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

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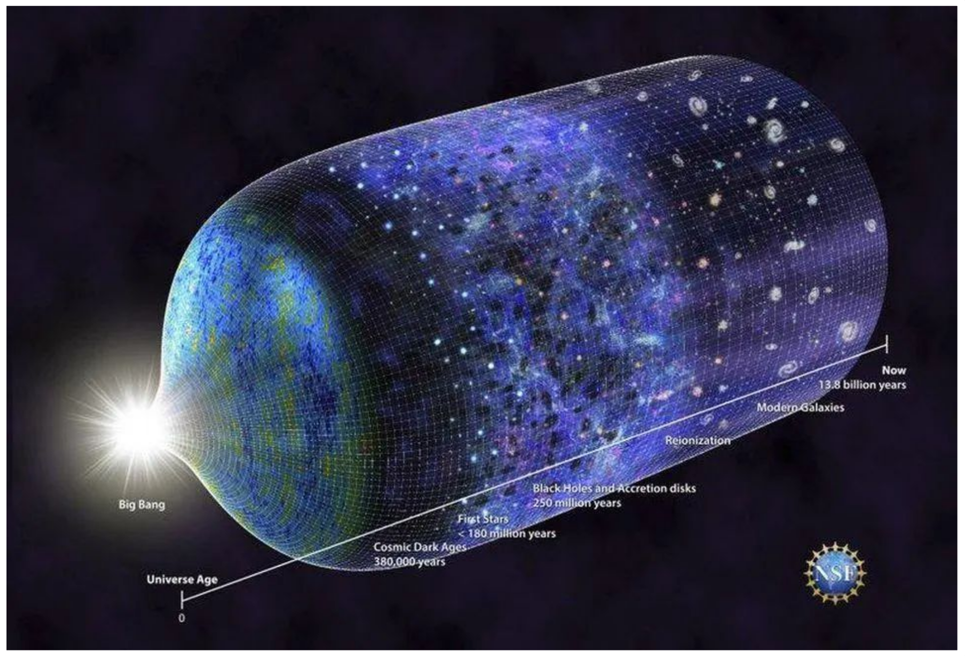
UC SANTA BARBARA
Kavli Institute for
Theoretical Physics

Outline

1. ***A quick primer on early universe cosmology***
2. The physics of BBN
3. Introducing *PRyMordial*
4. Indications for a Nonzero Lepton Asymmetry
    a. Tension in Measurements with the SM
    b. Primordial Lepton Asymmetries
    c. Results and Discussion

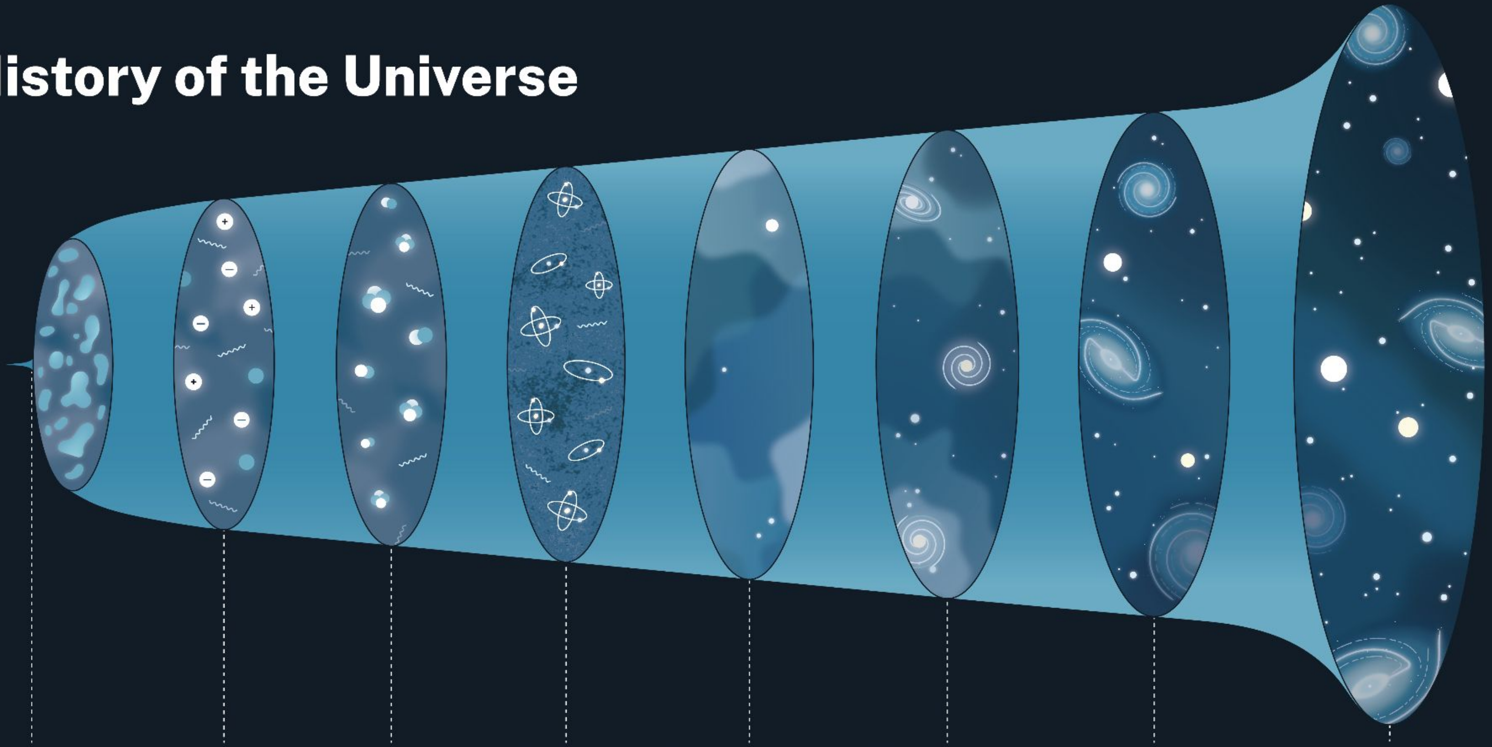
The Basics:
A Primer on Early Universe Physics



- At the instant the universe began the Big Bang Theory tells us that the universe was infinitely hot and infinitely dense
- We believe it has been cooling and expanding since that moment

