Title: BBN circa 2022: New Physics hints from the Early Universe?

Speakers: Mauro Valli

Series: Particle Physics

Date: October 28, 2022 - 11:00 AM

URL: https://pirsa.org/22100144

Abstract: Bang Nucleosynthesis (BBN) is one of the greatest outcome of the Standard Model of Particle Physics when put next to ?CDM cosmology. In this talk, I will first review the key aspects of standard BBN and illustrate a new code -- PRyMordial -- to make state-of-the-art predictions of primordial light-element abundances within and beyond the Standard Model. I will then highlight the latest measurements regarding the primordial abundance of helium-4 and deuterium, and present evidence at the 2 sigma level for a nonzero lepton asymmetry from BBN data jointly with the Cosmic Microwave Background. I will leave some final comments on how a large total lepton asymmetry can be consistently realized in the Early Universe.

Zoom Link: https://pitp.zoom.us/j/95011247645?pwd=S0EwZG9nSHQvTjV0QjBxeHNUWWtmUT09

PERIMETER INSTITUTE

Waterloo, Ontario, Canada — 10 / 29 / 2022

BBN circa '22: NP hints from the Early Universe ?

MAURO VALLI

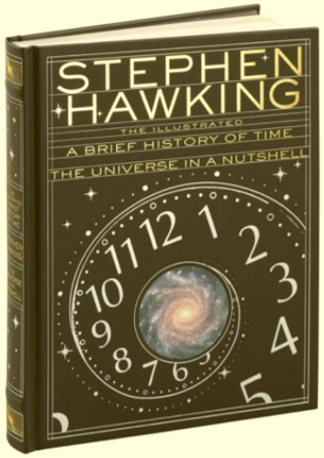
C.N. Yang Institute for Theoretical Physics

SIMONS FOUNDATION

Stony Brook University

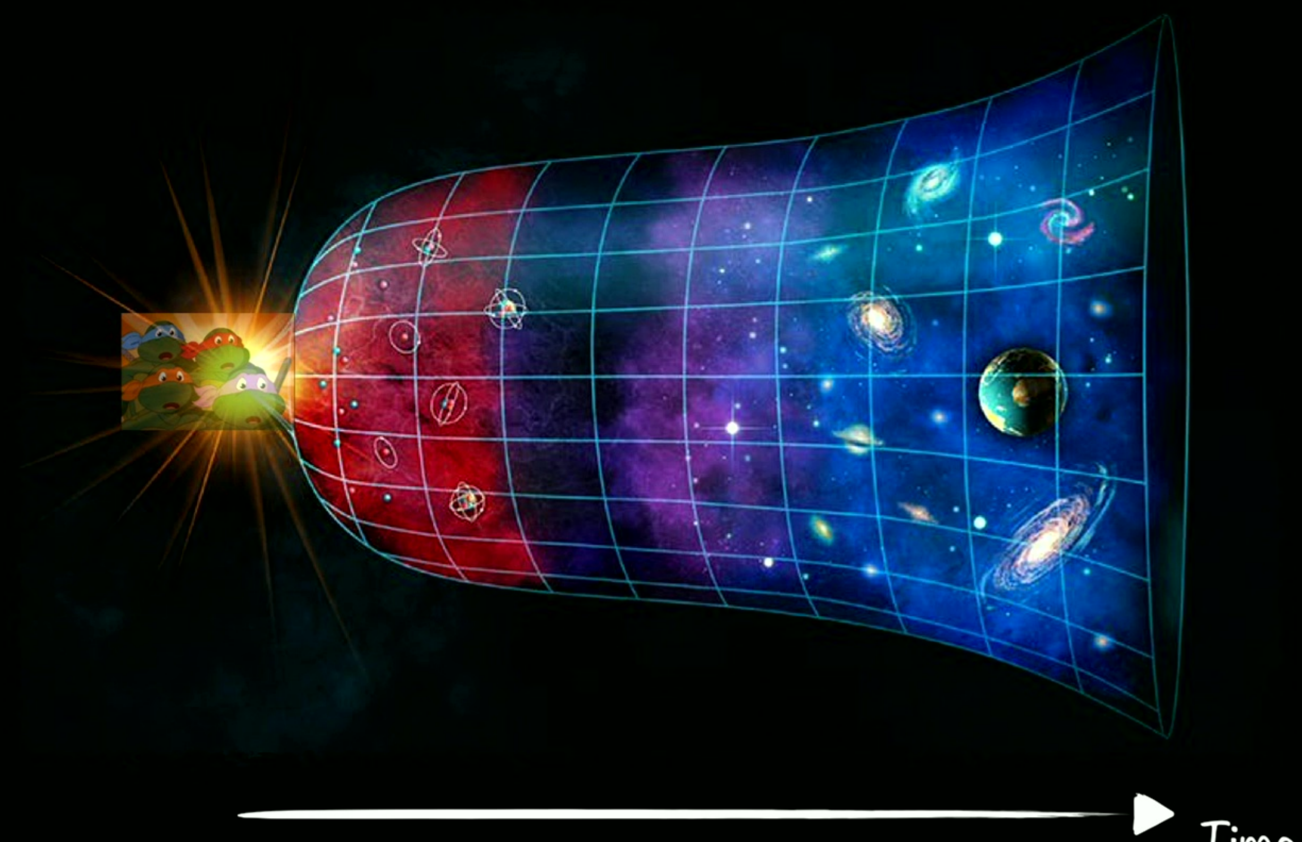
Based on 2206.00693 + work in progress

We know how EVERYTHING really started ...



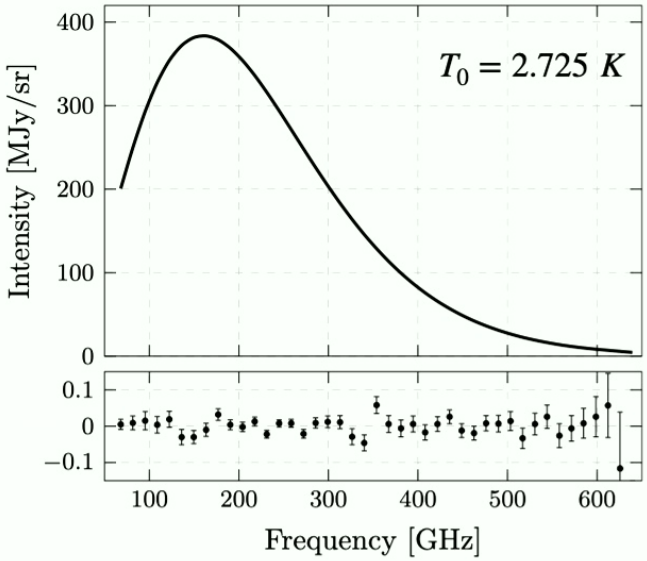
"What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise." The scientist gave a superior smile before replying, "What is the tortoise standing on?" "You're very clever, young man, very clever," said the old lady. "But it's turtles all the way down!"

... nevertheless, we know there's been much more than turtles:

