Indications for a Nonzero Lepton Asymmetry in the Early Universe

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Based on work by A.K. Burns, Dr. Tim Tait, and Dr. Mauro Valli [2206.00693]

Outline

1. The physics of BBN
2. Introducing *PRyMordial*
3. Indications for a Nonzero Lepton Asymmetry
    a. Tension in Measurements with the SM
    b. Primordial Lepton Asymmetries
    c. Results and Discussion

What is Big Bang Nucleosynthesis (BBN)?

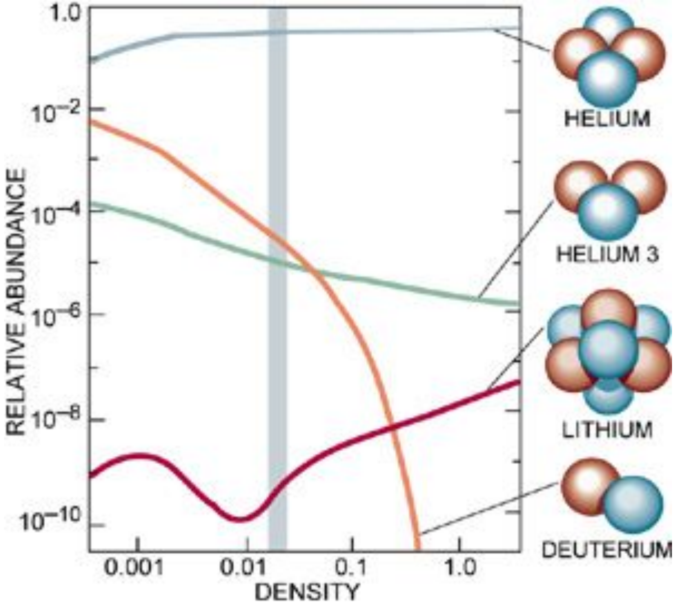
The production of **light element nuclei** in the early universe

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?

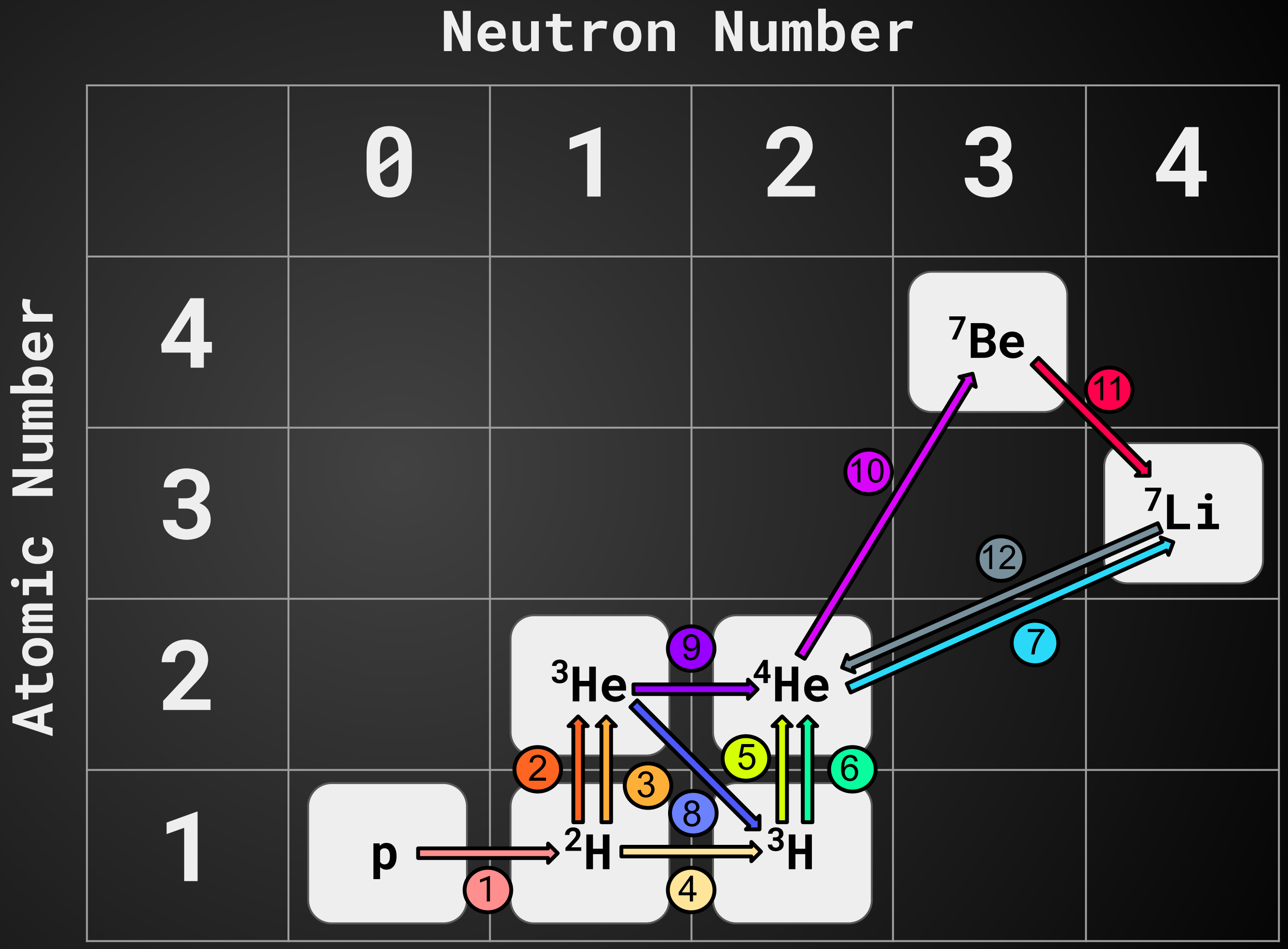
By determining **(a)** and **(b)** we can put constraints on New Physics



1. Big Bang Nucleosynthesis. UC Berkeley,w.astro. iberkeley.edu/~mwhite/darkmatter/bbn.html

Essential Nuclear Reactions

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



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.