Image: NSF

History of the Universe



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

Image: NASA

The Expansion History of the Universe

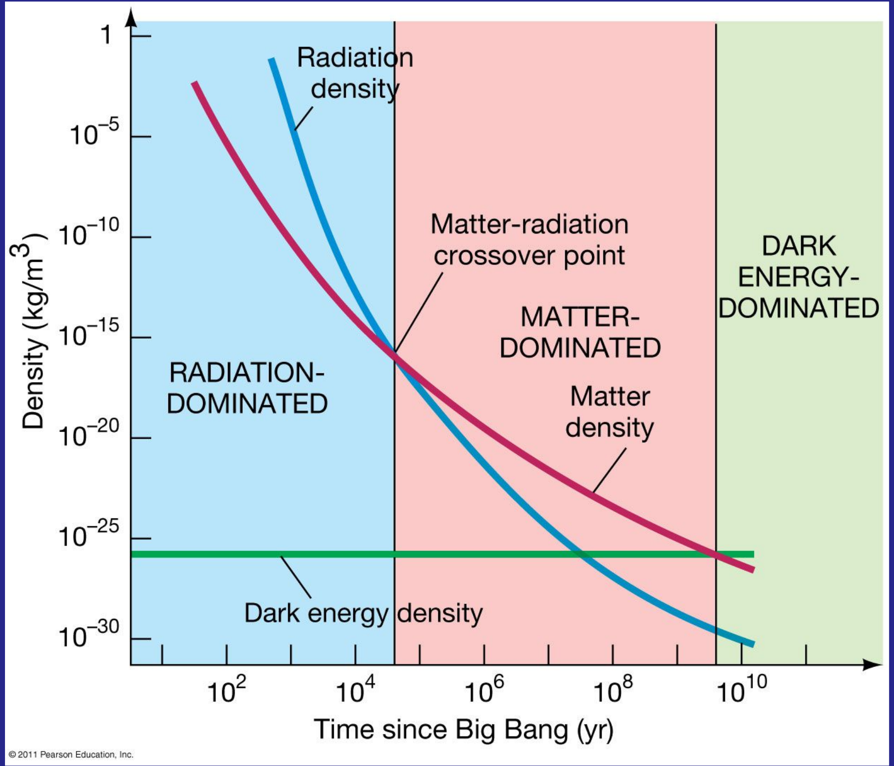


Image: University of Oregon

- We can track the expansion history of the universe by measuring the amount of radiation, matter, and dark energy present in the universe at any given time, all of which contribute to the expansion in different ways.

“Seeing” Back to Very Early Times

- Similarly to the environments we create using particle colliders, the early universe allows particle physicists to probe high energy phenomena
  (i.e. the production of very heavy particles)
- So, how can we “see” back to such unfathomably early times?

Key Early Universe Observables:

- *Big Bang Nucleosynthesis*
- *Cosmic Microwave Background*
- *Baryon Acoustic Oscillations*
- *And many more!*

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

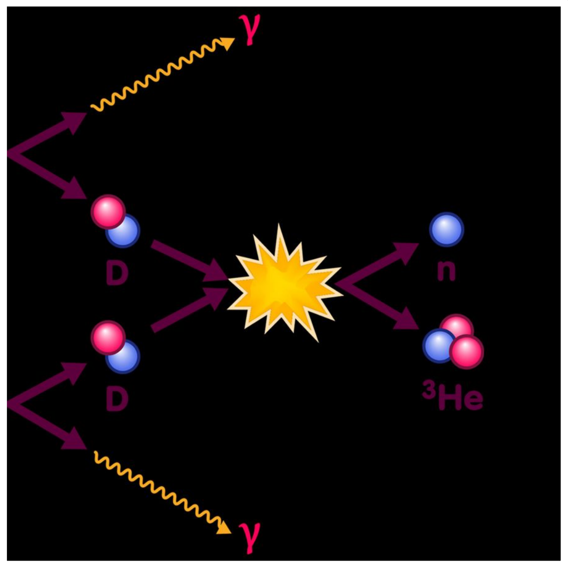


Image: Einstein Online

Cosmic Microwave Background (CMB)

What is the CMB?

A background of low energy photons which originate from the first combinations of nuclei with electrons

What is the purpose of studying it?

By observing very small differences in temperature, we can learn about the conditions of the early universe

(Stay tuned for future work from my collaborators and I!)

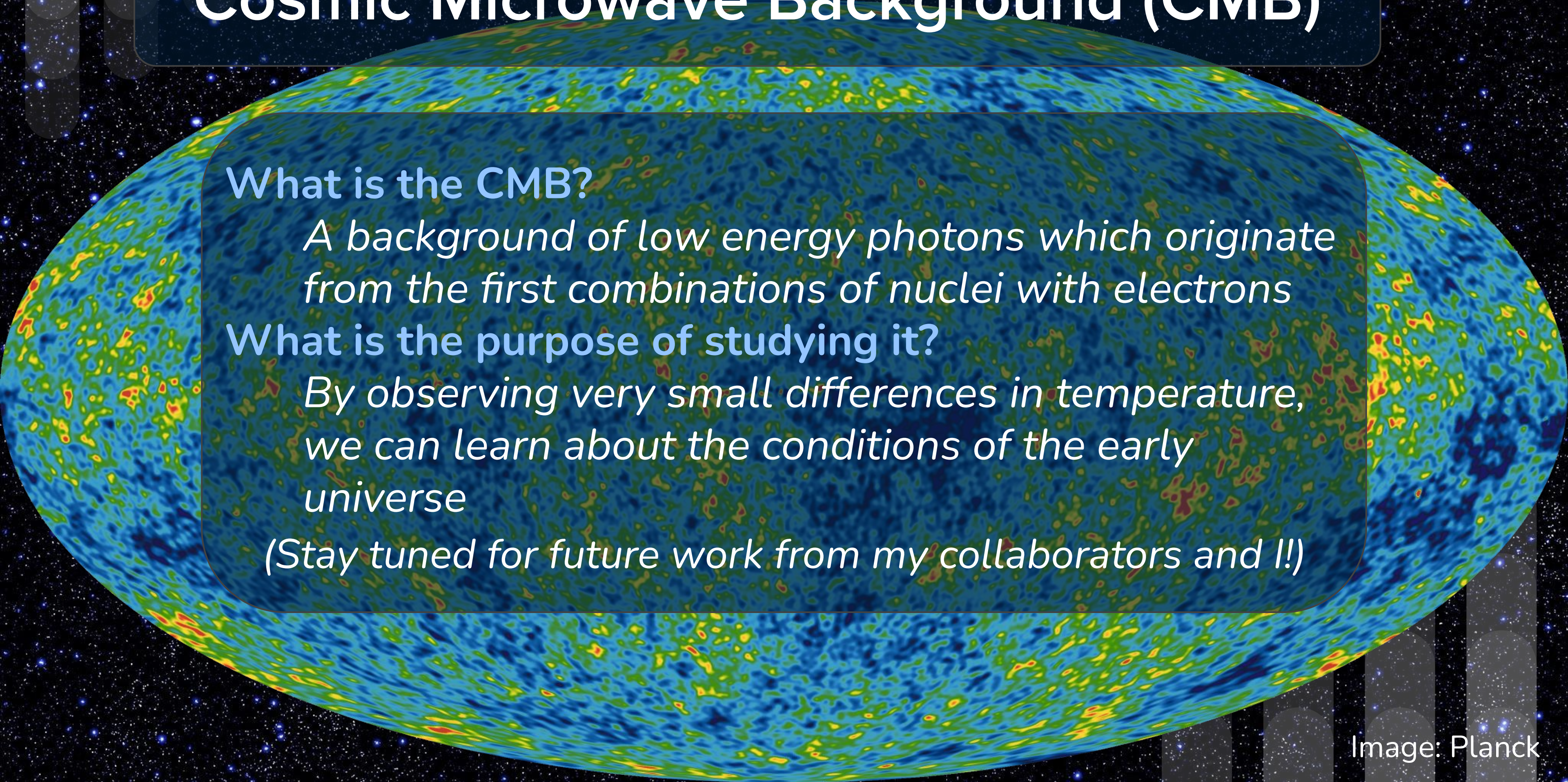


Image: Planck

Baryon Acoustic Oscillations (BAO)

- Alternating **gravity** and **pressure** in the early universe created sound waves which imprinted as "*wrinkles*" on the structure of matter in the universe
- As gravity pulled matter together in the early universe, the matter heated up and that heat generated outward pressure
- Size of oscillations is determined by the *amount of normal matter, dark matter, and dark energy that existed in the early universe*