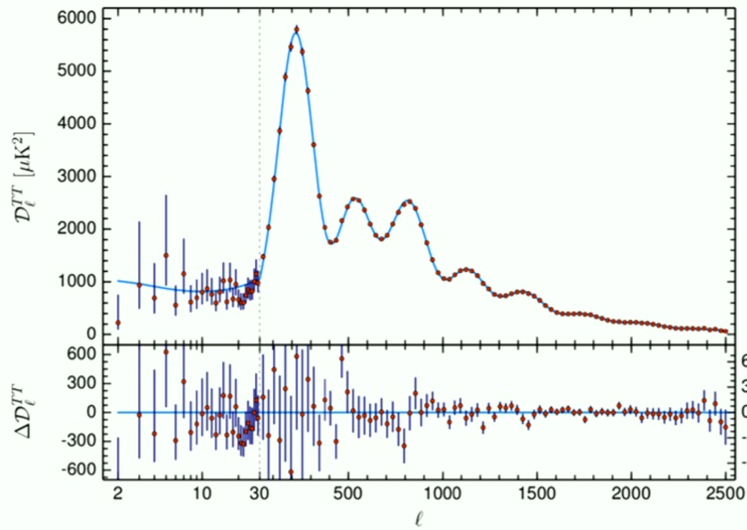


CMB <—> EARLY UNIVERSE INITIAL CONDITIONS

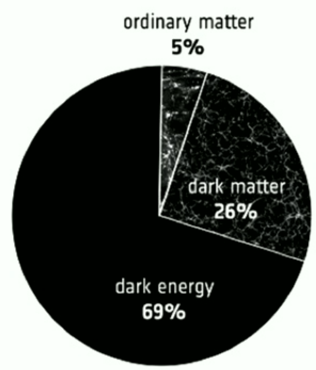
from COBE satellite



from PLANCK satellite



EARLY UNIVERSE
IN A STATE OF
THERMAL EQUILIBRIUM

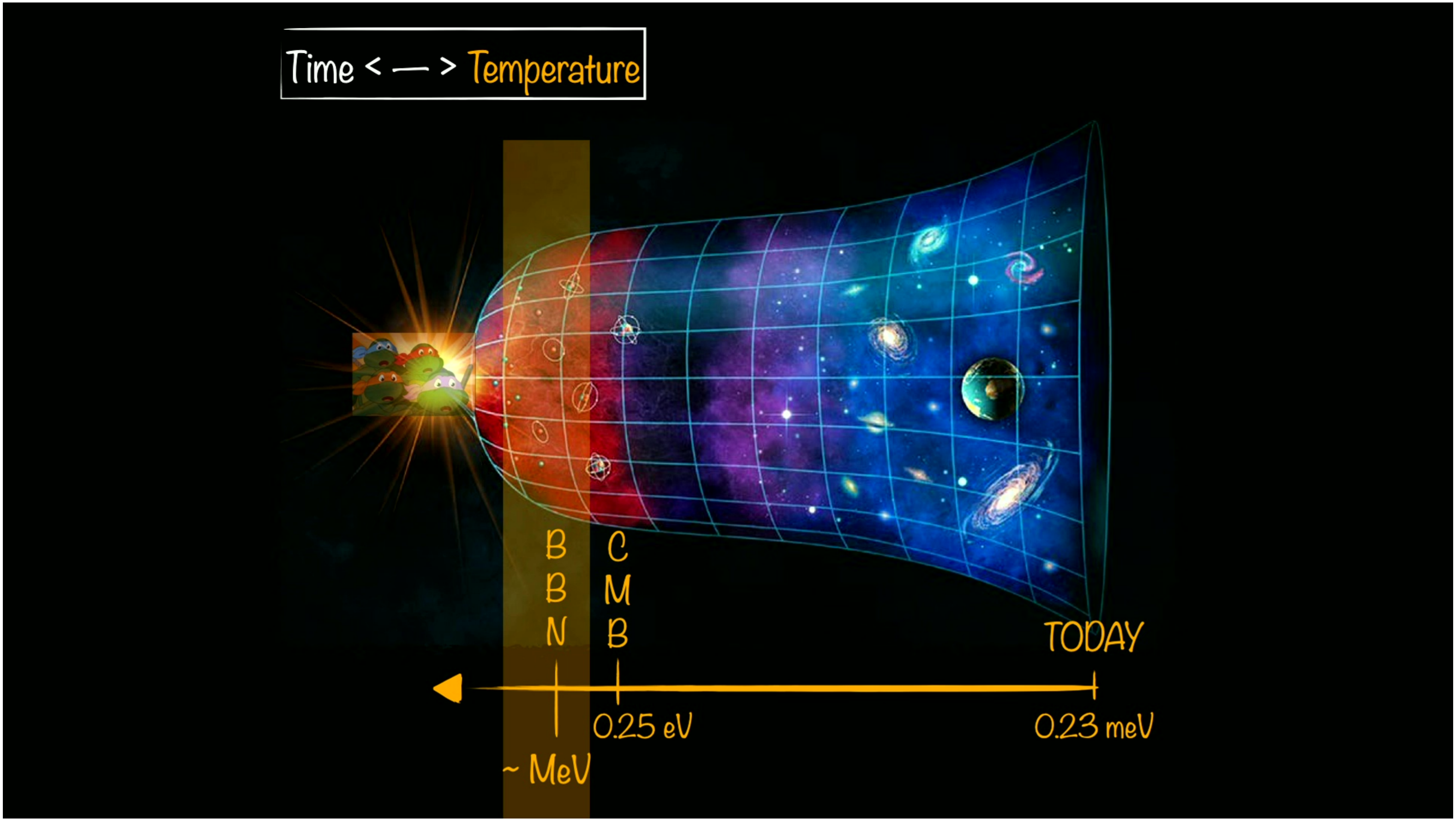


@ % level

$$\eta_B \equiv n_B/n_\gamma \simeq 6 \times 10^{-10}$$

@ 10 % level

measurement of helium-4
and of # relativistic d.o.f.s



Time < — > Temperature
BBN
CMB
TODAY
0.25 eV
0.23 meV
~ MeV

BBN era in ΛCDM

For T $\gtrsim$ 10 MeV, 3 relativistic species $(\gamma, e^{\pm}, \nu)$:

$$H^2 \simeq \frac{1}{3M_{Pl}^2}\,\frac{\pi^2}{30}\left(2 + 2\times 2\times\frac{7}{8} + 2\times\frac{7}{8}\,N_\nu\right)T_\gamma^4$$

From 1st law of thermodynamics + continuity eq.:

$$d(sa^3)/dt = 0 \quad , \quad s = (\rho + P)/T_\gamma$$

$\Rightarrow$ $T_\gamma(t)$, $T_\gamma(a)$ Universe background in radiation domination era

BBN era in ΛCDM

With Universe expansion/cooling, weak interactions freeze out:

$$H \sim \Gamma_{weak} \sim n\langle \sigma v \rangle \sim T^3 \times G_F^2 T^2 \quad \Rightarrow \quad T_{f.o.}^{(weak)} \sim \text{MeV}$$

Moreover, from entropy conservation, for $T_\gamma \leq m_e$:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \;\Leftrightarrow\; N_{eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{tot.} - \rho_\gamma}{\rho_\gamma}\right) = 3.044$$

SM prediction

see, e.g., arXiv: 2210.10307

$\Rightarrow$ $T_\gamma(t)$, $T_\gamma(a)$, $\boxed{T_\nu(T_\gamma)}$

BBN ERA IN ΛCDM

With Universe expansion/cooling, weak interactions freeze out:

$$H \sim \Gamma_{weak} \sim n\langle\sigma v\rangle \sim T^3 \times G_F^2 T^2 \quad \Rightarrow \quad T_{f.o.}^{(weak)} \sim \text{MeV}$$

Moreover, from entropy conservation, for $T_\gamma \leq m_e$:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \;\Leftrightarrow\; N_{eff} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{\rho_{tot.} - \rho_\gamma}{\rho_\gamma}\right) = 3.044$$

SM prediction

see, e.g., arXiv: 2210.10307

$$\Rightarrow \quad T_\gamma(t)\;,\; T_\gamma(a)\;,\; \boxed{T_\nu(T_\gamma)}$$

BBN ERA IN ΛCDM

$T_\nu(T_\gamma)$ relevant in BBN also for β-equilibrium of $n \leftrightarrow p$.

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

$\Rightarrow$

$$(n_n/n_p)|_{T \gtrsim MeV} \simeq \exp(-Q/T)$$

$m_n - m_p \simeq 1.3\,MeV$

$$(n_n/n_p)|_{T \simeq MeV} \simeq 1/6$$

Nucleosynthesis naively at $T_{nucl.} \sim B_D \simeq 2.2$ MeV … BUT:

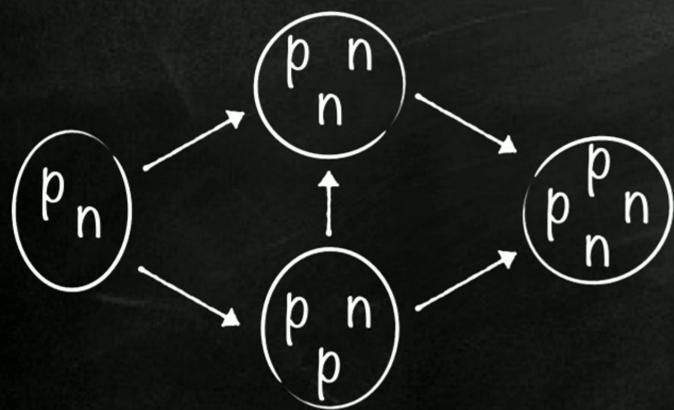
$$\Gamma(n + p \to D + \gamma) \sim n_B \langle \sigma v \rangle_{D\gamma}$$

$$\Gamma(n + p \leftarrow D + \gamma) \sim n_\gamma \exp(-B_D/T_\gamma) \langle \sigma v \rangle_{D\gamma}$$

i.e., it really starts at $T_{nucl.}$ such that: $\eta_B \simeq \exp(-B_D/T_{nucl.})$

BBN ERA IN ΛCDM

Deuterium "bottleneck" implies $T_{nucl.} \simeq 0.1$ MeV. After that :



~ all neutrons into helium-4

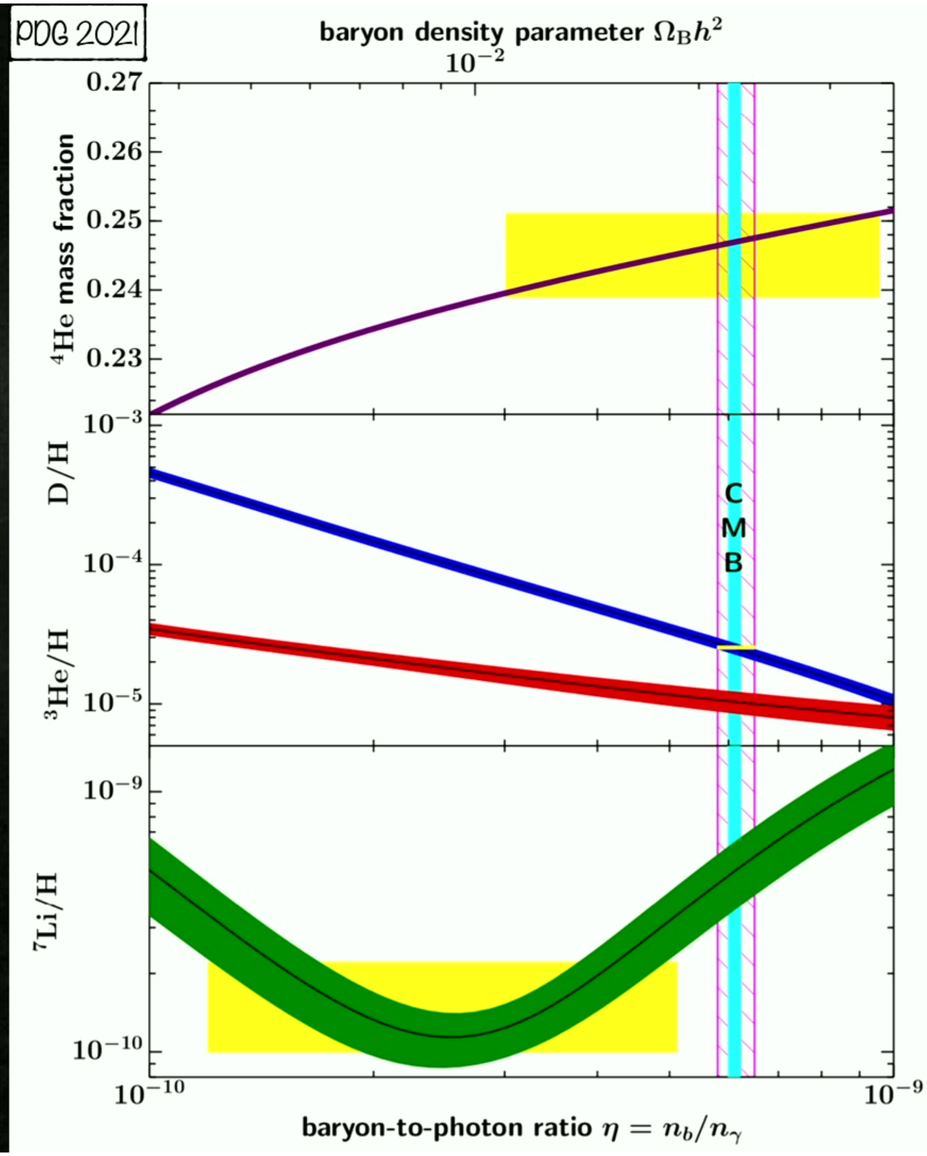
$$(n_n/n_p)\,|_{T\simeq 0.1MeV} \simeq 1/7$$

$$Y_P \equiv \frac{m_{^4He}}{m_B} \simeq \frac{4(n_n/2)}{n_n + n_p} \simeq 0.25$$

Baryon mass fraction in helium-4

$\mathcal{O}(10^{-5})$ residual amount of deuterium and helium-3 relative to p.

Lithium-7 "survives" in smaller relative abundance, $\mathcal{O}(10^{-10})$.