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!

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]

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

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

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

*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

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

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

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)

Primordial Lepton Asymmetries

$$\eta_L \equiv \frac{1}{n_\gamma} \sum_{i=e,\mu,\tau} (n_{\nu_i} - n_{\bar{\nu}_i}) \simeq \frac{\pi^2}{33\zeta(3)} (\xi_{\nu_e} + \xi_{\nu_\mu} + \xi_{\nu_\tau})$$

Degeneracy Parameters: $\xi_{\nu i} = \mu_{\nu i} / T_{\nu i}$

Primordial lepton asymmetry hidden in neutrino sector

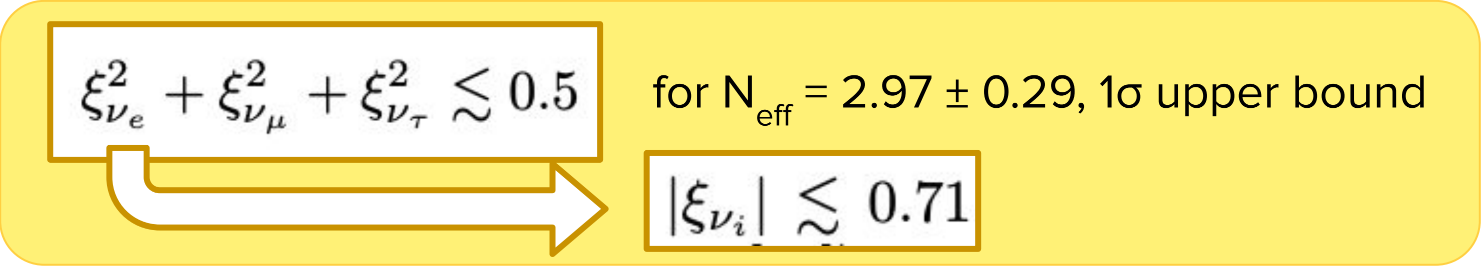
$$\frac{\Delta\rho_{\mathrm{rad}}}{\rho_\gamma} \simeq \frac{15}{4\pi^2} \left(\frac{4}{11}\right)^{4/3} \xi_{\nu_i}^2$$

Notes:

- *Flavor equilibration, $\xi_{\nu e} = \xi_{\nu\mu} = \xi_{\nu\tau}$ not required*
- *$|\xi_{\nu i}| < 1$ - O(1) degeneracy parameters ruled out by CMB observations*

Constraints on Degeneracy Parameters from the CMB

- Upper bound on degeneracy parameters can be derived from CMB
  - Using Planck constraint on N_{eff} and assume flat prior for Y_P
  - Likelihood analysis including **TTTEEE and low-ℓ measurements + BAO and lensing data**



$$\xi_{\nu_e}^2 + \xi_{\nu_\mu}^2 + \xi_{\nu_\tau}^2 \lesssim 0.5$$

for $N_{\mathrm{eff}} = 2.97 \pm 0.29$, 1σ upper bound

$$|\xi_{\nu_i}| \lesssim 0.71$$

- This bound is slightly more stringent for second and third generation neutrinos: $\boldsymbol{|\xi_{\nu\mu,\tau}| \lesssim 0.5}$

Constraints on Degeneracy Parameters from the BBN

- BBN gives stronger constraint on ν_e asymmetry because of electron neutrino participation in the weak rates, **$n + \nu_e \leftrightarrow p + e^-$, $p + \bar{\nu}_e \leftrightarrow n + e^+$** and **neutron decay**
- Positive $\xi_{\nu e}$ reduces neutron to proton ratio

$Q \equiv m_n - m_p = 1.293$ MeV

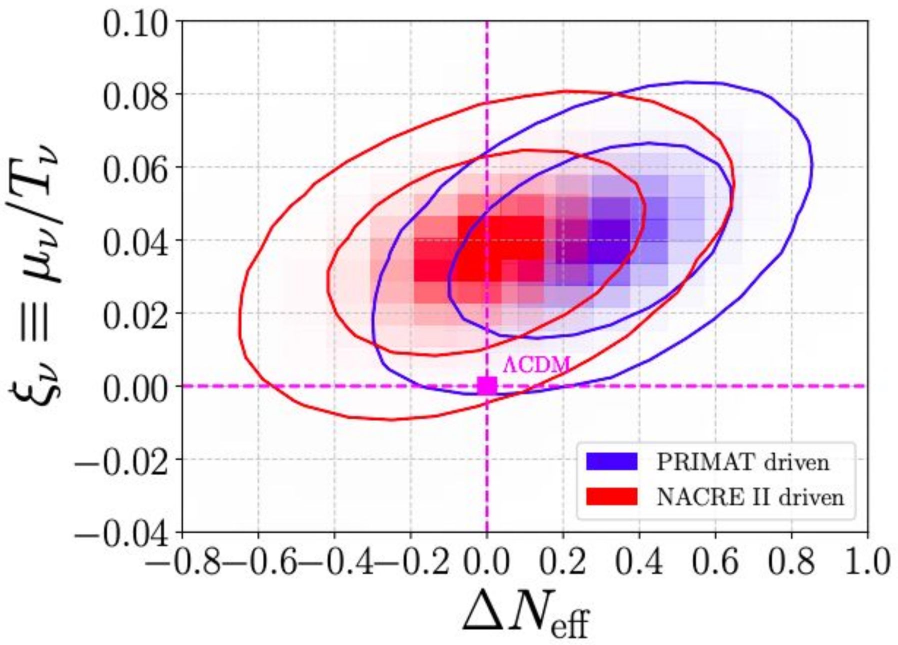
$$\boxed{(n_n/n_p)\big|_{\text{eq.}} \simeq \exp\left(-Q/T_\gamma - \xi_{\nu_e}\right)}$$