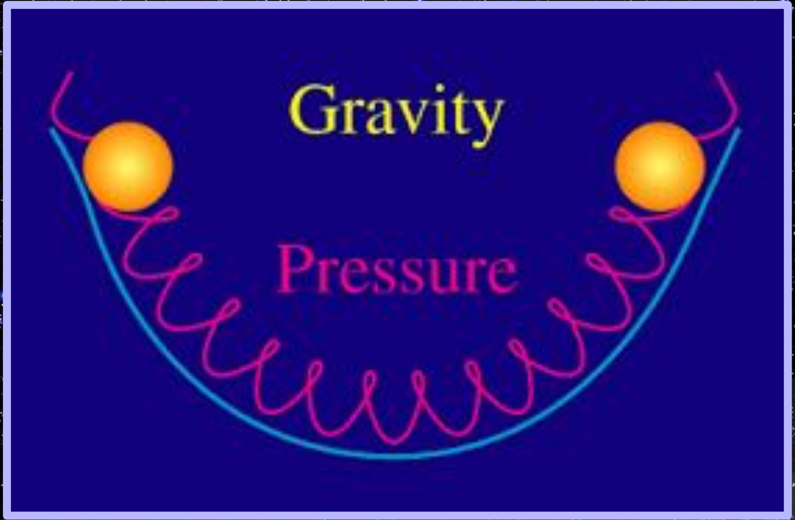


Image: U. Chicago

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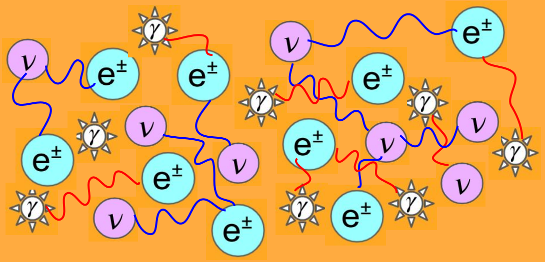
Electrons, positrons, photons, and neutrinos exist in a plasma. Photons and neutrinos are coupled.



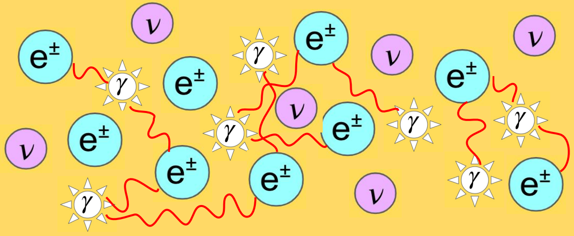
Neutron-proton conversion happens freely and regularly.

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

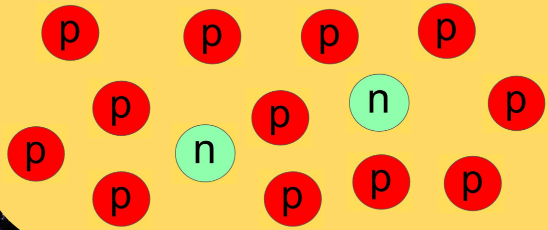
$$n + \nu \longleftrightarrow p + e^-$$

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

Neutrinos decouple non-instantaneously from the plasma.

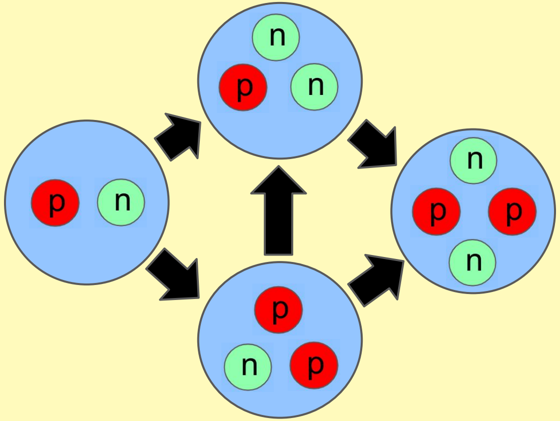


Weak rates freeze out and the proton to neutron ratio is set.



Nucleosynthesis occurs.

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

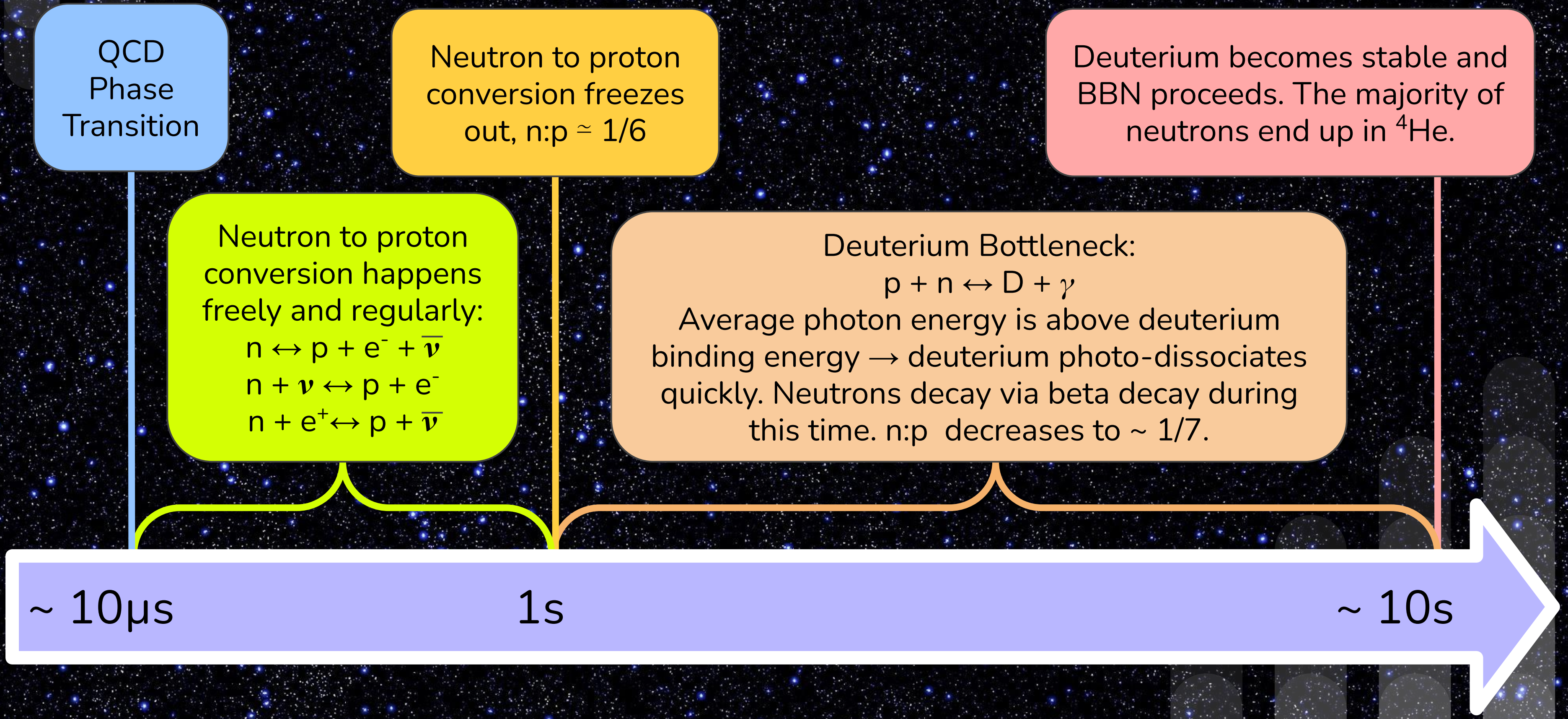


Temperature > O(1 MeV)

Temperature = O(1 MeV)

Temperature < O(1 MeV)

Neutron - Proton Conversion & Freeze Out



QCD Phase Transition

Neutron to proton conversion freezes out, n:p ≃ 1/6

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

Neutron to proton conversion happens freely and regularly:

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

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

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

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.