PDG 2021
baryon density parameter $\Omega_B h^2$
10^{-2}
0.27
0.26
0.25
0.24
0.23
^{4}He mass fraction
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
C
M
B
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio $\eta = n_b/n_\gamma$

BBN OBSERVATIONS

Primordial light elements predicted: D, ^3He, ^4He, ^7Li

- Helium-4 observed in extragalactic HII regions

  Emission spectra of gas clouds (detailed line modeling required)

- Deuterium observed in Quasar absorption systems

  Damped Lyman-α spectra from intervening gas along l.o.s.

- Helium-3 observed in the Solar neighborhood

  Solar winds, meteorites, ISM ... stellar nucleosynthesis uncertainties!

- Lithium-7 in the atmosphere of dwarf halo stars

  Physics of convection, depletion indicators ... needs support from data

BBN OBSERVATIONS

Primordial light elements predicted: D, ^3He, ^4He, ^7Li

✅ Helium-4 observed in extragalactic HII regions

Emission spectra of gas clouds (detailed line modeling required)

✅ Deuterium observed in Quasar absorption systems

Damped Lyman-α spectra from intervening gas along l.o.s.

❌ Helium-3 observed in the Solar neighborhood

Solar winds, meteorites, ISM ... stellar nucleosynthesis uncertainties!

❓ Lithium-7 in the atmosphere of dwarf halo stars

Physics of convection, depletion indicators ... needs support from data

arXiv:2204.03167

BBN OBSERVATIONS

Primordial light elements predicted: $D,\ ^3He,\ ^4He,\ ^7Li$

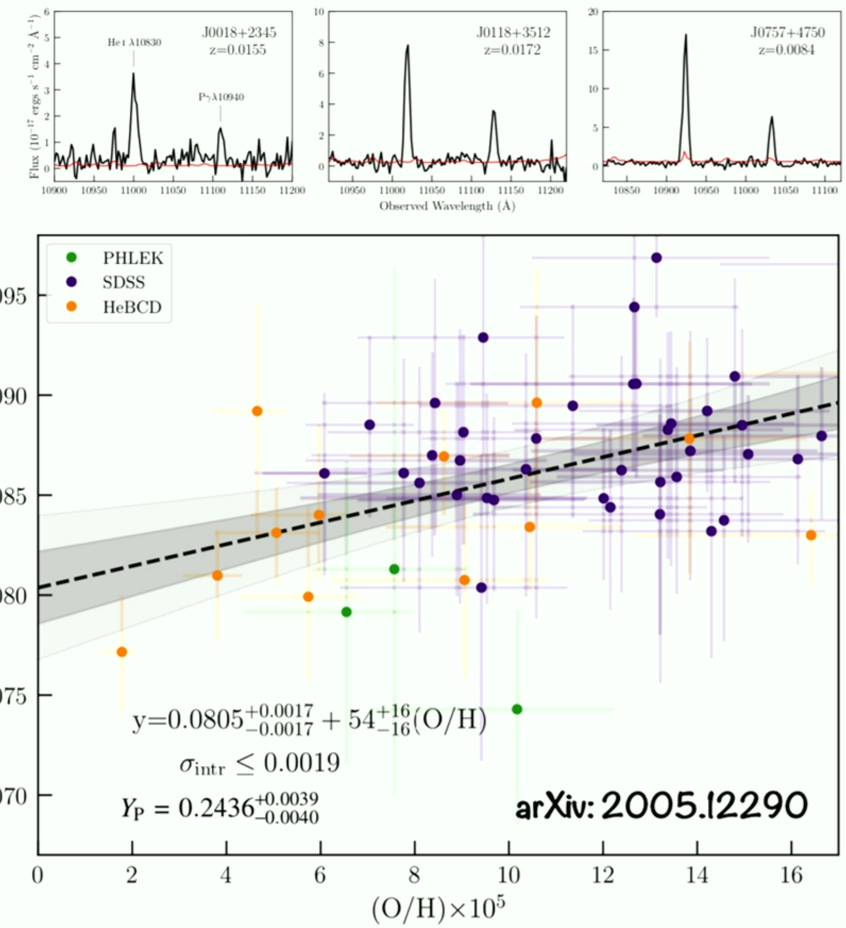
- ✅ Helium-4 observed in extragalactic HII regions
  - Emission spectra of gas clouds (detailed line modeling required)
- ✅ Deuterium observed in Quasar absorption systems
  - Damped Lyman-α spectra from intervening gas along l.o.s.
- ❌ Helium-3 observed in the Solar neighborhood
  - Solar winds, meteorites, ISM ... stellar nucleosynthesis uncertainties!
- ❓ Lithium-7 in the atmosphere of dwarf halo stars
  - Physics of convection, depletion indicators ... needs support from data

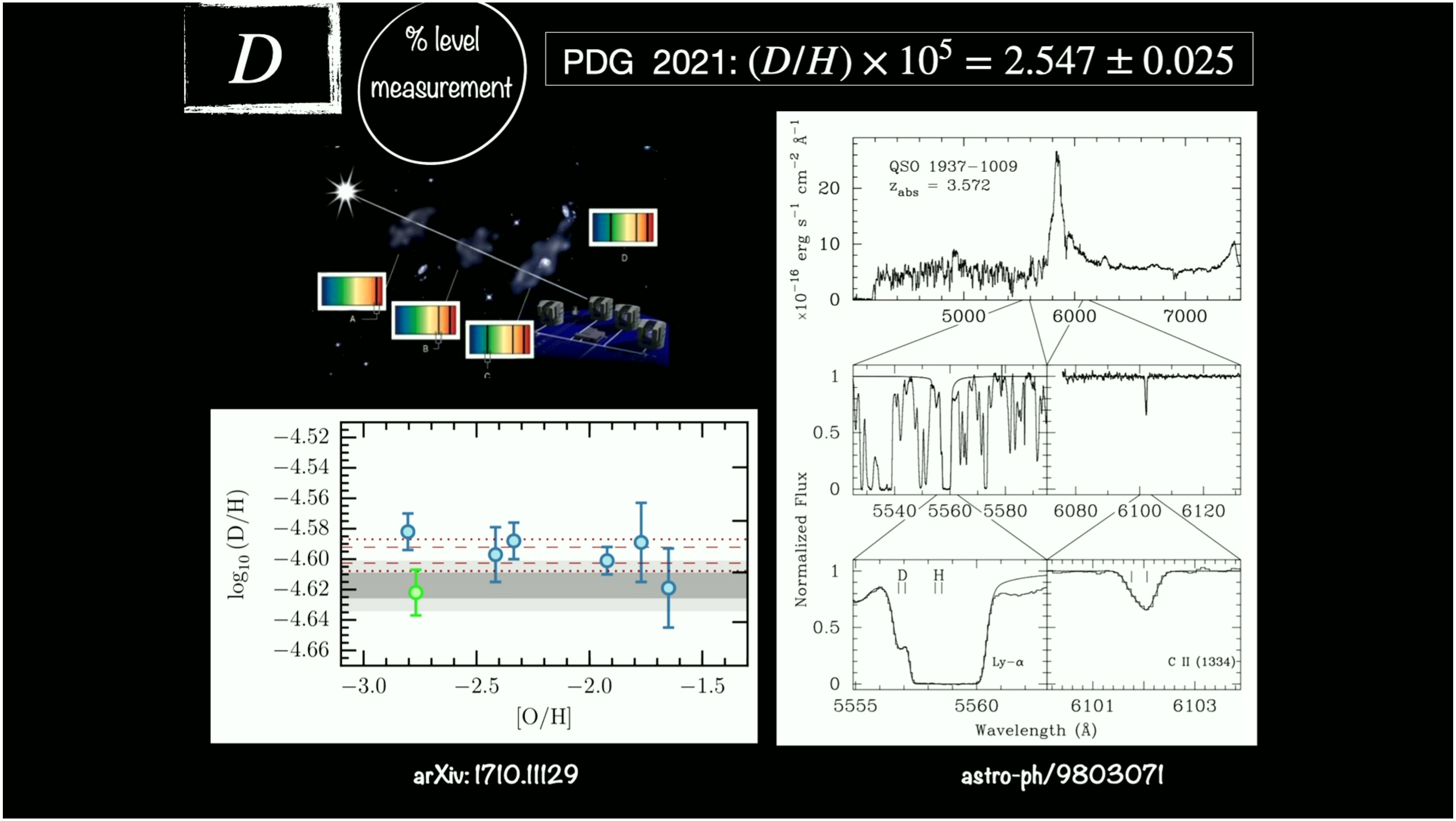
arXiv:2204.03167

^4He

PDG 2021: $Y_P = 0.245 \pm 0.003$

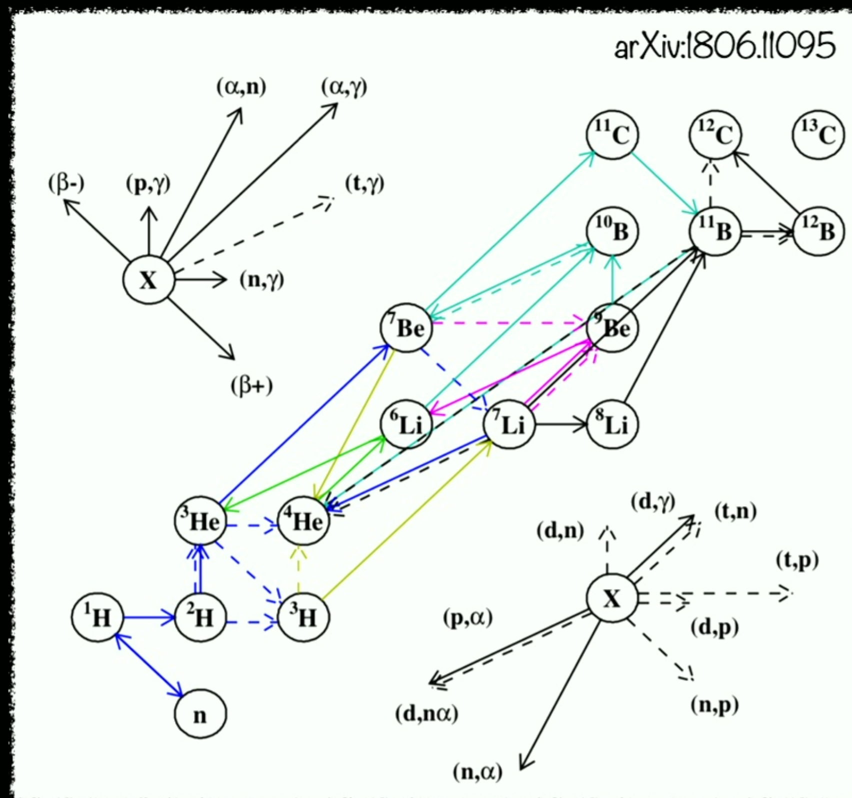
% level measurement




D
% level measurement
PDG 2021: $(D/H) \times 10^5 = 2.547 \pm 0.025$
A
B
C
D
$\log_{10}(D/H)$
−4.52
−4.54
−4.56
−4.58
−4.60
−4.62
−4.64
−4.66
−3.0
−2.5
−2.0
−1.5
[O/H]
QSO 1937−1009
z_{abs} = 3.572
$\times 10^{-16}$ erg s^{-1} cm^{-2} Å^{-1}
0
10
20
5000
6000
7000
Normalized Flux
0
0.5
1
5540
5560
5580
6080
6100
6120
D
H
Ly−α
C II (1334)
5555
5560
6101
6103
Wavelength (Å)
arXiv: 1710.11129
astro-ph/9803071