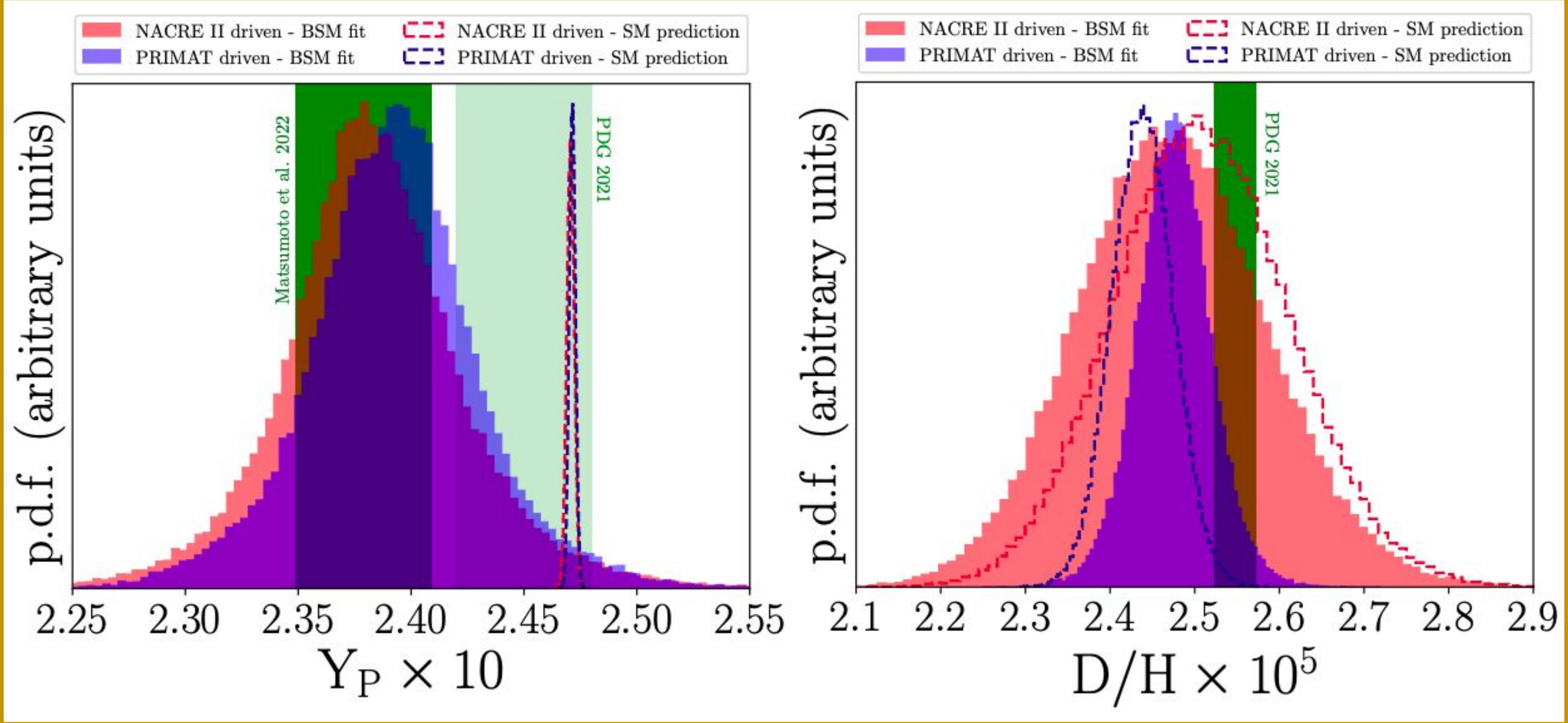
- The final Helium-4 abundance is especially sensitive to this ratio and is a primordial leptometer

Note: Assuming full flavor equilibrium, $\xi_\nu = 0.001 \pm 0.016$ but Froustey and Pitrou [2110.11889] showed that the degree to which full flavor equilibration is realized during the BBN era depends on θ_{13} and the initial values of $\xi_{\nu i}$

Results

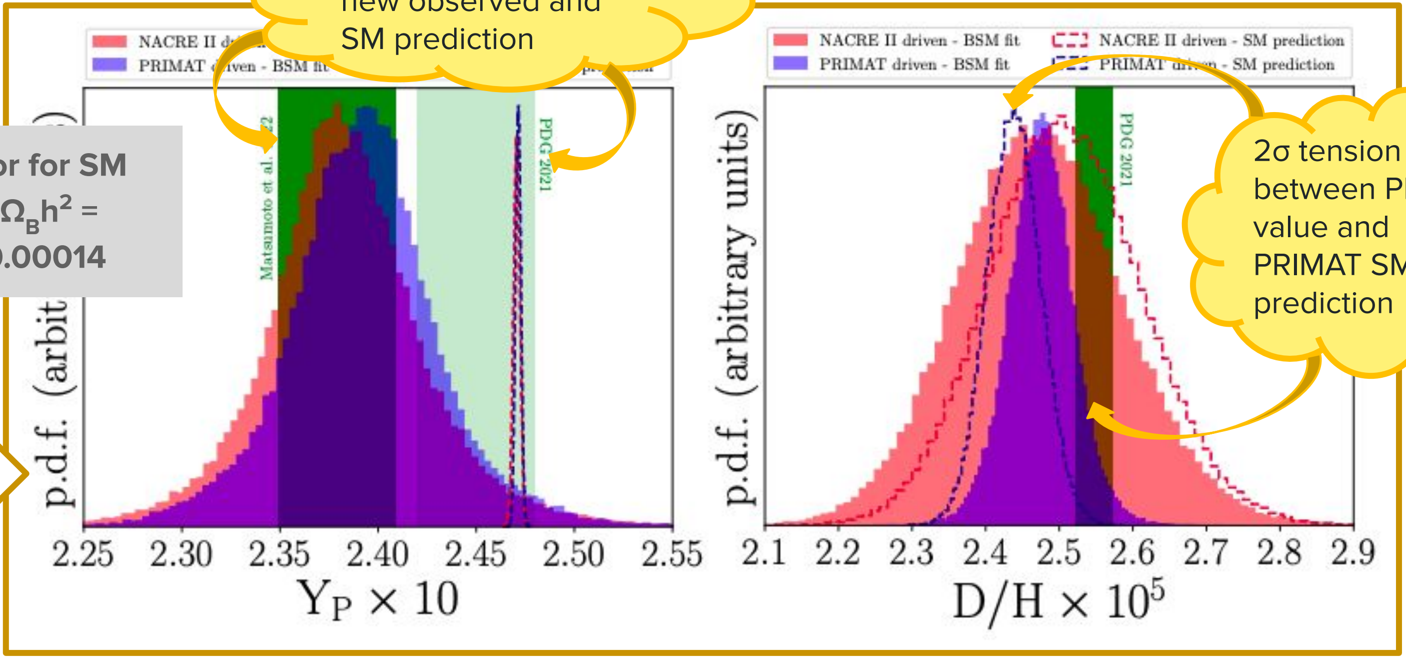
- 68% and 90% probability region for ξ_ν and ΔN_{eff} determined by a **minimized test statistic**
- a BSM fit **favors a non-zero asymmetry** in the neutrino sector
- O(1) shift in ΔN_{eff} from use of different nuclear rates simultaneously consistent with current data
- Size of shift in ΔN_{eff} could be the result of a large neutrino asymmetry in the muon-tau sector when *flavor equilibration has not been fully realized*