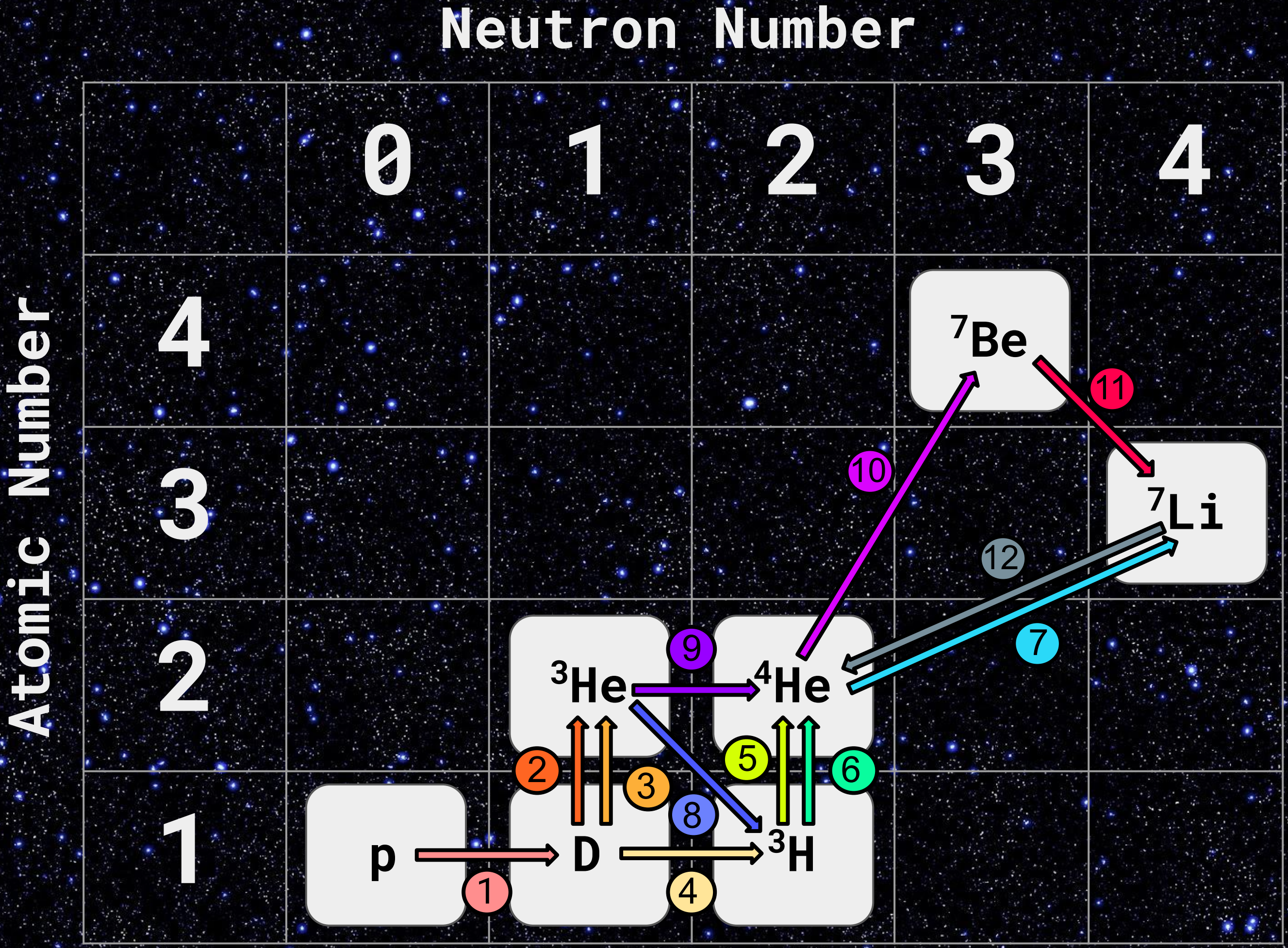
~ 10μs

1s

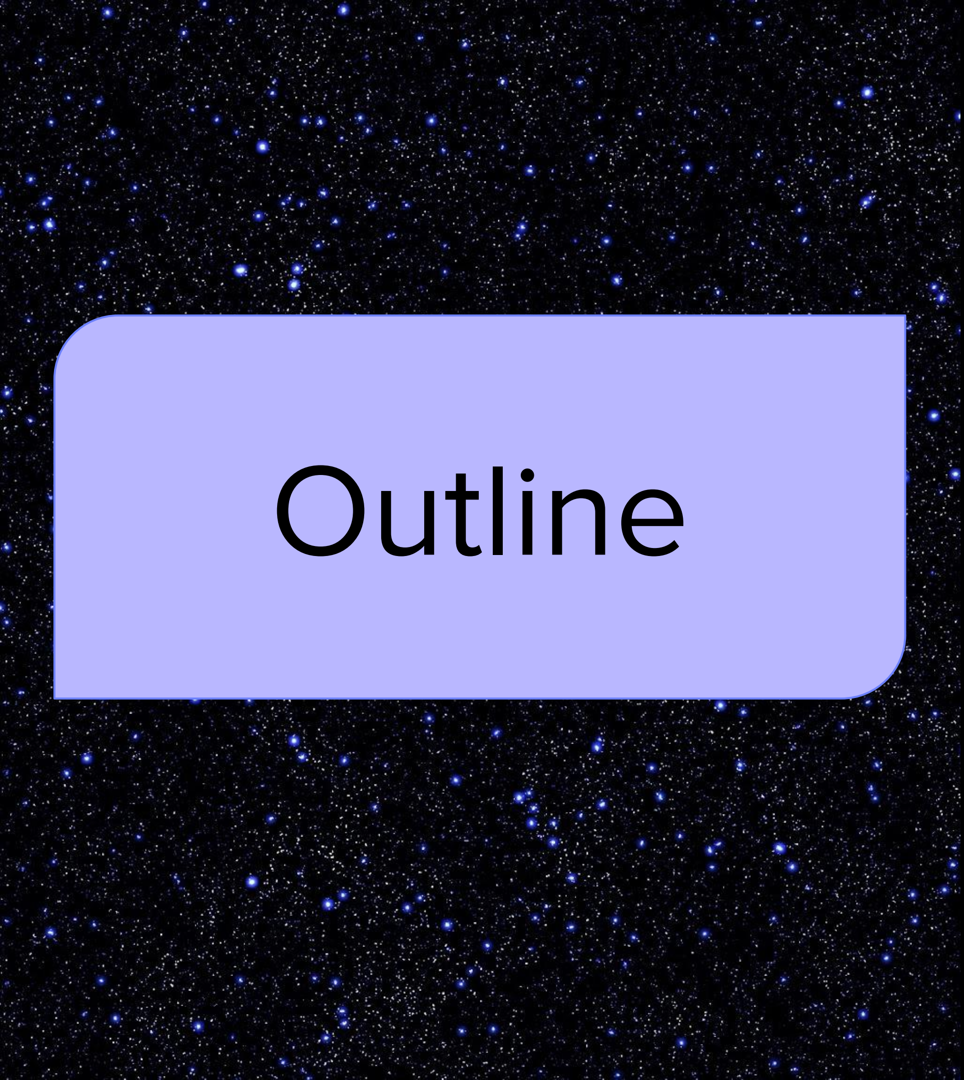
~ 10s

Essential Nuclear Reactions

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



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

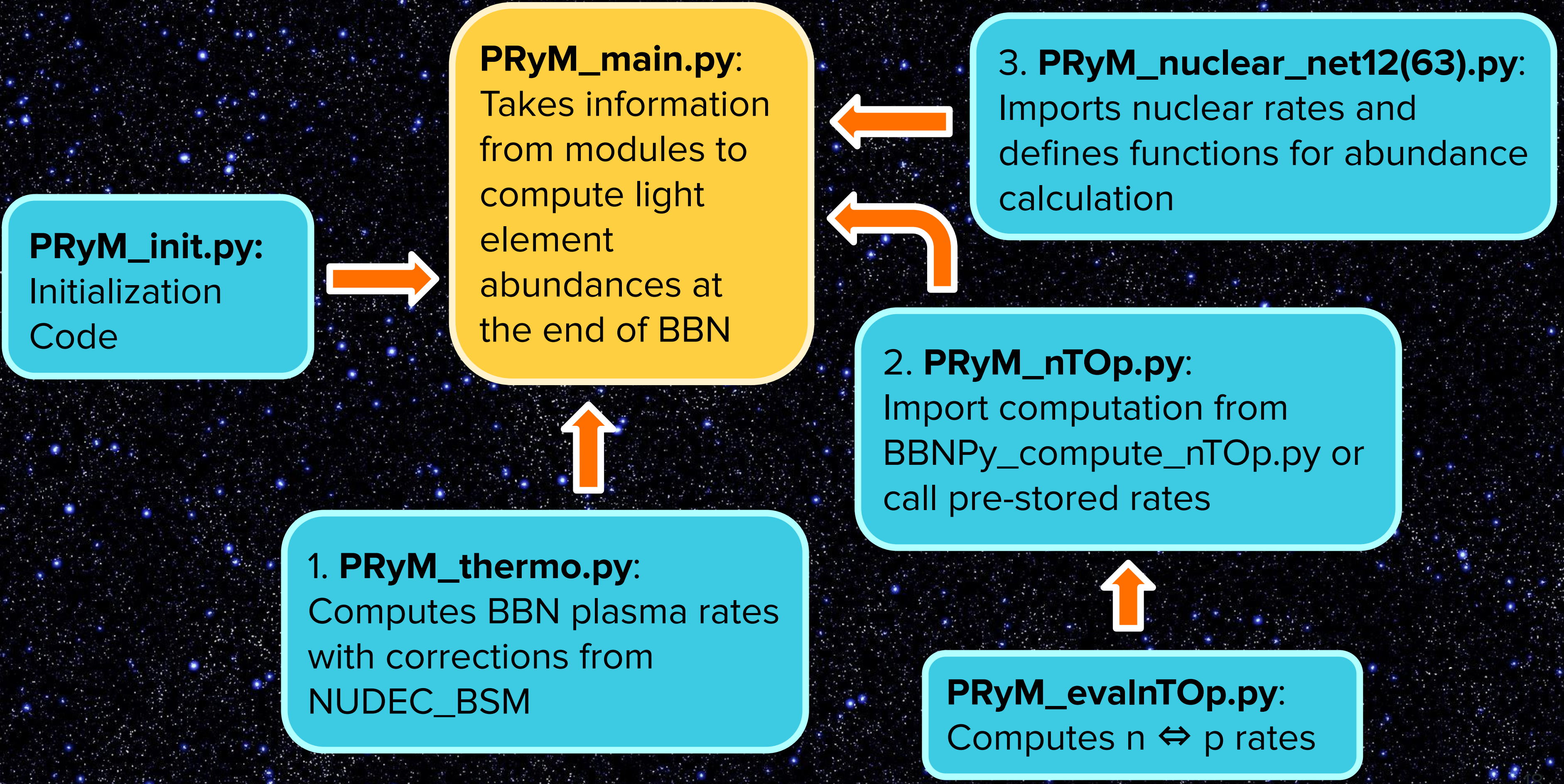
Quantities calculated: N_{eff} and the abundances of ^{4}He, deuterium, ^{3}He, tritium, and ^{7}Li

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

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



PRyM_init.py:
Initialization Code

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

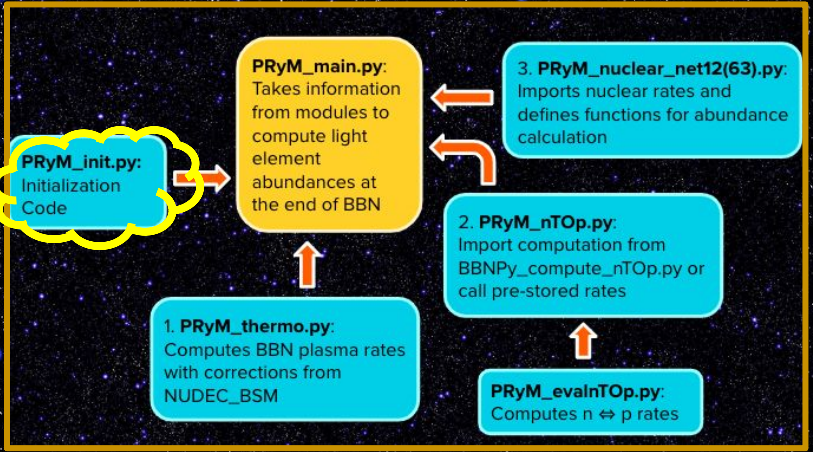
