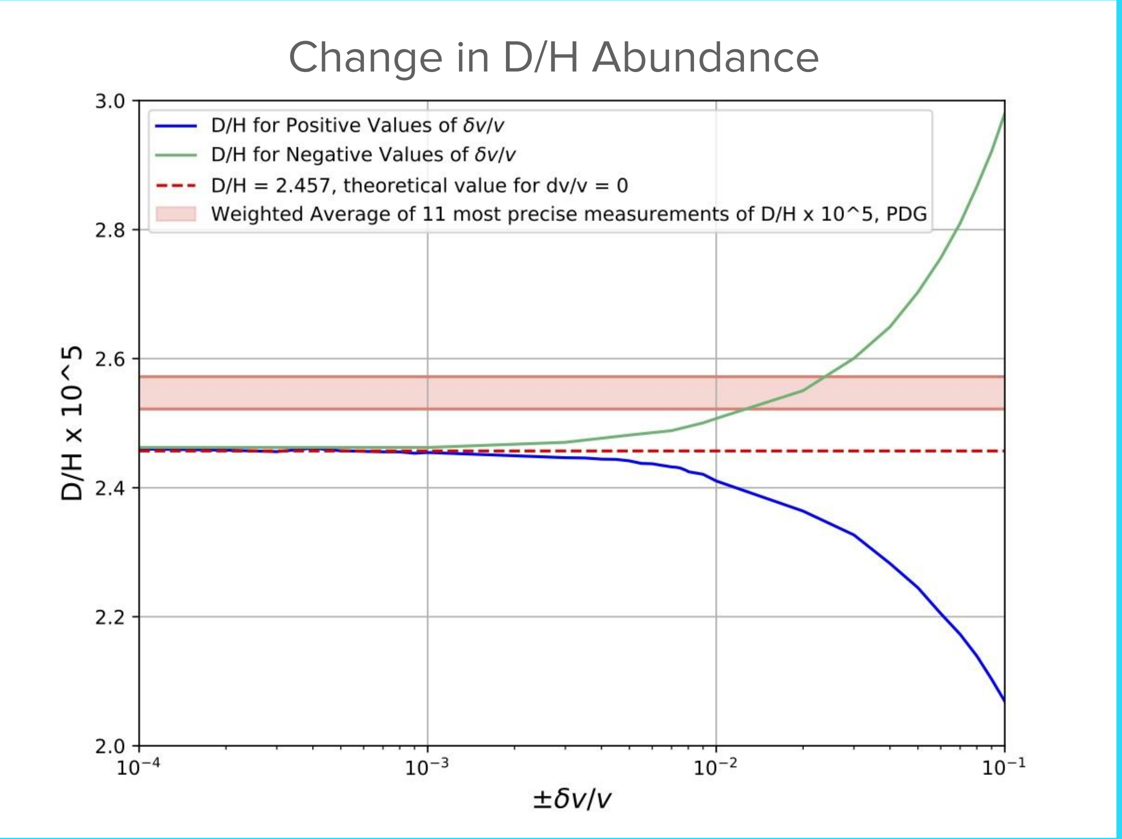
1. Variation of the Weak Rates
Quark and electron masses:
$m_{new} = m_{old} * (1 + \delta v/v)$
Proton-Neutron mass difference:
$m_n - m_p = 2.493\,(1 + \delta v/v) - 1.2$ MeV
Effects of Varying the Higgs VEV
Pion mass:
$m_\pi^2 \simeq (m_u + m_d) * f_\pi$
$m_{\pi,new} = m_{\pi,old} * (1 + \delta v/v)^{1.25/2}$
3. Variation of Thermonuclear reactions:
$\Gamma \propto \Lambda_{QCD}$
$\Gamma_{new} = \Gamma_{old} * (1 + \delta v/v)^{0.25}$
2. Variation of Deuterium Binding Energy
σ and ω meson masses:
$m_{\sigma,new} = m_{\sigma,old} * (1 + \delta v/v)^{0.25}$
$m_{\omega,new} = m_{\omega,old} * (1 + \delta v/v)^{0.25}$

Results: Effect on Helium-4 Abundance



- PDG: 2σ bounds on δv/v: *- 0.001 to 0.008*
- SUBARU: 2σ bounds on δv/v: *0.008 to 0.02*
- δv = 0 would be mildly excluded for SUBARU results