NACRE II driven - BSM fit
PRIMAT driven - BSM fit
NACRE II driven - SM prediction
PRIMAT driven - SM prediction
p.d.f. (arbitrary units)
Matsumoto et al. 2022
PDG 2021
2.25
2.30
2.35
2.40
2.45
2.50
2.55
$Y_P \times 10$
NACRE II driven - BSM fit
PRIMAT driven - BSM fit
NACRE II driven - SM prediction
PRIMAT driven - SM prediction
p.d.f. (arbitrary units)
PDG 2021
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
$D/H \times 10^5$

Results, cont.

- BSM fit varying both ξ_ν and N_{eff}
- Vertical dark green bands are the measurements adopted in our BBN analysis



3σ tension between new observed and SM prediction

2σ tension between PDG value and PRIMAT SM prediction

Gaussian Prior for SM Prediction: $\Omega_B h^2 = 0.02242 \pm 0.00014$

Probability density function

Discussion and Conclusion

- η_B << **$\eta_L \cong$ 0.01 - 0.26** today depending on neutrino oscillations and initial conditions
- What type of New Physics could generate this asymmetry?
  - At $T > T_{EWSB}$ electroweak sphalerons equilibrate B + L → the final total lepton and baryon asymmetries differ by a O(1) factor

For $\eta_L \gg \eta_B$ to persist:

Asymmetry must be generated after the sphalerons become inactive (T = O(100 GeV))