% LEVEL MEASUREMENTS —> PRECISION ERA …

… BBN details cannot be worked out by hand!



$$\dot{Y}_i \sim n_B\left(\langle\sigma v\rangle_{kl\to ij}Y_kY_l - \langle\sigma v\rangle_{ij\to kl}Y_iY_j\right)$$

PRyMordial: The first 3 min in $\mathcal{O}(10)$ sec

MacBook Pro (13-inch, 2018, Four Thunderbolt 3 Ports)
Processore 2,3 GHz Intel Core i5
Memoria 8 GB 2133 MHz LPDDR3

WARNING

The above claim in this slide is machine dependent :)

arXiv: 221X.XXXXX

A new tool to investigate Big Bang Nucleosynthesis (BBN) within the Standard Model (SM) and Beyond (BSM)

PRyMordial

The first 3 min in $\mathcal{O}(10)$ sec

Anne-Katherine Burns

Tim Tait

Younger Me

AlterBBN

NEW AlterBBN v2.2

arXiv:1106.1363,
arXiv:1806.11095

PRIMAT

PRImordial MATter

arXiv:1806.11095,
arXiv: 2011.11320

WHY A NEW BBN CODE?

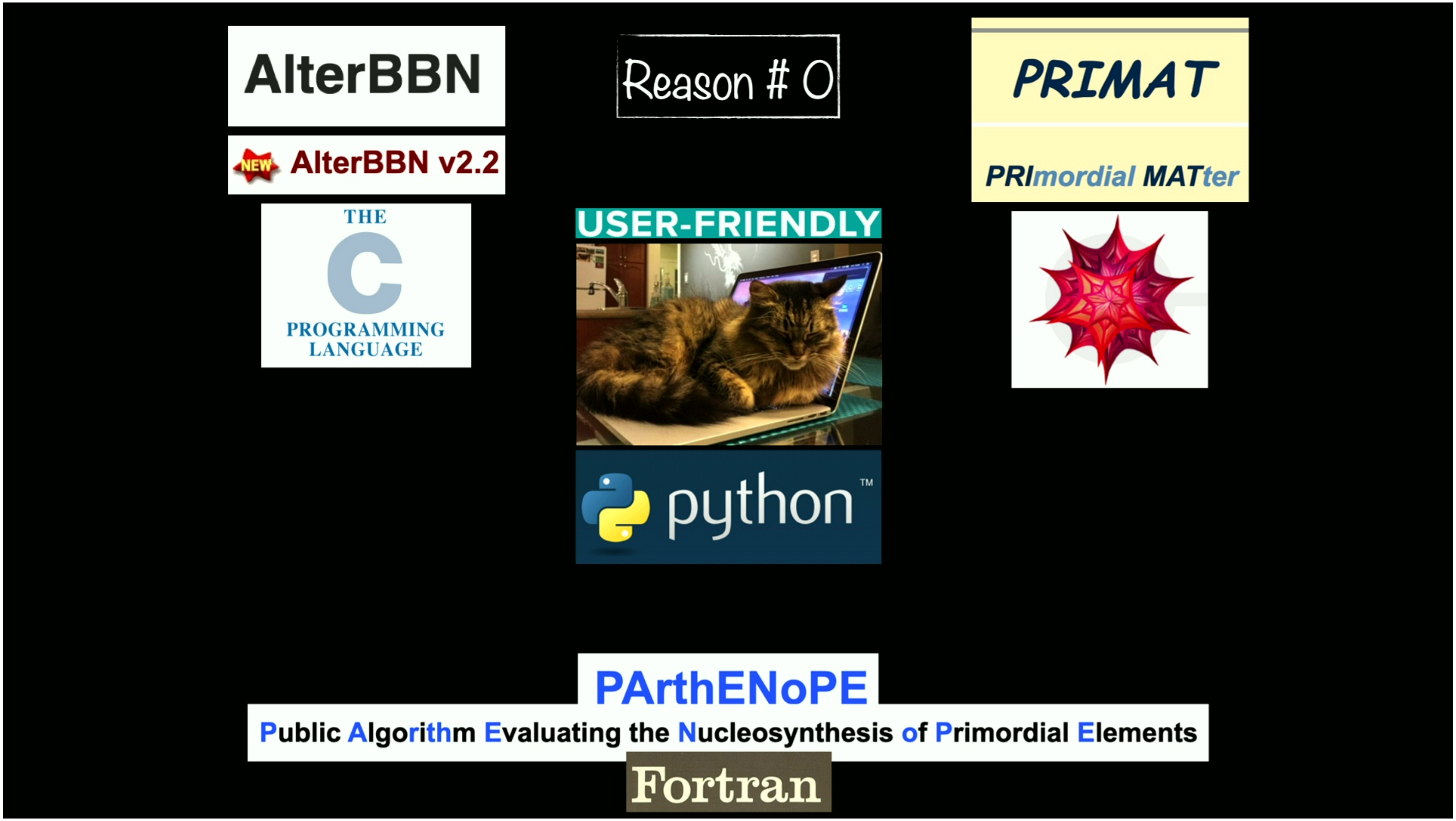
THERE ARE NO BUGS

IF YOU DON'T
WRITE ANY CODE

PArthENoPE

Public Algorithm Evaluating the Nucleosynthesis of Primordial Elements

arXiv:0705.0290, arXiv:1712.04378, arXiv:2103.05027


AlterBBN
NEW AlterBBN v2.2
THE C PROGRAMMING LANGUAGE
Reason # 0
USER-FRIENDLY
python™
PRIMAT
PRImordial MATter
PArthENoPE
Public Algorithm Evaluating the Nucleosynthesis of Primordial Elements
Fortran

Reason # 1

ν Decoupling & N_{eff}

Early Universe dynamics of neutrinos is an input for public BBN codes.

Why? Need to solve O(100) stiff integro-diff. eq.s otherwise:

$$\partial_t f_\nu - H\, p\, \partial_p f_\nu = \mathcal{C}[f_\nu]$$

BUT, dramatic simplification is possible [1812.05605 , 2001.04466]:

<< JUST GO THERMAL ! >>

$$\dot{T}_\nu = \dot{\rho}_\nu / \partial_{T_\nu} \rho_\nu = [-3H(\rho_\nu + p_\nu) + \delta\dot{\rho}_\nu] / \partial_{T_\nu} \rho_\nu$$

$$\dot{T}_\gamma = \dot{\rho}_{\gamma+e} / \partial_{T_\gamma} \rho_{\gamma+e} = [-3H(\rho_{\gamma+e} + p_{\gamma+e}) - \delta\dot{\rho}_\nu] / \partial_{T_\gamma} \rho_{\gamma+e}$$

OBS. $\delta\dot{\rho}_\nu = \delta\dot{\rho}_\nu(T_\gamma, T_\nu)$ <- - - -> $|\overline{\mathcal{M}}|^2_{\nu\leftrightarrow e}$ thermally averaged

$H^2 = (8\pi G_N/3)\rho_{\text{tot}}$ (Friedmann eq.)

Reason # 1

ν Decoupling & $N_{\rm eff}$

$$T_\gamma(t), T_\nu(t) \;\nearrow\; \frac{d(s_{\gamma+e}\, a^3)}{dt} = -\frac{\delta\dot{\rho}_\nu a^3}{T_\gamma} \Rightarrow a(T_\gamma),\ a(t)$$

$$T_\gamma(t), T_\nu(t) \;\searrow\; \frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\gamma} \quad \text{i.e.} \quad N_{\rm eff}$$

recovering state-of-the-art for these quantities @ per mille level!

i.e. PRETTY MUCH
A “FREE LUNCH”!

Reason # 1

ν Decoupling & N_{eff}

Early Universe dynamics of neutrinos is an input for public BBN codes.

Why? Need to solve O(100) stiff integro-diff. eq.s otherwise:

$$\partial_t f_\nu - H\, p\, \partial_p f_\nu = \mathcal{C}[f_\nu]$$

BUT, dramatic simplification is possible [1812.05605 , 2001.04466]:

<< JUST GO THERMAL ! >>

$$\dot{T}_\nu = \dot{\rho}_\nu / \partial_{T_\nu} \rho_\nu = [-3H(\rho_\nu + p_\nu) + \delta\dot{\rho}_\nu] / \partial_{T_\nu} \rho_\nu$$

$$\dot{T}_\gamma = \dot{\rho}_{\gamma+e} / \partial_{T_\gamma} \rho_{\gamma+e} = [-3H(\rho_{\gamma+e} + p_{\gamma+e}) - \delta\dot{\rho}_\nu] / \partial_{T_\gamma} \rho_{\gamma+e}$$

OBS. $\delta\dot{\rho}_\nu = \delta\dot{\rho}_\nu(T_\gamma, T_\nu)$ <- - - -> $|\overline{\mathcal{M}}|^2_{\nu\leftrightarrow e}$ thermally averaged

$H^2 = (8\pi G_N/3)\rho_{\text{tot}}$ (Friedmann eq.)

Reason # 1

ν Decoupling & $N_{\rm eff}$

$T_\gamma(t), T_\nu(t)$

$$\frac{d(s_{\gamma+e}\, a^3)}{dt} = -\frac{\delta \dot\rho_\nu a^3}{T_\gamma} \Rightarrow \boxed{a(T_\gamma)} \quad \boxed{a(t)}$$

$$\frac{\rho_{\rm rad} - \rho_\gamma}{\rho_\gamma} \quad \text{i.e.} \quad \boxed{N_{\rm eff}}$$

recovering state-of-the-art for these quantities @ per mille level!