1. **PRyM_thermo.py**:
Computes BBN plasma rates with corrections from NUDEC_BSM

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

PRyM_evalnTOp.py:
Computes n ⇔ p rates

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

PRyM_init.py



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PRyM_evalnTOp.py: Computes n ⇔ p rates

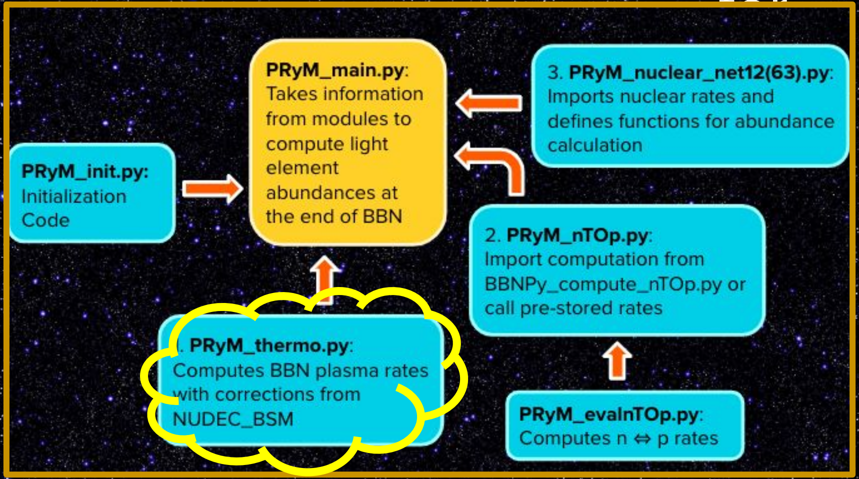
1. Defines units and constants
   a. Conversion factors
   b. Particle masses from PDG 2020
   c. CMB constants, i.e. baryon density today in MeV^3
   d. Defines CGS system for nuncleon & nuclear rates
2. Sets working directory
3. Defines Temperature Eras:

