The status of deuterium in Big-bang nucleosynthesis

Cyril Pitrou,
Alain Coc, Elisabeth Vangioni, Jean-Philippe Uzan

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The Origin of Chemical Elements

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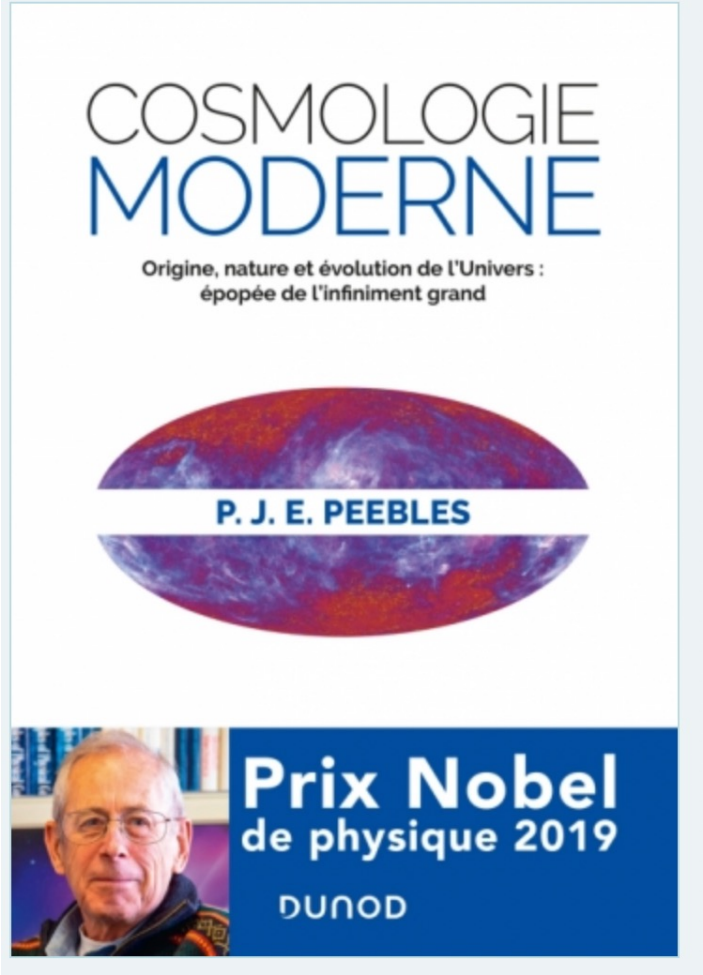
February 18, 1948

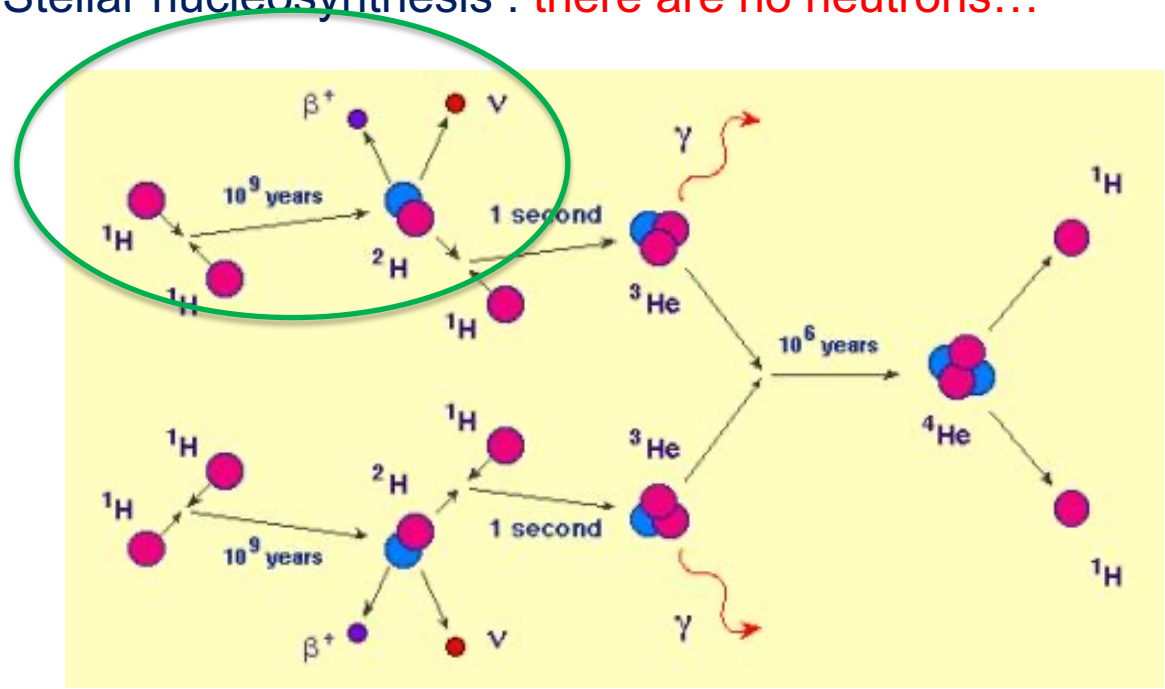


Outline

1. BBN in a nutshell
2. The hunt for precision
3. Deuterium

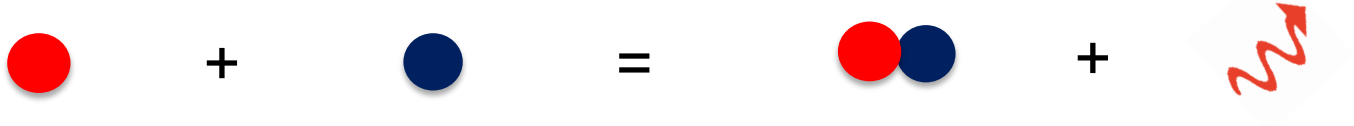
❑ Why primordial synthesis ?

1. Stellar nucleosynthesis : there are no neutrons…



2. Primordial nucleosynthesis : there was plenty of neutrons !

$$p + n \leftrightarrow D + \gamma$$



2.2 MeV

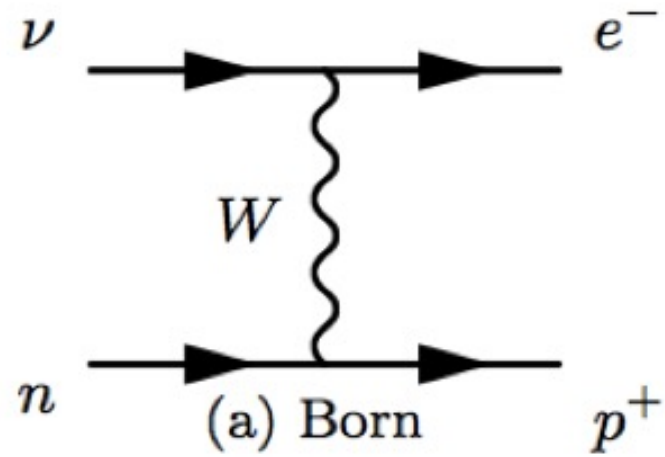
When does it happen ? How many neutrons were available ?

❑ Neutron/proton conversions

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

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

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



(a) Born

- If enough interactions, then statistical equilibrium

$$\boxed{n = \mathrm{e}^{-\frac{E}{k_B T}}}$$

Baryons are non-relativistic : $E \simeq m$

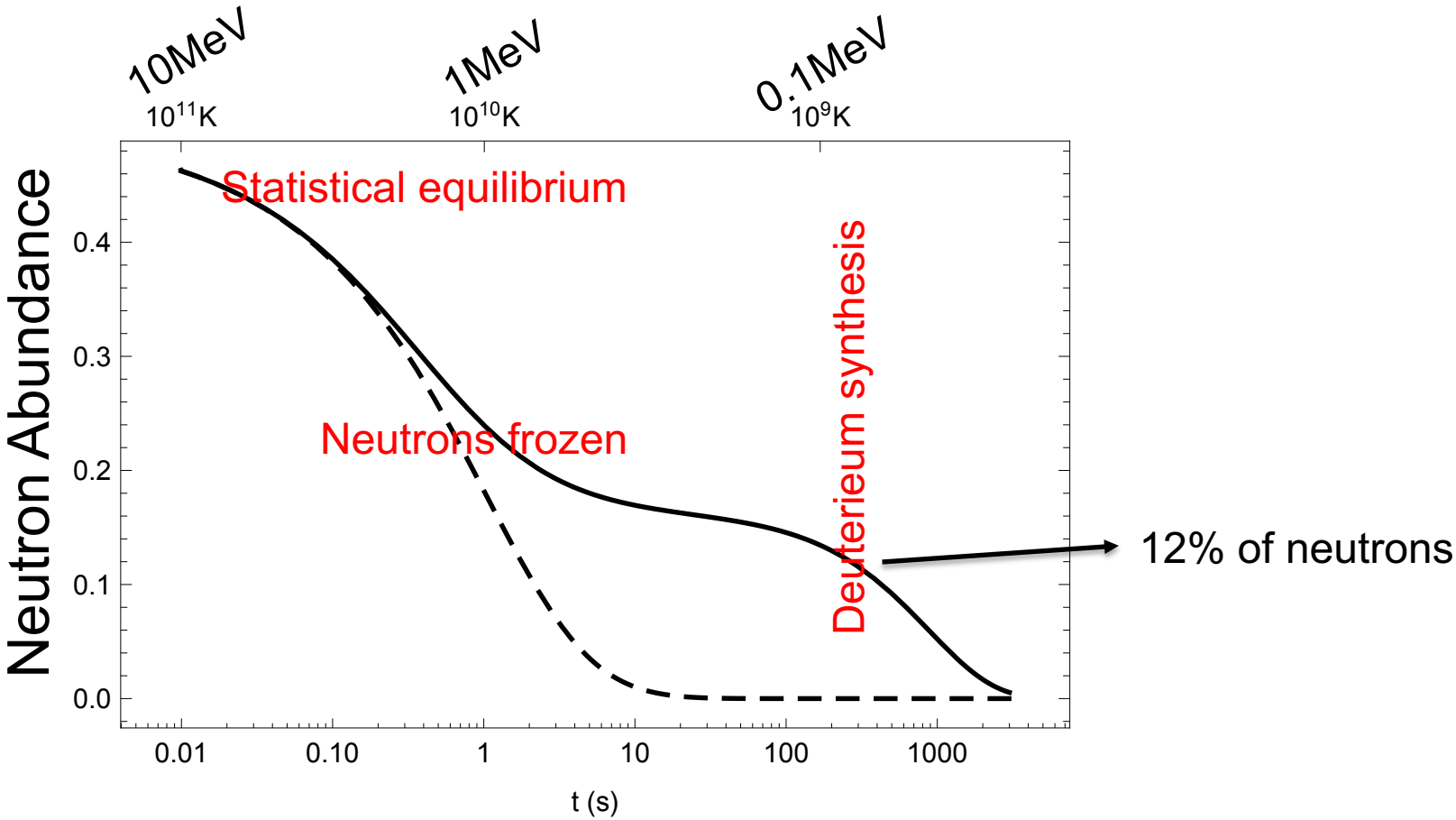
$$m_p = 938.2\,\mathrm{MeV}$$

$$m_n = m_p + 1.3\,\mathrm{MeV}$$

Protons $\quad n_p = \mathrm{e}^{-m_p/T}$

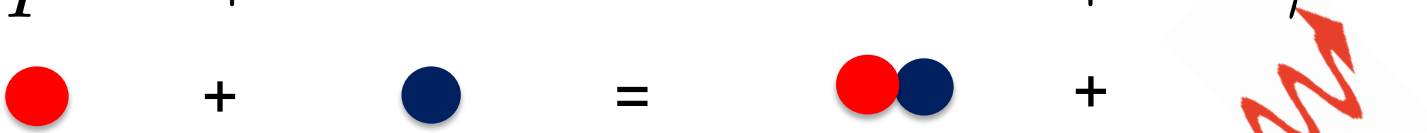
Neutrons $\quad n_n = \mathrm{e}^{-m_n/T} = n_p \boxed{\mathrm{e}^{-(m_n - m_p)/T}}$