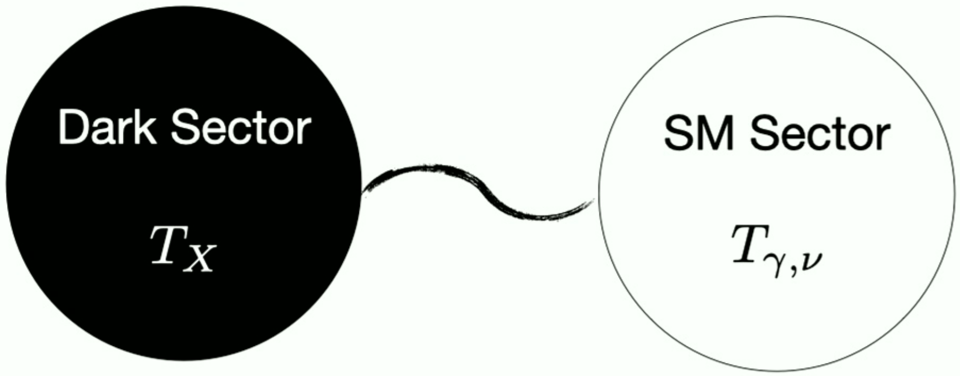
i.e. PRETTY MUCH
A "FREE LUNCH"!

Reason # 1

ν Decoupling & $N_{\rm eff}$

True reward: Approach extremely useful for BSM Physics!

E.g.:



$$T_\gamma(t), T_\nu(t), T_X(t)$$

→ $a(t)$, $a(T_\gamma)$

Primordial abundances affected in a 3-fold way:

$$H \,,\; \Gamma_{n\leftrightarrow p} \,,\; n_B$$

→ $N_{\rm eff}$

Constraint from "Planck 2018"

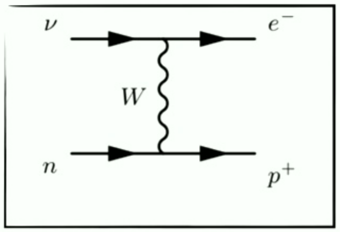
$$2.93 \pm 0.29 \quad @ \quad 68\,\%\,\mathrm{CL}$$

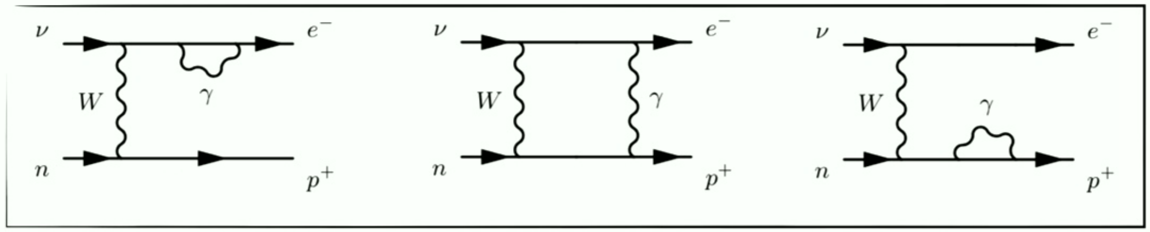
Reason # 2

Weak Rates $\Gamma_{n\leftrightarrow p}$

Both T_γ and T_ν relevant here !

Primordial ^{4}He & D/H precisely measured: **BBN precision tool**





LO: easy-peasy in Born ... ... but finite mass effects + $O(\alpha)$ corrections relevant for precision!

PRIMAT code offers a wonderful ab-initio computation, but takes time ...

BLUE SWORD VS RED SWORD

SciPy

vegas 5.0

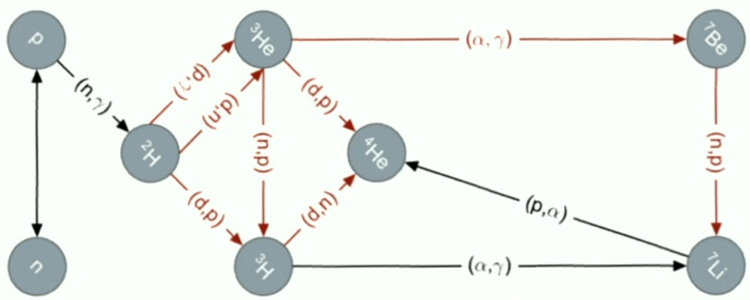
`pip install vegas`

WOLFRAM MATHEMATICA 12

Reason # 3

Nuclear Rates $\langle \sigma v \rangle_{\text{nucl}}$

Nuclear net dependent also on $\eta(t)$



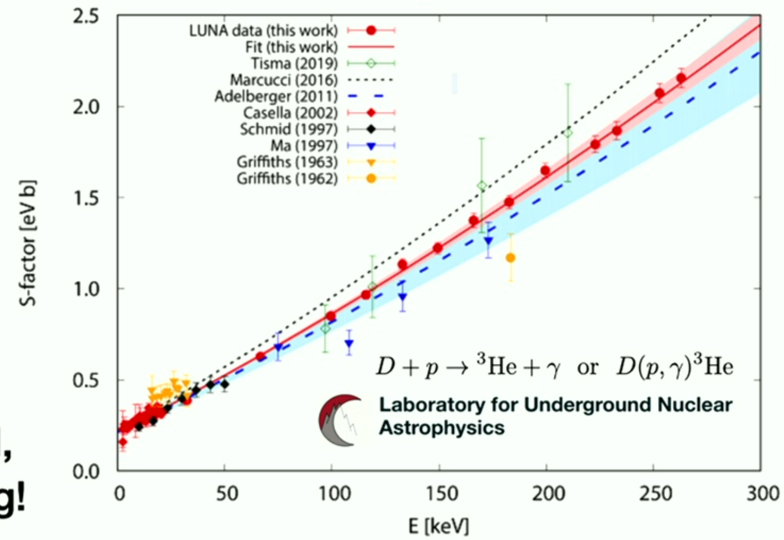
Existing codes implement own recipe for O(100) rates as function of T …

Key reactions to study primordial light elements are only O(10).

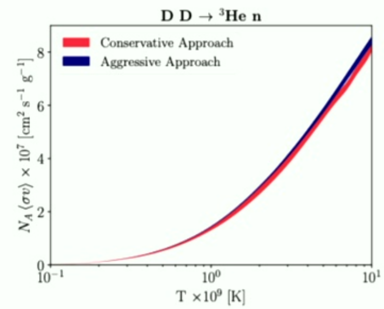
Even those vary from group to group though, unless data driven (LUNA)

Exploring these systematics crucial, but a ready-to-use tool been missing!

Nature **587**, 210–213 (2020)



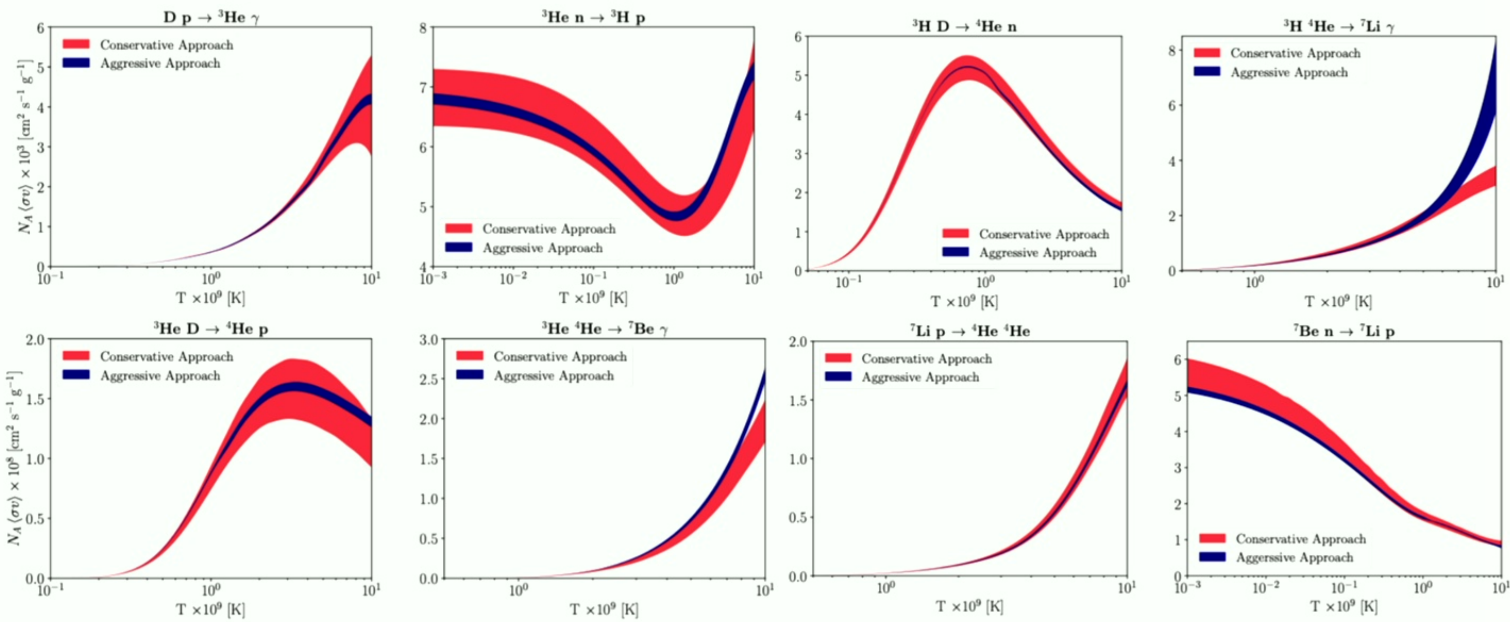
Nuclear Rates $\langle \sigma v \rangle_{\mathbf{nucl}}$