Results: Effect on Deuterium Abundance



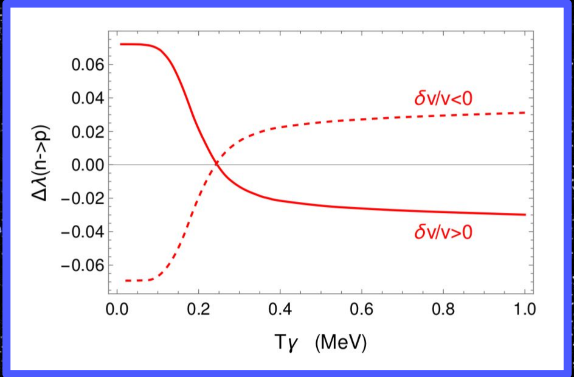
- Theoretical uncertainty is comparable to experimental uncertainty
- Bounds on δv/v: *-0.015 to - 0.025*
- Changing the VEV can only explain one anomaly at a time

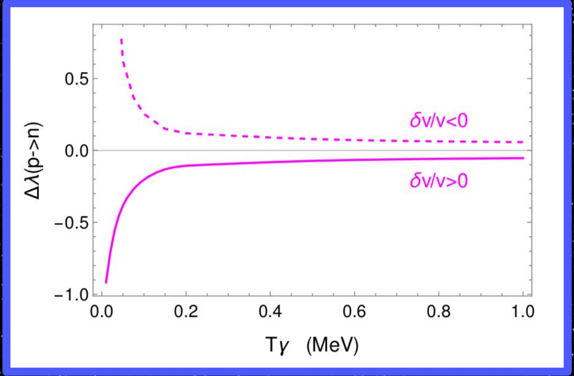
The Big Takeaways

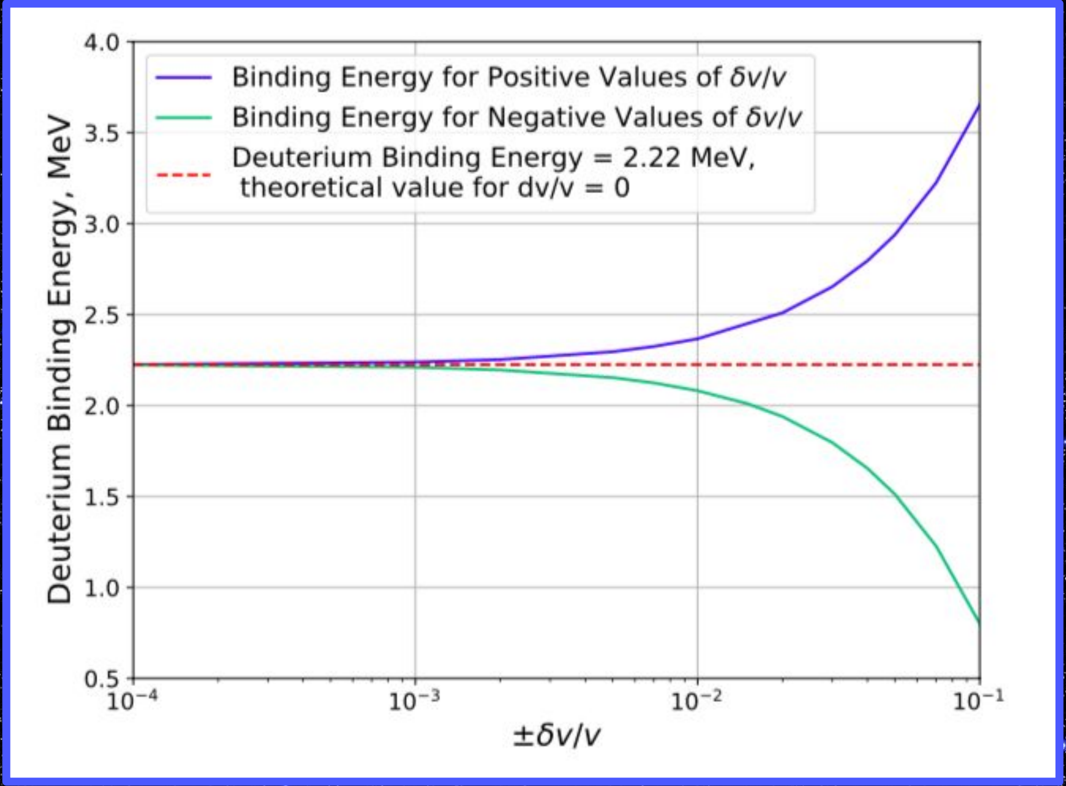
1. Analysis of primordial helium abundance using the Subaru Survey observation hints towards *variation in the Higgs VEV* between the BBN era and today✨
2. No value can explain both the SUBARU and deuterium anomalies, but can certainly explain either one✨
3. We can imagine an extended model in which the Higgs VEV slowly rolls to its current value but has not quite reached it at the MeV temperature scale ✨

Thank you!