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

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**



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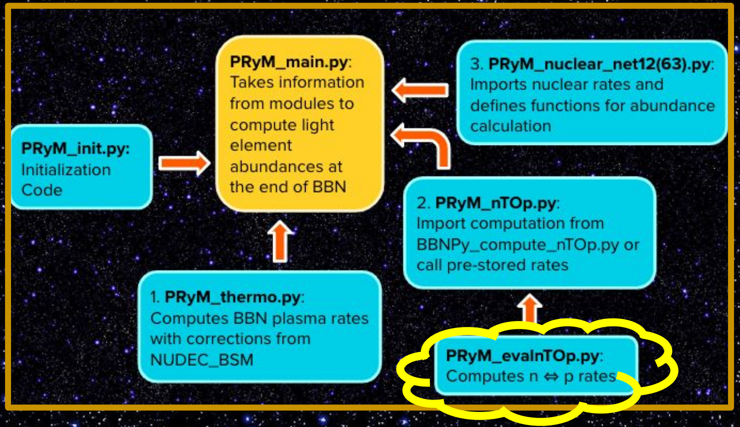
PRyM_evalnTOp.py

- 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



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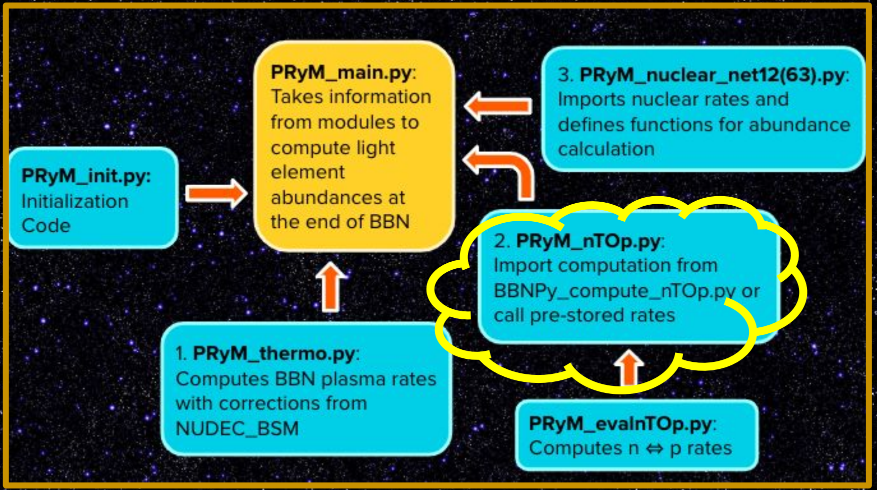
PRyM_nTOp.py

- **<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_nuclear_net12(63).py

This part of the code sets up the following equation:

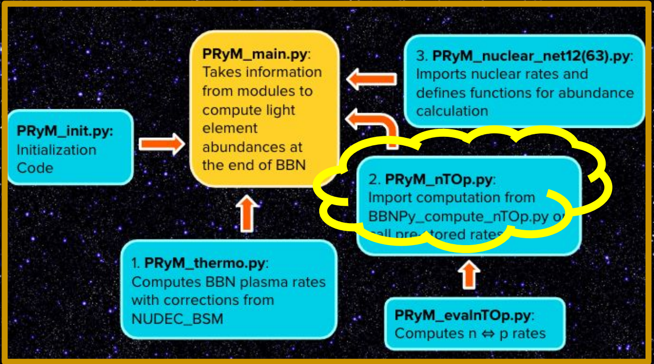
$$\dot{Y}_{i_1} = \sum_{i_2 \ldots i_p, j_1 \ldots j_q} N_{i_1} \left(\Gamma_{j_1 \ldots j_q \to i_1 \ldots i_p} \frac{Y_{j_1}^{N_{j_1}} \ldots Y_{j_q}^{N_{j_q}}}{N_{j_1}! \ldots N_{j_q}!} - \Gamma_{i_1 \ldots i_p \to j_1 \ldots j_q} \frac{Y_{i_1}^{N_{i_1}} \ldots Y_{i_p}^{N_{i_p}}}{N_{i_1}! \ldots N_{i_p}!}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

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: $i_1 + \ldots + i_p \Leftrightarrow j_1 + \ldots + j_q$

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



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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.

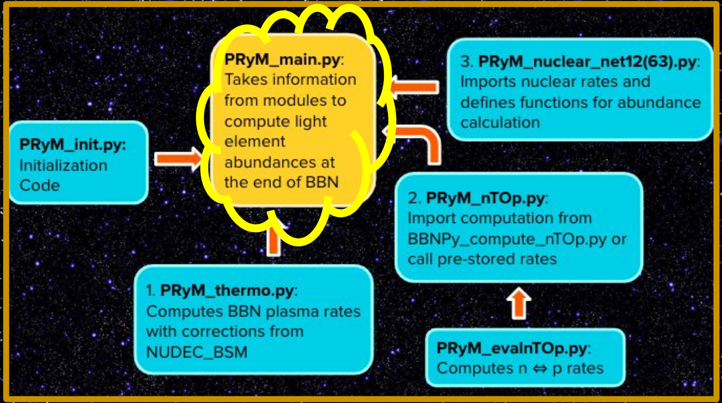
Two approaches for computation of key reaction rates, $\Gamma_{j1\ldots jq \Rightarrow i1\ldots iq}$

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.

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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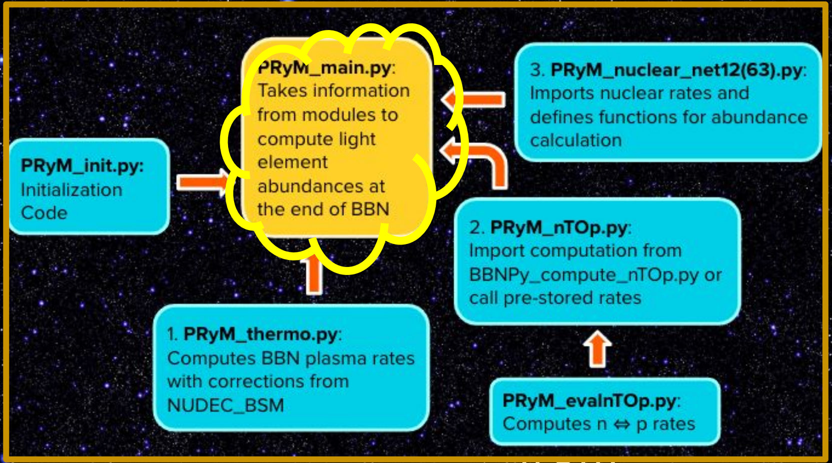
PRyM_main.py, cont.

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 effects from non-instantaneous decoupling
- *Defines* temperature eras and baryon calculation
- *Imports* n ⇔ p rates and nuclear rates modules



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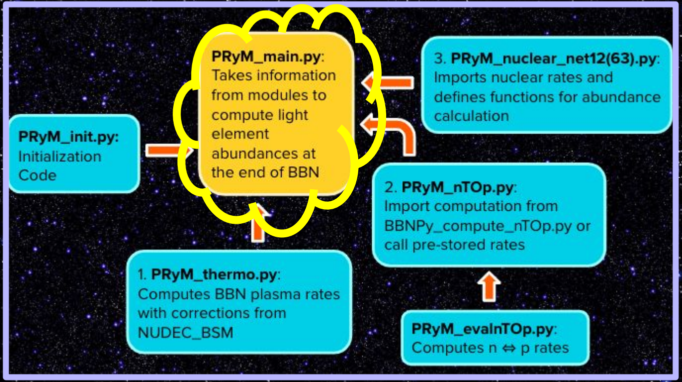
PRyM_main.py, cont.