OR

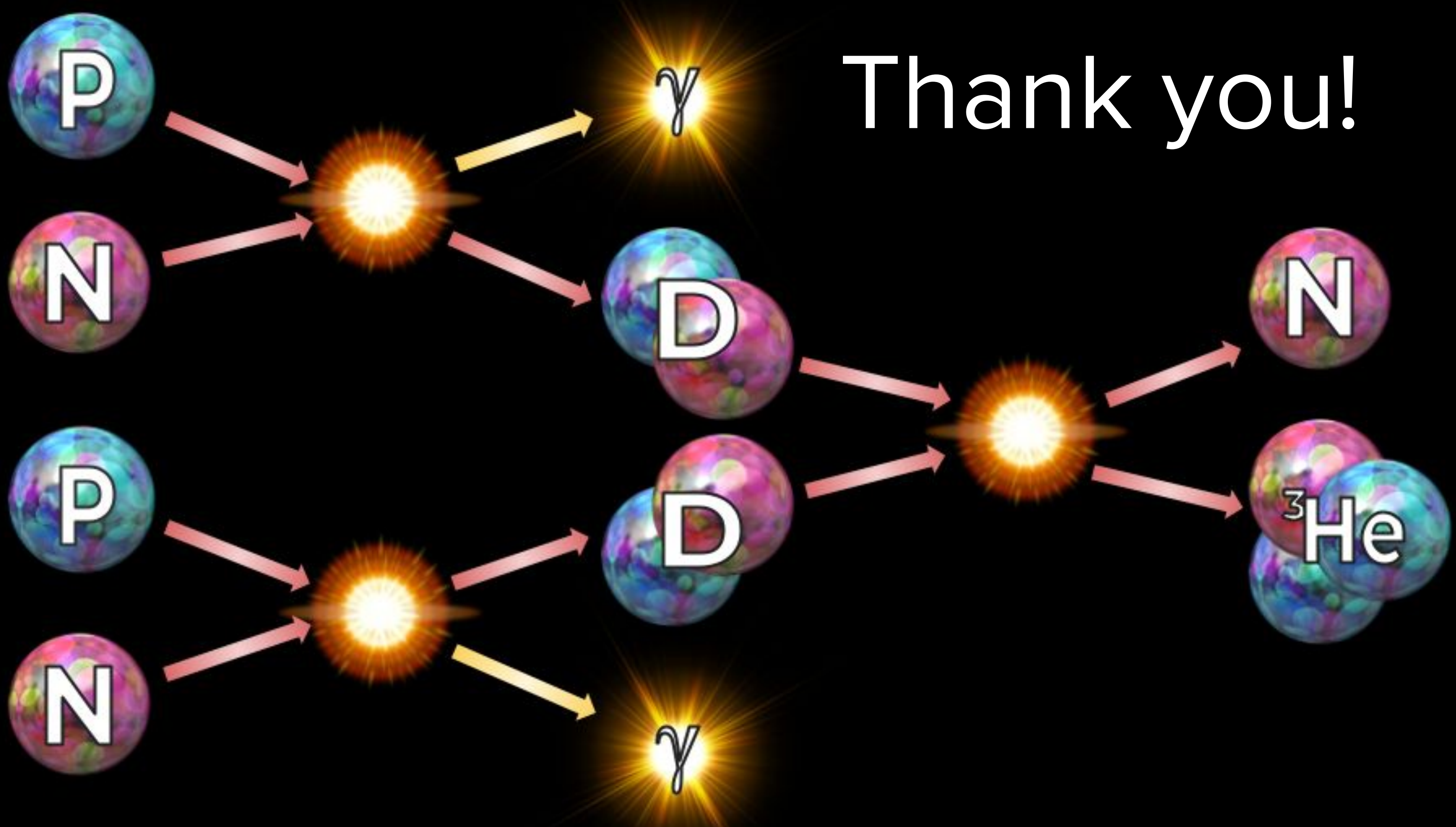
Flavor-dependent NP in lepton sector

The net lepton asymmetry must be << individual flavor asymmetries

The Big Takeaways

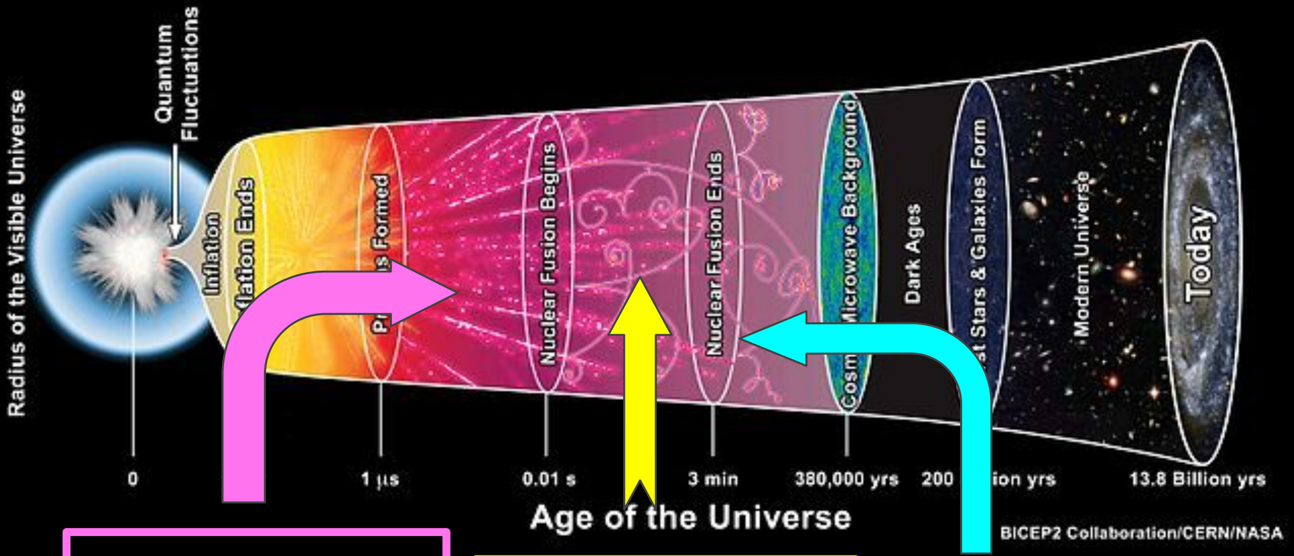
1. Analysis of primordial helium abundance using the Subaru Survey observation hints towards a *large total lepton asymmetry* originating in the early universe ✨
2. BBN and CMB data can be combined to derive powerful constraints ✨
3. Large total lepton asymmetry could be an important clue towards understanding the early universe ✨

Thank you!