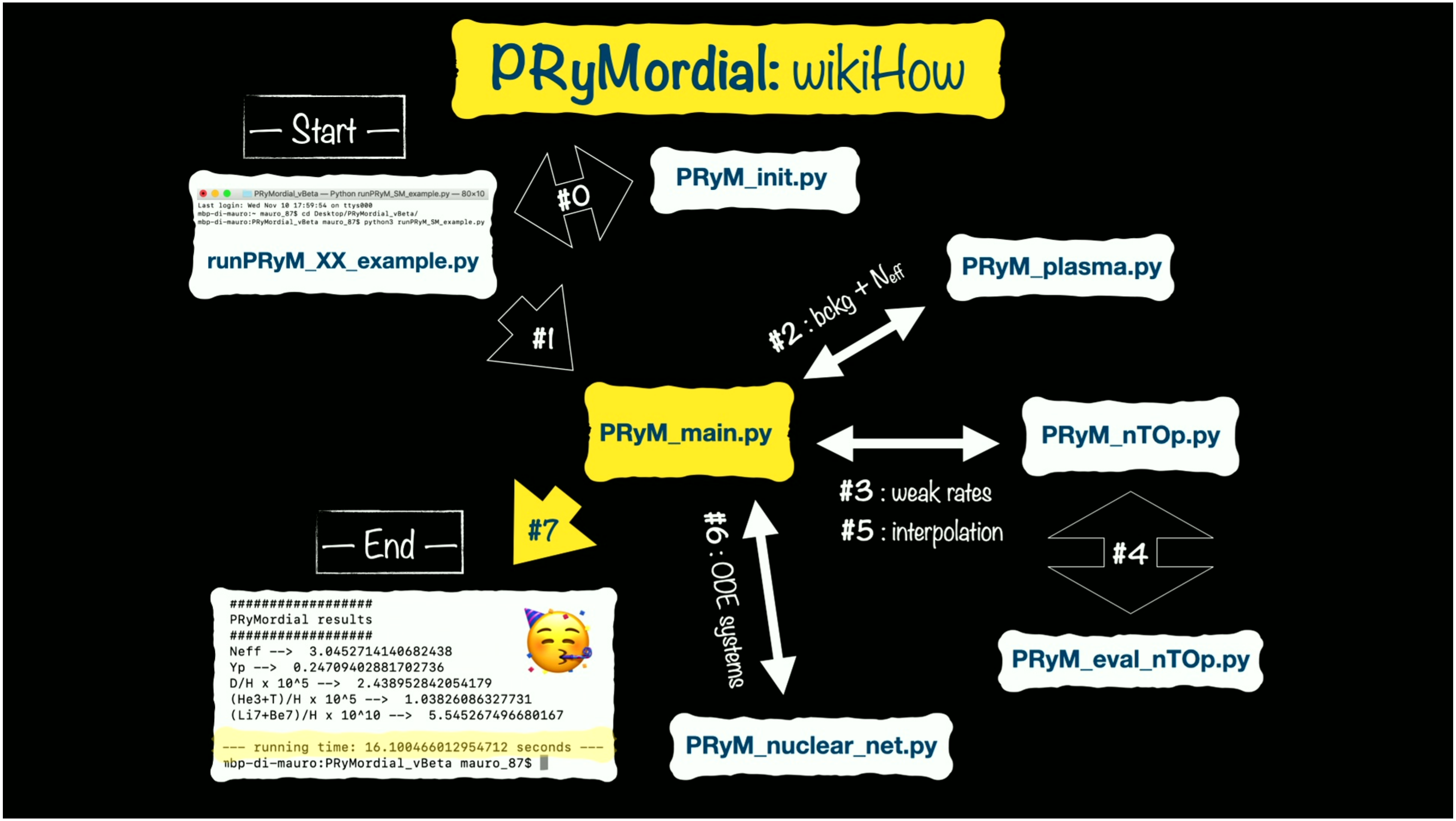


2 DIFFERENT APPROACHES IMPLEMENTED

NACRE compilation
polynomial fits
— data oriented —

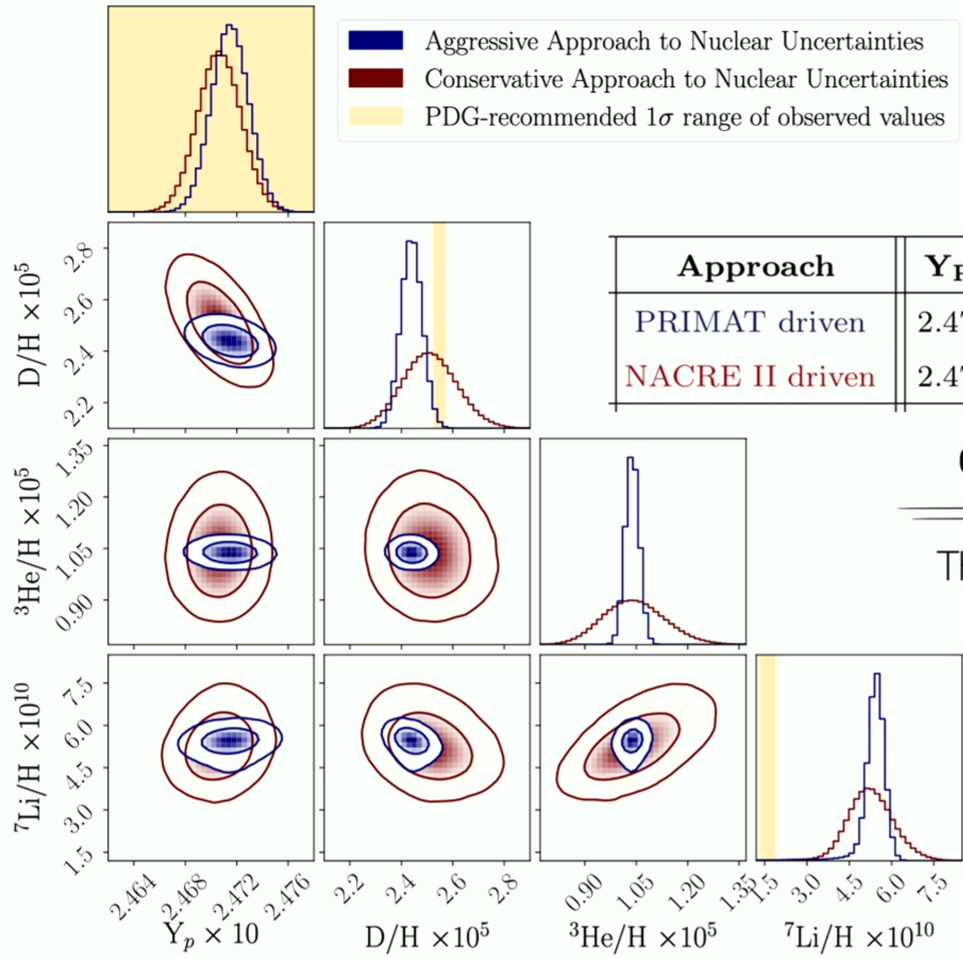
PRIMAT compilation
nuclear modeling
— theory oriented —





PRyMordial: wikiHow
— Start —
PRyMordial_vBeta — Python runPRyM_SM_example.py — 80×10
Last login: Wed Nov 10 17:59:54 on ttys000
mbp-di-mauro:~ mauro_87$ cd Desktop/PRyMordial_vBeta/
mbp-di-mauro:PRyMordial_vBeta mauro_87$ python3 runPRyM_SM_example.py
runPRyM_XX_example.py
#0
PRyM_init.py
#1
#2 : bckg + N_eff
PRyM_plasma.py
PRyM_main.py
PRyM_nTOp.py
#3 : weak rates
#5 : interpolation
#4
PRyM_eval_nTOp.py
#6 : ODE systems
PRyM_nuclear_net.py
#7
— End —
##################
PRyMordial results
##################
Neff --> 3.0452714140682438
Yp --> 0.24709402881702736
D/H x 10^5 --> 2.438952842054179
(He3+T)/H x 10^5 --> 1.03826086327731
(Li7+Be7)/H x 10^10 --> 5.545267496680167
--- running time: 16.100466012954712 seconds ---
mbp-di-mauro:PRyMordial_vBeta mauro_87$

PRyMordial: SM state-of-the-art



Approach	$Y_P \times 10$	$D/H \times 10^5$
PRIMAT driven	2.4715(14)	2.439(36)
NACRE II driven	2.4706(16)	2.51(10)

0.5‰ 1.5% VS 4%

THEORY PRECISION

PRyMordial: Summary

- **PRyMordial** **A new package for BBN phenomenology**
- Will be featuring:
  - — simplified, but precise, method for ν decoupling
  - — ab-initio efficient computation of n <—> p
  - — a customizable up-to-date nuclear network
  - — several built-in options for New Physics

Meets precision for state-of-the-art SM predictions.

Opens up uncharted territory for BSM in BBN era.

- Fully python-based, will be user-friendly & **numerically fast ...**

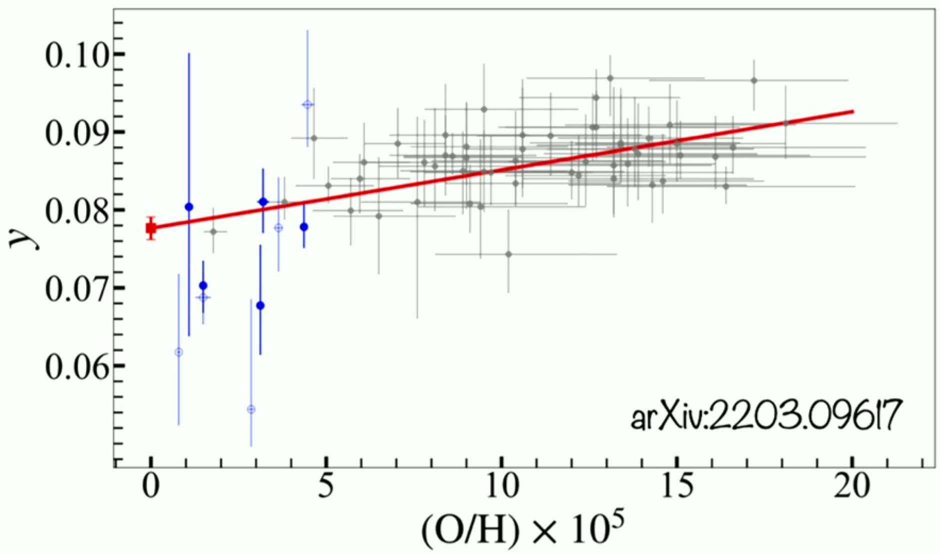
DiffEq.jl from Sci Machine Learning kit implemented in julia

A NEW HELIUM-4 MEASUREMENT

Extremely metal-poor galaxies (EMPGs): Pristine environments for primordial ^{4}He