Evolution of neutrons



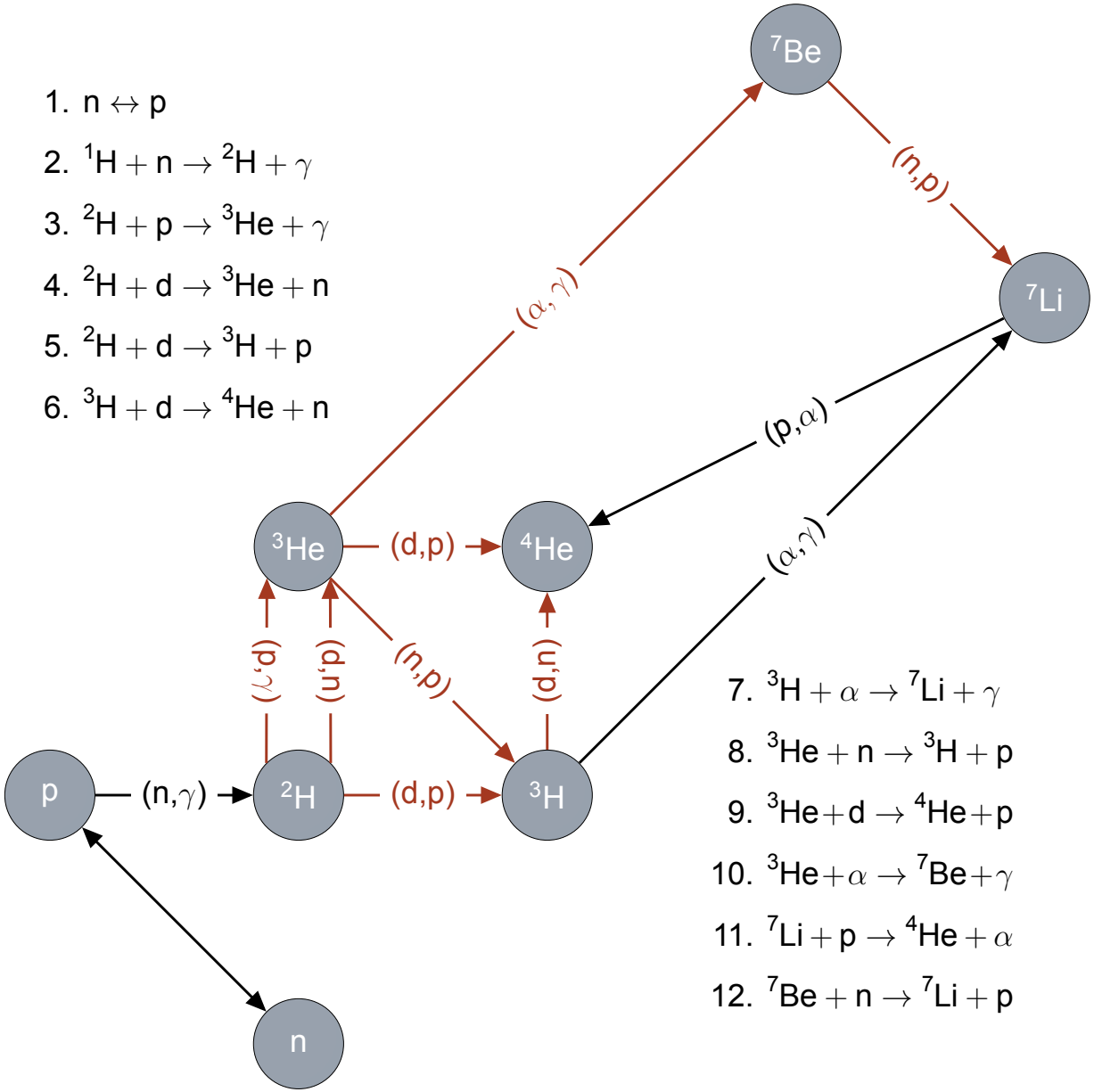
Deuterium

$$p + n \leftrightarrow D + \gamma$$



Nuclear network

1. $n \leftrightarrow p$
2. ${}^{1}H + n \rightarrow {}^{2}H + \gamma$
3. ${}^{2}H + p \rightarrow {}^{3}He + \gamma$
4. ${}^{2}H + d \rightarrow {}^{3}He + n$
5. ${}^{2}H + d \rightarrow {}^{3}H + p$
6. ${}^{3}H + d \rightarrow {}^{4}He + n$



7. ${}^{3}H + \alpha \rightarrow {}^{7}Li + \gamma$
8. ${}^{3}He + n \rightarrow {}^{3}H + p$
9. ${}^{3}He + d \rightarrow {}^{4}He + p$
10. ${}^{3}He + \alpha \rightarrow {}^{7}Be + \gamma$
11. ${}^{7}Li + p \rightarrow {}^{4}He + \alpha$
12. ${}^{7}Be + n \rightarrow {}^{7}Li + p$

❑ Evolution of abundances

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} + 3Hn_i = \mathcal{J}_i$$ ⟶ Source from nuclear reactions

$$\frac{\mathrm{d}n_\mathrm{b}}{\mathrm{d}t} + 3Hn_\mathrm{b} = 0,$$ Baryons are only diluted

$$Y_i \equiv n_i/n_b$$ ⟶ Removes dilution

- Two-body reactions of the type $i + j \leftrightarrow k + l$

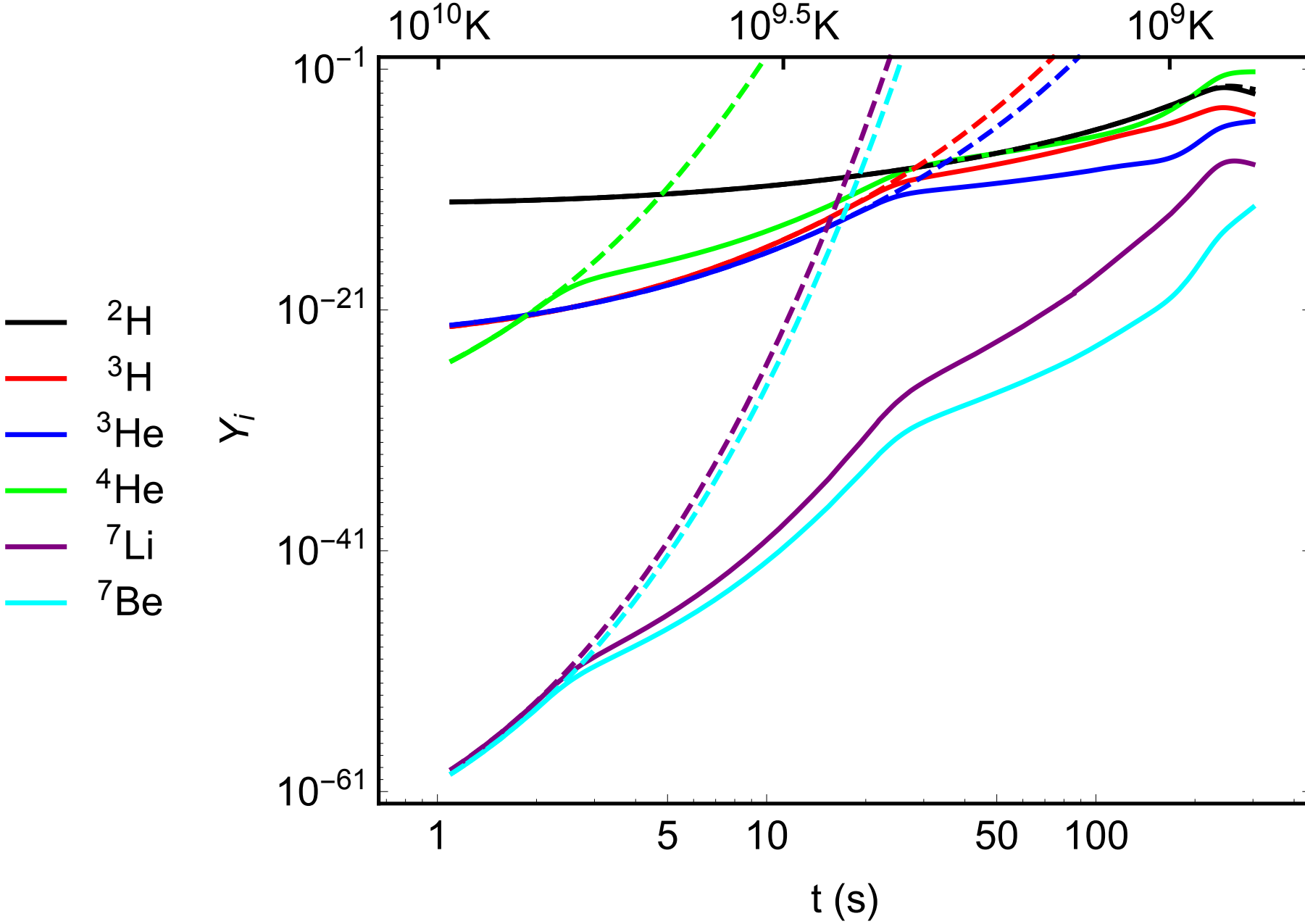
$$\mathcal{J}_i \supset n_k n_l \gamma_{kl\to ij} - n_i n_j \gamma_{ij\to kl}$$

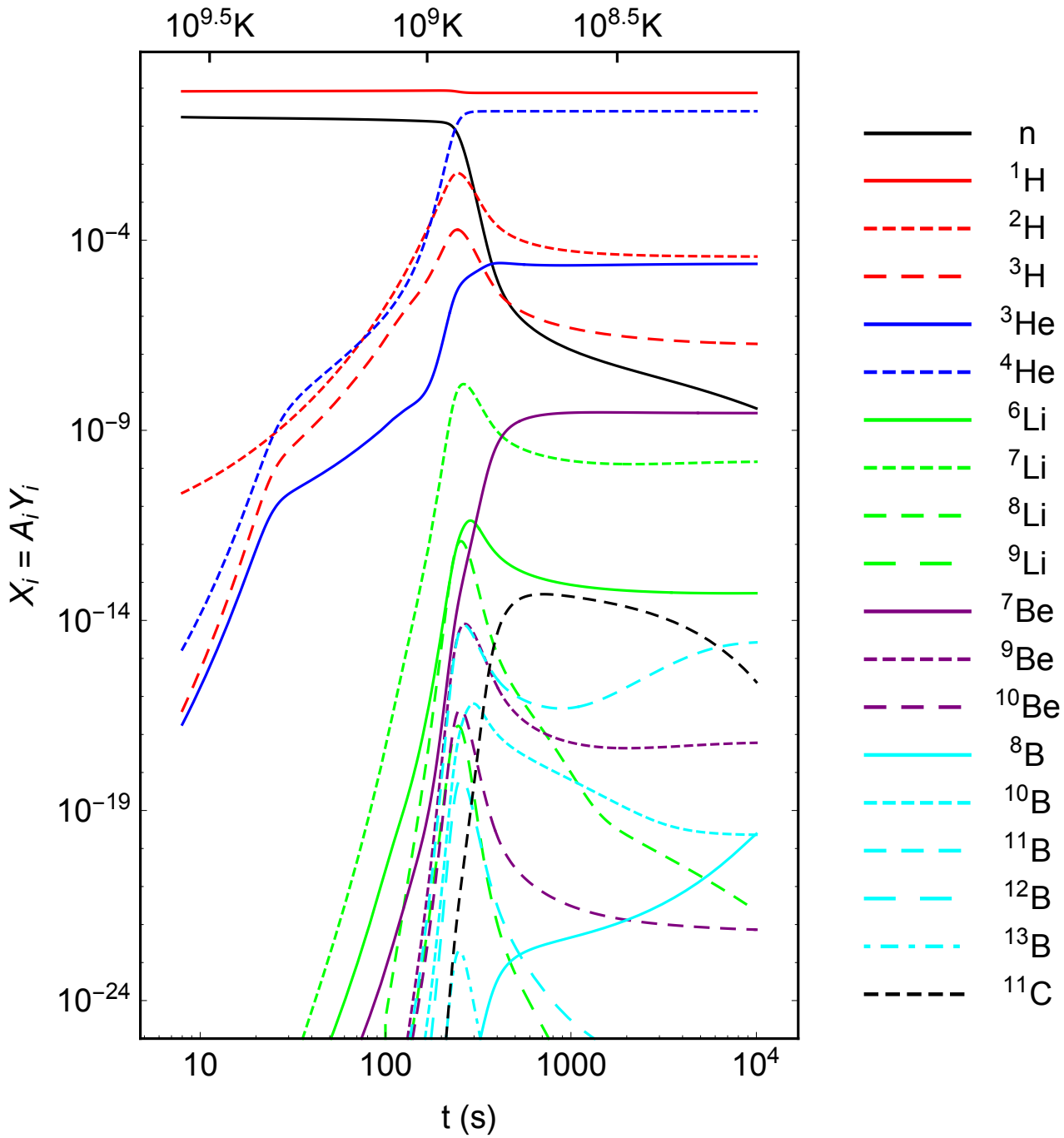
$$\gamma_{ij\to kl} \equiv \langle \sigma v \rangle_{ij\to kl}\,.$$

Average of cross-section over Maxwell-Boltzmann distribution

- General form

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


10^{10}K
$10^{9.5}$K
10^{9}K
10^{-1}
10^{-21}
10^{-41}
10^{-61}
Y_i
^{2}H
^{3}H
^{3}He
^{4}He
^{7}Li
^{7}Be
1
5
10
50
100
t (s)