Backup Slides

Relevant Time Scales to BBN

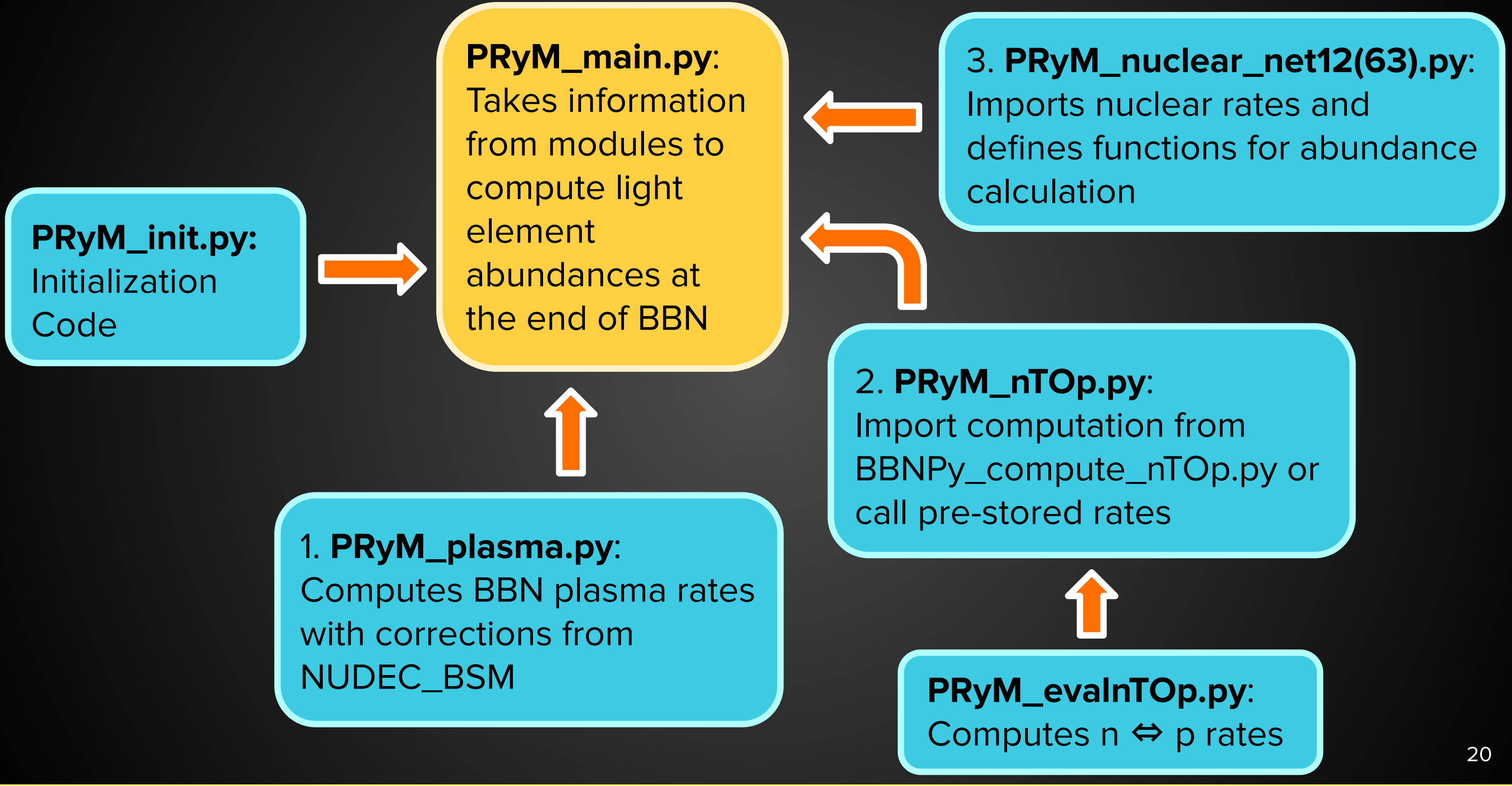


BICEP2 Collaboration/CERN/NASA

Hadron Epoch:
$T > 1$ MeV
$t \approx 10^{-6}$ s - 1 s

Neutrino Decoupling:
$T \approx 1$ MeV
$t \approx 1$s

BBN:
$T \approx 10^{9}K\text{-}10^{7}K$ $t \approx 10s\text{-}10^{3}$ s



PRyM_main.py: Takes information from modules to compute light element abundances at the end of BBN

PRyM_init.py: Initialization Code

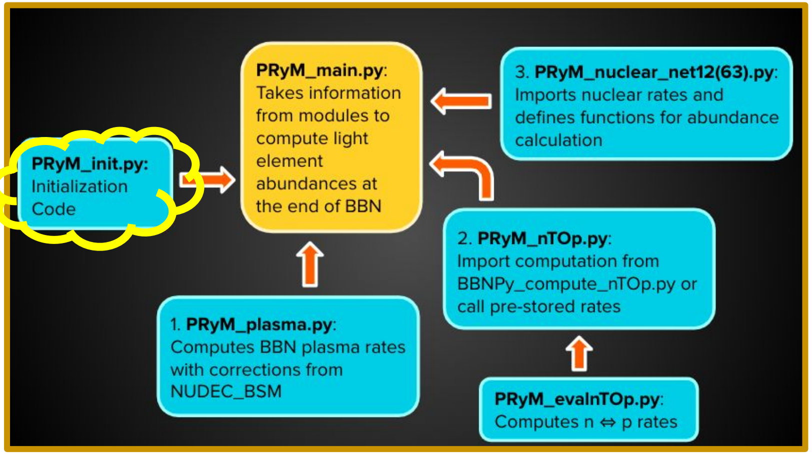
3. **PRyM_nuclear_net12(63).py**: Imports nuclear rates and defines functions for abundance calculation

2. **PRyM_nTOp.py**: Import computation from BBNPy_compute_nTOp.py or call pre-stored rates

1. **PRyM_plasma.py**: Computes BBN plasma rates with corrections from NUDEC_BSM

PRyM_evalnTOp.py: Computes n ⇔ p rates

PRyM_init.py



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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:

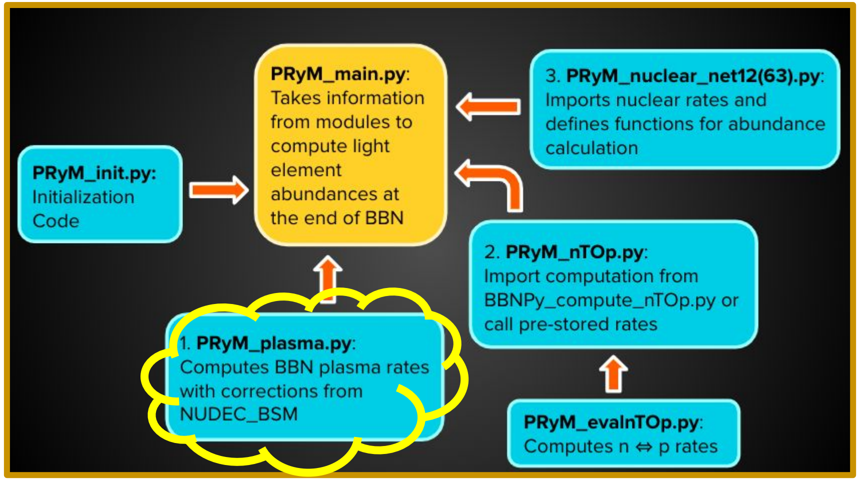
$$\mathbf{T}_{\textbf{start}} = 10^{11}\,\text{K},\ \mathbf{T}_{\textbf{middle}} = 10^{10}\,\text{K},\ \mathbf{T}_{\textbf{end}} = 6*10^{7}\,\text{K}$$