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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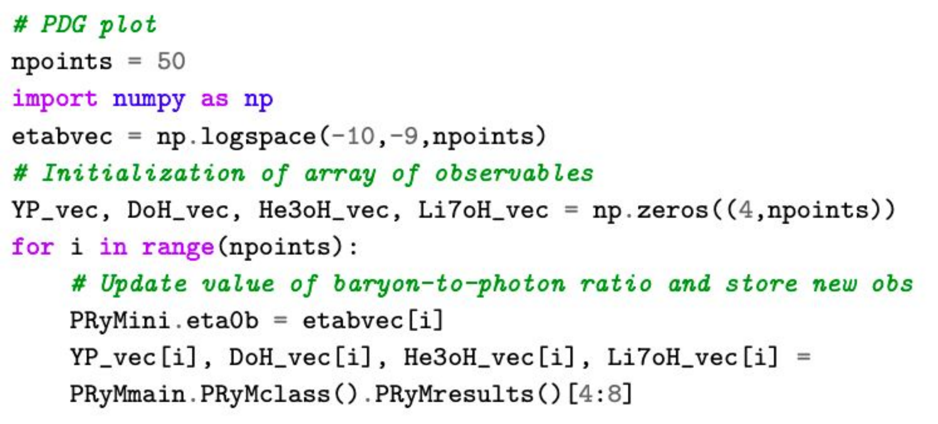
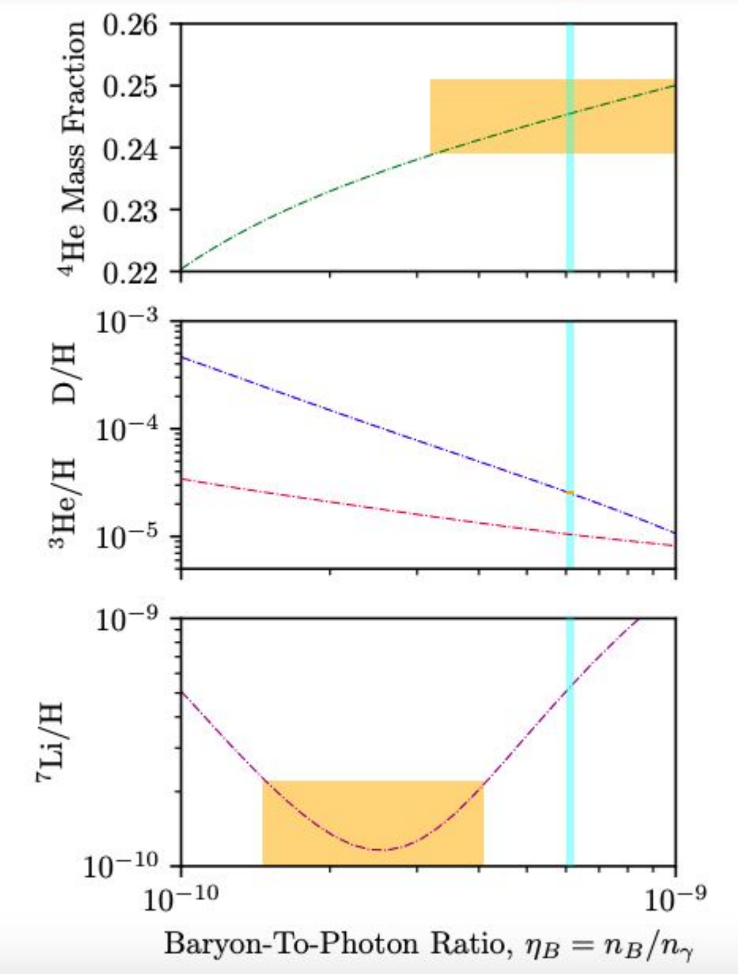
PRyMordial: Results

- 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!

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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 $\longrightarrow$ 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]

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

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

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

From Pitrou, et. al. 2018 [1801.08023]

$\longrightarrow$ 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

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

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

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, γ)^{3}He - important for BBN constraints on New Physics**

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*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

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

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_{eff} = 2.97 ± 0.29, 1σ upper bound

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

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

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

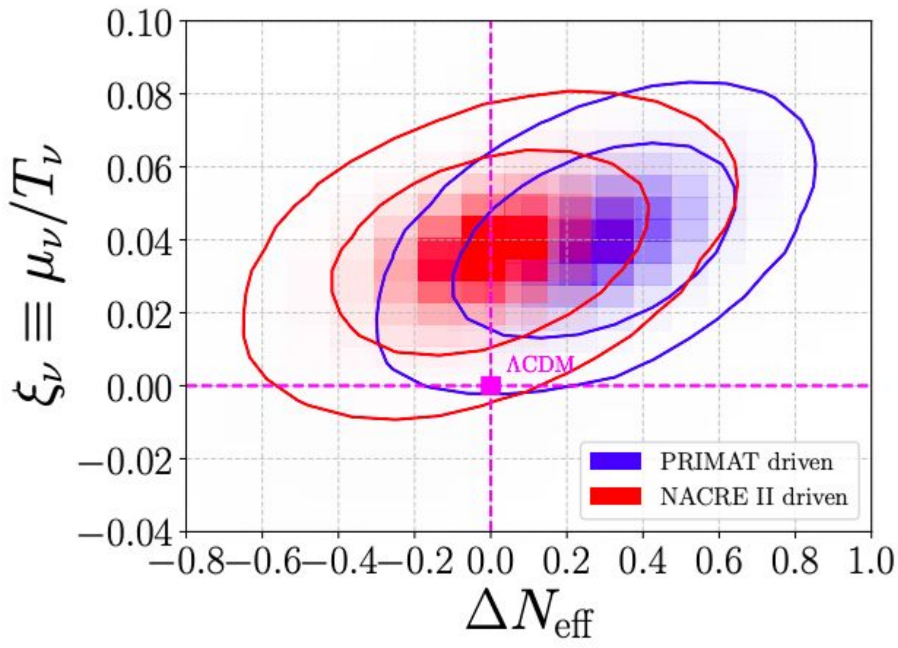
$$\boxed{(n_n/n_p)\big|_{\text{eq.}} \simeq \exp\left(-Q/T_\gamma - \xi_{\nu_e}\right)}$$