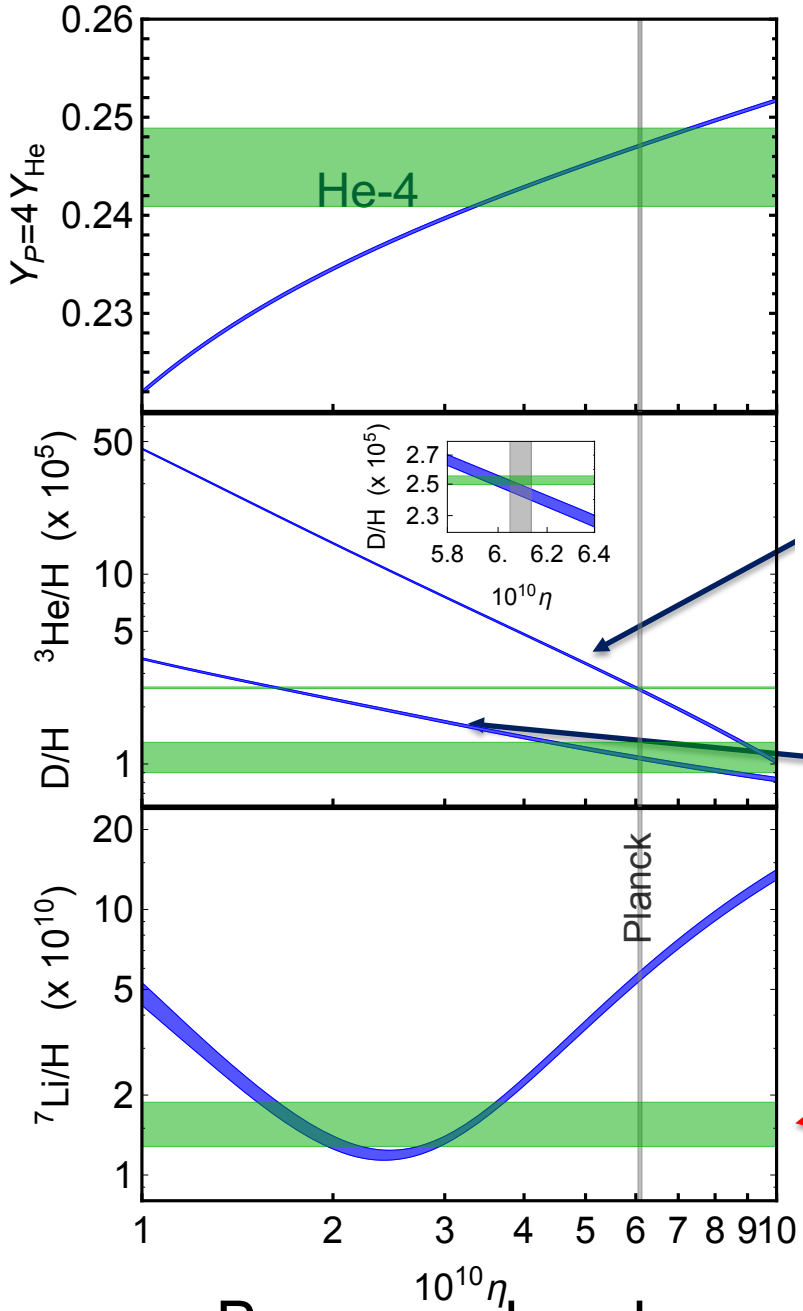


Public BBN codes:

PRIMAT

AlterBBN

PArthENoPE



Baryons abundance

Aver et al. 2020

$$Y_p = 0.2453 \pm 0.0034$$

1.4 %

Deuterium

$$\mathrm{D/H} = (2.527 \pm 0.030) \times 10^{-5}$$

1.2 %

Cooke et al. 2016

He-3

Li-7

Lithium problem

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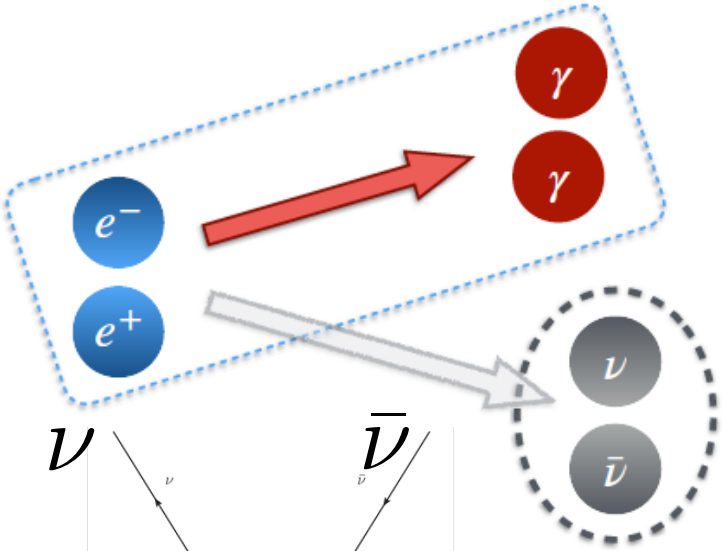
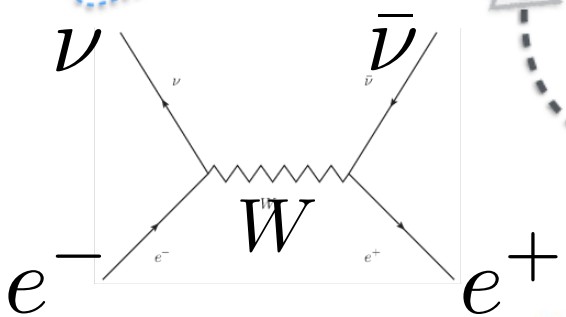
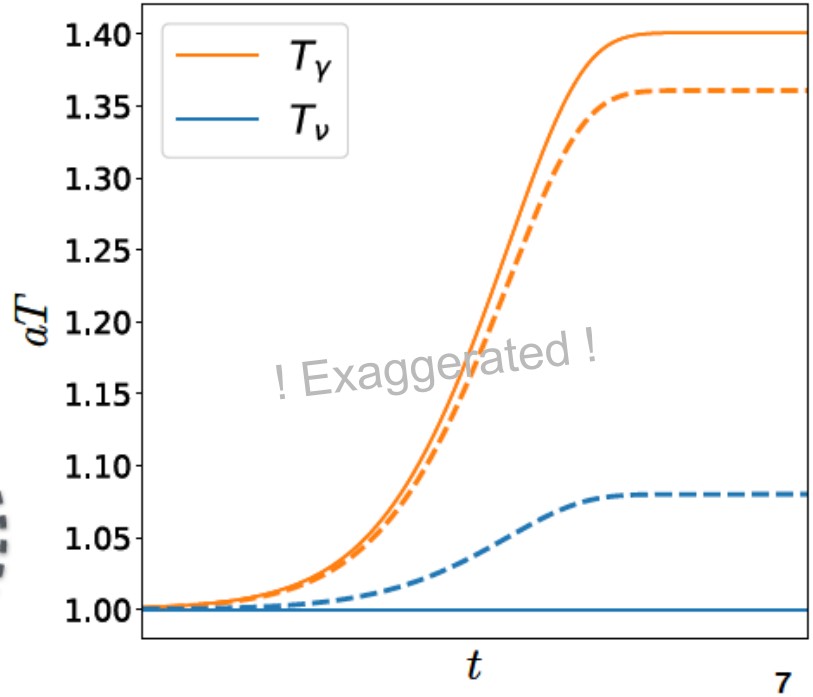
Beyond the instantaneous decoupling approximation

- Overlap between decoupling and $e^{\pm}$ annihilations

$\Longrightarrow$ smaller T_γ and increased T_ν







definition

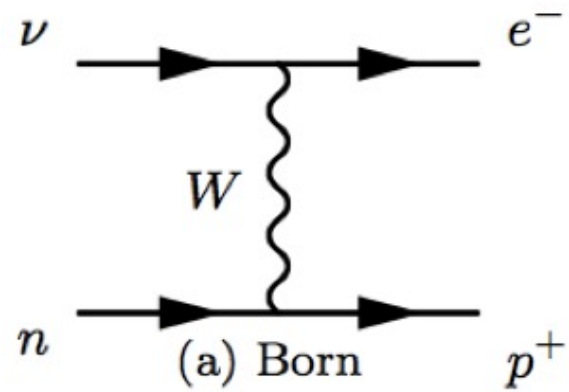
Froustey et al. 2020

$$\rho_{\rm R} = \rho_\nu + \rho_\gamma = \rho_\gamma \left(1 + \frac{7}{8} N_{\rm eff} \left(\frac{4}{11}\right)^{4/3}\right)$$

$$\boxed{N_{\rm eff} = 3.0440}$$

❑ Interaction Hamiltonian

$$\mathcal{H}_I = \frac{G_F}{\sqrt{2}} J^{\mu}_{e\nu} J_{pn,\mu}$$



(a) Born

$$J^{\mu}_{e\nu} = \bar{\boldsymbol{\nu}}\gamma^{\mu}(1-\gamma^5)\mathbf{e}$$

$$J^{\mu}_{pn} = V_{ud}\,\bar{\mathbf{p}}\left(\gamma^{\mu}(1-g_A\gamma^5) + \mathrm{i}\frac{f_{\mathrm{wm}}}{m_N}2\Sigma^{\mu\nu}q_{\nu}\right)\mathbf{n}$$

CKM angle

Axial current coupling

Weak-Magnetism

❑ BORN approximation

Simple integral on electron momentum :

$$\overline{\Gamma}_{n\to p} = \overline{\Gamma}_{n\to p+e} + \overline{\Gamma}_{n+e\to p}$$