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

PRyM_plasma.py

- Define neutrino, electron, and photon densities along with their time derivatives
- Compute SM matrix elements and Pauli Blocking factors for relativistic fermions
- Evaluate and interpolate matrix elements of neutrino electron scattering as implemented in NUDEC_BSM [1812.05605]
- Output =>

evolution of T_γ / T_ν



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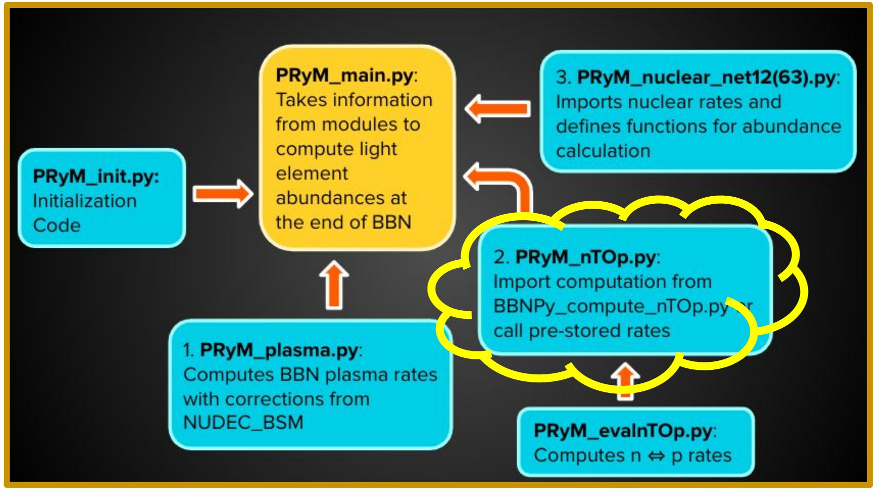
PRyM_nTOp.py

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



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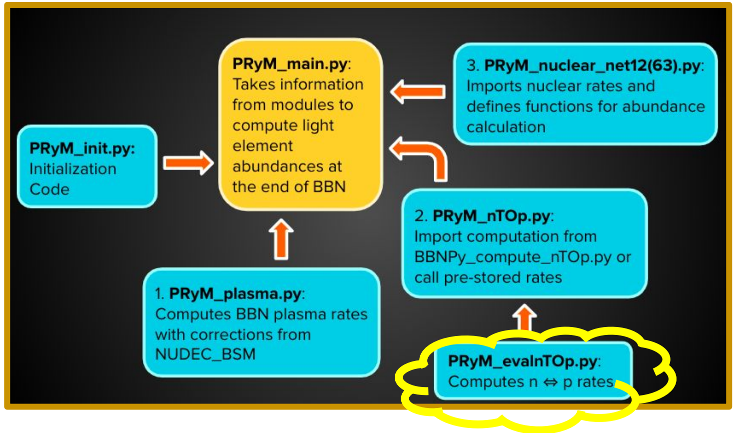
PRyM_compute_nTOp.py

- Define relevant constants
- Compute born approximation for λ_0 (neutron decay constant)
    - Compute radiative corrections to λ_0
    - Compute finite mass corrections λ_0
- Combine radiative and FM corrections to find total correction to λ_0
- Calculate the n ⇔ p rates with the born approximation
    - Corrections made: radiative, finite temperature, finite mass
- Combine all corrections to determine p ⇔ n rates



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PRyM_nuclear_net12(63).py

This part of the code sets up the following equation:

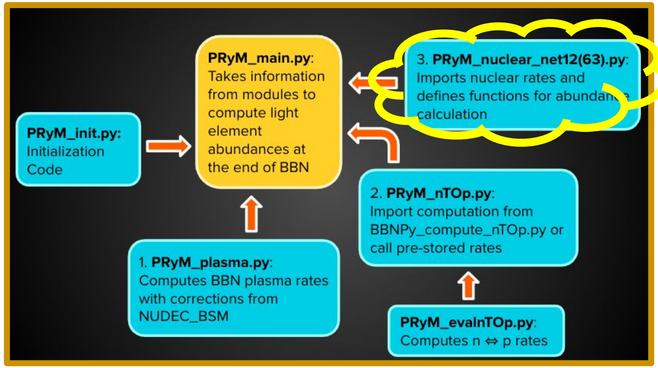
$$\dot{Y}_{i_1} = \sum_{i_2\ldots i_p, j_1\ldots j_q} N_{i_1} \left(\Gamma_{j_1\ldots j_q \to i_1\ldots i_p} \frac{Y_{j_1}^{N_{j_1}} \ldots Y_{j_q}^{N_{j_q}}}{N_{j_1}! \ldots N_{j_q}!} - \Gamma_{i_1\ldots i_p \to j_1\ldots j_q} \frac{Y_{i_1}^{N_{i_1}} \ldots Y_{i_p}^{N_{i_p}}}{N_{i_1}! \ldots N_{i_p}!}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

i, j = enumeration of each element in reaction: $i_1 + \ldots + i_p \Leftrightarrow j_1 + \ldots + j_q$

Y_i = abundance of i^{th} element

N_{ip} = the number of elements, i_p present in the reaction

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



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PRyM_nuclear_net12(63).py, cont.

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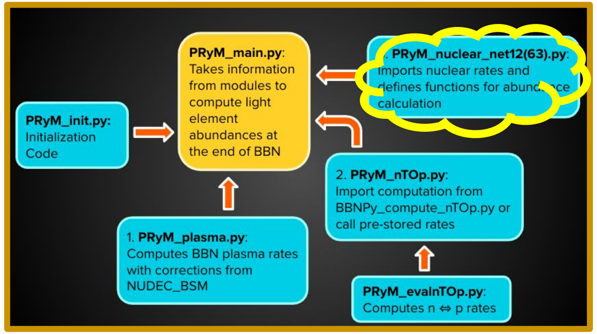

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PRIMAT driven: Nuclear rates are implemented according to the statistical determination of various groups. See refs [63–68] in 2206.00693. Follows theoretical energy modeling tuned to datasets.

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

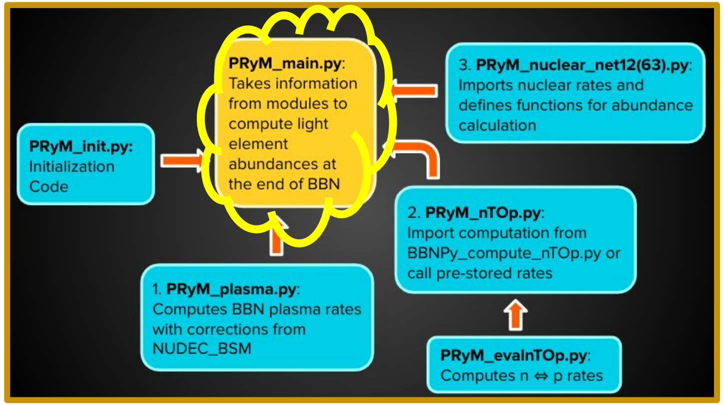
NACRE II driven: Nuclear rates are interpolated from the updated NACRE compilation [1310.7099], comprising charged-particle-induced reactions. For $D + p \to \gamma + {}^3He$ we use the LUNA result*; for ${}^7Be + n \to p + {}^7Li$ we adopt the baseline of 1912.01132.