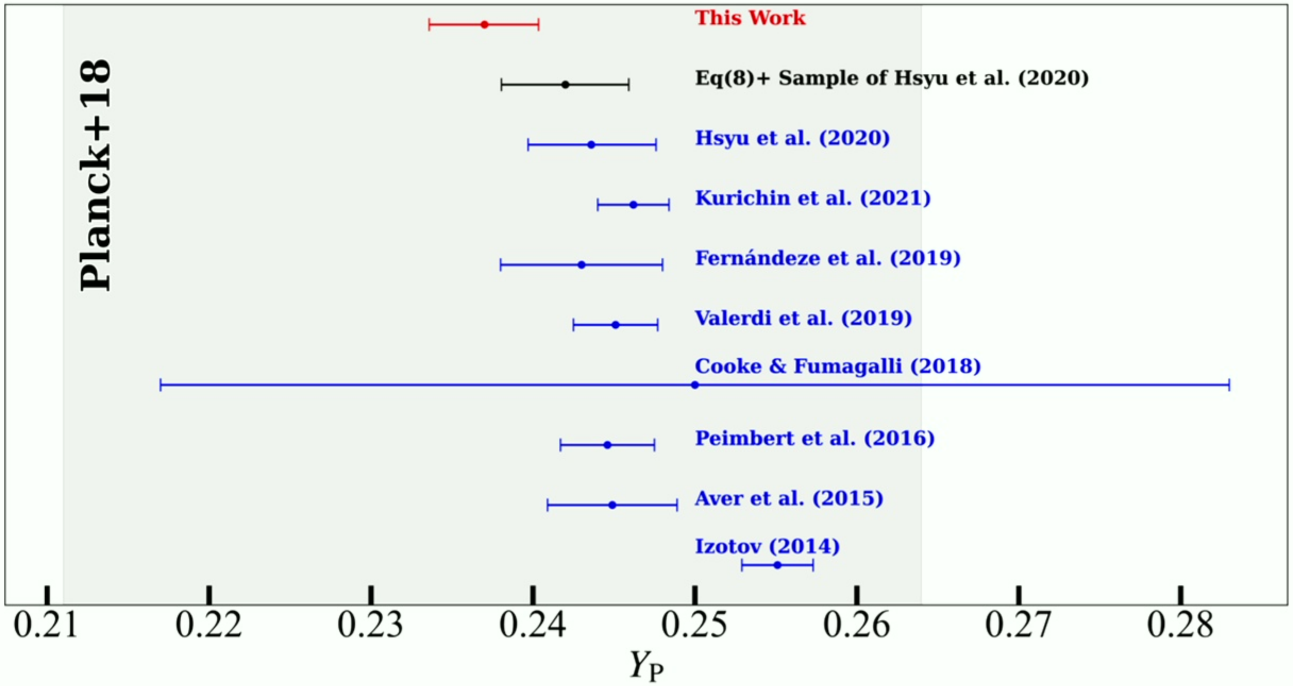
2021: 51 metal-poor galaxies + 3 EMPGs

2022: deep NIR spectroscopy from Subaru Telescope adds 10 new EMPGs!



A NEW HELIUM-4 MEASUREMENT

arXiv:2203.09617



BBN ERA WITH $\mu \neq 0$

In the Early Universe, chemical potential of photons must be 0:

$$e^- + e^+ \leftrightarrow 2\gamma\ ,\ 3\gamma \quad \Rightarrow \quad \mu_\gamma = 0\ ,\ \mu_{e^-} = -\,\mu_{e^+} \equiv \mu_e$$

From charge neutrality, chemical potential of $e^\pm$ must be small:

$$n_{e^-} - n_{e^+} = n_p \quad \Rightarrow \quad \eta_e \propto \mu_e/T_\gamma \lesssim \eta_B \sim 10^{-10}$$

LARGE LEPTON ASYMMETRIES EXCLUDED BY η_B …

NO LONGER TRUE IF ORIGINATING FROM ν SECTOR!

BBN ERA WITH $\mu \neq 0$

A non-zero ν chemical potential impacts total energy density:

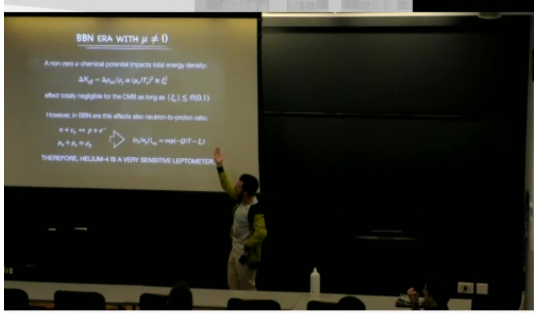
$$\Delta N_{eff} \sim \Delta\rho_{tot.}/\rho_\gamma \propto (\mu_\nu/T_\nu)^2 \equiv \xi_\nu^2$$

effect totally negligible for the CMB as long as $|\xi_\nu| \lesssim \mathcal{O}(0.1)$

However, in BBN era this affects also neutron-to-proton ratio:

$$n + \nu_e \leftrightarrow p + e^-$$
$$\mu_n + \mu_\nu \simeq \mu_p$$
$$\Rightarrow \quad (n_n/n_p)|_{eq.} \simeq \exp(-Q/T - \xi_\nu)$$

THEREFORE, HELIUM-4 IS A VERY SENSITIVE LEPTOMETER.



2206.00693

BBN 2022: A BAYESIAN ANALYSIS

Bayes Theorem : Posterior ~ Likelihood x Prior

JOINT ANALYSIS OF BBN DATA WITH CMB (W/ CORRELATIONS!)

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

$$\log \mathcal{L}_{\mathrm{CMB}} = -\frac{1}{2}\Delta\vec{v}^{\,T}\,\mathcal{C}_{\mathrm{CMB}}^{-1}\,\Delta\vec{v}$$

$$\Delta\vec{v} \equiv \vec{v}^{\,\mathrm{th}} - \vec{v},\ \vec{v} = (\mathrm{Y_P}, \Omega_B h^2, N_{\mathrm{eff}})^T$$

Planck 2018 TTTEEE + low-ℓ + BAO + lensing

$$\log \mathcal{L}_{\mathrm{BBN}} = -\frac{1}{2}\sum_X \left(\frac{X^{\mathrm{th}} - X}{\sigma_X}\right)^2$$

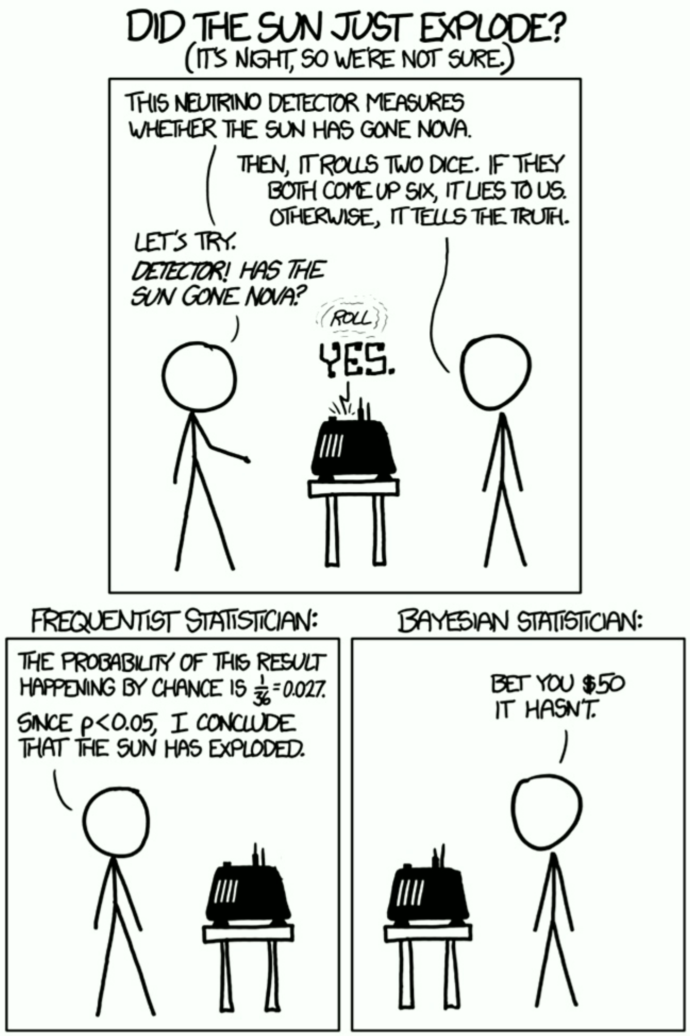
$X = {}^4He$ [Subaru 2022] , D [PDG 2021]

MAIN PARAMETERS

$-2 \le \Delta N_{eff} \le 2$	$1 \le \eta_B \times 10^{10} \le 10$	$-0.2 \le \xi_\nu \le 0.2$

NUISANCE PARAMETERS: neutron lifetime [PDG 2021] (gaussian prior), nuclear x-sec uncertainties (log-normal prior)

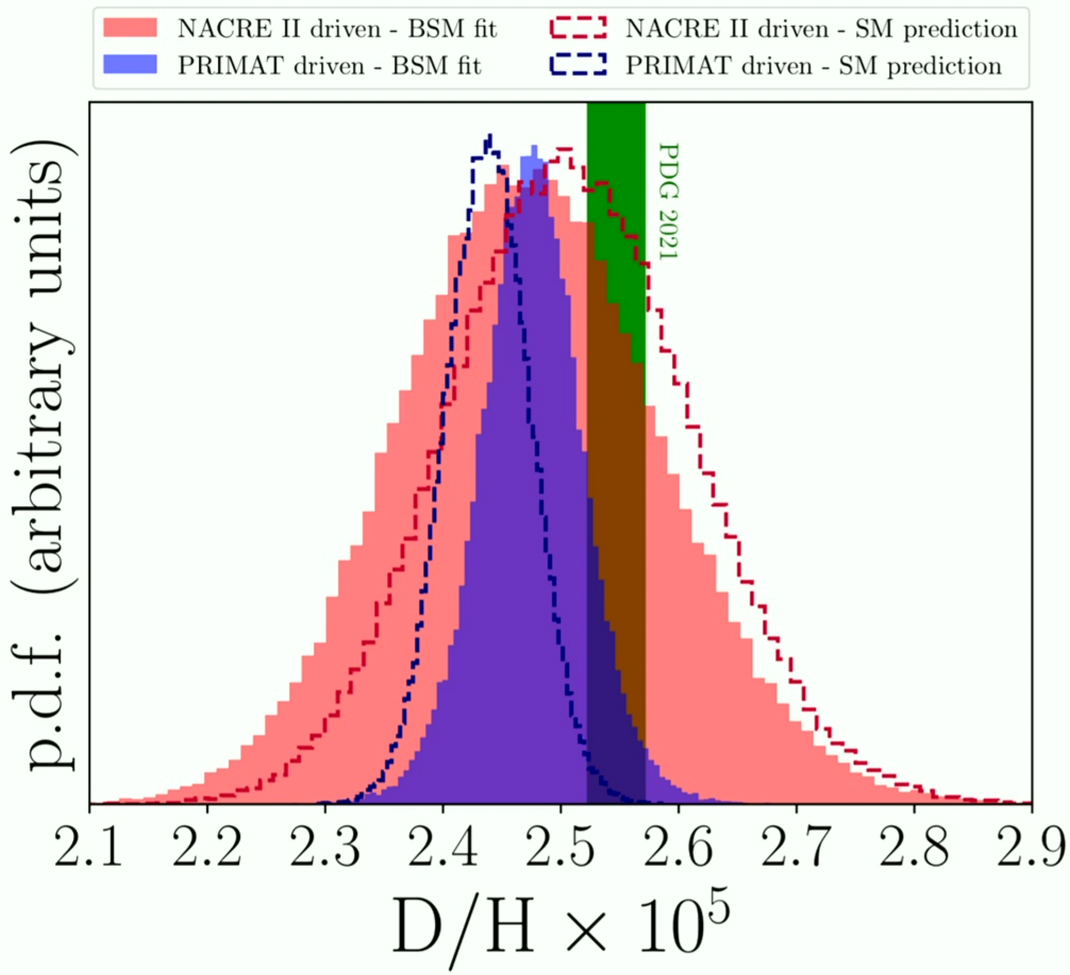
Why SO MUCH work?