$$\boxed{= K\int_0^\infty p^2 \mathrm{d}p[\chi_+(E) + \chi_+(-E)]}$$

$$K = \frac{4G_F^2 V_{ud}^2 (1+3g_A^2)}{(2\pi)^3}$$

CKM angle

$$V_{ud} = 0.97420(20)$$

Axial coupling

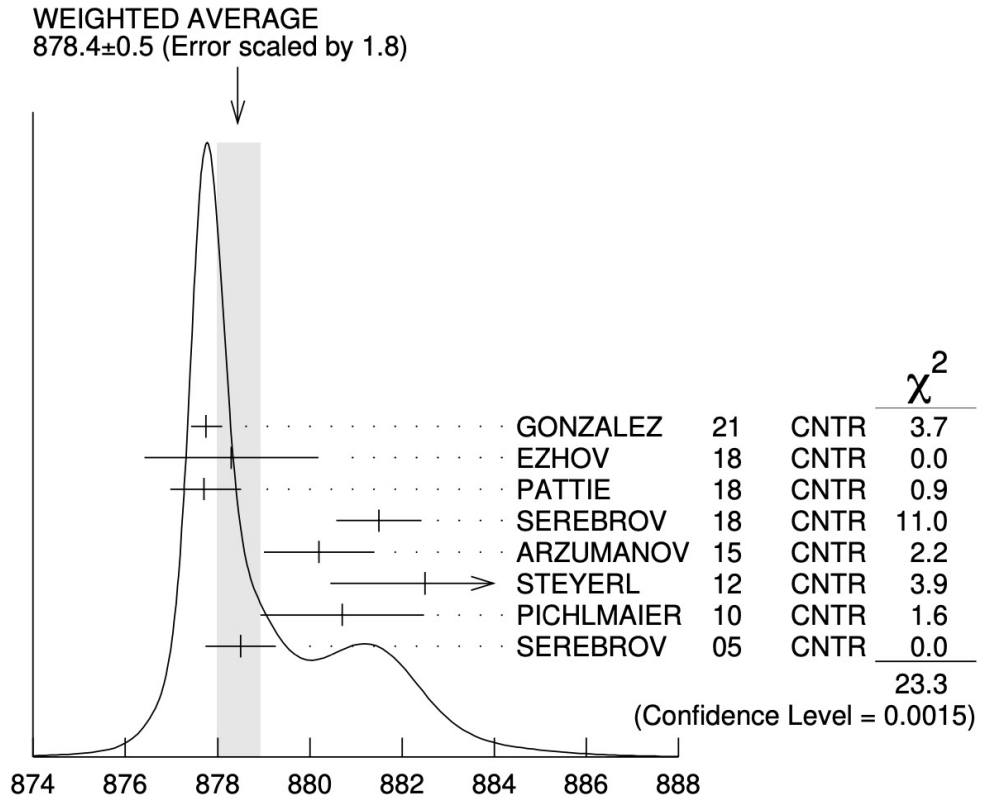
$$g_A = 1.2723(23)$$

Neutron lifetime as a proxy

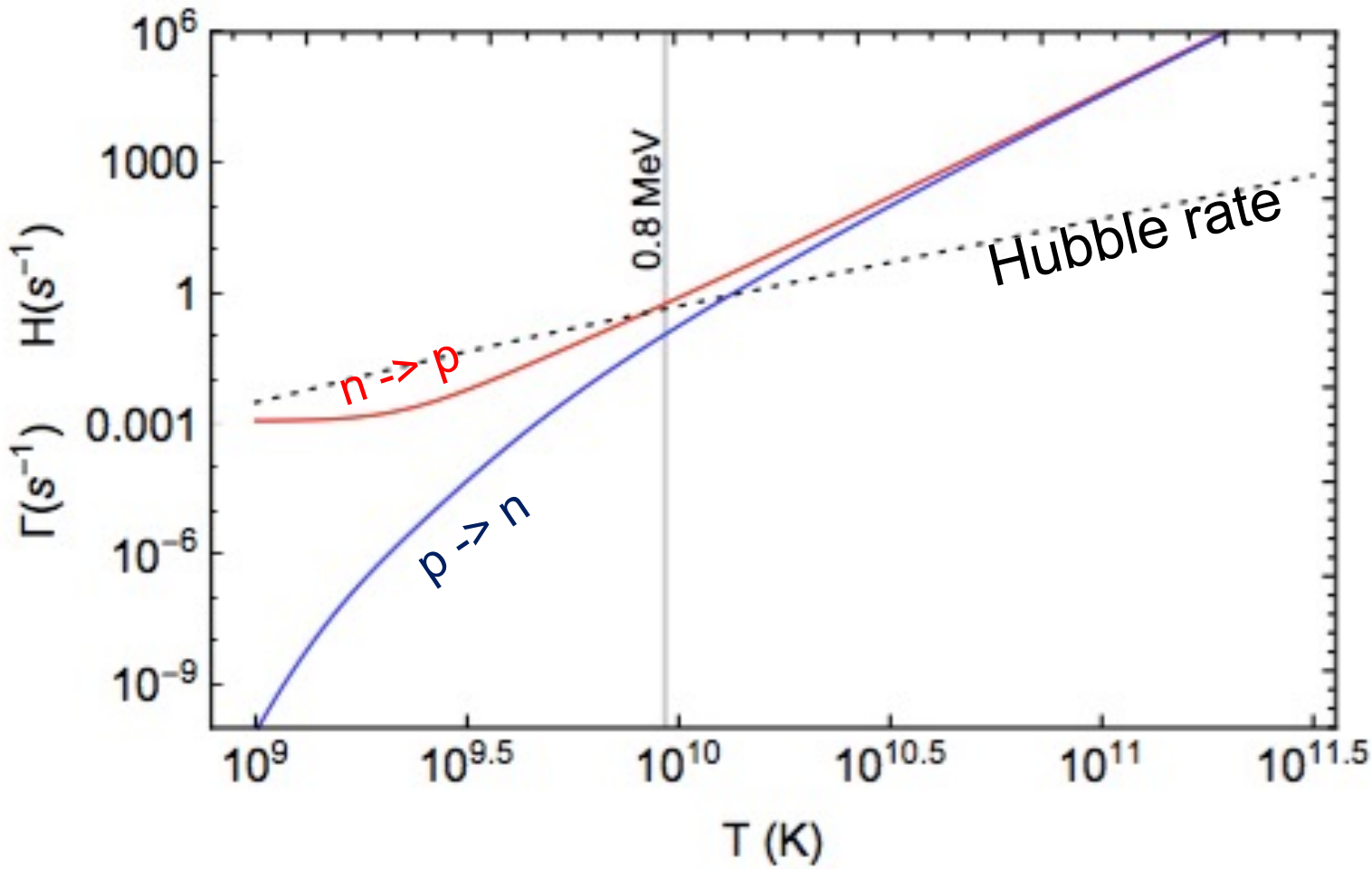
$$K = 1/(\tau_n \lambda_0 m_e^5) \qquad \lambda_0 \simeq 1.75474$$

$$\tau_n \simeq 879.4 \pm 0.6\,\mathrm{s} \qquad \boxed{\tau_n = 878.4 \pm 0.5\,\mathrm{s}}$$

PDG 2022

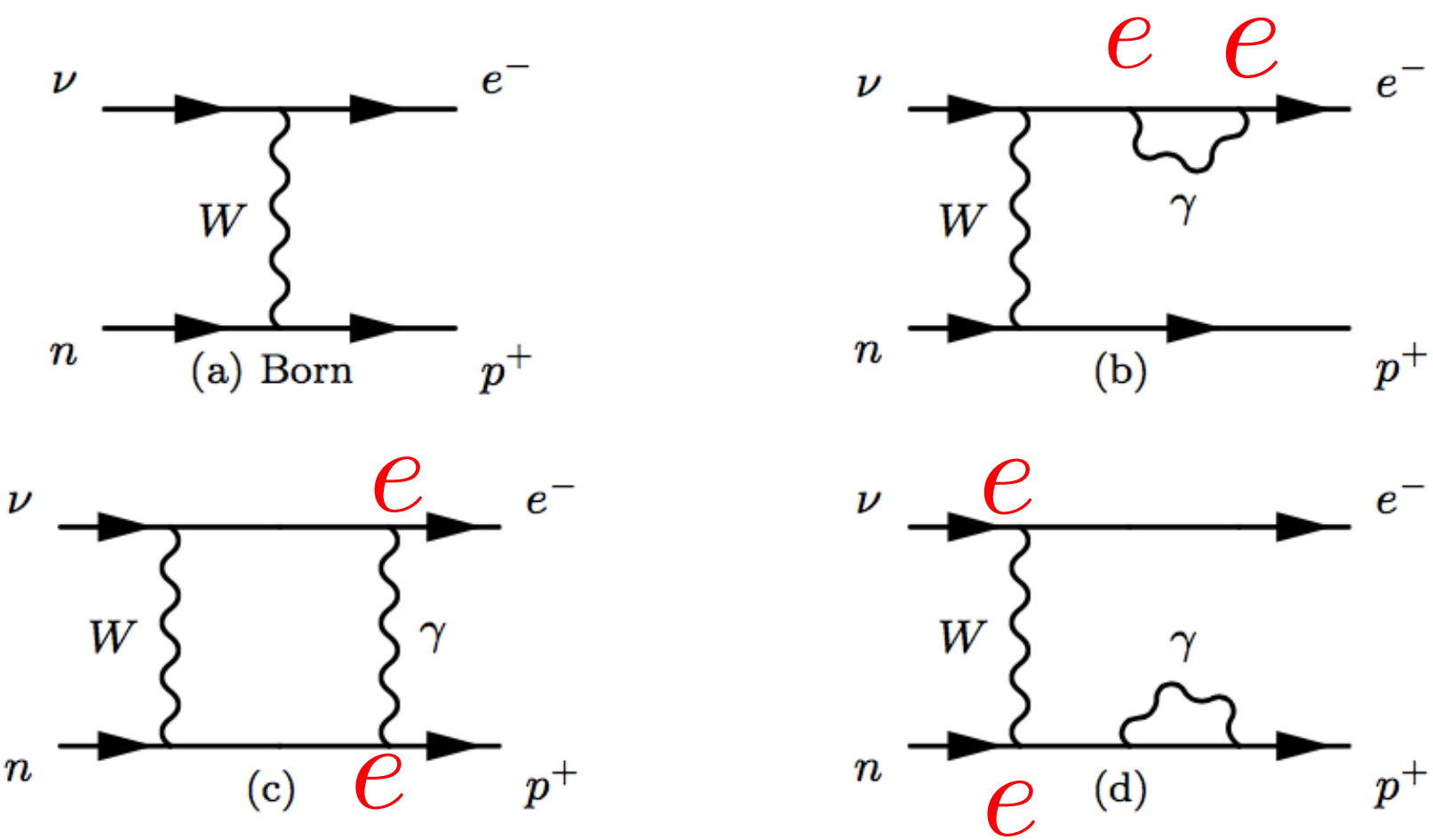


❑ BORN approximation rates vs Hubble rate

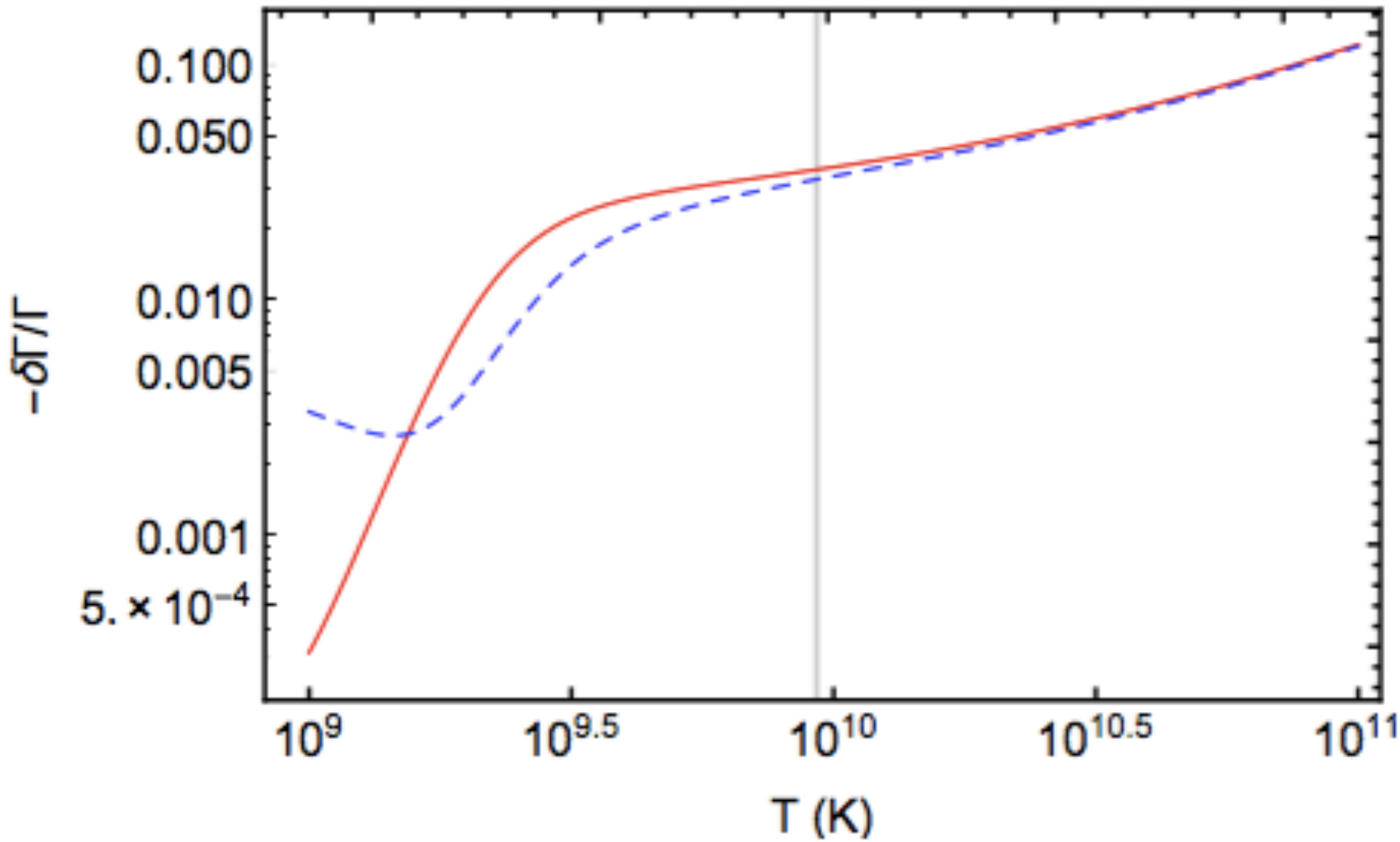


❑ Radiative corrections

$$\frac{e^2}{4\pi} = \alpha_{\mathrm{FS}} \simeq \frac{1}{137}$$



❑ Total corrections



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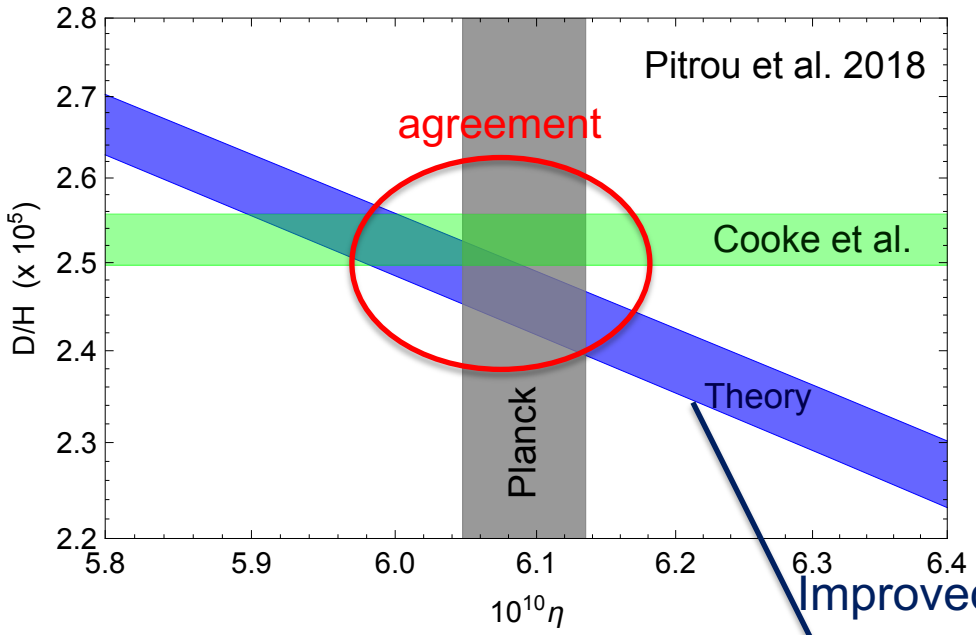
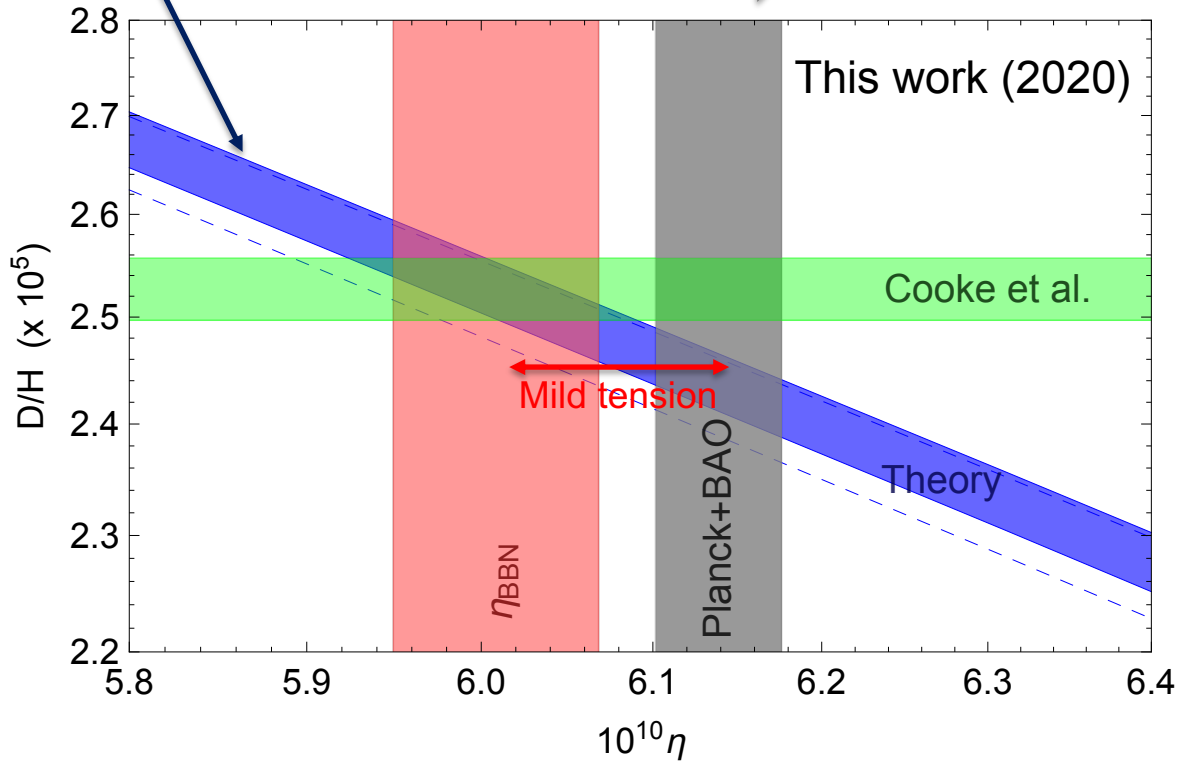