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

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}**



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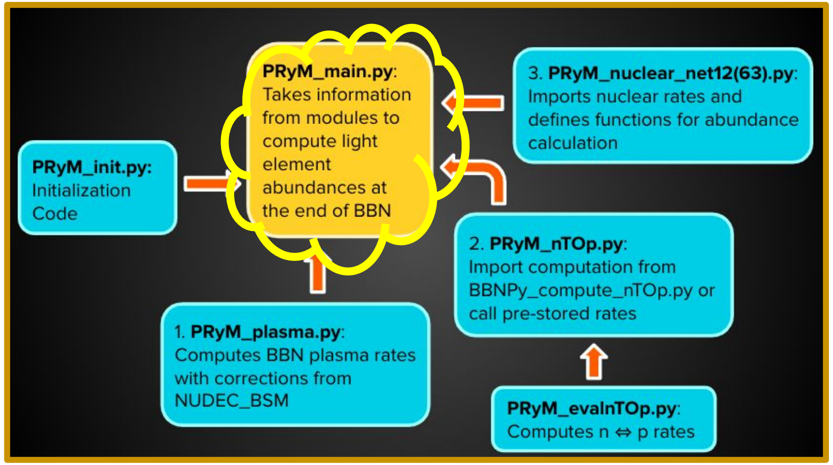
PRyM_main.py, cont.

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 entropy, including effects from non-instantaneous decoupling
- *Defines* temperature eras and baryon number for abundance calculation
- *Imports* n ⇔ p rates and nuclear rates from modules



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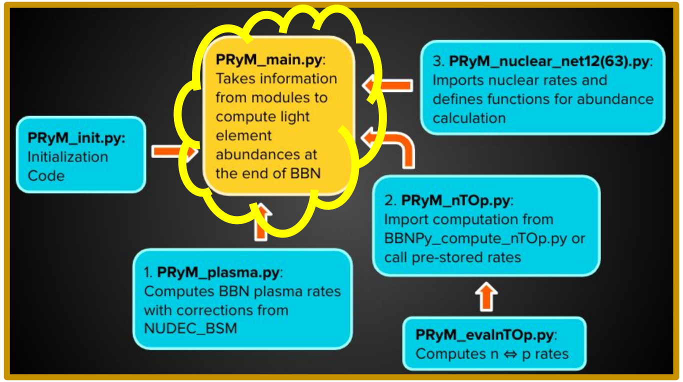
PRyM_main.py, cont.

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



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Methodology

- We modify *PRyMordial* to analyze the effect of varying N_{eff} and ξ_ν
  - Account for the possibility of a nonzero lepton asymmetry **$|\xi_{\nu\mu,\tau}| >> |\xi_{\nu e}|$** by varying ΔN_{eff}
  - Weak-interaction rates evaluated integrating over nucleon thermal distributions with chemical potential $\mu_Q \equiv \mu_n - \mu_p =$ **$-\mu_{\nu e} \neq 0$**
- Bayesian analysis of Early Universe data:

$$\boxed{\mathrm{TS}_{\mathrm{cosmo}} \equiv -2(\underbrace{\log\mathcal{L}_{\mathrm{CMB}}} + \underbrace{\log\mathcal{L}_{\mathrm{BBN}}})}$$

$$\boxed{\log\mathcal{L}_{\mathrm{CMB}} = -\frac{1}{2}\Delta\vec{v}^{\,T}\,\mathcal{C}_{\mathrm{CMB}}^{-1}\,\Delta\vec{v}}\qquad \boxed{\log\mathcal{L}_{\mathrm{BBN}} = -\frac{1}{2}\sum_X\left(\frac{X^{\mathrm{th}} - X}{\sigma_X}\right)^2}$$

$\Delta v \equiv v^{\mathrm{th}} - v$, $v = (Y_P, \Omega_B h^2, N_{\mathrm{eff}})^T$ and $X = \{Y_P, D/H\}$

Methodology, cont.

- Parameters varied according to the uniform priors:

$$-2 \leq \Delta N_{\mathrm{eff}} \leq 2 \qquad -0.2 \leq \xi_\nu \leq 0.2 \qquad 1 \leq (\eta_B \times 10^{10}) \leq 10$$

- Marginalize over the neutron lifetime and the adopted nuclear uncertainties
- Gaussian prior: $\tau_n = (879.4 \pm 0.6)$ s from PDG
- Assign log normal distributions to uncertainties in the nuclear rates as is done in [1403.6694]
- MCMC analysis via the emcee package (See [1202.3665] for more detail)
- From the best-fit values minimizing TScosmo we also compute the Information Criterion

$$\mathrm{IC} \equiv -2 \log \mathcal{L}_{\mathrm{BBN}} + 2k - 1$$

- k = the number of BSM parameters and accounting for the CMB information as an extra constraint in the fit.

ΔIC ~ O(1) (~ O(10)) provides positive (strong) support in favor of NP beyond ΛCDM

How to generate a sufficiently large and persistent lepton-flavored neutrino asymmetry?

1. John March-Russell, Hitoshi Murayama, and Antonio Riotto (1999)
    - Used minimal supersymmetric SM to to create large lepton asymmetry and small baryon asymmetry [9908396]
2. Alberto Casas, Wai Yan Cheng, and Graciela Gelmini (1998)
    - Used the Affleck-Dine (AD) mechanism in which the right handed neutrino acquires a large VEV during inflation to create asymmetry [9709289]
3. Masahiro Kawasaki and Kai Murai (2022)
    - Used AD mechanism as well - theorized L-Balls with lepton number confined in them. This protects L # from being converted to B # via the sphaleron process. [2203.09713]