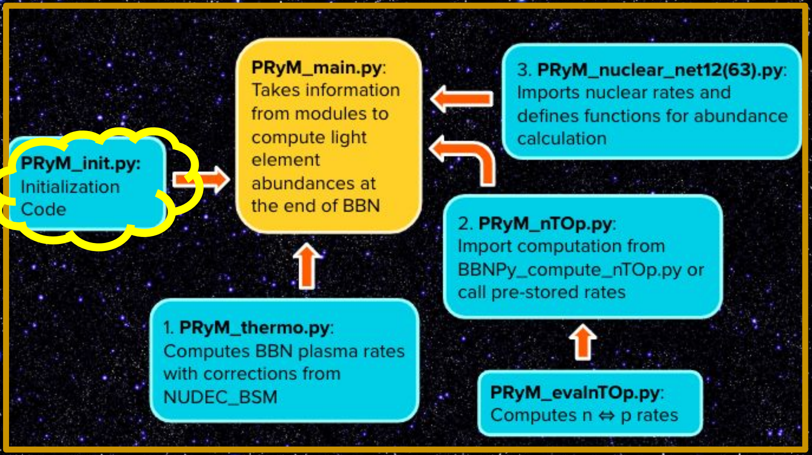
Results:
Effect on the Weak Rates & Deuterium Binding Energy







PRyM_init.py



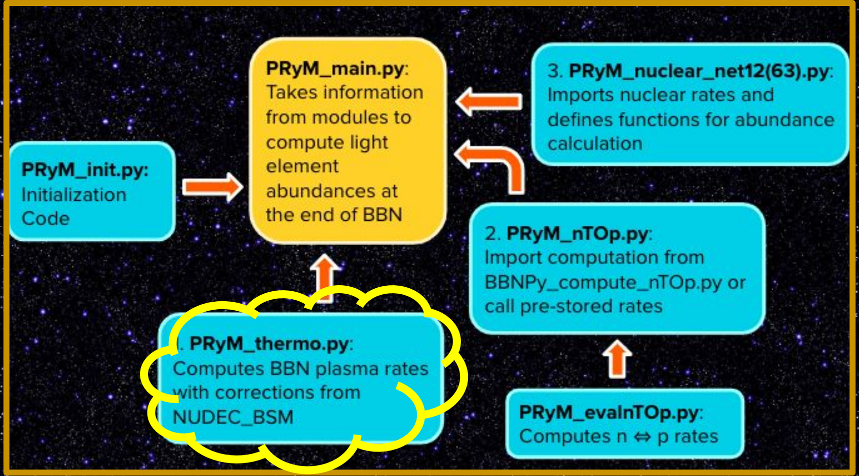
1. Defines units and constants
    a. Conversion factors
    b. Particle masses from PDG 2020
    c. CMB constants, i.e. baryon density today in MeV^3
    d. Defines CGS system for nuncleon & nuclear rates
2. Sets working directory
3. Defines Temperature Eras:

$$\mathbf{T}_{\mathbf{start}} = 10^{11}\,K,\ \mathbf{T}_{\mathbf{middle}} = 10^{10}\,K,\ \mathbf{T}_{\mathbf{end}} = 6*10^{7}\,K$$