Improved nuclear rates

Slightly better constraints from CMB



A new tension in the cosmological model from primordial deuterium?

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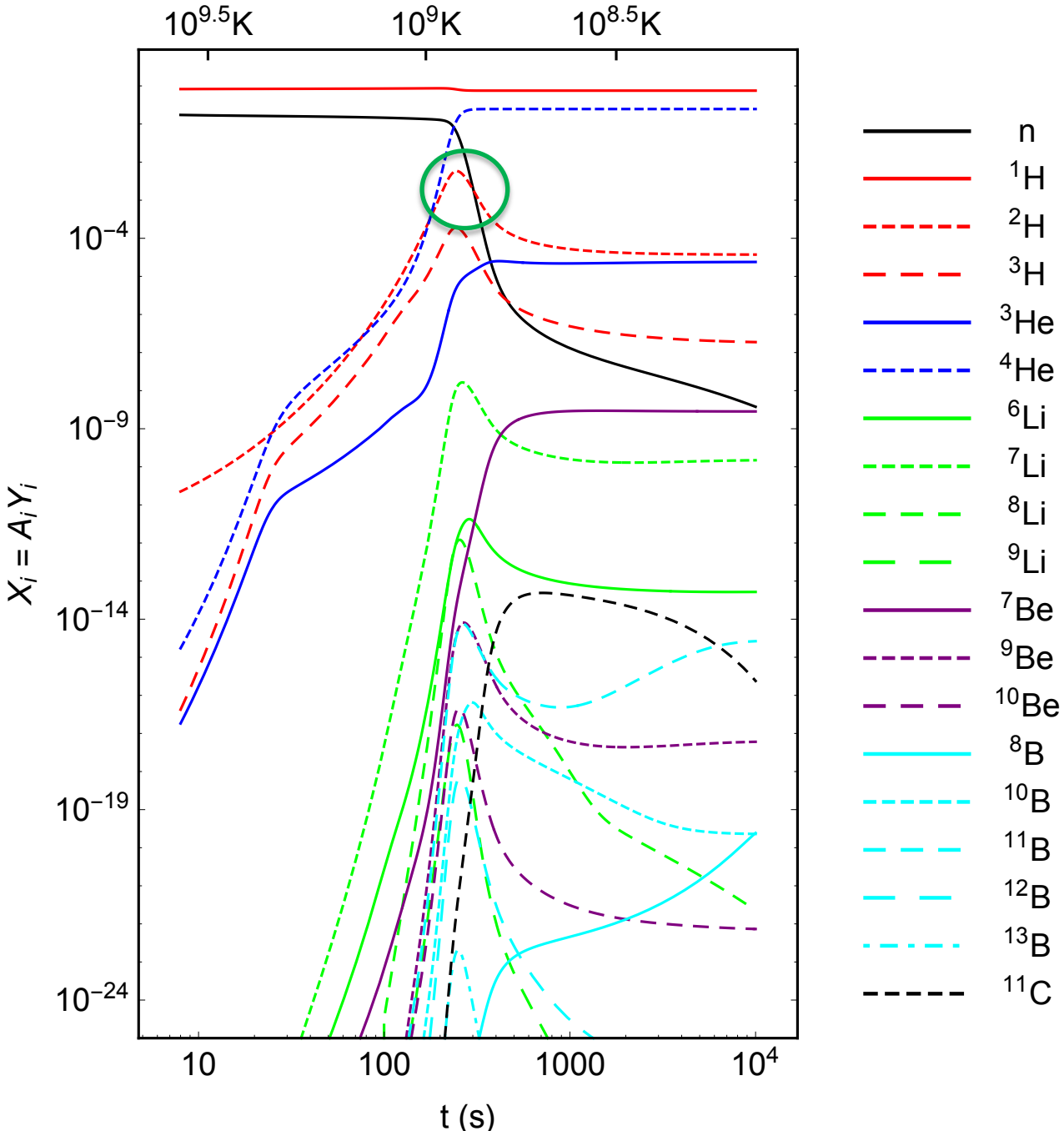
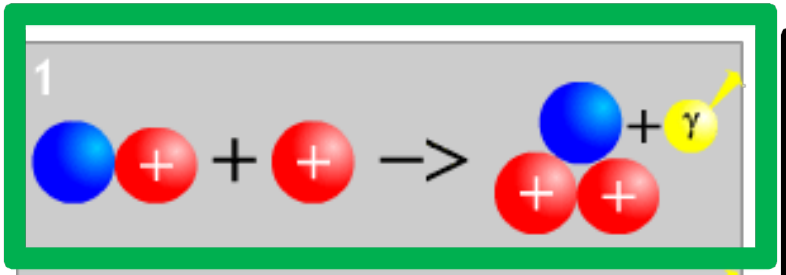
Primordial Deuterium after LUNA: concordances and error budget

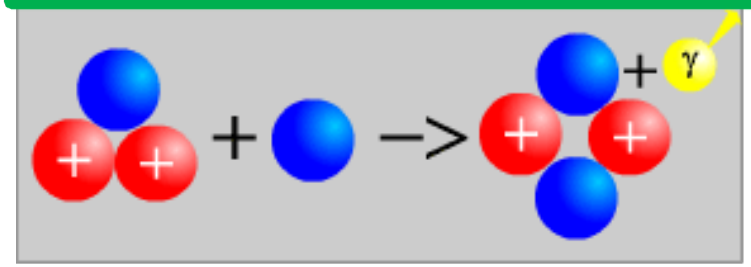
Ofelia Pisanti, Gianpiero Mangano, Gennaro Miele, and Pierpaolo Mazzella
Dipartimento di Fisica E. Pancini, Università di Napoli Federico II, and INFN, Sezione di Napoli, Via Cintia, I-80126 Napoli, Italy

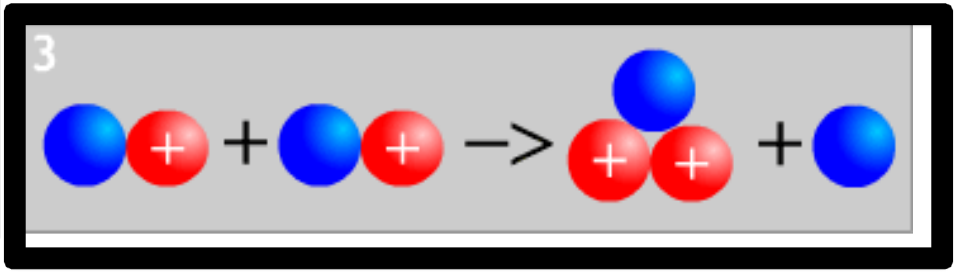
after the LUNA results, the value of Deuterium is quite precisely fixed, and points to a value of the baryon density in excellent agreement with the Planck result,

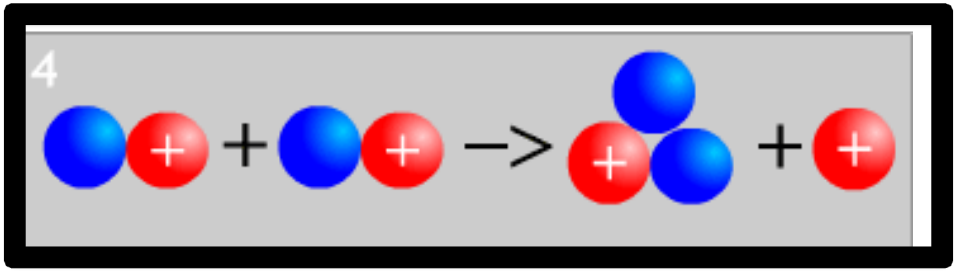

$10^{9.5}$K
10^{9}K
$10^{8.5}$K
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
$X_i = A_i Y_i$
10
100
1000
10^{4}
t (s)
n
^{1}H
^{2}H
^{3}H
^{3}He
^{4}He
^{6}Li
^{7}Li
^{8}Li
^{9}Li
^{7}Be
^{9}Be
^{10}Be
^{8}B
^{10}B
^{11}B
^{12}B
^{13}B
^{11}C