- 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 $\xi_{\nu i}$

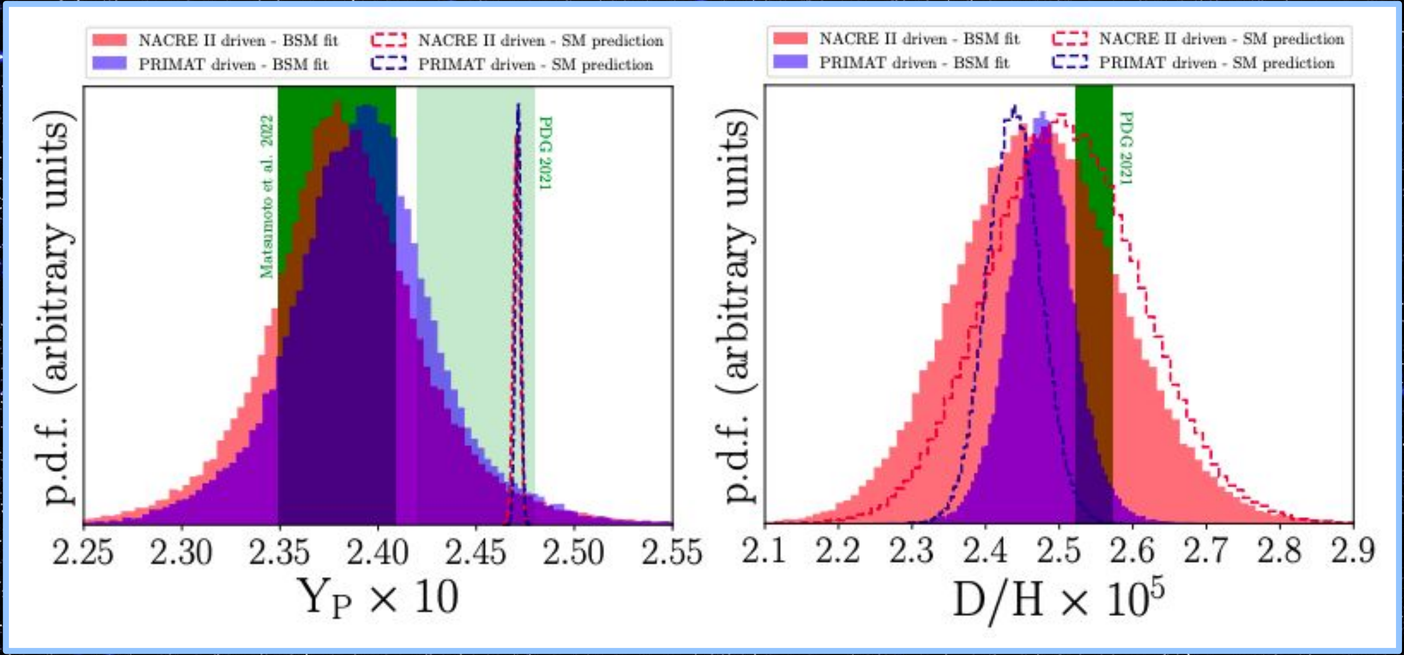
Results

- 68% and 90% probability region for ξ_ν and ΔN_{eff} determined by **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*



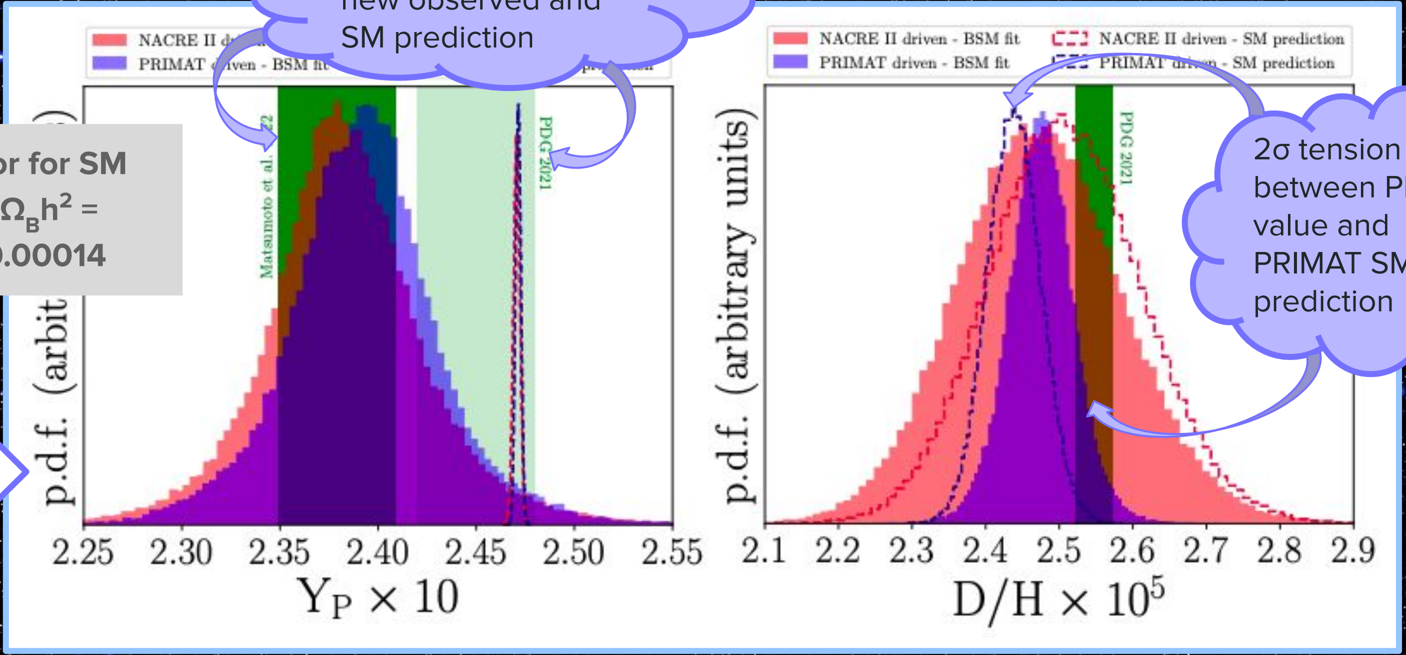
Results, cont.

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



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

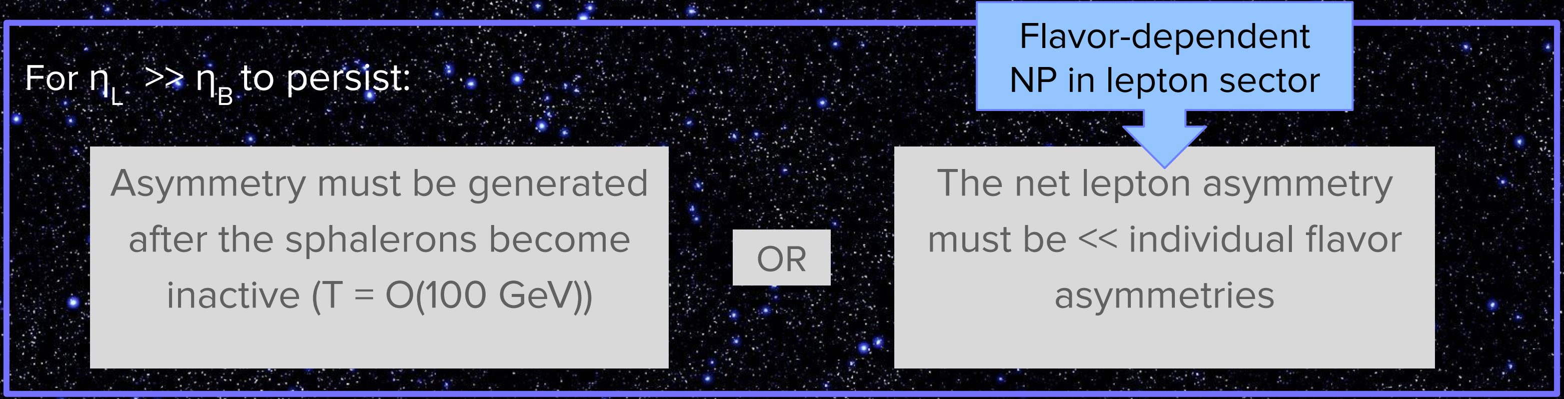
Gaussian Prior for SM Prediction: $\Omega_B h^2$ = 0.02242 ± 0.00014

2σ tension between PDG value and PRIMAT SM prediction

Probability density function

Discussion and Conclusion

- $\eta_B \ll \boldsymbol{\eta_L} \cong$ **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

The net lepton asymmetry must be << individual flavor asymmetries

Flavor-dependent NP in lepton sector

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 ✨

I’m applying for postdocs!

Other relevant skills:

- Will bring cookies into the office
- Can do a surprisingly good dolphin impression
- Has a very cute  cat
- Is somehow still mind blown about the whole wave-particle duality thing

My Publications:

BBN: 2307.07061 [hep-ph], 2206.00693 [hep-ph]

Quantum Gravity + Nonlinear Quantum Mechanics: 2204.03043 [gr-qc]

Dark Matter Modeling: 2010.11650 [astro-ph.HE], 2010.08563 [astro-ph.HE]

Thank you!