@ https://xkcd.com/1132

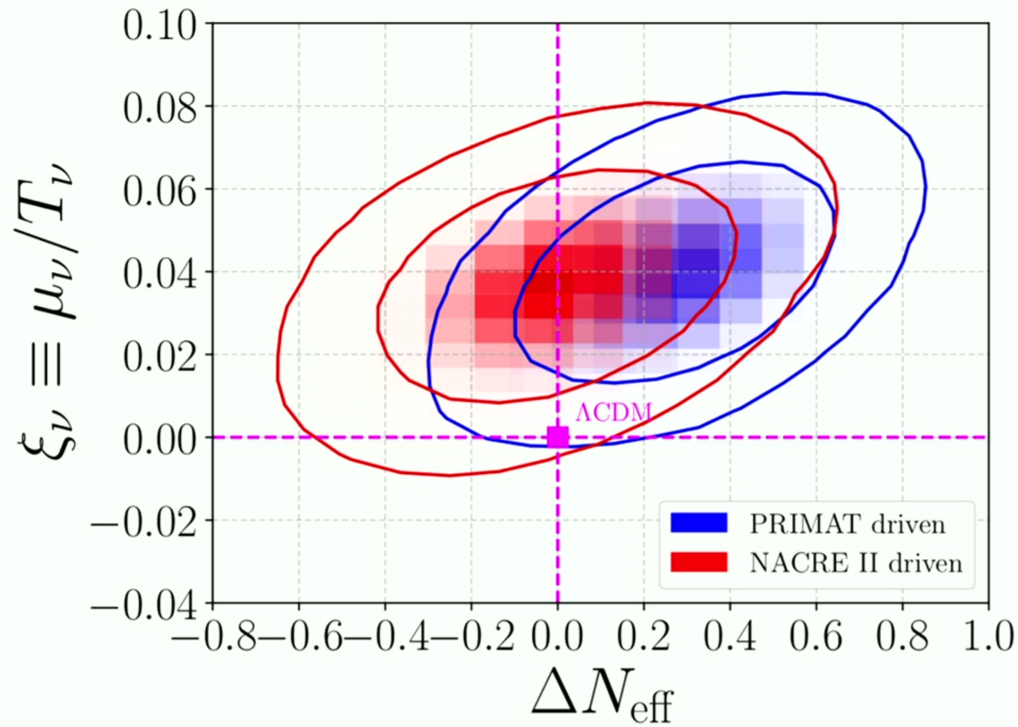
2206.00693

BBN 2022: RESULTS X DEUTERIUM



2206.00693

BBN 2022: NP INFERENCE



A **NON-ZERO LEPTON ASYMMETRY** IS DETECTED **@** THE **2σ** LEVEL.

2206.00693

BBN 2022: A SUMMARY

Scenario	Approach	$Y_P \times 10$	$D/H \times 10^5$	ΔN_{eff}	ξ_ν	$\eta_B \times 10^{10}$	ΔIC
SM prediction	PRIMAT driven	2.4715(14)	2.439(36)	–	–	6.137(38)	–
	NACRE II driven	2.4706(16)	2.51(10)	–	–	6.137(38)	–
ΔN_{eff} *BSM fit*	PRIMAT driven	2.472(11)	2.471(44)	0.02(18)	–	6.096(64)	2
	NACRE II driven	2.453(14)	2.46(11)	-0.28(23)	–	6.088(67)	0
$(\Delta N_{eff}, \xi_\nu)$ *BSM fit*	PRIMAT driven	2.393(38)	2.475(44)	0.27(24)	0.039(18)	6.120(67)	8
	NACRE II driven	2.383(41)	2.47(11)	-0.01(27)	0.036(19)	6.114(65)	5

$$\Delta IC = IC_{SM} - IC_{NP}$$

1 to 3	Not worth more than a bare mention
3 to 20	Positive
20 to 150	Strong
>150	Very strong

Kass and Raftery '95

Akaike Information Criterion (*IC*):

$$IC \equiv 2 \times (\#d.o.f.) - 2\log(\hat{L}_{BBN})$$

to perform model comparison.

Positive evidence for models with non-zero lepton asymmetry.

CONSIDERATIONS: PART I

Q: What does the inferred — $\overline{\xi_\nu} \simeq 0.04$ — really implies ?

Our inference *a priori* involves **only** the electron-flavor neutrino.

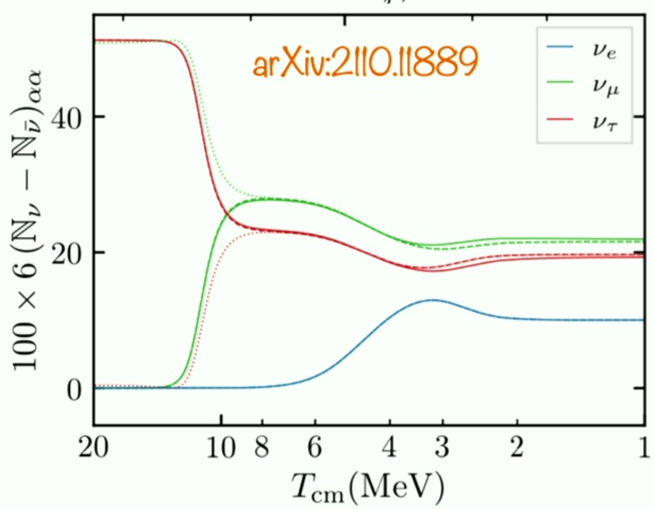
$$\eta_L \simeq \sum_{i=e,\mu,\tau} \frac{n_{\nu_i} - n_{\bar{\nu}_i}}{n_\gamma} \simeq \frac{\pi^2}{12\zeta(3)} \sum_{i=e,\mu,\tau} \left(\frac{T_{\nu_i}}{T_\gamma}\right)^3 \xi_{\nu_i} \quad \Rightarrow \quad \eta_L^0 \in (\,10^{-2},\, 1/4\,)$$

LOWER BOUND: $\xi_{\nu_e} = \overline{\xi_\nu}\ ,\ \xi_{\nu_{\mu,\tau}} = 0$

UPPER BOUND: $\xi_{\nu_e} = \overline{\xi_\nu}\ ,\ \xi_{\nu_{\mu,\tau}} = 0.5$

$(\Delta N_{eff} \sim 0.1)$

Initial conditions: $\xi_{e,\mu,\tau} = (\,0\,,0\,,0.5\,)$



Muon-tau sector mix efficiently ~ 10 MeV [astro-ph/0203442]

Lepton asymmetry today depends on initial asymmetries and details of PMNS matrix.

CONSIDERATIONS: PART II

$T \gtrsim 100\ GeV$

- EW symmetry unbroken, sphalerons equilibrate B+L —> $\mathcal{O}(\eta_L) \sim \mathcal{O}(\eta_B)$

POSSIBLE WAY OUT: "cook" model where tot. L asymmetry << individual ones

E.g., hep-ph/9908396:

The Small Observed Baryon Asymmetry from a Large Lepton Asymmetry

John March-Russell[a], Hitoshi Murayama[b,c], and Antonio Riotto[a]

BUT ...

arXiv:2208.03237: large lepton-flavored asymmetry —> large baryon asymmetry!

chiral plasma instability

$T < 100\ GeV$

- Asymmetry generated once sphalerons are inactive (but before BBN)

— Out-of-equilibrium processes w/ RH neutrinos

see, e.g., 2206.14722

— Variations of Affleck-Dine mechanism

see, e.g., 2203.09713

CONSIDERATIONS: PART II

$T \gtrsim 100~GeV$

- EW symmetry unbroken, sphalerons equilibrate B+L —> $\mathcal{O}(\eta_L) \sim \mathcal{O}(\eta_B)$

POSSIBLE WAY OUT: "cook" model where tot. L asymmetry << individual ones

E.g., hep-ph/9908396:

The Small Observed Baryon Asymmetry from a Large Lepton Asymmetry

John March-Russell[a], Hitoshi Murayama[b,c], and Antonio Riotto[a]

BUT …

arXiv:2208.03237: large lepton-flavored asymmetry —> large baryon asymmetry!

chiral plasma instability

$T < 100~GeV$

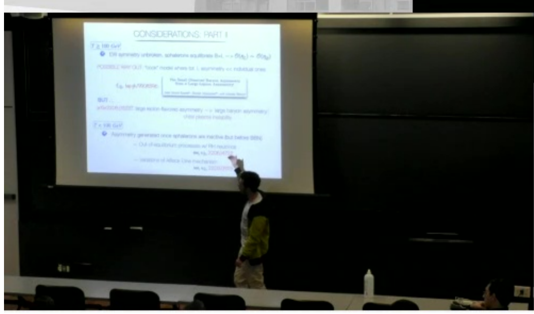
- Asymmetry generated once sphalerons are inactive (but before BBN)

— Out-of-equilibrium processes w/ RH neutrinos

see, e.g., 2206.14722

— Variations of Affleck-Dine mechanism

see, e.g., 2203.09713



Take Home

- BBN gives us a privileged view on BSM and the Early Universe

⇒ **PRyMordial** work in progress [arXiv: 221X.XXXXX]

(In use! See, e.g., 2210.12031)

- 2 ongoing "anomalies": Helium-4 (obs?) & Deuterium (theoy?)

$\eta_L \simeq \eta_\nu \gg \eta_B$ [arXiv: 2206.00693]

- Bucket list for the future:
  - — Measuring Helium-4 beyond % level
  - — More data on DD fusion x-sections
  - — Next-gen CMB observations (see projections in 2208.03201)