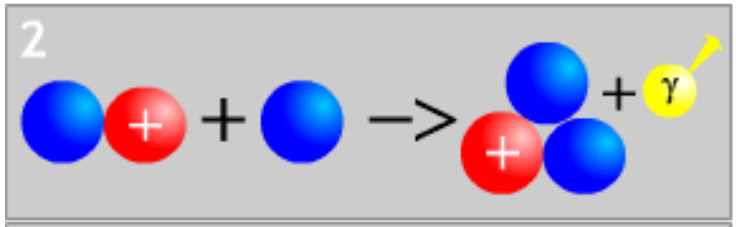
Main reactions for deuterium

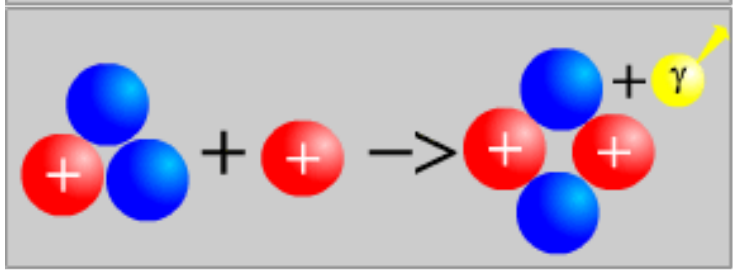


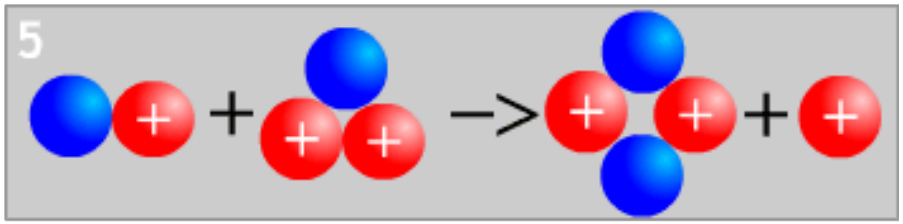








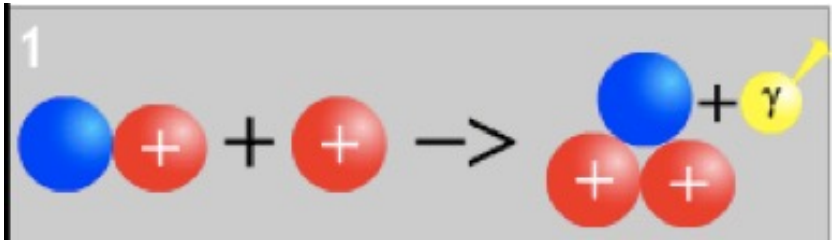




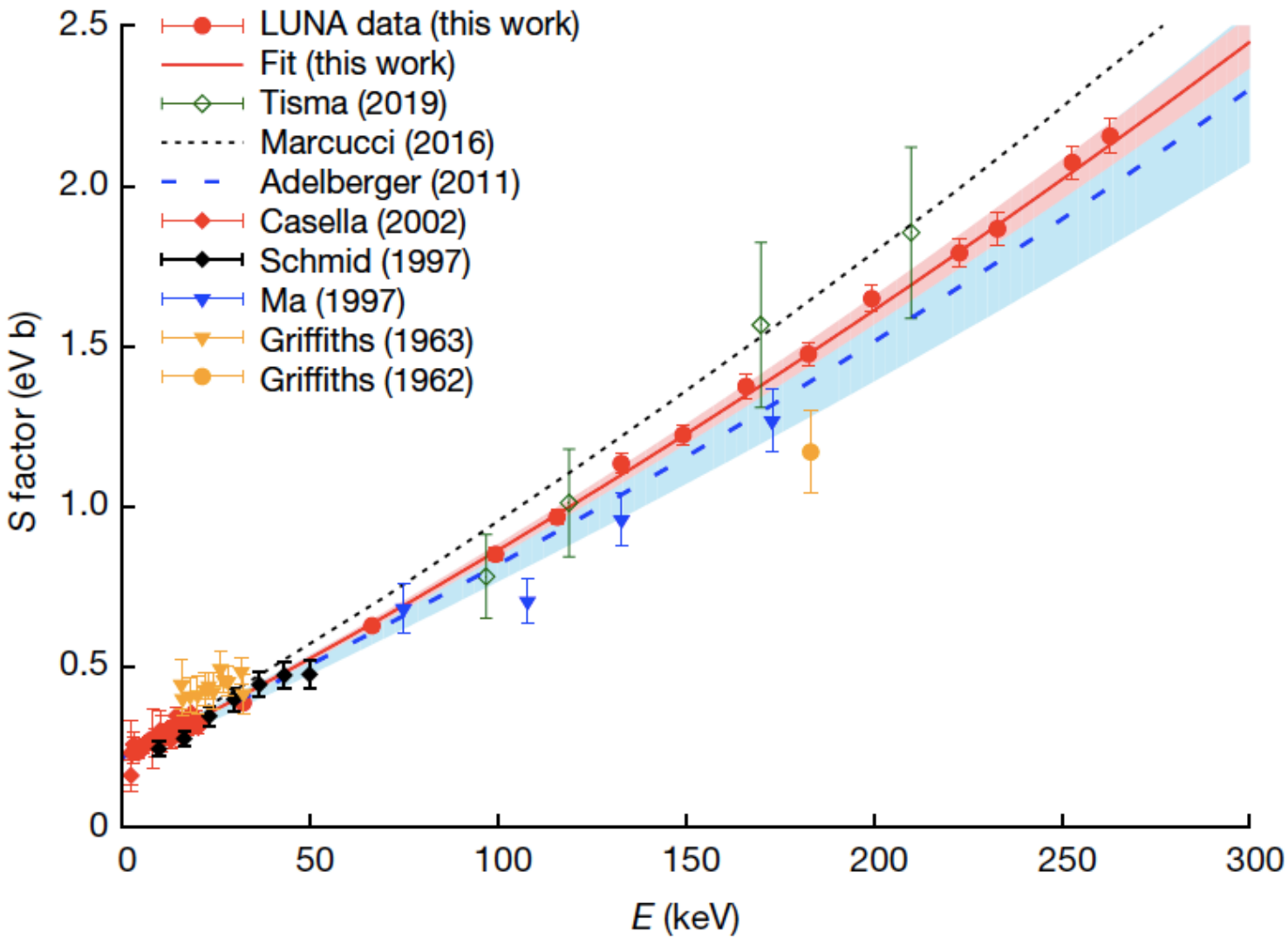
Final deuterium sensitivity

$$\frac{\Delta(\mathrm{D/H})}{\mathrm{D/H}} = -0.32 \times \frac{\Delta\langle\sigma v\rangle_{\mathrm{d(p,\gamma)^3He}}}{\langle\sigma v\rangle_{\mathrm{d(p,\gamma)^3He}}} - 0.54 \times \frac{\Delta\langle\sigma v\rangle_{\mathrm{d(d,n)^3He}}}{\langle\sigma v\rangle_{\mathrm{d(d,n)^3He}}} - 0.46 \times \frac{\Delta\langle\sigma v\rangle_{\mathrm{d(d,p)^3H}}}{\langle\sigma v\rangle_{\mathrm{d(d,p)^3H}}}$$

$D(p,\gamma)^3He$, $D(d,n)^3He$ and $D(d,p)^3H$ reaction rates need to be known at a few % level to match the 1.6% precision on observations!


1
+
+
->
+
γ

2020


LUNA data (this work)
Fit (this work)
Tisma (2019)
Marcucci (2016)
Adelberger (2011)
Casella (2002)
Schmid (1997)
Ma (1997)
Griffiths (1963)
Griffiths (1962)
S factor (eV b)
E (keV)
0
0.5
1.0
1.5
2.0
2.5
0
50
100
150
200
250
300

The Impact of New $d(p,\gamma)^3$He Rates on Big Bang Nucleosynthesis

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Department of Physics, University of Illinois, Urbana, IL 61801

Keith A. Olive

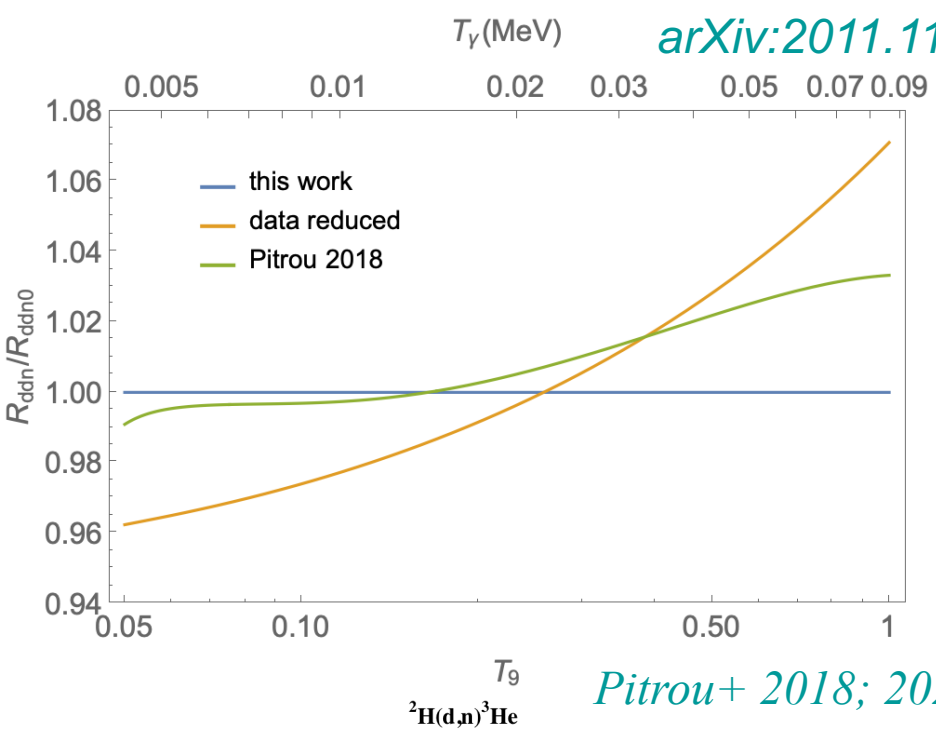
William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA

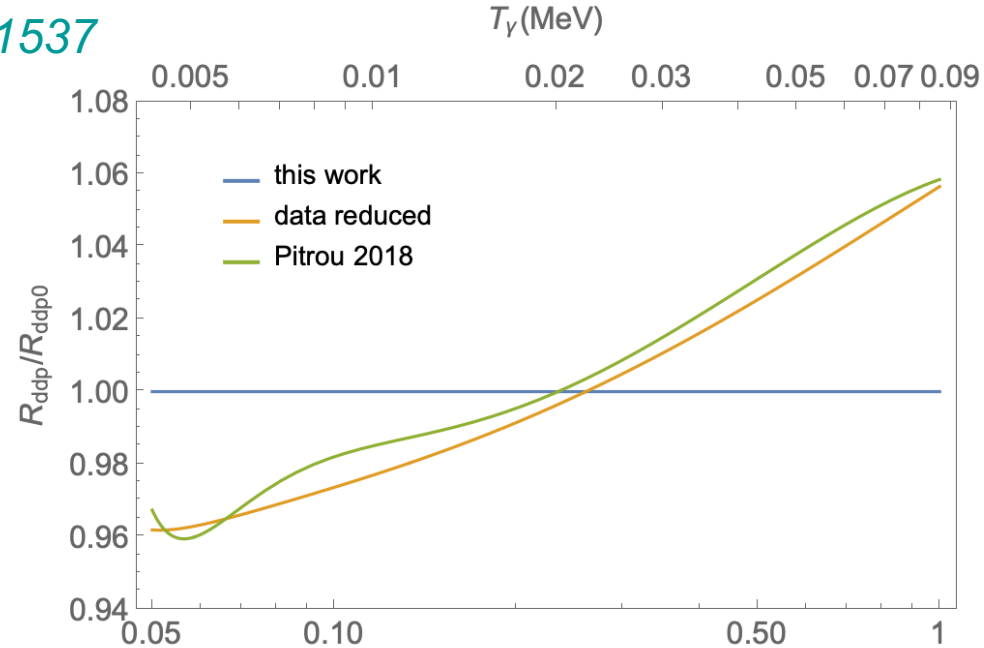
Brian D. Fields

Departments of Astronomy and of Physics, University of Illinois, Urbana, IL 61801

Finally, we note that the observed deuterium abundance continues to be more precise than the BBN+CMB prediction, whose error budget is now dominated by $d(d,n)^3$He and $d(d,p)^3$H.