4. Sets flags for computation of p ⇔ n rates and New Physics

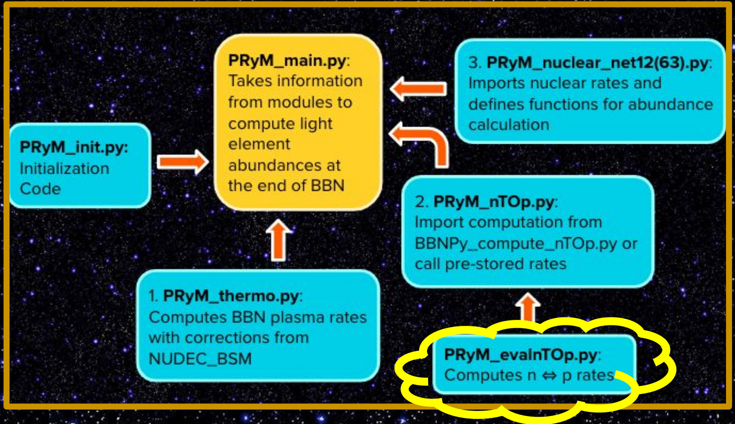
PRyM_thermo.py

- Sets up the Boltzmann equations for the electron-photon plasma and neutrinos assuming a thermal distribution for the species
- Includes:
  - NLO QED corrections for the plasma
  - Non-instantaneous decoupling effects for the neutrino sector
- Output => **evolution of T_γ / T_ν**



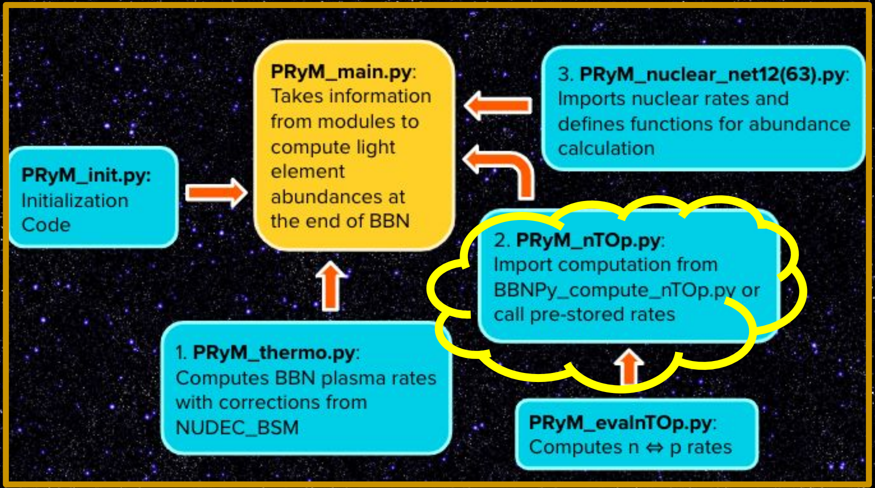
PRyM_evalnTOp.py

- Compute n ↔ p matrix elements beyond the Born approximation (i.e. infinite nucleon mass approximation) for the neutron decay constant
  - Corrections included:
    - Isospin-breaking contributions:
      - Finite-mass effects
      - QED corrections
    - Finite-temperature effects
- Combine all corrections to determine p ⇔ n rates



PRyM_nTOp.py

- **IF:** p ⇔ n rates have already been computed and stored (indicated in initialization code): do not recompute
- **ELSE**: Load and interpolate rates from PRyM_compute_nTOp.py



PRyM_nuclear_net12(63).py

This part of the code sets up the following equation:

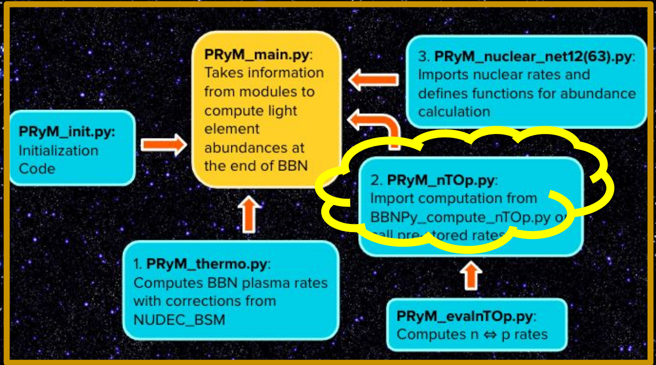
$$\dot{Y}_{i_1} = \sum_{i_2 \ldots i_p, j_1 \ldots j_q} N_{i_1} \left(\Gamma_{j_1 \ldots j_q \to i_1 \ldots i_p} \frac{Y_{j_1}^{N_{j_1}} \ldots Y_{j_q}^{N_{j_q}}}{N_{j_1}! \ldots N_{j_q}!} - \Gamma_{i_1 \ldots i_p \to j_1 \ldots j_q} \frac{Y_{i_1}^{N_{i_1}} \ldots Y_{i_p}^{N_{i_p}}}{N_{i_1}! \ldots N_{i_p}!}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

i, j = enumeration of each element in

Y_i = abundance of i^{th} element

N_{ip} = the number of elements, i_p present in the reaction: i_1 + ...+ i_p ⇔ j_1 + ...+ j_q