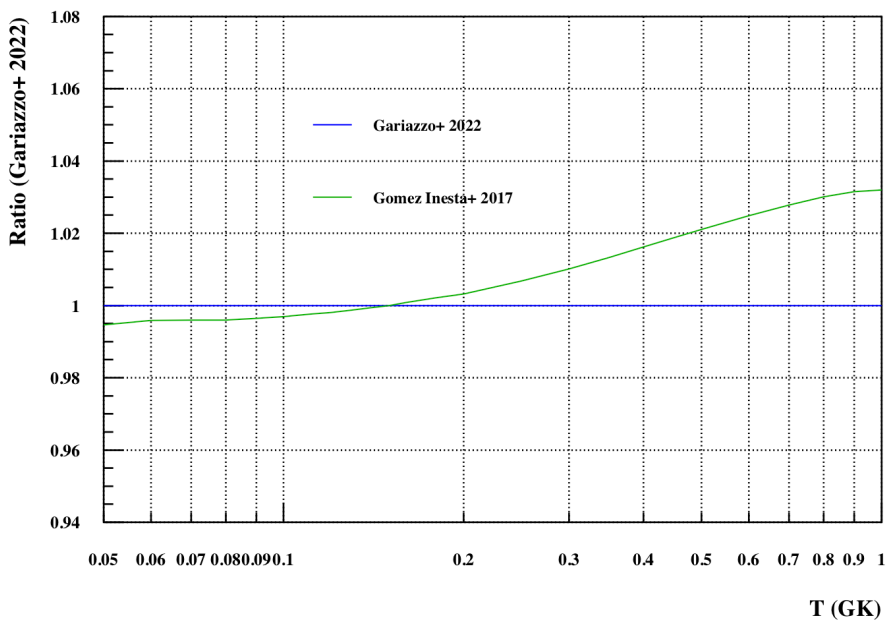
Pisanti+ arXiv:2011.11537



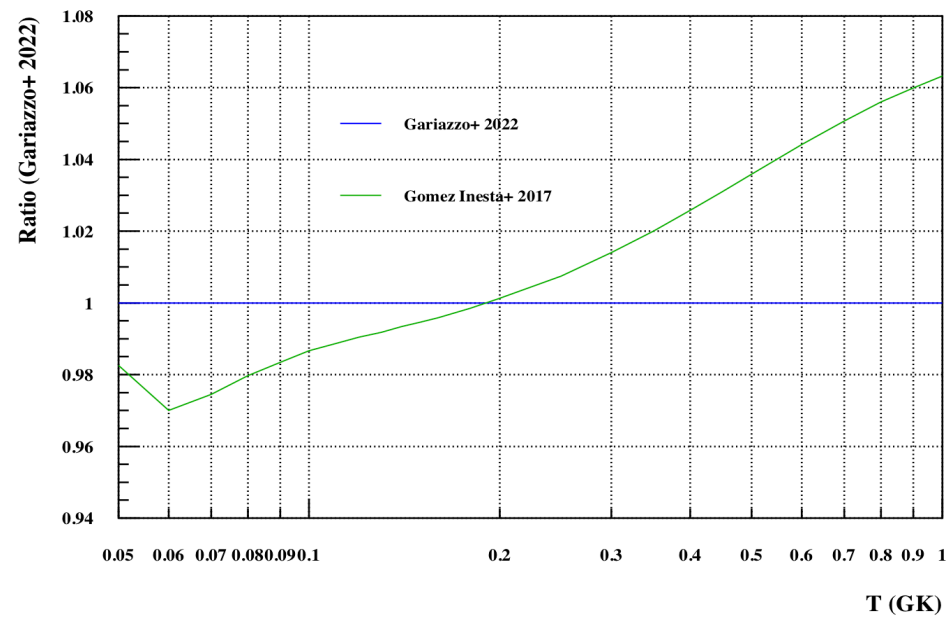


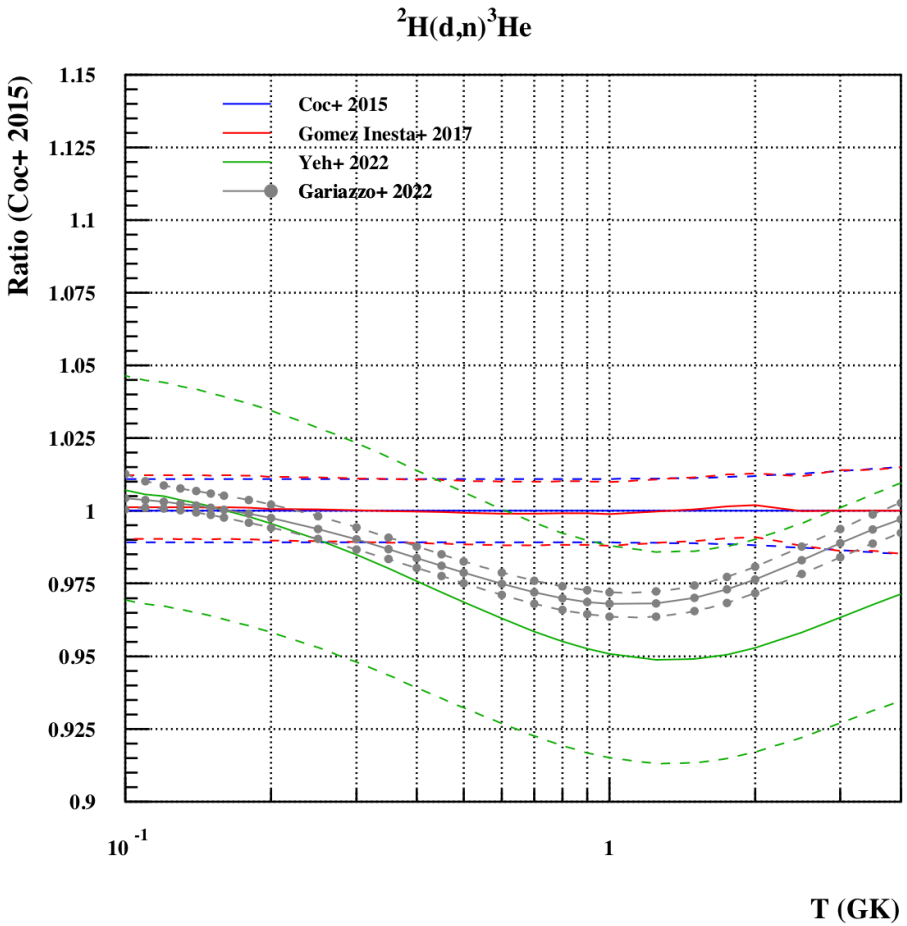
Pitrou+ 2018; 2021 = Gómez Iñesta+ 2017

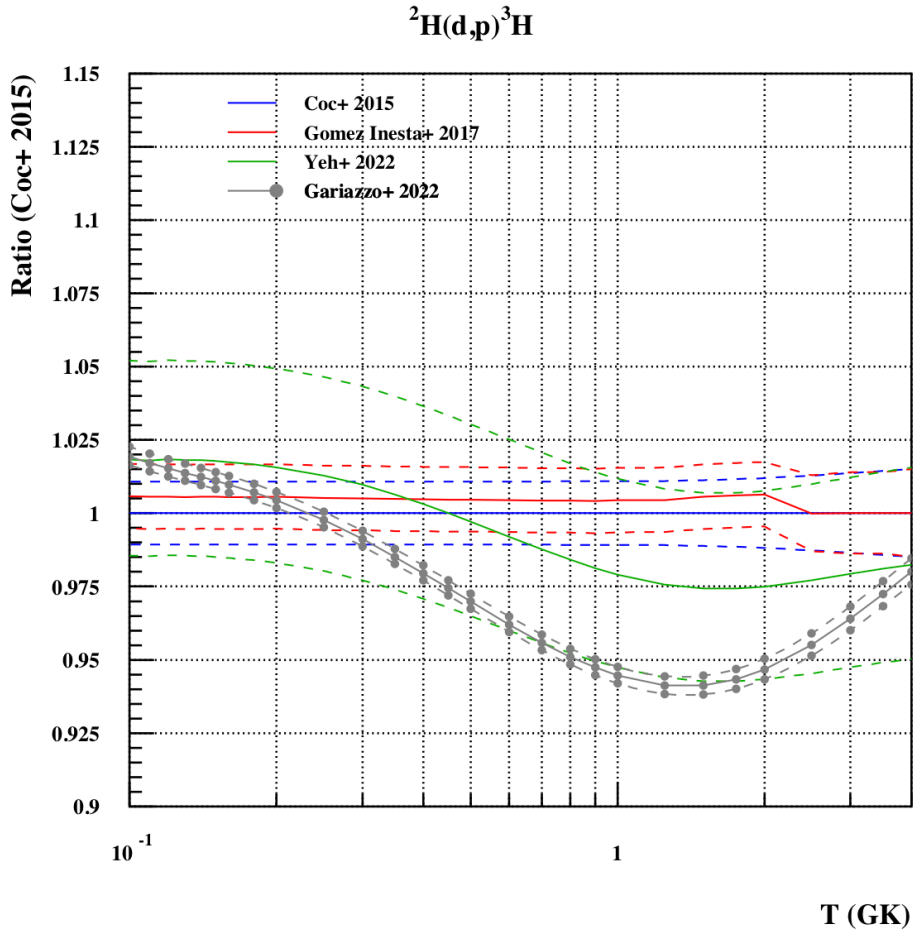
^{2}H(d,n)^{3}He

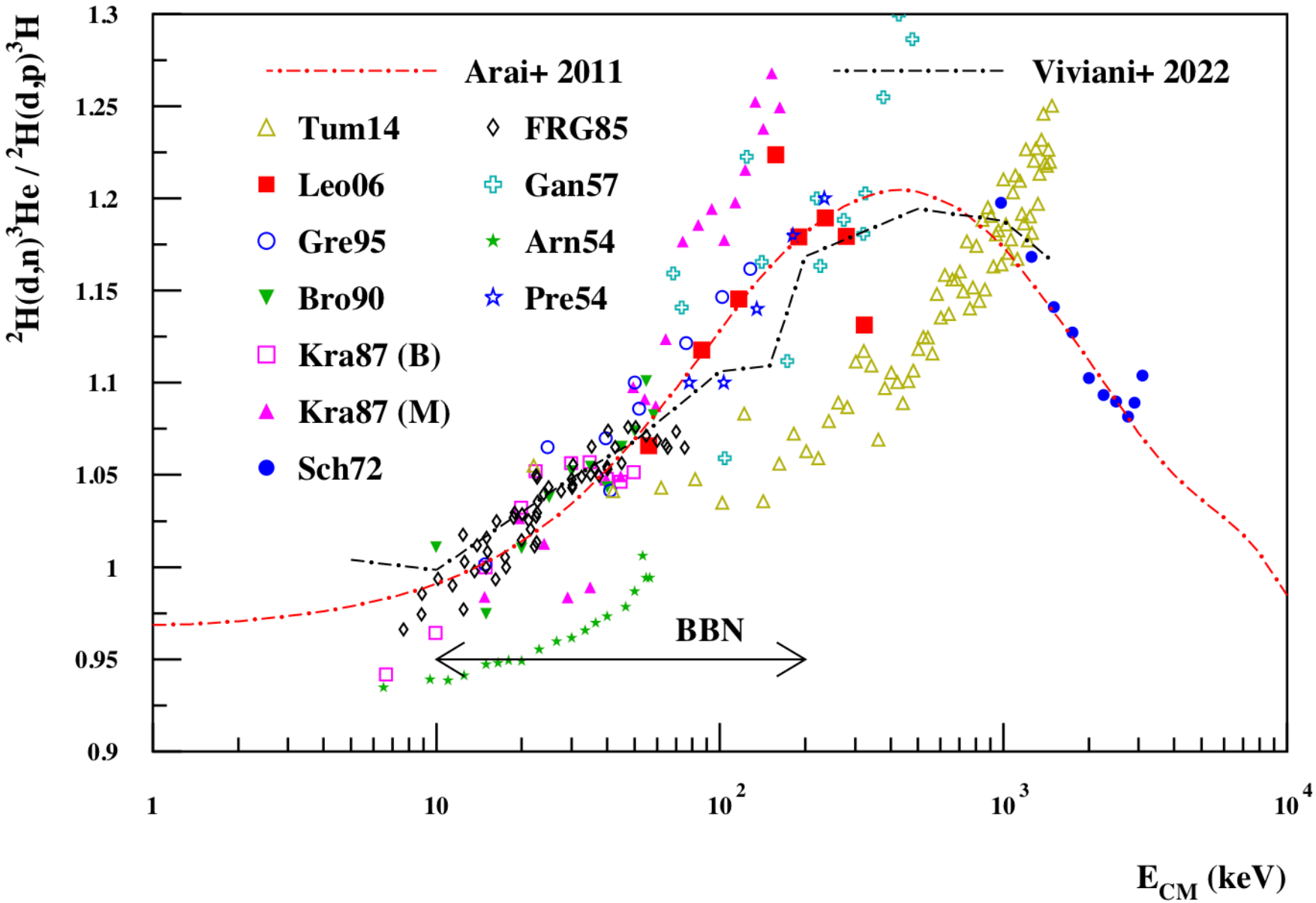


^{2}H(d,p)^{3}He



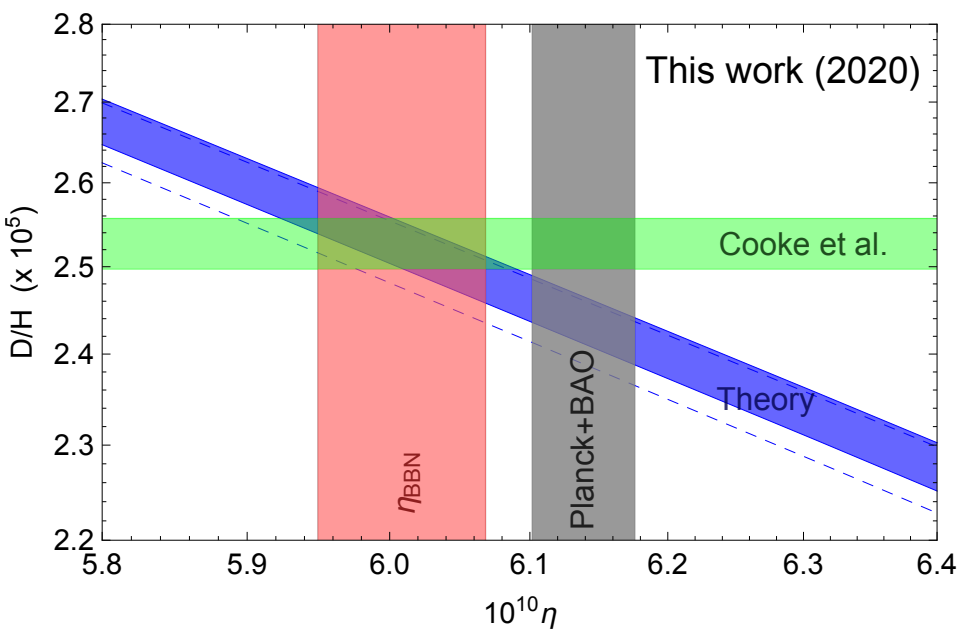

^{2}H(d,n)^{3}He
Ratio (Coc+ 2015)
Coc+ 2015
Gomez Inesta+ 2017
Yeh+ 2022
Gariazzo+ 2022
1.15
1.125
1.1
1.075
1.05
1.025
1
0.975
0.95
0.925
0.9
10 -1
1
T (GK)

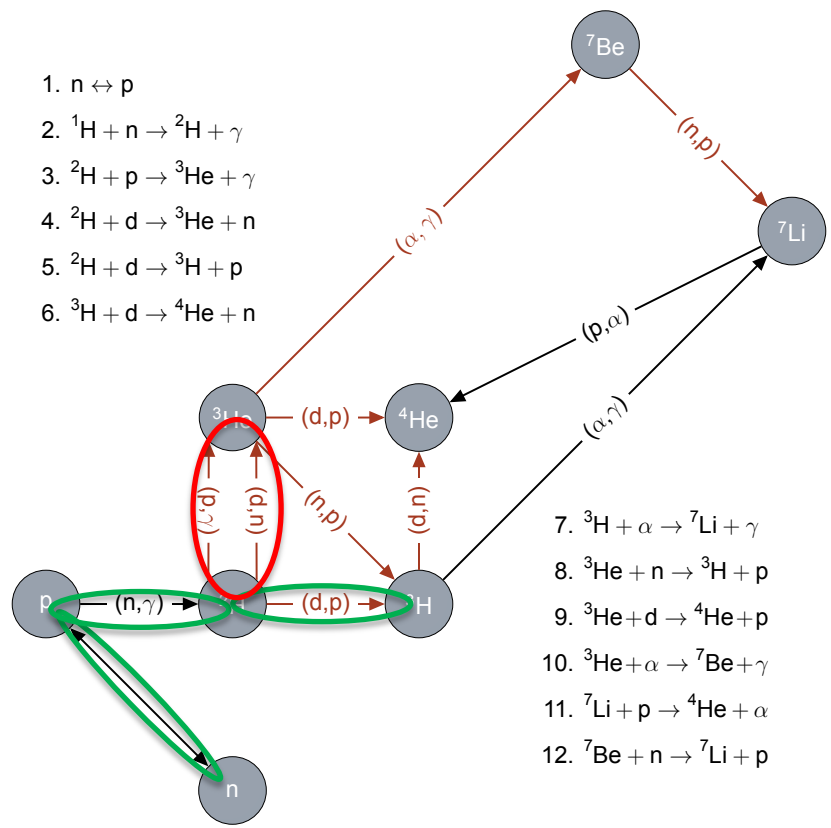

^{2}H(d,p)^{3}H
Ratio (Coc+ 2015)
Coc+ 2015
Gomez Inesta+ 2017
Yeh+ 2022
Gariazzo+ 2022
1.15
1.125
1.1
1.075
1.05
1.025
1
0.975
0.95
0.925
0.9
10 -1
1
T (GK)


Arai+ 2011
Viviani+ 2022
Tum14
FRG85
Leo06
Gan57
Gre95
Arn54
Bro90
Pre54
Kra87 (B)
Kra87 (M)
Sch72
BBN
$^2H(d,n)^3He$ / $^2H(d,p)^3H$
E_{CM} (keV)
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0.9
1
10
10^2
10^3
10^4

Conclusion

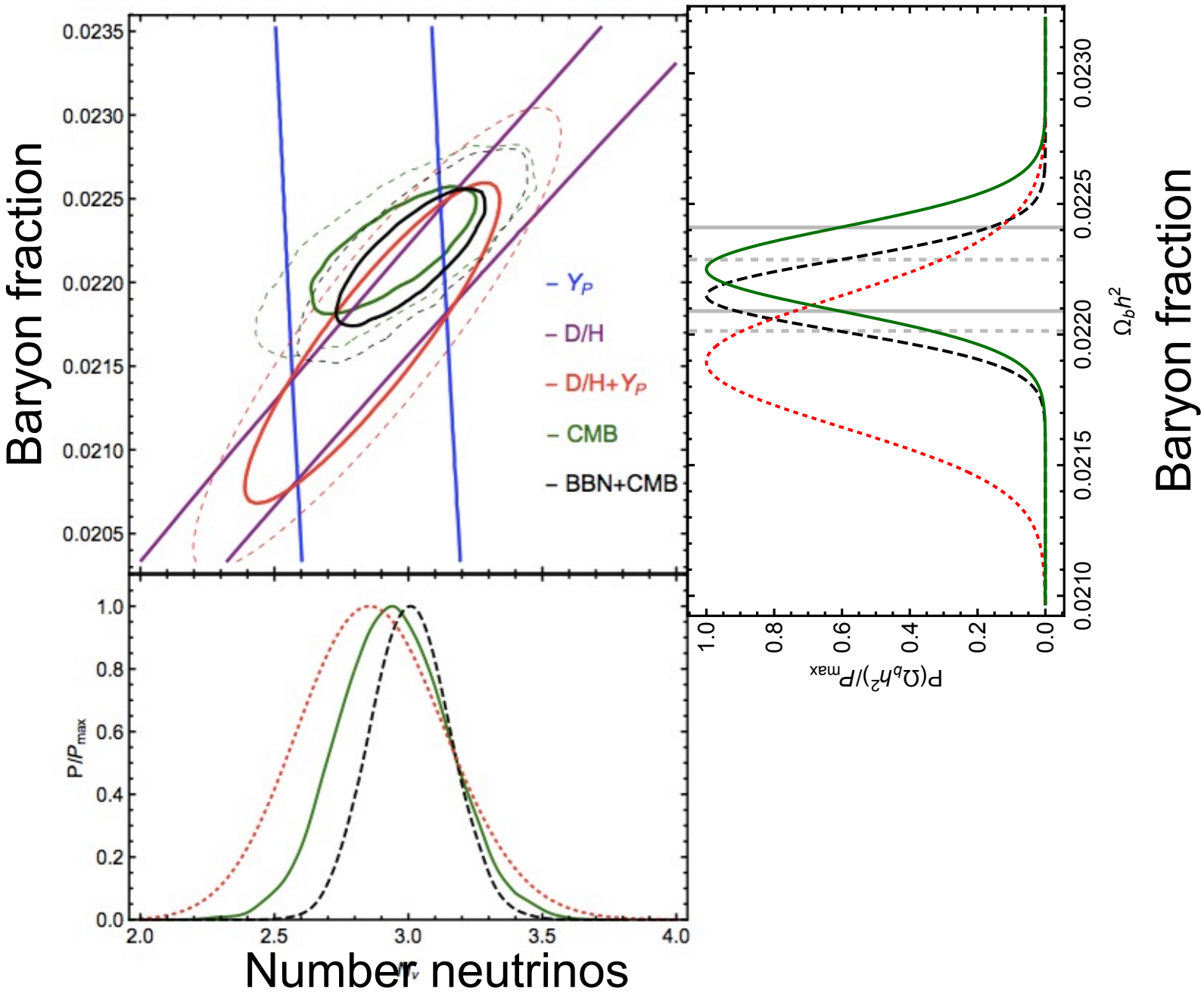
- Weak interactions (hence neutrons, hence helium) under control
- Need to measure d+d rates in the BBN range of energies
- Independent measurment of D abundance needed



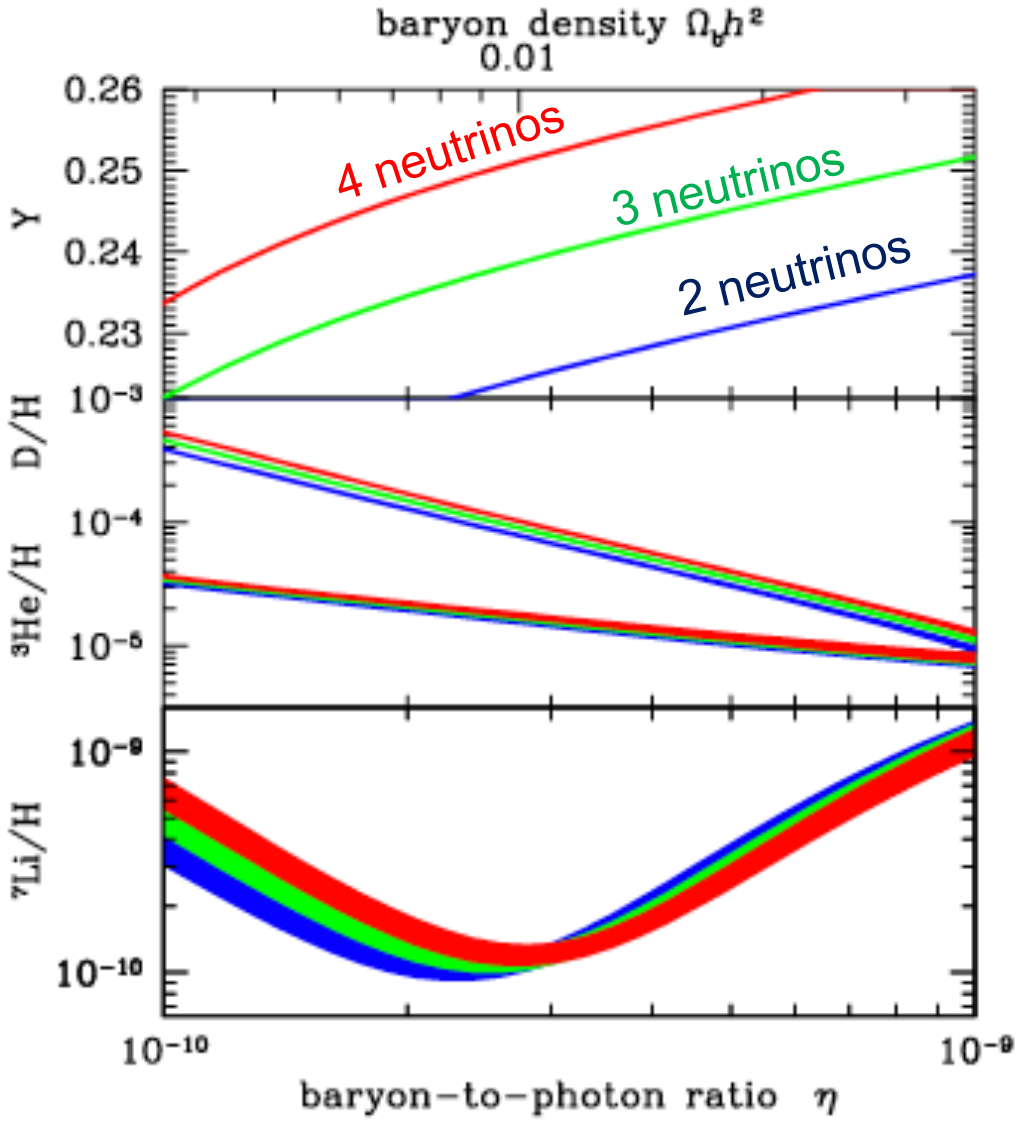


SUPPL MATERIAL

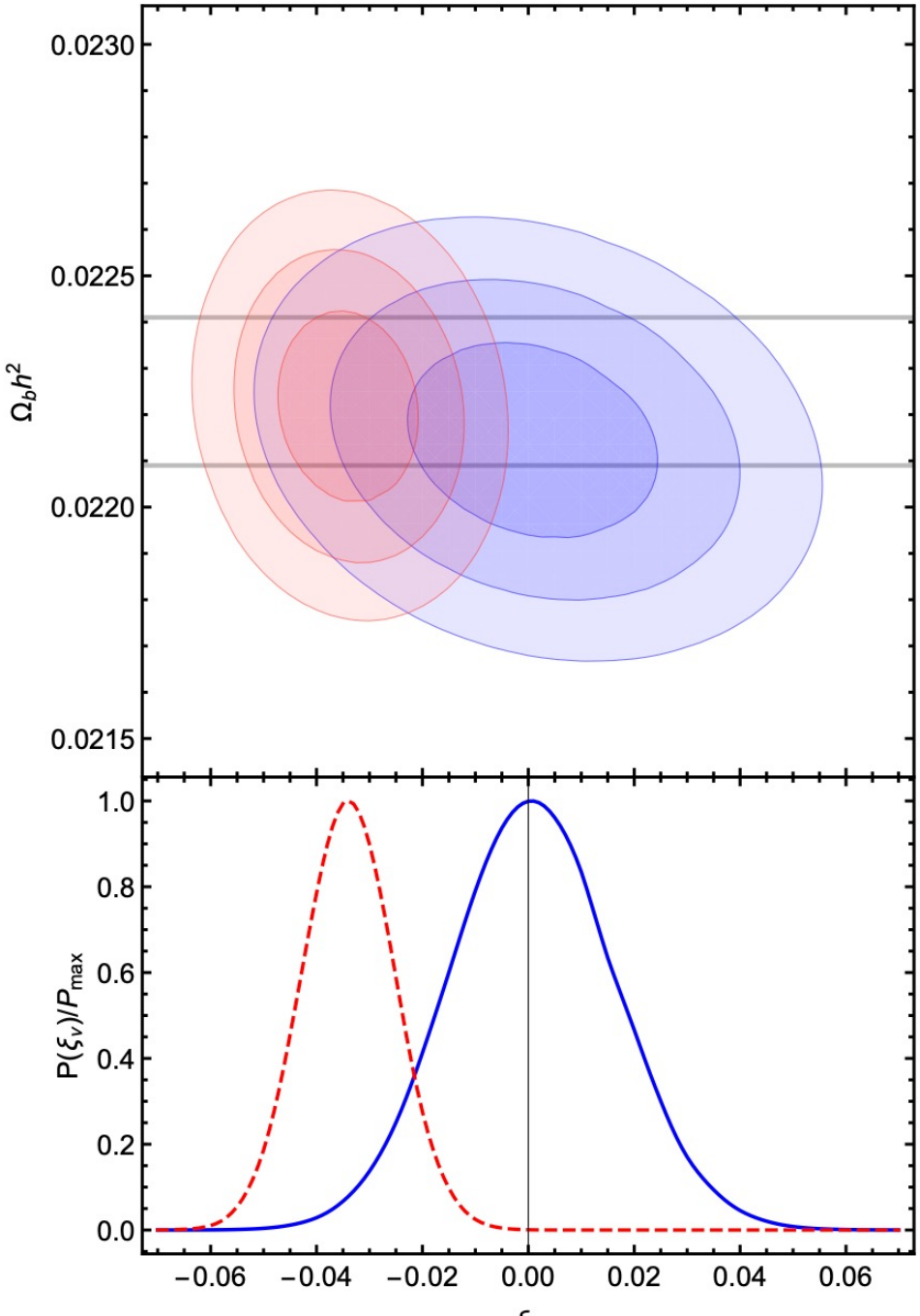
Combined constraints



❑ Dependance on number of neutrino species



Cyburt et al. 2015


0.0230
0.0225
0.0220
0.0215
$\Omega_b h^2$
1.0
0.8
0.6
0.4
0.2
0.0
$P(\xi_v)/P_{max}$
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06