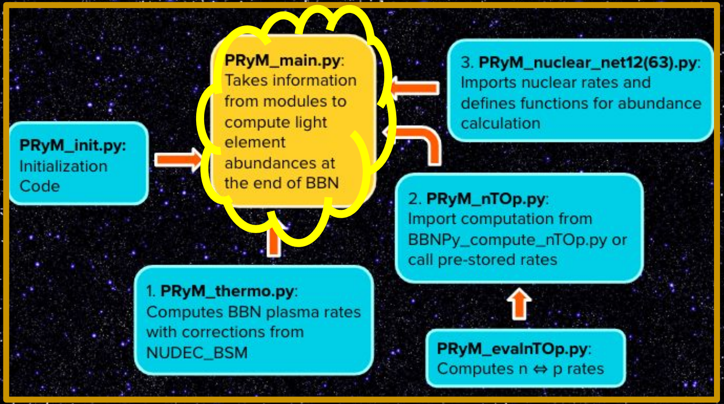
$\Gamma_{j1...jq \Rightarrow i1...iq} = n_b$^[($N_{i1}$+...+ N_{ip})-1] * $\langle\sigma v\rangle_{i1...ip \Rightarrow j1...jq}$



PRyM_main.py

PART I of III: THERMODYNAMICS OF THE PLASMA

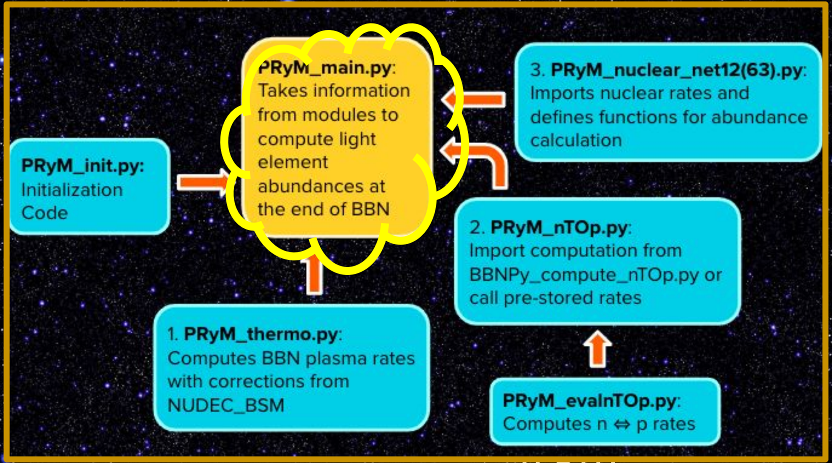
- *Imports* information from PryM_init and PRyM_plasma
- *Computes* the following initial conditions for plasma thermodynamics:
    - Total density and pressure of primordial bath
    - N_{eff}, the effective number of neutrino species
    - The neutrino temperature
    - The plasma temperature
- *Solves* for **T(t) and t(T) and N_{eff}**



PRyM_main.py, cont.

PART II of III: FRW COSMOLOGICAL BACKGROUND IN RADIATION DOMINATION

- *Defines* the plasma entropy and the Hubble rate
- *Computes* the scale factor, a(T) from the effects from non-instantaneous decoupling
- *Defines* temperature eras and baryon calculation
- *Imports* n ⇔ p rates and nuclear rates modules



PRyM_main.py, cont.

PART III of III: PRIMORDIAL ABUNDANCE CALCULATION

- ***Computes*** initial conditions for network of differential equations (thermal equilibrium distributions)
- ***Defines*** time derivatives of abundance functions for only p and n and solve network at high temperatures, $T = 10^{11} - 10^{10}$
- ***Imports*** time derivatives of abundance functions for **p, n, d, t, ^{3}He, ^{4}He, ^{7}Li, and ^{7}Be** from PRyM_nuclear_rates
- ***Solves*** system of differential equations at middle and low temperature eras and ***plots*** results